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# A High Efficiency Cosmic-Ray Veto Detector for the Mu2e Experiment

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The Mu2e experiment at Fermilab will search for new physics through the observance of the neutrino-less decay of a muon to an electron in the presence of a nucleus. The experiment will have a single-event sensitivity of $3 \times 10^{-17}$, requiring an active cosmic-ray veto to keep background from cosmic rays to fewer than one event over the three year lifetime of the experiment. The Mu2e Cosmic Ray Veto (CRV) has been designed to have an efficiency of 99.99%. The design and fabrication of the CRV will be discussed.

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## 1. The Mu2e Experiment

The Mu2e experiment at Fermilab will search for charged lepton flavor violation through the oberservance of $\mu^- N \rightarrow e^- N$, which produces a monoenergetic 104.97 MeV electron. Observing such a conversion would be unambiguous evidence of new physics [1]. Failure to observe a conversion would provide a strong constraint on potential extensions to the standard model.

Over the course of the three year run, the Mu2e experiment will generate approximately $10^{18}$ stopped muons with a single-event sensitivity of $3 \times 10^{-17}$ expected [2]. This represents a $10^4$ improvement over the current best results [3].

Cosmic-ray muons represent a substantial background to the Mu2e experiment. Approximately one conversion-like event is expected each day, requiring an active cosmic-ray veto system to suppress the cosmic-ray background to acceptable levels of less than half of an event over the lifetime of the experiment [2]. The Mu2e Cosmic Ray Veto has been designed to have a veto efficiency of at least 99.99%.

## 2. The Mu2e Cosmic Ray Veto

The Mu2e Cosmic Ray Veto (CRV) is designed to fully cover the detector solenoid. It is required to have a high efficiency while operating in a high-intensity environment without imposing a large deadtime on the experiment.

### 2.1 Dicounters

The CRV is constructed from layers of extruded planks of polystyrene coated with titanium dioxide. Two strips are glued together to form dicounters. Embedded wavelength-shifting fibers [4] transport photons to the ends of the dicounters and are aligned to readout electronics by plastic Fiber Guide Bars (FGBs). Silicon photomultipliers (SiPMs) detect the light from fibers. During fabrication, the faces of the FGBs are flycut to polish the surface for optimal readout.

### 2.2 Dicounter Quality Assurance

Each constructed dicounter undergoes a series of tests to ensure that its performance is adequate to achieve the 99.99% efficiency necessary for the entire CRV.

First, the ends of each dicounter are imaged using a high-resolution Pentax camera. Any surface damage to the fiber ends such as chips, cracks, scratches, or impurities can be easily detected at this stage. Damage can often be resolved by re-fly-cutting.

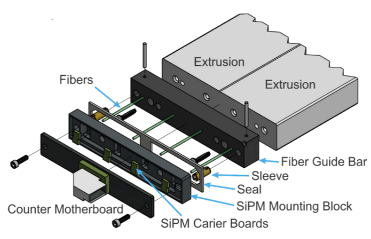


**Figure 1:** Schematic of a dicounter

Next, LEDs are flashed through each fiber end with a readout mechanism mounted on the opposite end. This test searches for inconsistencies between fiber readouts. As in the imaging step, no dicounters are discarded quite yet.

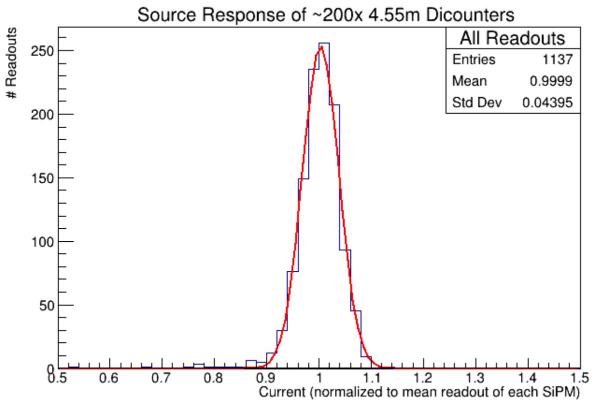


**Figure 2:** Normalized source response of ≈ 200 dicounters. The relative values of each SiPM readout to the mean value of the corresponding SiPM over all measurements (each mean normalized to be one) are calculated and shown plotted together.

Finally, dicounters are placed inside a dark box. A Cs-137 radioactive source is then placed on top of the box, one meter away from one end of the dicounter. The induced current is measured from the readouts for each channel and plotted with the dark current subtracted. This process is repeated with the source one meter away from the opposite end. The source test is the most important step in the quality assurance process because it is a realistic and complete test of the dicounter. If a dicounter produces outputs that are too low relative to the rest of the batch, it is eliminated from production in its current form [1].

### 2.3 Modules

Four offset layers of eight dicounters each are sandwiched between aluminum sheets to construct the CRV module. A total of 86 modules (about 2700 dicounters) will compose the CRV.

### 2.4 Module Quality Assurance

Modules will be tested to ensure they are light tight and perform up to expectations. Each module is exposed to bright lights to search for light leaks which are then sealed to ensure modules are optimally suited to detect cosmic rays.

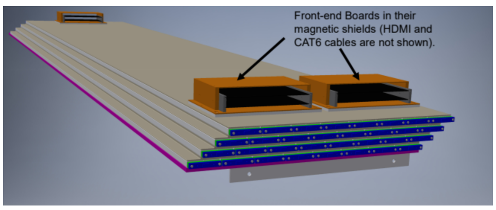


**Figure 3:** Schematic of a module

The performance of modules will be tested using the Mu2e Cosmic Ray Test Stand. The test stand consists of two cathode strip chambers triggered by scintillator paddles on either side with a space between for CRV modules. The test stand will be used to detect and reconstruct the tracks of cosmic rays. The efficiency of the CRV module can then be calculated by comparing the number of tracks which pass through the module to the number of signals recorded by the module.

### 2.5 Fabrication Status and Timeline

Fabrication of the CRV began in June of 2018 at the University of Virginia. As of December 1st, 2018 over 700 dicounters have been produced and tested. Module production from these dicounters is scheduled to begin in January 2019.

[1] Performance for some counters was measured in a test beam to provide an absolute reference for the light yield [5].

## References


[1] R. H. Bernstein and P. S. Cooper, "Charged Lepton Flavor Violation: An Experimenter's Guide," Phys. Rept. **532**, 27 (2013).

[2] L. Bartoszek *et al.* [Mu2e Collaboration], "Mu2e Technical Design Report," arXiv:1501.05241.

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[4] E. C. Dukes, P. J. Farris, R. C. Group, T. Lam, D. Shooltz and Y. Oksuzian, arXiv:1811.04874, to be published in JINST.

[5] A. Artikov *et al.* [Mu2e Collaboration], Nucl. Instrum. Meth. A **890**, 84 (2018).