

The high-energy proton instrument (HEPI), a compact Cherenkov radiation space weather monitor

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Abstract—The monitoring of near-Earth space radiation has been a key component of space agencies' strategies since their inception. The changes in these radiation fluxes, part of the broader space weather environment, originate from various sources, including high-energy protons emitted in solar particle events. These protons, with energies higher than 300 MeV, are a source of damage to satellites, space station infrastructure and personnel, and also have effects that are observed in aircraft and at ground level. Increasing the number of instruments monitoring the flux of these high-energy protons is vital for the next generation of space-based infrastructure. We present the development and characterisation of a compact Cherenkov radiation detector system for use on CubeSat missions: the high-energy proton instrument, HEPI. This detector displays particle species discrimination and has an inherent energy threshold via the Cherenkov radiation emission mechanism, enabling the system to monitor baseline levels of these high-energy protons and detect surges in the flux. The design of the detector as an instrument to be implemented in a multitude of small-volume satellite missions is presented, alongside the response of HEPI to electrons, galactic cosmic ray muons and protons produced at a beam facility.

Keywords: Cherenkov radiation / High-energy protons / Satellite instrumentation / Silicon photomultiplier

1 Introduction

Since the first satellite was launched in 1957, the near-Earth space environment has become increasingly more populated with platforms with the latest estimates reporting that over 15,000 satellites have been launched as of August 2023 (Gaston et al., 2023). As this number continues to grow, so too does the human presence in space with the advent of space tourism and the return to the moon by NASA's Artemis and other programs. Monitoring the exposure of personnel and equipment to the radiation environment is vital (Zheng et al., 2019). Of particular interest is the monitoring of space weather: the changes to the environmental conditions in near-Earth space. This includes the various proton and electron radiation belts around the planet; external sources such as the galactic cosmic ray (GCR) flux, solar emissions and emissions from the Jovian magnetosphere (Gopalswamy, 2022).

The effects of space weather on space, air, and ground infrastructure are being recognised internationally as a vital component of national risk registers (Pulkkinen, 2007; Fry,

2012). Of particular interest to governments and businesses are ground-level enhancements (GLEs), arising from high-energy proton emissions from the Sun (Shea & Smart, 2012) resulting in ground-level neutron flux increases. High-energy (>300 MeV) protons are emitted from the Sun in solar particle events (SPEs) such as solar flares or coronal mass ejections (Gopalswamy, 2022). These GLEs are currently monitored by a ground-based neutron monitor network, measuring the neutron products of the high-energy protons in the upper atmosphere. Future monitoring and early response systems will require an increase in information, including the aviation industry – a large event such as GLE05 in 1956 provided a dose of ~20 mSv at 40k feet, 100% of the annual dose allowance for aviation workers. As such, the High-Energy Proton Instrument (HEPI) is proposed – a compact, Cherenkov proton detector for CubeSat missions that can monitor the space weather environment, and provide data in the event of a SPE.

Since the 1960s missions have monitored the space weather environment using Cherenkov instruments, typically consisting of a radiator material (e.g. Perspex, fused silica etc.) coupled to photomultiplier tubes (PMTs) to detect the emitted photons. The first mission to perform these measurements was Ariel 1,

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launched in 1962. Ariel-1 used a 10-cm diameter hollow Perspex sphere to measure heavy GCRs, with the Cherenkov light detected in a PMT, investigating the latitude-dependence of the GCR flux (Durney et al., 1962, 1964). The Highly Eccentric Orbit Satellite (HEOS-1) mission was launched in 1968 to measure proton and GCR fluxes in an eccentric orbit (Dyer et al., 1974). HEOS-1 used two Perspex disk Cherenkov radiators as the detector mediums, in conjunction with plastic scintillators, coupled to PMTs. The 1977 mission ISEE-3 used a complex veto detector system to measure the high-energy electron flux at the L1 Lagrange point. The veto system used silicon detectors, CsI and plastic scintillators in combination with plastic and quartz Cherenkov radiators (Moses, 1987). PbF₂ Cherenkov radiation detectors coupled to PMTs were employed on the 1990 Ulysses mission for the Kiel Electron Telescope (KET). This system used Cherenkov radiators in coincidence with direct detectors, and anticoincidence with scintillators, to measure the abundance of H and He in the GCR spectrum, and electrons up to 500 MeV (Simpson et al., 1992; Heber et al., 2005). More recently, the Van Allen Probes launched in 2012 utilised Cherenkov radiation detectors as part of the Relativistic Proton Spectrometer (RPS) to provide coincidence channels for protons above 420 MeV. These detectors were comprised of MgF₂ radiators coupled to PMTs, which combined with coincidence was able to provide some information on the directionality of the proton spectra (Mazur et al., 2014a,b, 2023).

More recent missions, such as EIRSat launched in 2024, incorporate silicon photomultipliers (SiPMs) to detect the light produced in their detector mediums. For the EIRSat mission, the on board Gamma-ray Module (GMOD) includes a CeBr₃ scintillator coupled to a SiPM for detecting gamma-ray bursts (Murphy et al., 2022). SiPMs are an excellent substitute for PMTs in the process of developing a compact Cherenkov radiation detector, offering a significant reduction in a system's total size and mass (Korpar et al., 2008). SiPMs have been developed to optimise their active capture area to total volume ratio, to operate in strong magnetic fields, a key requirement for space missions, and to require low-voltage power draws that are suited to a small-scale CubeSat mission (Bencardino et al., 2005): typical voltages required for SiPM operation are 45 V, compared to 0.7 kV for PMTs. The advent of CubeSats as a viable, low-cost option for satellite missions has further encouraged the move to compact detector systems, constrained to volumes of 10 × 10 × 10 cm per unit (U). Cherenkov radiation detectors using small-volume radiators and SiPMs are an excellent option for integration into existing CubeSat missions (Zheng et al., 2022). These factors mean that a constellation of high-energy proton detectors is a feasible goal, providing vital space weather monitoring capability without the downsides of the cost of historical missions.

This paper provides a comprehensive overview of the development of the HEPI, a miniaturised Cherenkov radiation detector. HEPI is designed to be incorporated into multiple applications, including CubeSats missions, as a monitor for >300 MeV solar protons in the near-Earth space weather environment. We present the initial designs of HEPI, with the energy threshold determined by the Cherenkov radiation emission mechanism. The implementation of a coincidence-based particle species discrimination method is discussed, and the responses of HEPI to secondary GCR muons and a benchtop electron source are compared. Finally, the results from a high-

energy proton beam test performed at TRIUMF are presented, showcasing the capability of the compact detector system to function as a CubeSat-capable proton detector.

2 Cherenkov radiation detector design

HEPI has been designed to fulfil three key requirements: to detect protons above 300 MeV; to distinguish between these signals and that of the electron background; and to be suitable for CubeSat missions. For CubeSat integration, devices must meet strict mass and size restrictions. As discussed, CubeSats are made up of modules with dimensions 10 × 10 × 10 cm, and capitalise on the miniaturisation of much of modern technology. Masses are required to be in the order of 2–4 kg, with the cost of a mission increasing with total weight. The total power draw of a system is also vital to monitor, as the cost and weight of batteries and solar panels can impact a mission's viability.

The HEPI detectors utilise the Cherenkov radiation effect on pairs of radiators to detect charged particles. These radiators can have differing refractive indices, allowing detectors with different configurations to distinguish between a range of incoming particle energies, depending on the Cherenkov emission principle. First reported in 1932, Cherenkov radiation is a phenomenon that occurs when a charged particle travels through a dielectric medium at a velocity that is greater than the speed of light in that material (Bolotovskii, 2009). The particle induces an asymmetric polarisation disturbance in the medium, leading to the emission of coherent electromagnetic waves. The constructive interference of these waves, following the Huygens principle, produces Cherenkov radiation emitted in a characteristic cone along the particle's trajectory. This phenomenon is commonly observed in nuclear reactor pools and has been used to detect charged particles in many situations such as water-based Cherenkov radiation detectors used in the Kamioka NDE experiment to measure neutrinos (Hirata et al., 1989; Wurm, 2017); He-N₂, N₂O and He gas counters for kaons and proton detection at Fermilab for high-energy physics experiments (Frabetti et al., 1992) and atmospheric Cherenkov radiation telescopes at the High Energy Stereoscopic System in Namibia to measure cosmic rays (Aharonian et al., 2007).

Following on from this principle, a charged particle traversing a dielectric medium will emit light if its velocity exceeds the phase velocity of light in the medium. This condition can be expressed in terms of the particle's speed, v , and the refractive index, n , of the medium as:

$$\beta n > 1, \quad \text{where } \beta = \frac{v}{c}. \quad (1)$$

At the threshold velocity for Cherenkov emission, $\beta_{\min}$, the equality $\beta_{\min} n = 1$ holds. The corresponding minimum kinetic energy, $E_{\min}$, depends only on the particle's rest mass, m_0 , and n , and is given by:

$$E_{\min} = m_0 c^2 (\gamma_{\min} - 1),$$

$$\text{where } \gamma_{\min} = \sqrt{\frac{1}{1 - \beta_{\min}^2}} \text{ and } \beta_{\min} = \frac{1}{n}, \quad (2)$$

where $\gamma_{\min}$ is the Lorentz factor evaluated at threshold.

Additionally, the angle θ at which Cherenkov radiation is emitted relative to the particle's trajectory is related to the particle's velocity and the refractive index by:

$$\cos(\theta) = \frac{1}{\beta n}. \quad (3)$$

This relationship defines the opening angle of the Cherenkov cone for a given medium. A demonstration of the relationships between the proton and electron Cherenkov minimum energy thresholds and a material's refractive index, n , is shown in Figure 1. Previous space missions have used PbF_2 (Simpson et al., 1992; Heber et al., 2005) to measure electron flux and Perspex (Durney et al., 1962) to measure GCRs. For HEPI, with a proposed cut-off of 300 MeV for protons, a material such as fused silica would be chosen ($n = 1.50$, $E_{\min} = 320$ MeV). Further to the kinetic energy threshold, the number of photons, dN produced per unit path length, dx , and per unit wavelength interval of the photons, $d\lambda$, of a particle with charge z can be expressed as the following function, an adaptation of the Frank-Tamm formula (Frank & Tamm, 1991):

$$\frac{d^2N}{dx d\lambda} = \frac{2\pi\alpha z^2}{\lambda^2} \left(1 - \frac{1}{\beta^2 n^2(\lambda)} \right) \quad (4)$$

where α is the fine-structure constant and λ is the wavelength of the emitted photons and the refractive index, $n(\lambda)$, varies with wavelength.

Table 1 shows information for a range of materials typically used as Cherenkov detector radiators, with their Cherenkov energy thresholds reported for the refractive index in the wavelength range 300–400 nm. For this work, MgF_2 , fused silica and PbF_2 were used as test radiators as their respective proton energy Cherenkov radiation thresholds (167, 320 and 434 MeV) cover a range of energies surrounding the desired cut-off at 300 MeV.

The detector uses fundamental physics interactions to provide particle species discrimination between electrons and protons of energies expected in the LEO environment. For electrons expected in LEO, mostly in 100s of keV (Ozeke et al., 2024), energy is lost during the passage through a $1 \times 1 \times 1$ cm radiator such that the electron's energy falls below the Cherenkov energy threshold (e.g. 175 keV for fused silica). While protons passing through the radiators will lose energy to ionisation effects, for particles with energy greater than the Cherenkov radiation threshold, the protons will pass through both radiators while emitting light. Figure 2 shows the typical paths taken by a 480 MeV proton, 4 GeV muon and 1 MeV electron through two $1 \times 1 \times 1$ cm fused silica radiators, produced in Geant4 (Agostinelli et al., 2003; Allison et al., 2006, 2016). This simulation shows that while the muon and proton pass through the two blocks with little to no interaction, the electron scatters almost immediately upon entering the radiator. As a result of these interactions, the electron will lose the majority of its energy and pass swiftly below the Cherenkov radiation threshold. In comparison, a 400 MeV proton travelling through 1 cm of fused silica will only lose 5–6 MeV of energy to ionisation. By coupling each radiator to a different SiPM, coincidence gates can be applied to the data to distinguish between the electron background in the LEO environment and protons from SPEs.

Each HEPI module consists of two radiators, coupled independently of each other to two Broadcom AFBR-S4N66P014M SiPMs. These SiPMs were chosen for their high photodetection efficiency at low wavelengths of 63% at 420 nm, with a 6×6 mm active area. Though the SiPMs share a power supply,

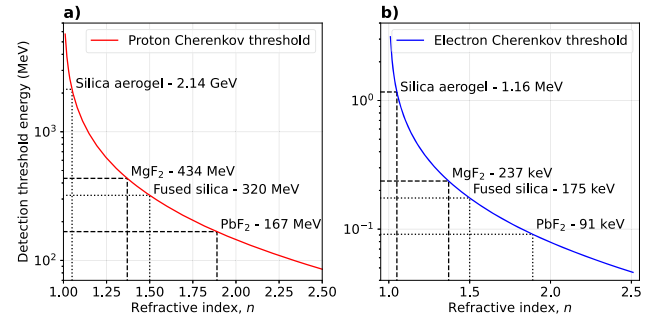


Figure 1. The minimum energy required for a) protons and b) electrons to produce Cherenkov photons as a function of refractive index, n .

Table 1. Comparison of optical properties of various Cherenkov radiators. The radiators used in the development of HEPI are highlighted in bold. Data collated from Cohen-Tanugi et al. (2003), Adachi et al. (2008), Tabata et al. (2012), El-Shemy et al. (2022), Yang et al. (2015), Connell et al. (2019), Amaré et al. (2014), Kratochwil et al. (2021).

Radiator	1 cc mass (g)	Refractive index @ 300–400 nm	Proton $E_{\min}$ (MeV)
Silica aerogel	0.5	1.05	2140
MgF_2	3.18	1.37	434
SiO_2	2.65	1.45	357
Perspex	1.18	1.50	320
Fused silica	2.2	1.50	320
Quartz	2.65	1.54	295
Sapphire	3.97	1.77	199
PbF_2	7.7	1.89	167
Diamond	3.52	2.42	92.1

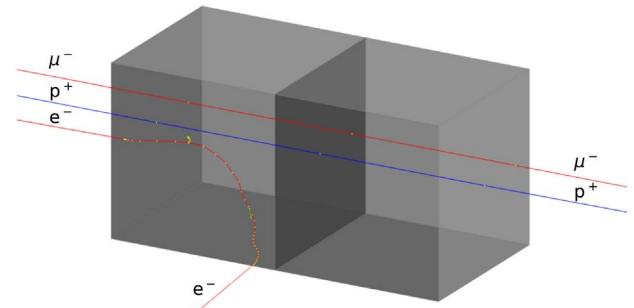


Figure 2. Typical paths for a 4 GeV muon, 480 MeV proton and 1 MeV electron passing through two $1 \times 1 \times 1$ cm fused silica cubes, produced in Geant4.

the readouts can be processed separately via a custom signal processing board (SPB). A circuit diagram of the SiPM interface and readout PCB is shown in Figure 3a. Photos of two configurations of the HEPI detector produced for this work are shown in Figure 3b, prior to radiator mounting.

To determine the number of photons expected per 355 MeV proton, a Geant4 simulation was performed in which the photon production, following equation 4, was calculated, and various impediments to light collection such as radiator transmission

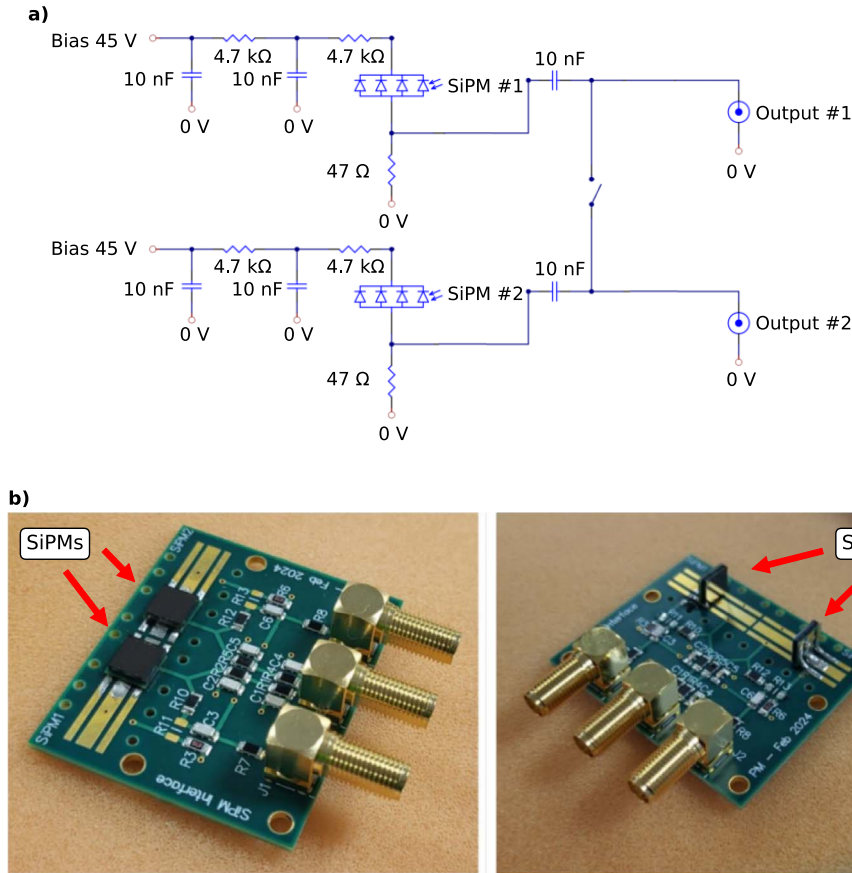


Figure 3. a) The circuit diagram for the SiPM power supply and readout PCB. b) Photographs of HEPI detectors, with different SiPM orientations, with the SiPM positions indicated by arrows.

and detector efficiency, were accounted for. It was determined for 1 cc of PbF_2 , 120 photons in the range 250–900 nm would be detected per 355 MeV proton. Steps were then taken to ensure a high light-collection efficiency from the radiator in the SiPMs. The radiator surfaces were polished and mounted onto the SiPMs with non-curing optical coupling gel, which also reduced vibrations between the radiator and the SiPM, a major source of noise in the system. The optical coupling gel used, SS-988 Non-Curing Optical Coupling Gel (Silicon Solutions), reports 99.45% light transmittance at 300 nm through 1 cm of material, ensuring little quenching of the UV emission of the Cherenkov radiation. Each radiator cube was wrapped in 0.5 mm of white PTFE tape to ensure high internal reflection and made light tight around the smaller SiPM face. Future designs will incorporate radiation shielding in preparation for the detector being implemented into satellite missions, including aluminium and tantalum casing to reduce the electron background and a divider between the two radiators to remove delta electrons produced by protons.

On the SPB, the pulses were amplified and shaped, then read out via two data acquisition (DAQ) systems: a nuclear instrumentation module (NIM) system into a multi-channel analyser (MCA); or further processed on the SPB via quad comparators into four channels that were stored in a microprocessor and readout via USB. The NIM system provides extra granularity to the Cherenkov radiation spectra, aiding in the initial

characterisation of the detectors. The SPB output has been designed as analogous to the systems that will be used as it is implemented into CubeSat missions. For the NIM system, timing gates for coincidence were made by passing the SiPM signals through a timing single-channel analyser to create logic gates which were processed in a coincidence module to gate on the MCA input. The SPB output can process coincidence via a simpler method – any event that triggers high channel signals in both SiPMs can be classed as a non-electron event. Given the reduction in number of channels from 2048 per SiPM in the MCA regime to 4 per SiPM with the SPB, the cost of the telemetry required to transmit the data is reduced.

In the development of the HEPI system, two testing regimes were devised: benchtop comparisons to larger Cherenkov radiation detectors and coincidence measurements; and a proton beam test performed to ascertain the device's response to protons of energy and flux comparable to that which would be observed in a SPE.

3 Laboratory tests and results

The first measurements performed were taken with a PMT and a large, $6 \times 6 \times 6$ cm quartz radiator, to determine a benchmark for the various particles inducing Cherenkov radiation signals. Figure 4a shows the PMT response to secondary

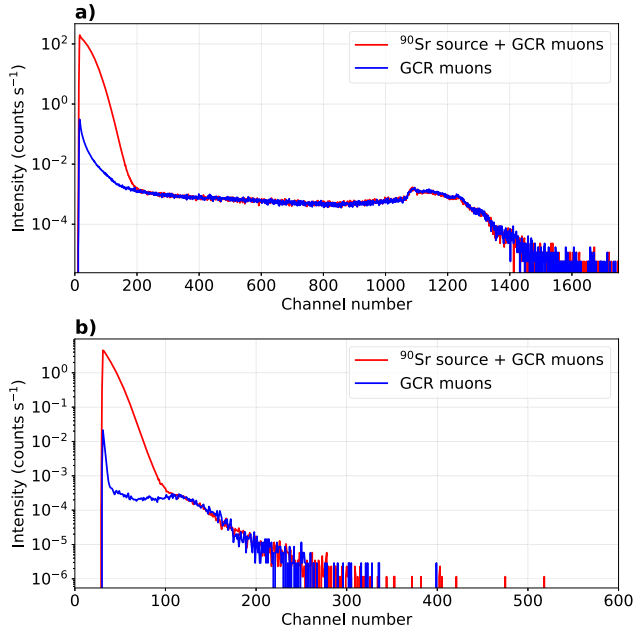


Figure 4. Time normalised Cherenkov radiation spectra taken with and without a ^{90}Sr -source, for a) a $6 \times 6 \times 6$ cm quartz radiator coupled to a PMT and b) a $1 \times 1 \times 1$ cm fused silica radiator coupled to a SiPM.

GCR muons and electrons from a ^{90}Sr -source (major emissions at 0.196 and 0.935 MeV), taken over 48 h. From this plot, there are two clear particle signatures. It can be seen that as the muons pass through the entire radiator, the spectrum seen from these particles is a broad continuum corresponding to photons being produced over long path lengths through the cube. The muons are neither monoenergetic nor unidirectional, which also broadens the measured spectrum.

Conversely, as electrons pass through the radiator they lose energy and pass below the electron Cherenkov radiation threshold – in this case, 161 keV for quartz ($n = 1.54$). This shows a clear example of how Cherenkov radiation detectors can perform particle discrimination, with a threshold set above the electron signal edge. As the detector design moves to a more compact setup, it was expected that with a smaller size radiator, this effect would be less pronounced as the relative photon yields of the two interactions would be closer in size, but can still be used. This was demonstrated with the HEPI detector.

The HEPI detector system was constructed as outlined in the previous section, with two radiators coupled to two optically isolated but adjacent SiPMs. Figure 4b shows the normalised response of a HEPI detector mounted with 1 cc fused silica radiators to GCR muons over 98 h and electrons from a ^{90}Sr -source, taken over 240 h. As with the PMT measurements, the x -axis channel number corresponds to the number of photons produced in a given Cherenkov radiation event, which can be described as a function of path length for particles above the threshold energies. Even with the smaller, $1 \times 1 \times 1$ cm cube of fused silica, the muon signal can be seen to be a broad continuum while the electron data is constrained to a low channel peak. However, the separation of the electron edge and the muon peak is less distinct, especially given the low fluxes

of muons ($0.01 \text{ particles s}^{-1} \text{ cm}^{-2}$), and so coincidence is required to remove the electron background.

The coincidence method was implemented to allow for particle species discrimination. By gating on events that are observed in both SiPMs, this system can be used to only record events that produce photons in both radiators. This is demonstrated in Figure 5. Data was taken of just the GCR muon background (Fig. 5b) and with a ^{90}Sr -source (Fig. 5c) with a fused silica HEPI detector, positioned with the two radiators in vertical alignment (SiPM #1 above SiPM #2). The signals from both SiPMs are shown, along with the coincidence signals. It can be seen that for both of the measurements, the only signals that are seen in the coincidence channel are the broad muon peak, as muons are able to pass through both radiators. No signal from the electrons is observed in the coincidence data.

The data from the SiPM closest to the ^{90}Sr -source, SiPM #1, has a greater number of counts in the low channel peak than the lower, SiPM #2. This is due to the majority of electrons above the Cherenkov radiation threshold passing through the top radiator and losing energy as they interact with the radiator medium, with only a small number of electrons emitted from the source window at an angle such that they reach the lower radiator. This demonstration shows that the system can be used to measure the electron background in the near-earth space environment, while still providing information about high-energy protons in an uncontaminated spectrum.

Further to the NIM/MCA system used to record the data for these benchtop measurements, a custom PCB was designed to be analogous to a CubeSat data handling system. As discussed previously, this SPB amplified and shaped the SiPM signals, and via a quad comparator binned the signals into four channels based on the signal voltage. The binning of the SPB was determined by obtaining a response function for the detector as a function of bin voltage. The GCR muon background was measured in 30-minute runs with each bin width set to 10 mV width, and the cumulative spectra recorded between 0 and 130 mV are shown in Figure 6a. The spectra can be seen to recreate the low channel noise peak and broad muon peak.

An example spectrum from the SPB taken with a HEPI detector mounted with fused silica radiators is shown in Figure 6b. The sharp peak at low channels is retained in CH0, to provide a baseline for any high channel peak. The muon peak is then distributed over three channels, with CH3 encapsulating all signals in the tail of the peak. This system can be used with two SiPMs to perform coincidence: signals that generate counts in channels above CH1 in both detectors simultaneously are flagged as protons.

4 Beam tests

A proton beam test was performed at the Proton Irradiation Facility (PIF) at TRIUMF, Canada, to demonstrate the detector's suitability for protons in the expected energy range of an SPE. The PIF BL1B beamline can provide proton beams at energies of 355 and 480 MeV, above the 300 MeV energy threshold that the HEPI detector is designed for.

The HEPI detectors gave a clear proton response. Figure 7b shows the time normalised Cherenkov radiation spectra taken with a HEPI detector mounted with PbF_2 radiators, impinged

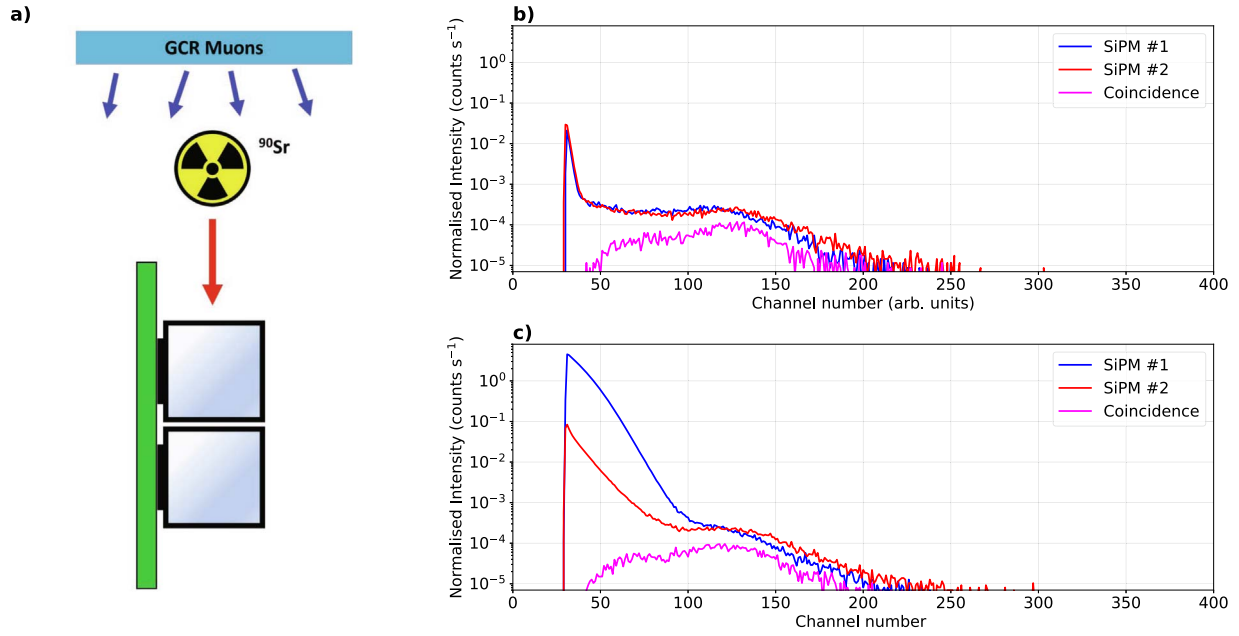


Figure 5. A demonstration of the HEPI coincidence capability. a) Schematic of the measurement setup. b) The time normalised Cherenkov response from both SiPM channels and their coincidence to background muons and c) background muons and a ^{90}Sr -source.

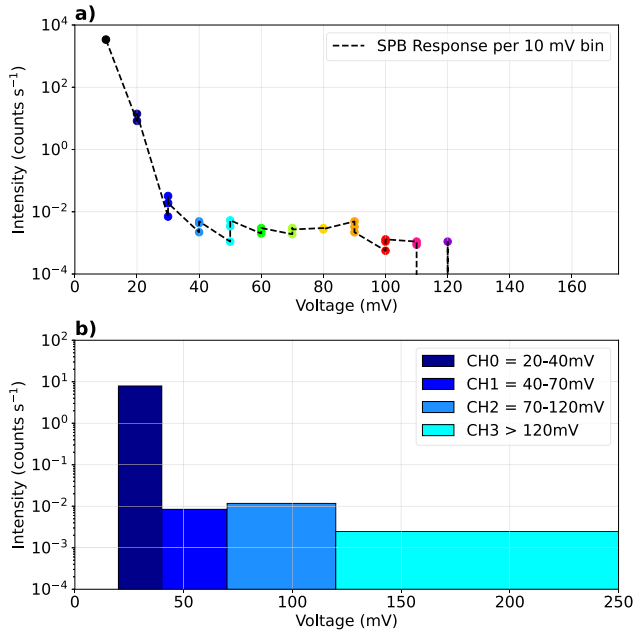


Figure 6. a) The response function of the SPB, determined from time normalised Cherenkov radiation fused silica measurements taken with the SPB bin voltages set to 10 mV wide channels. b) An example output of the SPB system, showing time-normalised Cherenkov radiation response for a fused silica radiator to background muons.

by a 480 MeV proton beam. Data was taken via an MCA for four channels: each SiPM's spectra and the coincident gated signals from those SiPMs. The protons can be seen to produce a peak, clearly separated from the noise edge, in the same channels that the muon spectra were previously observed.

The differences in peak position between the SiPMs are attributed to slight differences in the radiator optics and gain on the SiPM response and do not detrimentally impact the counting rate of coincident signals.

The same measurement was also performed with the spectra read out via the SPB discussed previously. The four channels established in the previous laboratory tests were used for the proton beam test, and are shown in Figure 7c. The channels above the noise edge can be seen to have far more counts than the muon measurement, matching the increased flux of Cherenkov radiation-inducing particles.

Figures 8a and 8b show the responses of HEPI detectors mounted with three different Cherenkov radiators (MgF_2 , fused silica and PbF_2), as impinged by the two beam energies available, 480 and 355 MeV. These spectra demonstrate Cherenkov radiation detectors' inherent ability to have a different response based on particle energy and refractive index. The radiator with the highest energy threshold, MgF_2 ($E_{\min} = 434$ MeV), did not measure a proton response at either energy. This shows that the practical energy threshold for a radiator is higher than that of the theoretical energy threshold, as the protons will lose energy during their passage through the radiator. The fused silica radiator ($E_{\min} = 320$ MeV) spectra in Figure 8a ii and Figure 8b ii, can be seen to produce a Cherenkov proton spectra for the 480 MeV beam measurement, but a greatly reduced signal for the 355 MeV. This can be compared to the laboratory data taken with GCR muons in Figures 5b and 5c, where the muons are far above the energy threshold and a peak can be seen. Comparisons between these two datasets must also account for the differences in incoming particle energy spread (monoenergetic for the beam test and broad for the GCR muons) and uniformity (unidirectional for the beam test leading to consistent path length through the radiator cubes and broader angular distribution for the GCR muons, leading to varying path lengths). Proton peaks are clearly seen in the PbF_2 ($E_{\min} = 167$ MeV)

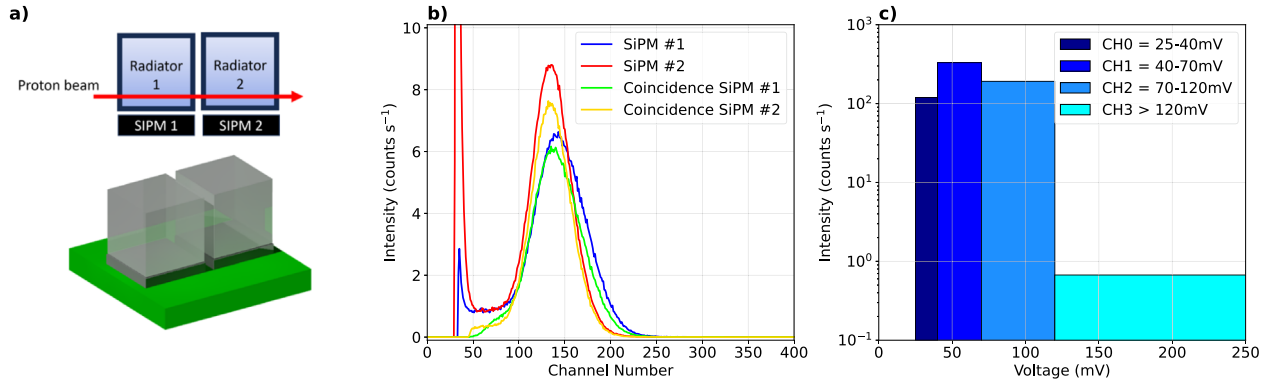


Figure 7. a) Schematic of beam test setup. b) Time-normalised Cherenkov radiation spectra taken with a 480 MeV proton beam at 10^3 particles $\text{s}^{-1} \text{cm}^{-2}$, as measured by a HEPI detector with PbF_2 radiators, with data recorded by an MCA in coincidence mode and c) the four channel SPB.

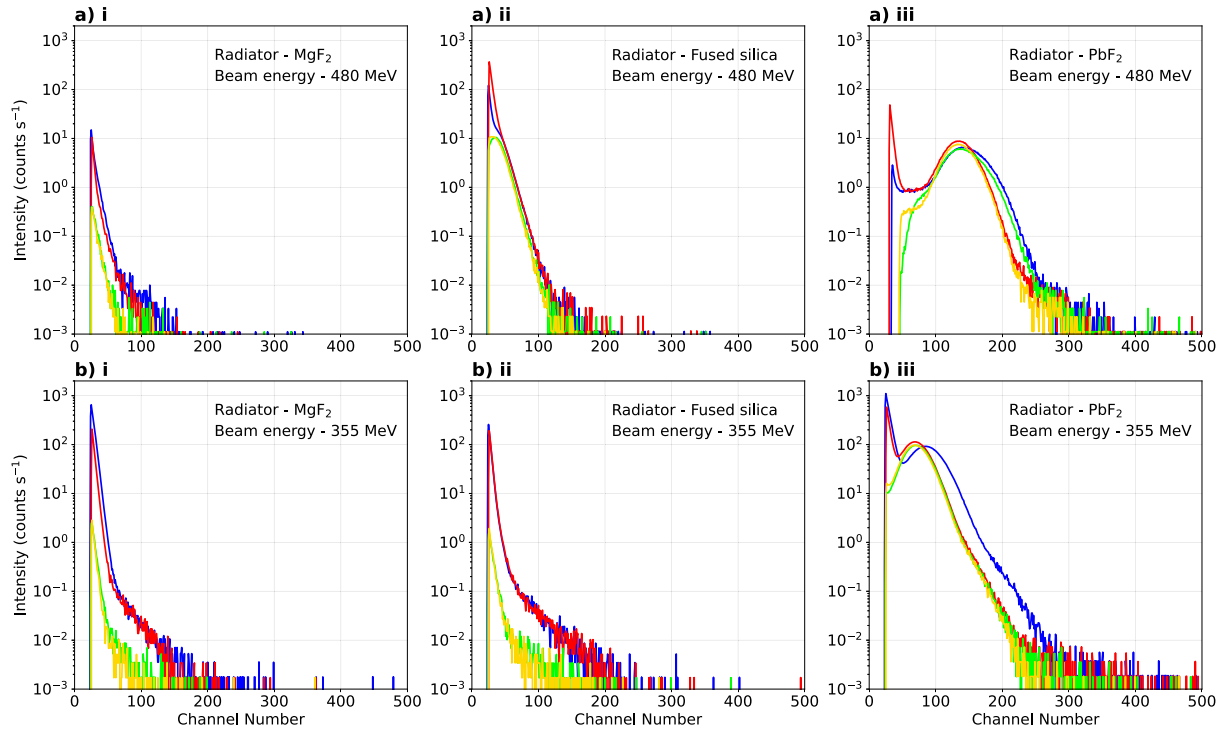


Figure 8. a) Time-normalised Cherenkov radiation spectra measured with a 480 MeV proton beam, taken with HEPI detectors mounted with a range of radiators: i: MgF_2 , ii: fused silica and iii: PbF_2 . b) The same HEPI configurations as a), impinged by a 355 MeV proton beam.

mounted HEPI spectra for both beam energies. The shift in the proton peak position to lower channel counts at the 355 MeV beam energy is consistent with the decrease in the number of photons generated per incident proton at energies approaching the threshold. During these measurements, we determined the threshold for the HEPI detectors as a function of proton energy as beams were attenuated incrementally to lower energies approaching each radiator's Cherenkov radiation thresholds. Further details on the response of HEPI detectors with different radiators are provided in a companion article, which is currently under review.

To investigate the performance of the HEPI detector in an environment similar to that of a LEO during an SPE, the proton beam flux was varied in the range 10^2 – 10^5 particles $\text{s}^{-1} \text{cm}^{-2}$, as measured by a plastic scintillator upstream of the HEPI instrument. The measurement was taken with a HEPI detector mounted with PbF_2 , with spectra recorded via both MCA and SPB channels. The MCA recorded spectra from the measurements are shown in Figures 9a and 9b, for an ungated SiPM and coincidence channel respectively. The proton peak can be seen to increase with the incoming proton flux, while the noise edge intensity remained consistent. The same

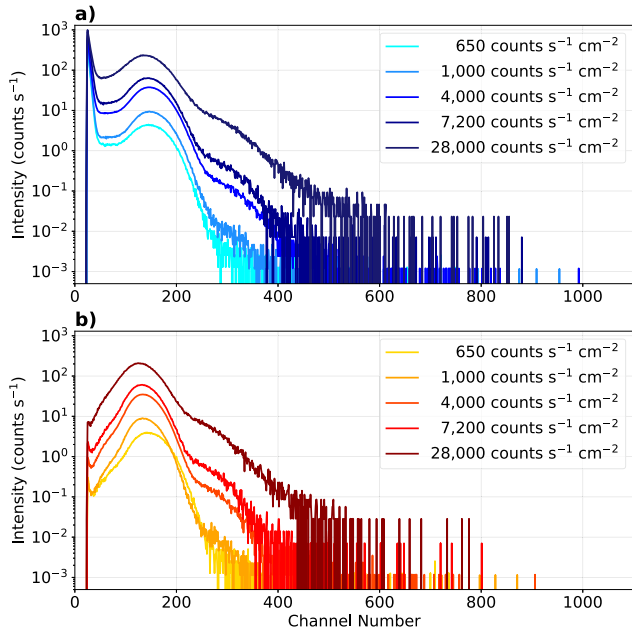


Figure 9. Time-normalised Cherenkov radiation spectra taken with a 480 MeV proton beam with flux in the range 10^2 – 10^5 particles $\text{s}^{-1} \text{cm}^{-2}$, for a) a SiPM channel and b) a coincidence gated SiPM channel.

measurement was recorded via the SPB, and the individual spectra from these are shown in Figure 10. In these plots, the channels above the noise edge can be observed to steadily increase in intensity as the beam flux increased, while the low voltage channel remained consistent at approximately 1000 counts s^{-1} .

Figure 11 shows a plot of proton beam intensity against the integrated area of the coincident channel of the MCA readout (shown in Fig. 9b) and the sum of channels 1–3 of the SPB (shown in Fig. 10). It can be seen from this plot that the peak area of detected protons increases with beam intensity. The flux varied by up to 15% as measured by the in-beam scintillator, but may have a larger variation than what was reported due to the difficulties experienced by the beam operators in supplying a beam of relatively low flux to the facility. That both the detectors, processed in different SPBs and read out via two methods follow the same general trend indicates that this is the cause of the as-measured detector response.

There is no evidence of pileup in the data – there is no systematic reduction in count rate at higher fluxes from multiple signals being processed as single events. If there were pileup at higher fluxes, it can be noted that this would not impact the ability of HEPI to discriminate between protons below and above the detection threshold. Cherenkov events that underwent pileup, and were placed in a higher channel, would not correspond to a higher particle energy as they would with a scintillator, but with a particle that had a longer path length through the material. Given this, an interesting characteristic of the spectra at higher fluxes is the presence of a shoulder at approximately channel 300 in the MCA data. This is also seen in SPB data, where the ratio of CH2 to CH3 increases with flux (2.57, 2.61, 2.78, 2.91, 3.40). Initial analysis indicates this could also be due to possible proton scattering paths with longer path

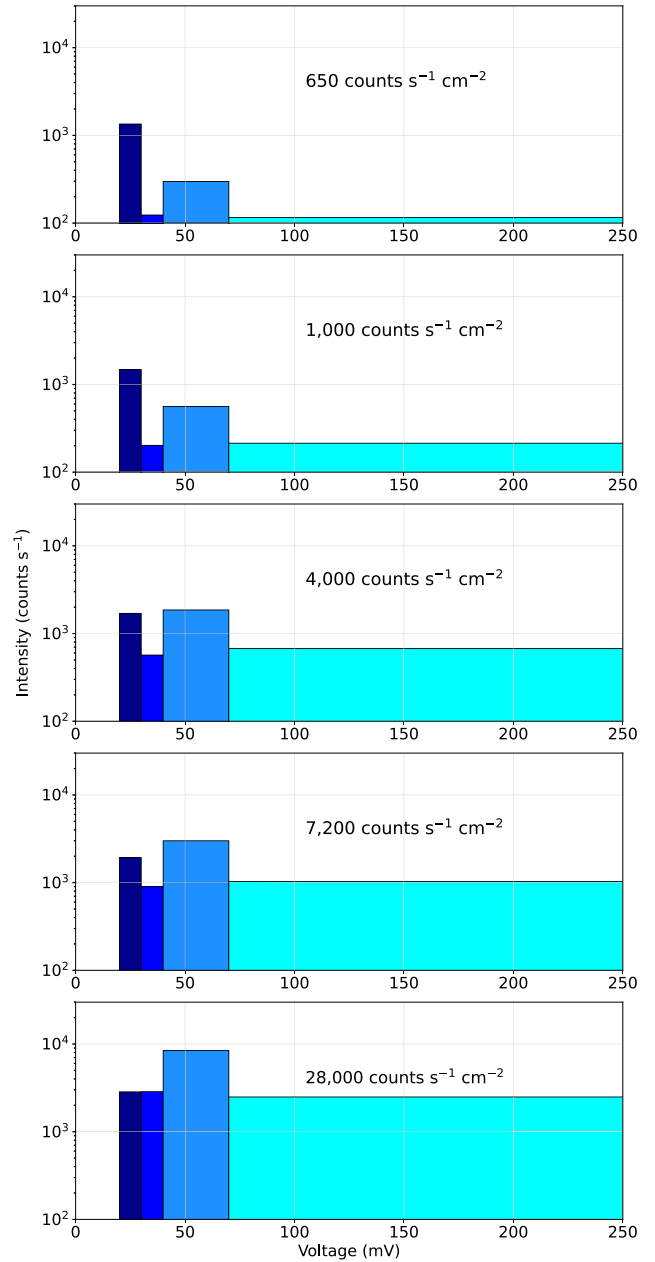


Figure 10. Time-normalised Cherenkov radiation spectra taken with a 480 MeV proton beam with flux in the range 10^2 – 10^5 particles $\text{s}^{-1} \text{cm}^{-2}$ recorded with the SPB.

lengths through the radiator becoming statistically significant at higher flux rates.

5 Conclusions

This paper discussed the steps taken to develop and implement a compact Cherenkov radiation detector for high-energy protons: HEPI. Given the requirements of a proton energy threshold of 300 MeV and particle species discrimination, the Cherenkov radiation emission mechanism provides inherent benefits to the detector system. As particles of different rest

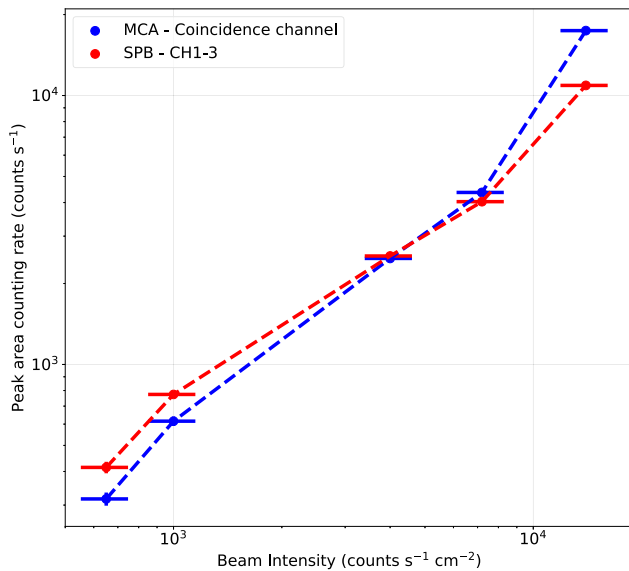


Figure 11. Plot of the integrated proton peak areas of the different HEPI detector readout methods as a function of beam intensity, in the range 10^2 – 10^5 particles $\text{s}^{-1} \text{cm}^{-2}$.

masses have inherent Cherenkov radiation thresholds, the energy cut-off can be tuned via the refractive index of the radiator used in the detector system, and implementation of a coincidence system allows the electron background to be separated from any proton signal due to the relative loss of energy. We demonstrate the ability of HEPI to distinguish between electrons and GCR muons in a laboratory scenario and to detect protons at fluxes similar to that seen during SPEs at a beam facility, and to operate at fluxes approaching the activity expected during SPEs.

The next steps in the development of the HEPI detector will prepare the system for satellite implementation. Optimisation of the signal-to-noise ratio of HEPI is underway, improving the SiPM efficiency, optimising the electronic noise and investigating any optical effects. The radiation hardness of the SiPMs used for light collection has been an area of study for recent work, with studies showing that dark current of SiPMs increases under radiation dose in orbit (Zheng et al., 2022). An investigation characterising the displacement damage to the system is underway and a paper is in preparation.

This initial design is planned to be augmented with the implementation of a larger array of radiators, forming a $2 \times 2 \times 2$ cube of these $1 \times 1 \times 1$ cm radiators. Such a configuration would have 13 different orientations of coincidence possibilities, providing a greater degree of directionality. This, combined with a range of radiator materials with varying proton energy thresholds would provide more insight into proton energy populations, and give insight into other properties of the local space weather including the pitch angle distribution. The light collection and readout electronics will also be optimised to minimise the noise level, although we are not pursuing single photon detection capability.

A detector that can monitor the electron background and give a clear signal during a period of high-energy proton flux is highly desirable. HEPI is an excellent device for CubeSat

implementation, as its low size and mass will allow it to be easily incorporated into many missions.

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Conflicts of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Data availability statement

The data files from the measurements taken to calibrate the detectors and from the beam tests that support the findings of this study are available from the corresponding author, JO, upon reasonable request.

Author contribution statement

JO, CD, FL, KR, and PS contributed to the conceptualisation of the study, in collaboration with MH, PJ, and GS. The detectors were designed and fabricated by JO, BC, and PM. Characterisation was performed by JO. The beam test was carried out by JO and FB. Analysis was performed by JO, with assistance from FL. Simulations for this work were performed by FL. All authors commented on the manuscript and aided in the reviewing process.

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