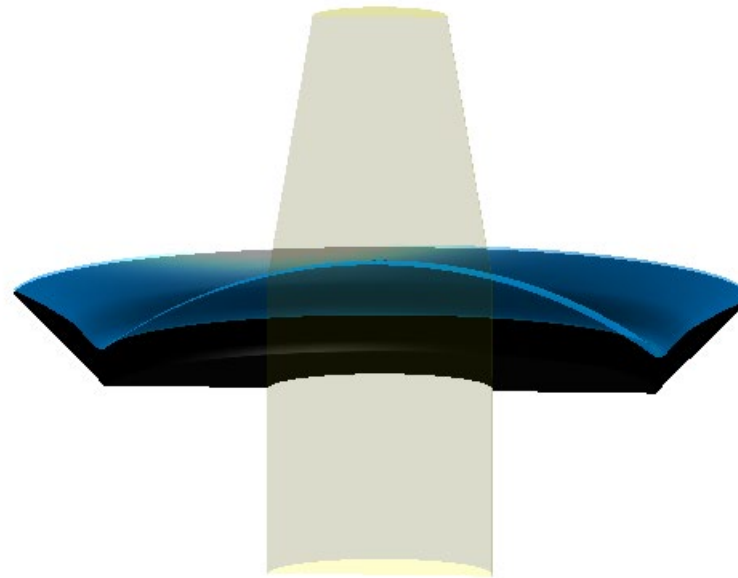
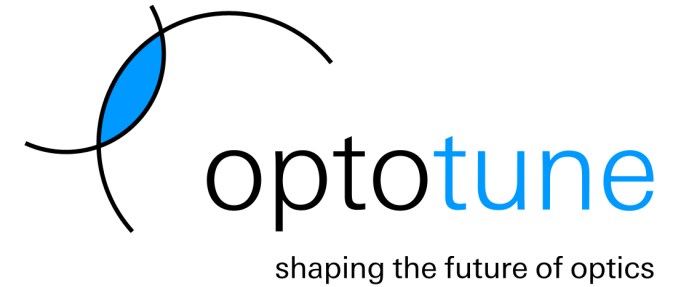


CONFIDENTIAL



Tunable Optofluidic Aperture

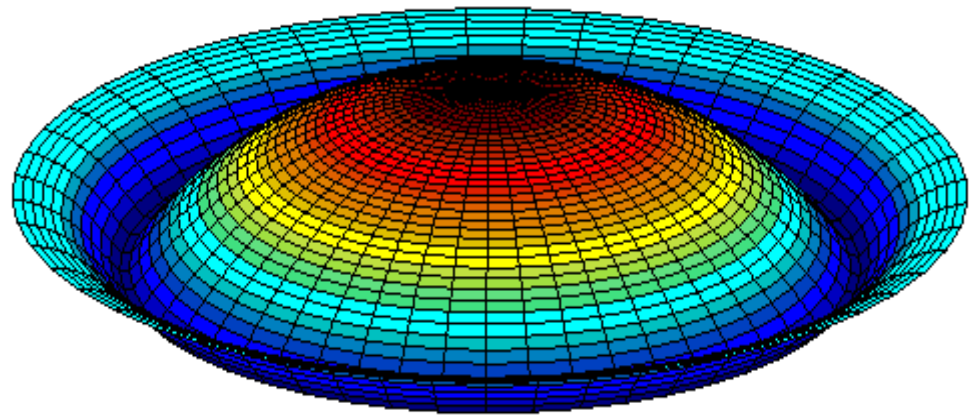
Master thesis presentation

Zürich, February 4th 2011

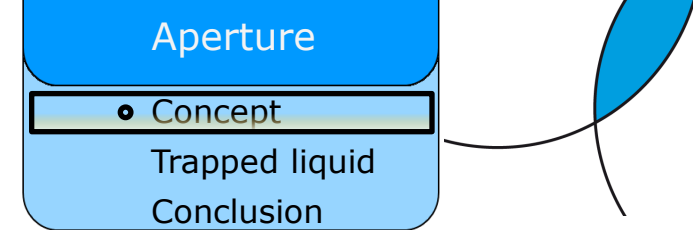
Joep Mutsaerts



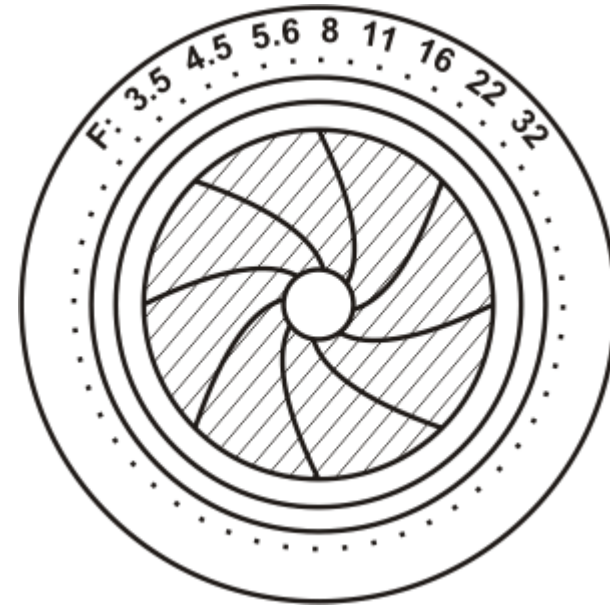
- **Tunable aperture**
 - Concept
 - Trapped liquid
 - Conclusion
- Membrane model identification
 - Experiments
 - Analysis
 - Simulations



What is a tunable aperture?



- Most common: Leaflet structure
- Control of:
 - Light
 - Depth of Field
 - Optical quality
 - F number



What is a tunable aperture?

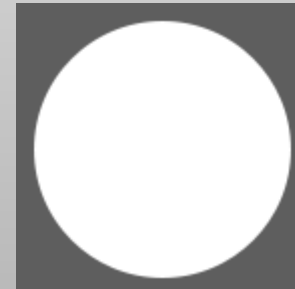
| |
|----------------|
| Aperture |
| • Concept |
| Trapped liquid |
| Conclusion |



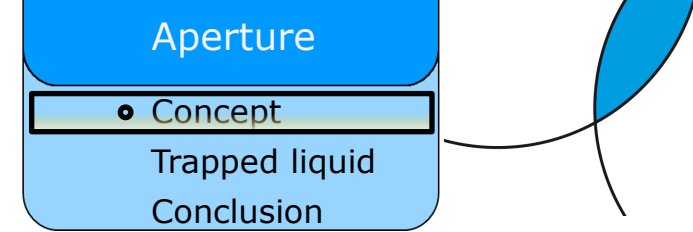
f/32 – slow shutter



f/5.6 – fast shutter



Why create a tunable aperture?

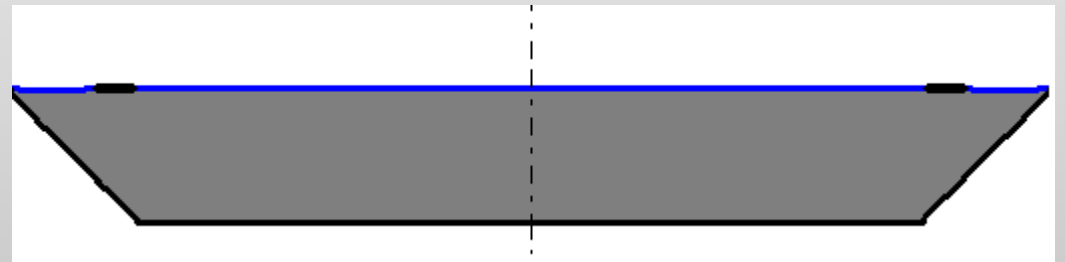
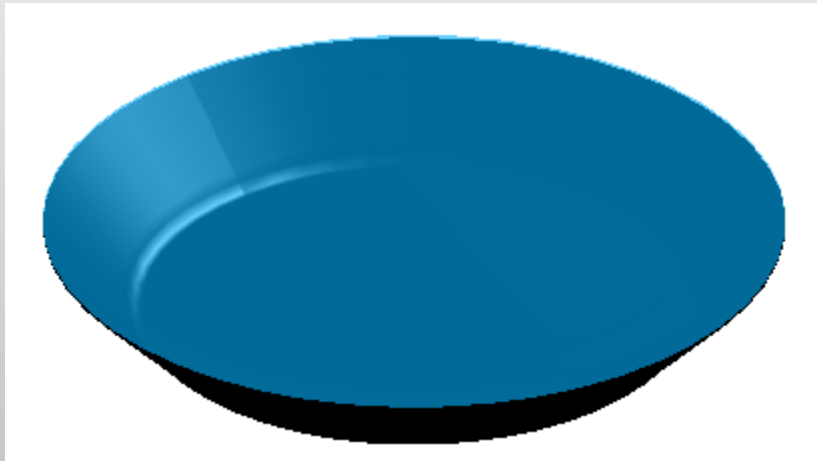


- Optical quality in mobile phone market
- Small size
- Low part count
- Available design



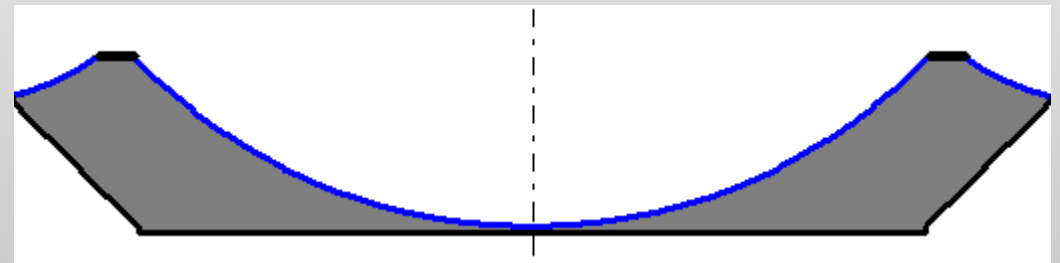
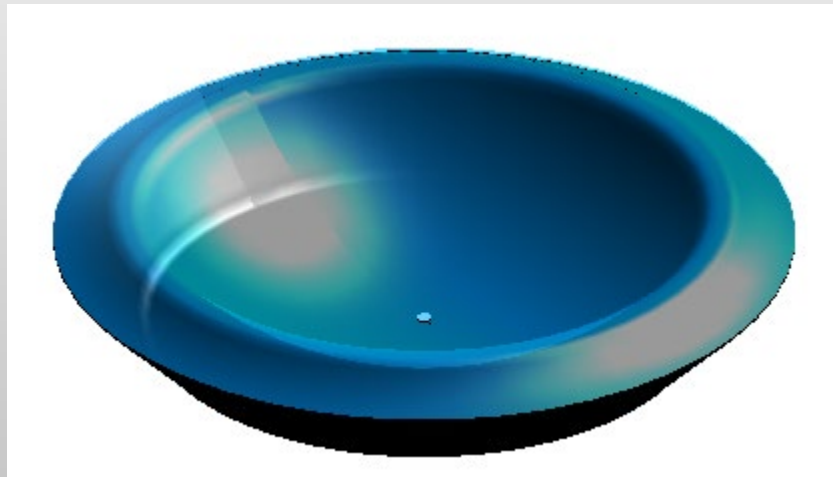
Aperture design

| |
|----------------|
| Aperture |
| • Concept |
| Trapped liquid |
| Conclusion |



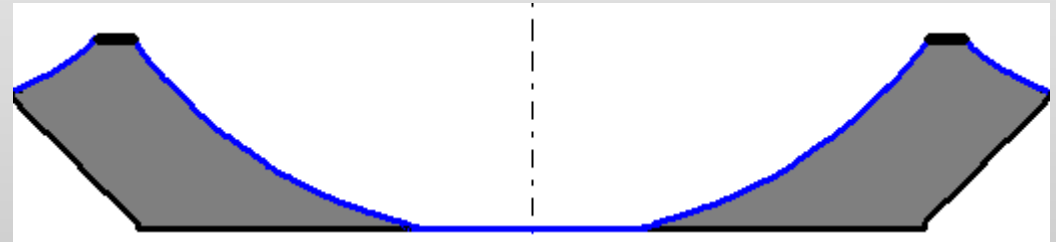
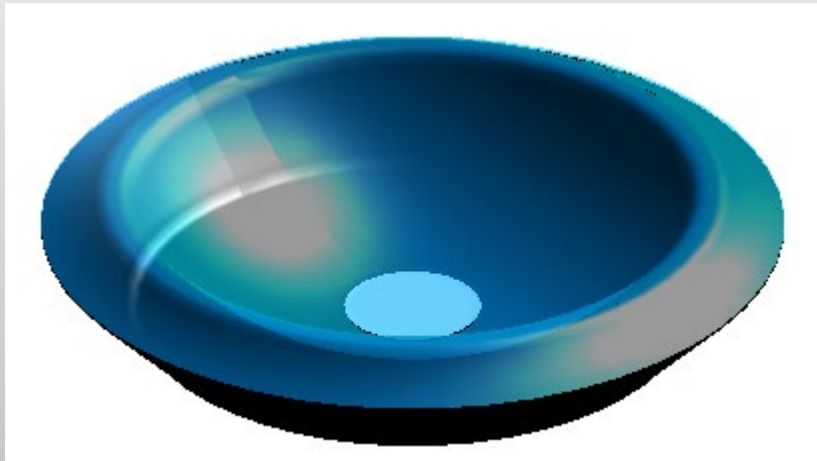
Aperture design

| |
|----------------|
| Aperture |
| • Concept |
| Trapped liquid |
| Conclusion |



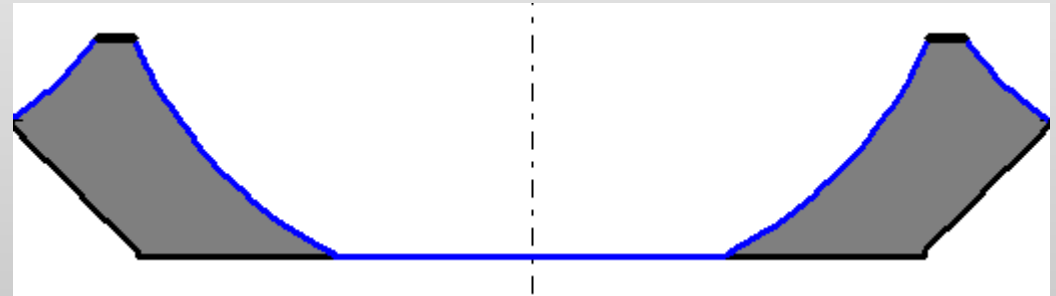
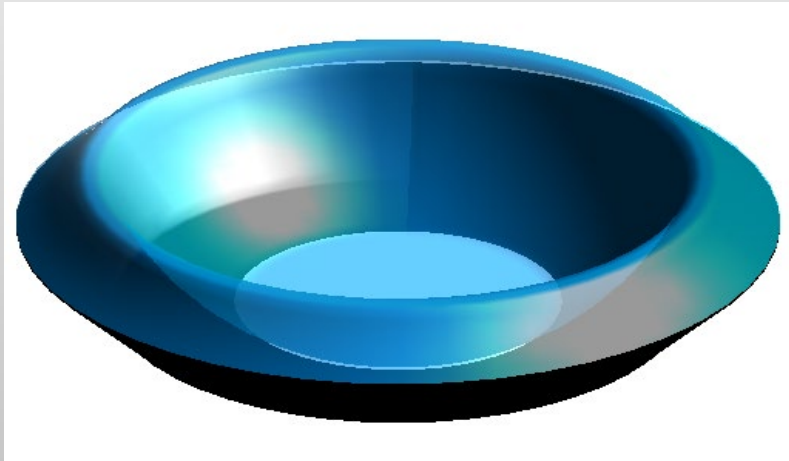
Aperture design

| |
|----------------|
| Aperture |
| • Concept |
| Trapped liquid |
| Conclusion |

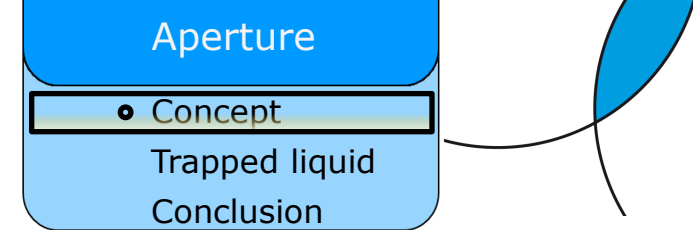


Aperture design

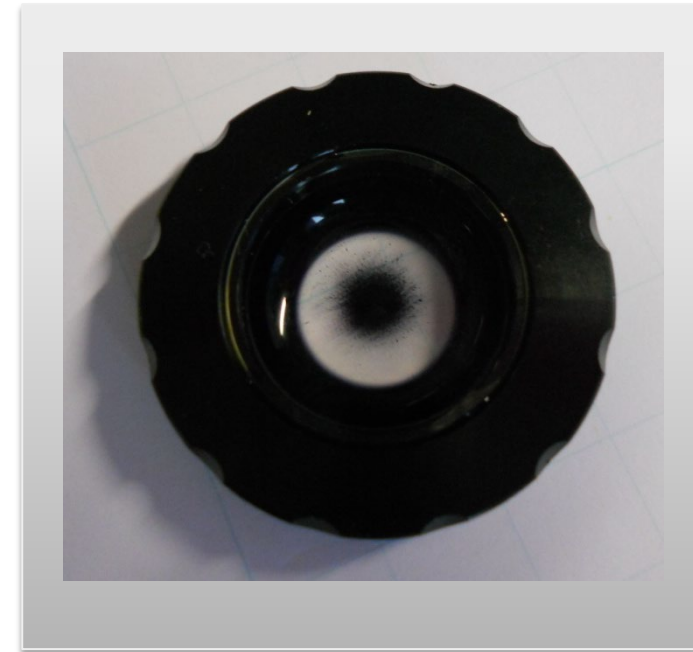
| |
|----------------|
| Aperture |
| • Concept |
| Trapped liquid |
| Conclusion |



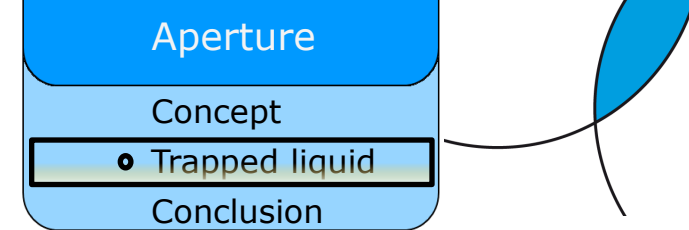
ML Demonstrator 1



- Trapped fluid problem
 - Spot depends on speed
- Identified possible causes
 - Particle size
 - Concentration

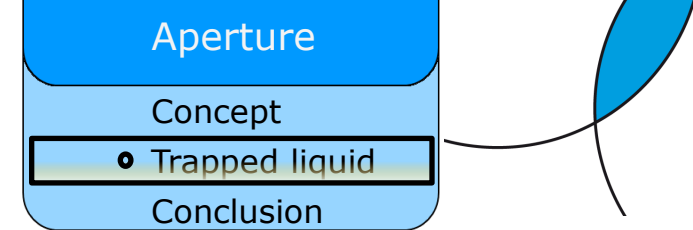


“trapped fluid” analysis



| Possible solution | Argument pro | Contra |
|---------------------|------------------|--------|
| Low concentration | Less aggregation | |
| Small particle size | Less aggregation | |
| | | |
| | | |
| | | |
| | | |



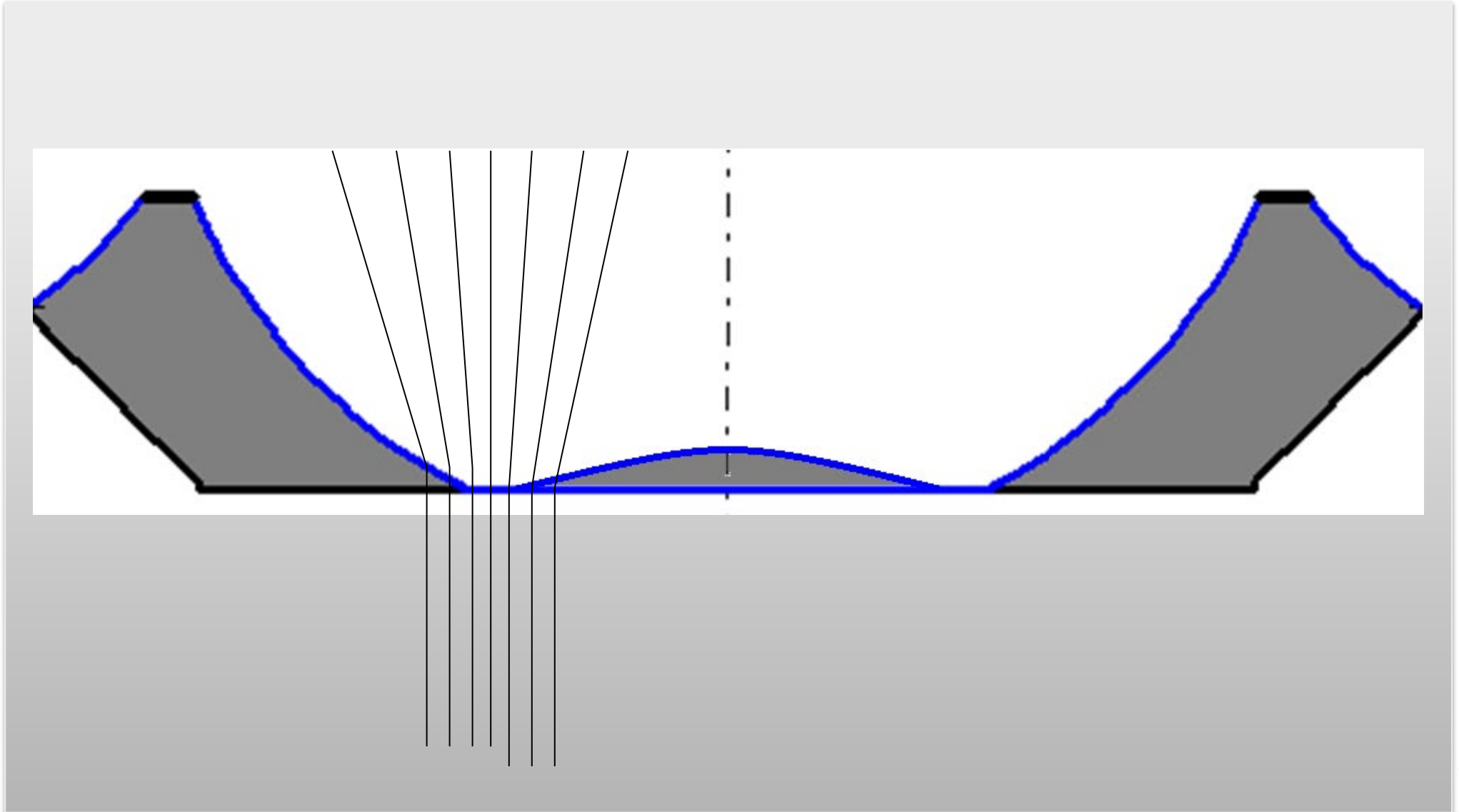


- Goal: test lower concentration, filtered particles ($< 1 \mu\text{m}$)
- Aperture seems clear, but:
 - Lens effect caused by remaining fluid
 - Optical quality depends on speed
 - Lens effect on aperture edge
- Identified possible solution
 - Surface tension
 - Coated glass

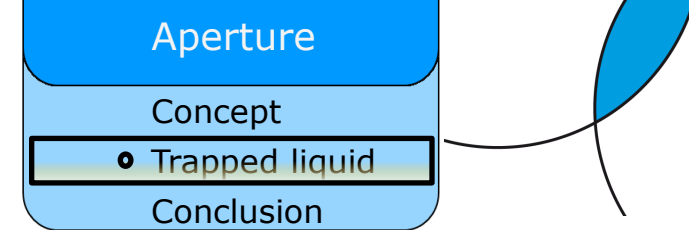


Lens effect

| |
|------------------|
| Aperture |
| Concept |
| • Trapped liquid |
| Conclusion |



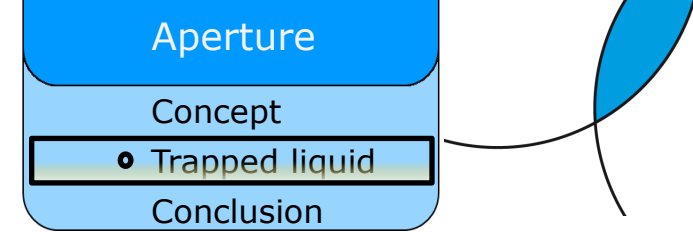
"trapped fluid" analysis



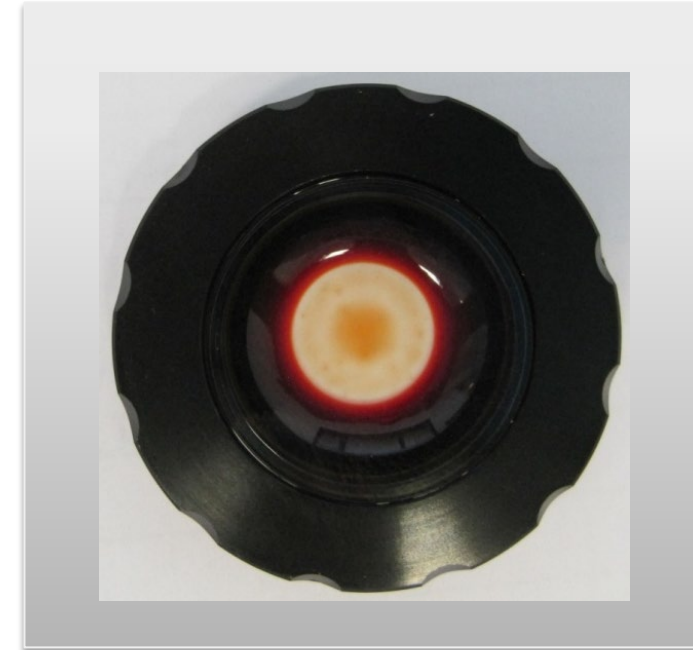
| Possible solution | Argument pro | Contra |
|----------------------|------------------|--------------------------|
| Low concentration | Less aggregation | Lens effect in soft edge |
| Small particle size | Less aggregation | Lens effect in soft edge |
| High surface tension | Less wetting | |
| Glass coating | Less wetting | |
| | | |
| | | |



ML Demonstrator 3



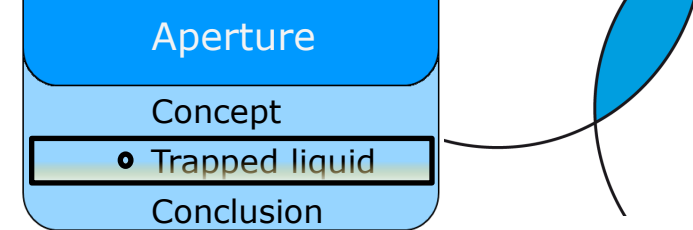
- Goal: Test influence of
 - Surface tension of water
 - Glass silicon coating
- Trapped fluid problem
 - High surface tension is not enough
 - Speed dependent
- Identified possible solution
 - Increase contact angle



| Fluid | Surface Tension |
|---------|-----------------|
| Mercury | 470 |
| Water | 73 |
| | << 60 |



"trapped fluid" analysis



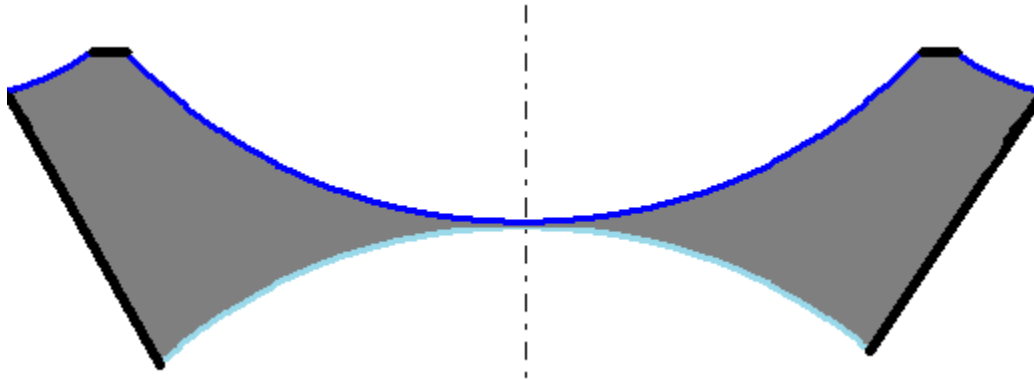
| Possible solution | Argument pro | Contra |
|----------------------|---------------------|--------------------------|
| Low concentration | Less aggregation | Lens effect in soft edge |
| Small particle size | Less aggregation | Lens effect in soft edge |
| High surface tension | Less wetting | Does not solve problem |
| Glass coating | Less wetting | Does not solve problem |
| Contact angle | Less wetting | |
| | | |



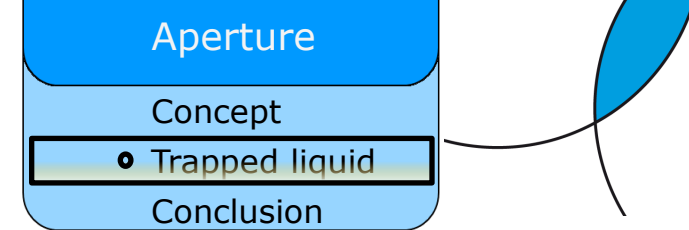
ML Demonstrator 4

| |
|------------------|
| Aperture |
| Concept |
| • Trapped liquid |
| Conclusion |

- Goal: test influence of contact angle
- Trapped fluid problem
 - Soft edge with lens effect



“trapped fluid” analysis



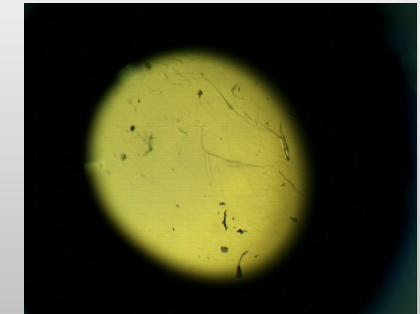
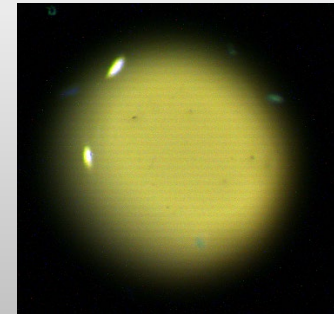
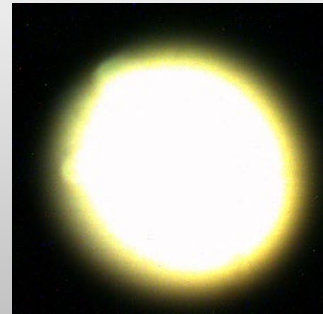
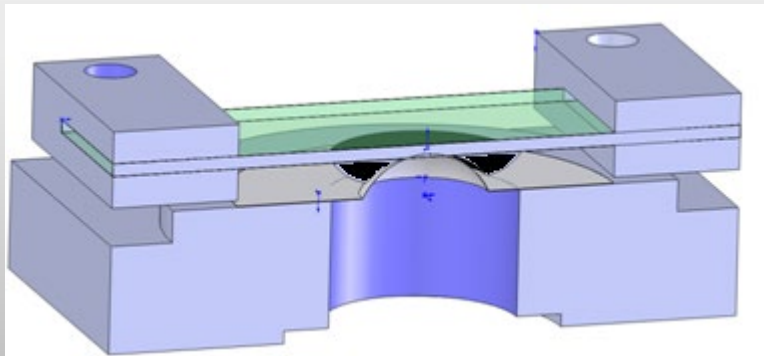
| Possible solution | Argument pro | Contra |
|--------------------------|---------------------------------|--------------------------|
| Low concentration | Less aggregation | Lens effect in soft edge |
| Small particle size | Less aggregation | Lens effect in soft edge |
| High surface tension | Less wetting | Does not solve problem |
| Glass coating | Less wetting | Does not solve problem |
| Contact angle | Less wetting | Does not solve problem |
| Positive pressure | Force pushes liquid away | |
| | | |



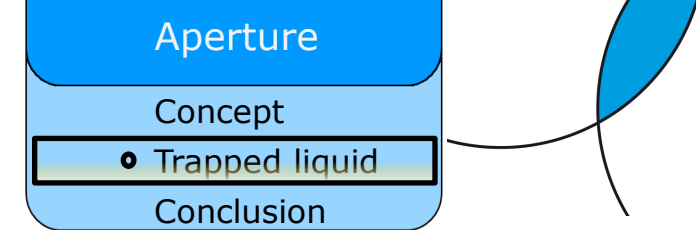
Positive Pressure Test

| |
|------------------|
| Aperture |
| Concept |
| • Trapped liquid |
| Conclusion |

- Air pressurized bulge pushes fluid away.
- Particles $< 5\mu\text{m}$: Clear aperture result but soft edge
- Particles $> 5\mu\text{m}$: trapped fluid problem



"trapped fluid" analysis



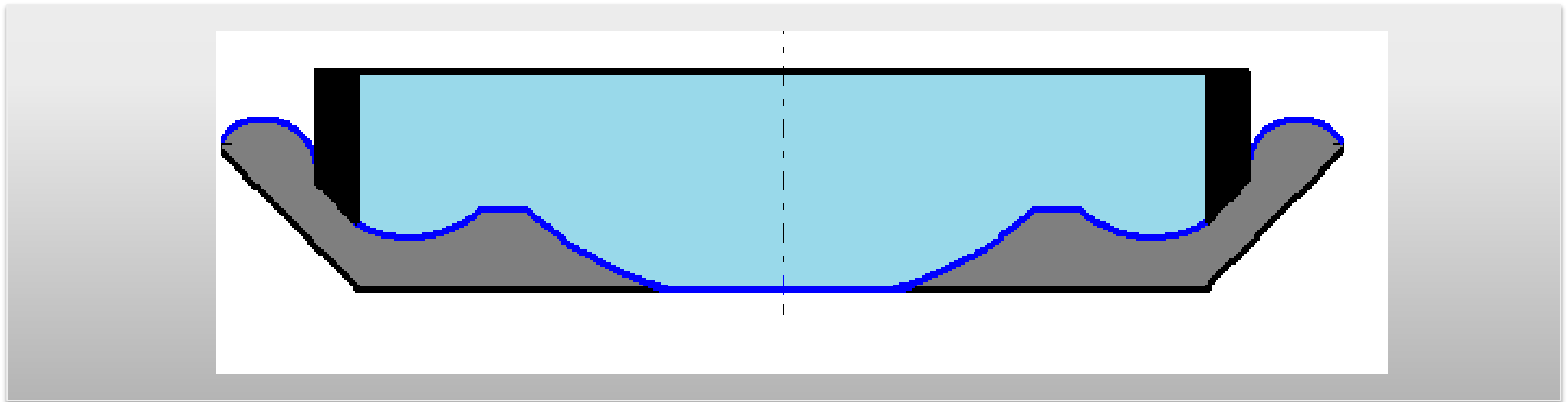
| Possible solution | Argument pro | Contra |
|----------------------|--------------------------|--------------------------|
| Low concentration | Less aggregation | Lens effect in soft edge |
| Small particle size | Less aggregation | Lens effect in soft edge |
| High surface tension | Less wetting | Does not solve problem |
| Glass coating | Less wetting | Does not solve problem |
| Contact angle | Less wetting | Does not solve problem |
| Positive pressure | Force pushes liquid away | Potential Solution |



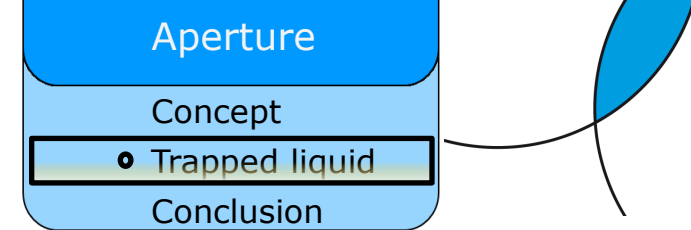
Double liquid positive pressure prototype

| |
|------------------|
| Aperture |
| Concept |
| • Trapped liquid |
| Conclusion |

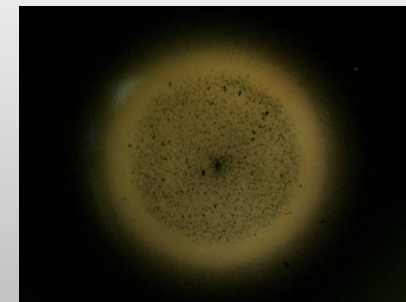
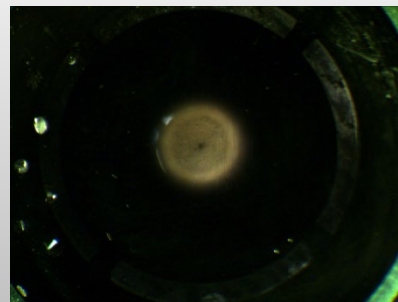
- Optotune lens design with two liquid compartments



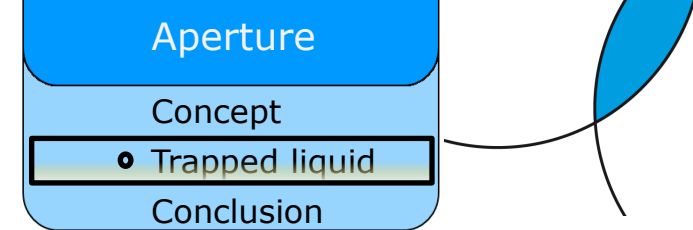
Double liquid positive pressure prototype



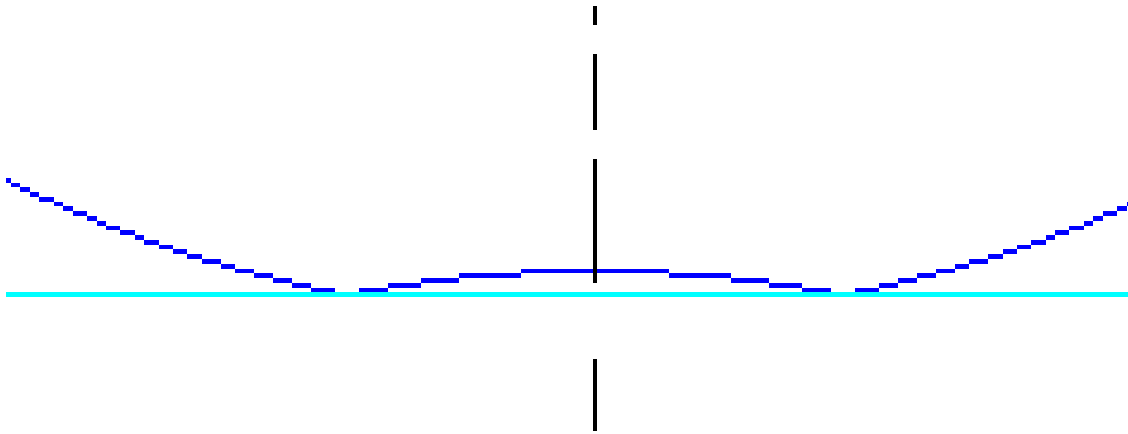
- Prototype results: trapped fluid appears again (speed dependent)
- Over time, pigments migrate through membrane into transparent fluid
- Particles were not filtered small enough



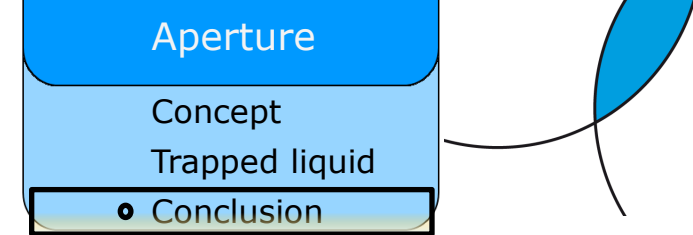
Feasibility of concept



- Use transparent fluid
- Is concept pigment dependent?



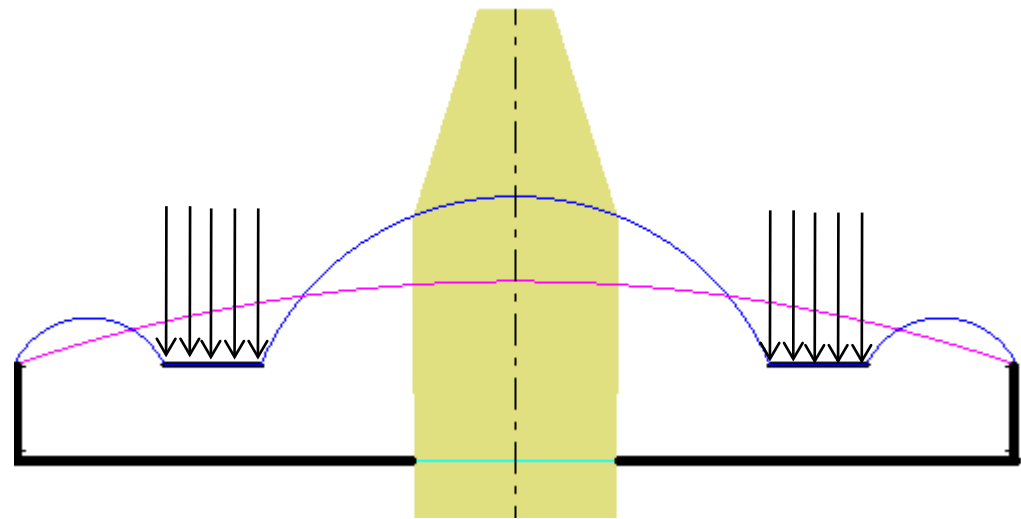
Aperture: Conclusions and Outlook



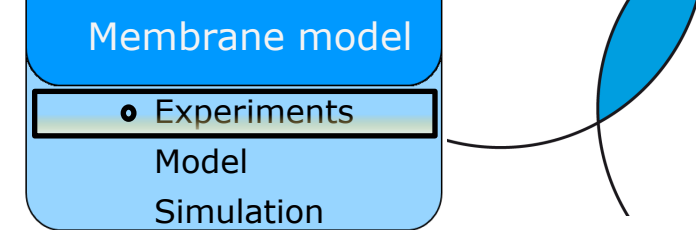
- Trapped fluid problem has not been solved
 - Surface profile of transparent lens should be measured
 - Particle size and concentration play a large role
- Lens effect can be solved by double fluid
 - Bigger and more complicated to produce
 - Pigments leak through the membrane
- Feasibility study advises to put the project on hold
 - Uncertainty of product quality and costs
 - *Not the lowest hanging fruit*



- Tunable aperture
 - Concept
 - Trapped liquid
 - Conclusion
- **Membrane model identification**
 - Experiments
 - Analysis
 - Simulations



Membrane model identification



Input: Membrane

- Material SE0904
- t Thickness
- ε_0 Prestrain
- r Aperture radius
- p Pressure

Process: Model

- Bulge test results
- Linear model
- Mooney Rivlin model

Output: Deflection

- Center
- Ring
- Visualisation tool

Membrane model identification

Membrane model

• Experiments

Model

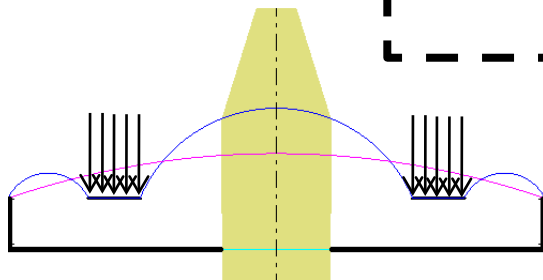
Simulation

Actuation force

Pressure

Deflection

Focal length



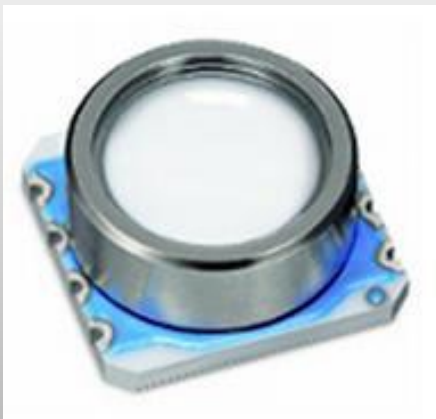
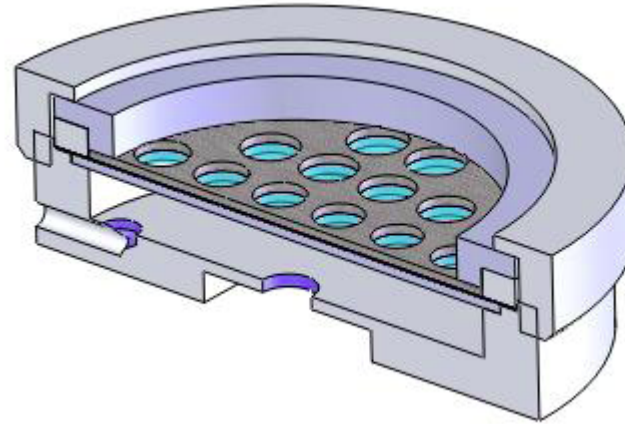
Design of experiment

Membrane model

• Experiments

Model

Simulation



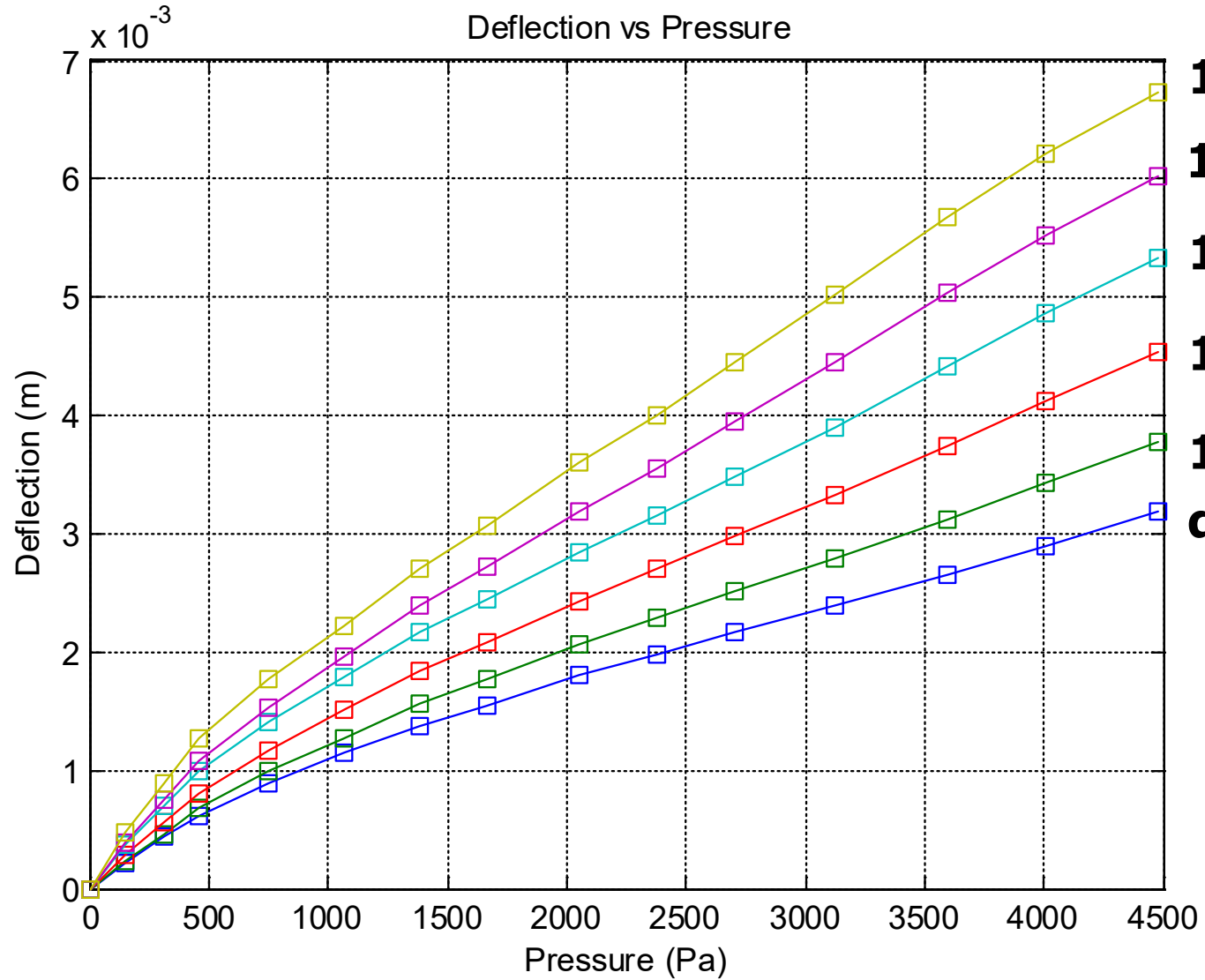
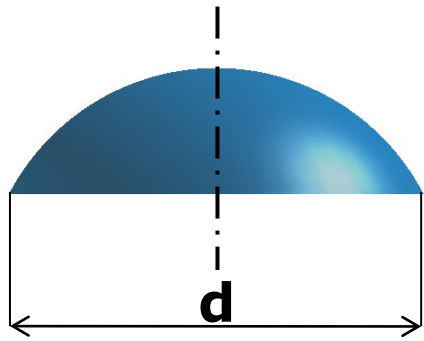
Deflection versus pressure - radius

Membrane model

● Experiments

Model

Simulation



15

14

13

12

11

d = 10 mm

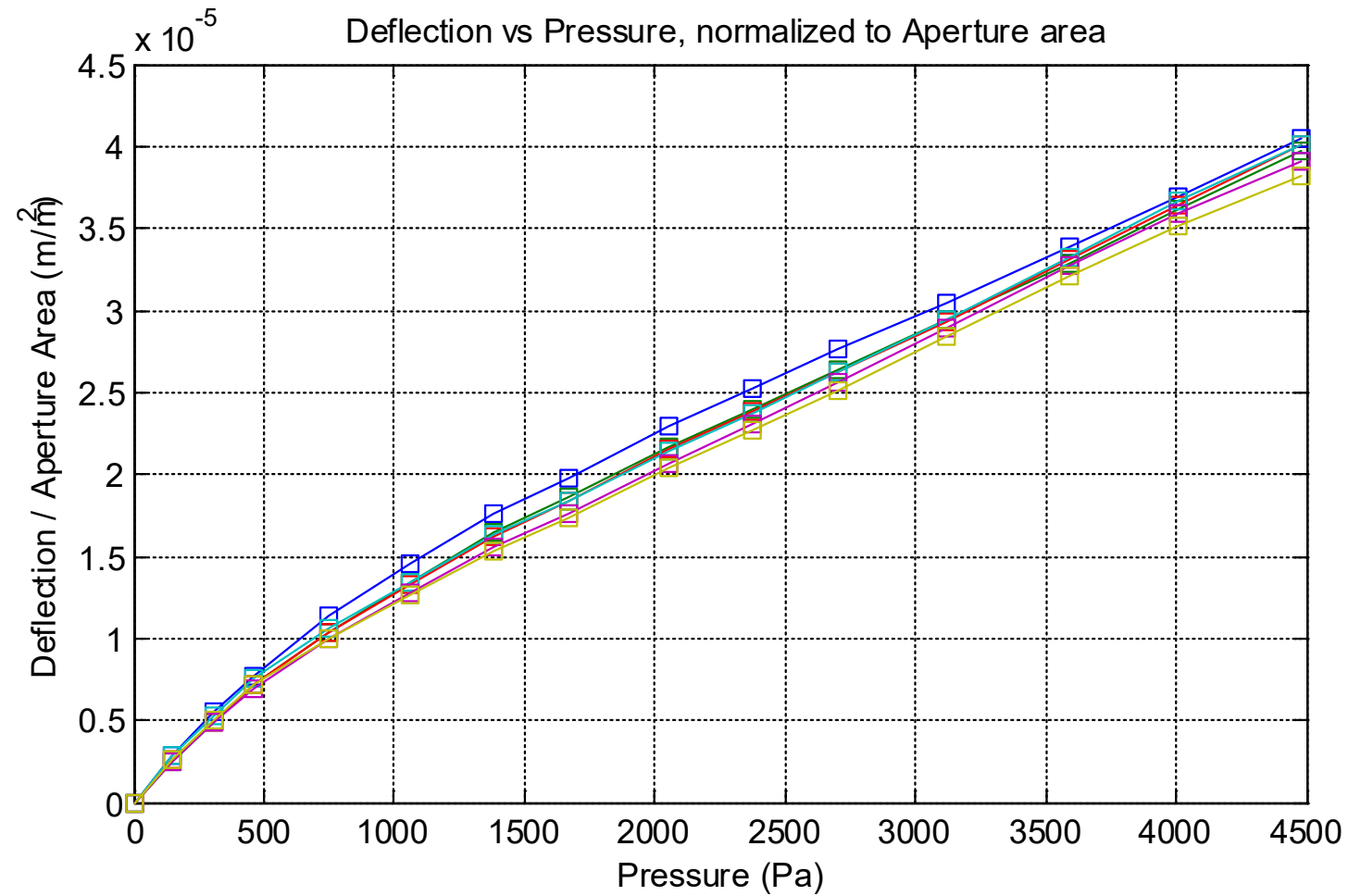
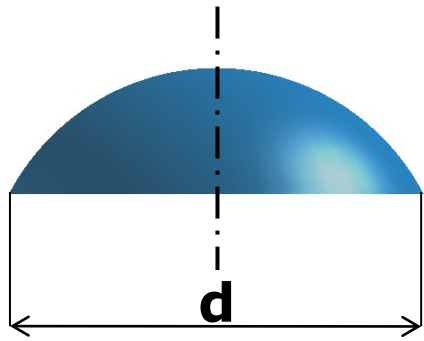
Deflection versus pressure - radius

Membrane model

● Experiments

Model

Simulation



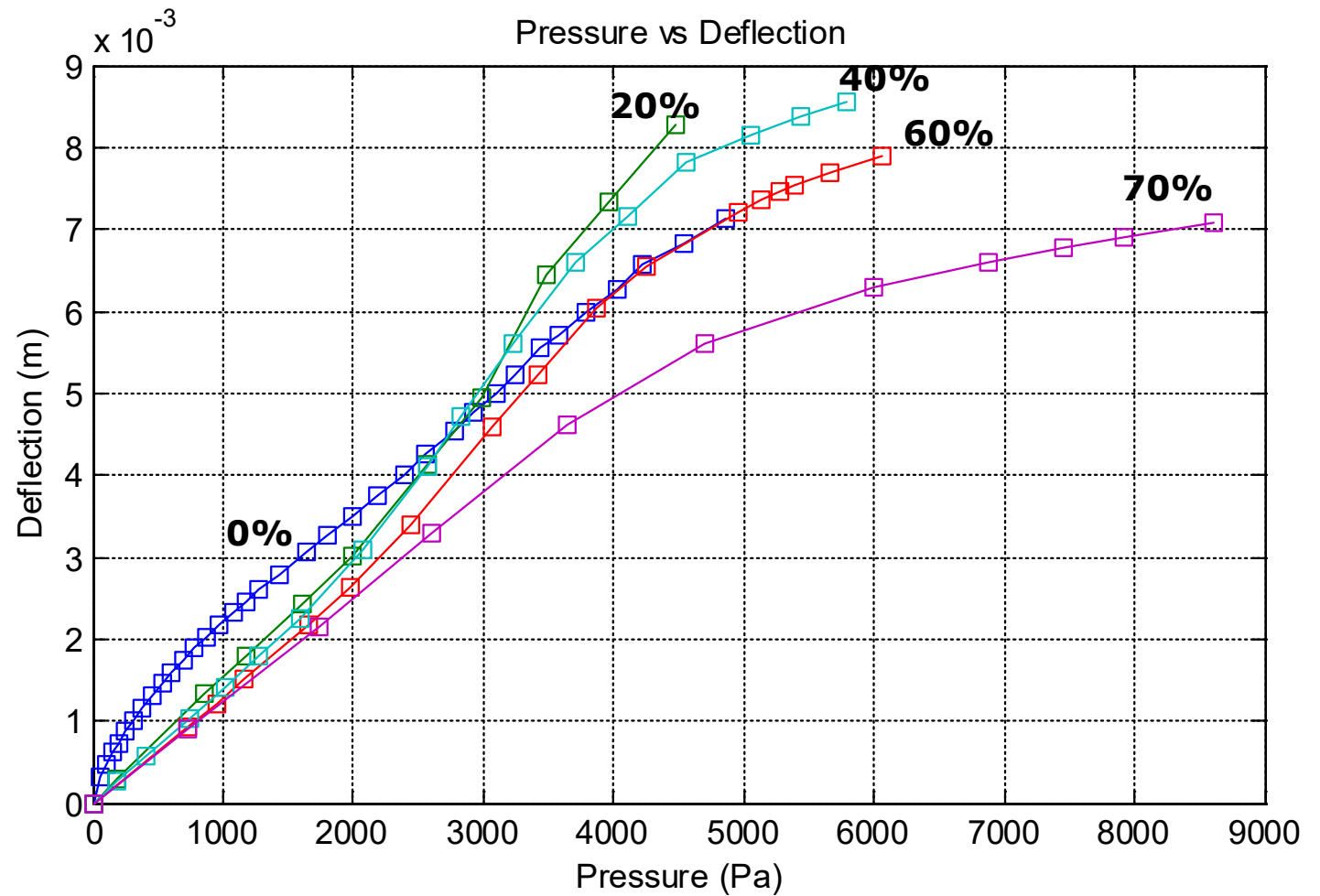
Deflection versus pressure - Prestrain

Membrane model

● Experiments

Model

Simulation



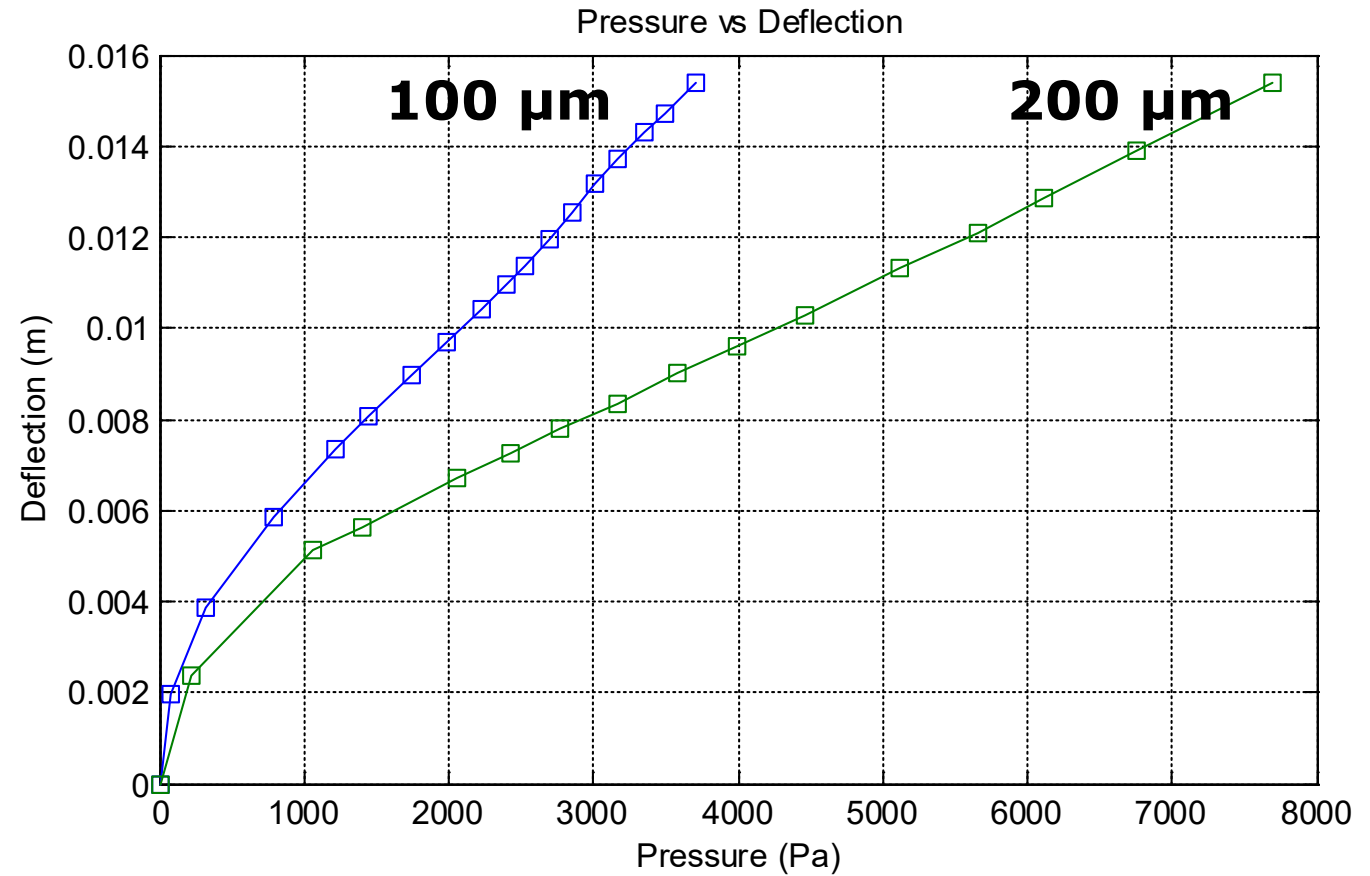
Deflection versus pressure - Thickness

Membrane model

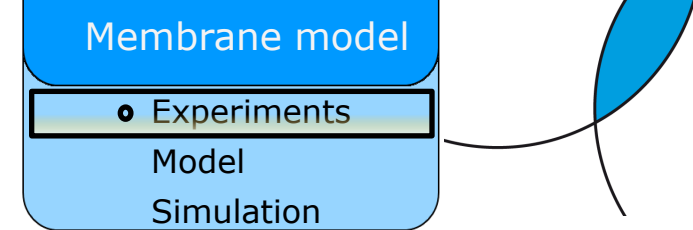
● Experiments

Model

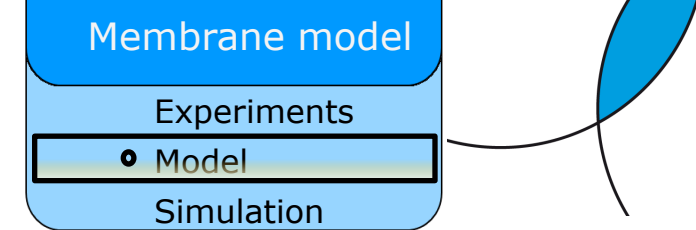
Simulation



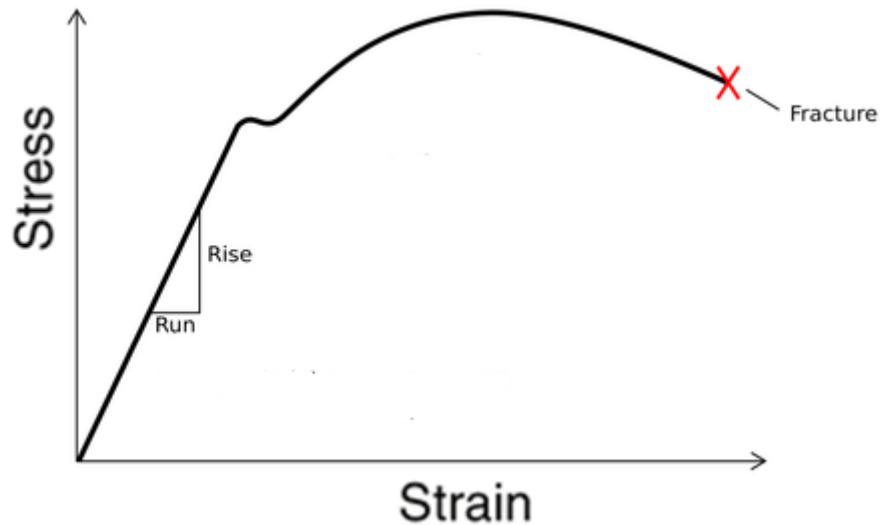
Measurements statistics



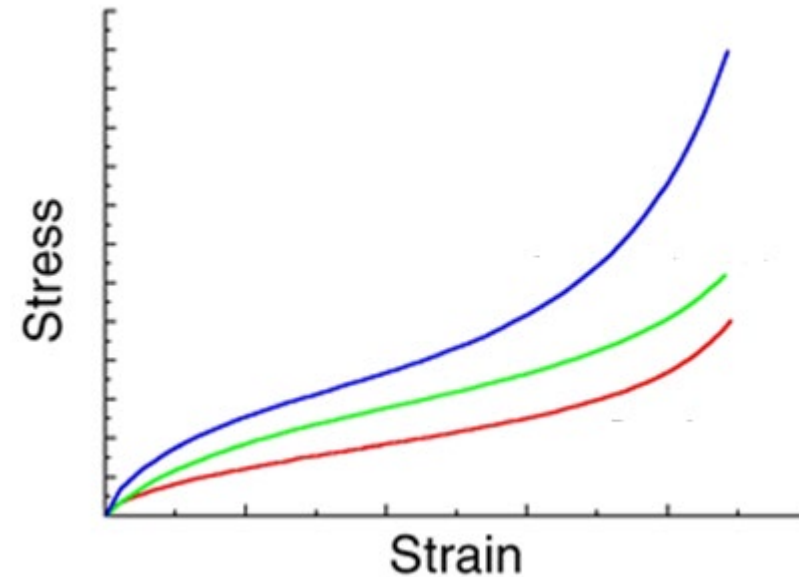
- 148 bulge measurements done
- Thickness 10 – 200 μm
- Radius 5 – 40 mm
- Pressure 0 – 30000 Pa



Isotropic – constant Youngs



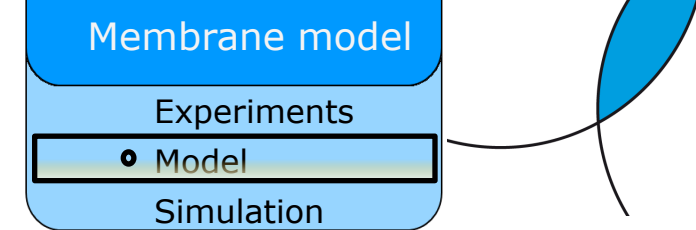
Non Isotropic – variable Youngs



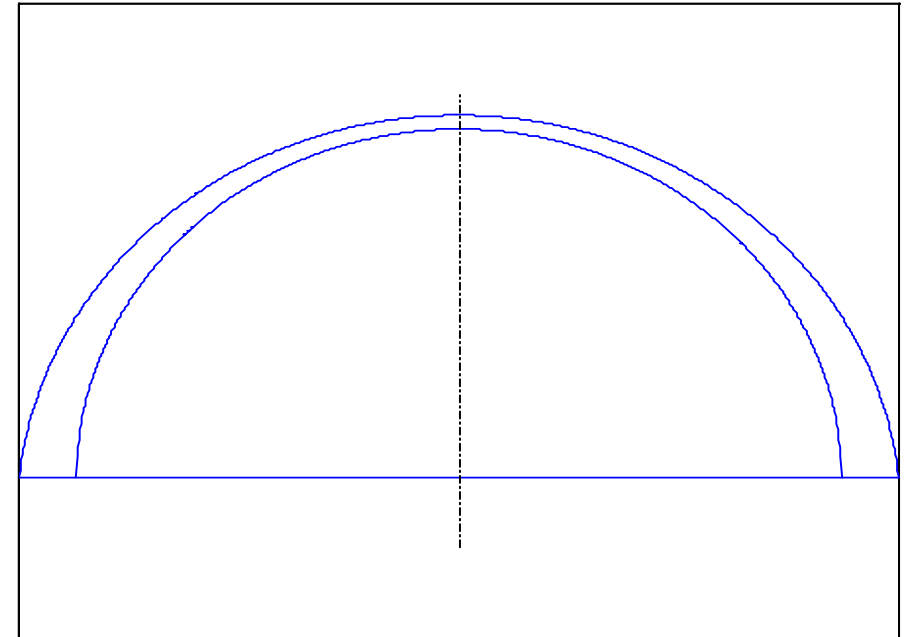
Further challenges

- Bulge loading
- Material model might change

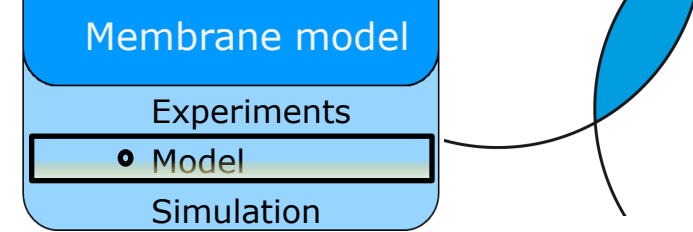
Bulge loading



- Thickness not constant
- Thickness proportional to stretch
- Where to measure thickness / stretch?



Stress calculation



- 'Math slide'

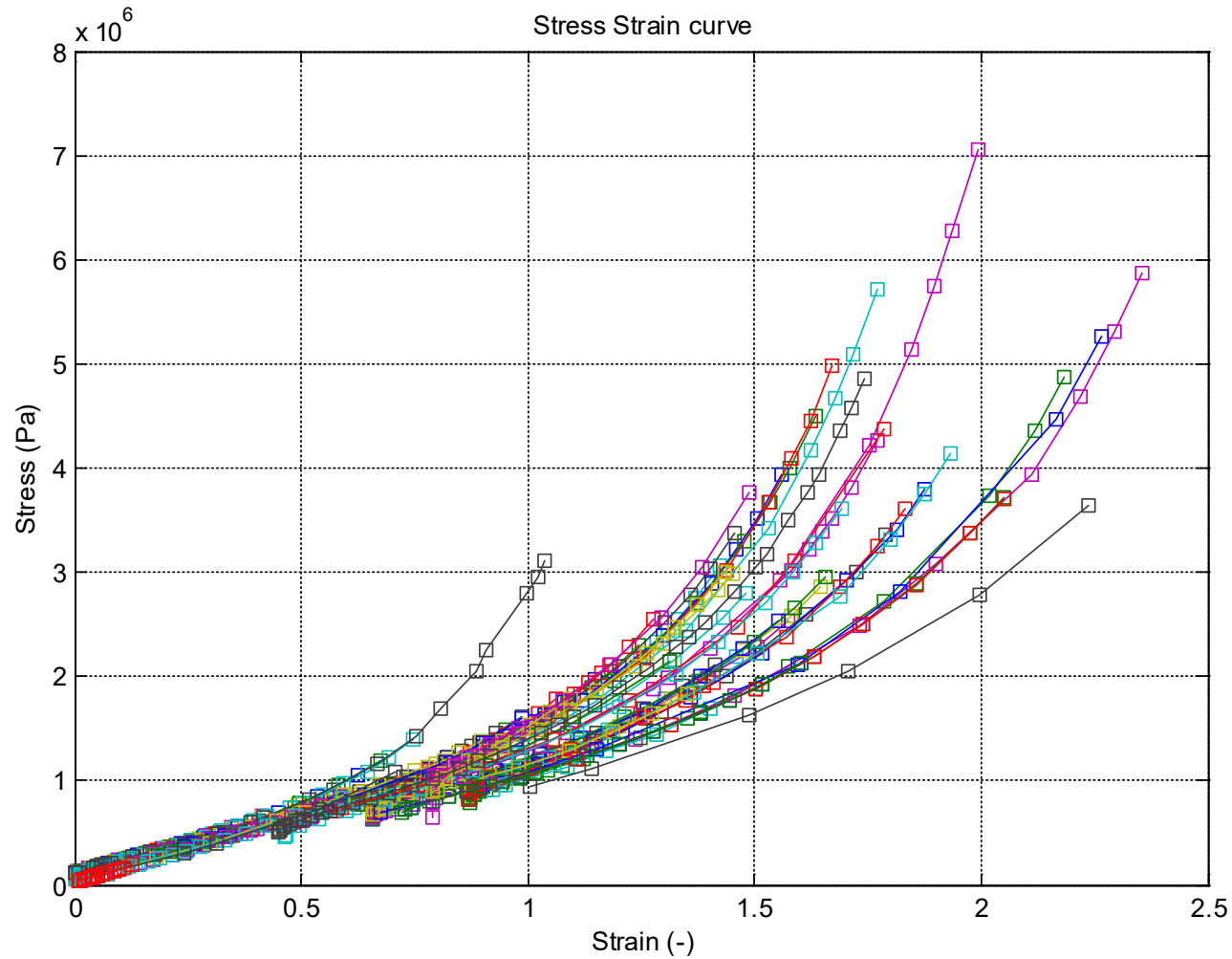
Stress Strain calculated

Membrane model

Experiments

● Model

Simulation



$$\lambda_p = \lambda_{pre} \lambda_{meas}$$

Stress strain fit

Membrane model

Experiments

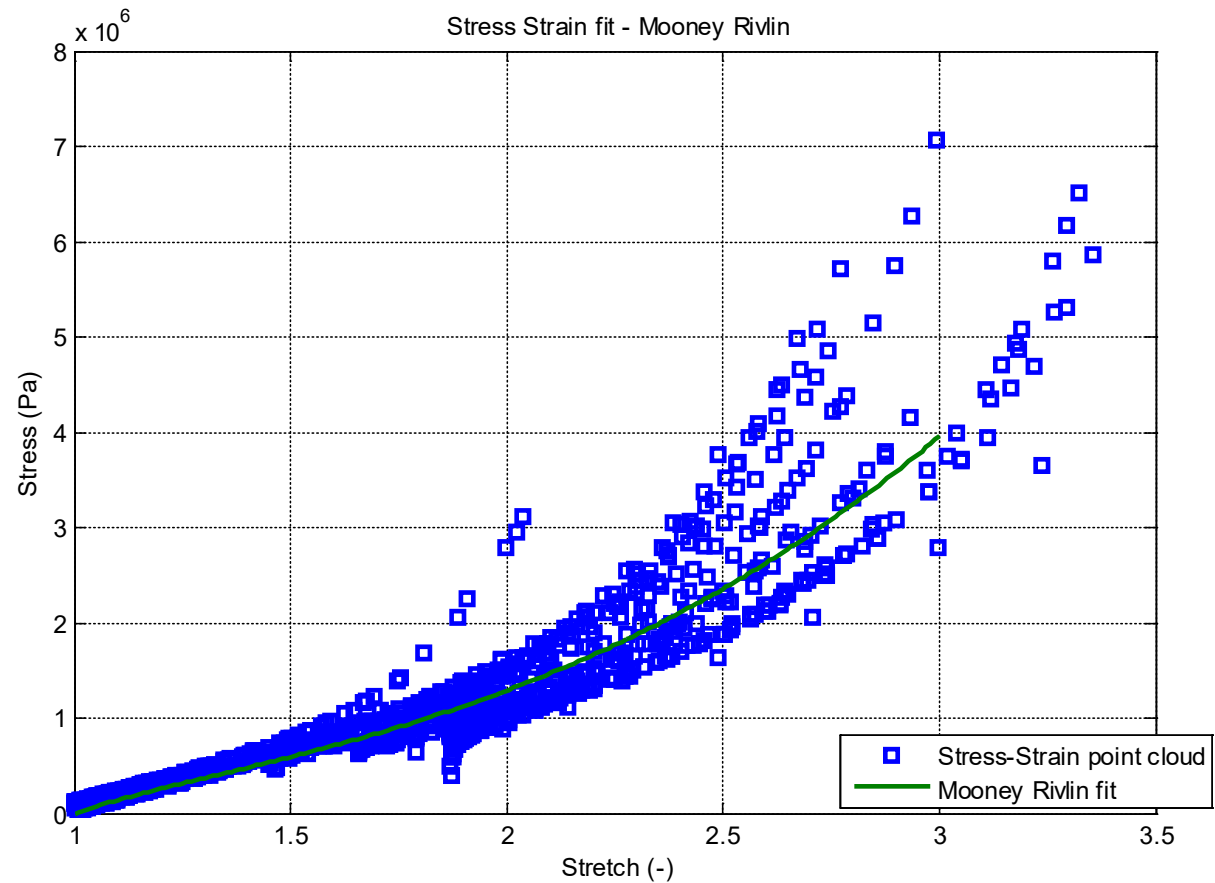
● Model

Simulation

$C_{10} = 210400 \text{ Pa}$

$C_{01} = 16005 \text{ Pa}$

$$\sigma_{MR} = c_{10} * (\lambda^2 - \lambda^{-4}) - c_{01} * (\lambda^{-2} - \lambda^4)$$



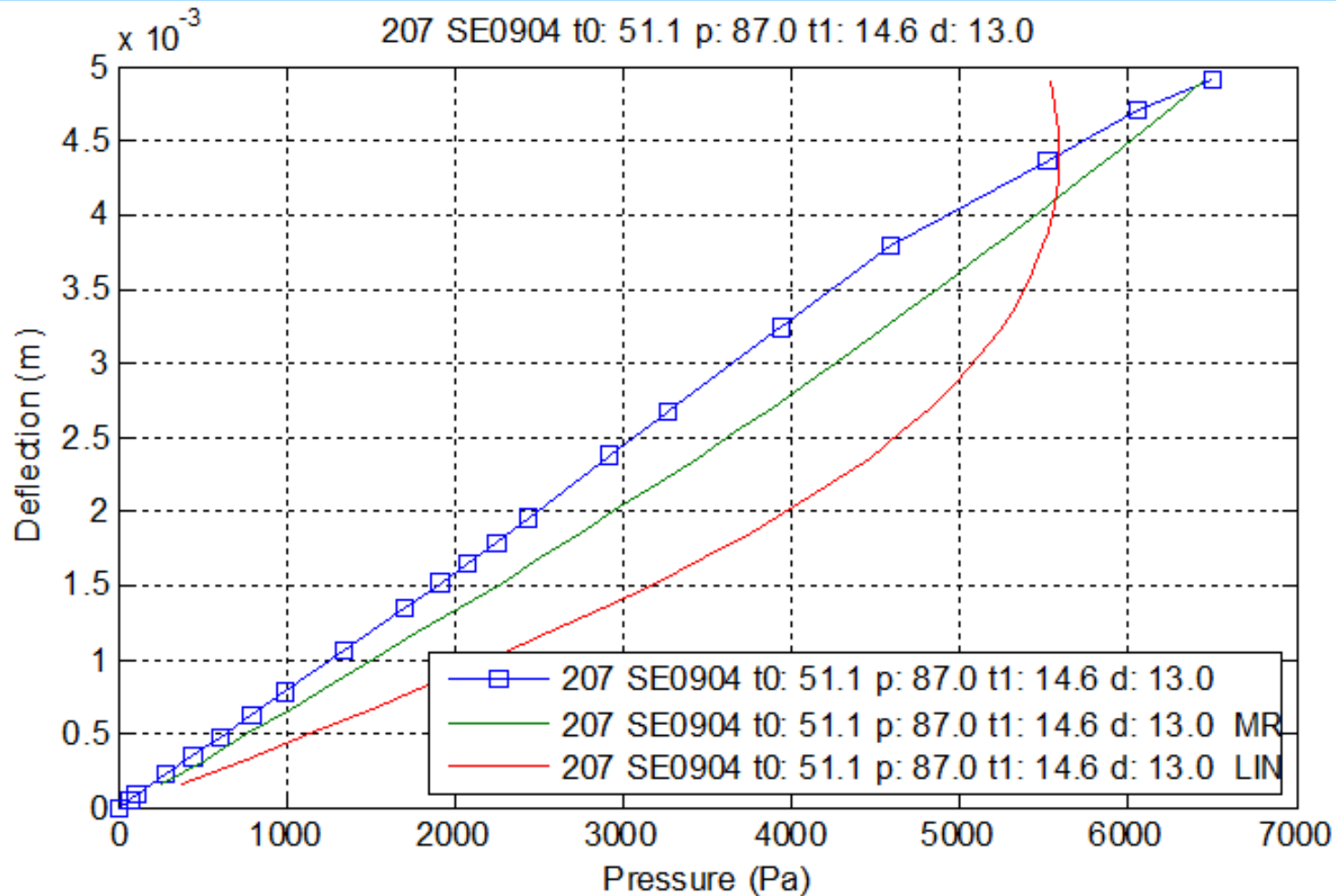
Deflection versus Pressure - Simulation

Membrane model

Experiments

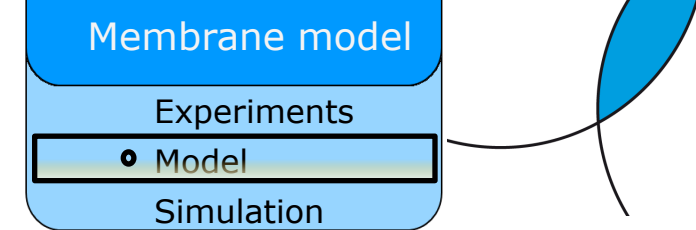
Model

• Simulation



| Error model | RMS |
|---------------|--------|
| Mooney Rivlin | 0.0549 |
| Linear model | 0.1146 |

Membrane model identification



Input: Membrane

- Material SE0904
- t Thickness
- ε_0 Prestrain
- r Aperture radius
- p Pressure

Process: Model

- Bulge test results
- Linear model
- Mooney Rivlin model

Output: Deflection

- Center
- Ring
- **Visualisation tool**

Shape Predictor

Membrane model

Experiments

Model

• Simulation

shape_calculator

File Tools Display Help

Use this tool to make a custom shape and calculate properties as volume, pressure, focal length etc. Go to Help section for explanation of symbols.

Current shape: ML-2000

One lensshaper: One lensshaper

Linear Model: Linear Model

Select a field to edit:

| | Field | Value |
|----|--------|-------------|
| 1 | r_a | 0.0101 |
| 2 | d_s | 9.0000e-04 |
| 3 | r_c | 0.0132 |
| 4 | h_t | -3.8690e-04 |
| 5 | h_u | 6.1310e-04 |
| 6 | s | -1.3317e-04 |
| 7 | V_o | -0.0013 |
| 8 | d | 5.0000e-05 |
| 9 | pre | 0 |
| 10 | Y | 2100000 |
| 11 | depth | 0.0034 |
| 12 | n_refr | 1.5588 |
| 13 | z_2 | -2.0065e-05 |
| 14 | s_max | 1.0000e-03 |
| 15 | s_min | -0.0012 |

Select a shape:

| | Name |
|----|--------------------|
| 1 | -ML-2000 |
| 2 | CL1 |
| 3 | pressure_ring_test |
| 4 | high_angle |
| 5 | ZL2000-top |
| 6 | ZL2000-bottom |
| 7 | two_liquids_2 |
| 8 | ML-2000_two_1 |
| 9 | Bare Lens |
| 10 | ML-2000_two_2 |
| 11 | Lukas |
| 12 | stress |

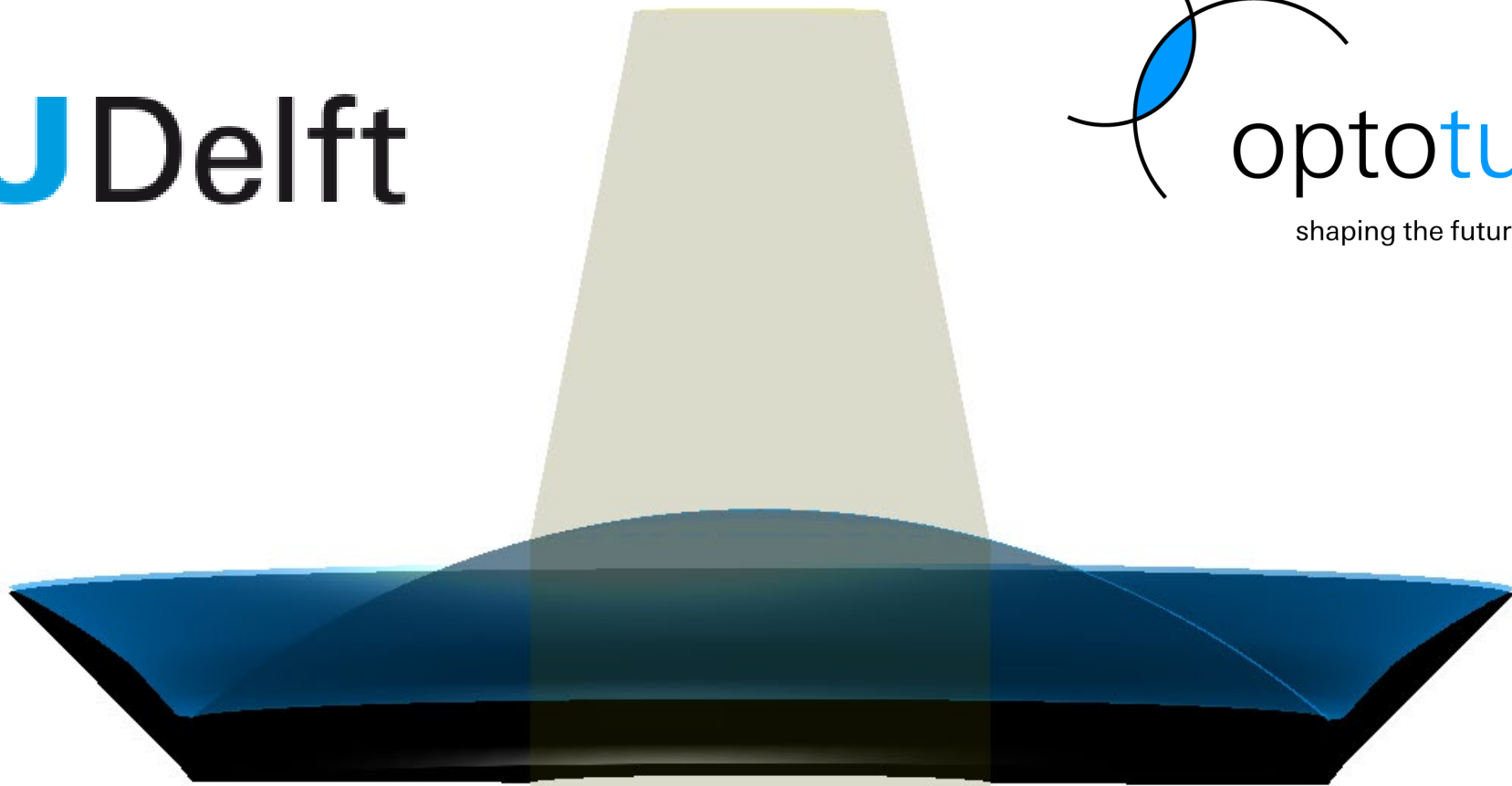
Calculated results:

| | | |
|-----------------|---------|-----------------|
| Fluid Volume | 1100.01 | mm ³ |
| Fill Volume | -347.47 | mm ³ |
| Depth Volume | 1447.47 | mm ³ |
| Bulge height | -1.72 | mm |
| Bulge radius | 30.54 | mm |
| Stretch | 5.48 | % |
| Pressure | -1.12 | mBar |
| Bobbin area | 102.28 | mm ² |
| Bobbin force | -11.44 | mN |
| Bobbin current | -4.25 | mA |
| Aperture radius | 0.00 | mm |
| Focal length | -54.65 | mm |
| CL Focal len | 0.00 | mm |

optotune
shaping the future of optics

This information is confidential to Optotune and is not to be copied or forwarded to any 3rd party without our prior written consent.

CONFIDENTIAL



Tunable Optofluidic Aperture

Master thesis presentation

Zürich, February 4th 2011

Joep Mutsaerts