Mu2e-II Calorimeter: Overview & Requirements

Workshop on a Future Muon Program At Fermilab
March 28, 2023

L. Morescalchi

Mu2e-II Calorimeter Session

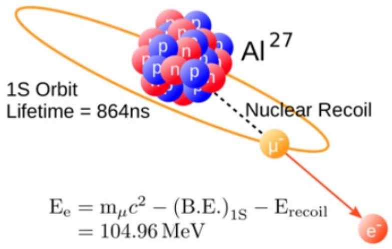
	Introduction	*Luca Morescalchi*	*469, Lauritsen*	08:30 - 09:00
09:00	**Crystals - 1**	*Ren-Yuan Zhu*	*469, Lauritsen*	09:00 - 09:30
	Crystals - 2	*Yury Davidov*	*469, Lauritsen*	09:30 - 10:00
10:00	**Photosensors**	*David Hitlin*	*469, Lauritsen*	10:00 - 10:30
11:00	**Alternatives**	*Ivano Sarra*	*469, Lauritsen*	11:00 - 11:30

The Mu2e Experiment

Mu2e searches for the muon to electron conversion in the field of an Aluminum nucleus.

→ CLFV process strongly suppressed in Standard Model: BR ≤10^{-52}

→ Its observation is BSM physics → Goal: 10^4 improvement w.r.t. current sensitivity



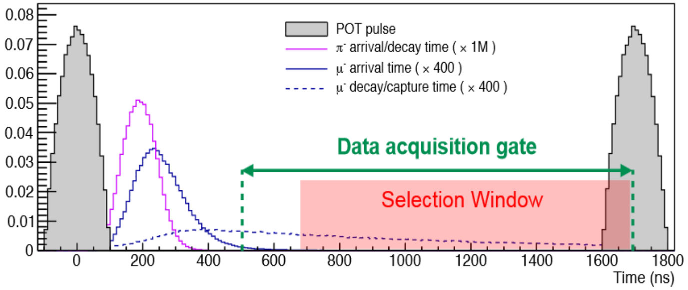
With 10^{18} muon stops — μ-e conversion in the presence of a nucleus

$$R_{\mu e} = \frac{\mu^- + N(A,Z) \rightarrow e^- + N(A,Z)}{\mu^- + N(A,Z) \rightarrow \nu_\mu + N(A,Z-1)} < 8.4 \times 10^{-17}$$

Nuclear captures of muonic Al atoms

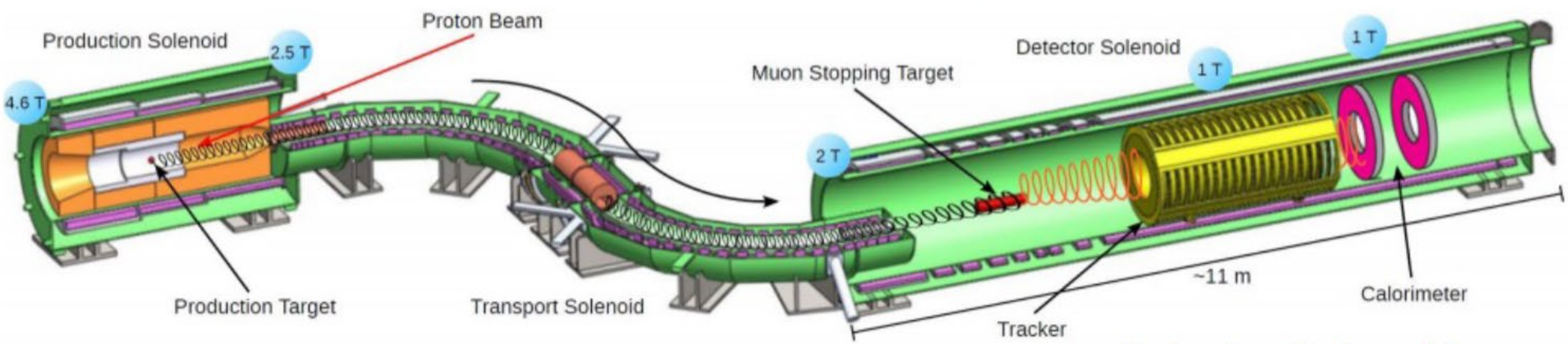
Beam Period: 1700 ns ~ 2 x τ_μ^{Al}

Beam Intensity: 3.9 x 10^7 p/muBunch



- ✗ Low momentum pulsed muon beam stopped in Al target (10 GHz)
- ✗ Muons trapped in orbit around the nucleus
- ✗ $\mu N \rightarrow eN$ signature → **mono-energetic electron @ 105 MeV**

Production & Transport Solenoids

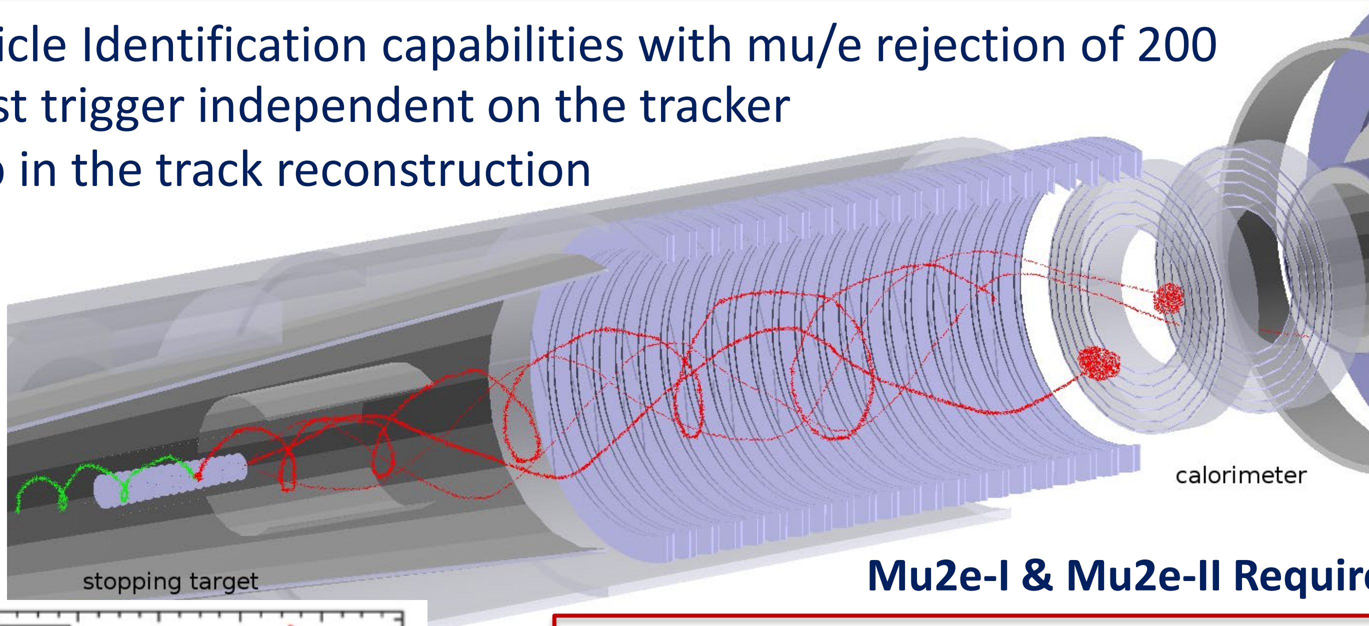


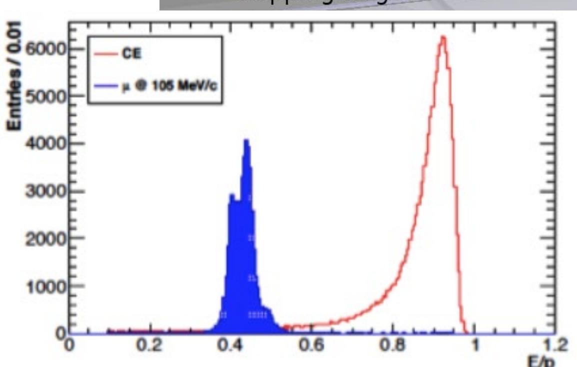
Detector Solenoid

Why a calorimeter in a Mu2e experiment?

For the muon to electron conversion search, the calorimeter adds redundancy and complementary qualities with respect to the tracker:

- Particle Identification capabilities with mu/e rejection of 200
- A fast trigger independent on the tracker
- Help in the track reconstruction



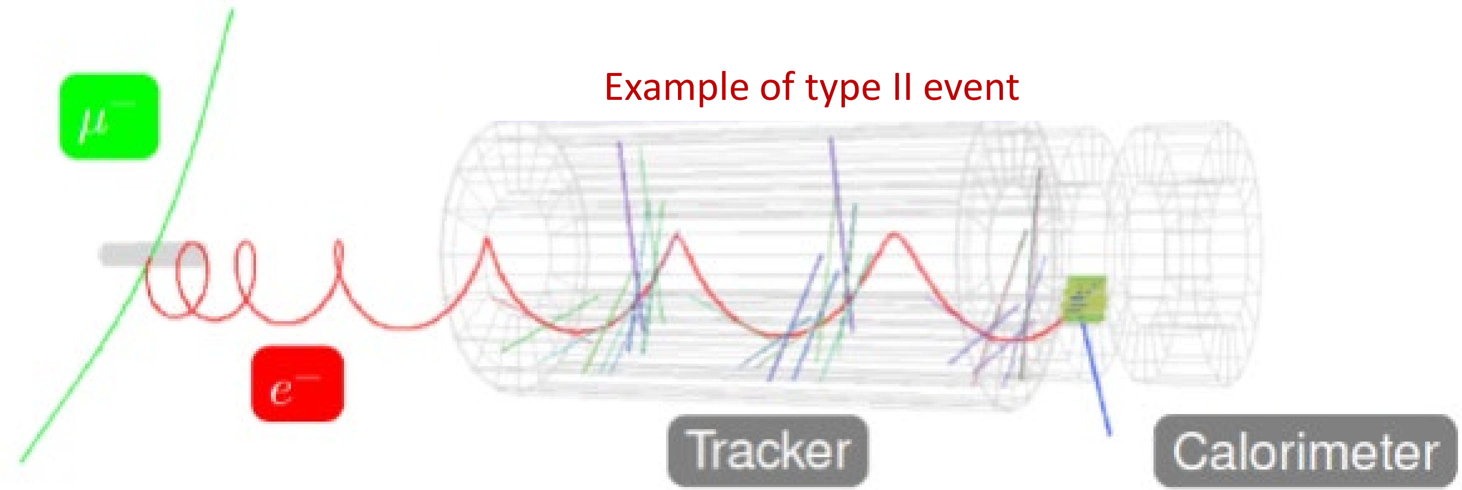


Mu2e-I & Mu2e-II Requirements

→ Provide energy resolution σ_E/E of O(10 %)
→ Provide timing resolution σ(t) < 500 ps
→ Provide position resolution < 1 cm
→ Work in vacuum @ 10^{-4} Torr and 1 T B-Field
→ Survive the harsh radiation environment

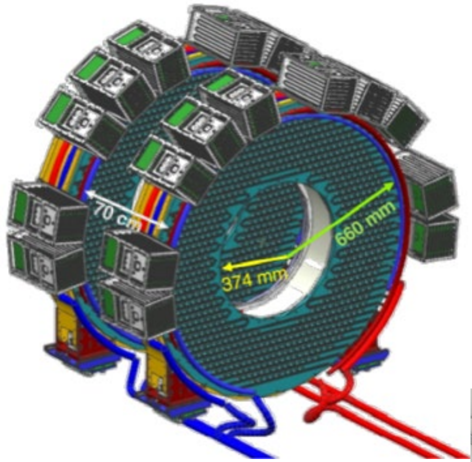
Cosmic Rays Background

- Charged cosmic rays background can be of different types:
    1. 105 MeV/c muons identified as conversion electrons (95%)
    2. delta rays of 105 MeV coming from the interaction of CR muon with the stopping target (5%)



- Calorimeter can help only with type-I events
- Type-II are irreducible once they pass the CRV
- The 200-rejection factor comes from the requirements to keep type-I evts negligible with respect to type-II evts.. so, **it is not dependent by the acquisition time**..
- Mu2e-II requirements for energy and time resolution are the same..

The Mu2e-I Calorimeter



Undoped CsI + UV-extended SiPMs

Undoped CsI

→ 60% LO after 100krad

→ τ = 30ns

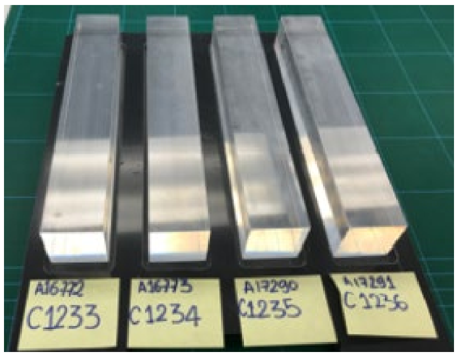
→ Emits at 310 nm

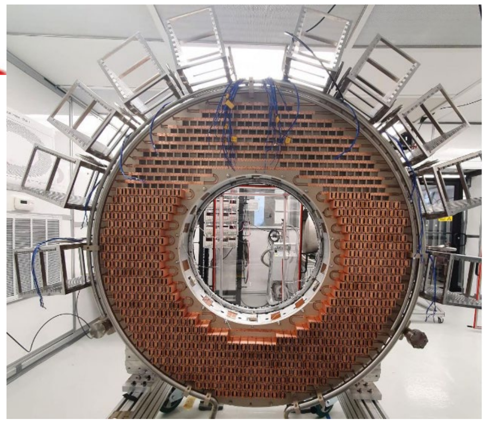
UV-extended SiPMs

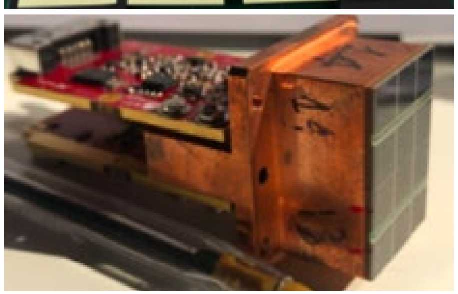
→ 30 % PDE @ 310 nm

→ New silicon resin window

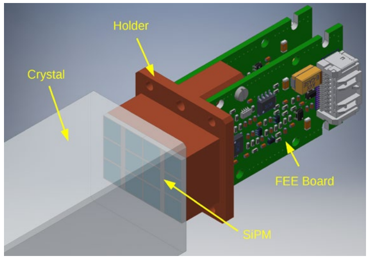
→ TSV readout, Gain = 10^6







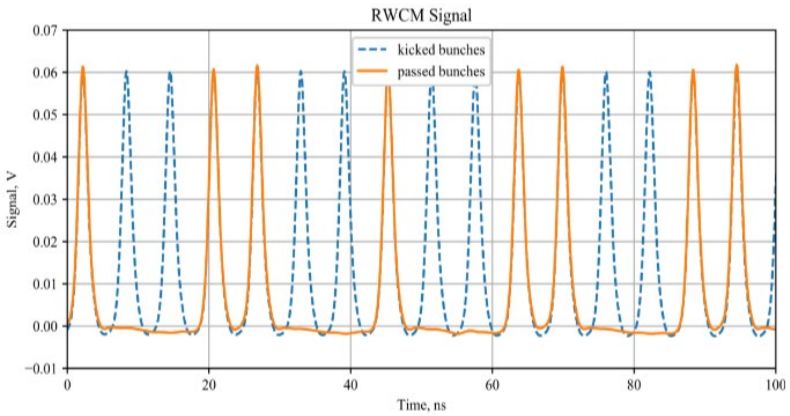
- Two annular disks, R_{in}=374 mm, R_{out}=660 mm, 10 X_0 length, ~ 70 cm separation
- 674 + 674 square x-sec pure CsI crystals, (34 × 34 × 200) mm^3, Tyvek + Tedlar wrapping
- Each crystal is read out by two large area UV extended Mu2e SiPM's (14x20 mm^2)

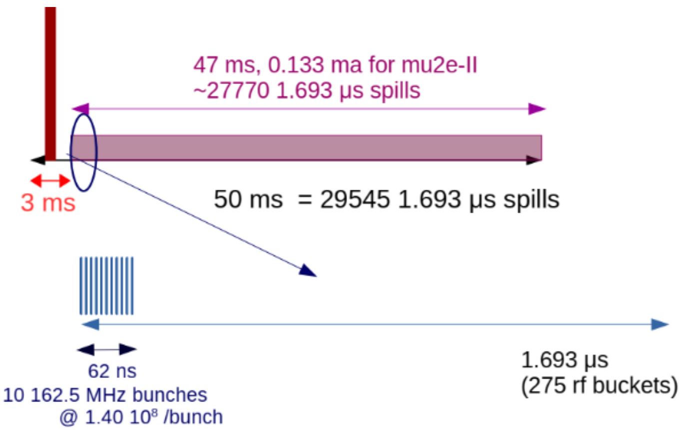


- Redundant readout: For each crystal, two custom arrays (2 × 3 of 6 × 6 mm2) large area UV-extended SiPM

What is different in Mu2e-II?

- Mu2e-II will use the **800 MeV** proton beam from the **PIP-II** Linac:
  - Chopper system can produce an arbitrary pattern of filled or empty **162.5 MHz** (6.25 ns) buckets
  - Mu2e-II will use **10 buckets** each composed of 1.4 x 10^8 protons, total 1.4x10^9 p in 62.5 ns
  - SMuons/POT ratio for 800 MeV p of 9x10^-5 -> **SM/muBunch of 1.2 x10^5 … 2 times Mu2e**
  - Only 3 ms out of every 50 ms are required - > **Duty Factor of 94% … 3,5 times Mu2e**

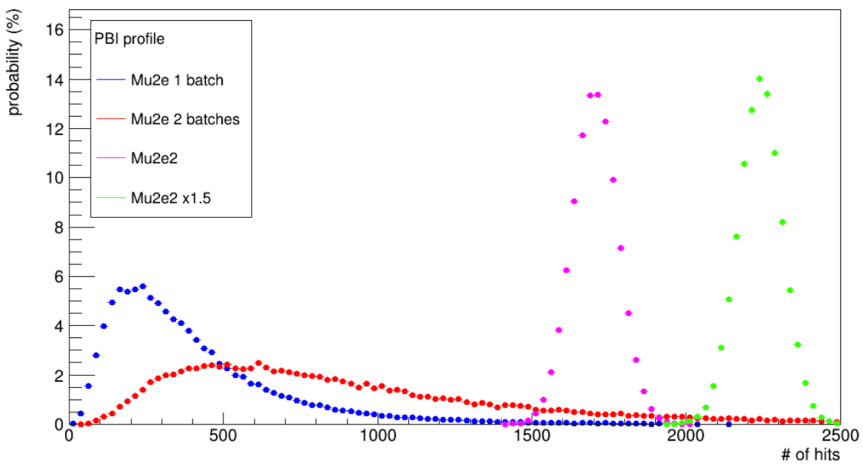


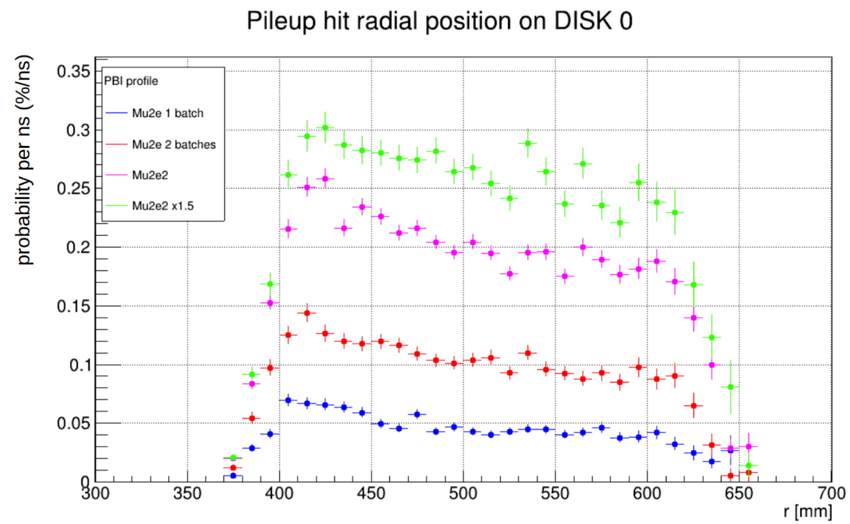


- Running **5 years** with PIP-II is possible to reach a **x10 SES** wrt Mu2e:
  - Detectors must increase **bkg rejection** to limit new total expected bkg events below 1 count
  - **Radiation hardness** requirements from x10 stopped muons and x10 (??) beam flash
  - New instantaneous luminosity poses new requirements on **pileup handling** and **data transmission**

Occupancy and Pileup Considerations

- The instantaneous luminosity is x 2 the average luminosity in the 2batch mode of Mu2e Run II (characterized by a large variability due to the slow resonant extraction)
  - In principle it can be also more intense, because Mu2e proton pulse was 250 ns and we are using only 65 ns of PIP-II stream.. the limit is the power dissipation in the PS and the pileup level

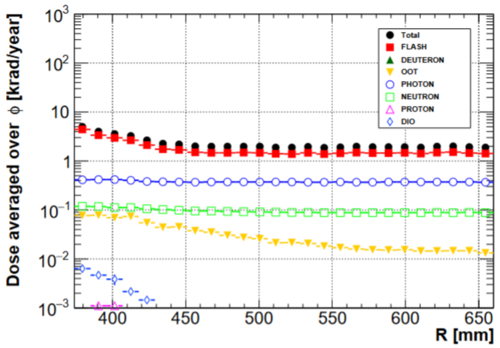


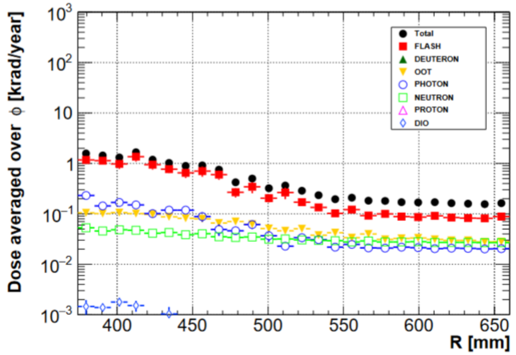


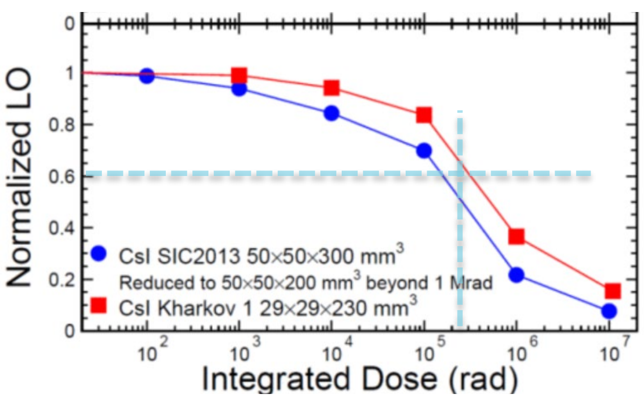
- The pileup with respect to CE seems to scale linearly with beam intensity, so to keep the same level we have in Mu2e (15%) with 150 ns we need to rescale the new signals lenght
  - The length for Mu2e-II should be 75 ns (50 ns for 1.5 times Mu2e-II)
  - Pileup resolution in the waveform fit is still under study and can loose this requirement

New TID requirements for crystals

- Under the **assumption** that the TID from the beam flash in the calorimeter from 800 MeV protons scales as the number of stopped muons wrt Mu2e 8 GeV beam, a **x10** is expected:





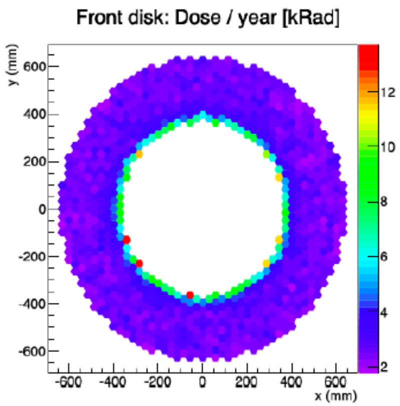


TID req = simulated TID x3 Safety Factor, x3 yrs, x10 Mu2-II

- R < 47 cm -> **600 krad**
- R > 47 cm -> **180 krad**

- R < 55 cm -> **160 krad**
- R > 52 cm -> **50 krad**

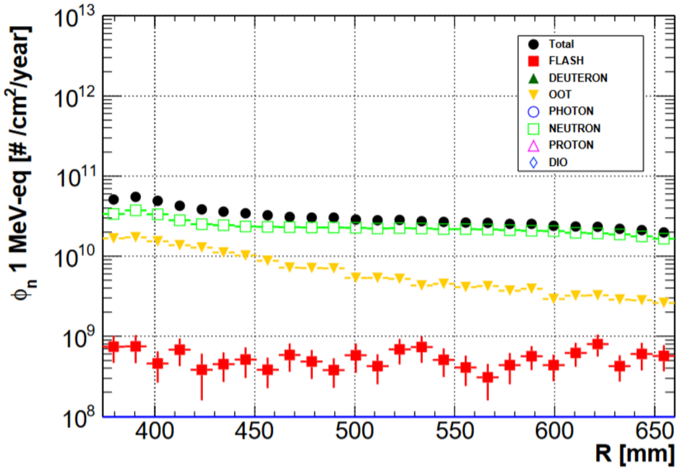
F. Yang, L. Zhang and R. -Y. Zhu, "Gamma-Ray Induced Radiation Damage Up to 340 Mrad in Various Scintillation Crystals," in *IEEE Transactions on Nuclear Science*, vol. 63, no. 2, pp. 612-619, April 2016, doi: 10.1109/TNS.2015.2505721.

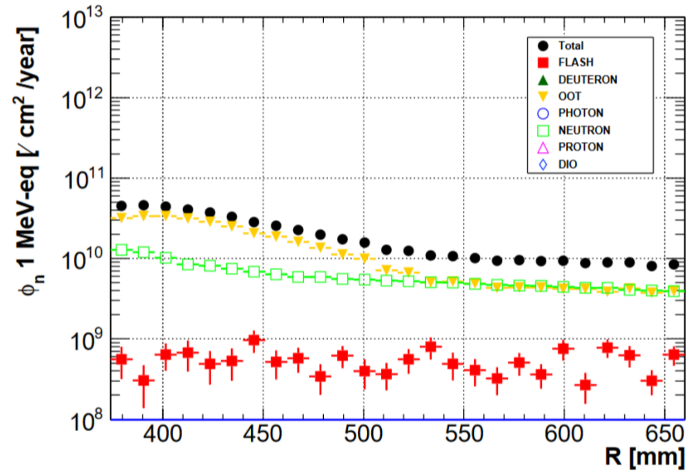


- Mu2e QA requirement for TID was a **LO after 100 krad > 60%**
  - The requirements on light collection was 30 p.e./MeV
- Dedicated simulation of the new beam flash and upgraded detectors materials are required to determine exact numbers, but so far wrt TID:
  - Disk 1 crystals should survive the new radiation level (??)
  - Disk 0 outer crystals should be in the same situation of disk 1 inner (??)
  - **Disk 0 inner crystals must be changed** -> BaF2, LYSO (??)

New Neutrons requirements for SiPMs

- Neutrons comes mainly from muonic atom decays, so a **x10 factor** wrt Mu2e is expected





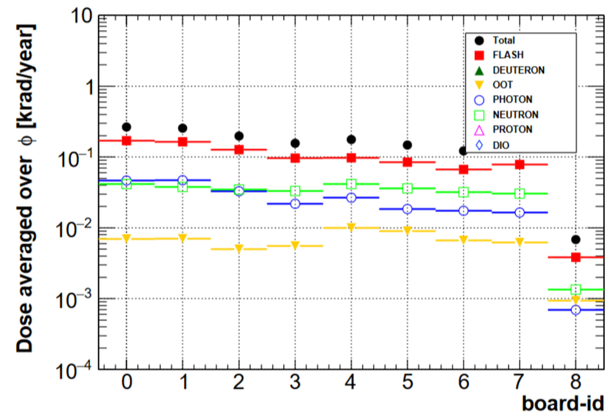
1MeV-eq n Fluence = simulated Fluence x3 Safety Factor, x3 yrs, x10 Mu2-II

5.4 X 10^12 n/cm^2

- The **dark current value after the neutron damage** is expected to be of the order of tens of mA, mitigable (??) with decrease of breakdown voltage or lowering the operational temperature (-40 C?)
  - We need to substitute the majority (or all) the photosensors -> more rad hard sipm? solar blind?
- Other than the dark current increase related to neutrons we need also to consider the new Radiation Induced Noise (RIN) level

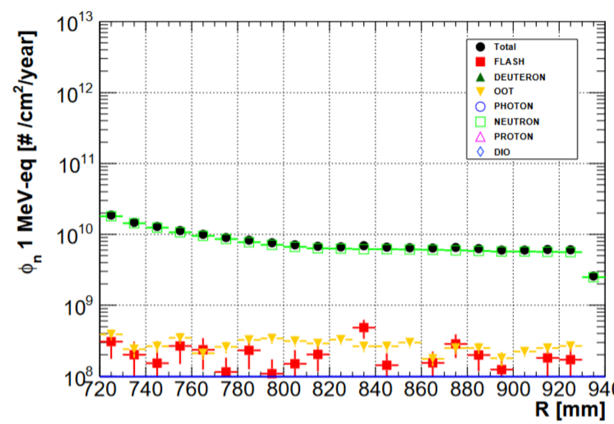
New Readout Electronics Requirements

- Readout electronics is hosted in crates around the calorimeter disks, so we expect an **increase of x10** in radiation hardness requirements
  - DiRAC board qualified only up to 20 krad and 10^12 1-MeV-eq n/cm^2
- More pileup requires narrower signals, so we need to change the amplifier shape
  - The 200 MHz sampling rate is doesn't allow to have enough points of the rising edge to reconstruct the time with needed resolution
- Increased occupancy in the calorimeter combined with the new duty cycle require a higher data transmission bandwidth
  - Increase the speed and/or the number of optical links
  - Increase the clock inside the FPGA



TID = simulated TID x3 Safety Factor, x3 yrs, x10 Mu2-II

30 krad x 3 batch safety factor -> 90 krad



1MeV-eq n = Fluence x3 Safety Factor, x3 yrs, x10 Mu2-II

5 X 10^12 n/cm^2

→ Electronics need to be completely redesigned

Fast ADC ? .. Multi threshold TDC ? .. TDC + slow AC?

Summary

- Even if the requirement about the energy [**σ_E/E of O(10 %)**] and time [**σ(t) < 500 ps**] resolution remain the same, a big part of the detector and all the electronics can't survive to the new radiation environment

  - What parts can we keep?

- To run Mu2e-II a new technological solution (crystal + photosensor) for the calorimeter is needed
  - TID of about 600 krad and 1-MeV-eq n fluence of 5x10^12
  - Signals with a maximum length of 75 ns, less is SM/ubunch will increase

- **As we will see in the session, a lot of R&D has been done in the past years and at the moment the baseline solution is to use BaF2 crystals + solar blind SiPM**

- Electronics will be developed tailored on the chosen detector signals
  - 100 krad on the electronics + ensure 500 ps time resolution

- Mu2e Phase I will help in better understand the safety factor due to the simulation..