ATHENA
THE ADVANCED TELESCOPE FOR HIGH ENERGY ASTROPHYSICS

A mission addressing *The Hot and Energetic Universe* science theme

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2 EXECUTIVE SUMMARY

The Hot and Energetic Universe (Nandra et al. 2013) has been selected as the Science Theme for the second large-class mission, due for launch in 2028, in ESA's Cosmic Vision program. The theme poses two key astrophysical questions: 1) How does ordinary matter assemble into the large-scale structures we see today? and 2) How do black holes grow and shape the Universe? To address the first question, we must map hot gas structures in the Universe - specifically the gas in clusters and groups of galaxies, and the intergalactic medium - determine their physical properties, tracking their evolution through cosmic time. To answer the second question we must reveal supermassive black holes (SMBH), even in obscured environments, out into the early Universe, and understand both the inflows and outflows of matter and energy as the black holes grow. Because most of the baryonic component of the Universe is locked up in hot gas at temperatures of around a million degrees, and because of the extreme energetics of the processes close to the event horizon of black holes, understanding the Hot and Energetic Universe requires space-based observations in the X-ray band.

Specifically, the theme calls for spatially-resolved X-ray spectroscopy and deep wide-field X-ray spectral imaging with performance greatly exceeding that offered by current X-ray observatories like *XMM-Newton* and *Chandra*, or by missions soon to be launched such as *Astro-H* and *SRG/eROSITA*. This capability requires an X-ray telescope combining unprecedented collecting area (2 m^2 at 1 keV) with an excellent angular resolution (5") and a wide field of view (40'x40'). New instrumentation providing spatially-resolved high resolution spectroscopy will yield the physical parameters of hot gas structures out to high redshift and map the intergalactic medium in the nearby Universe. A wide field instrument performing spectrally-resolved imaging over a broad energy band is required to determine the evolution of supermassive black holes into the early Universe, and shed new light on black hole accretion and ejection processes, over a wide range of masses from Galactic compact objects to the largest supermassive black holes.

A detailed analysis of the scientific questions underlying the Hot and Energetic Universe theme sets the key performance parameters for the mission. Mapping the dynamics and chemical composition of hot gas in diffuse sources requires high spectral resolution (2.5 eV) imaging with large area and low background; the same capabilities also optimize the sensitivity to weak absorption and emission features needed to uncover the hot components of the intergalactic medium. High resolution X-ray spectroscopy of distant gamma-ray bursts (GRBs) may reveal the signature of the first generation of stars, provided that the observatory can be repointed within 4 hours of an external trigger. An angular resolution lower than 5" is needed to disentangle point-source and sub-clump contaminants from the extended thermal emission in clusters, groups and galaxies. The same angular resolution is needed to resolve the dominant core emission and smaller accreting structures in galaxy clusters and groups up to redshift $z\sim2$. This resolution, when combined with the mirror effective area, also provides the necessary flux sensitivity ($\sim10^{-17}$ erg cm^{-2} s^{-1} in the 0.5-2 keV band) to uncover typical accreting SMBH at $z>6$. The areal coverage needed to detect significant samples of these objects within a reasonable survey time demands a large field of view instrument, combined with excellent off-axis response for the X-ray optics. The spectral resolution of the same instrument will reveal the most obscured black holes at the peak of the Universe's activity at z=1-4. High timing resolution and high count rate capability will shed new light on nearby accreting black hole systems.

All these capabilities combine in the *Athena* concept, which we propose herein to be implemented as the L2 mission to address the Hot and Energetic Universe science theme. *Athena* consists of a single X-ray telescope with a fixed 12 m focal length (Willingale et al. 2013), based on ESA's Silicon Pore Optics (SPO) technology. SPO provides an exceptionally high ratio of collecting area to mass, while still offering the necessary angular resolution. It also benefits from a high technology readiness level (TRL) and a modular design highly amenable to mass production, necessary to achieve the unprecedented telescope collecting area. The telescope focuses X-ray photons onto one of two instruments, which can be moved in and out of the focal plane using a movable instrument platform. In combination with the telescope, these two instruments provide the capabilities required to meet the Hot and Energetic Universe science goals.

The first instrument, the X-ray Integral Field Unit (X-IFU; Barret et al. 2013), provides spatially-resolved high resolution spectroscopy. The instrument is based on cooled Transition Edge Sensors (TES). These can deliver the necessary energy resolution, while providing exceptional efficiency compared to the dispersive spectrometers flown on the current generation of X-ray observatories. The TES technology has already demonstrated the required spectral resolution (2.5 eV) but needs to be developed further to provide this over a large field of view (5' diameter). Background in the X-IFU is mitigated using an active anti-coincidence layer, which is important to achieve the science goals for spectroscopy of faint extended sources.

The second instrument, the Wide Field Imager (WFI; Rau et al. 2013), is a Silicon-based detector using DEPFET Active Pixel Sensor (APS) technology. As X-ray spectroscopic imaging devices, the DEPFETs provide almost Fano-noise-limited energy resolution and minimal sensitivity to radiation damage. Because each pixel is addressed individually, readout modes can be highly flexible and extremely fast. With the development of appropriate readout ASICs, a time resolution of around 10μs is achievable as well as a count rate capability sufficient to deal with the brightest X-ray sources in the sky. The large field of view is achieved via a focal plane composed of several chips, where one of them will be enable fast readout to accommodate measurements of very bright targets.

To revolutionize our understanding of the Hot and Energetic Universe, the telescope and science instruments must employ state-of-the-art technology, which requires a vigorous technology development program in advance of mission adoption (2018-2019) to ensure that the implementation phase can be entered with minimal risk. The ESA-funded SPO program has made excellent progress and further investment should lead to a demonstration of the *Athena* angular resolution requirement with a representative module in the near future. Technology developments for the focal plane instruments require immediate investment by the ESA Member States (MS) and ESA where appropriate, to ensure all key elements reach TRL 5-6 by the time of mission adoption.

It is expected that *Athena* will be launched via an Ariane V-class launch vehicle into a halo orbit around the Sun-Earth second Lagrangian point (L2), with a nominal mission lifetime of 5 years. L2 provides a stable environment and high observing efficiency. The *Athena* spacecraft design is relatively conventional, and benefits from much heritage from *XMM-Newton*, and prior studies for the International X-ray Observatory (*IXO*) and the *Athena* concept proposed for the L1 slot (*Athena*-L1; Barcons et al. 2012). The current *Athena* concept incorporates important enhancements compared to *Athena*-L1, yet represents a realistic evolution in performance for a mission to fly in 2028. This includes a doubling of the telescope effective area (to 2 m^2 at 1keV); an improvement in the angular resolution by a factor ~2 (to 5") and quadrupling of the fields of view of both the WFI and X-IFU. Compared to the *IXO* concept, *Athena* offers similar capabilities, but is considerably simplified and better optimized to the Hot and Energetic Universe science goals. The shorter focal length telescope provides a larger field of view and lower background, and allows use of a fixed optical bench. The instrument complement also has been greatly simplified to focus only on those needed to satisfy the science of the Hot and Energetic Universe theme.

Athena will be operated as an observatory, in a similar fashion to prior missions such as *XMM-Newton* and *Herschel*. Users will access the observatory via open proposal calls. The Mission Operations Centre (MOC) and Science Operations Centre (SOC) will be under ESA management, with an additional contribution to the ground segment coming from the ESA MS.

The funding and management scheme for the implementation of the mission follows standard practice for ESA large observatories. ESA will be expected to take responsibility for provision of the spacecraft (including the movable instrument platform), the launcher, the MOC and the SOC, and the project management, advised by a team of scientists from the community. The X-ray telescope is also expected to be an ESA-provided item, as are the pre-coolers for the X-IFU. The ESA MS will fund and provide the focal plane instruments i.e. the X-IFU and the WFI. The entire *Athena* observatory including the focal plane instruments can be provided using only European technology. On the other hand, international partners have expressed interest in participating in the mission, and could be accommodated subject to satisfactory negotiation with ESA and the ESA MS. Such contributions may serve to reduce costs or mitigate risks.

The implementation of *Athena* for a launch in 2028 will guarantee a transformation in our understanding of The Hot and Energetic Universe, providing an essential complement to contemporary facilities working in other wavebands in that timeframe. *Athena* will exploit the strong European heritage in hardware development and scientific discovery in X-ray astronomy, maintaining leadership in high-energy astrophysics from *XMM-Newton* into the foreseeable future.

3 INTRODUCTION

As outlined above, the Hot and Energetic Universe science theme calls for answers to two fundamental questions in astrophysics:

- How does ordinary matter assemble into the large scale structures that we see today?
- How do black holes grow and shape the Universe?

These key questions will be answered with *Athena* (Nandra et al. 2013). In designing the mission, we must first formulate specific observational tests that address the science questions. To provide an illustrative example, a key issue in the formation and evolution of clusters of galaxies is the degree of turbulence and hence non-thermal pressure support in the cluster gas. Models predicting the expected level of turbulence lead to a requirement on the spectral resolution of the X-ray detector. The detector must at the same time be capable of spatially resolving the turbulence to see, for example, if it is related to energy injection by a supermassive black hole or is triggered by the hierarchical cosmological assembly of the galaxy clusters. Finally, the telescope must deliver sufficient photon collecting area so that observations of the physical properties of the hot gas structures can be traced to the formation epoch at $z\sim2$. A detailed analysis of the underlying science questions of the Hot and Energetic Universe and their translation into science requirements is provided in **Section 4**. Additional science enabled by the unique and revolutionary capabilities of the *Athena* observatory is also highlighted in that section (**Section 4.4**).

Athena will be operated in a relatively standard way as a space borne astronomical observatory observing a variety of celestial targets, with the mission profile detailed in **Section 5**. The science requirements dictate the required technologies for the telescope and instrument suite. The *Athena* payload is described in more detail in **Section 6**.

This payload is assembled in a relatively conventional spacecraft configuration, described in **Section 7**. The science operations concept for *Athena* will be standard for ESA observatories like *XMM-Newton* or *Herschel,* with similar communication and ground segment requirements, described in **Section 8**. Technology developments - discussed in **Section 9** - are minimal at spacecraft level. The telescope and the focal plane instruments, on the other hand, require a coordinated technology development effort by ESA and the ESA MS during phase A/B1 to raise the enabling technologies to TRL 5/6 at the time of mission adoption.

The cost of the mission will be shared by ESA and the ESA MS. ESA should provide the spacecraft, launcher, telescope, project management and operations. The ESA MS will lead the focal plane instruments and a contribution to the scientific ground segment. Programmatic issues and costs are discussed in **Section 10**.

4 SCIENTIFIC REQUIREMENTS

The Hot and Energetic Universe white paper (Nandra et al. 2013) describes a comprehensive and coherent science theme with many interlinked components, and the reader is referred to that document and the supporting papers for a full description of the science motivating the *Athena* mission (Pointecouteau, Reiprich et al., 2013; Ettori, Pratt et al. 2013; Croston, Sanders et al. 2013; Kaastra, Finoguenov et al. 2013; Aird, Comastri et al. 2013; Georgakakis, Carrera et al. 2013; Matt, Dovciak et al. 2013; Cappi, Done et al. 2013). Here, we have decomposed the science theme into a number of more specific science goals. We define Level 1 science goals (**SGx,** shown in red below) as comprehensive, overarching issues to be addressed under the theme. Level 2 science goals (**SGx.y**, shown in blue below) are specific questions for the Level 1 SG, to be addressed directly through observations with *Athena*. For each Level 2 SG, the observational aim is described. The required performance parameters are derived from the Level 2 SG. Note that most of the goals depend on many parameters, but we identify below only those key parameters that drive the final science requirements. The main science requirements are summarized in **Table 4.1**. The White Paper on the Hot and Energetic Universe also identifies a number of additional science cases that can be addressed with the performance needed to meet the main goals of the theme (Branduardi-Raymont, Sciortino, et al. 2013, Sciortino, Rauw et al., 2013, Motch, Wilms, et al., 2013, Decourchelle, Costantini, et al. 2013, Jonker, O'Brien et al., 2013). We highlight a representative set of this science at the end of this section (as **OSG** for Observatory Science Goals).

4.1 DERIVING REQUIREMENTS FROM SCIENCE GOALS

SG1 - FORMATION AND EVOLUTION OF GROUPS AND CLUSTERS OF GALAXIES

The largest gravitationally bound structures in the Universe formed by the accretion of baryons into deep dark-matter potential wells. Models for their formation can be tested by determining how these baryons accreted and dynamically evolved in groups and clusters of galaxies out to their expected formation epoch at $z\sim2$, and by quantifying the importance of non-gravitational processes in large-scale structure evolution.

SG1.1 - FINDING EARLY GROUPS: As a way to constrain models of large-scale structure formation, find the first building blocks of the dark matter structure filled with hot gas.

OBSERVATIONAL AIM: Detect 50 evolved groups at $z>2$ with $M_{500}>5 \times 10^{13}$ M_{sun} and determine the gas temperature of 25 of them (M_{500} is the mass contained within R_{500}, defined as the radius at which the mean mass density exceeds the critical density by a factor 500. A similar definition applies for M_{200} and R_{200}). Discover at least 5 groups at z>2.5 with M_{500}>5 x 10^{13} M_{sun}. This will be achieved as part of a multi-tiered *Athena*/WFI survey program, which addresses several science goals (see Aird, Comastri et al. 2013 for a discussion on a possible survey strategy).

KEY PARAMETERS: Effective area at 1 keV, WFI field of view, PSF HEW.

SG1.2 - MATTER ASSEMBLY IN CLUSTERS: Determine how baryons assemble and dynamically evolve into galaxy clusters, by measuring how gravitational energy is dissipated into bulk motions inside clusters and stored in gas turbulence.

OBSERVATIONAL AIM: Determine the energy stored in cluster gas in the form of either gas bulk motions or gas turbulence to 20% precision, assuming typical values of 200 km/s in the cores and larger values (400 km/s or more) outward to R_{500}. Gas bulk velocities and turbulence need to be measured to a precision of 20 km/s in the inner parts and to 40 km/s outwards.

KEY PARAMETERS: X-IFU spectral resolution, X-IFU energy calibration accuracy, X-IFU field of view, Charged particle background at 5 keV, Effective area at 6 keV.

SG1.3 – NON-GRAVITATIONAL HEATING PROCESSES: Determine the dominant physical process (e.g. AGN, supernovae, etc.) at each epoch in their cosmic history, which injected non-gravitational energy into clusters.

OBSERVATIONAL AIM: Measure entropy profiles in groups (down to ~5 × 10^{13} M_{sun}) and clusters (up to ~10^{15} M_{sun}) out to their virial radius (R_{200}) in the local Universe. Investigate their evolution out to z~2 within R_{500}. This requires X-ray surface brightness and gas temperature measurements down to the background-dominated regime.

KEY PARAMETERS: PSF HEW, WFI field of view, Charged particle background at 5 keV.

SG2 – CHEMICAL EVOLUTION OF HOT BARYONS

The massive dark matter haloes containing groups and clusters of galaxies are the largest baryonic reservoirs in the Universe and act as closed boxes, as far as the heavy element abundances are concerned. Metals are produced by stellar processes and released into the ISM via supernovae (SN) and AGB stars. The hot intra-cluster gas is chemically enriched by a variety of processes such as AGN and supernova winds, ram-pressure stripping etc. The metallicity pattern of the hot baryonic component is therefore very sensitive to the fraction of various SN types, the IMF, and the mechanisms at play to disperse the metals.

SG2.1 – METAL PRODUCTION AND DISPERSAL: Probe SN feedback and star formation activity through cosmic time and constrain the IMF through the metal enrichment of the ICM. Determine the mechanism whereby metals were dispersed within clusters.

OBSERVATIONAL AIM: Measure the abundances and distribution of metals in clusters from the core to the boundary of the virial regions (~R_{200}) using, e.g., Fe, C, O, Si and Mg. Constrain SN yields via, e.g., C, Ne, and for the first time ever, Cr and Mn. Study their evolution with a representative sample spanning a broad range in redshifts (0< z <2) and masses (5 × 10^{13} < M < 10^{15} M_{sun}) using Fe, O, Si in their cores (r < 0.3 R_{500}) and in their outer parts (0.3 <r <1 R_{500}).

KEY PARAMETERS: X-IFU field of view, WFI field of view, Charged particle background at 5 keV.

SG3 – AGN FEEDBACK IN CLUSTERS

AGN energy is often deposited on cluster scales, with the most obvious evidence seen in the relationship between cluster hot gas and AGN radio jets. Open questions include how much AGN mechanical energy is accumulated on cluster scales, how it is locally dissipated in the ICM and out to what distances from the cluster centre this phenomenon operates. In cluster cores, AGN prevent hot gas cooling towards massive central galaxies, largely suppressing cold gas phases through feedback in a very delicate balance, whose physical nature needs to be investigated.

SG3.1 – JET ENERGY DISSIPATION ON CLUSTER SCALES: Understand how AGN jets deposit energy in their environment, by excavating bubbles of relativistic plasma that displace group and cluster hot gas.

OBSERVATIONAL AIM: Measure the energy stored in hot gas around the bubbles in a volume-limited sample of galaxies and clusters. Determine mechanical energy to 20% precision through measurements of gas bulk motions and turbulence (both expected to be of the order ~200 km/s) down to 20 km/s error.

KEY PARAMETERS: PSF HEW, X-IFU spectral resolution, X-IFU field of view, X-IFU energy calibration accuracy, Absolute astrometric error.

SG3.2 – AGN RIPPLES IN CLUSTERS: Perform a population study of the AGN-induced perturbations (ripples) over a broad range of spatial scales, AGN and cluster properties, yielding an unbiased measurement of the occurrence and impact of these feedback phenomena.
OBSERVATIONAL AIM: Detect ripples in surface brightness, produced by AGN feedback mechanisms, across the full volume of the cluster for a volume-limited sample of nearby clusters.
KEY PARAMETERS: PSF HEW, WFI field of view.

SG3.3 – X-RAY COOLING CORES: Determine which gas fuels the AGN in order that its jets just balance the gas cooling rate and prevent the gas from cooling further.
OBSERVATIONAL AIM: Determine how much gas is at each temperature in cluster cores, via temperature-sensitive line ratios (e.g. OVII and FeXVII lines) for a representative sample of nearby clusters.
KEY PARAMETERS: X-IFU spectral resolution, X-IFU field of view.

SG3.4 – CUMULATIVE ENERGY DEPOSITED BY RADIO GALAXIES: Determine shock speeds and, from these, infer the corresponding radio-galaxy age by measuring the thermodynamical conditions of the shocked gas components in the environment of FRII radio galaxies, spanning a broad range of radio powers and sizes.
OBSERVATIONAL AIM: Obtain thermodynamical properties of the shocked gas regions in 40 FRII radio galaxies, to sample a sufficient range in radio powers and sizes. These shocked regions typically have 10% of the expanding lobe sizes (1'-15'), surface brightness profiles 2.5 times larger than the surrounding gas and higher temperatures that need to be distinguished at > 3σ from the un-shocked gas temperatures.
KEY PARAMETERS: PSF HEW, Absolute astrometric error, WFI field of view.

SG4 – MISSING BARYONS

A large fraction of baryons at z<1-2 is thought to populate the intergalactic medium, in the form of large scale filaments with gas temperatures in the range 10^5-10^7 K (WHIM). *Athena* will systematically characterize their physical and chemical properties of filaments, assess their contribution to the baryon budget, identify the prevalent mode of formation and metal circulation and measure their evolution out to z~1-2.

SG4.1 – A CENSUS OF WARM-HOT BARYONS: Measure the local cosmological baryon density in the WHIM to better than 10% and constrain structure formation models in the low-density regime by measuring the redshift distribution and physical parameters of WHIM filaments.
OBSERVATIONAL AIM: Detect 200 filaments against bright background sources: 25 nearby, bright AGN and about 40 distant GRBs, primarily through redshifted He- and H-like oxygen and possibly carbon resonant absorption lines.
KEY PARAMETERS: Effective area at 1 keV, X-IFU spectral resolution, X-IFU low energy threshold, X-IFU optical blocking filter attenuation, GRB trigger efficiency.

SG4.2 – THE PHYSICAL PROPERTIES OF WHIM FILAMENTS: Constrain structure formation models in the higher density WHIM regions by directly measuring their physical parameters.
OBSERVATIONAL AIM: Simultaneous emission spectroscopy of ~ 30% of absorption systems as described in SG4.1 will allow for direct measurement of the gas density and other parameters in tens of systems. Follow-up observations of strong absorption systems in GRBs.
KEY PARAMETERS: Effective area at 1 keV, X-IFU spectral resolution, X-IFU low energy threshold.

SG5 – FORMATION AND EARLY GROWTH OF BLACK HOLES

In order to understand how SMBH influence galaxies, the AGN population needs to be characterized – particularly the early and obscured growth of SMBH. Samples of moderate luminosity AGN need to be built to the highest redshifts, well into the re-ionisation epoch, when SMBH and their host galaxies were still young (z>6-8). In addition the first generation of stars populating galaxies at such early epochs needs to be characterised, to provide a full picture of the formation of the first galaxies at the epoch of reionisation.

SG5.1 – THE HIGH-Z AGN POPULATION AND THE SEEDS OF SMBH: Determine the nature of the seeds of the earliest growing SMBH (z>6), characterize the processes that dominated their early growth and investigate the influence of accreting SMBH on the formation of galaxies.
OBSERVATIONAL AIM: Construct a large sample of AGN up to z~6-8 and beyond, down to luminosities L_X~10^{43}-10^{44} erg/s, to populate the L_X-z plane at high redshift, specifically: identify more than 400 AGN at z>6; including more than 20 AGN with $10^{43}<L_X<10^{44}$ erg/s at z=6-7 and more than 20 AGN with $10^{44}<L_X<10^{45}$ erg/s at z=8-10. This will be achieved as part of the multi-tiered *Athena*/WFI survey program

(Aird, Comastri et al. 2013, for details), which addresses several science goals (e.g. SG1.1). Deep follow-up observations with the X-IFU may determine redshifts for the most distant obscured SMBH.
KEY PARAMETERS: Effective area at 1 keV, PSF HEW, WFI field of view, Reconstructed astrometric error.

SG5.2 – PROBING THE FIRST GENERATION OF STARS: Determine the elemental abundances of the medium around high-z GRBs to probe the first generation of stars, the formation of the first black holes formed in the Universe, the dissemination of the first metals and the primordial IMF.
OBSERVATIONAL AIM: Measure (or constrain) absorption features from heavy elements and derive relative elemental abundances distinctive of primeval (Pop III) explosions versus evolved stellar populations in the spectrum of GRB afterglows, using fast *Athena* Target of Opportunity (TOO) observations of 25 of the highest z-GRB.
KEY PARAMETERS: Effective areas at 1 keV and 6 keV, GRB trigger efficiency, X-IFU field of view

SG6 – ACCRETION THROUGH COSMIC TIME

During their growth, SMBH are expected to go through heavily obscured phases and to strongly influence their host galaxy through winds and outflows. The bulk of this process happens at z~1-4. The aim is to understand the physical conditions under which SMBH grew at that epoch, and in particular: find out what fraction of the accreting SMBH occur in heavily obscured environments, determine how frequent ionized absorbers around AGN are and finally measure the mechanical energy of outflows in luminous AGN/QSOs.

SG6.1 – COMPLETE CENSUS OF AGN AT THE PEAK OF ACTIVITY OF THE UNIVERSE: Determine the accretion energy density in the Universe, including the most heavily obscured AGN up to z~3.5.
OBSERVATIONAL AIM: Measure the X-ray luminosity function of the AGN population well within the Compton thick regime by identifying and measuring the intrinsic properties (accretion luminosity, obscuring column density) of at least 20 Compton thick AGN per luminosity bin (0.5dex) and redshift bins (Δz=1) up to redshift z~3.5.
KEY PARAMETERS: PSF HEW, Effective areas at 1 & 6 keV, WFI field of view, Charged particle background, Reconstructed astrometric error

SG6.2 – THE INCIDENCE OF OUTFLOWS IN LUMINOUS AGN AT Z=1-4: Determine the incidence of strong and ionized absorbers, implying the presence of outflows, among the population of luminous AGN from z=1 to 4.
OBSERVATIONAL AIM: Among luminous AGN (L_X>L*, L* is a typical luminosity at a given z defined as the knee of the luminosity function) at z>1 detected in a WFI multi-tiered survey, identify the X-ray spectral signatures of ionized absorption, and measure the absorber ionisation and column density.
KEY PARAMETERS: Effective area at 1 keV.

SG6.3 – MECHANICAL ENERGY OF AGN OUTFLOWS AT Z=1-4: Measure the mechanical energy of moderately ionized outflows in L_X>L* AGN at z=1-4, spanning a broad range of column densities and ionization parameters.
OBSERVATIONAL AIM: Use X-IFU to measure outflow velocities and infer the energetics of ionized absorbers in up to 100 luminous (L_X>L*) AGN at z=1-4. For mildly ionized absorbers (log(ξ/erg s^{-1} cm) ~2.5), we require the measurement of outflow velocities below 1000 km/s, i.e. borderline between local Seyfert warm absorbers and QSO fast outflows. The target sample will include ionized absorbers identified in a WFI multi-tiered survey.
KEY PARAMETERS: Effective area at 1 keV, X-IFU low energy threshold

SG6.4 – INCIDENCE OF ULTRA-FAST OUTFLOWS IN QSOS AT Z>1: Determine the incidence, duty cycle and energetics of transient Ultra-Fast Outflows (UFOs) in QSOs at z>1.
OBSERVATIONAL AIM: Detect the Fe XXV Kα (6.7 keV rest frame) absorption line from UFOs (0.1-0.2 c) at the 3σ level in the WFI spectra of luminous QSOs (L_X >5 × 10^{44} erg/s) at z~1-4. The requirement for the identification efficiency of such features, if present, is at least 80%.
KEY PARAMETERS: Effective area at 1 keV.

SG7 – GALAXY-SCALE FEEDBACK

AGN and star-forming activity are fed by gas inflow on galactic scales, but in turn also shape galaxy evolution, potentially terminating star formation when strong winds and outflows are launched. The aim is to measure the energy contained in the outflows and determine their interaction with the galaxy and its circum galactic medium.

SG7.1 – MECHANICAL ENERGY FROM AGN WINDS AND OUTFLOWS: Measure the kinetic energy in nearby AGN outflows and understand how accretion disks around SMBH launch winds and outflows.
OBSERVATIONAL AIM: Measure the total absorbing gas velocity in a representative sample of bright nearby AGN (20 to 30), along with the total gas mass and metal content in order to quantify the associated mechanical energy within a 10% precision. For a few bright, nearby AGN, perform time-resolved spectroscopy on typical timescales of 5-10 ks to constrain the wind launching mechanisms (radiation, momentum or magnetically-driven).
KEY PARAMETERS: Effective area at 6 keV, X-IFU optical blocking filter attenuation.

SG7.2 – INTERACTION OF WINDS FROM AGN AND STARBURSTS WITH THEIR ENVIRONMENT: Probe directly the interaction of winds from AGN and star-formation with their surroundings in local galaxies, to understand how the gas, metals and energy accelerated by winds are transferred into the circumgalactic medium, and to form a template for understanding AGN/starburst feedback at higher z.
OBSERVATIONAL AIM: Use spatially-resolved spectroscopy to map the velocity field of the hot gas with uncertainties of ~50-100 km/s on scales down to ~1 kpc in a statistically significant sample of 25-30 nearby AGN/ULIRG/starburst galaxies.
KEY PARAMETERS: X-IFU low energy threshold, X-IFU optical blocking filter attenuation.

SG8 – ACCRETION PHYSICS

Accretion onto SMBH drives AGN activity, whose influence on the galaxy scale must be understood. The physics of accretion under strong gravity conditions is not well known, and the geometry of the accretion flow is still to be determined. Black hole spins yield important information about the accretion-ejection process and the history of the black hole formation and evolution. It is important to build a unified picture of the accretion process across the compact object mass scale, from white dwarfs, neutron stars, stellar-mass black holes, ULXs, up to SMBHs.

SG8.1 – AGN REVERBERATION MAPPING: Determine the geometry of the hot corona-accretion disk system and constrain the origin of the hot corona.
OBSERVATIONAL AIM: Through reverberation soft X-ray time lag measurements, measure the response function in a representative sample of 8 bright AGN, chosen to span a large range in mass, luminosity and accretion rate, and where the presence of a reverberation lag has already been reliably established.
KEY PARAMETERS: Effective areas at 1 keV and 6 keV.

SG8.2 – MEASURING SMBH SPINS: Determine the SMBH spin distribution in the local Universe as a probe of the SMBH growth process (mergers vs accretion, chaotic vs standard accretion).
OBSERVATIONAL AIM: Measure the SMBH spin distribution in 30 objects, as required to distinguish between different growth histories.
KEY PARAMETERS: Effective area at 6 keV.

SG8.3 – MEASURING SPINS IN GALACTIC COMPACT OBJECTS: Measure black hole spins of Galactic Black Holes (GBH) to provide insight into black hole birth events (GRBs and/or SN) that set stellar-mass black hole spins, and to study the relationship between black hole spins and outflows (winds and jets).
OBSERVATIONAL AIM: Measure GBH spins through simultaneous Fe Kα emission line profile and continuum fitting both in time-averaged and in frequency-resolved spectra.
KEY PARAMETERS: Effective area at 6 keV, WFI spectral resolution at 6 keV, WFI count rate capability.

SG8.4 – REVERBERATION MAPPING OF X-RAY BINARIES: Determine the accretion geometry of GBH.
OBSERVATIONAL AIM: Measurement of the response of the time lag of the Fe Kα line to changes in the irradiating continuum, allowing a direct measurement of the geometry of the accretion flow close to the black hole.
KEY PARAMETERS: Effective area at 6 keV, WFI spectral resolution at 6 keV, WFI count rate capability.

4.2 SUMMARY OF MAIN SCIENCE REQUIREMENTS

Next we list the main science requirements for *Athena*. Note that the requirements on the mirror effective areas are given assuming the quantum efficiencies of the two *Athena* instruments, as quoted in **Section 6.**

Performance parameter	Requirement	Level 2 Science Goal
Effective area at 1 keV	2 m^2	SG1.1 Finding early groups; SG4.1 Census of warm-hot baryons; SG4.2 Physical properties of the WHIM; SG5.1 High *z* AGN population; SG5.2 Probing the first generation of stars; SG6.1 Complete census of AGN at the peak of activity of the Universe; SG6.2 Incidence of outflows in *z*=1-4 AGN; SG6.3 Mechanical energy of AGN outflows at *z*=1-4; SG6.4 Incidence of ultrafast outflows at *z*>1; SG8.1 AGN reverberation mapping
Effective area at 6 keV	0.25 m^2	SG1.2 Matter assembly in clusters; SG5.2 Probing the first generation of stars; SG6.1 Complete census of AGN at the peak of activity of the Universe; SG7.1 AGN winds and outflows; SG8.2 Measuring SMBH spins; SG8.3 Measuring spins in GBH
PSF HEW (at E<8 keV)	5" on axis 10" at 25' radius	SG1.1 Finding early groups; SG1.3 Non-gravitational heating processes; SG3.1 Jet energy dissipation in clusters; SG3.2 AGN ripples in clusters; SG3.4 Cumulative energy deposited by radio galaxies; SG5.1 High *z* AGN population; SG6.1 Complete census of AGN at the peak of activity of the Universe.
X-IFU spectral resolution	2.5 eV	SG1.2 Matter assembly in clusters; SG3.1 Jet energy dissipation on cluster scales; SG4.1 Census of warm-hot baryons; [SG3.3 X-ray cooling cores; SG4.2 Physical properties of the WHIM; SG5.2 Probing the first generation of stars, 3 eV]
X-IFU energy calibration accuracy (rms)	0.4 eV	SG1.2 Matter assembly in clusters; SG3.1 Jet energy dissipation on cluster scales
X-IFU field of view	5' diameter	SG1.2 Matter assembly in clusters; SG3.3 X-ray cooling cores; SG2.1 Metal production and dispersal; SG3.1 Jet energy dissipation in clusters; SG5.2 Probing the first generation of stars.
X-IFU low energy threshold	0.2 keV	SG4.1 Census of warm-hot baryons; SG4.2 Physical properties of the WHIM; SG7.2 Interaction of winds with their environment
X-IFU total optical blocking filter attenuation	Factor 10^{12} at 1200 Å	SG4.1 Census of Warm-Hot baryons; SG7.1 AGN winds and outflows; SG7.2 Interaction of Winds with their environment
WFI field of view	40' x 40'	SG1.1 Finding early groups; SG1.3 Non-gravitational heating processes; SG2.1 Metal production and dispersal; SG3.2 AGN ripples in clusters; SG3.4 Cumulative energy deposited by radio galaxies; SG5.1 High *z* AGN population; SG6.1 Complete census of AGN at the peak of activity of the Universe.
WFI spectral resolution at 6 keV	150 eV	SG8.3 Measuring spins in GBH; SG8.4 reverberation mapping of X-ray binaries
WFI count rate capability at 80% throughput	1 Crab=2.4 x 10^{-9} ergs s^{-1} cm^{-2} (2-10 keV).	SG8.3 Measuring spins in GBH; SG8.4 reverberation mapping of X-ray binaries
Charged particle background, determined to within a few %	<5 x 10^{-3} cts/cm^2/s/keV	SG1.2 Matter assembly in clusters; SG1.3 Non-gravitational heating processes; SG2.1 Metal production and dispersal; SG6.1 Complete census of AGN at the peak of activity of the Universe
Reconstructed astrometric error	1" (3σ)	SG5.1 High *z* AGN population; SG6.1 Complete census of AGN at the peak of activity of the Universe
Absolute astrometric error	3" (3σ)	SG3.1 Jet energy dissipation in clusters; SG3.4 Cumulative energy deposited by radio galaxies
GRB trigger efficiency[1]	40%	SG4.1 Census of warm-hot baryons; SG5.2 Probing the first generation of stars
TOO reaction time	< 4 hours	SG4.1 Census of warm-hot baryons; SG5.2 Probing the first generation of stars

Table 4.1: Key parameters and requirements for the *Athena* prime science goals. Those are achievable within a 5 year mission lifetime with a conservative 75% observing efficiency (see **Section 5.3**).

[1] Fraction of the time a GRB trigger produces a successful X-IFU observation within the TOO reaction time.

4.3 COMMENTS ON THE MAIN PERFORMANCE PARAMETERS

4.3.1 TELESCOPE-RELATED REQUIREMENTS

Effective area at 1 keV: The requirement of 2 m^2 is derived from many of the Hot and Energetic Universe science goals, which also set requirements on the effective area from 0.2 keV to 3 keV. A major driver is the required deliverables from the multi-tiered WFI survey, which requires 1 year of *Athena* observing time. This will yield the necessary sample of high z AGN (more than 400 at z>6, including >20 at z=8-10; SG5.1), populate the full L_X vs N_H parameter space for AGN up to z~2.5 (SG6.1), measure the incidence of outflows at z~2.5 (SG6.2) and find at least 50 galaxy groups at z>2 with mass M_{500}>5 x 10^{13} M_{sun} (SG1.1). Many pointed X-IFU observations also require long exposures which would be rendered infeasible with a smaller effective area. Examples include the full census of WHIM filaments (SG4.1) and the determination of their physical properties (SG4.2), and AGN reverberation mapping to probe accretion geometry (SG 8.1). Finally, probing the earliest generation of stars through GRB afterglow spectroscopy (SG5.2) strictly requires 2m^2, as longer exposures of declining afterglows would not collect enough counts.

Effective area at 6 keV: 0.25 m^2 is required to measure the spin of 30 SMBH in local AGN (SG8.2) and to detect z=2 Compton thick AGN (SG6.1). This is also required to perform time-resolved spectroscopy of local AGN in the search for fast (and variable) outflows on the appropriate timescales (SG7.1), as well as to perform Fe Kα line reverberation mapping in GBHs (SG8.4), because of the orbital periods involved. These time-resolved observations cannot be compensated for by longer observations with a lower effective area. They also require an effective area at 10 keV of 0.1 m^2, to measure the spectrum between 6 and 10 keV.

Point Spread Function (PSF): A PSF Half Energy Width (HEW) (at E<8 keV) of 5" on-axis is required to reach a confusion-limited sensitivity of 2.5 x 10^{-17} erg/cm^2/s in the deepest surveys, sufficient to find very faint moderate-luminosity high-z AGN (SG5.1, SG6.1). It is also required to enable highest signal to noise spectral extraction of faint sources (SG5.1, SG6.1). The average point source sensitivity across the WFI field of view required by this goal (PSF HEW of 10" at 25' radius) is such that only a configuration combining curved and conical-curved optics can deliver the required number of AGN within the observing time of the multi-tiered survey. At the same time, the centroid of these sources will be accurately determined to 1" across the WFI field of view, which is needed to find reliable counterparts, and also requires an oversampling of the PSF by a factor of 2 (pixel size <2.5"). This requirement on the PSF enables > 80% of the cosmic X-ray background to be resolved into sources, hence facilitating all sensitive low surface brightness observations, and in particular requires the excision of only a small sky area around the bright AGN in the centre of clusters or distant groups (SG1.1, SG1.3, SG3.1, SG3.3). A different type of requirement comes from the need to perform spatially-resolved high-resolution spectroscopy on low surface-brightness structures in clusters, such as shocks produced by radio-jets (SG3.1), expanding bubbles caused by AGN activity (SG3.3) or WHIM filaments in emission (SG4.2). The size of these structures requires both a PSF and an X-IFU pixel size of 5".

4.3.2 X-IFU-RELATED REQUIREMENTS

Spectral resolution: Measuring the local baryon density in the WHIM and its evolution to within 10% through absorption line spectroscopy against bright AGN and GRBs (total 200 absorption filaments, SG4.1), requires an energy resolution of 2.5 eV below 1 keV. This spectral resolution is a key factor limiting the weak line sensitivity. The same value is needed to measure bulk velocities to 20 km/s in local cluster cores (SG3.1) using the Fe Kα line (SNR=10), a goal which also requires an absolute energy calibration of better than 0.4 eV. A 3 eV resolution would be sufficient to use the OVII triplet as a temperature indicator in gas at around 3 x 10^6 K in cluster cores (SG3.3) and of the densest WHIM filaments (SG4.2). A similar requirement applies to the goal of probing the early generation of stars (SG5.2). The above requirements apply to sources fainter than ~1 mCrab. A throughput of high-resolution events larger than 80% would be required by WHIM absorption studies with bright (10 mCrab) GRB afterglows. Measurement of SMBH spins (SG8.2) and the mechanical energy from winds and outflows (SG7.1) with the X-IFU require an energy resolution below 30 eV for these brighter targets.

Field of view: A 5' diameter is needed to measure jet energy dissipation on cluster scales (SG3.1) and the thermal distribution in X-ray cooling cores (SG3.3) in single observations (a smaller field of view could be compensated by doing several pointings, but then the total time devoted will grow multiplicatively). This is also needed to integrate sufficiently large sky areas to detect the WHIM in emission (SG4.2), measure bulk velocities and turbulence in nearby clusters (SG1.2) and metal production and distribution in z>1 clusters (SG2.1). To perform afterglow spectroscopy (SG4.1, SG5.2), a field of view commensurate with the expected

GRB alert positional accuracy (typically 3' for coded-mask telescopes) is required.

Low energy threshold: The C V line (0.31 keV) is a key tracer of WHIM filaments (SG4.1 and SG4.2) and at modest redshift requires a low energy threshold of 0.2 keV with an effective area of 0.2 m². C V also traces the winds and outflows from AGN and starburst galaxies (SG7.2). It is also needed to detect the z>1.5 WHIM filaments through O VII resonance absorption against bright GRBs (SG4.1).

Optical blocking filters: A suppression factor of 10^{12} at 1200 Å is needed for stellar evolution observations (e.g. bright massive stars) with the X-IFU in order not to degrade its energy resolution, and possibly by observations of bright AGN (SG4.1, SG7.1). The filter(s) to be incorporated to the X-IFU filter wheel (on top of the instrument filters, e.g. aperture cylinder filters) will require detailed analysis during the study phase.

Absolute astrometric error: A precision of 3" (3σ) is required to relate features in the hot gas in clusters to emission in other bands, e.g. in the radio (SG3.1, SG3.4). A similar requirement is needed to ensure that the post-hoc astrometric error of point sources is achieved (see below).

4.3.3 WFI-RELATED REQUIREMENTS

Field of view: The combination of point source sensitivity and grasp of the multi-tiered survey requires a WFI field of view of 40'x40', both to get sufficient high-z AGN (SG5.1), Compton-thick AGN at z~3.5 (SG6.1) and early galaxy groups (SG1.1). The same field of view enables the measurement of entropy profiles (SG1.3) and metal production and dispersal (SG2.1) in clusters spanning a wide mass range and at redshifts from 0.15 to 2.

Spectral resolution: Measuring the spins of local SMBH (SG8.2) and GBH (SG8.3) using the Fe Kα line sets a requirement of 150 eV for the WFI spectral resolution at 6 keV, as does reverberation mapping of the GBH using the Fe Kα line (SG8.4).

High count rate capability: GBH timing and spectroscopy (SG83 and SG8.4) require a time resolution of 100 μs (also needed for observations of neutron stars). An additional requirement on absolute time calibration of 15 μs, will enable coordinated studies of pulsars with facilities operating at other wavelengths. Pileup, throughput and stability of dead-time will also have requirements that will need to be worked out in detail through simulations.

Reconstructed astrometric error: This is driven by the need to identify high redshift and obscured AGN with multi-waveband counterparts (SG5.1, SG6.1). This translates to a total on-axis positional accuracy of 1" (including statistical error) after reconstruction.

4.3.4 OTHER REQUIREMENTS

Charged particle background*:* All observations of low X-ray surface brightness sources at 6 keV, around the Fe line and at the energy of the bremsstrahlung exponential cutoff used to derive temperatures of the hot gas, place requirements on the charged particle background. A number of goals use the Fe Kα line at low z (SG1.2, SG2.1, SG3.1, SG3.3, SG6.1), which needs to be detected, typically with signal-to-noise ratio (SNR) larger than 5. SG1.3 requires accurate gas temperature measurements. Reproducibility of the background to a few % is also important for these goals. Continuous monitoring of background variations will thus be required. This might be achieved through some parts of the detector not being exposed to the sky.

TOO requirements: WHIM absorption (SG4.1) requires observations of 10 GRB per year with sufficient fluence to reach the limiting weak line sensitivity dictated by the X-IFU nominal spectral resolution (2.5 eV). This needs a pool of 200 GRBs per year, expected from external GRB triggers in the *Athena* era[2]. Assuming that 12% of the 200 GRBs will have sufficient fluence 4 hours after the trigger, obtaining 10 suitable GRBs per year translates to a field of regard (defined as the fraction of observable sky at any time) of 50% and a ground segment efficiency sufficient to get the X-IFU on target in at least 80% of the cases (see Table 4.1 for a definition of the GRB trigger efficiency).

[2] Implementing a sensitive GRB monitor on-board *Athena* would be too demanding in terms of resources, increasing the system complexity and cost. This would have a major impact on other mission parameters, such as the mirror effective area, absolutely critical for the overall success of the mission. *Athena* will thus rely on external GRB triggers.

4.3.5 GOALS

Athena would strongly benefit if some of the performance parameters required by the science goals could be exceeded. In some cases this will open up truly new territory in the mission capabilities and in other cases it will raise the observatory efficiency, enabling further scientific investigations to be performed. We now list those parameters where exceeding requirements will be most beneficial:

Effective area at 1 keV (2.5 m²): achieving this goal would reduce the time needed to execute the core science program of *Athena* leaving significantly more time available for additional science goals.

Effective area at 6 keV (0.3 m²): this goal would enable a larger sample of AGN reverberation measurements (SG8.1) using the Fe Kα line.

PSF HEW (3"): this would improve the deep survey speed, the ultimate sensitivity (via the confusion limit), and the positional accuracy, increasing the numbers of very high-*z* AGN (SG5.1) by up to a factor of 2.

X-IFU spectral resolution (1.5 eV): this goal will improve the weak absorption line sensitivity, increasing the number of WHIM filaments by a factor 2, and improve the accuracy with which the local baryon density is measured to a few % (SG4.1).

X-IFU field of view (7' diameter): lower redshift clusters can be mapped in a single exposure without the need for mosaic observations, and mapping the WHIM in emission more efficiently.

WFI field of view (50' x 50'): improved survey speed will yield larger samples of high-*z* galaxy groups and very high-*z* and obscured AGN (SG1.1, SG5.1, SG6.1).

4.4 ADDITIONAL SCIENCE ENABLED BY THE OBSERVATORY

Achieving the science goals described above provides *Athena* with unprecedented observatory capabilities, enabling breakthrough observations and new science to be performed for a wide range of objects, of great interest to astronomy at large. Below, we provide a non-exhaustive list of additional science goals to be addressed by *Athena*.

OSG1 – FEEDBACK THROUGH STELLAR WINDS: Stellar winds of massive stars are key players in feedback processes within individual galaxies. X-ray emission is a sensitive tool to probe wind structures and dynamics.

OSG1.1 – THE DYNAMICS OF STELLAR WINDS OF ISOLATED MASSIVE STARS: Determine the geometry of stellar wind structures, especially in the presence of magnetic fields.

OBSERVATIONAL AIM: Collect a significant sample of X-IFU spectra to investigate their line profiles (and any associated time variability) to diagnose large- and small-scale structures (porosity).

KEY PARAMETERS: X-IFU optical blocking filter attenuation, X-IFU spectral resolution, X-IFU low-energy threshold

OSG1.2 – WIND INTERACTION IN MASSIVE BINARIES: Map the hot gas distribution in the wind interaction zone of binary systems where the winds from both components collide.

OBSERVATIONAL AIM: Phase-resolved X-IFU spectroscopy of a sample of colliding wind binaries to Doppler-map the line emission regions of Fe Kα, Si XIV Lyα, etc.

KEY PARAMETERS: X-IFU spectral resolution, X-IFU energy calibration accuracy, X-IFU optical blocking filter attenuation

OSG2 – MAGNETIC PHENOMENA IN YOUNG AND VERY LOW-MASS STARS: Understand the response of the stellar photosphere and corona to accretion events and probe non-standard dynamos in X-ray faint ultra-cool dwarfs.

OSG2.1 – MAGNETOSPHERIC ACCRETION ONTO PHOTOSPHERE AND CORONA OF YOUNG LOW-MASS STARS: Probe the dynamics of the accretion process in young low-mass stars and investigate its contribution to the heating of the stellar photosphere (veiling) and corona.

OBSERVATIONAL AIM: Obtain time-series of high-resolution spectra to probe line-intensity variability from the accretion shock and post-shock plasmas, and the stellar corona.

KEY PARAMETERS: X-IFU spectral resolution, X-IFU low-energy threshold

OSG2.2 – MAGNETIC ACTIVITY OF ULTRA-COOL DWARF STARS (UCDS): Determine the strength of magnetic activity and underlying dynamo action, by measuring L_X/L_{bol}, and plasma temperature of young and old UCDs.

OBSERVATIONAL AIM: Measure the X-ray emission level and emitting plasma temperature of a sample of UCDs spanning a wide range of ages.

KEY PARAMETERS: Effective area at 1 keV

OSG3 – THE ASTROPHYSICS OF COMPACT OBJECTS: Determine the physical state of matter at supra-nuclear density, study the effects of magnetic fields in Galactic compact objects over ~6 orders of magnitude and solve the complex connection between accretion and ejection in compact binaries.

OSG3.1 – DETERMINING THE EQUATION OF STATE OF DENSE MATTER: Neutron stars provide the densest form of matter observable in the Universe. Accurate measurements of radius and mass with an accuracy of a few % can constrain the equation of state and determine the state of matter in neutron star cores.

OBSERVATIONAL AIM: Obtain X-ray spectra of a large sample (20) of quiescent X-ray binaries with a good distance estimate (e.g. from *Gaia*). Obtain energy-dependent folded light curves of a selected sample of (~10) millisecond pulsars. Perform high-resolution X-ray spectroscopy of ~10 neutron star surface absorption lines. Search for narrow absorption lines in type I X-ray bursts.

KEY PARAMETERS: X-IFU energy calibration accuracy, WFI time resolution, Absolute timing accuracy, Effective area at 1 keV, X-IFU spectral resolution, TOO reaction time, WFI count rate capability, X-IFU low energy threshold

OSG3.2 – THE CONNECTION BETWEEN ACCRETION AND WINDS: Determine how mass-loss develops in compact X-ray binaries and impacts the interstellar medium and how the process influences binary evolution. Understand the highest mass accretion rates in ULXs.

OBSERVATIONAL AIM: Perform multiple X-IFU observations on timescales shorter than the wind variability timescale, measuring velocities and ionisation states in the outflow.

KEY PARAMETERS: X-IFU spectral resolution, X-IFU energy calibration accuracy

OSG3.3 – SGR A*: Understand flare production in Sgr A*, the origin of the quiescent emission, and set constraints on the past AGN activity of Sgr A*.

OBSERVATIONAL AIM: Perform X-IFU observations with multi-wavelength coverage to measure the ionization process and physical properties of the plasma during the flaring and quiescent states.

KEY PARAMETERS: PSF HEW, X-IFU spectral resolution

OSG3.4 – SUPERNOVA PHYSICS: Understand the physics of core collapse and type Ia supernova remnants, quantifying the production of heavy elements, and the level of asymmetry in the explosion mechanism in terms of composition and velocity structures.

OBSERVATIONAL AIMS: 3D mapping of the hot ejected material (velocity, temperature, ionization state and composition) to determine the full geometry and properties of the different layers of shocked ejecta.

KEY PARAMETERS: X-IFU field of view, X-IFU spectral resolution, X-IFU effective area, PSF HEW, Absolute astrometric error

OSG4 – UNDERSTANDING THE STAR-PLANET INTERACTION

OSG4.1 – SOLAR SYSTEM BODIES: Establish how planetary magnetospheres and exospheres, and comets, respond to solar activity and to the interaction with the solar wind, in a global way that in situ observations cannot provide.

OBSERVATIONAL AIMS: Spectral mapping of Jupiter's atmosphere and aurorae, of the Io Plasma Torus, of Mars' exosphere and of the X-ray emission from comets. Fluorescence spectra of Galilean satellites for surface composition analyses. Search for Saturn's aurorae and sensitive constraints on Uranus' X-ray emission.

KEY PARAMETERS: X-IFU optical blocking filter attenuation, X-IFU field of view, X-IFU spectral resolution

OSG4.2 – EXOPLANETS: Explore the magnetic interplay between stars and planets in X-rays.

OBSERVATIONAL AIMS: Measure X-ray spectral variability over the activity cycle of the host star and over the planet's orbital period.

KEY PARAMETERS: Effective area at 1 keV

OSG5 –PROBING THE COMPOSITION OF DUST AND HOT GAS IN GALAXIES

OSG5.1 THE CHEMICAL COMPOSITION OF COLD PHASES IN THE INTERSTELLAR MEDIUM: Measure the absolute column density of dust along a given line of sight and the gas-to-dust ratio. Determine the split of the chemical elements between free atoms and different chemical bonds (e.g, atomic carbon, CO, ..). Determine the gas ionization ratio, the oxidation state of metals.

OBSERVATIONAL AIMS: X-IFU observation of X-ray-absorption fine-structure features (K and L edges) due to absorption by interstellar matter.

KEY PARAMETERS: X-IFU spectral resolution, Effective area at 1 keV, Effective area at 6 keV, PSF HEW, X-IFU low-energy threshold.

OSG5.2 X-RAY SCATTERING HALOS: Access the spatial distribution of dust around the line of sight.

Constrain dust models from the dust size distribution and dust composition. Estimate dust cloud distances, dust density profiles and grain alignment for haloes towards distant transient sources (e.g. GRBs) and towards nearby galaxies.

OBSERVATIONAL AIMS: X-IFU spectra of the scattering halo around bright point sources.

KEY PARAMETERS: X-IFU spectral resolution, Effective area at 1 keV, PSF HEW, X-IFU low-energy threshold

OSG5.3 HOT PHASES OF THE INTERSTELLAR MEDIUM: Determine the chemical composition, the heating and the dynamics of the hot gas of the interstellar medium, as a tracer of stellar activity in our and other galaxies. Constrain dust models.

OBSERVATIONAL AIMS: X-IFU spectrum of the hottest emission and absorption components of the ionized gas characterized by, e.g., OVII, OVIII, NeIX.

KEY PARAMETERS: X-IFU spectral resolution, Effective area at 1 keV, PSF HEW, X-IFU low-energy threshold

5 MISSION PROFILE

5.1 LAUNCHER AND PREFERRED ORBIT

Athena could be launched by Ariane V or another launch vehicle with equivalent lift capability and fairing size. It will operate at the second Sun-Earth Lagrangian point (L2) in a large halo orbit. The operational orbit will be reached with a direct transfer trajectory towards L2, with limited delta-V demands. This mission scenario is very well known to ESA thanks to missions such as *Herschel*, *Planck* and *Gaia*. The L2 orbit is preferred to alternative scenarios (e.g. low inclination LEO, HEO) as it provides a very stable thermal environment as well as good instantaneous sky visibility and high observing efficiency.

5.2 OPERATIONAL CONCEPT

Athena will predominantly perform pointed observations of celestial targets. There will be around 300 such observations per year, with durations ranging from 1 ks to 1 Ms, with typical duration 100 ks per pointing. This routine observing plan will be interrupted by TOO (e.g. GRBs and other transients) observations at a typical rate of twice a month. The observatory will have a set of standard operating modes (including normal pointing, manoeuvre, sun hold, and safe-mode), and a limited number of standard well-defined and calibrated science observing modes. The telemetry stream does not present significant drivers for the ground system and can be met with existing command and telemetry systems. Automated responses to contingency situations such as high levels of solar radiation can place the instruments into a safe configuration, and to later resume operations efficiently as soon as the alert has passed. *Athena* requires only standard ground-station coverage during launch, activation, cruise, and injection to L2. The orbit station-keeping and other L2 orbital characteristics do not in themselves require special coverage either.

5.3 MISSION LIFETIME

Athena has a baseline mission lifetime of 5 years, although for such an ambitious mission, consumables should be sized to enable an extension of at least 5 more years. A preliminary mock observation plan has been assembled using typical targets for both the driving science and the observatory science. Considering a conservative observing efficiency of 75%, this shows that *Athena* can reach the science goals of the Hot and Energetic Universe theme during the baseline mission, while preserving a large fraction (30-40%) of the available time for observatory science.

5.4 GROUND SEGMENT ASSUMPTIONS

Athena has no unusual ground system requirements for its operations. These can be met with a standard ESA ground segment approach for commanding, controlling and monitoring the spacecraft and instruments, and for the downlink of housekeeping and scientific data. The baseline is to locate the *Athena* Mission Operations Centre (MOC) at ESOC and the Science Operations Centre (SOC) at ESAC, with additional MS-funded contributions. The ground segment approach, including MS-provided elements, will be described in section 7.4.

5.5 COMMUNICATION REQUIREMENTS

For routine operations, the MOC should contact the spacecraft once a day, to downlink the science and housekeeping data, to uplink telecommand, and to perform health and safety checks of the spacecraft and science payload. Additional contacts will be required for TOO handling or to resolve anomalies. It is assumed that an appropriate network of ESA ground stations (e.g. Kourou, New Norcia) will be available to receive the telemetry, with no unusual requirements compared to past or planned missions in similar L2 orbits (e.g. *Herschel, Euclid*). The downlink capability from a spacecraft at the L2 Lagrange point using Ka band exceeds the requirement for *Athena*.

6 MODEL PAYLOAD

The *Athena* model payload comprises three key elements:

- A single X-ray telescope with a focal length of 12 m and an effective area of 2 m² at 1 keV.
- The X-ray Integral Field Unit (X-IFU), an advanced actively-shielded X-ray microcalorimeter spectrometer for high-spectral resolution imaging, utilizing cooled Transition Edge Sensors.
- The Wide Field Imager (WFI), a Silicon DEPFET Active Pixel Sensor camera with a large field of view, high count-rate capability and moderate resolution spectroscopic capability.

6.1 THE ATHENA X-RAY TELESCOPE

The *Athena* X-ray mirror design (Willingale et al., 2013) utilises SPO technology (Beijersbergen et al., 2004) which has now been under development by ESA for over a decade. SPO can provide the unique combination of large collecting area and good angular resolution across a large field of view, while meeting the mass budget: the areal density achievable with SPO is ~20 cm²/kg, which is more than a factor ~6 gain in mass compared with Ni electroformed optics used for *XMM-Newton*.

In SPO each pore acts as a very small sector of a Wolter I telescope. Two reflections from the inner surfaces of the pore bring the X-rays to a common focus. The pores have a cross-section of only a few mm², and ~1.5 million pores are required to provide the full collecting area. Arrays of pores are manufactured in modules using commercially available Si wafers that have excellent surface figure and roughness quality.

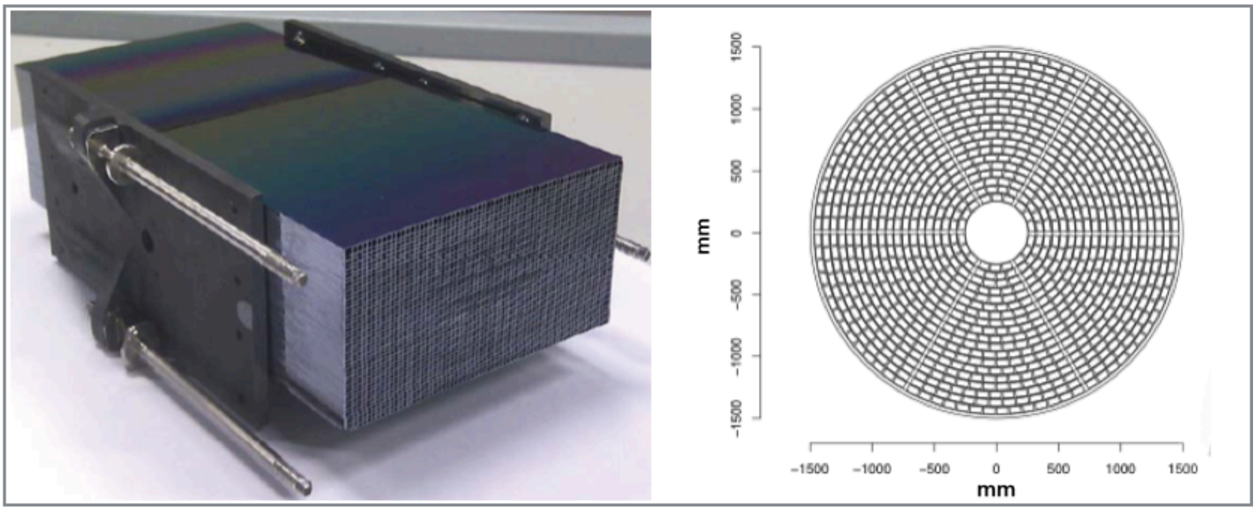

Figure 6.1: Left) A complete SPO module comprising two stacks. Right) Modules are arranged in 6 sectors and 19 rings to populate the aperture.

The wafers are diced into rectangles, typically 60 mm wide and with varying heights, and a thin wedge of material is deposited onto both sides of the wafer so that when they are stacked the reflecting surfaces are arranged in a radial pattern which provides a common in-plane focus. Regular rectangular grooves are cut leaving a thin membrane that supports the entire reflecting surface and ribs that form the sides of the pores. The wafers are curved to the appropriate radius of curvature using a precision mandrel so that reflecting surfaces match the surface of revolution required in a Wolter I optical system. The faces at the tops of the ribs are untouched and when the wafers are pressed together they cold-bond to the surface of the adjacent wafer, without any gluing, and form a rigid block containing an array of very regular, rectangular pores. Prior to bonding the reflecting surfaces can be coated with high-Z material, e.g. iridium, and an optional low density over-coating of e.g. B_4C to enhance the low energy reflectivity. This leaves uncoated strips, so that the top of the ribs of one wafer matches the pristine Si strips in the next wafer allowing the cold-bond to be made securely. An SPO module comprises two wafer stacks that form the paraboloid and hyperboloid surfaces of the Wolter I. Fig. 6.1 shows a complete module including mounting plates that incorporate 3 mounting lugs and pins used as an isostatic mount when integrating the complete SPO modules into the mirror aperture.

To achieve the required collecting area, the aperture diameter must be ~3 m and the focal length ~12m. Fig. 6.1 shows the aperture populated with 972 modules in 6 sectors and 19 rings. The radial support bars and the gaps between the modules are required to provide sufficient stiffness to maintain the module alignment under mechanical and thermal loads.

The radial width of the pores is fixed at d=0.605 mm by the manufacturing process and, in order to maximize the collecting area, the axial length of the surfaces must be inversely proportional to radius in the aperture, $L=4Fd/R$. The outer modules have L=2x20 mm while the inner modules have L=2x102 mm. These axial surface lengths are much shorter than conventional Wolter I telescopes, giving excellent off-axis performance. The best angular resolution across the field of view, up to off-axis angles of ~25', is obtained in a Wolter-Schwarzschild (W-S) configuration using a spherical surface of radius equal to the focal length (Chase & van Speybroeck 1973).

The on-axis HEW requirement is 5" at energies below 8 keV. Provided the manufacturing and integration tolerances for the modules are kept within a tightly specified error budget (Table 6.1), the angular resolution is limited by the axial curvature of the reflecting surfaces in the pores. The simplest approach is to use no axial curvature such that the reflecting surfaces are conical. Given the radial width and focal length the half energy width (HEW) of the PSF would be limited to >5". If, however, a very small axial curvature is introduced, e.g. by using a mandrel finely shaped via ion-figuring, the angular resolution can be improved. The optimum solution, which gives the minimum average HEW across the field, requires a conical first surface (no curvature) coupled with a second surface with curvature $-R/8F^2$ or a more general polynomial solution.

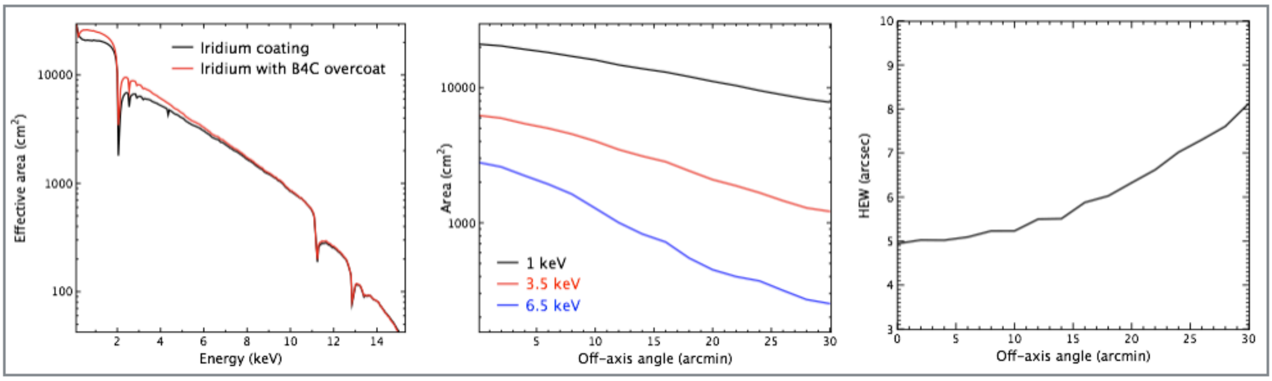

Figure 6.2: Left) On-axis area vs. energy. Black - iridium coating. Red - iridium with B_4C overcoat. Middle) The vignetting for a rib spacing of 3 mm at 1, 3.5 and 10.0 keV. Right) HEW as a function of off-axis angle.

The loss in off-axis collecting area (vignetting) is largely determined by the spacing between the ribs, which sets the azimuthal width of the pores. Provided this spacing is >3 mm then the off-axis area out to the edge of the field of view is close to the maximum possible, defined by the geometry of the stacked surfaces. The production of modules with optimum axial curvature and a rib spacing of 3 mm are currently under study. The performance of the optimized baseline design for the *Athena* X-ray optics is shown in Fig. 6.2.

Module	In-plane figure gradient errors	1.2" rms
	Out-of-plane figure gradient errors	1.5" rms
	Focal length (kink/wedge angle) error	1. mm
Integration	Module rotation error about optical axis	3"
	Module placement error in aperture	0.03 mm
	Module tilt error wrt optical axis	1'
MIP	Focal position error along optical axis	0.3 mm

Table 6.1: Allowed errors for various components for a 5" angular resolution

For a 40'x40' field of view, the grasp at 1 keV is 0.5 m^2 deg^2 and the average HEW across the field is 5.6", offering unprecedented capability for deep X-ray survey observations. If a coating of iridium with a B_4C overcoat is used for the reflecting surfaces, the 1 keV area can be increased from 2.0 to 2.5 m^2. Similarly, coating the reflecting surfaces of the inner modules with optimized multilayers can enhance the area at 6.5 keV from 0.26 to 0.3 m^2. The implementation of such coatings is currently under study. Note that the HEW will likely degrade at high energies (E>8 keV) because of X-ray scattering from surface roughness and manufacturing limitations associated with the inner aperture modules. However, such degradation does not affect the *Athena* capability to reach its driving science goals.

All Wolter I X-ray telescopes are susceptible to stray X-ray light that must be blocked to achieve the limiting sensitivity. This stray X-ray flux can be suppressed to an acceptable level (reduction by a factor of 10^3 is required for off-axis angle of 45') by mounting fine grids in front of the SPO modules and extending the silicon plates of the first stack forward a little to form baffles. Both these mechanical solutions have been implemented and tested in hardware. In addition to an X-ray baffle, a Sun shield will be required in front of the mirror. Optical stray light must also be mitigated. Magnetic diverters should be employed to deflect soft protons and electrons thereby reducing the particle background.

During SPO module manufacture the figure quality of the reflecting surfaces is monitored with high precision and an X-ray synchrotron beam is used to scan the reflecting surfaces in the stacks to set the kink angle. We therefore get important calibration data at the module level as a matter of course. After the modules are integrated into the support structure sectors (Fig. 6.1) the PSF and collecting area as a function of X-ray energy (especially the fine structures in the reflectivity around the edges) must be calibrated using wide aperture illumination at the MPE Panter X-ray test facility.

6.1.1 TRL AND DEVELOPMENT STATUS

The SPO, developed in Europe, is presently the most advanced X-ray optics technology applicable to *Athena*. SPO technology has reached TRL 4 within the last two years and is now approaching TRL 5. It has already demonstrated a HEW of 3.5" (double reflection from 4 plates of a stack of 45 layers), in representative X-ray test conditions. Moreover, environmental tests have already demonstrated that the qualification level requirements can be met and the issues of the large-scale production of the flight optics have been addressed, including process flow, manufacturing facilities, schedule and cost analysis.

Segmented Glass Optics (SGO) may have the potential to meet the *Athena* science requirements, and have been under development in the US and also Europe as part of the *IXO* programme and with ESA support (Pareschi, et al., 2011). SGO optics continue to be developed in Europe and have very promising performance potential, but they have not reached the level of technical maturity of the SPO. If deemed appropriate for the study phase, an assessment of the potential of SGO for the *Athena* mission should be conducted.

6.1.2 PROPOSED PROCUREMENT

The telescope is foreseen as an ESA-procured item. A MS-funded telescope scientist team should provide advice on the technology development, as well as performing the calibration and testing of the optics.

6.2 THE X-RAY INTEGRAL FIELD UNIT

The X-ray Integral Field Unit (X-IFU) is an evolution of the XMS instrument that was considered for *IXO* and *Athena*-L1 (den Herder et al. 2012). It therefore benefits from previous studies, and a large set of documentation already exists (e.g. *Athena* Payload Definition Document). Here we will focus on the main characteristics of the X-IFU. A description of the X-IFU is presented in more detail in Barret et al. (2013).

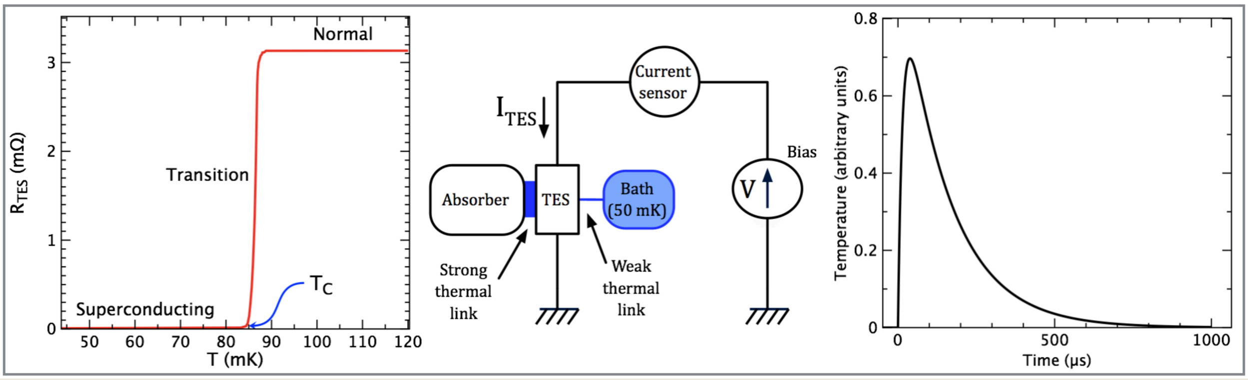

Figure 6.3: Working principle of a TES. Left) The TES is cooled to reside in its transition between its superconducting and normal states. Middle) The absorption of an X-ray photon heats both the absorber and the TES through the strong thermal link. Right) The change in temperature (or resistance) with time shows a fast rise (due to the strong link between the absorber and the TES) and a slower decay.

6.2.1 DETECTION PRINCIPLE

The X-IFU detector is a large array of absorbers read out by Transition Edge Sensors (TES). The TES micro-calorimeter senses the heat pulses generated by X-ray photons when they are absorbed and thermalized. The temperature increases sharply with the incident photon energy and is measured by the change in the electrical resistance of the TES, which must be cooled to temperatures less than 100 mK (the thermal bath is at 50 mK) and biased in its transition between super conducting and normal states (Fig. 6.3).

Two options are under consideration for the X-IFU sensors: Ti/Au bilayer TES with Cu/Bi absorbers or Mo/Au bilayer TES with Au/Bi absorbers. The absorber has a size of 250x250 μm². Either absorber can achieve the correct stopping power at 6 keV and provide low heat capacitance required for high spectral resolution. The small current of the TES is read out using a low noise amplifier chain, consisting of a superconducting quantum interference device (SQUID) (in the cold front end electronics (CFEE), see Fig. 6.4 showing the X-IFU block diagram). The signal is then amplified with SQUID array amplifiers at 2 K before reaching a semi-conductor low-noise amplifier (warm front end electronics (WFEE) in Fig. 6.4). Multiplexing allows the reduction of the number of readout channels and hence the thermal load on the detector. For Frequency Domain Multiplexing (FDM), each pixel is AC-biased with a specific carrier frequency, each matching the resonant frequency of an LC circuit. With a frequency range of ~1 to 5 MHz and a carrier separation of 100 kHz, up to 40 pixels can be multiplexed in a single readout channel. To match the X-IFU field of view requirement (5' diameter), in its current design, 3840 equal size absorbers are required. These are read out in 96 channels of 40 pixels each. The first stage SQUID needs to be linearized with a high gain feedback loop. A so-called base-band feedback technique ensures that the feedback signal carrier is properly phased with the TES signal carrier at the SQUID input. De-modulation of the summed signal enables the reconstruction of the shape of the signal in each pixel. Located closely underneath the TES array, an active anticoincidence layer screens the particle background. This comprises a 4 TES-array and its related cryogenic SQUID and warm electronics.

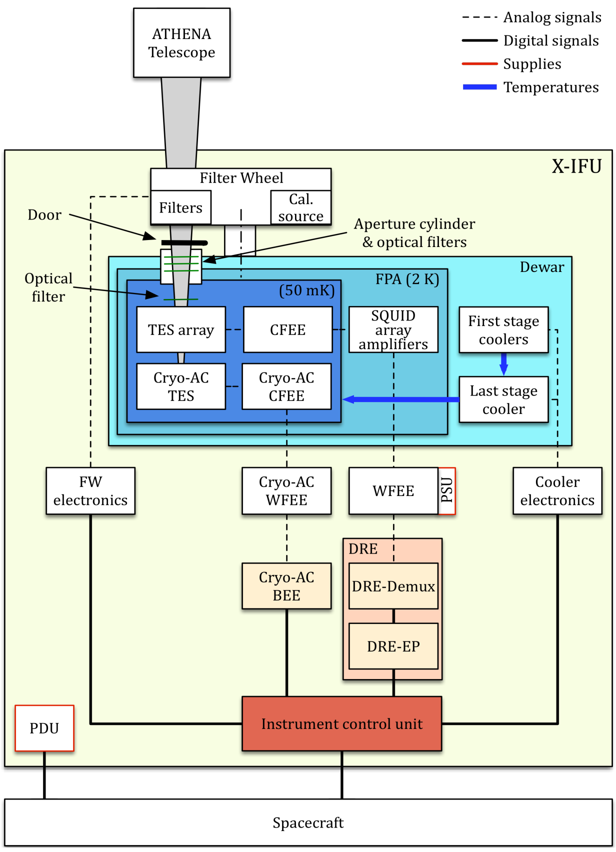

Figure 6.4: X-IFU functional block diagram.

The TES biasing, the SQUID multiplexer control, the data digitization, the generation of the feedback signals and the demultiplexing of the signals take place in the digital readout electronics (DRE-DEMUX), which also contains the event processor (DRE-EP). The latter includes two major functions: event triggering and pulse height analysis. The handling of the anticoincidence detector is done in the Cryo-AC electronics. The number of charged particles is sufficiently small that processing of the anticoincidence data can be performed on the ground. The Instrument Control Unit is responsible for operating the instrument with the desired settings. The power distribution unit (PDU) distributes the raw power over the cooler drives and the electronic boxes. Only for the WFEE, with its severe electromagnetic compatibility (EMC) requirements, is the power conversion, done in a separate power supply unit (PSU).

6.2.2 CONCEPTUAL DESIGN AND CHARACTERISTICS

The detector needs to be cooled and this requires a cryochain composed of several coolers and several intermediate temperature stages. This has been extensively studied for *IXO* and different designs have been proposed which can meet the requirements for *Athena*. A preliminary assessment of the X-IFU needs showed that no additional resources (mass/power) are required, mostly because the earlier design had to provide cooling for the more demanding time domain multiplexing used for *IXO*. An ADR-Sorption cooler is the baseline for the last stage cooler (from 2 K to 50 mK) whereas for the other stages a number of different options can be considered (2K Joule-Thomson (JT) cooler, Stirling coolers, 15 K pulse tube coolers). The design of the cooling chain is fully redundant and allows for the failure of a single mechanical cooler. The only exception is the last stage cooler which does not contain any movable part. The focal plane assembly provides the thermal and mechanical support to the sensor and the anti-coincidence detector. In addition it accommodates the cold front end electronics and provides the appropriate magnetic shielding. Inside the dewar, an optical aperture cylinder with optical filters protects the detector from the thermal and UV/optical/IR loads.

The filter wheel is located outside the cryostat: it contains additional filters (optical, neutral density, closed position) and an independent, pulsed electrical calibration source to monitor gain changes over time.

6.2.3 PERFORMANCE ASSESSMENT WITH RESPECT TO SCIENCE OBJECTIVES

The X-IFU top-level requirements are summarized in Table 6.2:

Parameter	Requirement
Energy range	0.2-12 keV
Energy resolution: E < 7 keV	2.5 eV (250 x 250 μm pixel)
Field of view	5' (diameter) (3840 TES)
Quantum efficiency @ 1 and @ 7 keV	>60% and >70%
Gain error (rms)	0.4 eV
Count rate capability – faint source	1 mCrab (>80% high-resolution events)
Count rate capability – bright source	1 Crab (>30% low-resolution events)
Time resolution	10 μs
Non X-ray background	5×10^{-3} cts cm^{-2} s^{-1} keV^{-1}

Table 6.2: X-IFU top-level requirements

For AC-biased (at 1.3 MHz) pixels, the best single pixel spectral resolution measured so far was 3.6 eV for 6 keV photons, thus approaching the required spectral resolution (see Fig. 6.5 left). The particle background spectrum has been estimated through GEANT-4 Monte Carlo simulations, accounting for the L2 radiation environment (including cosmic ray particles and low energy solar protons focused by the optics within and outside flares). Simulations by Lotti et al. (2012) have shown that to reach the required level of unrejected particle background (5×10^{-3} cts cm^{-2} s^{-1} keV^{-1}), a careful optimization of the materials surrounding the detector is required (see Fig. 6.5, right). This also requires the presence of a particle magnetic diverter.

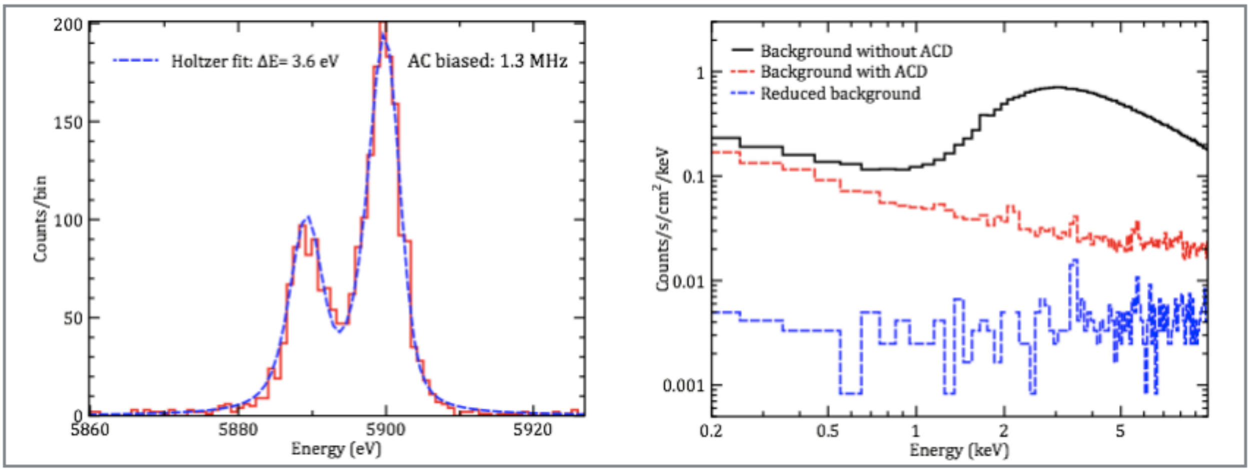

Figure 6.5: Left) Measured X-ray resolution (Fe^{55}) for a pixel biased under AC (1.3 MHz). The energy resolution is 3.6 eV. Right) The spectra of the X-IFU internal background expected: expected residual background without any shielding (black line), residual background with the implementation of the anticoincidence (red line), the final background using a graded shield (blue line).

6.2.4 POINTING AND ALIGNMENTS

Due to sensor array non-uniformity (e.g. quantum efficiency variations and time dependent gain variations), dithering observations (25" pattern) should be considered to distinguish true features in extended sources from instrumental artifacts. A dithering option should therefore be offered to users.

6.2.5 SPECIFIC INTERFACE REQUIREMENTS

In addition to electrical lines for power supplies and standard bus lines, the spacecraft (S/C) should provide the radiators to dissipate the heat generated by the coolers and by the electronic boxes, a baffle to protect the X-IFU field of view against direct radiation from the sky and the thermal control of all units except for the cryostat, independently of whether the X-IFU observes or not (this includes the thermal control of the outer shell of the dewar). At the interface between the instrument and the S/C, two additional requirements are worth mentioning: the static magnetic field outside the cryostat must be less than 10^{-4} T and the compressor-induced vibrations must be damped to prevent microphonic degradation of the X-IFU spectral resolution. Finally, the WFEE should be located <0.5 m from the dewar. Other components (about 10 units) can be placed at larger distances.

6.2.6 OPERATING MODES

The initial cool-down should take not more than 4 weeks. The X-IFU instrument can operate continuously for around 100 ks, after which the cooler must be recycled. This regeneration mode may take up to 10 hours, and should be done when the WFI is observing. The expected split of observation time is about 40% for the WFI and about 60% for the X-IFU. This is consistent with the required duty cycle of operation of the X-IFU to be larger than 70%. Following the regeneration of the cooler, the switch to normal observations will take less than 1 hour. Dedicated modes will be used for calibrations and the generation of pulse templates.

6.2.7 TRL AND DEVELOPMENT STATUS

Some components of the X-IFU have a TRL 4-5 based on heritage (e.g. filter wheel, instrument control unit). Focused activities in ESA MS are on-going (e.g TES array fabrication, cryo-AC, digital readout electronics). Taking advantage of the synergies existing between the X-IFU and the more advanced *SPICA/Safari* instrument (focal plane assembly, front-end electronics, digital readout electronics), most of the FEE requirements (noise floor, LC filter performance, SQUID, LNA performance, dynamic range, gain bandwidth) relevant to the X-IFU have already been met. In addition frequency multiplexed readout has now been demonstrated for 147 sensors, and for 38 sensors without increasing the noise. As shown above, AC-biased pixels have been shown to approach the required spectral resolution (see Figure 6.5).

For a purely European cryochain, multiple architectures exist and a trade-off analysis is required to define the optimum solution for the X-IFU, before building a demonstrator of the cyrochain. However, all the building blocks do exist (e.g. Pulse tube, Stirling, JT, Sorption, Sorption/ADR), although they do not all have the same TRL (estimated between 4 and 5). On the other hand, the baseline last stage cooler (Sorption/ADR) has a TRL of 6.

6.2.8 PROPOSED PROCUREMENT APPROACH

The X-IFU described above is based only on European technologies. The instrument will be proposed to be built by an ESA MS consortium which has been set up within the *Athena* team and is led by France (IRAP, CNES), with Netherlands (SRON) and Italy (INAF) as co-leads. Specifically, CNES is proposed to be prime of the X-IFU, lead the project management, the system team and the AIT activities. Major contributions are also anticipated from Belgium, Finland, Germany, United Kingdom, Spain and Switzerland. Its enabling technologies will be pursued in Europe, through a coordinated technology development plan between ESA and the ESA MS. We are nonetheless aware that teams outside Europe have expressed interest in contributing to some elements of the X-IFU, for example components of the cooling chain and the focal plane assembly. Any such contribution will need to be assessed within the context of the overall international contribution to *Athena* (see section 10.6), and should be agreed by the instrument consortium selected.

6.3 THE WIDE FIELD IMAGER

The technology and design of the Wide Field Imager (WFI) are built on the strong heritage of the WFIs proposed for the *IXO* and *Athena*-L1 and benefit from these previous studies and associated technology developments (see, e.g. *Athena* Payload Definition Document). Here we will summarize the main characteristics of the instrument. A more detailed description of the WFI is presented in Rau et al. (2013).

6.3.1 DETECTION PRINCIPLE

The WFI uses Active Pixel Sensors (APS) based on DEpleted P-channel Field Effect Transistors (DEPFETs; Fig. 6.6, left). Large matrices of these sensors offer the necessary field of view and oversampling of the PSF for the camera, along with near Fano-limited energy resolution. The high photon rates provided by the *Athena* mirror system also necessitate very high readout rates and flexible readout modes. The DEPFET APS is very well suited to this task as the signal charge is amplified directly in each pixel and not transferred over macroscopic distances. Every pixel consists of a p-channel MOSFET integrated onto a fully (sideways) depleted silicon bulk. Electrons generated by the interaction of incident X-ray photons with the bulk material are collected at the internal gate and laterally constrained to the region below the transistor channel. This increases the conductivity of the MOSFET proportional to the amount of stored signal charge and is therefore a measure of the energy of the incident photon. The internal gate persists regardless of the presence of a transistor current. Thus, each pixel row is switched on only for readout and switched off during the remainder of the time. The amount of integrated charge can then be sensed by turning on the transistor current and measuring the difference of the conductivity before and after the charge removal (Fig. 6.6, right).

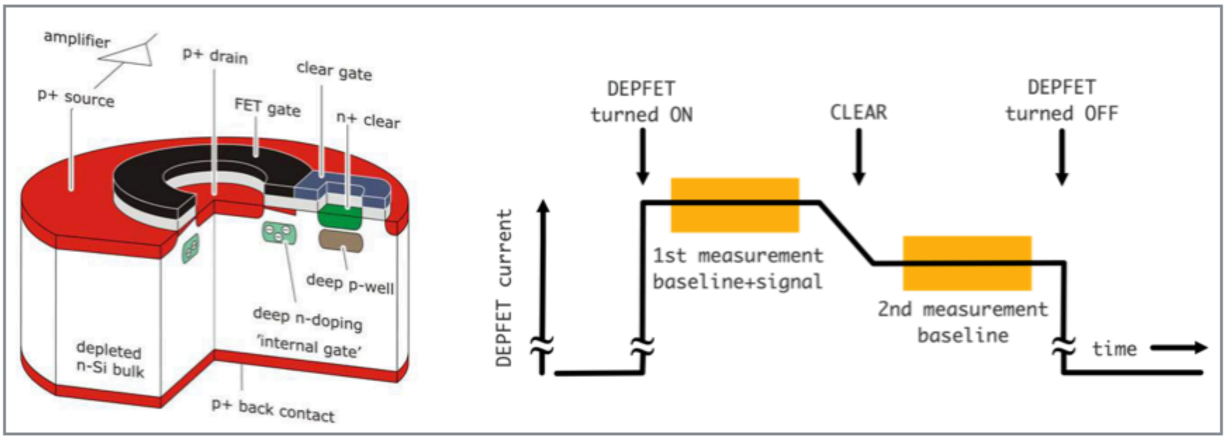

Figure 6.6: Left) Cutaway display of a circular MOS-type DEPFET. Right) Signal evaluation scheme for the readout of an active pixel sensor.

An electronic shutter can be implemented into each active pixel allowing suppression of X-ray photons that hit a pixel during the readout process. This improves the sensitivity and spectral response of the detector. Two layout concepts of these so-called gateable DEPFETs are currently being studied. In addition, advanced pixel layouts containing an intermediate storage region are in development. Here, charge generated during the readout is not lost but accumulated and preserved for later processing. This capability reduces dead time and the distortion of the spectral resolution while maximizing the throughput.

6.3.2 CONCEPTUAL DESIGN AND CHARACTERISTICS

The WFI will combine in a single focal plane array excellent wide field survey power with high-count rate and timing capabilities. Due to the physical size, the field of view cannot be realized with a single chip on a monolithic wafer. Instead, the current design foresees a mosaic of five matrices, a central, fast 256x256 pixel device with 100 micron pixels and a gateable intermediate storage design optimized for high-count rate observations, and four non-gateable 448 x 640 arrays of 130 micron pixel devices surrounding it. The instrument design is currently being optimized, with the goal of minimizing the distance between the sensors and the front-end electronics and the gaps between the chips.

Operation requires two types of front-end Application-Specific Integrated Circuit (ASIC) devices, the control front end (CFE) and the analogue front end (AFE). Pixels are controlled through SWITCHERs that toggle a sequence of voltages on the gate, clear gate, and clear contacts of each row, and sense the current through each column. For the analogue front end, a new low-noise multi-channel signal amplifier/shaper circuit with integrated sequencer and serial analogue output (VERITAS 2) is being developed. This combination will enable a readout time per row of about 2.5µs. The outputs of the analogue channels of VERITAS 2 are serialized by a 64:1 multiplexer with a clocking speed up to 32 MHz and sent to a fast fully differential output buffer. The architecture allows window-mode readout of the pixel matrices making it possible to address selectively arbitrary sub-areas of the DEPFET matrix or even to read out different sub-areas at different speeds.

The fast 256x256 matrix will be divided into two hemispheres, each readout in parallel by four ASICs. By doubling the number of readout channels, two rows per hemisphere can be readout simultaneously. This allows the full chip to be read out in 160µs, or a 16-row window (corresponding to 5 times the PSF) in 10µs.

The DEPFET arrays and front-end electronics are mounted on the camera head, which provides the structural stability and required cooling resources for the nominal operating temperature of <-60° C.

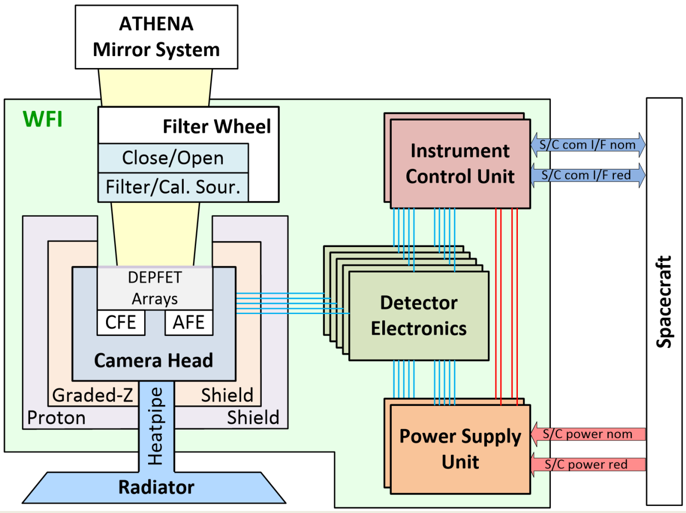

Figure 6.7: WFI block diagram.

The signal is then transferred to the detector electronic boxes (one for each DEPFET array) containing the analog-digital-converters, the frame processor and the sequencer. The frame processor performs the necessary offset calculation and subtraction, noise and threshold calculation, as well as gain and common mode correction, and performs pattern recognition, event identification and data compression. The electronics responsible for controlling the instrument is located in the instrument control unit which also hosts the instrument processor, power conditioner and mechanism controls (Fig. 6.7).

6.3.3 PERFORMANCE ASSESSMENT WITH RESPECT TO SCIENCE OBJECTIVES

The instrument specifications derived from the science requirements are summarized in Table 6.3:

Parameter	Requirement
Energy range	0.1-15 keV
Field of view	40'x40'
Array Format	Central chip: 256x256 pixel - Outer chips: 448x640 pixel
Detector quantum efficiency (incl. opt blocking filter)	@ 227 eV: 24%, @ 1 keV: 87%, @ 10 keV: 96%
Angular Resolution On-axis	<5" (oversampling by 2.8)
Spectral Resolution @ 6 keV	<150eV (FWHM)
Count rate capability for central chip	0.5 Crab: >88% throughput, <3% pile-up 1.0 Crab: >79% throughput, <6% pile-up
Time resolution in window mode	10µs
Non X-ray background	2×10^{-3} cts cm^{-2} s^{-1} keV^{-1}

Table 6.3: WFI top-level requirements

Optical/UV light-blocking will be achieved by a combination of a very thin entrance window and an Al filter hosted in a filter wheel. This provides excellent quantum efficiency in the energy range below 1 keV. At the same time, the 450 µm thickness of the fully depleted bulk allows for a high quantum efficiency between 1 and 10 keV and even beyond. The filter wheel will also host a calibration source as well as an open (no filter) and a closed position. The spectral performance is primarily limited by the statistical variation in the charge generated in the DEPFET by the interacting X-ray photon. The performance of the non-gated arrays has been verified with laboratory measurements by irradiating a prototype sensor matrix with photons from a ^{55}Fe calibration source. The spectral resolution achieved (<150 eV) is expected to remain constant throughout the mission lifetime.

6.3.4 POINTING AND ALIGNMENTS

Positional stability of the detector should be maximized to avoid degradation of the PSF provided by the Athena optics. Sufficient post-hoc positional accuracy is required from the AOCS to identify optical or NIR counterparts to faint X-ray sources (1" at 3σ confidence). The WFI count rate capability will be optimized if the focal spot is located and maintained in a relatively precise position on the detector which spreads the photons between the two readout hemispheres. The feasibility of such a scheme and the impact on the pointing accuracy and stability should be explored in the study phase.

6.3.5 SPECIFIC INTERFACE REQUIREMENTS

In addition to power supply lines and standard bus lines, the S/C is expected to provide the radiator space to dissipate the heat generated by the electronic boxes and a baffle and electron/proton diverters to protect the wide WFI field of view against direct photon and particle radiation from the sky.

6.3.6 OPERATING MODES

The majority of the time the WFI will be used in full frame mode, collecting the full information in each of the five pixel arrays over the entire sensitive area. For observations that require a high-time resolution and high-count rate performance, observations can be performed in a flexible cascade-window mode. The latter supports simultaneous observations with differently sized and differently positioned windows.

6.3.7 TRL AND DEVELOPMENT STATUS

64x64 pixel DEPFET sensors with the energy resolution required for the WFI but larger (300x300 μm) pixels have been produced for the MIXS instrument on board ESA's *BepiColombo* mission and are at TRL 6. Laboratory DEPFETs with smaller pixel size and larger matrices (e.g. 256x256 up to 512x512) have been fabricated at the MPG Semiconductor Laboratory. Development is required to increase the matrix size with sufficient yield to the required dimension for the outer arrays. Single pixels with different gateable intermediate storage designs have also been fabricated and are currently under test. Overall, the WFI camera head is at a current TRL of 3/4, the filter wheel at TRL 4 and the instrument control unit at TRL 5.

6.3.8 PROPOSED PROCUREMENT APPROACH

The WFI relies only on European technologies and will be proposed to be built by an ESA MS consortium led by MPE in collaboration with partners in Germany (ECAP, IAAT) and the United Kingdom (Leicester), with additional contributions also anticipated from Austria, Denmark, France, Italy, Poland and perhaps other ESA MS. The focal plane assembly is planned to be developed largely at MPE with the DEPFET sensors being fabricated by the MPG Semiconductor Laboratory. Financing for the instrument will be from the ESA MS. Non-European teams have expressed interest in contributing to parts of the WFI, specifically the Instrument Control Unit and filters. Such contributions should be discussed within the overall context of any international collaboration scheme for *Athena* (see also 10.6).

7 SYSTEM REQUIREMENTS AND SPACECRAFT KEY ISSUES

7.1 SYSTEM REQUIREMENTS

The science requirements outlined in Section 4 can be translated into lower-level system requirements needed to satisfy the Hot and Energetic Universe science goals. These are given in Table 7.1.

7.2 SPACECRAFT KEY ISSUES

7.2.1 TELESCOPE REQUIREMENTS

Attention is needed in the accommodation of the large diameter telescope and its long focal length within the fairing of the launch vehicle. Previous studies for *IXO* have shown that this is feasible for Ariane V or Atlas V. Studies for *Athena*-L1 show that this is close to the maximum feasible fixed focal length which can be accommodated in the Ariane V ECA fairing. The *Athena* concept also requires a Movable Instrument Platform (MIP), which may take additional space.

7.2.2 USE OF TWO INSTRUMENTS WITH A SINGLE TELESCOPE

A MIP was studied for *IXO* and considered technically feasible, but early development of this technology is desirable. Special attention should be given to a) the feasibility of repositioning the instruments with sufficient accuracy, b) issues arising from the mass and power of the X-IFU, c) the isolation of the dewar compressor vibrations for the two instruments and d) the reliability of the MIP.

7.2.3 SKY VISIBILITY AND TOO RESPONSE

Achieving some of the *Athena* science goals requires rapid TOO observations of GRBs: 4 hours of the trigger (with a goal of 2 hours). This response time can be decomposed into the following components: a) the availability of the ground segment to decide whether to execute the TOO, b) the time required to plan the observations on the ground, c) the communication time with the satellite and d) the slewing and settling time of the satellite, including the time for instrument exchange, if needed. In addition, GRB-related science requires that the average efficiency of this whole process, independent of the position of the GRB, to be 40%. This in itself can be also decomposed into a) the field of regard, and b) the efficiency in the TOO response within the required 4 hours. Potential solutions include a field of regard of about 50% (leading to a requirement on the angle normal to the sun direction of ±30 degrees) and an efficiency of 80%, although other schemes might be developed.

7.2.4 POINTING

Requirements are set by the need to locate the optical or near-IR counterparts of very faint X-ray sources, and to cross-identify structures in the X-ray images at other wavebands. An absolute pointing error of 3" (3σ) is required, and the on-ground a posteriori reconstructed astrometric measurements accuracy should be better than 1" (3σ).

7.2.5 CONTAMINATION

Contamination (particulate and molecular) both during ground handling and in-flight is a critical issue for both the optics and instruments. The requirement is for a loss of area of <10% at end of life at 0.3 keV. This has several implications: a) the optics should have a cover during launch to avoid contamination by particles, b) the telescope tube should have low outgassing properties and may need a dedicated cooled outgassing baffle (as for *XMM-Newton*), c) the X-IFU will have a dewar operating at room temperature and its outer filter can be heated and d) a cold trap in front of the WFI will reduce any potential contamination.

Parameter	Requirement	Comment
Operational lifetime	5 yr	Required to execute core science
Extended lifetime	10 yr	Extended exploitation of unique capabilities
Observing efficiency	>75%	Required with the nominal mission lifetime
Field of regard	>50%	GRB follow-up and observing efficiency
Sun pointing	±30 degree	To achieve 50% field of regard
Continuous obs. time	100 ks	Observing efficiency
Minimum obs. time	1 ks	Monitoring observations; shallow surveys
Target accessibility	2 weeks/ ½ year	Observations of a wide variety of targets
TOO reaction time	4 hr (80% of targets)	GRB follow-up, assuming 50% field of regard
Uplink availability	> 80%	For TOO commanding
Ground segment reaction time	0.5 hour	Following TOO trigger from other facilities
Slew rate	1 deg/min	TOO follow-up within field of regard
MIP exchange time	0.5 hour	TOO follow-up with X-IFU when WFI in field of view
Post slew settling and setup time	0.5 hour	Settling within the X-IFU field of view
Absolute astrometric measurement error	3" (3 σ)	Allows X-IFU imaging data to be matched with other imaging data at a level better than the PSF
Reconstructed astrometric error	1" (3 σ)	Faint source identification in WFI images after registering with known sources in the field of view
Dithering capability	25" pattern	Remove instrumental artifacts (non uniformities)
Mosaic/raster mode	Over ~10 deg^2	Allows efficient large area surveys
Instrument focusing	0.3 mm (3 σ)	Needed not to degrade the PSF
Detector position knowledge	50 μm (3 σ)	Taken to be 1/5th of the PSF
Detector position stability	< 50 μm (3 σ)	Compressor vibration should not degrade PSF
Absolute timing	50 μs	Neutron star timing
On-board memory	500 Gbit	Allows for storage of science data for >2 days
Telemetry	100 Gbit/day	Based on instrument characteristics
X-ray stray light rejection	<10^{-3} at 45' off-axis	Requires X-ray baffle
Contamination	<10% loss of area at 0.3 keV (EOL)	Minimize and mitigate pre- and post-launch contamination from particulate and molecular sources
Telescope temperature	20±1 C	Maintain PSF performance
Soft proton magnetic diverter	>95% of < 1 MeV protons	Requirement needs to be consolidated and depends on the soft proton environment at L2
Magnetic field outside of X–IFU	Static: < 10^{-4} T Drift: < 0.12 mT_{rms}	The X-IFU is sensitive to static & varying magnetic fields

Table 7.1: *Athena* top level mission requirements

7.3 BASELINE SPACECRAFT CONFIGURATION

Previous ESA and industrial studies for *IXO* and *Athena*-L1 have addressed many of the system and spacecraft requirements applicable to *Athena*, and considerable heritage exists also from *XMM-Newton*. A nominal spacecraft design would consist of three main parts, using a modular approach for the satellite construction.

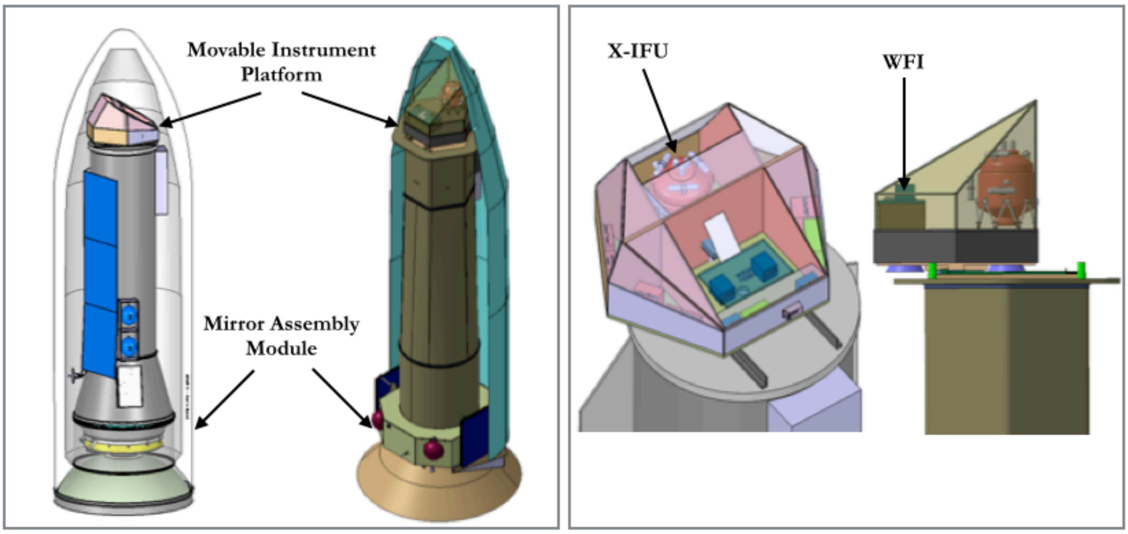

Figure 7.1: Left) Spacecraft configuration during launch from Thales-Alenia-Space (TAS, left) and Airbus Defence & Space (ADS, right). Right) MIP configurations from TAS (left) and ADS (right).

7.3.1 MIRROR ASSEMBLY MODULE (MAM)

The Mirror Assembly Module supports the X-ray optics and the associated supporting structure, and includes the straylight baffle, the thermal baffle and an expandable Sun protection baffle to maximise the field of regard. During ground operation and launch the X-ray mirror will be covered by a door, which can also be used for Sun protection, after deployment. To maintain the optics performance and simplify calibration, a thermal control system of the mirror will be required. Previous analysis for *Athena*-L1 indicated that maintaining the mirror to 20° C (± 1° C) is feasible through a combination of thermal baffles and electrical heaters. Magnetic diverters should be implemented to deflect soft protons and electrons thereby reducing the particle background.

Item	Mass (kg)	Power (W)
Mirror Assembly Module (MAM)	**1128**	**1800**
X-ray Integral Field Unit (X-IFU)	**541**	**1260**
Wide Field Imager (WFI)	**242**	**775**
Focal Plane Module (FPM)	**580**	**95**
Service Module (SVM)	**1707**	**700**
S/C dry mass and power	**4198**	**4630**
S/C dry mass and power (with 20% system level margins)	**5038**	**5556**
Propellant (no margin applied)	**315**	
Launch adaptor (no margin applied)	**172**	
***Athena* total mass**	**5525**	
Ariane 5 launch capacity	**6500**	

Table 7.2: Preliminary mass and power budgets. Spacecraft resources are based on industrial inputs. The current best estimate is shown at module or instrument level including a Design Maturity Margin (DMM) typically of 20%. A system level margin of 20% was applied to both mass and power. The total power is a maximum value assuming both instruments are operating at the same time.

7.3.2 SERVICE MODULE (SVM)

A fixed metering structure will be used between the MAM and the FPM to achieve the focal length. The SVM should be optimized for a low momentum of inertia (for fast repointing). It should accommodate standard functions including the attitude and orbit control system, propulsion, thermal, telemetry and telecommanding, power and data handling subsystems. Solar panels can be either mounted directly on the telescope structure or can be on separate panels (like *XMM-Newton*).

7.3.3 FOCAL PLANE MODULE (FPM)

The FPM accommodates the WFI and X-IFU, including the X-IFU cryogenic chain, and the MIP. Some of the instrument units can be accommodated in the fixed structure, but the MIP should include the cryocooler compressors and the propagation of their vibrations onto the MIP needs to be limited.

Analysis of preliminary spacecraft designs with the support of European industry suggests that the spacecraft can be realized well within the necessary mass and power budgets (see Table 7.2). In Fig. 7.1 we show *Athena* in the launch configuration and the MIP configuration from the two preliminary industry studies.

7.4 MISSION OPERATION CONCEPT

The proposed *Athena* Ground Segment follows the successful models of *XMM-Newton* and *Herschel*, consisting of the *Athena* Mission Operation Centre (MOC), the *Athena* Science Operations Centre (SOC), and ground segment components provided by MS-funded teams. The MOC and the SOC are proposed to be ESA-provided. The MOC is responsible for all aspects of the command, control and maintenance of the spacecraft in flight, and manages the payload globally. During nominal routine operations, the operations team at the MOC contacts the spacecraft once per day to downlink science data and telemetry accumulated in the mass memory; to uplink the set of telecommand blocks for the following days, and to perform health and safety checks of the spacecraft and payload. Provision will be made for longer communication periods when required for exceptional manual, maintenance or contingency operations. The SOC is the interface with the scientific user community (e.g. organizing calls for observing proposals, delivering the data to the users, maintaining the archives) and is responsible for the overall coordination of the *Athena* Science Ground Segment (ASGS), e.g. by providing the necessary requirements and standards to ensure its coherent development. The MS-funded elements include the Instrument Team Centres (ITCs) which are part of the consortia that developed the X-IFU, the WFI and additionally a telescope scientist team (see 10.1). The ITCs will be responsible for calibration, performance and safety checks during the mission operations, and will generally be responsible for the provision of detailed instrument knowledge. The ITCs are responsible for ensuring the successful operation of their respective instruments and each ITC performs tasks dedicated to their instrument and provides specialized data processing software.

The responsibility for the science data analysis software development, the routine data processing and re-processing, and the generation of standard products to feed the *Athena* archive, could be allocated to an *Athena* Science Data Centre, funded by the ESA MS. Alternatively this responsibility could also be subsumed into the ITCs, following some aspects of the *Herschel* model. We propose that a full trade-off study between the various GS models, applicable to an observatory like *Athena* is performed before the AO for the ground segment procurement. Whatever the approach taken, it should ensure that the project has access to the wider expertise and experience of external teams whilst still providing an efficient, coherent and cost-effective GS solution.

8 SCIENCE OPERATION AND ARCHIVING

8.1 COMMUNITY INTERFACES AND INTERACTIONS

Athena will operate as an observatory. Most of the observing time will be available to the worldwide scientific community as Open Time (OT), allocated via annual AOs issued by ESA and scientific peer review. The SOC will manage the calls for proposals, including any coordination between international agencies. An *Athena* Time Allocation Committee (ATAC), appointed by ESA, will peer review of all proposals, select those which are best motivated scientifically and arrange a ranked ordered list of potential observations.

It is proposed that a fraction of the observing time be allocated to the teams in the *Athena* collaboration (i.e. the instrument, ground segment and telescope teams) as Guaranteed Time (GT). GT ensures a fair return to the scientists that have been involved in the implementation of the mission. It also helps to guarantee that the instrument and telescope scientist teams remain actively involved in the optimization and calibration of the instruments and the X-ray telescope post-launch. GT proposals may also be subject to peer review.

Some of the *Athena* science goals require relatively large allocations of observing time. We therefore propose that there should be a separate open call for Key Programs, issued before launch. Key Programs could use OT, GT or both. The *Athena* observing program also needs to incorporate additional observation types, including Director's Discretionary Time (DDT), Targets of Opportunity (TOOs; for both previously known and new targets). Joint time observations coordinated with complementary ground and space-based facilities operating in the *Athena* time-frame are also envisaged.

The split between OT and GT and the fraction of time allocated to Key Programs, and their number, will be elaborated further in the Science Management Plan (SMP) at the appropriate time. The SMP will define the data rights for *Athena*, adopting normal ESA policies, to ensure the timely delivery of scientific data and results of the highest possible quality whilst also ensuring that the interests of the data owners are protected. Most observational data will have a proprietary period which will extend from the time the data are processed to acceptable quality until 12 months after delivery to the data owner.

8.2 SUPPORT FROM GROUND AND SPACE BASED OBSERVATIONS

Athena will start operating in the late 2020s when the pre-eminent facilities operating at other wavelengths are expected to include LOFAR, SKA, ALMA, JWST, E-ELT, LSST and CTA. Follow-up or coordinated observations with such facilities can provide complementary data to enhance the understanding of a wide range of astrophysical phenomena. The *Athena* surveys, the *Athena* follow-up observations of high-z GRBs or clusters discovered at high redshifts in SZ surveys are examples where this complementary between facilities will be essential. In the case of GRBs observations, the trigger for high-z candidates will likely have to go through automated ground-based observations with robotic telescopes, as is already the case currently.

8.3 SCIENTIFIC MISSION PLANNING, SCHEDULING OF OBSERVATIONS

Each observation will be expanded into a timed sequence of activities necessary to configure the instrument for the planned observation (e.g. instrument modes), to execute the observation for the specified duration and perform any associated calibration, if required. The observation is included into the long-term mission planning schedule in a time slot that complies with the target visibility constraints, and the duration of the observation. The planning constraints are significantly less than for *XMM-Newton*, due to the absence of perigee passes, radiation belts and ground station hand-over. Furthermore, at L2, with the anticipated solar constraints, up to ~50% of the sky may be observable at any time which considerably enhances the scheduling flexibility. The planning software should be designed to optimize the efficiency of operations (including for example the recycling time of the X-IFU coolers), while respecting the scientific priorities of the observations.

8.4 EXPECTED VOLUME AND FORMAT OF THE DATA

The *Athena* raw data rate of ~100 Gb daily average produces ~3 Tb of telemetry per month. Based on experience with *XMM-Newton*, we estimate an expansion from raw telemetry of a factor ~3 (compressed) in the processed data products, yielding ~36 TB/year of data or ~250 TB over five years (with >30% margin). With periodic reprocessing of all data increasing the volume by a factor of two, the *Athena* archive is sized to be ~500 TB after five years. This volume is comparable with the *Herschel* archive.

8.5 QUICK-LOOK ASSESSMENT OF THE DATA

Normal science operations of *Athena* require no specific quick-look assessment of the data, consistent with a standard operating mode with a single communication period once per day. Nevertheless quick-look assessment of *Athena* data after down-link will play a role in verifying the correct execution of instrument command uploads and for monitoring the instrument health. This data analysis will be the responsibility of the SOC, assisted by the ITCs, and it is assumed that this will be based on standard data processing pipelines, configured specifically for the quick-look requirements.

8.6 GROUND DATA PROCESSING STRUCTURE

Development of the data processing and analysis software will be a joint effort between the SOC and the MS-funded elements of the *Athena* GS. This approach optimises the distribution of expertise, where the SOC coordinates infrastructure elements while ensuring that data processing developments benefit from detailed instrument knowledge and expertise within the *Athena* collaboration. Instrument-specific software development will occur within the ITCs. For both instruments development of the analysis software will draw on previous experience for broadly similar instruments on other missions (e.g. *XMM-Newton*, *Astro-H*), but both will present new challenges, particularly so for the X-IFU due to its unprecedented ability to perform spatially-resolved high resolution spectroscopy. The standard data processing pipeline will be based on the science analysis tools developed for interactive analysis. The pipeline will be configured to carry out the analysis steps required to produce calibrated event lists together with observation-level data products, including images and detected source lists, complemented by time series data and X-ray spectra and spatial/spectral data cubes. The pipeline-processed observation data, calibration data and the original instrument, spacecraft and ancillary data will be provided in suitable (e.g. FITS) format and distributed to Guest Observers via the *Athena* Science Archive.

8.7 DATA DISTRIBUTION AND ARCHIVING

The *Athena* Science Archive (ASA) will utilise extensive ESAC experience in archive construction for ESA's science missions, will be Virtual Observatory (VO) compatible, and will provide access to all the data obtained during the mission, including secure access for observers during the proprietary period. The ASA will be provided by the ESAC Science Archives Team. The SOC will have the responsibility of guaranteeing core data access, and providing integrity, security and the appropriate level of content control and standards. Under most circumstances data are expected to be freely accessible to the worldwide astronomical community after a proprietary period (usually 12 months). Results in the form of images and source catalogues will be made available through the VO registries. External users will be able to access the ASA through normal web interfaces as well as through fully-compliant VO interfaces.

9 TECHNOLOGY DEVELOPMENT REQUIREMENTS

Meeting the science requirements of *Athena* requires a coordinated and focused technology development plan between ESA and the ESA MS. This plan, which should be overseen by the *Athena* Science Study Team, should gear up now and cover all enabling technologies for the mission. This includes the X-ray optics, the X-IFU focal plane assembly and readout electronics, the full cooling chain, the DEPFET detector for the WFI, and the MIP. The first item is part of an on-going program at ESA (see below), whereas the development of large TES sensor arrays and the building of the demonstration cooler will be both subject to dedicated TRPs to be released in the near future. Additional funding will be required in the ESA MS in support of these activities, e.g. for building up a demonstration model for the X-IFU and for developing the WFI detector. Within the ~4 years available, these efforts should safely bring all elements to the TRL 5/6 required at mission adoption.

9.1 X-RAY OPTICS

A comprehensive set of technology development activities is already planned for the optics, as listed below. Many can be executed in parallel and/or by different partners (e.g. multi-layer coatings, petal development):

- Demonstrate HEW < 5" for a fully populated SPO module made of 45 stacked layers.
- Change all production of SPO stacks/modules to a focal length of 12 m.
- Manufacture SPO stacks with a rib spacing of >3 mm to improve the vignetting function.
- Manufacture SPO stacks/modules with an azimuthal curvature of R=285 mm and axial length L=102 mm. This is required for the inner most ring of modules if the inner aperture radius is R=250 mm.
- Manufacture SPO stacks/modules with an azimuthal curvature of R=1440 mm and axial length L=20 mm. This is required for the outer most ring of modules if the outer aperture radius is R=1500 mm.
- Demonstrate the manufacture of SPO stacks with appropriate axial curvature commensurate with reducing the current HEW limit imposed by the conical approximation (5") to 1-2" for the innermost shells.
- Develop a petal structure into which the SPO units will be integrated with a curvature optimized to follow the optical design
- Prove a reliable mounting and alignment scheme for the SPO units on the petal, with verification by means of X-ray calibrations after integration.
- Demonstrate coating of inner modules with a multilayer to enhance the reflectivity at 6-7 keV. This should raise the effective area at 6.5 keV from 0.26 to ~ 0.3 m^2
- Design the support structure for the optics in order to assess the feasible filling factor and environmental (launch) conditions.
- Confirm the robustness of realistic optical modules for the appropriate launch conditions.

9.2 THE X-RAY INTEGRAL FIELD UNIT COOLING CHAIN

Under ESA and MS contracts, mechanical coolers have been developed over many years. Building a complete cooling chain is a major challenge for which the necessary key steps are listed below:

- Conduct a detailed design and trade-off of the cooling chain meeting the specific X-IFU requirements (regeneration time, temperature stabilities, heat loads, magnetic shielding, micro vibrations during operations) with the proper redundancy.
- Following the selection of the cooling chain components, bring them to the TRL level required for building the demonstrator model. Maintain development of closed cycle dilution cooler as an alternative to Sorption/ADR.
- Develop and test a cryostat assembly demonstrator allowing for the integration of a representative focal plane assembly.
- Develop X-ray filters to provide minimal stopping power over the energy range but meeting the environmental needs and the thermal properties for the dewar.

Most of these activities are currently part of a planned ESA TRP and should be completed by 2017. As part of this TRP, integration with a representative focal plane assembly is also foreseen. Emphasis will be put on the verification of the compatibility of the coolers with the detector assembly in terms of cooling power, intermediate stage intercepts, temperature profiles during cool-down/warm-up and cycling, temperature stability, micro-vibrations, EMC and magnetic fields. This activity will be phased with those aiming at building a demonstration model (DM) for the X-IFU planned for 2018, with the targeted goal of reaching TRL 5/6 at mission adoption at the X-IFU system level (see below).

9.3 THE X-RAY INTEGRAL FIELD UNIT

The technology developments specific to the X-IFU are listed below:

- Demonstration of 2.5 eV resolution at 6 keV with the baseline detector system, consisting of AC-biased TES sensors with representatively dimensioned absorbers, and relevant CFEE (SQUIDs, LC filters).
- Demonstration of this resolution with FDM readout of up to 40 sensors in one readout channel.
- Demonstrate the scalability of the detector and readout technology to realize the X-IFU field of view
- Development of a representative cryogenic anti-coincidence (cryoAC) detector which can be integrated into the FPA to verify the absence of any thermal, mechanical or electrical interference.
- Demonstration of a representative focal plane assembly (TES array & anticoincidence sensors, magnetic shielding, thermal suspension, cryo-harness and cold electronics).
- Development of low-noise warm analogue electronics, fast, low-power digital electronics, representative harness between the cold stage and the warm electronics, and the EMI-tight integration of these components into a cooler system.
- Optimization of basic technologies for the detector and its readout to allow for a compact and reliable design (e.g. cryo-harness).

Although most of these activities will be funded by ESA MS, ESA should in parallel support generic technology developments that may be also relevant to the X-IFU (e.g. thin filters, connectors, cryo-harness).

9.4 THE WIDE FIELD IMAGER

The DEPFET detectors that have been fabricated for a variety of experiments differ from those required for the WFI in aspects such as pixel size, spectral resolution and gateability. The following developments are required to bring the *Athena* WFI to TRL 5/6:

- Down-selection of the design for single 100μm pixels for the gateable DEPFET with intermediate storage region and performance verification under proper environmental conditions.
- Scale both the non-gateable (outer) DEPFETs and the gateable (inner) DEPFET with intermediate storage region to representative matrix sizes.
- Design the focal plane with minimized gaps between the DEPFET arrays mitigating the problem of having the front-end electronics located nearby the sensor arrays.
- Demonstrate the high-time resolution capabilities via development of the VERITAS 2 front-end ASIC (2.5μs readout per detector row).
- Demonstration of a breadboard processing chain (sensor, electronics, sequencer, ADC, frame processor).
- Development of light blocking filters integrated on the sensor entrance surface.

A realistic development plan has been defined, and will be supported by the institutes in the ESA MS.

10 PROGRAMMATIC AND COST ESTIMATES

10.1 PROGRAMME MANAGEMENT PLAN

The programme management plan is expected to be similar to that of previous ESA observatories (e.g. *XMM-Newton, Herschel*). ESA should be responsible for the overall project management, including the development, procurement, manufacturing, assembly, integration, test, verification and delivery of the spacecraft (including the MIP), and the launch services. ESA should also be responsible for the procurement of the X-ray telescope and the pre-coolers of the X-IFU. The Science Operations Centre (SOC) and the Mission Operations Centre (MOC) should also be under ESA responsibility.

The X-IFU and WFI instruments and associated instrument team centers will be developed by European-led consortia selected via a competitive AO and funded by the ESA MS. The community contribution to the ground segment should also be selected competitively, through the instrument AO and/or a separate call for the ASDC, depending on the model (see section 7.4). A MS-funded telescope scientist team should be set up with the responsibility of advising ESA on the optics development, preparing the calibration plan, providing access to calibration facilities, and conducting the on-ground and space calibration programs. Such a team should also be selected through a competitive AO to ensure that the community expertise is fully exploited. After mission adoption, an *Athena* Science Team should be formed to follow the development phases of the mission, oversee the preparations and execution of scientific operations, and the distribution of the data products to the community.

This proposal is the result of contributions from over 400 scientists affiliated to a wide variety of institutions, mostly in ESA MS, with significant additions from the United States and Japan. The leadership team responsible for the *Athena* proposal was involved in *XEUS*, *IXO* and *Athena-L1*. Major European institutions with experience in high-energy astrophysics hardware (e.g. INAF, IRAP, Leicester, MPE, SRON) are part of the X-IFU and WFI instrument proto-consortia. Their experience in previous ESA astronomy missions like *EXOSAT*, *XMM-Newton* and *Integral* (also *Planck*, *Herschel* and others), contributing to both flight hardware and components of the ground segment secures the best outcome from this ESA partnership with its MS.

10.2 INTEGRATION/VERIFICATION APPROACH - MODEL PHILOSOPHY

X-ray testing of the telescope is possible in existing test facilities (e.g. PANTER/MPE). These tests will allow full characterisation of the optics and verification of the alignment of the mirror module. Thermal testing of the full S/C is not considered to be necessary (e.g. a combination of testing at module level and correlation modelling will suffice). Vibration and acoustic tests can be performed at full S/C level and are compatible with existing facilities in Europe (e.g. LSS, HYDRA, LEAF).

X-IFU models and development philosophy: It is proposed to simplify programmatic, technical and schedule interfaces between the consortium and ESA in order to maximize flexibility and robustness of the development schedule (Fig. 10.1). The Structural-Thermal and Avionic models (STM and AVM) will be delivered to ESA. The STM will be mechanically representative of the X-IFU (e.g. first Eigen frequency). Thermally, it will be representative of conductive and radiative external interfaces. The AVM will be a functional model representative of interfaces with the satellite both at data and power levels. It will include both the instrument control and power distribution units dedicated models. A qualification model (QM, not delivered to ESA) will be developed to sustain mechanical, thermal, electrical and performance tests. Once the qualification review is completed, it will evolve into a Consortium AVM (C-AVM), used during the flight model (FM) development (delivered in Q4/2026), and for the commissioning and operational phases.

WFI models and development philosophy: The intended WFI model and development philosophy and verification plan follows ECSS-E-ST-10-02c/03c. A demonstration model of the signal processing chain will be completed as part of the technology development during the assessment and definition phases (Fig. 10.1). The STM will be delivered to ESA in Q4/2021. Subsequently, a QM will be developed and tested for mechanical, thermal, electrical, and performance qualification. Following the qualification review in Q4/2024, the development of the FM will commence, which will finish with the delivery (incl. FM spare) to ESA in Q4/2026 and the subsequent acceptance review.

10.3 PRELIMINARY RISK ANALYSIS

Certain risk items were identified in the technical and programmatic review of the *Athena*-L1 mission study (SRE-PA/2011/117). These included the achievement of the X-IFU (then XMS) spectral resolution and the telescope angular resolution, the system-level impact of the X-IFU, international (non-ESA) participation, and schedule risks associated with the X-IFU and telescope. While some science requirements have been made more demanding for the current *Athena* L2 concept (e.g. telescope angular resolution), in broad terms many of these risks are mitigated by the additional development time for an L2 launch. Technical and schedule risks are being mitigated by a thorough development plan to ensure that all critical mission elements are at TRL5/6 at mission adoption. For L2, *Athena* is baselined as a fully European mission, eliminating the risk of non-participation of NASA and JAXA. The system complexity of the X-IFU, the telescope angular resolution coupled to its large effective area and the MIP are items that will need early attention in the study phase.

10.4 PRELIMINARY COST ANALYSIS OF THE MISSION

A detailed cost estimate will be the subject of studies by ESA and the ESA MS. The ESA cost evaluation of the strawman mission concept presented in the white paper indicated a cost at completion to ESA between 1.2 and 1.3 G€ for *Athena*. During the assessment of the white paper, it was stated by ESA that a reasonable assumption for ESA MS contribution to the L2 mission should be less than 400 M€. Based on previous studies (*IXO*, *Athena*-L1) our preliminary assessment of the ESA MS provided items for *Athena* is well within this limit.

10.5 BASIC PROGRAMME SCHEDULE

The basic program schedule for *Athena* and its payload is shown in Figure 10.1.

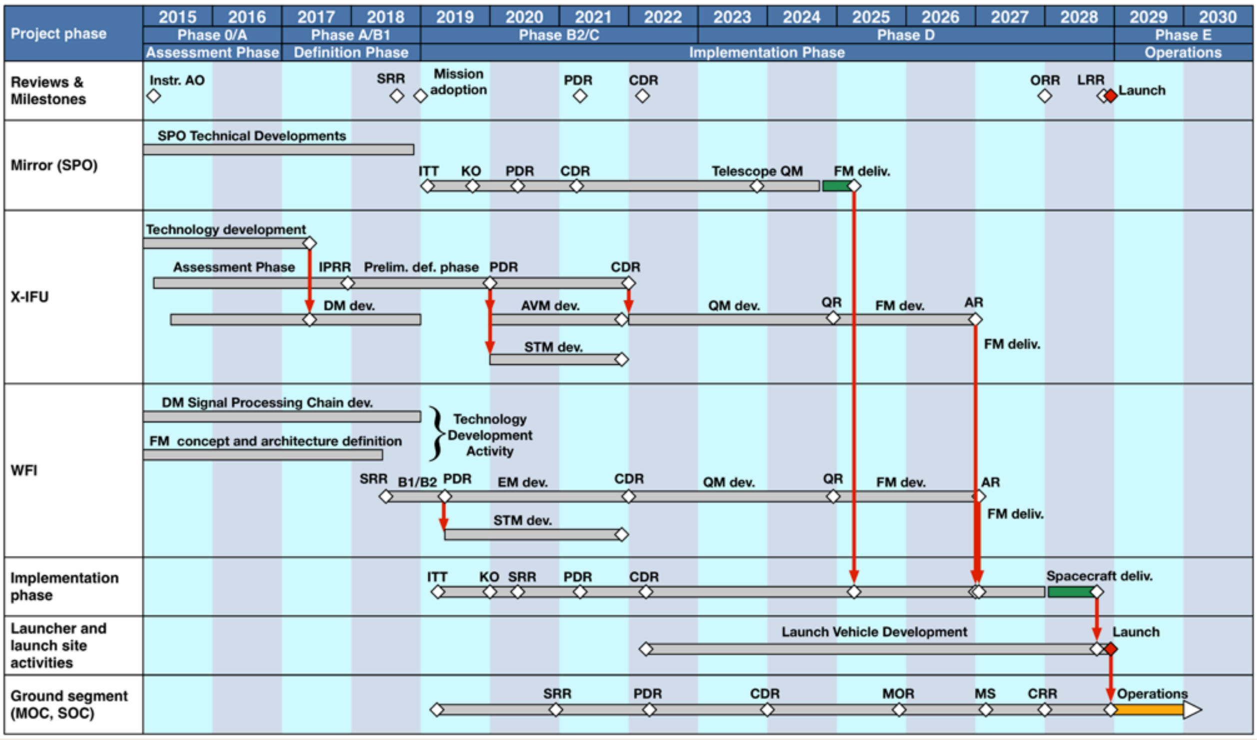

Figure 10.1: Basic program schedule for *Athena*

10.6 INTERNATIONAL CONTRIBUTION TO ATHENA

The baseline instruments and community contribution to the ground segment require no international partners and are based purely on European contributions and heritage. We are nonetheless aware that NASA and JAXA have expressed interest in making contributions to *Athena*, and other international partners may express such interest in the future. In particular, we recognize that an involvement in *Athena* is a top priority of the Japanese X-ray community. Further discussions on any international contributions to *Athena* are very welcome, particularly to the extent that the adopted solutions reduce cost, lower risk, or increase technology readiness. We expect that any international contribution to ESA-responsible items will be negotiated with ESA, and community contributions to the focal plane instruments and ground segment will be negotiated with the relevant European-led consortia. Any international element of the mission that affects the scientific performance should be discussed with and be subject to input from the ESA-appointed Science Study Team.

11 ACKNOWLEDGMENTS

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[3] The list of Athena supporters is available from http://www.the-athena-x-ray-observatory.eu/ (SUPPORTERS)

13 LIST OF ACRONYMS

ADR	Adiabatic Demagnetization Refrigerator
APS	Active Pixel Sensor
ASIC	Application Specific Integrated Circuit
ATAC	*Athena* Time Allocation Committee
Athena	The Advanced Telescope for High-Energy Astrophysics
ASDC	*Athena* Science Data Center
AVM	Avionic Model
DEPFET	DEpleted P-channel Field Effect Transistors
DM	Demonstration Model
DMM	Design Maturity Margin
EMC	Electromagnetic Compatibility
FM	Flight Model
FPM	Focal Plane Module
GRB	Gamma-Ray Burst
GBH	Galactic Black Hole
HEO	High-Earth Orbit
HEW	Half Energy Width (refers to the Point Spread Function)
ICM	Intra-Cluster Medium
IMF	Initial Mass Function
ITC	Instrument Team Centre
IXO	International X-ray Observatory
LEO	Low-Earth Orbit
LNA	Low Noise Amplifier
MAM	Mirror Assembly Module
MOSFET	Metal–Oxide–Semiconductor Field-Effect Transistor
MS	Member State
MOC	Mission Operation Centre
OSG	Observatory Science Goal
PSF	Point Spread Function
QM	Qualification Model
QR	Qualification Review
R_{200}	Radius at which the mean mass density exceeds the critical density by a factor of 200
R_{500}	Radius at which the mean mass density exceeds the critical density by a factor of 500
SMBH	Supermassive Black Hole
SG	Science Goal
SN	Supernovae
SNR	Signal-to-Noise Ratio
SPO	Silicon Pore Optics
SOC	Science Operation Centre
STM	Structural Thermal Model
SVM	Service Module
TES	Transition Edge Sensors
TOO	Target of Opportunity
TRL	Technology Readiness Level
UFO	Ultra-Fast Outflows
ULIRG	Ultra-Luminous Infrared Galaxy
ULX	Ultra-Luminous X-ray source
X-IFU	X-ray Integral Field Unit
XMS	X-ray Microcalorimeter Spectrometer
WFI	Wide Field Imager
WHIM	Warm Hot Intergalactic Medium

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