CHAMP⁺: a powerful array receiver for APEX

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ABSTRACT

CHAMP⁺, a dual-color 2×7 element heterodyne array for operation in the 450 μm and 350 μm atmospheric windows is under development. The instrument, which is currently undergoing final evaluation in the laboratories, will be deployed for commissioning at the APEX telescope in August this year.

With its state-of-the-art SIS detectors and wide tunable local oscillators, its cold optics with SSB filters and with 2 GHz of usable IF bandwidth per pixel, CHAMP⁺ will provide unmatched observing capabilities for the APEX community. The optics allows for simultaneous observations in both colors. For both sub-arrays a hexagonal arrangement with closest feasible spacing of the pixels on sky ($2 \cdot \Theta_{\text{mb}}$) was chosen, which, in scanning mode, will provide data sampled with half-beam spacing. The front-end is connected to a flexible autocorrelator array with a total bandwidth of 32 GHz and 32768 spectral channels, subdivided into 32 IF bands of 1 GHz and 1024 channels each.

Keywords: submillimeter array receivers, heterodyne array

1. INTRODUCTION

Located at 5107 m altitude on Llano de Chajnantor in the Chilean High Andes, on what is considered one of the world's outstanding sites for submillimeter astronomy, the Atacama Pathfinder Experiment (APEX, see Güsten et al.^{[6][7]} for a description of the facility) offers unique atmospheric conditions: from the ALMA site characterization and excluding the Bolivian winter, the 50 and 25% quartile columns of precipitable water (PWV) are 1.0 and 0.6 mm, respectively. The latter corresponds to zenith transmission of the atmosphere in its submm windows of $\sim 50\%$ (Fig. 1).

Fig. 1. The two frequency bands of CHAMP⁺, shown superimposed on the zenith atmospheric transmission at the APEX site

To make best use of these unique conditions, CHAMP⁺, a dual-color heterodyne array for spectroscopy in the 450 and 350 μm atmospheric windows is under development. The instrument is a re-furbished version of the former 16-pixel 625 μm carbon heterodyne array CHAMP^[8], which was successfully operated for several years at the Caltech Submillimeter Observatory (CSO).

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The CHAMP⁺ development is a joint collaboration with SRON-G, providing the SIS-mixer devices for both colors, and JPL. The receiver will be operated as a Principal Investigator (PI) instrument, but will be available to the APEX² community on a collaborative basis with MPIfR.

2. SYSTEM DESIGN - OVERVIEW

The array will operate simultaneously in both, the 350 μm and 450 μm atmospheric windows, with state-of-the-art performance and widest feasible frequency coverage. It is composed of 14 pixels, divided into two sub-arrays of 7-pixels each, arranged in a hexagonal configuration. The two sub-arrays operate at orthogonal signal polarizations. The RF tuning range is 620-720 GHz for the 450 μm and 780-950 GHz for the 350 μm sub-array. The beam-spacing is $2 \cdot \Theta_{\text{mb}}$ for both sub-arrays, so only the central pixels of the two sub-array will be spatially co-aligned on sky (see Fig. 2 for the

Fig. 2. The CHAMP⁺ footprint is superimposed on an image of the nucleus of M83. The half-power beam widths Θ_{mb} are 7 and 9" for the 350 and 450 μm sub-arrays, respectively; the spacing between the pixels is $2 \cdot \Theta_{\text{mb}}$. Data taken in the *on-the-fly* scanning mode, with the array rotated by 19.1 deg, will be sampled with half-beam spacing.

footprint of the array). For best system sensitivities the design allows for cold optics (20 K) and single-sideband operation (the image sideband is also terminated at 20 K). The Local Oscillator (LO) signal is distributed by collimating Fourier gratings. The front-end will be connected to an autocorrelator back-end, providing up to 2 GHz of bandwidth for each detector pixel, with spectral resolution between 250 kHz and 1 MHz, depending on the correlator configuration.

For efficient operation at a site as remote as Llano de Chajnantor, the instrument has been designed for remote operation. We will review the technical implementations in detail in the following sections.

3. THE RECEIVER DESIGN

The cryogenic and mechanical concept follows the design of CHAMP^[8]. For the commissioning and first observing runs cooling will be provided by a Daikin 3-stage closed-cycle cooler, consisting of a two-stage Gifford-McMahon cooler with an additional Joule-Thomson stage to operate at 4 K. The replacement of this aged cooler by a Sumitomo 3-stage Gifford-McMahon cooler is scheduled for the near future.

The configuration of the instrument, as rigidly mounted to the elevation flange in the Nasmyth cabin B, is illustrated in Fig. 3. The complete dewar can be rotated to compensate for image rotation on the sky while tracking an astronomical source. An the offset-angle can be added in order to position the dewar with the correct tilt of 19.1 deg for optimal beam spacing for “on-the-fly” mapping (see Fig. 2). For calibration a hot-load (outside the cryostat) and a cold-load (20 K, located inside the cryostat) are provided.

² APEX is a collaboration between the Max-Planck-Institut für Radioastronomie, the European Southern Observatory, and the Onsala Space Observatory.

Fig. 3. The CHAMP⁺ instrument is mounted to the elevation flange of the Nasmyth cabin B. The telescope beam, re-imaged by the tertiary mirror M1 (not shown), enters the Nasmyth cabin through the elevation bearing. M1 and M2 form a Gaussian telescope with a magnification of 4.8. After the flat folding mirror, a second Gaussian telescope, composed of M3 and a HDPE-lens (the latter already inside the cryostat), guide to beam through the cold optics (compare Fig. 4) to the individual sub-arrays. On top of the dewar the Local Oscillator units are located. The Daikin cooling machine as well as the two sub-array modules enter from below. For easier handling the complete assembly can be lifted electrically by a build-in lifter mechanism, which can also be used to crane-up the vacuum vessel only, thus providing free access for work on the inner parts of the cryostat.

3.1 The optics layout of CHAMP⁺

Due to the long optical path length towards the Nasmyth cabins, a re-imaging tertiary mirror (M1) inside the Cassegrain cabin is required to guide the telescope beam through the elevation bearing. This tertiary mirror is mounted on a rotary support to select between the two Nasmyth foci and to clear the optical path for the bolometer pick-up mirror (on the floor of the Cassegrain cabin). In the following discussion, we separate the down-stream optics (inside the Nasmyth cabin) into the signal path and the LO distribution optics. Their only common elements are the diplexers and the fly's-eye lenses in front of the mixers.

3.1.1 The optics of the signal path

For a dual-frequency receiver the prime optical design requirement is to optimally match both frequency channels simultaneously to the telescope. The optical interface to the telescope in the focal plane is nearly frequency independent. The optics of CHAMP⁺ follows a Gaussian telescope set-up^[3], which provides both, linear scaling of the beam-sizes and frequency-independent waist-positions. The tertiary mirror (M1) in the Cassegrain cabin and the first mirror (M2), located already inside the Nasmyth cabin, form a Gaussian telescope with a magnification factor $3168/662 = 4.78$. Between the two mirrors the signal passes the elevation bearing (Fig. 3). The most critical design driver (in order not to taper the off-axis beams) has been the limited aperture of the elevation tube (the clear aperture is only ≈ 350 mm in diameter). After the flat folding mirror, M3 and a HDPE-lens (already inside the cryostat) form a second Gaussian telescope (with a magnification of $826/413 = 2$), which serves to minimize the mechanical size of the cold optics and to gain additional path length for the SSB-filters and the diplexer optics.

Fig. 4. The cold optics of CHAMP⁺. The top picture shows the assembly inside the dewar. The picture below details the filter block as seen from the top-plate (where the LO-unit is located). The arrangement of the individual optical components and the resulting beam path is visualized.

Between mirror M3 and the HDPE-lens the signal passes the dewar window and a cross-wire grid to separate the two linear polarizations. Each polarization is associated with one of the two colors (660 GHz and 850 GHz, respectively) of the array and therefore allows simultaneous observations with both sub-arrays. A Martin-Puplett interferometer, used as SSB-filter, follows in both paths (see Fig. 4 for more details). The image bands of these filters are terminated on a 15 K absorber cone. The LO-signals are injected with a polarizer grid and finally combined with the astronomical signal using a second Martin-Puplett interferometer as diplexer. In a last step a so-called fly's-eye lens, combining seven individual lenses in one piece, matches the common optics to the individual horn antennas of the array.

Fig. 5. Results of the optics simulations: the figures (left hand side for the center pixel at 850 GHz; right hand side for the more critical off-axis pixel at the same frequency) show the phase-distribution in grayscale, with black contours in steps of 15° . The white contours display the field amplitude in steps of 10% of the maximum amplitude. The overlap-integral yields 99.8% Gaussicity for the center and $\geq 97.0\%$ for the off-axis pixels.

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Simulations of the complete optics, solving the Maxwell-equations numerically at the mirror surfaces, show a coupling efficiency to the Gaussian fundamental mode for the – most critical – off-axis beams $\geq 97\%$ (Fig. 5).

3.1.2 The LO distribution optics

The design of the LO chains follows the experience gained during the development of the Herschel/HIFI Local Oscillators^[20]. A synthesizer signal in the range of 11 – 18 GHz is first multiplied by a factor of 6 to generate 1 mW RF power at the input of the W-band power amplifier provided by JPL^[21]. The amplifier produces up to 250 mW of RF signal power and drives the cascaded tuner-less frequency multiplier stages which are cooled to 120K. In the 450 μm channel a doubler/doubler/doubler combination is used, whereas a doubler/doubler/tripler cascade generates the output in the 350 μm channel. To cover the wide tuning range of the 350 μm channel, two LO-chains are necessary. A rotary mirror selects between these two LO signals (Fig. 6).

A critical requirement for building a heterodyne focal-plane array is the equal distribution of the LO-signal to each individual mixer. For frequencies above 500 GHz this can be achieved by quasi-optical LO-coupling only. Submillimeter phase gratings have been developed for this purpose and were successfully applied^{[15][16][4]}. They need a flat phase distribution to work properly, which is ensured by imaging optical elements within the LO beam path. For CHAMP⁺ we decided to use so-called collimating Fourier-gratings (CFG)^{[9][5]} as LO beam divider. At the reflection point of a parabolic mirror the phase distribution of a Gaussian beam is flat. CFGs combine a parabolic mirror with a phase grating by superimposing the grating structure onto the mirror surface. The advantage is a rather simple optics layout for the LO distribution scheme with, of course, a high efficiency of the beam divider ($> 70\%$ for this special diffraction pattern, which means that $> 10\%$ of the injected LO power is finally directed to each of the seven mixers). The usable bandwidth is of the order of $\pm 8\%$ with respect to the design frequency.

Fig. 6. CAD-drawing of the CHAMP⁺ LO-unit. To cover the wide tuning range of the 350 μm channel two separate LO-chains are necessary. In the figure only the beam path of the lower-frequency LO chain is shown. Rotating the “flat 350 μm mirror” by 90° clockwise switches between the two high-frequency chains. Tilting the three flat-mirrors and the CFGs ensures proper alignment. All three LO-chains are operated cold ($< 120\text{ K}$) to improve the performance as well as the lifetime of the multipliers. Cooling is provided by a commercial Stirling-cooler with $\approx 9\text{ W}$ cooling power at 80 K. The warm air from the Stirling-cooler is directed towards the dewar windows to prevent condensation.

Fig. 7. The figure on the left hand side shows two unit-cells of the phase-sensitive structure of the CFG. For a hexagonal arrangement of the diffraction-pattern a $\sqrt{3}$ side-ratio of the unit cell is required. The figure at the right hand side displays a simulation of the resulting diffraction pattern.

3.2 SIS Mixers

The SIS mixers are developed by SRON-G (NL), the SIS-Junctions are manufactured at the University of Delft. For the 660 GHz band a classical Nb-AlO_x-Nb junction is used, while for the 850 GHz band a Nb-NbTiN-junction has been developed. All mixers are fixed-tuned double side-band waveguide devices with a commercial corrugated feed horn.

3.4.1 Mechanical Design

The SIS mixers for CHAMP⁺ have the same cylindrical envelope for both colors. The disassembled mixer is shown in Fig. 8: it consists of a corrugated horn, made by RPG Meckenheim (Germany), and a back-piece that is held together by a phosphor copper nut which slots are made such that it presses the back-short cavity with constant force even when

cooled to 4.2 K. The back-piece contains a fixed back-short cavity and a substrate channel machined across it. We use a reduced height waveguide with dimensions $400 \times 100 \mu\text{m}$ for the low-frequency band and appropriately scaled dimensions for the higher frequency band.

Fig. 8. Mechanical components of a disassembled CHAMP⁺ mixer (left). To the right, a SEM photograph of the central part of the substrate of a $450 \mu\text{m}$ band mixer is shown, with the SIS junction, the strip-line tuning structures, and the bow-tie waveguide probe.

A $40 \mu\text{m}$ thick quartz substrate is glued in the substrate channel by UV curing epoxy. The substrate contains the SIS junction and associated superconducting tuning elements to match the waveguide probe impedance to the impedance of the SIS junction and to provide choke filters for separating the RF and IF/DC signal. One side of the substrate is grounded to the body of the back piece and the other side is contacted to a central pin of a GPO-type IF connector. We use a limited detent connector at the mixer side and a smooth bore GPO connector at the IF/DC distribution board to be able to easily remove the mixer from the array frame by sliding it along the axis of the cylinder. This mechanical design is similar to the one used for the ALMA mixers^[2].

Fig. 9. View of the $450 \mu\text{m}$ mixer array. The horns are shown in the left hand picture, while the bottom view (to the right) shows the individual mixer blocks and the location of the various connectors.

The magnetic field that is required for mixer operation at higher frequencies, is applied to the junction by using cylindrical field conductors, which are mounted perpendicular to a substrate channel. These conductors are then contacted with the general magnetic field distribution using spring supported leaves. This arrangement allows to mount and dismount individual mixers without disassembly of the complete array block. The magnetic field itself is created by a superconducting coil. Each mixer has its own magnetic field coil to allow for independent adjustment.

3.2.2 Mixer design and performance for the 450 μm band

The photograph of the low band mixer chip is shown in Fig. 8. The mixer design is similar to the one developed for ALMA band 9^[2]. A Nb-SiO₂-Nb micro-stripline was integrated with the Nb-AlO_x-Nb SIS junction. The 3-D EM field simulation (Microwave Studio) was used to obtain the probe impedance, and the Mattis-Bardeen theory was applied to model the superconducting striplines. In Fig. 10 we display the instantaneous bandwidth of a set of low-frequency band mixers. Responses are uniform and demonstrate a peak sensitivity around 690 GHz (LO) frequency. The mixer noise temperatures, as summarized in Fig. 11, were measured in a liquid helium cryostat at 4.2 K operation temperature. The IF chain included a 4 – 8 cryogenic isolator and a 4 – 12 GHz cryogenic amplifier made by NRAO^[18].

Fig. 10. Direct response measurements of several of the low- and high-frequency band mixers of CHAMP⁺, using a Fourier transform spectrometer.

3.2.3 Mixer design and performance for the 350 μm band

The high-frequency band of CHAMP⁺ is above the Nb gap frequency, and therefore normal Nb technology cannot be used. Instead, a Al-SiO₂-NbTiN material combination was used to form the micro-striplines. The Nb-AlO_x-Nb SIS junction of 8 kA/cm current density was integrated into the stripline. This technology is similar to the one used for the HIFI band 3 mixers working in the same frequency range^{[1][12]}. The electromagnetic design consists of a modified single-sided waveguide probe, a micro-stripline transformer and a twin junction circuit, which allows covering the complete high-frequency band as demonstrated in Fig. 10. The peak sensitivity is around 810 GHz. The lowest mixer noise temperature of 250 K was measured at around 800 GHz; the noise temperatures of all CHAMP⁺ mixers are displayed in Fig. 11.

Fig. 11. Summary of mixer noise temperatures, as measured at 4.2 K operating temperature, for both CHAMP⁺ bands.

3.3 Electrical design

3.3.1 Mixer-control

The mixer control provides a stable bias-circuit (most critical for reliable operation) and a protection circuit for the mixers, a magnet current for suppressing the DC-Josephson current at the superconductive mixer junction, and a heater current to remove trapped magnetic flux quanta from the device, if necessary. In total there are 16 individual units available, one for each mixer (plus two spares). The complete system can be controlled remotely, but also manually if desired. To optimize the mixer tuning, IV-curves and also the conversion curves of the mixers can be displayed online.

3.3.2 Local Oscillator control

The concept of using a high power W-band signal fed into cascaded frequency multiplier diodes to generate the submm local oscillator signal requires that these devices are operated at their limit. The voltage swing induced in the 1st multiplier stage easily can be large enough to damage or even destroy the device, if the input power is too high or the device is not operated at the right bias point. Therefore the low noise DC supply voltages of the local oscillator chains are generated in a dedicated control unit, a development copied from the Herschel/HIFI program. Many safety features have been implemented in this unit to avoid that the LO chains can be damaged by wrong handling or main supply failure. The internal microprocessor manages the switch-on and switch-off procedure of the chain components in a safe order. Even in case of a failure of the main, the unit is capable to switch-off the active chain in the right (safe) order. Hardware current limits are implemented to avoid excessive forward or reverse currents of the multipliers. Programmable current limits for the amplifier drain stages decrease the likeliness of damaging the amplifier by wrong biasing of the stages.

3.3.3 IF electronics

The first stage of the IF consists of a HEMT amplifier with ~ 4 K noise temperature (Fig. 12), a second low-noise amplifier operating at 300 K is mounted directed on the dewar. This is followed by an IF processor which converts the mixer IF output of 4 – 8 GHz to the (correlator) base band 0 – 1 GHz, after further amplification and filtering (Fig. 11). Each of the 16 IF modules splits the 4 – 8 GHz signal into two 0.5 or 1.0 GHz wide subbands, which frequencies are selectable independently within the 4 GHz wide IF input band. As an example, the two subbands can be configured such that 2.0 GHz of bandwidth are covered continuously. The amplitude of the video band signal is leveled to nominal $2 (\pm 0.2)$ dBm. A total power signal is provided for each of the modules to calibrate the output spectrum of the correlator (see Sect. 3.4). The IF processor is controlled remotely by SCPI protocol^[19]. In preparation for future, complementary arrays each IF module can handle two input signals. This will allow switching remotely and on short timescale between arrays operating at, e.g., different frequencies and atmospheric transmissions.

Fig. 11. Block diagram of one of the 16 IF processor units for CHAMP⁺

Fig. 12. Typical gain and noise response of the 4 – 8 GHz HEMT amplifiers developed in-house.

The photograph to the left shows the complete IF-processor unit, integrated in its 19" rack.

3.4 MACS – the MPI Array Correlator System

As backend for CHAMP⁽⁺⁾ a wide-band and multiple IF-input autocorrelator, MACS (MPIR Array Correlator Spectrometer), has been developed [22]. MACS provides a total bandwidth of 32 GHz and 32768 spectral channels, which is subdivided into 32 IF bands of 1 GHz and 1024 channels each. The analog-to-digital conversion is realized by a combination of two comparators per IF channel, each sampling at 2 GHz, which gives MACS a 2-bit/3-level resolution. Due to the limited dynamic range of a 2-bit sampler, a two-fold sampler control strategy has been implemented: first, the IF input level is auto-gain controlled on a short time constant within 0.2 dB. This prevents over driving the sampler inputs and thus minimizes propagation delays due to over amplification and distortions due to input clipping. Second, the levels and the symmetry of the threshold voltages of the two comparators are controlled digitally on a long(er) term basis. For this a real-time level control program inspects the result of each correlation function to get the statistics of the mean value and the content of the first correlation channel. If one or both values have to be adjusted, the digital-to-analog converters, placed on each sampler board, are forced to adjust the sampler threshold levels to the comparators. Both control loops can be separately switched off for test purposes.

The most important components in MACS are the correlator chips. In 1993, the year when the design of MACS started, no correlator chip was suitable to process a single 2 GHz data stream. But with a good speed and channels-per-chip performance, it was possible to combine correlator chips by applying parallel structures. In MACS the NAIC/NASA 1024 lag/channel correlator chip developed by John Canaris is used, which provides a high density (1024 lags) as well as a processing clock of minimum 100 MHz. For MACS the correlator chips are over clocked with 125 MHz, which allows processing of a single 2 GHz data stream by combining 16 Canaris chips. In total, MACS comprises $32 \times 16 = 512$

correlator chips to provide a bandwidth of 32 x 1 GHz /32 x 1024 channels. For observations which need higher frequency resolution, the flexible MACS architecture allows to decrease the total bandwidth by a factor of two and to increase the effective channel numbers by two in the same step, thus providing a four times better spectral resolution. The technical data of MACS are compiled in Table 1.

Fig. 13. Block diagram of the IF processor and the MACS autocorrelator

The final Fast Fourier Transforms (FFT) of the integrated auto-correlation functions, the normalizations as well as the van Vleck corrections due to the limited bit-sampling are implemented on a fast Linux-PC. In addition to signal processing, this PC interconnects MACS to the APEX control system (APECS) using the SCPI protocol^[19]. MACS was operated successfully at the CSO for several years, servicing CHAMP. For APEX the spectrometer, which has a peak power consumption of 15 kW, has been upgraded for operation at high-altitude (5100 m): a dedicated cooling system provides an air flow of up to 7200 m³/h. Since the reliability of the cooling system is critical for safe operation, a microcontroller-based monitor system has been implemented to protect the spectrometer against overheating as well as power peaks.

Table 1. Technical data of the autocorrelator backend MACS

Number of IF inputs	32	
Bandwidth per IF	05 GHz	1.0 GHz
Digital channels per IF	1024 – 2048*	1024
Sampler resolution	2 bits / 3 level	
Sampler degradation factor	1.23 – 1.12*	1.23
Data acquisition	32 spectra with up to 2048 channels every 100 ms	

Note: * 2048 digital channels with degradation factor 1.12 in over sampling mode

The increase in sampling rate of commercial analog-to-digital converter and of the computing power of Field Programmable Gate Array (FPGA) chips has made possible to develop wide-band Fast Fourier Transform Spectrometers (FFTS)^[14]. Because a prototype FFTS showed excellent performance even under the harsh operating conditions at APEX, two facility units have been build and delivered recently, now providing 1 GHz bandwidth with 16384 channels each^[13]. While the FFTS development is progressing rapidly towards larger instantaneous bandwidths with even better spectral resolution, at decreasing costs per unit, replacement of the MACS correlator by a novel array-FFTS is planned in the next 1-2 years.

4. CONCLUSION

The sensitivity of CHAMP⁺, operated at the world's leading submm facility, will be unparalleled. With its state-of-the-art mixers and wide tunable local oscillators, minimized losses due to its cold optics and image band termination, this novel mapping device will make accessible a wide variety of astronomical targets to submm spectroscopy that due to lack of sensitivity were difficult, if not impossible to investigate before.

After successful commissioning of the instrument (scheduled for summer 2006) the instrument will be available to the APEX community on a collaborative basis with MPIfR.

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