

SCINTILLATOR-BASED LOW ENERGY PARTICLE IMAGING SPECTROMETER FOR NANOSATELLITES

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Abstract

Physical Sciences Inc. (PSI), in cooperation with the Boston University Center for Space Physics, and under the sponsorship of the Air Force Research Laboratory Space Vehicle Directorate, has developed and tested a lightweight, multi-configuration sensor to monitor the space weather environment. The scintillator-based Low Energy Particle Imaging Spectrometer (LEPIS) is ideally suited to monitoring the lower energy (20 to 1000 keV) charged particle environment. The LEPIS design is also compatible with the weight, volume, and power requirements of nanosatellites (<0.5 kg, <0.5 W). The LEPIS design does not rely upon a magnetic sector to discriminate between particle types; rather it takes advantage of particle cross-section characteristics and scintillator properties to discriminate. We have already proven the feasibility of our approach; i.e., using thin films of materials to create particle-specific detectors, fiber-optically coupled to a position-sensitive photomultiplier tube. The result is a tremendous savings in sensor weight and volume.

Background

Space Weather

The need to monitor space weather is becoming essential because of the potential for satellite loss or service interruption during periods of high geomagnetic activity or severe radiation conditions. Space weather is the manifestation of the intimate connection between the earth and the sun. The space surrounding the earth is a highly dynamic environment that responds to changes in the sun. The sun is constantly bombarding the earth with high-energy particles and radiation. The dynamic interaction between this solar wind, the earth's magnetic field and the sun's magnetic field determines the space weather. Since the space environment responds dramatically and sensitively to changes in the electromagnetic fields, particles and magnetic fields arriving from the sun, it is important to have early warning of such events. This response occurs with time delays of hours to days,^{1,2} and is at the core of space weather.

Satellites in earth orbit interact continuously over many years with this highly dynamic space environment. Rapid changes in the space environment cause increased radiation damage, single event upsets, spacecraft charging and damage to materials. All of these effects degrade satellite performance. Most often satellite systems degrade gradually in time; however, there are striking examples of sudden, unpredicted spacecraft failures caused by correlated with geomagnetic activity.³

The LEPIS, as part of a constellation of space weather monitoring nanosatellites, would provide a crucial early warning of enhanced geomagnetic activity. A warning of days or even hours of an impending geomagnetic event would allow satellite operators to take action to minimize damage or service interruptions caused by the accompanying increased radiation. To protect against damage and service outages, spacecraft operators might

choose to shift transmission bandwidth to satellites in less disturbed regions of space. By taking simple mitigation steps, satellite operators and users can minimize the risk and cost of losing a satellite, suffering interruption in service, and extend the orbital life.

Early Warning Measurements

Because of broad ranging effects of space weather and society's increasing reliance on satellite systems, it is paramount to monitor the space environment that affects those systems. Two of the missions of primary importance for monitoring the space weather environment are measuring the ring current and the in-situ environment surrounding operational satellites. The ring current is one of the major components of the earth's magnetosphere. It encircles the earth along the equator at distances of 2 to 7 earth radii and comprises charged particles in the 10 to 200 keV energy range.⁴ Particles trapped in the earth's magnetic field exhibit three distinct motions: spiraling about field lines, bouncing between mirror points, and drifting longitudinally (electrons to the east, protons to the west). This longitudinal drifting creates the ring current. A sensor monitoring the ring current can provide several hours warning of an imminent geomagnetic disturbance thereby allowing satellite operators to react accordingly. To understand the ring current dynamics, one must measure the particle-energy distributions as well as the pitch angle distributions.

The ring current responds very quickly to geomagnetic activity by several mechanisms.⁵ During periods when the interplanetary magnetic field turns southward, particles are convectively transported from the nightside plasma sheet deep into the inner magnetosphere. Also during magnetospheric substorms, plasma is injected into the inner magnetosphere. This activity also energizes the ring current. The growth of the ring current occurs over several hours, but its decay can take several days. For example, during a particularly strong storm that occurred in February 1986, the ring current required more than 1 month to recover to its quiescent state.^{6,7}

The Role of Nanosatellites

While scientific understanding of geospace has matured, and technologies have advanced, constellations of microsatellites represent the next step forward in developing a global understanding of, and early warning system for, the space weather threat environment.⁸

Nanosat missions require the data from many (35 to 100) low-mass (10 to 20 kg), low-volume (0.007 m³), low-power (5 to 10 W), and well-instrumented (magnetic, plasma and energetic particle instruments) spacecraft. The LEPIS sensor is compatible with physical and performance requirements of a baseline nanosat energetic particle instrument.⁹ While LEPIS is designed primarily as an engineering threat sensor, it has sufficient capability to significantly contribute to the understanding of the global space weather environment. We are using the DRACO nanosatellite as our baseline design benchmark for a host satellite.

Sensor Configuration

We have designed, fabricated, and tested a breadboard model of a highly compact, lightweight, multi-configuration sensor to monitor the orbital charged particle environment. Our scintillator-based sensor is ideally suited to monitoring the lower energy (20 to 1000 keV) charged particle environment that contributes to the space weather and charging threat. Unlike many sensors designed for this energy region, the Low Energy Particle Imaging Spectrometer (LEPIS) does not rely upon a magnetic sector to discriminate between particle types (protons versus electrons versus ions).¹⁰⁻¹² Rather, the LEPIS sensor design takes advantage of the cross-section characteristics of different particles, and the properties of scintillators to discriminate particle types. To date, we proved that by using thin films of metals and plastic scintillators, we could create particle-specific detectors that serve as the core of a small charged-particle spectrometer. Figure 1 shows a schematic view of the basic sensor concept. The particle-specific detectors are fiber-optically coupled to a high-gain, low-noise position-sensitive photomultiplier tube. By eliminating the magnetic sector and creating a more innovative design, we can produce a sensor that is extremely small and lightweight, and suitable for nanosatellite applications.

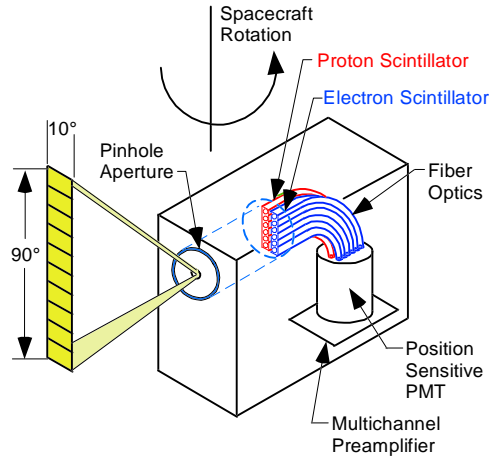


Figure 1. The Low Energy Particle Imaging Spectrometer sensor is configured as a pinhole camera-type, one-dimensional imager. Spacecraft rotation provides the second imaging axis. Particles enter the collimator aperture and are incident on particle-specific scintillator focal planes. The scintillator photons are fiber-optically coupled to a multianode photomultiplier tube.

The LEPIS sensor offers several advantages:

- Simple spectrometer design that eliminates magnetic and electric sectors
- Lightweight (<0.5 kg), low power (<0.5 W), small volume (150 x 150 x 83 mm³) sensor compatible with nanosatellite requirements
- Simple design built on inexpensive, readily available components resulting in a low cost sensor
- Sensor that meets the engineering requirements of a space weather threat sensor, with sufficient energy resolution to provide valuable data to improve the understanding of solar-terrestrial interactions
- Flexible design that is easily adaptable to different energy regimes and missions
- Small cross-contamination between protons and electrons.

A compelling aspect of the LEPIS concept is its flexibility. Although during this development phase we optimized the sensor to detect low energy charged particles (20 to 1000 keV), the design is completely adaptable to different energy regimes - and different missions. For example by simply changing the scintillator thickness and materials, the LEPIS can be configured to monitor the higher energy trapped radiation and solar proton environments. We envision the LEPIS as a basic nanosatellite core sensor that can easily be configured to monitor the space weather environment in a variety of orbits and environments – from LEO to GEO, from the van Allen belts to the magnetotail. For the ring current monitoring mission, we are using the following set of parameters as our baseline performance specification.

Parameter	Baseline Value - ring current monitoring
Particles	Protons electrons
Energy range	20-1000 KeV
Energy resolution	dE/E=0.2 to 0.3
G-factor	$1 \times 10^{-4} \text{ cm}^2 \text{ sr}$
Count rate	$< 2 \times 10^5 \text{ cps}$

The LEPIS is a pinhole camera-type, one-dimensional imager. The spacecraft rotation provides the second imaging dimension. Particles enter the collimator aperture and are incident on the scintillator focal plane. The focal plane comprises two or more distinct scintillators. We have demonstrated that by judiciously choosing the scintillator thickness and metallic coating, we can design scintillators that are sensitive only to electrons and only to protons (over an energy range of interest). By analogy, we could also design scintillators that are responsive only to

heavy ions. This simple sensor design does not rely on a magnetic sector, and consequently has the advantages of small size and mass. The design takes advantage of the cross-section characteristics of different particles and the properties of scintillators to discriminate particle types.

We design the scintillators to specifically detect a particular type of particle (proton, electron, or heavy ion). We achieve this specificity by carefully selecting the scintillator material, its thickness, and its coating. We have demonstrated this concept by using thin sheets of plastic scintillator as the base material. Plastic scintillators consist of a solid solution of organic scintillating compounds in a plastic matrix.

For protons, the detector concept is a very thin absorber to stop visible photons followed by a thin scintillator to stop protons up to some energy but too thin for electrons to deposit a detectable energy. Initial simulations suggested a proton sensor comprising a submicron Al dead layer (absorber) followed by a scintillator several microns thick.

For electrons, the detector concept uses a relatively thin absorber to stop protons up to some energy followed by a much thicker scintillator to stop electrons of the same energy. Our initial simulations suggested an electron sensor comprising a several micron thick polymer dead layer (absorber) followed by a several millimeter thick scintillator.

Figure 2 shows a photograph of the actual Phase I breadboard focal planes. The left-hand scintillator is the electron-specific detector. The right-hand scintillator is the proton-specific detector. For flight, both scintillators will be coated with a submicron thick Al layer to reject visible photons and enhance collection efficiency.

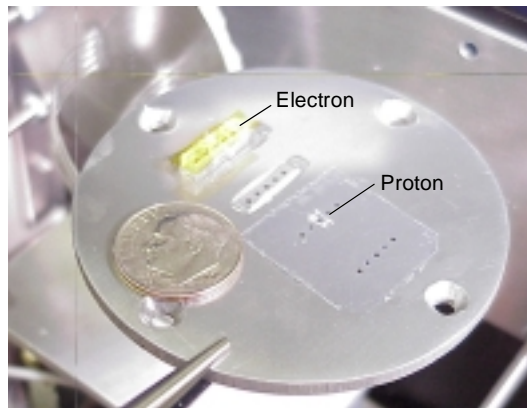


Figure 2. The Phase I LEPIS scintillator focal planes.

The scintillator photons are coupled to a position sensitive photomultiplier tube via optical fibers. The fibers direct the photons away from the focal plane and allow us to place the PMT out of the direct line-of-sight of interfering particles and photons. High-energy protons and X-rays impinging directly on the PMT could produce spurious signals. In Phase I we achieved good results using commercially available, 0.75 mm diameter clear waveguide fibers.

The PMT provides essentially noise-free gain of 10^3 to 10^6 with modest bias voltages (<900 V). The Hamamatsu H7260 represents a new generation of compact (24 mm x 52 mm x 33 mm), metal dynode, multianode (32 channel) PMTs. Each anode corresponds to a single particle type-angle position on the focal plane.

Modeling

We developed models to design the sensor and predict its performance. The model is based on the CERN GEometry ANalysis Tool (GEANT) Monte Carlo particle propagation code. The GEANT-based model incorporates all the geometry and material properties of the sensor. It tracks the trajectory of each particle and the energy deposited as the particle penetrates the detectors.

Using the GEANT simulation tool, we created a preliminary model of the LEPIS sensor to determine its applicability as an in-situ, charged-particle monitor. The model is based on known material properties, known geometries and measured quantities (such as gain and noise). There are no other free parameters. Once validated with calibration data, the model can be used with confidence to predict, extrapolate and interpolate the sensor performance for any relevant orbital or calibration environments. We have used this model approach effectively on prior sensor development programs.

For protons, the detector concept is a very thin absorber to stop light followed by a thin scintillator to stop protons up to some energy but too thin for electrons to deposit a detectable energy. A scatter plot of the energy deposited in layer 2 (the active detector) versus the incident energy is shown in Figure 3. The window for proton detection is visible above the maximum electron energy deposited.

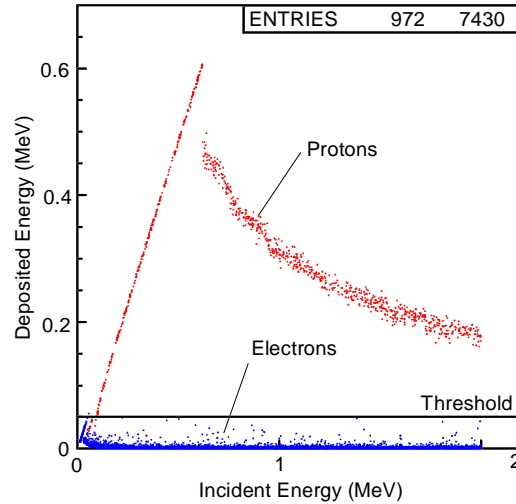


Figure 3. The energy deposited (MeV) in the active detector is plotted versus the incident energy (MeV). Electrons are shown with blue dots and protons with red. Electrons easily penetrate the thin scintillator, depositing little energy. Protons < 700 keV deposit all their energy within the scintillator.

The energy deposited increases monotonically until the proton energy reaches 800 keV, where it penetrates the scintillator and energy deposition drops. Electrons, on the other hand, are much more penetrating than protons. Electrons > 15 keV completely penetrate the scintillator. The electron signal rises with increasing energy until the particle penetrates the detector. At energies higher than the penetration energy, the energy deposited declines because of the decreasing cross-section. By thresholding the signal, we can create a detector that is only sensitive to protons in the 15 to 1000 keV energy range.

For electrons, the detector concept uses a relatively thin absorber to stop protons up to some energy followed by a much thicker detector to stop electrons of the same energy. Polymeric low Z materials efficiently block protons, but have lower attenuation for electrons than high Z materials. A scatter plot of the energy deposited in layer 2 (the active detector) versus the incident energy is shown in Figure 4. The window for electron detection is visible below the penetrating protons. The thin polymer coating blocks protons up to 700 keV, but allows electrons with energies > 20 keV to penetrate into the scintillator.

Performance

Initially, we verified the performance of the particle-specific scintillators using radio-isotope sources. For testing, we used a Ru-106 beta source as an electron source. We also used Po-210 and Am-241 alphas sources as proton simulants. Figures 5 and 6 show the key data that prove the feasibility of the particle-specific scintillator-based detectors.

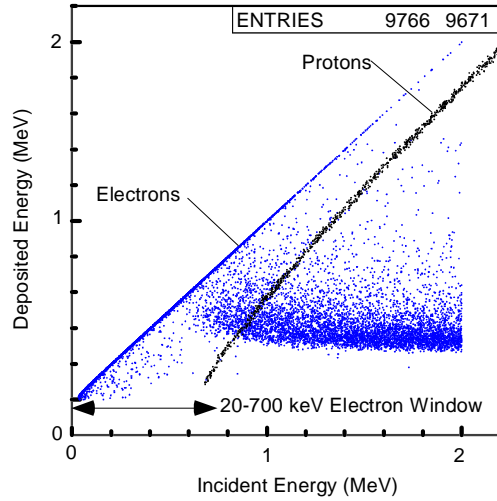


Figure 4. The energy deposited (MeV) in the active detector is plotted versus the incident energy (MeV). Electrons are shown with blue dots and protons with black. The thin shield blocks motors < 700 keV, while allowing electrons to penetrate into the thicker scintillator.

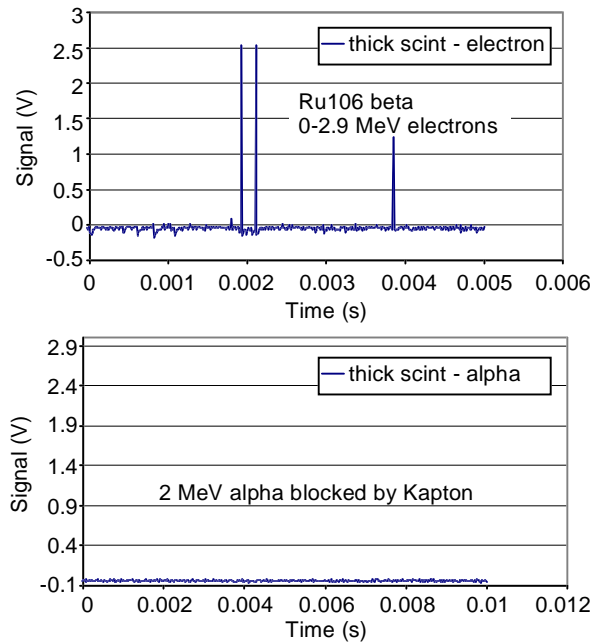


Figure 5. The electron-specific scintillator shows the expected response. (top) The beta electrons provide a large signal in the electron-specific scintillator. (bottom) The alphas on the other hand are completely stopped by the thin polymer film.

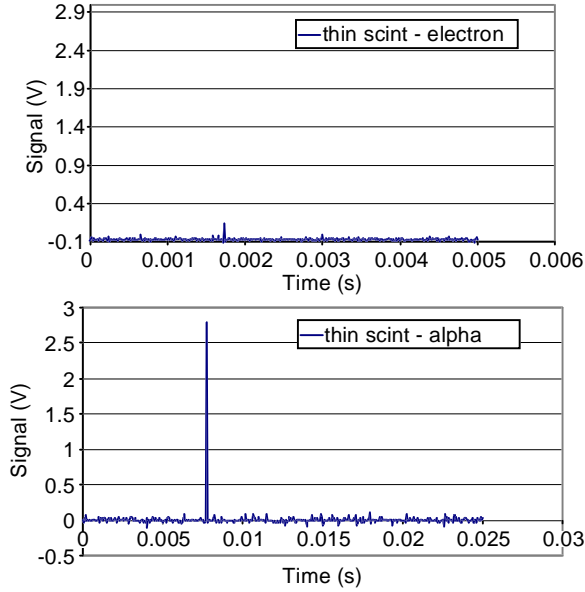


Figure 6. The response for the proton-specific scintillator to electrons and alphas (proton simulant). (top) The beta electrons deposit very little energy in the thin plastic scintillator sheet (estimated 10 KeV). (bottom) As expected, the alphas produce large signals.

Figure 5 shows the response of the electron-specific scintillator to both beta electrons and alphas (used as a proton simulant). The scintillator shows the expected response. The beta electrons provide a large signal in the electron-specific scintillator. The alphas on the other hand are completely stopped by the thin polymer film.

Figure 6 shows the response for the proton-specific scintillator. The beta electrons deposit very little energy in the thin scintillator sheet (estimated 10 KeV), while the alphas produce large signals, thereby providing good rejection of electrons.

We also measured the energy resolution of the sensor initially using alpha particles (see Figure 7). In plastic scintillators, the photon efficiency for alpha particles is much less than that of protons, by approximately a factor of 10X. Therefore, the 5 MeV Po-210 alpha produces a signal, equivalent to a proton of 500 keV. As such, the higher energy alpha provides a reasonable simulation of the proton signals.

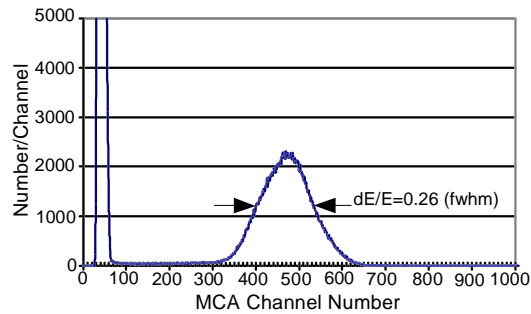


Figure 7. The response of the proton scintillator to a Po-210 alpha particle. Although the alpha particle energy is approximately 5 MeV, it produces a signal comparable to a 500 keV proton due to the low alpha efficiency of the plastic scintillator. The signal magnitude and energy resolution meet the requirements for the space weather threat sensor.

The observed energy resolution is approximately $dE/E=0.28$ (fwhm). The source energy spread is approximately $dE/E=0.1$, as measured with an SSD; therefore, we estimate the scintillator resolution to be $dE/E=0.26$ (fwhm). These data demonstrate that the signal levels and energy resolution not only meet the performance requirements of the space weather threat sensor, but also match our predictions.

Summary

We have developed and tested a breadboard model of a novel, scintillator-based low energy particle imaging spectrometer. The LEPIS design does not rely upon a magnetic sector to discriminate between particle types; rather it takes advantage of cross-section characteristics and scintillator properties to discriminate. The result is a tremendous savings in weight and volume. The sensor physical parameters are compatible with the requirements of nanosatellites. The LEPIS is lightweight (<0.5 kg), low power (<0.5 W), and small volume ($150 \times 150 \times 83$ mm³).

We have proven the feasibility of our approach; i.e., using thin films of materials to create proton-specific and electron-specific detectors, fiber-optically coupled to a position-sensitive photomultiplier tube. Initial performance data indicate that the detectors have high specificity and energy resolution ($dE/E=0.26$ fwhm) sufficient to support magnetospheric science and space weather early warning missions.

A compelling aspect of the LEPIS concept is its flexibility. The design is completely adaptable to different energy regimes - and different missions. By simply changing the scintillator thickness and materials, the LEPIS can be configured to monitor the higher energy trapped radiation and solar proton environments. We envision the LEPIS as a basic nanosatellite core sensor that can easily be configured to monitor the space weather environment in a variety of orbits and environments – from LEO to GEO, from the van Allen belts to the magnetotail.

Acknowledgements

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