R&D ideas for CRV at Mu2e-II

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Mu2e and Mu2e-II Proton Beam Parameters

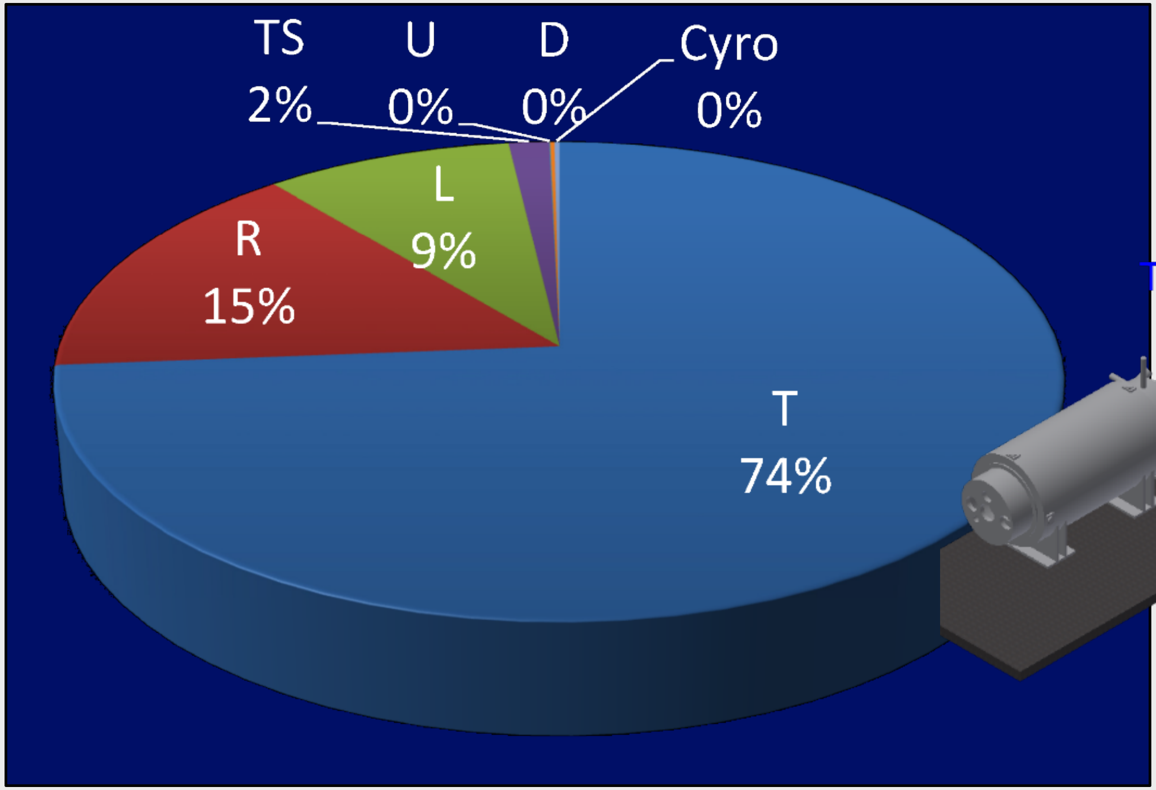
Parameter	Mu2e	Mu2e II	Units
Total Protons on Target (3 yr)	4.7×10^{20}	5.2×10^{22}	protons
Pulse Repetition Rate	590	500 - 1250	kHz
Time Between Pulses	1695	800 - 2000	nsec
Pulse Base Width	250	100	nsec
Extinction Level	10^{-10}	10^{-11}	
Average Intensity per Pulse	3.9×10^{7}	1.4×10^{9}	protons/pulse
Pulse-to-Pulse Intensity Variation	<50	<10	%
Beam Kinetic Energy	7946	800	MeV
Beam Power	7.3	100	kW
Duty Factor	25	90	%

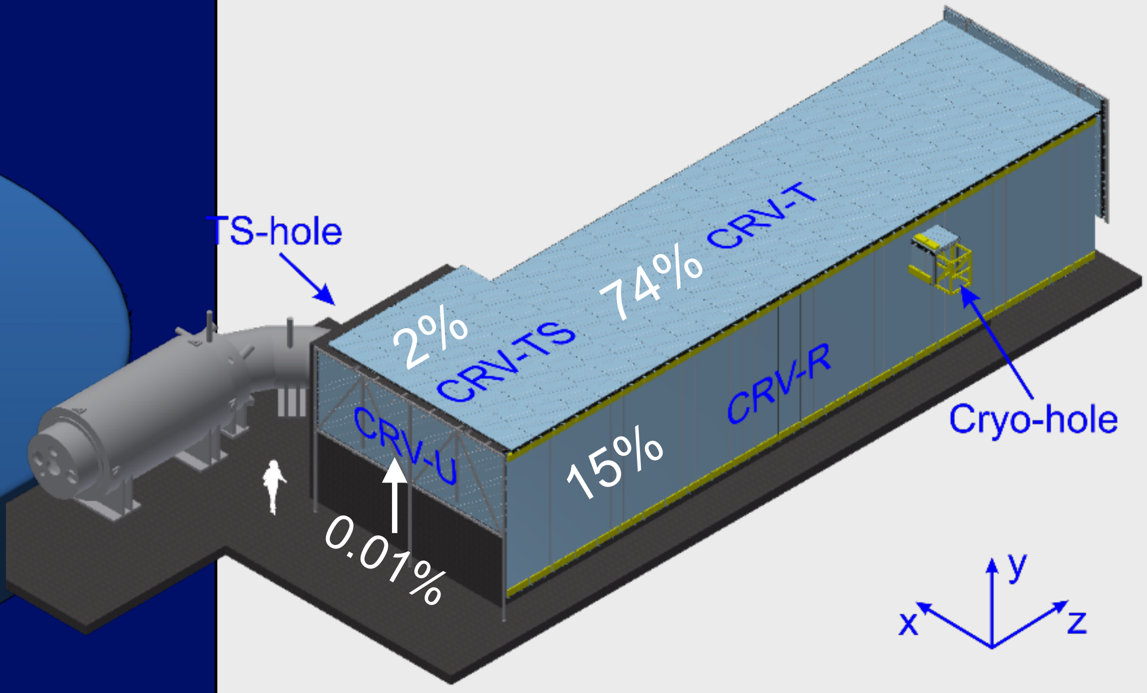
NOTEs:

- Blue numbers are calculated from the other parameters.
- Total POT assumes 63% accelerator up-time (2×10^{7} sec/yr)

CR background: CRV coverage

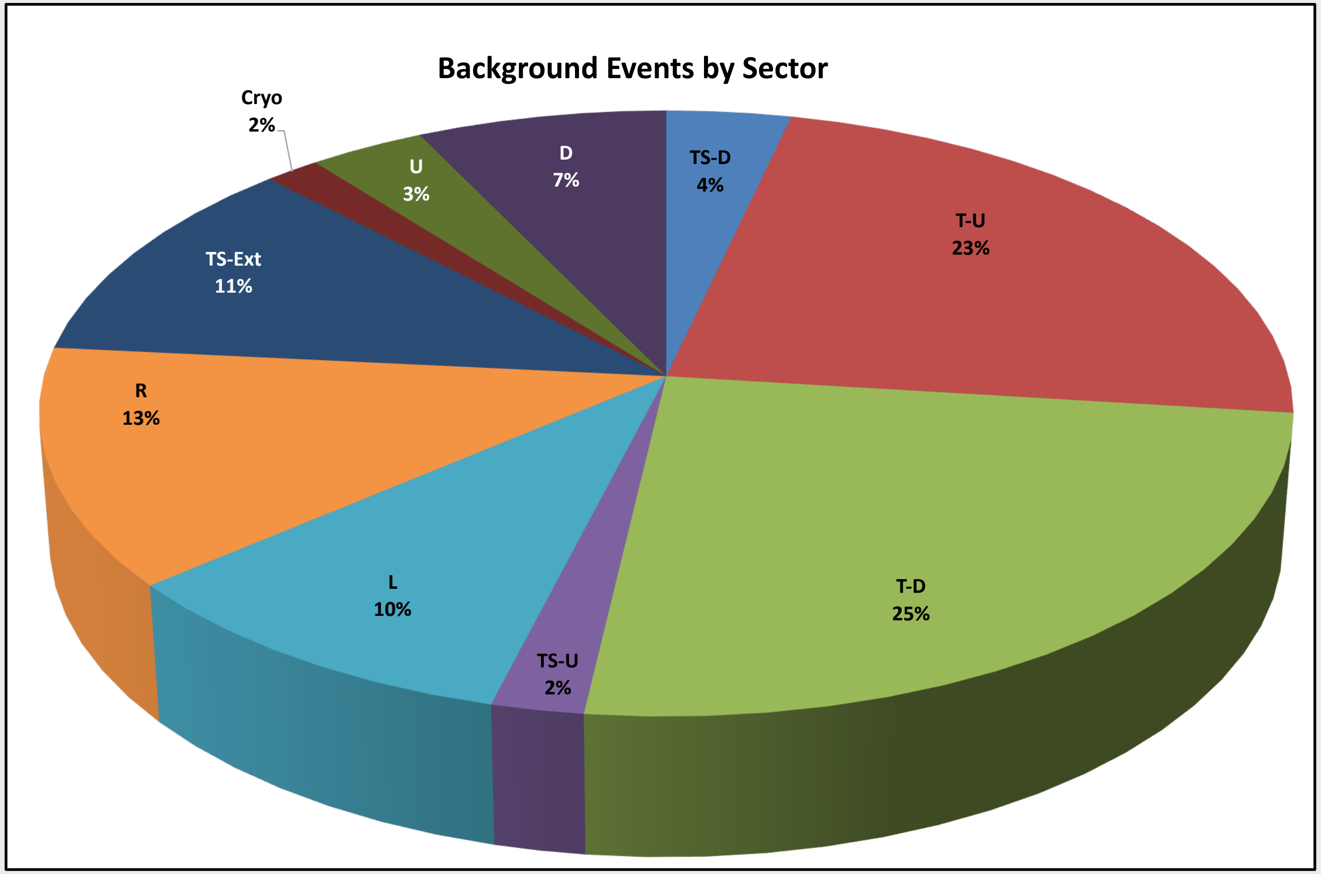
- CRV needs to reject 780 events over its lifetime
- Dominant (74%) fraction of muons enter from from the top
- Other CRV regions reject much smaller fraction of muons, and require much smaller efficiencies
- CR background component : 0.075 events





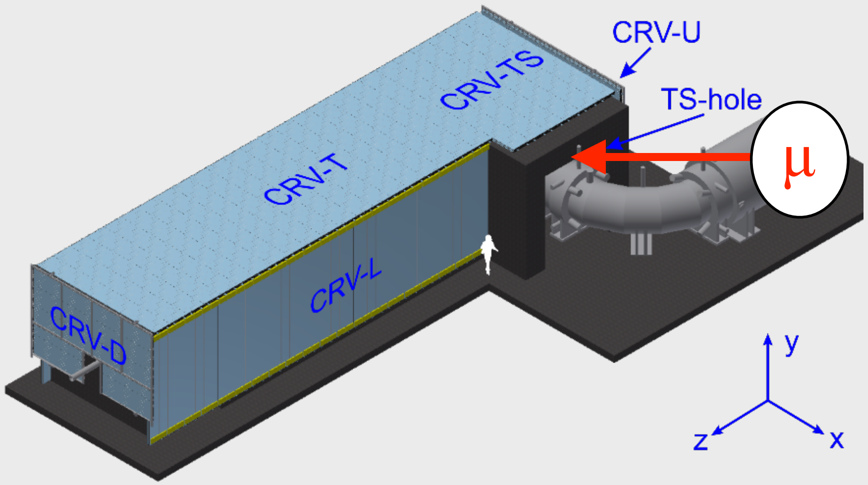
CR background: CRV coverage

- We optimize coincidence requirements such that critical CRV regions have the highest efficiency possible
  - CRV-Top efficiency is > 99.99%
  - CRV-U efficiency is ~ 5%
- Dominant contribution comes from CRV-Top, CRV-L and CRV-R

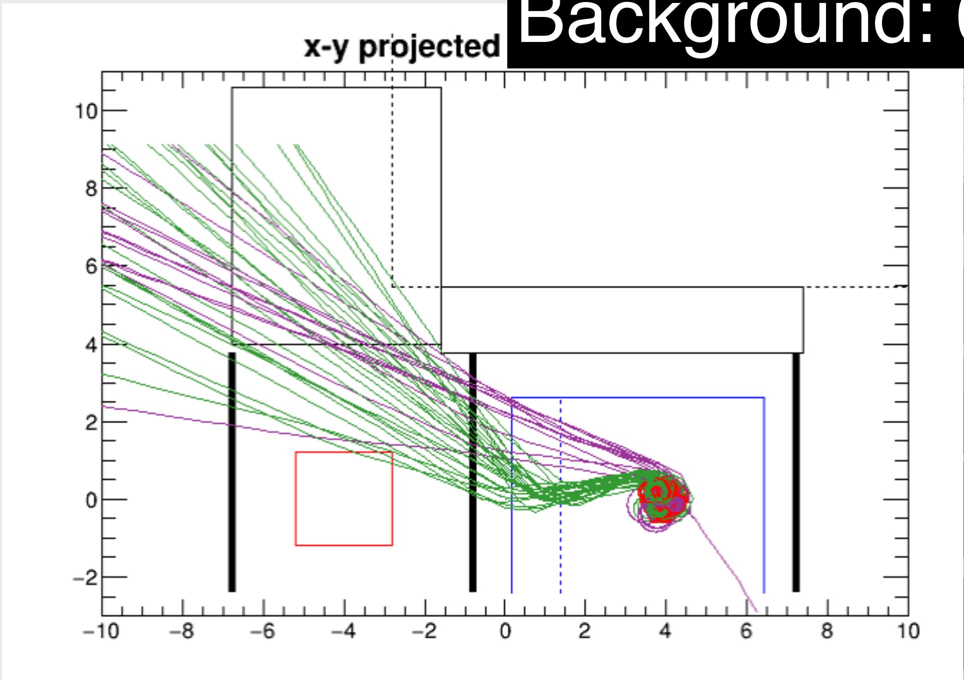


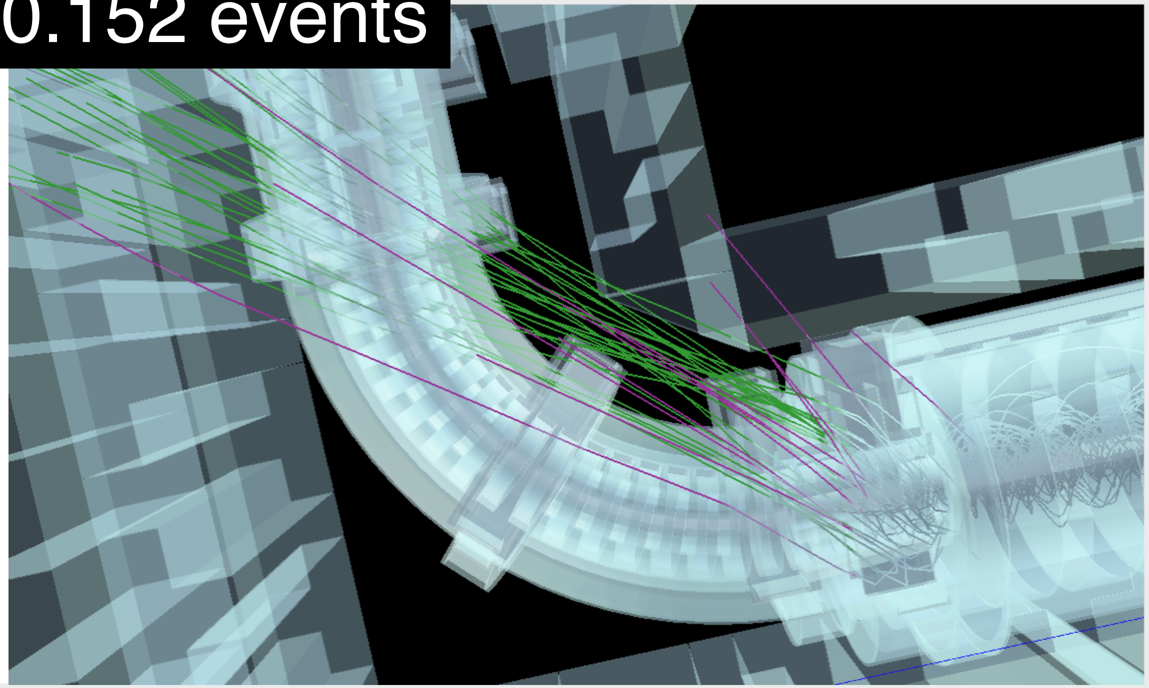
CR background: No CRV coverage

- A special simulation of events going through the TS hole with 257X the total live time (770 years) we found 39 events that mimic conversion electrons
- This was the largest background for Mu2e
- Two-thirds of this component can be reduced by absorbers and CRV-TS extension



Background: 0.152 events





Cosmic Ray estimates for Mu2e-II

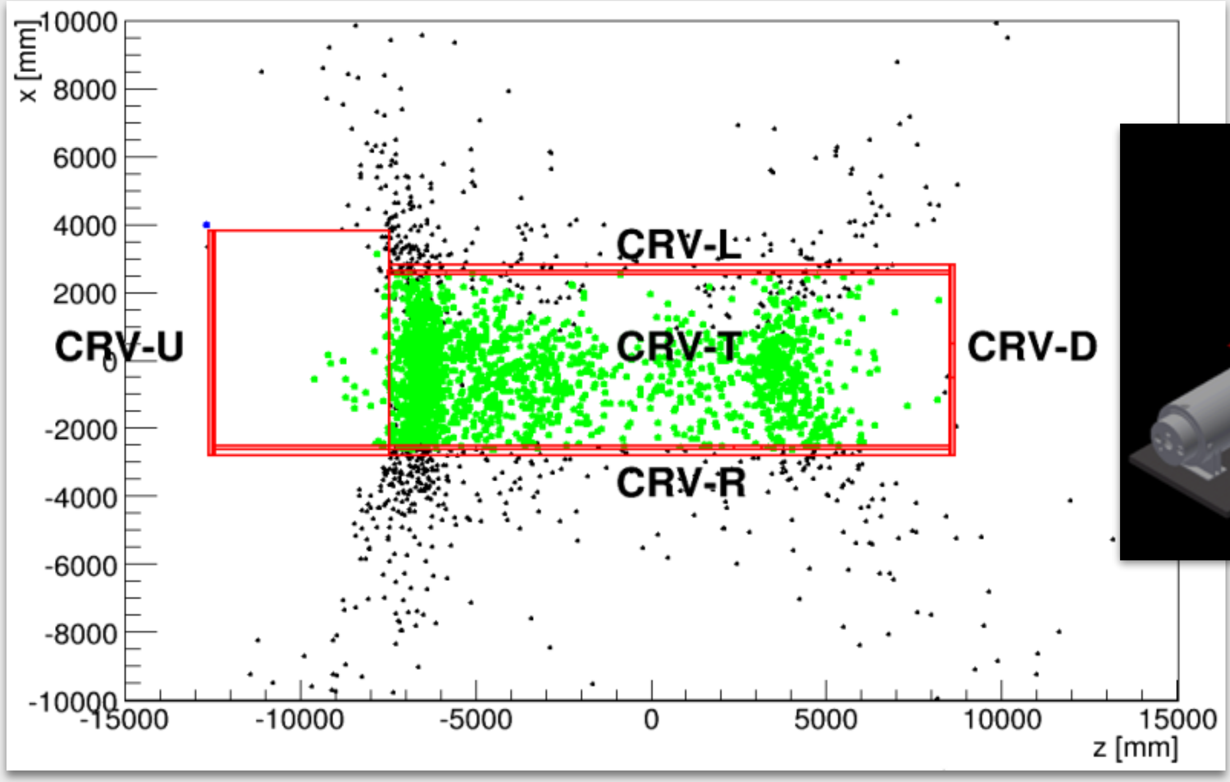
- CR background estimate for Mu2e-I (docdb-7464):
  - Total: 0.247
  - CRV coverage: **0.075**
  - No CRV coverage: **0.152**
    - has been recently reduced to 0.05
  - Updated total CR background is 0.125 = **0.075** + **0.05**
- Mu2e-II will operate at x3 higher duty factor
  - Expected CR background at Mu2e-II: 0.375 = **0.225** + **0.15**
  - Assumed CR background at Mu2e-II: 0.16

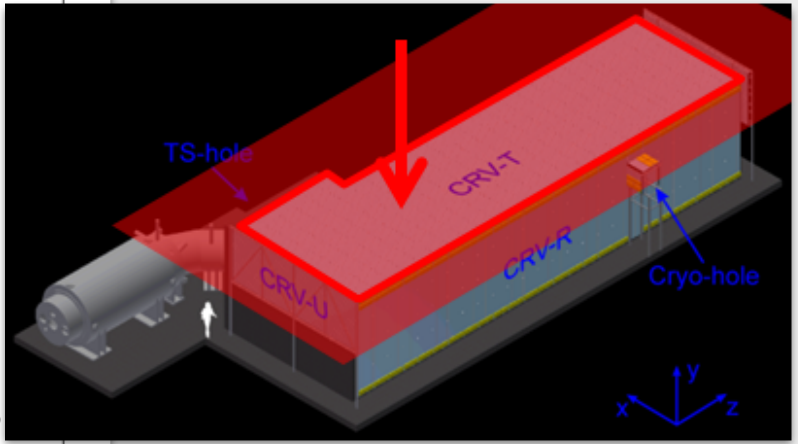
Category	Source	Events (Al)	Events (Ti)
Intrinsic	μ decay in orbit	0.26	1.19
	Radiative μ capture	<0.01	<0.01
Late Arriving	Radiative π capture	0.04	0.05
	Beam electrons	<0.01	<0.01
	μ decay in flight	<0.01	<0.01
	π decay in flight	<0.01	<0.01
Miscellaneous	Anti-proton induced	--	--
	Cosmic ray induced	0.16	0.16
Total Background:		**0.46**	**1.40**

Table 1: Estimated background yields for the Mu2e-II experiment assuming an aluminum (Al) or a titanium (Ti) stopping target. These studies were performed for a proton beam energy of 1 GeV. The total uncertainty is about 20%. Reproduced from arXiv:1307.1168. Note that, unlike in the case of aluminum, the titanium analysis has not yet been rigorously optimized.

Improving CRV efficiency

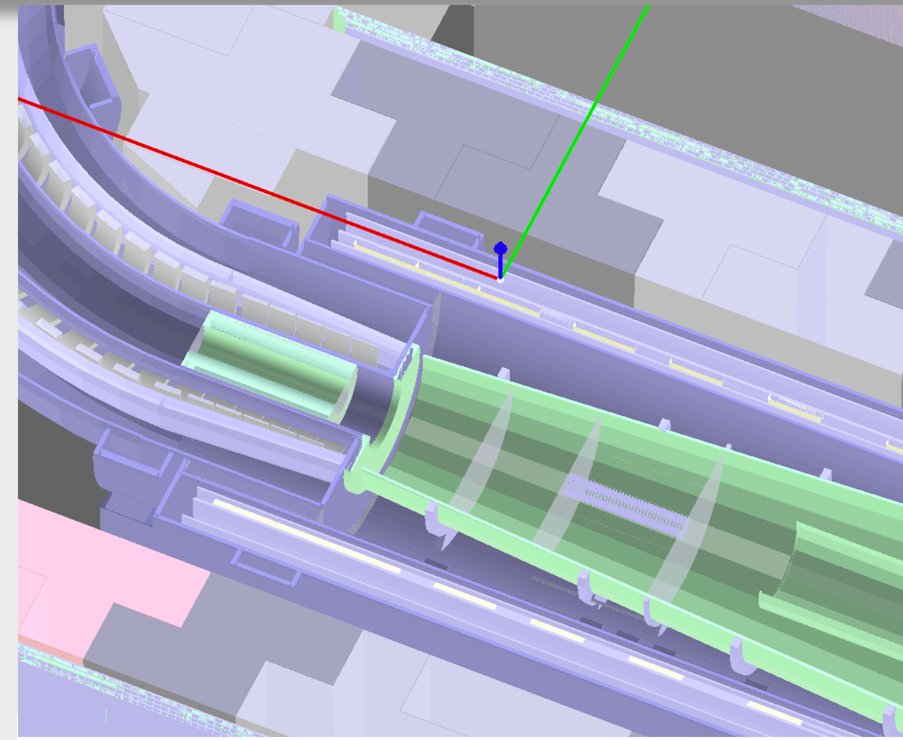
- The dominant fraction of CR background enters through CRV-Top in stopping target and calorimeter regions
- CRV inefficiency is driven by the gaps between di-counters and modules
  - Build modules with reduced gaps: remove shims between di-counters, shim strong-backs
  - Additional CRV coverage between module gaps
- Higher light yield will further improve efficiency
  - Fill counters with silicon/epoxy in a critical regions
- Other high efficiency veto detector technology?

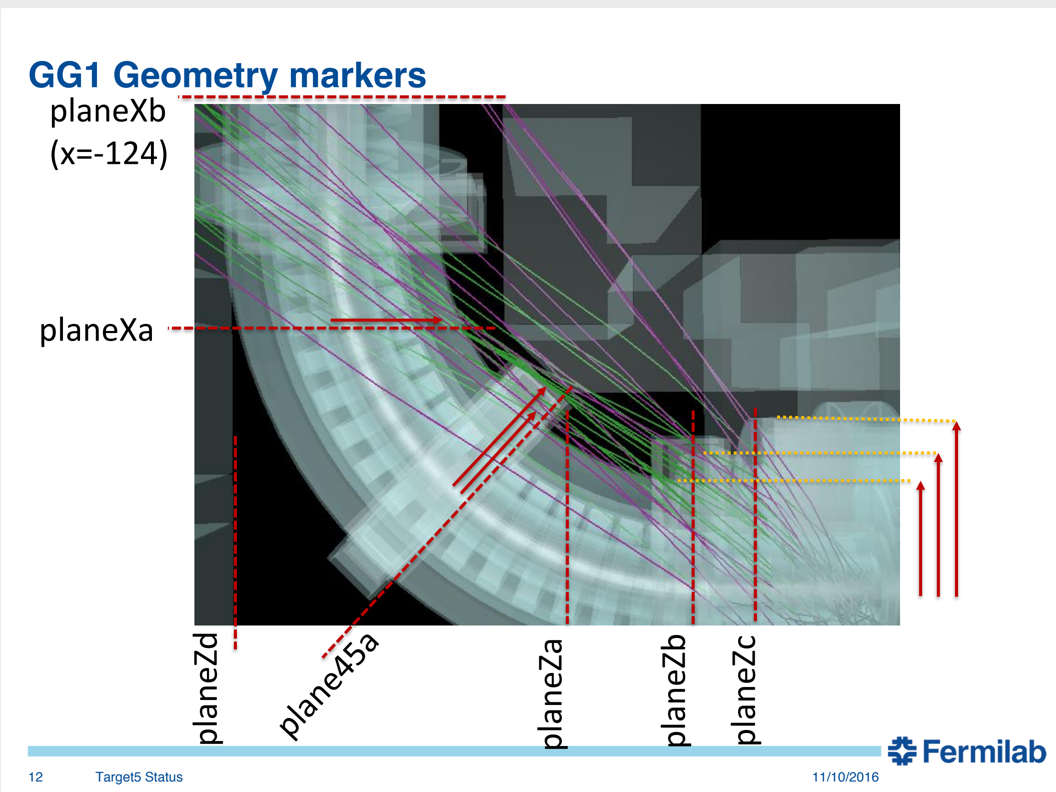


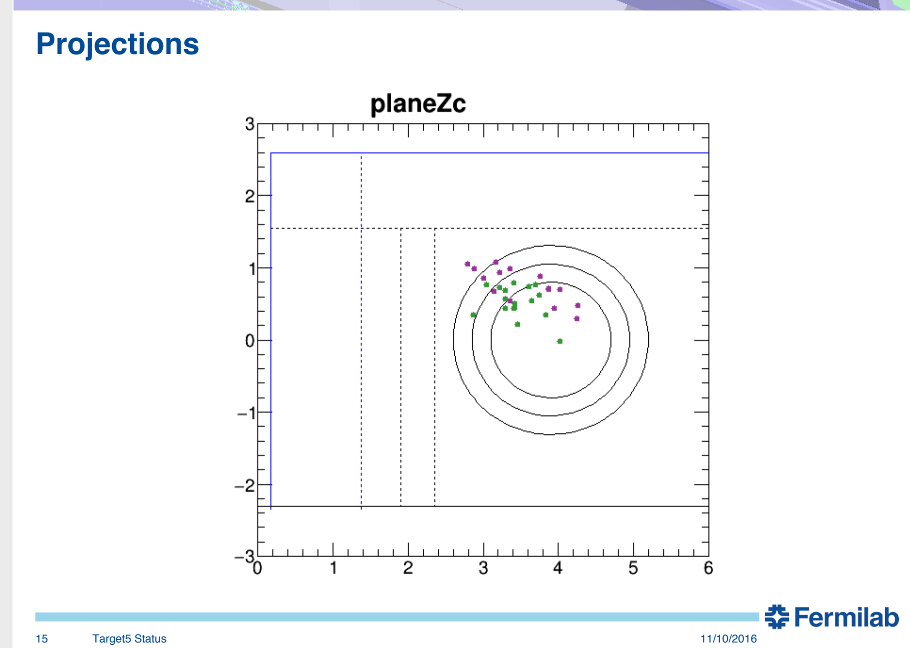


Reducing irreducible

- CR background entering through TS hole is a major background at Mu2e-II
- We currently reduce this background with passive absorbers
- We can consider:
  - Additional passive absorbers
  - CRV along the beam-line or inside DS

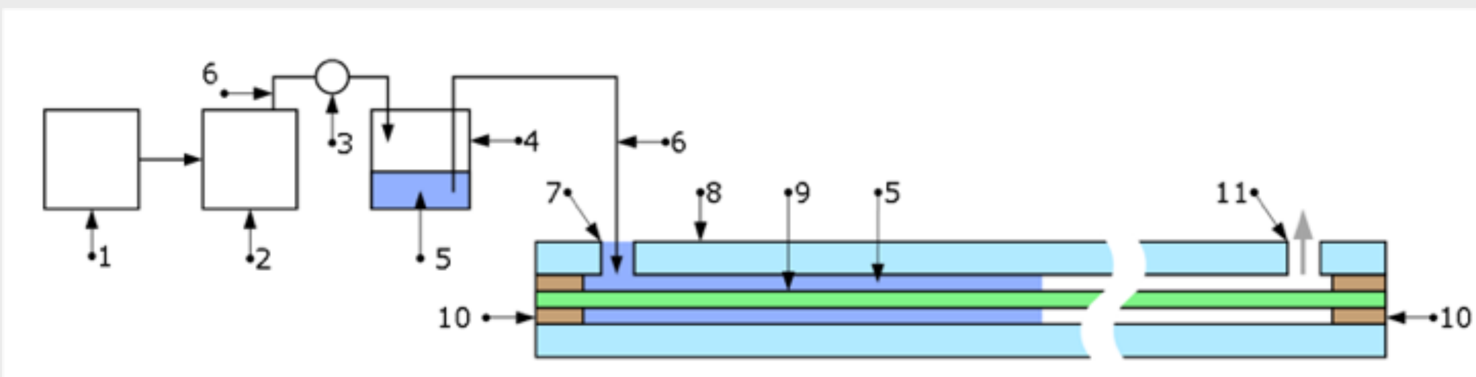


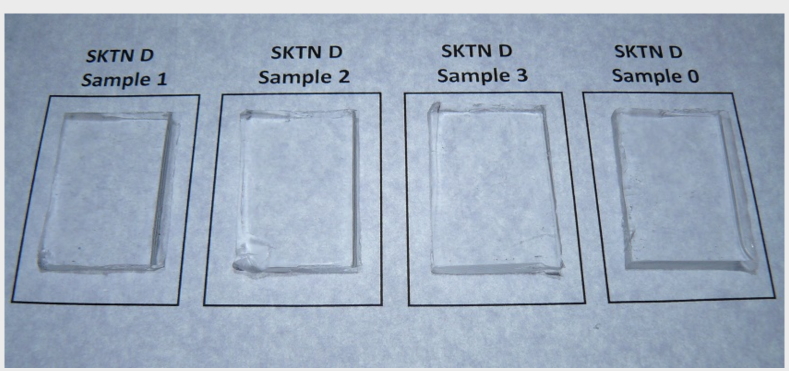


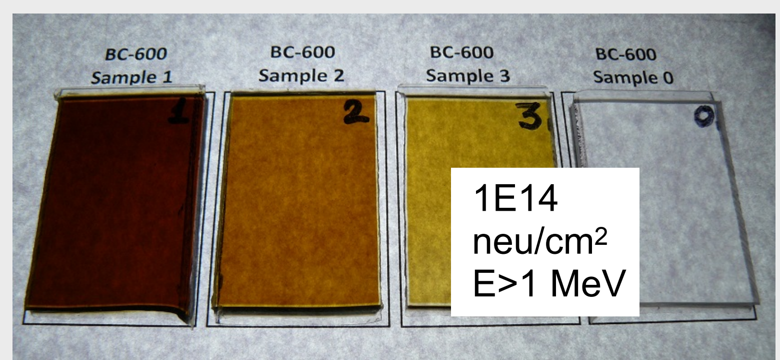


Filling counters

- Dubna/UVa group has developed a plan to fill counters with silicone resin
- The light yield improves by 40% after filling
- Silicone is rad hard, unlike BC-600
- Natural aging doesn't show any transparency degradation of silicone resin
- Silicone resin remains liquid which might leak during modules production
- Find a filler that solidifies at filling holes: UV cured epoxy, BC-600 with hardener at holes only…
- Fillers need to be tested for rad hardness and aging







1E14 neu/cm^2 E>1 MeV

Rates and dead-time

- Currently, there is a bug in art that prevents me from estimating CRV rates and dead-time. Rob is working on a fix
- From previous studies, neutron/gamma fluxes at Mu2e are expected to be higher by a factor of 2-3
  - Rates in CRV-U and CRV-Ext regions are > 1 MHz
    - Investigate finer (2x2.5 cm) granularity CRV
    - Other CRV technology?
  - Dead-time is >10% and sensitive to beam intensity fluctuations
  - Enhanced shielding
    - More effective concrete shielding
    - More effective shielding at PS. Tungsten HRS will be beneficial against fast neutrons

CRV Aging

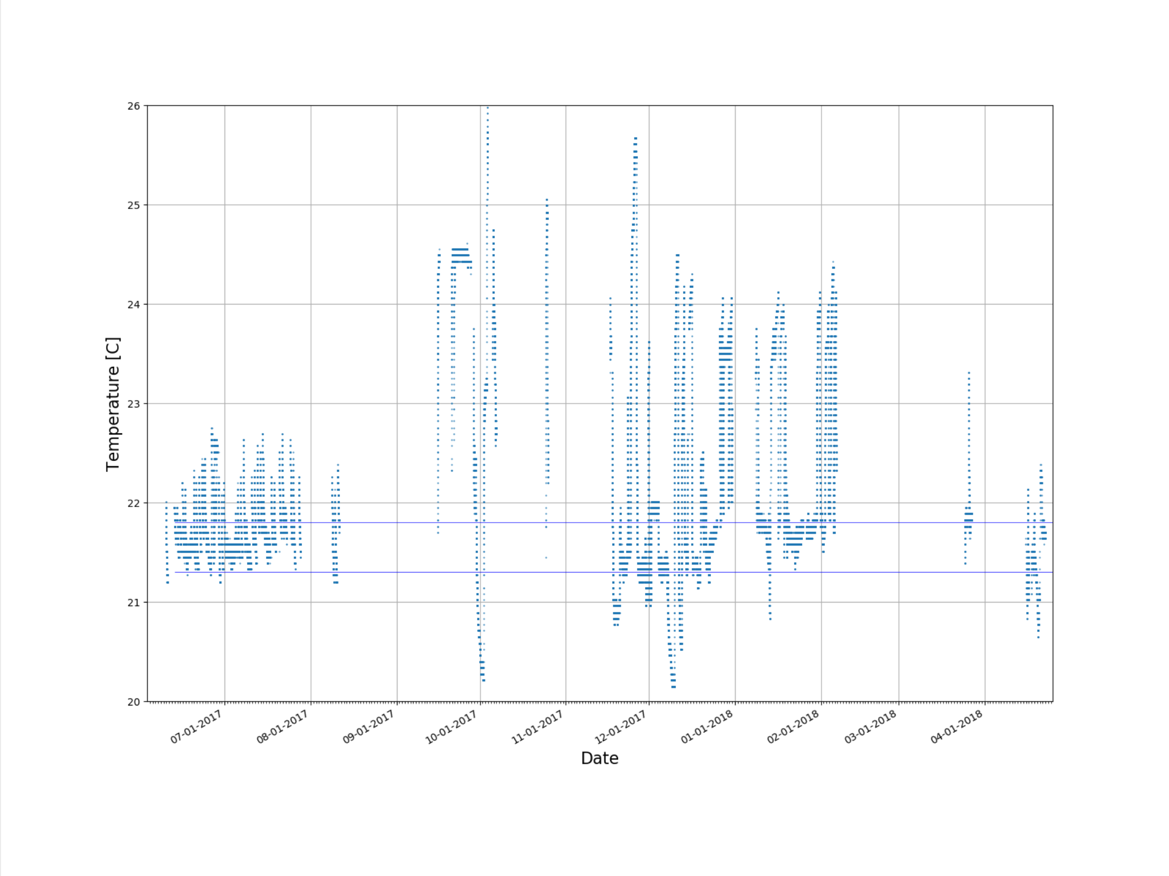
- Polystyrene aging can be caused by various phenomena: oxidation, crazing due to stress dissipation, interaction with solvents in air
- We've been studying CRV di-counters aging:
  1. Natural aging using source yields 10% aging in the first year
  2. Natural aging at the test beam yields 10% aging in the first year
  3. Accelerated aging yields
     - 5% aging in the first year
     - 2% aging average rate over 10 years
- Plans:
  - Continue measuring the aging rate
  - If counters keep aging at 10%/year, we need to consider rebuilding CRV for Mu2e-II
  - Identify and address the dominant process responsible for aging

Backup

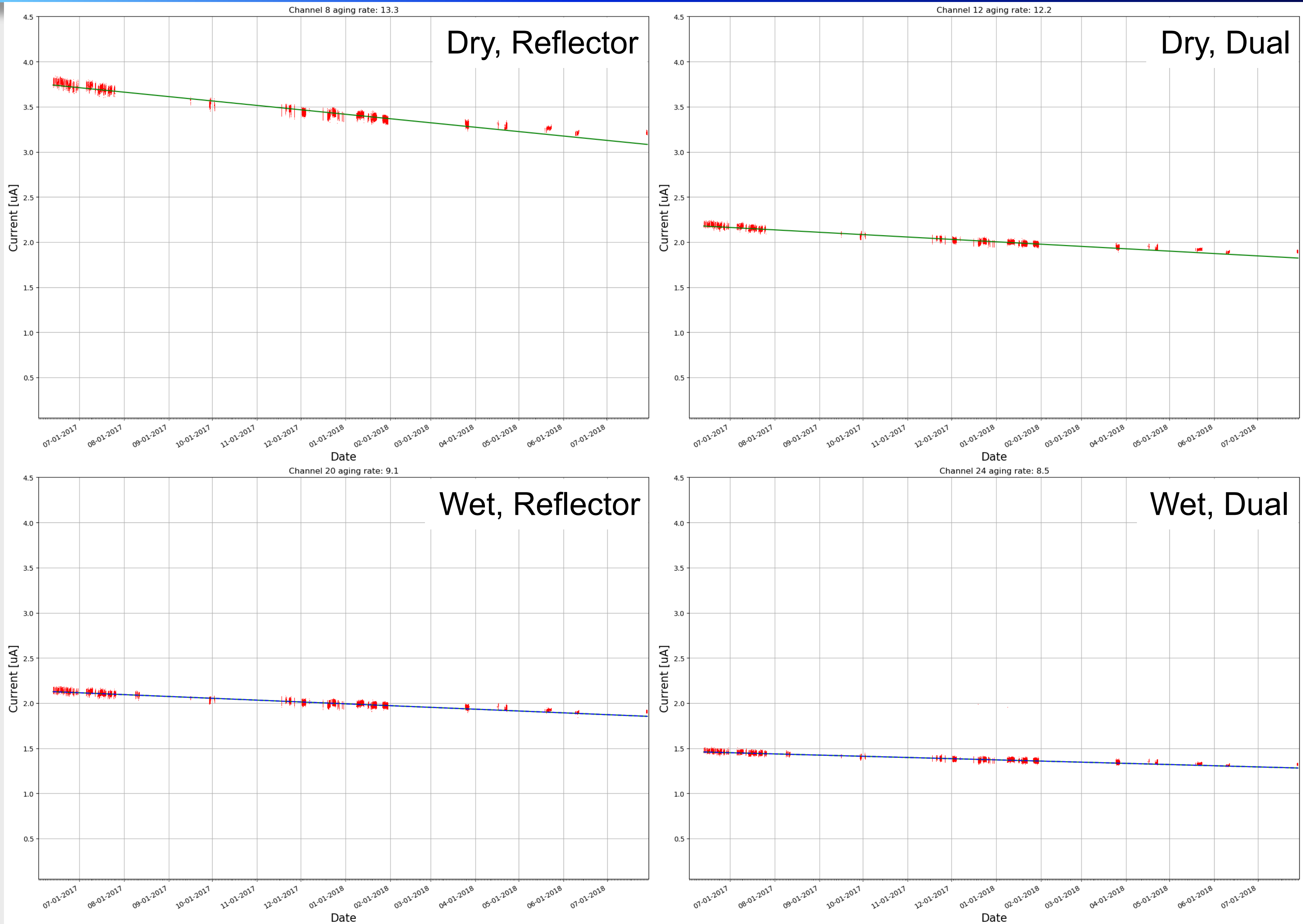
Natural aging setup

- Assembled 3m long di-counters in 2017
  - Dry counters
    - 1st - baseline CRV counter with a reflector on one side
    - 2nd - baseline CRV counter with a dual readout
  - Wet counters
    - 3rd - counter holes are filled with resin and reflector on one side
    - 4th - counter holes are filled with a dual readout
- Occasionally put Cs-137 (1 mCi) to measure SiPM currents

- Collected the data starting from July 2017
- Considered only the data that is within a temperature range of [21.3; 21.8] C
- Look at current (dark current subtracted) trend vs time to extract the aging rate

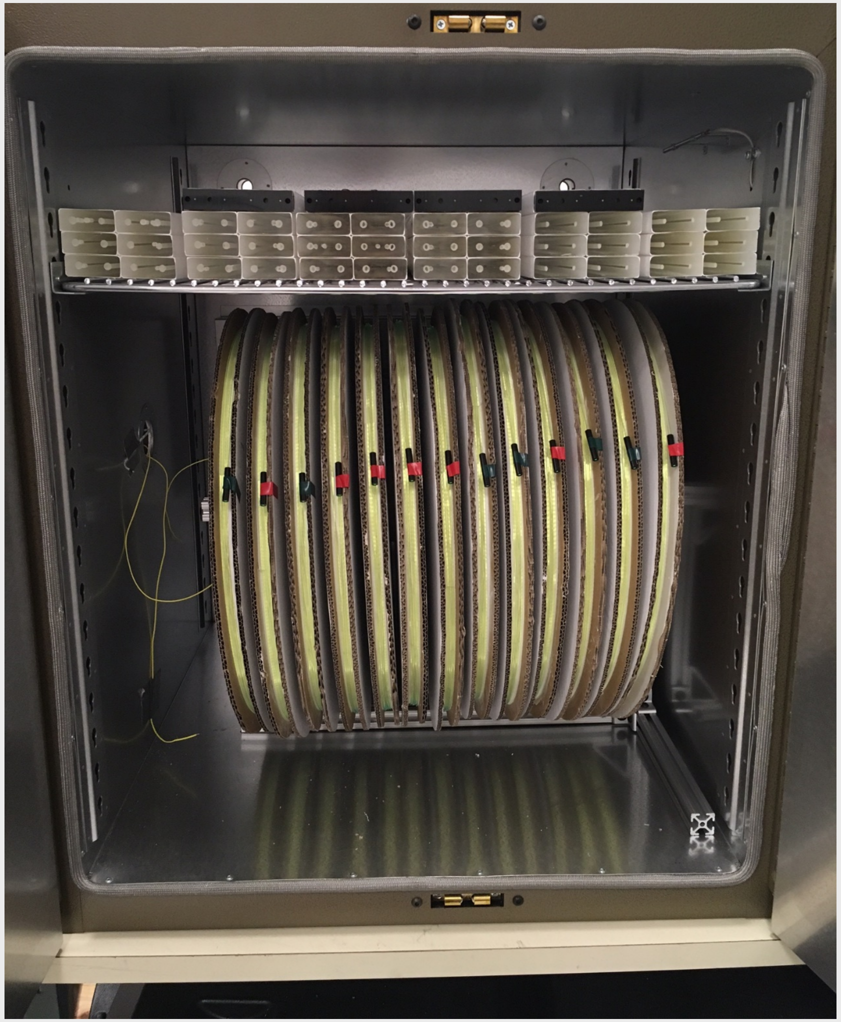


Currents for dry counter with reflector



Accelerated aging

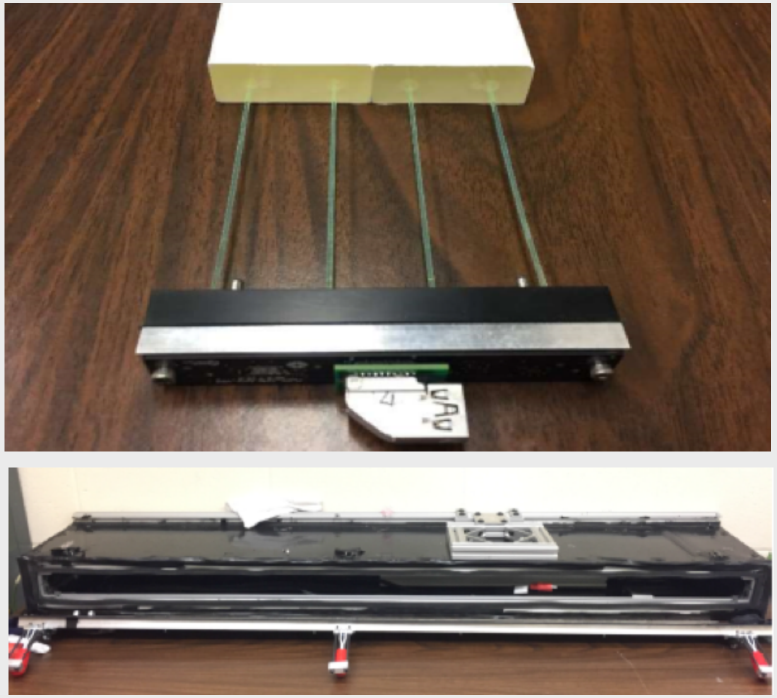
Setup



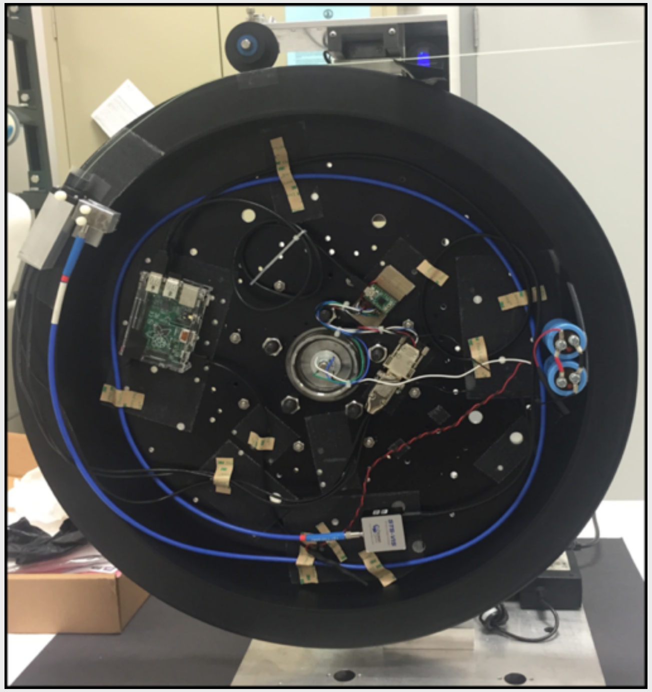
- Twelve dicounter and fiber samples were put in an oven for aging.
- One sample of each set was removed periodically to have multiple data points through time.

Accelerated aging

Measurement



Dicounter measurement apparatus



Fiber measurement apparatus

- After all samples were removed from the oven, they were measured.
- The light yield from the dicounters was measured with a removable jig made of fibers attached to the counter electronics to ensure consistency.
- The output current from the electronics was used to indirectly measure the light gain from the dicounters.
- The light through the fibers was measured using a rotating drum to obtain light as a function of distance.
- The light gain was measured using a photodiode outputting ADC counts.

Accelerated Aging of Polystyrene

- The fiber and dicounter aging can be accelerated by heating samples in an oven.
- An aging factor between the heated samples and a sample kept at a reference temperature can be found using the Arrhenius equation:

$$f_{aging} = e^{\frac{E_a}{R}\left(\frac{1}{T_{ref}} - \frac{1}{T_{high}}\right)}$$

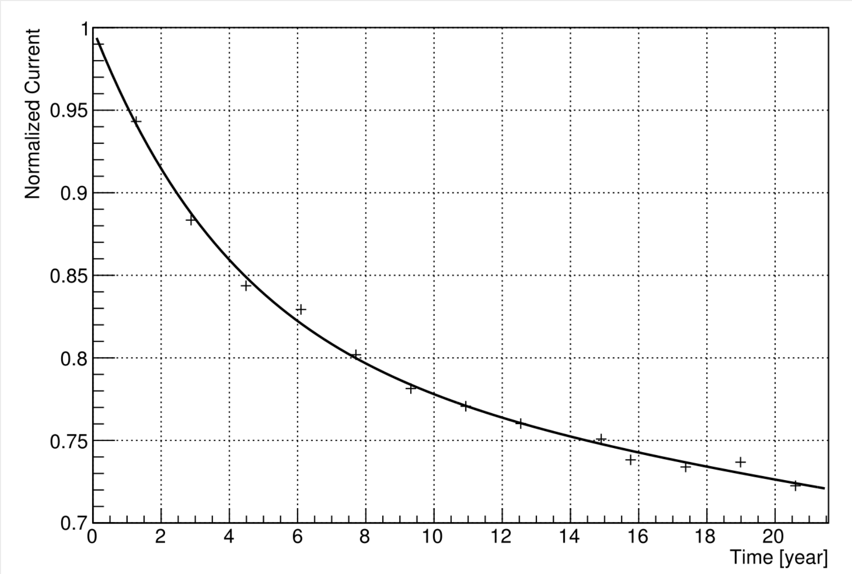
- E_a is the activation energy of the reaction, and R is the universal gas constant.
- Using the aging factor, the effective aging time can be found:

$$time_{eff} = f_{aging} * time_{in\ oven}$$

Accelerated aging

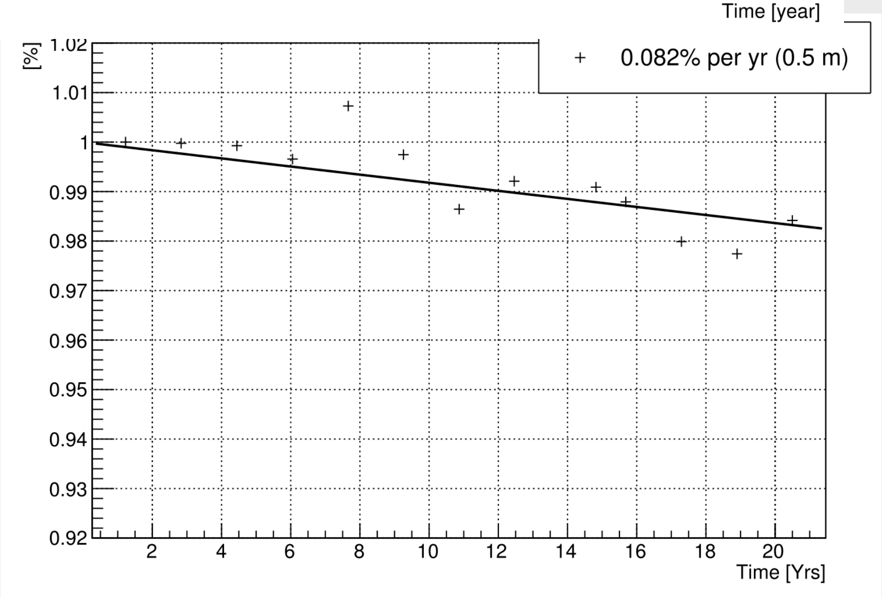
Results

- After measurement, the samples were normalized to their initial values and plotted vs effective time



The dicounter aging fit a double exponential, indicating a non-constant decay.

The aging is 8% in the first 2 years (4% per year avg) but 23% in the first 10 years (2.3% per year avg).

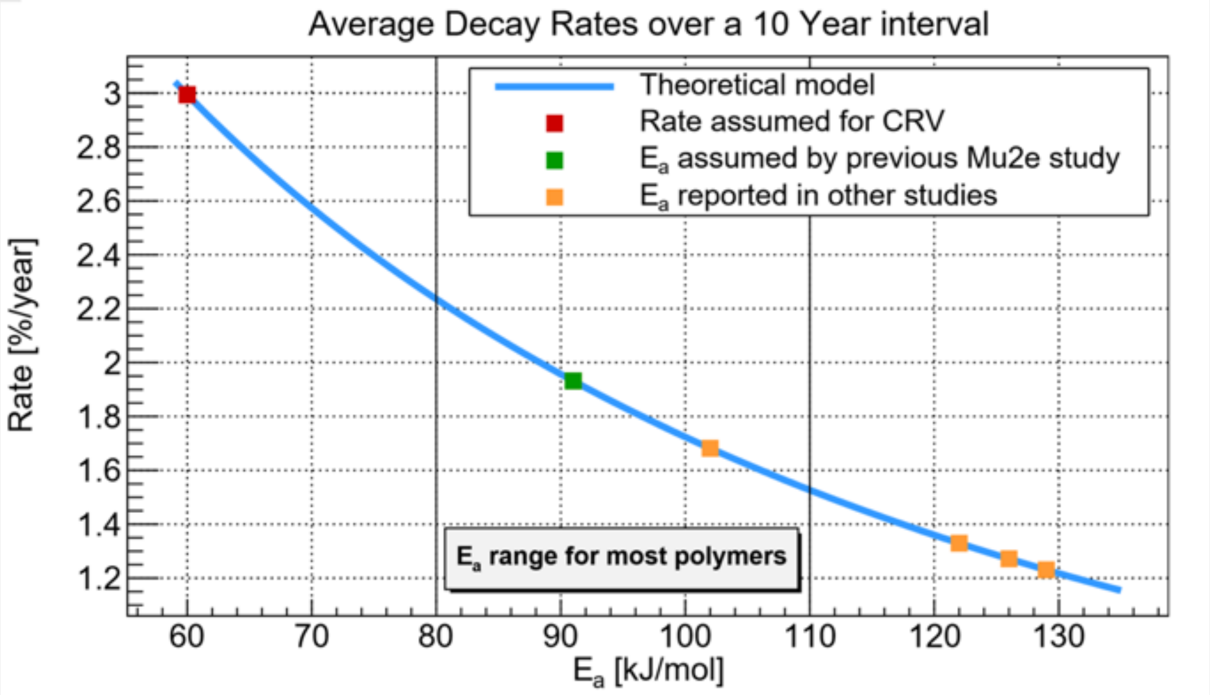


The fiber aging fit with a simple exponential.

The fiber aging is trivially small — less than 1% aging per year.

Conclusion

- The dicounter aging has a non-constant decay with a transient fast component and a persistent slow component.
- The current estimate for aging is 30% aging after 10 years, however the studies show 23% aging.
- The activation energy is not well known, the plot below shows the decay rate as a function of activation energy.



The curve was generated by fitting the data for increasing values for activation energies.

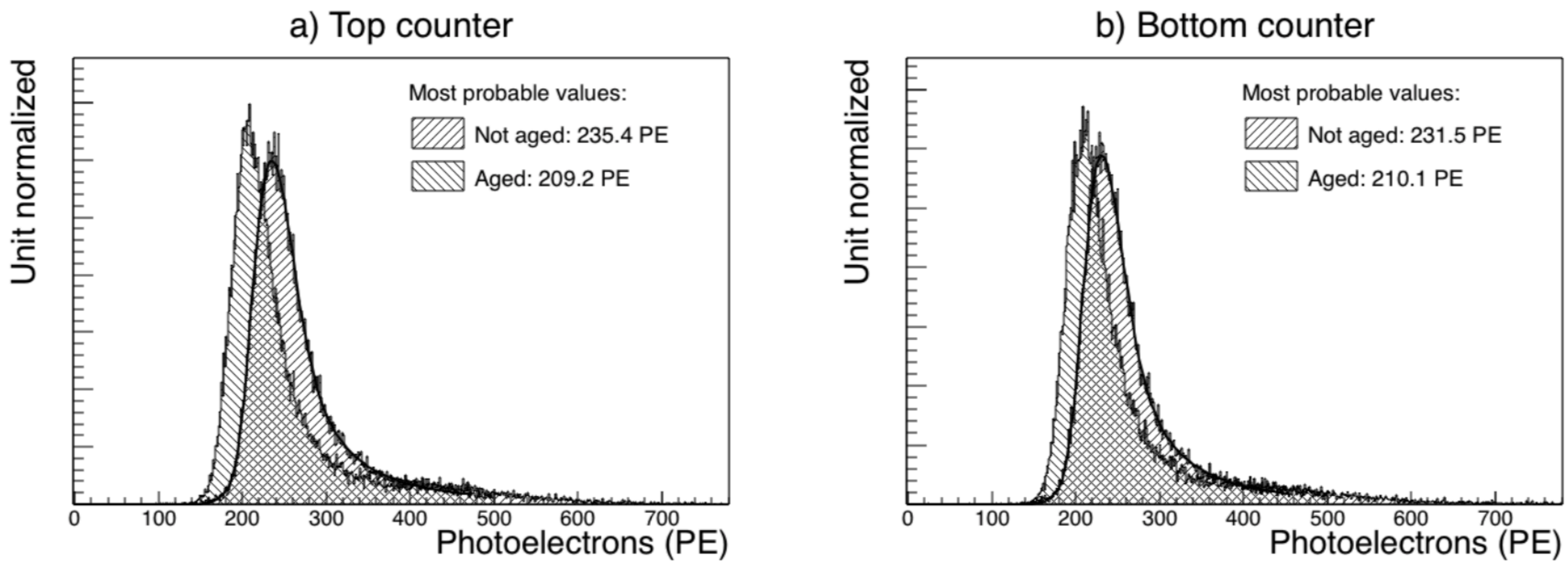


Figure 6. A comparison between the PE distributions for a counter that was used in the 2016 and 2017 test beam run. The result from the top(left) and bottom(right) counters in a dicounter are shown.

	PE Yield	Width	Width / PE Yield	Ratio
Top counter				
2016	235.4	66.0	0.28	
2017	209.2	60.0	0.29	0.89
Bottom counter				
2016	231.5	64.0	0.28	
2017	210.1	60.0	0.29	0.91