The Development of the Compact Cherenkov Detector HEPI - the High Energy Proton Instrument for Satellite Missions

Dr Fan Lei

IRENE Workshop 2025

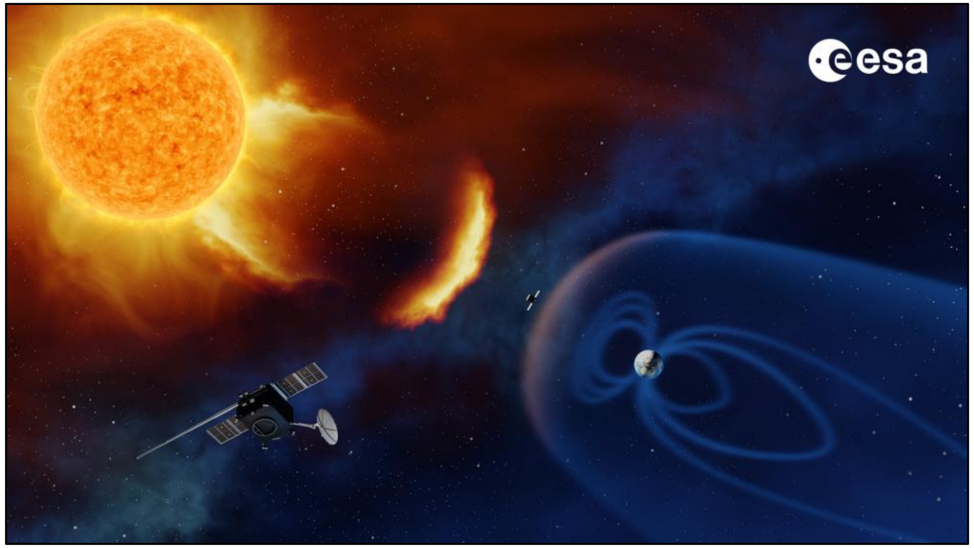
20-22 May | Sykia, Greece

UNIVERSITY OF SURREY

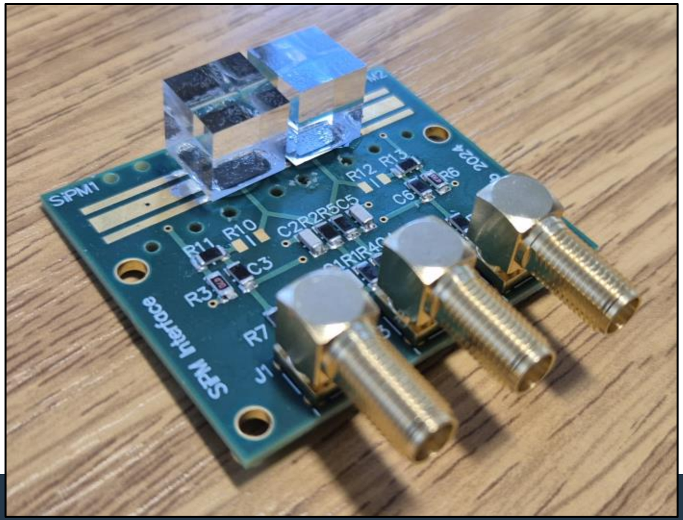
SURREY SPACE CENTRE

Outline

- What is Space Weather, and what are SPEs?
- How do Cherenkov detectors work?
- HEPI's design
- Lab benchmark tests
- Beam test investigations
- Future work and missions

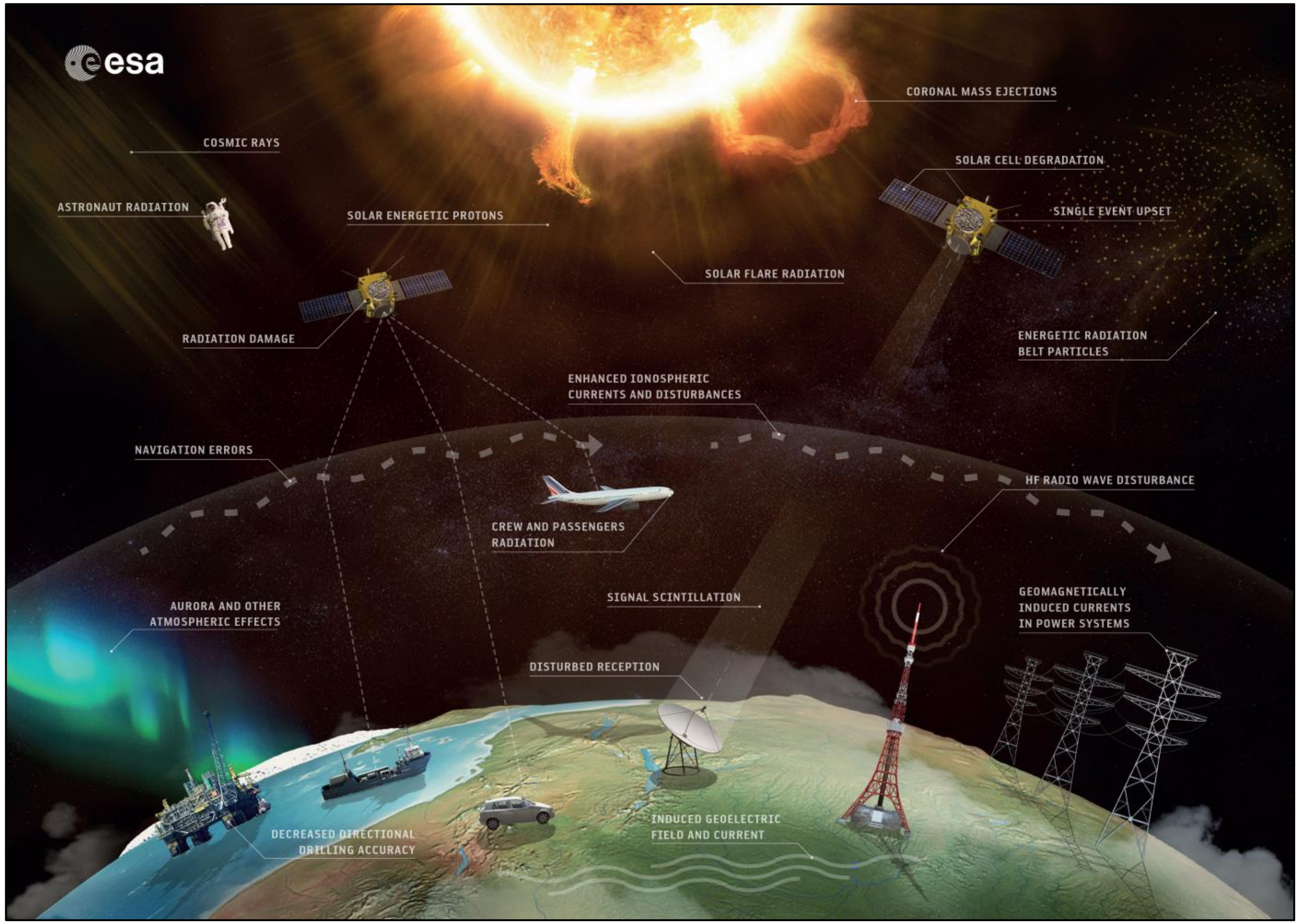


From ESA website



Motivation – What Is "Space Weather"?

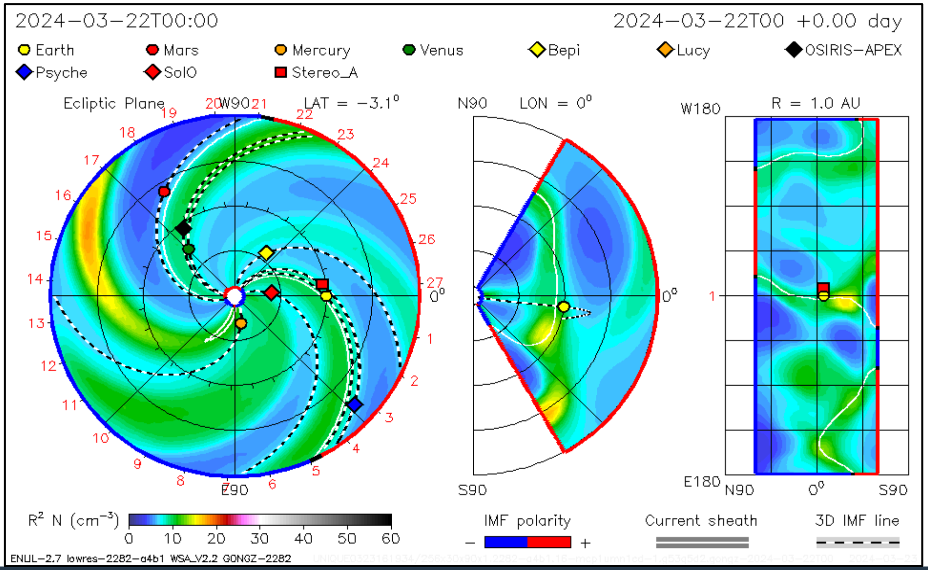
- Space weather describes the environment of near-Earth space
- Space – Satellite degradation, astronaut dose, lunar base impacts
- Air – Cabin crew and passenger dose, instrumentation
- Land – Impact on satellite reception, power infrastructure



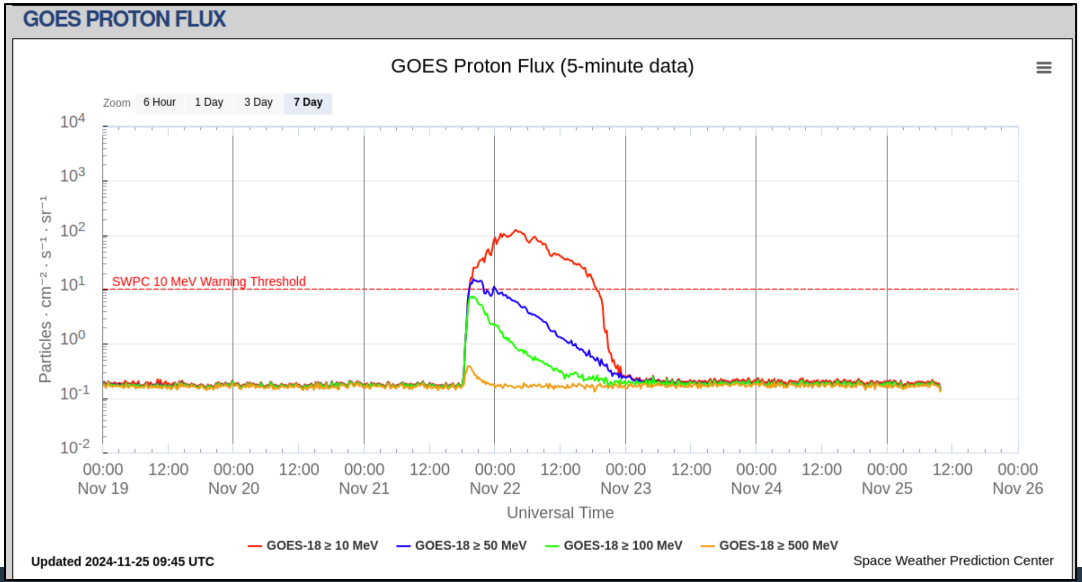
From ESA website

Motivation – What Are SPEs?

- Protons emitted in Solar Particle Events (flares, coronal mass ejections) can be accelerated to GeV levels
- These high-energy protons can damage space, air and ground infrastructure
- Few instruments are monitoring the near-Earth space weather environment
- A constellation of Cherenkov >300 MeV proton detectors would aid the understanding of the environment, and provide information during SPEs



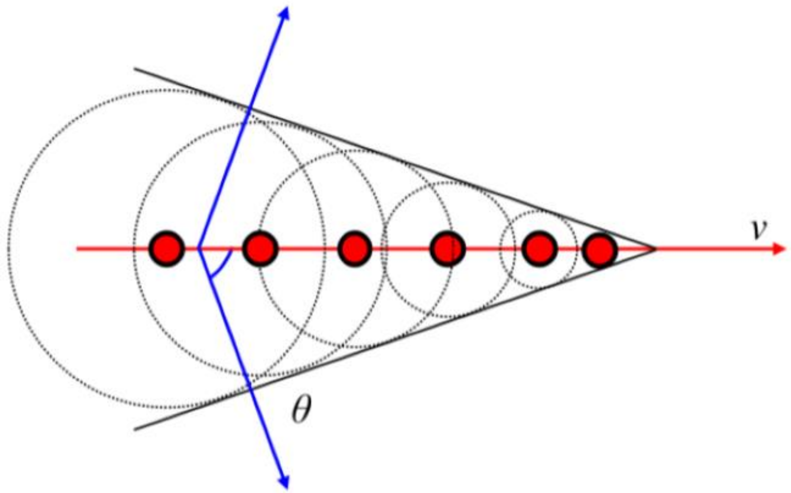
Taken from spaceweather website

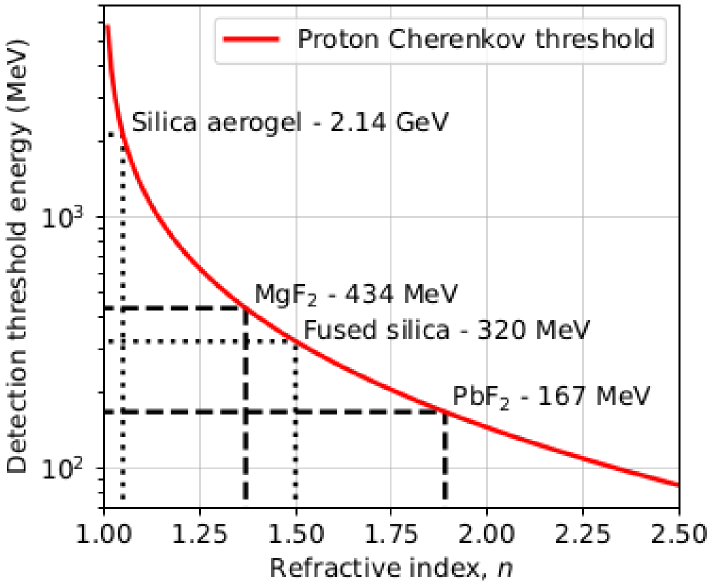


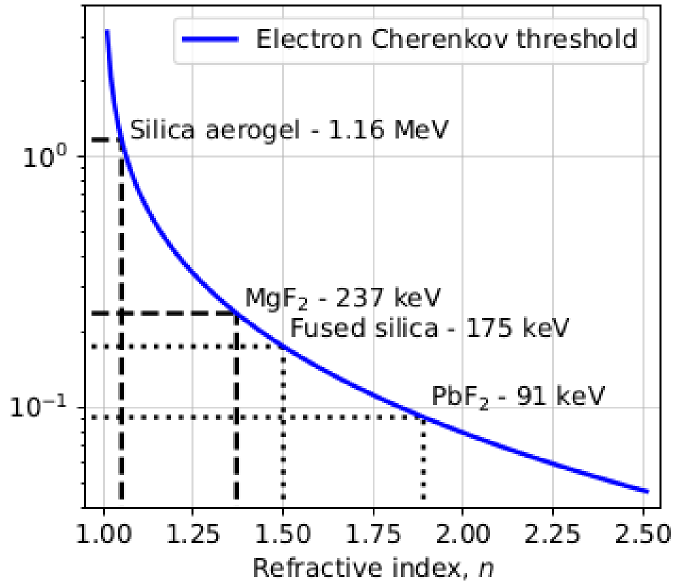
Taken from Space Weather Prediction Center website

Mechanism – How Do Cherenkov detectors Work?

- Cherenkov radiation is emitted by charged particles travelling faster than the speed of light in a dielectric medium
- Each particle species will have an inherent Cherenkov threshold energy, dependent on the refractive index of the medium
- Previous missions have used large volume Perspex, quartz and PbF_2 radiators to measure heavy GCRs, proton and electron fluxes



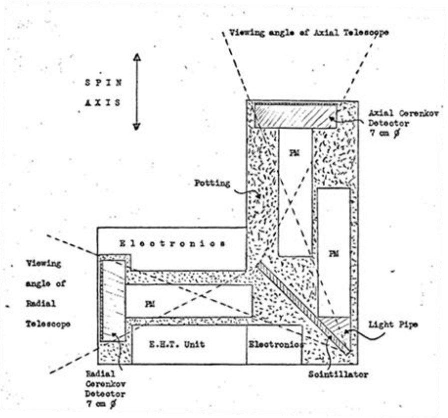


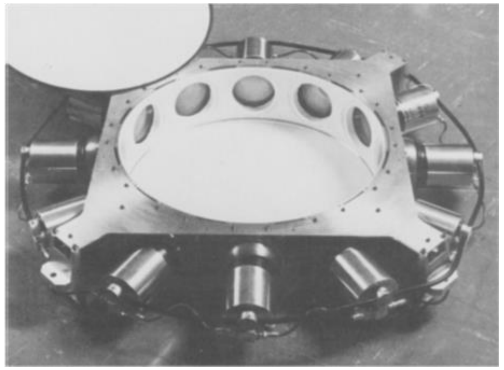


Missions Utilising Cherenkov Detectors

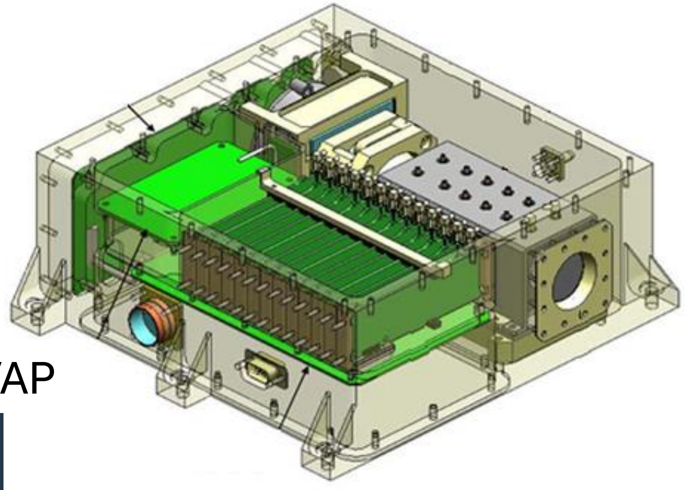
Mission	Date	Orbit	Cherenkov	Scintillator	SSD	Readout
Ariel-1	1962	400x1200km	Perspex	N	N	PMT
POGO	1966		Sapphire	N	Si(Li)	PMT
HEOS-1	1968 -1970	1800x222300km	Perspex	NE1021A	N	PMT
OV1-20	1971	139x1950km	Lucite	Y	N	PMT
Pioneer-10,11	1972 -		Water-methanol Fused Silica	N	Y	PMT
ISEE-3/ICE	1977 -2014	L1	Ethylene, Quartz	CsI, Plastic	Y	PMT
HEPAD	1974 - 2017	GEO	Fused Silica	N	Y	PMT
IMP 7	1972 - 1978	2000,000 km	Sapphire	CsI, Plastic	Y	PMT
CRNC/IMP 8	1973-2001	25-45 Re	Sapphire	CsI, Plastic	Y	PMT
HEAO-3 C2	1979 -1981	500km	Lead glass, Aerogel, Teflon	N	N	PMT
HEAO-3 C3	1979 -1981	500km	Lucite (Pilot 425)	N	N	PMT
Ulysses KET	1990 - 2009		Aerogel, Lead Fluoride	NE104	Y	PMT
RPS/RBSP	2012 - 2019	618x30314km	MgF_2	Y	Y	MCP

HEOS-1





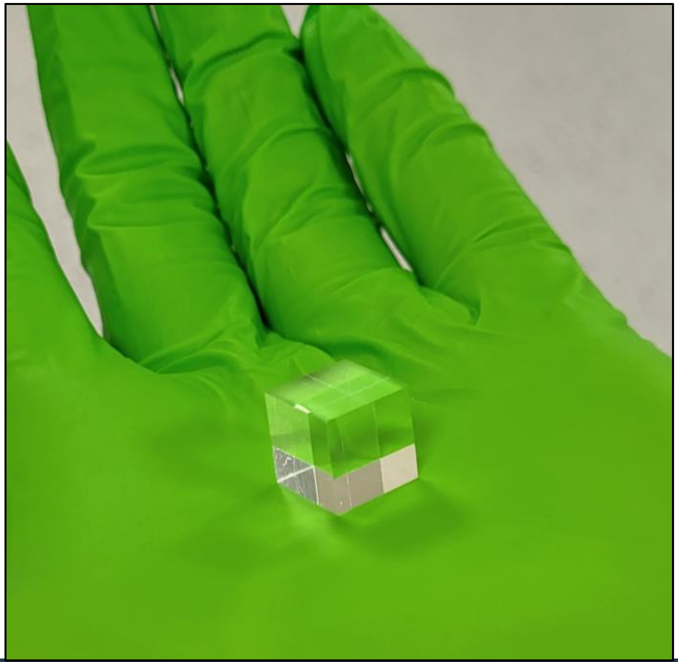
HEAO-3 C2

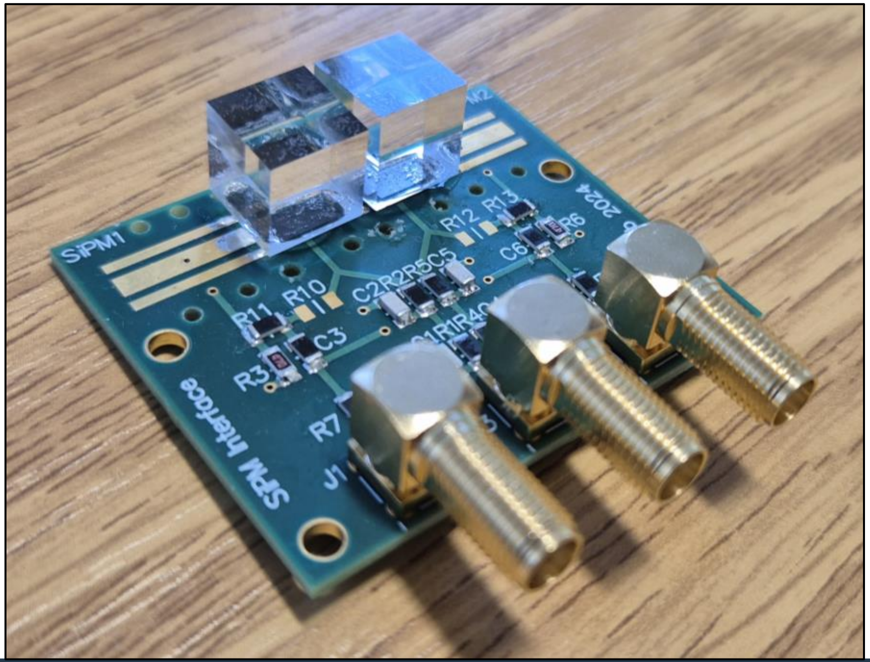


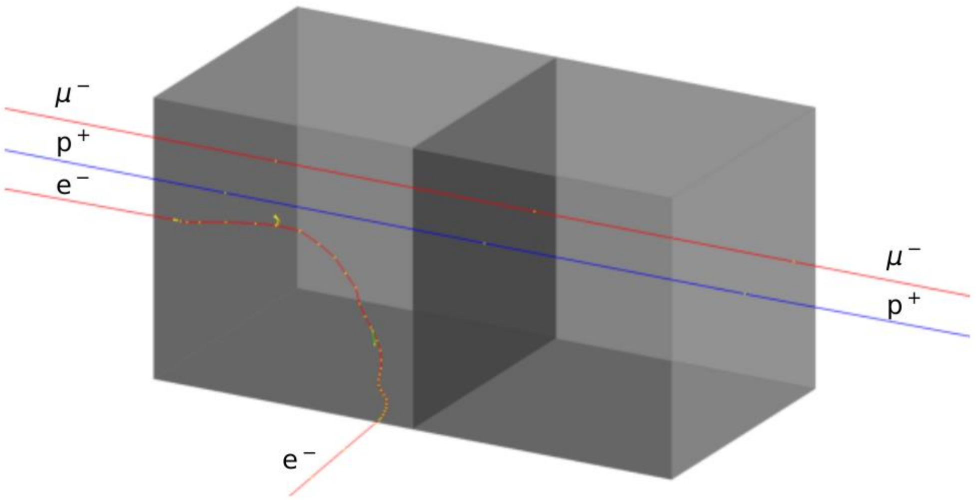
RPS/VAP

HEPI – Detector Design

- The High-Energy Proton Instrument (HEPI) consists of two Cherenkov modules – each consisting of a 10x10x10 mm radiator coupled to a 6x6 mm SiPM
- Several materials with Cherenkov thresholds ~300 MeV for protons were chosen to investigate – fused silica, MgF_2, PbF_2, Perspex
- The two radiators are used to provide particle species discrimination between protons and electrons in the energy ranges expected in LEO

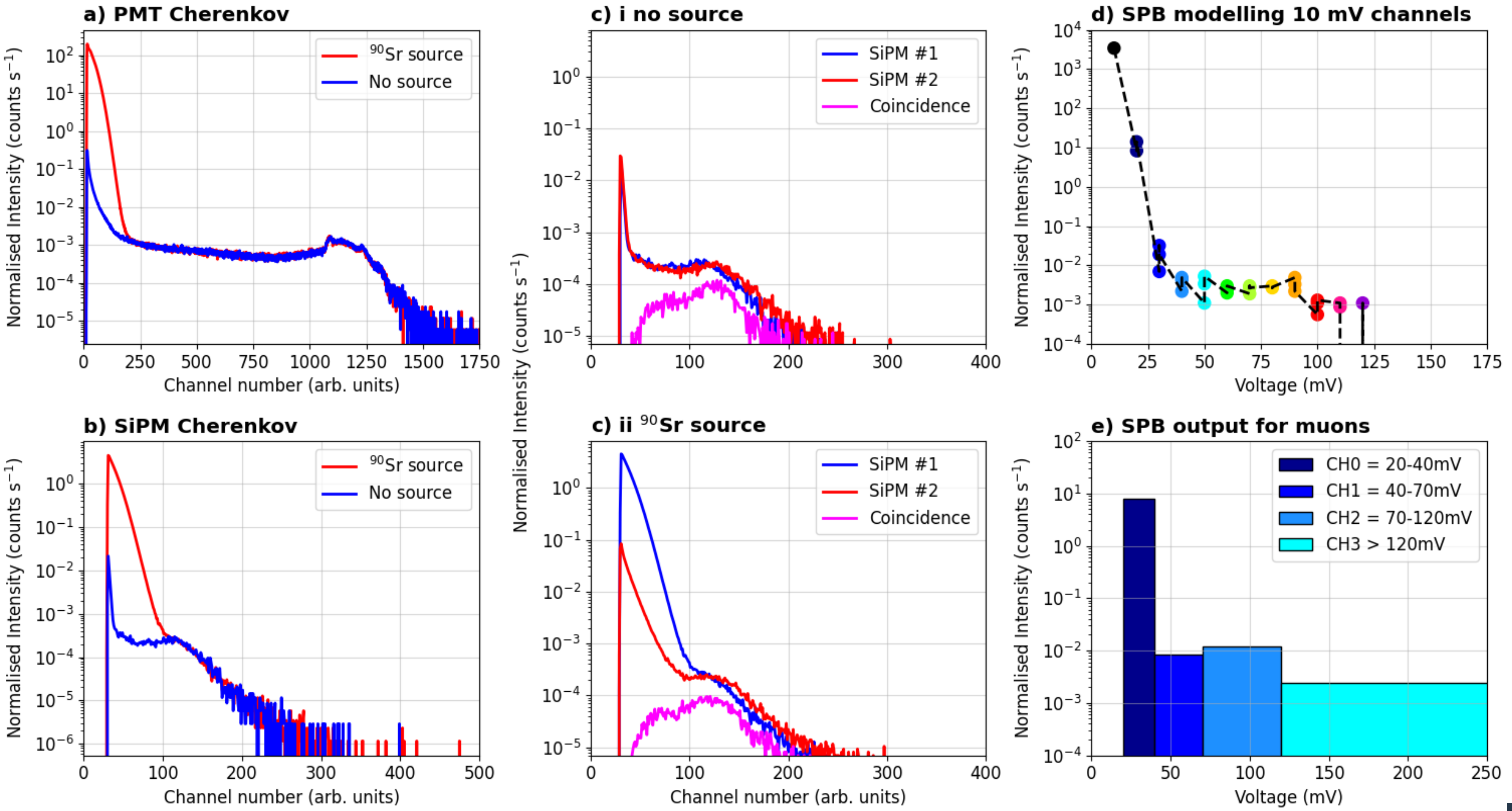






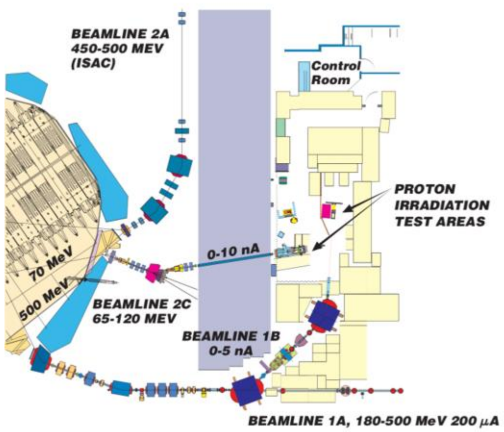
HEPI – Benchtop Measurements

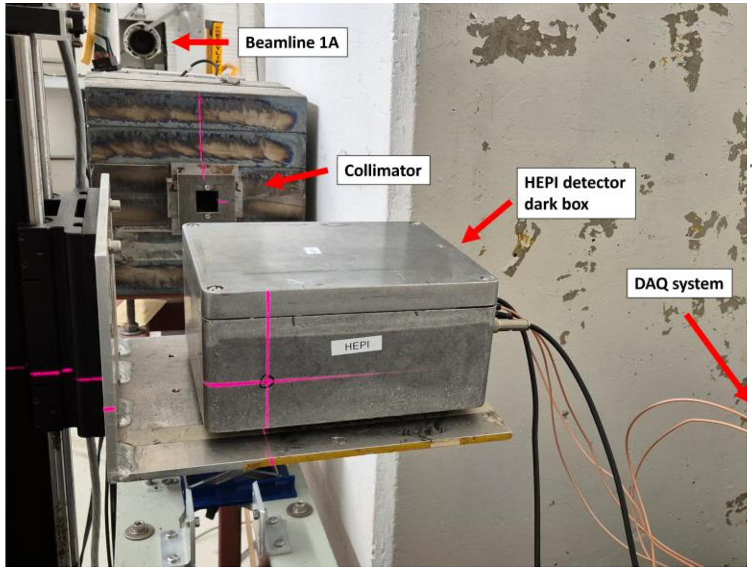
- Benchtop measurements using beta sources and muons to stand in for protons
- Muon coincidence can be seen to remove electrons and noise
- SPB output can be used , with gates set to distinguish between electron edge and the muon signals

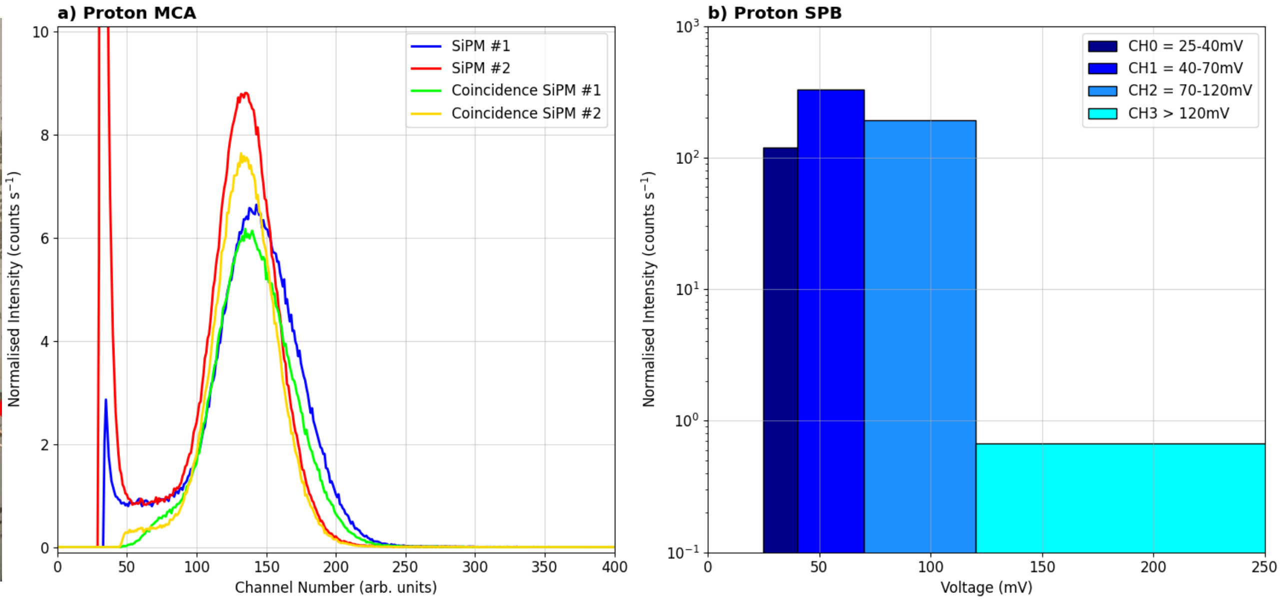


HEPI – Beam Measurements

- Beam test performed at TRIUMF in July 2024, with 355 and 480 MeV proton beams
- 44 configurations investigated over 3 shifts
- Main studies: proton response, SPB performance, energy response, flux response







(J., O'Neill, et al., 2025, JSWSC, in print)

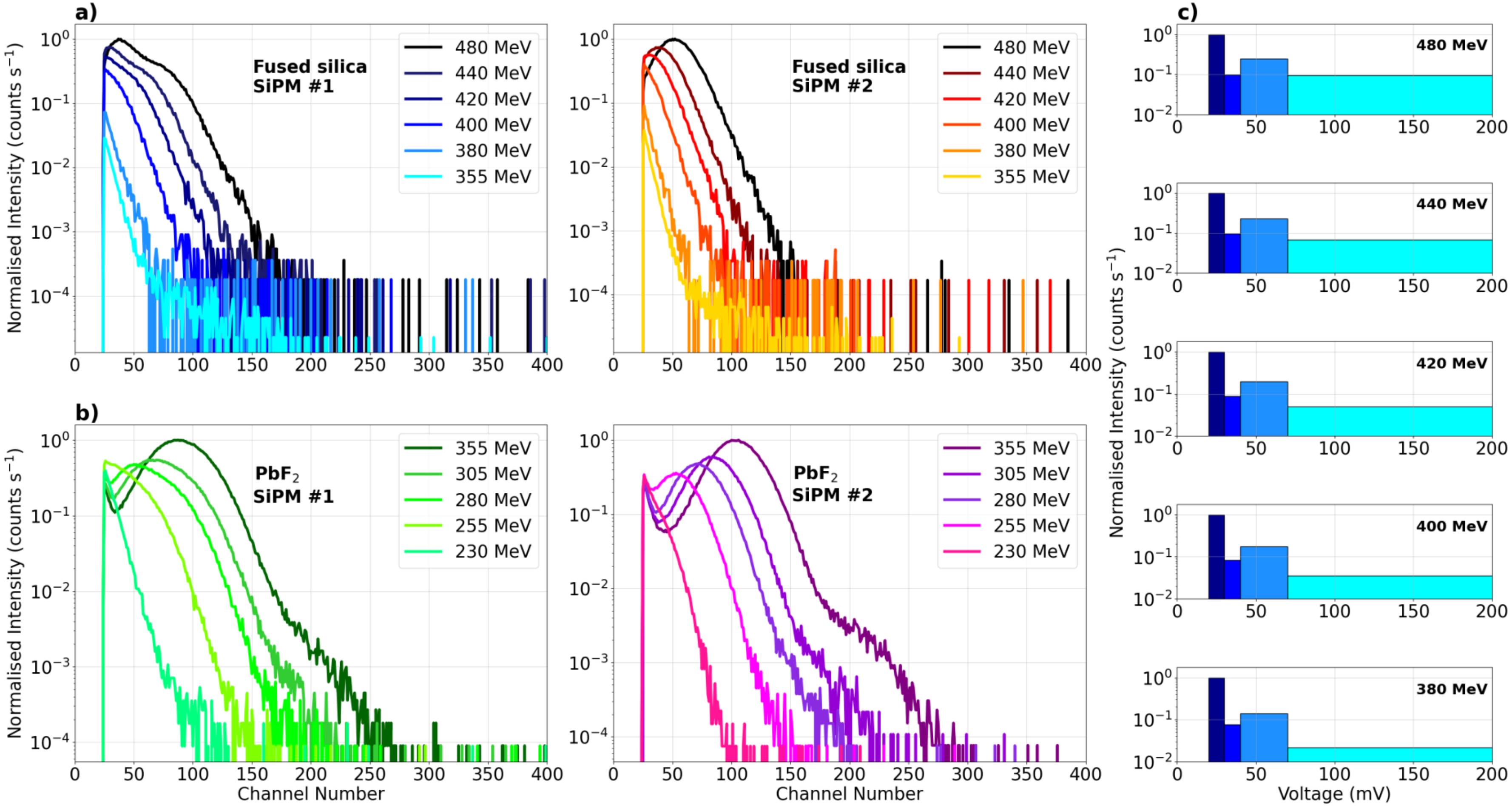
HEPI – Beam Measurements Energy Study

- Beam energy decreased using steel attenuators : 480-380 MeV and 355-230 MeV

- Measurements taken such that the energy approaches each radiator's Cherenkov threshold

- Can be seen that as the energy approaches the threshold, the light yield decreases

- This corresponds to protons losing energy as they pass through the radiator crossing the threshold

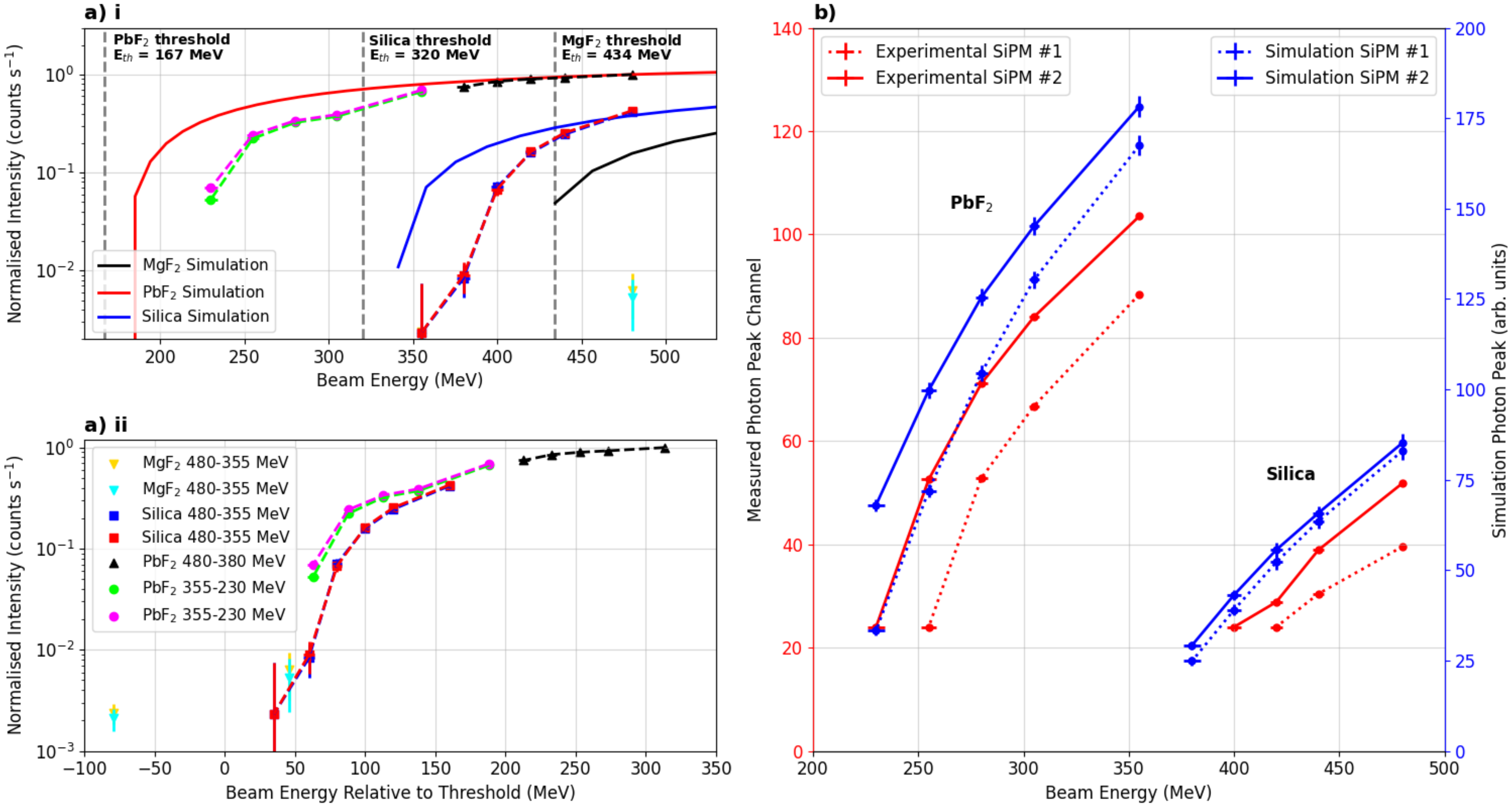


HEPI – Beam Measurements Energy Study

- Comparing energies relative to each threshold, the response as the materials reach the thresholds can be determined

- The detector system has a blind spot within ~50 MeV of the as predicted threshold

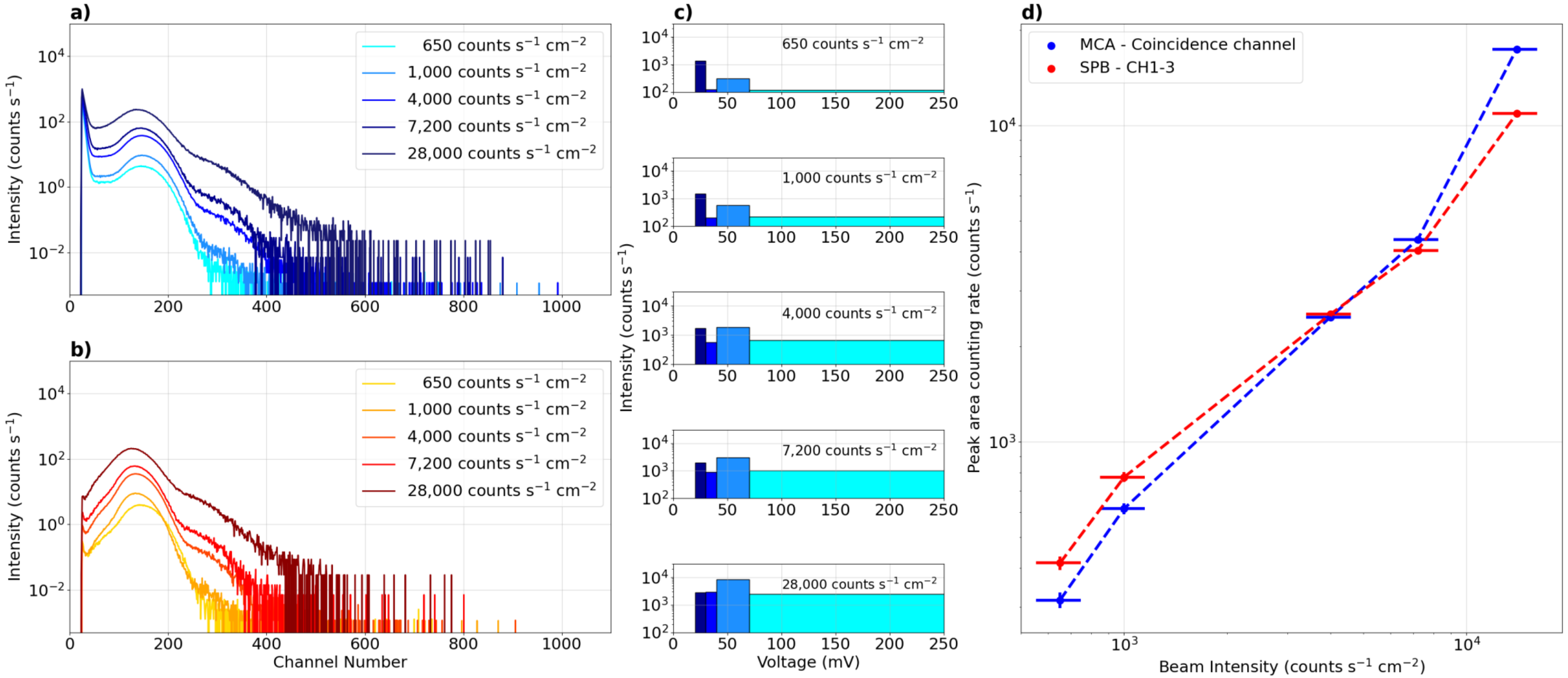
- The impact of the direction of the emitted Cherenkov photons relative to the SiPM can be seen



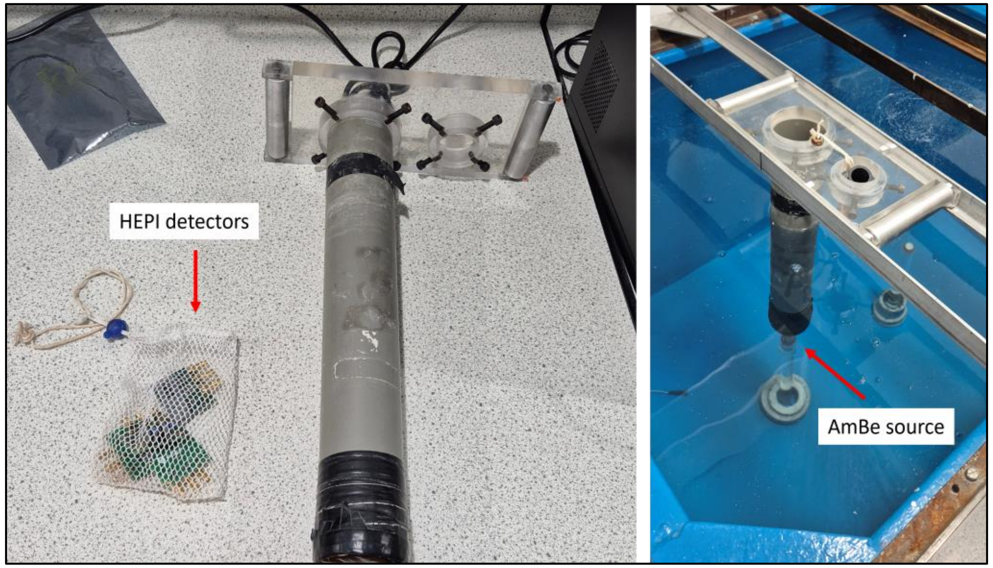
(J. O’Neill, et al., 2025, NIM-A , in print)

HEPI – Beam Measurements Flux Study

- Measurements taken at 480 MeV with varying beam flux 10^2-10^5 counts s^{-1} cm^{-2}
- Noticeable displacement damage in the SiPM observed in the dark currents of the detectors at higher fluxes
- Systematic offset in the reported beam flux



HEPI – Next Steps

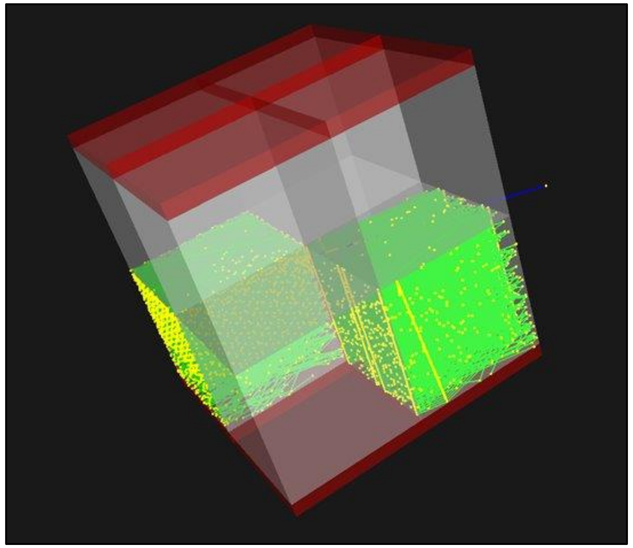


Ongoing studies

- Radiation damage study – electrons, neutrons, protons
- Simulation package in Geant4

Advanced SPaceweather Instruments for Radiation Environments (ASPIRE)

- New ESA project, started 1/5/2025
- WPs on HEPI – update readout optics & electronics



Future work

- Development of an Engineering Model (EM)
- Characterisation with beam tests
- Analysis software
- Expanding geometry – Cherenkov telescope!
- Radiators with different energy thresholds
- Preparations for CubeSat integration for launch next year, looking towards ISS and lunar missions!
- As a candidate instrument for SWORD!

HEPI – High Energy Proton Instrument

HEPI is a very compact proton telescope utilising the Cherenkov radiation process as the detection mechanism. Its base detector unit is a 1cc Cherenkov radiator coupled to a SiPM, readout in 4 channels. Its simplest configuration consists of 2 base units operated independently and in coincidence, providing the omni-directional as well as directional, ~ π sr FoV, measurements. The channel thresholds are programable and can be adjusted according to the type of radiator used and the mission requirements.

The design is expandable to allow more complex configurations, e.g., a 2x2x2 array will provide flux measurements in 13 different directions. It is also possible to use multiple radiators for better energy sampling.

Trapped electron contamination is minimised using shielding and signal discrimination techniques. Heavy ions can be also be identified by signal discrimination if required.

HEPI is currently at TRL4/5, after a very successful test campaign at TRIUMF with 10 proton energies between 200 and 480 MeV. We are on a fast track to develop the engineering modules and pursuing multiple in-orbit demonstration opportunities.

General properties:		
	Mass:	< 1kg
	Size:	< 10x10x10 cm
	Power:	0.5 - 1W
	I/O interface:	CAN or UART
	Supply voltage:	>= 5V
	Rad Hardness:	COTS
	Operating temperature:	-20 - 40C ?
Telescope parameters		
	Radiator:	1cc radiator
	SiPM:	6x6 mm2
	Effective thresholds:	~200 MeV (PbF2)
		~250 MeV (Sapphire)
		~370 MeV (Fused Silica)
		~480 MeV (MgF2)
	Energy resolution:	in 4 adjustable channels
	Effective area:	1.4 cm2 (per radiator)
		0.5 cm2 (coincident mode)
	Field of View:	4π sr (independent mode)
		~π sr (conicdence mode)
	Time resoltion:	configurable 10s - 10mins
	Sensitivity:	0.1 – 10^5 particles/s/cm2

HEPI – Missions!

Scheduled

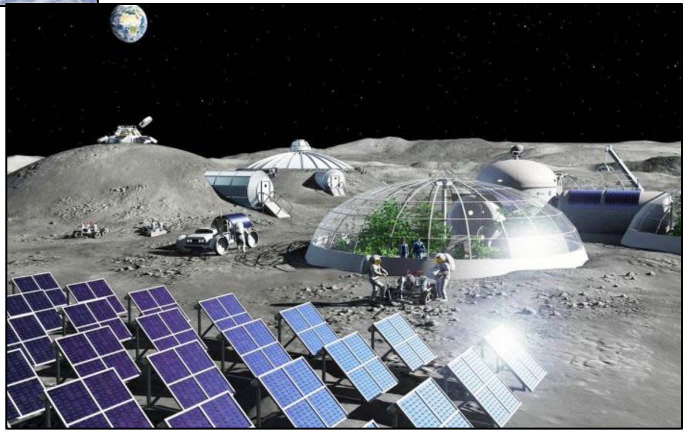
From BBC website

Potential/Aspirational

From NASA website

From NASA website

From ESA missions update



From NASA website

Acknowledgements

My thanks to my colleagues on this work:

Surrey: Joseph O'Neill, Fraser Baird, Ben Clewer, Clive Dyer, Paul Morris, Keith Ryden, Paul Sellin

ESA: Melanie Heil, Piers Jiggens, Giovanni Santin

Joseph O’Neill prepared most of the slides of this talk!

ANY QUESTIONS?

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