X-IFU
X-ray Integral Field Unit

The Athena X-ray Integral Field Unit (X-IFU)

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&
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On behalf of the X-IFU Consortium, led by France, The Netherlands, Italy, with additional ESA member state contributions from Belgium, Finland, Germany, Poland, Spain, Switzerland, and international contributions from the United States and Japan

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X–IFU top level baseline requirements

- As required for Athena, the X–ray Integral Field Unit of Athena will measure the physical properties (velocities, turbulence, abundances, temperatures…) of X-ray emitting plasmas in a variety of environments from galaxy clusters to solar system bodies, e.g.
  - to study matter assembly in clusters, to map AGN feedback on galaxy and cluster scales, …
  - to characterize metals in clusters, detect the missing baryons in the WHIM, probe GRB hosts, …

Parameter	Baseline requirement
Spectral resolution	2.5 eV (@ 6 keV)
Field of view (requirement)	5′ (equivalent diameter)
Pixel size	< 5″ (mirror PSF HEW)
Instrumental background level	<5 10^{-3} count/s/cm^2/keV
Energy range	0.2–12 keV
Count rate capability	1 mCrab (80%, high-res)
Detection quantum efficiency	> 75% @ 1 keV > 83% @ 6 keV
Time resolution	10 μs

The X-IFU in a few words

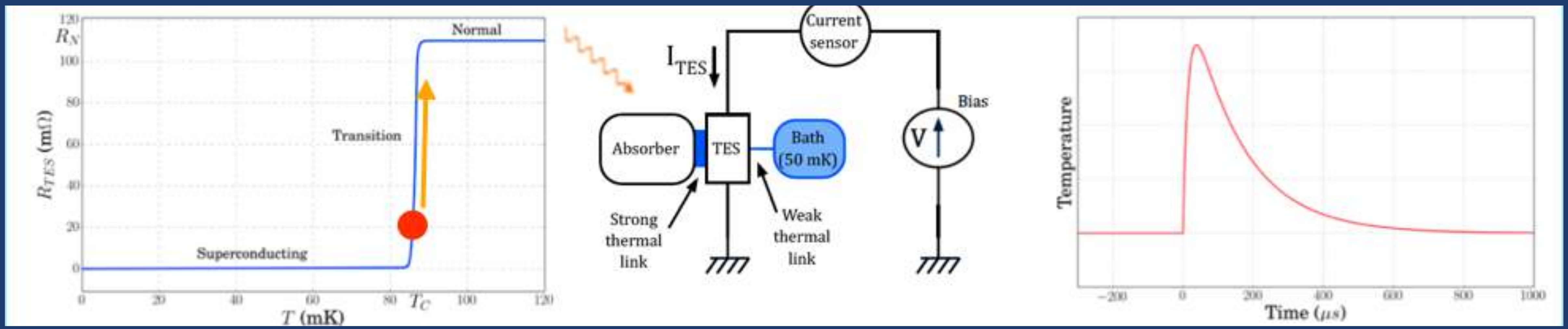
- Achieving the high spectral resolution and large field of view requires the implementation of a large format array of actively cooled (~100 mK) micro calorimeters to be read out by a low-noise multiplexed electronics

- The X–IFU is based :
  - on Transition Edge Sensors (TES) developed by NASA/GSFC/NIST/Stanford,
  - read out using a Frequency Domain Multiplexing (FDM) technique developed under the leadership of SRON,
  - actively shielded by a TES based cryogenic anticoindence developed under the leader of IAPS,
  - actively cooled by a multi-stage cryogenic chain involving European and Japanese mechanical coolers.

- The X-IFU will be developed under the management of the French Space Agency (CNES) by an international consortium led by France, The Netherlands, Italy
  - with ESA member state contributions from Belgium, Finland, Germany, Poland, Spain, Switzerland
  - and international contributions from the United States and Japan

Basic detection principle

Transition Edge Sensor principle

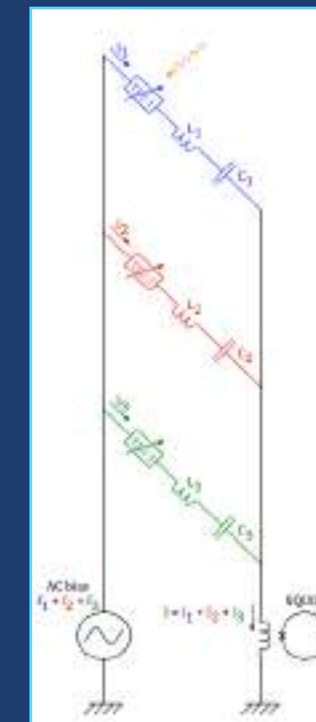


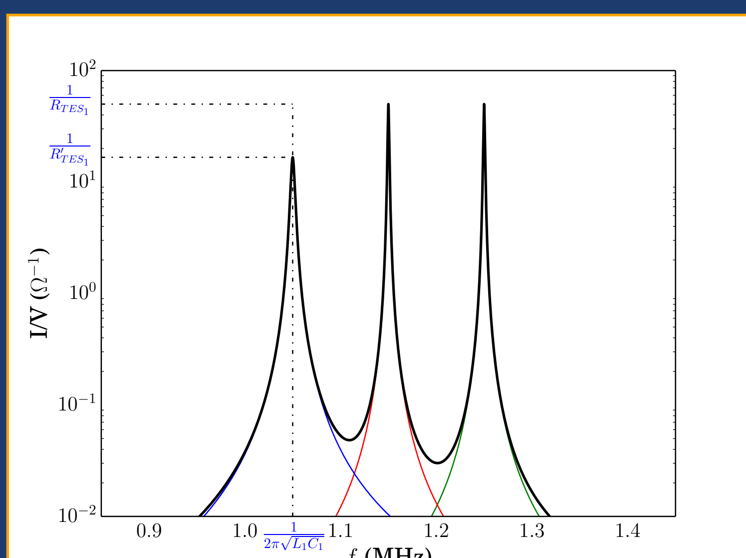
See Poster: S. Bandler et al.

- The TES is a micro-calorimeter that senses the heat pulses generated by X-ray photons when they are absorbed and thermalized
  - The TES is cooled to lie in its transition between the superconducting and normal states
  - An X–ray heats up both the absorber and the TES, whose resistance increases
  - Applying a constant voltage bias (V), the TES resistance change leads to a change of the current passing through the TES (I_{TES})
  - The change in temperature (or resistance) shows a fast rise and a slower decay

Basic FDM readout principles

- Each TES (R) is associated with an inductance (L) and a capacitance (C) to form a RLC circuit
- Each TES can then be AC biased with a specific carrier frequency, each matching the resonant frequency of the RLC circuit





- The amplitude of the resonant frequency peak changes with the TES resistance
- Frequency spacing and band pass define the multiplexing factor (~40 between 1 and 5 MHz)

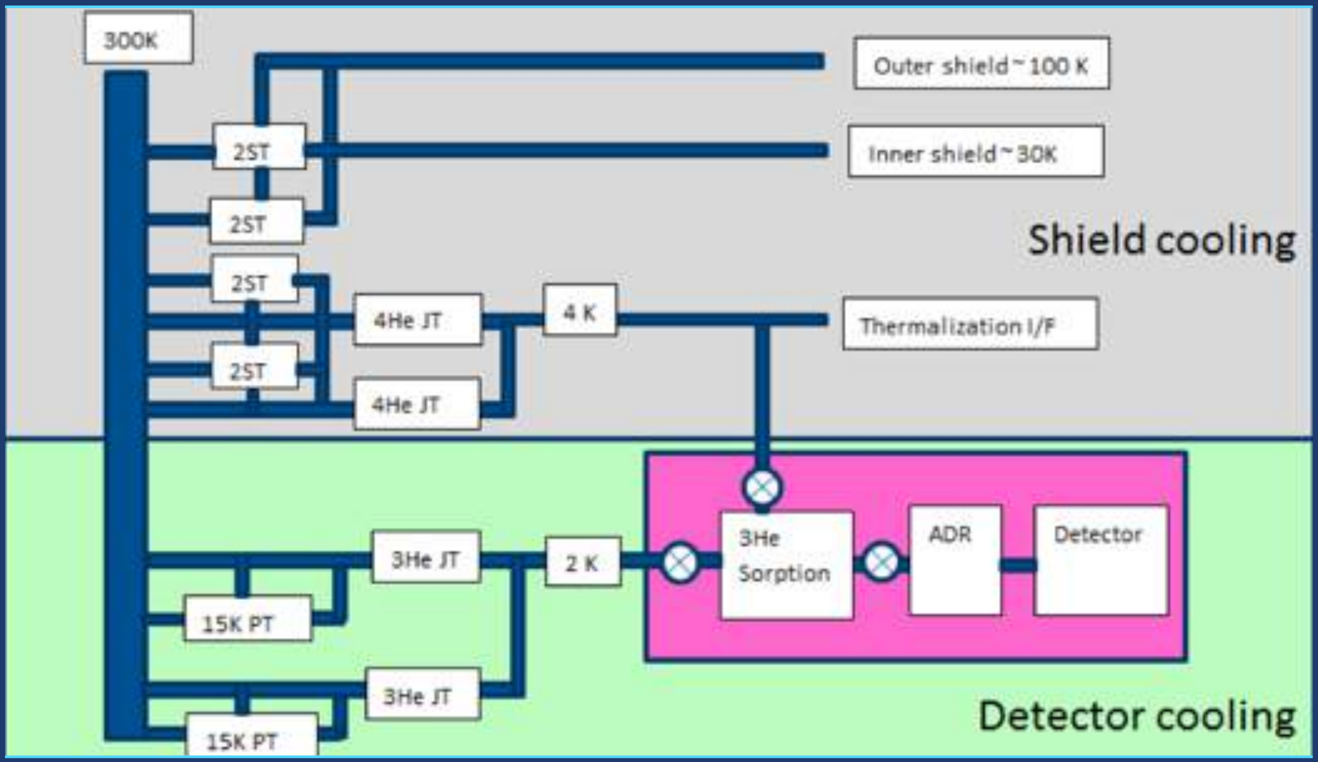
- Additional complexity arises from the need 1) to linearize the first stage superconducting quantum interference device (SQUID) amplifier, using a base-band feedback technique 2) to further amplify the signal to the digital readout electronics (using a combination of SQUID arrays and Low Noise Amplifiers)

Cooling chain characteristics

- Two cooling blocks are required
  - One to cool the thermal shields
  - One to cool the focal plane assembly

- Several redundant cooling chain architectures could be considered:
  - the pre-cooling chains are a combination of Stirling, Joule Thomson, Pulse Tube coolers, while an Sorption-Adiabatic Demagnetization Refrigerator (ADR) is baselined as the last stage cooler

Baseline cooling chain architecture



Courtesy of ESA (CDF)

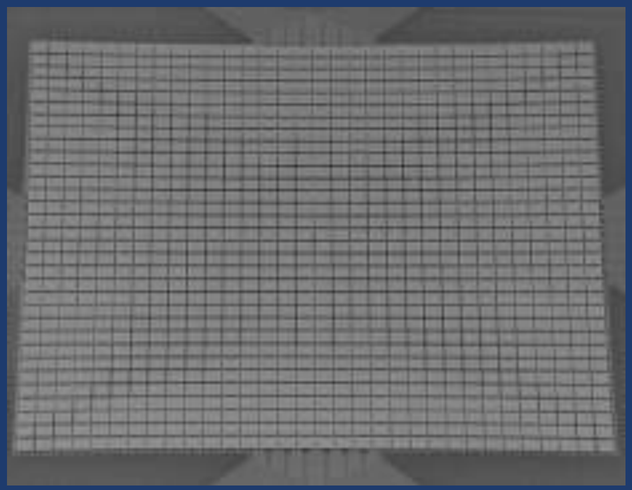
Last stage ADR (Safari)

Courtesy of CEA-SBT

Technical challenges

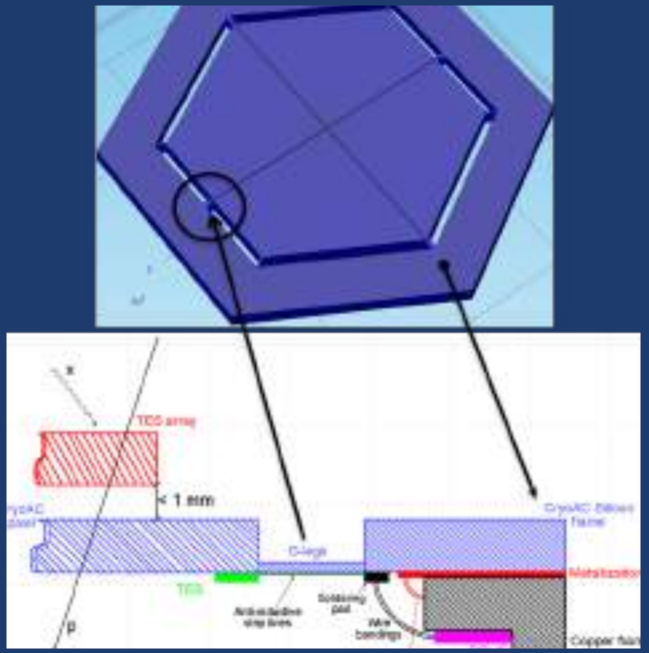
- Building a large format array of TES sensors high yield and homogenous response, matching both the spectral resolution, the spectral coverage, the quantum efficiency, and the count rate requirements
- Developing a cooling chain based on mechanical coolers to meet the Athena mission lifetime requirement of 5 yr (6.25 yr), while minimizing the perturbations to the instrument itself
- Developing a TES based cryogenic anticoindence detector and assembling it as closely as possible to the main TES array to meet the instrumental background requirement

Large format TES array to be extended by a factor of ~4 with larger pixels



See Poster: S. Bandler et al.

CryoAC mounting



See Poster: C. Macculi et al.

Technical challenges

- Developing an innovative FDM based readout electronics maximizing the pixel multiplexing factor and minimizing its contribution to the spectral resolution budget

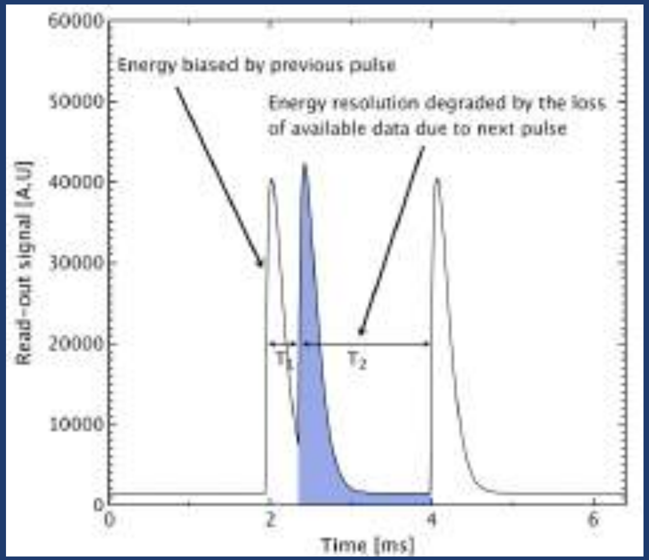
- Performing the event reconstruction on-board (energy, arrival time & position)

- Optimizing the design and defining the calibration strategy with the support of an end-to-end simulator

- Making the X-IFU affordable within the resources available from the Athena mission profile

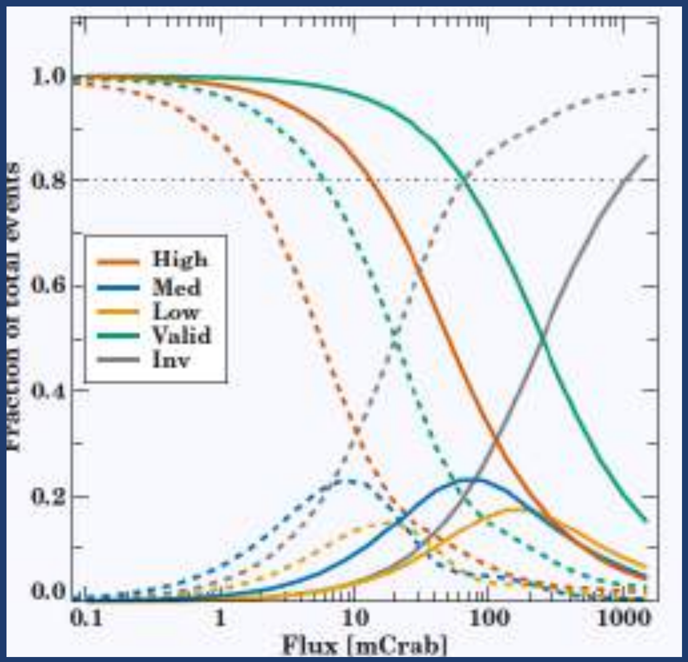
- Building and characterizing an X–IFU demonstration model to reach the appropriate technology readiness level at mission adoption (Q1-2020) as required by ESA

Event reconstruction



See Poster: Ceballos, Peille et al.

Count rate capability assessment

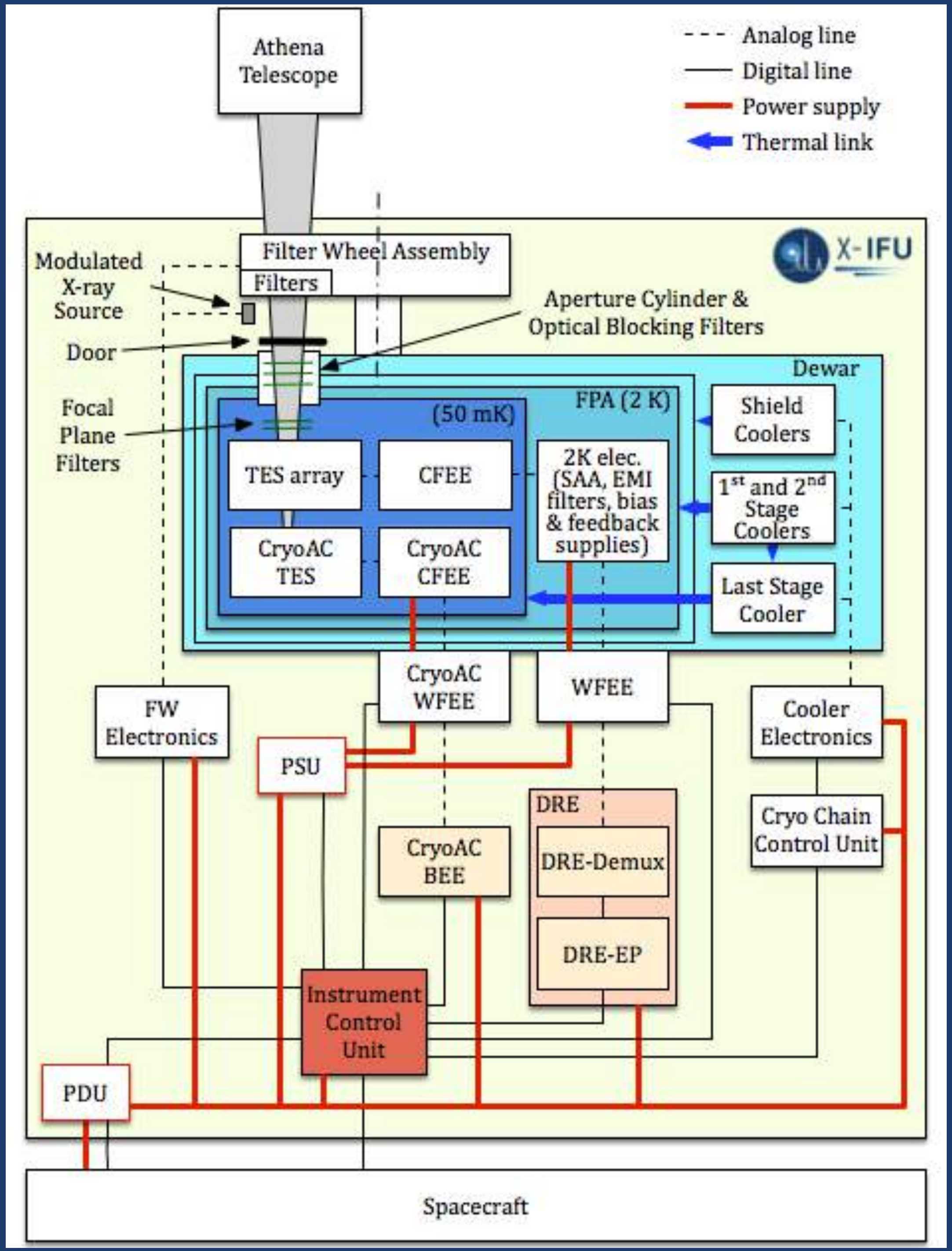


See Posters: Wilms, Dauser, Peille et

Didier Barret

X-IFU functional diagram

Transition Edge Sensor principle



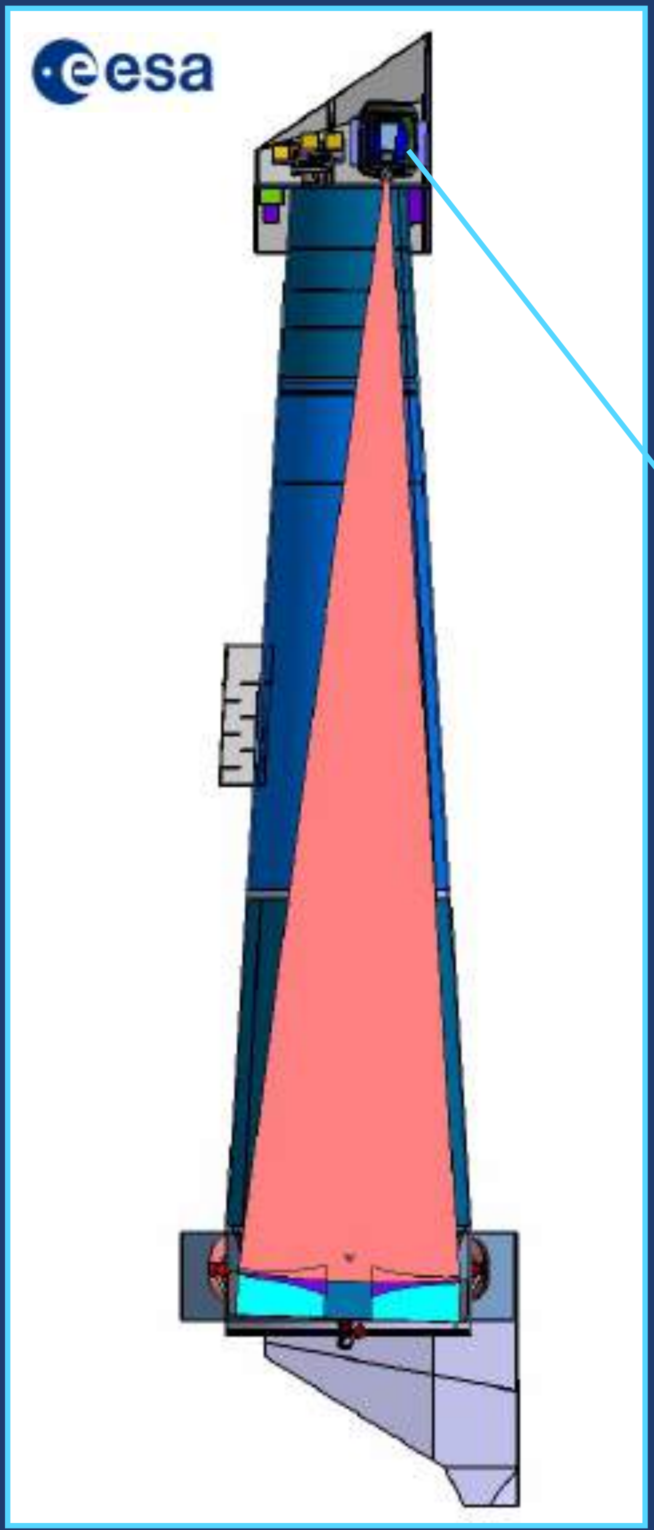
Ravera et al. (SPIE, 2014)

Mass and power budget (no system margins)

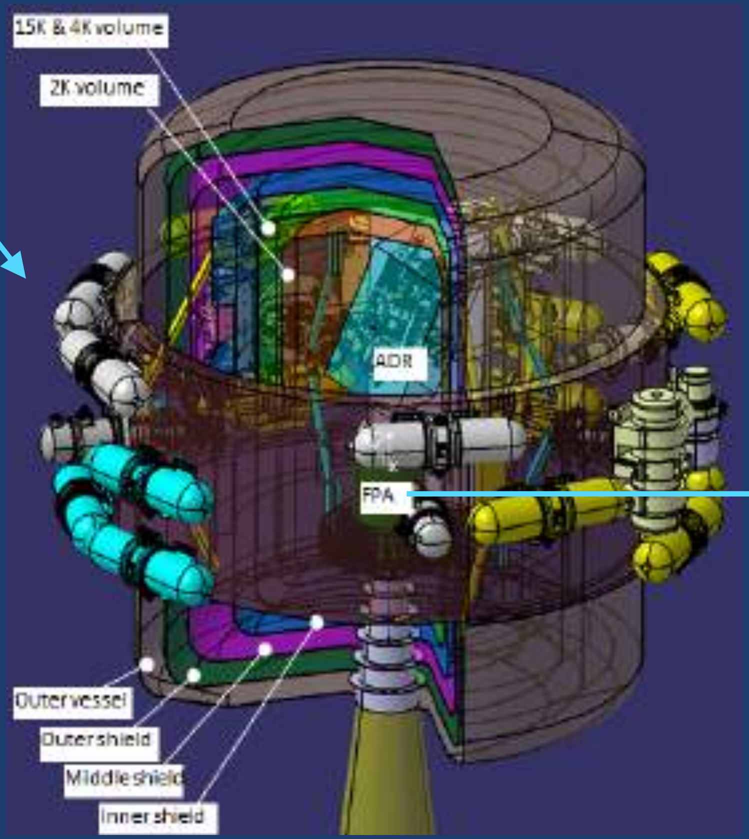
Focal plane assembly mass	6 kg
Cryogenic chain mass & power	320 kg/580 W
Mass and power of electronics	180 kg/523 W
X-IFU mass and power budget	506 kg/1.3 kW

Current best estimates (for the ESA CDF study)

X-IFU preliminary design

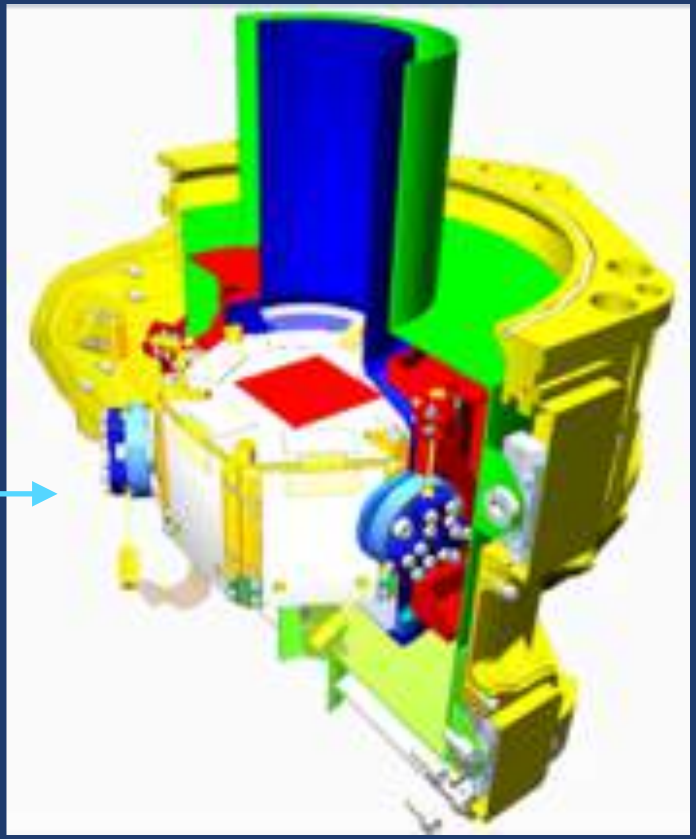


First & preliminary drawing of the X-IFU Dewar



Courtesy of A. Pradines (CNES)

X-IFU focal plane assembly

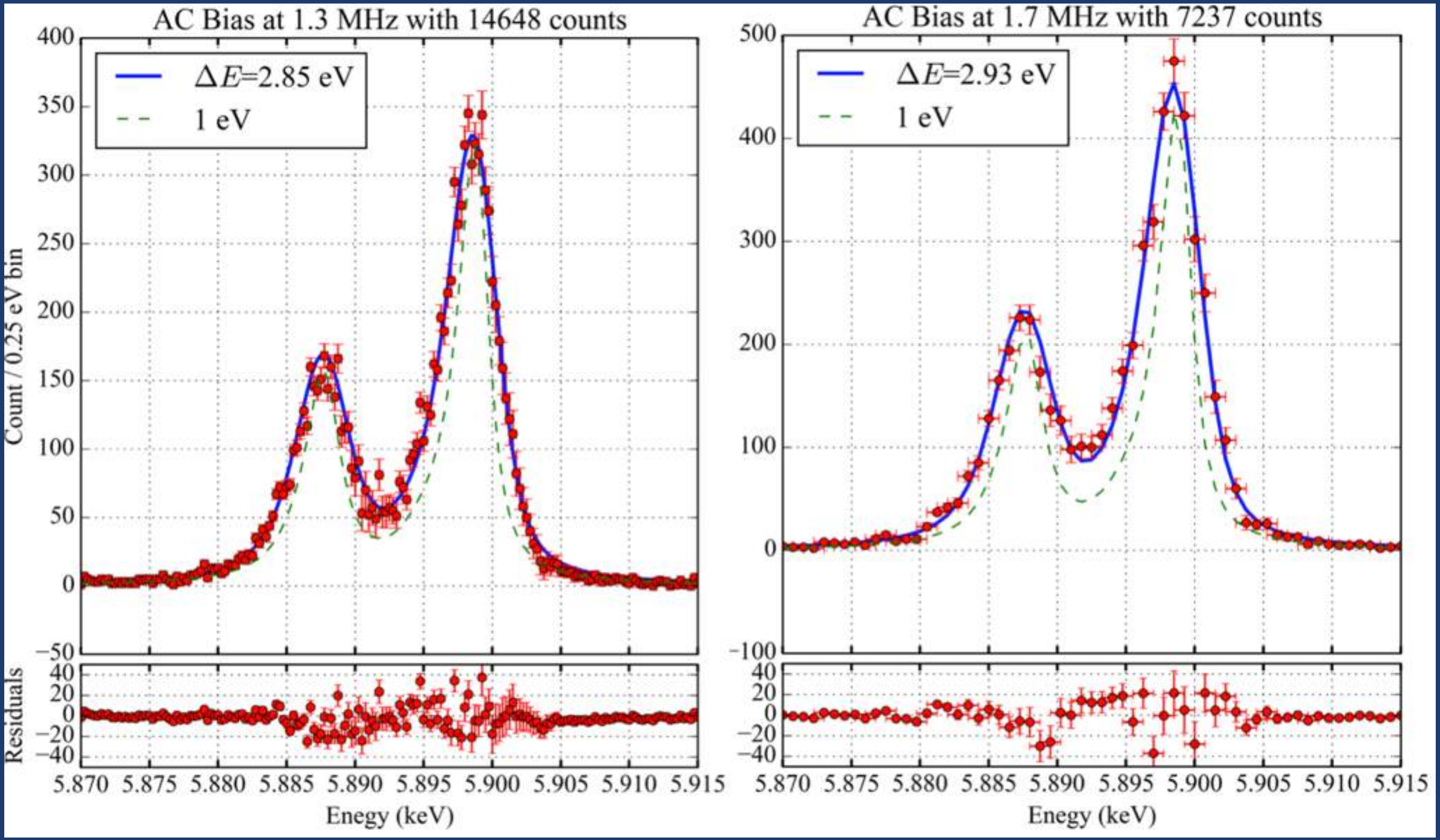


Courtesy of H. van Weers (SRON)

Performance update: spectral resolution

- FDM readout development shows remarkable progresses and consistent spectral resolution performance (below 3 eV up to frequencies of 4 MHz)

Spectral resolution measurements of 2 multiplexed pixels read out simultaneously (400 kHz frequency separation)

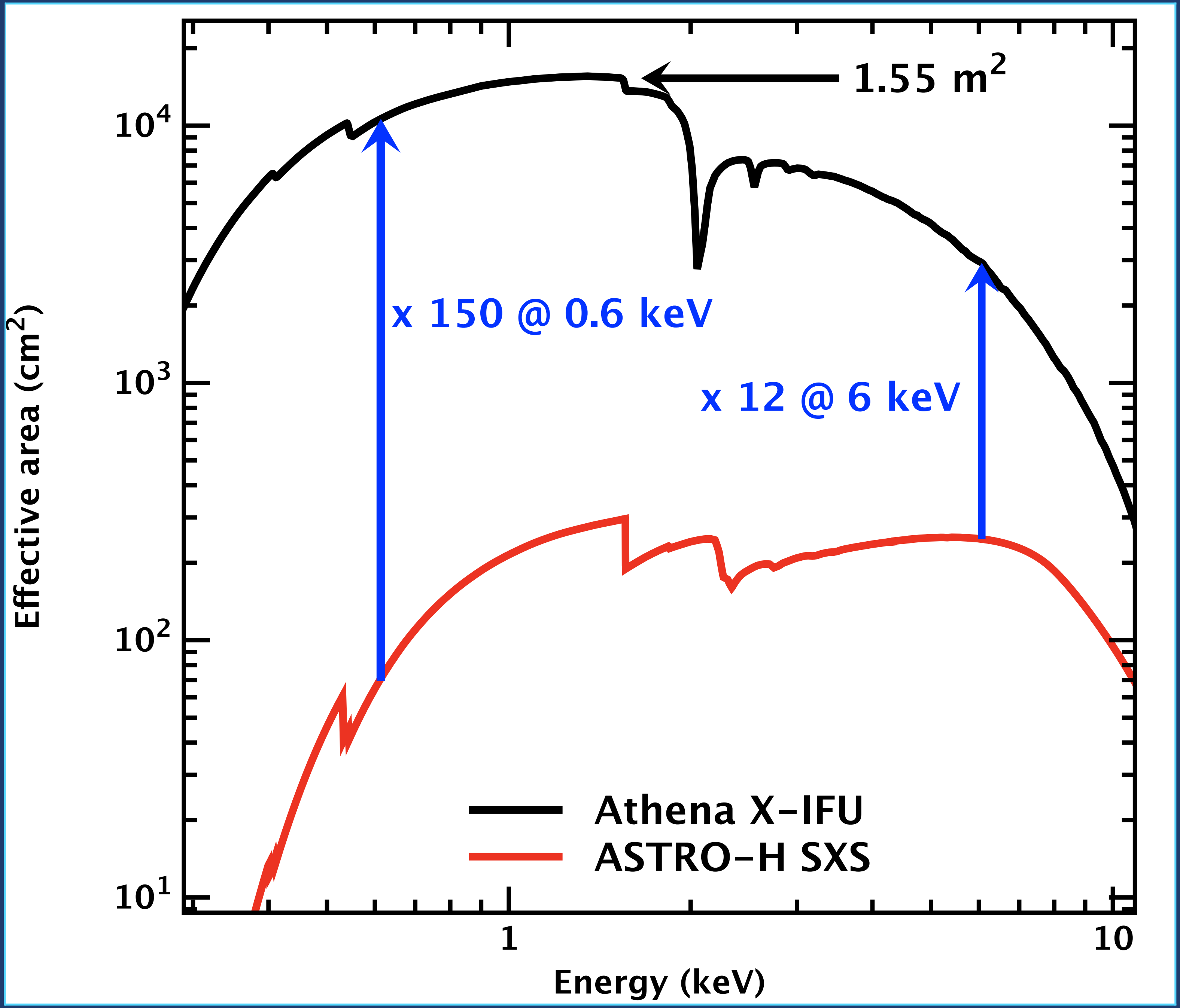


Courtesy of H. Akamatsu (SRON/JSPS fellow), L. Gottardi, J. van der Kuur (SRON): Team: SRON, VTT, GSFC, NIST, Stanford

Performance: Effective area

X-IFU
X-ray Integral Field Unit

Effective area comparison with ASTRO-H SXS



X-IFU effective area Includes filters, pixel filling factor and detector quantum efficiency

The TES array optimization exercise

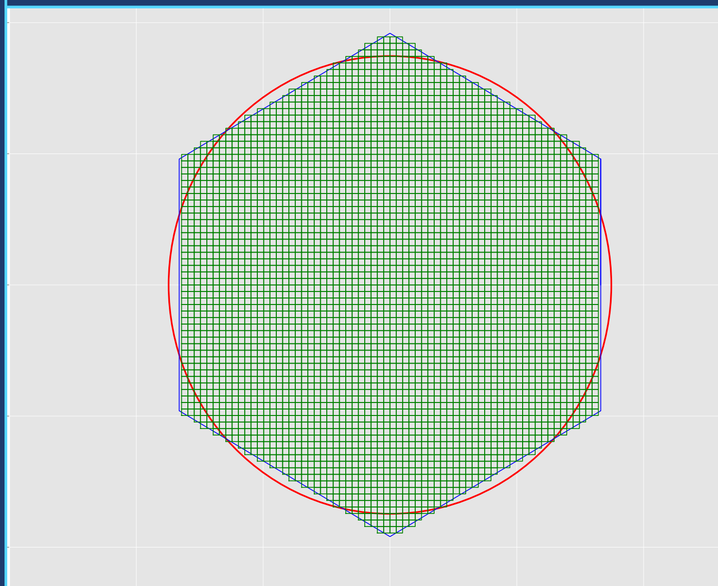
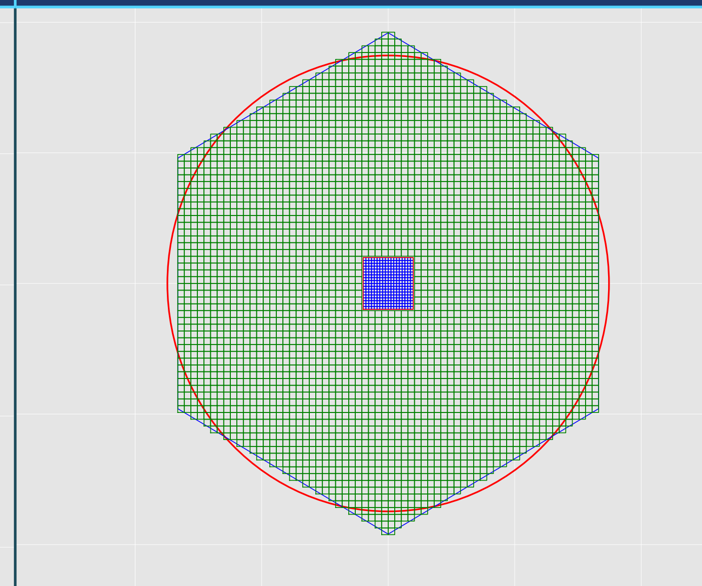
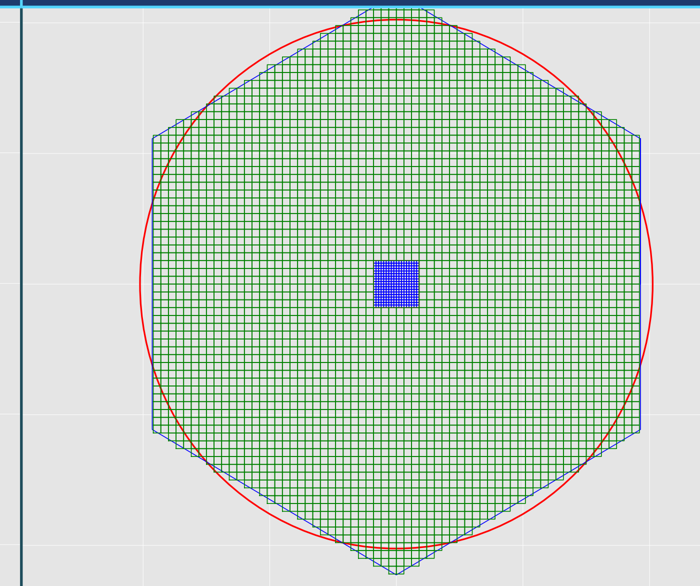
- The TES sensor array optimization exercise was proposed to and endorsed by the Athena Science Study Team (December 2014)
- Its scope is to determine how the TES sensor array configuration could be optimized as to
  - meet the baseline requirements more easily (splitting the count rate capability between bright point sources and faint extended sources)
  - investigate in parallel, ways to approach the X-IFU goal specifications (as stated in the mission proposal)

Parameter	Baseline requirement	Goal	Comment
Point source count rate capability	1 mcrab (~100 cps) High resolution throughput = 80%	10 mCrab (~1000 cps) High resolution throughput = 80%	Improve instantaneous sensitivity for bright sources
Spectral resolution	2.5 eV (E < 7 keV)	1.5 eV (E < 7 keV, tbc)	Improve weak line sensitivity
Field of view	5′ (equivalent diameter)	7′ (equivalent diameter)	Increase observing speed

- Strict boundary conditions: no increase of resources compared to the baseline X-IFU configuration studied in the CDF

Didier Barret

Three TES array configurations studied

Configuration a (baseline)	Configuration b	Configuration c
		
Single size pixel array - 5′ (pixel of 4.2″)	Small Pixel Array (SPA) - 33″ x 33″ (1.8″)	SPA - 30″ x 30″ (1.6″) LPA - 5.8′ (5.1″)

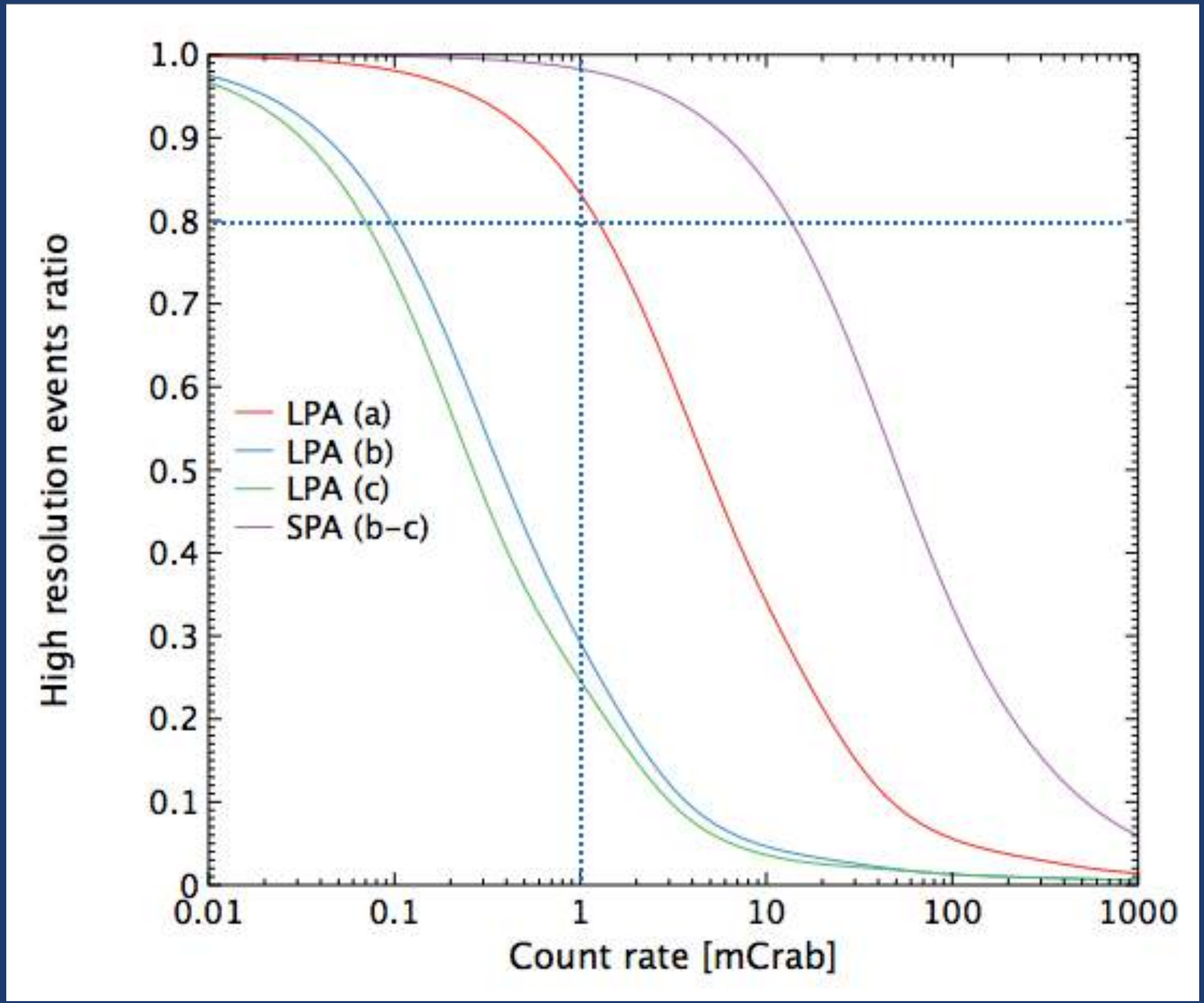
- Detailed assessment by the X-IFU Science Team, supported by the end-to-end simulator Team, concludes that configuration b has substantial advantages over configuration a
  - Increased potential for WHIM detection with bright GRB afterglows and for observatory science (e.g. X-ray binaries)
  - Smaller pixels with improved spectral resolution would increase weak line sensitivity (e.g. increasing the # of WHIM filaments detected)
  - Configuration c should be investigated provided that it preserves the spectral resolution, as it would increase the observing efficiency and ease the monitoring of the background

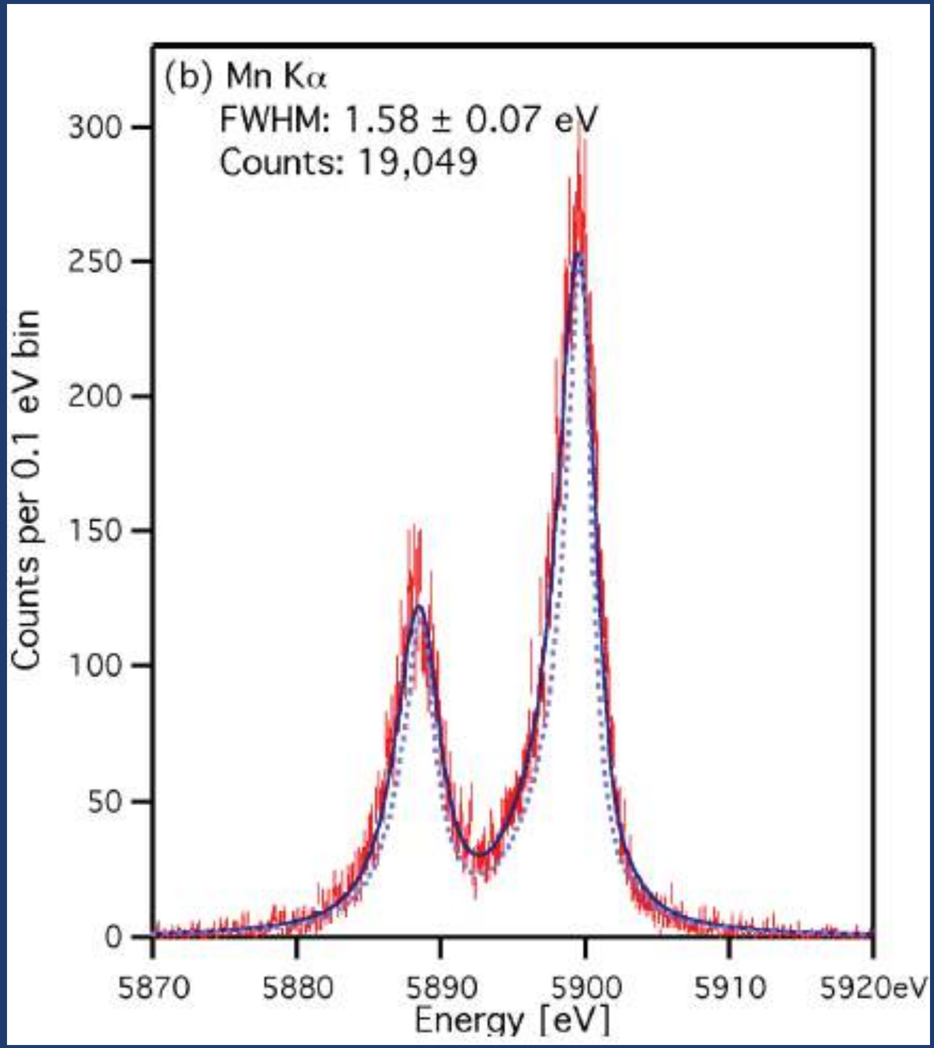
- Technical/programmatic assessment of the three configurations as part of the phase A study

Count rate capability improvement

- A small pixel array provides better count rate capability (due to the PSF oversampling) and potentially better spectral resolution (lower heat capacity)

Count rate capability assessment of the three TES array configurtaions





See Posters: Ph. Peille et al., Th. Dauser et al., S. Bandler et al.

- Technical assessment to be performed

X-IFU consortium organization

Country	Lead	Main hardware & ground segment contributions
France	D. Barret, PI	CNES: Project & system management, Dewar Manager, Warm Electronics Manager, AIT IRAP: Digital Readout Electronics, Instrument Control Center (ICC), Calibration APC: Warm Front End Electronics CEA-SBT: Sorption-ADR CEA-SAP: Event Processor software and hardware Néel: Dilution refrigerator
The Netherlands	J.W. den Herder, co-PI	SRON: Focal Plane Assembly, Cold Front End Electronics, Modulated X-ray Source
Italy	L. Piro, Co-PI	IAPS-INFN-IFN-Genova-Milano: Cryogenic Anti-Coincidence, background characterization… IASF-Bologna: Instrument Control Unit Univ. Palermo: Thermal filters (for focal plane and aperture assemblies) Obs. Roma: Contribution to the X-IFU ICC
Spain	M. Mass-Hesse	CAB-INTA: Cryostat & harness CSIC: Event reconstruction algorithm, Contribution to the X-IFU ICC, Science team lead
Switzerlands	S. Paltani	UniGe: Filter wheel assembly, Contribution to the X-IFU ICC
Belgium	G. Rauw	ULG & CSL: Aperture assembly
Poland	A. Rozanska	CamK & CBK: Dewar door, Power Units (tbc)
Germany	J. Wilms	ECAP: Instrument end-to-end simulator
Finland	J. Huovelin	VTT: SQUID amplifiers
United states	R. Kelley	GSFC/NIST/Stanford: TES array & ASTRO-H expertise
Japan	K. Mitsuda	ISAS: Shield coolers and pre-coolers & ASTRO-H expertise

Conclusions

- The X-ray Integral Field Unit is required to address the Hot and Energetic Universe science theme

- The X-IFU will be the first X-ray Integral Field Unit ever flown, providing 2.5eV spectral resolution at arcsecond spatial resolution
  - The X-IFU has an extraordinary discovery potential for a wide range of science investigations beyond the hot and energetic Universe science theme

- The X-IFU is a very complex, yet very exciting instrument to build
  - Many critical technology developments are under way with support from ESA, from the ESA member state funding agencies (e.g. CNES, SRON, ASI), NASA and JAXA
    - Sensors, readout electronics (cold and warm), coolers, filters…
  - Large efforts devoted in the L2 (and soon L1) environment characterization & end-to-end instrument performance simulations
  - The ultimate performance of the X–IFU will depend on the Phase A studies and the successful completion of the Demonstration Model by the end of 2019

The X-IFU consortium

X-IFU X-ray Integral Field Unit

irap astrophysique & planétologie

cnes CENTRE NATIONAL D'ÉTUDES SPATIALES

SRON Netherlands Institute for Space Research

iaps Institute for Space Astrophysics and Planetology Istituto di Astrofisica e Planetologia Spaziali

CNRS INSU Observer & comprendre

Université Toulouse III Paul Sabatier

Observatoire Midi-Pyrénées OMP

NWO

asi agenzia spaziale italiana

Consiglio Nazionale delle Ricerche

INAF Istituto Nazionale di Astrofisica National Institute for Astrophysics

cea

INAC Institut Nanosciences et Cryogénie

sbt

INTA

CSL Centre Spatial de Liège

Université de Liège ULg

NÉEL institut

INFN

IFN Istituto di Fotonica e Nanotecnologie

VTT

University of Helsinki

Université de Genève

CBK PAN

IFCA Instituto de Física de Cantabria

CSIC Consejo Superior de Investigaciones Científicas

ecap Erlangen Centre for Astroparticle Physics

OAR

Observatoire astronomique de Strasbourg

UCL MSSL

Universiteit van Amsterdam

Universiteit Leiden

Universitat d'Alacant Universidad de Alicante

Hiroshima University

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