Managing the mass production for the LAD instrument onboard eXTP

Minervini G.[a], Argan A.[a], Feroci M.[c], Trois A.[b], Del Monte E.[c], Brienza D.[d], Ambrosi, G.[e], Antonelli, M.[f], Barbera, M.[h,i], Baudin, D.[p], Bayer, J.[j], Bellutti, P.[k], Bertucci, B.[l], Xingzi, Bi[n], Bonvicini, W.[f], Bozzo, E.[o], Bouyjou, F.[p], Cadoux, F.[q], Campana, R.[r], Jiewei, Cao[s], Cavazzuti, E.[d], Ceraudo, F.[c], Tianxiang Chen[s], Wen Chen[n], Cirrincione, D.[t], Collura, A.[i], D'Anca, F.[i], De Angelis, N.[q], De Rosa, A.[c], Di Cosimo, S.[c], Didillo, G.[c], Evangelista, Y.[c], Favre, Y.[q], Fiandrini, E.[l], Ficorella, F.[k], Na, Gao[s], Gevin, O.[p], Guedel, M.[v], Xingbo, Han[n], Huilin, He[s], Hedderman, P.[j], Hynek, R.[g], Kole, M.[q], Karas, V.[z], Komarek, M.[g], La Marra, D.[q], Hong, Liang[n], Limousin, O.[p], Rui, Liu[n], Lo Cicero, U.[i], Loehring, J.[aa], Lombardi, G.[c], Fang-Jun, Lu[s], Tao, Luo[s], Merkl, M.[g], Meuris, A.[p], Michalska, M.[bb], Morgante, G.[r], Munnini, R.[f], Mussolin, L.[l], Novák, P.[cc], Nowosielski, W.[bb], Nuti, A.[c], Orleanski, P.[bb], Ottensamer, R.[v], Pacciani, L.[c], Paltani, S.[o], Pepponi, G.[k], Piazzolla, R.[d], Picciotto, A.[k], Pliego Caballero, S.[j], Putz, A.[j], Rachevski, A.[f], Rashevskaya, I.[dd], Samusenko, A.[k], Santangelo, A.[j], Schanne, S.[p], Sciortino, L.[i], Skup, K.[bb], Sveda, L.[z], Svoboda, J.[z], Tenzer, C.[j], Todaro, M.[i], Vacchi, A.[f,gg], Hao, Xiong[j], Jian, Wang[y], Xianqi, Wang[j], Winter, B.[ff], Xin, Wu[q], Zampa, G.[f], Zampa, N.[f], Zdziarski, A. A.[hh], Shu-Nan, Zhang[s], Xiaoli, Zhang[t], Zhen, Zhang[y], Zijian, Zhao[s], Yupeng, Zhou[t], and Zorzi, N.[k]

[a]INAF HQ, Viale del Parco Mellini 84, Rome, Italy
[b]INAF-Osservatorio Astronomico di Cagliari, Via della scienza 5, Selargius, Italy
[c]INAF-IAPS, Via del Fosso del Cavaliere 100, Rome, Italy
[d]ASI, Via del Politecnico snc, Rome, Italy
[e]INFN, Sezione di Perugia, Via Alessandro Pascoli, 23c, 06123, Perugia, Italy
[f]INFN, Sezione di Trieste, Padriciano 99, 34149, Italy
[g]L.K. Engineering, s.r.o. Vídenská 55 63900 Brno Czech Republic
[h]Università di Palermo, Dipartimento di Fisica e Chmica, Via Archirafi 36, 90123, Palermo, Italy
[i]INAF, Osservatorio Astronomico di Palermo, Piazza del Parlamento, 1, 90134, Palermo, Italy
[j]Institut fur Astronomie und Astrophysik, Eberhard Karls Universitat, 72076 Tuebingen, Germany
[k]Fondazione Bruno Kessler, Via Sommarive, Povo, 38123, Trento, Italy
[l]University of Perugia, Dip. Fisica e Geologia, Via Pascoli snc, 06123, Perugia Italy [m]Shanghai Institute of Microsystem and Information Technology, Chinese Academy of Sciences Shanghai ICP No. 05005483-1, No. 865 Changning Road, Shanghai
[n]Innovation Academy for Microsatellites of CAS, Xueyang Road No.1, Pudong district, Shanghai, China
[o]Department of Astronomy, University of Geneva, Chemin d'Ecogia 16, 1290, Versoix, Switzerland
[p]CEA Paris-Saclay, DRF/IRFU, 91191 Gif sur Yvette, France
[q]Department of Nuclear and Particle Physics, University of Geneva, CH-1205, Switzerland
[r]INAF, Osservatorio di astrofisica e scienza dello spazio di Bologna, Via P. Gobetti 101, Bologna, Italy

Modeling, Systems Engineering, and Project Management for Astronomy XI,
edited by Sébastien Elias Egner, Scott Roberts, Proc. of SPIE Vol. 13099,
130991D · © 2024 SPIE · 0277-786X · doi: 10.1117/12.3020230

[s]Key Laboratory for Particle Astrophysics, Institute of High Energy Physics, CAS, Beijing 100049, China
[t]Beijing Institute of Spacecraft System Engineering, CAST, Beijing 10094, China
[v]Universität Wien, Universitätsring 1, 1010 Wien, Austria
[y]North Night Vision Technology Co. Ltd, Nanjing 211106, China
[z]Astronomical Institute, Czech Academy of Sciences, Bocni II 1401, CZ-14100 Prague, Czech Republic
[aa]European Space Agency, Keplerlaan 1, PO Box 299 NL-2200 AG Noordwijk, The Netherlands
[bb]Space Research Center, Polish Academy of Sciences, Bartycka 18a, 00-716 Warszawa, Poland
[cc]Frentech Aerospace s.r.o. Jarní 48 CZ S 614 00 Brno
[dd]TIFPA, Istituto Nazionale di Fisica Nucleare, Via Sommarive 14, 38123 Povo, Trento, Italy
[ee]Institute of Physics, Silesian University in Opava, Bezrucovo nam. 13, CZ-746 01 Opava, Czech Republic
[ff]Mullard Space Science Laboratory, UCL, Holmbury St Mary, Dorking, Surrey, RH56NT, UK
[gg]University of Udine, Via delle Scienze, 206, 33100, Udine, Italy
[hh]Nicolaus Copernicus Astronomical Center, Polish Academy of Sciences, Bartycka 18, PL-00-716 Warszawa, Poland

ABSTRACT

The Enhanced X-ray Timing and Polarimetry (eXTP) mission is a flagship astronomy mission led by the Chinese Academy of Sciences (CAS) and scheduled for launch in 2029. The Large Area Detector (LAD) is one of the instruments on board eXTP and is dedicated to studying the timing of X-ray sources with unprecedented sensitivity. The development of the eXTP LAD involves a significant mass production of elements to be deployed in a significant number of countries (Italy, Austria, Germany, Poland, China, Czech Republic, France). This feature makes the Manufacturing, Assembly, Integration and Test (MAIT), Verification and Calibration the most challenging and critical tasks of the project. An optimized Flight Model (FM) implementation plan has been drawn up, aiming at a production rate of 2 Modules per week. This plan is based on the interleaving of a series of parallel elementary activities in order to make the most efficient use of time and resources and to ensure that the schedule is met.

Keywords: Project Management; Mass production; X-ray instrumentation; X-ray polarimetry; X-ray timing; space mission: eXTP; Astrophysics - Instrumentation and Methods for Astrophysics; Astrophysics - High Energy Astrophysical Phenomena

1. INTRODUCTION

The enhanced X-ray Timing and Polarimetry (eXTP) is the flagship mission of the Chinese Academy of Sciences (CAS) with a possible European participation (IT, ES, DE, CH, FR, CZ, PL, NL, DK, AU, TR) and a planned launch date in late 2029.

The scientific purpose of the mission is to study the state of matter under extreme conditions of density, gravity and magnetism. Primary goals of the mission are the determination of the equation of state of matter at supra-nuclear density, the measurement of Quantum Electrodynamics (QED) effects in the radiation emerging from highly magnetized stars and the study of matter dynamics in the strong-field regime of gravity. The eXTP mission aims at revolutionize areas of fundamental research that are among the uncharted territories of fundamental physics, as the matter inside neutron stars (NSs), the space-time close to Black Holes (BHs), and

Further author information: (Send correspondence to Gabriele Minervini)
Gabriele Minervini: E-mail: gabriele.minervini@inaf.it,
Andrea Argan: E-mail: andrea.argan@inaf.it

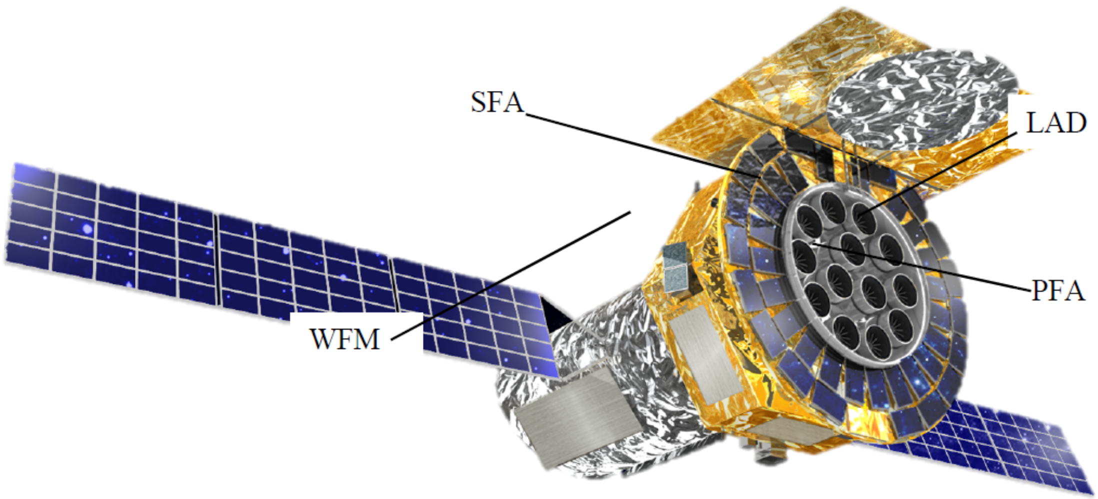

Figure 1. The current configuration of the eXTP satellite, showing the accommodation of the four instruments of the scientific payload. From Ref. 1

the extremely magnetized vacuum close to magnetars, by high precision X-ray measurements of NSs across the magnetic field scale and BHs across the mass scale.
To achieve its goal, the eXTP satellite payload consists of a suite of state-of-the-art X-ray imaging and non-image scientific instruments, enabling for the first time ever the simultaneous spectral-timing-polarimetry studies of cosmic sources in the energy range from 0.5-30 keV.
The payload consists of two main components (SFA and PFA) and two concept complementary components (LAD and WFI):

- the Spectroscopic Focusing Array (SFA): a set of eleven identical X-ray telescopes operating in the 0.5-10 keV energy band with a field-of-view (FoV) of 12 arcmin each and a total effective area of 0.8 m^2 and 0.5 m^2 at 2 keV and 6 keV respectively. The telescopes are equipped with Silicon Drift Detectors offering < 180 eV spectral resolution.
- the Large Area Detector (LAD): a deployable set of 640 Silicon Drift Detectors, achieving a total effective area of 3.4 m^2 between 6 and 10 keV. The operational energy range is 2-30 keV and the achievable spectral resolution better than 250 eV. LAD is a non-imaging instrument, with the FoV limited to $< 1°$ FWHM by the usage of compact capillary plates.
- the Polarimetry Focusing Array (PFA): a set of four X-ray telescopes, achieving a total effective area of 900 cm^2 at 2 keV, equipped with imaging gas pixel photoelectric polarimeters. The FoV of each telescope is 12 arcmin and the operating energy range is 2-10 keV.
- the Wide Field Monitor (WFM): a set of three coded mask wide field units, equipped with position-sensitive Silicon Drift Detectors, covering almost a third of the sky sphere and operating in the energy range 2-50 keV.

Two of these four instruments, the LAD and the WFM, are under the European responsibility of Italy (INAF) and of Spain (CSIC) respectively.

The configuration for eXTP at satellite level is shown in figure 1.

2. THE LARGE AREA DETECTOR (LAD)

2.1 LAD overview

The LAD payload will be a large array of X-ray detectors with a total geometric area of about 5 m^2 and an effective area that reaches $\sim 3.4m^2$ at 6 keV. It is designed to perform photon-by-photon observations of X-ray sources on a large collecting area in the energy range of 2-30 keV that can be extended up to 80 keV by dynamic range for the out-of-field-of-view burst events. The LAD energy resolution will be 250 eV at 6 keV. The arrival time and the energy resolution of each photon will be measured with high resolution and for a very large statistics of events, enabling unprecedented spectral-timing studies in the X-rays. Mechanical collimators will be implemented to reduce source confusion and the X-ray background, limiting the FoV to $\sim 1°$ FWHM.
The LAD technology innovations rely in the large-area SDDs and in the capillary plate collimators. In a comparison with respect proportional counters and mechanical collimators used in the large area instruments of past generation, these elements of the LAD allow the realization of X-ray detectors with highly efficiency. These detectors are only a few mm thick and a few hundred grams in weight, allowing a requirements reduction for weight, volume and power by about an order of magnitude with respect to proportional counters and mechanical collimators used in the past generation of large area instruments [Ref. 2]. The LAD main specifications are listed in Table 1.

Parameter	**Value**
-Energy Range (nominal)	2 - 30 keV (extended 30 - 80 keV)
-Effective area	$3.4m^2$ at 8 eV
	$0.37m^2$ at 30 keV
-Energy resolution (FWHM at 6 keV)	< 260 eV (all events)
	< 200 eV (40% of events)
-Field of View	< 60 $arcmin$
-Time resolution	10 μs
-Dead time (at 1 Crab)	$< 0.5\%$, (goal $< 0.1\%$)
-Background	< 10 $mCrab$
-Maximum source flux (continuous)	> 300 $mCrab$
-Maximum source flux (for 8 hrs)	> 15 $Crab$
-Total mass	~ 360 kg
-Power	~ 400 W

Table 1. LAD main specifications. From Ref. 3

2.2 LAD Module

The LAD instrument is made of 40 Modules of the same type developed for the LOFT mission [Ref. 4]. The LAD provision will consist of 640 detectors, electrically and mechanically organized in the 40 Modules containing 16 of them (see figure 2). Each Module will consist of a set of 4 x 4 basic detection elements composed of a Silicon Drift Detector (SDD) , the Front End Electronics (FEE) and the Collimator, supported by two grid-like frames. Each Module hosts also the power supplies and the read-out electronics, organized in the FEE and Module Back-End Electronics (MBEE). The assembly philosophy employs a hierarchical approach: Detector, Module, Detector Panel and LAD Assembly. The read-out electronics are organized as follows: the FEEs of 8 Detectors converge in one MBEE, so that each Module is equipped with two MBEEs. One Panel Back-End Electronics (PBEE) is in charge of interfacing in parallel 10 Modules, i.e. 2x10 MBEEs. The PBEE sends commands to the MBEEs, and distributes the clocks and the primary power and commands to the Modules. It receives data (science and HK) from the 20 MBEEs, and transmits it on to the Instrument Control Unit (ICU). The ICU manages the PBEEs; handles Telecommands (TCs) and Telemetries (TMs); manages modes, configuration and time; and monitors instrument health and performance.

The Module is then considered the basic unit for the LAD instrument.
The LAD Module contains:

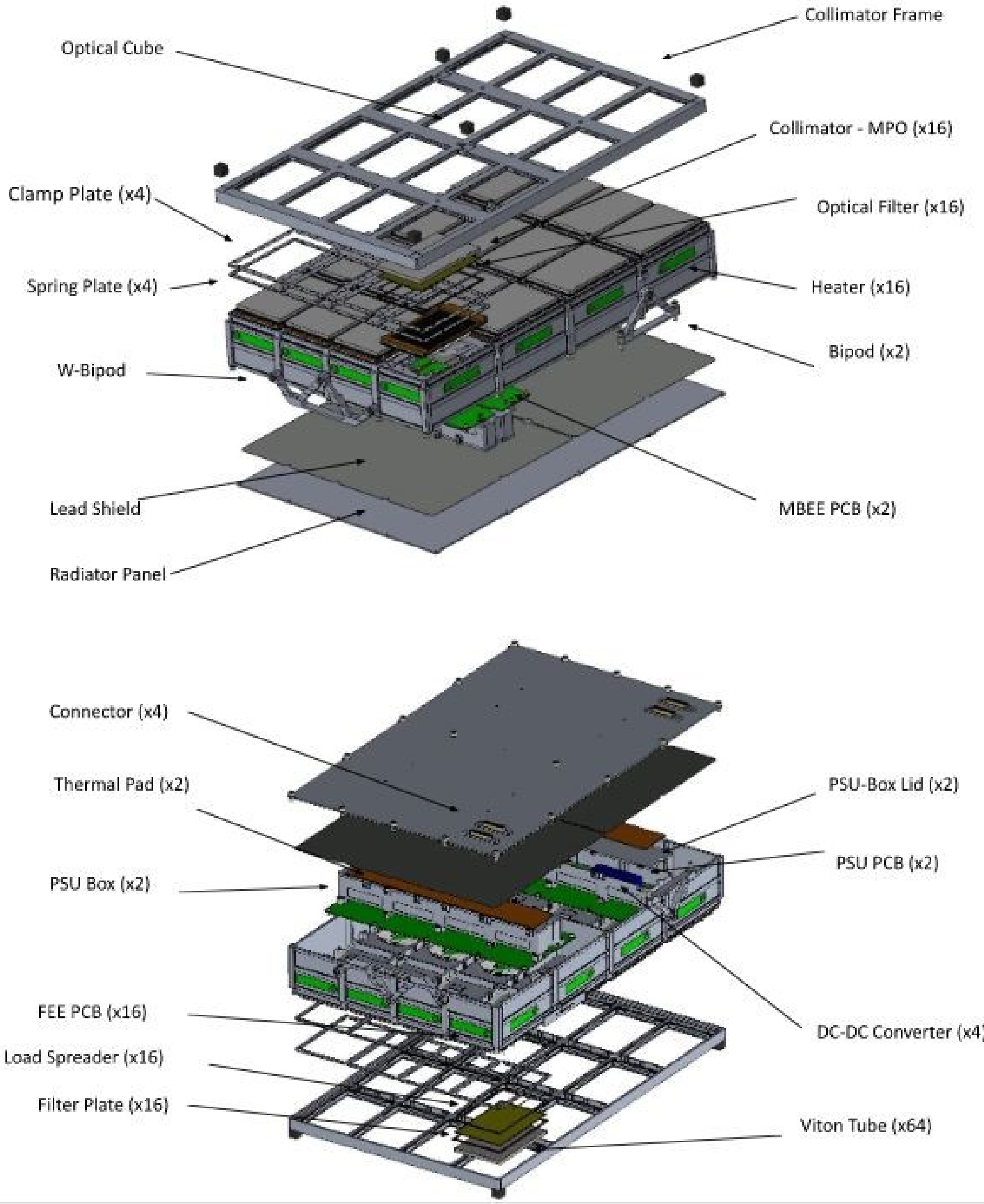

Figure 2. Exploded view of Module From Ref. 5

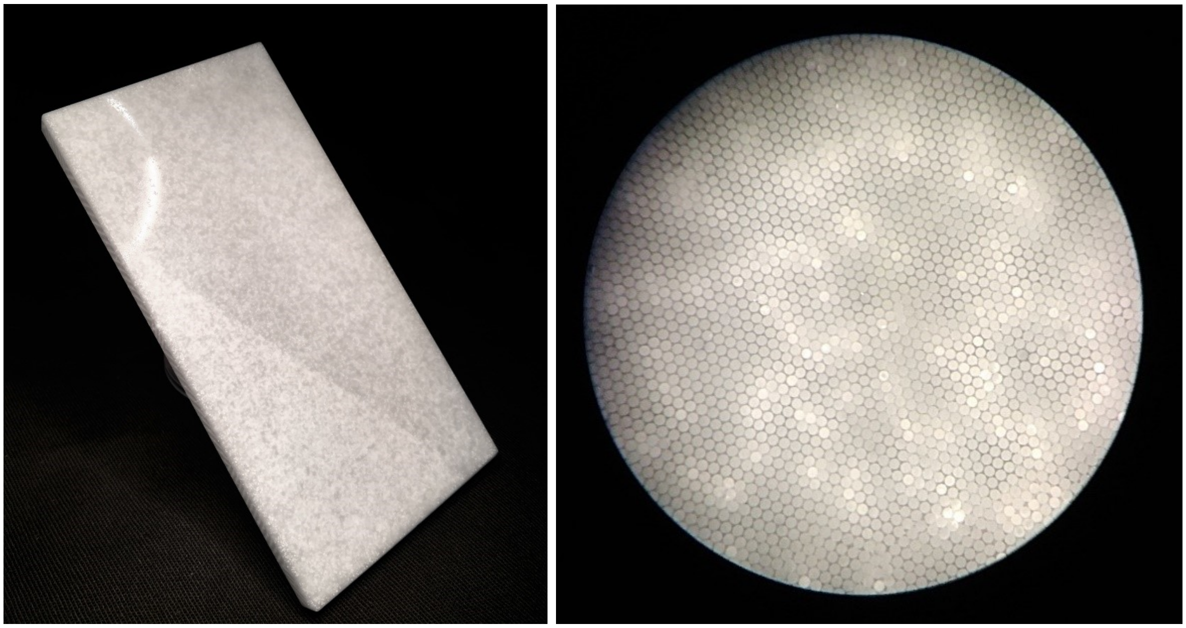

Figure 3. Example of the LAD Collimator design: full tile (left) and zoom-in of the micropores (right) From Ref. 5

- An aluminium alloy collimator tray containing 16 co-aligned CP tiles (one per SDD). Figure 3 shows a sample of the collimator.
- A detector tray containing 16 SDD+FEE (one per CP). Each SDD has 224 anodes. Each FEE has 28 AFEE ASICs, to read out the signals from the anodes and two DFEE ASICs to digitise the anode charge pulses resulting from X-ray events.
- Between the collimator tray and the detector tray is a thin (1-2 μm) Kapton film, coated with 100 nm Al on each side. This filters out IR, visible and UV light, allowing through X-rays of $>\sim$ 2 keV.
- HV/MV PSU: This is the power supply for the SDDs.
- MBEE: This controls the ASICs and HVPSU, and reads out the digitised events. It formats and time-stamps each event and transmits it to the PBEE.
- A Pb back-shield, to reduce the background events in the SDDs.
- A radiator to dissipate heat from the Module (lower SDD temperature improves the energy resolution)

3. LAD MAIT

The large number of units in the LAD makes MAIT (Manufacturing, Assembly Integration and Test), verification and calibration major and critical activities for the project. The current plan is to interleave the MAIT with the calibration, verification and qualification activities to provide the most efficient use of time and resources and to ensure that the schedule milestones are met. A synchronous, lock-step approach will be adopted for the programmatic aspects of the Module AIT process. Each sub-activity of the MAIT will be performed by the responsible group at a rate compatible with two Modules by week. This approach ensures the greatest tolerance for unforeseen incidents, a delay of one task does not delay the other tasks.

The LAD deliverables include: LAD Modules, PBEEs, ICU and flight software.

The Collimator Plates (CP) are provided by IHEP (Institute of High Energy Physics of CAS, China) realized on specifications provided by INAF (Istituto Nazionale di AstroFisica, Italy) based on LAD performance models. IHEP will be in charge also of the early assessment of performance of the CP. The industry supplier identified

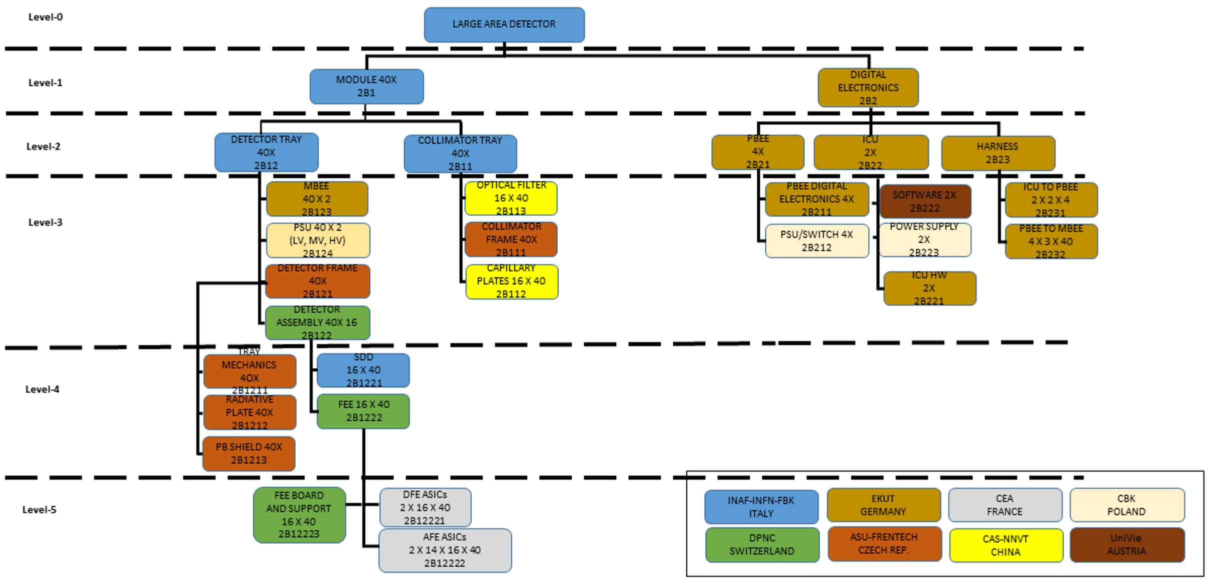

Figure 4. The LAD product tree.

to the provision is the NNVT (Nanjing, China). Once manufactured, the collimator plates will be tested before being delivered and accepted by INAF (in pre-arranged batch sizes).

The delivery of SDD device will be managed by the INAF (Italy). INAF is in charge of the detailed design of the SDD, of its early performance assessment and of the setting up of full scale production through an industrial contract. Once manufactured by industry, the SDDs will be delivered directly to the Département de physique nucléaire et corpusculaire (DPNC, Switzerland), on pre-defined dates and in pre-agreed batch sizes, for integration into the Module detector sub-system.

The delivery of the Analogue Front-End ASICs (AFE ASICs) and the Analogue-to-Digital ASICs (DFE ASICs) will be managed by CEA (France). The activity carried on by CEA will include their detailed design and early performance verification. Industry will manufacture the ASICs (mainly due to the size of the production run) and deliver directly to DPNC for integration into the detector sub-system. ASIC verification will be performed at the end of the manufacturing process at die level through specific equipment.

FEEs implementation will be carried out by the DPNC. This activity of DPNC on FEEs includes their detailed design and early performance verification. Equipment will be produced by industry. FEE equipment will remain at DPNC in support of the detector sub-system integration activity.

The LAD Detector Assembly (DA) will consist of an SDD bonded to a Printed Circuit Board (PCB). The PCB contains the FEE (which consists of 28 AFE ASICs, 2 DFE ASICs and associated electronics).
The LAD DA AIT will be under the responsibility of DPNC. This task includes the detailed design of the detector AIT and the identification of an industry group able to complete this task in the time available. The industry involved in the AIT activity will use a number of AIT lines in order to achieve a throughput of 32 FEEs (plus the spares) by week corresponding to the needs of two Modules. Once accepted the detector assembly will be shipped directly to INAF for integration into the detector tray.

The procurement of Module optical filters will be managed by IHEP (China) and on specification provided by INAF, again based on LAD performance models. To achieve this task IHEP will identify of a supplier. Filters will be supplied in batches to INAF. Once tested and accepted, they will be integrated into the collimator tray during the AIT process.

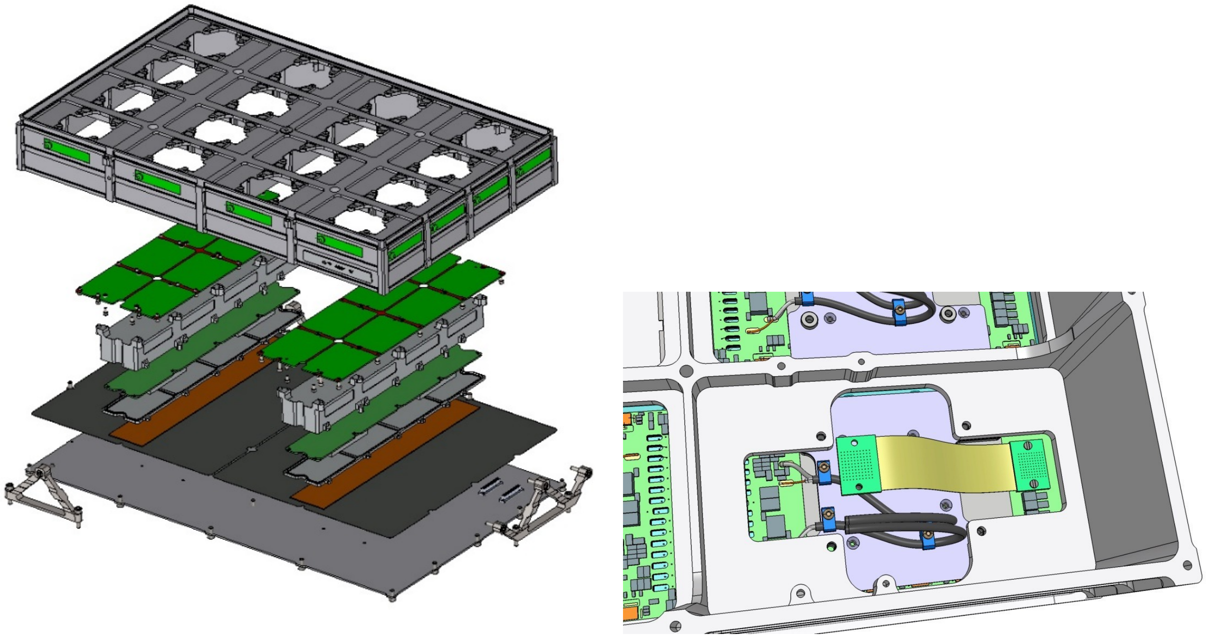

Figure 5. Schematic view of the Module. LEFT: exploded view of the Detector Tray (including Detector Assemblies, MBEEs and PSUs), RIGHT: The Detector Assembly fitting the Detector Frame. From Ref. 5

The MBEE will be managed by the Eberhard Karls Universitaet Tuebingen (EKUT, Germany). The activities will include the MBEE detailed specification, early performance evaluation and identification of an industry supplier. Following their manufacture, the MBEE will be tested before being delivered to INAF in support of the LAD Module AIT&V process.

The LAD PSUs will be managed by the CBK (Centrum Badań Kosmicznych, Poland). This task includes their detailed specification and early performance evaluation. The PSU will be manufactured under the responsibility of CBK and the models will be delivered to INAF following their manufacture and equipment level testing for integration into the LAD Module (Module AIT).

The Pb shields and radiators will be integrated as part of the Module mechanics. The PBEE will also be managed by EKUT, following a similar specification and early evaluation approach as the MBEE. Again, the PBEE will be delivered to INAF after the performance verification.

The eXTP LAD product tree is shown in figure 4.

3.1 LAD Manufacturing

The mass production of a number of components required for the eXTP Large Area Detector will lead to a heavy reliance on industry during the manufacturing process. As described in section 2.2 (LAD Module) the Module is considered as the basic unit for the LAD.

The DA consists of an SDD bonded to a PCB, containing the FEE (which consists of 28 AFE ASICs, 2 DFE ASICs and associated electronics). In figure 5 is possible to see an exploded view of the detector tray (left) and of the DA (right).

The SDDs will be manufactured by industry: the FBK (The Fondazione Bruno Kessler), Trento, Italy, has been identified as a potential baseline SDD manufacturer for the flight model of eXTP since its relevant heritage in the manufacturing of Silicon detectors for space (AMS-02 experiments) and mass production (AMS-02, 700 units, and ALICE double-sided microstrip detectors, 700 units). Typical production yield is 65%. The mass production of the SDD detectors (640 flight units) is planned in 2 years adopting a single working shift.

The ASICs prototypes have been designed and tested by CEA as well as the production responsibility. The industry AMS (Austria Micro Systems), that has relevant heritage in the manufacturing of ASICs for space and

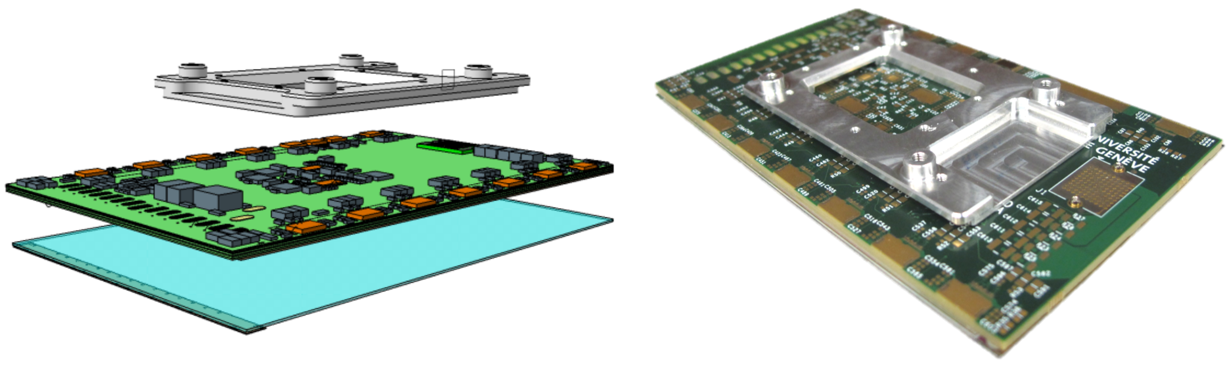

Figure 6. Views of the thermo-mechanical prototype of the FEE. From Ref. 5

mass production, has been identified as a potential baseline ASIC manufacturer for the flight model of eXTP (17920 AFE ASICSs + 1280 DFE ASICs flight units). On the basis of previous production experience and the eXTP requirements, the mass production required for eXTP is planned over less than 1.5 year (with the total fabrication at AMS requiring less than 4 months).

The complete production of SDD and ASICS is planned to be completed before the start of the FM AIT, leaving the additional margin of a serial production-AIT locked sequence.

The FEE consists of a PCB which is glued directly on to the bottom side of the SDD and corresponds to the mechanical assembly interfacing and supporting the SDD and its associated Electronics. It is connected with a flex circuit to the MBEE that will provide HV, MV and LV supply signals. The SDD anodes are bonded directly to the ASIC inputs, while cathodes (HV, MV. . .) are located on both TOP and BOTTOM sides of the detector and must be connected to the PCB with a special mechanism (Tab connection + holes in PCB). In figure 6 the thermo-mechanical prototype of the FEE.
The LAD FM will contain 640 FEEs, each of them containing 28 AFE ASICs and 2 DFE ASICs. The nominal duration to complete a batch of 16 FEEs for one Module is 34 days. To reduce the total time for the ASICs bonding steps to 3 days (baseline requirement), two parallel lines will be used for the this task. An additional bonding machine will be used for the SDD bonding step. To achieve the hot thermal-vacuum operation and tests of 10 days each, four thermal vacuum chambers could be used.
With this configuration, it is possible to maintain the flow of one Module produced every 3 days after a production queue of 34 days.

Each Module will host 2 Power Supply Units (PSU) boxes, each one interfacing one MBEE and serving 8 DA and the MBEE itself. The LAD istrument will thus host a total of 80 PSU boxes.
The PSU of the Module will provide a Low Voltage ($\sim 3-5\ V$, negative and positive), a Medium Voltage ($\sim 100\ V$) and a High Voltage ($\sim -1300\ V$).
The power supplies will be designed and developed at CBK (PL), while the manufacturing will be carried out by Polish industry under the same production rate as the MBEE.

The EKUT (Germany), is in charge of developing the design and of the production of the MBEE and of PBEE bread-board model.
The manufacturing, assembly and test of MBEE and PBEE will be carried out a selected industry, where qualified soldering process technologies are available and with a heritage in building space qualified parts.
The current planning for the MBEEs is that the initial 12 MBEEs will be assembled, tested and delivered to INAF in 4 weeks ($\pm$3 days) following when the 'go-ahead' is given. The mass production of the remaining 76 MBEEs will then be completed within 3 months ($\pm$2 weeks). A total of 88 MBEEs will support the FM, plus the spares. The company will conduct partially automated test benches and electrical tests on the MBEE boards. Once completed these, a test of all functions and performance will be carried on at EKUT with a maximum duration of 2 weeks per board. The flight models of the MBEE will be functional tested with an automated test bench.
The PBEE box mechanics will be manufactured at EKUT.

Figure 7. Full-scale LAD filter prototype, mounted in its support Ni frame. From Ref. 5

The manufacturing of the collimators is in charge of the company NNVT (Nanjing, China) since its great deal of experience regarding mass production of Microchannel plates (MCPs). The company will produce a total of about $5m^2$ of collimators for the FM. NNVT recently manufactured the capillary plate optics for the Chinese LEIA experiment, currently operating in orbit.
The manufacture schedule discussed foreseen a planned production capability of 350 units per year, so that the total production of the 640 flight units will thus be completed in less than 2 years.

The IHEP will develop the eXTP-LAD filters (see Figure 7), on the heritage of the filters currently flying on board the HXMT mission. Because of the large production required by the LAD FM, the final production of the filters will be carried out in an industry, under process control by IHEP.

The collimator frames and the radiator panels (one per Module of each of them) will be designed under the responsibility of ASU (Czech Republic) and manufactured by industry (Frentech). The collimator frame is technically the most challenging of the Module structure elements to manufacture due to the strict tolerances required. A discussion with industry about the collimator frames and radiator panels manufacture rates defined that they are compatible with the proposed MAIT program.

The ICUs consist of a DHU, processing electronics, a power supply, mass memory and software. With the exception of the power supply, which is contributed by CBK (Poland), all of them will be provided by EKUT (Germany).
The ICUs will be manufactured by Tecnotron, as for the MBEEs and PBEEs.
EKUT will be responsible for providing the harness from the PBEE to the MBEE: the Gore (Germany) has been identified as the industrial partner who will manufacture the harnesses. Once manufactured, the harnesses will be tested at EKUT, followed by precision cleaning and QA inspection before being shipped to INAF.

3.2 LAD AIT, Verification, Calibration and Qualification

The large number of units which make up the LAD requires extensive and careful planning to ensure that the program milestones are met. The following aspects need particular attention:

- the schedule constraints, to ensure that all LAD Module equipment is manufactured on-time, since the impact on the Module assembly that a delay of one part could produce;
- the transportation requirements, identifying shipping companies which can be relied upon for careful and considerate services, since the LAD equipment is being manufactured and tested at locations throughout Europe;
- the manufacturing, assembly and verification processes consolidation needed before the flight model production of some technologies that could requires updates and mass production optimization;
- AIT facilities to identify and to be certificated since the cleanliness requirements;
- export control and Product Assurance activities;
- Consortium/IHEP/Prime Contractor interactions to ensure good communication between all parties;
- the requirements of all electronic and mechanical supporting equipment that need to be defined well in advance of the flight build program.

3.2.1 LAD single Module approach

The single Module assembly, integration and tests flow can be divided into two sections: the detector tray AIT flow and the Collimator tray AIT flow.
The detector Tray includes 16 Detector Assemblies, 2 MBEEs and 2 PSUs (each inside its enclosing box), all supported by an Aluminum Detector Frame, carrying on its backside a radiative panel and a Pb shield. On the other side, the collimator tray is composed of 16 CP, 16 Optical Filters, 1 Collimator frame, the Collimator clamping mechanism and 1 Optical Cube.
The LAD Module will be assembled at INAF based on the delivery of the relevant parts. Starting with the detector tray, the current baseline process for its assembly is:

1. Take the detector frame and fit it into its assembly jig;
2. Place each of the 16 DAs into position, being careful to handle at the edges where possible;
3. Take each of the 2 MBEEs and put into position and interconnect to the 8 relevant DAs through dedicated harness;
4. Take each of the 2 PSUs and put into position and interconnect to the 8 relevant DAs through dedicated harness.

Once completed the detector tray, the Collimator Tray assembly will follow the steps:

1. Take the collimator frame and fit it into its assembly jig;
2. Mount the Optical Cube to the Collimator Frame;
3. Place each filter into position, being careful to handle at the edges where possible;
4. Place each CP tile into position, being careful to handle at the edges where possible;
5. Once all 16 tiles are in position, place the clamping mechanisms into position.

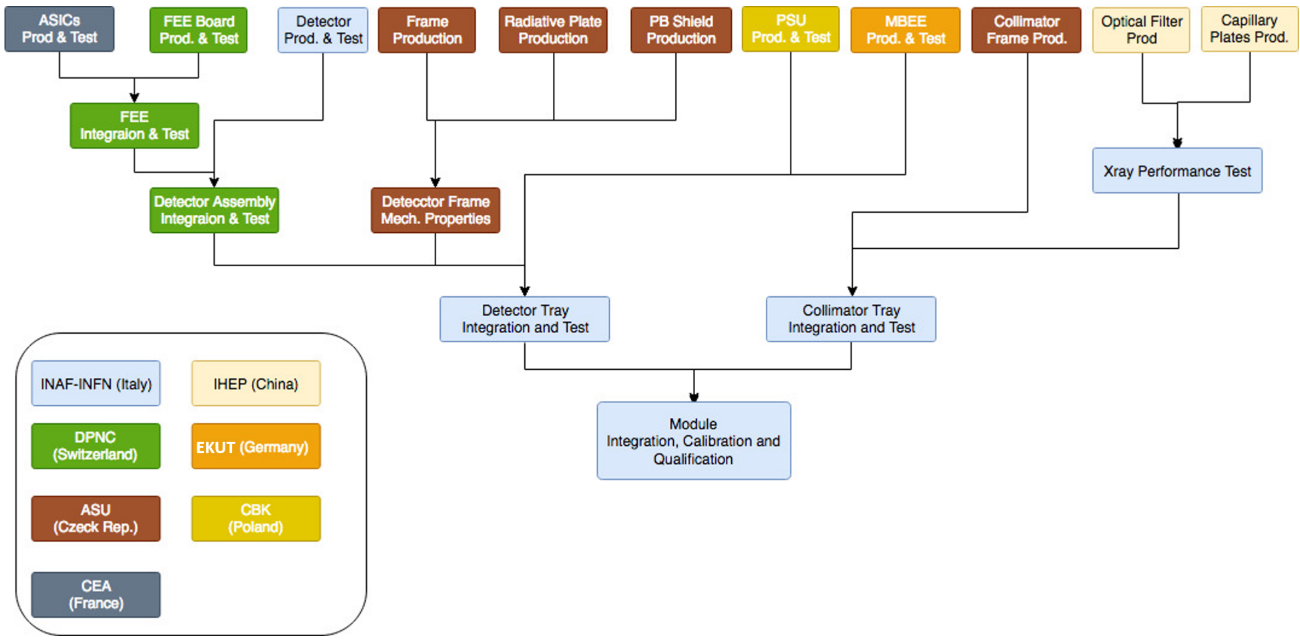

Figure 8. AIT/V planning for the Module FM, illustrating equipment responsibilities and transport within the consortium. From Ref. 5

Once the Collimator Tray is fully integrated, a metrology campaign will record the alignment and position of each CP and verify the alignment of the optical cube with respect to the reference frame of the Collimator Tray. The alignment between the detectors themselves is in principle not at all critical in comparison to the micropore optics in front of them: the key to the alignment between the detectors is in the co-alignment of the micropore optics. The critical alignment, requiring verification at each step of the integration, is the co-alignment of the 16 individual collimators and their alignment to the optical reference mounted on the Collimator Tray.
Functional tests will interleave the above assembly sequences, by testing each half Module separately after its integration, and the whole Module at the end of the integration process.

The detector trays and collimator trays will then be integrated together, still at INAF, to form a LAD Module.

In figure 8 is represented the Module FM AIT/V planning and the equipment responsibilities.

3.2.2 LAD mass production approach

In order to meet the schedule and deliver the LAD flight models on time despite the mass production, an uncommon assembly approach is being used. The basic assumption is that the production of all the Long Lead Items (LLIs), CPs, Detectors, Optical Filters and ASICS, will be completed before starting the AIT&V processes. In order to optimize the MAIT schedule, the production of pre-assembled parts (collimator frame, detector frame, DAs, MBEEs, PSUs) will be interleaved with the AIT, Verification, Qualification and Calibration activities.
In the scheme shown in figure 9 are represented different blocks of activities. Different colours are used to distinguish the activities blocks.
In the first row is represented the assembly of the CPs in the collimator tray with a rate of 2 per week. During this first week the pre-assembled parts for the next collimator trays should been completed and delivered to INAF.
In the second row is represented the assembly of detector tray, again with a rate of two tray per week.
Starting from the second week, each of the detector trays assembled in the first week will start their respective energy calibration campaign: in the third row is shown these activities that will be performed on 2 detector trays per week.
In the third week, during the assembly of the third couples of collimator and detector trays, the first two LAD

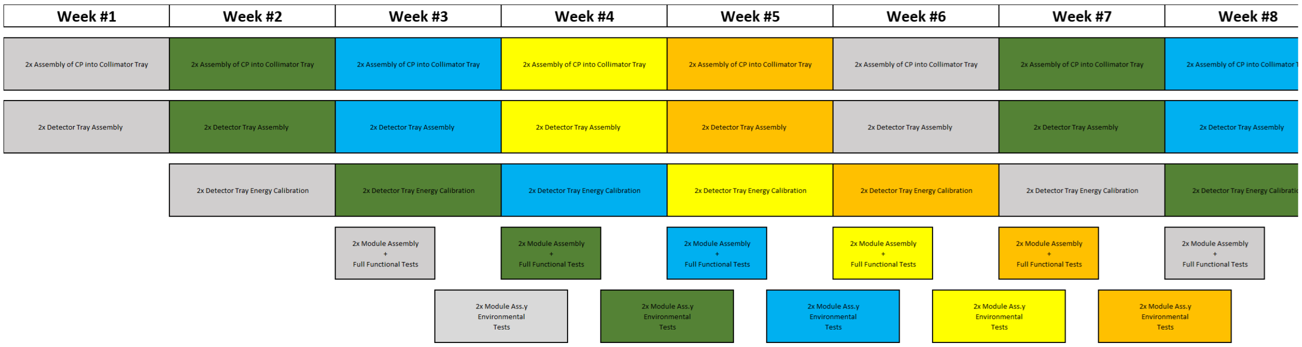

Figure 9. eXTP-LAD simplified MAIT flow. From Ref. 5

Modules will be assembled and functionally tested (see fourth row of figure 9). Once completed these last activities these two first LAD Modules will undergo in environmental test, as represented in the fifth row of figure 9. Once that five couples of Modules will be completed and tested in the representative environment, the relative 10 Modules will be shipped for Effective Area calibration campaign. As shown in the sixth row of figure 10-left, the Effective Area of the Modules will be calibrated with a rate of two Modules per week. This campaign will complete the AIT, Verification, Calibration and Qualification related to the first 10 Modules on time for the arrival of the second batch of 10 Modules (seventh row of figure 10-left), assembled and tested in the meanwhile. Once completed the Effective Area calibration campaign, the 10 Modules will be shipped back to INAF for the bench integration. As shown in the eighth row of figure 10-left this activity will start during the 14th week and will last two weeks.
As shown in figure 10-right, with this operational philosophy the assembly and tests of the 44 Modules (40 nominal FMs and plus 4 Flight Spare Modules) of the LAD will be completed in 25 weeks, the Effective area calibrations during the 30th week and the last Modules bench integration will be completed during the 31st week.

To increase the robustness of the proposed schedule, a contingency of 3 months on the overall LAD MAIT has been allocated in order to mitigate the risk.
The activities described in this section will be carried out sequentially by different teams, as favoured by the large LAD teams in Italy, allowing for a phased activity. For the AIT flow purpose, no Module delivery should exceed duration of 3 days, as this would lead to an accumulation of delays and late final delivery. A number of activities have been multiplexed in order to accommodate this shipping rate. The Module AIT schedule allows for a phased activity with a 3-day shift (in lock step) from one Module to the next. This applies at all times during the AIT process, except at the beginning and end of the process when "boundary effects" may occur due to equipment availability, e.g. for manufacturing or Module subsystem AIT.

4. RISK ANALYSIS

The LAD program will face different potential issues. Several decisions have been put in place to mitigate these risks. To de-risk the equipment manufacture it has been decided the use of industries as far as possible to support mass-production runs. To mitigate potential risk and delays on the FEE manufacturing, there are discussions currently underway with the potential industrial partner for them to put in place additional laboratory equipments and facilities providing a significant margin on the critical items (in case of failure).
The AIT/V program has been designed to ensure (and minimise where possible) the efficient transport of equipment from sub-groups to INAF. In addition, a contingency of 3 months on the overall LAD MAIT plan has been allocated in order to mitigate the risk. In addition, even if the eXTP-LAD program shows the start of LLIs procurement programs at I-PDR in order to meet the delivery requirements, an additional contingency of 12 months on the procurement of the LLIs (on 24 months nominal duration) will be considered.
An early verification of critical items will be carried out to reduce the risk of late failure identification. The verification approach of the eXTP-LAD instrument has been defined to confirm, through demonstration, that the equipment will be compatible with the requirements of the mission and also to enable the early production

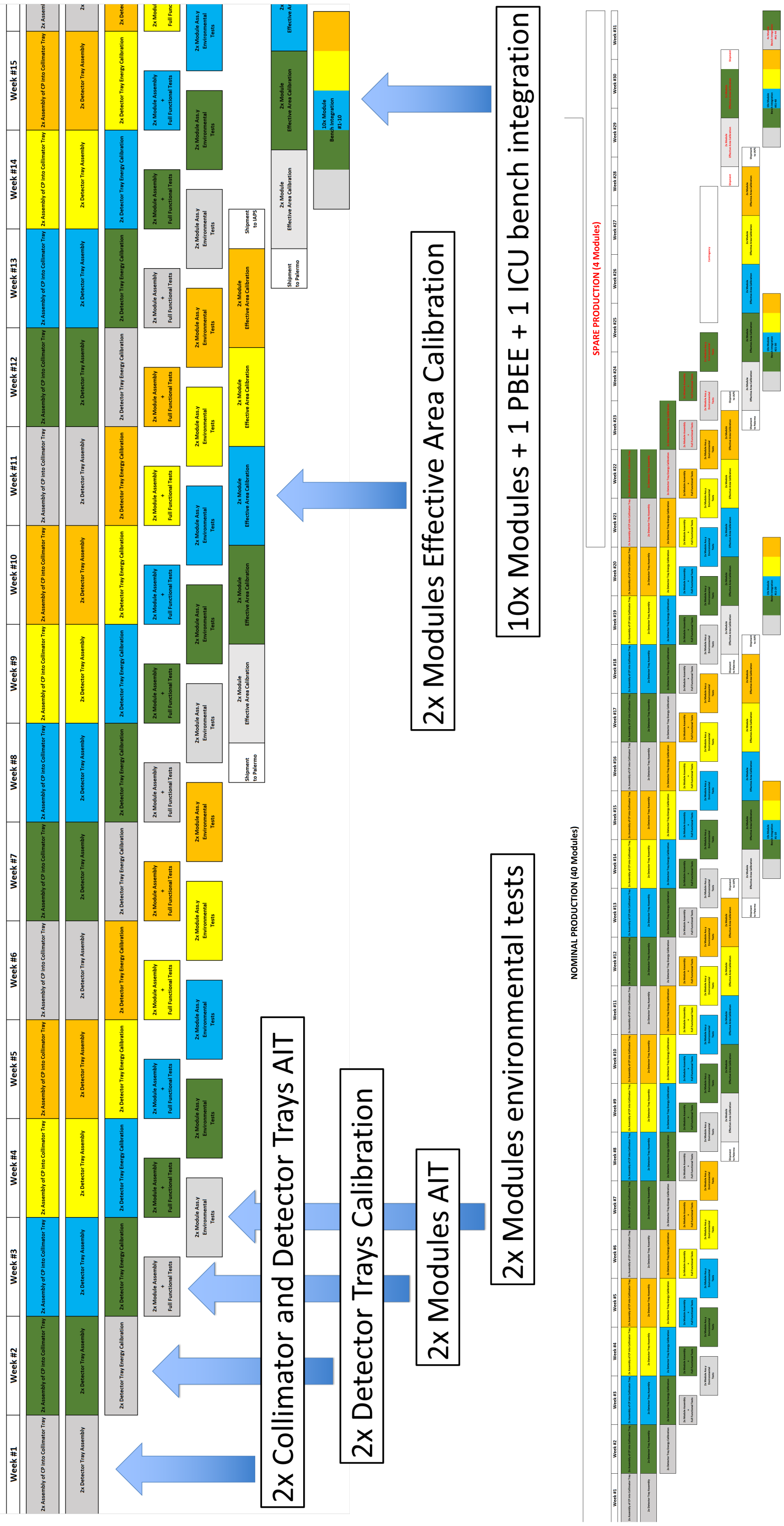

Figure 10. eXTP-LAD simplified AIT flow. Left side: AIT schedule. Each colored box represents the 1 week of activities on 2 Modules. Right side: overall plan for FM AIT and Spare Models AIT. From Ref. 5

of equipment in order to meet the schedule needs of the program. On the transportation side, the packaging should be made of either plastic or metal: cardboard will not be desirable as it provides no physical support, no humidity control and a contamination risk (particles could be shed from the cardboard). A sealed metal container will be the preferred packaging for the transportation of the LAD Module equipment.

5. CONCLUSION

The mass production of the LAD instrument onboard the eXTP mission makes challenging and risky the LAD MAIT and Verification processes. An innovative approach has been defined in order to fit the mission schedule and to de-risk the activities. The adopted philosophy defined is to use industries as far as possible and to interleave the calibration, verification and MAIT activities. The philosophy adopted will see the start of the AIT activities during the manufacturing of all the element in several European countries and in China, with interleaved steps. This approach should lead to the production of 2 Modules per week and the completion of the entire provision and integration of all 44 Modules (40 nominal Modules and 4 spare Modules) in 31 weeks.

5.1 Acknowledgments

The Authors acknowledge funding support by the Italian Space Agency under agreement n. 2020-3-HH.0.

REFERENCES

[1] Feroci, M. and et al., "The large area detector onboard the extp mission," *Proceedings of the SPIE* **Volume 12181, id. 121811X 18 pp.** (2022).

[2] Feroci, M. and et al., "The large area detector onboard the extp mission," *Proceedings of the SPIE* **Volume 10699, id. 106991C 15 pp.** (2018).

[3] Zhang, S. N., Santangelo, A., Feroci, M., and et al., "The enhanced x-ray timing and polarimetry mission extp," *Scince China Physics Mechanics & Astronomy* **Volume 62, Issue 2, article id. 29502** (2019).

[4] Feroci, M. and et al., "The large area detector onboard the extp mission," *Space Telescopes and Instrumentation 2010: Ultraviolet to Gamma Ray. Proceedings of the SPIE* **Volume 7732, article id. 77321V, 14 pp.** (2010).

[5] Trois, A. and Argan, A., "Lad design development, mait and verification plan," *eXTP-INAF-LAD-PL-0001* , Version 2.0 (2023).