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Studies of Radiation Damage to Silicon Photomultipliers

(on behalf of the Mu2e collaboration)

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(For a description of the CRV system, see R. Erhlich, this conference, or the Mu2e TDR at mu2e.fnal.gov)

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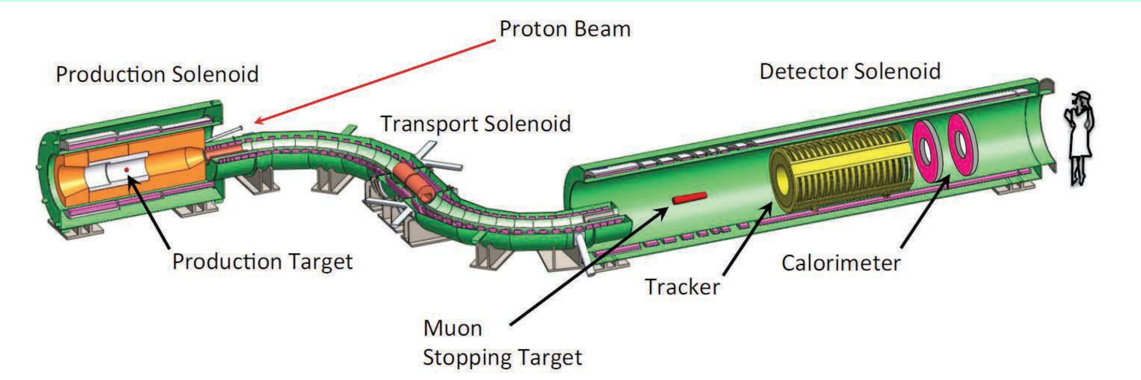
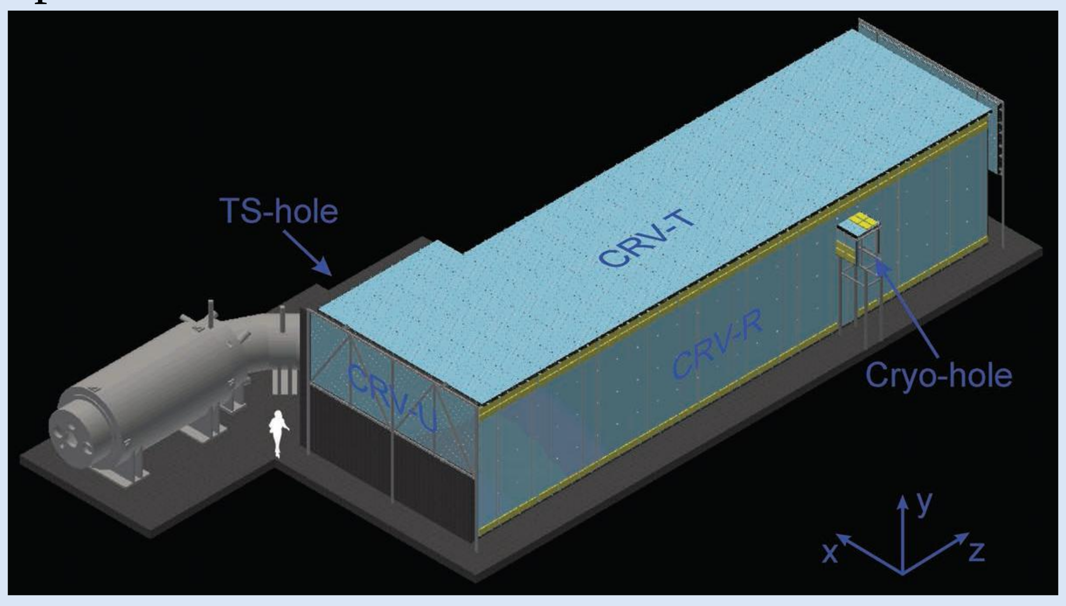
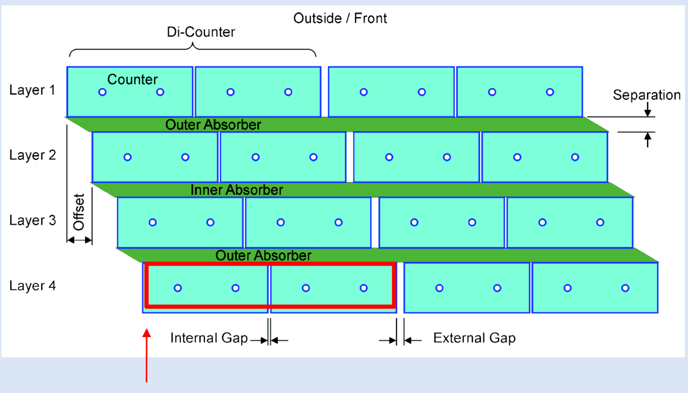


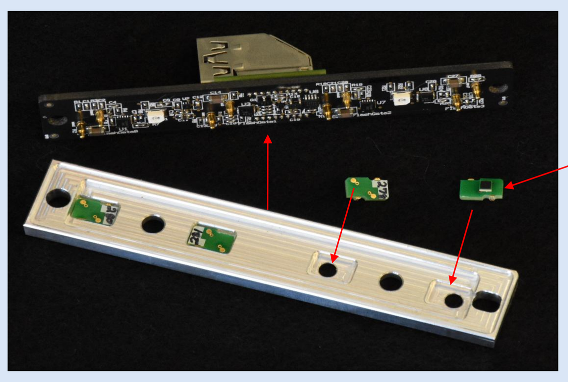
Abstract

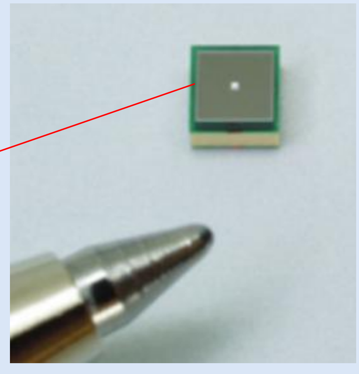
Results of radiation tests of Hamamatsu 2x2 mm^2 through-silicon-via (S13360-2050VE) silicon photo-multiplier (SiPM) sensors are presented. Distinct sets of eight SiPMs were exposed to four different 1 MeV neutron equivalent doses of 200 MeV protons. Measurements of the breakdown voltage, gain and noise rates at different bias overvoltages, photoelectron thresholds, and LED illumination levels were performed before and after irradiation. These studies were undertaken in the context of photo-sensor requirements for the Cosmic Ray Veto system (about 5500 counters, 20,000 SiPMs utilizing 1.4 mm embedded fibers, with a typical counter 2x5x500 cm^3) of the Mu2e experiment.



The assembled CRV system covering the Mu2e detector solenoid.





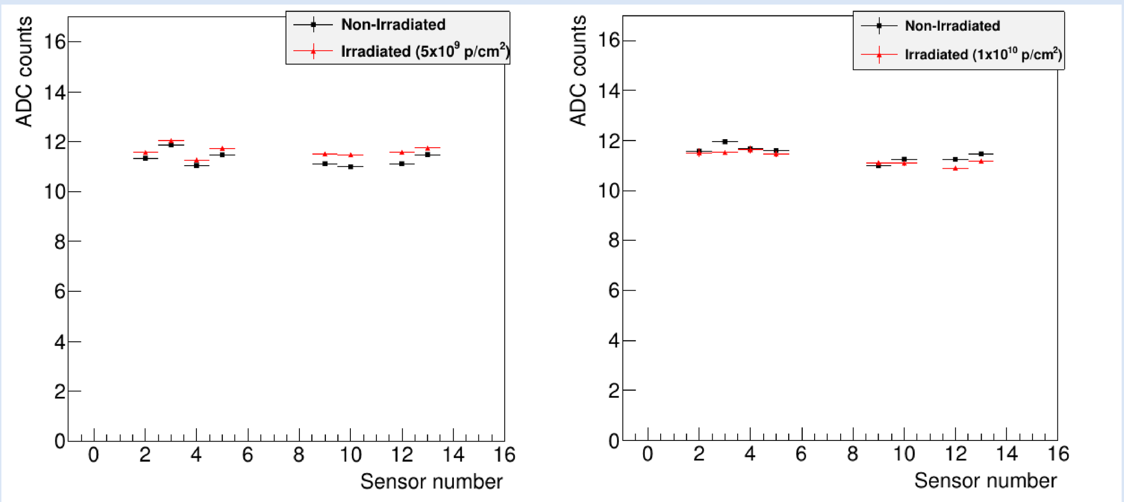


The four layers of CRV counters (top); the SiPM mounting block (bottom left); the 2.0x2.0 mm^2 s13360-2050VE Hamamatsu sensor (bottom right).

Dark counts rates (DCR)

The mean DCR (2.0x2.0 mm^2 sensors) at Vbreakdown+2.5V bias voltage		
Irradiation level (p/cm^2)	Threshold (PE)	DCR (kHz)
No radiation	0.5	124 ± 4
No radiation	3.5	0.0
$5x10^9$	3.5	284 ± 58
$5x10^9$	5.5	8.5 ± 2.4
$1x10^{10}$	3.5	2550 ± 200
$1x10^{10}$	5.5	260 ± 45

Effect of irradiation on sensor's gain

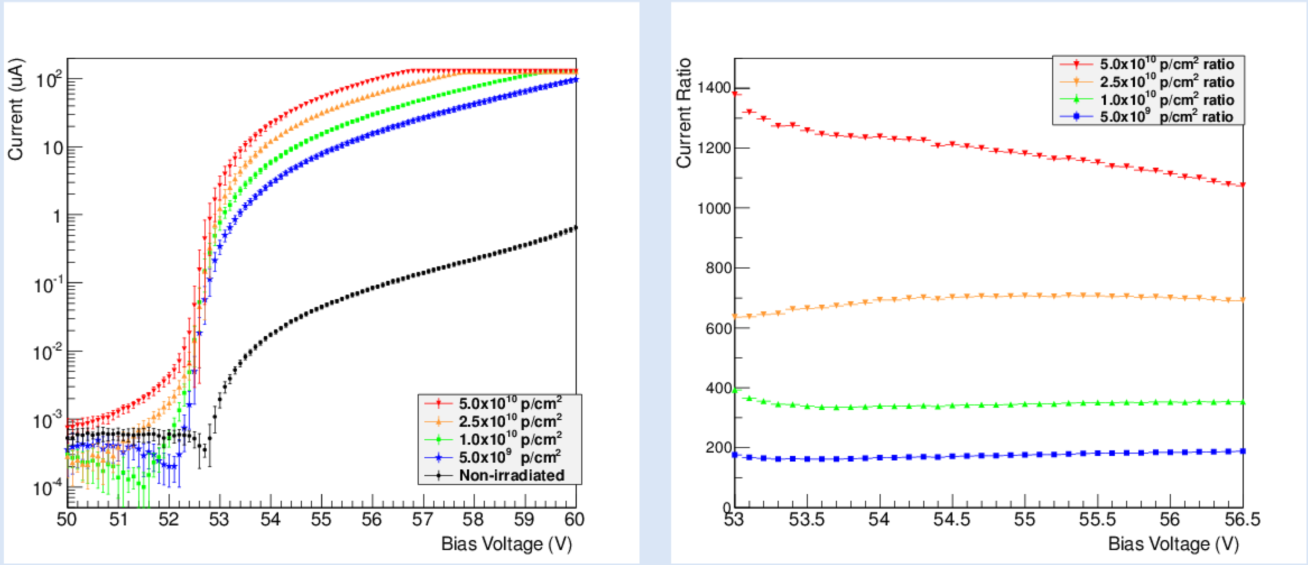


The MPPC gain as a function of the SiPM number at Vo = 2.5V for (left) $5x10^9$ p/cm^2 and (right) $1x10^{10}$ p/cm^2 , the black points show the gain for the non-irradiated packs and the red points show the gain for the irradiated packs corrected to the same voltages as the non-irradiated SiPMs.

CRV (Cosmic Ray Veto) SiPM requirements

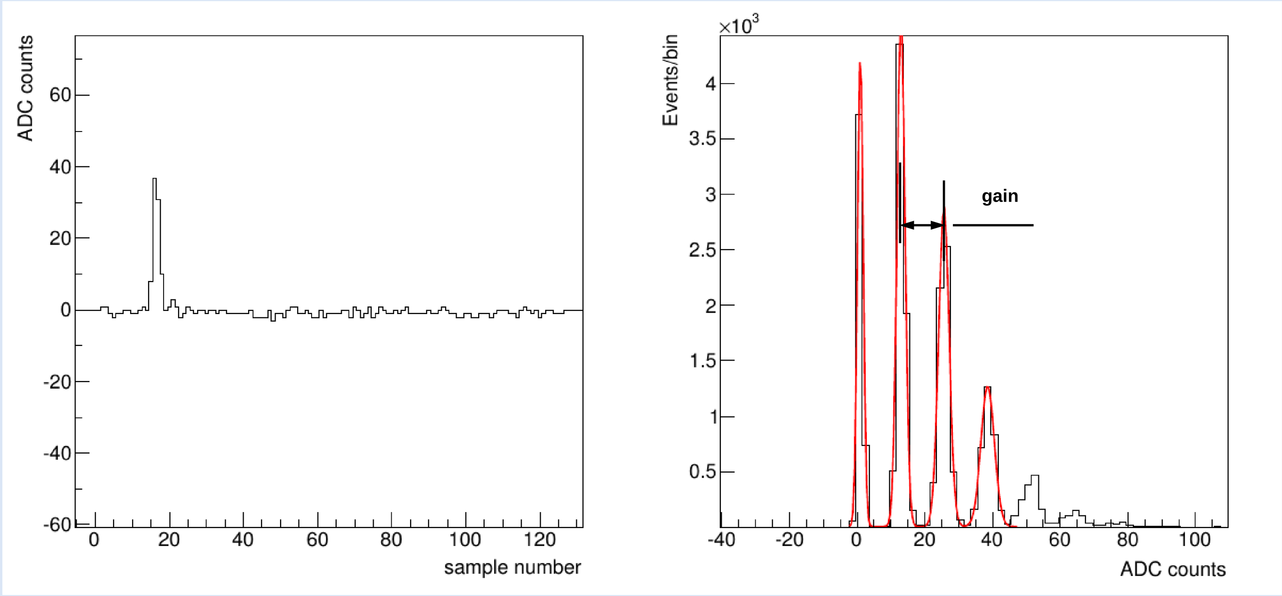
- Two SiPM photodetectors are placed at each end of a CRV counter. This is needed: (1) to obtain the required photostatistics, (2) for calibration purposes, and (3) to provide redundancy. The sum of the two photodetectors on each end should provide a photoelectron (PE) yield of at least 25 PE/cm from a muon at one meter from the counter end in order to keep the CRV system efficiency at the required level of 99.99% .
- The SiPM noise rate at the largest expected dose must allow single photoelectrons to be identified so 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 a 1 T magnetic field.

I-V scans



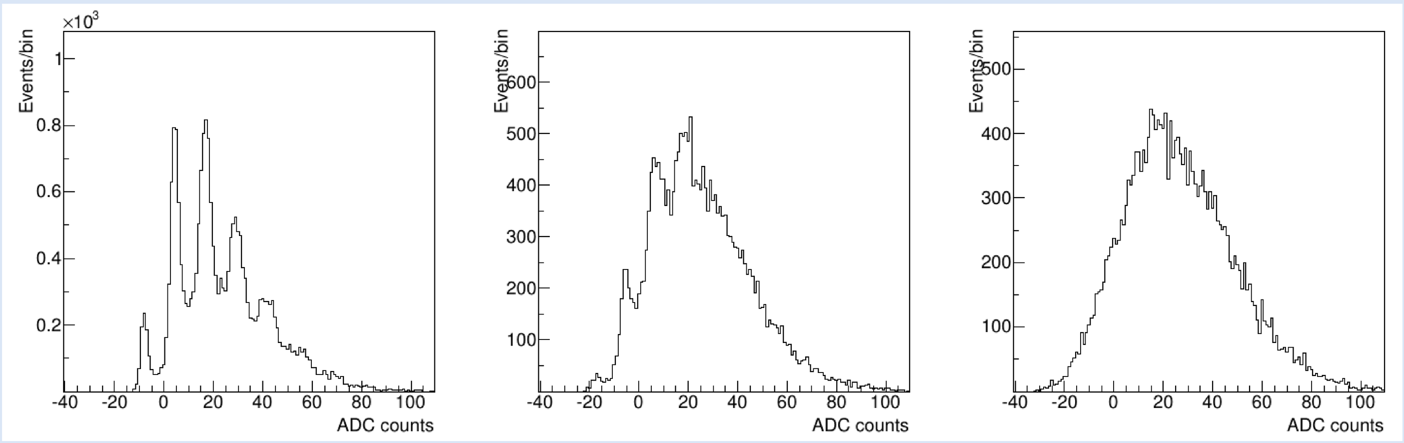
Left: I-V scans for 2.0x2.0 mm^2 SiPM sets irradiated with $5x10^9$ p/cm^2 (blue), $1x10^{10}$ p/cm^2 (green), $2.5x10^{10}$ p/cm^2 (orange), $5x10^{10}$ p/cm^2 (red) and non-irradiated (black). Right: ratios of current measurements for 2.0x2.0 mm^2 with respect to the non-irradiated scan, plotted starting at roughly 0.5V above the breakdown voltage.

Signal waveform and photoelectron spectrum



The signal waveform (left) and the single photoelectron (PE) spectrum (the histogram of ADC counts in the signal bin of the waveform) from non-irradiated 2.0x2.0 mm^2 SiPM illuminated with an 11 ns LED pulse. Each peak corresponds to a specific number of photo-electrons starting from zero (pedestals). The distance between peaks defines the gain of the device.

PE spectra of irradiated sensors



The PE spectra from 2.0x2.0 mm^2 SiPMs after exposure to $5x10^9$ p/cm^2 (left) , $1x10^{10}$ p/cm^2 (center) and $2.5x10^{10}$ p/cm^2 (right) fluxes. At the $2.5x10^{10}$ p/cm^2 irradiation level PE peaks are no longer visible.

Radiation Damage Measurement

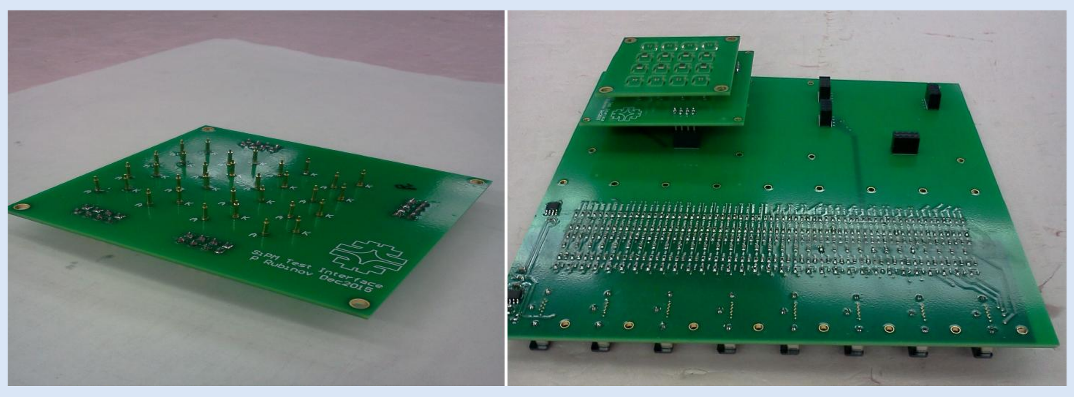
- The single photoelectron spectrum, the response to a LED pulse, the dark count rates at thresholds of up to ~5.5 PE, and the SiPM current as a function of applied bias voltage (I-V scans) were measured for 40 (five sets of eight) non-irradiated 2.0x2.0 mm^2 devices.
- One set of sensors was not irradiated while the other four packs were exposed to different doses of 200~MeV protons in the range [$5x10^9$ p/cm^2 , $5x10^{10}$ p/cm^2] at the Northwestern Proton Therapy Facility in Warrenville, IL.
- Post-irradiation, the sensor sets were annealed. Annealing was accelerated by holding the sensors at 60° C for 80 minutes, correspond to about ten days of room temperature annealing. The performance measurements were then repeated.
- For testing and irradiation the SiPMs were mounted on carrier boards. Electrical contact with the carrier boards was made through a passive board populated with pogo-pins. Each SiPM set was placed in a light-tight box to take measurements with and without LED (type LED5-UV-400-30).

Hamamatsu S13360-2050VE specification

All values at 25° 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/°C

Part Number: S13360-2050VE



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

Summary

- I-V curves, noise rates, gains, and LED response of Hamamatsu 2.0x2.0 mm^2 SiPMs were measured before and after irradiation with proton beams
- Both the current and noise rates increased with radiation dose. A threshold of 5.5 PE is required to obtain a 200 kHz noise rate at a dose of $5x10^{10}$ p/cm^2.
- Gain, as measured by the separation of PE peaks, increases with overvoltage and is independent of dose.
- At doses above $1x10^{10}$ p/cm^2 PE peaks become increasingly difficult to extract, and the calculation of the gain becomes difficult because of the increase of noise with dose.

Acknowledgments

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