Stellingen
toegevoegd aan het proefschrift

Design considerations
for very high speed
electron beam writing

doors Jan Simons
The HISSEL system can be built on the basis of this thesis. It will have a writing speed of about 1 cm²/s.

Application of Jansen's theory to high brightness electron sources can only be expected when strongly varying field strengths and strongly varying beam current densities are taken into account.

Models attempt to describe realistic situations in nature. Therefore science always lags behind nature.

In vacuum, capacitance only depends on the form and size of conductors. Therefore capacitive sensors are very well suited for the measurement of geometric variables.

Physics is an exact science in spite of the fact that it is based on the intuition and associative abilities of physicists.

The use of calculators in high school has led to more realistic education. Now the students do not only make computational errors, they also face typing and read-out errors.

Most European people can learn the language Esperanto much more easily than English. Therefore Esperanto could form an independent connection between the different countries in the European Community, which would allow for the preservation of the national cultures of all countries.

Exponential growth of the economy made it possible for the economically strong countries to receive more money from the third world countries than was ever invested in them. Therefore it is not correct to think that the economically strong countries have a right to influence the economies in the third world on the basis of the large debts of these countries.
1

Dit proefschrift geeft voldoende basis voor het bouwen van het HISEL systeem, dat een schrijfssnelheid heeft van 1 cm³/s.

2

Brede toepassing van Jansen's theorie op zeer heldere elektronenbronnen is alleen te verwachten als rekening wordt gehouden met sterk veranderende veldsterkten en sterk veranderende stroomdichtheden.

3

Modellen beschrijven de werkelijkheid. In die zin is de wetenschap altijd achter bij de natuur.

4

In vacuum wordt capaciteit alleen door de vorm en afmeting van geleiders bepaald. Daarom lenen capacitiève sensoren zich bijzonder goed voor het meten van geometrische variabelen.

5

Natuurkunde is een exacte wetenschap ondanks dat zij stoelt op de intuïtie en het associatievermogen van haar beoefenaars.

6

Het gebruik van rekenmachines in het onderwijs heeft geleid tot meer realiteitszin, aangezien de leerlingen en studenten nu naast rekenfouten ook type- en uitleesfouten maken.

7

De taal Esperanto is voor vrijwel alle Europeanen veel gemakkelijker te leren dan het Engels. Daarom zou het Esperanto in de Europese Gemeenschap de plaats in kunnen nemen van een onafhankelijke schakel tussen de verschillende landen, die het mogelijk maakt dat de nationale culturen bewaard blijven.

8

Exponentiële groei van de economie heeft het mogelijk gemaakt dat de westere landen meer geld ontvangen uit de derde wereld dan zij er ooit hebben ingestopt. Het is daarom verkeerd te denken dat de westere landen enig recht op invloed in de derde-wereld-economieën kunnen onlenen aan de schulden van de derde wereld.
Propositions

added to the thesis

Design considerations
for very high speed
electron beam writing

by Jan Simons
DESIGN CONSIDERATIONS FOR
VERY HIGH SPEED
ELECTRON BEAM WRITING
Proefschrift

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op gezag van de Rector Magnificus, Prof. drs. P.A. Schenck,
in het openbaar te verdedigen ten overstaan van een
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Jan Simons

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<th>unit</th>
<th>meaning</th>
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<tbody>
<tr>
<td>a</td>
<td>-</td>
<td>relative shape area</td>
</tr>
<tr>
<td>a_v</td>
<td>m^2</td>
<td>minimum shape area</td>
</tr>
<tr>
<td>A</td>
<td>m^2</td>
<td>total wafer area</td>
</tr>
<tr>
<td>B_r</td>
<td>A/cm^2/sr/V</td>
<td>reduced beam brightness</td>
</tr>
<tr>
<td>c</td>
<td>-</td>
<td>area coverage (percentage of total area to fill)</td>
</tr>
<tr>
<td>C</td>
<td>m</td>
<td>constant (for spherical and chromatic aberration)</td>
</tr>
<tr>
<td>d_c</td>
<td>m</td>
<td>channel thickness</td>
</tr>
<tr>
<td>d_E</td>
<td>m</td>
<td>electrostatic deflector plate distance</td>
</tr>
<tr>
<td>D</td>
<td>m</td>
<td>minimum feature size</td>
</tr>
<tr>
<td>e</td>
<td>C</td>
<td>electron charge</td>
</tr>
<tr>
<td>E</td>
<td>eV</td>
<td>electron (beam) energy</td>
</tr>
<tr>
<td>f</td>
<td>-</td>
<td>beam intensity profile</td>
</tr>
<tr>
<td>F</td>
<td>m</td>
<td>focal length of a lens</td>
</tr>
<tr>
<td>g</td>
<td>-</td>
<td>circuit constant</td>
</tr>
<tr>
<td>G</td>
<td>-</td>
<td>illumination constancy level</td>
</tr>
<tr>
<td>h</td>
<td>Js</td>
<td>Planck's constant</td>
</tr>
<tr>
<td>I</td>
<td>A</td>
<td>beam current</td>
</tr>
<tr>
<td>j</td>
<td>A/cm^2</td>
<td>beam current density</td>
</tr>
<tr>
<td>k</td>
<td>J/K</td>
<td>Boltzmann's constant</td>
</tr>
<tr>
<td>L</td>
<td>m</td>
<td>beam section length</td>
</tr>
<tr>
<td>m_e</td>
<td>kg</td>
<td>electron mass</td>
</tr>
<tr>
<td>M</td>
<td>-</td>
<td>transverse magnification (s: shaper to target ..)</td>
</tr>
<tr>
<td>N</td>
<td>-</td>
<td>number of electrons in a detail</td>
</tr>
<tr>
<td>N_s</td>
<td>-</td>
<td>total number of shots needed to write a pattern</td>
</tr>
<tr>
<td>N_v</td>
<td>-</td>
<td>number of pixels in a (variable-) shaped spot</td>
</tr>
<tr>
<td>NA</td>
<td>-</td>
<td>numerical aperture of the last (optical) lens</td>
</tr>
<tr>
<td>p</td>
<td>kgm/s</td>
<td>impulse of the electron</td>
</tr>
<tr>
<td>r</td>
<td>m</td>
<td>radius of the emitting area</td>
</tr>
<tr>
<td>R</td>
<td>m</td>
<td>electron beam landing position (dR positional distribution spread)</td>
</tr>
<tr>
<td>R_s</td>
<td>/s^2</td>
<td>data positional rate</td>
</tr>
<tr>
<td>S</td>
<td>m</td>
<td>beam emitting area</td>
</tr>
<tr>
<td>t</td>
<td>s</td>
<td>time</td>
</tr>
<tr>
<td>T_e</td>
<td>K</td>
<td>(electron) temperature of the emitter</td>
</tr>
<tr>
<td>U</td>
<td>V</td>
<td>beam voltage</td>
</tr>
<tr>
<td>v</td>
<td>m/s</td>
<td>electron speed</td>
</tr>
<tr>
<td>W</td>
<td>m^2/s</td>
<td>system writing speed</td>
</tr>
<tr>
<td>x</td>
<td>m</td>
<td>coordinate in image plane</td>
</tr>
<tr>
<td>y</td>
<td>m</td>
<td>coordinate in image plane</td>
</tr>
<tr>
<td>z</td>
<td>m</td>
<td>axial coordinate</td>
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### List of Greek Symbols

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<thead>
<tr>
<th>symbol</th>
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<th>meaning</th>
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<tr>
<td>$\alpha$</td>
<td>rad</td>
<td>beam semi opening angle</td>
</tr>
<tr>
<td>$\beta$</td>
<td>rad</td>
<td>deflection angle</td>
</tr>
<tr>
<td>$\gamma$</td>
<td>-</td>
<td>beam current exponent in Boersch effect</td>
</tr>
<tr>
<td>$\delta$</td>
<td>m</td>
<td>edge roughness</td>
</tr>
<tr>
<td>$\Delta$</td>
<td>m</td>
<td>positioning accuracy of details (and spots)</td>
</tr>
<tr>
<td>$\varepsilon_0$</td>
<td>F/m</td>
<td>dielectric constant</td>
</tr>
<tr>
<td>$\lambda$</td>
<td>m</td>
<td>optical wavelength</td>
</tr>
<tr>
<td>$\eta$</td>
<td>-</td>
<td>emitter efficiency</td>
</tr>
<tr>
<td>$\sigma_r$</td>
<td>C/m$^2$</td>
<td>resist sensitivity</td>
</tr>
<tr>
<td>$\Omega$</td>
<td>sr</td>
<td>beam solid angle</td>
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### Indices

<table>
<thead>
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<th>symbol</th>
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<tbody>
<tr>
<td>1288</td>
<td>12% - 88% width measure of the distribution</td>
</tr>
<tr>
<td>c</td>
<td>chromatic aberration, partial contribution</td>
</tr>
<tr>
<td>d</td>
<td>diffraction contribution</td>
</tr>
<tr>
<td>dof</td>
<td>depth of focus, partial contribution</td>
</tr>
<tr>
<td>D</td>
<td>contribution within a feature</td>
</tr>
<tr>
<td>e</td>
<td>electron reference (in $\lambda_e$, $T_e$ etc.)</td>
</tr>
<tr>
<td>EC</td>
<td>chromatic aberration in electrostatic deflector</td>
</tr>
<tr>
<td>E</td>
<td>electrostatic deflector</td>
</tr>
<tr>
<td>E1</td>
<td>electrostatic deflector number 1</td>
</tr>
<tr>
<td>E2</td>
<td>electrostatic deflector number 2</td>
</tr>
<tr>
<td>fwhm</td>
<td>full width at half maximum of the distribution</td>
</tr>
<tr>
<td>g</td>
<td>gaussian beam profile</td>
</tr>
<tr>
<td>gm</td>
<td>geometrical dimension</td>
</tr>
<tr>
<td>l</td>
<td>image coordinates</td>
</tr>
<tr>
<td>l</td>
<td>lens coordinates</td>
</tr>
<tr>
<td>m</td>
<td>demagnifying section</td>
</tr>
<tr>
<td>max</td>
<td>maximum occuring value</td>
</tr>
<tr>
<td>min</td>
<td>minimum occuring value</td>
</tr>
<tr>
<td>o</td>
<td>object coordinates</td>
</tr>
<tr>
<td>p</td>
<td>projection section</td>
</tr>
</tbody>
</table>
s  shaper section
sa  spherical aberration, partial contribution
so  source reference (jso)
tot  total effect
tr  transverse value (U_tr)
TD  trajectory displacement, partial contribution
v  reference to variable-shaped beam system
vac  vacuum indication (I_vac vacuum emission current)
x  beam profile of idealized shape (to be written)
z  axial component (of speed e.g.)

δ  contribution within a pixel
Δ  contribution within part of a pixel
INTRODUCTION

This thesis will address the problem of writing very fine lithographic patterns. Near the year 2000 line widths in the order of 0.1 μm will be requested. In chapter 1 it will be argued that these patterns can only be fabricated using electron beam systems. This chapter will further refine the demanded specifications for lithographic patterns. Chapter 2 will focus on the well known techniques of electron beam writing. In this chapter both focussed beam and variable-shaped beam systems are introduced. For both techniques of writing a characteristic system is presented. The behaviour of these systems is described with respect to the writing pattern specifications, presented in chapter 1. This illustrates that a thorough look at the system design is required. Chapter 3 describes the new developments in electron optical systems with respect to electron beam writing. This leads to a new design of an electron beam writing system for which the boundary conditions are determined.

Chapter 4 introduces the electron sources that will be used in the design loop. Both the well known ones and some newly developed sources are described. In chapter 5 the error budgets of electron beam writing systems are introduced. Chapters 6, 7 and 8 then describe the design of different parts of electron beam writing systems with optimizations with respect to the total system. In these chapters the traditional error budgets are extended with the electron–electron interaction effects described by [Jansen, 1988]. It turns out that trajectory displacement effect plays an important role in the shapers and in the projection lens section. Also the energy spread resulting from Boersch effect is calculated for all sections. Both of these electron–electron interaction effects strongly influence the electron beam writer design. Chapter 9 presents the conclusions with respect to the final design.
1 LITHOGRAPHIC TECHNIQUES,
INTRODUCTION AND PATTERN SPECIFICATIONS

This thesis will address the problem of writing very fine lithographic patterns. These patterns are used for the fabrication of integrated circuits (IC's). Optical lithography has been in use for many years to produce ever finer patterns. The minimum line width in the circuits is normally used as a critical parameter. It has steadily decreased by factor of two every six years for the last 25 years (ref. [Sze, 1983]). Following these developments it is expected that the minimum line width will be in the order of 0.1 μm near the end of the 1990's. There are strong indications that none of the light optical reproduction techniques in use today will be able to provide this minimum line width.

To meet the requirements for the fabrication of much smaller line width integrated circuits, a High Speed Electron Lithography (HISEL) project was defined. This project proposed the usage of electron beams for the fabrication of the IC patterns. Electron beam lithography has long been in use for the production of masks required for optical lithography and other lithographic techniques. Apart from a few special applications electron beam lithographic systems are at present not fast (and cheap) enough, to be used in mass production for directly writing the wafers. This thesis will detail the design steps that may lead to a HISEL direct-write system.

1.1 Introduction to lithography

Lithography is used for the fabrication of integrated circuits. On a single silicon wafer (4 inch or 10 cm diameter) some 100 integrated circuits are fabricated in parallel. The circuits on the wafer are fabricated by projection of the patterns onto a photosensitive resist layer. The exposure is followed by a development step in which either the illuminated parts or the dark parts of the pattern are removed. Thus parts of the underlying wafer are exposed, allowing for etching, diffusion, ion implantation, metallization etc..
In figure 1.1 a small part of an integrated circuit pattern is depicted. The cell in this figure functions as a memory for one bit. It is part of a random access memory device which is able to hold 16,000 bits. The left hand side of the figure shows the functional diagram of the circuit. The right hand side of the figure shows how five different pattern layers are combined to form the physical circuit.

![Diagram of an integrated circuit pattern](image)

Figure 1.1: Example of a single cell of a 16k bit static RAM IC.

Each of the patterns contains a different layer of the complete circuit. Two of the patterns used to form the circuit of figure 1.1 are displayed in figure 1.2. The patterns have to be positioned very accurately with respect to one another. The overlay of the patterns is normally specified to be somewhat smaller than the minimum dimension that occurs in the pattern. This minimum dimension (or critical dimension) occurs for example as the width of the thinnest lines. An important feature is that the patterns are highly regular, containing only rectangular and 45° lines.
Figure 1.2: Two of the lithographic patterns required for the circuit of figure 1.1.

For the application of each pattern a complete lithographic step is required. A typical circuit is fabricated in 6 to 25 of these lithographic steps. In figure 1.3 a schematic drawing is given of one

bare silicon

application of resist

illumination

developing

diffusion

resist removal

Figure 1.3: Schematic drawing of the processing (sub) steps required for the fabrication of one pattern layer.
complete lithographic step. In the first phase of this lithographic step the resist layer is applied to the bare silicon wafer. Then the pattern is illuminated, followed by the development of the pattern. In this case the illuminated parts of the resist are removed (this is a positive resist). In the figure a diffusion (sub) step is applied in which the active areas are formed where the gas is allowed to diffuse into the silicon. In the last (sub) step the unexposed resist is removed. The wafer is then ready for application of the next lithographic step. More complete introductions can be found in [Alles, 1987/2] and [Sze, 1983].

1.2 Introduction to lithographic systems

As mentioned, different lithographic techniques might be applicable in the production of 0.1 μm line width patterns.

Optical systems

Optical lithography is the oldest technique. At the moment this is the only technique that is in practical use in IC production lines. In some methods the whole wafer is exposed in one illumination step; in others each separate chip site is sequentially illuminated. The typical production speed is in the order of 30 to 60 wafers (4 inch diameter) per hour. At such high speeds the time to position the mask forms a significant part of the total wafer processing time. At the moment standard step and repeat cameras with minimum line widths between 0.7 and 1.0 μm are in use. These systems use light of wavelengths which are as short as possible. It is therefore logical to go to UV and even soft X-ray projection systems. For hard X-rays there are no refractive materials available.

X-ray projection

As an alternative hard X-rays can be used in shadow projection. The speed of this technique can be very high, whilst attaining very high resolution (about 60 wafers of 4 inch diameter per hour, ref. [Wilson, 1986]). In these systems a mask is projected, using shadow projection
with X-rays. The registration of the wafer position is done by illuminating only parts of the masks and detection of X-ray markers on the wafer. The accuracy of this technique is very high but because of the small marker areas the positioning time is rather long with respect to the mask illumination time. The technique does not require any other optical elements than the mask itself. The shadow mask is held very close to the wafer to produce a projection of the pattern. The minimum feature size (and the minimum line width) in this technique is determined by the X-ray diffraction in the gap between the mask and the wafer. With very small mask-to-wafer gaps this technique is (currently) limited to about 0.2 μm as well (ref. [Heuberger, 1988]). There is little hope that a factor of two reduction of the gap would be possible.

**Electron beam systems**

Since the beginning of the 1980's there has been much activity in the field of electron beam lithography. Many electron beam systems were designed for the 0.5 μm design rules, then seen as a practical goal (ref. [HP journal, 1981]). Some of these systems turned out to be of good use for mask making in the 0.5 μm minimum line width range. None of the systems were fast (and cheap) enough to be used for direct wafer writing. Even today this field is only entered for some very specific applications like gate array interconnection at the IBM quick turn around time (QTAT) line (see [Moore, 1983]). For the EL-3 system applied there, [Pfeiffer, 1975] mentions a throughput in the range of 2 to 3 wafer levels per hour (4 inch wafers with 60 cm² effective area). It has been well established that electron beam writing can be used to produce 0.1 μm line width patterns. The equivalent (de Broglie-) wavelength is much lower for this technique than for optical waves. The resolution limits for electron beam systems are determined by the stability of the systems used and by the resist technology. For the different systems in use, speed is still too low. The positioning and registration accuracy with electron beam systems is very good (refer to section 1.5 and 2.2).

**Electron projection systems**

There is also the possibility of using electron beam projection and proximity printing (equivalent to shadow projection). One type of these systems uses electrons patterns formed by masks. In this technique 1X and 5X demagnification factors are used. The other type of electron projection systems uses cathodes in the form of the pattern which are
projected with 1X magnification (allowing for a large field of view). The main problem in the first type of electron projection systems lies in finding a good mask material for electron beams [Zapka, 1985]. It is not oftenly used. With the second type of system minimum line widths of 0.1 μm have been demonstrated by [Ward, 1981, 1985] and [Livesay, 1986]. Realistic production machines have not been built for either technique.

Since electrons are used the resolution is, again, very good. Because of the parallel illumination of many picture elements these systems have high speeds. The registration is also very good for these systems. The pattern masks or cathodes have to be made with conventional techniques.

**Ion beam systems**

Shaped or focussed ion beam systems can also be used for the illumination of very thin resist layers. The main applications of ion beam systems at the moment are in maskless implantation and mask repair. For these systems the resolution is very good (ref. [Slingerland, 1988]), but the speed is very low. Markers can only be used in ion beam systems, when the resist over the markers is removed before registration of the wafer position.

**Discussion**

Unexpectedly, optical step and repeat cameras have kept up resolution improvements down to 0.7 μm. As mentioned by Lin at the ME 1987 conference [Lin, 1987] the optical step and repeat cameras might even be used down to 0.18 μm minimum line widths. For designs with a minimum line width of 0.1 μm, it seems that none of the optical reproduction techniques will be of use. This can be deduced from the most essential resolution limit (see also [Sze, 1983]), minimum feature size $D$ (in m) is

$$D = \frac{\lambda}{NA}$$

where $\lambda$ is the wavelength (in m) and $NA$ is the numerical aperture. This equation holds for all optical waves. It therefore sets the limits to all forms of electromagnetic waves: visible light, UV and X-rays.

A rough estimate of the lower limit of optical projection systems can be deduced from this equation, by looking at the physical limits in the
system. At the moment research in light sources concentrates at the fabrication of short wavelength (highly monochromatic) lasers. The best systems have wavelengths of about 230 to 250 nm. The theoretical minimum to the usable wavelength is in the order of 100 nm for lenses, since below that value the optical transmission of glasses is strongly reduced (ref. [Burggraaf, 1987]). Analogously, the reflectivity of mirror coatings reduces sharply for wavelengths below 200 nm. (X-ray mirrors for lower wavelengths have been fabricated, but they require very special materials and designs.) The numerical aperture cannot be much larger than 0.5. This value may even be somewhat lower in designs where large fields of view are required (to illuminate a large number of image elements in parallel).

With optical wavelengths in the range of 100 to 250 nm, the numbers given indicate that the physical limit of line width is in the order of 0.2 to 0.5 \(\mu m\) for all optical systems. Therefore, optical projection techniques will not be applicable for the production of 0.1 \(\mu m\) line width patterns. This is in line with the conclusions of [Lin, 1987], who mentions that a minimum feature size of 0.18 \(\mu m\) could be achieved with optical step and repeat cameras, but only using 5X (or 10X) reduction systems. In this case there will be no need for mask making systems with improved resolution. As mentioned, the wafer-to-mask gap in X-ray projection systems (currently) limits these systems to a minimum line width of about 0.2 \(\mu m\). It is unlikely that this gap can be reduced by a factor of two, so therefore this technique will not be able to provide 0.1 \(\mu m\) line widths either. The main applications of ion beam systems are in maskless implantation and mask repair. It will probably not become of any importance for the writing in resists, or for mask fabrication. Since electron beam writing works mainly in these last two fields, the two technologies do not compete. Therefore only electron optical projection and writing techniques will be usable for the production of (future) IC patterns.

This thesis will concentrate on electron beam writing systems. These systems will be applicable to the direct writing of wafers. Electron beam direct writing may become a competitive technique for the production of integrated circuits. An extra advantage of directly writing the pattern with an electron beam might be that masks would no longer be needed. This would completely obviate the need of mask production, handling and application. In the case of electron projection being used for mass IC-production, there would still be the need for IX
mask fabrication. Even when X-ray projection systems would be used in future IC-production lines, there would still be the requirement to fabricate IX masks. The fabrication of these masks will be done using electron beam writing systems.

It will be demonstrated that very high writing speeds may become attainable within a few years, by making use of the most recent developments in design of electron optical sources, lenses and deflectors. The IC production systems in use today produce some 40 to 60 (4 inch) wafers per hour (see [Wilson, 1986, Oberai 1987]). A production speed of 60 wafers per hour would result in an average writing speed, W, of about $1 \text{ cm}^2 / \text{s}$. For electron beam writing this would mean a speed improvement of about two orders of magnitude. This may be attainable. The pattern properties will be obtained from the patterns used in industry today, scaled down for 0.1 $\mu$m line width. This thesis will outline the design of an electron beam direct-write system, called HISEL (High Speed Electron Lithography) system. In table 1.1 the requirements for the HISEL system are summarized.

<table>
<thead>
<tr>
<th>parameter</th>
<th>value</th>
<th>unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>minimum linewidth</td>
<td>D</td>
<td>0.1 $\mu$m</td>
</tr>
<tr>
<td>writing speed</td>
<td>W</td>
<td>1 $\text{ cm}^2 / \text{s}$</td>
</tr>
</tbody>
</table>

Table 1.1: General HISEL system requirements.

1.3 Resolution requirements

As chip fabrication technology improves, the designs of 0.1 $\mu$m line width chips will become more and more complex. This section will outline several ways to describe the pattern resolution requirements. The results apply to both electron beam and electron projection systems. At the moment some 0.1 $\mu$m line width chips are fabricated in laboratories, but these only contain some simple 0.1 $\mu$m line width details. It is likely that future patterns will have the same level of complexity, as is standard in today's (2 $\mu$m) chip fabrication. The electron beam writing system will therefore be based on current chip design specifications, scaled down to 0.1 $\mu$m minimum feature size. This means
that for many pattern features (all over the chip) a minimum dimension of 0.1 µm (D) will be required. The corresponding edge roughness tolerated will be in the order of 25 nm (D/4), with a still smaller tolerance on the positioning accuracy (~ 6 nm, D/16). Extra demands for accuracy may be required for the fabrication of chips for integrated optics. A special requirement for these circuits is the generation of smooth lines and curves in all directions, as opposed to the mainly rectangular patterns for electronic components. These smooth edges require very fine pattern divisions. The divisions may become as fine as the edge roughness of the pattern!

Edge roughness and resolution requirements for integrated optics circuits cannot be fully specified yet. At the moment the design specifications for these circuits are much narrower than those for electronics chips. They are in the same range, though, as the specifications for the system that will be investigated in this thesis. In general it can be stated that the wavelength used in the integrated optics circuit is an indication for the required detail size, resolution and edge roughness. This wavelength processed is directly dependent on the semiconductor material used for fabrication of the circuit. So when the current materials would be used in future integrated optics chips, one would expect that the specifications for feature size and edge roughness will not be so much different from those for the future electronics chips. It is therefore expected that these demands can be introduced in a later stage without too many changes in the design.

As for the writing of lines in all possible directions, some variable-shaped beam systems already include a shaping aperture for writing 45° lines. These systems need somewhat less pattern refinement. A more recent idea of [Van der Mast, 1987] even makes it possible to have a shaping aperture sheared. With this system it is possible to write straight and even curved lines in all directions. As the applications of integrated optics chips are growing, this diamond shaper section may become of interest (ref. section 3.5.2).

The simplest way of producing a pattern of variable size is by filling it in with Gaussian spots. This method is called Gaussian or focussed beam (FB) writing; the resulting pattern is illustrated in figure 1.4. The figure illustrates how lines in the pattern are made up of a minimum of four Gaussian spots of full width at half maximum (FWHM) δ (in m). The line has a total width D (in m) and it has an edge roughness which is in the order of δ. The positioning accuracy of the spots is also indicated (Δ, in m). Figure 1.5 illustrates the intensity profile for a
Figure 1.4: Simple line detail in a pattern written with a Gaussian beam writer.

cut through such a line. The average intensity in the central part of the line is increased by less than 10%, due to illumination from neighbouring points. It is illustrated that the full width at half maximum, $\delta$, of the line is very close to (but slightly less than) four times the FWHM value of an individual illumination profile.

Figure 1.5: Summation of Gaussian beam profiles.
Another method for producing the line is by the projection of rectangular shapes. In a variable-shaped beam (VSB) system a beam shaping system with two apertures is used (depicted in figure 1.6). This system was first introduced by [Le Poole and Fontijn, 1968], see also [Pfeiffer, 1978]. The image of aperture 1 can be shifted with respect to aperture 2 using the shape deflectors. The final beam shape is a rectangle with variable side lengths.

![Diagram of variable spot shaping using two beam limiting apertures.](image)

Figure 1.6: Variable spot shaping using two beam limiting apertures.

In these systems the edge roughness is measured as the distance between the 12 and 88 % points in the intensity profile (see figure 1.7 a). This value corresponds to the full width at half maximum of a Gaussian beam profile which is scanned over the feature imaged with the shaped beam. The edge roughness in a variable-shaped beam system is the result of image unsharpness. This image unsharpness is described by the diameter of the Gaussian beam profile just mentioned. The edge roughness value enables one to compare the quality of the images for variable-shaped and focussed beam writing systems. For the determination of the feature placement accuracy, or the address grid size Δ (in m) of pattern elements it is necessary to look at the intensity profiles. Both for focussed beam and variable-shaped beam writers the intensity profile is approximated with that of the variable-shaped beam.

A simple case of two lines of width D is investigated to find the sensitivity for shifting of the lines. With a small gap between the
Figure 1.7: Total intensity profiles for overlapping lines with different line intensity profiles.

lines the intensity distribution will show a minimum, as depicted in figure 1.7. In this figure the intensity profiles for overlapping lines are drawn, given three simple profiles. Figure 1.7 a illustrates the rectangular profile, in figure b the effect is shown for a single triangular profile, while figure c illustrates the profiles for lines with finite slopes in the edges. The figures illustrate the change in
Lithographic techniques

intensity profile near the point of ideal matching. Moving in the direction $+\Delta$ results in overlapping profiles, while the direction $-\Delta$ indicates a gaps between the lines. The last figure is the most realistic approach of drawing lines with Gaussian edge profiles.

Furthermore in figure 1.8 intensity profiles are depicted for the case when the lines are formed with Gaussian edge profiles. In figure 1.7 a the 12-88% edge width is indicated (with $\delta$). This value is also the size (FWHM) of the corresponding Gaussian beam that could be used to fabricate this pattern. Figures 1.7 b and c illustrate the intensity profiles when writing lines that are not exactly next to each other. For the overlapping case a maximum occurs. Sideway shifts of distance $+\Delta$ and $-\Delta$ give changes in the intensity level $G$ indicated with $+$ and $-\Delta G$ (for figures b and c respectively).

Figure 1.8: Line intensity profiles for a variable-shaped beam writing system.
As mentioned, this profile can be described as the convolution of a rectangle with a Gaussian spot. The electron intensity distribution is described by the convolution of a block function for the pattern shape:

\[
 f(x) = \begin{cases} 
 0 & (x < 0 \text{ or } x > D) \\
 1 & (0 < x < D) 
\end{cases}
\]  
(1.2)

and a Gaussian beam profile

\[
 f(x) = \frac{4}{\delta^2} \frac{x^2}{e^2} 
\]  
(1.3).

Convolution gives the total intensity profile:

\[
 f_{tot}(x) = \int_{-\infty}^{\infty} f_x(y) f_\delta(x-y) \, dy
\]  
(1.4).

From the allowed variation in \( f \) the allowable pattern shift values (\( \Delta \)) have been calculated in table 1.2. The columns in this table represent progressively wider lines. For \( D > 3 \delta \) the values show very little change. Both linewidth \( D \) and pattern shift \( \Delta \) are expressed in units of the edge roughness \( \delta \). It is concluded that for a required illumination constancy of 5% a placement accuracy of \( \delta/20 \) would be needed. For 20% illumination constancy only \( \delta/5 \) accuracy would be needed. In general it is found that, for lines wider than \( 3 \delta \), the allowed positioning accuracy values (relative to \( \delta \)) are approximately equal to the intensity variation \( G \).

In literature, some practical numbers for detail size, edge roughness and placement accuracy are given:

[Broers, 1985 ] \( \Delta = \delta / 3 \)

[Veneklasen, 1985/1] \( \Delta = \delta / 5 \quad \delta = D / 3 \)

[Moore, 1983 ] \( \delta = D / 4 \quad \text{overlay 2} \delta. \)
Table 1.2: Allowed gap values (Δ) for specified linewidth D and illumination constancy level G. All sizes are expressed in units of δ, the edge roughness.

Moore only gives the pattern overlay. This is the relative pattern placement between two different patterns written in sequence on the same wafer. It does not give a clear indication for the absolute pattern placement in one illumination step (Δ). None of the systems mentioned works in the noise limit of the resist.

The noise limit is described here since it gives the absolute minimum number of electrons required to generate the patterns specified. Therefore the statistical behaviour of the electrons for very small pixels is examined. The number of electrons hitting one pixel should be compared to the statistical variation in the amount of electrons in the small edges (ref. [Sze, 1983]). If \( N_δ \) is the number of electrons hitting an area of \( δ^2 \) (part of the edge of a pixel), \( σ_r \) is the resist sensitivity (in C/m²), and \( e \) is the electron charge (in C) then

\[
N_δ = \frac{σ_r δ^2}{e} \implies δ = \sqrt{\frac{e N_δ}{σ_r}} \tag{1.5}
\]
Since there is an integer number of electrons hitting each pixel the electron distribution will be of the Poisson type. The standard deviation in the number of electrons hitting the pixel will thus be $\sqrt{N_{\delta}}$. Therefore the illumination constancy level within a single pixel will be of the order of

$$G_{\delta} = \frac{\sqrt{N_{\delta}}}{\delta} = \frac{1}{\sigma_r} \sqrt{e}$$

(1.6).

The positioning accuracy $\Delta$ will have corresponding edges of size $\Delta^2$, with an illumination constancy level

$$G_{\Delta} = \frac{1}{\Delta} \frac{\sqrt{e}}{\sigma_r} \frac{\delta}{\Delta} = \frac{G_{\delta}}{\Delta}$$

(1.7)

But $\Delta$ is also the accuracy with which two features are placed. In Table 1.2 it was found that this $G_{\Delta}$ is 1 (or 100 %) ! This discussion is closed by stating that the mathematically defined illumination level cannot be correctly determined for the edges of the profile with this simple approximation. A more thorough analysis of these statistics is outside the scope of this work. The edges are mainly determined by statistical variations of the electron distribution in the resist. Concluding from discussions with various people who fabricate IC patterns, an illumination constancy level for features of 5 % was found to be realistic,

$$G_{\delta} = 5 \%$$

With $\delta = 25$ nm

$$\Delta = 6 \text{ nm}, \text{ this gives } G_{\Delta} = 23 \%$$

and $D = 100$nm, gives

$$G_D = 1.4 \%.$$  

where $G_D$ is the constancy level for the whole line.

This is a typical value specified for electron beam pattern generators. With the equation (1.6) this implies a number of electrons in the feature (of area $\delta^2$) of
\[ N_\delta = 400. \]

And equation (1.7) gives for the noise limited resist sensitivity

\[ \sigma_r = 8.0 \mu C/cm^2. \]

A target sensitivity of \( \sigma_r = 10 \mu C/cm^2 \) will be used. In designing an electron beam writing system the expected \( \sigma_r \)-value cannot be changed too much. Therefore this value is taken to be a fact. From this value and the system writing speed of \( 1 \text{ cm}^2/\text{s} \) a target beam current requirement \( (I) \) of \( 10 \mu A \) results.

As mentioned by [Veneklasen, 1985/2] the resist itself does not have infinitely fine resolution either. One should specify the tolerated illumination variation as a function of detail size. In the area of very high resolution resists noise limited, highly sensitive resists are not (yet) available. From more recent articles [Frackowiak, 1987] a trend is

<table>
<thead>
<tr>
<th>parameter</th>
<th>value</th>
<th>unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>minimum linewidth</td>
<td>D</td>
<td>100</td>
</tr>
<tr>
<td>edge roughness</td>
<td>( \delta )</td>
<td>25</td>
</tr>
<tr>
<td>pattern placement accuracy</td>
<td>( \Delta )</td>
<td>6</td>
</tr>
<tr>
<td>illumination constancy level</td>
<td>G</td>
<td>5</td>
</tr>
<tr>
<td>writing speed</td>
<td>( W )</td>
<td>1</td>
</tr>
<tr>
<td>resist sensitivity</td>
<td>( \sigma_r )</td>
<td>10</td>
</tr>
<tr>
<td>final beam current</td>
<td>I</td>
<td>10</td>
</tr>
</tbody>
</table>

Table 1.3: HISEL resolution related demands.
showing towards more sensitive resists, also for the 0.1 μm minimum feature sizes. It can be concluded that in future very sensitive resists will be available. These resists will come close to the noise limit just mentioned. This noise limit is not dependent on beam voltage.

Some practical values for the target system are chosen, taking into account the values in table 1.2 and the remark that statistical variation in the edges cannot be determined with infinite accuracy. The resulting demands are accumulated in table 1.3 for the HISEL system. (Note: coverage will be discussed in section 3.4. In this approximation it is supposed that all possible positions in the pattern have to be accessed.)

1.4 Proximity effect

The proximity effect produces partial illumination of a feature when neighbouring features are exposed. This effect is caused by back scattered electrons which have a rather big range in the resist (several μm at 20 kV). The effect is a severe problem since it depends on the patterns written, substrate type and resist thickness. Several schemes have been developed which provide compensation for the proximity effect. The effect is also very thoroughly investigated by [Mulder, 1991].

As mentioned by [Nagarajan, 1987] these schemes are very different:

dose compensation [Parikh, 1978]

Here the intensity is varied over the pattern written, such that all points in the pattern receive the same dose.

pattern shape correction [Sewell, 1979]

In this technique the pattern shapes are adjusted, such that the pattern after development will be correct. All points in the transferred pattern receive the same dose.
multi layer resist technique [Moran, 1979]

With multi layer resists the electron sensitive (imaging) resist layer is placed on a thick, electron-absorbing, insensitive layer. Thus backscatter electrons do not reach the top layer anymore. The process takes several extra steps for application, image transfer to the bottom layer and removal of the toplayer. This process is currently getting much extra attention since it has the special feature of step coverage (ref. [White, 1983]). That is, it allows for the use of a resist layer that is much thinner than the height variations of the underlying substrate. This reduction of resist height variations also reduces demands on the depth of focus of the imaging system.

high or low beam voltages [Kyser, 1979] and [Howard, 1983]

Indications are that a beam voltage of 20 kV generates about maximum proximity effect. When no proximity correction is done, the minimum attainable linewidth of 4 μm at 20 kV reduces to 1 μm at both 10 kV and 50 kV. The explanation given for this is twofold. For the higher beam voltage the beam is spread over a wider range, therefore the average illumination level from backscattered electrons will be lower. And on the other hand the electrons at the lower beam voltage have a smaller penetration range.

At present, for most of the current electron beam writing systems a beam voltage of 50 kV is considered. The higher voltage does put somewhat higher demands on the deflector fields. It outweighs the lower beam voltage option though, since all stray field effects and chromatic aberrations (including Boersch effect, see further) are reduced too. A disadvantage of increasing the beam voltage will be the lower sensitivity of the resists (ref. [Roberts, 1984]). It should be noted that the noise limit in equation (1.5) is not dependent on beam voltage.

Ghost exposure [Owen, 1983]

This is the most recent correction method mentioned. It implies writing the backscattered electron distribution to all non illuminated points.
Since this distribution can be rather well simulated by a defocused Gaussian electron beam the scheme is very simple:

write the pattern with a focussed beam and write the rest of the wafer with a defocussed beam.

It does imply that the beam has to write on all of the chip area, but with only two levels of dose. The same defocussing can be done in a variable-shaped beam writing system.

Dose compensation is currently applied most; it requires about 5% overall illumination accuracy in practical applications. Pattern shape correction is rather complicated, but it is good for high production volumes, since it only complicates the preprocessing of the pattern. For parallel imaging systems, such as projectors and multibeam systems, it is the only applicable method. Probably the pattern complexity for pattern shape correction will not go up as much as that required for the dose compensation scheme. It has not yet been applied to patterns with 0.1 μm minimum feature size.

Multi layer techniques receive much attention currently. They are very promising, but they put all of the complications on the resist processing. As mentioned before, higher beam voltages are already being implemented on most electron beam writers, but this will not fully solve the proximity effect problems. Finally, Ghost exposure is a simple and very promising method. It has not been demonstrated for the required 0.1 μm minimum linewidth yet. The main drawback of this method is that it always requires the illumination of all of the wafer area. Questions remain as to whether more or less shapes will be used to describe any of the patterns using any of the proximity correction methods mentioned.

The use of dose compensation is the main reason why intensity variation occurs in the patterns written. The required accuracy of the final illumination level is determined by the development process (see also section 1.1). Schemes that work with one (or two) dose level(s) have been studied especially for electron proximity printing and electron projection [Nicholas, 1985]. They can also be of help to electron beam writing systems since they reduce the amount of pattern data.
1.5 Marker search

Marker search is the registration of the substrate position. This is normally done by measuring the backscattered light or electrons from markers on the substrate. The markers can be heavy metal dots or topographic features of the substrate material. Thus the coordinate system of the electron beam writer and that of the substrate are matched. When all patterns are fabricated on the same machine only the reproducibility of that machine is of interest.

For mask writing marker search is only required to compensate for drift in the position control system. Since the current laser interferometers have tolerances below 10 nm (3 σ) it seems that hardly any marker searching will have to be done while writing the masks. In the field of mask writing, using mixed X-ray and electron beam projection systems, there is much research going on [Rottmann, 1984], [Heerens, 1988], [Freyer, 1986]. In principle only a position conversion system is required, supplying corresponding machine coordinates for given real coordinates. All electron beam writing systems have some form of position conversion implemented, but it seems that the so called mix and match strategies have not yet fully matured.

For direct-write applications the beam has to be positioned relative to the underlying structures of the integrated circuit. Therefore the machine has to perform a marker search (3 or 4 markers) for each chip (also called a die) that is written. See also [Davis, 1981].

When estimating the marker search time for the HISEL system it can very generally be stated that this will not pose much of a problem. Currently the Philips EBPG-3 can find heavy metal markers at 1 nA beam current in 1 second with an accuracy of about 10 nm (3 σ, ref. [Fontijn, 1986]). The number of backscattered electrons is proportional to the primary beam current. With the requirements summarized in table 1.3 (section 1.3) a primary beam current of 10 μA is found. Since this beam can be directed to the marker locations it is fully available for detection of the marker positions. This holds for both the focussed beam (FB) and variable-shaped beam (VSB) versions of the HISEL system. This in effect reduces the marker searching time to some milliseconds on the HISEL system. Marker searching and system alignment will therefore not be significant design problems on the HISEL system.
2 ELECTRON BEAM SYSTEMS FOR HIGH SPEED ELECTRON BEAM WRITING

The general task of an electron beam pattern generator (EBPG) consists of the writing of a given pattern within the shortest possible time. Basically there are two methods of writing the patterns, as already introduced in chapter 1: Gaussian or focussed beam (FB) writing and variable-shaped beam writing (VSB).

2.1 Introduction to focussed beam writing

Focussed beam writing uses a television like filling of the pattern with a very small spot. The focussed beam has the size of one pixel. This intensity distribution is determined by the demagnified gun image including geometrical aberrations. This is normally well approximated by a Gaussian profile. Line size control demands are generally stated as mentioned in section 1.3. To fulfill these demands lines have to be built up of at least four Gaussian spots. Figure 2.1 illustrates two methods of writing a pattern with a focussed beam: raster and vector scan modes. The left figure illustrates the raster scan writing mode. All writing positions are accessed, switching the beam on and off very quickly. The right figure illustrates the vector scan mode, where the figures to be written are filled in. Between writing the figures the beam is switched off and jumps to the next figure.

These two techniques are completely different with respect to the electronics required. For the raster scan system only a very high speed beam blanker is required. The beam scanning deflectors in this system can have a bandwidth which is about an order of magnitude lower than the bandwidth required for the beam blanker. The vector scan strategy makes higher demands upon the bandwidth of the beam positioning deflectors. On the other hand it has the advantage of only accessing those positions where actual illumination is required. When only half of the pattern has to be filled (area coverage $c = 0.5$), the overall speed can be twice as high for the same beam current, as in the raster scan case ($1/c$). It should be noted that the vector scan strategy cannot be applied to multi focussed beam systems and it has lesser advantages when applying it to
the writing of patterns with many different illumination levels. Often it is still possible, however, to make a subdivision of the original pattern in blocks of equal illumination intensity with reasonable efficiency. Therefore the requirement of having multiple intensity levels does not pose too much of a problem.

Figure 2.1: Example pattern for delineation with a focussed beam system. The figure illustrates the raster scan and vector scan modes.

Since normally not all of the area needs to be illuminated the vector scan technique is preferable. Because of the very small spot that is illuminated very high deflection speeds are required for a reasonable total writing time. Therefore the positioning deflectors are split up in (very) high speed, low (relative) accuracy and low speed, high accuracy deflectors. This modifies the writing strategy into main field / sub field concepts, where the sub field can be scanned using only the high speed deflectors. Also, per sub field fewer bits are required to describe a shape position, as was mentioned in section 1.4. In the Philips EBPG-3 a special hardware processor is used which, during writing, expands the data of the form "write a rectangle size (width, height) at position (x, y)" into rastering data for the scanning beam. This effectively decouples the data rate from the pixel transfer rate. For the Philips EBPG-3 the data rate is as low as for a corresponding variable-shaped beam writer, or even lower. This has no influence on the number of pixels to be transferred in the electron optical column. The
pixel transfer rate for this system is the same as in any other focussed beam writing system. The focussed beam system design is also used in the EBES-4 machine [Alles, Thomson, 1987] and in two Japanese machines of NTT [Iwadate, 1987] and Hitachi [Saitou, 1986, 1987].

2.2 Introduction to variable-shaped beam writing

The second method of writing the patterns in an EBPG is called variable-shaped beam writing. This method was already introduced in section 1.3. The illustration of figure 1.6 shows an intermediate lens for the imaging of the first shaping aperture onto the second. Figure 2.2 illustrates the possibility of shadow imaging of the two apertures onto each other. This method is applied, for instance, in the AEBLE-150 system as described by [Veneklasen, 1985/2]. Shadow imaging can be used because of the large depth of focus in the plane of the shaping apertures (they are strongly demagnified towards the target). This implies that there is no intermediate source cross-over in the shaping section. As depicted this situation requires two deflectors for each aperture shifting direction. The paired deflectors have to be adjusted in such a way that the source cross-over does not shift when the image of the first aperture is shifted with respect to the second aperture. The beam deflectors in figure 1.6 (one per aperture shifting direction) are placed around the source cross-over. Therefore they do not affect the source cross-over itself. (In the first order approximation electron deflectors only generate ray bending at the center of the physical deflector.) In the case of figure 1.6, the beam cross-over position is adjusted with the condensor lenses in such a way that it is not shifted when the shaping deflector is activated.

Variable-shaped beam writing makes use of the property of most patterns written that they are mainly rectangular (as in figure 1.1). With the values for minimum feature size, D, and edge roughness (or pixel diameter), δ, from section 1.3, each shot of a variable-shaped beam writer will contain 16 or more pixels. This setup is used in the EL-3 at IBM [Moore 1983, Pfeiffer 1975, 1978, 1983], in the AEBLE-150 [Veneklasen, King 1985], the FEPG [Chambost 1986/1, 1986/2] and in Toshiba's EX-7 [Horiike 1986, Tamamushi 1988].

Normally, variable-shaped beam writers illuminate the first aperture with a beam of constant current density. The illumination time at
constant dose level will thus be fixed. And the total beam current varies in proportion with the area of the shaped spot. The patterns designed are preprocessed to determine the exact positions and sizes of the shapes to be written from the designer format. Several hundreds of pixels can be illuminated in a single shot. There are some limits as to the total number of pixels illuminated per shot however. To minimize total pattern writing time the pattern should be broken up in as few rectangles as possible, this results in the maximum size of the rectangles with a corresponding maximum in the total beam current. For writing very fine details one will have to write many small rectangles. For the variable-shaped beam systems, the requirement of having a non-uniform intensity distribution on the target also significantly reduces their advantages. Intensity variation is not too much of a problem, as was mentioned with respect to the focussed beam writers. It is expected that not too many intensity levels will be required and these (sub) patterns can be described by using rectangles as well.

2.3 General electron beam writing considerations

The most important spot size limit comes from the electron optical behaviour of the system. As will be demonstrated in later chapters some aberrations determining the sharpness of the final spot in these systems come from electron-electron interactions. These interactions determine the energy spread in the beam, the focal length of the negative lens formed by the space charge in the beam, and finally trajectory displacement which is an uncertainty in the exact position of the electron trajectories in the final image. All of these effects increase with increasing beam current. The geometrical aberration equations for the systems will be introduced in chapter 5. Since the electron-electron interactions cannot be expressed in explicit equations these effects are calculated for each individual beam section in the succeeding chapters.

The above has a strong influence on the design of an electron beam writing system. As part of the design will be based on numerical optimizations, the design process is split into separate steps. First the different beam sections are identified and general parameters per section are obtained. After this step the explicit, analytical equations can be used to obtain the order of magnitude of the effects. With these values the beam sections can be adjusted in order to minimize aberrations. This step results in analytically optimized beam sections.
In the last step the beam sections found are used as input for numerical optimization. Electron-electron interactions are accounted for in this step. This involves making a set of tables (or figures) for each beam section. The design-loop could go on forever applying the analytical aberration calculations to the numerically optimized beam sections. Normally the process is stopped after application of the analytical aberration calculations to the numerical results. The result is a set of optimized beam sections which can be used to describe different possible systems. It will be demonstrated that the numerical tables can be applied to different versions of both FB and VSB writing systems.

So far, both focussed and variable-shaped beam writing have been implemented in systems with field sizes varying from 0.16 x 0.16 (mm)$^2$ to 5 x 5 (mm)$^2$. Since wafers of 4 to 10 inch diameter (and square wafers with 4 to 10 inch sides) are used in the semiconductor industry a wafer holding stage is used to position the wafer (or mask) under the electron optical column. It is not yet clear what wafer sizes are required for the HISEL system. Since this thesis will focuss on the electron optical aspects and not on the size and the speed of the wafer holding stage, the wafer size is not too great a problem. The field of view to be handled by the HISEL system will be kept to a conventional 1 x 1 (mm)$^2$. For a 4 inch wafer with 1 cm$^2$/s electron beam writing speed, this results in a table speed of 1 m/s and a total wafer writing time of 60 s. The wafer exchange- and alignment time must be well below 60 s in order not to degrade the system production speed. These values can be realized with today's stages. In conclusion table 2.1 gives the general speed related figures for the HISEL system. System availability / down time should be only a small part of its continuous production time (up-times of 98 .. 99 % are reported).
<table>
<thead>
<tr>
<th>parameter</th>
<th>value</th>
<th>unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>writing speed</td>
<td>W</td>
<td>cm²/s</td>
</tr>
<tr>
<td>field of view</td>
<td>1</td>
<td>(mm)²</td>
</tr>
<tr>
<td>wafer diameter</td>
<td>4-10</td>
<td>inch</td>
</tr>
<tr>
<td>table speed</td>
<td>1</td>
<td>m/s</td>
</tr>
<tr>
<td>wafer exchange and alignment</td>
<td>&lt;10</td>
<td>s</td>
</tr>
</tbody>
</table>

Table 2.1: HISEL speed related requirements.

The systems most recently designed do not wait for the stage to come to rest, in order to reach maximum writing speed. They are writing the patterns while the stage is moving the wafer. This is called writing on the fly. The stage position is continually measured by laser interferometers. Positional error signals from the stage are fed into the electron beam deflectors. In some systems local wafer height sensors are even provided to adjust the focussing lenses continuously. The electron beam can be moved a great deal faster than the wafer. The outcome is that one would like to write with as large a field of view as possible (reducing the number of stage movements).

Recently [Mulder, 1989] has been looking into the order of writing the different rectangular shapes. Since the settling times of all deflectors depend on the absolute step the beam has to make, the steps in deflector voltage should be minimized. There is no general solution to the "travelling sales man" problem of accessing all rectangle positions in the shortest possible time. Mulder has shown that heuristic algorithms might significantly reduce the total deadtime of the deflectors in writing the pattern as compared with the currently used writing sequences.
2.4 A characteristic focussed beam writer

As a characteristic example for the focussed beam writing systems a short analysis of the EBES-4 system will be given. This system cannot fulfill the HISEL writing conditions, but the discussion will illustrate which problems arise in designing a focussed beam writing system. A complete description of this system is given by [Alles, 1987/1, /2] and [Thomson, 1987]. Figure 2.2 presents a schematic drawing of it.

![Schematic drawing of the EBES system](image)

Figure 2.2: Schematic drawing of the EBES system as described by [Alles, 1987/1, /2] and [Thomson, 1987]. The beam outer radius for a ray imaging the electron source is drawn. Above the figure the different sections and their (approximate) sizes are indicated. Below the figure the focal lengths of the lenses are indicated in italics.

The system consists of a high brightness ZrW thermal field emitter, with a tip radius of about 1 μm, and three magnetic lenses. The first lens is integrated in the gun optics. It forms a slightly converging beam at 20 kV acceleration voltage. The second lens is placed before the cross-over. An aperture in this lens determines the opening angle of the beam that is passed through the rest of the system.

Centered around the cross-over behind the second lens there is a high speed beam blanker, which has a pulse-on time of about 2 ns. After this
blanker there is about 350 mm of drift space to the final lens. This drift space accommodates some electrostatic deflectors: two sets of plates for a minor field deflector (32 μm range) and a single high speed fill-in deflector (2 μm range). The magnetic low speed main field deflector and a fast refocussing coil are in the drift space before the final lens too. A refocussing coil inside the last lens is used for substrate height corrections (upto ±/− 32 μm) on a sub field by sub field basis within the 256 μm main field.

2.4.1 Estimation of the EBES error budget

The final lens images the beam cross-over onto the writing surface with 8 times demagnification. Its working distance of about 40 mm is dictated by the mechanical design and by the lens aberrations allowed over the 256 μm field of view. Since the final lens is demagnifying, it also demagnifies all image aberrations of the intermediate lenses. Thus, for aberration calculations the final lens is of main importance.

With a focal length

\[ F \approx 40 \text{ mm} \]

a very rough estimate for the constant of spherical aberration of the final lens is \( \left(C_{sa} \right) \approx F \), for magnetic lenses:

\[ C_{sa} \approx 40 \text{ mm} \]

and for the constant of chromatic aberration (also \( C_c \approx F \), for magnetic lenses):

\[ C_c \approx 40 \text{ mm} . \]

Now for a given half opening angle \( \alpha_0 \), we can calculate the final spot size from:

\[ \delta_t^2 = \sqrt{\delta_{gm}^2 + \delta_{sa}^2 + \delta_c^2 + \delta_d^2 + \delta_{T\!D}^2} \]  \hspace{1cm} (2.1).

With \( \delta_{gm} \) the geometrical source size (diameter) and with \( \delta_{sa} \) the spherical aberration determined spot
\[
\delta_{sa} = \frac{1}{2} C_{sa} \alpha_0^3 
\]
(2.2)

the constant is usually 2, but with optimal focusing only a quarter of the spherical aberration is left (ref. [Van der Mast, 1984]). The spot, determined by chromatic aberration spot is

\[
\delta_c = C_c \alpha_0 \frac{\Delta U_{fwhm}}{U} 
\]
(2.3)

and the diffraction spot is

\[
\delta_d = \frac{0.5 \lambda_e}{\alpha_0} 
\]
(2.4)

where \( \lambda_e \) is the electron wavelength is,

\[
\lambda_e = \frac{h}{\sqrt{2 m_e e U}} 
\]
(2.5)

\( \delta_{TD} \) is the trajectory displacement determined spot which has been calculated using the equations given in Jansen's thesis [Jansen, 1988]. The results are shown in table 2.2.

From this table it is concluded that \( \delta_{TD} = 66 \text{ nm} \). From table 2.2 it can also be concluded that the energy spread generated by the Boersch effect is small as compared to the energy spread that is generated in the electron gun. The average energy spread generated in the electron gun is estimated to be about 1 eV. Since this value is determined by the extraction optics it will not vary much for the different accelerating voltages. It cannot be correctly calculated with Jansen's equations. The above equations give at \( U = 20 \text{ kV}, \alpha_0 = 10 \text{ mrad} \):

\[ \lambda_e = 8.7 \text{ pm}, \delta_d = 0.4 \text{ nm}. \]
| Table 2.2: Electron–electron interactions in the final image plane of the EBES-4 system at 250 nA beam current, 20 kV accelerating potential. BE is the Boersch effect, TD is the trajectory displacement effect. SC, the refocusing distance is given. This effect can be fully compensated for in cylindrical beams.

<table>
<thead>
<tr>
<th></th>
<th>( BE_{fwhm} )</th>
<th>( TD_{fwhm} )</th>
<th>SC</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>eV</td>
<td>nm</td>
<td>( \mu m )</td>
</tr>
<tr>
<td>illuminating section</td>
<td>0.066</td>
<td>60</td>
<td>0.05</td>
</tr>
<tr>
<td>blanker and deflectors</td>
<td>0.361</td>
<td>19</td>
<td>5.5</td>
</tr>
<tr>
<td>final lens section</td>
<td>0.033</td>
<td>1.9</td>
<td>0.6</td>
</tr>
<tr>
<td>total effect</td>
<td>0.438</td>
<td>66</td>
<td>6.1</td>
</tr>
</tbody>
</table>

It is concluded that the diffraction limit is of no importance. From the values given we find:

\[
\delta_{sa} = 20 \text{ nm}
\]

and with \( \Delta U_{fwhm} = 2 \text{ eV} \), \( \delta_c = 40 \text{ nm} \).

For this system a final spot diameter of about 125 nm is reached at a beam current \( I = 250 \text{ nA} \) (ref. [Alles, 1987/1]).

According to [Jansen, 1988] the trajectory displacement effect will follow the equation

\[
\delta_{TD} = C_{TD} \frac{I^{2/3}}{U^{4/3}} \frac{L^{2/3}}{\alpha_0^{4/3}}
\]

(2.6).

(This equation holds for moderate variations of the parameters around the operating conditions.) For the above values and \( L = 115 \text{ mm} \) and \( \alpha_0 = 0.417 \text{ mrad} \) (the major contribution is from the illuminating
$$C_{TD} = 0.0817 \, m \, V^{1/2} \, mrad^{4/3} / A^{2/3}.$$  

For more precise estimation of $\delta$, the constant $C_{TD}$ is taken as a function of $I$, $L$, $U$, $\alpha_0$. These more exact equations given in Jansen's thesis [Jansen, 1988] will be extensively used in later chapters.

The space charge effect given in table 2.2 is proportional to the beam current. It can be compensated for, but this is not yet done in the EBES system. Since the system is refocussed at the average current to be used the space charge effect will not be precisely as big as mentioned in the table.

![Diagram](image)

Figure 2.3: Energy spread generated in the EBES system for different beam currents and beam voltages. Each bar represents the summation of the effects of the different sections of the system as depicted in figure 2.2. Because the energy distribution is non-uniform the simple summation is not correct. The total effect correctly summed up is given beside every bar.

Energy spread and trajectory displacement values for the EBES system with the dimensions of figure 2.2 have been done for a range of beam
currents and voltages. These results are displayed in figures 2.3 and 2.4.

In these figures the effect of every section (as depicted in figure 2.2) is represented as the parts of a bar. The total bar height forms the linear summation of all effects. According to [Jansen, 1988] the total results should be calculated using weighted summation. The weight factors are determined by the dimensions of the beam, together with beam current and voltage settings. These values are different for each of the bars in the figures and therefore the total effect is drawn separately immediately next to each of the subdivided bars.

Figure 2.4: Trajectory displacement effect generated in the EBES system for different beam currents and beam voltages. The effect is represented as a blurring in the final image plane. Each bar represents the summation of the effects of the different sections of the system as depicted in figure 2.2. Because the trajectory displacement distribution is non-uniform the simple summation is not correct. The total effect correctly summed up is given beside every bar.
2.4.2 Behaviour of the EBES system for high beam currents

The figures are divided in three distinctive parts for which the beam current, the reduced beam brightness, or the beam voltage is constant respectively. The first part indicates the improvements that could be realized if only the beam voltage were to be increased. To keep the beam current constant the source brightness would thereby have to be decreased. The second part of the figure indicates the system behaviour in case the beam voltage is increased, keeping the same source settings. Since (absolute) source brightness increases proportionally to beam voltage, and the resist sensitivity (in first approximation) reduces with beam voltage, the absolute values here indicate total system performance. The third part of the figure indicates the beam current dependance of the effects for the high beam voltage.

It can be seen that the effects rapidly increase when beam current is significantly higher. At 2.5 μA beam current the Boersch effect would become 6 eV. The trajectory displacement would then be 8 μm! Increasing the beam voltage to 100 kV would reduce the Boersch effect to about 3 eV and the trajectory displacement would be about 400 nm. Both effects have then become far too large.

The parts of figures 2.3 and 2.4 with constant, reduced beam brightness show the effect with increasing beam voltage. It can be seen that then the absolute Boersch effect then increases, while the trajectory displacement is reduced. The right part with constant, reduced brightness has been calculated for a source ten times brighter than the one used in the real system. Such a high brightness source would be needed in order to increase the system writing speed. For the high current ranges the trajectory displacement will limit this system completely. It is concluded that the system design would have to be changed drastically to realize a focussed electron beam pattern generator for the demands mentioned in chapter 1.

2.5 A characteristic variable–shaped beam system

As an example of a characteristic variable–shaped beam writer the AEBLE–150 as described by [Veneklasen, 1985/1, 1985/2] and [King, 1985]
was chosen. As in section 2.4 the detailed description of this system will provide indications of the problems in designing a variable-shaped beam system. A dimensional graph is depicted in figure 2.5.

Figure 2.5: Schematic drawing of the AEBLE system as described by [Veneklasen, 1985/1, /2] and [King, 1985]. As in figure 2.2 the sections and (approximate) focal lengths are indicated. The dashed ray images the electron source in the cardinal plane of the last lens. The other ray images the shaping apertures onto the target. (This system has a shadow shaper. The shadow images of the apertures, near the center of the shaping section, are imaged onto the target.)

The system consists of an LaB<sub>6</sub> electron source which through a tri-state blanker illuminates one of the squares in the first shaping aperture. The shot time for this system is in the order of 100 ns (1 to 10 ns on/off transition times). It is operated at 20 kV accelerating voltage. Both shaping apertures are placed in field lenses in order to realize parallel illumination of the apertures. With the second field lens a source image is formed just before the demagnifying lens. With the demagnifying lens the shape image is reduced about 26 times. The final lens has a magnification of about 1/3. The system around this final lens is thus rather long, providing for electrostatic and magnetic deflectors for positioning of the shape. The shape size on the target can be varied from 0.5 to 2.0 µm.
This system contains a shaping aperture that is imaged onto the target. Therefore image rotation, magnification errors and image distortion of the shape image will determine edge sharpness. This system is clearly more complex than the focussed beam system. It has extra apertures which can charge up. Therefore these apertures are normally heated. Another problem in the shaped beam writers (in general) is the varying beam current. This demands an extremely high stability of the high voltage supply. The number of lenses in this system is also significantly larger, though not as many lenses are used as in electron microscopes.

2.5.1 Estimation of the AEBLE error budget and behaviour for high beam currents

Analogously to section 2.2 this system was investigated for conditions varying from those mentioned in literature to the higher beam currents mentioned in chapter 1. The beam current is limited to 1.5 µA due to electron-electron interactions. Therefore the maximum shape size is 1.5 µm². [King, 1985] also gives a complete overview of the different errors contributing to the final edge sharpness. The edge sharpness ($D_{128}$) is in range of 0.15 µm; this corresponds to $\delta$ in equation 2.2.1. Other imaging errors will be in the same order of magnitude in both systems (the shape imaged is small, therefore imaging errors are ignored for the moment). In figures 2.6 and 2.7 Boersch effect and trajectory displacement for this system are shown. Already for the typical 1.5 µA beam current and 20 kV the Boersch effect is in the range of 2.6 eV. This corresponds to a chromatic aberration of $\delta = 60$ nm ($C = 40$ mm, $\alpha_o = 10$ mrad).

Trajectory displacement for this system is in the range of 100 nm. This value is somewhat higher than that given by King and Veneklasen. It is very much larger than all of the other image aberrations mentioned in section 2.2. It can be seen that the Boersch effect increases by a factor of two in the range of 20 to 100 kV, at constant, reduced beam brightness. The absolute energy spread increases in this range, whereas the trajectory displacement effect only decreases by a factor of two.
Figure 2.6: Energy spread generated in the AEBLE system for different beam currents and beam voltages. Each bar represents the summation of the effects of the different sections of the system as depicted in figure 2.5. Because the energy distribution is non-uniform the simple summation is not correct. The total effect correctly summed up is given beside every bar.

In this system edge roughness is completely determined by trajectory displacement. The total beam current is limited in order to keep the edge roughness within the limits mentioned. The average writing speed at the typical settings given is in the order of 0.08 cm/s. As can be seen from figures 2.6 and 2.7 the use of brighter sources would not suffice to get a higher writing speed. Therefore the effects of the Boersch effect and trajectory displacement on the design of all beam sections will be investigated.

As for the focussed beam system it is concluded that a variable‐shaped beam writer cannot easily be made to work in the high current regime, required for the HISEL writing conditions. The following chapters will review the design criteria for electron beam writing systems with special attention to the HISEL pattern specifications as described in
chapter 1. This method will enable us to refine the design of the beam sections as encountered in both focussed and variable-shaped beam systems. In that way a system can be designed that meets the requirements for high speed lithography.

Figure 2.7: Trajectory displacement effect generated in the AEBLE system for different beam currents and beam voltages. The effect is represented as a blurring in the final image plane. Each bar represents the summation of the effects of the different sections of the system as specified in figure 2.5. Because the trajectory displacement distribution is non-uniform the simple summation is not correct. The total effect correctly summed up is given beside every bar.
3 NEW ASPECTS IN HIGH SPEED WRITING

3.1 Introduction

In this chapter the new aspects that were of influence on the initiation of this research will be introduced. As the technology is advancing in all areas of electron optics, the question arised whether improvements could be made on the design of electron beam writing systems. Several of the recent advances in electron optics will be dealt with.

3.2 Recent developments in beam voltage

Most of today’s electron beam pattern generators have been designed to operate at 20 kV accelerating potential. Almost all of the systems are currently being modified to work at 50 kV. The major reason for this is the reduction of the proximity effect (as was mentioned in section 1.4). Since at a higher potential the electrons are scattered over a larger range, the intensity of the back scattered distribution will be significantly lower than for 20 kV electrons. Electron-electron interaction effects are also lower for higher voltages, see [Jansen, 1988] and chapters 6 through 8. With respect to the geometrical lens aberrations, the chromatic aberration in particular will be reduced.

For this higher accelerating potential, the strength of the lenses and the deflector voltages will have to be increased. The resist sensitivity will decrease with increasing beam energy, but will be partly compensated by the increase in (absolute) beam brightness. It should be mentioned that the noise limit of the resist sensitivity is not influenced by the accelerating potential. In theory it is therefore possible that more sensitive high voltage resists will be fabricated.

It seems very well possible to go to 100 kV accelerating potential for the electron beam writers. Higher values are hardly ever used. [Jones, 1987] mentions an electron energy threshold of about 150 keV above which
electrons will produce crystal damage in silicon. [Jones, 1985] also described the improvement of the image quality of an electron beam pattern generator in the range of 20 to 100 kV. A voltage of 100 kV is decided to be realistic as an upper limit for electron beam writers (in general).

For accelerating potentials lower than 20 kV the proximity effect is reduced too. This is mainly due to the reduction of the range of the electrons in the resist. The main problem here is that the electron-electron interactions will become intolerably high. As was demonstrated in the examples of chapter 2, an improvement of the geometrical aberrations of the systems is required in order to realize the demands of chapter 1. It is therefore a logical step to increase the beam energy. The low voltage option is ruled out and will only be partly considered in the coming chapters. The relevant voltage range for the HISEL system is indicated in table 3.1.

<table>
<thead>
<tr>
<th>parameter</th>
<th>value</th>
<th>unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>beam voltage</td>
<td>U 5 .. 100</td>
<td>kV</td>
</tr>
</tbody>
</table>

Table 3.1: Variable range for the HISEL system voltage

3.3 Selection of the electron sources

As for the sources, the main problems are the high demands for stability and for uniformity over the shaping aperture. About 5% intensity variation is tolerated on the longer term (several minutes). An overall intensity variation of 1 to 2% intensity variation is allowed. The long term instability is normally kept within these limits by the application of active feedback mechanisms on regular time intervals. Because of the large area written simultaneously in variable-shaped beam writers, these systems do not require the highest possible beam brightness. Illumination uniformity demands were determined in section 1.3. Brightnesses will be determined in section 4.1. The additional source constraints for the HISEL system are summarized in table 3.2.
<table>
<thead>
<tr>
<th>parameter</th>
<th>value</th>
<th>unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>stability long term</td>
<td>≈ 5</td>
<td>%</td>
</tr>
<tr>
<td>stability short term</td>
<td>≈ 1..2</td>
<td>%</td>
</tr>
<tr>
<td>beam current</td>
<td>1 2..10</td>
<td>μA</td>
</tr>
</tbody>
</table>

Table 3.2: Typical variable ranges for the HISEL source

A higher writing speed implies a high current in the electron beam. Since the spots (due to a smaller design rule) will decrease, electron sources with a high brightness are needed. The demands on uniformity and stability are very high. Three types of sources that can be used are LaB$_6$, PN-emitters and thin film field emitters. The LaB$_6$ guns [Broers, 1979] are increasingly applied in variable-shaped beam systems. Field emitters and Schottky enhanced field emitters have been proposed, but these are not yet in widespread use. The total beam current will be in the order of several μA. At the moment this is still too high for these emitters.

Arrays of thin film field emitters [Spindt, 1976] have also been proposed. With these cathodes higher total beam currents are realized. The stability requirement is still a problem. PN-solid state emitters [van Gorkom, 1984, 1986, 1987] are very promising. They have a very high brightness and a large emitting area (implying a large total emission current). These emitters might also be modulated by control of their primary current. In this way, no separate beam blanker would be required. At present, PN-emitters are not being used in electron beam writing.

3.4 Estimation of data transfer rates

From the general speed and resolution specifications, stated in chapter 1, the required rate of pixels transferred in the electron beam writer is derived. The required system writing speed $W$ is in the order of $1 \text{ cm}^2$/s. This implies that the system should be able to write 4 inch
wafers in about 60 s, which is about five times faster than the values given for the AEBLE-150 by [King, 1985] (see also section 2.3).

Focussed beam systems

For a focussed beam writing system the pixel transfer rate \( R_f \) is derived from (ref. chapter 1):

\[
\text{minimum pixel size } : \delta = 25 \text{ nm (equals the resolution)} \\
\text{exposure coverage } : c = 50 \% \text{ (this is a rough estimate)}
\]

thus

\[
R_f = \frac{W c}{\delta^2} \tag{3.1}
\]

which gives

\[
R_f = 8 \times 10^{10} \text{ s}^{-1}.
\]

For vector scanned, single Gaussian beam systems \( R_f \) corresponds to the stepping frequency. Raster scanning systems have to scan over all of the surface, which corresponds to \( c = 100 \% \). In practice it seems impossible to fabricate electron optical systems with deflectors and blankers at the pixel rate mentioned. In multiple focussed beam systems the above pixel rate can be realized. These systems are discussed at the end of this section.

Variable-shaped beam systems

For a shaped beam writer the division of the pattern in rectangles results in a drastically lower data transfer rate. An estimate of the minimum shaped spot required to write such a pattern is set to 100 nm x 300 nm. Thus the minimum area (in m²) of the shaped spot is taken

\[
a_v = N_v \delta^2 \tag{3.2},
\]
where \( N_v \) is the minimum number of pixels transferred in each shot. The patterns are mainly rectangular with minimum line width 100 nm. In this example \( N_v \) is 48. Furthermore, most elements of the pattern are larger than \( a_v \). (Veneklasen, 1985) mentions an average value of about 90 pixels.) For completely random patterns the Gaussian beam writing system is a degenerate case \( (N_v = 1) \). The rate of minimum shapes transferred per second equals to

\[
R_v = \frac{T_p e}{N_v \delta^2}
\]  

(3.3)

With \( N_v = 48 \) that gives

\[
R_v = 1.7 \times 10^9 \text{ s}^{-1}.
\]

\( R_f \) and \( R_v \) form the highest data transfer rates in focussed and variable-shaped beam systems respectively. These rates will have to occur in the transfer of electronic data to electron optical information, like beam position etc. It should be noted that general data transfer rates in the controlling electronics and storage systems are about equal for both types of systems. With pipe lined processing, the data can be expanded from high-level, compressed format, to Gaussian beam rastering information. And even more data compression could be realized with real-time expansion of repetition and with more general drawing primitives.

In variable-shaped beam writers the information transferred is in the values of width, height, and in the position of consecutive shaped spots written. This is an enormous parallelism as compared to a Gaussian beam system, where beam on or off is the only information transferred. As for the vector scanning focussed beam systems (e.g. Philips EBPG), the speed is determined by the clock speed of the fill-in deflector.

\( R_v \) is the highest rate of shapes transferred in shaped beam systems. The average value for this rate is determined by the flexibility and range of the shaper (see e.g. the keyhole shaper in the next section) and by the actual pattern written. Also the maximum total beam current imposes
a limit on the maximum size of the shape allowed. Because of the very high pixel and shape transfer rates the system must transfer in parallel as much of the data as possible. Even with very small ranges of shape size and position the variable-shaped beam systems provide more parallelism in data transfer. It is therefore concluded that demands on high speed electronic circuits in variable-shaped beam systems can be lower (roughly by a factor of 100) than those for vector scanning Gaussian beam systems. In the design of the system it should be ensured that no other factors limit the writing speed. The high speed components should therefore be activated some ten to 100 times between every change of lower speed parts such as sub field deflectors or correctors for height, astigmatism and distortion.

Multiple focussed beam systems

Parallelism can also be obtained in electron beam writing systems by writing with multiple (focussed) beamlets, see [Roelofs, 1984] and [Van der Mast, 1984]. In such a system multiple spots are imaged onto the same target. Since each spot can be separately switched on or off, a great amount of parallelism is achieved. The amount of parallelism indicates the gain in speed obtainable with such a system. The discussion on these systems has been focussing on the high complexity of the beam modulation. It might be possible to make a multiple source with PN solid state emitters. Still, separate connections would be required for every spot written. Systems with upto 1000 spots have been proposed.

Multiple focussed beam systems have to access all possible writing positions, implying a coverage of 100%. According to the specifications in chapter 1 such a system would have to scan a very fine address grid to provide for placement accuracy of 6 nm for every 25 nm pixel. This corresponds with an area coverage, c, of

\[ c = 400 \% \]

Hopefully, this demand can be reduced to a rastering grid of 25 nm (with 6 nm placement accuracy). In that case multibeam systems have no principal disadvantage in comparison to variable-shaped beam systems. When 100 to 400 pixels can be written in parallel these systems may be equally fast as variable-shaped beam systems.
New aspects in high speed writing

The main advantage of multiple focussed beam systems lies in the fact that only the exposure coverage \( c \) determines the average number of pixels transferred per shot, and thus the pixel transfer rate is only slightly dependent on the pattern properties and the maximum data rates are reduced. Fluctuation of data rates and average beam current will still be pattern dependent. As the multiple beams overlap in large parts of the system, the strong effects of electron-electron interactions remain.

A multibeam scheme with multiple focussed beams, one per chip, has also been proposed by [Brodie, 1981]. In this design all beams transfer the same information. Though this seems to be a highly simplifying setup the die size will be fixed in the hardware of this system. This system is seemingly unfit to be applied in general.

In conclusion, the use of parallelism in a variable-shaped beam writing system can reduce the required data rates by a factor of about 48. This corresponds to a highest transfer rate of \( 2 \times 10^9 \text{ s}^{-1} \), which may become achievable in the near future. In the next paragraph the achievable average number of pixels transferred in a variable-shaped beam system, \( N_v \), is more closely investigated. By using more different shapes to form the beam a higher average may be realized. Typical HISEL values are taken together in table 3.3.

<table>
<thead>
<tr>
<th>parameter</th>
<th>value</th>
<th>unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>pattern coverage</td>
<td>( c )</td>
<td>0.5</td>
</tr>
<tr>
<td>FB pixel transferrate</td>
<td>( R_f )</td>
<td>( 8 \times 10^{10} \text{ s}^{-1} )</td>
</tr>
<tr>
<td>VSB minimum rectangle</td>
<td></td>
<td>100x300 (nm)²</td>
</tr>
<tr>
<td>VSB minimum number of pixels per shot</td>
<td>( N_v )</td>
<td>48</td>
</tr>
<tr>
<td>shot transferrate</td>
<td>( R_v )</td>
<td>( 1.7 \times 10^9 \text{ s}^{-1} )</td>
</tr>
</tbody>
</table>

Table 3.3: Variable ranges for the HISEL system
3.5 Shapers

These system elements will be discussed here since there are many recent developments that may lead to improved designs. Furthermore, the technology of beam shaping enables the use of electron sources with lower brightnesses, from which a more substantial part of the current can be used to form the final spot (ref. chapter 4).

3.5.1 Shaping range determination

As finer patterns are written the distribution of the electron beam current has to be refined more. Therefore shaping and positioning deflectors will have to be faster. The required shaping deflector range is determined by the pattern complexity. It is expected that the patterns written for future IC fabrication will be comparative to today's patterns in complexity. Usually the deflector range is about ten times the minimum shape size. [Roelofs, 1984] has given a general description of the relation between maximum shape size and the average size of rectangles if the pattern is subdivided in rectangles of maximum possible size. This gives an idea of the range required for shaping. Roelofs does not give the relations between the design rule and the average shape size. Analogously [Takamoto, 1988] showed the relation between the number of shots required, \( N_s \), and a maximum shape size, \( D_{\text{max}} \), in \( \mu \text{m} \). He derived the equation

\[
N_s = g_1 D_{\text{max}}^{-g_2}
\]

(3.4),

where \( g_1 \) and \( g_2 \) are parameters in the model. For two different circuits Takamoto found the following values

- LSI-A: \( g_1 = 7.5 \times 10^7 \text{ cm}^{-2} \), \( g_2 = 0.68 \)
- LSI-B: \( g_1 = 5.2 \times 10^7 \text{ cm}^{-2} \), \( g_2 = 1.20 \).
A very simple approximation gives some indicative values for comparison:

For an average rectangle side length $\langle D_{\text{pat}} \rangle$ the number of shots required to write a pattern with area coverage factor $c$ equals to:

$$N_s = \frac{c}{\langle D_{\text{pat}} \rangle^2} \quad (3.5).$$

For some typical values this gives:

$$\langle D_{\text{pat}} \rangle = 1 \mu m, \quad c = 0.5 \implies N_s = 5.0 \times 10^7 \text{ cm}^{-2}$$

$$\langle D_{\text{pat}} \rangle = 5 \mu m, \quad c = 0.5 \implies N_s = 2.0 \times 10^6 \text{ cm}^{-2}.$$

And by comparing equations (3.4) and (3.5) one finds that the average side length in Takamoto’s article must be in the order of 0.8 $\mu m$ for circuit A and 1.0 $\mu m$ for circuit B (with $c = 0.5$). This simple approximation always gives $g_2 = 2$.

With the given $g_1$- and $g_2$-values equation 3.4 gives for $D_{\text{max}} = 1 \mu m$

LSI-A: $N_s \approx 7.5 \times 10^7 \text{ cm}^{-2}$

and LSI-B: $N_s = 5.2 \times 10^7 \text{ cm}^{-2}$.

Figure 3.1 is a reproduction of figure 5 from [Roelofs, 1984] with logarithmic scales. Roelofs uses the variables:

P: maximum number of pixels writeable by the system
F: gross average fraction of P actually written
R: average number of pixels per rectangle of arbitrary size.

These variables can be expressed in the terms proportional to those used by Takamoto with the following conversions:

number of shots required: (Roelofs) $\frac{R}{PF} \sim (Takamoto) N_s$

maximum shape size: (Roelofs) $\sqrt{\frac{P}{R}} \sim (Takamoto) \frac{D_{\text{max}}}{R}$
Roelofs divides a pattern into maximum size rectangles. In this process he takes an unlimited biggest rectangle. The average rectangle side length found from this process is a circuit constant, here designated as $\langle D_{\text{pat}} \rangle$. This value is used to scale the other variables. The division of the pattern for which the largest rectangle is unlimited also gives the theoretical minimum number of shots required to write the whole pattern. The different marker types in figure 3.1 represent different circuits analyzed by Roelofs in this way. As a second step Roelofs determined the real value of $N_s$ as a function of the largest shaped spot that can be written $D_{\text{max}}$.

Figure 3.1: Pattern property of several circuits analyzed by [Roelofs, 1984]. The figure shows a plot of the number of shots needed for writing a pattern as a function of the maximum shape side length, $D_{\text{max}}$. The average rectangle side length, $\langle D_{\text{pat}} \rangle$, is used to scale the results.
It follows from figure 3.1 that the number of shots required to write the pattern decreases continuously in the range $D_{\text{max}}/<D_{\text{pat}}>$ = 0.1 to 1. This behaviour is similar to the behaviour described by Takamoto. It leads to a corresponding value of $g_2$ = 1.66. The corresponding $g_1$-value cannot be determined because of scaling. For higher $D_{\text{max}}/<D_{\text{pat}}>$ values (about 1.5 and higher) the number of shots required to write the pattern no longer decreases. In that range it approaches the theoretical minimum number of shots. This range is not considered by Takamoto.

In general, it can be concluded that the analysis of several electronic circuits, three by Roelofs and two by Takamoto, gives a range of $g_2$-values. Of course, the general trend shows a reduction of the number of shots when the maximum shape size is increased. Because both authors scaled their results the actual number of shots cannot be related to the minimum shape size (or design rule). It is therefore impossible to determine the exact range of shape sizes required to write the pattern.

[Veneklasen, 1985] also mentions some design values for the AEBLE-150 variable-shaped beam writer. He gives the total number of shots for a 4 inch pattern (effective area, $A$ = 88 cm$^2$). He also derives an equation similar to equation (3.5). From the number of shots per cm$^2$, $N_s$, the average shape size, $<D_{\text{pat}}>$ can be determined. For a 0.5 $\mu$m minimum line width pattern Veneklasen gives a figure of $N_s$ = 3.1 $10^7$ cm$^{-2}$. With an estimated area coverage factor of 0.5 this corresponds to $<D_{\text{pat}}>$ = 1.0 $\mu$m. From figure 3.1 (and Roelofs) it may be concluded that a maximum shape size $D_{\text{max}}$ of 2.0 times the average rectangle size would suffice to write more than 90 % of all rectangles in the pattern without subdivision. For $D_{\text{max}}$ equal to the average rectangle size this would be about 60 %. It is concluded that a realistic shaper range for the circuits mentioned by Takamoto, Roelofs and Veneklasen would be 0.5 .. 2.0 $\mu$m. This corresponds to a HISEL shaping range in the order of 0.1 .. 0.5 $\mu$m. The minimum useful shape size of 0.1 x 0.3 ($\mu$m)$^2$ mentioned could well be realized as a practical value. Demanding the latter for all patterns fabricated with the HISEL system, though, may be a problem.
3.5.2 Forms of the shaped beam

As for the shaper, the original idea, mentioned in section 1.3 (and figure 1.6), has been implemented in several ways. The shaper can have apertures of equal size or it can be designed with differently sized apertures. Since the source is imaged at the shaping deflector center, one may want to have some space around this image to provide for a long and sensitive deflector. This is in contradiction with the Boersch effect and trajectory displacement generated in the shaper. These effects increase with the length of the shaper section. The optimization of shaper imaging conditions is further investigated in chapter 6.

Another extension is the idea of a keyhole shaper in Toshiba's EX-7 [Tamamushi, 1988, Horiike, 1987]. There, the second shape is not a simple square aperture but it has the form of a keyhole. This combination of a square and such a keyhole form makes it possible to generate variable size rectangular shapes and variable size 45° triangles with rectangular sides to connect to the variable size rectangles. The figures that can be written can be more complex, so by using this shaper the pattern data can be better compacted and the average number of pixels written per shot is increased. This can be seen especially for curved and slanted lines. These lines require less fine division than when these lines were formed using only rectangles.

In the AEBLE-150 [Veneklasen 1985, King 1985] 45° lines are formed using a selection of aperture sets (ref. figure 2.6). Here the beam blanker is placed before the first shaping aperture which contains two square holes. The blanker has three states: beam off, aperture A or aperture B. In this system the second aperture contains two squares one of which is tilted over 45°. This provides rectangles and triangles for both sets of forms.

The shaper can also be designed to have shadow imaging of the two apertures. This is the case for the AEBLE-150. This system has no real imaging of the first shaping aperture onto the second (see figure 3.2). But because of the large demagnification of both shaping apertures towards the target there is a large depth of focus providing sufficiently sharp images of both apertures without a shaper lens.
Figure 3.2: Beam traces in a shadow shaper. Two deflectors are required in order not to move the source cross-over position, as seen from aperture 2.

As can be seen from the keyhole shaper the range of the shaping deflector will have to be increased to provide for triangle forms next to the variable size rectangles. An investigation of this is shown in the left column of figure 3.3. It is concluded that for the normal keyhole shaper the range is $2 \times 4 \left(D_{\text{max}}\right)^2$, where $D_{\text{max}}$ is the maximum shape size. This type of aperture is usually made by etching silicon wafers. A new idea might be to take advantage of possibility to fabricate random shapes with silicon etching. The forms of the shaping apertures in the right column of figure 3.3 require a lower shaper deflection range. With the apertures in the right column the shaper range required is only $2 \times 2 \left(D_{\text{max}}\right)^2$!
Yet another type of shaper was proposed by [Van der Mast, 1987/3]. This system consists of three quadrupoles and two lenses for imaging the first aperture onto the second. With this diamond shaper, sheared rectangles with all shearing angles can be fabricated, and even curved shapes. A conventional shaping aperture might have to be added for the interconnection of the different patterns. This makes the diamond shaper a much longer and more complicated system. Its main application will be in the fabrication of integrated optics circuits.

The exact HISEL system requirements are not known; the system will have to be applicable to both regular IC patterns and to the fabrication of integrated optics circuits. The diamond shaper was therefore not further investigated. As far as the writing of 45° lines is concerned, it is concluded that this can easily be realized with specially formed apertures. From figure 3.3 it follows that the writing of 45° lines has
the effect of enlarging the range of the shaping deflectors by a factor of two to four. This leads to the shaper range in table 3.4.

<table>
<thead>
<tr>
<th>parameter</th>
<th>value</th>
<th>unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>minimum shape width</td>
<td>D</td>
<td>0.1</td>
</tr>
<tr>
<td>minimum shape size</td>
<td></td>
<td>16</td>
</tr>
<tr>
<td>average shape side length</td>
<td>$&lt;D_{pat}&gt;$</td>
<td>0.2</td>
</tr>
<tr>
<td>average shape size</td>
<td></td>
<td>100</td>
</tr>
</tbody>
</table>

with only rectangle forms

| maximum shape side length        | D_{max} | 0.5  | μm   |

with 45° lines possible

| maximum shape side length        | D_{max} | 1.0  | μm   |

Table 3.4: Shaper range for the HISEL variable-shaped beam system

3.6 Other possibilities for improving electron beam writing speed

[Van der Mast, 1985] came up with the idea, mentioned in section 3.1, to apply dynamic brightness to the solid state emitters. This implies that the intensity is varied inversely proportional to the shape area written. Thus the beam current in the system after the second shape will be constant and the current can always have the maximum value determined by electron interaction effects in this part of the system. Trajectory displacement, Boersch effect and space charge effect will be constant. A problem with this proposal is that it will require a varying illumination time per shape written. Other ideas, such as the shower beam reduction of trajectory displacement and the use of chromatic aberration to correct for spherical aberration of the final lens, are also based on the use of PN solid state emitters. (The shower beam effect is depicted in figure 3.4. It is described by [Van der Mast,
1984] and it is based on the reduction of trajectory displacement effect for very thin beamlets.) These emitters allow the designer to put electrostatic lenses and deflecting electrodes very close to the emitter. One possible application for this is the use of several emitting rings with intermediate ring electrodes. These electrodes make it possible to force the angular distribution of the emitter to be more homogeneous over the shaping aperture. Possible emitter configurations will be treated in chapter 4.

Figure 3.4: Multi beam system with low trajectory displacement because of the shower beam effect. The electrons in the thin beamlets only experience longitudinal forces.

In all electron beam systems the positioning deflectors are split into different stages. There are high speed, low(er) accuracy sub field positioning deflectors in combination with high precision, low speed (mostly magnetic) main field deflectors. Here, the range of the high speed deflectors is determined by the high speed electronic components used and by the absolute precision required. This deflector positions a shape with side lengths of 0.1 to 1.0 μm.

With the theory of electron-electron interactions from G. Jansen a very complete understanding of Boersch effect and trajectory displacement has been gained. The complexity of the theory is such, however, that detailed calculations are required in order to get accurate estimations of the effects. A complete system calculation is required for the
correct system optimization. This involves the imaging parts of a variable-shaped beam system: shaper, demagnifying system and projection lens with positioning deflectors. In chapters 5, 6 and 7 investigations of each of these parts will be presented separately.

3.7 Target HISEL specifications

From the different sections in this chapter the target (HISEL) specifications are collected in table 3.5. These have to be compared with the pattern specifications in chapter 1 and the resulting global electron beam conditions mentioned in chapter 2. It is concluded that the (single) focussed beam cannot be a realistic candidate for realizing these specifications. The system will not be completely discarded, however, since it could be interesting to see what specifications might be reached with a highly optimized focussed beam writing system. The variable-shaped beam is the most realistic candidate for realizing the HISEL specifications. The address-grid is specified as being smaller than the edge roughness in the pattern (see section 1.3). To provide for the free placement of features on the target a multibeam system would, therefore, require an area coverage of more than 100%. Also, none of the high beam current sources can be applied to the design of a multi beam system. The sources will be treated more extensively in chapter 4. For these reasons the multibeam system is not considered any further.

Temperature effects are of great importance for the specifications under study. There have been long discussions whether or not it would be possible to provide the beam current mentioned in table 3.5, without heating the resist layer too much. This question can not be answered from the electron optical point of view alone. During the last years improvements in resist sensitivity have continuously progressed. The lowest possible resist sensitivity required for the system is determined by the noise limit (as derived in section 1.3). Temperature effects were not studied in more depth in this research In parallel with this research a specialized study of temperature effects and a detailed design of the required shaping systems were performed by [E. Mulder, 1991].
<table>
<thead>
<tr>
<th>parameter</th>
<th>value</th>
<th>unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>beam voltage</td>
<td>U</td>
<td>5..100 kV</td>
</tr>
<tr>
<td>current stability long term</td>
<td>≈ 5</td>
<td>%</td>
</tr>
<tr>
<td>current stability short term</td>
<td>≈ 1..2</td>
<td>%</td>
</tr>
<tr>
<td>beam current</td>
<td>I</td>
<td>2..10 μA</td>
</tr>
<tr>
<td>pattern coverage (typical)</td>
<td>c</td>
<td>0.5</td>
</tr>
<tr>
<td>pixel transfer rate</td>
<td>R</td>
<td>$8 \times 10^{10}$ s$^{-1}$</td>
</tr>
<tr>
<td>minimum rectangle</td>
<td></td>
<td>100x300 (nm)$^2$</td>
</tr>
<tr>
<td>minimum number of pixels per shot</td>
<td>$N_v$</td>
<td>48</td>
</tr>
<tr>
<td>shot transfer rate</td>
<td>$R_v$</td>
<td>$1.7 \times 10^9$ s$^{-1}$</td>
</tr>
<tr>
<td>minimum shape width</td>
<td>$D_{min}$</td>
<td>0.1 μm</td>
</tr>
<tr>
<td>minimum shape size</td>
<td></td>
<td>16 pixels</td>
</tr>
<tr>
<td>average shape side length</td>
<td>$&lt;D_{pat}&gt;$</td>
<td>0.2 μm</td>
</tr>
<tr>
<td>average shape size</td>
<td></td>
<td>100 pixels</td>
</tr>
<tr>
<td>with only rectangle forms</td>
<td></td>
<td></td>
</tr>
<tr>
<td>maximum shape side length</td>
<td>$D_{max}$</td>
<td>0.5 μm</td>
</tr>
<tr>
<td>with 45° lines possible</td>
<td></td>
<td></td>
</tr>
<tr>
<td>maximum shape side length</td>
<td>$D_{max}$</td>
<td>1.0 μm</td>
</tr>
</tbody>
</table>

Table 3.5: HISEL system specifications.
4 ELECTRON SOURCES FOR HIGH SPEED WRITING

4.1 Introduction

The electron source is of vital importance for the HISEL system. The targets specify a very high beam current in a very small spot. As will be discussed in chapter 5, the aberrations in the system require a final opening angle in the conventional range (2 to 10 mrad) in order to be able to realize the small tolerances in positioning and spot imaging and the high deflection speed of the system. The next sections will shortly investigate different types of emitters that are in use today and their applicability to electron beam lithography. Electron sources were not the main issue of this research. Before thoroughly investigating the source, design calculations had to be done in order to select requirements for the source and to determine the design of the rest of the system. Electron sources for the HISEL system are currently being investigated by J. Koffeman, in a related research project at Delft University of Technology. Special attention will be given here to the silicon PN-emitters recently developed at Philips Natlab (ref. [Van Gorkom, 1987]) since these emitters open several possibilities of improving the design of electron beam pattern generators.

Electron sources are generally characterized by their current I, current density j, semi opening angle \( \alpha \), and by the energy spread of the beam after extraction and acceleration to a voltage U. Space charge effects in the gun are very important. The general approach is to characterize the gun together with its extraction and accelerating optics. This means that the electron beam parameters will be given after acceleration. These give a valid description of the virtual source: looking back at the gun through ideal, accelerating optics. The reduced brightness is defined as

\[
B_r = \frac{I}{d\Omega \, dS \, U}
\]  

(4.1)

where \( d\Omega \) is the solid angle of emission, \( dS \) is the emitting area. This equation is in principle defined for an infinitely fine beamlet on the
axis of the system \(d\Omega \to 0\), \(dS \to 0\). As such, the average reduced brightness for the whole beam (full \(\Omega\) and \(S\)) is of more importance. For beams with even current density and angular current distributions, the average and the axial reduced brightnesses are equal. This is one of the design goals of electron beam writing systems because it leads to the most efficient use of lens areas and to an even current distribution on the target (as was put forward in the requirements). The axial reduced beam brightness is therefore approximated by the average reduced beam brightness

\[
\langle B \rangle = \frac{I}{\Omega S U} \approx \frac{I}{\pi^2 \alpha^2 r^2 U}
\]  

(4.2)

since \(\Omega \approx \pi \alpha^2\) (for small \(\alpha\))

(4.3)

and \(S = \pi r^2\)

(4.4)

where \(r\) is the radius of the emitting area.

Ignoring space charge effects, the transverse energy of the electrons is not influenced by the accelerating field. The Lagrange–Helmholtz relation is an invariant under these conditions

\[
\alpha r \sqrt{U} = \text{Constant}
\]

(4.5)

in any plane in the system (see also [Septier, 1967] p.41, [Grivet, 1971] p.107 and [Jansen, 1988] p.34). From this relation it follows directly that in the system \(B_r\) is constant. Since \(B_r\) is defined for the Gaussian imaging rays and all lens fields are perfect near the axis, \(B_r\) will be constant through all lenses and apertures. The integral beam brightness will decrease when the beam passes imperfect lenses. It also decreases by beam spreading effects such as imperfect lenses and Boersch effect. The average (reduced) brightness can be increased by selecting the central part of the beam with apertures. Furthermore equation (4.5) indicates that the current in a spot can be increased by increasing the beam voltage (for constant radius and semi opening angle). This explains why beam brightness is often used in literature, without reduction by division by the beam voltage as in equations (4.1) and (4.2). Since beam brightness is defined in that manner it is not constant throughout the system and different beam voltages will be applied in the calculations, only reduced beam brightness will be used.
The current density \( j \) follows from
\[
j = \frac{dI}{dS} \approx \frac{I}{\pi r^2}
\] (4.6).

The reduced brightness of a gun is directly related to the energy distribution of the electrons at emission. [Young, 1959] derived the energy distributions and the current density of the electrons upon emission for thermionic and for field cathodes. He derived these characteristics from the solid state physical condition of the electrons as described by the Schrödinger equation.

As for the emission barrier, the different regimes are mainly determined by the extraction electrostatic field at the emitter surface. For low fields pure thermionic emission occurs. At medium field strength the work function is lowered by the electric field, but the electrons emitted still have to be thermally excited to overcome the work function. This is called Schottky emission. At very high field strengths the electrons directly tunnel through the surface barrier (field emission). Here heating may also increase the emission. This is called thermal field emission. These regimes are also distinguished by [Tuggle, 1985/2].

The reduced brightness can be related to the source parameters as derived by [Grivet, 1971] and [v. Gorkom, 1987]. This relation can be easily found by assuming a plane (indicated with the index \( l \)) at voltage \( U_l \), close to the emitter (index \( s_0 \), for source).

The following conditions are assumed:
- current density equal to that at the source \( j_l = j_{s_0} \)
- \( U_l \gg \) equivalent forward voltage at the source
- the average transverse energy is equal to that at the source
  \[ e U_{itr} = k T_e \]
  \( (k \) is Boltzmann's constant, \( e \) is the electron charge and \( T_e \) is the absolute temperature of the emitter).

Thus
\[
\alpha_l = \sqrt[2]{\frac{U_{itr}}{U_l}}
\]

and with equations (4.2) through (4.6) we obtain the average reduced brightness for a thermal emitter
Some typical reduced brightness values can now be derived for the HISEL system. As was mentioned at the beginning of this section, conventional opening angles will be required in the final beam projection optics. Taking a beam semi opening angle of $\alpha = 10$ mrad, in combination with the writing specifications in chapters 1, 2 and 3 gives for a FB system

- spot size $\delta = 25$ nm
- beam current $I = 5$ $\mu$A
- beam voltage $U = 100$ kV

which gives $B_r = 3.2 \times 10^4$ A/cm$^2$/sr/V.

The minimum spot of the VSB system is much bigger and the corresponding reduced beam brightness is proportionally lower

- minimum spot $S = 100 \times 300$ (nm)$^2$
  (this corresponds to a diameter of 195 nm)

which gives $B_r = 1060$ A/cm$^2$/sr/V.

Both reduced brightness values are very high and can only be met with special electron sources. These will be further discussed in the next sections.

The current at the electron source required for 10 $\mu$A final beam current may have to be a great deal higher than 10 $\mu$A. Firstly, in the case of a VSB system, the source opening angle and emission area of the source have to be selected in order to provide the illumination constancy level in the spot as mentioned in the writing specifications in chapter 1. The FB system analogously requires a (lower) beam opening angle reduction to select the central part of the emitted beam which approximates a Gaussian profile. Secondly, a reasonable level of constancy in the angular emission intensity must be selected in order to create optimum conditions for the electron optical lenses in the system. Since this is only for optimization, 10 to 20% angular intensity variation could well be allowed. Depending on the source characteristics a total beam current...
reduction factor of 3 to 10 for FB and 10 to 100 for VSB systems is typical.

As for the case of the VSB system, the electron source is used to create an even intensity distribution for illumination of the first shaping aperture. The beam shaping section will then be used to select only a part of the total beam beam. In this case the beam current is also affected by the area of the shaped spot. Since the biggest spot must be evenly illuminated, smaller spots result in a beam current reduction proportional to the area of the spots. The ratio of average spot size to maximum spot size determines the reduction factor of the average beam current in the shaper section. With a beam shaper range of 1 to 33, as was considered for the HISEL specifications (section 3.5), the maximum current reduction factor is 33 times. To have 10 \( \mu \text{A} \) in the smallest spot of a VSB system, a beam current of 330 \( \mu \text{A} \) through the first shaping aperture will be required! This value is also the maximum current required for a VSB system in dynamic brightness mode. The average shaped spot in a system in fixed brightness mode must have a beam current of 10 \( \mu \text{A} \). With an average shaped spot of (roughly estimated) 0.4 x 0.5 (\( \mu \text{m} \))^2 the maximum current through the first shaping aperture would be in the order of 50 \( \mu \text{A} \).

4.2 Hairpin cathodes

In electron optics the tungsten hairpin cathode is well known. The LaB\(_6\) cathodes were derived from the W cathodes by mounting a small piece of crystalline LaB\(_6\) onto the tungsten wire. Because of the lower work function (see table 4.1), an LaB\(_6\) gun yields three to four times higher current density and higher reduced brightness. Since it is operated at lower temperatures, the LaB\(_6\) gun also has lower energy spread. Most of the VSB writers today use LaB\(_6\) cathodes, see [Moore, 1983], [Davis, 1983], [Veneklasen, 1985], [de Chambost, 1986] and [Tamamushi, 1988]. The LaB\(_6\) cathodes have also been applied to some Gaussian beam writers: [Chen, 1988], Philips EBPG–3 and EBPG–4 [–, 1984].
<table>
<thead>
<tr>
<th>cathode</th>
<th>size</th>
<th>φ</th>
<th>T_e</th>
<th>I</th>
<th>J</th>
<th>B_r</th>
<th>ΔE</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>μm</td>
<td>eV</td>
<td>K</td>
<td>μA</td>
<td>A/cm²</td>
<td>A/cm²sr/V</td>
<td>eV</td>
</tr>
<tr>
<td>W hairpin</td>
<td>15</td>
<td>4.5</td>
<td>2800</td>
<td>70</td>
<td>10</td>
<td>5</td>
<td>1.5</td>
</tr>
<tr>
<td>LaB₆</td>
<td>10</td>
<td>2.4</td>
<td>1900</td>
<td>60</td>
<td>50</td>
<td>20</td>
<td>1</td>
</tr>
<tr>
<td>Field-emitter</td>
<td>0.02</td>
<td>4.5</td>
<td>700</td>
<td>0.01</td>
<td>&gt;1000</td>
<td>3000</td>
<td>0.25</td>
</tr>
<tr>
<td>Zr-Schottky em.</td>
<td>2.5</td>
<td>2.5</td>
<td>1850</td>
<td>350</td>
<td>&gt;1000</td>
<td>1000</td>
<td>0.3</td>
</tr>
<tr>
<td>Si PN-em. (no Cₘ)</td>
<td>1.5</td>
<td>4.7</td>
<td>4400</td>
<td>4</td>
<td>50</td>
<td>2.2</td>
<td>0.9</td>
</tr>
<tr>
<td>Si PN-em. (Cₘ)</td>
<td>0.5</td>
<td>1.7</td>
<td>5700</td>
<td>8</td>
<td>1000</td>
<td>650</td>
<td>1.2</td>
</tr>
<tr>
<td>ZrO W</td>
<td>0.5</td>
<td>2.7</td>
<td>1800</td>
<td>20</td>
<td>2600</td>
<td>3600</td>
<td>2</td>
</tr>
</tbody>
</table>

Table 4.1: Summary table comparing some important emitters. From [Simons, 1985], [Wolfe, 1980], [Pfeiffer, 1971]. The size is a typical value for the average diameter of the emitter. φ is the work function of the material and T_e is the effective electron temperature. I and J are typical current and current densities. B_r is the resulting reduced brightness and ΔE gives the energy spread of a typical gun.

Electron guns require a minimum extraction field strength in order for the electrons to escape from the space charge cloud just outside the material. Attempts to calculate this extraction field analytically were done by [Child, 1911] and by [Langmuir, 1923]. Child approximated the emitter as a parallel plate geometry with injection of zero velocity particles on one side and an electric field generated by the particle cloud. With an extraction electrode at voltage U_1 at an axial position z_1, Child’s law gives the current density

$$ j_{so} = \frac{4 \epsilon_0}{9} \sqrt{\frac{2e}{m}} \frac{U_1^{3/2}}{z_1^2} $$

(4.8)

which gives

$$ j_{so} = 2.33 \times 10^{-6} \frac{U_1^{3/2}}{z_1^2} \text{ (in A/m}^2) $$

(4.8a).
[Langmuir, 1923] also provided a correction for the initial velocities of the electrons but this gives only a change in equation (4.8). In Langmuir’s approach there exists a potential minimum in front of the emitter into which the electrons are injected because of their initial velocity. From this potential minimum to the extraction plate the Child approximation holds. Langmuir’s correction describes the position and the value of the potential minimum. As mentioned by [Van den Broek, 1986] the potential minimum is very close to the emitter (1 .. 10 μm) and its value is very low (0.1 .. 0.5 V).

If in a given extraction system the current density comes close to the value predicted by Child’s law, space charge effects will dominate the brightness of the gun. Then both current density and reduced brightness are severely degraded by the space charge cloud. In normal operation the extraction field is chosen sufficiently high. The theoretical models mentioned are not sufficiently accurate for application to high brightness sources in electron beam writing systems. They can be used to check the order of magnitude of the results. More accurate field calculations were done by [Van den Broek, 1986] for CRT-type emitters, taking into account the space charge of the extracted beam of electrons. In this program the current density calculation is directly related to the extraction field strength. This limits the applicability of the program to thermal emitters. [Jansen, 1988] extended his Monte Carlo simulation program for electron beam systems to support linear acceleration of electron beams. These programs have no been applied to measured gun setups, though. Especially in the case of high brightness PN-emitters, problems arise with the change of the sample length and with the very high field strengths applied to the emitters.

Considering the aims of the HISEL project and the data in table 4.1, both W and standard LaB₆ emitters provide too low a brightness. It might be possible to apply an extremely well engineered LaB₆ emitter in a variable−shaped beam HISEL system.

4.3 Field emitters

As was indicated in table 4.1, field emitters have brightness values that approach those required for the HISEL system. These emitters consist of a very fine pointed tungsten (W) crystal mounted on a W heater wire. The surface of the emitter is cleaned by heating the
emitter (flashing). This has to be done regularly. The emitter can only be operated in an ultra high vacuum system. Application of an extraction voltage of some kV results in a very high extraction field strength because the tip has a very small radius of curvature (< 0.1 μm). Therefore, the electrons in the material are able to tunnel through the surface barrier into the vacuum. This tunneling does not heavily depend on temperature and therefore it is not necessary to heat the emitter. If the emitter temperature determined the energy spread it would be about 64 meV at room temperature. The energy spread given in literature ([van der Mast, 1983] and [Tuggle, 1985/1]) is about 0.25 eV, which implies that electron interaction effects are very important here.

Since field emitters are normally operated at room temperature the emitter surface is rather sensitive to contamination. This implies a somewhat larger drift in the emission current density as compared to W emitters. The very small emitting point must also be mechanically very well fixed to the optical system to prevent movements of the final spot. The current density of these emitters is very high; the total current is limited by the emission area to some 100 nA. Field emitters are usually imaged with a magnifying system. Therefore lens aberrations of all lenses have to be taken into account. Flashing also severely influences the DC emission characteristics of the gun. Because of this, field emitters are hardly used in electron beam pattern generators.

A very special type of field emitter was fabricated by [Spindt, 1976]. This source consists of a thin film device with many (100 .. 5000) very small field emitting points. It is fabricated by using integrated circuit fabrication techniques. The total emission of this gun can be relatively high, but the instability reported is still too high (25%). Spindt mentions the possible failure of single emitters in the array. This cannot be tolerated when the array is imaged onto the target. It seems possible to insert complex surface electrodes in order to enable the modulation of every emitter separately, but this has not yet been done. With some extra facilities for stabilization of the emitted current, this type of emitter might be of use in a multibeam writing system. The arrays could be used to have multiple beamlets imaged in the principal plane of the final lens. In that case every single emitter has to keep working. It seems more appropriate to use these multiple emitters with Köhler emission in a VSB system. By adjusting the bias voltage of each beamlet the spherical aberration of the final lens could even be corrected. [Van der Mast, 1985] termed this type of imaging system 'the showerbeam' (ref. section 3.3).
4.4 Thermal Field emitters

Thermal field emitters were pioneered by [Swanson, 1975]. They were well described by [Tuggle, 1985]. The emitters consist of a tungsten crystal with a zirconium surface layer for lowering the work function from 4.5 eV to 2.7 eV. This work function depends on the crystallographic plane of the tungsten which opens the possibility to reduce the side lobes of the emission. The emitters have tip radii of 0.5 .. 5 µm and they are operated at about 1800 K. The fabrication process still poses some problems with respect to these emitters. Because of their high brightness these emitters are applied in several Gaussian electron beam writing systems: [Kelly, 1981], [Thomson, 1987], [Iwadate, 1987], [Nakazawa, 1988] and [Gesley, 1988].

It should be noted that the thermal field emitters may well become used in electron beam writing systems. The achievable total current of emitters in use today is in the order of 8 µA, because only a small part of the tip is emitting electrons. With the aims of the HISEL variable-shaped beam system this beam current limit reduces the application of the emitters to FB systems. For VSB systems it is too low since the beam shaper strongly reduces the total beam current. Dynamic brightness modulation as mentioned in section 3.6 is impossible with these emitters.

4.5 PN-emitters

The PN-emitter was developed at Philips Nalab in recent years by [Hoeberechts and v. Gorkom, 1984, 1986, 1987]. The device consists of a shallow PN-junction near the surface of a silicon chip. A schematic view is given in figure 4.1. The junction is reverse biased with 5 .. 10 V and it is made in such a way that the electrons flow towards the surface. Since the Si work function is in the order of 4.7 eV some of the electrons are able to gain enough energy to overcome the work function and escape from the material. In the case of a bare silicon surface no more than 1 in every 10^6 electrons will escape. By depositing a mono layer of caesium on the silicon the work function is reduced from
4.7 eV to about 1.7 eV. This effect may increase the efficiency to 5% and higher, though 3% is a realistic value. The efficiency, \( \eta \), is hereby defined as the ratio between the current emitted into the vacuum, \( I_{\text{vac}} \), and the total current flowing through the device, \( I_{\text{tot}} \).

\[
I_{\text{vac}} = \eta I_{\text{tot}} \quad (4.9)
\]

![Figure 4.1: Geometry of a simple (rotationally symmetric) PN solid state emitter as described by [Van Gorkom, 1984]. There is a direct relation between the current density \( j_{d1} \) in the material and that on the vacuum side \( j_{\text{vac}} \). The channel, of thickness \( d_c \), is highly doped \( n^{++} \)-silicon. On top of the emitter is a mono layer of \( C_s \) to lower the work function. The gate is an isolated electrode providing the extraction field.

The top channel is very thin (\( d_{ch} \approx 10 \text{ nm} \)) in order to obtain maximum vacuum current density. Therefore the current density \( j_{d2} \) (ref. figure 4.1) limits the total junction current. This is called current crowding. Since the current density in the material can be very high, this still leaves a high current density on the vacuum side of the emitter. The top channel has to be very thin. Its thickness is determined by the doping level reached in the channel. The vacuum current density is directly proportional to the forward junction current density, \( j_{d1} \). The total current through the device and the vacuum current density, \( j_{\text{vac}} \), follow from the geometrical dependence

\[
I_{\text{tot}} = I_{\text{vac}} + I_2 \quad (4.10)
\]

with

\[
I_{\text{tot}} = \pi r_0^2 j_{d1}, \quad I_{\text{vac}} = \pi r_0^2 j_{\text{vac}} \quad \text{and} \quad I_2 = 2 \pi r_0 d_c j_{d2}
\]
for small $I_{\text{vac}}$ this gives

$$j_{d1} = \frac{2 \ d \ c}{r_0} j_{d2}.$$ 

And combining this with equation (4.9) results in

$$j_{\text{vac}} = \eta \ \frac{2 \ d \ c}{r_0} j_{d2}$$

(4.11),

where the maximum current density is $j_{d2} = 2.5 \times 10^6 \ \text{A/cm}^2$

and the channel is very thin $d_c = 10 \ \text{nm}$.

The optimum doping level and channel thickness were determined in practice by Van Gorkom. He varied these values in a wide range. The maximum current density is directly dependent on the doping level of the channel.

Because the top layer is very thin the current density, $j_{d2}$ (see figure 4.1), limits the total current through the device. This phenomenon is called current crowding and as a result of it, the forward current density, $j_{d1}$, will never come near its maximum value. Current crowding is the reason why smaller emitters provide higher beam current densities, as was found in equation (4.1). Some realistic parameter values for PN-emitters are:

$$\eta = 2 \ \% \ \text{and} \ r_0 = 0.5 \ \mu\text{m} \implies$$

$$I = 16 \ \mu\text{A}, \ j_{d2} = 2.5 \times 10^6 \ \text{A/cm}^2, \ j_{\text{vac}} = 2000 \ \text{A/cm}^2.$$ 

$$\eta = 2 \ \% \ \text{and} \ r_0 = 1.5 \ \mu\text{m} \implies$$

$$I = 47 \ \mu\text{A}, \ j_{d2} = 2.5 \times 10^6 \ \text{A/cm}^2, \ j_{\text{vac}} = 670 \ \text{A/cm}^2.$$ 

Hoeberechts and Van Gorkom have extensively studied the electron emission from these emitters, (private communications with Hoeberechts and Van Gorkom and [Van Gorkom, 1986]). They describe the electrons in the cathode as a hot electron gas the temperature of which is not in equilibrium with the solid state lattice. The electric field accelerates
the electrons and generates a total energy distribution that can be approximated with a Maxwellian curve, as depicted in figure 4.2.

\[
\frac{dN}{dE} (E) \sim E \exp \left( -\frac{E}{kT} \right)
\]

Figure 4.2: Arbitrarily scaled plot of the Maxwellian electron energy distribution.

The maximum of the distribution is found at \( E = kT_e \)
and it has a full width at half maximum \( \Delta E_{\text{FWHM}} = 2.45 \, kT_e \).
For the PN-emitters a value of \( \Delta E_{\text{FWHM}} = 1.20 \, \text{eV} \) has been measured.
This corresponds to an effective electron temperature \( T_e = 5700 \, \text{K} \).
In the special case of selecting electrons emitted at very small angles \( T_e = 3000 \, \text{K} \) and \( \Delta E_{\text{FWHM}} = 0.3 \, \text{eV} \) have been measured. But this cannot be applied to the HISEL system, because in this system the highest possible emission current is required.

With equation (4.7) the reduced brightness can be calculated for the above mentioned PN-emitters:
\[ r_0 = 0.5 \, \mu m \implies B_r = 1300 \, \text{A/cm}^2/\text{sr}/V, \]
\[ r_0 = 1.5 \, \mu m \implies B_r = 430 \, \text{A/cm}^2/\text{sr}/V. \]

Even higher brightness may be possible since the emitter efficiency is not yet fully optimized. Under ideal laboratory conditions efficiencies of 7% have been reached (with 500 V extraction voltage under ion bombardment for thinning of the top channel). This increases the attainable vacuum current and the brightness proportional to the efficiency.

First measurements at Philips Natlab indicate a Gaussian profile for the angular emission distribution. (The central part of this distribution roughly resembles the familiar cosine distribution of hairpin cathodes.) The Gaussian angular emission distribution poses a severe problem on the demand for uniform illumination of the shaping apertures. For an illumination inhomogeneity level of 5%, about 5% of the total current emitted in a Gaussian profile can be used.

On the sides of the emitter there is a first extraction electrode mounted by metal vapor deposition with a silicon dioxide isolation layer. This electrode is called the gate, and by applying a small positive voltage to it the extraction field strength can easily be brought above the level required for overcoming space charge problems (ref. Child’s law, equation (4.8)).

![Diagram of a ring type PN-emitter](image)

**Figure 4.3:** Geometry of a ring type PN-emitter. The current can only flow away through the n''-channel outer ring.

Since the PN solid state emitters are fabricated using IC fabrication technology the exact form of the emitting area can be determined by the designer. Several ideas were proposed of filling a circular region with emitting rings and with intermediate electrodes. By applying bias
voltages to these electrodes the angular distribution may be smeared out. As an example of the above mentioned geometrical argument, the optical parameters for an emitter ring will be calculated. Even with only current removal through the outer radius the emitter current can be increased because of the material current density limit (see figure 4.3).

Supposing an inner radius of \( r_1 = 3.0 \, \mu \text{m} \), outer radius \( r_2 = 4.5 \, \mu \text{m} \):

\[
I_{\text{tot}} = \pi (r_2^2 - r_1^2) j_{d0} = 2 \pi r_c d_0 j_{d2} \]

\[
j_{\text{vac}} = \eta \frac{2 r_c d_2}{r_2^2 - r_1^2} \tag{4.11a}
\]

\[
\Rightarrow I_{\text{tot}} = 7.1 \, \text{mA}, \quad j_{\text{vac}} = 2.0 \times 10^4 \, \text{A/cm}^2.
\]

As can be seen the current is proportional to the outer radius of the current draining region. The vacuum current density can be maximized by making \( r_1 \) about equal to \( r_2 \). A width of 0.5 \( \mu \text{m} \) of the ring is mentioned as a practical value. But in that case one obtains a hollow beam. This might be of good use. In the final lens a sharp image of the source can be formed. Since spherical aberration follows from variation of the lens strength as function of the radial position in the lens used, using a hollow beam could reduce it.

Choosing this spherical aberration correction implies, for the rest of the system, a less efficient use of the beam cross sectional area. In order to allow for both high current and high current density meandering emitter patterns within a circular region would be required. The electrodes also drain the current in the top layer of the emitter more efficiently than the \( \text{n}^{++} \)-channel (see figure 4.4). Another manner of filling the area could be using multiple rings. In that case the forward voltage of each emitter ring might be adjusted to compensate for spherical aberration in the final lens. This idea has been extended to the so called 'forced angular distribution'. However, it was found that the idea of a forced angular distribution is very difficult to realize, since the high beam current emitters have to be provided with a means to reduce the ion bombardment. This ion bombardment from the column onto the emitter is reduced with an ion trap. The trap cannot be made to work with such a large emitter without blurring the beam so much that the rings can no longer be sharply imaged. The image of the emitter in the
cardinal plane of the final lens will therefore be unsharp. This renders the spherical aberration correction of the last lens impossible. The inter-ring electrodes might be used to make the homogeneous central part of the beam as big as possible. This would reduce the beam current loss at the first shaping aperture.

![Diagram](image)

Figure 4.4: Different line patterns that could be applied to fill the emitting area of PN-emitters.

The modulation of the PN-emitters is now limited in bandwidth to some 100 MHz. This is mainly due to the design of the gate structure which forms a big capacitance from ground to the $n^{++}$-channel. Redesign of the emitter may very well make modulation possible, thereby creating the possibilities of both blanking and intensity variation. (The latter is required for the implementation of dynamic brightness.) The intrinsic switching time of a small circular emitter is known to be in the order of 10 ps. As mentioned in chapter 3 the writing rate for shapes is expected to have a maximum of about $1.7 \times 10^9$ s$^{-1}$. This requires a modulation bandwidth of some 3.5 GHz. Blanking may require a bandwidth of 10 GHz. Since one also has to take into account the space charge build up the focus of the final spot changes as the total current in the beam is varied.

In general the PN-solid state emitters are very promising but the currently available emitters cannot be applied directly to VSB writing.
Depending on the emitter structure total current and brightness could be made sufficiently high to provide an electron source for the conditions mentioned in chapters 1 through 3. The research of a forced angular distribution, providing for a very good illumination constancy over a beam shaping aperture, is beyond the scope of this thesis. As are the remaining problems with PN–solid state emitters concerned with cleaning procedures, ion sputtering and extraction optics. Research in this direction is progressing fast and it seems reasonable to assume that high brightness, high current PN-emitters will become available in the near future. Total beam current and beam brightnesses mentioned in this chapter could then be realized.

As an alternative source for a shaped beam HISEL, well engineered LaB$_6$ guns should be considered. These may be able to provide beams in the correct range of current, with reduced beam brightnesses in the order of 20 to 100 A/cm$^2$/sr/V. It is expected that the energy spread of such a source would be in the order of 1 to 5 eV. For a focussed beam HISEL system only the very high brightness sources, like (thermal) field emitter, provide an alternative for a PN-emitter. In this case the stability of the sources requires more engineering. Such sources might provide reduced brightnesses in the order of 2000 to 3000 A/cm$^2$/sr/V, which is still about one order of magnitude too low for the HISEL system specifications.

All in all the design of the HISEL system is seen to pose very high demands upon the source. It requires the very high current and the very high (reduced) brightness of PN-emitters. Only very well engineered LaB$_6$ may be usable as an alternative. Neither of these sources has been demonstrated to work in practice.
5 ERROR BUDGETS IN AN ELECTRON BEAM PATTERN GENERATOR

5.1 Introduction

As already mentioned, the system has to be optimized with respect to the total error budget. The analytical aberration effect equations with respect to the error contributions in the different sections are presented in this chapter. The different beam sections that make up any electron beam writing system will be presented here. With the developments described in chapter 3 the boundary conditions for all beam sections will be determined. With regard to the different electron sources it was mentioned before that it will be difficult (if not impossible) to realize a focussed beam HISEL system. The VSB version of the HISEL system will therefore receive most attention. In each of the intermediate images of the shaping apertures the system error budget is expressed in terms of the final beam size, beam current, opening angle and beam voltage. This approach leaves open the choice for different magnifications from shaper to final image and for an accelerating section. It allows for splitting of the electron beam writing system into a number of independent beam sections. The final imaging conditions can be used to select realistic setups for each of the beam sections.

The reduced beam brightness, $B_r$, is a quantity which is conserved in the system. It is independent of absolute beam size and beam potential. The image specifications in chapter 1 correspond to very bright sources. Only the high brightness PN-emitters can be used. For these emitters the brightness values indicated in section 4.5 will be used. Another related subject is the design of very high bandwidth deflectors for both shapers and XY-deflectors. Dr. ir. E. Mulder (one of the members of our group) was involved in the design of 3.5 GHz bandwidth deflectors which could be used in the system.

In this chapter the optical error budget will be presented disregarding the errors from electron-electron interactions. From this budget realistic imaging conditions will be derived leading to the electron-electron effect calculations in chapters 6, 7 and 8. Conventional aberration calculations can be done very accurately using design
software by e.g. Munroe or Lencová. In order to get sufficient design insight, simple analytical expressions are sufficient. Therefore only the well known approximation equations will be used. These illustrate the parameter dependence more clearly than numerical results. The electron-electron interaction effects are not linearly dependent on beam size and beam voltage. These effects will be accounted for in chapters 6, 7 and 8.

The following beam sections are considered:

- **source** (index so)

  The source section is designed to illuminate the beam shaping apertures with sufficient illumination uniformity. The source instability and drift should be very low (<< 1%, long term) during several days of writing (ref. table 3.5). The system will be regularly tuned (every few minutes or every hour) but the system down time must be extremely low. Reduced brightnesses in the range of 100 (VSB) to 1000 (FB) A/cm²/sr/V and beam voltages from 2 to 100 kV will be considered. As was mentioned in section 4.5, different emitters may be able to provide these high brightnesses.

- **shaper** (index s).

  The shaper section is only required for the VSB version of the HISEL system. It was introduced in section 1.3 and in section 3.5, which described some recent developments in shaping design and shaping range determination. The first type of shaper considered is the imaging shaper which uses a shaper lens (figure 1.6). The second type uses shadow projection (figure 3.2). Before the second shaping aperture the beam current varies from 10 to 330 μA in dynamic brightness mode. When the dynamic brightness mode is not used, the beam current depends upon the maximum and the average shape sizes. Beam currents in the shaper from 5 to 180 μA will be investigated. This corresponds to an average shaped spot of 0.2 x 0.2 (μm)² and a maximum shaped spot size of 1 x 1 (μm)². As was mentioned in section 4.1, the maximum beam current may even be lower if a larger average shaped spot can be realized.

  The electrostatic deflector will be denoted with index E for the imaging shaper. E1, E2 will be used for the double deflector of the shadow shaper. It will be shown in chapter 6 that with very fast
shaping deflectors in dynamic brightness mode it is still possible to select a certain smallest area with which all of the pattern is written (disregarding shape setup times). In that case the beam currents will not vary, only the form of the shape will.

- **demagnification section** (index m).

This section creates a demagnified image of the second shaping aperture using a strong (magnetic) lens. In the case of a FB system, too, a source demagnification is sometimes required. This is the case, for example, when a large PN-emitter would be used, from which only a small part of the beam current has the required Gaussian spot properties. Because of the large amounts of Boersch effect and trajectory displacement (see calculations) only 20 and 100 kV beam energy can be realistically considered. Therefore an accelerating section is included for the low voltage sources and shapers. It will be found that, in order to minimize Boersch effect, this section should be as short as possible. A strong magnetic lens will therefore be considered, compared to a longer set-up (with a weaker magnetic lens). Boersch and trajectory displacement effects of this section will be determined in chapter 7.

- **projection section** (index p).

This section contains the positioning deflectors and a strong lens with a large field of view. The field of view of this lens is usually in the order of 1 x 1 (mm)$^2$. This field of view in most cases limits the focal length of the lens to about 30 to 40 mm (ref. [Veneklasen, 1985/2] for the AEBLE-150). As in the IBM EL-3, a variable axis immersion lens (VAIL) will be considered. With a VAIL it may be possible to have about 5 mm focal length for the same field of view, which strongly reduces the length of the projection section and thus the trajectory displacement. Calculations for trajectory displacement and Boersch effect will be presented in chapter 8. The parameters for this section are almost the same for both FB and VSB systems.

The total image resolution (in all sections) is described using the following variables (see also section 1.3 for the specifications of the
minimum feature size \( D_p = 0.1 \mu m \)

edge roughness \( \delta_p = 25 \text{ nm} \)

positioning accuracy \( \Delta_p = 6 \text{ nm} \)

(axial) image position \( z_p \)

axial depth of focus \( \Delta z_p = 0.5 \ldots 2 \mu m \)

maximum spot size (1 \( \mu m \)) \( D_p = 1 \mu m \)

shaped area relative to maximum shape size \( a = 0.03 \ldots 1 \).

The final spot area is: \( D_p^2 a \).

The values presented will be applied in the next chapters. The total unsharpness in the final image has contributions from

- depth of focus:
  \[ \delta_{dof,p} = \alpha \Delta z_p \]  
  where \( \alpha_p \) is the beam semi opening angle in the projection section and \( \Delta z_p \) is the depth of focus

- spherical aberration:
  \[ \delta_{sa,p} = C \alpha_p^3 \]  

- chromatic aberration:
  \[ \delta_{c,p} = C \alpha_p \Delta U_p / U_p \]  
  where \( C_{c,p} \) is the chromatic aberration coefficient of the projection lens and \( \Delta U_p \) (FWHM) is the energy spread in the beam at the position of the projection lens

- deflector chromatic aberration:
  \[ \delta_{EC,p} = D_p \Delta U_p / U_p \]  
  where \( U_p \) and \( \Delta U_p \) are the beam voltage and voltage spread at the shaper respectively. \( D_p \) is the side length of the second shaping aperture. This value is also equal to half the maximum shape deflection in the image of the second shaping aperture.
In chapter 8 the design of a realistic projection section will be based on computations done by B. Lencová. These computations take into account the aberrations mentioned and also the landing error and higher order aberrations. These effects only occur in the projection section and they are determined by the input conditions of the beam entering the projection section. They are not further investigated here since they give no insight into the design of the other beam sections.

The contributions of different effects are usually added quadratically since linear summation yields an overestimation of the blurring of the spot. The weighting factors are not very important since all effects are determined only in approximation. The electron beam writing system considered is pushed to the limits of all the effects mentioned and hence the effects will be comparable in size. This is captured in the equation for total edge roughness

\[
\delta_{\text{tot},p}^2 = \delta_{\text{dof},p}^2 + \delta_{\text{sa},p}^2 + \delta_{\text{c},p}^2 + \delta_{\text{EC},p}^2 + \delta_{\text{TD},p}^2
\]  

(5.5)

Each contribution is considered to be equally important. Therefore, each contribution will be set to one fifth of the total (squared) edge roughness.

Thus:

\[
\delta_{\text{dof},p}^2 = 0.2 \delta_{\text{tot},p}^2 \Rightarrow \delta_{\text{dof},p} = 0.45 \delta_{\text{tot},p}
\]  

(5.6)

Thus every one of the edge roughness contributions may have a value of roughly up to \( \delta_{\text{tot},p} = 25 \text{ nm} \)

\[
0.45 \delta_{\text{tot},p} = 11 \text{ nm}
\]

for the values mentioned.

### 5.2 Depth of focus

From the writing specifications described in section 1.3 a relation between source brightness and depth of focus is derived. It turns out that for realistic sources the depth of focus will be significantly lower than in today's electron beam writers. Depending on the
application of the writing system (mask making or direct wafer writing) this reduction of depth of focus may become a problem. A range of three values of depth of focus is selected with corresponding source brightnesses. The main contributing factors are found to be topography, resist thickness and optical focusing accuracy (and stability).

Depth of focus requirements depend on the application of the electron beam writer. For direct-writing of wafers the topography of the underlying layers is of importance. In the feasibility studies for very high resolution optical systems, [Lin, 1987], [Arden, 1987], height variations due to topography are mentioned of about 1.0 μm for today's IC's. Both authors foresee a reduction of the topographical height variations to about 0.5 μm in the near future, either by changes in the processes for IC-fabrication or by planarization with resist layers.

Many resist systems are being designed in which a thin top layer is activated by the electron beam illumination. An intermediate step is then the transfer of this image into the lower resist layer, often using reactive ion etching (because of its steep wall profiles). [Moran, 1979] has reported on a three layer resist which reduces topographic height variations from 1.0 to about 0.3 μm. About the same numbers are mentioned by [White, 1983]. Multi layer resists are also described by [Sugito, 1988], [Babich, 1988] and [Leuschner, 1988]. [Gillespie, 1983], [Schellekens, 1988] and [Coopmans, 1986] even mention the imaging of the top layer of a thicker resist (1..2 μm). The thickness of the active imaging region is not mentioned by them. The advantage of top imaging resists lies in the fact that the thickness of the resist layer is not very critical. (Resist layers, which are applied by spin coating, cannot be much thinner than 0.5 μm without forming pinhole defects.) The required depth of focus for future resists systems is therefore in the order of 0.3 μm and it may even be lower when top imaging is further refined.

The focusing properties of the system are related to the optical components and to the writing strategy of the system. The writing strategy is to split up the field of view of the projection lens into several sub fields. The actual writing position is addressed with two deflectors. Next to the speed improvement of the sub field deflector in comparison with the main deflector there are several other reasons to use multiple positioning deflectors. There is a (physical) data compression by describing an absolute position relative to a sub field origin, as was mentioned in section 3.4. Furthermore the deflector
aberrations are corrected on a shot by shot basis. These correction values are interpolated within a sub field and the interpolation coefficients can be set (or measured) for every new sub field. The same holds for deflector aberrations and corrections for position measurement of the stage. In general, one focus setting per sub field is used, which compensates for the curvature of field of the projection lens and the tilt, bowing and non-flatness of the wafer. Other projection lens aberrations, such as rotation and magnification errors, are corrected on a sub field by sub field basis. Position correction schemes can also compensate for thermal expansion of the wafer and for expansion and deformation due to wafer processing. [Alles, 1987/1] mentions for the EBES-4 a main field of 256 μm (square), a sub field of 32 μm with a positioning accuracy of 1/64 μm (1/8 μm diameter pixels). Thus a sub field contains some 16000 pixels and with 50% coverage that is 8000 pixels or 90 shots of 90 pixels. [Moore, 1983] mentions the LEARN system of IBM which achieves the same corrections by mapping the wafer prior to writing on it.

The remaining contributions to the depth of focus are topography and (imaging) resist thickness. All other height variations with low spatial frequency can be corrected in the electron optical beam settings. As these are not corrected in optical lithography [Lin, 1987] and [Arden, 1987] have to calculate with much stricter depth of focus budgets. For mask writing, where no underlying topography exists, only the resist thickness will be of importance. All in all a range of depth of focus values 0.5 μm, 1.0 μm and 2.0 μm will be regarded.

Assuming the reduced brightness is only limited by the depth of focus values just mentioned, we find the minimum required brightnesses from equation (4.1). These are summarized in tables 5.1 and 5.2.

A final opening angle of 25 mrad is not allowed even for the shortest projection focal lengths considered. Realistic final opening angles will be below 13 mrad, allowing for 1.0 μm depth of focus at all times. Reduction of the opening angle is allowed, but it leads to a quadratic increase of the required beam brightness. To allow for the full shaping range (table 5.2) the final beam potential must be in the range 20 to 100 kV.
<table>
<thead>
<tr>
<th>$\Delta z_p$ ($\mu$m)</th>
<th>0.5</th>
<th>1.0</th>
<th>2.0</th>
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</thead>
<tbody>
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<td>U (kV) $\alpha_p$ (mrad)</td>
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<td>12.5</td>
<td>6.25</td>
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<td>255</td>
<td>1020</td>
<td>4070</td>
</tr>
<tr>
<td>5</td>
<td>102</td>
<td>407</td>
<td>1630</td>
</tr>
<tr>
<td>20</td>
<td>25.5</td>
<td>102</td>
<td>407</td>
</tr>
<tr>
<td>100</td>
<td>5.1</td>
<td>20.4</td>
<td>81.5</td>
</tr>
</tbody>
</table>

Table 5.1: Minimum required source brightnesses as a function of depth of focus and the HISEL writing specifications. The values in the matrix are $B_p$-values (in A/cm$^2$/sr/V) for the case of a full size shaped spot.

<table>
<thead>
<tr>
<th>$\Delta z_p$ ($\mu$m)</th>
<th>0.5</th>
<th>1.0</th>
<th>2.0</th>
</tr>
</thead>
<tbody>
<tr>
<td>U (kV) $\alpha_p$ (mrad)</td>
<td>25</td>
<td>12.5</td>
<td>6.25</td>
</tr>
<tr>
<td>2</td>
<td>8500</td>
<td>$3.4 \times 10^4$</td>
<td>$1.4 \times 10^5$</td>
</tr>
<tr>
<td>5</td>
<td>3400</td>
<td>$1.4 \times 10^4$</td>
<td>$5.4 \times 10^4$</td>
</tr>
<tr>
<td>20</td>
<td>850</td>
<td>3400</td>
<td>$1.4 \times 10^4$</td>
</tr>
<tr>
<td>100</td>
<td>170</td>
<td>680</td>
<td>2720</td>
</tr>
</tbody>
</table>

Table 5.2: Minimum required source brightnesses as a function of depth of focus and the HISEL writing specifications. The values in the matrix are $B_p$-values (in A/cm$^2$/sr/V) for the case of the smallest shaped spot (0.1 x 0.3 (µm)$^2$, $a = 0.03$).

In case of the shadow shapers, the depth of focus is determined by the unsharpness in both of the imaged apertures of the shaper. Since the axial magnification is the inverse square of the transverse magnification, $M_s$, the depth of focus in the target plane is related to the axial length of the shaper according to

$$
\Delta z_{dof} = \frac{L_s}{M_s^2}
$$

(5.7)

where $L_s$ is the length of the shaper (between the apertures). This value also contributes to the total unsharpness in equation (5.5) through $\delta_{p,dof}$. 
For example, the numbers for the AEBLE-150 are $L_s = 25$ mm and $\Delta z_{dof} = 4.4 \mu m$. This gives, in combination with a final aperture angle of 10 mrad, an unsharpness of 44 nm, which is within the specifications for this system. This method will be used in chapter 6 to determine the dimensions of the shaper.

For the HISEL system the relevant range of depth of focus values 0.5 $\mu m$, 1.0 $\mu m$ and 2.0 $\mu m$ will be regarded.

5.3 Spherical aberration

Most electron optical systems are designed with the last lens demagnifying so much that spherical aberration is fully determined by the last lens. The only demand to be fulfilled is that the demagnification of this lens is sufficiently high. This demand is not compatible with the large working distance and the large field of view requested in electron beam lithography. As with depth of focus the range of acceptable values should be chosen carefully.

The newest type of lens developed for projection systems are the variable axis immersion lens (VAIL, ref. [Sturans, 1983], [Pfeiffer, 1983]). This lens combines a large field of view with a very short focal length by placement of deflectors in the lens field. As a consequence the target (wafer) is also immersed in the magnetic field. With the VAIL a mathematical concept is provided for describing the integration of beam deflectors into the final lens. The superposition of the fields leads to a shifted lens field with a shorter overall length. The same method is applied to moving object lenses (MOL) and swinging objective immersion lenses (SOIL, ref. [Chen, 1988]). It will be shown that a realistic field of view can be realized using a variable axis immersion lens. When using conventional lenses only a very small field of view and a very small working distance are allowed. A separate aspect of the VAIL lens is its transverse chromatic aberration. This error only occurs for a deflected beam (within each of the sub fields addressed). It is therefore compensated on a sub field by sub field basis. The relative size of the sub field as compared to the total field of view of the final lens has not yet been fixed.
With equation (5.2) for spherical aberration the following values will be considered:

\[ \delta_{\text{sa,p}} = 0.45 \times 25 \text{ nm} = 11 \text{ nm} \]

In chapter 8 an optimized projection section will be introduced with a VAIL for which

\[ C_{\text{sa}} = 3 \text{ mm} \Rightarrow \alpha_p = 15.5 \text{ mrad}. \]

This section will be compared with a more conventional projection lens section with

\[ C_{\text{sa}} = 30 \text{ mm} \Rightarrow \alpha_p = 7.2 \text{ mrad}. \]

The upper values for realistic beam semi opening angles are indicated for each of the sections.

5.4 Chromatic aberration

For a single lens (index \( x \)) the chromatic aberration is defined by

\[ \delta_{\text{c,x}} = \frac{C_{\text{c,x}} \alpha_x}{U_x} \frac{\Delta U_x}{x} \]

(5.8)

where \( C_{\text{c,x}} \) is the coefficient of chromatic aberration of the lens, \( U_x \) and \( \Delta U_x \) are the beam voltage and voltage spread (FWHM, directly related to the energy spread) in the beam at the position of the lens. Thus, in order to combine the chromatic aberration of the demagnification and the projection lenses, the total effect in the final image plane is found by adding the contributions linearly according to

\[ \delta_{\text{c,m}} = C_{\text{c,m}} \alpha_m \frac{\Delta U_m}{U_m} \]
\[
\delta_{c,p} = M_{mp} \delta_{c,m} + C_{c,p} \alpha_p \frac{\Delta U}{U_p}
\]

\[
= M_{mp} C_{c,m} \alpha_m \frac{\Delta U}{U_m} + C_{c,p} \alpha_p \frac{\Delta U}{U_p}
\]

\[
\delta_{c,p} = \alpha_p \left( M_{mp}^2 C_{c,m} \frac{\Delta U}{U_m} + C_{c,p} \frac{\Delta U}{U_p} \right)
\]  \hspace{1cm} (5.9)

here \(M_{mp}\) is the magnification factor of the projection section (from demagnifying section intermediate image to projection section final image). In most cases the projection lens realizes some demagnification of the image. This corresponds to a factor \(M_{mp}\) smaller than one. Equation (5.9) indicates that mainly the \(C_c\)-value of the projection lens is importance. It also follows that the total effect is linearly dependent on \(\alpha_p\). The equivalent coefficient of chromatic aberration for the whole system is about equal to the \(C_c\)-value of the projection lens.

Some realistic values illustrate the order of magnitude for the total effect:

\[
\delta_{c,p} = 0.45 \times 25 \text{ nm} = 11 \text{ nm}
\]

demagnification section: short \(C_{c,m} = 3 \text{ mm}\)
long \(C_{c,m} = 30 \text{ mm}\)

projection section: short \(C_{c,p} = 3 \text{ mm}\)
long \(C_{c,p} = 30 \text{ mm}\)

with a demagnification short \(M_{mp} = 0.2\)
long \(M_{mp} = 0.3\)
thus for the whole system

<table>
<thead>
<tr>
<th>Type</th>
<th>C_{c,tot}</th>
<th>\alpha_p</th>
</tr>
</thead>
<tbody>
<tr>
<td>short</td>
<td>3.1 mm</td>
<td>37.0 mrad</td>
</tr>
<tr>
<td>long</td>
<td>32.7 mm</td>
<td>3.7 mrad</td>
</tr>
</tbody>
</table>

for $\frac{\Delta U}{U} = 10^{-4}$ this gives

The product of relative beam voltage spread and beam semi angle will have to be in this range. Therefore beam opening angles upto 19 mrad in the short system may be realistic with a maximum $\frac{\Delta U}{U}$ of $10^{-4}$. For the long system either the beam opening angle or the allowed energy spread must be reduced (the product must be reduced by a factor of 10).

5.5 Deflector transverse chromatic aberration

Because of the very high deflection speed required, shaping deflectors have always been fabricated with electrostatic deflectors. In common practice a bandwidth of tens of megahertz is often used. When the electron beam potential in an electron optical column is much higher than 20 kV, magnetic deflectors will require about the same amount of energy for deflection as electrostatic ones. Magnetic deflectors require very high driving voltages to overcome the coil inductances. Therefore it seems most likely that electrostatic deflectors will be used for high speed deflectors.

A first order estimate of the required deflector length can be deduced directly from a simple approximation method. In this approximation the transverse force on the electron is simply integrated along the axis during its flight through the deflection field.

Given a parallel plate configuration as in figure 5.1, with plates at plus and minus $U_E$ and with a separation $d_E$, the change in momentum is determined by

$$\Delta p_E = e E \int_E E d_E$$  \hspace{1cm} (5.10),
where $E_x$ is the electric field in the deflector and $t_E$ is the time during which the electrons experience the deflecting force, and $e$ is the electron charge. This results in a deflection angle, $\beta_x$, of

$$\beta_x = \frac{v_{tr}}{v_z} \Rightarrow \beta_x = \frac{e}{m} \frac{2U_x L_x}{v_z^2} \Rightarrow \beta_x = \frac{U_x}{U_{s}} \frac{L_x}{d_x} \quad (5.11),$$

with $v_z$ the forward velocity, $v_{tr}$ the transverse velocity due to the change in impulse $\Delta p_x$ and $U_s$ the beam voltage in the deflector (shaper).

In this approximation the electrons appear to be deflected at the center of the deflection plates. The lateral beam shift at the second shaping aperture of the deflectors used in sections 6.2.1 and 6.3.1 (see also figures 5.2 and 5.3) is

$$\Delta x = \frac{U_x}{U_s} \frac{L_x^2}{d_x} \quad (5.12),$$
Figure 5.2: Dimensions and geometry of the imaging shaper with a simple electrostatic parallel plate deflector.

with \( C_e = 0.5 \) for figure 5.2
and \( C_e = 1.5 \) for figure 5.3.

Figure 5.3: Schematic drawing of the shadow shaper with double deflector geometry as used in chapter 6.

Proposals were made to design the shaper for a lower beam potential than the 100 kV at the target, for example 5 kV. In that case an accelerating section would be inserted after the beam shaping section. This does not
make any difference in the imaging conditions in the shaper, since the reduced beam brightness is constant in the whole system.

The unsharpness relative to the size of the shaping apertures has to be calculated at the beam shaper potential. The relative unsharpness is independent of the final projection voltage. Furthermore, the Boersch effect generates an absolute energy spread. The demagnifying and projection sections could be operated at higher voltage, proportionally reducing the chromatic aberrations there. The low voltage shaper may well make it possible to have a shorter illuminating system. According to equation (5.12) this also allows for shorter shaping deflectors. The beam voltage dependence will be investigated by choosing beam voltages from 2 to 100 kV. From equation (5.12) an estimate can be made for a very short shaper:

\[ L = 8 \text{ mm}, U_{E} = 8 \text{ V}, U_{s} = 2 \text{ kV}, d_{E} = 1 \text{ mm} \Rightarrow \Delta x_{E} = 260 \mu \text{m} \]

and the same \( \Delta x_{E} \) is found for \( U_{E} = 20 \text{ V}, U_{s} = 5 \text{ kV} \)
\( U_{E} = 80 \text{ V}, U_{s} = 20 \text{ kV} \)
\( U_{E} = 400 \text{ V}, U_{s} = 100 \text{ kV} \).

In the last case the deflector voltage has become too high. Since at higher beam voltages the Boersch effect is significantly lower, it might be reasonable to increase the deflector length for 100 kV beam potential:

\[ L = 50 \text{ mm}, U_{E} = 10 \text{ V}, U_{s} = 100 \text{ kV}, d_{E} = 1 \text{ mm} \Rightarrow \Delta x_{E} = 250 \mu \text{m}. \]

Since the deflection is proportional to the beam potential in the deflector (see equation 5.12), the relative image blurring \( \delta_{s,BE} \) due to a beam voltage spread \( \Delta U_{s} \) in the beam potential \( U_{s} \) is

\[
\frac{\delta_{s,BE}}{\Delta x_{E}} = \frac{\Delta U_{s}}{U_{s}} \quad (5.13).
\]

This is the first order chromatic aberration of the deflector.
An electron with an energy $U_s + \Delta U_s$ will be shifted in the plane of the second shaping aperture by a distance proportional to the maximum deflection (which is again related to the shape size at the target). Therefore the allowed energy spread from the Boersch effect is directly related to the shape size and the edge roughness allowed.

For maximum shift $\Delta x_E = D_s/2$ and an allowed relative edge blurring of 10 nm (according to equation (5.13)) in a 1 x 1 (µm)$^2$ spot this gives

$$\frac{\delta_{s,BE}}{D_s} = \frac{11 \text{ nm}}{1 \mu\text{m}} = 1.1 \times 10^{-2}.$$ 

Thus, the allowed energy spread is 2 percent of the beam potential

$$\Delta U_s = 2.2 \times 10^{-2} U_s \tag{5.14}.$$ 

This implies that the energy spread due to the shaper is not a problem for most accelerating voltages. The chromatic aberration in the final lens will put a more severe limit upon $\Delta U_p$. For example, reasonable beam voltages in the shaper are supposed to be 2 kV and higher. For $\Delta U_s$ this implies a value of 40 V. Even this very high energy spread may be acceptable in designing the projection lens.

The final edge roughness is found with

$$\delta_{EC,p} = \frac{D_p}{D_s} \delta_{BE,s} \tag{5.15}.$$ 

It should be noted that the positions of the source cross-overs are not shifted by the shaping deflectors. Therefore there is no shift due to chromatic aberration of the deflectors in the source cross-overs either. (This holds for both the imaging and the shadow shapers.)

Two characteristic geometries are considered. As will be shown in chapter 6 the electron-electron interaction effects dominate the shaper behaviour. Therefore it is best to choose a long and a short shaper section for both the shadow and imaging setups. These will be extensively studied in chapter 6. In this respect 8 mm is considered to be the shortest realistic deflector length. This value will be compared to deflectors of 50 mm length.
The following conditions determine the deflector geometry for both the imaging and the shadow shapers:

- beam shift is equal to half the aperture side length \( \Delta x_{s2} = \frac{D_{s2}}{2} \)
- the deflector plates are \( 2 \frac{D_s}{s} \) apart, \( d_e = 2 \frac{D_s}{s} \)
- and total shaper length is \( \Delta z_s = 24 \text{ mm} \).

From the target parameters in the projection section the depth of focus and (edge) beam opening angle are used to determine the size of the apertures in the shaper section. For this setup the deflector plate voltages are represented in table 5.3.

<table>
<thead>
<tr>
<th>( U_s ) (kV)</th>
<th>( \Delta z_p ) (( \mu \text{m} ))</th>
<th>0.5</th>
<th>1.0</th>
<th>2.0</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>( \alpha_p ) (mrad)</td>
<td>25</td>
<td>12.5</td>
<td>6.25</td>
</tr>
<tr>
<td>2</td>
<td></td>
<td>0.336</td>
<td>0.167</td>
<td>0.084</td>
</tr>
<tr>
<td>5</td>
<td></td>
<td>0.84</td>
<td>0.417</td>
<td>0.210</td>
</tr>
<tr>
<td>20</td>
<td></td>
<td>3.36</td>
<td>1.67</td>
<td>0.84</td>
</tr>
<tr>
<td>100</td>
<td></td>
<td>16.8</td>
<td>8.3</td>
<td>4.20</td>
</tr>
</tbody>
</table>

Table 5.3: Typical deflector plate voltages (\( U_p \)) in V for a short deflector setup (total length 24 mm). From the target parameters in the projection section the depth of focus and (edge) beam opening angle are indicated. These determine the size of the apertures in this section.

Analogously table 5.4 contains the deflector plate voltages for the long shaper setup:

\( \Delta z_s = 150 \text{ mm} \).

As the values in the tables can all easily be realized, it is concluded that the design of the shaping deflectors will not be difficult. This is for the largest part due to very small number of pixels imaged by the shaper. This is translated here into the very small (relative) range required for these deflectors. For the final positioning deflectors a larger deflection length is available. These rough estimates will be used for the calculations of trajectory and Boersch effect in the shaper (chapter 6) and the projection system (chapter 8).
(chapter 6) and the projection system (chapter 8).

<table>
<thead>
<tr>
<th>$U_e$ (kV)</th>
<th>$\Delta z_p$ (um)</th>
<th>$\alpha_p$ (mrad)</th>
<th>0.5</th>
<th>1.0</th>
<th>2.0</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>0.053</td>
<td>0.0266</td>
<td>0.0133</td>
<td></td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>0.133</td>
<td>0.067</td>
<td>0.0334</td>
<td></td>
<td></td>
</tr>
<tr>
<td>20</td>
<td>0.53</td>
<td>1.67</td>
<td>0.133</td>
<td></td>
<td></td>
</tr>
<tr>
<td>100</td>
<td>2.67</td>
<td>8.3</td>
<td>0.67</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 5.4: Typical deflector plate voltages ($U_e$) in V for a long deflector setup (total length 150 mm). As in table 5.3 the target parameters are indicated.

5.6 Trajectory displacement and Boersch effect

Several analytical equations for the electron-electron interactions are presented in [Jansen, 1988]. Boersch effect is the stochastic forward energy spread generated by electron-electron interactions during the flight of the electrons through the system. [Jansen, 1988] derives an electron distribution in image planes, which corresponds to sideways electron displacements. He correlates this to an angular deviation which the electrons experience during their flight through the system. The distribution of electron landing positions contains a correctable spread. This is called the space charge effect. It is due to the outside directed force on the electrons and it is based on the average charge density in the beam (and therefore correctable). It can be corrected by appropriately refocussing the lenses in the case of round beams. The remaining uncertainty in the actual landing position of the electrons is described by a width measure of the positional distribution in (intermediate) image planes. This is denoted by the term trajectory displacement; it is a statistical effect.

[Van der Mast, 1985] attempted to use one of the analytical equations for optimization of an electron beam writing system. Several simplifying assumptions were made in these approximations. Only the trajectory displacement effect in the projection section was investigated. Furthermore, an optimization for spherical aberration and trajectory displacement was made. The approximation for trajectory displacement
used was
\[
\delta_{TD,p} = C_{TD} \frac{I_p}{\alpha_p U_p^{4/3}} \quad \text{(5.16)}
\]

where \( C_{TD} \) is a system constant (in a range near the working point) which is in the order of
\[
C_{TD} = 0.34 \text{ m} V^{4/3} \text{ mrad}^{4/3} / A^{2/3}
\]

for the system proposed by Van der Mast. (This equation was also used in section 2.4.1, equation (2.6).) By combining it with the equation for spherical aberration (5.2), an optimum is found for reduced beam brightness
\[
B_r = 0.24 \frac{U_p^{1/2}}{N \delta_p C_{TD}^{3/2}} \quad \text{(5.17)}
\]

where \( N \) is the minimum number of pixels written in every shot \( (N = 50) \). The achievable current is found to be
\[
I_{max}^{13/6} = 2 \frac{\alpha_p U_p^{2/3}}{C_{TD} C_{sa,p}^{3/2}} \quad \text{(5.18)}
\]

at an optimum angle of
\[
\alpha_p = \left( \frac{\delta_p C_{sa,p}}{C_{TD}} \right)^{1/3} \quad \text{(5.19)}
\]

For the system investigated by Van der Mast with
\[
C_{sa,p} = 0.5 \text{ m, } V_p = 50 \text{ kV}
\]
it follows that

\[ \delta_p = 25 \text{ nm} \]
\[ B_r = 7.7 \times 10^6 \text{ A/m}^2 /\text{sr}/V \Rightarrow B_r = 770 \text{ A/cm}^2 /\text{sr}/V \]
\[ I_{\text{max}} = 0.54 \mu\text{A} \]
\[ \alpha_p = 3.7 \text{ mrad.} \]

For a 100 kV system with a very short focal length last lens (\(C_{sa,p} = 3 \text{ mm}\)) this gives

\[ B_r = 1.5 \times 10^7 \text{ A/m}^2 /\text{sr}/V \Rightarrow B_r = 1500 \text{ A/cm}^2 /\text{sr}/V \]

and \(I_{\text{max}} = 66 \mu\text{A} \)
\[ \alpha_p = 20 \text{ mrad.} \]

In general it can be concluded from this approximation that the system proposed may be realistic.

More accurate calculations are presented in [Jansen, 1988]. These all rely on determination of the interaction regime (in a section between two lenses). Per regime an approximation equation is presented.

5.6.1 The SLICE method

Especially for trajectory displacement calculations [Jansen, 1988] proposed a numerical integration method. In this method the electron beam is sliced into short cylindrical parts. The angular deflection in each slice is then calculated (see figure 5.4). The total effect is found by summing up the local effects as if they were independent. A big advantage of this method is the fact that it enables one to display the location within the segment where the effect is most important. Furthermore the method adapts to the local type of displacement distribution, which may be important near cross-overs.

An implementation of this method, with a variable step size algorithm, is described in appendix SB (manual for the program SLICE). An example system with the resulting trajectory displacement effect is drawn in figures 5.5 and 5.6.
Figure 5.4: Calculation of the slice effect in a beam segment between two lenses. The local effect of every slice is added.

From the example figures the following can be concluded:

- As the effect is calculated is a local angular deflection, it is zero in the intermediate image planes of the shaping apertures.
- The effect is highest in beam cross-overs.
- As a consequence of the above trends a maximum in the effect is not found at the intermediate images of the shaping apertures, but it is very close to these intermediate images.

The actual height of this maximum depends critically on step size (slice thickness) and calculation accuracy of the effect.

It was found that the program would tend to lower the step size near the intermediate images of the shaping apertures. The adaptation of regimes for the routine that calculates the effect is not seen in practice, this is due to a difficulty in calculating the particle density parameter for very short beam slices. A problem, mentioned already by [Jansen, 1988], is that this method only works well for low current densities. Especially near the cross-overs the current density increases and the program accuracy should be questioned. Furthermore it should be mentioned that the approximation of a cylindrical beam with uniform (or Gaussian) spatial and angular distributions is only approximately correct. Also the independence of the effect for different beam slices becomes questionable when step size in the program reduces.
Figure 5.5: Sample variable shaped electron beam writing system. Intermediate images of the source and of the shaping aperture are marked.

Figure 5.6: Trajectory displacement effect in the sample system of figure 5.5. The height of the function corresponds to the local contribution.
It is concluded that this method may give some insight in the effective location of trajectory displacement effect contributions. The general trend can be obtained, but not the actual value of the total effect. Such a trend is visualized in figure 5.6. Special care has to be taken to control the step size even though a very robust step size controlling algorithm was used. For reliable calculation of the total effect the method cannot be advised. Jansen’s analytical equations were numerically adjusted to fit to the Monte Carlo simulations for total beam segments. These should be much more reliable.

The determination of Boersch effect and trajectory displacement in separate beam sections will be the issue of the next three chapters. The optimization of the beam sections with these equations can only be done using numerical optimization. A problem with this is also the limited range of validity of these equations. Therefore, all calculations done start with determining some realistic setups. After this, the electron-electron interaction trends and values are calculated.
6 SHAPERS

6.1 Introduction

Each of the shapers presented here requires different demagnifying and projection sections. Since design choices can be made separately (to a certain extent), the calculations for the three imaging sections of a variable-shaped beam (VSB) system are presented in three different chapters. As was mentioned in section 5.5, proposals have been done to let the shaper work on a lower beam potential. After the shaper the electrons could be accelerated to minimize further electron-electron interactions in the system. This possibility does not require separate investigation since the beam potential for the shaper section is one of the input parameters. It will be varied in the range from 2 to 100 kV. Addition of an accelerating section will be investigated in chapter 7 (demagnifying section). The issue of chapter 9 will be the combination of all the different sections.

In this chapter the shaper section as used for VSB writing systems will be investigated. The shaper section forms the shape of the beam which is directly conjugated to the spot on the target. Possible apertures in later sections of the system will only be used to select the illumination solid angle of the final spot. The use of two shaping apertures with image shifting deflectors enables the continuous variation of the size of the final spot (figures 1.6 and 3.2 are reproduced in figure 6.1).

An image of the electron source itself or the image of its angular distribution can be used to illuminate the first shaping aperture. Both types of imaging are depicted schematically in figure 6.2. The latter is called Köhler illumination (refer to [Essig, 1986]). It is frequently used since the angular distributions of W and LaB₆ sources are more homogeneous than their positional distribution. In the calculations in this chapter Köhler illumination is assumed. This does not imply a loss of generality, since there are always two conjugated sets of planes defining the distribution of positions and the distribution of emission angles of electron rays that irradiate the final pattern. In the case of
source imaging, the source itself is imaged onto the shaping apertures and there is another aperture (somewhere in the system) that limits the beam solid angle. This (usually round) aperture can be positioned either before or after the shaper section. Ring type emitters can only be used with Köhler illumination.

Special attention must be given to the concept of dynamic brightness as proposed by [van der Mast, 1985]. This implies the use of the maximum current in all sections following the beam shaper. To realize a constant current in the final spot, the primary beam current will have to be adjusted inversely proportional to the area of the actual spot written.

Several electron-electron interaction calculations were done using the simulation program and the analytical equations of [Jansen, 1989]
(called MONTEC and INTERAC, respectively). The effects generate an unsharpness in the plane of the second shaping aperture (trajectory displacement) and an energy spread of the beam (Boersch effect). The energy spread results in a chromatic aberration at the lenses following the shaper.

Figure 6.2: Source and Köhler imaging in a VSB system.

Van der Mast also proposed a three aperture shaper. This system uses mainly the first two apertures for the shaping of the spot at low beam potential. The third aperture is placed after the accelerating section, such that it sharpens the edge of the first aperture somewhat more. The beam current in this system is much smaller between the second pair of apertures than it is between the first pair. Therefore, the effects (both Boersch effect and trajectory displacement) are much smaller in the second half of this type of shaper. The results obtained in this chapter could be used to obtain the magnitude of the effects in three aperture shapers as well. This shaper is not of interest for this research, however, since it will be shown that the configurations considered allow for fulfilling of the specifications.

6.2 Selection of general HISEL imaging conditions

The total current in the shaper can be very large, since the average spot size is much smaller than the maximum spot size. The numbers
presented in chapter 3 have been used to determine the beam current in chapters 4 and 5. In sections 3.4 and 3.5 the following values were determined:

- minimum shaped spot: $0.1 \times 0.3 \,(\mu m)^2$ 48 pixels
- average shaped spot: $0.2 \times 0.3 \,(\mu m)^2$ 90 pixels
- maximum shaped spot: $1 \times 1 \,(\mu m)^2$ 1600 pixels.

Here, the average shaped spot as was mentioned by [Veneklasen, 1985/1] is taken. When fixed brightness mode is used this value is very important, since it determines the maximum current in the beam shaper section (ref. section 5.1). This gives an area shaping range factor of 1 to 33. The beam current between the second shaping aperture and the target will vary between the beam current in the shaper and $1/33^{th}$ of that current.

In section 3.5 the size of the shaping apertures was related to the design rule of the circuit. From figure 3.1 it is seen that the actual number of shots required to write a pattern stops decreasing at a maximum side length of about

$$D_{\text{max}} = 1.2 \langle D_{\text{pat}} \rangle$$  \hspace{1cm} (6.1),

where $D_{\text{pat}}$ is the average rectangle side length in the pattern written.

Thus, the average size of the shaped beam written is (relative to the maximum area)

$$\langle D_{\text{pat}} \rangle = \frac{1}{1.2} D_{\text{max}}$$  \hspace{1cm} (6.2).

This means that the maximum shape size (side length) should be about 1.2 times the average rectangle size in the pattern (determined with unlimited shape size). In that case the gross average number of shots needed to write the pattern is

$$N_s = 1.2 \langle D_{\text{pat}} \rangle^{-2}$$  \hspace{1cm} (6.3),
(in cm$^{-2}$), which comes very close to the minimum number of shots achieved when writing with arbitrary shape sizes. A problem is that in the above equations the minimum dimension in the pattern (design rule) is completely left out. Neither [Roelofs, 1984] nor [Takamoto, 1987] relate the size of the shaping apertures to the design rule of the pattern.

If the minimum shape size occurring in figure 3.1 is taken as the design rule of the pattern, the absolute shaping range can be determined. Correspondingly the number of shots is found for different shaped beam size ranges. For example, for a low shaping range one could expect (referring to figure 3.1):

$$D_{\text{max}, \text{pat}} = 0.28 \quad \Rightarrow \quad N = 12 \quad \langle D \rangle^{-2}.$$ 

While a large shaping range would be in the order of

$$D_{\text{max}, \text{pat}} = 1.20 \quad \Rightarrow \quad N = 1.20 \quad \langle D \rangle^{-2}.$$ 

As was mentioned in section 3.5.1, the exact shaping range cannot be related to the design rule of the pattern specification due to scaling of the values. It is expected that the actual shaping is somewhere between the values given above.

It is concluded that $D_{\text{pat}}$ is about 0.36 μm (0.1/0.28), in the case of a design rule of 0.1 μm. An acceptable shaping range would be 0.1 .. 0.4 μm. In this case, the total number of shots required to write the pattern would only be 20% more than the minimum number of shots required with an infinite shaping range, according to equation 6.3.

A shaping range of 0.1 .. 0.3 μm was chosen as most realistic. As can be concluded from figure 3.1, this implies a gross average number of shots needed to write the pattern of

$$N = 1.8 \quad \langle D \rangle^{-2} \quad \text{(6.4).}$$ 

A practical maximum shaping range would be about 0.1 .. 1.0 μm. This range is not further considered.
In dynamic brightness mode the beam writing current is constant. Therefore the time to write a detail is inversely proportional to the area of the detail (a $D_p^2$). Because of this proportionality the time required to fill an area $A$ with shots is (in first approximation) independent of the rectangle division of the total area. This was described by [Mulder, 1991]. In this way the shot setup times will completely dominate the total writing time of the area. Two dead times have to be taken into account: the shaper setup time and the positioning deflector setup time. A blanker is required when PN-emitters with sufficiently high modulation frequencies do not become available for use in electron beam writing systems. Blanker dead times are considered to be very short and are therefore not considered any further.

It is clear from the above reasoning that an optimum writing strategy is reached when the number of rectangles in the pattern division is lowest for long shaper setup times. It could also be advantageous to divide the pattern into shapes of one and the same area. With the minimum shaped spot area written equal to $0.1 \times 0.3\ (\mu\text{m})^2$, this would imply that the shapes take all forms between $0.1 \times 0.3$ and $0.3 \times 0.1\ (\mu\text{m})^2$. In that case the primary beam current could constantly be 30 $\mu$A for a beam current after the shaper of 10 $\mu$A. The same reduction in primary beam current is always achieved when the maximum shaped spot size is reduced. It is therefore very important not to select too large a maximum size of the shaped spot.

This imposes severe limits on the beam current between the shaping apertures. In conclusion, the modes of operation that are considered realistic have been taken together in table 6.1.

For each of these modes the electron-electron interaction effects will be estimated with the help of several sets of calculations that are presented in this chapter.

Electron-electron interaction effects are calculated in the beam shaper current range:

$$I_s = 10 \ldots 500\ \mu\text{A}.$$
<table>
<thead>
<tr>
<th>description</th>
<th>( D_{\text{max}} ) ( \mu \text{m} )</th>
<th>shaping range</th>
<th>( I_s ) ( \mu \text{A} )</th>
<th>( I_m ) ( \mu \text{A} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 fixed ( B_r ), full range</td>
<td>1.0</td>
<td>0.1-1.0</td>
<td>167</td>
<td>5-167</td>
</tr>
<tr>
<td>2 fixed ( B_r ), limited range</td>
<td>1.0</td>
<td>0.1-0.3</td>
<td>167</td>
<td>5-15</td>
</tr>
<tr>
<td>3 fixed ( B_r ), reduced range</td>
<td>0.3</td>
<td>0.1-0.3</td>
<td>15</td>
<td>5-15</td>
</tr>
<tr>
<td>4 dynamic ( B_r ), full range</td>
<td>1.0</td>
<td>0.1-1.0</td>
<td>10 -330</td>
<td>10</td>
</tr>
<tr>
<td>5 dynamic ( B_r ), limited range</td>
<td>1.0</td>
<td>0.1-0.3</td>
<td>110-330</td>
<td>10</td>
</tr>
<tr>
<td>6 dynamic ( B_r ), reduced range</td>
<td>0.3</td>
<td>0.1-0.3</td>
<td>10 -30</td>
<td>10</td>
</tr>
</tbody>
</table>

Table 6.1: Beam current regimes for the different modes of writing in the HISEL system. \( I_s \) is the current in the shaper, while \( I_m \) denotes the current in the demagnifying section (after the shaper).

Above, only probe sizes are mentioned. The size of the shaping apertures is determined by the maximum probe size and the demagnification of the system components following the beam shaper. The apertures must have a practical size (e.g. \( D_s = 100 \mu \text{m side length} \)), ref. [Pfeiffer, 1978/1]. They normally consist of metal (platinum) in order to allow heating. This heating is done in order to avoid contamination and subsequent electric charging. Some systems use anisotropically etched silicon apertures. The apertures are optically demagnified to the actual spot size of about 1 \( \mu \text{m} \) (maximum shape). This 100 times demagnification (for example) corresponds to a 100 times magnification of the angle of illumination, assuming constant reduced brightness. The size and angular distribution of the source has to be matched to this system with the extraction optics and (optionally) with intermediate condenser lens(es).

Practical source setups were discussed in chapters 4 and 5 (see also tables 5.1 and 5.2). In those chapters the final depth of focus \( (\Delta z_p) \) was used to determine the required reduced source brightnesses:
$$\Delta z_p = 0.5 \, \mu m, \quad B_r = 170 \, A/cm^2/sr/V$$
$$\Delta z_p = 1.0 \, \mu m, \quad B_r = 680 \, A/cm^2/sr/V$$
$$\Delta z_p = 2.0 \, \mu m, \quad B_r = 850 \, A/cm^2/sr/V.$$ 

The final beam opening angle can be very large (25 mrad) in the case of the smallest depth of focus. The real problem here lies in the fact that such a large opening angle may not be allowed by the projection optics. This would imply that a brighter source has to be used. Because of this the reduced source brightness will be varied to about 1000 $A/cm^2/sr/V$. With these very bright sources the minimum depth of focus could be realized. This would only give a reduction of the beam semi opening angle in the projection section. It has no implications for the shaper setup. This means that the lowest depth of focus value is not completely unrealistic.

Since the cross-sectional area of the final lens is fixed by other imaging errors, it is limited. Given this cross-sectional area and the accelerating voltage, the brightness determines the amount of beam current density that can reach the target. To enable as high a beam current density as possible, the cross-sectional area of the final lens should be as large as possible. When using Köhler illumination the electron source itself is imaged in the cardinal plane of the final lens. The beam shaping action is not allowed to change the effective area of the final lens used since this would result in a different illumination profile or in unstable beam current. The center of deflection of the shaping deflectors is therefore placed in the source image.

From the sensitivity of electrostatic deflectors realistic deflector lengths for 2 to 100 kV electron beam voltage have been obtained (see section 5.5). It follows that two characteristic lengths will be considered:

$$L_E = 8 \, mm \quad \text{and} \quad L_E = 50 \, mm.$$ 

The total shaper length will be related to this value by the rough estimate that

$$L_s \approx 3 \, L_e \quad (2 \, \text{kV} \ldots 100 \, \text{kV}) \quad (6.1)$$

for both the imaging and the shadow shaper.
6.3 Imaging shapers

For the imaging shaper an intermediate lens is required to image the first shaping aperture onto the second. This implies a source cross-over between the shaper lens and one of the shaping apertures. The opening angle for the illumination of the shaping apertures is defined by the electron source (Köhler illumination) or by the beam limiting aperture.

The cross-over can be either before or after the shaper lens, as was mentioned in the first section of this chapter. Furthermore the shaper can be designed to magnify the first shaping aperture or to demagnify it. Since the image of the shaping apertures on the target has to be further reduced it would be better to use the shaper in demagnifying mode. Demagnification with the shaper lens also gives some space on one side of the lens for the shaping deflectors. The obtainable demagnification factor is mainly determined by the quality of the shaping apertures that can be obtained. With the last shaping aperture as small as possible, the projection optics would require the smallest demagnification. For given lens strengths this reduces the total system length. Of course there is a trade off between the shaper size (both transverse and axial) and the imaging system demagnification. Therefore some realistic shaper system sizes will be investigated.

It should be mentioned that the trajectory displacement effect is the same both for magnifying and for demagnifying shapers, when it is referred to the final image. The method of calculating the effects assures the symmetry of the problem. The effects found for both beam sections are equal. The local trajectory displacement and Boersch effect in any of the beam sections is calculated in an image plane conjugated with the shaping apertures. From there on the image unsharpness follows exactly the same rules as the images of the shaping apertures. Since both shaping apertures are imaged onto one another the relative unsharpness at the last shaping aperture is exactly the same for both shaper types.

The pivot point of the shaping deflector must be placed in the source image plane. In an imaging shaper there is a real source cross-over. The
shaping deflector can be placed around it. By adjusting the shaper lens the source cross-over can be placed exactly in the pivot point of the deflector. (The displacement of the image of the shaping aperture is thereby not critical since there is a large depth of focus.) This results in a shaper with the approximate dimensions as depicted in figure 6.3.

![Diagram](image)

Figure 6.3: Dimensions and geometry of the imaging shaper with a simple electrostatic parallel plate deflector. This is the demagnifying version. The magnifying version was used in the calculations.

6.3.1 Imaging conditions for the imaging shaper

As mentioned in section 6.3 two shapers with the following characteristic electrostatic deflector lengths are considered:

\[ L_E = 8 \text{ mm} \quad \text{and} \quad L_E = 50 \text{ mm}. \]

From this the total shaper length \( (L_s) \) and, as illustrated in figure 6.3, the shaper-lens strengths \( (F_s) \) are determined:

\[ L_s = 24 \text{ mm}, \quad F_s = 5.3 \text{ mm} \]

and \[ L_s = 150 \text{ mm}, \quad F_s = 16.7 \text{ mm}. \]
The (de)magnification of the last shaping aperture to the final image, $M_s$, must be sufficiently high to have a depth of focus at the shaping apertures in the order of 8 and 50 mm respectively. This is the same order of magnitude as that of the shadow shaper in section 6.4. The side lengths of the shaped beam at the target ($D_p$) and at the second shaping aperture ($D_{s2}$) are related according to

$$D_p = M_s D_{s2} \quad (6.2).$$

The final depth of focus is related to the depth of focus near the shaping apertures through

$$\Delta z_p = M_s^{-2} \Delta z_s. \quad (6.3).$$

From this equation the size of the shaping apertures are deduced:

- $L_s = 24$ mm
  - $\Delta z_p = 0.5 \mu$m: $B_r = 170$ A/cm$^2$/sr/ V, $D = 220 \mu$m, $M = 4.6 \times 10^{-3}$
  - $\Delta z_p = 1.0 \mu$m: $B_r = 680$ A/cm$^2$/sr/ V, $D = 155 \mu$m, $M = 6.5 \times 10^{-3}$
  - $\Delta z_p = 2.0 \mu$m: $B_r = 850$ A/cm$^2$/sr/ V, $D = 110 \mu$m, $M = 9.1 \times 10^{-3}$

- $L_s = 150$ mm
  - $\Delta z_p = 0.5 \mu$m: $B_r = 170$ A/cm$^2$/sr/ V, $D = 548 \mu$m, $M = 1.83 \times 10^{-3}$
  - $\Delta z_p = 1.0 \mu$m: $B_r = 680$ A/cm$^2$/sr/ V, $D = 387 \mu$m, $M = 2.58 \times 10^{-3}$
  - $\Delta z_p = 2.0 \mu$m: $B_r = 850$ A/cm$^2$/sr/ V, $D = 274 \mu$m, $M = 3.65 \times 10^{-3}$.

The chromatic aberration of the shaper lens is determined by means of equation (5.3) with chromatic aberration constant $C_c \approx F$ (for a weak lens). By applying this equation it can easily be seen that chromatic aberration of the imaging lens will not be of any significance because of the very small opening angle of the beam in the shaper.
e.g. $C_c = 10 \text{ mm}$, $\alpha_p = 25 \text{ mrad}$, $M = 4.56 \times 10^{-3}$

$$\Rightarrow \alpha_s = 0.52 \text{ µrad}, \quad \frac{\Delta U_s}{U_s} = 0.01$$

$$\Rightarrow \delta_{p,c} = 2.4 \text{ pm}.$$  

The distortion of the shaper lens determines the allowable field size which corresponds to the size of the shaping apertures. Applying the equations presented in appendix A.5 it follows that both spherical aberration and distortion are negligible for all shapers investigated. This is due to the fact that the number of pixels imaged in the shaper is very small (some tens of pixels). Another very simple estimate for the (radial) distortion of a magnetic lens is given by [Riecke, 1982, p.197] in his notation:

$$\rho_r = S_1 h_0^3 = C_r r_1^3 / L_1^2$$

(6.4)

where $r_1$ is the maximum radius in the image and $L_1$ is the distance between the lens and the image. $C_r$ is a constant that depends on the lens design. For all lenses investigated by Riecke, $C_r \leq 10$. For the shaper in figure 6.3 this gives, as a very rough estimate:

$$\rho_r = 0.1 \text{ µm}$$

(in the plane of shaping aperture 2) which is small enough in all cases. The spiral distortion is about a factor six smaller.

6.3.2 INTERAC calculations in imaging shapers

The electron-electron interactions in the shaper of figure 6.3 have been calculated using the equations given by [Jansen, 1988]. The effects generate an image unsharpness in the plane of the second shaping aperture (trajectory displacement) and an energy spread of the beam. The energy spread results in chromatic aberration in the sections following the shaper.
Jansen presented his analytical results in the form of equations in which different regimes of interaction are represented with an effective gamma value $\gamma_e$

\begin{align*}
\gamma_e &= 2.0 \quad \text{Gaussian regime} \\
\gamma_e &= 1.5 \quad \text{Holtsmark} \\
\gamma_e &= 1.0 \quad \text{Lorentz} \\
\gamma_e &= 0.5 \quad \text{parallel force distribution} \\
\gamma_e &= 0.33 \quad \text{perpendicular force distribution}.
\end{align*}

This effective gamma value turns out to be the key parameter in the determination of the resulting positional and energy spread distributions. The value will be presented as one of the output parameters from INTERAC, next to trajectory displacement and energy spread values. When the values are plotted as a function of beam current, $\gamma_e$ is the inverse power of the beam current. $\gamma_e$ must also be used as a power factor in the summation of the effects of independent beam sections. Jansen programmed the analytical equations into a program called INTERAC. This program substitutes values in the equations, taking the different $\gamma_e$-regimes into account. The analytical equations have been tested by Jansen using his Monte Carlo simulation program (for the lower beam currents). It should therefore be expected that the INTERAC results are rather well in correspondence with the MONTEC results. Jansen, though, could not be certain that the results for beam currents higher than (roughly) 100 $\mu$A would be correct. Therefore in the high current regime the results can only be used to estimate the order of magnitude of the effect and to see the effect of design decisions on the sections.

The shaper of figure 6.3 with the afore mentioned beam conditions was run through the INTERAC program to find the size of trajectory displacement and Boersch effects in the different geometries. One of the input files has been reproduced in table 6.2, for

\begin{align*}
B &= 170 \text{ A/cm}^2/\text{sr/V} \\
U &= 2 \text{ kV} \\
I &= 10 \mu\text{A}.
\end{align*}

Detailed information about the parameters presented can be found in [Jansen, 1989].
Table 6.2: INTERAC input file, each shaper (sav02010.in, U = 2 kV, I = 10 μA) consists of two sections, beginning with a square aperture, ending at the second shaping aperture. The interaction effects will be related to the second shaping aperture. The lines marked with an asterisk (*) are comment; they are ignored by the program.

As a result of earlier system proposals, all calculations have been done for the magnifying shapers. As was mentioned in section 6.2, this has no effect on the absolute value of the answers, since the Boersch effect will be the same for both shapers, and the trajectory displacement effect will be taken relative to the size of the second aperture. As a relative effect trajectory displacement will also be the same.

The results have been plotted as a function of beam current in appendix A.6 (figures A6.1 through A6.13). These figures are split into three the total set of results becomes far too large to present it here. In figures 6.4 through 6.7, some figures have been extracted from the whole set in order to illustrate the results. The figures are split into two sets, one for the short and one set for the long shaper. Within these sets figures a, b and c (in appendix A.6) denote the different values of
Figure 6.4: Boersch effect calculation results using INTERAC for the short imaging shaper. (These figures correspond to figures A6.1b and A6.2b from appendix A.6) The effect (in eV) is displayed as a function of beam current in the shaper. The bottom graph egE gives the $\gamma_e$-values of the effect.

The following settings apply to this figure:

$$\Delta z_{dof} = 1.0 \ \mu m, \ B = 680 \ A/cm^2/sr/V, \ D_{s1} = 155 \ \mu m, \ D_{a2} = 310 \ \mu m.$$
Figure 6.5: Trajectory displacement calculation results using INTERAC for the short imaging shaper. (These figures correspond to figures A6.3b and A6.4b from appendix A.6) The effect (in units of 0.1 nm) is displayed on a logarithmic scale as a function of beam current in the shaper. The bottom graph $egR$ gives the $\gamma_r$-values of the effect.

The following settings apply to this figure:

$$\Delta z \quad _{dof} = 1.0 \ \mu m, \quad D_{z2} = 310 \ \mu m, \quad \delta \quad _{dof} = 3.9 \ \mu m.$$  

logarithmic. Most effects plotted are on a linear scale. For the 12–88% edge width and the FWHM of the rectangular spots, the vertical scale is the $10$-logarithm of the parameter. In that way the absolute value can easily be deduced from the graphs.
Figure 6.6: Boersch effect calculation results using INTERAC for the long imaging shaper. (These figures correspond to figures A6.5c and A6.6c from appendix A.6) The effect (in eV) is displayed as a function of beam current in the shaper. The bottom graph egE gives the $\gamma_e$-values of the effect.

The following settings apply to this figure:

$$\Delta z = 2.0 \, \mu m, \quad B = 850 \, A/cm^2/sr/V, \quad D_{s1} = 550 \, \mu m, \quad D_{s2} = 1100 \, \mu m.$$
Figure 6.7: Trajectory displacement calculation results using INTERAC for the short imaging shaper. (These figures correspond to figures A6.7b and A6.8b from appendix A.6) The effect (in nm) is displayed on a logarithmic scale as a function of beam current in the shaper. The bottom graph $egR$ gives the $\gamma_r$-values of the effect.

The following settings apply to this figure:

$$\Delta z_{\text{dof}} = 2.0 \, \mu m, \quad D = 1100 \, \mu m, \quad \delta_{\text{dof}} = 13.7 \, \mu m.$$  

For each parameter setting plots have been made for Boersch effect, energy spread $\gamma_e$-value (indicated as $egE$), trajectory displacement effect and trajectory displacement $\gamma_e$-value ($egR$). As a characteristic value for the trajectory displacement $dR_{fwhm}$ is plotted. This value is equal to $\delta_{TB}$ mentioned in chapter 5 ($dR_{fwhm}$ is the diameter of the beam spreading function). The figures summarize the effects for beam voltages...
2, 5, 20 and 100 kV, and for beam currents in the range 10 to 1000 μA. The effects for the short imaging shapers are contained in figures 6.4 and 6.5 (A6.1 through A6.6). The same calculations have been done for the long shaper; these are shown in figures 6.6 and 6.6 (A6.7 through A6.13). The figures in appendix A.6 indicate that the $\gamma_e$-values fall in the range from 1.5 to 2.0 for the shaper sections investigated. Since the equations have different forms depending on these values there is no single expression for trajectory displacement and Boersch effect.

6.3.3 Monte Carlo simulations in imaging shapers

In the case of the shaper of figure 6.3, the electron–electron interaction calculations were also done using the simulation program MONTEC from [Jansen, 1989]. This in order to check the results obtained from INTERAC. In appendix A.6 these results are presented in the same form as the INTERAC graphs discussed in section 6.3.2. The vertical values plotted for MONTEC are:

- (lin) the FWHM of the energy spread
- (log) the FWHM of the positional displacement distribution
  (this value is taken from routine TBR).

Since the results are not exactly the same as those found from INTERAC it is important to have a sufficient number of MONTEC calculation results in order to compare the different parameter dependencies and to determine the correct order of magnitude of the effect. All simulations were done with three samples of 600 particles, using the two particle approximation (DRIFT2). The most important problem with Monte Carlo simulations is that they have to be done repeatedly with slightly different parameters in order to find the behaviour of the system. Many trials have been done before some confidence in the parameter settings was obtained. In tables 6.3 and 6.4 examples of the (system and data) input files have been reproduced.

This research mainly builds upon the theoretical approximations derived by Jansen. Therefore the simplified two particle approximations in DRIFT2 were used as opposed to the more accurate DRIFT1 routine, which calculates all effects according to the exact electron-force equations. This simplification resulted in a significant improvement of the speed of the calculations done. Application of the MONTEC results is therefore limited to the lower current ranges (where INTERAC and MONTEC results behave correspondingly).
C *****  OPTICAL ELEMENTS:
C first shaping aperture (square source)
C/source/ z  / Xctr / Yctr / lds (1) / Xhw / Yhw /
C  / ida (1) / Ahw / tca /
/SOURCE/ 0.0DO / 0.0DO / 0.0DO / 3 / 110.0D-6 / 110.0D-6 /
/   / 1   / 7.99D-4 / 0.0DO /
C to shaper lens, 8 mm
C/drift2/ z0  / zl / bV / bV /* Inter ***/ ips (1)/
/DRIFT2/ -1.0DO / 8.0D-3 / -1.0DO / -1.0DO / 1 / 0 /
C shaper lens
C/lens / z  / Xctr / Yctr / f / Cs / Co /
/LENS / -1.0DO / 0.0DO / 0.0DO / 5.333D-3 / 0.0DO / 0.0DO /
C to second shaper aperture 16 mm length
C/drift2/ z0  / zl / bV / bV /* Inter ***/ ips (1)/
/DRIFT2/ -1.0DO / 24.0D-3 / -1.0DO / -1.0DO / 1 / 0 /
C second shaping aperture
C/apertr/ z  / Xctr / Yctr / Xhw / Yhw / ishp (1) /
C/APERTR / -1.0DO / 0.0D / 0.0D / 100.0D-6 / 100.0D-6 / 2 /
C *****  ACCUMULATION AND STORAGE OF COORDINATES OF PARTICLES:
/ACCUm / /STOREc /
C/READC / C
C *****  STATISTICAL DATA PROCESSING:
C/symbr /
/SYMEBR /
C get values without refocussing
C/rectbr/ Zref / ifoc (1) /
/RECTBR / -1.0DO / 0 /
C get values WITH refocussing (in rectbr), niet betrouwbaar
C/rectbr/ Zref / ifoc (1) /
C/RECTBR / -1.0DO / 1 /
C get values WITH refocussing (in tbr)
C/rectbr/ Zref / ifoc (1) /
/TBR / -1.0DO / 0 /
/TBR / -1.0DO / 1 /
/RECTBR / -1.0DO / 2 /
C *****  STORAGE OF POSITIONS OF PARTICLES IN PLANE OF BEST FOCUS:
C/STOREP/ Zref / ifoc (1) /

Table 6.3: MONTEC system input file, the shaper described is the same as in table 6.2. The system consists of two sections, beginning with a square aperture (source), ending at the second shaping aperture. The interaction effects will be related to the second shaping aperture. The lines marked with C or an asterisk (*) are comment, they are ignored by the program.
The particles are electrons:

C/ pm  / pq  / 9.10956D-31/ 1.0D0 / 

C

General system parameters

C/ bI  / bV  / FWe  / Ide (1)  / Icons (1) / 330.0D-6 / 2.0D3 / 0.0D0 / 1 / 2 / 

C

ICONS is very important for the direction of the electrons.
C 1: related to the Z-direction, 2: total energy is determined.

C/* Inter (1)*/ Nsam (1) / Nseed (1) / Nfield(1) / Nrand (1) / 1 / 600 / 3 / 100 / 153895 /

C

The interaction may be on/off or limited in range
C Iproc: correction of end effects 0: off, 1: on
C/ Nstep (1) / IstepA (1) / IRlim (1) / Nint (1) / Iproc (1) / 100 / 1 / 0 / 1000 / 0 /

C

Here are the polynomial coefficients

C/ NDe (1) / NTe (1) / NEXPe (1) / IFIXe (1) / PMAXe / 40 / 6 / 1 / 3 / -2.50D0 /
C/ Ndt1 (1) / NTt1 (1) / NEXPt1 (1) / IFIXt1 (1) / PMAXt1 / 40 / 5 / 1 / 3 / -2.50D0 /
C/ Ndt2 (1) / NTt2 (1) / NEXPt2 (1) / IFIXt2 (1) / PMAXt2 / 60 / 6 / 1 / 3 / -2.50D0 /

C

This is for storage of the distributions: energy/ t.d. /org. distrib.
C/ ISTOREe (1)/ ISTOREt1(1)/ ISTOREt2(1)/ 1 / 1 / 1 /

C

These parameters control the focussing methods
C/ IMt1 (1) / IMt2 (1) / 1 / 1 / 

Table 6.4: MONTEC data input file for a shaper at 2 kV, with beam current 330 μA. The settings describe a source with no initial energy spread. Furthermore the particle simulation parameters are set according to practical experience. (For detailed information see [Jansen, 1989].)
It was found that the routine that allows the simulation program to refocus the rectangular spot (RECTBR) did not work sufficiently accurate. This was found to be due to inaccuracies in the determination of the edge profile. (Only a small part of the 600 electrons simulated is found in the edge.) The depth of focus is large, this should therefore not present a problem, but it was found that random changes of focus plane resulted in rather big (statistical) changes in edge profile. To overcome this problem the TBR routine was used for the main results. This routine determines the displacement due to the space charge forces on each of all the electron trajectories. From this displacement the edge blurring of a square beam easily can be found according to [Jansen, 1988]. (This methods holds for the supposition that the spot can be described by a focussed spot, scanned over an aperture of the same form and size of the intended spot.) Since only the effects in the shaper section are of importance, the effects are determined in the plane of the second shaping aperture. From this value of the effect in the final plane could be calculated (where the actual depth of focus is much smaller), but in the program this is done using perfect lens equations. Therefore the inaccuracy in the refocussing routine should not be very important. This has been confirmed by comparing the displacement values found with and without refocussing. By using the TBR routine all electrons simulated are used to determine the effect. This reduces the statistical variations as much as possible. The variations are still rather large (upto 20% for high beam currents).

Also, because of the large beam diameter the sample length has become rather small for large beam currents (typically 10 mm for 10 μA to 0.1 mm for 1000 μA). In general the beam current range below 50 μA should give reasonable results. For beam currents higher than 100 μA (sample length ≈ 1 mm) the beam simulated becomes a flat disc. The interaction effects can then no longer be calculated correctly. Both, end effect correction (from space charge blow up) and the use of field particles (extra particles simulated to represent the beam-part not in the sample), have been used in order to somewhat relieve the problem. It was found that the values found this way do not differ very much from the values without the corrections (as presented in the figures) for beam currents below 330 μA. The results presented can therefore be used in this range of currents.

The MONTEC results for the short imaging shaper are presented in appendix A.6, in figures A6.10 \((\text{d}E_{\text{fwhm}})\) and A6.11 \((\text{d}R_{\text{fwhm}})\). In figures
A6.12 and A6.13 the calculations for the long imaging shapers are shown. As in the last section the figures are divided in part a, b and c for the different depths of focus (and reduced beam brightnesses). The figures present the comparison between the short and the long imaging shaper in dynamic brightness mode for the different reduced brightnesses and corresponding sizes of the shaping apertures mentioned.

6.3.4 Results from the calculations for imaging shapers

For the full range dynamic brightness mode the beam current in the shaper will range from 10 to 330 μA. Thus trajectory displacement will be in the range 4.4 .. 43 μm for the short imaging shaper. For the shaper of figure 6.3, only 5.5 μm trajectory displacement is allowed, so only 20 and 100 kV shapers can be used there. With up to 2% energy spread the Boersch effect of this shaper is acceptable for voltages of 5 kV and higher. The short imaging shaper could be usable. As an example figure A6.11a presents the trajectory displacement effects found for the short imaging shaper with the highest reduced beam brightnesses. Here dR_{rwhm} is in the order of 1 μm, which is acceptable as compared to the shaping aperture of

\[ D_{s2} = 440 \mu m. \]

For this setup the 2, 5 and the 20 kV options are unacceptable because of too high trajectory displacement effects. The same holds for figures A6.11b and A6.11c. Boersch effect is, in the case of the short imaging shaper, allowable for beam voltages of 5 through 100 kV.

The figures with the analytical results show very large deviations from the simulation results. (The analytical results are in the order of 100 times smaller, while the Boersch effect is in the order of six times smaller for the analytical results !) It is concluded that for the cases calculated the validity of the equations is questionable. The Monte Carlo results are most trustworthy for these cases. The expected behaviour as a function of beam current was described in equations 2.6 and 5.16. This behaviour is only partly found in all figures and in all cases the \( \gamma_{e} \)-values differ from the constant value of 2/3.

The main conclusion is that the short imaging shaper has lower effects by a factor of about 2.5. Furthermore the bigger apertures have the
(relatively) smallest effect. Both Boersch effect and trajectory displacement are almost linear in $D_s$. A very important result is that for the cases of depth of focus equal to 0.5 and 2.0 $\mu$m only the beam brightness differs. Both the electron-electron interaction effects are almost independent of this change in beam brightness (beam opening angle in the shaper).

6.4 Shadow shapers

As mentioned in section 6.2 shadow projection of the two shaping apertures can be used because of the large depth of focus. The principle of shadow shaping was described in section 3.5 and it was illustrated in figures 3.2 [reproduced in figure 6.1]. As an example the numbers for the AEBLE-150 are used. This system contains a shadow shaper with 150 $\mu$m apertures. With an $\text{LaB}_6$ gun of 20 $A/cm^2/sr/V$ and a nominal beam current of 2 $\mu$A this implies an opening angle of 0.13 mrad. With a 20 $\mu$m diameter electron source and a diverging beam from the source it is easiest to use the angular emission for illumination of the first shaping aperture. This means that no intermediate lenses are required and the illumination system can be very short. Electron beam writing systems are normally designed for a depth of focus of 2 to 10 $\mu$m. The AEBLE-150 has a depth of focus of 9 $\mu$m and it has a 75 times demagnification. Combination of these values implies that the depth of focus, in the plane of the shaping apertures, is about 50 mm. Since the whole shaper could be fabricated within this length no shaper lenses are required.

The inverse reasoning can be followed by stating that there is a maximum beam semi opening angle. This is determined by the unsharpness allowed in the edge of the second shaping aperture:

$$\delta_{sh} = \alpha \frac{L_s}{s}$$  \hspace{1cm} (6.5).

This $\delta_{sh}$ should be well below the edge roughness allowed on the second shaping aperture $D_s/40$. It adds directly to the imaging unsharpness contributions in equation (5.5). Since the source brightness gives a relation between the illumination angle and the size of the shaping aperture, $D_s$, there is a maximum to the length of the shaper, $L_s$, with equation (4.1):
\[ B_r = \frac{1}{\pi \alpha_s^2 D_s^2 U} \Rightarrow \alpha_s = \frac{1}{D_s} \sqrt{\frac{1}{\pi B_r U}} \]

which gives with equation (6.3)

\[ L_s < \frac{D_s}{40 \alpha_s} \Rightarrow L_s < \frac{D_s^2}{40} \sqrt{\frac{\pi U B_r}{I}} \] (6.6)

With a very short deflector \( L_E = 8 \text{ mm} \) the total shaper length could be 3 \( L_E \), as described in equation (5.3).

For a shaping aperture with \( D_s = 100 \mu\text{m} \) and a very bright \( \text{LaB}_6 \) gun with \( B_r = 100 \text{ A/cm}^2/\text{sr}/\text{V} \), \( U = 2 \text{ kV} \) and \( I = 20 \mu\text{A} \) this yields \( L_s \leq 5.5 \text{ mm} \).

For this emitter the following minima for the parameters are realistic:

\[ U \geq 5 \text{ kV}, \ I \leq 20 \mu\text{A}, \ D_s \geq 170 \mu\text{m} \Rightarrow L_s < 24 \text{ mm}. \]

Increasing the beam brightness by using a PN-emitter (\( B_r \approx 150 \ldots 3000 \text{ A/cm}^2/\text{sr}/\text{V} \)) would increase the beam current to some 100 \( \mu\text{A} \). Still higher beam currents can only be reached by increasing the beam voltage and increasing the size of the shaping apertures.

In figure 6.8 the geometry of the shadow shaper as simulated is depicted.

\[ \text{source} \quad \text{crossover} \quad \text{field aperture} \quad \text{deflector} \quad \text{deflector aperture} \]

\[ \text{lens} \quad 1 \quad 1 \quad \phi \quad 2 \quad 2 \]

\[ \text{Figure 6.8: Schematic drawing of the shadow shaper with double deflector geometry as used in the calculations.} \]
6.4.1 Imaging conditions for shadow shapers

The input of the shadow shaper is described as one single beam section from the first to the second aperture. The length of the shapers in figures 6.3 and 6.8 is determined by the deflector sensitivity (refer also to sections 5.5 and 6.3.1). The cases presented in section 6.3.1 have been calculated. For all of the shapers $D_{s1} = D_{s2}$. Thus, the demagnifying section has exactly the same input conditions (in terms of shaping apertures and source brightnesses).

6.4.2 INTERAC calculations for shadow shapers

The INTERAC calculations were applied to the shadow shaper presented in figure 6.8, in the same way as described in section 6.3.2. In this case the opening angle of the beam is very small, which is necessary to obtain the depth of focus required for shadow shaping.

The INTERAC results are presented in figures B6.1 through B6.8 (in appendix B.6), with the same conventions as in section 6.3.2. Again, the reader is referred to the appendix for the detailed results. The figures B6.1a through c should be compared to the figures B6.8a through c. These pairs of figures represent the comparison between the short and the long imaging shaper in dynamic brightness mode. The figures in appendix B.6 given an overview of the effects for all the reduced brightnesses and the corresponding sizes of the shaping apertures mentioned.

6.4.3 Monte Carlo simulations for shadow shapers

For this setup an even larger depth of focus is found and therefore only the TBR routine can be used to obtain trajectory displacement. In this case the opening angle of the beam is very small (to allow for shadow imaging).
The MONTEC results are presented in figures B6.9 through B6.13. As in section 6.3.3 the results are split into a short shaper: figures B6.9 (\(dE_{\text{fwhm}}\)) and B6.10 (\(dR_{\text{fwhm}}\)) and a long shaper (B6.12 and B6.13).

6.4.4 Calculation results for the shadow shapers

The opening angle of the beam is very small (to allow for shadow imaging). With the very high brightnesses used here, this severely limits the usage of the INTERAC results. The behaviour of the MONTEC DRIFT2-routine for these conditions is also not very accurate. Both programs were applied mainly to imaging sections by [Jansen, 1988]. In this case it would be more appropriate to trust the INTERAC results. As the ranges of answers do not match very well the validity is again difficult to establish. The appropriate behaviour as a function of beam current is found in all figures. It is therefore concluded that the total effects (both Boersch effect and trajectory displacement) are clearly smaller than in the case of the imaging shaper (ref. section 6.3.4). Also the short shadow shaper has lower effects by a factor of about 1.5. Furthermore the bigger apertures have the smallest effect. Both Boersch effect and trajectory displacement are almost linear in \(D_g\). Here too it is found that for the cases of depth of focus equal to 0.5 and 2.0 \(\mu\)m both the electron-electron interactions effects are almost independent of this change in beam brightness (beam opening angle in the shaper).

The beam voltage increase from 2 to 100 kV does not have as much influence as was suggested in equation (5.16). With a factor of 50 in beam voltage a factor of about 1/4 is found for both effects. This can only be explained from the corresponding change in \(\gamma_e\)-values. Clearly these tabulations are the only manner in which insight in the interaction effects can be obtained.

The general conclusion from the shadow shapers is that most configurations proposed here can be used. Only the ones with 2 kV voltage should be discarded.
7 THE DEMAGNIFYING SECTION

7.1 Introduction

The demagnifying section performs the optical adaptation of the shaper sections presented in chapter 6 to the different projection sections in chapter 8. Next to demagnifying the shaper image, the demagnifying lens has to image the source cross-over into the cardinal plane of the projection lens.

As was argued in section 3.2, the final beam potential for a realistic system (meeting the writing specifications) will be in the range of 20 to 100 kV. Since a source cross-over in this section cannot be avoided the beam should first be accelerated to the final beam potential, in order to get the lowest possible electron-electron interactions in the cross-overs. Therefore an accelerating section will be inserted into the systems with low voltage shapers (immediately after the second shaping aperture).

The INTERAC calculations for this section are more reliable than those for the shaper and projection sections. Therefore the MONTEC calculation results will only be provided to support the INTERAC results. As the effects are lowest for the short versions of the demagnifying section, these will get the most attention.

7.2 Design criteria for the demagnifying lens section

The main function of this section is to provide a (strong) demagnification of the image of the shaping apertures (see figure 7.1). The total system demagnification factor is determined by the combination of the size of the shaping apertures and the writing specifications. It is completely determined by the size of the last shaping aperture in the shaper section chosen. The partial demagnification factors of the projection lens section are determined in chapter 8.
Figure 7.1: The demagnifying section between the last shaping aperture and the projection lens system. The source cross-over and shape cross-over are indicated with x.

The choice of the demagnifying lens strength is governed by the allowable geometrical aberrations in the intermediate image of the shaping apertures. As in the case of the shaping lens the demagnifying lens will only have to provide a relatively small field of view. The major contribution will therefore result from spherical aberration. In the first instance the requirement put up by electron-electron interactions will be that the section should be short. Both spherical aberration and the electron-electron interaction effects will be lowest for the strongest possible demagnifying lens.

With a strong lens ($F_m$ in the order of 0.5 to 1.1 mm) the required demagnification can be realized using a single lens. In the case of the version with a weaker demagnification lens the total section length would become too big. In the case of a weak demagnifying lens and a large demagnification factor more demagnifying lenses would be required to keep the section length realistic (some tens of centimeters).

When the imaging shaper is used, it may be impossible to place the source intermediate image sufficiently far beyond the second shaping aperture, allowing for a very strong demagnification in one step. In these cases, given the strength of the demagnifying lens, its demagnification factor is fully determined by the imaging conditions. A field lens and a second demagnifying lens are required to realize the
required demagnification factor and the placement of the source cross-over (see figure 7.2).

![Diagram of a demagnifying section](image)

**Figure 7.2:** A possible demagnification section for those cases where the source cross-over is close to the last shaping aperture. In this case two demagnifying lenses and a field lens are required.

For the low voltage shaper sections (2 and 5 kV) an accelerating section has to be inserted. The principal plane of the lens effect (maximum ray bending) of this accelerating section is localized in the beginning of the field. By placing the accelerating section close to the last shaping aperture it will behave as a field lens. Therefore it does not influence the quality of the final image of the shaping apertures. The only effect remaining from the accelerating section is the reduction of beam opening angle. This is correctly accounted for when using the constant reduced source brightness.

The accelerating section creates a (source) cross-over. In this case the position of the first demagnifying lens is completely determined by the intermediate images of the source and the shaping aperture(s). Therefore a second demagnifying lens may be required to realize the total demagnification. This might also require a field lens at the position of the demagnified shaping aperture. This field lens forms an intermediate source image close before the (last) demagnifying lens, which is then imaged by that demagnifying lens into the principal plane of the projection lens (see figure 7.2).
In conclusion it can be stated that the accelerating section does not influence the imaging conditions of the shaping aperture(s) very strongly. The length of this section is determined by the isolation length required for a voltage difference of 80 to 95 kV (some millimeters of beam length). A problem of the electron-electron interaction equations of Jansen is that the effects cannot be calculated analytically in accelerating sections. In the simulation package accelerating sections are supported.

As the section can be made very short, with a wide beam with no cross-over inside it, the effects of the accelerating section will be small in all cases. It will be shown that it is not necessary to do detailed calculations for the accelerating section. The effects in this section are small as compared to the effects in the shaper section. In the same way the different placements of field lenses will not show strong variations in electron-electron interactions. The detailed calculations will not focus on the field lenses either.

7.3 Selection of the setups for simulation

The maximum lens strength for magnetic lenses is limited because of the properties of the magnetic materials. It is proportional to the square root of the beam potential. The following lens strengths were concluded to be realistic (ref. [van der Mast, 1984/2]):

for the strong demagnifying lens

\[ F_m = 0.5 \text{ mm (20 kV) and } F_m = 1.12 \text{ mm (100 kV)} \]

are realistic, obtainable values.

And for the weak lens we arbitrarily take:

\[ F_m = 8.94 \text{ mm (20 kV) and } F_m = 20.0 \text{ mm (100 kV).} \]

In some of the earlier calculations \( F_m = 4.0 \) and \( F_m = 20 \) mm were applied to the cases of the strong and the weak demagnifying lenses respectively. Some of the tables will show interaction effects for these values, indicating trends in the effect for variation of parameters.
The input conditions for this section are determined by the shaper sections in chapter 6. Three values of reduced source brightness are investigated. These values are related to three different depths of focus investigated (ref. section 5.2). Together with a long and a short version of the shaper, and imaging and shadow types, twelve different shapers are distinguished. (It should be noted that the imaging shapers presented in chapter 6 will be used in demagnifying mode.) Combined with the four beam voltages of the shaper, this gives a total of 48 different shaper sections. For the shadow shapers the imaging conditions are fully determined by the field lens (close to the second shaping aperture). In these cases the only demands are that the beam lengths in the demagnifying section are chosen realistically.

As the effects of the field lenses are of minor importance, the six sizes of the last shaping aperture and the four beam voltages will be used as input conditions for the demagnifying section. This set is complete for the shadow shapers; it gives indicative values for the cases in which an imaging shaper section is used. Different target $D_m$ sizes are used:

$$D_{m1} = 5.67 \ \mu m \quad \text{and} \quad D_{m2} = 34.7 \ \mu m.$$  

these values are dependent on the projection section which will be discussed in chapter 8. For each of the values mentioned the partial demagnification in the demagnifying section ($M_{m1}$ and $M_{m2}$) will be indicated. In tables 7.3.2 and 7.3.4 the following set of input conditions is used:

for the long shapers

A: $D = 550 \ \mu m \ B = 170 A/cm^2/sr/V \Delta z = 0.5 \mu m \ M_{dof} = 1/97 \ M_{m1} = 1/15.9$

B: $D = 385 \ \mu m \ B = 680 A/cm^2/sr/V \Delta z = 1.0 \mu m \ M_{dof} = 1/68 \ M_{m1} = 1/11.1$

C: $D = 550 \ \mu m \ B = 850 A/cm^2/sr/V \Delta z = 2.0 \mu m \ M_{dof} = 1/97 \ M_{m1} = 1/15.9$

and for the short shapers

D: $D = 220 \ \mu m \ B = 170 A/cm^2/sr/V \Delta z = 0.5 \mu m \ M_{dof} = 1/38.8 \ M_{m1} = 1/6.3$

E: $D = 155 \ \mu m \ B = 680 A/cm^2/sr/V \Delta z = 1.0 \mu m \ M_{dof} = 1/27.3 \ M_{m1} = 1/4.5$

F: $D = 220 \ \mu m \ B = 850 A/cm^2/sr/V \Delta z = 2.0 \mu m \ M_{dof} = 1/38.8 \ M_{m1} = 1/6.3.$

In the case of imaging shapers the demagnification factor of the (first) demagnifying lens is fixed. Then the characteristic length in the shaper
L also corresponds to the distance between the second shaping aperture and the source cross-over. This results in the following (partial) demagnification factors:

long imaging shaper (\(L_E = 50 \text{ mm}\))

\[\begin{align*}
F_m &= 0.5 \text{ mm (20 kV)} & M_m &= 1/99 \\
F_m &= 1.12 \text{ mm (100 kV)} & M_m &= 1/41.4 \\
F_m &= 8.94 \text{ mm (20 kV)} & M_m &= 1/4.59 \\
F_m &= 20.0 \text{ mm (100 kV)} & M_m &= 1/1.5 \\
\end{align*}\]

short imaging shaper (\(L_E = 8 \text{ mm}\))

\[\begin{align*}
F_m &= 0.5 \text{ mm (20 kV)} & M_m &= 1/15 \\
F_m &= 1.12 \text{ mm (100 kV)} & M_m &= 1/10.4 \\
F_m &= 8.94 \text{ mm (20 kV)} & M_m &= 1/9.5 \\
F_m &= 20.0 \text{ mm (100 kV)} & M_m &= 1/1.67. \\
\end{align*}\]

As will be seen all demagnification factors can be realized, but most systems do require a second demagnification lens. A field lens at the position of the second shaping aperture could help to reduce the distance \(L_E\). This means that a lower demagnification factor (closer to one) can always be realized.

The imaging conditions for the projection section are determined in chapter 8. As will be described in that chapter, the design of the projection section is dominated by geometrical aberrations, positioning deflector aberrations and the physical size of detectors, stage etc. A well designed projection section will be used. This projection section will again be compared with a section based on a weaker projection lens. The proposal with a weaker lens more or less resembles the projection lens sections found in conventional systems. The demands for the demagnifying section can be summarized as:
The demagnifying section

intermediate shape images:

strong projection lens: \( D_m = 5.67 \, \mu \text{m} \)

weak projection lens: \( D_m = 34.7 \, \mu \text{m} \)

(Here \( D_m \) is the maximum side length of the intermediate image projected by the demagnifying section.)

intermediate source images:

the source has to be imaged into the cardinal plane of the projection lens. This plane will be in the order of 200 mm beyond the intermediate shape image. (The diameter of the source crossover is fixed by the reduced brightness values given.)

beam voltages:

20 and 100 kV.

beam current:

in the case of dynamic brightness the beam current in this section will be fixed at 10 \( \mu \text{A} \). For the fixed brightness mode a beam current range of 5 to 100 \( \mu \text{A} \) would be of interest. (Optimization of the beam current ranges will be done in chapter 9.)

With these values the partial demagnification in the demagnifying section varies from \( M_m = 1/4.3 \) to \( M_m = 1/97 \).

Demagnifying sections for the complete set of (second) shaping aperture sizes have been calculated for the short focal length demagnifying lens. For the purpose of comparison some of the longer demagnifying sections have been calculated. These were the ones with very large and very small demagnification factors. Table 7.3.2.c also summarizes some of the earlier calculations done with \( F_m = 4.0 \) and \( F_m = 20.0 \, \text{mm} \).

Following the idea of dynamic brightness, the reduced beam brightness values are specified for the nominal beam current of \( I = 10 \, \mu \text{A} \). Beam current variation in the calculations is done without changing the source size and opening angles. This corresponds to beam brightness variations proportional to the beam current.
In Table 7.1 an example input file for the INTERAC program is shown. With this simple section all of the input beam brightness and beam voltage conditions were run through the program. The results of this are summarized in Tables 7.2 and 7.3. None of the effects are very critical and thus the MONTEC program has not been used intensively. Table 7.5 presents some of the MONTEC input files. The major results from MONTEC simulations are summarized in Tables 7.6 and 7.7. A more complete set of calculation results can be found in Appendix A.7.

Table 7.1: Sample input file for the INTERAC program. This file describes a single demagnifying section, with a lens of focal length \( F_m = 0.5 \) mm. The section ends at the shape intermediate image \( (D_m = 5.67 \text{ \mu m}) \), which is applied to the projection section.
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Table 7.2: Analytical electron-electron interaction effects for the short demagnifying sections. This table presents the versions for the small intermediate image, \( D_m = 5.68 \ \mu m \), with

- MAV: \( B_r = 170A/cm^2/sr/V, D_{s2} = 220 \ \mu m \)
- MBV: \( B_r = 680A/cm^2/sr/V, D_{s2} = 155 \ \mu m \)
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Table 7.3: Analytical electron-electron interaction effects for the short demagnifying sections. This table presents the versions for the large intermediate image, $D_m = 34.7 \mu m$, with

\[
\text{NAV: } B_r = 170 \text{A/cm}^2/\text{sr}/\text{V}, \ D_{s2} = 220 \mu m
\]

\[
\text{NBV: } B_r = 680 \text{A/cm}^2/\text{sr}/\text{V}, \ D_{s2} = 155 \mu m
\]
The demagnifying section

--- \fma v20330.sys --------------------------------------------

c first edited: 9-3-1989, j. simons, imaging shaper
c last edited: 23-7-1989, br=680, demag system

c/source/ z / xctr / yctr / ids (i) / xhw / yhw /
c / ida (i) / ahw / tca /
/source/ 0.0E0 / 0.0E0 / 0.0E0 / 3 / 155.0E-6 / 155.0E-6 /
/ / 1 / 80.15E-6 / 0.0E0 /
/drift2/ -1.0E0 / 21.88E-3 / -1.0E0 / -1.0E0 / 1 / 1 /
c/lens / z / xctr / yctr / f / cs / cc /
/lens / -1.0E0 / 0.0E0 / 0.0E0 / 4.00E-3 / 0.0E0 / 0.0E0 /
/drift2/ -1.0E0 / 26.78E-3 / -1.0E0 / -1.0E0 / 1 / 1 /
symebr/
/rectbr/ -1.0E0 / 0 /
/tbr / -1.0E0 / 0 /
/tbr / -1.0E0 / 1 /
/rectbr/ -1.0E0 / 2 /

Table 7.5: Sample input file for the MONTEC program. This file describes a single demagnifying section, with a square source (the last shaping aperture), a drift section, a lens (focal length F_m = 4.0 mm) and a final drift section. The section ends at the shape intermediate image (D_m = 5.67 µm), which is applied to the projection section.
Table 7.6: Monte Carlo simulation results of the electron-electron interaction effects for the short demagnifying sections. This table presents the effects for the longer sections of table 7.5.
7.4 Electron–electron interactions in the demagnifying section

By comparing the tables in detail the following (partial) conclusions are reached:

- In the case of large demagnification, table 7.2 indicates very small trajectory displacement effects and a significant Boersch effect. At 10 μA nominal beam current, the Boersch effect is 3 to 3.5 eV both for 20 and 100 kV beam voltage. The trajectory displacement in the same setups is in the order of 0.3 to 0.1 nm (20 and 100 kV respectively). Only 0.14 nm is acceptable since $\delta_{TD}$ should be within 1/40 of $D_m$. For 100 μA both effects get 3 to 5 times worse.

  20 kV: $dE \approx 18$ eV, $dR_{fwhm} \approx 2$ nm
  100 kV: $dE \approx 24$ eV, $dR_{fwhm} \approx 0.9$ nm.

These conditions cannot be combined with the cases of large demagnification in this section.

- The case of small demagnification (table 7.3) indicates that all setups at all beam voltages and beam currents are acceptable:

  10 μA 20 kV: $dE \approx 0.7$ eV, $dR_{fwhm} \approx 60$ pm
  100 kV: $dE \approx 0.65$ eV, $dR_{fwhm} \approx 30$ pm
  100 μA 20 kV: $dE \approx 4.5-5.5$ eV, $dR_{fwhm} \approx 300$ pm
  100 kV: $dE \approx 5.6-6.3$ eV, $dR_{fwhm} \approx 160$ pm.

- The calculations for the long systems with the large demagnification factors are unreliable. Effects for the small demagnification can be deduced from table A7.4, systems NAV.2 and NEV.2. These indicate acceptable results as well. The beam brightness values indicated in table A7.4 are calculated for a nominal beam current of 330 μA (as opposed to 10 μA, for tables A7.2 and A7.3).

  10 μA 20 kV: $dE \approx 1.5-2$ eV, $dR_{fwhm} \approx 0.5 -3.3$ μm
  100 kV: $dE \approx 1 -1.4$ eV, $dR_{fwhm} \approx 0.1 -0.4$ μm
  100 μA 20 kV: $dE \approx 6 -8$ eV, $dR_{fwhm} \approx 2 -15$ μm
  100 kV: $dE \approx 4.5 -6$ eV, $dR_{fwhm} \approx 0.29 -2$ μm.
- Comparison of the Boersch effect and the trajectory displacement between tables A7.6 (nav02) and table A7.4 (NAV.1, 2 kV) gives for the Boersch effect INTERAC and MONTEC shows closely matching results for $I < 200 \mu A$. For the trajectory displacement effect INTERAC results are continuously a factor 8 bigger.

- The 5 kV tables 7.6 (mav05) and A7.4 (NAV.1, 5 kV) show about equal Boersch effects (for all currents). The INTERAC program indicates that the trajectory displacement effects are about 3 times bigger, for the same setups.

- The 20 kV tables A7.7 (mav20) and A7.4 (NAV.1, 20 kV) show about equal Boersch effect results. The INTERAC results for trajectory displacement are 3 to 5 times bigger in this case.

- The 100 kV tables A7.7 (mav99) and A7.4 (NAV.1, 100 kV) also show about equal Boersch effects. The INTERAC results in this case are about 3 times bigger.

Beam currents will never be higher than 10 $\mu A$ when applying the dynamic brightness concept. In that case the Boersch effect in this section will always be lower than 4.0 eV (both 20 kV and 100 kV). The higher beam current required for fixed brightness writing can only be kept within realistic bounds in the case of the larger beam opening angles. Therefore the demagnifying section does not generate excessive Boersch effect for low current and dynamic brightness mode. With the larger beam currents only the lower brightnesses can be allowed.

The trajectory displacement is rather high. In order for the trajectory displacement, $\delta_{m,TD}$, to be within 142 nm (5.67/40) only the higher beam voltages can be used. Correspondingly the larger projection sections have an intermediate image of 34.7 $\mu m$, thus $\delta_{m,TD} = 868$ nm trajectory displacement is allowed. All of the sections come near this value at the higher beam currents at 20 kV beam potential. In a 100 kV system 10 $\mu A$ beam currents results in small enough effects.

The Monte Carlo simulations in table 7.6 illustrate that the processing of end coordinates is required for Boersch effect (only). The results in tables 7.6 and A7.7 can be compared to the cases NAV.1 and NEV.1 in table A7.4. The Boersch effect values at the lower beam currents in
table A7.4. The Boersch effect values at the lower beam currents in section 7.3.4 closely match the INTERAC results of table A7.4. The trajectory displacement values show the same parameter dependence, but the INTERAC results (comparing the first $dR_{\text{FWHM}}$ value) are constantly two to three times higher. Related to the size of the imaged shaping aperture $D_m$, this corresponds to a trajectory displacement effect (in the INTERAC calculations), which is 4 to 6 times larger. As the effect is strongly dependent on reduced beam brightness, this is no more than expected.

The order of magnitude of the effects can be estimated from the calculations. In conclusion it can be stated that the analyticals equation do give reasonable results for the Boersch effect in this section. The trajectory displacement results closely follow the analytical equations. There is an error in the absolute values of the results, though. Comparison of the results obtained from the Monte Carlo simulation and from the values found using the analytical equations shows that these results differ by an approximately constant factor.

The accelerating section does not impose any difficulties. Comparing table A7.7 (20 kV) and table A7.8, clearly indicates that for a maximum length accelerating section the total effects are equal within 40 % (both Boersch effect and trajectory displacement).

It should be noted that the Monte Carlo simulation were done for lower reduced beam brightnesses than those required for the target system. As can be seen from the INTERAC results the effect will be sufficiently low and if just the order of magnitude is correct, the total effects in this section will be negligible.

The conclusion with respect to the HISEL system specifications is that a short demagnifying section will be acceptable ($f_m$ in the order of 0.5 mm at 20 kV or 1.1 mm at 100 kV). The beam voltage is selected to be 20 kV or 100 kV. The low voltage shaping sections can be used if the beam is accelerated at the beginning of the demagnifying section. This does not have significant influence on the total Boersch and trajectory displacement effect.
8 THE PROJECTION SECTION

8.1 Introduction

This section projects the demagnified image of the shaping apertures onto the final target. It contains the positioning deflectors that define the exact position of the spot on the target. For the final lens a long and a short focal length, both realistic, will be selected to demonstrate the parameter dependence. The optimized setup has been determined with the help of B. Lencová herself, who developed the optimization programs for lens and deflector aberrations described in [Lencová, 1989].

The high speed sub field deflectors in this section are again electrostatic as is the case with the shaping deflectors. The same length argument as for the electrostatic shaping deflectors (section 5.6) is therefore applicable. A schematic view of the section is depicted in figure 8.1.

![Schematic view of the projection section](image)

Figure 8.1: Schematic view of the projection section. Optimum use of the lens is made when a source intermediate image is placed in the cardinal plane of the lens. Several deflector positions and the place of the backscatter detector are indicated.
8.2 Design of the projection lens section

In this thesis the assumption is made that all possible dynamic corrections will be implemented and that the writing strategy is close to optimum. In such systems the electron optical limitations determine the theoretically feasible speed of the system. In this limit only the non-correctable aberrations have to be taken into account. The theoretical limit determined in this way should be a good indication of what can be reached with a realistic system.

The following design considerations apply to the projection section:

As mentioned, the major function of this section is positioning of the final spot onto the target. An intermediate source image is thereby positioned in the cardinal plane of the projection lens. This will assure the use of the maximum opening angle (maximum effective lens area) under variation of the shape size.

Especially the first part of this section (in front of the lens) has to be long enough to allow for (pre) deflectors with a range corresponding to a sufficiently large field of view (0.2 .. 5 mm values are mentioned in literature).

The length of the last part of this section (between the lens and the target) is determined by the required free space for stage movement and by the physical size of the electron backscatter detectors, used for measuring the position of the electron beam on the target. These demands limit the maximum lens strength that can be used.

The absolute size of the field of view is related to the attainable speed of the table, given the high resolution demands. Current systems (EL-3, FEPG) have table speeds in the order of 0.1 m/s with fields of view in the order of $0.5 \times 0.5$ (mm)$^2$. This size of the field of view as compared to the speed of the table can only be optimized when very detailed information about the table is known. This question is not further addressed.

Writing on the fly is considered in order to reach maximum writing speed (the system does not have to wait until the table has come to a halt at the next writing position). As [Spehr, 1989] derived, the eddy currents,
generated by wafer movement, are sufficiently low not to cause significant beam shifts. It is therefore allowed to immerse the wafer in the lens field and write on the fly. As a conclusion it is proposed to use a strong variable axis immersion lens (VAIL) for the projection lens section. Such a system is already in use in IBM's EL-3.

The writing strategy is to split into main field and sub field deflectors, where subfieldds are addressed with slower, high accuracy deflectors. Even at a writing rate of \(1 \text{ cm/s}^2\) \(= 10^{10}\) pixels/s), sub fields of sizes from 50 to 100 \(\mu\text{m}\) imply that the system will be several milliseconds in every sub field. This determines that the setup time for the sub field deflectors has to be only an order of magnitude smaller than that (100 \(\mu\text{s}\) to 1 ms). [Alles, 1987] mentions a main field of 256 \(\mu\text{m}\) (square), a sub field of 32 \(\mu\text{m}\).

For such small fields it suffices to correct for lens aberrations by using interpolation. The interpolation settings are adjusted for every sub field. The same holds for deflector aberrations and corrections on the positional error (and thermal expansion) of the wafer. Usually, per sub field one focus setting is used which compensates for the average height and tilt of the wafer.

An optimization has been done for a final VAIL lens system (variable axis immersion lens) taking several different aberrations into account. The aberrations in this system which determine the field of view are:

- spherical aberration
- coma (both isotropic and anisotropic)
- curvature of field
- astigmatism (both isotropic and anisotropic)
- distortion (" " " " )
- axial chromatic aberration
- chromatic magnification and rotation errors
- deflector chromatic aberration.

Since this system has a rather large field of view, the first order approximations cannot be used for this case. With the programs of
[Lencová, 1989] these effects can be approximated to the same order of magnitude as the image details in the pattern. Especially for the deflectors the programs of Lencová have been optimized since the deflector fields are partially within the lens field of the final lens.

These programs were used to determine an optimum system design for a 100 kV VAIL lens. It turned out that a system with $F_p = 5.44$ mm and a field of view of $1.0 \times 1.0$ (mm)$^2$ can only just be designed within the required tolerances. A schematic view of the system used is given figure 8.2. Since the electron optical aberrations in the final lens system contribute significantly to the total system aberrations it is good to merge the theoretical limitations of the other sections with a properly designed projection lens.

![Diagram](image.png)

Figure 8.2: Detailed view of the VAIL lens design. From the projection lens only the pole pieces above the target are shown. The form of the lens and the position and strength of all three deflectors have been optimized to give minimum aberrations.
8.3 Setup of the electron-electron interaction calculations

Normally a lens is used, which is not too strong, allowing a relatively large field of view (1 x 1 (mm)$^2$). Thus the long projection section corresponds to a conventional projection section, whereas the short version corresponds to the VAIL section discussed in the previous section. The short section has been designed by B. Lencová, to have minimum geometrical aberrations and minimal deflector aberrations in a VAIL setup ($C_{sa} = 6.7$ mm).

For the VAIL setup the following configuration is used:

final lens: $F_p = 5.4$ mm $M_p = 1/35.7$

object distance: $A_{po} = 200$ mm

image distance: $A_{pi} = 5.5$ mm.

(Optimization for chromatic aberration has been done for a beam voltage of 100 kV, with a total energy spread in the order of 10 eV.) Exactly the same system will be used for the 20 kV calculations since the geometrical sizes are more significant than the beam voltage.

In an analogous system with a lower demagnification electron-electron interactions have been calculated:

final lens: $F_p = 5.4$ mm for $M_p = 1/5.67$

object distance: $A_{po} = 36.0$ mm

image distance: $A_{pi} = 6.4$ mm.

Here the demagnification is the minimum required to ensure that geometrical aberrations of earlier lenses in the system do not contribute too much to the overall geometrical aberrations.
For the long configuration the following setup is used:

final lens \( F_p = 30 \text{ mm} \) for \( M_p = 1/35.7 \):

object distance: \( \Delta z_{po} = 1040 \text{ mm} \)

image distance: \( \Delta z_{pi} = 30.9 \text{ mm} \).

and

final lens \( F_p = 30 \text{ mm} \) for \( M_p = 1/5.67 \)

object distance: \( \Delta z_{po} = 200 \text{ mm} \)

image distance: \( \Delta z_{pi} = 35.3 \text{ mm} \).

The version with the large demagnification is not realistic. It is concluded that the large demagnification is not possible with the long final lens, as this system is far too long.

The beam voltage in the projection section is varied from 2 to 100 kV. Beam currents as in the demagnifying section from 10 to 100 \( \mu \text{A} \) are of interest. Sample input files for the INTERAC program and for the MONTEC program have been reproduced in tables 8.3.1 and 8.3.2.

### 8.4 Results from the electron–electron interaction calculations

The results of the INTERAC calculations are presented in figures 8.3 through 8.4. Again these figures are extracted from appendix A.8, where a more complete set of results is presented. Part of the corresponding Monte Carlo simulations is presented in figures 8.4 and 8.5.

In dynamic brightness mode the beam current will not exceed 10 \( \mu \text{A} \). The results of the higher beam currents (higher than about 50 \( \mu \text{A} \)) from MONTEC and INTERAC results diverge.
Figure 8.3: INTERAC calculations for the projection section. Dynamic brightness mode is assumed with the brightness indicated for 330 μA. This is the short projection section, with $F_p = 5.4$ mm and $pav: B_r = 170 \text{ A/cm}^2/\text{sr}/\text{V}$. 
As can be seen, the Boersch effect is in the order of 2 to 9 eV for beam currents of 10 μA. The trajectory displacement is rather high. Only for 100 kV, it is in the order of 10 to 20 nm (at 10 μA). In all other cases it is much higher. It is also concluded that the shortest possible section should be chosen.

Figure 8.4: MONTEC calculations for the projection section. Dynamic brightness mode is assumed with the brightness indicated for 330 μA. This is the short projection section with \( F_p = 5.4 \) mm. The \( dR_{\text{fwhm}} \) values have been obtained from the TBR statistical processing routine.

\[
pbv: \quad B = 170 \text{ A/cm}^2\text{/sr/V}
\]
Figure 8.5: MONTEC calculations for the projection section. Dynamic brightness mode is assumed with the brightness indicated for 330 μA. This is the long projection section with \( F_p = 30.0 \) mm. The \( dR_{fwhm} \) values have been obtained from the TBR statistical processing routine.

\[
pdv: B \left( \frac{A}{cm^2 /sr/V} \right)
\]
9 DESIGN OF AN ELECTRON BEAM PATTERN GENERATOR

9.1 Introduction

This thesis has illustrated that electron beam writing will play an important role in future chip production. The design rule of the chip-pattern was taken to be 0.1 μm. For this design rule it was indicated that electron beam direct-writing is the best technique. In the first four chapters, therefore, the specifications for a HISEL (High Speed Electron beam Lithography) system were refined. These chapters also described the new developments which are required to enable the high performance demanded of a future direct-write system.

After the introduction of the pattern specifications different existing electron beam writing systems were presented in chapter 2. It was shown that the specifications cannot be attained with only simple improvements in some parts of these systems. It was found that the conventional systems are too long to meet the HISEL specifications. After that, some new developments in electron optics were introduced. These developments enable the redesign of an electron beam writing system according to the HISEL demands. At first the shaper design considerations were mentioned, since variable beam shaping enables one to get a high degree of parallel pixel illumination while still allowing for very tight pattern specifications. Then PN-emitters were introduced, as these electron sources allow the system to work with very high brightness. As a last point the VAIL (Variable Axis Immersion Lens) system was mentioned. The VAIL system allows one to reduce the length of the projection part of the system significantly.

The central issue then became how to design an optimal electron beam writer, taking into account the different aberrations in the system parts. As a new aspect in these calculations the aberrations due to electron-electron interactions was introduced. This effect was described in detail by [Jansen, 1988]. Taking this effect into account resulted in numerical calculations of the aberrations for each of the beam sections of the electron beam writing system. Therefore, optimization of the design of each section was done separately. From the calculations in
chapters 6, 7 and 8 it can be concluded that each of the beam sections of the conventional systems should be redesigned in order to enable the usage of very high brightness electron sources.

This chapter will combine the results from the different beam sections. This enables one to draw some general conclusions about system optimization and about the HISEL system in particular. After that the practical results for the HISEL conditions are presented in sections 9.5.1 and 9.5.2. Finally, some results will be presented for a system with a well engineered LaB$_6$-emitter (in section 9.5.3). This system seems to be more realistic at present, but the improvements in the various beam sections do not suffice to realize the HISEL system requirements. This case will be illustrative for the wide range of applicability of the various calculations in this thesis.

9.2 Specification of the HISEL system

The specification of the patterns to be written in a future electron beam writing system was introduced in chapter 1. It was indicated that the specifications mentioned in literature are not sufficiently detailed. Especially the application of the variable-shaped beam writing technique requires that more details of the pattern be specified (this is also further elaborated in chapter 3). Furthermore, many possibilities for correcting pattern writing errors were mentioned in chapter 1. The pattern writing errors result both from the electron beam itself (e.g. proximity effect) and from the electron optical system used (e.g. dynamic focus and deflector aberration). The application of each of the correction methods was not yet fully clear. For the sake of an electron optical system design study this discussion was not very important. Therefore, the correction methods were supposed to be applied in the best possible form. This does not seem impossible, although it may be a rather optimistic assumption.

Detailed system specifications were given chapter 3. On the basis of these system specifications different types of electron beam writing systems were compared in general. The noise limited resist sensitivity is (more or less arbitrarily) taken as $\sigma = 10 \, \mu C/cm^2$ (see section 3.2). This corresponds to an average beam current required in the system of 10 $\mu A$ (when not taking coverage into account).
Gaussian beam

For the HISEL system the address-grid specification would require that focussed beam writers access every position of the address-grid (6 nm). This is rather inefficient since the pixels written are much larger (25 nm) and the smallest feature size is still larger (100 nm). With respect to the electronic system the comparison of a variable-shaped beam writer and a Gaussian beam writer are comparable in complexity. From the electron optics point of view, however, there is a clear gain in writing speed for a variable-shaped beam writer. For a Gaussian beam writer the depth of focus combined with a finite source brightness limits the total beam current to some 0.7 μA.

As in section 5.3 the following settings were applied:

\[
\begin{align*}
B_r &= 3000 \text{ A/cm}^2/\text{sr}/\text{V} \\
D_p &= 25 \text{ nm (round)} \\
U &= 100 \text{ kV} \\
\Delta z_{dof} &= 1.0 \mu\text{m} \\
\alpha_p &= 12.5 \text{ mrad}.
\end{align*}
\]

This very high brightness of upto 3000 A/cm²/sr/V is allowed for PN-emitters with small beam currents. The system throughput will be too low with this beam current together with the noise limited resist sensitivity. Given the average beam current required, of about 10 μA, it is argued that a single focussed beam system is impossible. The required source brightness and the required pixel transfer rate are far too high. This in fact eliminates the possibility of using a Gaussian beam writer.

Multi Focussed beam

Systems with multiple focussed beams provide for parallelism and thus for increased writing speed. This might therefore be a useful method of writing. For trajectory displacement and Boersch effect the calculations do not show much difference from the shaped beam systems further on presented, since the beams are overlapping completely in large parts of the system. A problem with this method of writing is the variation of the beam current (proportional to the area written) and thus also the variation of energy spread occurring in the system.
It should be mentioned that there is a simple increase in the electronics complexity for this system just like the comparison between a single Gaussian beam and a variable-shaped beam writer. In a multi Gaussian beam system the average number of pixels written will be determined by the pattern density and the total number of parallel beams.

A multi-focussed beam system would also have to access every grid-position. This implies that the system would have a 400 % coverage (in terms of pixels), which is unrealistic. For such a system it would be much more convenient to have a 25 nm address-grid (but with 6 nm accuracy in the grid positions). Given the pattern specifications mentioned, these systems were not further studied.

Variable-Shaped beam

For the shaped beam system the smallest shaped spot is determined to be about 0.1 x 0.3 (μm)². This corresponds with a minimum shaped spot of 48 pixels. The range of side lengths that has to be supported by the beam shaper is deduced to be between 0.1 to 0.5 and 0.1 to 1.0 μm. This writing strategy offers the best possibilities for parallelism in the beam writing system. The disadvantage that the gain factor is dependent on the pattern written is inevitable. In the design phase of this thesis all beam sections calculated relate to the variable-shaped beam writing concept. The sections themselves are of course independent of the writing strategy used.

The general conclusion from the HISEL system requirements is that a variable-shaped beam writing system would be the best system. In order to find realistic estimates for the performance of this system, it was found that the specifications were required to be more precise. The amount of pixels illuminated in an average shot is dependent on the type of the pattern written.

In chapter 4 the high brightness electron sources required to meet the HISEL specifications are introduced. Since these could not be studied in detail only the general characteristics are treated. The applicable electron sources are PN- and LaB₆-emitters. The brightnesses of these sources can be up to about 500 to 1000 A/cm²/sr/V (for VSB
applications). Since these emitters have a very large emitting area the maximum beam current emitted can also be very high (up to about 1000 μA). This high beam current is required in order to get a sufficiently homogeneous illumination of the shaping apertures. Next to the normal fixed brightness writing mode, the dynamic writing mode could be realized with PN-emitters. In this mode the source brightness is varied dynamically, which allows one to keep the total beam current after the shaper section constant. From the conventional sources only the LaB₆-sources might be applicable to the HISEL system requirements. The highest brightness attainable with a well engineered LaB₆-emitter is expected to be about 100 A/cm²/sr/V. This source only allows the fixed brightness mode writing and its maximum beam current is in the order of 100 μA. This could be sufficient if a large part of the emitted current can be used for the homogeneous illumination of the shaping apertures.

To keep argumentations in this thesis limited to electron optical aspects a realistic wafer stage was used, based on several systems found in literature. Both stage speed and field of view were chosen from conventional systems. The required writing accuracy will exact higher demands upon the position measurement and stability of the stage. No work on these issues has been done yet. The continuing improvements in writing stage designs have not been taken into account since this is not an electron optics design issue. Also because of the very fine details written with the HISEL system it seems that even very small fields of view will suffice.

9.3 Global optimization

In chapter 5 the general design equations for all beam sections of a variable-shaped beam writer are introduced. As was illustrated in chapter 2 the HISEL specifications imply that the beam current and the beam brightness have to be very high. Because of this, the Boersch effect and the trajectory displacement are the most important sources of electron optical aberrations. For these effects [Jansen, 1989] deduced equations both in analytical form and with simulation of the electron beam system. Since these equations are in a very complex form, the parameter dependence for each section can no longer be expressed explicitly in the boundary conditions of the beam section. As the boundary conditions for each beam section differ, deduction of the total effects from the effect per beam section is impossible. The total effect
found in the system has to be expressed in a numerical form. This has a significant impact on the way system optimization has to be done.

It should be mentioned that the equations Jansen derived are not valid over an equally big range of input conditions like the other design equations given in chapter 5. Especially for the high brightness and the very high beam currents Jansen could not test the validity of the results. The results can therefore only be used to indicate the order of magnitude of the aberrations and behaviour of the aberration under variation of the beam conditions. This also leads to the approach taken to divide the system into realistic beam sections which could each be compared to conventional system parts. Among them are: the source, the shaper, the demagnifying section and the projection section. It is essential that each of the sections can be replaced by different versions of it without any effect on the rest of the system. This makes it possible to do independent optimizations.

When connecting beam sections the reduced brightness must be kept constant (even at different accelerating voltages). As such, the reduced beam brightness is as essential a parameter as the total beam current. For each part optimization consisted of finding a good version of the beam section under the new electron beam conditions: higher beam current and higher beam brightness. The beam sections were compared on the basis of a very rough error budget resulting from the design equations in chapter 5. Of course global optimization criteria have to be taken into account (e.g. one or two demagnifying lenses, depending on the sizes of the shaping apertures). It is thus clear that using different optimization conditions different total systems will result. The synthesis of the total system will be limited to the HISEL system.

On the one hand the Monte Carlo simulations (MONTEC) rely upon fewer presuppositions than the analytical equations (INTERAC). On the other hand the Monte Carlo simulations require many parameter variations to find the correct settings and to establish confidence that end-effect compensation and averaging have been performed adequately. There was no time to do such detailed calculations for each of the beam sections under all possible conditions. Therefore, the effects were calculated with the correct settings for the low (and medium) beam currents. (End-effect correction and field particles were only applied to the calculations of the projection section.) Then the simulations were done with the same settings for higher beam currents (I > 330 μA). Comparison with the analytical calculations gives an indication of the range of
validity. Where the parameter dependencies differ too much the results are unreliable.

Since the Monte Carlo simulation has the fewest presuppositions the MONTEC results seem somewhat more trustworthy than the INTERAC results. In general it can be seen that the validity of the lower current simulations (\(I < 100 \, \mu A\)) is correct. For the higher beam currents (generally \(I > 330 \, \mu A\)) MONTEC results diverge. Here a more thorough control of Monte Carlo simulation parameters is required to ensure confidence in the results. The use of end-effect correction and field particles to simulate the beam outside the sample simulated has helped to drive the results to the beam currents mentioned. In general, however, the quality of the extrapolation of these methods has not been established. More accurate interaction calculations remain to be done, once the detailed design of the system has been decided upon.

As a conclusion from the figures in sections 6.3 and 6.4 it should be mentioned that under normal conditions the results of INTERAC (the analytical equations of Jansen) and MONTEC (the Monte Carlo simulation package) agree very well. As the results are corresponding rather badly in sections 6.3 and 6.4 it should be concluded that the ranges of validity of the model are passed (for the higher beam currents with shortest beam sample lengths).

An important result from the electron-electron interactions tables in chapters 6, 7 and 8 is the difference in parameter dependence as compared to the theoretical equations of [Jansen, 1988] for single beam sections. Different reasons for this deviation can be distinguished. Firstly, Jansen never validated his equations for the very high beam brightness and beam current applied in this system and hardly any practical measurements have been done, even today. Because of the high beam current Monte Carlo simulation is more difficult, since there is a maximum on the total number of particles used. Secondly, the choice of the beam sections is not completely in accordance with the way in which Jansen normally distinguishes beam sections. His criterion was that a beam section is any part of the system, in which the electrons fly unperturbed as far as electron optical lenses are considered. Furthermore the complex summation of effects results in a different behaviour for the complete section.

From the results the most general parameter dependencies can be concluded. These results take the place of the simple power dependencies like the effective gamma factor in Jansen's equations:
\[ dR_{fwhm} \sim I^{\frac{1}{\gamma_r}} \quad \text{and} \quad dE_{fwhm} \sim I^{\frac{1}{\gamma_e}} \quad (9.1). \]

These equations no longer hold in general for the total effects found. Therefore the full theory of Jansen is required, taking into account different effective gamma values for each of the beam sections of the system. The (effective) gamma values are dependent on physical beam parameters. Realistic beam sections between intermediate images are distinguished in order to be able to compare all image aberrations in the intermediate images. Thus, realistic conditions are required to select the correct (local) parameter dependencies. This variation of effective gamma values also indicates that the analytical determination of the total effect for all beam sections together is impossible.

9.4 Design guidelines from the results

The process of optimization has resulted in very many calculations which give a clearer understanding of the electron-electron interaction effects. The total electron beam pattern generator can be synthesized from the former calculations by combination of the individual beam sections. It will be shown that the total error budget is not very different from scaled conventional systems. Absolute values are smaller and electron-electron interaction effects are stronger, but in every other respect the same calculations hold.

For the HISEL system the very highest demands are made upon the electron beam source. The source has to be modulated at the rectangle writing speed compensating for varying beam currents in the final system. Thus the final beam current can be kept constant at 10 \( \mu \text{A} \). The corresponding beam current in the source section is in the range of 100 to 1000 \( \mu \text{A} \) for the limited and full range shaping techniques described in section 6.2, assuming one third of the total current emitted can be passed through the first shaping aperture. The tables show the effects as a function of the beam current. This comparison is made with the dynamic brightness mode in mind. Therefore, the reduced brightness mentioned only holds for the nominal beam current of 330 \( \mu \text{A} \). This beam current is reduced by a factor of 33 in the shaper. (Maximum source current occurs when writing the smallest rectangle.) For lower beam currents the reduced source brightness was reduced proportionally, since a larger part of the total beam current was then passed through the shaper to the target.

For the characterization of the other beam sections the following system setups have been considered:
Dynamic brightness mode:
I = 10 .. 330 μA, before the shaper (330 μA nominal)
I = 10 μA, after the shaper (10 μA nominal)

Fixed brightness mode:
I = 10 .. 500 μA, before the shaper (330 μA nominal)
I = 10 .. 100 μA, after the shaper (10 μA nominal)

with the final beam size from a 0.1 x 0.3 (μm)² sized spot:

$$D_p = 0.173 \, \mu m \Rightarrow R_p = 86.6 \, nm$$

where $R_p$ is half the side length of a rectangular spot. In this way the result is always the upper boundary for a variable-shaped beam writer with a range from the value given down to $0.1 \times 0.3 \, (\mu m)²$. (Note that $\alpha_p$ is used to indicate the beam semi opening angle.)

$$U = 100 \, kV$$

$$\begin{align*}
B_r &= 170 \, 680 \, 850 \, A/cm^2/sr/V \\
\Delta z_{dof} &= 0.5 \, 1.0 \, 0.9 \, \mu m \\
\alpha_p &= 25 \, 12.5 \, 11.2 \, mrad \\
D_{s2} &= 548 \, 387 \, 548 \, \mu m \\
D_{s2} &= 220 \, 155 \, 220 \, \mu m
\end{align*}$$

$$U = 20 \, kV$$

$$\begin{align*}
B_r &= 170 \, 680 \, 850 \, A/cm^2/sr/V \\
\Delta z_{dof} &= 0.22 \, 0.45 \, 0.5 \, \mu m \\
\alpha_p &= 55.9 \, 27.9 \, 25 \, mrad \\
D_{s2} &= 548 \, 387 \, 548 \, \mu m \\
D_{s2} &= 220 \, 155 \, 220 \, \mu m.
\end{align*}$$

The columns (100 kV, $B_r=170$) and (20 kV, $B_r=850$) have the same target conditions in term of the final beam parameters $\alpha_p$, $\Delta z_{dof}$. When the $B_r=680$ column is taken as the central value, a slight brightness increment and a stronger reduction in brightness are considered. With the reduction in brightness, the shaping apertures are slightly increased. This only affects the shaper and the demagnification sections.
considered. The above columns have been calculated for all shapers and for many demagnification sections. The $B_r = 680$ column has a rather large final opening angle. This is always a problem in case of the 20 kV systems. A reduction of this opening angle could be based on an increase of the average shaped spot size written.

9.4.1 Source selection

One of the main developments is the increase in (reduced) beam brightnesses, becoming possible with the aid of the newly developed PN-emitters and by developments in thermal field emitters. The use of very high beam brightness will demand higher performance of all beam sections. The idea to use dynamic brightness modulation also came from the possibility to apply PN-emitter sources. It is based on the fact that the total beam current in the projection section is limited (mainly) by trajectory displacement (see the calculations in chapter 8). This allows one to use all beam sections after the shaper at their maximum beam current.

One of the newest ideas of [van der Mast, 1989] has risen from the possibility to place deflectors on top of PN-emitters. When ring-type emitters with intermediate ring-deflectors are used one is able to force the angular beam distribution of the electrons. This enables a more homogeneous distribution of the electrons. This idea, however, is not yet technologically feasible. For that reason it was discarded.

For a limited opening angle in the final projection system (even at 100 kV) it was shown in section 5.3 that emitters with a reduced brightness of 100 .. 900 A/cm$^2$/sr/V are required. It was shown that the practical demands made upon the system require final beam currents in excess of 10 µA. Such large currents cannot be generated using single pointed high brightness field emitters. Both PN-emitters and multiple field emitter arrays could be used to generate the required beam current. A big problem is that none of the solutions mentioned has yet been practically demonstrated.

It is concluded that PN-emitters would be the most desirable. Especially for dynamic brightness modulation, high current and the use of Köhler illumination, their use seems to be inevitable. As the beam current is very high and the beam voltage is not, the boundary conditions in the
source section are: short accelerating part (cut off much current at low potential and low power), the use of high brightness PN-emitters, without cross-overs, and the decision to use Köhler illumination.

9.4.2 Shaper design

The highest beam currents appear in the shaper and the source sections. They strongly vary in these sections, depending on the area of the shaped spot. Therefore, the general trends of the analytical equations for Boersch effect and trajectory displacement (ref. eq. 5.16) provide some guidelines for the design of this section. The effect is low if the beam section is as short as possible and if the accelerating voltage is high. Jansen also found that a parallel beam section and a beam section with a cross-over have comparable trajectory displacement (if the beam radii in the lenses are comparable). The Boersch effect in a section with a cross-over is much larger however. The idea to use dynamic brightness modulation makes high demands upon the design of the shaper, since in that case the total beam current will be even higher. It should be noted that because of the high beam current both the Boersch effect and the trajectory displacement effect are important in the shaper section.

The required length of the deflector with respect to the size of the apertures determines the dimensions of the shaper. It was found in chapter 6 that it is possible to realize the HISEL beam current demands with both the long and short shapers. The numerical results are distinguished in the imaging shaper (section 6.3) and the shadow shaper (section 6.4). For the imaging shaper it is found that the short version has lower effects by a factor of about 2.5. It is also found that the versions with larger apertures have somewhat smaller effects. The effects are found not to be very sensitive to reduced beam brightness.

The results for the shadow shaper are lower in all cases. These shapers are therefore applicable to fulfill the HISEL. The bigger variations for the shadow shapers indicate a poorer quality of the results in general. For these shapers the shorter versions have lower effects by about a factor of 1.5. Both the long and the short shadow shapers have low enough effects. The essential point derived in chapter 6 is that shadow shaping strongly reduces the Boersch effect. Using shadow shaping a low voltage beam shaper may even be possible.
9.4.3 Demagnifying section design

In general very many different setups are required in order to connect the different beam shaper sections to all possible projection sections considered. Most of these do not pose any problems. This is determined by comparing some of the most different demagnifying sections. Both a very strong lens and a conventionally used lens are compared. For both lenses some of the beam sections are then considered. It is found that the effects are within the HISEL requirements for all possible uses of the strong demagnifying lens. The important conclusion in chapter 7, regarding the demagnifying lens, section is that the lens should be very strong. This makes the beam section as short as possible. The demagnifying lens can be made as short as the physical design of the lens allows for, since it has a very small field of view.

The special case of a low voltage shaper is also addressed in chapter 7. It is found that a small accelerating section does not have much influence on the total effect generated in this section. The low voltage beam shapers can therefore be used and the design of these sections does not have to take the accelerating section into account.

9.4.4 Projection section design

The projection lens section is dominated by the detectors required for beam positioning and by the required field of view. These demands dictate a minimum image distance of some 5 mm. Choosing a strong final lens therefore implies the use of a variable axis immersion lens. The VAIL system has a good performance for beam currents up to about 50 μA. VAIL projection sections are already being implemented on many systems. The demagnification that can be realized with such a section is large. It can only be of help when it is taken into account in an early stage of the system design.

The design guidelines for the projection section found in chapter 8 can be summarized as: the beam voltage should be high (100 kV); the beam current should be limited. (In the order of 10 to 20 μA is allowable,
may be 50 μA can be tolerated in the case of the fixed brightness mode.) Geometrical aberrations and field of view are determined in the traditional way (this was done by using software by [B. Lencova, 1990]). The effect of trajectory displacement is in the same order of magnitude as the various geometrical aberrations found, among which also the chromatic aberration due to Boersch effect and source energy spread. The wafer holding stage has not been subject of the optimization. A traditional stage was supposed in the design, with increased positioning accuracy as required by the HISEL specifications.

Unfortunately, the results in the tables of chapter 8 are not very useful, since most of the results were calculated for a nominal beam current of 330 μA. It was found in a later stage of the research that these input values should have been taken relative to a nominal beam current of 10 μA. Because of this the tables were calculated for too low reduced brightnesses (by a factor of 6). The tables can be used to indicate the trends for the very high beam currents though. Once the exact design is known, more precise input parameters can be selected to refine the results. For the overall design of the system this does not have much effect.

9.5 Calculation results

With the conditions for all beam sections determined from the HISEL requirements, a variable-shaped beam writing system can be synthesized. This section presents the detailed conclusions from chapters 4 through 6. A general overview of the HISEL system is given in figure 9.1.
9.5.1 Results for a PN-emitter with dynamic brightness

For the use of a PN-emitter in dynamic brightness mode the conditions in table 9.1 are applicable. As was mentioned in section 9.4.2 this current can be handled by a shadow shaper. Even though the results from MONTEC and INTERAC (in sections 6.3 and 6.4) show rather large deviations, the most negative values still result in a beam shaper with allowable aberrations. The deviations in the results indicate that only the order of magnitude of the values can be trusted. Since there are no practical measurements for this situation, these values are the best approximations available for the design beam shapers for such a high beam current. The demagnifying and the projecting sections were designed in chapters 7 and 8. For these sections the short versions have sufficiently low effects for the 10 μA beam current.
<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>$I$</td>
<td>10 - 330 $\mu$A</td>
</tr>
<tr>
<td>$U$</td>
<td>100 kV</td>
</tr>
<tr>
<td>$B_r$</td>
<td>680 $A/cm^2/sr/V$</td>
</tr>
<tr>
<td>$\Delta z_{dof}$</td>
<td>1.0 $\mu$m</td>
</tr>
<tr>
<td>$\alpha_p$</td>
<td>12.5 mrad</td>
</tr>
<tr>
<td>long shaper</td>
<td>$D$</td>
</tr>
<tr>
<td>short shaper</td>
<td>$D_s$</td>
</tr>
</tbody>
</table>

Table 9.1: HISEL operating conditions.

The Monte Carlo results from figure A.8.5e (appendix A.8) are much more pessimistic. As all of these calculations were done with only indicative input values the Monte Carlo results are further discarded (these have to be done more carefully). This indicates that only the order of magnitude of the results presented can be used for the design. The maximum beam current of 10 $\mu$A should be allowable in all cases, though.

Therefore, it is possible to design an electron beam writing system for these conditions. The short demagnifying section in chapter 7 and the short VAIL projection system in chapter 8 were proposed for the implementation of the HISEL system. For the beam shaper both the long and the short shadow shaper would suffice. Thus, the long version is proposed, since it allows for larger, more sensitive deflectors. (These very high speed deflectors were described by [Mulder, 1991].) It is supposed that the beam current can be supplied using a PN-electron emitter, from which about 330 $\mu$A has to be used after the first shaping aperture. (The PN-emitters are the subject of another research by [Koffeman, 1991].)

9.5.2 Results for a PN-emitter with fixed brightness

The same beam conditions as in the last section hold. But here, the continuous variation of source brightness in order to keep the final beam current constant is rejected. With constant source brightness the total beam current in the demagnification and in the projection section
varies proportional to the area of the shaped spot. The tables for interaction effects in the demagnifying and the projection sections now determine the upper limits to the beam current in the shaped spot (for I= 10 .. 330 μA). This could on the one hand be realized by a proportional reduction of beam current for all spots (and thus an overall reduction of system writing speed). On the other hand the beam current (area) shaping range could be somewhat reduced for this sake (refer to section 3.5.1). An optimization of this kind was not completely done, but some of the first results are presented in this section.

As an example of a reduced shaping range the following shaped spot sizes could be chosen realistically according to table 9.2. With the HISEL pattern writing specifications only 11 nm edge unsharpness is allowed for the total trajectory displacement. From Appendix A.8, figure A8.2h (B_F=680 A/cm^2/sr/V) this implies that a beam current of only 100 μA is allowed. Therefore, the shaping range should be reduced to 0.1x0.3 to 0.5x0.5 (μm^2). With the data from section 3.5.1 this would mean that about four times as many shots are required for writing the total pattern. This means that for the overall system writing speed only a reduction factor of 4 is found. This value applies to the same system as that described in section 9.5.1.

<table>
<thead>
<tr>
<th>spot size (μm^2)</th>
<th>proportionality factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.1 x 0.3</td>
<td>1</td>
</tr>
<tr>
<td>0.4 x 0.4</td>
<td>5</td>
</tr>
<tr>
<td>0.5 x 0.5</td>
<td>8 (~ 10)</td>
</tr>
<tr>
<td>0.7 x 0.7</td>
<td>17 (~ 20)</td>
</tr>
<tr>
<td>1.0 x 1.0</td>
<td>33</td>
</tr>
</tbody>
</table>

Table 9.2: Shaping ranges considered.

The Monte Carlo results from figure A.8.5e (appendix A.8) are much more pessimistic. As in the last section, the design will therefore be based on the INTERAC calculations only. If the maximum beam current were limited to 50 μA in the above design parameters, this would result in doubling the number of shots needed to write the pattern (see section
3.5.1). Thus the overall writing speed for the system with PN-emitters in fixed brightness mode is in the order of 0.125 to 0.25 cm²/s.

9.5.3 Results for a well engineered LaB₆-emitter with fixed brightness

This section presents the synthesis of a system that is realized with today's technology. With a standard LaB₆-gun, in the system proposed in sections 9.5.1 and 9.5.2 conclusions from the calculations can also be drawn. It is assumed that fixed brightness mode is used, with a beam voltage of 100 kV. This is the most realistic possibility at the moment. It is very interesting to see what performance could be expected from a conventional system if all other design decisions were optimal. The case for an LaB₆-emitter can be deduced from the last section, with the difference that the highest beam brightness is reduced to about 100 A/cm²/sr/V.

The projection section was designed to allow opening angles of up to 10 to 12.5 mrad. This limits the beam current in the smallest spot to 1.5 μA. That means that the shaping ranges mentioned in table 9.2 could also be supported with the LaB₆-emitter. The short system components described in chapters 6 and 7 can also be applied. As in the last section the shaper range has to be reduced significantly, reducing the maximum total beam current to about 20 to 50 μA. This means that the shaping ranges allowed are from 0.1 x 0.3 (μm²) to about 0.4 x 0.4 and 0.5 x 0.5 (μm²) respectively. As the total beam current has been reduced with a factor of 7, the overall writing speed for this system would be in the order of 0.02 to 0.04 cm²/s.

9.6 Concluding remarks

Exciting new designs of direct-write electron beam systems have come into view with the invention of PN-emitters. The high brightness, high beam current and fast modulation are all very important. The technology to realize all this is not yet mature however. More high brightness emitters emerge, field emitters, both the pointed tips and the crystallographic ones and thin film field emitters have been fabricated. Even in LaB₆, crystallographic orientation makes it possible to reach higher brightnesses. All this was a good reason for doing research into
the general design of a high current, high brightness system like an electron beam writer. As such, for the first time the design was directly based on the depth of focus limit inherently connected with the specification of the patterns to be written and with the reduced beam brightness.

The central issue of this thesis was the optimization of electron beam pattern generator performance. As was pointed out in the first chapters, improving the writing speed of an electron beam pattern generator implies a higher beam current. But this quickly leads to the problem of electron-electron interaction effects. These effects generate additional energy spread (Boersch effect), trajectory displacement and space charge effect. The last effect only occurs in non-round beams. It can be seen as a higher order effect in terms of the beam size, and it was not studied extensively.

Because of the numerical nature of the equations for the trajectory displacement and the Boersch effect described by [Jansen, 1989] all sections of the electron beam writing system were separately optimized in chapters 6, 7 and 8. From the simple design calculations in chapter 5 the input conditions for all beam sections were easily derived.

It was found that it is still very difficult to establish confidence in the electron-electron interaction equations of Jansen for the very high beam currents in the HISEL system. From the order of magnitude of the effects found in all beam sections the general conclusion is drawn that it will be possible to realize a HISEL system. This system can only be realized with all of the most advanced electron optical elements taken together: PN-emitters with a reduced brightness of up to 680 A/cm²/sr/V, the application of dynamic brightness modulation of the emitter, shadow shapers, a very strong demagnifying section and a VAIL projection lens. The high beam currents and beam brightnesses can be applied in electron beam writers but only when they are accounted for in the design phase.
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SUMMARY

This thesis addresses the design of very high speed electron beam writing systems. It is foreseen that in the near future the required line width for such systems will be in the order of 0.1 μm. The target system for this research was therefore defined to have 0.1 μm line width and the aim was to reach a writing speed in the same order of magnitude as today's optical projection systems (1 cm²/s). From the general demands put upon the pattern writing system it is argued that this system should most probably be based upon electron beam writing. The target system was termed the High Speed Electron Lithography (HISEL) system.

In this research the focus is kept on the electron optical problems encountered in an electron beam writing system. The first steps are to consider the exact specifications of the requirements put on the HISEL system. It is found that the pattern placement accuracy required for the system is in the order of 6 nm, whereas the edge roughness of the patterns produced has to be in the order of 25 nm (as compared to the 100 nm minimum line width). The wafer holding stage of the system is considered to have about the same quality as that for systems currently in use. (The supposition is made that a higher position reading accuracy can be attained for the table.) Given the very high speed, the resist used will have to fulfill much higher demands. The system is considered to use resists which are practically noise-limited.

After looking at some characteristic electron beam writing systems, it is illustrated that these systems will never be able to fulfill the HISEL writing conditions. As was indicated by Jansen [1988] the electron-electron interaction effects play a very important role in the design of this system. Calculation of these effects also lead to the above conclusion. From these effects both trajectory displacement and Boersch effect have to be accounted for in the design of each section of the system. (Space charge effects are not taken into account since these can be compensated in a round, homogeneous beam.)

It is argued that the patterns written have many rectangular forms and therefore a variable size rectangle can be used to describe the pattern in a compressed format. It is therefore also advantageous to write with a variable size rectangle (variable shaped beam writing) when using an
electron optical system. An alternative manner of writing the patterns is by making use of a single focussed beam. From the general demands mentioned it is determined that the source brightness for a system writing with a single focussed beam is far too high to be realistic. There is also the possibility of writing the patterns with multiple beamlets. Such a system can not fulfill the positioning and edge roughness demands however. The second half of the thesis concentrates on finding a better total design for a variable shaped beam writing system.

The HISEL system is supposed to be designed from scratch in this thesis. Therefore the most recent developments in electron optical design are taken into account. As a possible source, the PN-emitter developed by Van Gorkom [1986] is considered. Other high brightness sources are also mentioned. The general problem of finding a sufficiently bright source for the system is not treated here. (This is part of a related research done by Koffeman [1990]). Furthermore, the system is built with a shadow shaper section, a short demagnifying section and a projection section with a Variable Axis Immersion Lens (VAIL). Using these system parts, the total error budget is calculated.

The calculation of electron-electron interactions can only be done by filling in complex equations from Jansen [1988]. Therefore the design of each section of the HISEL system is considered seperately. First the required dimensions of each section are determined from the well known electron optical equations. Then these conditions, related to the writing specifications at the target plane, are used to determine the relevant beam current in the section. Using these boundary conditions the input for the interaction calculations is found. The results from these equations are put into figures (and tables) in the appendices (A.6 .. A.8). By making these calculations per section and by allowing a large range of beam currents in the equations these figures can also be used in other designs of electron optical systems.

The resulting system is a variable shaped beam writing system with a PN-emitter. The shaping section has to be based on the shadow shaping principle and it can not be too long (about 60 mm is allowed). After the shaper a strong demagnifying lens is proposed. Because of the electron-electron interactions beam cross-overs should in general be avoided. The cross-over in the demagnifying section is inevitable however, and it is the first cross-over in the beam forming section. After that a strong VAIL lens section is used to project the demagnified image of the shaping apertures onto the target. This section was based on a realistic design done by Lencová.
SAMENVATTING

In dit proefschrift wordt het ontwerp van hoge snelheids elektronen-lithografiesystemen beschreven. In de nabije toekomst zal de toegestane lijnbreedte voor dergelijke systemen in de orde van 0.1 \( \mu \text{m} \) zijn. Het onderzoek richtte zich daarom op het ontwerp van een systeem met een lijnbreedte van 0.1 \( \mu \text{m} \) en een schrijfsnelheid, vergelijkbaar met de huidige systemen voor optische lithografie (1 \( \text{cm}^2/\text{s} \)). Uitgaande van de algemene eisen die aan het systeem worden gesteld is afgeleid het de ontwerpen systeem zeer waarschijnlijk op elektronenlithografie gebaseerd zal zijn. Het te ontwerpen systeem wordt aangeduid met HISEL of HIgh Speed Electron Lithography system.

In het onderzoek ligt de nadruk op de elektronen-optische aspecten die een rol spelen bij het ontwerp van een elektronenlithografiesysteem. Eerst zijn de precieze eisen die aan het HISEL systeem worden gesteld geanalyseerd. Daarbij is voor de plaatsingsnauwkeurigheid van de patronen een tolerantie van 6 nm afgeleid. De kantscherpte van de patronen moet circa 25 nm zijn (een kwart van de minimum lijnbreedte, 100 nm). Voor de tafel waarop de wafer wordt vastgehouden zijn ongeveer dezelfde eisen gehanteerd als gebruikelijk in huidige lithografiesystemen. (De uitleesnauwkeurigheid van de posisitie is echter wel beter verondersteld.) Gegeven de bijzondere hoge schrijfsnelheid t.o.v. de huidige elektronenlithografiesystemen, is aangegeven dat de eisen die aan de resist worden gesteld veel hoger zijn dan die voor huidige systemen. De vereiste resistgevoeligheid in het target-systeem zal bijna door de ruisgrens bepaald moeten zijn.

Aan de hand van enkele karakteristieke systemen is aangegeven dat de huidige systemen niet in staat zullen zijn om aan de gestelde eisen te voldoen. Zoals ook door Jansen [1988] is aangegeven spelen elektron-elektron-interacties een belangrijke rol bij het ontwerp van deze systemen. Deze effecten zijn dan ook de reden voor bovengenoemde conclusie. Voor wat betreft de elektron-elektron-interacties worden de invloeden van trajectory displacement en Boersch effect in de berekeningen voor elk van de secties van een nieuw systeemontwerp meegenomen. (Space charge effecten zijn buiten beschouwing gelaten, want voor uniforme, ronde bundels kunnen deze volledig worden gecompenseerd.)
Aangezien de patronen die met het apparaat geschreven moeten worden voornamelijk bestaan uit rechthoeken kan het totale patroon worden beschreven met behulp van rechthoeken van variabele grootte. Dit biedt aan de ene kant een compressie van de gegevens die het patroon beschrijven. Aan de andere kant zal het daarom ook voordeel bieden om het patroon met een bundel te schrijven die gevormd wordt tot een variabele rechthoek. Dit heet "variable shaped beam writing". Het alternatief is dat het patroon geschreven wordt met een enkele gefocussed bundel (focussed beam). Aan de hand van de algemene systeemseisen wordt aangetoond dat de focussed beam technologie een irregel hoge helderheid van de elektronenbron vergt. Ook is het in principe mogelijk patronen te schrijven met meerdere parallelle bundels. Vanuit de positioneringseisen van de patronen en vanwege de vereiste hoge helderheid van elk van de bronnen blijkt echter dat ook dit niet een reëel optie is. In de tweede helft van dit proefschrift wordt het ontwerp van een variable shaped beam systeem verder uitgewerkt.


De berekening van elektron-elektron-interacties wordt uitgevoerd door het gebruik van bijzonder complexe formules van Jansen [1988]. Daarom is het ontwerp van ieder van de systeemsecties van het HISEL systeem apart beschouwd. Ten eerste worden steeds de afmetingen van de gehele sectie bepaald. Dit wordt gedaan met behulp van bekende elektron-optische formules. Vervolgens worden deze condities, gerelateerd aan de specificaties in het eindvlak, gebruikt om de stroom in de sectie te bepalen. Aan de hand van de genoemde condities worden de invoerwaarden van de interactieberekeningen bepaald. De resultaten van de interactie-berekeningen zijn in figuren (en tabellen) weergegeven in de appendices (A.6 .. A.8). Door de berekeningen per sectie uit te voeren met een groot bereik van bundelstromen is het mogelijk de resultaten van dit
werk ook bij andere ontwerpen van elektronen-optische systemen te gebruiken.

Het resultaat is een eerste ontwerp van een variable shaped beam systeem met een PN-emitter. De shaping-sectie is gebaseerd op shadow shaping en mag niet al te lang zijn (circa 60 mm is toegestaan). Na de shaper volgt een sterk verkleinende lens. Om redenen van elektron-elektron interacties moet in het algemeen worden voorkomen dat er teveel bundel cross-over in het systeem zijn. Voor wat betreft het bundelvormend stelsel is dit het eerste optredende cross-over, in de verkleinende sectie is het onvermijdelijk. De laatste sectie van het systeem is een sterke VAIL-sectie. Deze wordt gebruikt om het verkleinde beeld van de shaping-diafragma's op het target af te beelden. Deze sectie is gebaseerd op een realistisch ontwerp uitgevoerd door Lencová.
Curriculum vitae

Jan Simons was born in Rotterdam, on February 10th, 1961. In 1965 his family moved to the village of Capelle a/d IJssel, close to Rotterdam. There he finished elementary school and high school (atheneum). By that time it had already become clear that Jan had a large interest in technical research, with an emphasis on electronics and physics.

In 1979 Jan began to study applied physics at Delft University of Technology. During his stay at the university he worked in the group of particle optics. His areas of work were electric field calculations for capacitance measurements and electron ray tracing, which resulted in an article in the Journal of Applied Physics. In his last year he worked in cooperation with T. van Zutphen and G. van Gorkom (at Philips Physics Laboratory), looking into a fabrication process of GaAs PN-emitters. Jan graduated from Delft University of Technology in 1985.

After graduating he did research at the Delft University of Technology in the area of electron beam writing system design. This research resulted in this PhD thesis.

The period for doing the research was limited and the work was not yet finished when, in 1989, Jan started a new occupation at PTT Research in Groningen. At that same time he got married. He completed this thesis in the evening hours. Jan is now active in the work of telecommunication systems, focussing on OSI-communication and Intelligent Networks.
Appendix A.5:

**Simple approximations for isotropic third order aberrations**

In first order approximation electron lenses are assumed to be thin, the lens action takes place in the cardinal plane of the lens. There lens action can be described as an angular deflection proportional to the height of the ray in the lens for small objects. Spherical aberration comes into this approximation as a third order disturbance of the proportionality of deflection. Note that because of rotational symmetry of the lens no second order disturbance is expected. Second order disturbances are important for the determination of fabrication tolerances of the lens though. Most other third order aberrations can be directly estimated in this way. The method gives a very direct idea of the order of magnitude and of behaviour under different imaging conditions for third order aberrations.

The lens with a paraxial ray is taken as in figure A5.1. The following indices are used: \( o \) : object, \( l \) : lens and \( i \) : image. Coordinate \( z \) is the axial coordinate and \( x \) is used as a radial coordinate. In paraxial approximation the following equations hold for imaging distances and magnification \( M \)

\[
\frac{1}{z_{1} - z_{o}} + \frac{1}{z_{l} - z_{1}} = \frac{1}{F} \tag{A5.1}
\]

\[
M = \frac{x_{1}}{x_{o}} = -\frac{z_{1} - z_{l}}{z_{l} - z_{o}} \quad \Rightarrow \quad M = 1 - \frac{z_{l} - z_{o}}{F} \tag{A5.2}
\]

The angles of the rays with respect to the optical axis are denoted by \( \frac{dx}{dz} \) \( x' \) and \( x'_{o} \), with \( x'_{o} = \frac{dx}{dz} \).

Now the lens action is described as a change of the angle with the optical axis at the position of the cardinal plane of the lens for very small objects:

\( x_{o} \ll x_{l}, x_{1} \ll x_{l} \)
\[ x'_0 = \frac{x_0}{z_1 - z_o} \quad \text{and} \quad x'_1 = -\frac{x_1}{z_1 - z_1} \]

using equation (A5.1), this yields

\[ x'_1 - x'_o = -\frac{x_1}{F} \]

(A5.3).

The aberrations are calculated by including a third order term, \(C_3\), in this equation

\[ x'_1 - x'_o = -\frac{x_1}{F} + C_3 \frac{x_3}{x_1} \]

(A5.4).

This term has direct consequences for the ray equation in this approximation. The adjusted ray equation is found by following a ray with general coordinates \(x'_0, x'_1\) to the image \(x_1', \ x'_1\) for which in general

\[ x'_0 = \frac{x_0 - x'_0}{z - z'_0} \quad \text{and} \quad x'_1 = \frac{x_1 - x'_1}{z - z'_1} \]

(A5.5a, 5b).

This gives from A5.4, using A5.5a to remove the \(x'_1\) terms

\[ \frac{x_1}{z_1 - z} = -\frac{x_0}{z - z_0} + x_1 \left\{ \frac{1}{z_1 - z_0} + \frac{1}{z - z_0} - \frac{1}{F} \right\} + C_3 \frac{x_3}{x_1} \]

\[ x_1 = x_0 \left\{ 1 - \frac{z_1 - z_0}{F} \right\} \quad \text{(magnification term)} \]

\[ + x'_0 \left\{ \frac{1}{z_1 - z_0} + \frac{1}{z_1 - z_0} - \frac{1}{F} \right\} (z - z_0) (z - z_1) \quad \text{(imaging term)} \]

\[ + x'_0^3 C_3 (z - z_0)^3 (z - z_1) \quad \text{(spherical aberration)} \]

\[ + 3 x'_0^2 x_0 C_3 (z - z_0)^2 (z - z_1) \quad \text{(coma)} \]
Simple approximations

\[ + 3 x'_1 x^2 _o \frac{C_3}{z - z'_0} (z - z) \]

\[ + x^3 _o C_3 \frac{1}{z - z} \]

\[
\text{field curvature and astigmatism (distortion)}
\]

(A5.6).

The condition for imaging is that the imaging term is equal to zero. Then \( x _1 \) is not dependent on \( x'_0 \). This results in eq. (A5.1) again. The magnification term is exactly equal to eq. (A5.2). Field curvature and astigmatism both have \( x^2 _o x' \) dependence, but they are not rotationally symmetric. By checking all combinations of \( x'_0 \) and \( x'_1 \) up to twice the amount of field curvature is found. The order of magnitude of all other aberrations is correct.

The \( C_3 \) value can be directly related to the spherical aberration of the lens by considering the ray \( (x = 0) \) and \( (\lim _{z \to -\infty} ) \), for which \( C_{sa} \) is defined with

\[ x_1 = C_{sa} x^3 _1. \]

The imaging condition is in this case \( z_1 - z'_1 = F \).

Because \( x = 0 \) only the spherical aberration term remains in equation (A5.6) and for \( x_1 \gg x'_1 \) eq. (A5.5) results in

\[ x'_1 = \frac{z - z}{z - z'_0} x'_0 \]

\[ \Rightarrow x_1 = -C_3 (z - z'_0)^4 x^3 _1 = -C_3 F^4 x^3 _1 \]
Equation (A5.6) is the general x-coordinate in the image which holds for all imaging conditions. Therefore the unsharpness in the image due to spherical aberration is in general

\[
\delta x_{1,sa}^1 = x_0^3 C_3 (z-z_1)^3 (z-z_1)
\]

(A5.8)

and the distortion unsharpness is thus

\[
\delta x_{1,\text{dist}}^1 = x_0^3 C_3 (z-z_1)
\]

(A5.9).

The anisotropic third order aberrations are described in Mast [1985/2] and Zworykin [1945]. They have about the same order of magnitude but no simple approximations are known as for the isotropic third order aberrations.

Figure A5.1: Coordinates in a lens imaging an object in paraxial (and higher order) approximation.
Program description: Slice.pas

1) Abstract and purpose of the program

Some stochastical electron interaction effects can be calculated with this program. It takes complete electron optical systems in which the effects are calculated using a slice approximation. The effects are: trajectory displacement, Boersch effect and the space charge effect. The effect chosen is calculated in each slice and it is reduced to the target plane. The effective contributions can be visualised along the the system length. The approximating equations of the effects have been taken from an internal report by G.H. Jansen.

The system description is entered in the form of a text file. Output comes in several files describing the effect as it is plotted and the total effect as well as the effect found per segment. At the end of the program the effect can be plotted on the graphics screen. The graphics data can also be saved and plots can be made over existing graphics files. The graphics file format corresponds to that of the graphics screen editor SCREDIT which allows for more extended editing features. By entering three parameters on the DOS command line this editor is automatically executed after the calculations have been done. This program expects the user to completely define the optical properties of the system. As such the program is only meant as a development tool.

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(The last version that supports the 8087 mathematical coprocessor)

The program was written using Turbo Pascal 3.01 A (PC-DOS) from Borland 1985. For coprocessor support Borland provides a second compiler that generates coprocessor supporting code (both have the same version number). The programs SLICE and SLICE87 thus have exactly the same source code, only their internal representation of numerical data is different. In this manual reference will only be made to SLICE.

The program runs on IBM personal computers (XT and AT). It normally supports the color/graphics board in 640*200 pixel resolution mode with two colors. It can also be used with an enhanced graphics adaptor (EGA). The EGA card is then used in the color/graphics mode. It is recommended that the Color constant in line __ of the main program be adjusted for the EGA card since this will give a clearer picture. (It should be made 0 to produce green on black pictures. The default for the color/graphics card is 15.) After this change the program must be recompiled.

Use is made of the standard graphics functions supported by the files: GRAPH.P and GRAPH.BIN. These must be available in the current directory when compilation is attempted. All screen interaction routines are provided in these files so these are not machine dependent.

3) General description of the program and references

It has been found that an approximation of the electron interaction effects can be made by the division in thin slices. The contributions of the slices are supposed to be independent and are added to form the total effect. An important advantage of this method is that it allows the user to locate the contributions of each slice in the system. For the slice approximation of a system it suffices to know:
- General properties (that can be constant over several segments):
  voltage, current, maximum stepsizes,
  type of effect, distribution type
  image plane, magnification to the target plane.

- Local properties:
  begin position and beam radius,
  end position and beam radius,
  (if needed) crossover position and beam radius.

A complete electron optical system is therefore divided in segments for
which the interaction effects are calculated. Within one segment the
reference plane (image plane) is constant. So a segment must not include
a lens. A segment is not allowed to have more then one crossover. If
necessary a beam segment can be split in more program segments to
accomodate for more crossovers or varying current or beam voltage. The
radius and possibly its distribution type (uniform/ Gaussian, round/
square) can thereby be altered at any slice.
The contributions in every slice are calculated by treating it as a
short parallel beam segment:

**Trajectory displacement**

The 12-88 % value of the angular distribution is referred to
the image plane by multiplying with the distance to the nearest image
plane. The magnification of that image plane is then used to refer
the displacement to the target plane (final image plane).

**Boersch effect**

This is the longitudinal energy broadening of the electrons. Here
the FWHM value is taken. In principle the total energy broadening
until a slice should be used to find the chromatic distortion. This
should then be referred to the target plane using the magnification
factor. As mainly the chromatic aberration of the projection lens
in demagnifying systems is of importance all contributions are
simply added. The total energy broadening can then be used to
calculate the chromatic aberration of the spot.
In this case the magnification factors are only used to give a
multiplication constant for the effect. It is therefore important
to set all magnification factors to 1.

**Space charge effect**

This effect results in a displacement of the image plane after the
current section. In the current version of the program only the
angular distortion is calculated. The magnification is provided as
a constant factor for the calculation of the final value.

For the trajectory displacement effect this method is reasonably safe.
It has not yet been extensively tested for the Boersch effect but the
intermediate results are positive. The space charge effect has not been
extensively tested yet. For determination of the final values of the
effects it is still recommended to check with the Monte Carlo simulation
program. All contributions are added linearly. In future it should also
be possible to add quadratically for the contributions that have a
Gaussian regime (see Jansen [1]).
The input file (default name 'In') consists of command lines describing the system. In the output file (default name 'Out') the program stores the Z-positions that it samples and the corresponding values of the effect there. It can later be used for reading by the program while rescaling to another curve. Separate output comes in the file 'Out.txt', which provides logging of the most recent results in text format. This file is not generated if no output at all is specified.

At the end of the system the program switches to its graphical mode. The current system is drawn on the screen and some interactive graphics commands are provided to the user. These include the drawing of previously calculated systems and the scaling of different systems on the same picture.

References:

4) Flowchart of the program:

![Flowchart Image](image-url)
5) Operating Instructions

In the program start up line the standard input and output files can be specified as parameters one and two. As the program immediately asks for confirmation of the filenames one can also specify these names by not accepting the defaults shown. A third parameter can also be specified indicating to the program that after processing a jump is to be made to SCREDIT.COM the graphics screen editor. This third parameter may contain anything but spaces.

The input file (default name 'In') consists of command lines describing the system in normal text. This file can be edited with a standard wordprocessor (eg. Wordstar in non-document mode).

In the output file (default name 'Out') the program stores the Z-positions that it samples and the corresponding values of the effect there. This file can be stored either in parameter format (with text added to identify the different values printed) or with only the real numbers (converted to ASCII format). If the program finds that the output file already exists it will append all the output to the end of the existing file. The original file is renamed to *bak. Separate output comes in the file 'Out.txt', which provides logging of the most recent results in text format. This file is not generated if IP = 0 (see further). In modes IP = 2 and 3 these data also appear on the screen. The logging simply overwrites any existing file of the name 'Out.txt'.

After all calculations on the current system have been done the program switches to its graphical mode. The current system is drawn on the screen and some interactive graphics commands are provided to the user. These are:

- **Exit** : Exit from the program.
- **Screen to file** : Save the current screen on a file (a file name is requested). Type "quit" if this option is to be abandoned.
- **File to screen** : Get a screen from a file (a file name is requested). Type "quit" if this option is to be abandoned.
- **draw s Ystem** : Draw the system over the current screen. The segments are divided by lines marked +. The positions where a crossover occurs are marked with a single perpendicular line.
- **draw Beam** : Draw the beam outer radius over the current screen.
- **Get effect from file** : Get the data from an output file describing an earlier calculated curve (file name and type are requested). Type "quit" if this option is to be abandoned.
- **Clear screen** : Clears the screen (with Y/ N confirmation).
- **Rescale** : Set scaling parameters to the newest curve data so these fill the full screen (horiz. & vertically).
- **Draw effecT** : Draw the newest curve data (Trajectory Displacement).
6) Example session

The sample input file (see appendix 2) describes a demagnifying system of one lens projecting a shape image onto a target. A source image is thereby formed just before the lens. This situation implies an unsharp source image in the main plane of the lens for which a characteristic radius value is taken.

One can start the calculation of this system by typing:
"slice demo.in demo.out".
The program then waits for confirmation of the file names given. This confirmation can be given by pressing ENTER. The progress of the calculation can be followed on the screen. After the calculations the program displays an output table of the system description found. Having read this one should press ENTER to continue to the graphics part of the program.
The program now reacts on any of the keys of the upper case letters in the bottom line.
Pressing 'q' returns one to the operating system.
The program should have made the files Out.txt and Demo.Out which can both be read by normal wordprocessors. Listings of these are also provided (in part) in appendix 2.

7) Specifications of the input data

The total number of slices allowed is 1000. (This is also the maximum number of slices in one segment.) The total number of segments allowed has been set to 50. Both are determined in constants in the top of the main program.

The input file (default name 'In') consists of command lines describing the system. This file can be edited with a standard wordprocessor (eg. Wordstar in non-document mode).
A segment is entered with a number of command lines. The order in which command lines are entered is for the largest part free. Superfluous spaces are properly elimintated. Upper/ lower case and the inclusion of comment are up to the user.
The relevant parameters should be given with their values seperated by a space, ";" or ";=\). The command should begin within the first 12 characters, otherwise the line is considered to be empty. Lines beginning with ";" or "\" as the first non-space character are considered to be comment and are ignored by the program. Also all characters behind the numerical value of a command line is ignored.

Comment lines and errors encountered are shown on the display (if IP >= 2) during processing of the input file. Most of the parameter values are retained if they are not altered when a new segment is read.
The commands recognized are:

**param** 1: meaning

<table>
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<tr>
<th>TYPE: which effect is calculated</th>
</tr>
</thead>
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<tr>
<td>(can not be altered later within the same input file)</td>
</tr>
<tr>
<td>1: trajectory displacement (default if none is entered</td>
</tr>
<tr>
<td>before segment 1)</td>
</tr>
<tr>
<td>2: Boersch effect</td>
</tr>
<tr>
<td>3: space charge effect</td>
</tr>
</tbody>
</table>

| IP: output status for the file describing the curve                 |
| (needed if the same drawing is to be made on an other scale)       |
| 0: no output is generated (default)                                |
| 1: file in real numbers                                            |
| 2: file in reals and screen in parameter format                    |
| 3: both in parameter format                                        |

| V beam voltage (must be specified)                                 |
| I beam current in SI units (must be specified)                     |

| L Total length of the system. This value is not needed by the      |
| program. If entered it is used by the program to set a default     |
| stepsize of L/100.                                                 |

**SEGMENT** Initialise the reading of a new segment. (see also flowchart, page 4). An integer number should be provided here. It is not used for segment numbering though since this resulted in some ordering problems.

**GO** Stops the read loop and starts the calculation of the current |
| segment. Every segment **MUST** be terminated with this command or  |
| the calculation will not be done (see also flowchart page 3). It   |
| is not required to give a numerical value here.                    |

**Zstep** maximum stepsize (slice length) in SI units               |
| (*) The stepsize is varied to accommodate an integer number of    |
| steps in every segment. The point where Zstep is adjusted to the  |
| new value corresponds to the last Z value encountered. This change |
| is allowed only once per segment.                                 |

**Z** coordinate entry (along the optical axis) of the system. Can be |
| used instead of ZB, ZC, ZE, ZL. (See also note 1).                 |

**R** (***) beam radius entry for the point corresponding to the last |
| Z value entered.                                                  |

**ZB** begin of the segment coordinate entry.                       |

**RB** (***) radius entry, defining the begin of the segment to be at |
| the last Z value entered.                                          |

**ZC** crossover coordinate entry.                                  |

**RC** (***) radius entry, defining crossover to be at the the last Z |
| value entered. Only one crossover is allowed per segment.          |
param : meaning

**ZE** end of the segment coordinate entry.

**RE (⋆)** radius entry, defining the end of the segment to be at the last Z value entered.

When this command is encountered the end coordinate and radius values of the last segment are assigned to the begin coordinate and radius of the current segment.

**ZI** image plane coordinate entry.

**M (⋆)** magnification entry, defining image plane to be at the last Z value entered.

**IDR (⋆)** specification of the spatial current density distribution type

1: uniform spatial distribution.
2: Gaussian spatial distribution with its HWHM-value given.
3: uniform spatial distribution in rectangular beam (with square crosssection) with its half side length given.

The point of change to the new distribution corresponds to the last Z value encountered. This change of the distribution type is allowed only once per segment only.

Notes:

1) All the commands marked (⋆) have a corresponding Z value (ZB, ZC, ZE, ZI) at which they become active. This Z value must always be given first. A provision has been built in to allow a definition of Z without a second letter to precede the command since the command type is uniquely defined by the corresponding R command (or M, ZSTEP, . . .). This provision also allows for giving M and ZC on the same Z value by entering:

\[ Z = 12E-3 \text{ m} \]
\[ M = 0.1 \]
\[ RC = 15E-6 \text{ m}. \]

2) Commands recognized but not used here are: Sc, Si, Ida, AO, Am, RO.

3) Z-values can be negative. They should be in increasing order.

**Automation during read in:**

When RE is read by the program RB and ZB are first replaced with the old RE and ZE values. This provides for normal continuity of the segments and the beam radius. Where this is not wanted ZB (or Z) and RB should be redefined AFTER ZE (or Z) and RE have been defined. The segments should always be defined connective.

Example:

\[ Z = 40E-3 \text{ m} \]
\[ RE = 25E-6 \text{ m} \]
\[ Z = 15E-3 \text{ m} \]
\[ RB = 100E-6 \text{ m}. \]
8) Specifications of the output data

In the output file (default name 'Out') the program stores the Z-positions that it samples and the corresponding values of the effect there. This file can be stored either in parameter format or with only the real numbers.

Parameter format: (IP=2, 3) In this format the file will be read by the same routine that reads the input data file. So it also supports comment. For output the variables z and r are used here (r represents the effect calculated). In the comment part of the 'z-lines' the radius value of the current slice is printed.

Example:

.SLICE: Calculation of trajectory displacement effect, Boersch effect
.and space charge effect using a slice approximation.

.14-5-1986, Version 5     (C) J. Simons

z = 2.5000E-04, R(z)= 6.7400E-06  L
r = 1.0247E-07  (e)
z = 7.5000E-04, R(z)= 8.2200E-06  L

Real format: This output option is provided for data transport to other programs. Output is done in ASCII characters representing z and respective r-values for the slices. This output can also be used for interfacing with other languages.

Example:

2.5000000000E-04  1.024718341E-07
7.5000000000E-04  2.462679856E-07
1.2500000000E-03  3.4001229426E-07

The output file 'Out.txt' serves for logging of the most recent results in normal text format. In modes IP= 2, 3 these data also appear on the screen.

It contains an abstract of the effect values found and a description of the system segments as they were encountered during processing of the input file.
Program description: ScrEdit.pas: A graphics screen editor

1) Abstract and purpose of the program

This program is meant for filling and editing of graphics screens on IBM XT and AT computers. Color/graphics screens (640*200 pixels) can be viewed, filed and merged. It also allows for typing over the screen and printing on a Fujitsu DPL 24 dot matrix printer.

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APPENDIX

7 Printout of the program.
2) Specifications hard and software

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<thead>
<tr>
<th>Name</th>
<th>byte</th>
<th>date</th>
<th>time</th>
<th>note</th>
</tr>
</thead>
<tbody>
<tr>
<td>SCR CREDIT</td>
<td>3401</td>
<td>4-16-86</td>
<td>4:41p</td>
<td>Main program</td>
</tr>
<tr>
<td>SCR CREDIT</td>
<td>15825</td>
<td>4-16-86</td>
<td>4:40p</td>
<td>Library functions</td>
</tr>
<tr>
<td>SCR CREDIT</td>
<td>22549</td>
<td>4-16-86</td>
<td>4:42p</td>
<td>DOS executable code</td>
</tr>
</tbody>
</table>

The program runs on IBM personal computers (XT and AT). It normally supports the color/graphics board in 640*200 pixel resolution mode with two colors. It can also be used with an enhanced graphics adaptor (EGA). The EGA card then is used in the color/graphics mode.

It is recommended that the Color constant in line 15 of the main program be adjusted for the EGA card since this will give a clearer picture. (It should be made 0 to produce green on black pictures. The default for the color/graphics card is 15. This instruction has been underlined in the appendix.) After this change the program must be recompiled.

The program was written using Turbo Pascal 3.01 A (PC-DOS) from Borland 1985. Coprocessor support is not used since hardly any calculations are done.

Extended use is made of the standard graphics functions supported by the files: GRAPH.P and GRAPH.BIN.

These must be available in the current directory when compilation is attempted. All screen interaction routines are provided in these files so these are not machine dependent.

The PrintScreen routine is strongly machine dependent. It is written with direct access to the memory positions where the high resolution screen is stored by the color/graphics card. Furthermore it directly accesses the serial I/O circuits of LPT1 for 9600 baud output of the data.

Also the escape sequences used for printer directives are specific to this particular printer (24 bit dot matrix printer). The printer can be used to its full resolution (1/180 inch). Another printing mode is also provided for making bigger pictures. It is not yet possible to use all of the 24 needles of the Fujitsu printer.
3) General description of the program and references

At start up the program immediately sets high resolution mode. It either displays the screen requested or an appropriate error message. Pressing any of the keys from the capital letters in the bottom line now immediately activates that action. Internally the full screen is buffered so that this bottom line will not be displayed on the printout or in the files. Following is a flowchart of the program:

References:

[1] The Turbo Pascal handbook provides descriptions of the graphics procedures used.

[2] The XT technical reference manual has been used for access of the color/graphics screen and for direct (high speed) access of the LPT1 printer port.

[3] The Fujitsu manual was used for the printer mode commands.
4) Specifications of the input data and short instruction

The program uses the standard subroutine provided to save the screen into a buffer variable. This buffer can then be written to a file. The data format of this buffer is described in ref. [1]. Only files saved in this way can be used as input for this program.

The number of parameters provided on the DOS commandline determines the startup mode of the program:

no parameters : startup from an empty screen
1 parameter : startup from graphics file in which a screen must be in the correct format
2 parameter : startup from an empty screen
>2 parameters: immediate startup on current HiRes screen (can be left in the correct state by an earlier program)

In the editor mode all letters and cursor commands can be used in the normal way. Tab and shift Tab are provided for 10 position jumps. The editor mode can be ended in two ways:

Control S: normal exit and save the screen in the internal buffer.
Control Q: quit from editing and do not save the screen in the internal buffer. This implies that all corrections since last entering the editor mode are undone.

When saving or retrieving a screen a test is run whether or not the file name entered refers to an existing file. The user is then prompted with

"Fname" bestaat al/NIET, Ok ?

When pressing <Enter>, 'J', 'y' or 'I' the original file of this name is replaced with the new information. Any other key results in a prompt to the user to enter a new file name.

5) Specifications of output data

The program outputs bit image files of length 16128 byte. The data format of these files is described in ref. [1].
6) Example session

Type SCREDIT DEMO.GR <enter>
From the bottomline you can now
type E
and you can type or move the cursor anywhere on the screen.
End this with <control> S
You now see the screen with the text you just typed over it.
You can now get back the original file DEMO.GR by
typing F
Answer DEMO.GR <enter> to the prompt.
If the program has found the screen you can now
press <enter> again.
Now you can quit from the program by
pressing Q.

7) Operating instructions

The number of parameters provided on the DOS commandline determines the
startup mode of the program:

no parameters : startup from an empty screen
1 parameter  : startup from graphics file in which a screen
               must be in the correct format
2 parameter  : startup from an empty screen
>2 parameters: immediate startup on current HiRes screen
               (can be left in the correct state by an earlier program)

At start up the program immediately sets high resolution mode. It either
displays the screen requested or an appropriate error message. Pressing
any of the keys from the capital letters in the bottom line now
immediately activates that option.

The following options are provided:

Quit Quit from the program
Edit Allow typing over the current screen. Text replaces the
graphics. This can be used for labelling of function
plots and dating of files.
Screen to file Save the screen in a file (a file name is requested)
File to screen Get the screen from a file (a file name is requested)
Print screen Dump the screen on a printer
Res high Set or reset the resolution mode
           High : small dump using the full printer resolution
           Small: big dump using a lower printer resolution
Merge Merge the current screen with another file
           (a file name is requested)
While in the editor mode all letters and cursor commands can be used in the normal way.
Tab and shift Tab are provided for 10 position jumps. The editor mode can be ended in two ways:

Control S: normal exit and save the screen in the internal buffer.
Control Q: quit from editing and do not save the screen in the internal buffer. This implies that all corrections since last entering the editor mode are undone.

When saving or retrieving a screen a test is run whether or not the file name entered refers to an existing file. The user is then prompted with

"Fname" bestaat al/NIET, Ok?

When pressing <Enter>, 'J', 'y' or 'I' the original file of this name is replaced with the new information (if it already existed). Any other key results in a new prompt to the user to enter a new file name.

The file name 'quit' can be used to escape from the command without its execution (capitals are converted to lower case).

File names ending with '.bak' are not accepted.
Appendix A.6: INTERAC and MONTEC results for imaging shapers

This appendix illustrates the energy spread and trajectory displacement values found in imaging shapers. In the figures the effect under consideration is plotted as a function of beam current. The beam current scale is thereby logarithmic. As vertical value the following values are plotted (linearly and logarithmically as indicated):

**from INTERAC:**

- (lin) the FWHM of the energy spread
- (lin) the $\gamma_\alpha$ for the energy spread
- (log) the 12-88% edge width of a rectangular shape
  (this value is not always plotted)
- (log) the FWHM of a rectangular shape
- (lin) the $\gamma_\alpha$ for the positional displacement distribution

**from MONTEC:**

- (lin) the FWHM of the energy spread
- (log) the FWHM of the positional displacement distribution
  (this value is taken from routine TBR).

The value for a beam current of 330 $\mu$A did not fit into the logarithmic scale of the beam current. It is therefore separately plotted. As such the slope in the graphs towards the 330 $\mu$A values do not have any meaning!

Where the vertical scales are logarithmic, these values indicate the 10-logarithm of the parameter. In that way the absolute value can easily be deduced from the graphs.
* First edited: 4-8-1989, J. Simons
* Last edited: 4-8-1989, savin.txt (from 12v2.dat, 12-6-1989)

* input:

```
NOTE: S square: half side length !!
```

* output: effective gamma value, average effect

```
Sum(i) [GE(i) FW50(i)]
```

* EG: 2.0 Gaussian
* 1.5 Holtsmark
* 1.0 Lorentz
* 0.5 Par. force distrib. FWXe = (Sum(i) FWX(i)^EGa) ^ (1/EGa)
* 0.33 Perpend. force distrib.

```
C I V L Sc S1
C lda a0 am
C ldr r0 rm
C ldrp r0p rmp
C beam type f1 tm
```

```
\sav02010.in
```

```
10.0E-6 2.0E3 8.0E-3 0.0 0.0
1 0.799E-3 1.0E-15
4 110.0E-6 1.0E-15
1 1.0 1.0E-15
1 1.0 2.0
```

```
10.0E-6 2.0E3 16.0E-3 1.0 1.0
1 0.400E-3 1.0E-15
4 220.0E-6 1.0E-15
1 1.0 1.0E-15
1 1.0 1.0
```
Figure A6.1: Boersch effect calculations using INTERAC for the short imaging shaper. The effect (in eV) is displayed as a function of beam current in the shaper.

For figures a through c the following settings hold:

a $\Delta z_{dof} = 0.5 \mu m$, $B = 170 A/cm^2/sr/V$, $D = 220 \mu m$, $D = 440 \mu m$

b $\Delta z_{dof} = 1.0 \mu m$, $B = 680 A/cm^2/sr/V$, $D = 155 \mu m$, $D = 310 \mu m$

c $\Delta z_{dof} = 2.0 \mu m$, $B = 850 A/cm^2/sr/V$, $D = 220 \mu m$, $D = 440 \mu m$. 
Figure A6.2: Effective gamma values of the energy spread, as calculated with INTERAC for the short imaging shaper. (ref. figure A6.1).
Figure A6.3 : Trajectory displacement values for the short imaging shaper (calculated with INTERAC). For the beam settings refer to figure A6.1. The vertical value is the logarithm of the positional spread in nm.

Each of the systems will have a different demagnification from shaping apertures to the final image. The trajectory displacement values tolerated have to be taken relative to the second shaping aperture side length \( D_{e2} \). For the different figures they are:

\[ a \, \Delta z_{dof} = 0.5 \, \mu m, \, D_{e2} = 440\mu m, \, \delta_{dof} = 5.5 \, \mu m \]
\[ b \, \Delta z_{dof} = 1.0 \, \mu m, \, D_{e2} = 310\mu m, \, \delta_{dof} = 3.9 \, \mu m \]
\[ c \, \Delta z_{dof} = 2.0 \, \mu m, \, D_{e2} = 440\mu m, \, \delta_{dof} = 5.5 \, \mu m. \]
Figure A6.4: Trajectory displacement effective gamma values, as calculated with INTERAC for the short imaging shaper. (ref. figure A6.1).
Figure A6.5: Boersch effect calculations using INTERAC for the long imaging shaper. The effect (in eV) is displayed as a function of beam current in the shaper. (See also to figure A6.1).

For figures a through c the following settings hold:

a $\Delta z_{dof} = 0.5 \ \mu m$, $B = 170 A/cm^2/sr/V$, $D_1 = 550 \mu m$, $D_2 = 1100 \mu m$

b $\Delta z_{dof} = 1.0 \ \mu m$, $B = 680 A/cm^2/sr/V$, $D_1 = 385 \mu m$, $D_2 = 770 \mu m$

c $\Delta z_{dof} = 2.0 \ \mu m$, $B = 850 A/cm^2/sr/V$, $D_1 = 550 \mu m$, $D_2 = 1100 \mu m$. 
Figure A6.6: Effective gamma values of the energy spread, as calculated with INTERAC for the long imaging shaper. (ref. figure A6.5).
Figure A6.7: Trajectory displacement values for the long imaging shaper (calculated with INTERAC). For the beam settings refer to figure A6.5. The vertical value is the logarithm of the positional spread in nm.

Each of the systems will have a different demagnification from shaping aperture to the final image. The trajectory displacement values tolerated have to be taken relative to the second shaping aperture side length ($D_{s2}$). For the different figures they are:

a $\Delta z_{dof} = 0.5 \mu m$, $D_{s2} = 1100\mu m$, $\delta_{dof} = 13.7 \mu m$

b $\Delta z_{dof} = 1.0 \mu m$, $D_{s2} = 770\mu m$, $\delta_{dof} = 9.7 \mu m$

c $\Delta z_{dof} = 2.0 \mu m$, $D_{s2} = 1100\mu m$, $\delta_{dof} = 13.7 \mu m$. 
Figure A6.8: Trajectory displacement effective gamma values, as calculated with INTERAC for the long imaging shaper. (ref. figure A6.5).
The particles are electrons:

- pm: 9.10956D-31, pq: 1.0D0

General system parameters:

- b1: 330.0D-6, bV: 2.0D3, FWe: 0.0D0

ICONS is very important for the direction of the electrons.

- 1: related to the Z-direction, 2: total energy is determined.

The interaction may be on/off or limited in range:

- Iproc: correction of end effects 0: off, 1: on

Here are the polynomial coefficients:

- NDe: 40, NTe: 40, NEXPe: 40, IFIXe: 1, PMAXe: -2.5000

This is for storage of the distributions: energy/ t.d. /org. distrib.

These parameters control the focussing methods:

- IMt1: 1, IMt2: 1
C *******************************************************************************************************
C system input file: 1330v2.SYS
C First edited: 9-3-1989, J. Simons
C Last edited: 12-6-1989, Br=170
C *******************************************************************************************************
C
C *****     OPTICAL ELEMENTS:
C first shaping aperture (square source)
C/source/  z   /  Xctr  /  Yctr  /  lds (1)  /  Xhw  /  Yhw  /  
C       /  1da (1)  /  Ahw  /  tca  /  
C/SOURCE/  0.0DD  /  0.0DD  /  0.0DD  /  3  /  110.0D-6  /  110.0D-6  /  
C       /  1  /  7.99D-4  /  0.0DD  /  
C to shaper lens, 8 mm
C/drift2/  z0  /  z1  /  bV  /  bV  /  ** Inter **/  ips (1)/
C/DRIFT2/  -1.0DD  /  8.0D-3  /  -1.0DD  /  -1.0DD  /  1  /  0  /  
C shaper lens
C/len2/  z   /  Xctr  /  Yctr  /  f   /  Cs   /  Cc   /  
C/LENS/  -1.0DD  /  0.0DD  /  0.0DD  /  5.333D-3  /  0.0DD  /  0.0DD  /  
C to second shaper aperture 16 mm length
C/drift2/  z0  /  z1  /  bV  /  bV  /  ** Inter **/  ips (1)/
C/DRIFT2/  -1.0DD  /  24.0D-3  /  -1.0DD  /  -1.0DD  /  1  /  0  /  
C second shaping aperture
C/apertr/  z   /  Xctr  /  Yctr  /  Xhw  /  Yhw  /  ishp (1)/  
C/APERTR/  -1.0DD  /  0.0D0  /  0.0D0  /  100.0D-6  /  100.0D-6  /  2  /  
C *****     ACCUMULATION AND STORAGE OF COORDINATES OF PARTICLES:
C/ACCUM/  
C/STOREC/  
C/READC/  
C
C *****     STATISTICAL DATA PROCESSING:
C/symebr/  
C/SYMEBR/  
C get values without refocusing
C/rectbr/  Zref  /  ifoc (1)/  
C/RECTBR/  -1.0DD  /  0  /  
C get values WITH refocusing (in rectbr), niet betrouwbaar
C/rectbr/  Zref  /  ifoc (1)/  
C/RECTBR/  -1.0DD  /  1  /  
C get values WITH refocusing (in tbr)
C/rectbr/  Zref  /  ifoc (1)/  
C/TBR/  -1.0DD  /  0  /  
C/TBR/  -1.0DD  /  1  /  
C/RECTBR/  -1.0DD  /  2  /  
C *****     STORAGE OF POSITIONS OF PARTICLES IN PLANE OF BEST FOCUS:
C/STOREP/  Zref  /  Ifoc (1)/  
C
Figure A6.10: Boersch effect calculated using the Monte Carlo simulation program, for the short imaging shaper. The effect (in eV) is displayed as a function of beam current in the shaper. For figures a through c the same conditions as for figure A6.1 hold:

a $\Delta z_{dof} = 0.5 \mu m$, $B = 170 A/cm^2/sr/V$, $D = 220 \mu m$, $D = 440 \mu m$

b $\Delta z_{dof} = 1.0 \mu m$, $B = 680 A/cm^2/sr/V$, $D = 155 \mu m$, $D = 310 \mu m$

c $\Delta z_{dof} = 2.0 \mu m$, $B = 850 A/cm^2/sr/V$, $D = 220 \mu m$, $D = 440 \mu m$. 
Figure A6.11: Trajectory displacement calculated using the Monte Carlo simulation program, for the short imaging shaper. The value shown is \( dR_{Iwhm} \). It is the full width at half maximum of the positional distribution in the plane of the second shaping aperture. (This value corresponds to the D1288 edge width of the edges of the first shaping aperture at this position.) The logarithm of the positional spread value is given in nm.

The conditions are the same as in figures A6.1 and A6.10. The allowed unsharpness contributions are the same as for figure A6.3.
Figure A6.12: Boersch effect calculated using the Monte Carlo simulation program, for the long imaging shaper. The effect (in eV) is displayed as a function of beam current in the shaper. For figures a through c the same conditions as for figure A6.5 hold:

- a $\Delta z_{dof} = 0.5 \mu m$, $B = 170 A/cm^2/sr/V$, $D = 550 \mu m$, $D_r = 1100 \mu m$
- b $\Delta z_{dof} = 1.0 \mu m$, $B = 680 A/cm^2/sr/V$, $D = 385 \mu m$, $D_r = 770 \mu m$
- c $\Delta z_{dof} = 2.0 \mu m$, $B = 850 A/cm^2/sr/V$, $D = 550 \mu m$, $D_r = 1100 \mu m$. 
Figure A6.13: Trajectory displacement calculated using the Monte Carlo simulation program, for the long imaging shaper. The value shown is \( \text{dR}_{\text{FWHM}} \): it is the full width at half maximum of the positional distribution in the plane of the second shaping aperture. The logarithm of the positional spread value is given in nm.

The conditions are the same as in figures A6.5 and A6.12. The allowed unsharpness contributions are the same as for figure A6.7.
Appendix B.6: INTERAC and MONTEC results for shadow shapers

This appendix illustrates the energy spread and trajectory displacement values found in shadow shapers. It is structured in the same way as appendix A.6, to enable a fair comparison. In the figures the effect under consideration is plotted as a function of beam current. The beam current scale is thereby logarithmic. As vertical value the following values are plotted (linearly and logarithmically as indicated):

from INTERAC:

- (lin) the FWHM of the energy spread
- (lin) the $\gamma_e$ for the energy spread
- (log) the 12-88% edge width of a rectangular shape
  (this value is not always plotted)
- (log) the FWHM of a rectangular shape
- (lin) the $\gamma_e$ for the positional displacement distribution

from MONTEC:

- (lin) the FWHM of the energy spread
- (log) the FWHM of the positional displacement distribution
  (this value is taken from routine TBR).

The value for a beam current of 330 $\mu$A did not fit into the logarithmic scale of the beam current. It is therefore seperately plotted. As such the slope in the graphs towards the 330 $\mu$A values do not have any meaning!

Where the vertical scales are logarithmic, these values indicate the 10-logarithm of the parameter. In that way the absolute value can easily be deduced from the graphs.
Figure B6.1: Boersch effect calculations using INTERAC for the short shadow shaper. The effect (in eV) is displayed as a function of beam current in the shaper. Refer also to the figure A6.1 for the short imaging shaper.

For figures a through c the following settings hold:

- a \( \Delta z = 0.5 \, \mu m, \frac{B}{sr/V} = 170A/cm^2/sr/V, D = 220\mu m \)
- b \( \Delta z = 1.0 \, \mu m, \frac{B}{sr/V} = 680A/cm^2/sr/V, D = 155\mu m \)
- c \( \Delta z = 2.0 \, \mu m, \frac{B}{sr/V} = 850A/cm^2/sr/V, D = 220\mu m \).
Figure B6.2: Effective gamma values of the energy spread, as calculated with INTERAC for the short shadow shaper. (ref. figure B6.1).
Figure B6.3: Trajectory displacement values for the short shadow shaper (calculated with INTERAC). For the beam settings refer to figure B6.1. The vertical value is the logarithm of the positional spread in nm.

Each of the systems will have a different demagnification from shaping apertures to the final image. The trajectory displacement values tolerated have to be taken relative to the second shaping aperture side length (D, both shapes have equal size in a shadow shaper). For the different figures they are:

- \( \Delta z \) (D, \( s \)) = 0.5 \( \mu \text{m} \), \( D = 220\mu \text{m} \), \( \delta \) (s, \( \text{dof} \)) = 2.8 \( \mu \text{m} \)
- \( \Delta z \) (D, \( s \)) = 1.0 \( \mu \text{m} \), \( D = 155\mu \text{m} \), \( \delta \) (s, \( \text{dof} \)) = 1.9 \( \mu \text{m} \)
- \( \Delta z \) (D, \( s \)) = 2.0 \( \mu \text{m} \), \( D = 220\mu \text{m} \), \( \delta \) (s, \( \text{dof} \)) = 2.8 \( \mu \text{m} \).
Figure B6.4: Trajectory displacement effective gamma values, as calculated with INTERAC for the short shadow shaper. (ref. figure B6.1).
Figure B6.5: Boersch effect calculations using INTERAC for the long shadow shaper. The effect (in eV) is displayed as a function of beam current in the shaper. (See also to figure B6.1).

For figures a through c the following settings hold:

a $\Delta z_{dof} = 0.5 \, \mu m$, $B = 170 \, A/cm^2/sr/V$, $D = 550 \, \mu m$

b $\Delta z_{dof} = 1.0 \, \mu m$, $B = 680 \, A/cm^2/sr/V$, $D = 385 \, \mu m$

c $\Delta z_{dof} = 2.0 \, \mu m$, $B = 850 \, A/cm^2/sr/V$, $D = 550 \, \mu m$. 
Figure B6.6: Effective gamma values of the energy spread, as calculated with INTERAC for the long shadow shaper. (ref. figure B6.5).
Figure B6.7: Trajectory displacement values for the long shadow shaper (calculated with INTERAC). For the beam settings refer to figure B6.5. The vertical value is the logarithm of the positional spread in nm.

Each of the systems will have a different demagnification from shaping aperture to the final image. The trajectory displacement values tolerated have to be taken relative to the second shaping aperture side length \( D_s \). For the different figures they are:

a \( \Delta z \_\text{dof} = 0.5 \, \mu m, \ D = 550 \mu m, \ s \_\text{dof} = 6.9 \mu m \)

b \( \Delta z \_\text{dof} = 1.0 \, \mu m, \ D = 385 \mu m, \ s \_\text{dof} = 4.8 \mu m \)

c \( \Delta z \_\text{dof} = 2.0 \, \mu m, \ D = 550 \mu m, \ s \_\text{dof} = 6.9 \mu m. \)
Figure B6.8: Trajectory displacement effective gamma values, as calculated with INTERAC for the long shadow shaper. (ref. figure B6.5).
Figure B6.9: Boersch effect calculated using the Monte Carlo simulation program, for the short shadow shaper. The effect (in eV) is displayed as a function of beam current in the shaper. For figures a through c, the same conditions as for figure B6.1 hold:

- a $\Delta z_{dof} = 0.5 \mu m$, $B = 170 A/cm^2/sr/V$, $D = 220 \mu m$
- b $\Delta z_{dof} = 1.0 \mu m$, $B = 680 A/cm^2/sr/V$, $D = 155 \mu m$
- c $\Delta z_{dof} = 2.0 \mu m$, $B = 850 A/cm^2/sr/V$, $D = 220 \mu m$. 
Figure B6.10: Trajectory displacement calculated using the Monte Carlo simulation program, for the short imaging shaper. The value shown is \( dR_{1/2} \). It is the full width at half maximum of the positional distribution in the plane of the second shaping aperture. (This value corresponds to the DI288 edge width of the edges of the first shaping aperture at this position.) The logarithm of the positional spread value is given in nm.

The conditions are the same as in figures B6.1 and B6.9. The allowed unsharpness contributions are the same as for figure B6.3.
Figure B6.12: Boersch effect calculated using the Monte Carlo simulation program, for the long shadow shaper. The effect (in eV) is displayed as a function of beam current in the shaper. For figures a through c the same conditions as for figure B6.5 hold:

a $\Delta z_{\text{def}} = 0.5 \mu m$, $B = 170 A/cm^2/sr/V$, $D = 550 \mu m$

b $\Delta z_{\text{def}} = 1.0 \mu m$, $B = 680 A/cm^2/sr/V$, $D = 385 \mu m$

c $\Delta z_{\text{def}} = 2.0 \mu m$, $B = 850 A/cm^2/sr/V$, $D = 550 \mu m$. 
Figure B6.13: Trajectory displacement calculated using the Monte Carlo simulation program, for the long imaging shaper. The value shown is $dR_1_{\text{whm}}$. It is the full width at half maximum of the positional distribution in the plane of the second shaping aperture. The logarithm of the positional spread value is given in nm.

The conditions are the same as in figures B6.5 and B6.12. The allowed unsharpness contributions are the same as for figure B6.7.
This appendix illustrates the energy spread and trajectory displacement values found in shadow shapers. It is structured in the same way as appendix A.6, but the output is given in tabular format.

The following values are given:

from INTERAC:
- the FWHM of the energy spread
- the $\gamma_e$ for the energy spread
- the 12–88% edge width of a rectangular shape
  (this value is not always given)
- the FWHM of a rectangular shape
- the $\gamma_e$ for the positional displacement distribution

from MONTEC:
- the FWHM of the energy spread
- the FWHM of the positional displacement distribution
  (this value is taken from routine TBR).
* First edited: 15-8-1989, J. Simons ****************************
* Last edited: 21-10-1990, mavin.txt (IDA ... RO)
* Ds2 = 220, Dm = 5.67, Mn = 1/38.8, Br = 170, long, dz = 0.5 µm
*.
* input: NOTE: S square: half side length !!
* ---------
* Sc = Lc / L, S1 = L1 / L
* ida = (0, 1, 2, 3, 4) = (invalid, U, G, T, S) SAME: idr, idrp
* beamtype = (0, 1, 2) = (undefined, C, P)
* fl = end segment / image plane (for beamtype P only)
* output: effective gamma value, average effect
* --------- Sum(1) [GE(1) FW50(1)]
* EG: 2.0 Gaussian EGa = ---------------
* 1.5 Holtsmark Sum(1) [FW50(1)]
* 1.0 Lorentz
* 0.5 Par. force distrib. FWXe = {Sum(1) FWX(1)^EGa}^-(1/EGa)
* 0.33 Perpend. force distrib.
*-------------------------------
* C I 1.0E-05 V 2.0E+03 L 4.9E-03 SC 1.0 SI 1.0
* C IDA 1 AO 5.67E-04 AH 1.0E-15
* C IDR 1 RO 1.55E-04 RM 0.0
* C IDR 1 ROP 5.0E-06 RMP 0.0
* C BEAM TYPE 0 FL 0.0 TH 1.0
* \fmav20005.in
*-------------------------------
* 5.0E-6 20.0E3 19.9E-3 0.975 0.0
* 4 5.67E-3 1.0E-15
* 1 854.0E-9 1.0E-15
* 1 0.0 1.0E-15
* 1 0.0 0.0258
*-------------------------------
* 5.0E-6 20.0E3 0.513E-3 1.0 1.0
* 1 1.71E-3 1.0E-15
* 4 2.84E-6 1.0E-15
* 1 0.0E-6 1.0E-15
* 1 0.0 1.0
*

TABLE A7.1: Sample input file for the INTERAC program. This file describes a single demagnifying section, with a lens of focal length F_m = 0.5 mm. The section ends at the shape intermediate image (D_m = 5.67 µm), which is applied to the projection section.
### MAV

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<th>dR 1288 m</th>
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### MBV

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**TABLE A7.2:** Analytical electron-electron interaction effects for the short demagnifying sections. This table presents the versions for the small intermediate image, \( D_m = 5.68 \text{ µm} \), with

\[
F_m = 0.5 / 1.12 \text{ mm (20 / 100 kV)}
\]

- MAV: \( B = 170 \text{ A/cm}^2 / \text{sr} / \text{V}, D = 220 \text{µm} \)
- MBV: \( B = 680 \text{ A/cm}^2 / \text{sr} / \text{V}, D = 155 \text{µm} \)
- MCV: \( B = 850 \text{ A/cm}^2 / \text{sr} / \text{V}, D = 220 \text{µm} \)
- MDV: \( B = 170 \text{ A/cm}^2 / \text{sr} / \text{V}, D = 550 \text{µm} \)
- MEV: \( B = 680 \text{ A/cm}^2 / \text{sr} / \text{V}, D = 385 \text{µm} \)
- MFV: \( B = 850 \text{ A/cm}^2 / \text{sr} / \text{V}, D = 550 \text{µm} \).
### mcv

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## Results for demagnifying sections

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**TABLE A7.3:** Analytical electron-electron interaction effects for the short demagnifying sections. This table presents the versions for the large intermediate image, D_m = 34.7 µm, with

\[
F_m = 0.5 / 1.12 \text{ mm (20 / 100 kV)}
\]

NAV: B_r = 170 A/cm^2 /sr/V, D = 220µm

NBV: B_r = 680 A/cm^2 /sr/V, D = 155µm

NCV: B_r = 850 A/cm^2 /sr/V, D = 220µm

NDV: B_r = 170 A/cm^2 /sr/V, D = 550µm

NEV: B_r = 680 A/cm^2 /sr/V, D = 385µm

NFV: B_r = 850 A/cm^2 /sr/V, D = 550µm.
## Results for demagnifying sections

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TABLE A7.4: Other analytical electron-electron interaction effects calculations for the demagnifying section. In this table some of the earlier calculations are presented for demagnifying lenses with $F_m = 4.0$ and $F_m = 20.0$ mm. The nominal beam brightnesses mentioned here are at $I = 330 \mu A$, in contrast with the $10 \mu A$ nominal beam current in tables A7.2 and A7.3. The table numbers do refer to the former tables.

NAV.1: $B = 170 A/cm^2/sr/V$, $D = 220 \mu m$, $F_m = 4.0$ mm, $D_m = 34.7 \mu m$

NAV.2: $B = 170 A/cm^2/sr/V$, $D = 220 \mu m$, $F_m = 20.0$ mm, $D_m = 34.7 \mu m$

NCV.1: $B = 850 A/cm^2/sr/V$, $D = 220 \mu m$, $F_m = 4.0$ mm, $D_m = 34.7 \mu m$

NEV.1: $B = 680 A/cm^2/sr/V$, $D = 220 \mu m$, $F_m = 4.0$ mm, $D_m = 34.7 \mu m$

NEV.2: $B = 680 A/cm^2/sr/V$, $D = 220 \mu m$, $F_m = 20.0$ mm, $D_m = 34.7 \mu m$

MBV.1: $B = 680 A/cm^2/sr/V$, $D = 220 \mu m$, $F_m = 4.0$ mm, $D_m = 5.68 \mu m$

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c last edited: 23-7-1989, Br=680, Demag System
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TABLE A7.5: Sample input file for the MONTEC program. This file describes a single demagnifying section, with a square source (the last shaping aperture), a drift section, a lens (focal length $F_m = 4.0$ mm) and a final drift section. The section ends at the shape intermediate image ($D_m = 5.67$ $\mu$m), which is applied to the projection section.
Results for the demagnifying section with and without processing of the end coordinates (PROCCO)

(NOTE: a minus sign indicates equality with the unprocessed result +/- 2 in the third decimal place)
(NOTE: a star sign indicates a warning because of reduced accuracy)

from mav02

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TABLE A7.6: Monte Carlo simulation results of the electron-electron interaction effects for the short demagnifying sections. This table presents the effects for the longer sections of table A7.4.
### Results for demagnifying sections

#### from mav05

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from mav99
Appendix A.8: INTERAC and MONTEC results for projection sections

This appendix illustrates the energy spread and trajectory displacement values found in different projection sections. In the figures the effect under consideration is plotted as a function of beam current (as in appendices A.6 and B.6). The beam current scale is thereby logarithmic. As vertical value the following values are plotted (linearly and logarithmically as indicated):

from INTERAC:

- (lin) the FWHM of the energy spread
- (lin) the $\gamma_e$ for the energy spread
- (log) the 12-88% edge width of a rectangular shape
  (this value is not always plotted)
- (log) the FWHM of a rectangular shape
- (lin) the $\gamma_e$ for the positional displacement distribution

from MONTEC:

- (lin) the FWHM of the energy spread
- (log) the FWHM of the positional displacement distribution
  (this value is taken from routine TBR).

The value for a beam current of 330 $\mu$A did not fit into the logarithmic scale of the beam current. It is therefore separately plotted. As such the slope in the graphs towards the 330 $\mu$A values do not have any meaning!

Where the vertical scales are logarithmic, these values indicate the 10-logarithm of the parameter. In that way the absolute value can easily be deduced from the graphs.
TABLE A8.1: INTERAC sample input files for the projection lens system.
FIGURE A8.2: INTERAC calculations for the projection section. Dynamic brightness mode is assumed with the brightness indicated for 330 μA. This is the short projection section, with

\[ F_p = 5.4 \text{ mm} \]

\[ \text{pav: } B = 170 \text{ A/cm}^2/\text{sr/V} \]

\[ \text{pbv: } B = 680 \text{ A/cm}^2/\text{sr/V} \]

\[ \text{pvc: } B = 850 \text{ A/cm}^2/\text{sr/V} \]
FIGURE A8.3: Same as in figure A8.2 for the long projection section with \( F_p = 30.0 \) mm,

\[
pdv: \ B_r = 170 \text{ A/cm}^2 \text{/sr/V}
\]
\[
pev: \ B_r = 680 \text{ A/cm}^2 \text{/sr/V}
\]
\[
prv: \ B_r = 850 \text{ A/cm}^2 \text{/sr/V}.
\]
TABLE A8.4: MONTEC sample input files for the projection lens system.
FIGURE A8.5: MONTEC calculations for the projection section. Dynamic brightness mode is assumed with the brightness indicated for 330 µA. This is the short projection section with \( F_p = 5.4 \) mm. The \( dR_{\text{fwhm}} \) values have been obtained from the TBR statistical processing routine.

- pav: \( B_r = 42.6 \frac{A}{cm^2/sr/V} \)
- pbv: \( B_r = 170 \frac{A}{cm^2/sr/V} \)
- pcv: \( B_r = 213 \frac{A}{cm^2/sr/V} \)
Results for projection sections
FIGURE A8.6: MONTEC calculations for the projection section. Dynamic brightness mode is assumed with the brightness indicated for 330 μA. This is the the long projection section with \( F_p = 30.0 \) mm. The \( dR_{\text{fwhm}} \) values have been obtained from the TBR statistical processing routine.

pdv: \( B_r = 170 \text{ A/cm}^2/\text{sr/V} \)
pev: \( B_r = 680 \text{ A/cm}^2/\text{sr/V} \)
pfv: \( B_r = 850 \text{ A/cm}^2/\text{sr/V} \)
Acknowledgement

I would like to thank my parents, who stimulated me in doing this research. I would very much like to thank my wife, Lidulne, for the support that she has given to me during my long hours of work. Together we lived through all the difficulties encountered in finishing this work. I would also like to thank Pim Heerens very much. Pim stimulated me in doing new and fundamental research in the areas of capacitance and electric field calculations.

The research was conducted in a pleasant working environment. For that I would like to thank all members of the Particle Optics Research group at Delft University of Technology. Especially the discussions with Karel van der Mast and Era Mulder contributed to a better understanding of the effects encountered in electron beam systems. For helping me out with the many logistics and computer problems I would especially like to thank Erik van Straten.

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