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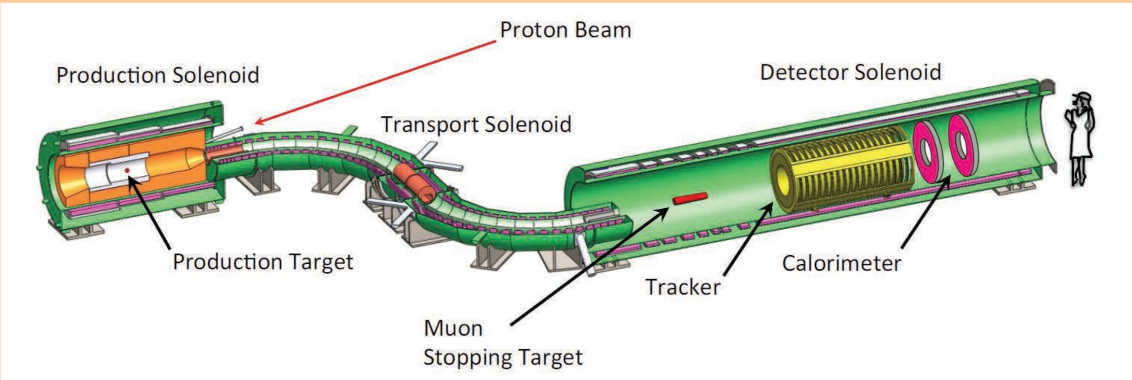


Radiation damage tests of Silicon Photo-multipliers (SiPMs) for the Cosmic Ray Veto system of the Mu2e experiment

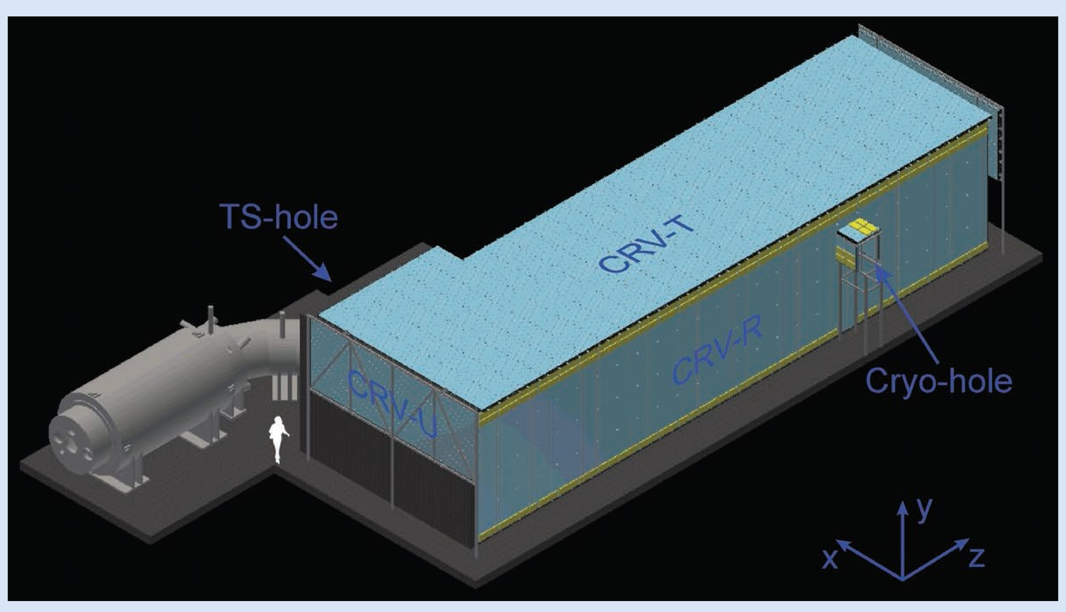
S. A. Uzunyan, G. Blazey, A. Dyshkant, K. Francis, D. Hedin, J. Kalnins, V. Zutshi, *NICADD, NIU*; S. Hansen, P. Rubinov, ***Fermilab, USA***

Fermilab

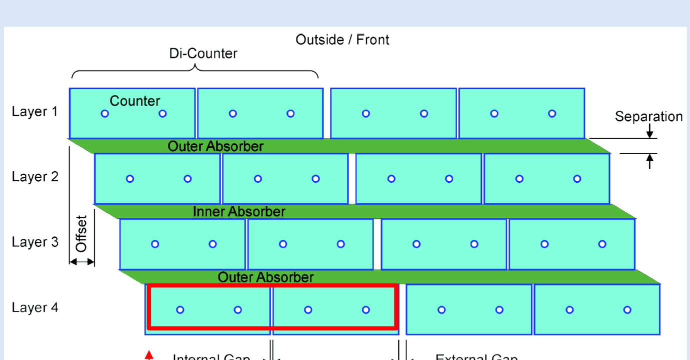
Northern Illinois University

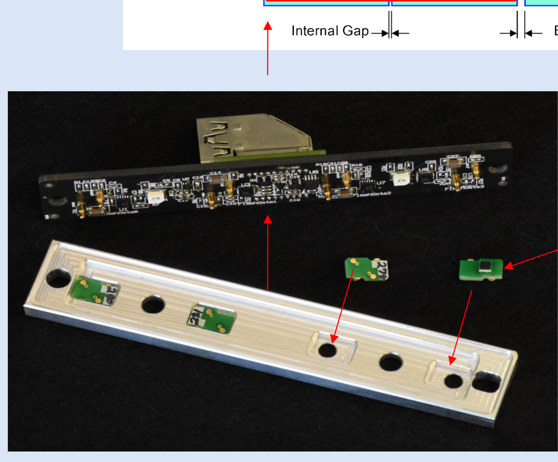
Abstract

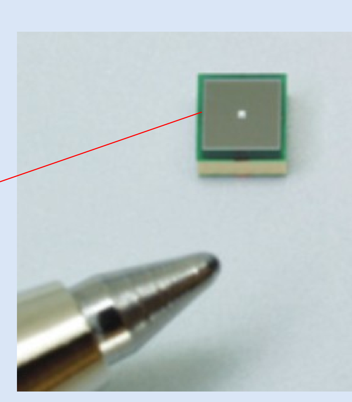
The cosmic ray veto (CRV) system of the Mu2e experiment is designed to suppress background signals induced by the cosmic rays during 3-years of the detector operations. The background detection is provided by four layers of scintillator counters with inserted wave length shifting fibers connected to SiPM devices. The entire system will require ~21000 SiPMs which are expected to obtain a maximum radiation dose of $1x10^{10}$ neutrons/cm^2 over the lifetime of Mu2e experiment. We present results of radiation damage tests of the Hamamatsu SiPM sensors similar to those will be used in the CRV system.



The assembled CRV system covering the Mu2e detector solenoid.







The four layers of CRV counters (top); the SiPM mounting block (bottom left); the 2.0mm x 2.0mm s13360-2050VE Hamamatsu sensor (bottom right).

Dark counts rates

1.3mm x1.3mm, **S13360-1350**		
V_bias (V_over), V	52.4(0.6)	53.3(1.5)
Clean, PE, KHz	13-25	25-40
Clean, PE, KHz	0.0	0.0
$5x10^9$ p/cm2, DCR@3.0 PE, KHz	0.6-1.6	11-25
$5x10^9$ p/cm2, DCR@3.5 PE, KHz	0.0-0.1	2-5
$1x10^{10}$ p/cm2, DCR@3.0 PE, KHz	3-10	22-96
$1x10^{10}$ p/cm2, DCR@3.5 PE, KHz	0.3-1.7	4-25

1.0mm x1.0mm, **S12571-050P**		
V_bias (V_over), V	65.2(1.3)	66.4(2.5)
Clean, PE, KHz	33-54	88-127
Clean, PE, KHz	0.6-1.2	3 - 11
$5x10^9$ p/cm2, DCR@3.0 PE, KHz	7-18	250-380
$5x10^9$ p/cm2, DCR@3.5 PE, KHz	0.6-3.8	150-250
$1x10^{10}$ p/cm2, DCR@3.0 PE, KHz	10-30	2700-5300
$1x10^{10}$ p/cm2, DCR@3.5 PE, KHz	2-14	2300-3500

Crosstalk (DCR@1.5 PE/DCR@0.5 PE)

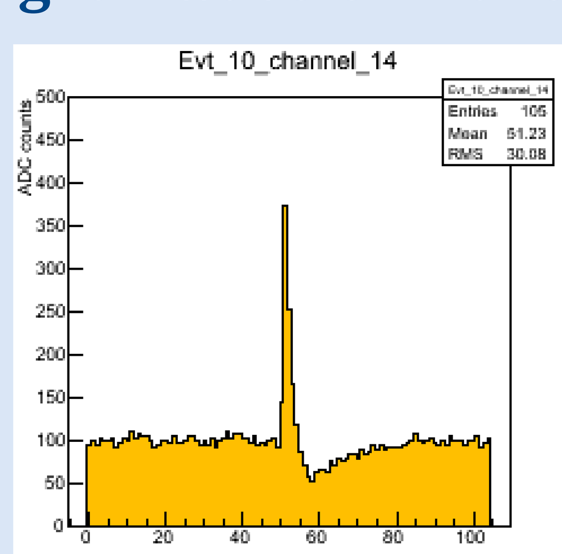
1.3mmx1.3mm, **S13360-1350**		
V_bias (V_over), V	52.4(0.6)	53.3(1.5)
Clean, %	0.0 - 0.9	0.2 - 2.6
$5x10^9$ p/cm2, %	4.4 - 6.3	10.8 - 13.2
$1x10^{10}$ p/cm2, %	6.8 - 9.8	12.5 - 19.3

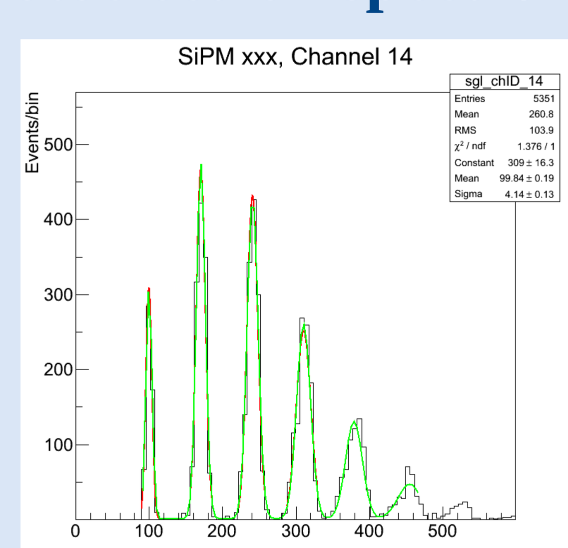
1.0mmx1.0mm, **S12571-050P**		
V_bias (V_over), V	65.2(1.3)	66.4(2.5)
Clean, %	7.5 – 19.4	20.8 – 32.4
$5x10^9$ p/cm2, %	10.0 – 11.4	27.8 – 31.1
$1x10^{10}$ p/cm2, %	9.5 - 16.3	28.1 – 33.6

Requirements to the CRV SiPM sensors

- There should be at least two photodetectors at each counter end. Readout at both ends is needed if at all possible: (1) to determine within 1 meter the longitudinal position of the cosmic-ray muon track stub, (2) in order to facilitate a constant energy threshold over the entire counter, and (3) to provide redundancy. Having two photodetectors on each end is needed: (1) to obtain the required photostatistics, (2) for calibration purposes, and (3) to provide redundancy. The sum of the two photodetectors on each end should meet the photoelectron yield requirement in order to achieve the desired veto efficiency.
- The SiPM noise rate at the largest expected dose must allow single photoelectrons to be identified in order that a reliable energy threshold can be set.
- The hit rate from neutrons/gammas in each SiPM should be no more than 1 MHz.
- The SiPM photoelectron threshold from the above requirement must be less than the threshold needed to meet the overall CRV efficiency requirement.
- The SiPM and associated front-end electronics must produce a timing resolution no worse than 5 ns at 90% CL.
- The SiPM must be able to meet the above requirements after a total radiation dose of $1x10^{10}$ 1 MeV n/cm^2 over the course of the experiment.
- The photodetectors must be able to meet the listed requirements in the ambient magnetic fields of the TS and DS.

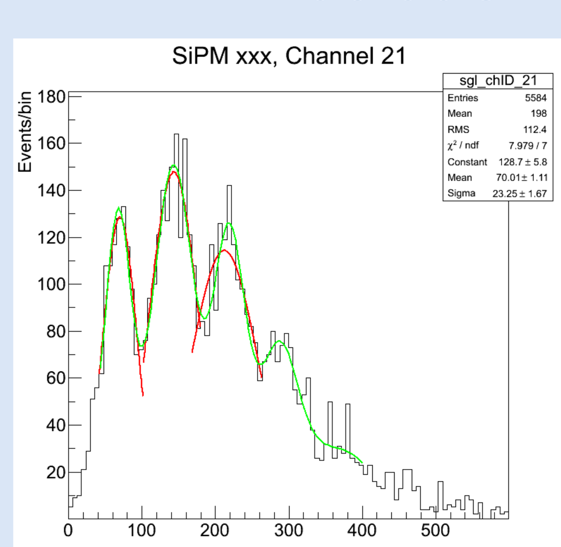
Signal waveform and photoelectron spectrum

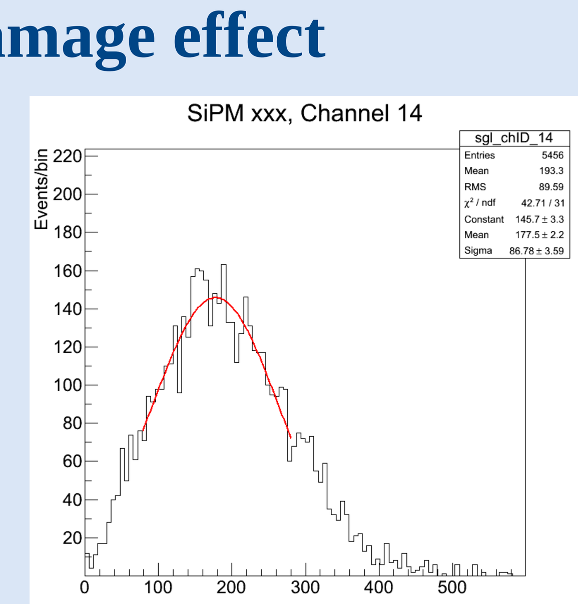




The signal waveform (left) and the single photoelectron (PE) spectrum from non-irradiated 1.3mm x 1.3mm SiPM illuminated with 12 ns LED pulse. Each peak corresponds to a certain number of photo-electrons starting from zero (pedestals). Distance between subsequent peaks defines the gain of the device.

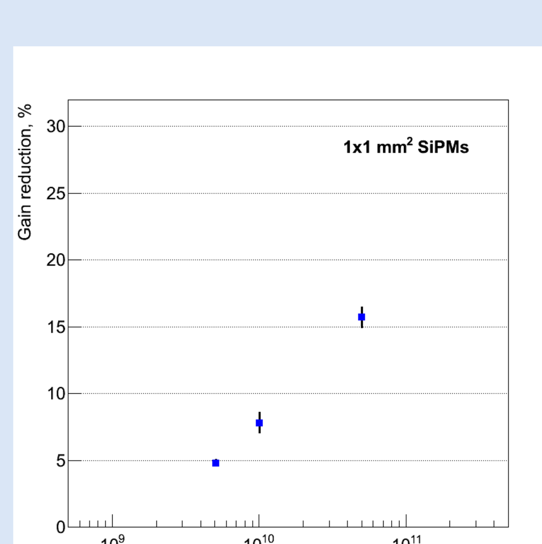
Radiation damage effect

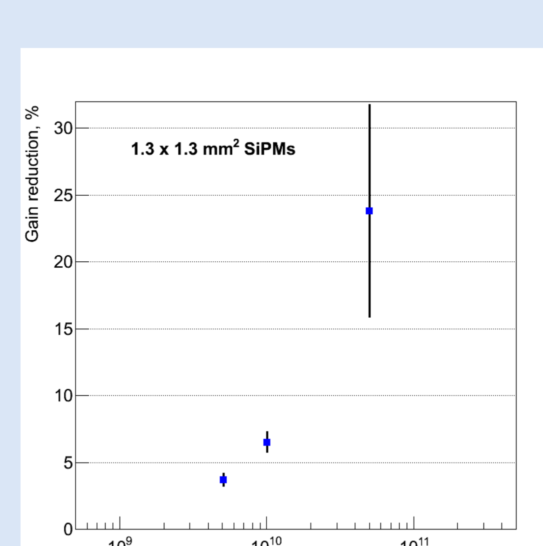




The PE spectrums from 1.0mm x 1.0mm (left) and 1.3mm x 1.3mm(right) SiPM after exposing to $5x10^{10}$ protons/cm^2 flux. For the 1.3mm x 1.3mm sensors the PE peaks are no longer visible.

Gain reduction

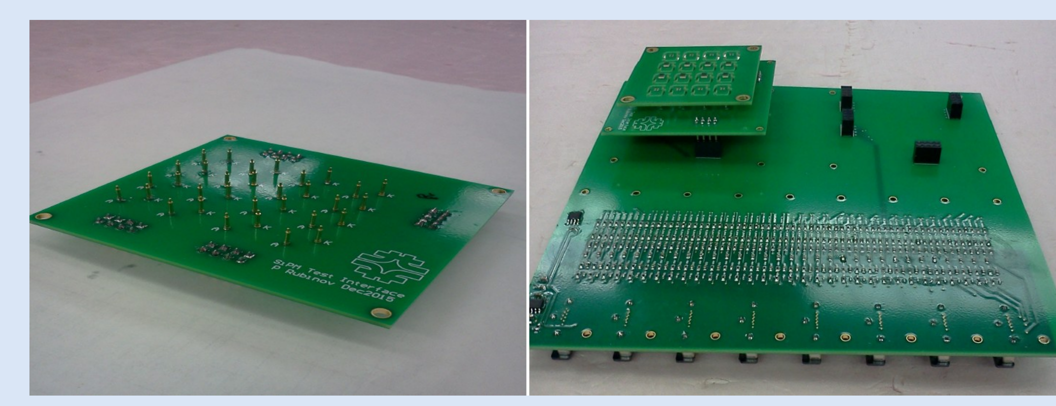




SiPM gain reduction after different irradiation doses observed for 1.0mm x 1.0mm (left) and 1.3mm x 1.3 mm (right) sensors. For the 1.3mm x 1.3 mm devices the reduction for the $5x10^{10}$ p/cm^2 irradiation level obtained from comparison of signals induced by long (16 ns) LED pulses.

SiPM testing

- The critical photodetector parameters (the single PE spectrum, the response to LED pulse, the dark current rate and the cross talk) are measured for a non-irradiated sets of devices of a given type.
- The same sets of sensors are exposed under different dose at CDH proton beam (200 MeV) facility at Naperville, IL
- The measurements are repeated after a short annealing period after irradiation and compared with the original results
- We have tested the 1.0 mm x 1.0 mm and 1.3 x 1.3 mm sensors, and have started tests of the 2.0mm x 2.0 mm devices



The 16-SiPM carrier board mounted on top of the data acquisition card.

Sensor specification

All values at 25^o C at overvoltage of 2.5V:

1) 2mm x 2mm, 50 µm pixel
2) Surface-mount, TSV packaging
3) PDE > 35% (530 nm)
4) Gain ≥ 1.0*10^6
5) Pulse rise time < 5 nsec
6) Dark rate < 250 kHz @ 0.5 PE threshold
7) X-talk (inter-pixel) < 2%
8) Bias spread: ±0.5V (within batch); ±1.5V (full sample)
9) Temperature dependence ≤ 50 mV/^{o}C

Part Number: S13360-2050VE

Summary

- Radiation damage measurements done for 1.0mm x 1.0mm and 1.3mm x 1.3mm devices
- The results shown have already given us a very good idea of what to expect (the 1.3 x 1.3 mm^2 sensors use the same silicon).
- The 2mm x 2mm devices are in the process of being tested
- At the expected doses no show-stoppers present themselves
- Expect to (and can) work without SPE separation in the advanced stages of the experiment for a certain % of the devices
- Possible mitigation strategies: modified shielding and/or, if necessary, replacement of a certain % (< 10) of devices

Acknowlegements

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