CCD detectors for spectroscopy and imaging of X-rays with the eROSITA space telescope

N. Meidinger*[,a,c], R. Andritschke[a,c], S. Ebermayer[a,c], J. Elbs[a,c], O. Hälker[a,c], R. Hartmann[b,c], S. Herrmann[a,c], N. Kimmel[a,c], P. Predehl[a], G. Schächner[a,c], H. Soltau[b,c], L. Strüder[a,c], and L. Tiedemann[a]

[a]Max-Planck-Institut für extraterrestrische Physik, Giessenbachstrasse, 85748 Garching, Germany;
[b]PNSensor GmbH, Römerstrasse 28, 80803 München, Germany;
[c]MPI Halbleiterlabor, Otto-Hahn-Ring 6, 81739 München, Germany

ABSTRACT

A special type of CCD, the so-called PNCCD, was originally developed for the focal plane camera of the XMM-Newton space telescope. After the satellite launch in 1999, the MPI Halbleiterlabor continued the detector development for various ground-based applications. Finally, a new X-ray PNCCD was designed again for a space telescope named eROSITA. The space telescope will be equipped with an array of seven parallel oriented X-ray mirror systems of Wolter-I type and seven cameras, placed in their foci. This instrumentation will permit the exploration of the X-ray universe in the energy band from 0.3 keV up to 10 keV with a time resolution of 50 ms for a full image comprising 384 x 384 pixels. eROSITA will be accommodated on the new Russian Spectrum-RG satellite. The mission was already approved by the responsible German and Russian space agencies. The detector development is focussed to fulfil the scientific specifications for detector performance under the constraints of all the mechanical, power, thermal and radiation hardness issues for space instrumentation. This considers also the recent change of the satellite's orbit. The Lagrange point L2 was decided as new destination of the satellite instead of a low-Earth orbit (LEO). We present a detailed description of the detector system and the current development status. The most recent test results are reported here. Essential steps for completion of the seven focal plane detectors until satellite launch in 2012 will be itemized.

Keywords: CAMEX, eROSITA, PNCCD, Spectrum-RG, X-ray imaging, X-ray spectroscopy, X-ray telescope.

1. INTRODUCTION

The excellent energy resolution in combination with a quantum efficiency close to 100% over the eROSITA[1] energy band (0.3 keV – 10 keV), provides an essential performance characteristic of the PNCCD detector. A further important feature of the eROSITA telescope with respect to the all-sky survey is its very high grasp, i.e. the product of effective area and the field of view (FoV). The large FoV of 1.0° in diameter is obtained with a PNCCD detector image area of nearly 3 cm x 3 cm in the focal plane. A CCD format of 384 x 384 pixels provides the required spatial resolution, which is determined by the angular resolution of the mirror system. The pixel size of 75 µm x 75 µm is exactly as large as specified. The readout time of an image is minimized to 10 ms by the parallel signal transfer and processing architecture of the PNCCD and its readout ASIC, called CAMEX. As a result, we achieve a high time resolution along with low-noise performance of 2 electrons rms read noise.

Each of these features gives an essential contribution to the scientific power of the eROSITA telescope. After the introduction of the motivation for the PNCCD detector, we describe in the next section briefly the concept.

---

* nom@hll.mpg.de, phone: ++49 89 83940022, fax: ++49 89 83940011, hll.mpg.de, mpe.mpg.de

2. DETECTOR CONCEPT

The development of the early PNCCDs got a great impulse when this detector type was proposed and selected for one of the three focal plane cameras for the XMM-Newton X-ray telescope of ESA.[2] After successful launch of the satellite in 1999 and successful commissioning of the PNCCD camera, the further development of the PNCCD detector for future space applications was mainly driven by the following three topics:

a) Optimization of energy resolution: For this purpose we reduced the detector read noise as well as the charge transfer losses.[3]
b) Improvement of detector response to low-energy X-ray photons. The improvement of the photon entrance window was achieved by optimization of the fabrication process.[3]
c) Suppression of image smearing due to out-of-time events. We solved the problem by adding a frame store to the chip and operating the PNCCD in frame transfer mode.[3]

The most important conceptual features of the present PNCCD detector are itemized subsequently. The chip thickness of 450 µm is fully depleted by use of the principle of sideward depletion and thus sensitive. X-ray photons enter the CCD from the back side which is equipped with an ultra-thin unstructured pn-diode. As a result, we obtain high quantum efficiency for a broad band of X-ray photon energies. The values are at least 90% at photon energies from 0.3 keV up to 11 keV. The shift registers also realized as pn-diodes are implemented on the front side. Signal charge collection and transfer is done in a depth of about 7 µm, which allows for relatively large pixel sizes. In frame transfer mode (alias frame store mode), the signal charge of all pixels of the image area is transferred rapidly (≈ 0.2 ms per eROSITA image) into the adjacent frame store section (see Figure 1). Since the frame store is shielded against X-rays, only photons entering the image area during this short period of charge transfer, become out-of-time events, i.e. show a wrong position in transfer direction. This applies for only 0.4% of the photons in the case of eROSITA. No serial charge transfer is necessary because each transfer channel is equipped with an anode and a n-channel JFET for signal amplification. All PNCCDs are thereby fully column parallel CCDs. A multi-channel analog signal processor chip, the CAMEX, completes the parallel detector architecture. Each CCD channel is connected to a dedicated CAMEX channel. Low-noise filtering of the signals, when they are transferred to the anodes, is accomplished by 8-fold correlated double sampling. While the next CCD row is processed, the shaped analog signals are multiplexed to the output buffer of the CAMEX. From there they are fed into a fast 14-bit ADC for digitization. Processing of the digital signals starts with a subtraction of the individual pixel pedestals (offset values). The parallel processing allows for a common mode correction of the signals of each row. Finally, the slightly different gains of the channels are normalized and their charge transfer losses are corrected to obtain an optimum energy resolution.

For the development of a very compact camera for space, we shortened the pixel size to 51 µm x 75 µm in the frame store section in order to minimize the area of the CCD chip. Additionally, a thin light filter is directly deposited on the photon entrance window, which supersedes an external filter in front of the CCD detector.

3. EROSITA DETECTOR DESIGN

The 37 mm x 56 mm large PNCCD chip contains an image area of 28.8 mm x 28.8 mm, a frame store section with the same number of pixels, an anode and amplifying transistor per channel, charge clear structures, an inject electrode for test purposes and temperature diodes (Figure 1). The CCD is glued on a six-layer detector hybrid board together with the CAMEX ASICs (Figure 2).

A five-layer rigid-flex printed board with 133 lines connects the CCD module with the further supply, control and data acquisition electronics outside the focal plane. Since the detector is cooled to a temperature of about -80°C, its power consumption has to be minimized and the detector board must be thermally decoupled from the warm electronics, which is more power consuming and thereby heat dissipating. The power consumption on the detector board is reduced by switching the CAMEX ASICs into standby mode after the readout of an image has been finished. The ASIC is powered again when the next frame should to be processed. We obtain by increasing the integration time to 50 ms a total active heat load of only 0.7 W per detector (at the expense of time resolution).

Thermal decoupling of the detector board from the warm electronics is achieved by an appropriate design of the rigid-flex printed board. The wire cross section was therefore minimized to less than 2 mm^2 and the length enlarged to about 25 cm. As a result, the total heat load in the focal plane including the power consumption amounts to only 2 W per detector. It will be dissipated on the satellite via heat pipes to the radiators.[4] The cooling concept of eROSITA is described in detail by Fürmetz et al.[5]

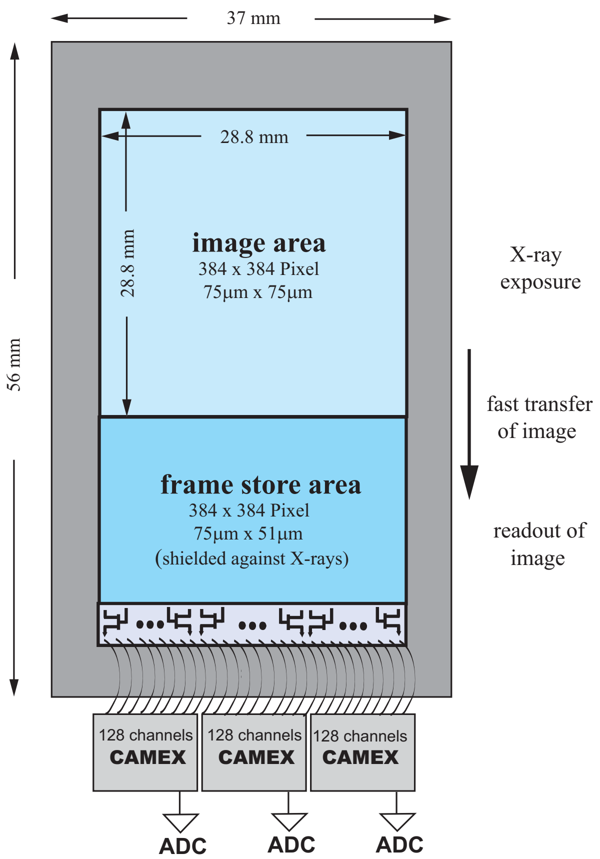

Figure 1: Diagram of one eROSITA PNCCD detector showing the dimensions and illustrating the structure. Every 50 ms a signal image is transferred rapidly to the frame store area of the CCD. The 384 CCD channels are read out simultaneously by three 128-channel VLSI CAMEX chips. During signal processing of the next row, the signals of the previous row are serialized to the CAMEX output buffer, which feeds the analog signals into an ADC for digitization. The seven eROSITA detectors are identical. The total camera array is thus equipped with seven PNCCDs, 21 CAMEX ASICs and 21 ADCs.

The recent decision to fly the eROSITA telescope not in a low-Earth orbit (600 km altitude, 30° inclination), but at Lagrange point L2, means a substantial change of the radiation environment. Calculations with "The Space Environment Information System" (SPENVIS) showed for the planned mission time from 2012 to 2017 an ionization dose between 20 krad and 60 krad (depending on the model) behind a shielding of 1 mm aluminum. The eROSITA PNCCD detector needs a thicker shielding because it collects, stores, transfers and amplifies analog signals consisting of only several ten up to a few thousand electrons. It is therefore relatively susceptible to radiation damage. Protons are the most critical radiation component in space because of their high flux and high ionizing and non-ionizing energy loss. A proton shield around the detector was designed with the specification to shield the protons up to an energy of 160 MeV.[4] An estimate of the proton fluence to the detector behind the shielding gives under these assumptions a number of 2×10^9 protons per cm^2 and five year mission time.

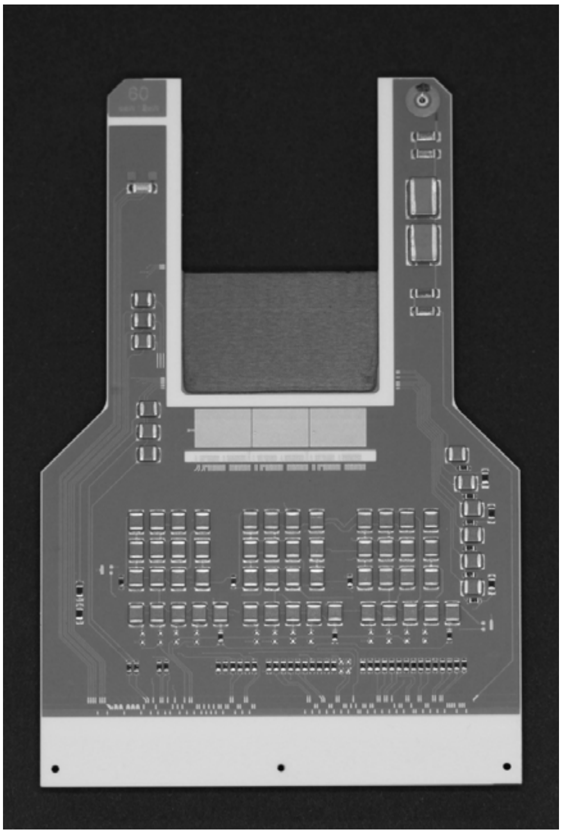

Figure 2: Detector hybrid board produced in thick film technology on an Al_2O_3 ceramic substrate (shown without PNCCD and CAMEX chips). The board is equipped with RC-filters in SMD technology for the voltage supplies. The three CAMEX chips will be mounted in the central part of the board, adjacent to the large-area PNCCD. In the upper part of the picture, we see the cut-out in the board where the double-sided processed PNCCD will be placed, only touching the board at the edges. At the bottom, we see the interface for a rigid-flex printed board connecting the detector board to the further electronics outside the focal plane.

4. DEVELOPMENT STATUS

4.1. PNCCD

The layout and fabrication process sequence is based on that of the PNCCD devices developed for the DUO project having a format of 256 x 256 pixels in the image area.[6] The CCD performance was tested and the detectors are meanwhile used in various ground-based applications. For eROSITA the format was enlarged to 384 x 384 pixels while keeping the layout of the pixels. As a result of our tests with the DUO CCDs, we optimized the charge clear of the anodes for the eROSITA devices. If solar or cosmic protons penetrate the CCD, they generate by orders of magnitude higher signal charge in the device than the X-rays focussed through the telescope. A fast drain of the charge, as soon as it is transferred to the anode and sampled, is necessary for an accurate measurement of the charge amounts of subsequent X-ray photon signals. The first CCD wafers were produced and the eROSITA CCDs studied in laboratory tests (see Figure 3). We measured a read noise of the detector system between 2.0 and 2.5 electrons rms. The energy resolution parameterized as full width at half maximum (FWHM) of relevant spectral lines is presented in Table 1. The measurements were carried out at a temperature of -80°C and with a rate of 20 images / s, i.e. under conditions as planned for the space telescope. After verification of the eROSITA CCD function and quality, a second batch of eROSITA wafers was produced in the MPI Halbleiterlabor and is presently finished. It will basically provide the flight CCDs for the space project. The performance of each produced CCD will be tested in order to select the seven best CCDs for the camera array. For this purpose the so-called cold-chuck probe station was upgraded. It was actually developed for testing and selection of the XMM-Newton PNCCDs. The set-up permits full operation and spectroscopic test of the CCDs just by contact of probe needles without mounting the chips on boards. The CCDs are cooled and tested by use of a Fe55 source. First tests with eROSITA CCDs proved that the important performance parameters can be determined by use of the probe station.

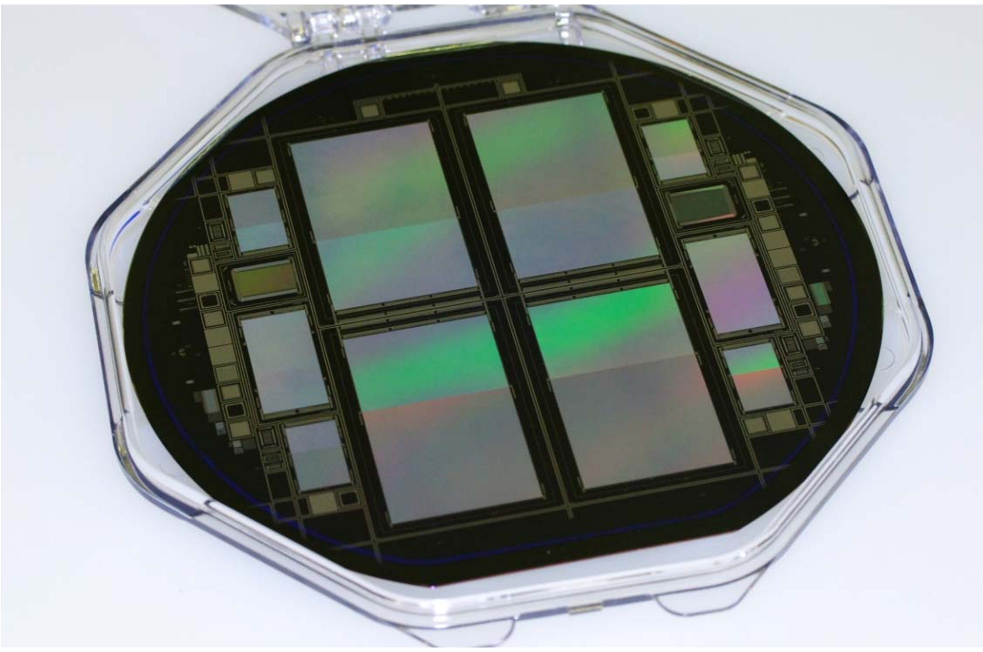

Figure 3: eROSITA wafer with four of the large-area CCDs in the centre. The outer devices serve for test purposes.

Table 1: Energy resolution of spectral lines measured with eROSITA CCDs in frame transfer mode. The analysis of the spectra comprises all event pattern types, single events as well as split events where the signal electrons are collected in up to four pixels.

X-ray energy	FWHM
277 eV	53 eV
1.5 keV	74 eV
5.9 keV	134 eV

4.2. CAMEX

Concurrently with the PNCCD development, its analog signal processor CAMEX (see Figure 4) was optimized. All measurement results were achieved using this mixed signal ASIC. A current source in the input stage of each channel biases the PNCCD on-chip n-channel JFET for operation in source follower mode. Eight-fold correlated double sampling is applied for signal filtering. This yields low noise and allows, due to parallel processing in the 128 channels, fast signal readout. A digital sequencer implemented in the CAMEX permits a compact design. Programming is done via a serial LVDS interface. Slight deviations among the three CAMEX chips per eROSITA detector can be adjusted by appropriate programming of the CAMEX bias DACs. The prototype eROSITA CAMEX was tested and the flight eROSITA CAMEX is presently produced in a 5 V process with JFET-CMOS technology, the same as used for the prototype CAMEX.

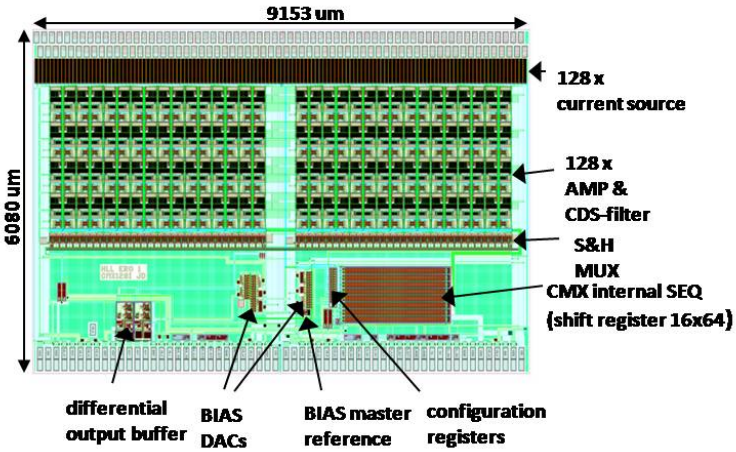

Figure 4: CAMEX chip developed for the readout of the eROSITA PNCCD signals. The signals of 128 CCD channels are simultaneously processed in the mixed signal ASIC and finally multiplexed to one differential output buffer (see also Figure 1).

4.3. Detector board

For performance testing of the eROSITA PNCCDs and CAMEX ASICs in the laboratory, we developed an appropriate detector board.[4] It was used for verification of the performance of the first eROSITA CCDs. Based on the same process technology and schematic diagram, the detector board for the eROSITA cameras was designed. This flight design had to meet a few more conditions. The layout was made even more compact in order to minimize the total weight of the camera with its proton shield. The layout is matched to the size of the qualified SMD-components. An interface to the rigid-flex printed board is provided as well as to the support and cooling interface made of ceramics and titanium. The support structure is equipped with a graded-Z shield in the area of the PNCCD frame store.[4] The inner most layer of the graded-Z shield next to the PNCCD is made of boroncarbide (B_4C) featuring the required small atomic numbers Z of 5 and 6. The adjacent image area of the CCD is as a matter of course not obstructed. The entire detector structure has to resist the loads caused by thermal cycling during detector testing and by vibrations during satellite launch.

First boards are produced and equipped with SMD components. They are ready for integration and will soon be tested with CAMEX and CCD.

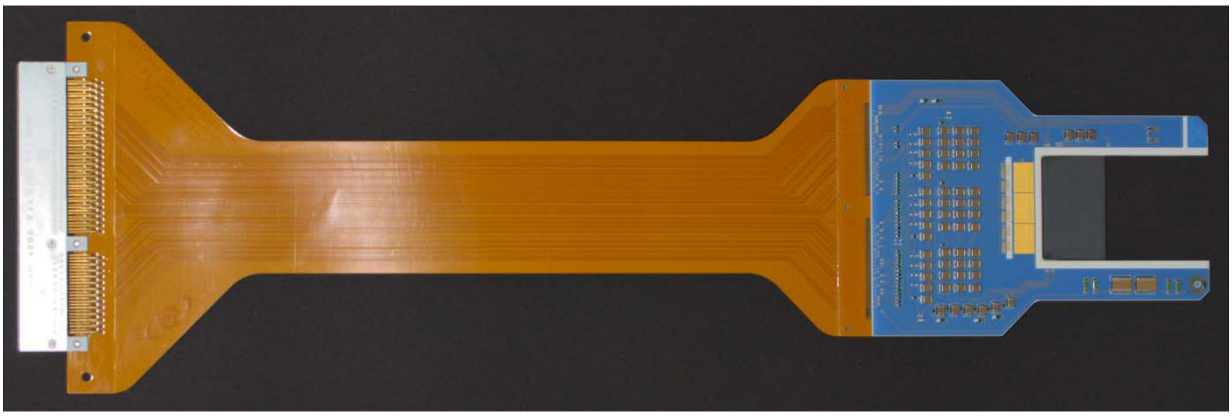

Figure 5: Rigid-flex printed board (left hand) connected to the detector board (right hand).

4.4. Rigid-flex printed board

The rigid-flex printed board is connected to the detector board by wedge bonds. The other terminal is equipped with a connector as interface to the electronics outside the focal plane. The concept is the same as already tested for the DUO detectors with a CCD format of 256 x256 pixels.[4] A prototype rigid-flex printed board for eROSITA has been designed, produced and is awaiting integration (see Figure 5).

4.5. Front-end board

The rigid-flex printed board is directly connected to the frontend-board which carries performance susceptible electronics such as the drivers generating the analog pulses for charge transfer. A prototype of this board was designed and produced (Figure 6). It is used to verify the circuit design and for a first test of the flight detector system.

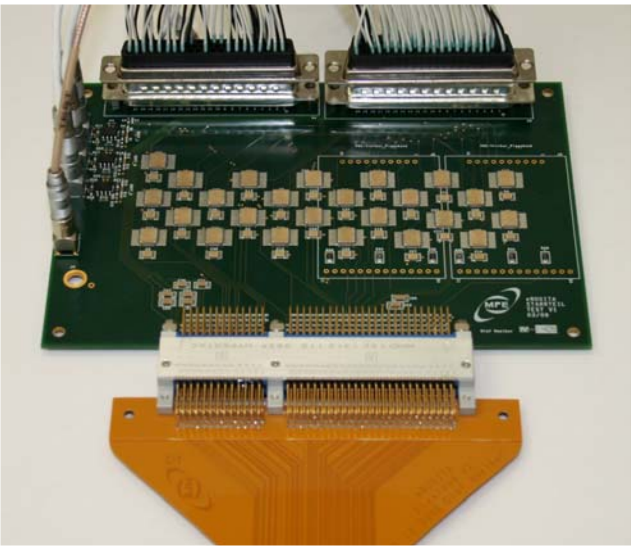

Figure 6: Prototype of the front-end board (top) connected with rigid-flex printed board (bottom).

4.6. Tests

A first verification of the flight detector concept was obtained by various tests of DUO modules.[4] They were tested at the MPI Halbleiterlabor and the Max-Planck-Institut für extraterrestrische Physik and applied at the BESSY synchrotron and the FLASH VUV free electron laser (FEL).[7],[8]

Function and performance of the eROSITA PNCCD and CAMEX were successfully tested with lab modules and breadboard electronics.

We have to test the radiation hardness of the eROSITA CCDs because the results will presumably differ from those obtained with the XMM-Newton PNCCD. The reason for this is based on the fact that although the PNCCD concept is the same, the wafer starting material, process technology, CCD layout and operating conditions were changed. In a first radiation hardness test, we exposed a lab detector module to a proton fluence, equivalent to that after five years in L2 orbit. No malfunction of the lab detector module or any single event upset occurred. The degradation of energy resolution due to dark current increase and charge transfer efficiency decrease is under study.

Presently, the integration of flight-type modules for electrical and first environmental tests (thermal cycling and vibration tests) is in preparation. These tests will be finally completed by ESD (electrostatic discharge) and EMC (electromagnetic compatibility) tests.
The following detector models present the milestones in the eROSITA camera development: Our detector design will be tested with an engineering model (EM) and then qualified by a so-called qualification model (QM). The seven flight detectors (FM1 – FM7) will be integrated successively. Integration, test and calibration of the seven detectors however will overlap because of time constraints.

5. SUMMARY AND OUTLOOK

After the conceptual design had been determined for the eROSITA detector, we prepared a detailed design and produced the components of the detector system: the eROSITA PNCCD, its analog signal processor CAMEX for readout of the CCD signals, the detector board, the rigid-flex printed board and the front-end board. The key components, PNCCD and CAMEX, were already tested with respect to performance in a lab setup. The results, an improved read noise of nearly 2 electrons rms and an energy resolution of 134 eV FWHM at 5.9 keV energy and 53 eV FWHM at 277 eV energy respectively, provide the building blocks for excellent flight cameras. The other detector components are presently prepared for integration.

Recently the decision was made to fly eROSITA on the Spectrum-RG satellite in a L2 orbit. We have started to test the effects of this radiation environment on our custom-made PNCCD and CAMEX devices.

Based on the test results achieved with the upcoming engineering module, the final design will be determined next year. Until satellite launch, which is scheduled for 2012, the final design has to be verified in tests as well as the seven flight detectors set up, tested, calibrated and integrated into the eROSITA telescope.

ACKNOWLEDGMENTS

The authors are grateful to all colleagues who supported the detector development, fabrication and tests, in particular the staff of the MPI Halbleiterlabor, the Max-Planck-Institut für extraterrestrische Physik, the Max-Planck-Institut für Physik, PNSensor, the Ingenieurbüro Werner Buttler and bonerz engineering. This work was also supported by the DLR and the Heidenhain foundation.

REFERENCES

[1] Predehl, P., Andritschke R., Bornemann W., et al., "eROSITA," Proc. SPIE 6686, 17 1-9 (2007).
[2] Strüder, L., Briel, U., Dennerl, K., et al., "The European Photon Imaging Camera on XMM-Newton: The pn-CCD camera," Astronomy & Astrophysics, 365(1), L18-L26 (2001).
[3] Meidinger, N., Andritschke, R., Hälker, O., et al., "Next generation of pnCCDs for X-ray spectroscopy and imaging," Nucl. Instr. & Meth. A, 568, 141-148 (2006).
[4] Meidinger, N., Andritschke, R., Elbs, J., et al., "eROSITA camera design and first performance measurements," Proc. SPIE 7011, 0J 1-12 (2008).
[5] Fürmetz, M., Pfeffermann, E., Predehl, P., Rohé, C., Tiedemann, L., "The cooling concept of the X-ray telescope eROSITA," Proc. SPIE 7011, 3Y 1-12 (2008).
[6] Meidinger, N., Andritschke, R., Dennerl, K., et al., "First measurements with DUO/eROSITA pnCCDs," Proc. SPIE 5898, 0W 1-9 (2005).
[7] Leitenberger, W., Hartmann, R., Pietsch, U., Andritschke, R., Starke, I., and Strüder, L., "Application of a pnCCD in X-ray diffraction: a three-dimensional X-ray detector," J. Synchrotron Rad., 15, 449-457 (2008).
[8] Reich, C., Hartmann, R., Soltau, H., et al., "Experiments with fast spectroscopic pnCCDs at BESSY and FLASH VUV-FEL," IEEE Nuclear Science Symposium Conference Record, N30-434, 2585-2589 (2008).