Silicon Photomultipliers for the Japanese Experiment Module – Extreme Universe Space Observatory (JEM-EUSO) Focal Surface

Report by:
John W. Batke

College of DuPage
425 Fawell Boulevard
Glen Ellyn, Illinois 60137

Mentored by:
Juan Estrada

Supervised by:
Karen Kephart

Particle Physics Division
Fermilab National Accelerator Laboratory
Batavia, Illinois 60510

This work was supported in part by the U.S. Department of Energy, Office of Science, Office of Workforce Development for Teachers and Scientists (WDTS) under the Community College Internships (CCI) Program.

Community College Internship (CCI) Program

August 8, 2014

Table of Contents

Abstract.....3

1. Introduction.....4

    1.1 JEM-EUSO Overview.....4

    1.2 Silicon Photomulitipliers.....5

2. Progress.....5

    2.1 Dark Box…….....5

    2.2 Dewar Experiment.....8

3. Future.....8

4. Impact.....9

5. Conclusion.....9

6. Acknowledgements.....9

References.....10

Abstract

The Japanese Experiment Module – Extreme Universe Space Observatory (JEM-EUSO) mission is designed to explore the most energetic particles known to occur in nature, ultra-high-energy cosmic rays (UHECRS). By looking down at the night sky from the International Space Station (ISS), JEM-EUSO will be able to see the fluorescence and Cherenkov photons produced by air showers generated by UHECRS in our atmosphere. JEM-EUSO will have the highest exposure of any UHECRS test ever attempted. Current plans for its design call for a focal surface utilizing photomultiplier tubes (PMTs). While PMTs have been used in similar projects before, a new technology may be replacing them as the better alternative. Silicon photomultipliers (SiPMs) are quickly becoming this new option. SiPMs demonstrate many of the same qualities of PMTs while also improving qualities in certain areas. One characteristic is that SiPMs are smaller than PMTs and so can provide higher angular resolution. SiPMs are also not affected by external magnetic fields which gives them an advantage while in orbit. Given that SiPMs are a developing technology, optimization of such detectors still must be researched and understood. [SiPMs also have the potential for higher detection efficiency than PMTs.] For SiPMs to replace PMTs, a more power efficient and noise canceling scheme must be developed. Since the SiPMs intrinsic background is affected by ambient temperature, the focus of this research is to test the capabilities of these detectors at cryogenic temperatures. The current goal of the research on SiPMs at Fermilab is to create a small photon detection module (PDM) to be tested for the JEM-EUSO focal surface.

1. Introduction

1.1 JEM-EUSO Overview

The Extreme Universe Space Observatory on board the Japanese Experiment Module (JEM-EUSO) of the International Space Station (ISS) is a space mission to study the ultra-high-energy universe. The primary goal of the JEM-EUSO project is to study ultra-high-energy Cosmic Rays (UHECRS) and their sources, with exploratory objectives of studying high-energy neutrinos and particle physics beyond the Standard Model. Cosmic rays are not a rare phenomenon, and most cosmic rays have been subjected to research since Victor Hess discovered them in 1912 [1]. While the name "cosmic ray" may suggest they are made of light (photons), they are actually made of particles like protons and atomic nuclei. When a cosmic ray particle reaches Earth, it will collide with a nucleus in the upper atmosphere, which will create an air shower of many secondary particles (muons, protons, electrons, pions, neutrons, positrons, antiprotons, alpha particles). The secondary particles will typically travel in the same direction as the primary particle and also have a fair amount of kinetic energy. These secondary particles will generate fluorescence light isotropically from the excitation of nitrogen molecules in the air, and they will also produce Cherenkov light, since the particles will be traveling faster than the speed of light because it is within the Earth's atmosphere [2].

The UHECRS have energies above 10^{18} eV. This makes them more energetic than any man-made accelerated particle. The difficulty in researching these cosmic rays is that they have a very low flux, with UHECRS air showers having a frequency of 1 per km^2 per century for energies above 10^{20} eV [3]. The most notable UHECRS experiment to date is the Pierre-Auger Observatory in Argentina, which consists of 1 600 water tank detectors spread out over 3 000 square kilometers. The large area of the Pierre-Auger Observatory was meant to account for the low flux of the UHECRS.

The JEM-EUSO experiment will be able to observe a much larger portion of the sky than the Pierre-Auger Experiment since it is orbiting at ~400 km above sea level. JEM-EUSO will observe both the fluorescence light and the Cherenkov light produced from the UHECRS air showers. The observatory is designed to have a wide field-of-view (+/-30°), three Fresnel lenses focusing the incident UV photons, and a focal surface with single photon counting capability, highly pixelated and optimized for the near-UV (330-400 nm) [3]. Current plans for the focal surface call for more than 5 000 Hamamatsu R11265-03-M64 multi-anode photomultiplier tubes (MAPMTs), giving a total of ~300 000 readout channels. These would be arranged into photo-detector modules (PDM), which will cover the 2.35 m diameter of the focal surface [4].

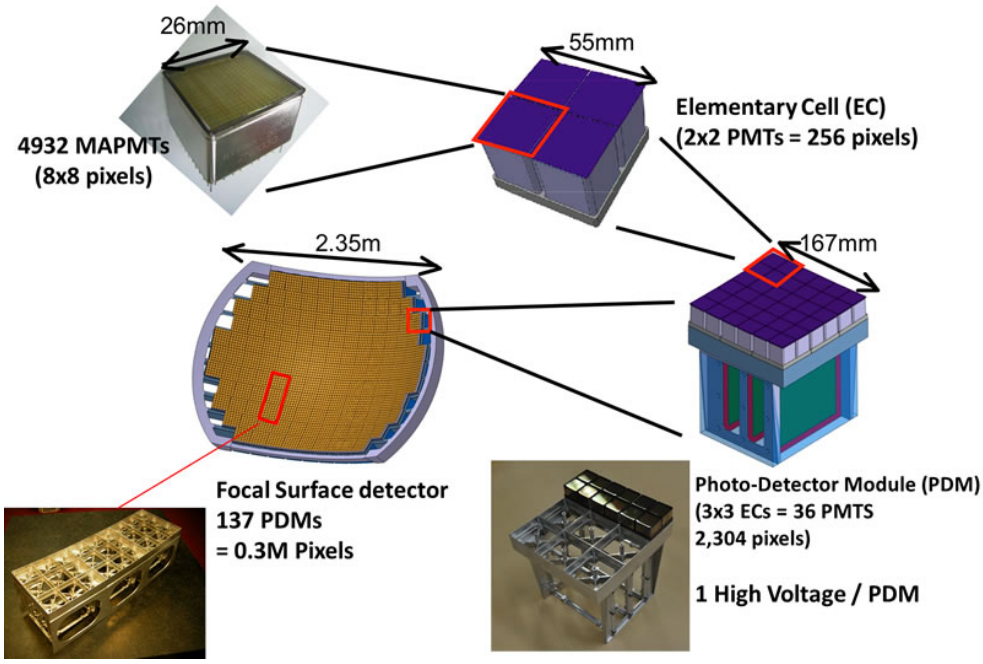

Figure 1. JEM-EUSO focal surface.

1.2 Silicon Photomultipliers

The research goal for the JEM-EUSO telescope at Fermilab is to see if silicon photomultipliers (SiPMs) are a viable replacement for the MAPMTs on the focal surface. SiPMs are solid-state photon counters with many advantages over MAPMTs. They contain multiple micro-pixels of avalanche photodiodes (APDs) that are uniquely operated at a reverse bias voltage above the APDs breakdown voltage [5]. This overvoltage ($V_{bias} - V_{breakdown}$) creates an electric field in the APD that becomes high enough to cause an avalanche breakdown from very weak light entering the APD. The avalanche breakdown is the result of impact ionization from a single photon striking a silicon atom inside the diode.

SiPMs have many characteristics that make them suitable replacements for photomultiplier tubes (PMT). MAPMTs have a photon detection efficiency of ~40% while operating at 900 volts for the near UV photons generated in air showers. SiPMs possess photon detection efficiencies between 40%–60%, while also operating at voltages around 20 V–80 V. SiPMs also have a small pixel size so a higher angular resolution can be established as compared to MAPMTs.

2. Progress

2.1 Dark Box

The main goal for establishing SiPMs as the replacement for PMTs on the focal surface of JEM-EUSO is the control of dark count rate in the SiPMs (< ~100 kHz) at a power below 0.5

mW per channel. This will be done through controlling the temperature of the detectors. This is the focus of the research currently being done at Fermilab. Smaller scale experiments inside a dark box were done to test the capabilities of the SiPMs at temperatures varying from 20 °C to -30 °C. A single Hamamatsu S10362-11-050U MPPC (multi-pixel photon counter) was used in these experiments. The MPPC was connected to a front-end readout ASIC (application-specific integrated circuit) called the EASIROC. The EASIROC was purposely built for the readout of SiPMs. It contains 32 channels and single adjustable discriminator threshold set by a 10-bit DAC (Digital to Analog Converter) common to all 32 channels [6]. Each channel has two parallel AC coupled voltage preamplifiers. A Keithley 2400 DC power supply set the reverse bias voltage for the channels on the EASIROC. An oscilloscope was also connected to the EASIROC. The EASIROC's settings were established using a LabView program through a computer that was connected to the EASIROC through a USB cable. The LabView software was provided with the EASIROC and allows for easy configuration of the board's pre-amplifiers, 10-bit DAC, 8-bit DACs, capacitors, and bus settings. The software allows for easy data acquisition.

Figure 2. Hamamatsu S10362-11-050U MPPC.

Since SiPMs are known to behave differently at varying temperatures, the first step in the project was to acquire data from an I-V curve at several temperatures in the dark box's allowed spectrum. The operating voltage for MPPCs is ~70 V, but since the 10-bit DAC steals some volts in the EASIROC, the power supply used a voltage between 74 V–75 V. The Hamamatsu MPPC I-V curve shows a steady and gradual increase in current (~0.05μA) as the voltage is stepped up, until it reaches its breakdown voltage. After the breakdown voltage is passed, the current will escalate at an increasing rate. This point in the I-V curve can be reached at lower voltages if the temperature is reduced.

The second step in the dark box project was to observe the dark count at a steady temperature. Dark count is a pulse from a SiPM that is generated by a thermal carrier. For this portion of testing, a rate counter was connected to the EASIROC. Since no light could get into the dark box, the test could be conducted with full knowledge that the pulses being counted were from thermal carriers and not photons. With the SiPMs at -30 °C, the discriminator 10-bit DAC was swept at varying threshold voltages. Lower DAC values meant only pulses with high enough current would be registered on the rate counter. Higher DAC values allow lower current pulses, which means more noise is being read out. The threshold voltages at which the dark count rate abruptly decreases correspond to the level of one photoelectron, two photoelectrons, and so on from left to right [5].

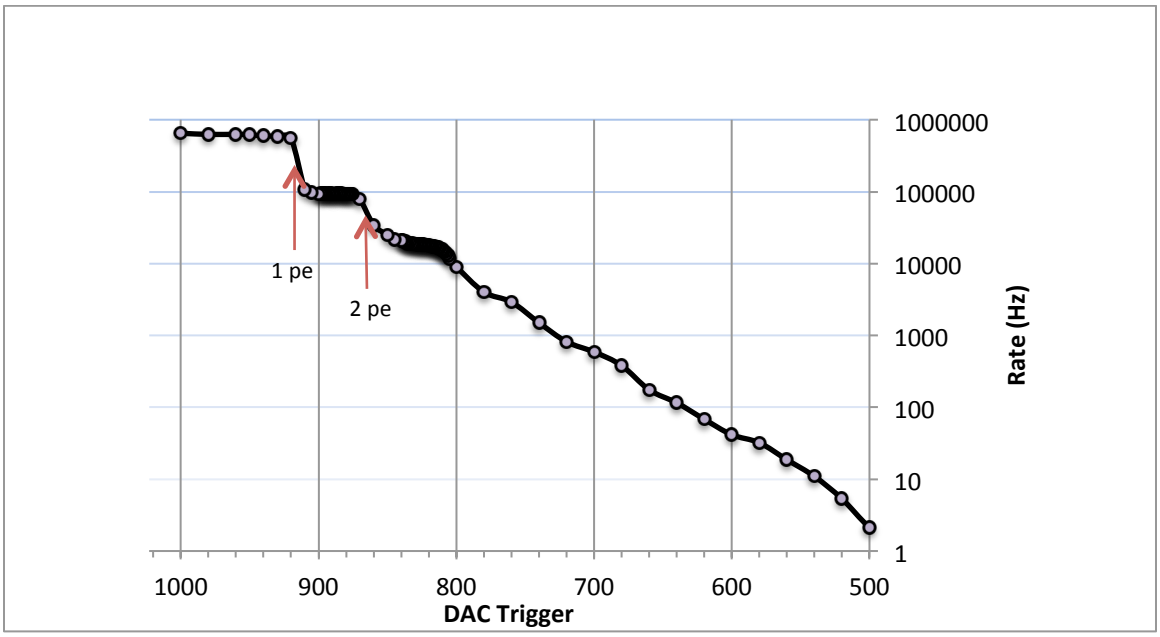

Figure 3. Dark count rate as a function of discriminator threshold in DAC trigger units.

The third step in the dark box was to find the breakdown voltage of the SiPMs at different temperatures. This required the use of the LabView software. The program could complete a sweep of DAC triggers and read out the trigger efficiency for each value. This was completed using different bias voltages at a constant temperature. Each of these graphs had three levels of constant, horizontal values and two distinctly abrupt changes in efficiency. The first abrupt change drove the efficiency to 100% and represented 0 photoelectrons striking the detector. This change had a DAC value of ~915. The second abrupt change drove the efficiency up to 30%-40% efficiency and represented 1 photoelectron. This change occurred at different DAC triggers for different bias voltages. The difference between a threshold of 1 photoelectron and 0 photoelectrons corresponds to a single avalanche breakdown. Since no avalanche breakdowns will occur at the breakdown voltage, we can interpolate the difference values at the separate bias voltages to locate the breakdown voltage. Completing this process at distinct temperatures confirmed the result that SiPMs can be operated with less voltage if they are cooled down.

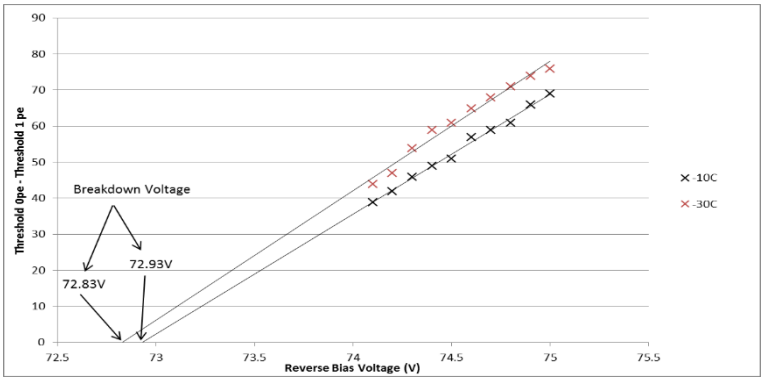

Figure 4. Interpolation of reverse bias voltage and threshold data to determine the breakdown voltage.

2.2 Dewar Experiment

The next step in the progression of SiPM research and optimization at Fermilab is to start to cool SiPMs down to cryogenic temperatures. This has been done using an IRLabs custom dewar. It contains a vacuum chamber with an elevated cold fingerplate on one half of the dewar, and a liquid nitrogen (LN_2) reservoir on the other. The vacuum can be achieved by connecting a Pfeiffer HiCube 80 Eco pump. This pump has two stages. The first stage works as a moderate vacuum pump, while the second stage contains a fan that operates at 1500 Hz. The two stages could bring the pressure inside the dewar down to 2.0 x 10^{-4} mbar. When cooling down the dewar with LN_2, a Lakeshore 336 temperature controller was connected. This temperature controller works in a PID loop. As the LN_2 cooled the dewar down, a resistance temperature detector (RTD) would sense the temperature passing a setpoint, and the temperature controller would turn on a heater. As the heater warmed, the RTD would pass the setpoint in the other direction and the heater would be turned off. This process of heating and cooling would eventually balance and keep the dewar at a constant temperature.

Five SiPMs were put into the dewar for testing at cryogenic temperatures. One was the Hamamatsu used in the dark box. The others were CPTA (Russian) SiPMs. The SiPMs were connected to the EASIROC through a cable that attached on the outside of the dewar. Testing was done to see where the operating and breakdown voltage was for these SiPMs, but technical difficulties with the connections to the EASIROC and also the EASIROC itself held back progress. After several problems were discovered and corrected, the dewar is finally in a position to begin full testing.

3. Future

The near future goals for SiPM research for JEM-EUSO at Fermilab involve the development of an optimized PDM. This PDM will consist of a new generation of SiPMs that has been created by Hamamatsu. These TSV-MPPC (through silicon via multi-pixel photon counter) have a greater fill factor and less dead space between detectors. The PDM will consist of 64 of these new SiPMs and will be tested in the dewar at temperatures comparable to the tests being done with the current SiPMs. The long-term goal for Fermilab's involvement in JEM-EUSO will be to test this PDM in a mock telescope setup in Utah. These tests in the mock

telescope will be a crucial step in seeing if SiPMs will replace MPPCs on the focal surface of JEM-EUSO.

4. Impact

The work that was completed this summer allows for a stronger understanding of SiPMs by the staff working on the PDM at Fermilab. Several problems were corrected with the EASIROC and Dewar and will be accounted for in future efforts. Work and tests done on the single SiPM will make optimizing the SiPM PDM easier. This new understanding of the SiPMs can be further used as the project is continued in coming months. If the SiPMs are successful in replacing PMTs in JEM-EUSO, Fermilab will have played a key role in the research.

5. Conclusion

The work done during this internship will reduce the time needed to optimize a silicon photomultiplier photon detection module for its eventual testing for the JEM-EUSO focal surface. This project will prove to be invaluable if JEM-EUSO utilizes SiPMs instead of photomultiplier tubes.

6. Acknowledgements

This project was conducted at Fermi National Accelerator Laboratory with the assistance of Juan Estrada, Leland [Lee] Scott, Kevin Kuk, Javier Tiffenberg, and Paul Rubinov. Juan's close mentoring was a valuable resource for which I am grateful. Lee's help with the EASIROC board and LabView software was a tremendous asset in the research conducted with the SiPMs. Kevin's technical assistance gave me the proper materials and hands-on safety training to work with the dewar and LN_2. I want to thank Javier for being an excellent physics and cosmic ray resource. I would also like to thank Paul for providing many of the SiPMs used during the testing. Their supervision and help made Fermilab a safe and rewarding environment in which to learn and grow. The knowledge they provided in their respective specialties provided enough background for me to conduct my research in a professional manner. I want to thank everyone at SiDet and the entire Particle Physics Division at Fermilab for being welcoming during my internship. I also appreciate Tanja Waltrip for her wonderful help and coordination and Karen Kephart who provided me with this opportunity to further my academic growth.

References

[1] Angela V. Olinto. 2005. "The Highest Energy Cosmic Rays," American Institute of Physics. [Internet] [Cited 15 July 2014]. Available from: extras.springer.com/2005/978-0-7354-0229-4/cdr_pdfs/indexed/stage4.

[2] A. Santangelo (2013). The JEM-EUSO mission: Context and status. EPJ Web of Conferences [Internet]. [Cited 26 June 2014]. Available from: http://www.epj-conferences.org/articles/epjconf/abs/2013/14/epjconf_uhecr2012_09001/epjconf_uhecr2012_09001.html

[3] Juan Estrada, Paul Rubinov, Angela Olinto. "Development of Focal Surface Photodetector Module for JEM-EUSO Using Silicon Photo-Multipliers." [Internet] [Cited 3 June 2014].

[4] Y. Kawasaki, M. Casolino, P. Gorodetzky, A. Santangelo, M. Ricci, F. Kajino and T. Ebisuzaki. 2011. The Focal Surface of the JEM-EUSO Instrument [Internet]. American Institute of Physics. [Cited 10 July 2014].

[5] MPPC, "MPPC modules. [Internet]. [Cited 2014 Jun 3]. Available from: http://www.hamamatsu.com/resources/pdf/ssd/mppc_techinfo_e.pdf

[6] D. Impiombato, S. Giarrusso, and T. Mineo. 2013. Evaluation of the optical cross talk level in the SiPMs adopted in ASTRI SST-2M Cherenkov Camera using EASIROC front-end electronics. [Internet]. [2 Dec 2013; cited 9 July 2014].