VERT-X Design of Vertical X-Ray Test Facility for ATHENA

FINAL REPORT

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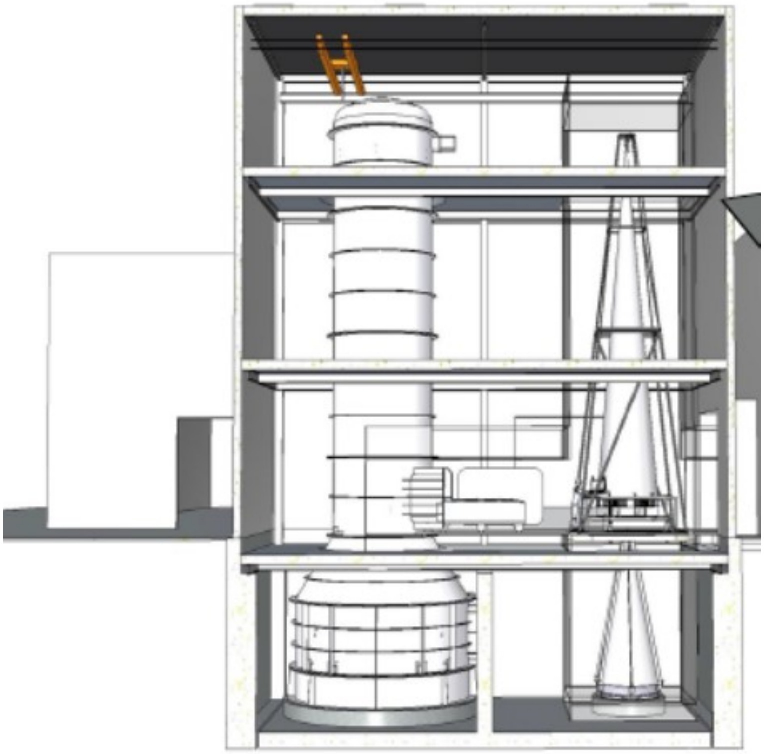

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AUTHORS AND RESPONSIBLES			
Document:	VTX-OAB-ISE-REP-004		
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Date:	18/09/2020		
Prepared by:	A. Moretti (INAF)	Signed by:	
	M. Tordi (EIE)		
	F. Marioni (MLS)		
	M. Uslenghi (INAF)		
	F. Amisano (GPAP)		
	G. Parodi (BCV)		
	G. Sironi (INAF)		
	D. Spiga (INAF)		
Checked by:	A. Moretti (INAF - OAB)	Signed by:	
Approved by:	S. Basso (INAF - OAB)	Signed by:	
Released by:	A. Moretti (INAF - OAB)	Signed by:	

CONTRIBUTING ENTITIES	
INAF – OAB	Partner
INAF - IASF	Partner
Media Lario	Partner
EIE	Partner
GP Advanced Projects	Partner
BCV	External Service

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1. INTRODUCTION

1.1. SCOPE

The scope of the present document is the overall illustration of the activities performed in the VERT-X facility study, from the requirements analysis to the detailed design definition.

Specifically, the document reports the analysis and design results at the VERT-X previous milestones, namely the System Requirements Review (SRR), Preliminary Design Review (PDR) and Detailed Design Review (DDR) milestones, as well as the outcomes of the study final phase.

1.2. APPLICABILITY

The present document is one of the formal deliverables related to the Final Review (FR) milestone outcomes. It is intended to outline the main aspects of VERT-X facility, providing a final illustration of the results of all the activities that have been performed in the study up to the final phase.

1.3. ROADMAP

Document section	Content description
Section 2 (Applicable and reference documents)	List of applicable documents and reference documents.
Section 3 (Requirements analysis and definition)	Analysis of SOW requirements and individuation of VERT-X facility top requirements.
Section **Error! Reference source not found.** (Trade-offs)	Presentation of main trade-offs for VERT-X design definition.
Section 4 (Configuration and design)	Presentation of VERT-X detailed design.
Section 8 (Programmatic aspects)	Illustration of VERT-X facility development programmatic aspects, specifically development planning, critical areas, technological readiness and expected costs.

Table 1-1: Roadmap of the document

2. APPLICABLE AND REFERENCE DOCUMENTS

2.1. APPLICABLE DOCUMENTS

AD1	AO/1-9549/18/NL/AR - SOW	X-ray Raster Scan Facility for the ATHENA Mirror Assembly SOW
AD2	VERT-INAFOAB-001	VERTICAL X-Ray (VERT-X) Technical Proposal
AD3	ESA-TECMMO-RS-014713	Updated Requirements for the ATHENA VERT-X following the System Requirements Review
AD4	VTX-OAB-IPM-MIN-004	11 February Conference Call Minute

2.2. REFERENCE DOCUMENTS

RD1	VTX-OAB-ISE-REP-001	TN1 Vacuum Chamber
RD2	VTX-OAB-ISE-REP-002	TN2 X-ray Source and Collimator System
RD3	VTX-EIE-ISE-TEC-001	TN3 Raster Scan System
RD4	VTX-EIE-IFF-SPC-001	TN4
RD5	VTX-OAB-ISE-TEC-003	TN5 X-ray detector and (x, y, z) stage
RD6	VTX-EIE-ISE-TEC-002	TN6 Gravity Release Structure/Mechanism
RD7	VTX-EIE-ISE-TEC-004	TN7 Metrology System
RD8	VTX-MLS-ISE-TEC-001	TN8 Ground Segment Equipment
RD9		
RD10	VTX-EIE-ISE-TEC-003	TN10 Interface Specifications
RD11	VTX-OAB-IOP-TEC-001	TN11 Concept of Operation
RD12	VTX-OAB-ISE-TEC-001	TN12 Technical Budgets
RD13	VTX-OAB-IPA-TEC-001	TN13 Requirement Compliance Matrix
RD14	VTX-OAB-IPA-TRE-001	TN14 Product Tree
RD15	VTX-OAB-IPA-LIS-001	TN15 Critical Item List
RD16	VTX-OAB-IPM-PLN-001	TN16 VERT-X Development Plan
RD17	VTX-OAB-IPM-SCH-001	TN17 VERT-X Schedule
RD18	VTX-OAB-IPM-REP-001	TN18 VERT-X Costs
RD19	VTX-OAB-IPM-SCH-002	TN19 Verification and Calibration schedule
RD20	VTX-OAB-IPM-REP-002	TN20 Verification and Calibration costs
RD21	VTX-EIE-ISE-ANR-001	Requirements Analysis Report
RD22	VTX-MLS-ISE-REP-001	X-Ray Source Selection and Preliminary Collimator Design
RD23	VTX-OAB-ISE-ANR-001	Verification and Calibration Requirements Analysis Report
RD24	VTX-BCV-ISE-REP-001	Mirror Assembly - Gravity Mitigation Supports
RD25	VTX-GPAP-ISE-REP-001	Detector (x, y, z) Stage Analysis and Design Report
RD26	VTX-IASF-ISE-REP-001	Camera Design Report
RD27	VTX-OAB-ISE-SPC-001	D1 System Requirements Specification Document
RD28	VTX-OAB-ISE-REP-001	D2 Conceptual Design Report
RD29	VTX-OAB-ISE-REP-002	D3 Trade-off Report

2.3. GENERAL SPECIFICATIONS AND STANDARD DOCUMENTS

SD1	ECSS-M-40A	Configuration management
SD2	ECSS-M-50A	Information/documentation management

2.4. LIST OF ACRONYMS

AD	Applicable Document
DDR	Detailed Design Review
EIE	European Industrial Engineering
ESA	European Space Agency
FR	Final Review
GPAP	GP Advanced Projects
I/F	Interface
IASF	Istituto di AstroFisica Spaziale (INAF, Milano)
INAF	Istituto Nazionale di AstroFisica
ITT	Invitation To Tender
MA	Mirror Assembly
ML	Media Lario S.r.l.
MM	Mirror Module
OAB	Osservatorio Astronomico di Brera (INAF, Milano)
PDR	Preliminary Design Review
RD	Reference Document
ROM	Rough Order of Magnitude
RS	Raster Scan
SOW	Statement of Work
SRR	System Requirements Review
TBA	To Be Assessed
TBC	To Be Controlled
TBD	To Be Defined
TN	Technical Note
TVC	Thermal Vacuum Chamber
XSA	X-ray Source Assembly
XTA	X-ray Tube Assembly
XYZS	(x, y, z) stage

3. REQUIREMENTS ANALYSIS AND DEFINITION

3.1. OVERVIEW

The ESA Advanced Telescope for High-Energy Astrophysics (ATHENA) will be the largest X-ray optics ever built.

The ESA Advanced Telescope for High Energy Astrophysics (ATHENA) is the second Large mission of the Cosmic Vision Science program. The phase A study has been completed at the end of 2019 and the adoption is scheduled in June 2022, with the launch planned in 2031.

ATHENA will represent a powerful X-ray observatory for all astrophysics fields [1]. The ambition of the mission will be the study of the Universe hot baryonic components, from super massive black holes (SMBH) in the early Universe to galaxy clusters and their large structures. These goals will be achieved through the largest ever built X-ray mirror which will focus 0.2-12.0 keV photons

on two state-of-the-art instruments for spatially resolved high resolution spectroscopy (the X-ray Integral Field Unit, X-IFU) and for wide field imaging and low-resolution spectroscopy (the Wide Field Imager, WFI) respectively. The mirror will be built using the ESA Silicon Pore Optics (SPO) technology which provides large effective area with excellent angular resolution.

The ground calibration of the ATHENA MA raises significant difficulties due to its unprecedented size, mass and focal length. While currently operational facilities cannot meet mission requirements, the VERT-X project aims to design an innovative calibration system which will be able to accomplish to this extremely challenging task.

The VERT-X concept is based on the idea that a parallel beam can be also produced by a point-like source located in the focus of an error-free X-ray collimator. This concept is not novel and it is already under construction for the BEATRIX facility. Since, for evident construction reasons, the beam amplitude has to be much smaller than the ATHENA mirror, the source-collimator system it is thought to be moved by a raster-scan mechanism which covers all the optics to be calibrated. This results in the design of a calibration facility much smaller in size (as shown in Figure 3-1) with respect to the traditional long tube.

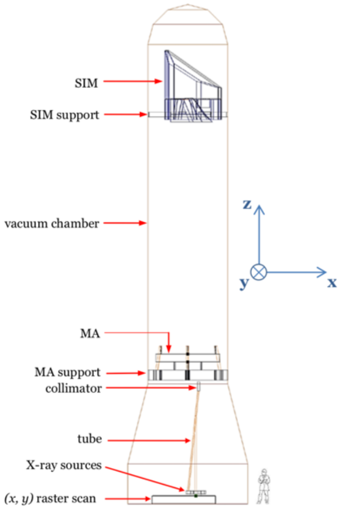

Figure 3-1 The VERT-X concept.

Beside the smaller amount of involved resources, there are also other evident benefits generated by the compactness of this concept. First, it allows a vertical geometry which largely simplifies the mirror support and reduces to zero the PSF degradation due to the lateral (perpendicular to optical axis) gravity. This would also allow to host the MA integrated with the SIM in order to perform the end-to-end calibration campaign, although, at the moment this is not foreseen in the ATHENA project development schedule. Moreover it allows to characterise the contribution of the single modules to the over-all mirror performance.

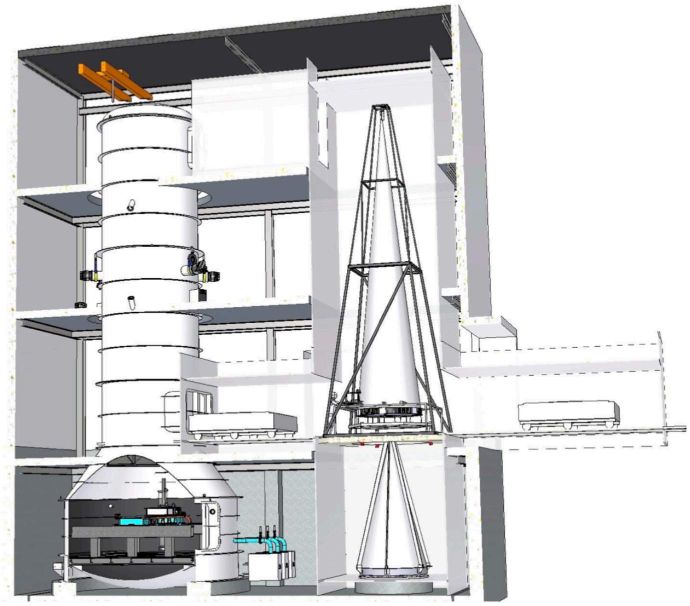

Figure 3-2 Lay-out of the VERT-X and AIT facilities

Finally, thanks to the compact design, the location of the facility can be chosen flexibly and according to the project needs. In particular the selected site is adjacent to the AIT facility in such a way that the MA can be moved from facility to the other through a trolley moving in a cleaned environment (Figure 3-2).

3.2. TOP-LEVEL REQUIREMENTS LIST

Req. ID	Requirement definition (with post-SRR updates)
R01	The XRS Facility shall allow the functional and performance verification of the partially or fully integrated ATHENA MA, as well as its final calibration, by scanning the MA with a vertical small-aperture highly-collimated and actively controlled X- ray beam and collecting the output beam at the focal plane of the MA.
R02	The XRS Facility shall be able to perform any manipulation of the MA, inside the vacuum chamber, required to satisfy the verification and calibration requirements, without breaking the vacuum. Note: this requirement is schedule-derived, alternative approaches can be proposed if compliance with schedule requirements.
R03	The XRS Facility shall be able to routinely perform beam-characterization measurements (direct beam on detector) while the MA is in the chamber under vacuum.
R04	The XRS Facility shall provide the possibility to arbitrarily isolate the Point Spread Function (PSF) of each MM.
R05	The scanning speed of the XRS shall be defined following a trade-off between requirement R25 and R50.
R06	The absolute knowledge error of the HEW for the verification and calibration of the MA and for different energies used and off-axis angles shall be ≤ 1 arcsec (goal: 0.5 arcsec) with a confidence level of 99.73% (3σ).
R07	The maximum effective area loss introduced during verification and calibration of the MA for different energies and off-axis angles shall be ≤ 1%, with a confidence level of 99.73% (3σ).
R08	The absolute knowledge error of the effective area loss introduced during verification and calibration of the MA for different energies and off-axis angles shall be ≤ 1%, with a confidence level of 99.73% (3σ).
R10	The closed-loop control system shall feedback information in order to keep X-ray beam, MA and detector in the required alignment and to consequently allow the automatic tip-tilt adjustment of the collimated X-ray beam (ref. to requirement R30 and R32).
R11	The vacuum chamber shall be designed in a way to contain and structurally support the following three systems, preferably arranged in a vertical configuration as depicted in SOW Figure 1, and in sequence as per the following: - The X-ray source and collimator system, together with the raster scan system (all to be designed/procured); - The MA (provided by SC-Prime - physical characteristics and interfaces as per SOW [AD1]; - The detector (to be designed /procured) or the SIM (provided by SC-Prime - physical characteristics and interfaces as per SOW [RD7] - [RD9]).
R12	The vacuum chamber shall allow the insertion and removal of the fully assembled MA and detector stage (note: top end of the vacuum chamber shall be designed to be removable if needed, e.g. via a flange).
R13	The vacuum chamber shall offer at least an ISO 5 environment in presence of the MA without protective cover.
R14	The vacuum chamber shall offer openings that allow the entrance of operators and GSE as required to perform all the operations necessary to run and maintain the XRS Facility for the execution of the performance verification campaigns for the Qualification Model (QM) and Flight Model (FM) MA and calibration campaign for the FM MA.
R15	The vacuum chamber shall be equipped with a vacuum generation system to create an internal pressure down to 10^{-6} Torr and in a time compatible with the foreseen operations necessary to execute the performance verification and calibration campaigns for the QM/FM MA, as per SOW [AD1] (<LBF-URD> tab of the annexed excel file), SOW [RD4] and [RD5]. Goal: pressurization time should be less than 5 hours.

Req. ID	Requirement definition (with post-SRR updates)
R16	The vacuum chamber shall be equipped with a thermal control system to keep the MA temperature at 20°C ±1°C. Note: The MA will use its own thermal control system, consisting of heaters, but a lower sink temperature on the facility is needed.
R17	The vacuum chamber should offer suitable windows in correspondence of the collimator, MA and detector/SIM to allow optical metrology to sense inside the vacuum chamber.
R18	The vacuum chamber shall be equipped with interface flanges to allow power and data cables connection between internal and external GSE during operational (vacuum) and non-operational conditions.
R19	The X-ray source and collimator system shall be compatible with operations in high vacuum conditions (as per requirement R15).
R20	A set of X-ray sources shall be selected to perform the required performance verifications and calibration campaigns of the MA at 7 energies: C-K, Al-K, Ag-L, Ti-K, Fe-K, Cu-K, Ge-K.
R21	The selected set of X-ray sources shall be integrated in a system that can automatically change the X-ray source to be operated and without breaking vacuum.
R22	The X-rays emitted by the source shall be collimated in a beam having the largest cross-section possible.
R24	The collimated X-ray beam shall be directed to the plane of the MA, i.e. in the *z* direction (with reference to the coordinate system).
R25	Sufficient X-ray flux shall be generated to characterize the local PSFs of the MA, without being significantly affected by statistical uncertainties.
R27	The absolute knowledge error of the flux during the scan of the whole MA shall be ≤ 3%, with a confidence level of 99.73% (3σ). Note: this requirement drives a) the need to perform direct beam measurements with enough range on the detector to cover the whole aperture, and b) the sensitivity of the detector.
R29	The X-ray source and collimator system shall be mounted on a *(x, y)* translation stage (with reference to the coordinate system), which shall be compatible with operations in high vacuum conditions (as per requirement R15).
R30	The positioning of the X-ray beam (i.e. the X-ray collimator) shall be controlled by an external metrology system.
R31	It shall be possible to tip-tilt the direction of the collimated X-ray beam in a range of ±3° around the z-axis (as per reference system of Figure 1). A maximum absolute knowledge error of 0.2 arcsec shall be achieved with a confidence level of 99.73% (3σ) for off-axis angles up to 20 arcmin during scanning. Note: This is in principle a derived requirement. It is not necessary to have a very good static accuracy on the set point, but it is important to have a good relative knowledge during scanning. This can be achieved by either having a very dynamically stable system or by having a good metrology (to be able to accurately track the angle for a faithful reconstruction of the PSF during data processing).
R32	The tip/tilt of the X-ray beam shall be controlled rapidly enough to maintain the require alignment - verticalization of the beam with the MA and the detector in a dynamical way during the raster scanning.
R34	The XRS Facility shall offer suitable mechanical interfaces to sustain the MA, in compliance with SOW [AD1], and preferably with the MA optical axis in vertical direction, i.e. in the z direction (with reference to the coordinate system.
R35	The XRS Facility shall also offer a removable gravity-release structure / mechanism to counteract the gravity effects on the MA structure in accordance with SOW [AD1].
R38	The detector shall be compatible with operations in high vacuum conditions (as per requirement R15).
R39	The detector and its (*x, y, z*) stage shall be designed in compliance with the requirements in SOW [AD1], and with reference to SOW [RD3], [RD4].
R40	The detector shall be placed at the focal plane of the MA.
R41	The detector shall be mounted on a high-vacuum compatible (*x, y, z*) translation stage, for focus alignment (by adjusting position in the *z*-direction, i.e. along the direction of the optical axis of the MA), and for out-of-field acquisitions (by moving the detector on the *x-y* plane).

Req. ID	Requirement definition (with post-SRR updates)
R42	The detector (x, y, z) stage shall move in the z-direction of at least ±50 mm, with steps of 0.25 mm or larger, and with an accuracy ≤ 0.25 mm. The distance from the detector to the MA along the beam axis shall be known with an accuracy of 0.25 mm, with a confidence level of 99.73% (3σ).
R43	The detector (*x, y, z*) stage shall have sufficient translation range in the *x* and *y* direction to allow out-of-field measurements up to at least ±180 arcmin.
R44	The XRS Facility shall be equipped with systems (e.g. crane) and suitable interfaces to lift and manoeuvre MA to be placed in the vacuum chamber and fixed in its position.
R45	The Contractor shall foresee and report all the optical, mechanical, electrical and electronic equipment needed to run the XRS Facility, including computer systems to control any operation and to acquire and store testing data.
R46	The XRS Facility infrastructure shall include, in addition to the vacuum chamber, at least - An air-lock/clean-room ISO 5 connected with the vacuum chamber; - As a goal: A room for the receipt, storage and handling of the MA (dimensions of MA container reported in SOW [AD1); - As a goal: A control room for operating and controlling the XRS and the vacuum chamber and for data collection; - As a goal: A meeting room for at least 20 people; - As a goal: Offices and rooms as needed to support the foreseen operations and operators.
R49	The MA shall be handled, if outside of the transport container and without protective covers, in an ISO 5 (at least) environment at all times.
R50	The XRS Facility shall allow to execute the performance verification campaign tests for the MA QM/FM verification campaign, and the calibration campaign for the MA FM, in the modality and schedule as required in SOW [AD1], with reference also to SOW [RD4] and [RD5].
R51	The XRS Facility design shall be compliant with the European safety regulations.
R52	The useful lifetime of the XRS Facility (equivalent to full life) is the sum of operational life and shelf life. The XRS Facility useful lifetime shall be a minimum of 15 years considering an average usage of the XRS Facility of about seven (7) months/year, i.e. about 1000 hours/year, and considering regular maintenance as required by the different items.
R53	The XRS Facility shall allow preventive maintenance to maintain the functions and performances of the system during its lifetime.
R54	The XRS Facility design shall favor the procurement of parts from European manufacturers, manufactured in Europe or at least available in Europe.

4. DESIGN

4.1. THE PRODUCT TREE

The VERT-X project is divided in 6 top-level subsystems, namely: the ground segment equipment, the vacuum chamber, the raster-scan mechanism, the x-ray+collimator system, the metrology and the focal-plane, i.e. the detector and its moving stage (Figure 4-1).

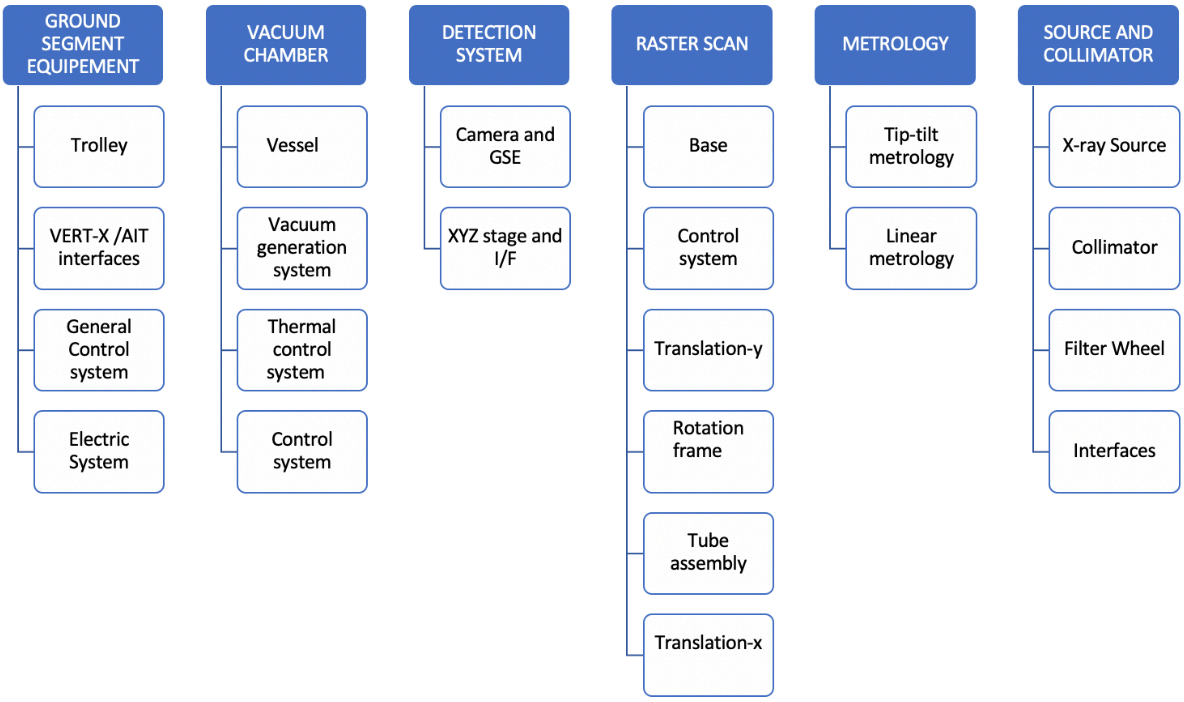

Figure 4-1 The VERT-X product tree

4.2. THERMAL VACUUM CHAMBER

X-ray testing can only be performed inside an environment where the atmospheric pressure is small enough to make the X-ray absorption negligible. The Thermal Vacuum Chamber (TVC), is a 20 m tall and 4 to 7 m wide cylindrical vertical vessel subjected external pressure. It houses the X-Ray Raster Scan, the Mirror Assembly, and the Detector (Figure 4-2).

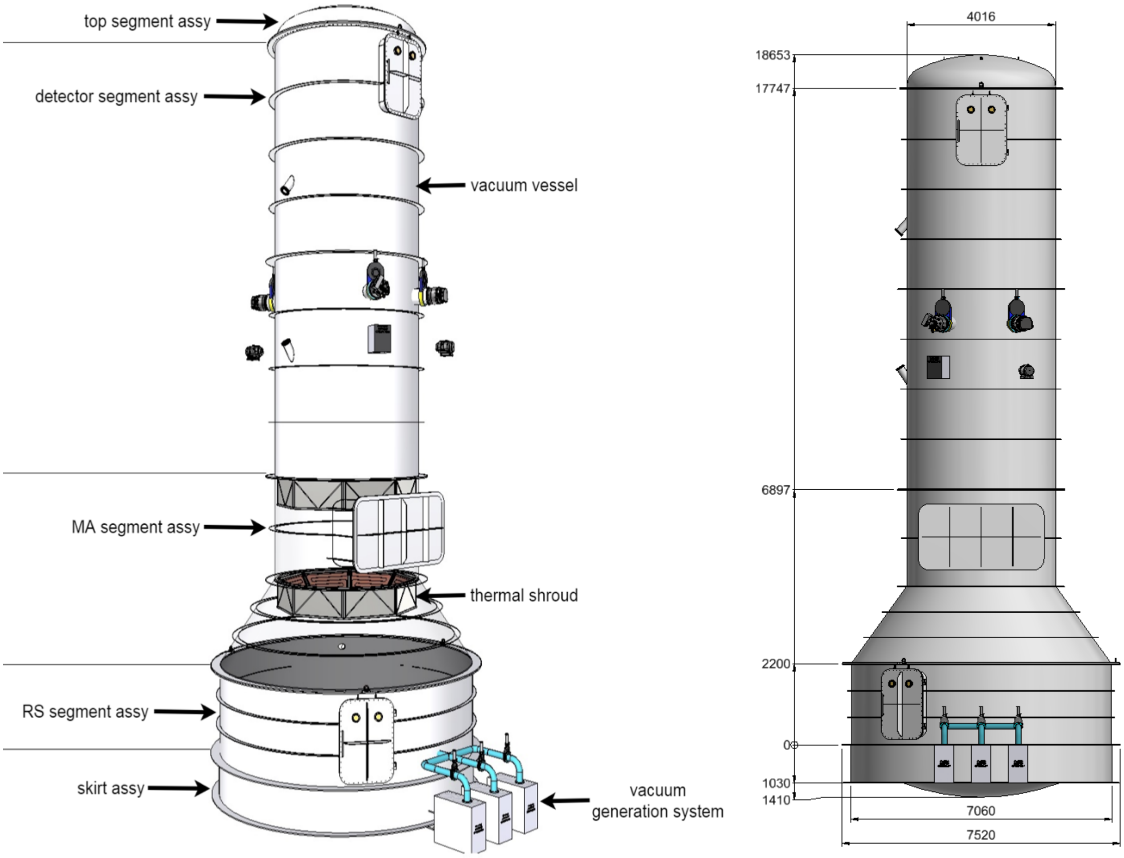

Figure 4-2: Thermal vacuum chamber elements and main dimensions.

A total of 4 openings are foreseen in the vessel:

- One small door at the -1 (Raster Scan) level (clear aperture 1.7 m x 1.2 m), for personnel access and small pieces insertion/extraction;
- One small door at the 2nd (Detector) level (clear aperture 1.7 m x 1.2 m), for personnel access and small pieces insertion/extraction;
- One large door at the Mirror Assembly level (clear aperture 3.2 m x 1.6 m), for MA insertion/extraction;
- One opening at the top of the vessel, corresponding to the top end of the chamber (clear aperture Ø 4 m), for detector insertion/extraction;

Both the MA and the detector openings are connected to ISO 5 clean rooms in such a way that when the vessel is open, it remains at an environmental cleanliness level corresponding to ISO 5.

The vacuum vessel has a cylindrical geometry of different size: **7m diameter for the bottom part**, **4m diameter for the middle and top parts**. Given its very large height, it is divided into segments (or modules), namely 5 segments. A cylindrical shape, instead of a box-like shape, has been selected for all segments of the vessel for structural reasons, since it allows a significant reduction in total mass of the steelwork. A cone segment is foreseen to provide a smooth transition between the 7m and 4m cylinder diameters. The 5 modules composing the TVC are the following, in order from bottom to top (Figure 4-2):

1. Skirt segment
2. Raster Scan segment
3. Mirror Assembly segment
4. Detector segment
5. Top segment

The most relevant elements which are placed inside the vacuum vessel are:

- The support of the X-Ray Detector unit
- The support of the Gravity Release System
- The Thermal Shroud

To provide a mean of temperature control for the Mirror Assembly, a **thermal shroud system** inside the vacuum chamber has been designed (). It is made of two series of radiating panels: the first series is installed at a level above the MA aperture door, while the second one is installed at a level below such aperture. This geometry maximizes the radiative transfer between the MA and the panels, to provide to the MA a heat flux large enough to allow the testing of the MA thermal control system.

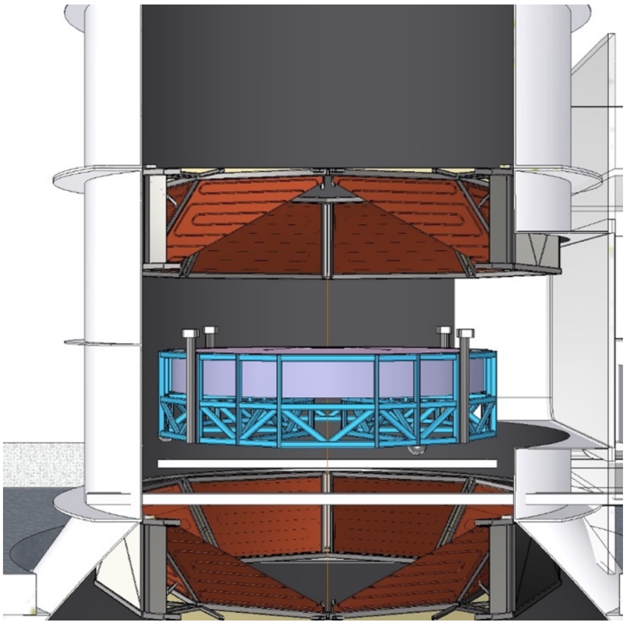

Figure 4-3 Thermal shroud sandwich configuration

The **supports of the XRD and of the GRS** are represented by kinematic mounts.

The design of the vessel takes into consideration several load cases, including self-gravity, gravity loads of the systems installed inside the vessel, air pressure load due to the vacuum generation, earthquake loads based on the installation of the vessel close to the AIT facility.

The thermal model provides a preliminary identification of the design of the shroud, including the effects of the temperature on the raster scan, within a temperature range of few Celsius degrees around the working temperature of the MA.

A preliminary sizing of the vessel **vacuum pumping system** is provided, with the identification of the configuration in terms of primary vacuum system (model type and number of pumps), and of secondary vacuum pumps (model type and number of turbo-molecular pumps and cryo-pumps).

4.3. RASTER SCAN SYSTEM

The RS is a two-axes scanning machine: its “head” is the X-ray tube assembly which can rotate around X and Y axis as well as translating in X & Y direction. This head is the core of the RS, hosting the main X-ray source and its collimator.

The main elements of the RS are (Figure 4-4):

- The Base, which provides the mechanical interface with the vacuum vessel
- The X translation frame
- The Y translation frame
- The rotation X frame
- The X-ray tube assembly, which includes the second rotational degree of freedom

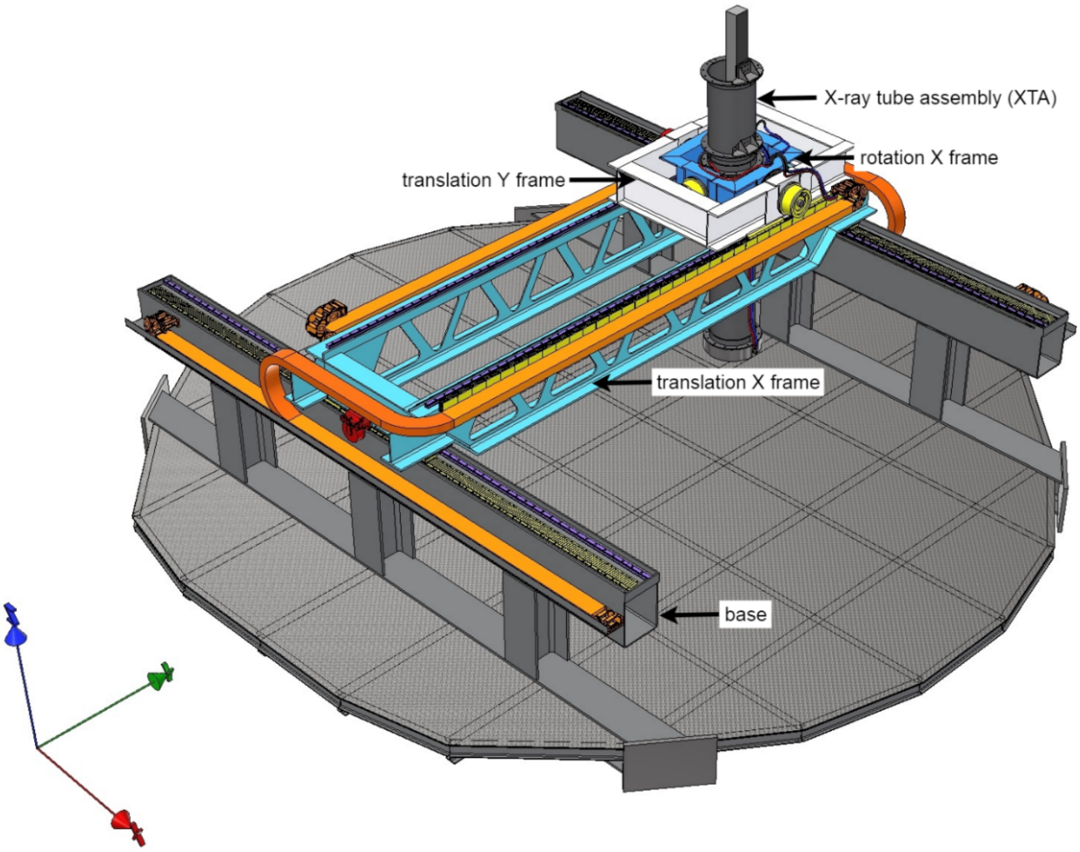

Figure 4-4: RS system design 3D with main assemblies. Estimated weight 8300 kg.

The mechanical design of the raster scan is such to avoid the generation of hidden surfaces, to allow the cleaning of the mechanics in compliance with the ISO 5 cleanliness requirement.

The linear axis motion is achieved by means of direct drives: the bridge and the trolley slides over linear guides, the motion is provided by the current that flows through coils which are placed close to arrays of permanent magnets. The same principle is used for the rotation, with magnets and coils arranged in a circular shape.

The motor sizing has been performed by taking into account the duty cycle of the machine, the expected frictions, and the loads.

The encoder system is made of strip encoders for the linear motion, and rotary encoders for the rotations.

Cable routing is provided by means of cable wraps, the junctions between the segments of the cable wrap are made of PEEK to minimize the generation of contaminants.

Specific safety devices (brakes, end-of-run) are included in the motion system.

Every component is vacuum compatible: in particular, the drive system is sufficiently oversized with respect to the required forces (linear) and torques (angular) to avoid the need to cool the motors. The X-ray source requires a cooling circuit, which is transported by a dedicated cable wrap.

The FEM model has been built in ANSYS Workbench, and it is suitable for global structural analyses — both static, modal, and transient. It includes the Vacuum Vessel structure (not shown or described here for the ease of comprehension), which is fixed to the ground and which acts as supporting constraint for the Raster Scan. This allows to capture accurately the structural behaviour of the whole system in its deployed configuration.

A comprehensive analysis has been performed, as reported in RD3, which has been used to model the dynamical behavior of the machine. Two independent servo models have been created: one for the tip/tilt axes (Tube attitude) and one for the linear XY axes (Bridge and Trolley motion).

The compliance of the machine to the requirements was then assessed by analysing the velocity error and the position error for each degree of freedom; in particular, velocity error was addressed in the study of the linear motion, while the position error was studied to verify to what extent the system is capable to keep the same attitude while translating beneath the MA surface.

Four different materials have been considered for the construction: Stainless Steel 304, Industrial quartz **Carbon fiber composite (CFC)** and **Invar 36 alloy**. They have been evaluated w.r.t. their mechanical proprieties (Young’s Modulus, UTS, stiffness to mass ratio), thermal stability (CTE), outgassing and cost.

4.4. METROLOGY

During the measurement of the area efficiency and of the Half Energy Width several factors can affect the accuracy of the data. The system must be capable to disentangle the contribution to the measured value due to internal misalignments of the measuring system itself, from the contribution due to the MA, which is the real quantity of interest.

To this aim, a metrology system provides the information needed to:

- Measure the relative position of the MA w.r.t. the XRD. This part of the metrology is called "**Linear Displacement Metrology**".
- Measure the instantaneous orientation of the X-ray beam w.r.t. the orientation of the MA. This part of the metrology is called **"Tip-tilt Metrology"**.

The configuration of the two systems is outlined in **Error! Reference source not found.**, where an error budget for the two systems is also included. Such error budget is part of the more general error budget, which takes into account for other quantities affecting the measurement and which does not depends on the geometrical orientation and position of the MA, XRS, XRD, like for instance the source size and the X-ray collimator optical quality. Such general error budget is described in **Error! Reference source not found.**.

The **linear displacement metrology** (LDM) shall measure the in-plane displacement between the MA and the XRD (X and Y component of the displacement), and the longitudinal displacement between the two (i.e. the defocus). The former error component is measured by providing a reference optical beam, by means of a laser stabilization system, and by monitoring the signal generated by 4-quad detectors, each solidly attached to the object of interest. The stabilization of the beam is provided to separate the error contribution due to possible rotations of the mechanical base supporting the laser head (which might be caused by temperature gradients), from the real displacement of the objects of interest, i.e. MA and XRD.

The longitudinal component of the displacement is measured by using a laser tracker that instantaneously measures the displacement between two alignment scopes, each pointing at targets placed on board the MA and the XRD unit.

The **tip-tilt** measurement is performed in auto collimation, by placing references on-board the raster scan unit. The optical path form the autocollimator head to the reference mirror includes points where a folding of the beam is required: this folding is performed by using a penta-prism, to minimize the error contribution which might be due to attitude variation of the raster scan, occurring during the translation because of the imperfections of the mechanical assembly: in this way, the metrology is only sensitive to the true rotations of the reference mirrors.

The electro-optical systems foreseen by each metrology systems are commercially available.

4.5. X-RAY SOURCE

The baseline X-ray source is Sigray FAAST (sigray.com), a microfocus sealed tube with a diverging beam refocus by a double parabolic mirror in order to minimize the apparent source size (Figure 4-5). Main specifications of the source are shown in Table 4-1 Source characteristics.

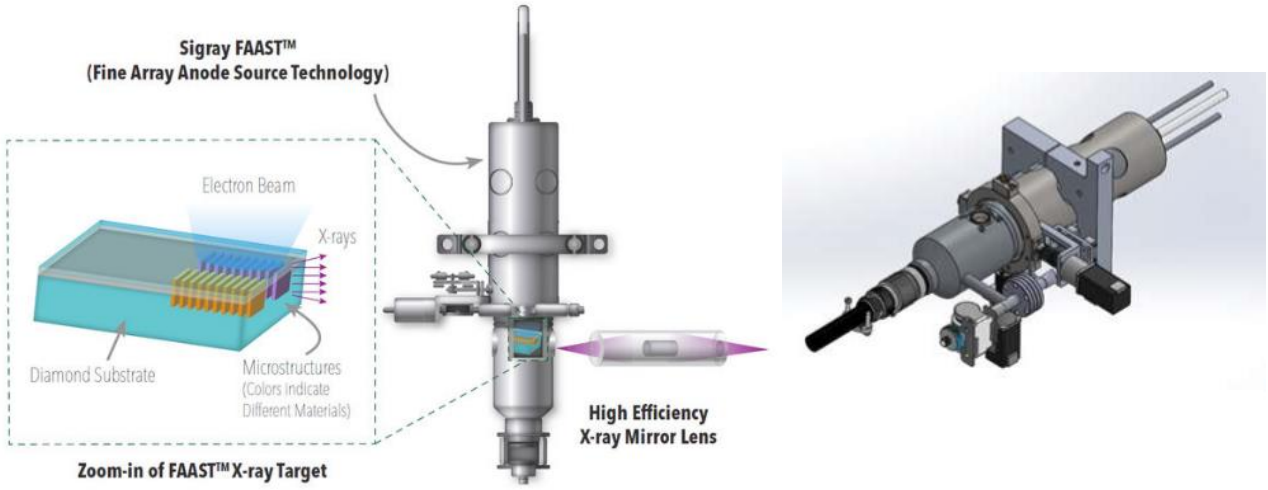

Figure 4-5: Pictorial image of the Sigray FAAST-Micro™ X-ray source

The source is provided with a Be window, 15 µm thick, to maintain ultra-high vacuum (10^{-9} mTorr) at the target. However, such window has a strong stopping power at photon energy below about 1 keV. The source manufacturer is available to customize the product by changing the Be window to other material, e.g. based on polymers or graphene.

The minimum dimension of the source at the exit of the double-parabolic mirror is 10-15 µm, which corresponds to beam divergence of the beam the order of 1-1.5 arcsec. However, the effective source at the exit of the double-parabolic mirror is accessible to insert a pin hole to further reduce the source size, if necessary.

Table 4-1 Source characteristics

Parameter	**Sigray FAAST**	**Comments**
Available anodes	Cu, Cr, Mo, Fe	Other material available
Minimum source size	8 µm	FWHM
Divergence	15°	
Peak flux	$26\cdot10^{9}$ ph/s·mm^2·mrad^2	For Cu anode
Power	50W	
Cooling	water	
Window	Be, 25 µm (customized)	
Internal pressure	10^{-9} mTorr	

4.6. COLLIMATOR

The collimator design, based on a Wolter I configuration, has been derived assuming an average grazing incidence angle at about 0.4° in order to have enough reflectivity up to 12 keV. The Wolter I design provides a much lower sensitivity to source-to-mirror alignment and to source dimension.

The resulting design, dubbed Wolter B in the following, is shown in Figure 4-6 .The length of the mirror is of the order of 1 m.

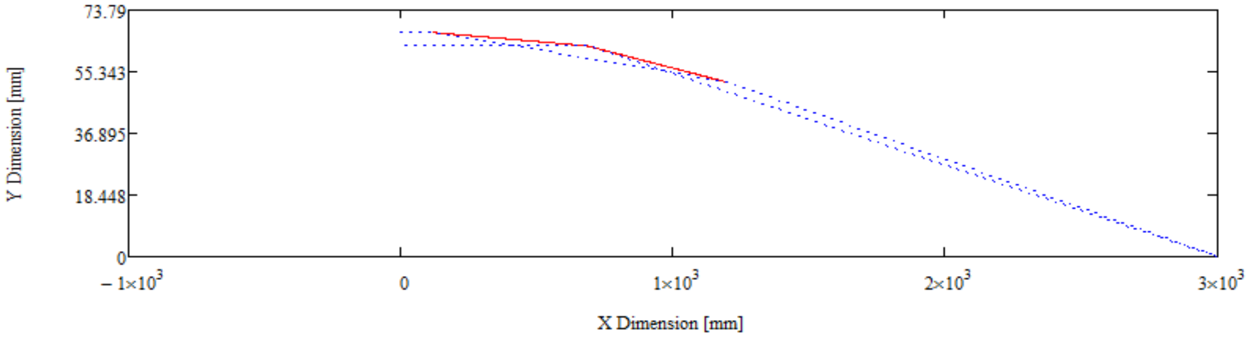

Figure 4-6: Wolter B design – not to scale

The optical prescriptions of the Wolter B design are provided in a cylindrical reference system, in which the Z axis is the optical axis. The origin is at the source focus and the Z axis points toward the output collimated beam. Geometric data are provided in Table 4-2

Parameter	Entrance	Vertex	Exit	Unit
Axial position	1799.2447	2315.000	2882.4498	mm
Radius	52.1381	63.0464	67.0818	mm

Table 4-2: Geometric data of the Wolter B design

The parameters defining the parabolic and the hyperbolic section of the Wolter are reported in Table 4-3 with reference of the following equations:

$$\frac{(z-c)^2}{a^2} - \frac{r^2}{b^2} = 1$$

$$z = ar^2 + c$$

for the hyperbola and parabola, respectively.

Parameter	**a**	**b**	**c**	**Unit**
Hyperbola	989.8021827	19.7898758	-990.0000000	mm
Parabola	1.0806025	-	-1980.2313524	mm

Table 4-3 – Parameters of the Wolter B design

The azimuthal extension of the collimator is mainly determined by manufacturing considerations. At this stage, a width between 40 mm and 60 mm seems feasible (TBC).

Relevant design parameters and performance are listed in Table 4-4

Parameter	**Wolter B**	**Unit**
Min. distance of mirror from source (on axis)	1800	mm
Min. collected angle	1.56	°
Max. collected angle	1.66	°
Mirror length	1083.21	mm
Min. radial distance of the beam from axis	52.14	mm
Radial extension of the beam	4.06	mm
Efficiency[a] at 0.5 keV	0.82	-
Efficiency at 1 keV	0.83	-
Efficiency at 5 keV	0.62	-
Efficiency at 10 keV	0.52	-

[a] Efficiency is the ratio between output and input power

Table 4-4 – Summary of optical parameters and performance

A preliminary mechanical model has been defined (see Figure 4-7) and structural analysis has been performed to validate the concept of the VERT-X Wolter collimator. Zerodur® or equivalent is assumed as the collimator material (see Table 4-5 for material properties). The nominal mass is 36.892 kg, which is increased by 20% for contingencies in the finite element model.

The following load cases have been analysed:

- LC1 – Modal Analysis – cantilever base support
- LC2 – Modal Analysis – cantilever base support and lateral support
- LC3 – Gravity: optical axis direction
- LC4 – Gravity: 3° tilt with respect to optical axis (rotation around Z)
- LC5 - Gravity: 3° tilt with respect to optical axis (rotation around Y)

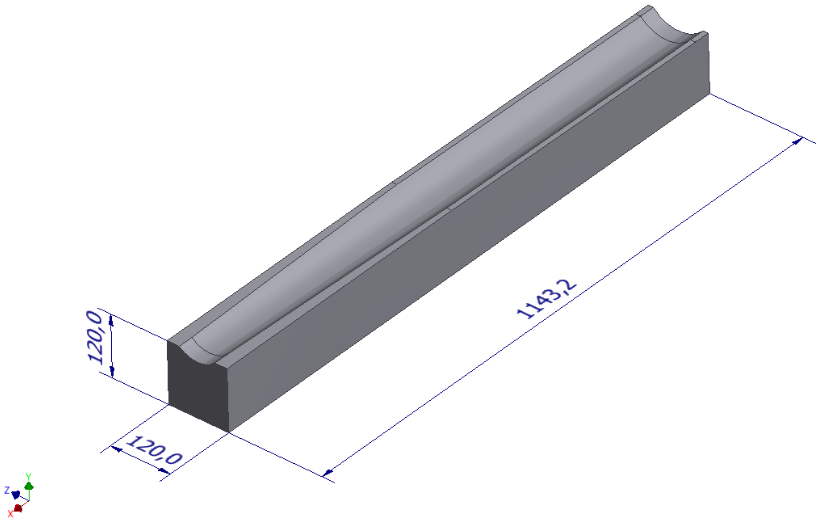

Figure 4-7 - Preliminary mechanical design

Material	**ρ [kg/m³]**	**E [N/mm²]**	**ν**	**σu [MPa]**
Zerodur®, Clearceram®, or equivalent	2530	90300	0.24	10

Table 4-5 – Material properties

The first 5 eigenfrequencies of the mirror for both flexible and rigid blade support are reported in the Table 4-6

Mode	**LC1 Simple Cantilever [Hz]**	**LC2 Cantilever + back support [Hz]**
#1	78.7	359.4
#2	86.0	381.9
#3	447.4	539.6
#4	499.5	646.0
#5	675.2	918.3

Table 4-6 - Modal analysis results

RMS FEA deformation of load cases LC3, LC4, and LC5 are reported in Table 4-7. Since the mirror deformation due to gravity has a very low spatial frequency content, the contribution to the HEW is estimated in Table 4-7 by dividing the RMS figure error in Y by 550 mm (roughly half the length of the collimator) and multiplying the result by $4\sqrt{2}$. In any case such contribution is extremely small.

Load Case	**FEA RMS error in Y [nm]**	**HEW contribution [arcsec]**
LC3 - Gravity: optical axis direction	6.5	~0.01
LC4 – Gravity: 3° tilt with respect to optical axis (rotation around Z)	27.34	~0.12
LC5 - Gravity: 3° tilt with respect to optical axis (rotation around Y)	15.17	~0.06

Table 4-7 :Gravity contribution to figure error of the collimator mirror

4.7. X-RAY DETECTION SYSTEM

4.7.1. Detection Camera

For the design of X-ray detection system of VERT-X facility, commercial solutions based on soft X-ray silicon sensors with photon counting capabilities have been investigated. The choice of these devices is due to the required range of sensitivity, large format, spatial resolution, and moderate energy resolution.

Until the SRR the **Sydor FastCCD** instrument has been considered as the baseline choice for VERT-X detection equipment because it was the only commercial camera fulfilling all the relevant requirements. A critical requirement is given by the necessity of high frame rate along with low noise. Classical CCDs sensors does not perform well due to the serial nature of their readout mechanism. The FastCCD is peculiar since its architecture has a high level of parallelism.

After the SRR, alternative low-cost solutions based on **back- illuminated sCMOS sensors** have been investigated. These sensors have an intrinsic parallel architecture, thus are better suited for high frame rate operation. However, they have lower noise performance if compared to best CCDs, and the commercial availability of cameras for vacuum operations is currently very limited. Moreover, for soft X-ray detection the sensor must be back illuminated, and the entrance window must be thin: very few sCMOS are available with these characteristics.

GSENSE400BSI is a back-illuminated sCMOS from Gpixel available in two coating versions: visible and UV. The UV device is suitable for soft X-ray detection. Synchrotron SOLEIL currently uses this sensor for soft X-ray coherent scattering. QE absolute calibration has been carried out by this group in the range 30-2000 eV.

Papers about the GSENSE400BSI characterization have been published by the Chinese group working on the focal plane R&D for Einstein Probe, since this sensor is considered as a pathfinder for the Wide field X-ray Telescope (WXT). Specifically, for Einstein Probe, Gpixel developed a new, larger sCMOS sensor, HR4040BSI.

Performance comparison between the above-mentioned detectors under evaluation is summarized in Table 4-8

Parameter	Sydor FastCCD	AXIS-SXR	Custom HR4040BSI thick
QE@0.2 KeV/QE@12KeV	**>75%/>50%**	35%/**4%**	35%/8%
Sensor type	CCD BI FD SFT	sCMOS BI	sCMOS BI
Pixel size	30 µm	11 µm	15 µm
Sensor format	960 x 960	2048x2048	4096x4096
Shutter	Frame transfer (dead time, need ext.shutter for high frame rate)	Rolling shutter (rows readout @ different time)	Rolling shutter (rows readout @ different time)
Sensitive area size	28.8 x 28.8 mm^2	22.5 x 22.5 mm^2	**61.4 x 61.4 mm^2**
Max frame rate	120 frames/s	24 frames/s (48 frames/s limit STD)	49 frames/s

Readout noise rms	24 e- [possible 10 e-@lower frame rate]	2 e- (but noise dominated by other factors)	5 e-
Dark current	< 1 e-/pixel/s @ T=-50°C	5 e-/p/s (@ -25 °C)	~200e/pixel/s @room T
Full Well Capacity	100 Ke-	80(70) Ke-	10 Ke-
Vacuum compatibility	$<10^{-7}$ torr	$5 \cdot 10^{-7}$ mbar	yes

Table 4-8: Candidate detectors performance comparison

Several commercial cameras (not for vacuum operations) implements the visible version of GSENSE400 (Front or back illuminated). However only one equipment has hitherto resulted to be commercially available for soft-X, vacuum-compatible operations, i.e. **AXIS-SXR**, a new **camera** for soft-X implementing GSENSE400BSI-UV, developed and characterized by the detector group and SEXTANTS team of SOLEIL Synchrotron, FR, and commercialized by Canadian company Axis-Photonique (the Front-illuminated version of the sensor, only for visible light, appeared few years before the BSI, X-ray compatible, version, which has been commercialized only recently).

As non-commercial alternative, the Chinese group working on Einstein Probe and led by Shuang-Nan Zhang could provide possible collaboration. They are developing an X-ray optimized camera based on G400BSI, including photon counting processing at full frame rate, mechanical interface on CF100 flange and possibility of full vacuum operations. A camera based on HR4040 will be ready in the next few months: a model mounting a thick version of the HR4040, then available, would be an interesting solution for VERT-X.

More details about the detector and camera analysis and design results are reported in RD5.

To summarize, the three investigated options for VERT-X detection camera and their main features are presented in the following.

The **Sydor camera** main blocks are:

- the vacuum-compatible ($<10^{-7}$ torr) camera head which includes:
    - the sensor
    - the front-end electronics
    - the mechanical mounting with a temperature stabilization subassembly
- the cooling subsystem
- the power supply subsystem
- the data acquisition readout system based on a Z'NYX 1900 ATCA System Crate and 10GbE/1GbE Hub Blade

Sydor FastCCD head characteristics are:

- Weight: 4 Kg
- Size: 9 x 11 x 12 cm
- Power: 300 W

The **AXIS-SXR camera** characteristics are:

- Weight: 4 Kg
- Size: 12 x 12 x 12 cm (new version 12 x 12 x 14 cm)
- Cooling: TEC + recirculating water
- Frame rate limited to 24 fps due to USB3 communication limits, AXIS is currently working on a solution to overcome this limitation
- All the required vacuum feedthroughs are included (USB3, electrical and water)

Finally, for the **Chinese camera**, the preliminary characteristics as from a private communication by Zhixing Ling, are:

- weight :4kg
- power: 150 W
- size: 22x18x18 cm^3

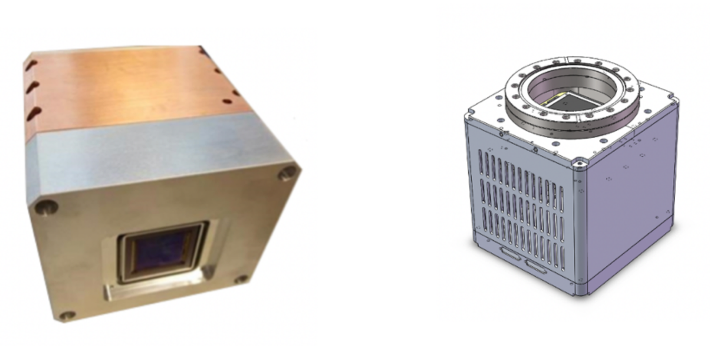

Figure 4-8 The two options for the camera

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4.7.2. XYZ Positioner

The detector (x, y, z) stage (XYZS) has the function of providing the translation of the detector along the x, y and z axes for the performance of VERT-X required measurements.

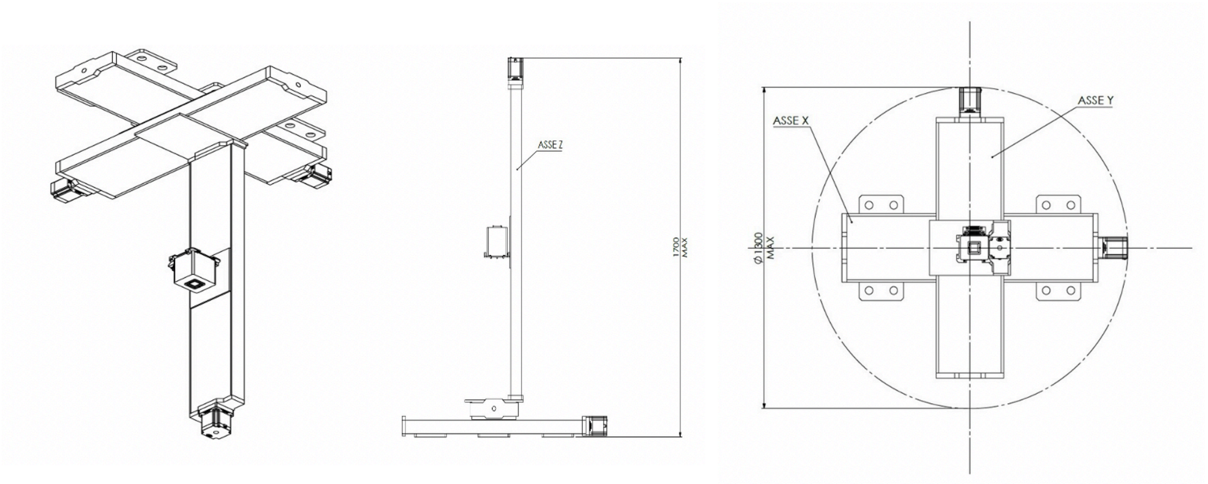


Figure 4-9 XYZS design Option 1 with its side and x-y plan views. The camera is meant to look down toward the MA, that is in the negative direction of VERT-X z axis.

The detector will be moved for several reasons during the calibration operations. First along the direction parallel to the optical axis in order to perform out of focus measure as foreseen by the calibration plan. Then, since the detector is smaller than the field of view, translation within the focal plan will be necessary to test both the off-axis performance and the stray-light contamination.

Finally, a translation of the order of ~ 60 cm will be included for the purposes of the effective area calibration. In fact, calibration of the MA effective area can be achieved as the ratio of the focused beam with the beam directly incident on the detector. For the direct beam, the easiest path would be, of course, through the central aperture in the MA.

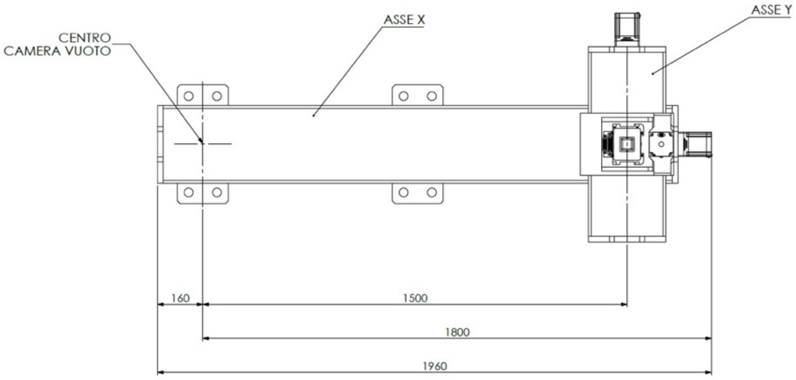


Figure 4-10 Option 2 x-y plan view

The **option 1** design is shown in *Figure 4-9*, assuming the maximum expected distance of 30 cm from the MA center of the free area. A margin is added to the nominal dimensions, to allow the translation of the camera to the required positions. The camera is meant to look down toward the MA, that is in the negative direction of VERT-X z axis.

However, if the central area of the MA will not be suitable for the calibration purposes, the only alternative solution will be moving the detector at the edge of the whole MA (**option 2,** Figure 4-10). In this case the detector stage will have to guarantee an additional translation of ~ 150 cm in the focal plane. Preliminary budget data for the XYZS translation equipment are reported in Table 4-9.

Table 4-9 Technical budget for both options

Parameter	**OPTION 1**	**OPTION 2**
Along x translation tracks length	≤ 1300 mm (TBC)	≤ 600 mm (TBC)
Along y translation tracks length	≤ 1300 mm (TBC)	≤ 1800 mm (TBC)
Translation assembly mass	≤ 200 kg (TBC)	≤ 300 kg (TBC)
Voltage supply lines (translation motors)	380 VAC / 400 VAC 3P	380 VAC / 400 VAC 3P

4.8. GROUND SEGMENT EQUIPMENT

One of the most important and qualifying features of the VERT-X project is the continuity with the ATHENA integration facility. In this context, the main part of the Ground Support Equipment is the **trolley** (Figure 4-11) which is necessary to move the MA unit from the AIT area into VERT-X.

Such trolley shall perform the following actions:

- To lift the system represented by the MA and the GR
- To insert the above-mentioned system into the vessel

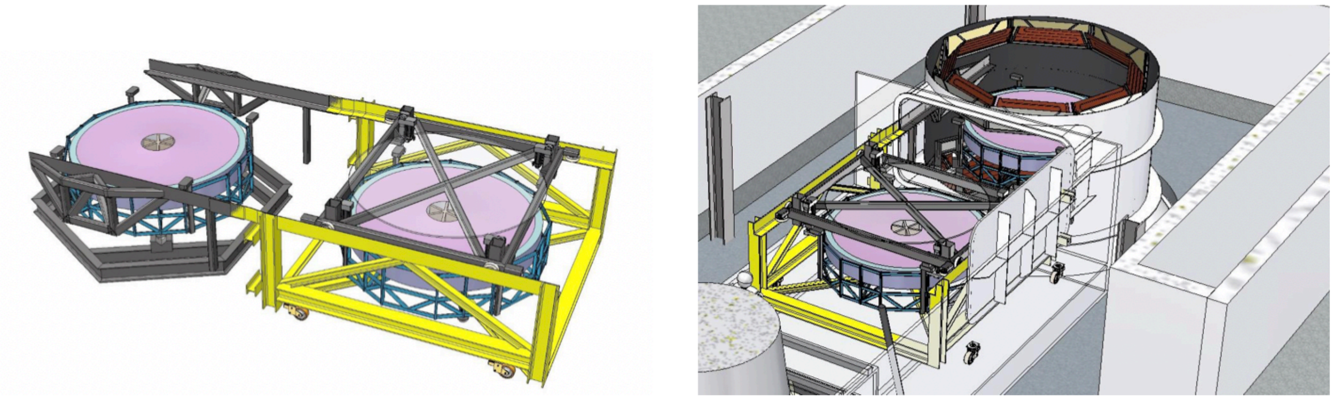


Figure 4-11 The MA trolley, with the HT component in Grey and the GT component in Yellow.

The trolley is made of two parts. The handling trolley (HT), which is responsible for lifting and releasing the MGA, and for introducing it inside the vessel. The HT is hosted by a second trolley, the guiding trolley (GT), which moves the entire assembly (HT + MGA) inside the AIT facility and between the AIT facility and VERT-X. **Guiding trolley** collects mainly the HT on its guiding rails. It will be pushed, positioned and attached to the TVC for the transfer of the MA, GRS and positioner inside. It is mounted on spring wheels for chock absorption. The **handling trolley** is composed of four vertical actuators clamping the GRS during its handling. Four motorized vertical wheels drive the GRS, MA and positioner in and out the vacuum vessel autonomously while four horizontal wheels guide them in the testing position. The shield assures the MA protection from falling parts.

5. TECHNICAL BUDGETS

5.1. HEW ERROR BUDGET

Systematics in the HEW measured in VERT-X will be the pointing uncertainty (HEW_{PNT}), the source dimension (HEW_{SOU}), the mirror error (HEW_{MIR}), the relative position between source and collimator (HEW_{FOC}) and the gravity induced distortions (HEW_{GRV}) the as the major ones. The HEW that we will measure at VERT-X will be given by:

$$HEW_{VTX}^2 = HEW_{MA}^2 + HEW_{PNT}^2 + HEW_{SOU}^2 + HEW_{MIR}^2 + HEW_{FOC}^2 + HEW_{GRV}^2,$$

where HEW_{MA} is the quantity we aim at calibrating and HEW_{VTX} is what we measure. As shown in RD8 the two quantities HEW_{MIR} and HEW_{SOU} combine together linearly. Hereafter we consider them as one single term, named HEW_{SYS}. Inverting the equation we have that

$$HEW_{MA}^2 = HEW_{VTX}^2 - HEW_{PNT}^2 - HEW_{SYS}^2 - HEW_{FOC}^2 - HEW_{GRV}^2.$$

which is nothing else than a de-convolution. HEW_{MA} measure will be obtained by de-convolving the known error terms. The calibration requirement on the HEW AKE (HEW < 0.1”, RD4) has to be compared with the error on this de-convolution $\sigma^2_{\mathrm{HEW\_MA}}$.

The uncertainty on the HEW_{MA} will be given by the (quadratic) sum of the uncertainties of each single term, weighted by the ratio with the intrinsic HEW_{MA}. The amplitudes of different contributions to the total error budget are discussed in separate documents and are here reported in Table 5-1 Estimate of different contributions to the HEW error budget.
As it is clear from the table, since all the systematic contributions are kept at the level ≅ 1’’ or less, their weights in the error budget are minor, with the main term being the statistical error.
Indeed, the statistical term is the only one with a weight of the order of the unity. As discussed in RD11, for each energy bin, we plan to collect 50,000 photons from the calibration source corresponding to an expected statistical uncertainty of 0.05”.

Table 5-1 Estimate of different contributions to the HEW error budget

ERROR SOURCE	HEW[“]	σ_{HEW} ['']	REFERENCE
POINTING	0.27	0.24	RD7
SOURCE	1.00	0.20	RD8
COLLIMATOR	0.55	0.15	RD8
SYS (SOU.+COLL.)	1.55	0.35	RD8
SOU-COLL displ.	0.1	0.1	RD8
GRAVITY	0.1	0.05	RD1
VERT-X MEASURE	5.14	0.05	RD9

(*) in the case of WOLTER geometry mirror. For a single reflection this value is expected much higher (RD8).

Filling the equation with the numbers here reported, we find that the expected measure HEW, will be 5.14” which allows us to estimate the intrinsic HEW_{MA} with an error of 0.09” at 68% confidence, compliant with the requirements.

5.2. HEW STATISTICAL ERROR

As explained in the previous session, the statistical error in the HEW measure is the main error source. It follows that its proper assessment is of particular importance. We started from the ray-tracing output (Willingale 2019, **Figure** 5-1: this has been produced with 1,5 10^6 events at 1 keV energy on axis and contains a full treatment of error terms.

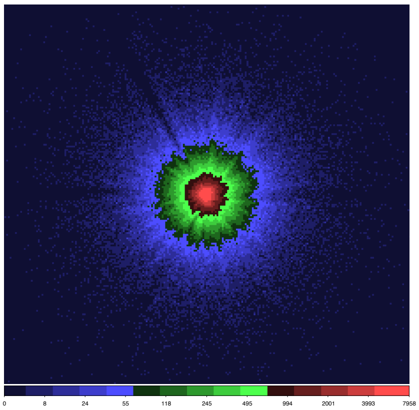


Figure 5-1 *Output image of a ray-tracing simulation at 1Kev on axis.*

PSF model allows us to estimate the expected statistical error in the HEW calibration as function of the number of photons collected during the calibration tests. To this aim, starting from the analytical model used to fit the ray-racing PSF we simulated PSF with different numbers of photons, ranging from 1000 to 100,000. At a given number of collected events we simulated 100 times PSF and measured the HEW. In Figure 5-2, for each number of photons, we report the standard deviation of the 100 measures. The HEW measure accuracy follows the number of counts with a slope of 0.5: this is expected since the HEW error can be considered as an error on the mean. ***In order to keep the statistical uncertainty at the level of 0.1" ~50,000 counts per energy bin are required.***

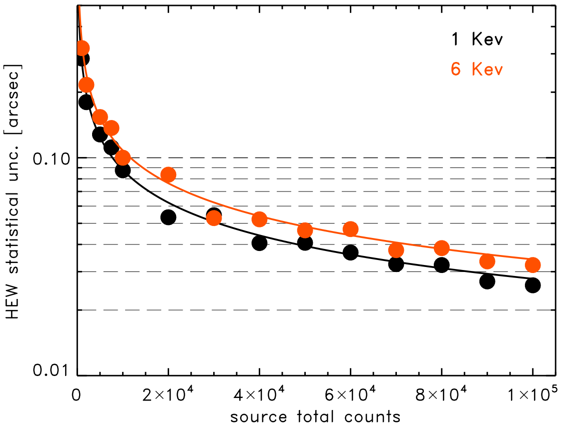


Figure 5-2 *HEW statistical error as function of collected photons on-axis at two different energies*

5.3. EFFECTIVE AREA STATISTICAL ERROR

Absolute calibration of the MA effective area can be achieved by combining measures of the focused beam (R_{foc}), already described in the PSF calibration Section, with measures of the beam directly incident on the detector through the central aperture of the MA (R_{det}) (hereafter flat-field, FF). In this way the EA measure is straightforward. For each energy E, assuming a complete and uniform scan of the area A_{foc} (which includes MA), at uniform velocity, the effective area is given by

$$A_{eff}(E) = A_{foc}\ (C_{foc}(E)/\Delta t_{foc})\ /\ (C_{fla}(E)/\Delta t_{fla})$$

$$A_{eff}(E) = A_{foc}\ R_{foc}(E)\ /\ R_{fla}(E)$$

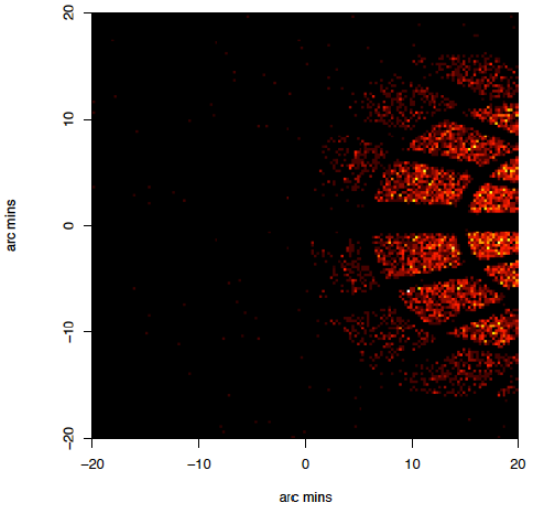
where C_{foc} are the events registered on the detector during Δt_{foc} which is the time spent scanning the area A_{foc} including the MA. C_{fla},Δt_{fla} and R_{fla} are the values relative to the flat-field (FF) measure before, after and during the calibration test.

The required AKE for the absolute measure of the effective area is 6% at 10 monochromatic energies.

The required AKE for the relative measure of the effective area are 2% and 3% for on- and off-axis measure respectively. Since the relative effective area will be the result of the ratio between focused and direct beams, 5,000 photons for both beams are required. As described in previous Section, for HEW and PSF calibrations a number of 50,000 is required in 1 keV bins. This would mean that the same PSF calibration data-set would provide the needed accuracy for the effective area calibration in bins of 0.1 keV to be compared with the required 0.33 time the WFI spectral resolution.

5.4. STRAY-LIGHT STATISTICAL ERROR

Required AKE of the stray-light calibration is 5% with a confidence level of at least 99.73%, on scale of 9 arcmin^2 out to an off-axis angle of 20 arcminutes and for energies in the range 0.5–3 keV. Since we expect that stray-light covers 2 quadrants of the FOV, this means that for each out FOV required position, a 20’x10’ area should be covered. With the current baseline detector (FOV 8’x8’, [RD9]) this means 6-9 different observations with the detector shifted in adjacent positions within the FOV.



Since the detector area can be covered by 10 9-arcmin^2 circles and that 5% with a confidence level of 99.73%, imposes 1000 counts per circle, a 10x1000 photons should be collected to satisfy the requirement on average for each detector positions.

6. OPERATIONS

Verification goals and requirement are summarized in the following table.

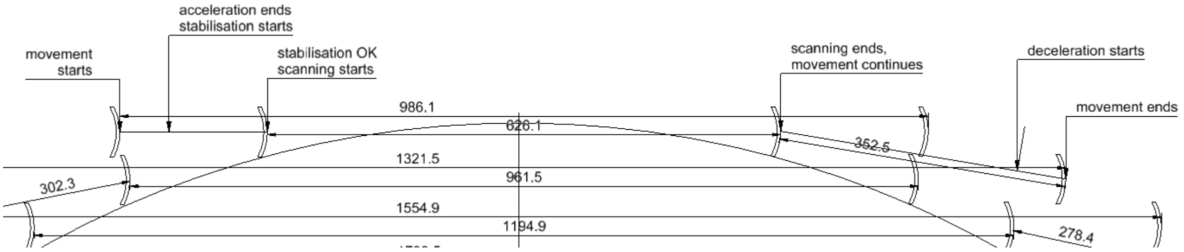
WHERE	GOAL	ACCURACY	ENERGY	TESTS	REQ	WHEN	WHAT
On Axis	FOCAL LENGTH	1mm (99.7%)	1 (Al-Kα)	10	LB-URD-365	AA, IAC	QM,FM1-3, FM1-8, FM1-12, FM.
On Axis	OPTICAL AXIS	10'' (68%)	3 (C,Al,Ti-Kα)	15	LB-URD-365-366	AA, IAC	QM, FM1-3, FM1-8, FM1-12, FM.
On Axis	HEW	2% (68%)	1 (C,Al,Ti-Kα)	1	LB-URD-368	AFT	QM, FM1-3, FM1-8, FM1-12, FM.
On Axis	A_{eff}	10% (68%)	1 (C,Al,Ti-Kα)	1	LB-URD-368	AFT	QM, FM1-3, FM1-8, FM1-12, FM.
On Axis	HEW	2% (68%)	3 (C,Al,Ti-Kα)	1	LB-URD-365-366-368-369	AA, IAC, FULL	QM, FM1-3, FM1-8, FM1-12, FM.
On Axis	A_{eff}	10% (68%)	3 (C,Al,Ti-Kα)	1	LB-URD-365-366- 368-369	AA, IAC, FULL	QM, FM1-3, FM1-8, FM1-12, FM.

Calibration goals and requirements are summarized in the following table.

WHERE	GOAL	ACCURACY	ENERGY	TESTS	REQ
ON Axis	Focal length	1mm (99.7%)	3(Al-Kα,Ti-Kα,Cu-Kα)	10	LB-URD-374 CAL-AST-R-002
On Axis	Optical axis	36'' (99.7%)		15	LB-URD-373 CAL-AST-R-005
On Axis	HEW	0.1'' (68.3%)	7 (C-K / Ge-K)	1	LB-URD-376 CAL-PSF-R-001
On Axis	PSF	5% (68.3%)	7 (C-K / Ge-K)	1	LB-URD-376 CAL-PSF-R-001
Off-Axis	HEW	0.1'' (68.3%)	7 (C-K / Ge-K)	1	LB-URD-376 CAL-PSF-R-001
Off-Axis	PSF	15% (68.3%)	7 (C-K / Ge-K)	1	LB-URD-376 CAL-PSF-R-001
On Axis	A_eff (abs)	6% (68.3%)	10 (TBD 0.2-12.0 keV)	-	LB-URD-379 CAL-EEF_R-001

On Axis	A_eff (rel)	2% (68.3%)	0.2-12.0 keV continuum, step 1/3 spectral resolution	-	CAL-EEF_R-003
Off Axis	A_eff (rel)	3%(68.3%)	0.3-7.0 keV continuum, step 1/3 spectral resolution	-	LB-URD-382 CAL-EEF-R-004
OUT Fov	Stray-light	5% (99.7%)	2 (Al-Kα,Fe-Kα)	10	LB-URD-383 CAL-PSF-R-003
Out focus	HEW	0.5'' (99.7%)	Not specified	10	LB-URD-377

6.1. SCAN TIME



Since the beam size, orthogonal to the scan direction is 60 mm, 40 adjacent rows are necessary to cover the ATHENA MA with a the total scan path of ~ 100 m. With a nominal maximum scan velocity is 30 mm/s (RD3) this means ~ 1 hr for the total nomina scan time accounting for 14 s of settling time at the start and end of each row.

6.2. PILE-UP

Given that the scan time is of the order of 1.0 hours, the expected limiting factor for the calibration operations is given by the performance of the detector in terms of sustainable flux. Requirements on pile-up fraction is at 1%. Accurate pile-up assessment is therefore mandatory in order to estimate the maximum count-rate suitable in order to meet the requirement. The extreme importance of this estimate is that the calibration duration is linear function of this value.

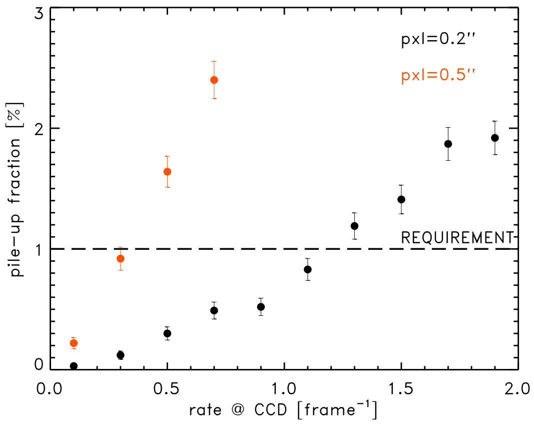


Figure 6-1 The pile-up fraction two different pixel sizes as function of the count rate per frame of a point-like source (in order to have the count rate of the source this should be multiplied by frame time).

At the moment, for the detector different options with different pixel and sensor sizes are suitable (RD11). In the first option the pixel size is 0.11” with a frame time of 40 s^{-1}. In the second case the pixel size is 0.5” with a frame time of 120 s^{-1}. As it is shown in the plot, in terms of source count rate they yield similar number, which is ~ 40 count s^{-1}. In these simulations we assumed all the events as single pixel events.

6.3. HEW AND EA CALIBRATION OPERATIONS

Given that the necessary amounts of photons are similar, we are planning to use the same data-sets for the aims of both effective area and PSF calibration. Since the required number is much higher than CCD_{RATE} x T_{SCAN}, the limiting factor in this kind of tests is the sustainable count rate.

In the case of Bremsstrahlung continuum, the calculation of necessary exposure time T_{EXP} is not straightforward. This is because photon distribution is not uniform over the required energy band.

In order to calculate T_{EXP} we started from a Bremsstrahlung continuum produced by a target of Ge with KT=40keV and a power of 50W. The spectrum is normalized to match the maximum flux produced by the source (2.6 ph s^{-1} msterd^{-1} mm^{-2} as reported in [RD8]). The spectrum is then multiplied by the effective area of the collimator, which has been calculated as the product of its geometrical area (250 mm^{2}) with the expected reflectivity, accounting for the double reflections. In order to have the focused photons we multiply by the expected reflectivity of the ATHENA MA and re-normalize the spectrum by a factor of 0.4 to account for geometrical vignetting. Finally, both the simulated focused and direct beams are multiplied by the QE of the detector.

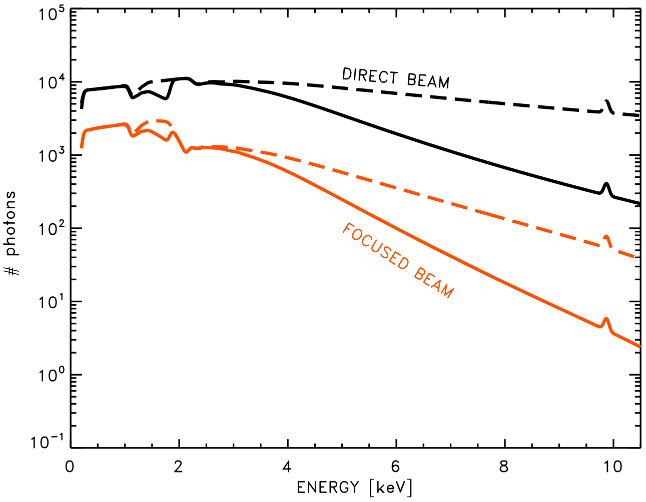


Figure 6-2. Simulated spectrum of Bremsstrahlung emission including reflectivity and detector QE. Dashed and continuous lines correspond to Sydor and CMOS QE, respectively.

Given the intrinsic spectral shape and the reflections on the collimator and on the MA, for the on-axis observation, where a large coverage is required, it is more convenient splitting the observations in different bands. This can be achieved using high-pass filters like Be window at different thickness levels. The example shown produces the count distribution shown in ~10 hours with ~30% of the time used for the flat field.

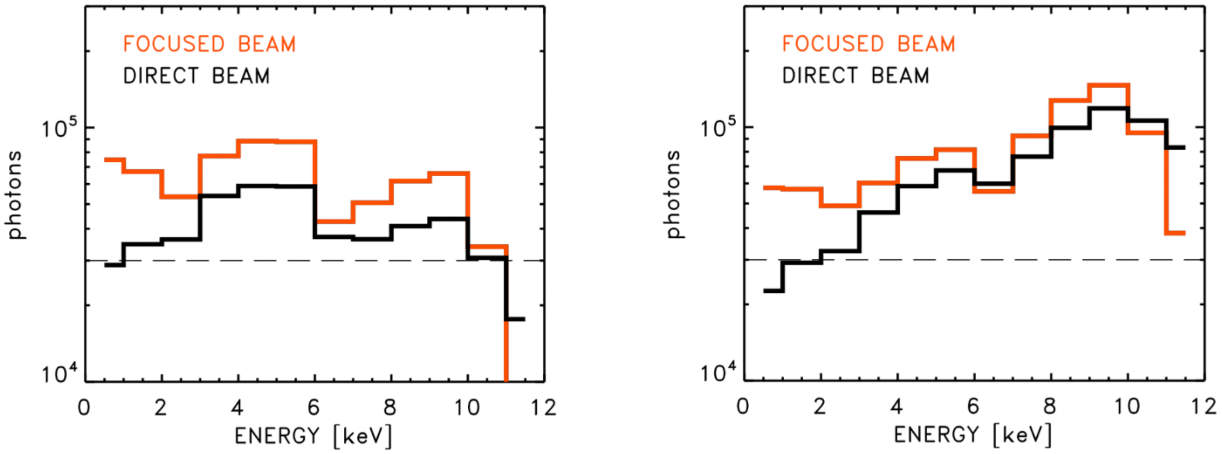


Figure 6-3 Photon distribution registered at the detector in the simulation described in the text and previous figure. Left panel assumes the CMOS QE, while right panel SYDOR QE

6.4. CHARACTERIZATION OF SINGLE MODULES

The small size of the VERT-X parallel beam, in principle, allows the characterization of the single modules PSF and effective area. Assuming a scan velocity of 10 mm/s, even the in the worst case, with a detector time frame of 0.025 s we would have a spatial resolution of 250 micron which is largely adequate to map the single modules contribution.

However, according to the current baseline the beam is of the same size of the single modules and is significantly larger than the ribs. This would prevent this kind of test. We simulated a path for the scan and we registered which fraction of each module uniquely covered, which is the fraction of each module covered by the beam without touching any other adjacent module.

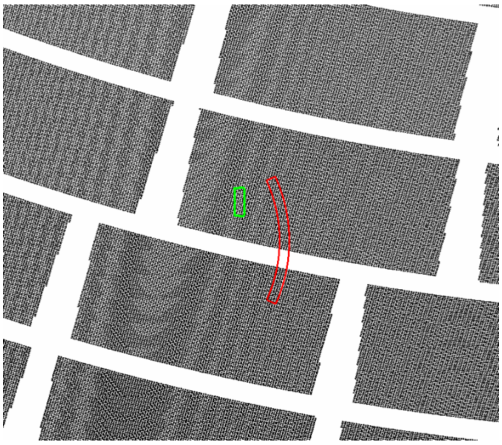


Figure 6-4 Different sizes of the beam. Red is the baseline (~ 6cm height); green is the beam with the reduced size for the purpose of the single module characterization test

Reducing the beam to the 20% of the baseline size we can obtain an adequate characterization of each single module. In this case all the modules can be characterized with 97% of the modules being uniquely covered for fraction higher than 98%.

7. COMPLIANCE WITH REQUIREMENTS

Req. ID		NOTES
R01	**C**	In the VERT-X preliminary design the low-divergence X-ray beam (~1”), needed for verification and calibration, is produced placing a source in the focus of an X-ray collimator. This system is mounted on a raster-scan mechanism which covers the entire ATHENA optics (**RD13**). This facility will allow the MA verification and calibration tests in compliance with verification and ground calibration plans (**AD4**, **AD5, AD6**).
R02	**C**	All the components installed within the chamber are compliant with operations in vacuum and they will be remotely controlled. No manipulation of the MA is foreseen during the verification and calibration operations (**RD1-RD13**).
R03	**C**	The detector stage is designed to directly expose the detector to the X-ray beam. This will be through the MA central aperture or at the MA edge (**RD5).** Direct beam measures are functional to the purposes of the EA calibration (**RD11)**.
R04	**C**	Raster scan mechanism has the capability of moving the parallelized beam in order to illuminate each single module. This is provided by scaling-down, the beam footprint by means of a mask. A reduction of 80% of the beam size allows the characterization of each single module.
R05	**C**	Raster scan can be moved with the required pointing accuracy up to ~ 30 mm/s (**RD3**). As discussed in **RD11**, maximum speed is not necessary for the large part of the calibration and verification tests. This is because the duration of the PSF and EA calibration measures will be determined by the detector pile-up limit.
R06	**C**	The VERT-X measure of HEW is the result of the (quadratic) sum of HEW_{MA} with several independent contributions: the pointing uncertainty, the source dimension, the mirror error and the gravity induced distortions. As discussed in **RD11,** the estimated uncertainty on the HEW is ~ 0.1” (1 sigma), also accounting for the statistical error.
R07	**C**	In conical approximation design, the loss of effective area (EA_{loss}) due to geometrical vignetting of a divergent beam is given by EA_{loss} = 2 theta/alpha; where alpha is the parallel incident angle for a parallel beam and theta is the beam divergence. Since the minimum alpha for ATHENA MA is 0.3° a 1% vignetting factor would be given by a divergence of ~6.0”, as minimum. This is much larger than the designed beam divergence.
R08	**C**	The expected beam divergence is discussed in RD12, in the HEW error budget Section. Using the design value and the formula linking EA_{loss} to beam divergence we find that value of EA_{loss} and its uncertainty are well below 1%.
R10	**C**	The measurement of the relative displacement between the MA and the XRD, are performed by the linear displacement metrology. The orientation of the X-ray beam with respect to a given reference is determined by the tip-tilt metrology. The orientation of the MA and the XRD is measured against the gravity, by using tilt-meters (**RD3**, **RD7**).
R11	**C**	In the PD the TVC, is a 20 m tall and 4 to 7 m wide cylindrical vertical vessel subjected external pressure. It houses the X-Ray Raster Scan, the Mirror Assembly, and the Detector (**RD1**).
R12	**C**	One large door at the Mirror Assembly level (clear aperture 3.2 m x 1.6 m), for MA insertion/extraction is included in the design (**RD1**). One opening at the top of the vessel, corresponding to the top end of the chamber (clear aperture Ø 4 m), for detector insertion/extraction is also designed (**RD1**).
R13	**C**	Both the MA and the detector openings are connected to ISO 5 clean rooms in such a way that when the vessel is open, it remains at an environmental cleanliness level corresponding to ISO 5 (**RD1**).
R14	**C**	One small doors at the -1 (Raster Scan) level (clear aperture 1.7 m x 1.2 m), for personnel access and small pieces insertion/extraction (**RD1**).

Req. ID		NOTES
R15	**C**	The general configuration of the vacuum generator system consists of three different subsystems. (i) primary vacuum until 1e-2 mbar: 3 dry pumping groups (~2200m3/h) in parallel with ISO 160 valves and ISO 160 tubes; (ii) secondary vacuum until 1e-3 mbar: 2 turbomolecular pumps (4000l/s) with ISO 320 valves, a primary vacuum line with a unique dry pumping; (iii) high vacuum until 1e-6 mbar 2 cryogenic pumps (8000, 10000, 12000 l/s for N2, 18200, 30000, 28550 l/s for water respectively) with ISO 400 & 500 valves, a primary vacuum line with a unique dry pumping (**RD1**).
R16	**C**	To keep the MA in the requested thermal conditions, a thermal shroud assembly has been designed in a sandwich configuration to allow the MA going in and out the TVC (**RD1**).
R17	**C**	A preliminary layout of the main viewports for the optical metrology has been defined. The layout will be updated in the Detailed Design. They will be integrated in a further development step being related to the main elements location confirmation (namely the metrology and vacuum generation system).
R18	**C**	Interfaces flanges and feedthroughs will be included in the DD. They will be integrated in a further development step being related to the main elements final location (metrology, vacuum generation).
R19	**C**	The baseline X-ray source is Sigray FAAST, which can be operated in vacuum and moved by the raster-scan mechanism. It is described in **RD2**.
R20	**C**	The baseline X-ray source can be equipped with four different targets. In **RD11** we discuss the possibility of accomplishing the verification and calibration task using the continuum spectrum and exploiting the detector energy resolution.
R21	**C**	This is included in the baseline X-ray source capabilities (**RD2**).
R22	**C**	The size of the collimated beam is presented in **RD2**. It consists in a portion of a circular corona with 60 and 64 cm of internal and external radius respectively for a total are of 258 mm^2 .
R24	**C**	By design of the tube which hosts the X-ray source and the collimator and which is moved by the raster-scan mechanism (**RD3**).
R25	**C**	The statistical uncertainties in the HEW and PSF calibration as function of the number of collected photons are discussed in **RD11**. The statistical error is one of the terms of the HEW error budget.
R27	**C**	According to the planned operations (**RD11**) a fraction of the exposure time used for EA calibration will be devoted to direct measure of the beam. Cadence of these measures will be such that X-ray source expected variations will be well below 1%. X-ray flux will be also monitored by a detector positioned at ~ 20 cm from the source.
R29	**C**	Raster-scan mechanism design is reported in **RD3.** This is fully compatible with high vacuum operations.
R30	**PC**	The zero of the position can be determined by the metrology. The position relative to the zero is obtained from the linear encoders of the motion system (**RD3**).
R31	**PC**	**RD7** describes the tip/tilt servo model which has been created to prove the capability of the envisaged system (control, plus mechanism, plus structure) to effectively move and control the X-ray beam attitude. The reported position errors of the tube attitude measured at the encoders are 0.16” and 0.06” (RMS) for ROT-X and -Y respectively. We note that this requirement only concerns one term of the entire HEW error budget, which is made up by several terms (**RD11). ** As **Req. 31** is derived and functional to the **Req. 6**, the resulting error budget allocation is slightly different from the one derived from the requirements, and it is fully compliant with **Req. 6**, which is the parent one.
R32	**C**	The Raster Scan tip / tilt control system consist of (i) an inner loop — based on the encoder signal — that controls tube angular position by chasing the set point; (ii) an outer loop — based on tip / tilt metrology — that fixes the tube attitude by correcting the set point of the inner loop. Performance of the control system on the X-ray beam attitude has been assessed by servo analysis (**RD3, RD7**).

Req. ID		NOTES
R34	**C**	The gravity mitigation consists in a supporting system contrasting axial gravity effects, limiting the PSF degradation induced by gravity during alignment/integration, testing and calibration. Both MA support system and gravity release are considered together at the same time in **RD6, i**n continuity with AIT facility.
R35	**C**	MA distortions related to gravity release, for different possible support patterns, have been investigated by FEA. Consequent MM misalignments have been then post-processed by raytracing, to assess the impact on PSF. The minimum PSF degradation is obtained by six axial supports along the outer ring and six inner supports at the intersection between ring 6 and the spokes (**RD6**).
R38	**C**	Detector system is described in **RD5**. Currently we have two options which are both fully compatible with the required vacuum conditions.
R39	**C**	The design solution for the XYZS involves the use of a hexapod for the detector fine positioning along x, y and z, according to the requirements. For the purposes of direct beam measures (i.e. flat field), if free space at the centre of the MA is not made available, the hexapod may be mounted on a support that can be moved along a longitudinal track. In its turn, the track is mounted on a central pin that allows a 360° rotation. In this case, the combination of longitudinal translation and rotation of camera and hexapod assembly will allow covering all the points in a circle of more than 240 cm diameter (**RD5**).
R40	**C**	The XYZS can move the detector camera along the z axis, for the range derived from the requirements i.e. 100 mm (1 mu steps). This allows to place the detector in the MA focal plane (**RD5**).
R41	**C**	The XYZS is designed to provide the needed accommodation for the detection camera. It shall be vacuum compliant, and it will provide a fine positioning of the detector along the x-y-z axis, for the ranges derived from the requirements (**RD5**).
R42	**C**	The XYZS is designed to provide a translation of the detector along z axis on a range of ± 50 mm (10 cm). Hexapods can achieve a minimum incremental motion of 1 µm, as well as an equivalent repeatability (**RD5**). The distance of the MA and the detector is controlled by linear displacement metrology with the required accuracy (**RD3**).
R43	**C**	The requirement is defined according to the need of performing out-of-field measurements giving the fraction of out-of-axis X-ray flux falling within the detector field of view (FOV). To achieve compliance the XYZS shall provide a fine positioning of the detector along the x and y axes on a range corresponding to FOV area. This is equivalent to a translation of ±70 mm (14 cm) along both the axes.
R44	**C**	The assembly represented by the MA and the gravity release is transported form the AIT facility to the VERT-X facility using a handling trolley (**RD10** and references herein).
R45	**C**	
R49	**C**	In continuity with AIT facility
R50	**C**	A preliminary verification and calibration plan is presented in **RD11**. This is fully compliant with calibration requirements (**AD4**, **AD5, AD6**).
R51	**C**	All the electrical plants and mechanisms are designed in accordance with the applicable norms.
R52	**TBC**	
R53	**C**	The RAMS analysis is the modelling instrument that is used to identify the preventive maintenance. MTBF values of all the parts of the system must be collected to work out the spare parts list.
R54	**C**	

8. PROGRAMMATIC ASPECTS

8.1. DEVELOPMENT PLANNING

The VERT-X development plan consists in two main phases. In the first phase the most critical parts of the systems will be realized and tested. These are the X-ray source assembly (**XSA**), including both the x-ray source and mirror, and the raster scan mechanism (**RS**), including the tip/tilt metrology. This phase of the plan coincides with the activities proposed in response to the RFQ Request for Quotation RFQ/3-16555/20/NL/IB/gg, with title *Demonstration of critical items for x-ray scanning facility,* RD2.

In the second phase the plan foresees the realization the Thermal Vacuum Chamber together with the remaining elements of the testing system, namely the completion of the RS, the camera and its stage. The integration of the facility in the ML AIT building is the final task of the second phase.

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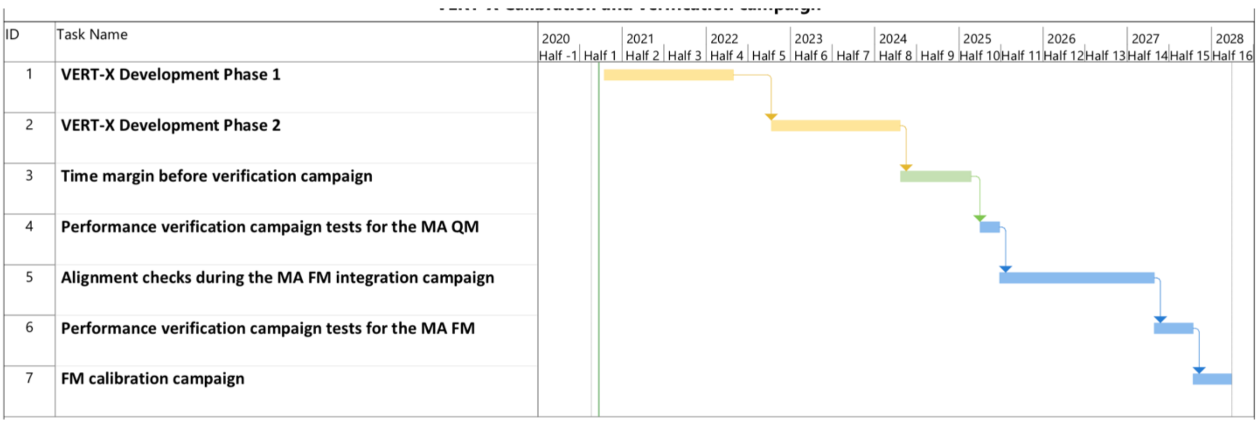
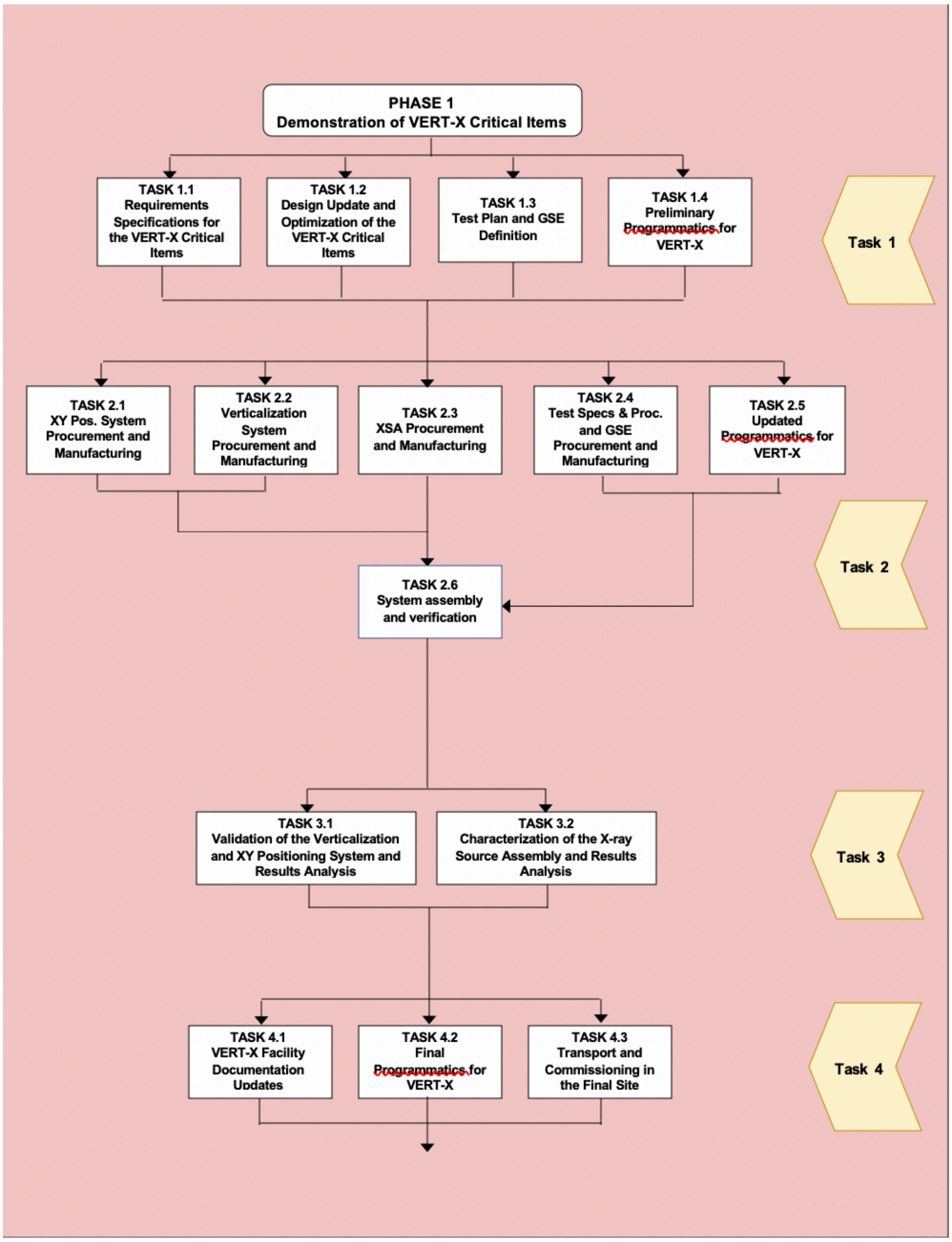


Figure 8-1 VERT-X development versus Verification schedule

From the point of view the schedule, first phase is expected to start in Oct 2020 and lasting for 20 months, ending June 2022. As reported in the development plan, for the second phase we foresee a duration of 18 months. If we assume to start in Sep 2022 the VERT-X development should be completed by Apr 2024, almost 12 months before the start of the QM verification phase (Apr 2025).

8.2. WORK BREAK DOWN AND LOGIC

First phase task are listed here.



1-1.1: Requirements Specifications for the VERT-X Critical Items

1-1.2: Design Update and Optimization of the VERT-X Critical Items

1-1.3: Test Plan and GSE Definition

1-1.4: Preliminary Programmatics for VERT-X

1-2.1: Y Positioning System: Procurement and Manufacturing

1-2.2: Verticalization System: Procurement and Manufacturing

1-2.3: X-Ray Source Assembly: Procurement and Manufacturing

1-2.4: Test Specs & Procedures and GSE Procurement and Manufacturing

1-2.5: Updated Programmatics for VERT-X

1-2.6: System Assembly and Verification

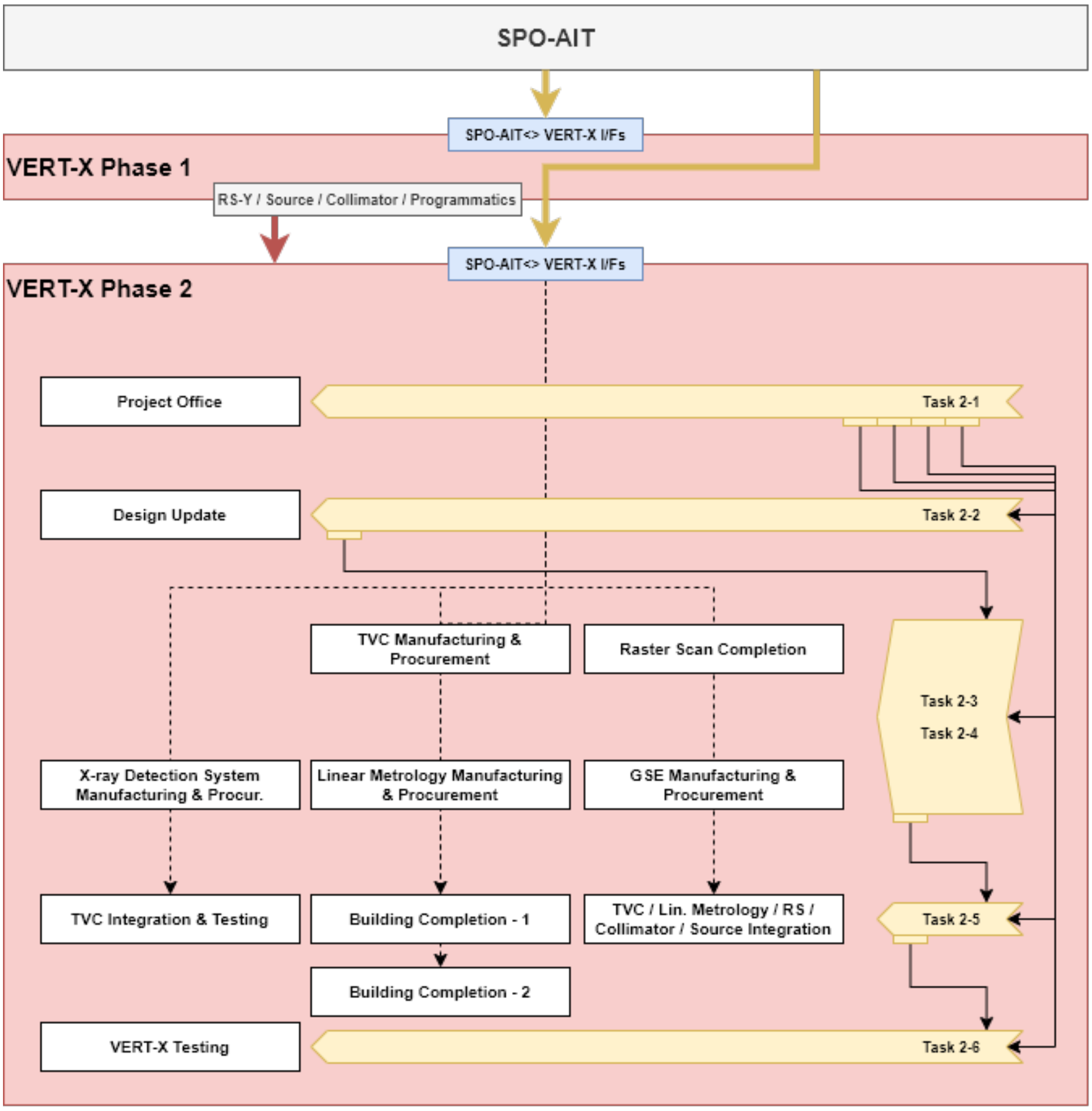
1-3.1: Validation of the Verticalization and XY Positioning System and Results Analysis

1-3.2: Characterization of the X-ray Source Assembly and Results Analysis

1-4.1: VERT-X Facility Documentation Updates

1-4.2: Final Programmatics for VERT-X

1-4.3: Transport and Commissioning of Critical Items in the Final Site



2-1: Project Office

2-2: Design Update and Optimization

2-3.1: Manufacturing and Procurement of the Thermal Vacuum Chamber

2-3.2: Completion of the Raster Scan

2-3.3: Manufacturing and Procurement of the Camera System

2-3.4: Manufacturing and Procurement of the Linear Metrology System

2-3.5: Manufacturing and Completion of the GSE

2-3.6: Definitive acquisition of the X-ray source

2-4.1: TVC Factory Testing & Acceptance

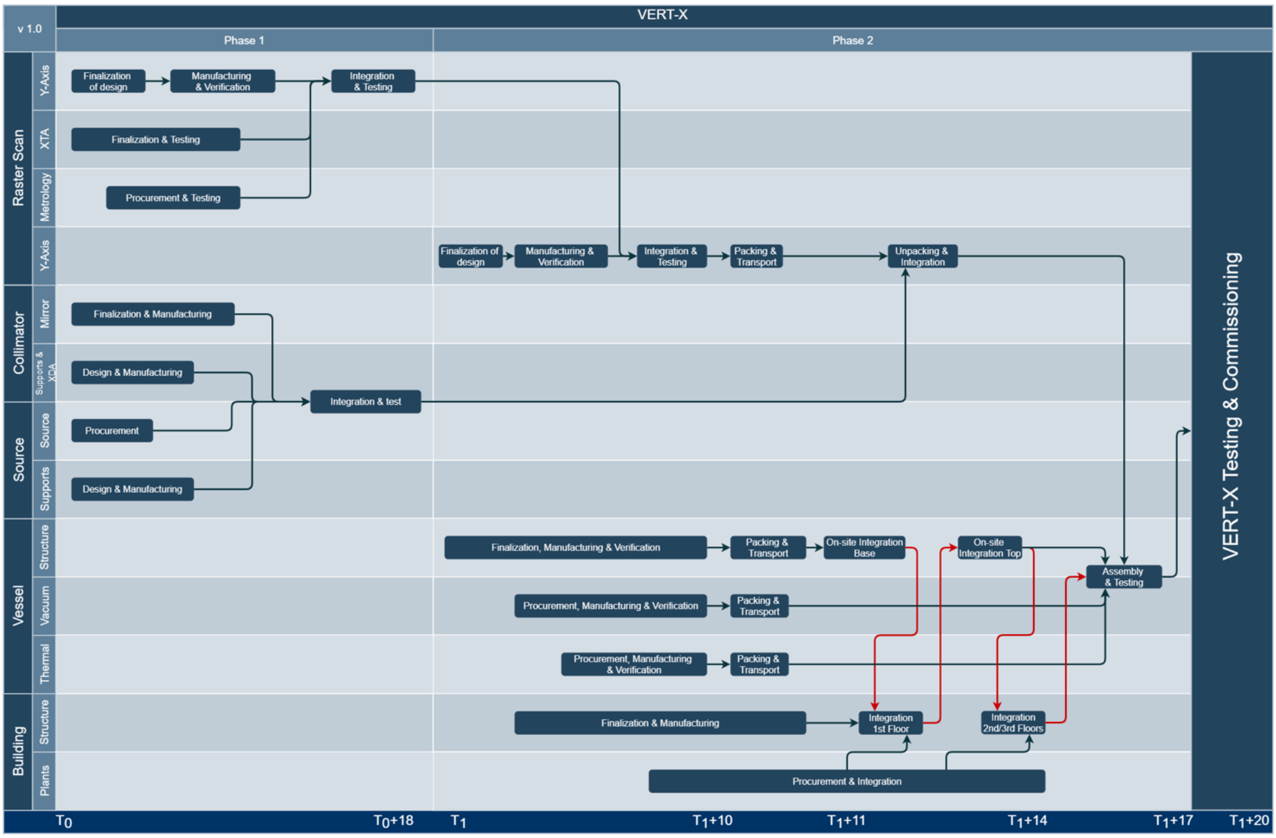
2-4.2: Raster Scan Factory Testing & Acceptance

2-4.3: Detection System Factory Testing & Acceptance

2-4.4: Linear Metrology Testing & Acceptance
2-4.5: GSE Testing & Acceptance

2-5.1: TVC Integration, Site Testing & Acceptance
2-5.2: Building Completion - 1
2-5.3: Building Completion - 2
2-5.4: RS / Source / Collimator / Linear Metrology | TVC Integration

2-6.1: RS Site Testing & Acceptance
2-6.2: Source Site Testing & Acceptance
2-6.3: Detection System Site Testing & Acceptance
2-6.4: Linear Metrology Site Testing & Acceptance



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