Prototype Development and Calibration of the CUbesat Solar Polarimeter (CUSP)

SPIE Optics+Photonics:

Hard X-Ray, Gamma-Ray, and Neutron Detector Physics XXVII

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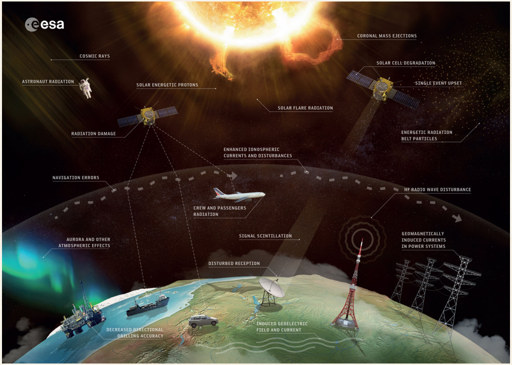
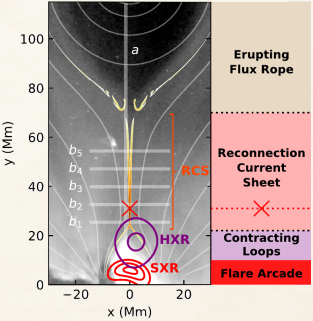
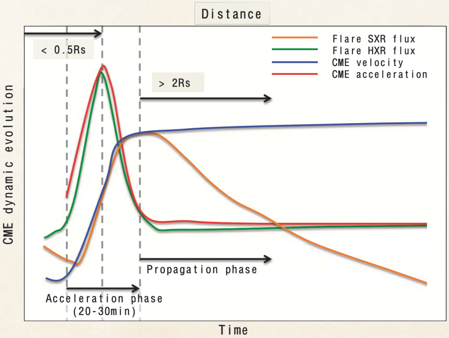
- Solar activity, including **Solar flares (SFs)**, can be disruptive for human technological activities in space and on ground
- The occurrence of SFs is very often associated to **Coronal Mass Ejection (CME)** and **Solar Energetic Particle (SEPs)** events on the ground
- SF **can also occur** alone producing a **direct acceleration** of particles towards the Earth



- Most powerful eruptions associated to powerful flares
- HXRs are related to CME acceleration $\Longrightarrow$ **HXR polarimetry** could improve the knowledge of the **initial conditions** of the eruption of most powerful CME
- SXRs are related to CME velocity
- The rapid CME development in the lower corona during the acceleration phase strongly correlates with the associated flare activity.



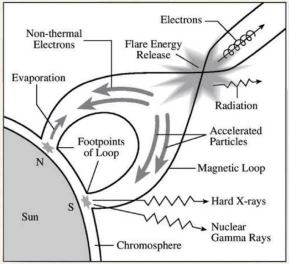
Chen B. et al. (2020), Nat. Astron.

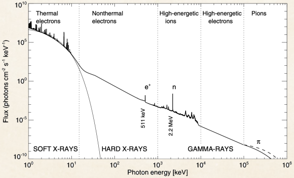


Temmer (2016), Astron. Nachr.

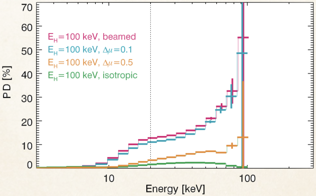
Motivation for X-ray Polarimetry of SFs

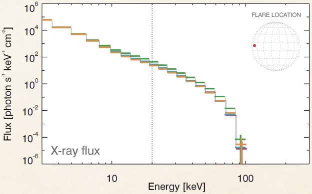
- SFs originate from **magnetic reconnection** in loop structures in solar corona
- SFs energy spectrum in the X-rays is dominated by:
  - **thermal Bremsstrahlung** (due to plasma heating, expected weakly polarized by Emslie&Brown 1980) + emission lines < 10 keV
  - **non-thermal Bremsstrahlung** (at the loop top and footprints, due to particle acceleration along magnetic field lines) expected highly polarized [Zharkova+ 2010] >10-20 keV
- (Linear) **X-ray polarimetry** would allow to **disentangle degeneracies in models** of particle beaming and magnetic field structure (also without imaging of the SF)





Aschwanden (2005)



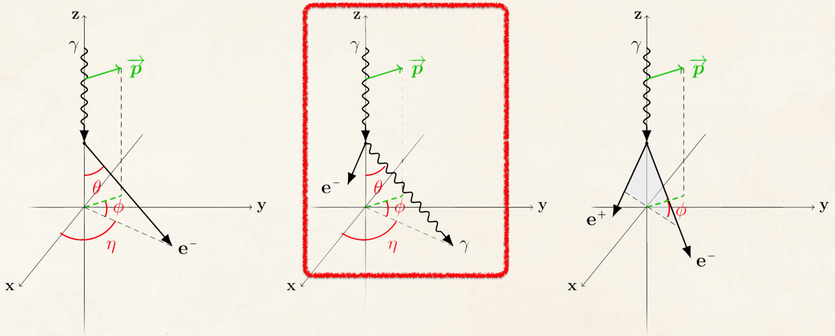


Jeffrey+ 2020 (A&A)

Photon interaction with matter

- Photons interact with matter through three processes:

Photo-electric effect | Compton scattering | Pair production



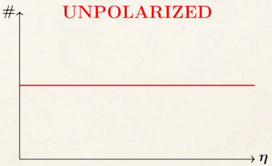
- Each process is dominant at different energies
- The azimuthal distribution of the secondary products is correlated with the polarization direction of the primary photon: $\frac{d\sigma}{d\Omega} \propto 1 + \mu \cos(2\phi)$
- **Compton scattering** is the dominant process in the energy band where the **SF non-thermal emission lies (20-100 keV)**

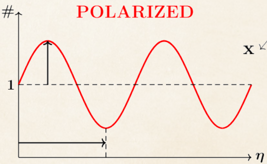
Compton scattering can be used to determine the polarization of a source:

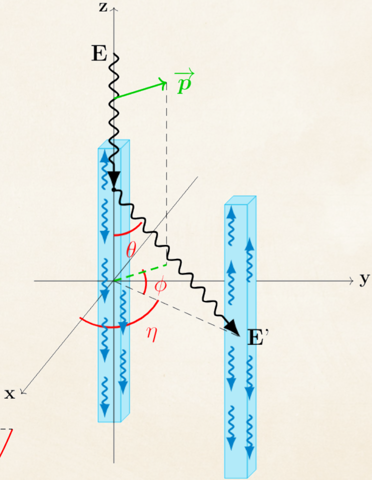
- Azimuthal scattering angle distribution provides information on PD and PA
- Modulation curve parameterized by the Klein-Nishina cross-section:

$$\frac{\mathrm{d}\sigma}{\mathrm{d}\Omega} = \frac{r_e^2}{2}\left(\frac{E'}{E}\right)^2\left[\frac{E'}{E} + \frac{E}{E'} - 2\sin^2(\theta)\,\cos^2(\phi)\right]$$

- Relative amplitude $\leftrightarrow$ PD, phase $\leftrightarrow$ PA
- **A segmented array of scintillators can be used to measure the scattering angle distribution (aka modulation curve)**

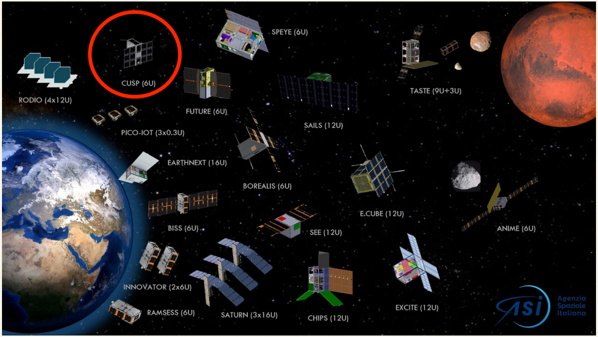






The Project Framework

- The **Italian Space Agency (ASI)** started a new national program named **Alcor** for funding the development of CubeSat technologies and missions
- **CUSP** is one of the 20 selected missions among 49 proposals
- 22 participants from Research Institutes and Universities and 78 companies, mainly Small and medium-sized ones



The CUSP Collaboration

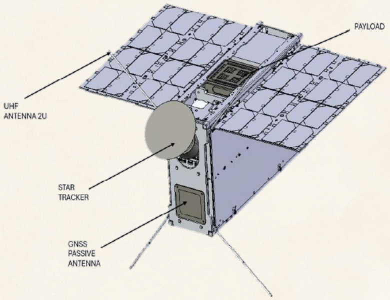
- INAF: **IAPS-Roma:** Prime contractor, PI-ship, and Payload; **OAS-Bologna:** Detector Simulation; **OAR-Roma:** Lab SW Support
- IMT s.r.l.: Satellite Platform
- DEDA Connect s.r.l.: Payload Electronics
- Università di Bologna – CIRI AERO: Mission Analysis
- Università della Tuscia: Ground Segment
- Italian Space Agency (ASI): Project Control

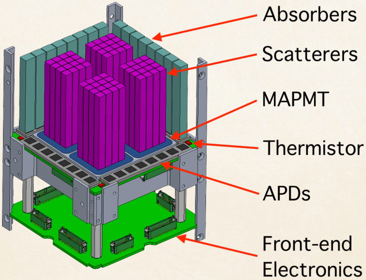
Websites: https://www.iaps.inaf.it/it/missioni-spaziali/cusp

https://www.asi.it/tecnologia-ingegneria-micro-e-nanosatelliti/micro-e-nanosatelliti/il-programma-alcor/cusp/

The CUSP Mission Preliminary Design

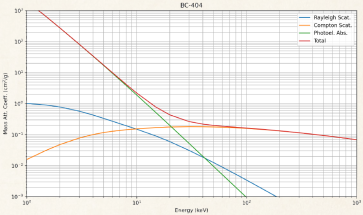
- **6U-XL CubeSats** orbiting the Earth on SSO orbit (∼500-600 km) to observe the Sun
- Monitoring of the Sun with a time fraction ∼45% during the 3 years nominal life-time
- X-ray polarimetry of Solar Flares in the 25-100 keV energy band
- The satellite hosts a **dual-phase Compton scattering polarimeter** that exploits **coincidence** measurements between plastic (scatterer) and inorganic (absorber) scintillator rods
- **1 RPM rotation** of the spacecraft around the polarimeter symmetry axis pointing the Sun allows to reduce the systematic effect known as spurious polarization



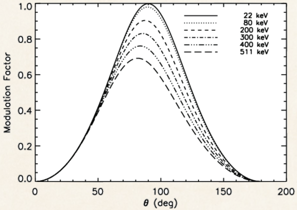


Dual Phase Design

- High probability of **scattering in plastic** material (4 MAPMTs read out with a MAROC-3A ASIC by WEEROC)
- 90° scattering produces maximum modulation of the signal
- @20 keV only 750 eV of Compton energy deposit for scattering at 90°, PMT needed (1-3 optical photons to collect)



NIST XCOM



Fabiani & Muleri 2014

- High probability of **photoelectric absorption** in the absorber (**GAGG**) material (32 APDs read out with a SKIROC-2A ASIC by WEEROC)
- Measurement of **coincidences** Scatterer/Absorber allows effective **background reduction**
- **Fast schedule, no R&D possible,** we need heritage and space proven items as much as possible. We selected APDs from past TSUBAME mission unfortunately lost in 2015 and similar MAPMTs (Y. Yatsu 2014, SPIE Proc.)

Laboratory Test of the Acquisition Chains

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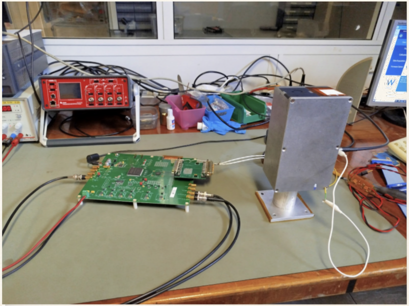
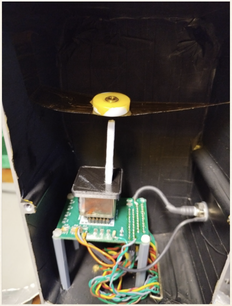
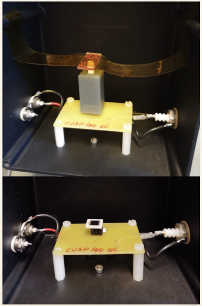
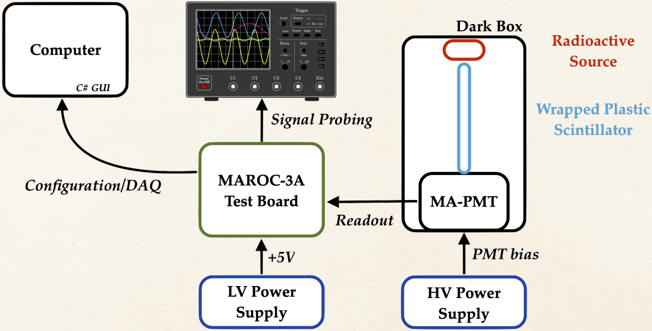
IAPS ISTITUTO DI ASTROFISICA E PLANETOLOGIA SPAZIALI

- CUSP is employing **2 acquisition chains** for the **Absorbers** (GAGG + APD + SKIROC-2A) and **Scatterers** (Plastic + MA-PMTs + MAROC-3A)
- Preliminary tests are being conducted based on ASIC Test Boards (WEEROC) and single scintillator bars coupled to sensors

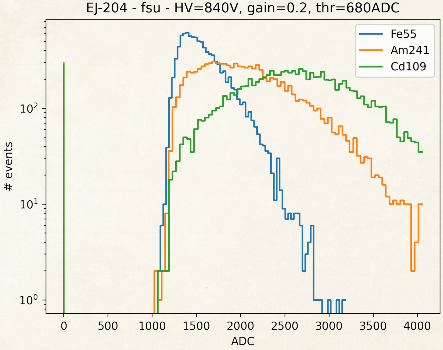
Single Channel Energy Calibration

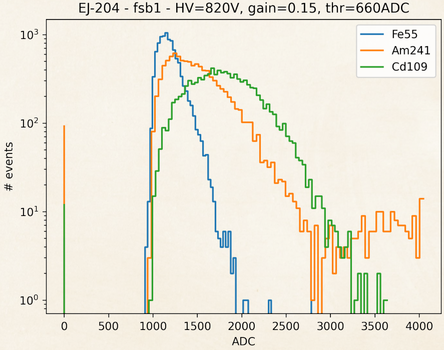
- CUSP is employing **2 acquisition chains** for the **Absorbers** (GAGG + APD + SKIROC-2A) and **Scatterers** (Plastic + MA-PMTs + MAROC-3A)
- Preliminary tests are being conducted based on ASIC Test Boards (WEEROC) and single scintillator bars coupled to sensors



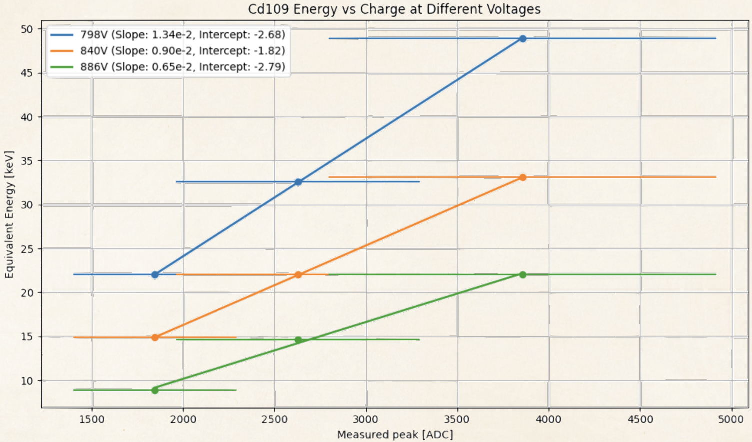
EJ-204 Plastic Scintillator - fsu vs. fsb1

Spectrum of Fe55 (5.9 keV), Cd109 (22 keV), Am241 (18 keV from Compton of 59.5 keV)





Charge [ADC] to Energy [keV] conversion



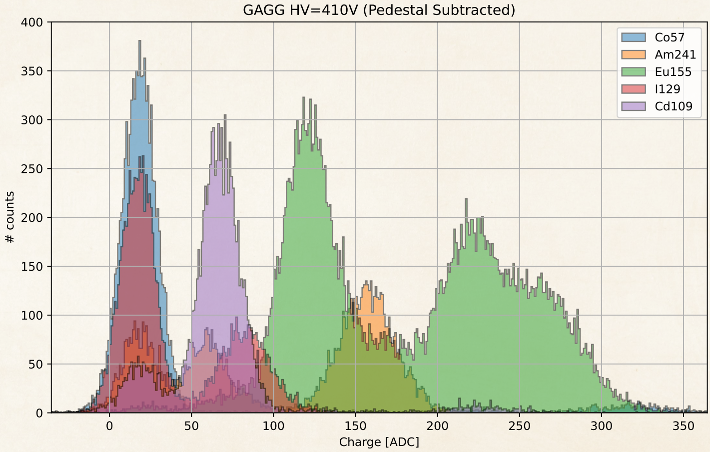
Real HV [V]	798	840	886
Energy threshold [keV]	7.52	5.07	2.13
Max. Energy (4096 ADC)	52.14	35.24	23.71

Energy Range Requirements

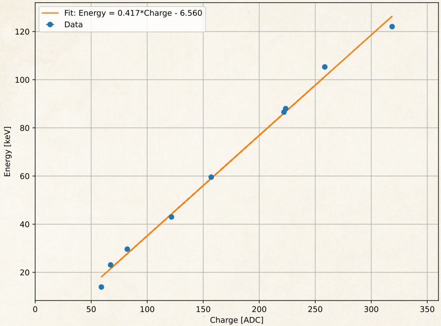
→ from 0.7 keV to 16 keV:

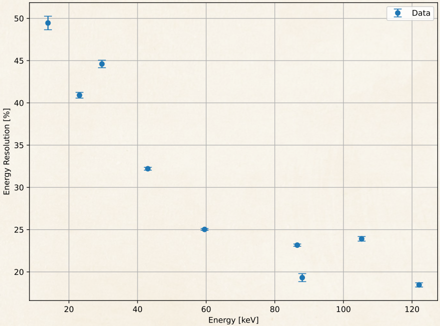
Impinging Energy (keV)	**Scattering angle (deg)**	**Compton energy deposit (keV)**
20	90	0.753
25	90	1.17
30	90	1.66
40	90	2.90
50	90	4.46
60	90	6.31
80	90	10.8
100	90	16.4
	65	10.2

Spectra of various sources with absorber



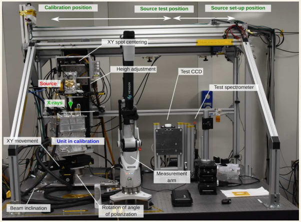
Energy calibration and FWHM resolution





Payload Calibration Plan

- Currently using **calibration sources** (Fe55 – 5.9keV, Cd109 – 22 and 88 keV, Am241 – 59.5 keV, Co57 – 123 keV) with single channel absorber/scatterer read out by ASIC development boards provided by WEEROC
- Soon building a reduced version of the instrument with **4×4 scatterers surrounded by 16 absorbers** to be read out by a **custom FEE** embedding both ASICs and an FPGA to apply the coincidence trigger logic
- This reduced module will be **calibrated in-house using calibration facilities** developed for IXPE's GPD calibration based on X-ray tubes combined with Bragg diffraction crystals to get a highly polarized X-ray flux
- Possibility of **calibration at ESRF** (Grenoble, France) with synchrotron polarized beam in the 20-500 keV range



ICE setup @INAF-IAPS

Conclusions and Project Status

- A **6U-XL CubeSats** is under development in the frame of ASI's Alcor project
- Its main scientific goal is to perform **hard X-ray polarimetry of solar flares**, allowing to better understand the physics of coronal mass ejection and to probe magnetic reconnection sites in the Sun's atmosphere
- **12-month Phase B** will end next December
- Representative prototype of the polarimeter being built, will be tested for functionality and performance in Sept-Nov 2025
- Next step would be to propose a **15-month combined Phase C/D**
- Model Philosophy:
  - 1 detector prototype at the end of Phase B. Representative of the detector front-end (from TRL 3 to TRL 4)
  - 1 payload sub-system Structural Model at the end of Phase B (scintillator bars holding system)
  - 1 payload EQM (design phase B, production and test phase C). Representative of the payload (from TRL 4 to TRL 7)
  - Trade-off assessment to allow ASI to decide if to continue with a 2 CubeSats constellation or with a single CubeSat. Depending on the outcome of the trade-off:
  - 1 Proto-flight Model (PFM). To qualify at proto-qualification level
- Current launch window: **late 2027/early 2028**