Design and status of the Mu2e Crystal Calorimeter

S.Miscetti
LNF/INFN Frascati, Italy
On behalf of the Mu2e calorimeter group

SCINT-2017
18 Sept 2017
Chamonix - France

Talk layout

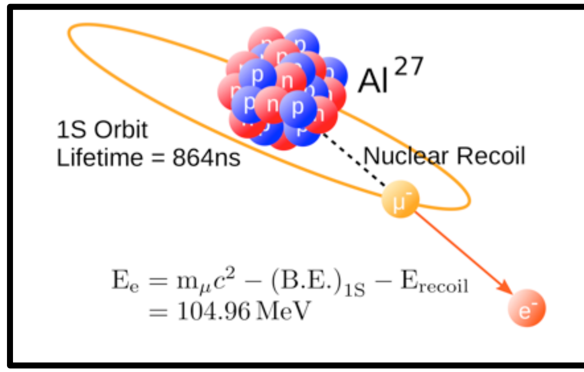
- Requirements and design considerations
- Tech Choice: un-doped CsI + Mu2e SiPMs
- Simulation and prototyping
- Pre-production of crystals and Mu2e SiPMs
- Engineering design and Module-0
- Next plans and perspectives

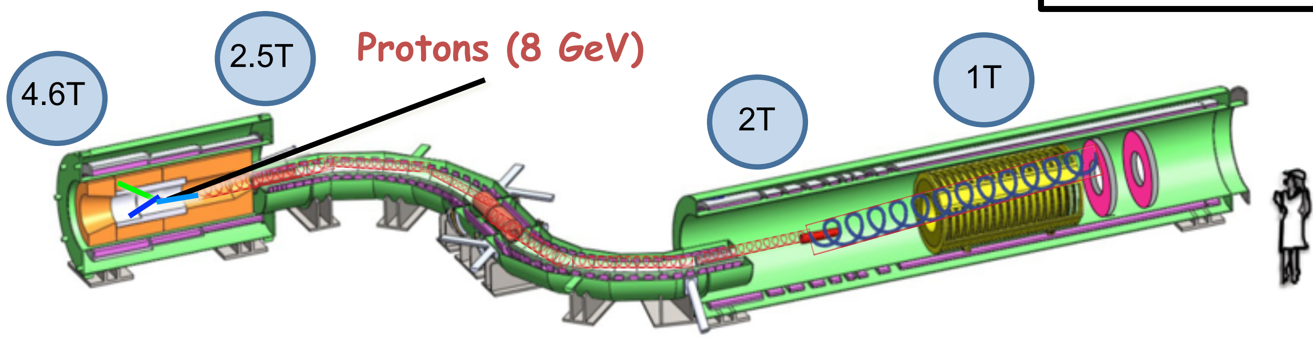
The Mu2e experiment at Fermilab

Mu2e search for the Muon to electron conversion in the field of an Aluminium nucleus.
It is a CLFV process strongly suppressed in Standard Model: BR $\lesssim 10^{-52}$
$\Rightarrow$ **its observation indicates New Physics** → Goal: 10^4 improvement w.r.t. current limit

$$R_{\mu e} = \frac{\Gamma(\mu^- + N(A,Z)) \to e^- + N(A,Z)}{\Gamma(\mu^- + N(A,Z) \to \text{ all muon capture})} \leq 6 \times 10^{-17} \text{ (@90\%CL)}$$

- ✗ Beam of low momentum muons stopped in Al target
- ✗ Muons trapped in orbit around the nucleus
- ✗ mN→eN events with signature → **single mono-energetic electron**





Production & Transport Solenoids

Production, selection and transport of low momentum muon beam stopped at 10 GHz on Al target

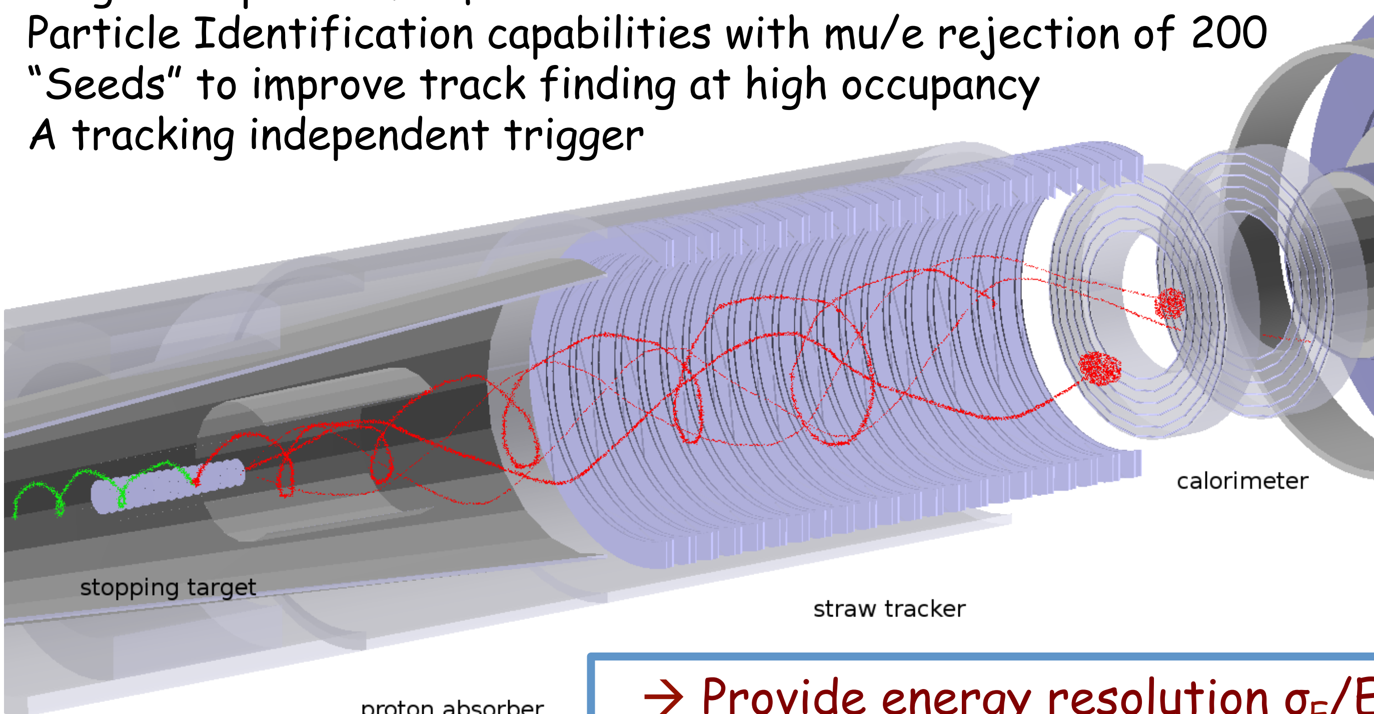
Detector Solenoid

- Muon capture on Al target
- High precision Tracker (180 keV res. at 105 MeV/C)
- EM Calorimeter
- Cosmic Ray Veto system

Calorimeter Requirements

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

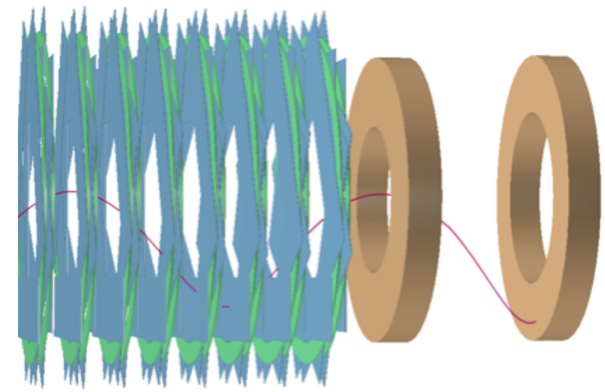
- Large acceptance for $\mu \rightarrow e$ events
- Particle Identification capabilities with mu/e rejection of 200
- "Seeds" to improve track finding at high occupancy
- A tracking independent trigger



→ Provide energy resolution σ_E/E of O(5 %)
→ Provide timing resolution $\sigma(t) < 500$ ps
→ Provide position resolution < 1 cm
→ Work in vacuum @ 10^{-4} Torr and 1 T B-Field
→ Survive the harsh radiation environment

Technical specifications

- Technical Solution → Crystal calorimeter with SiPMs
- 2 Disks (Annuli) geometry
- Crystals with high Light Yield for timing/energy resolution → **LY(photosensors) > 20 pe/MeV**



- **2 photo-sensors/preamps/crystal** for redundancy and reduce MTTF requirement → **1 million hours/SIPM**
- Fast signal for Pileup and Timing → **τ of emission < 40 ns + Fast preamps**
- **Fast Digitization (WD) to disentangle signals in pileup**

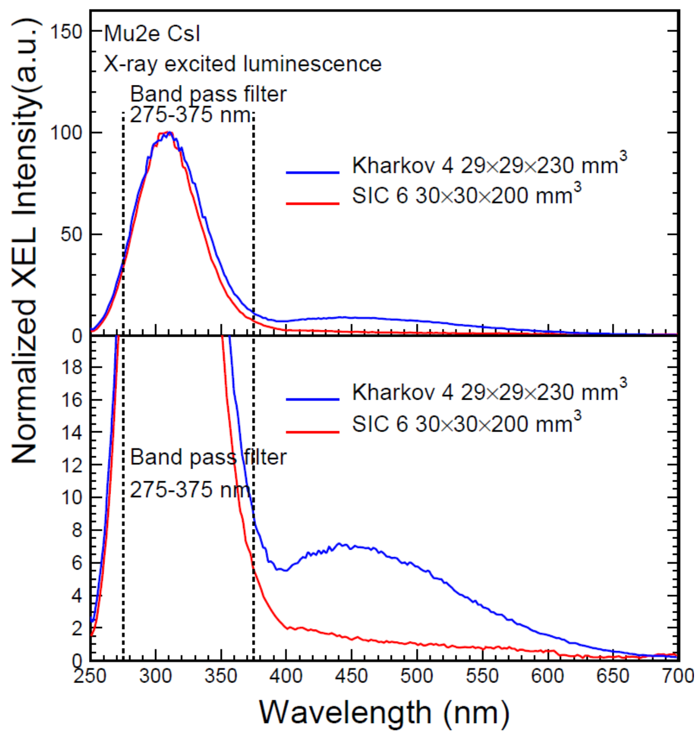
Safety Factor = 3
5 years of run

- **→ Crystals should survive a TID of 90 krad and a fluence of 3×10^{12} n/cm^2**
  → Photo-sensors should survive 45 krad a fluence of 1.2×10^{12} n_1MeV/cm^2

Undoped CsI + UV extended SiPM

Undoped CsI is a good choice for Mu2e calorimeter:

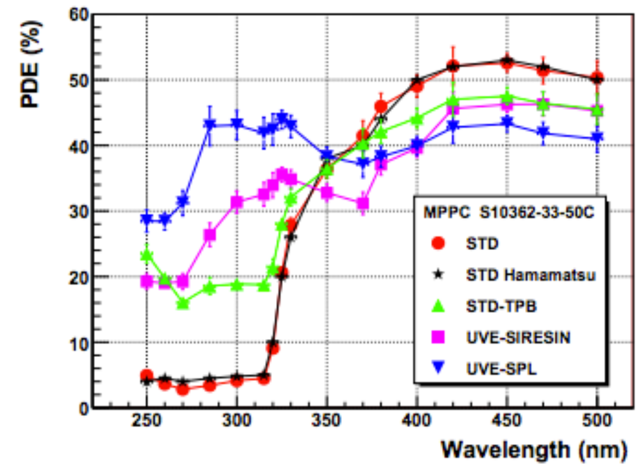
→ It is enough radiation hard for our purpose
→ It has a fast emission time
→ It has a large enough LY
→ It emits @ 310 nm.

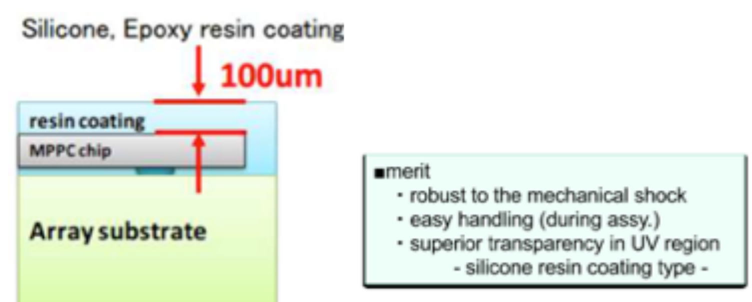


PDE of UV-enhanced MPPC is much higher below 350 nm

→ **30 % @ 310 nm (CsI pure wavelength)**
→ **New silicon resin window**
→ **TSV readout, Gain = 10^6**

Imaging with SiPMs in noble-gas detectors: arXiv 1210.4746

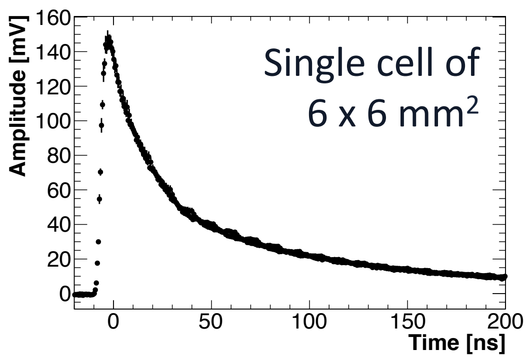


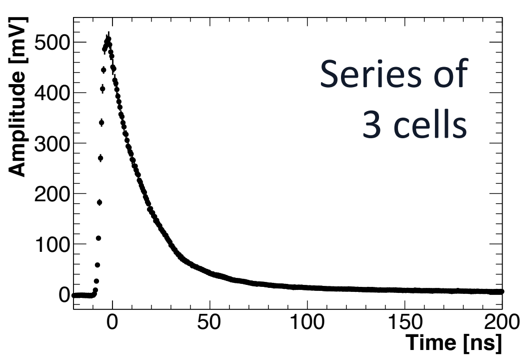


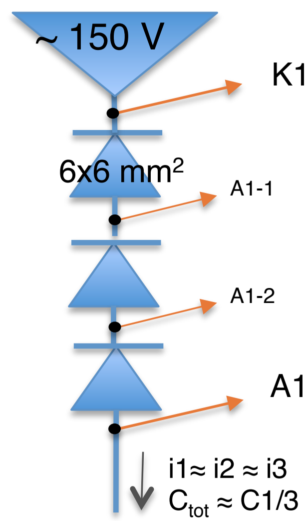
Mu2e custom SiPMs design

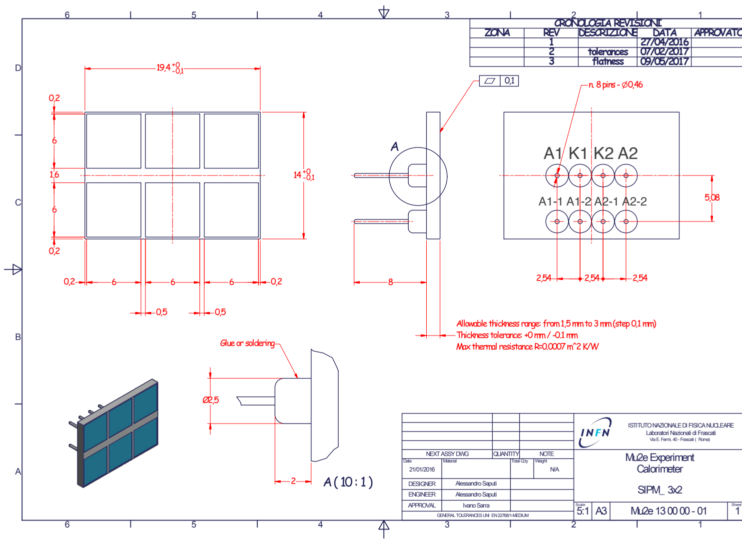
- 2 arrays of 3 6 x 6 mm² UV-extended SiPMs for a total active area of (12x18) mm²

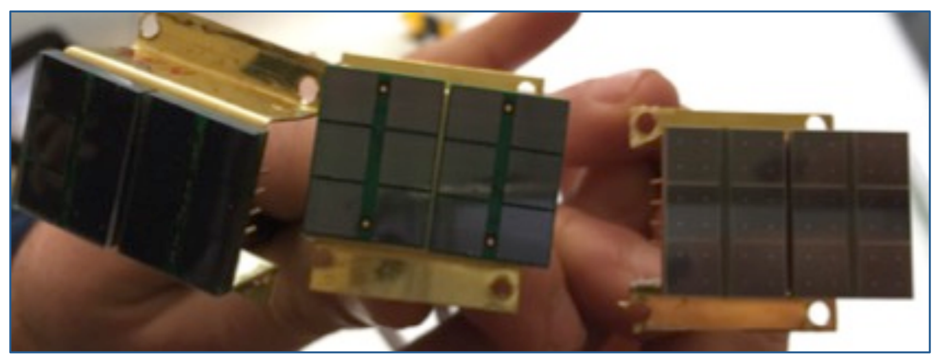
- The series configuration reduces the overall capacity and allows to generate narrower signals







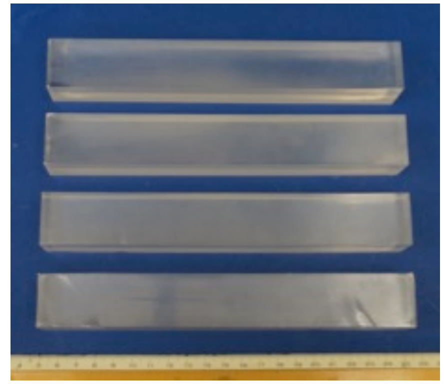


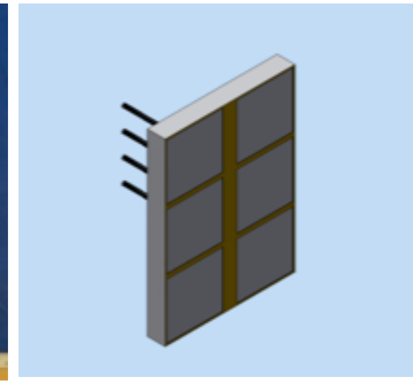


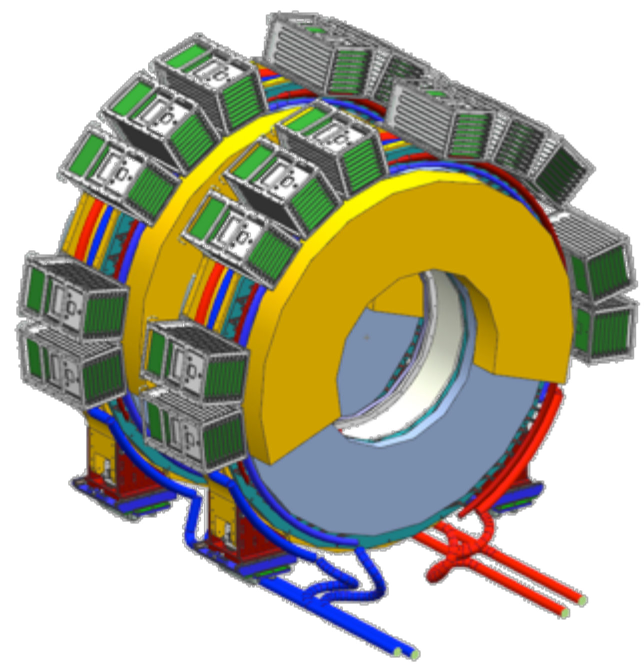
Mu2e Calorimeter design

The Mu2e Calorimeter consists of two disks with 674 un-doped CsI 34x34x200 mm^3 square crystals:

- Each crystal is readout by two large area UV extended Mu2e SiPM's (14x20 mm^2)
- Fast analog FEE is on the SiPM while digital electronics at 250 Msps is located in near-by electronics crates
- Radioactive source (ala Babar) and laser system provide absolute calibration and monitoring capability

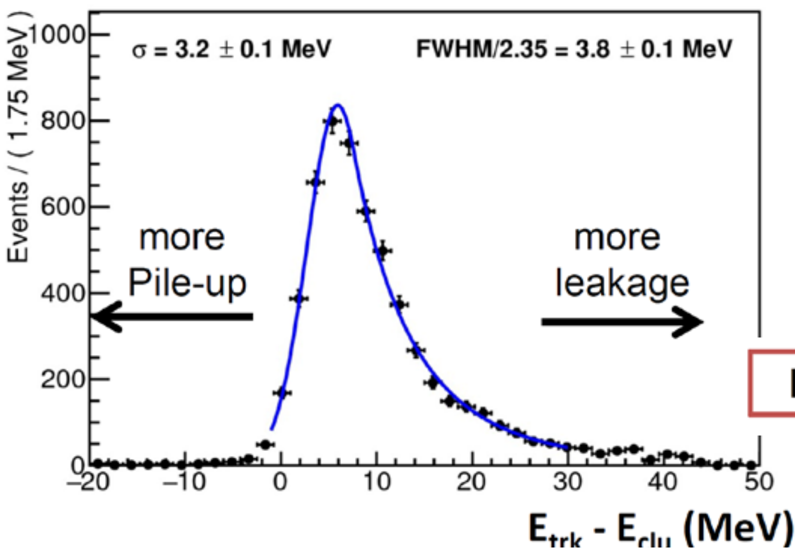




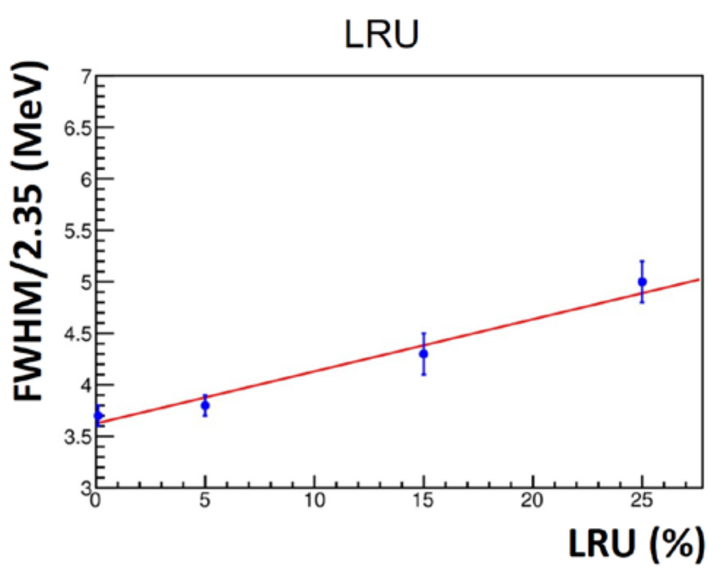


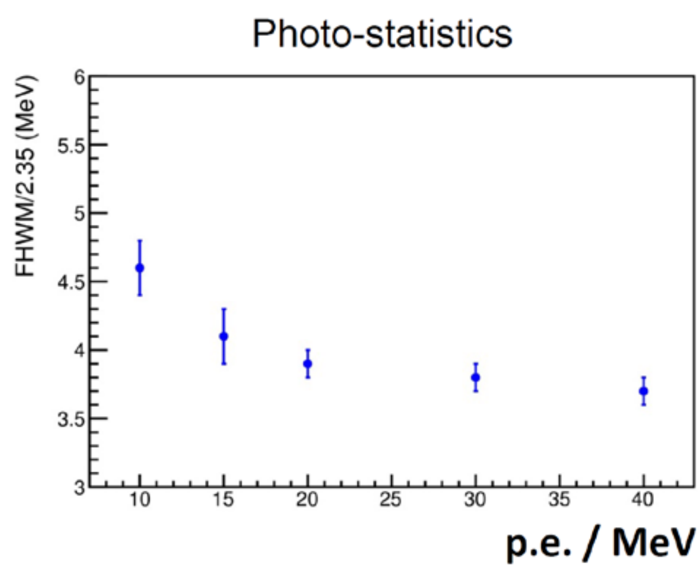
Mu2e EMC: simulated performance

Simulation includes full background and digitization and cluster-finding, with split-off and pileup recovery



FWHM / 2.35 = 3.8 ± 0.1 MeV

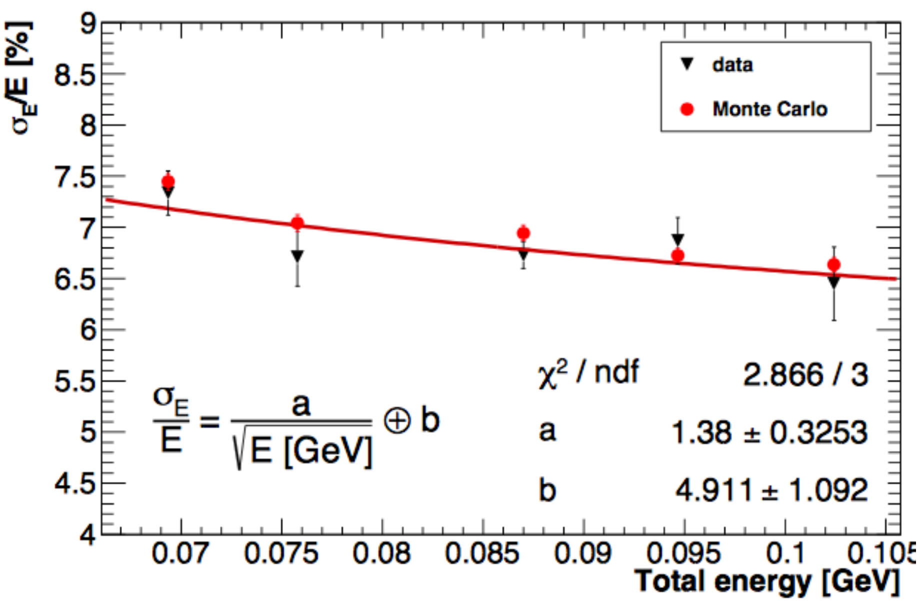


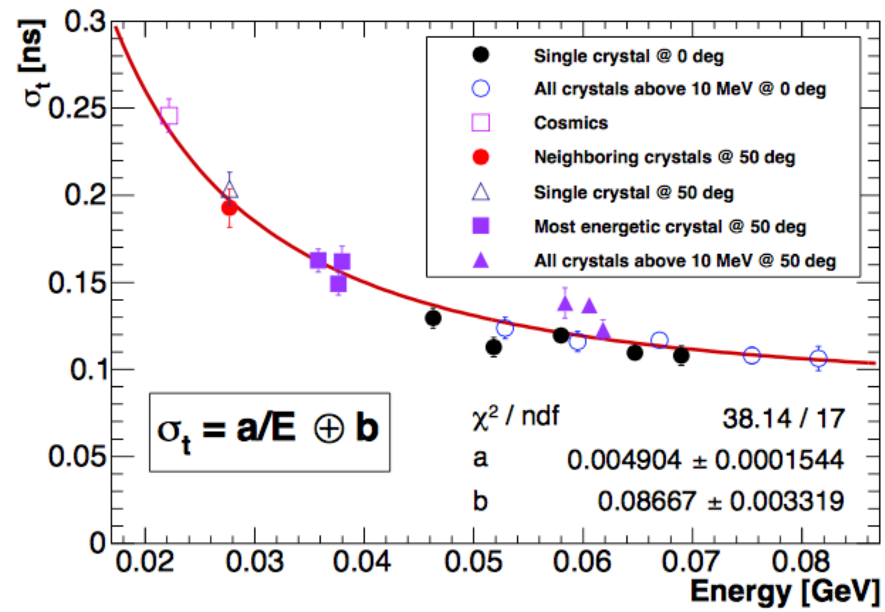


Small size prototype

- Small prototype tested @ BTF (Frascati) in April 2015, 80-120 MeV e^-
- 3×3 array of 30×30×200 mm^2 undoped CsI crystals coupled to UV-extended Hamamatsu SiPM array (12x12) mm^2 with Silicon optical grease
- DAQ readout: 250 Msps CAEN V1720 WF Digitizer

JINST 12 (2017) P05007





σ_E ~ 6.5% at 100 MeV

σ_T ~ 110 ps at 100 MeV

Significant leakage contribution due to the matrix dimensions

Pre-production of Crystals

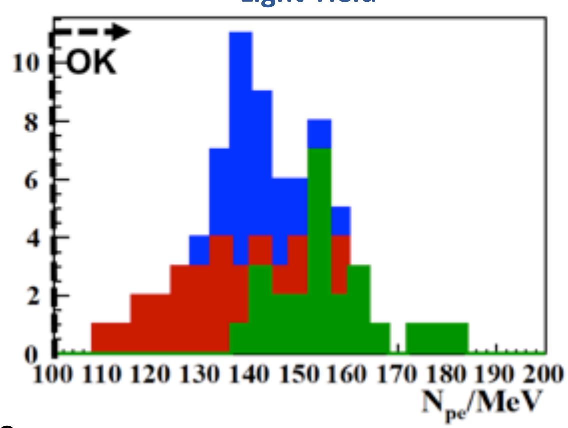
- 24 crystals from three different vendors: **SICCAS**, **Amcrys**, **Saint Gobain**
- Optical properties tested with 511 keV γ's along the crystal axis
- Crystals wrapped with 150 μm of Tyvek and coupled to an UV-extended PMT

Un-doped CsI crystals perform well

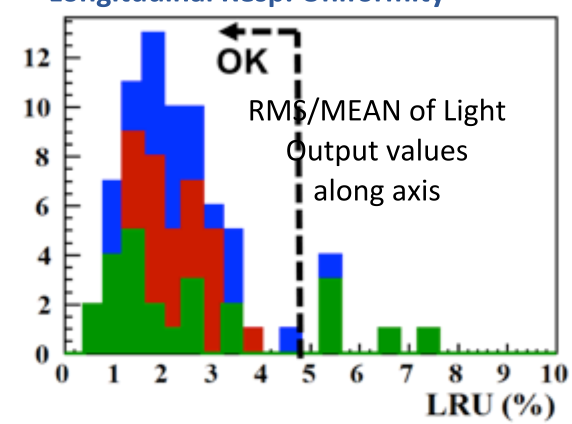
- ❑ **Excellent LRU and LY:**
  - -100 pe/MeV with PMT readout
  - LRU < 5%
- ❑ τ of 30 ns with small slow component
- ❑ **Radiation hardness OK for Mu2e**
  Smaller than 40% LY loss @ 100 krad
- ❑ Small Radiation Induced Noise (Phosphorescence)

MORE INFORMATION ON R.Y. Zhu POSTER

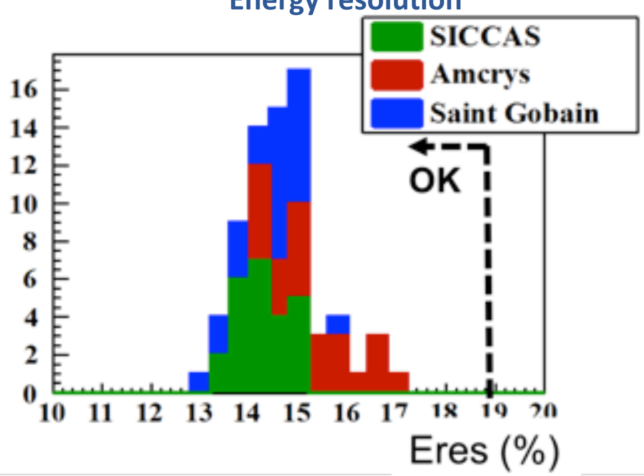
Light Yield



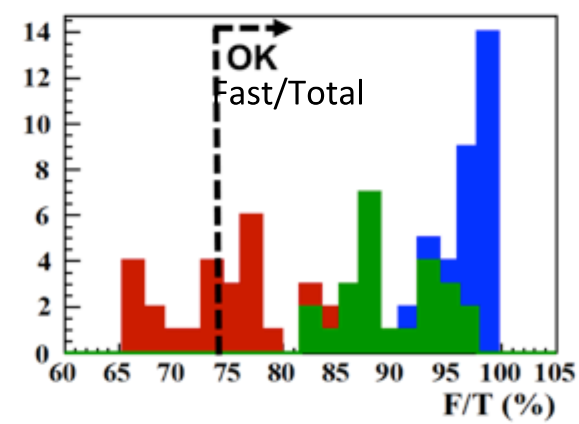
Longitudinal Resp. Uniformity



Energy resolution



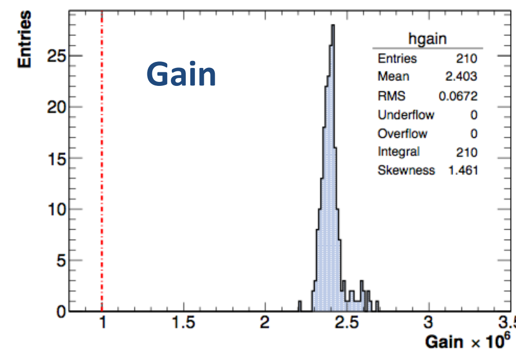
Q(200 ns)/Q(3000 ns)

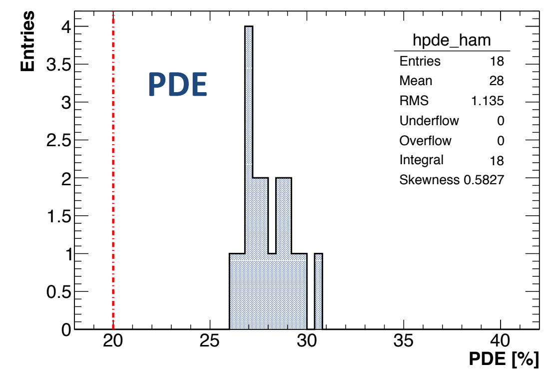


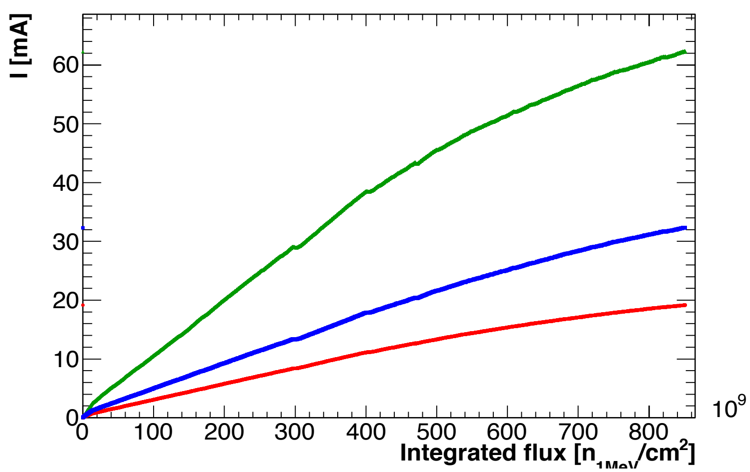
Pre-production of Mu2e SiPMs

150 Pre-production SiPMs
(3×50 Mu2e SiPMs from HPK, SenSl and ADV):

- 3×35 were fully characterized for all six cells in the array (Vop, G, Idark, PDE)
- 1 sample/vendor exposed to neutron up to a fluence of 8.5×10^{11} n_{1MeVeq}/cm^2 (@ 20 °C)
- MTTF estimated by operating 15 SiPM at 50 °C for 3.5 months → MTTF > 0.6 10^6 hours.



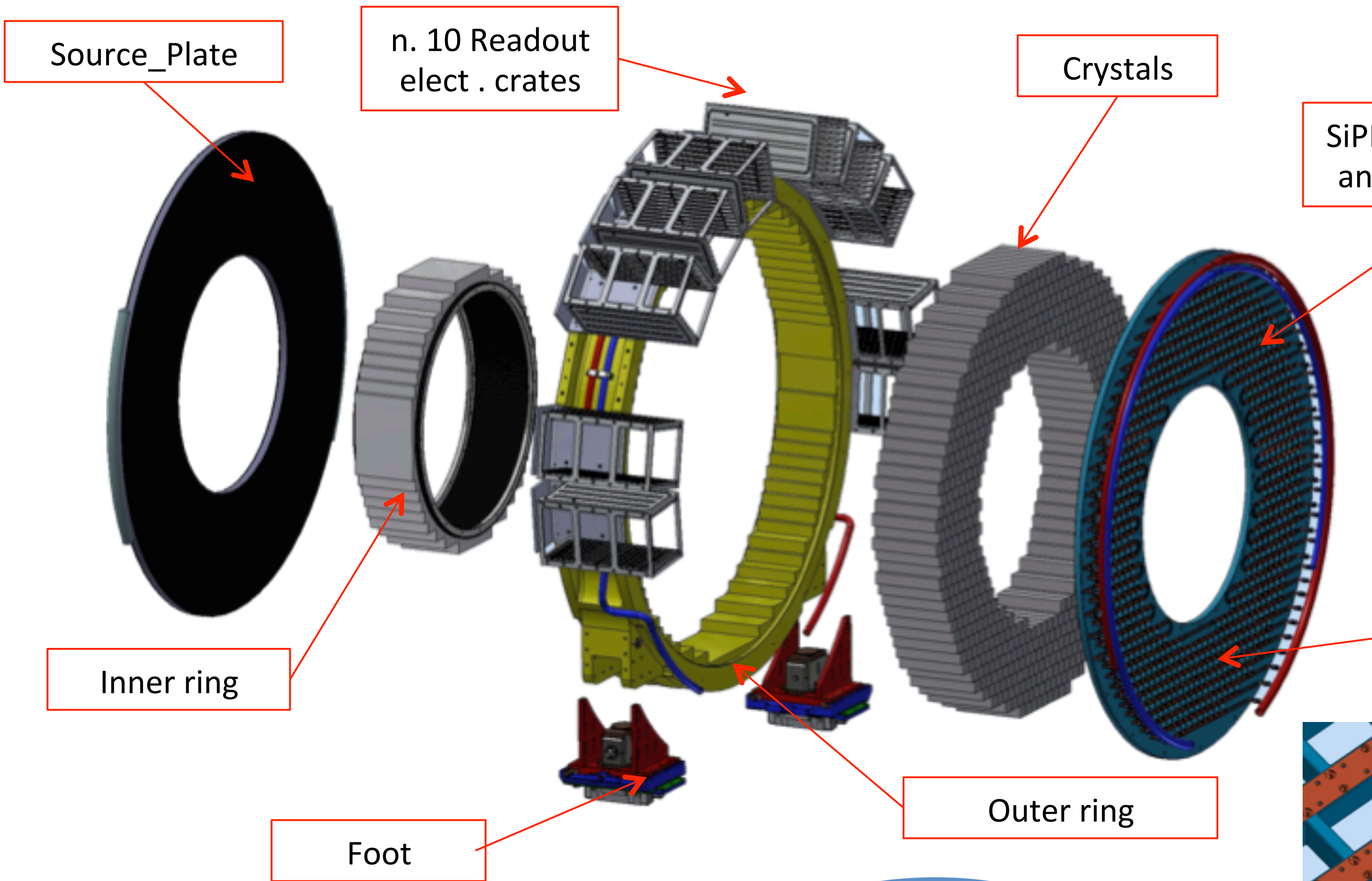




During the experiment, SiPMs needs to be operated at 0 °C

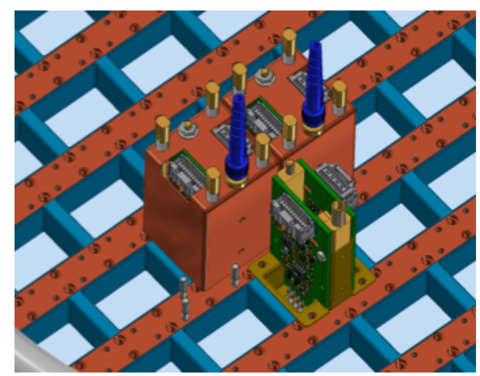
MORE INFORMATION ON E. DIOCIAIUTI POSTER

Mu2e calorimeter engineering

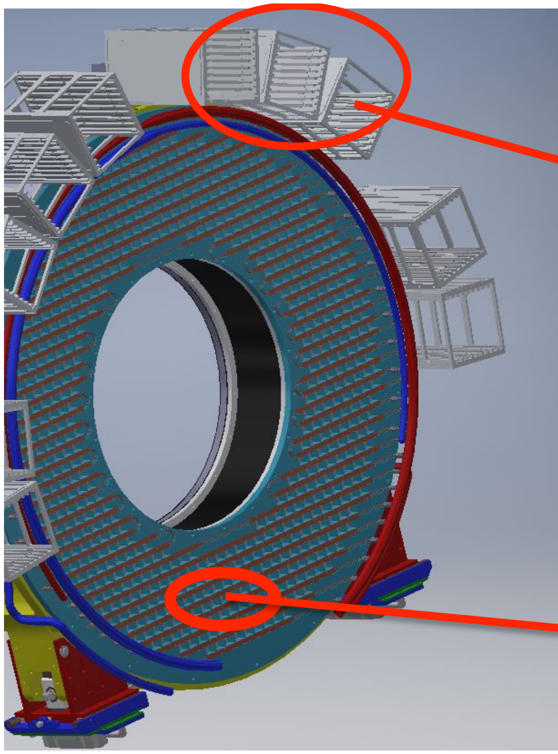


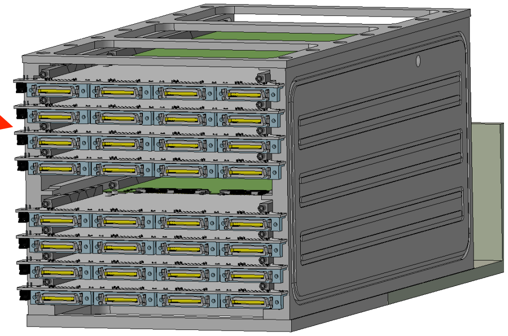
- Manifolds
- Hydraulic connections
- Inner steps
- Outer steps
- Alignment targets
- **SiPM running temperature at 0 °C, Coolant at -10 °C**

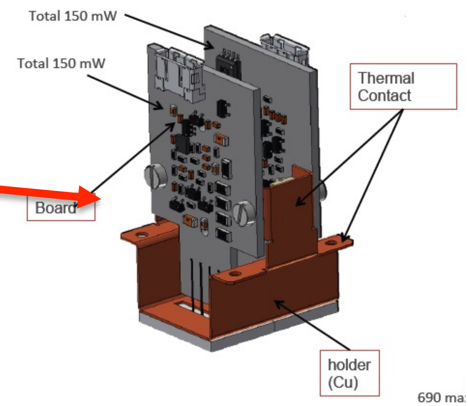
Zoom of
SiPM/FEE disk
And holders



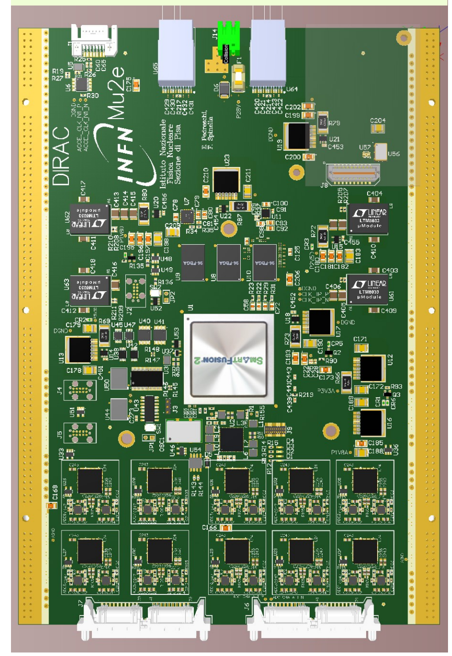
FEE and Digitization scheme







WD 20 ch Prototype

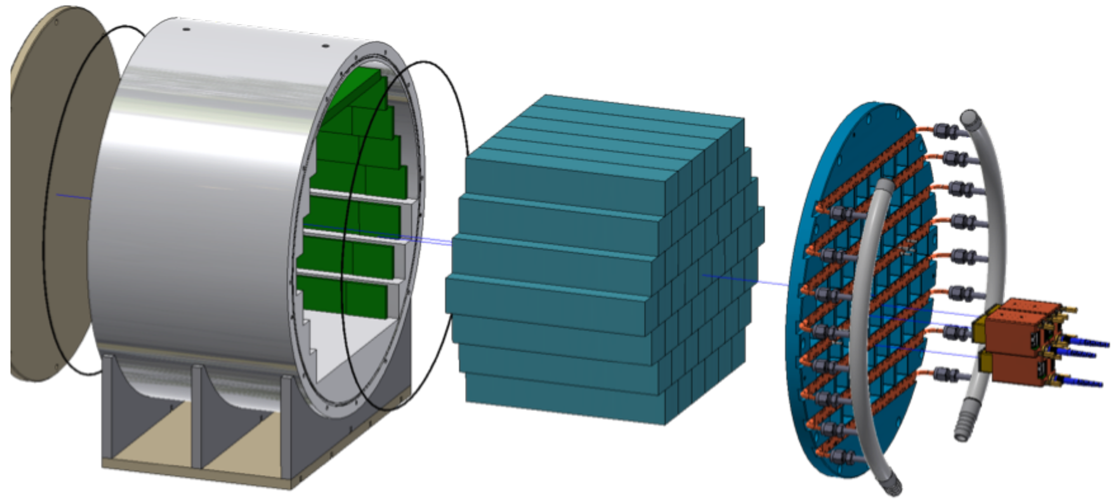


- ✓ **1 FEE chip (amplification and HV regulation) locally on the SiPM pins** + Independent amplification, HV & readout for Left/Right SiPMs
- ✓ **8 (Digitizer + Mezzanine) boards in 10 crates → 20 chs format.** Digitizer @ 200 Msps (5 ns binning), Mezzanine to set/read HV of each SiPM. Alternate Left and Right boards in crate.

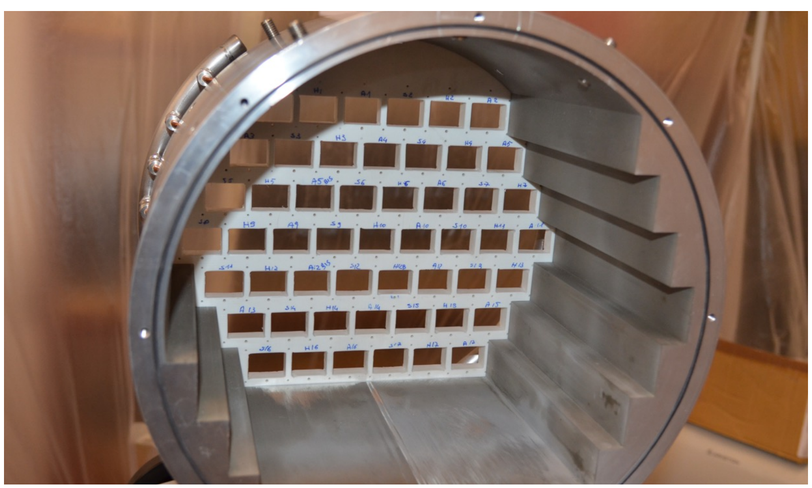
Module-0 preparation

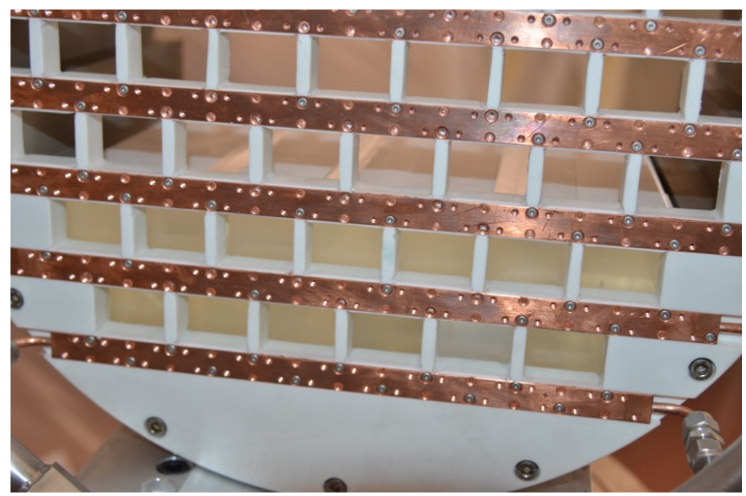
Large size prototype of the disk assembled April 2017

- 51 crystals, 102 sensors,
- 102 FEE chips
- Cooling lines and readout.

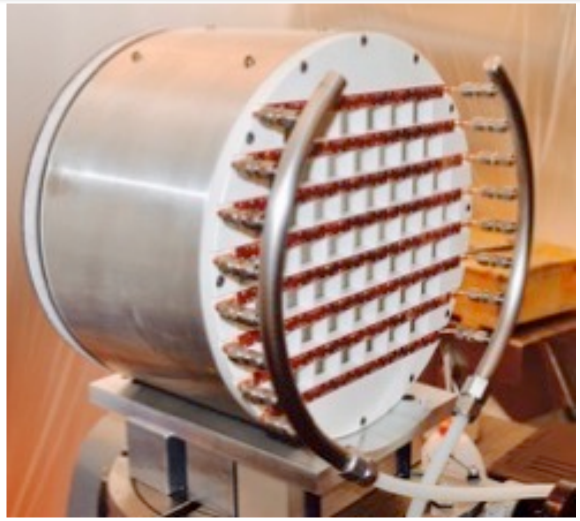


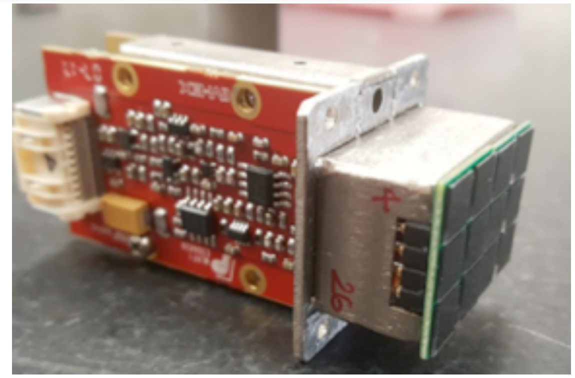
Assembly of ZEDEX FEE disk on Al support disk → final version PEEK

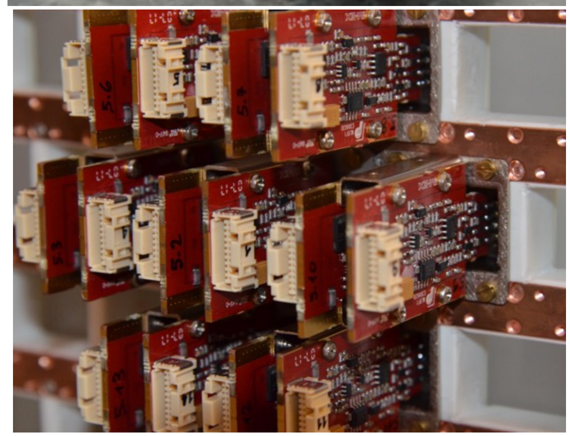




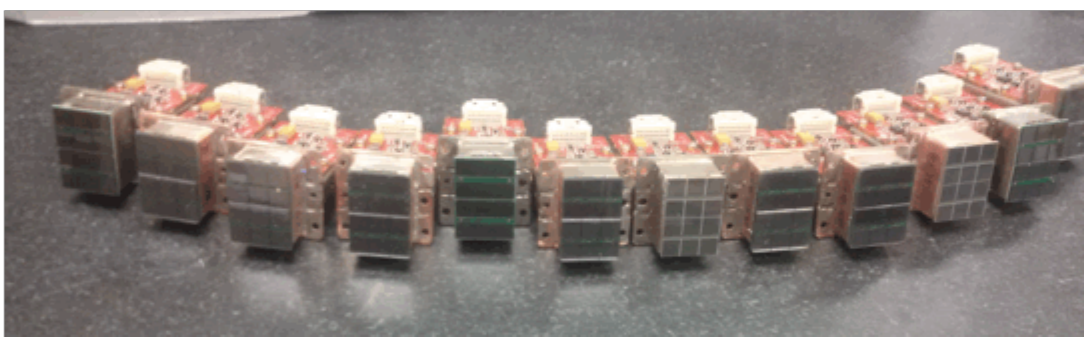
Module-0 preparation

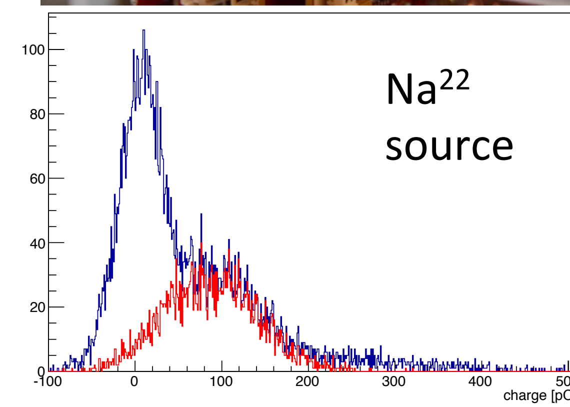






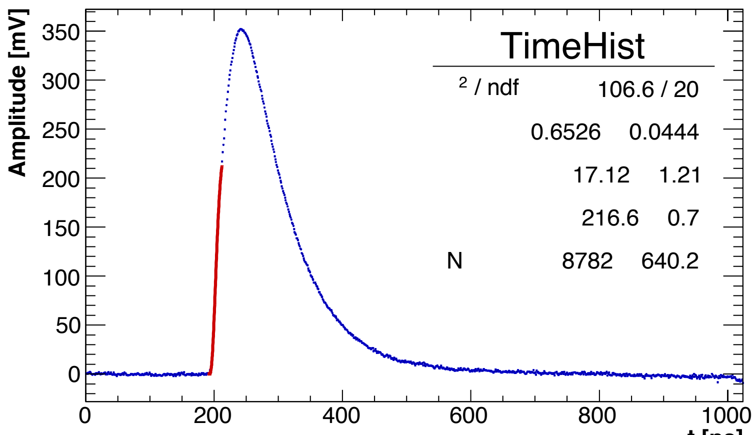
- Insertion of wrapped crystals
- Check of cooling lines
- Gluing of SiPMs on SiPM holders
- Add FEE chips, test with LED + source
- Insertion in FEE back disk

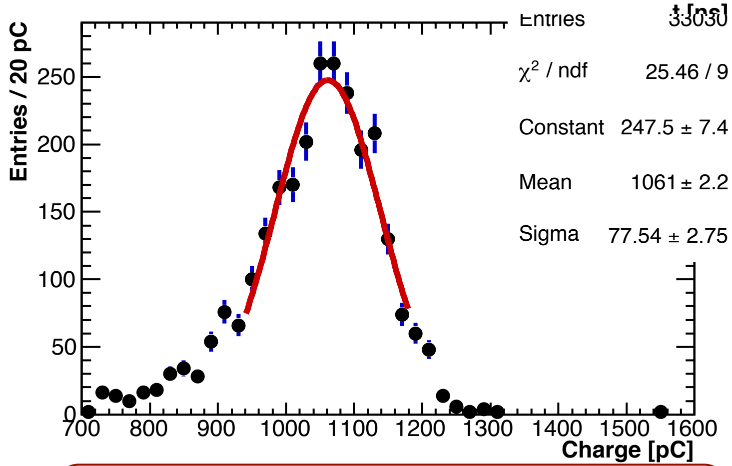




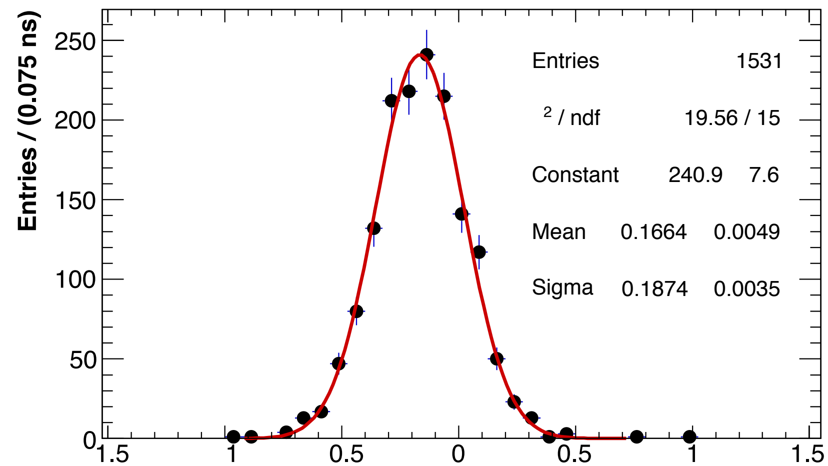
Test Beam preliminary results

Module-0 exposed to an e- beam (60-140 MeV) test @ LNF → May 8-15 2017





σ_E ~ 7.3% within 1° ring
@ E_{beam} = 100 MeV



Central crystal time ($T_{SiPM\,1} - T_{SiPM2}$) (ns)

$\sigma_{(T1+T2)/2}$ ~ 94 ps
@ E_{beam} = 100 MeV

- Log-normal fit on leading edge, Constant Fraction method used (CF = 5%).
- Noise in Test beam too high to extend clustering after first ring around central crystal.
- Data quality allowed to extract preliminary resolution in agreement with small size prototype.

Plans and perspectives

- Mu2e calorimeter is a state of the art Crystal Calorimeter with excellent energy (5 %) and timing (< 500 ps) resolution and great pileup solving capability.

- **The most demanding request is to do all of the above in presence of 1 T field, under vacuum and in a radiation harsh environment with a fast analog electronics and digitization with high sampling (5 ns).**

  → Engineering of cooling and calorimeter mechanics is crucial
  → SiPMs work under neutron irradiation but need to be cooled down to 0 °C

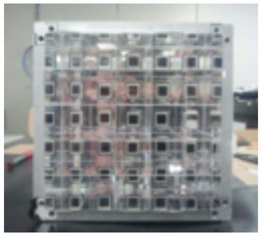
- **Pre-production of crystals and SiPM done.**
  Final vendors selected → production will start at the end of 2017.

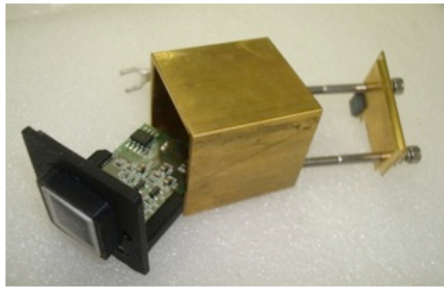
- **Module-0 has been built → Full Size Mockup underway**

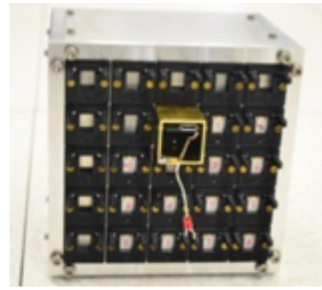
- **Schedule is to start assembly first real disk in fall 2018 and complete construction at the beginning of 2020.**

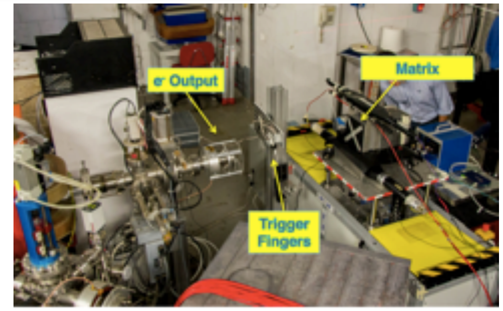
ADDITIONAL MATERIAL

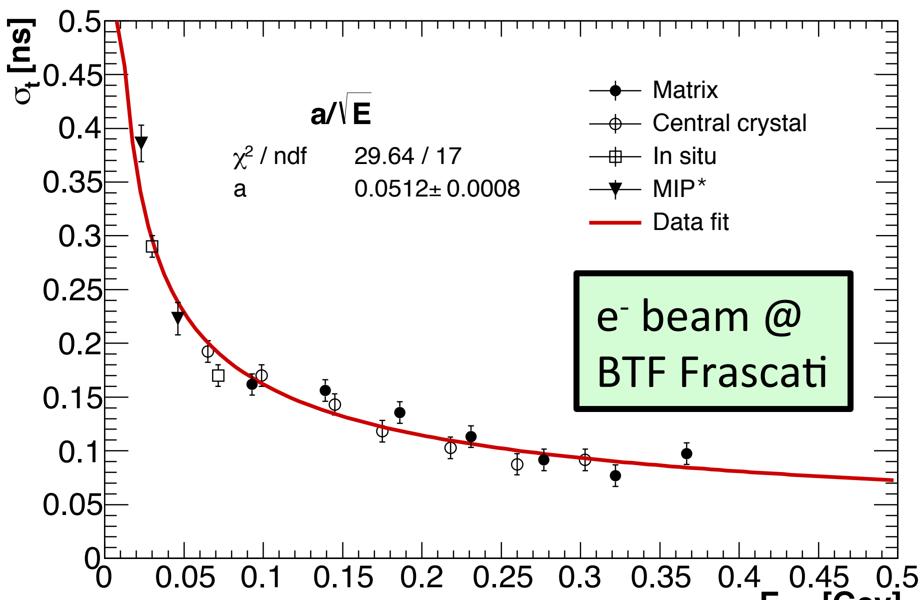
LYSO Legacy



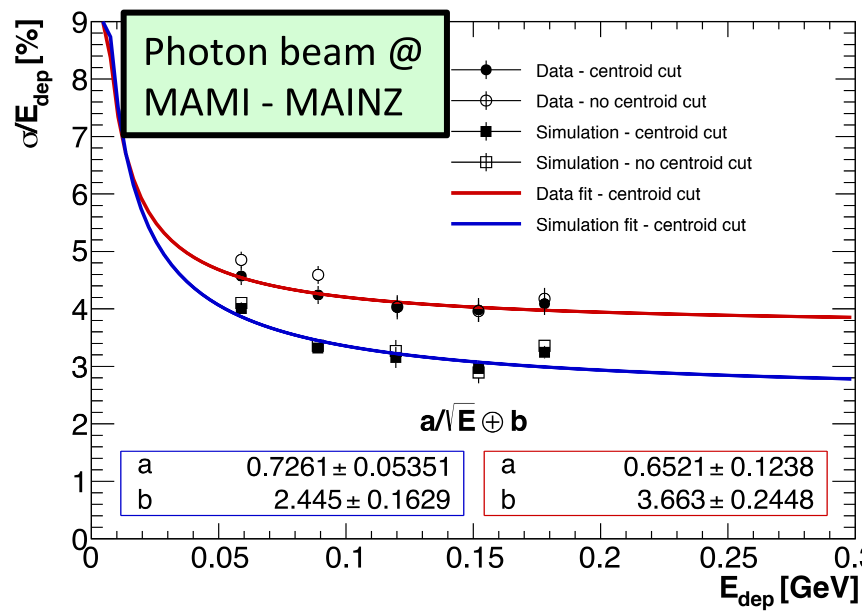








*Time resolution with MIPs from Mu2e DocDB 4409



σ_T = 51 ps/sqrt(E/GeV) compare with KLOE ~ 55 ps/sqrt(E/GeV)

Energy resolution as a function of the energy deposition fitted with the function:

~ 4% @ 100 MeV

$$\frac{\sigma_E}{E} = \frac{a}{\sqrt{E}} \oplus \frac{b}{E} \oplus c$$

Noise term *b* considered negligible (~0.1% in quadrature).

Crystal Choice

	~~LYSO~~	~~BaF_2~~	CsI
Radiation Length X_0 [cm]	1.14	2.03	1.86
Light Yield [% NaI(Tl)]	75	**4**/36	3.6
Decay Time[ns]	40	**0.9**/650	20
Photosensor	APD	**R&D APD**	SiPM
Wavelength [nm]	402	**220**/300	310

LYSO

CDR

- Radiation hard, not hygroscopic
- Excellent LY
- Tau = 40ns
- Emits @ 420 nm,
- Easy to match to APD.
- High cost > 40$/cc

Barium Fluoride (BaF_2)

BASELINE-TDR

- Radiation hard, not hygroscopic
- very fast (220 nm) scintillating light
- Larger slow component at 300 nm. should be suppress for high rate capability
- Photo-sensor should have extended UV sensitivity and be "solar"-blind
- Medium cost 10$/cc

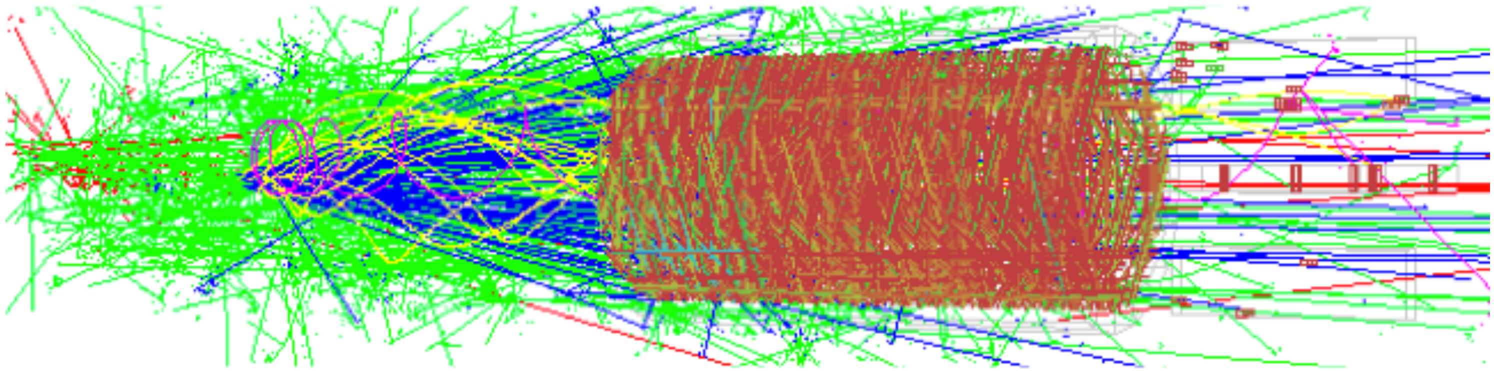
CsI(pure)

FINAL CHOICE

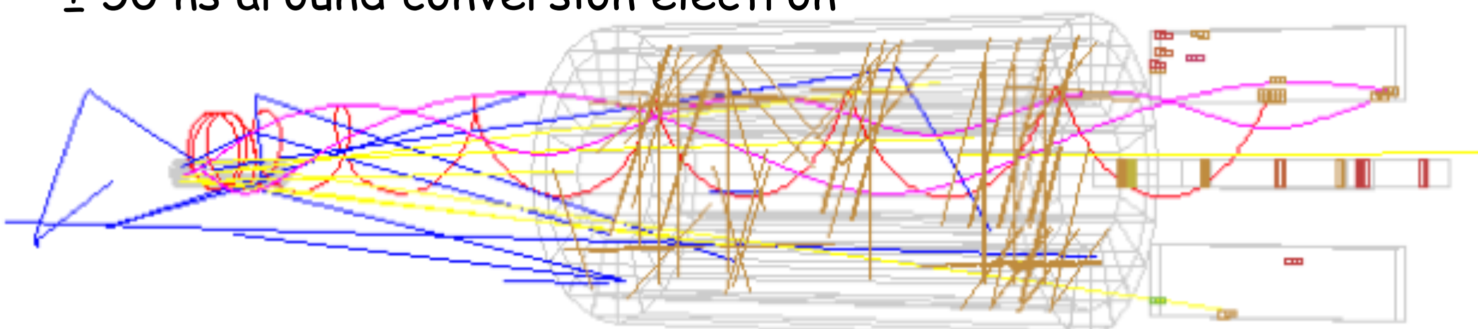
- Not too radiation hard
- Slightly hygroscopic
- 15-20 ns emission time
- Emits @ 320 nm.
- Comparable LY of fast component of BaF_2.
- Cheap (6-8 $/cc)

EMC based track seeding

500 – 1695 ns window

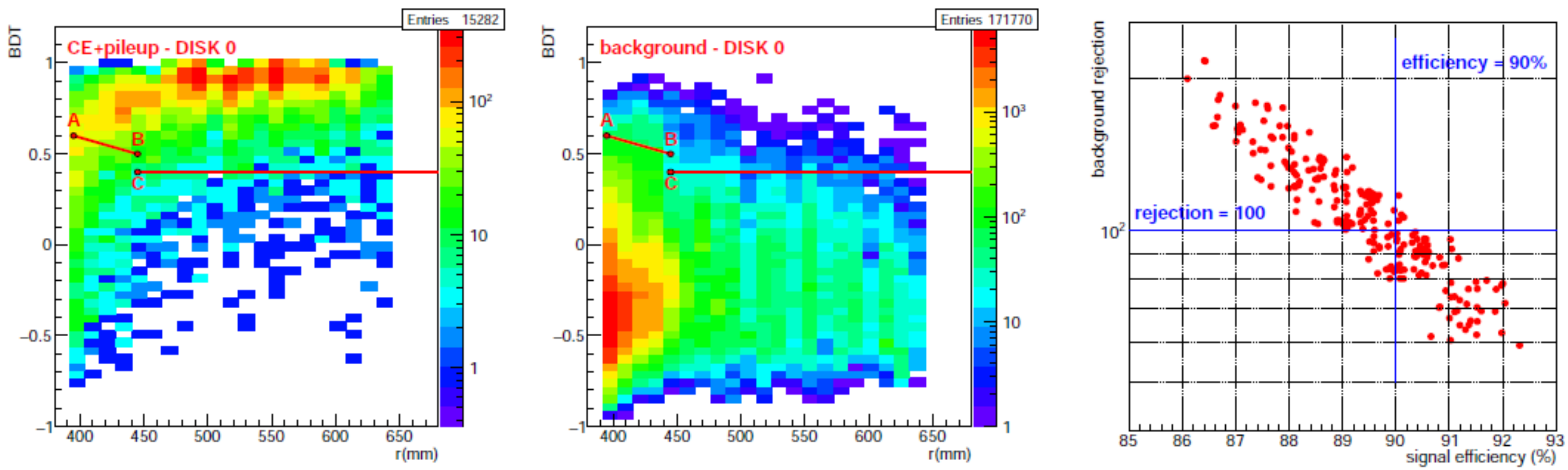


± 50 ns around conversion electron



The speed and efficiency of tracker reconstruction is improved by selecting tracker hits compatible with the time ($|\Delta T| < 50$ ns) and azimuthal angle of calorimeter clusters → simplification of the pattern recognition.

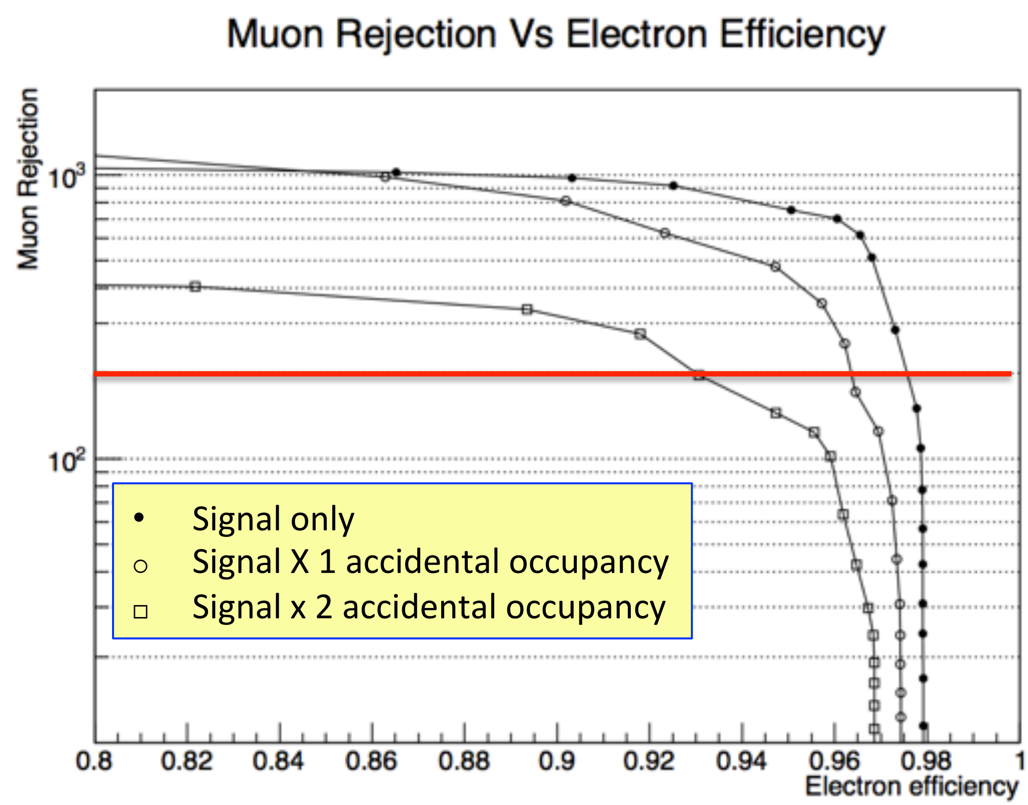
Calorimeter-based Trigger



- acceptance: > 90% of events with good tracks have a cluster E > 60 MeV
- **standalone calorimeter-based Online Trigger needed**
  - Tracker momentum calibration (i.e., $\pi^+ \rightarrow e\nu$)
  - Measurement of tracking efficiency
  - DAQ storage limitations → 100 times reduction of background events
  - Fast algorithm

Performance: PID (muon vs electrons)

- Full simulation with pileup background included.
- Pre-selection based on track to cluster matching (space & time).
- PID is based on LogLikelihood with E/P and ΔT



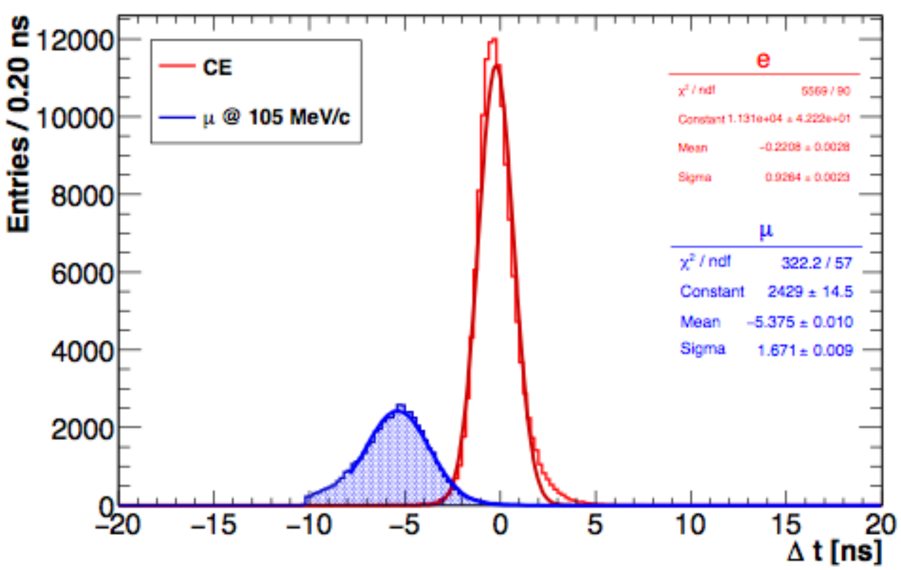
✓ For a muon rejection of 200 → **Electron ID efficiency is 98%**
✓ Adding pre-selection cuts → **Total PID efficiency is > 93% with twice the exp. background**

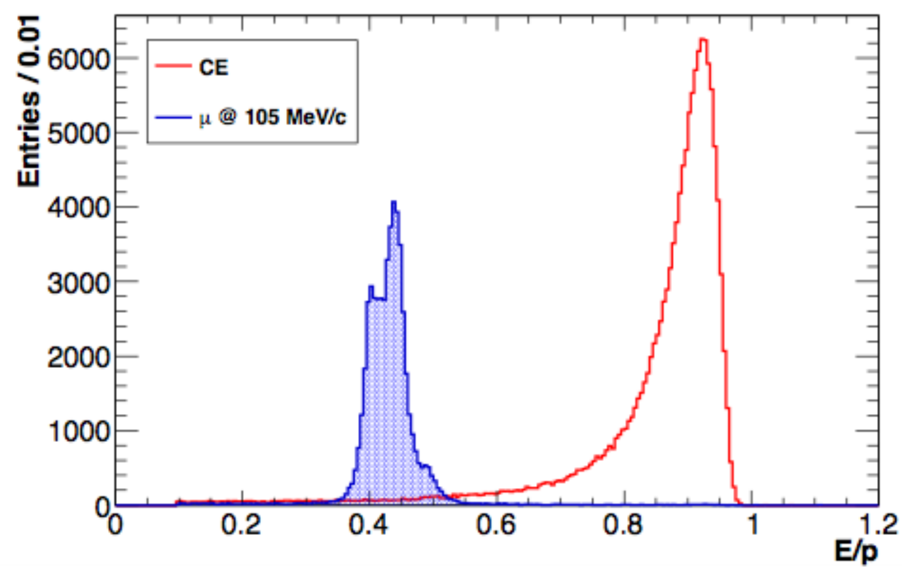
PID calorimeter-tracker – basic idea

$$\beta = \frac{p}{E} \sim 0.7, \; E_{kin} = E - m \sim 40 \text{ MeV}$$

Compare the reconstructed track and calorimeter information:

- $E_{cluster}/p_{track}$ & $\Delta t = t_{track} - t_{cluster}$,
- Build a likelihood for e- and mu- using distribution on E/p and Δt



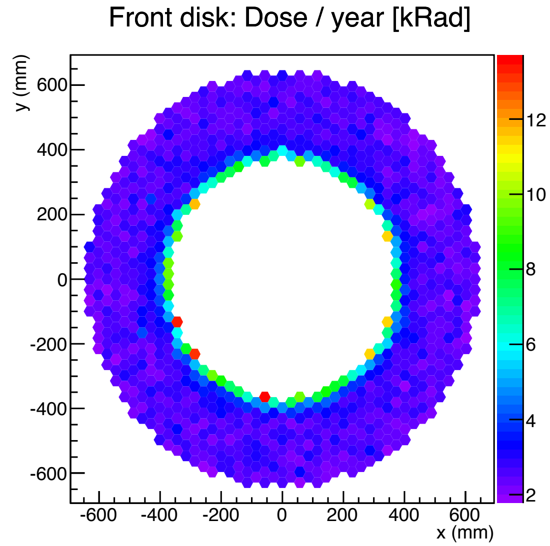


Get very high efficiency (> 95%) with Rejection factor > 200

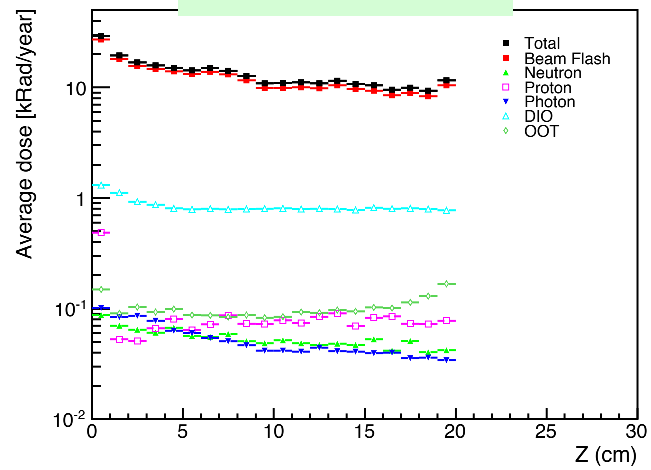
→ Needs energy res 5-10 % and timing < 500 ps.

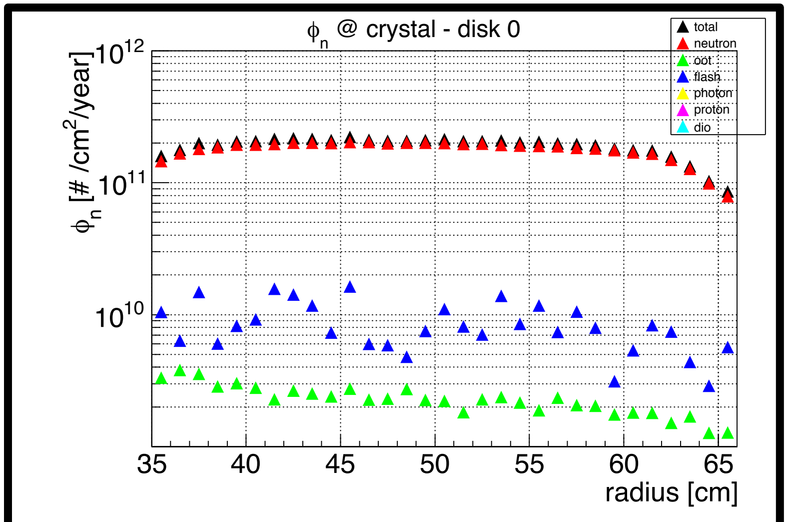
Radiation hardness (simulation)

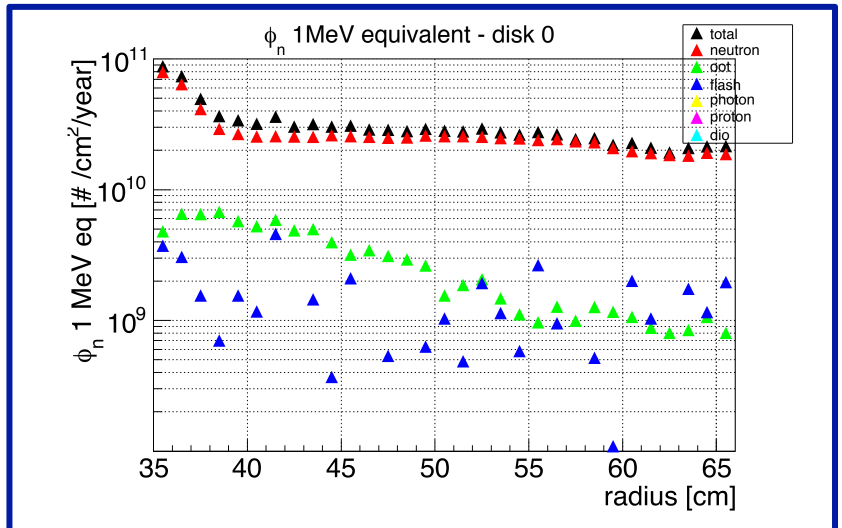
- Radiation dose driven by Beam flash (300 ns from interaction on target). **Dose from Muon capture x 10 smaller**
- Strongly limited to inner radius (up to 400 mm)
- **Highest dose/year ~ 10 krad**
- **Highest n flux/year on crys. ~ 2x10 ^{11} n/cm^2**
- **Highest dose/year on APD ~ 6x10^{10} n_1Meveq/cm^2**



Radius = 36 cm

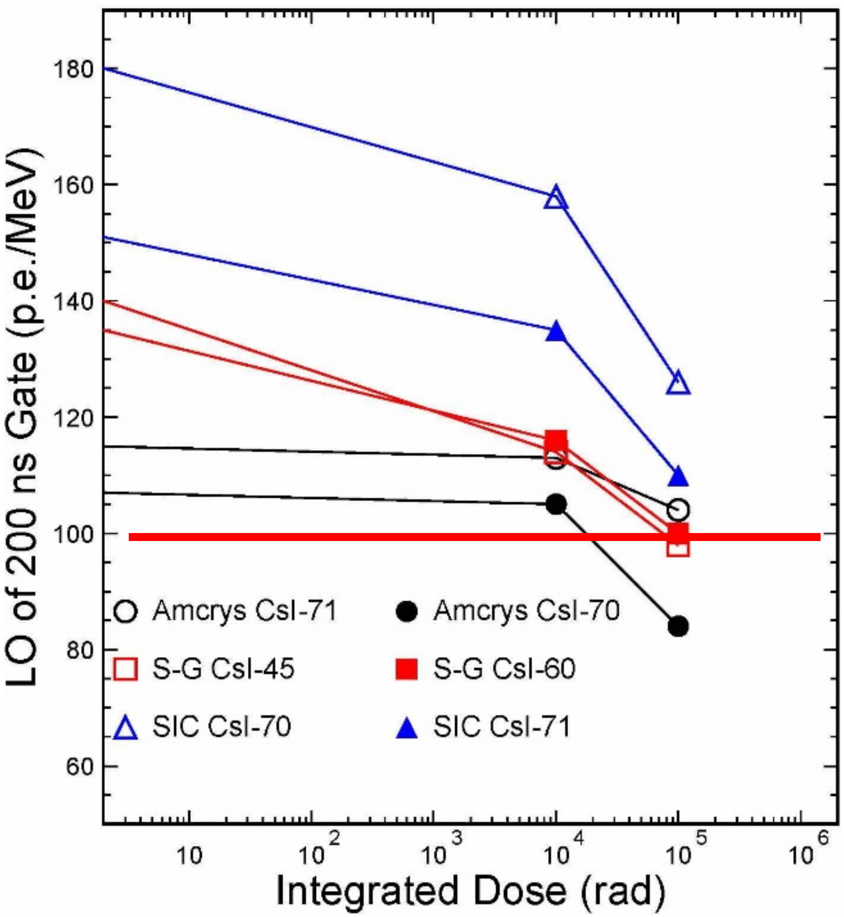


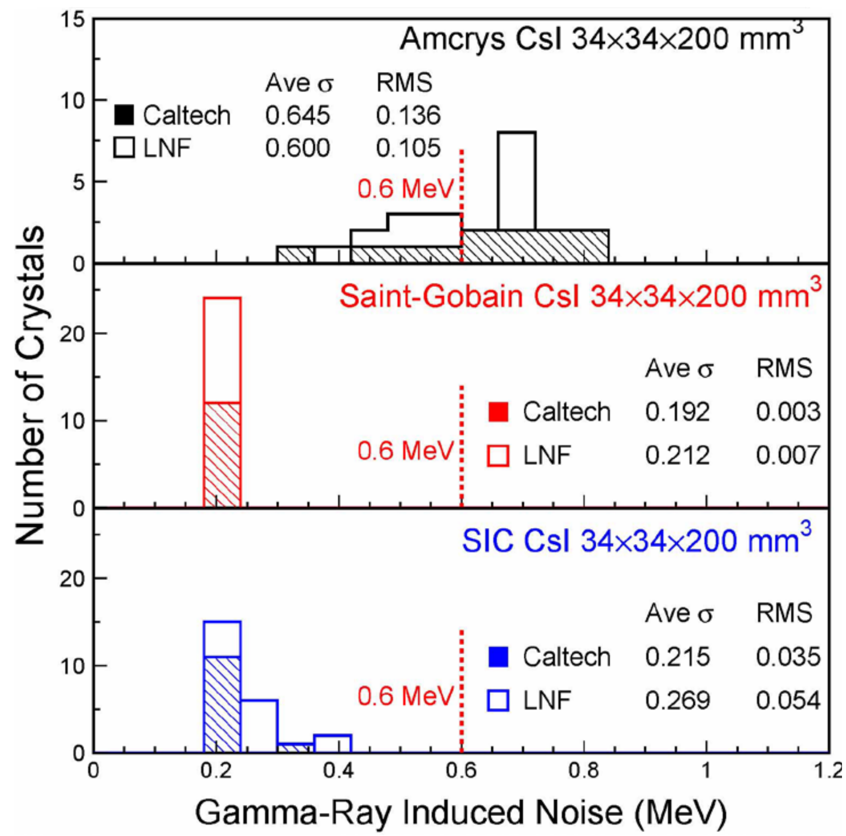




Rad-Hard test: qualify crystals up to 100 krad , 10 ^{12} n/cm^2
Qualify photo-sensors up to 10^{11} --- 3x10^{11} n_1MeV/cm^2

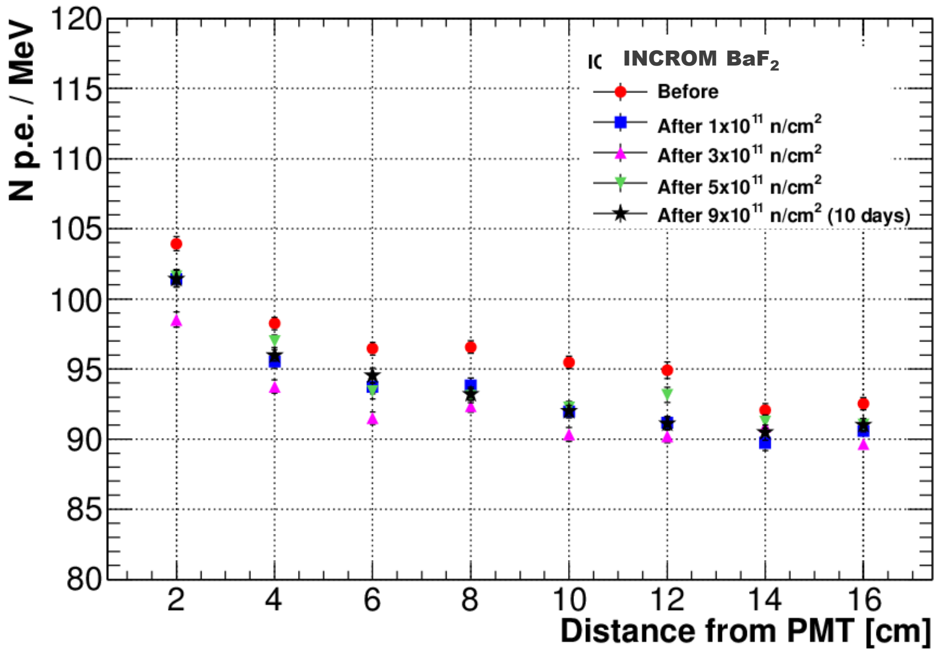
Radiation hardness: dose & neutrons

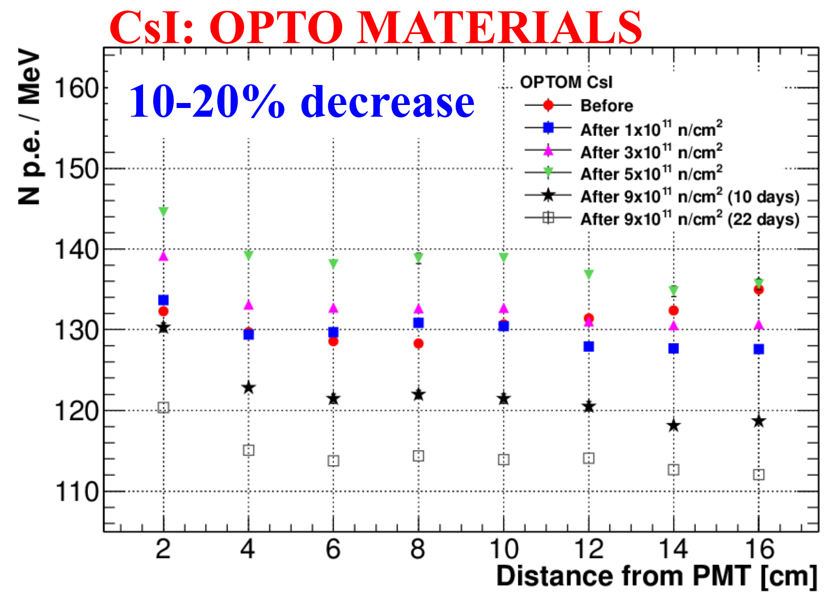


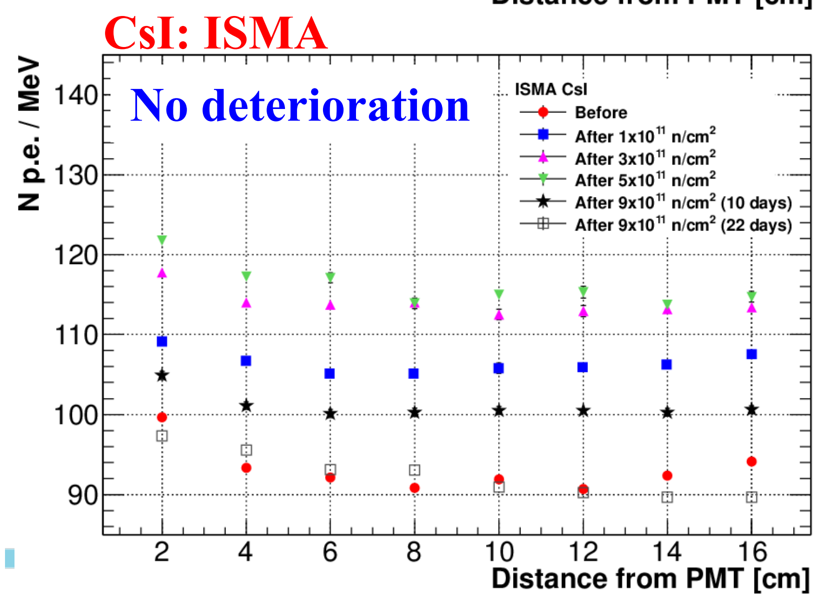


- CsI crystals rad-hard for expected dose in Mu2e-I
- No recovery after annealing
- RIN is larger for ionizing dose than for neutrons

Crystal radiation hardness: neutrons



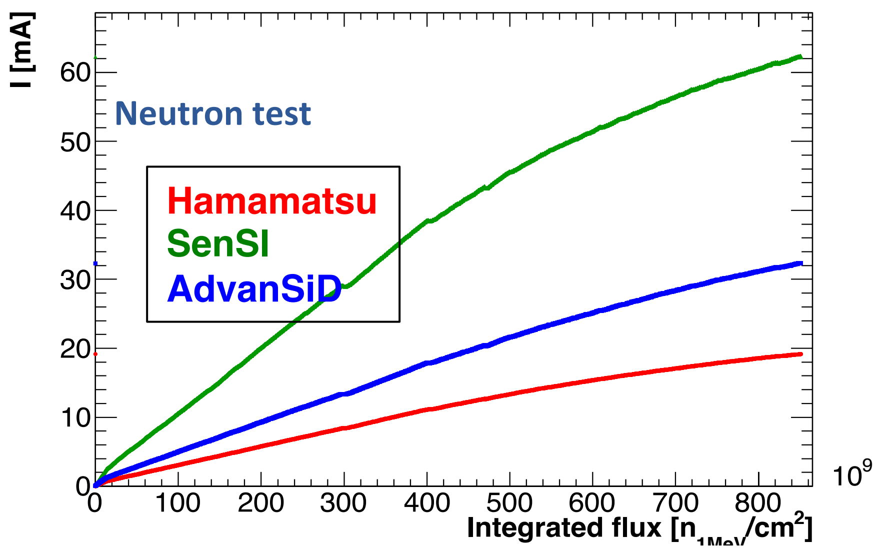


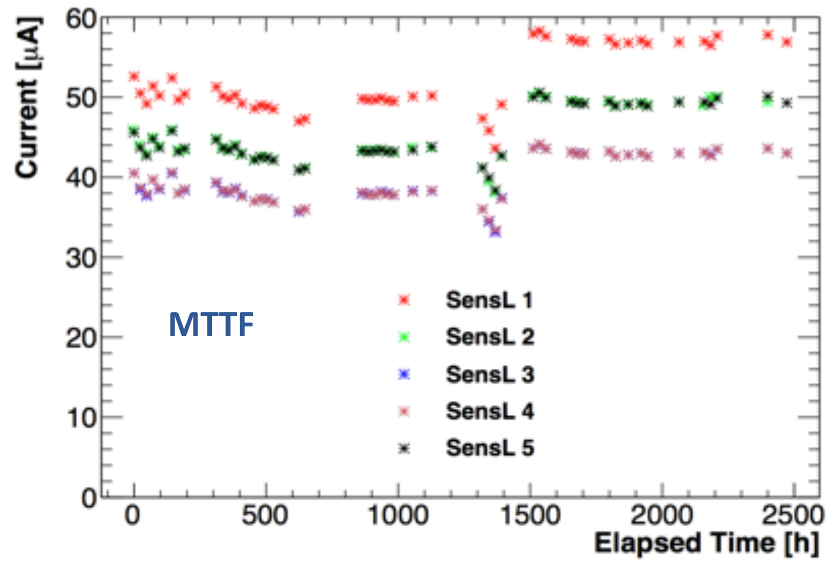


- Both crystals are radiation hard for the expected flux of neutrons.
- Losses in transmittance and LY contained at the 10% level

Irradiation and MTTF of SiPMs

- ✓ 1 sample/vendor have been exposed to neutron flux up to $8.5\times10^{11}\ n_{1MeVeq}/cm^2$ (@ 20 °C)
- ✓ 5 samples per vendor have been used to estimate the mean time to failure value
  Requirement: grant an MTTF of 1 million hours when operating at 0 °C





In Mu2e SiPMs will operate @ 0 °C

→ a decrease of 10 °C in SiPMs temperature corresponds to a I_d decrease of 50%
→ Lower V_{op} also helps to decrease I_d

Thumb Rule: -1 V, 10% loss, -2V 40% loss

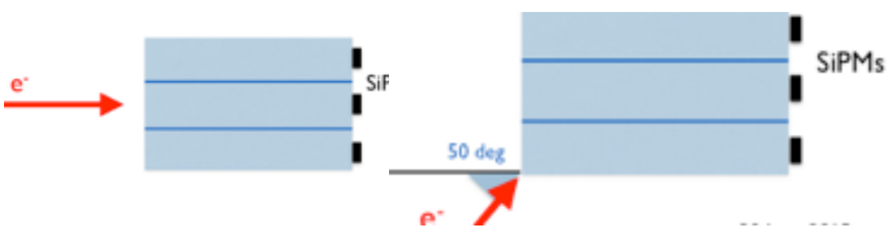
- MTTF evaluated operating SiPMs @ 50 °C for 3.5 months
- No dead channels observed

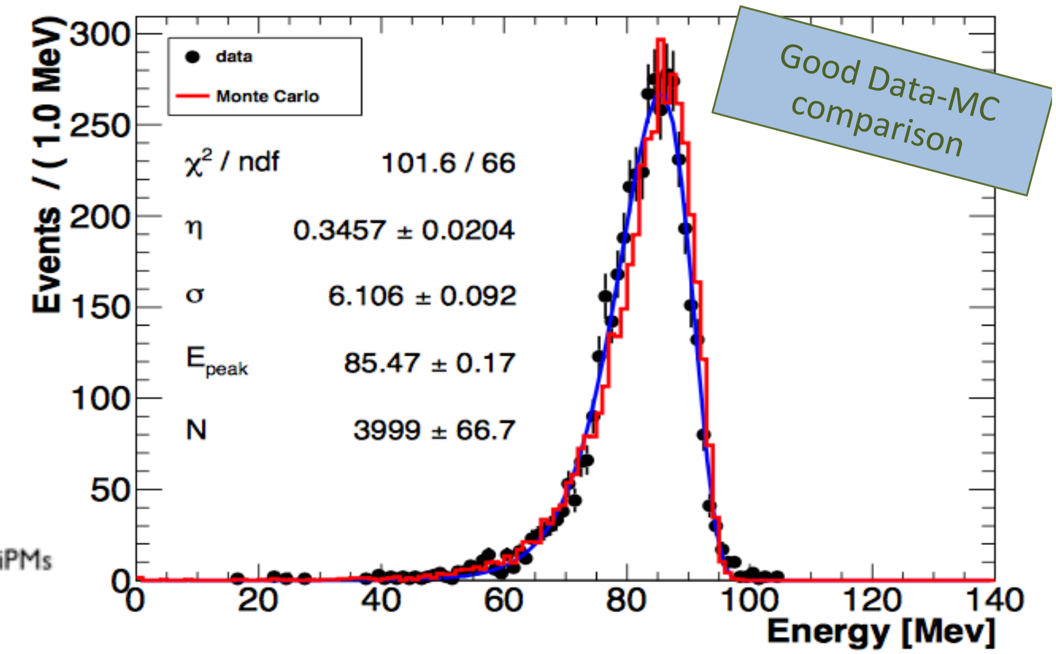
MTTF ≥ 6×10^5 hours

Small size prototype (1)

- Small prototype tested @ BTF (Frascati) in April 2015, 80-120 MeV e^-
- 3×3 array of 30×30×200 mm^2 undoped CsI crystals coupled to one Hamamatsu SiPM array (12x12) mm^2 with Silicon optical grease
- DAQ readout: 250 Msps CAEN V1720 WF Digitizer

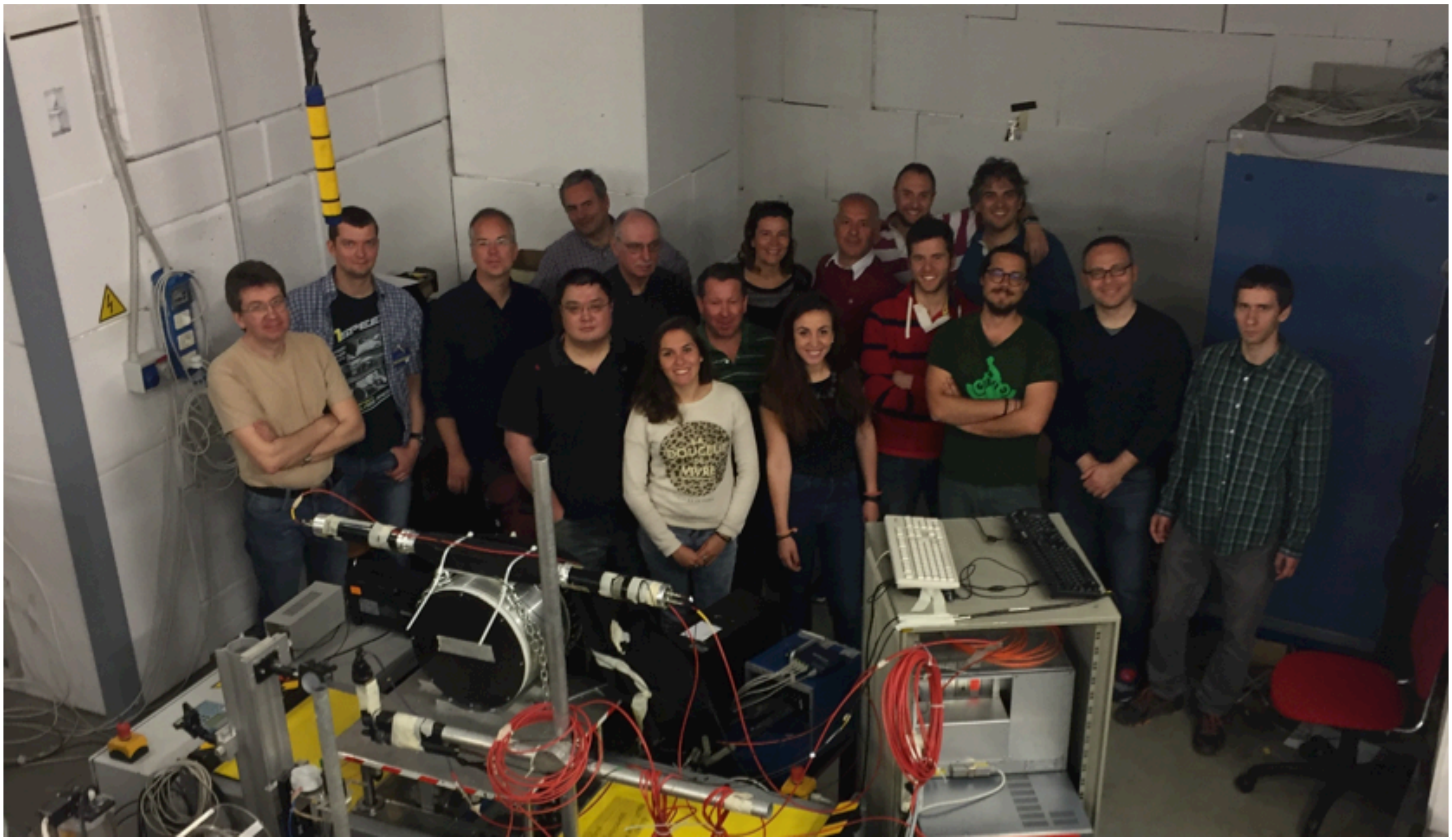
JINST 12 (2017) P05007



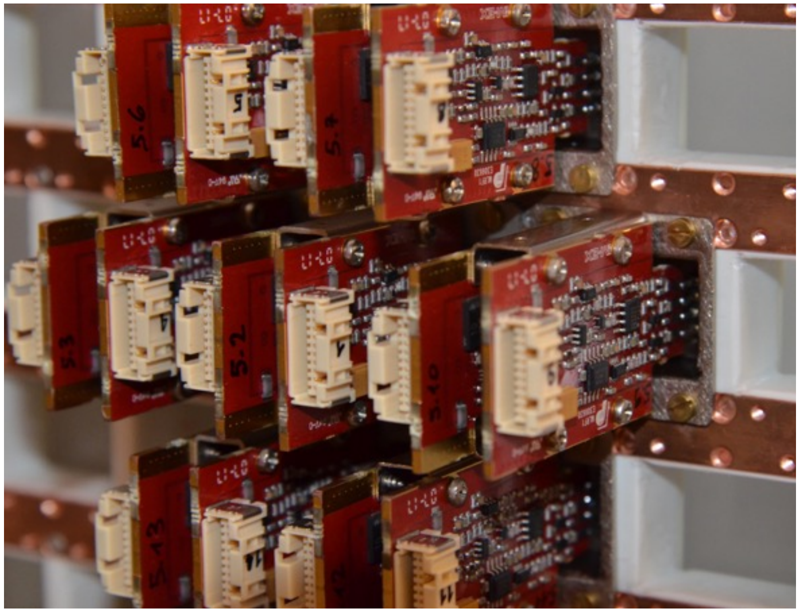


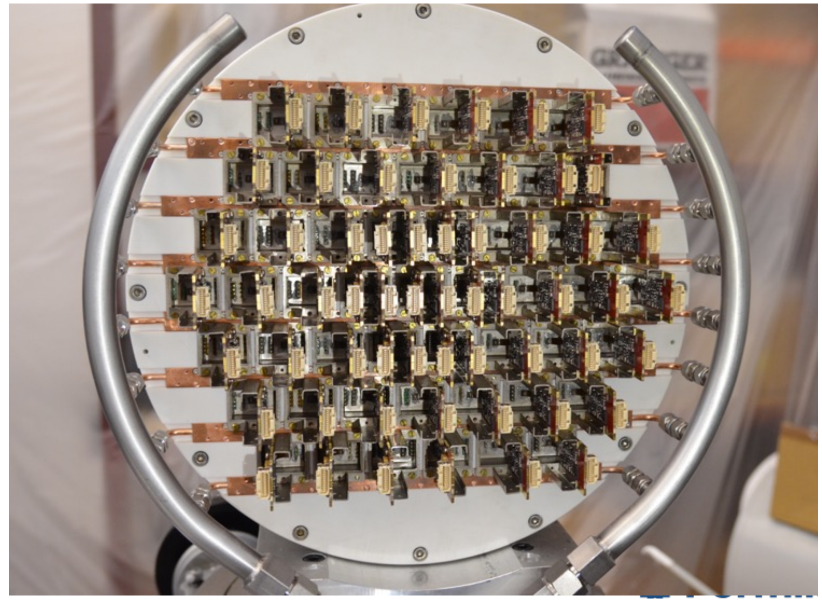
Test Beam of Module-0

Module- 0 has been transported to the area for an electron beam test @ LNF.
16 people (INFN, Caltech, JINR) worked on this test beam **May 8-15 2017**



Module-0 preparation: step-2

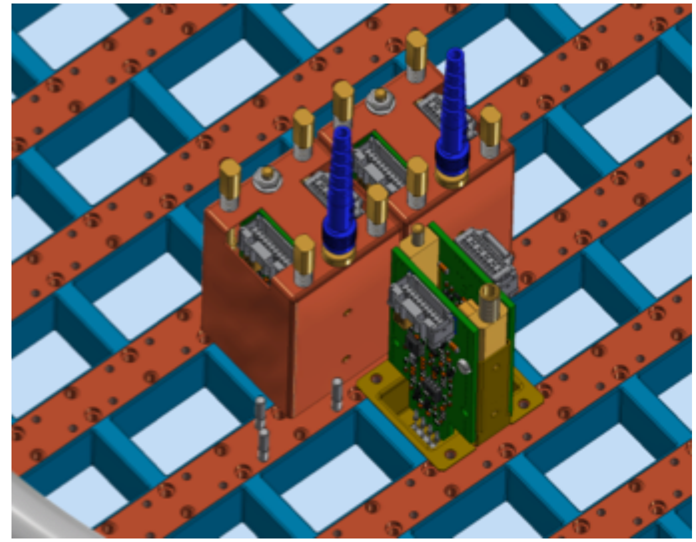


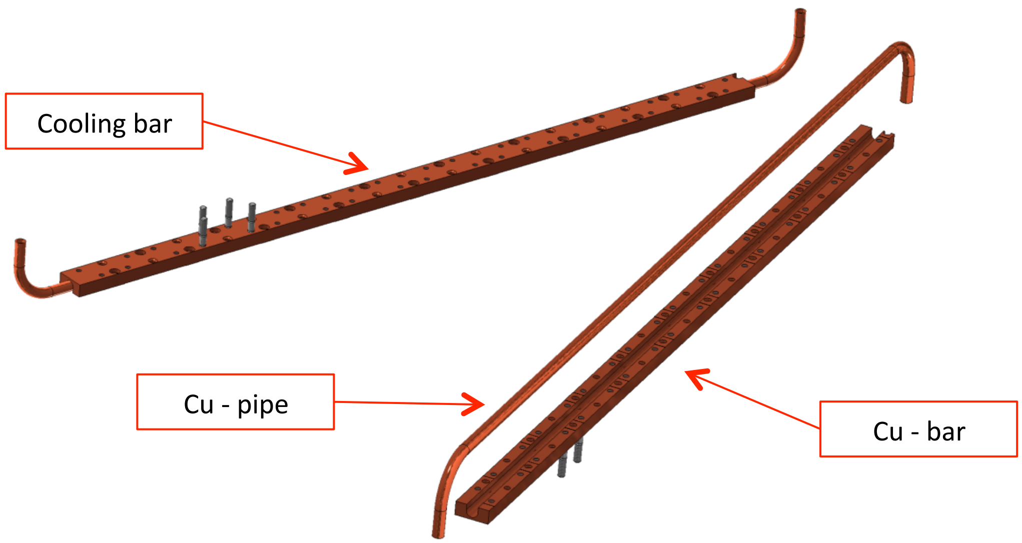


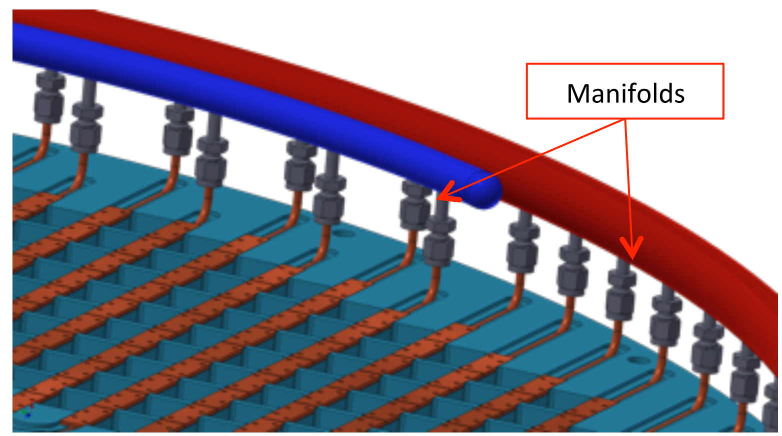
- Mount SiPM+FEE on back plate.
- Readout with 4 NIM Mboard 16 channel each
- Total readout of 58 channels.
  The 7 central crystals had two FEE chips (and cable)/Holder
- Final readout via 2 CAEN WD (DRS4) chips, 32 channels, 1 Gsps

End-plate design and Cooling

- The FEE plate houses the Front End electronics and photosensors holders and provides cooling.
- The coolant runs inside the cooling channels, at ~ -10°C.
- The manifolds are jointed to the cooling channels by means of tube fittings (Swagelok type).
- The SiPM holders are bolted to the cooling channels by means four stud screws. It is in thermal contact with the cooling channels.
- The plate is thermally isolated from the outer ring and from the crystals.
- Thermal simulation indicates SiPM to run at 2.7 °C

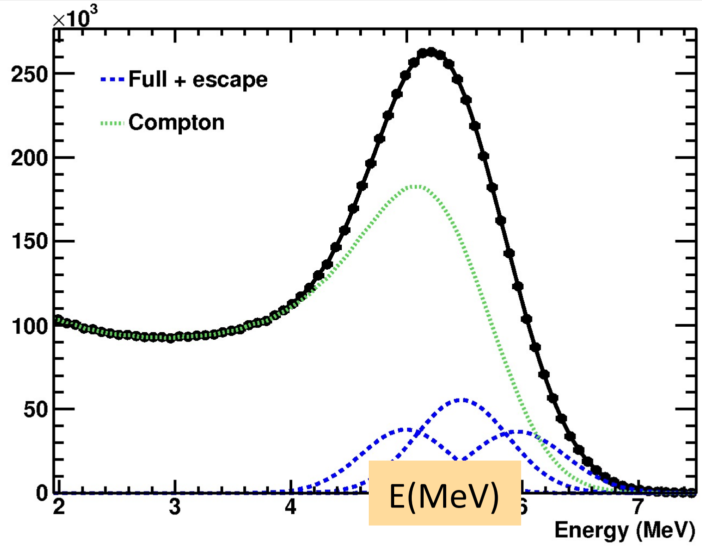






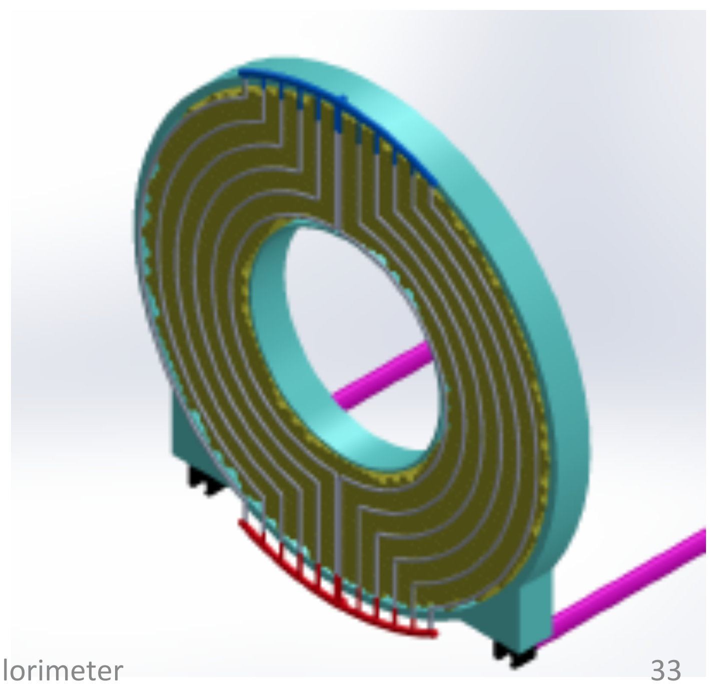
Calibration and monitoring system (1)

- Neutrons from a DT generator adjacent to the Detector irradiate a fluorine rich fluid (Fluorinert).
- The activated liquid is piped to the front face of the disks.
- Few per mil energy scale in a few minutes.
- Final experiment scale (E/P) is set using DIO's.



Based on BABAR scheme & salvage of their components

→ Salvage of BABAR DT generator done @ Caltech
→ Integration of pump, mechanics and controls done
→ **First tests done in summer 2015**



Calibration and monitoring system (2)

Laser system adapted from CMS calibration system.
UV light to monitor continuously the variation of the APD gain and as the first tool for calibrating the timing offsets

→ Green laser prototype used for LYSO test.

→ Distribution system with Silica optical fibers developed

→ Successful

→ **UV laser and monitoring system still to be optimized.**