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The Wide Field Imager instrument for Athena

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Abstract. ESA's next large X-ray mission Athena will be equipped with two focal plane cameras, a Wide Field Imager (WFI) and an X-ray Integral Field Unit (X-IFU). The WFI instrument is designed for imaging and spectroscopy over a large field of view, and high count rate observations up to and beyond 1 Crab source intensity. Both cameras share alternately a mirror system based on silicon pore optics with a focal length of 12 m and an unprecedented large effective area. Main scientific requirements for WFI are described here and the corresponding conceptual design to meet them. The instrument employs active pixel sensors of DEPFET type, which are fully depleted, back-illuminated silicon devices of 450 µm thickness. In combination with front-end electronics ASICs tailored to the project, the resulting detectors provide high quantum efficiency over the 0.2 keV to 15 keV range with state-of-the art spectral resolution and extremely fast readout speeds compared to previous generations of Si detectors for X-ray astronomy. The focal plane comprises a Large Detector Array (LDA) with over 1 million pixel of 130 µm × 130 µm size, providing oversampling of the PSF by a factor > 2 over the 40 arcmin × 40 arcmin large field of view, complemented by a smaller Fast Detector (FD) optimized for high count rate applications.

Key words: Athena – Wide Field Imager – X-ray camera

1. WFI Overview and Requirements

The Athena mission had been proposed in 2013 by a large community of European X-ray astrophysicists (Nandra et al., 2013). Its scientific payload consists mainly of two focal plane cameras sharing alternately one mirror system based on silicon pore optics (Bavdaz et al., 2017). While the X-ray Integral Field Unit (X-IFU) permits high-resolution spectroscopy employing transition edge sensors operated at cryogenic temperatures, the Wide Field Imager (WFI) features a large field of view and high count rate capability by the use of novel active pixel sensors of DEPFET type (Meidinger et al., 2017a), (Treberspurg et al., 2017).

For these purposes, the WFI instrument comprises a large detector array (LDA) and a fast detector (FD) as shown in Fig. 1 (Meidinger et al., 2017b). Both shall perform spectroscopy of X-ray photons in the energy range from 0.2 keV to 15 keV. Energy resolutions of <80 eV and <170 eV FWHM are scientifically required for energies of 1 keV and 7 keV respectively, over the

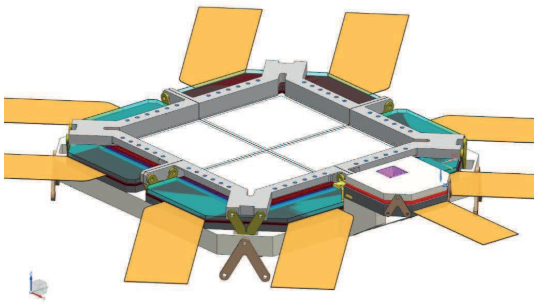

Figure 1. WFI detectors: the LDA with the four large-area quadrants, each with two flexible leads, and the small FD in the front right-hand corner of the image.

field of view and until end of life. The LDA spans the large field of view of 40 arcmin × 40 arcmin by 1024 × 1024 pixels, each with a size of 130 µm × 130 µm. They are grouped in four independent quadrants. This configuration allows a simultaneous readout of the four quadrants in rolling shutter mode which is necessary to achieve the required time resolution of 5 ms in full frame mode. The time resolution can optionally be improved by operating the LDA in window mode which means to read out a small region of the detector area where the X-ray source of interest is imaged. The FD with a field of view of $143'' \times 143''$ is designed for observations of bright point sources and is therefore composed of only 64 × 64 pixels which facilitates high time resolution. It is operated in split full frame mode, i.e. the detector architecture permits a simultaneous readout of two sensor halves which improves the time resolution by a factor of two, resulting in a time resolution of 80 µs. By defocussing the detector by 35 mm, a more uniform distribution of the photon hits over the sensor area is achieved and thus a pile-up $\leq 1\%$ for an observation of a 1 Crab source.

The DEPFET sensor is also sensitive to visual and UV light. Therefore an optical blocking filter is necessary yielding a reduction of visual light transmission by about six orders of magnitude. It will be split in two parts: an aluminum layer of 90 nm will be directly deposited on the photon entrance window of the sensor chip and the other part will be accommodated as foil in the filter wheel. The foil has a thickness of 150 nm of polyimide and 30 nm of aluminum. For the WFI instrument, no vacuum enclosure is foreseen and therefore the filter foil has to survive the acoustic noise loads arising during launch of the satellite. Analysis and tests are currently performed to verify that a mesh support prevents any performance degradation of the ultra-thin and fragile filter foil, e.g. by a rupture. Both optical blocking filters affect of course the quantum efficiency (QE) of the detector at low energies. At the carbon line (277 eV), the required quantum efficiency of >20% will be achieved. For higher energies the quantum efficiency

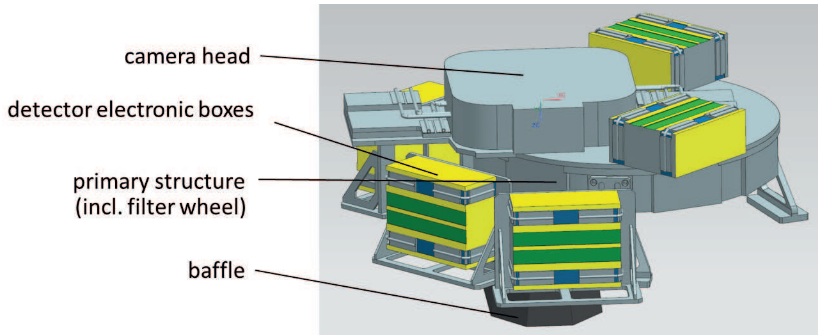

Figure 2. WFI instrument with its main subsystems: camera head comprising the detectors, five detector electronic boxes surrounding the camera head, the primary structure which is part of the filter wheel housing and the mounting interface to the science instrument module (SIM) of the satellite, the filter wheel and the optical stray–light baffle in front of it. Note that the two Instrument Control and Power Distribution Units, which are outside of the focal plane, are not shown here.

suffers little from the absorption by the optical blocking filters. At 1 keV energy, the QE is already >80% and at 10 keV even above 90% which meets the scientific requirements. The DEPFET sensor itself (i.e without coating) shows a high quantum efficiency due to the concept of backside illumination in combination with the implementation of an ultra-thin photon entrance window (accomplished by a shallow implant). Another stringent requirement to the WFI instrument is to achieve a non-X-ray background of $<5 \times 10^{-3}$ counts s^{-1} cm^{-2} keV^{-1} in the energy range from 2 keV to 7 keV in 60% of the observing time according to the science requirements. Coating of both sensor surfaces as well as anti-coincidence analysis by identification of particle hits with the detector itself will facilitate the attainment of this challenging goal. Furthermore, the contribution of low-energy electrons and protons, which are transmitted through and imaged by the mirror system, will be minimized. While typically on X-ray satellites only electrons are deflected, Athena employs for this purpose a magnetic diverter accommodated in front of the WFI, which deflects also low-energy protons from the LDA.

2. WFI Conceptual Design and Development

The conceptual design of the WFI instrument with its subsystems is shown in Fig. 2. X-ray photons are focussed by the Athena mirror system, which has a focal length of 12 m, onto either the WFI or the X-IFU instrument (Fig. 3). Regarding the WFI camera, there are actually two different focal points depending whether the LDA or the FD detector observes the X-ray sky. Pointing to any of the three focal points is accomplished by a tiltable mirror system mounted

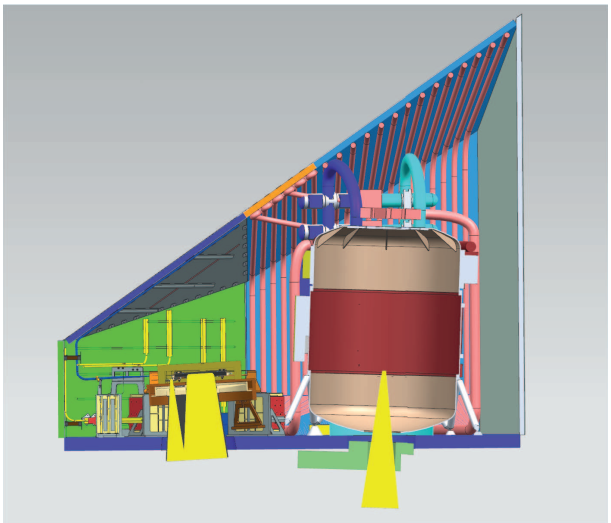

Figure 3. WFI instrument on the left and X-IFU instrument on the right accommodated on Athena's science instrument module (SIM). The related field of views for the FD and LDA of WFI and for the X-IFU detector are indicated at the bottom in the figure (image credits: ESA and MPE).

on a hexapod (Bavdaz et al., 2017). The source X-ray photons pass at first through the magnetic diverter and the optical stray-light baffle of WFI. Then they pass the filter wheel, which provides four positions for each of the two WFI detectors: I) the optical and UV blocking filter, II) the radioactive onboard calibration source to irradiate the sensor area with monochromatic X-ray photons for performance verification, III) the open position for optimum venting and outgassing as well as for special observations without filter (of the filter wheel) but higher quantum efficiency, and IV) the closed position whereby the detector is mechanically protected on ground and shielded against radiation in space. Finally, the X-ray photons hit the DEPFET sensor chip and generate signal electrons which are collected in the internal gate of the DEPFET (DEpleted P-channel Field Effect Transistor). This causes an increase of the transistor current which is proportional to the signal charge and thus to the photon energy. The Switcher-A ASICs select the lines for readout row by row, while the 64-channel Veritas-2.1 ASICs perform the readout of all pixels of a row in parallel. The signals are then multiplexed to one output per ASIC to minimize the number of ADCs. The detector is supplied and controlled by the Detector Electronics (DE) and the output signals are processed there in real-time in order to reduce the data to an acceptable rate. Electrical interface between the detector and the DE is a flexible lead integrated in the detector as shown in Fig. 1. The five DEs, four for the individual LDA quadrants and one for the FD, are controlled and supplied by the Instrument Control and Power distribution Unit (ICPU), which is implemented in cold redundancy. In contrast to the other subsystems of WFI, the two ICPU boxes can be accommodated outside the focal plane at a relatively large distance to the instrument. The ICPU is the electrical, command and data interface between the DEs and the spacecraft. It performs further data analysis and data compression before transmission to the mass memory onboard of the satellite.

The sensors, the front-end electronics ASICs, and the DEs require cooling but to different temperatures (Meidinger et al., 2017a). Therefore, different cooling chains are implemented which link the subsystem by heat pipes to dedicated radiator panels that are exposed to the cold space. The accurate control and stabilization of the detector temperature is performed by heater units.

The most complex development for the WFI instrument is that of the detectors, which are the key element of the camera. Prototype DEPFET sensors using different transistor design, fabrication process technology, and readout options have been developed with the goal to identify by measurements the optimum type. The Switcher-A ASIC as well as the Veritas-2.1 ASIC have been designed and tested for the Athena-WFI project, first just the ASIC characteristics and then integrated in the detector system. Such a small prototype detector, comprising a 64 × 64 pixel matrix, is shown in Fig. 4.

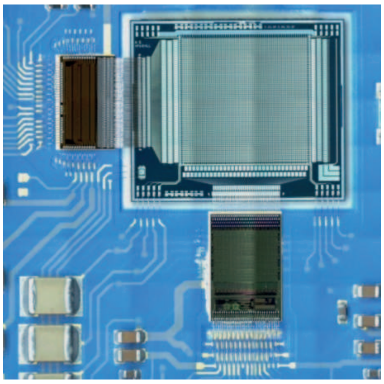

Figure 4. Prototype detector of WFI with 64 × 64 pixel sensor, the Switcher-A control ASIC to the left and the Veritas-2.1 readout ASIC at the bottom. The three silicon devices are connected by wire bonds.

With appropriate types of the sensor, spectra as shown in Fig. 5 have been measured. They yield full width at half maximum (FWHM) values of 130 eV at 5.9 keV photon energy and read noise values between 2.0 and 2.5 electrons rms under relevant operating conditions, in particular for the required fast readout of

2.5 µs per row for the FD (Meidinger et al., 2017a). For the LDA, a readout time requirement of 5 ms is defined corresponding to 9.8 µs per row. With a matrix of 256×256 pixels, which is a quarter of the flight-size matrix, a performance of 135 eV FWHM at 5.9 keV photon energy and a read noise of 3.2 electrons rms was measured for a readout time of 5 µs per row. This is a promising result, facing the fact that larger detectors require typically longer readout times per row because of larger RC time constants. The fast readout of large DEPFET arrays (matrices) is facilitated by a special readout mode enabled by Veritas-2.1, called drain readout. However this readout can only be used if the transistor currents of all pixels are quite uniform (Treberspurg et al., 2017). The alternative source follower readout mode is slower but less affected by inhomogeneities of the transistor currents over the sensor area. The final decision on the readout mode will be taken after further tests and analysis have been performed providing better statistics.

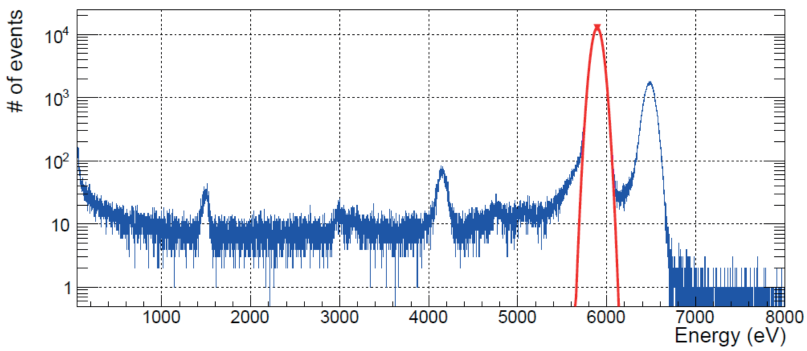

Figure 5. ^{55}Fe source spectrum measured with a small 64×64 pixel prototype DEPFET detector. At 5.9 keV photon energy of the Mn-K$_\alpha$ line, a FWHM of 130 eV is obtained.

3. WFI Status and Outlook

In the present phase A of the project, the conceptual design of WFI is defined and the necessary development of technologies is performed. Critical subsystems with respect to the development are the verification of detector function and performance, the real-time capability of the onboard signal processing chain and whether the ultra-thin large-area optical blocking filter withstands the acoustic noise loads which arise during launch in ambient conditions. The latter is critical as no vacuum enclosure is planned.

In the course of the technology development, various prototype detectors comprising the key components: DEPFET sensor, Switcher-A ASIC and Veritas-2.1 ASIC, have been developed and tested as described in section 2. The results determine in particular the design and technology of the pre-flight DEPFET sensors, which will be the first devices of flight-size, but drive also the redesign of Veritas-2.1 to achieve optimized performance.

For verification of the signal processing chain, a breadboard is developed using a Microsemi RTG4 FPGA as central element. All necessary steps for signal correction and filtering will be tested in particular to evaluate the time needed for this and to verify the real-time processing capability. A rigorous data reduction onboard of the satellite is mandatory because of the high frame rate combined with the large number of pixels. Otherwise, the WFI data rate would far exceed the allowed telemetry rate to ground.

Tests in acoustic noise facilities complemented by vibration tests shall demonstrate that the 17 cm x 17 cm large and 180 nm thin optical blocking filter survives the satellite launch. This should be possible by support of the filter foil with an appropriate mesh and by a design of the filter wheel which minimizes the loads. First tests have already been performed and the verification test will be conducted within the current technology development phase.

Furthermore, an optimized thermal system has been studied and designed. It is subdivided in three different thermal chains, all based on passive cooling.

Trade-offs have been performed for various concept options to obtain an architecture of the WFI instrument compliant with the requirements to the instrument, especially with respect to energy, time, and spatial resolution, quantum efficiency, instrumental background, as well as technical budgets like mass, volume, power consumption, and radiator area.

After the technology development and breadboarding phase, which shall be finished in 2018, an engineering model and a structural-thermal model of the WFI will be developed and tested, followed by the qualification model, and finally the flight model. The launch of Athena is scheduled for 2028/2029 with destination to Lagrange point L2.

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