Design and status of the Mu2e crystal calorimeter

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On behalf of the MU2E Calorimeter group

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Istituto Nazionale di Fisica Nucleare

Talk layout

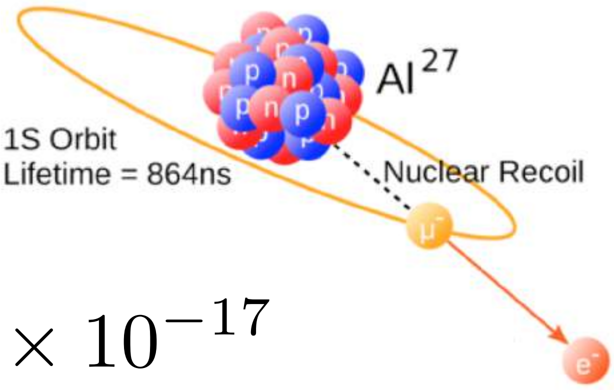
- **The Mu2e experiment**
  - Physics case
  - Experiment beamline

- **Mu2e Electromagnetic Calorimeter**
  - Requirements and components
  - Undoped CsI Crystals
  - MU2E UV-extended SiPM arrays
  - CsI-MPPC prototype
  - Pre-production of CsI and Mu2e SiPMs
  - Module 0 structure and test beam performances
  - Mechanical structure
  - QC of production and present status

The MU2E experiment

- CLFV processes are forbidden in SM
  - Even allowing neutrino oscillation BR ~ 10^{-54}
- **Observation of a CLFV process will be a clear evidence of New Physics**
- Mu2e : Coherent muon conversion in the electric field of a nucleus
  - Broad sensitivity across different models
  - Very clear signature: **monoenergetic electron**

$$E_e = m_\mu c^2 - (B.E.)_{1S} - E_{recoil} = 104.96 MeV$$



μ-e conversion in the field of a nucleus

$$R_{\mu e} = \frac{\mu^- + N(A,Z) \rightarrow e^- + N(A,Z)}{\mu^- + N(A,Z) \rightarrow \nu_\mu + N(A,Z-1)} < 8 \times 10^{-17}$$

Nuclear capture of muonic Al atom

- Improve of **4 orders of magnitude** the previous limit set by the SINDRUM II experiment (6.1×10^{-13})

The MU2E beamline

- ***Production Solenoid:***

➡ Proton beam strikes target, producing mostly π

➡ Graded magnetic field contains backwards π/μ and reflects slow forward π/μ

- ***Detector Solenoid:***

➡ Capture muons on Al target

➡ Measure momentum in tracker and energy in calorimeter

➡ Graded field "focuses" e^- in tracker fiducial

- ***Transport Solenoid:***

➡ Select low momentum, negative muons

➡ Antiproton absorber in the mid-section

The MU2E calorimeter requirements

General

High acceptance for reconstructing energy, time and position to provide:

- **Particle Identification: e/μ separation → reject μ background**
- **A seed to improve track pattern recognition**
- **A calorimeter standalone trigger**
- **Operation for 1 year w.o. interruption in DS w/o reducing performance**

@ 105 MeV

Calorimeter requirements

- energy resolution $\sigma_E/E < 10\%$
- timing resolution $\sigma(t) < 500$ ps
- position resolution < 1 cm
- Work in vacuum @ 10^{-4} Torr
- Work in 1 T Magnetic Field

Crystals coupled with Silicon PhotoMultipliers (SiPM)

- Light Yield (SiPM)>20 pe/MeV
- Fast signal for pileup and timing
- **Survive a high radiation environment**
  - Total Ionizing Dose (TID) of 90 krad/5 years for crystals
  - TID of 75 krad/5 years for sensors
  - 3×10^{12} n/cm^2 for crystals
  - 1.2×10^{12} n/cm^2 for sensors

Calorimeter Structure

The calorimeter consists of two disks to optimize acceptance for spiraling electrons **with 674 34x34x200 mm^3 undoped CsI crystals:**

→ R_{inner} = 375 mm, R_{outer}=657 mm

→ depth = 10 X_0 (200 mm) but CE angle of 55°

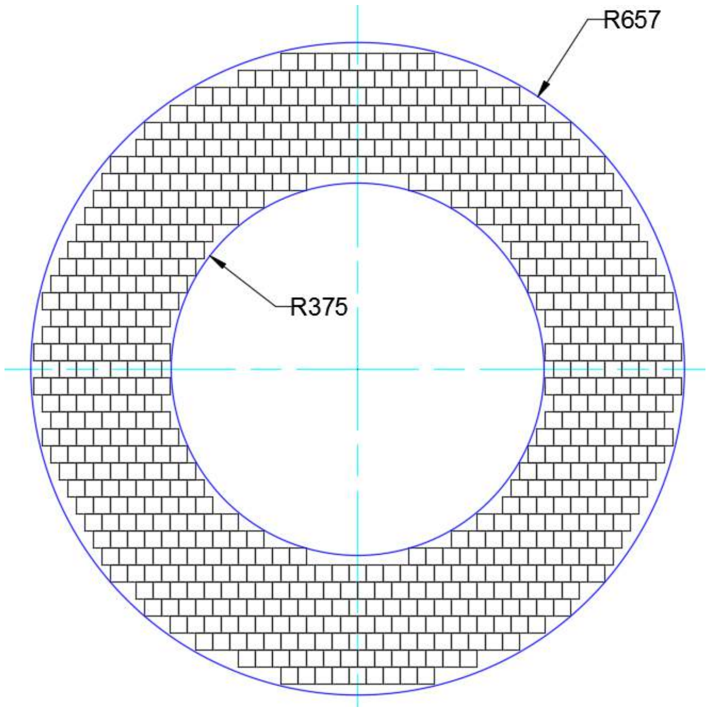
→ Disks separated by 75 cm

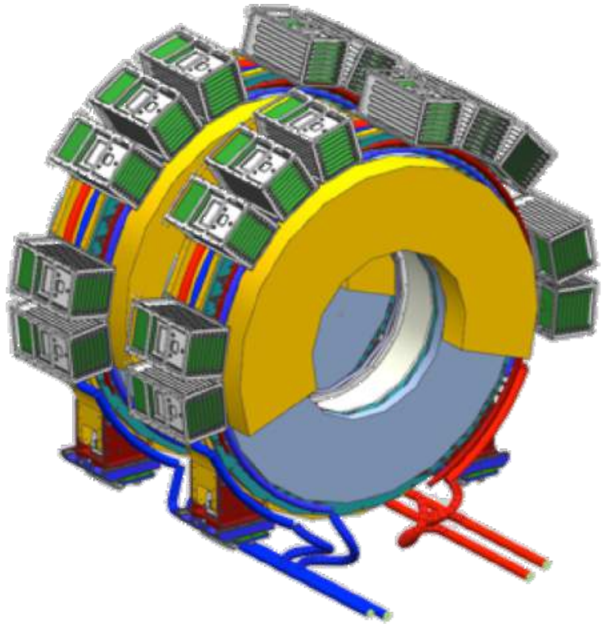
→ Each crystal is readout by two large area UV extended SIPM's (12x18 mm^2) for redundancy

→ Analog FEE is on the SiPM and digital electronics located in near-by electronics crates

→ Radioactive source and laser system provide absolute calibration and monitoring capability

→ Crystals and sensors should work in 1 T B-field and in vacuum of 10^{-4} Torr





Crystal requirements and R&D

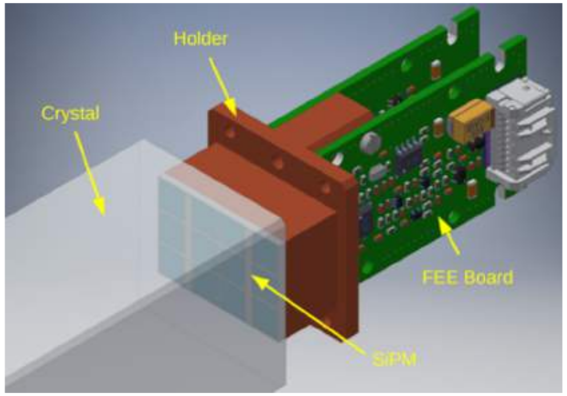
- High light output (LO) > 100 p.e./MeV by standard bialkali PMT with air gap and crystal wrapped with 150 μm Tyvek paper

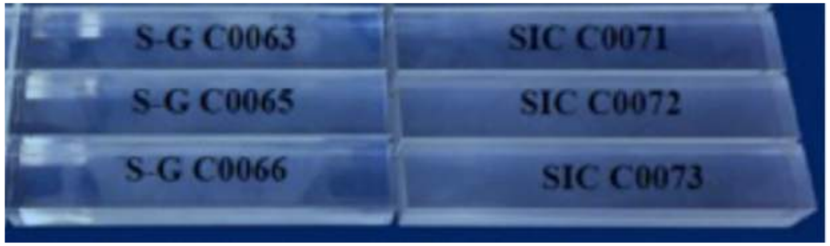
- Good light response uniformity (LRU) < 10 %

- Fast signal with small slow component:

  τ < 40ns and

  F/T = F(Integral in 200 ns)/T(Integral in 3000 ns) >75%





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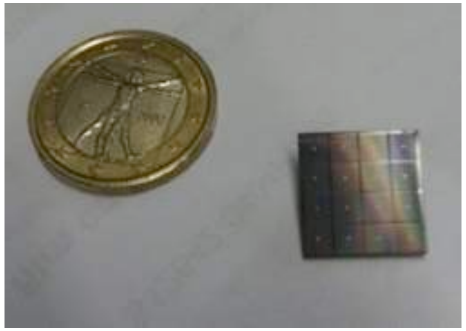
	~~LYSO~~	~~BaF_2~~	CsI
Radiation Length X_0 [cm]	1.14	2.03	1.86
Light Yield [% NaI(Tl)]	75	**4**/36	3.6
Decay Time[ns]	40	**0.9**/650	20
Photosensor	APD	**RMD APD**	SiPM
Wavelength [nm]	402	**220**/300	310

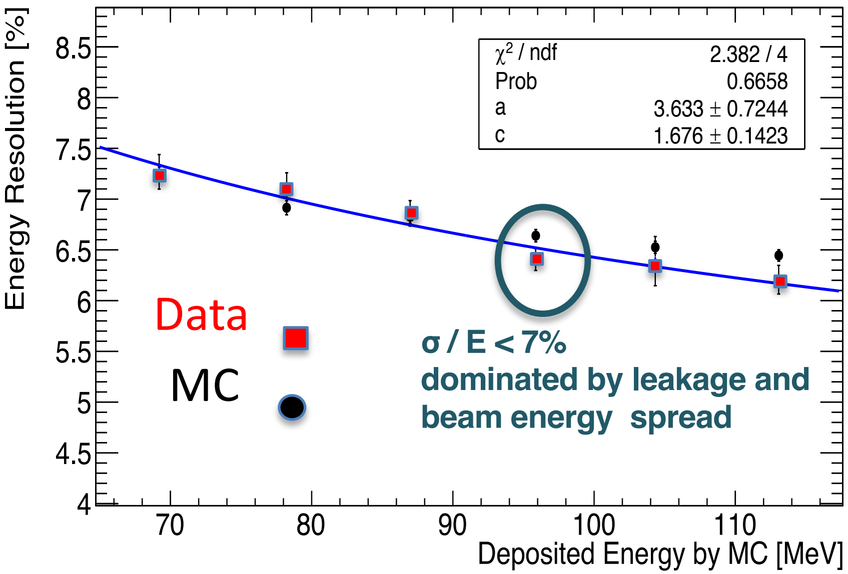
CsI(pure)

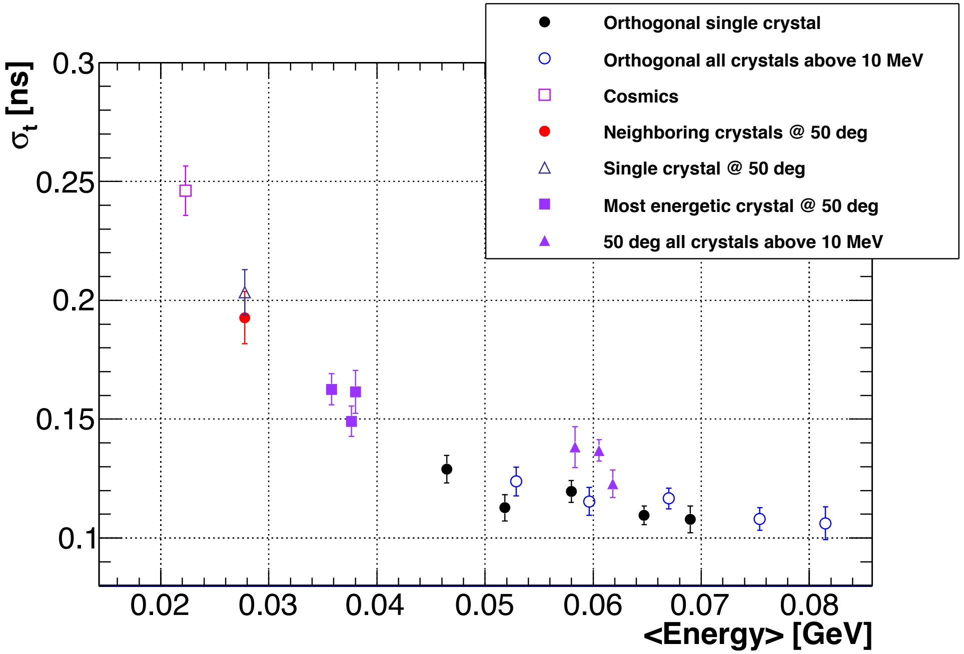
- Adequate radiation hardness
- Slightly hygroscopic
- 30 ns emission time, small slow component.
- Emits @ 310 nm.
- Comparable LY of fast component of BaF_2.
- Lower cost (6-8 $/cc)

CsI+MPPC test

- A small crystal prototype has been built and tested in Frascati in April 2015
- 3x3 matrix of 3x3x20 cm^3 un-doped CsI crystals coupled with UV-extended MPPC (standard 4x4 matrix of 3x3mm^2 TSV).
- Test with e- between 80 and 120 MeV



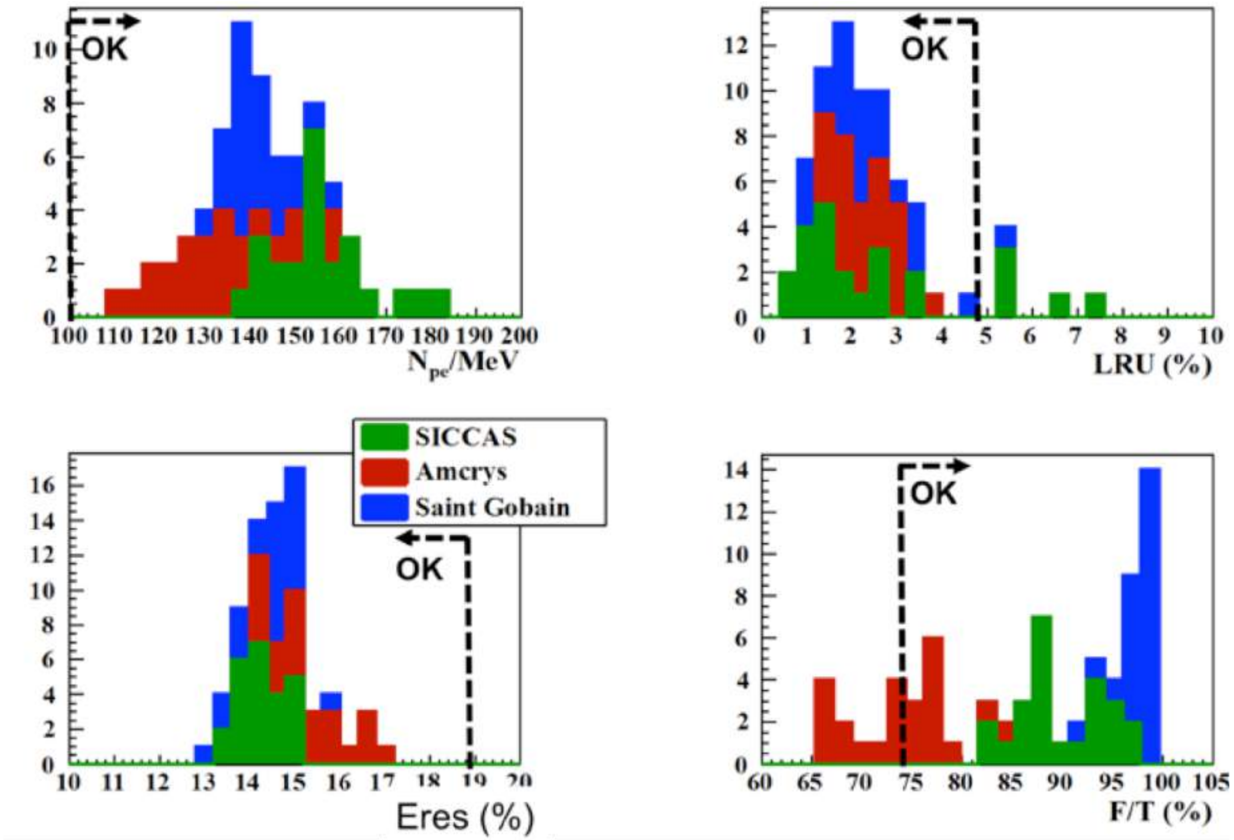




- Good energy (7%) and timing (110 ps) resolution
  Matching EMC requirements

Crystal pre-production

- Crystal dimension increased to 34x34 mm^2 to house two 2x3 arrays of 6x6mm^2 UV-extended SiPM
- 24 crystals from three different vendors: **SICCAS**, **Amcrys**, **Saint Gobain**
- ^{22}Na source to test crystal properties along the crystal axis
- Crystals coupled in air to an UV-extended PMT



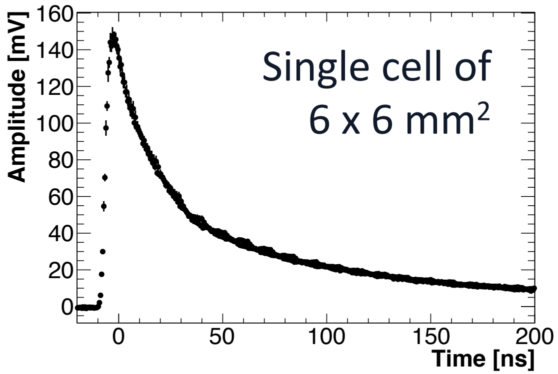
- **Optical properties:**
  - 100 pe/MeV with PMT readout
  - LRU < 5%
  - Fast/Total>75%
- **Radiation hardness**
  - Smaller than 40% LY loss @ 100 krad
  - Radiation Induced Noise <0.6 MeV

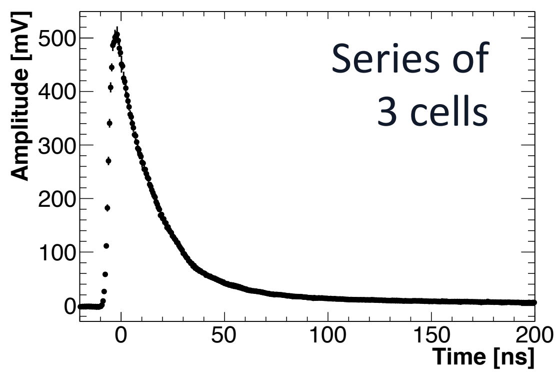
Selected vendors: SICCAS and Saint Gobain

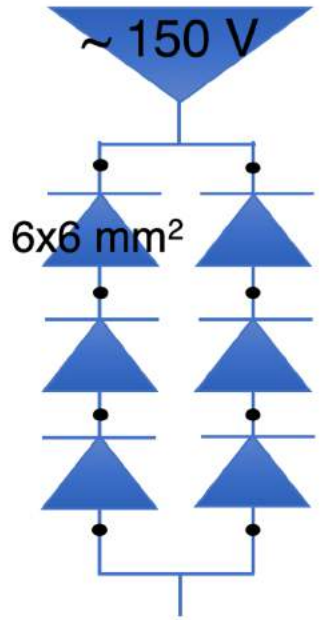
SiPM pre-production

Mu2e custom silicon photosensors:
→ **2 arrays of 3 6x6 mm² UV-extended SiPMs: total area (12x18) mm²**
The readout series configuration reduces the overall capacitance → faster signals

See I.Sarra poster

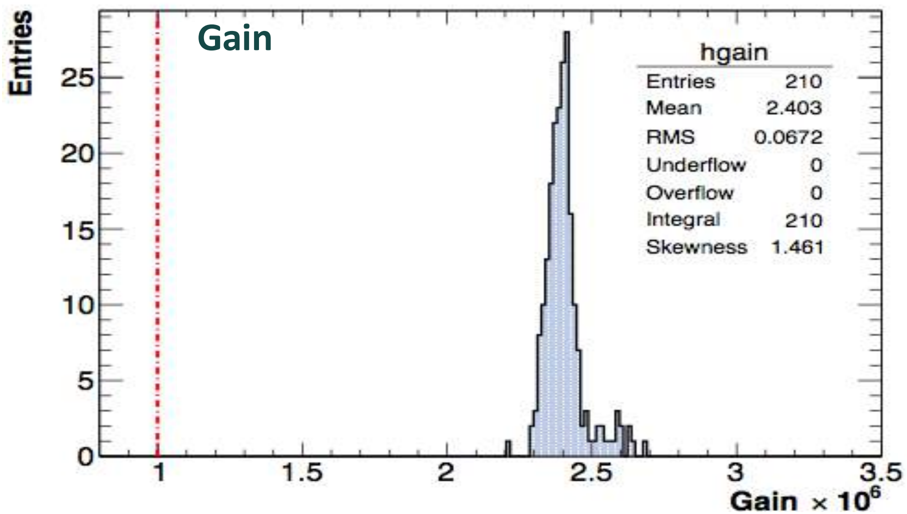


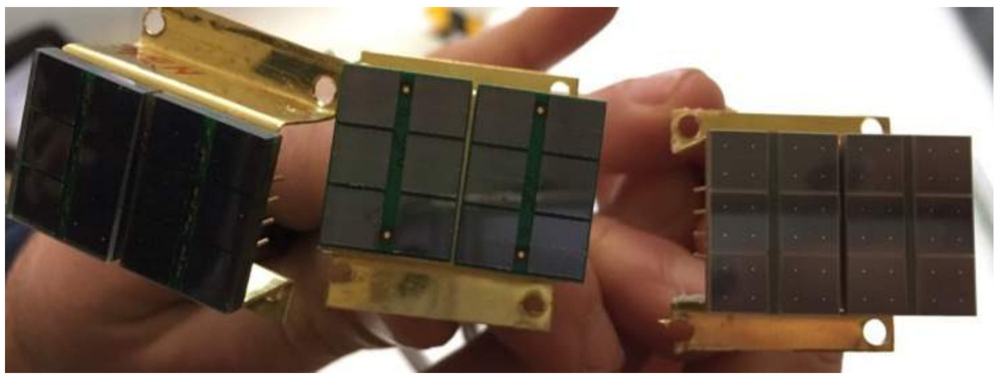




150 sensors: 3×50 Mu2e pre-production SiPMs from Hamamatsu, SenSl and AdvanSiD

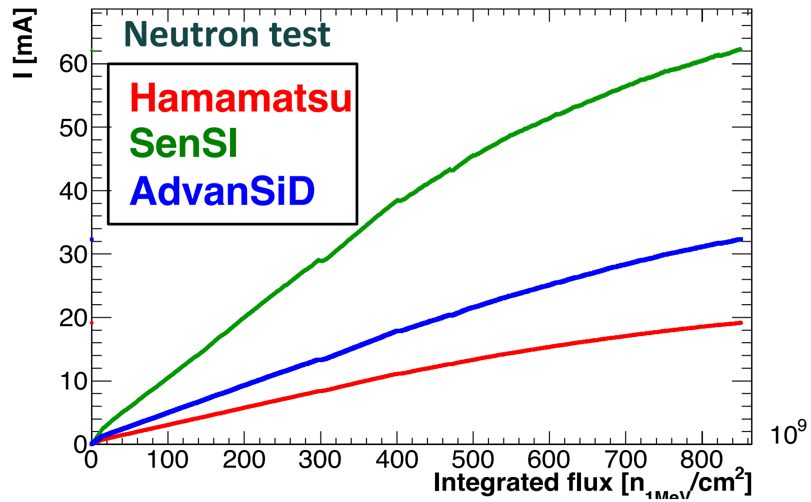
- 3×35 were fully characterized for all six cells in the array





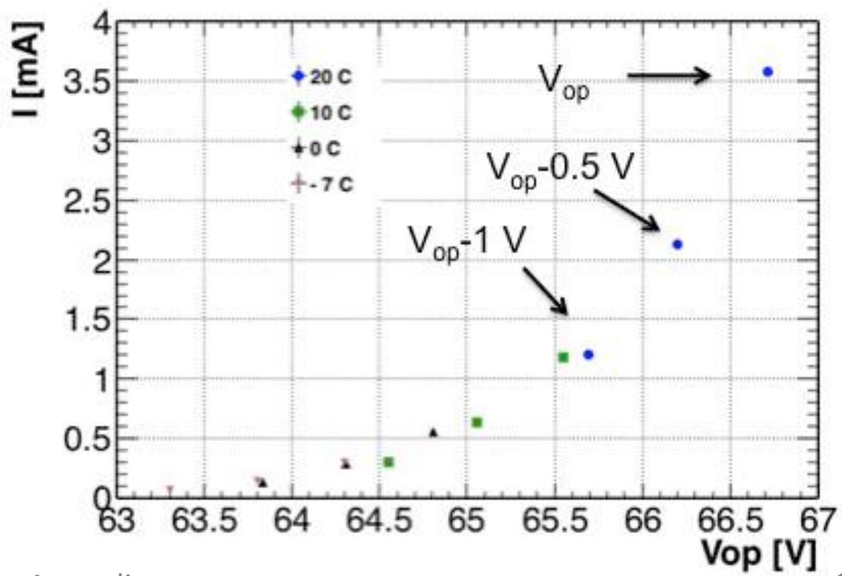
SiPM irradiated at ENEA Casaccia with 20krad ^{60}Co photon source producing negligible effect on the response and on leakage current

- Neutron irradiation tested at ENEA Frascati (FNG) with 14 MeV neutrons.
- Total flux $2.2\text{x}10^{11}$ n/cm^2 (2.2 times the experiment lifetime)
- Leakage current increases to too high values asking for cooling at lower temperatures the sensors.



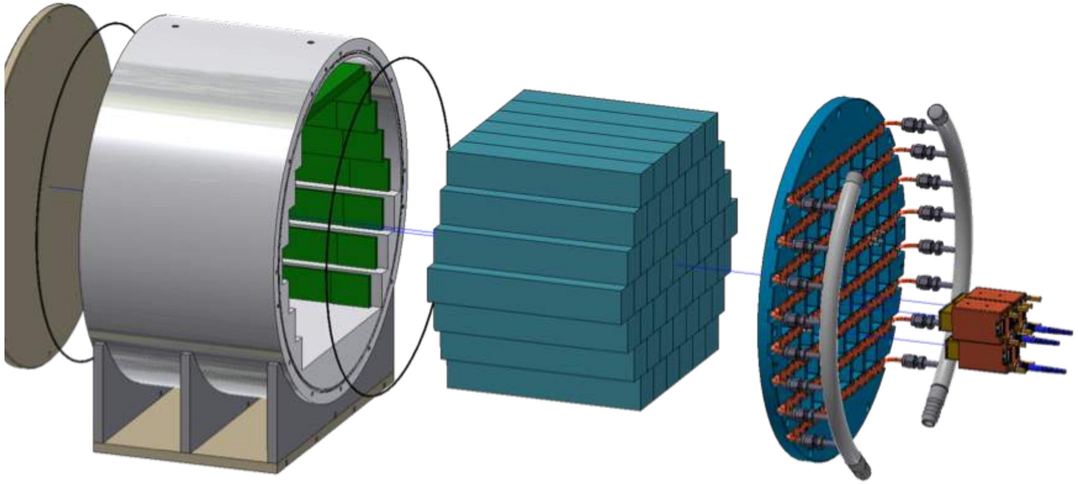
By measuring the dependence of the leakage current as a function of temperature, we observe a factor of 10 reduction in Idark when working at T = 0 °C that is acceptable.

So, we require to cool down all SIPMs to a running temperature of ~ 0 °C.

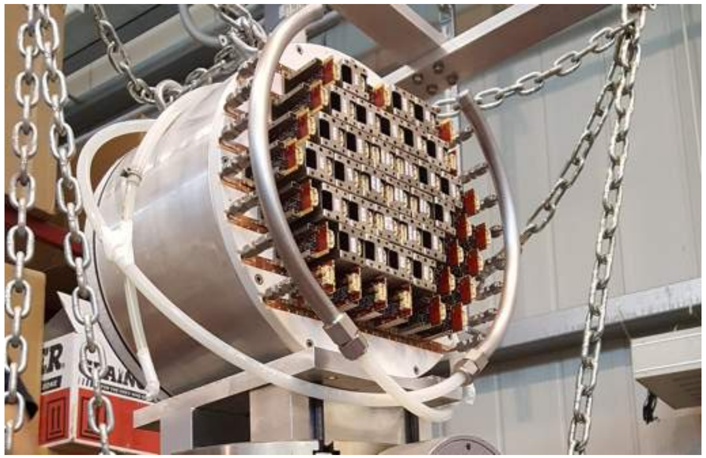


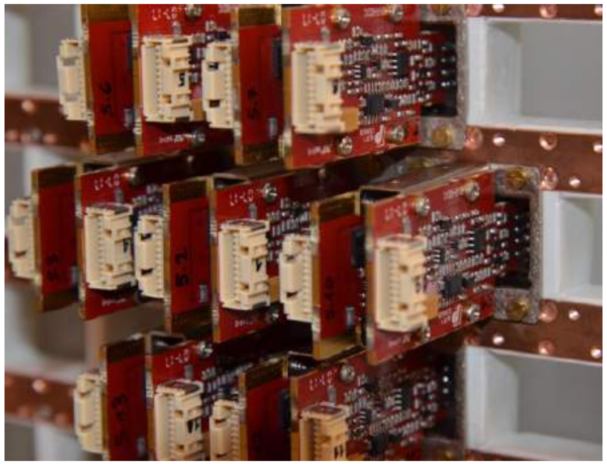
Module 0

Large size prototype: 51 crystals coupled to 102 sensors

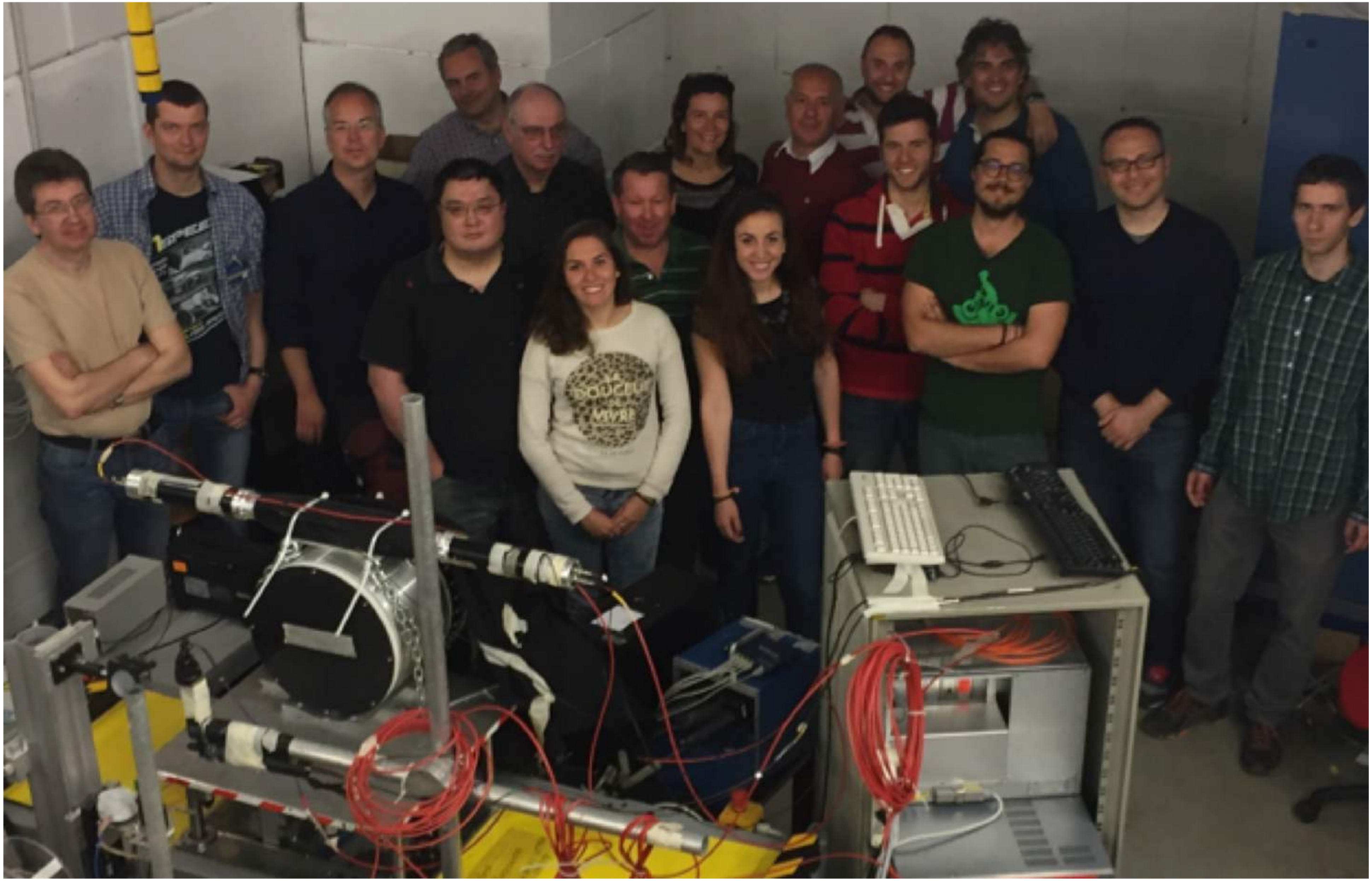


- Goals:
  - Test the performances
  - Test integration and assembly procedures
  - e⁻ beam (60-120 MeV), May 2017
    - **Orthogonal and 50° incidence (CE)**
  - Operate under vacuum, low temperature and irradiation tests
- Readout: 1 GHz CAEN digitizers (DRS4 chip), 2 boards x 32 channels





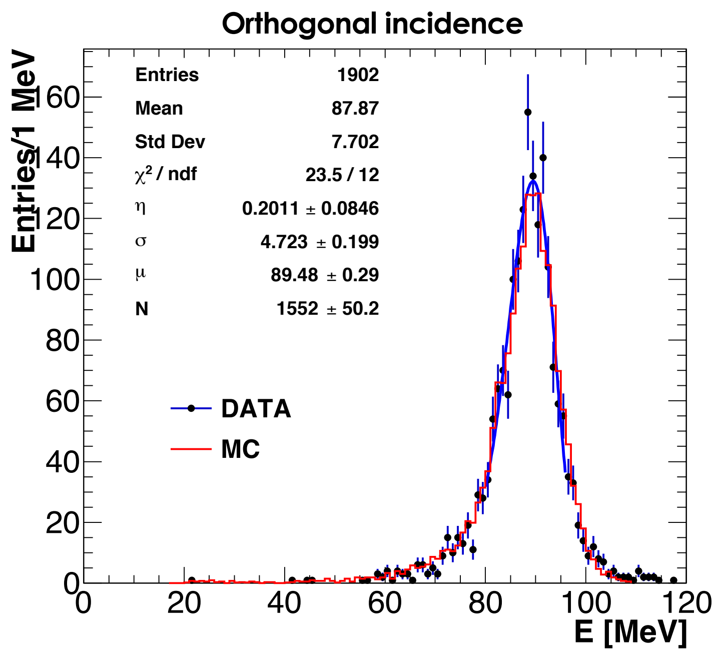
Module 0 Test Beam

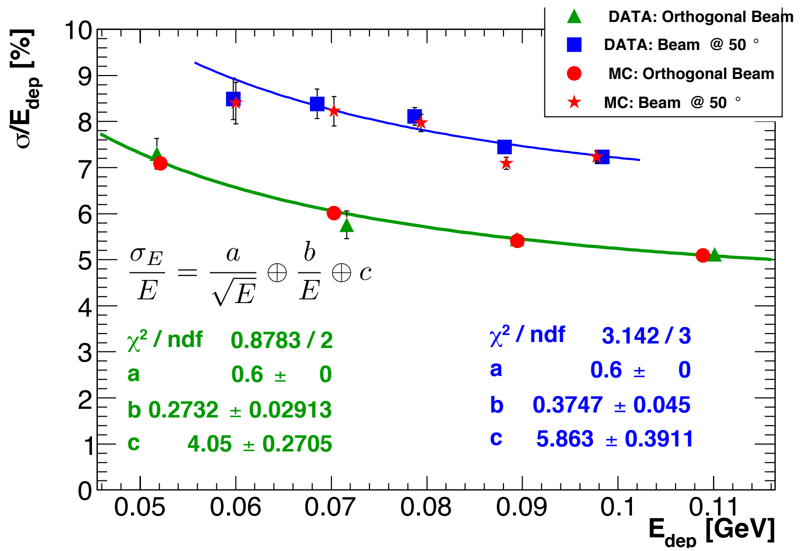


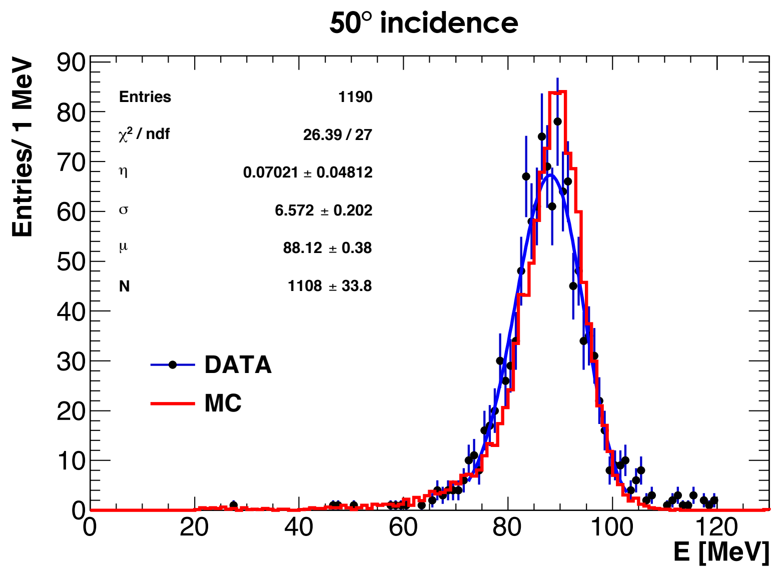
Module 0 – Energy resolution

- Single particle selection
- Calibration:
  - Cosmic
  - Beam

Orthogonal Run:
σ_E~ 5%
Tilted Run :
σ_E~ 7.5%
@ E_{beam} = 100 MeV

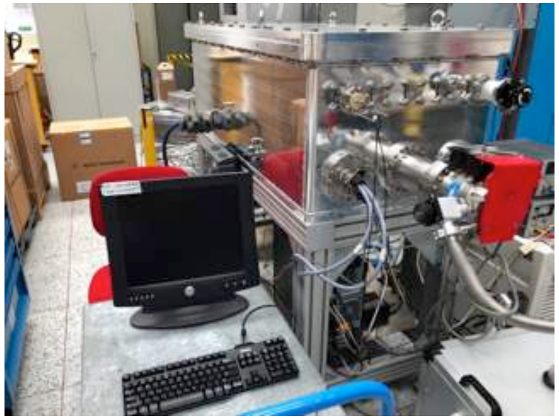




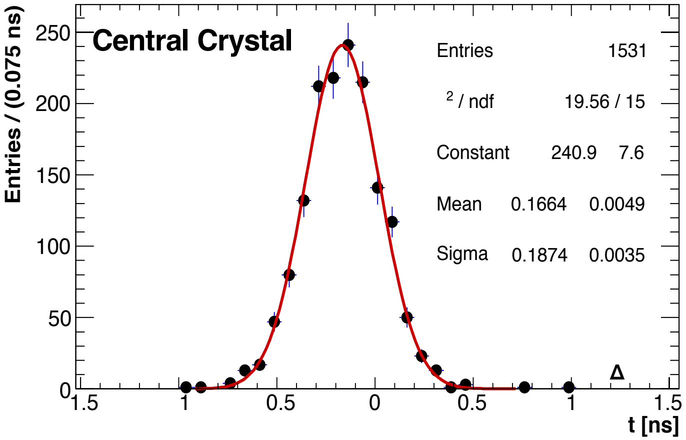


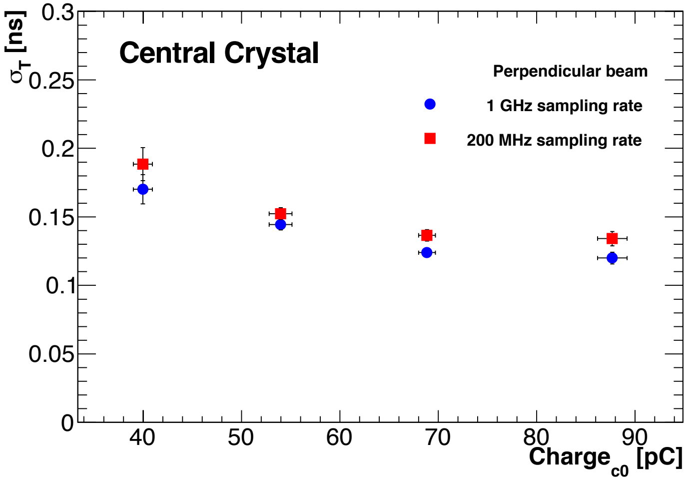
Module 0 – Time resolution

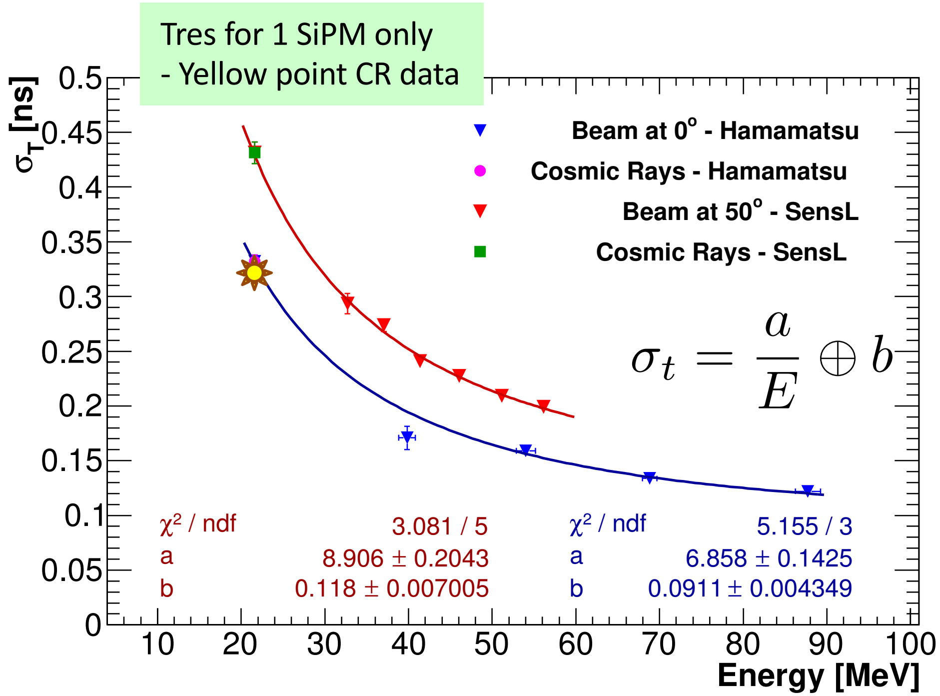
- Log Normal fit on leading edge
- Constant Fraction method used CF = 5%
- Comparison between 1GHz (TB sampling) and 200 MHz (Mu2e sampling) shows no deterioration in the resolution
- Test with CR at low temperature in vacuum (scint trigger)



σ (T1+T2)/$\sqrt{2}$ ~ 132 ps
@ E_{beam} = 100 MeV



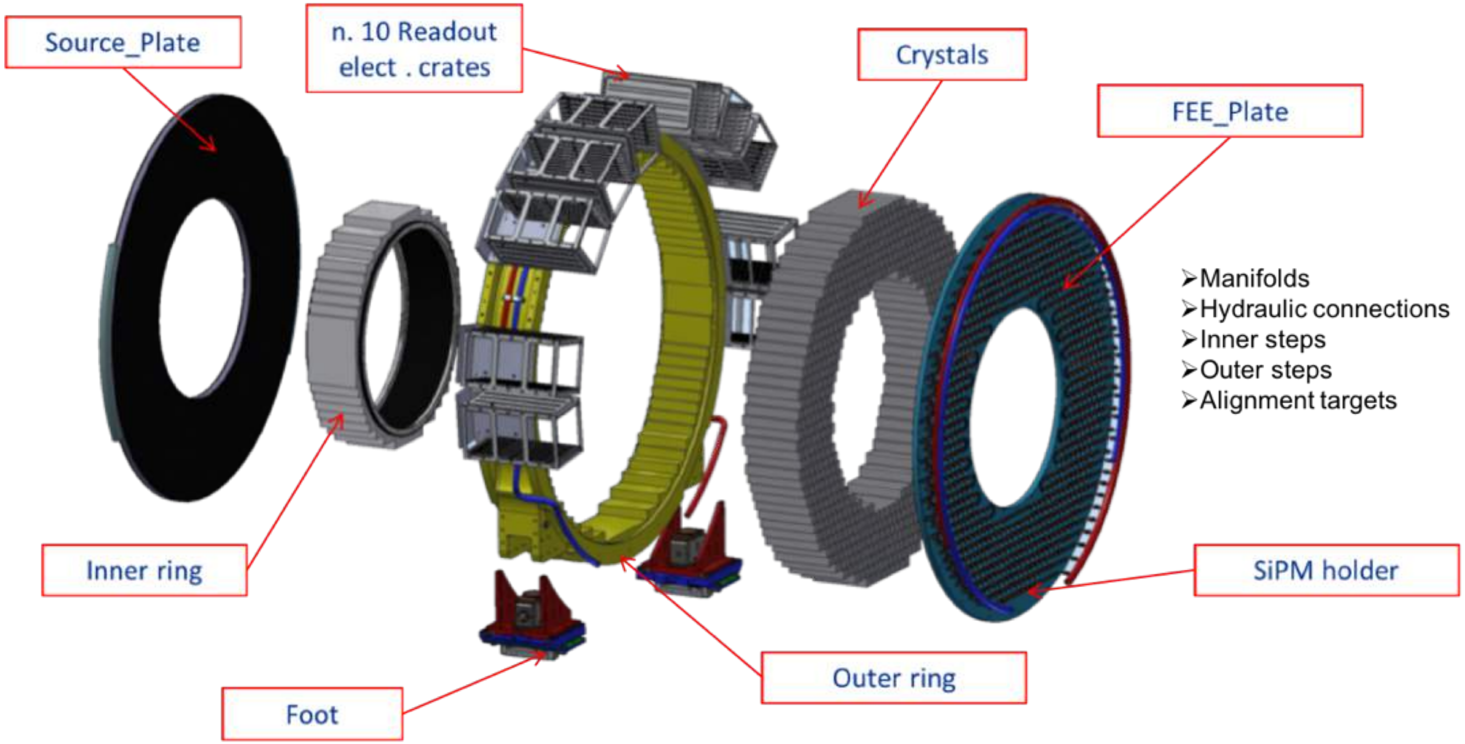




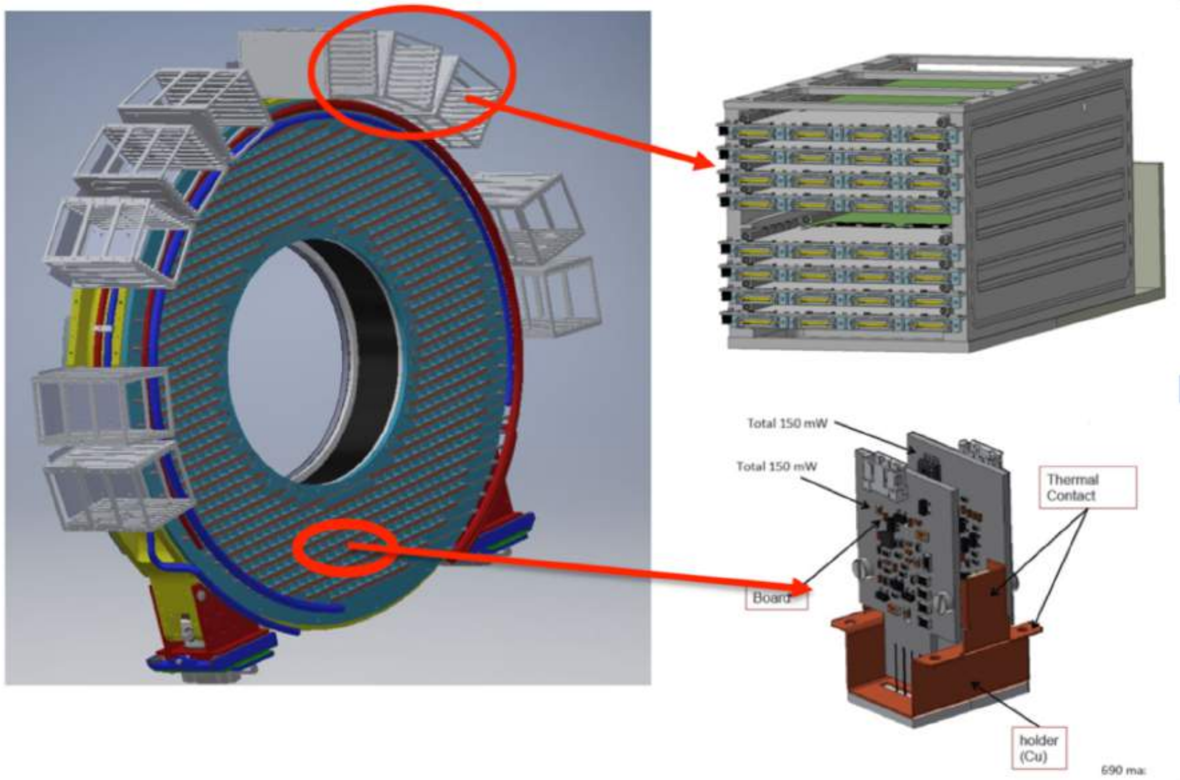
Final mechanical design

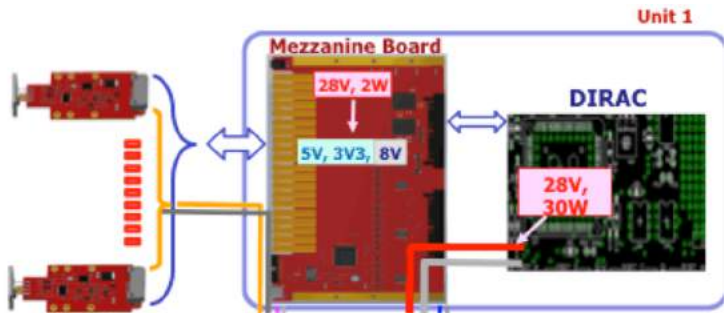
- Square crystals stacked from the bottom for increasing rows inside an external stainless steel cylinder
- Inner cylinder in composite material
- FEA completed, good stability of the system, small stress on legs
- Readout back plate in PEEK used for FEE positioning and cooling SiPMs at low temperature.
- Front face integrated with routing of Source Tubing
- FEE crates connected to the external cylinder

Detector 1:1 mockup with fake iron crystals



FEE





Dedicated board on each SiPM for:

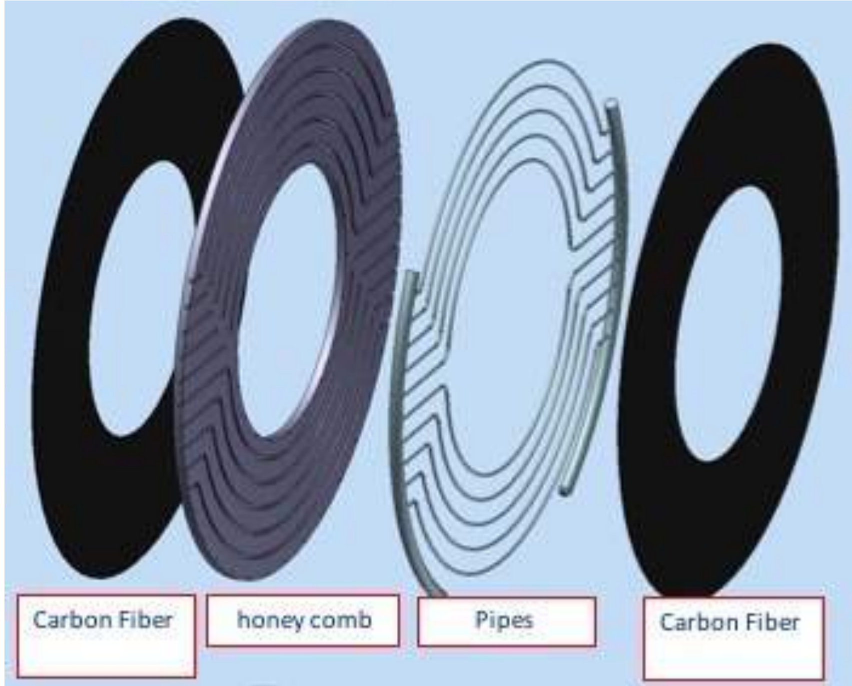
- Amplification stage (x15, x30)
- Linear regulation of bias
- Rise time 15 ns
- Dynamic range 2V
- Monitoring of the current
- Pulse signal for testing
- Therma-Bridge to dissipate heat

10 crate per disk with 8 differential channels boards:

- HV distributor (1st board)
- WD boards (2nd board) with:
  - FPGA PF300T
  - 200 Msps-12 bit ADC
  - DCDC converter
  - Optical connection

See E.Pedreschi poster

Calorimeter calibration

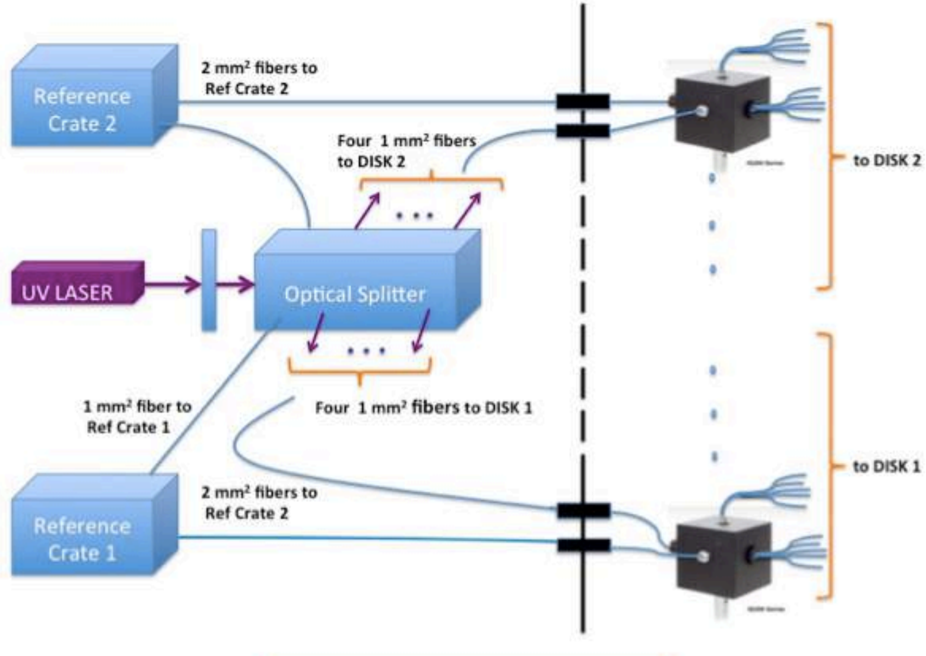


6 MeV gamma source:
Low energy neutron from DT generator irradiate Fluorinert fluid outside detector

$$^{19}F + n \rightarrow {}^{16}N + \alpha$$
$$^{16}N \rightarrow {}^{16}O^* + \beta \quad t_{1/2} = 7\ \mathrm{s}$$
$$^{16}O^* \rightarrow {}^{16}O + \gamma(6.13\ \mathrm{MeV})$$

DT generator: d+t→ n(14.2 MeV): 10^9 n/s

- **Pre-insertion calibration with 6 MeV source**
- **Weekly crystal-by-crystal calibration with 6 MeV source**
- **Monitor readout on shorter time scale with Laser system**
- **Monitor electronics gains with pulser**
- **Monitor temperatures**



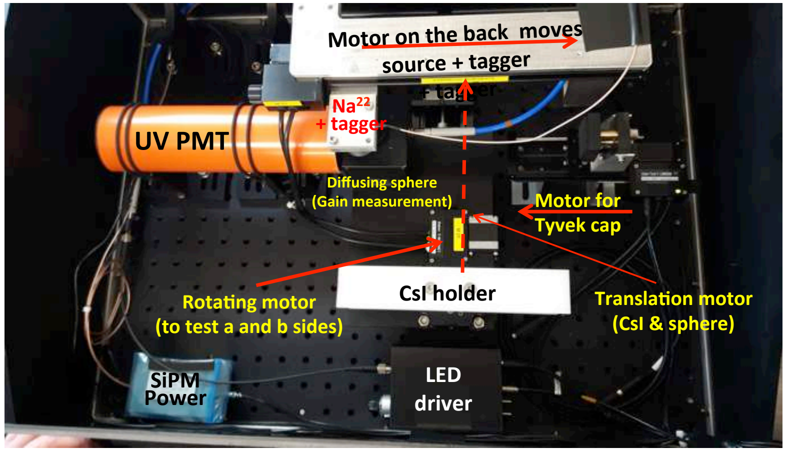
Laser system scheme

QA stations @ FNAL

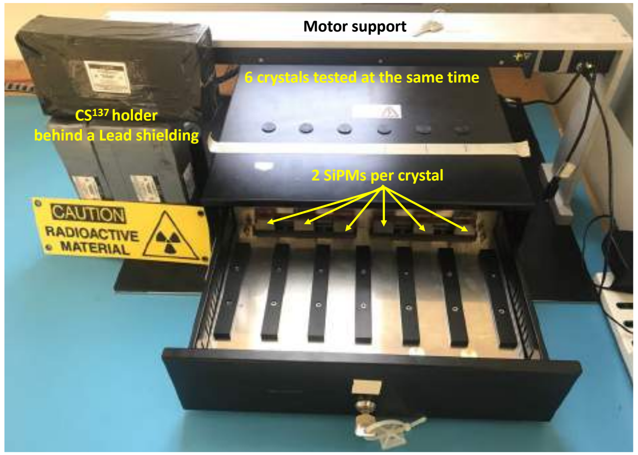
- Crystal and SiPM production started on February 2018. QC started on March 2018.
  - ~2000 SiPMs tested
  - ~500 crystals

CsI dimensional test

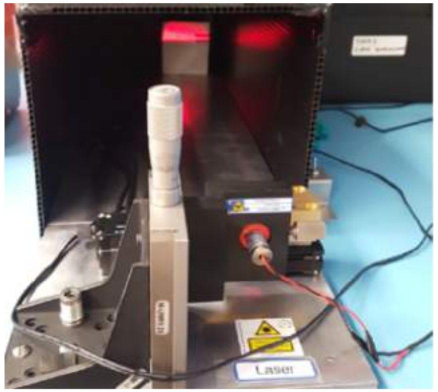
CsI QA



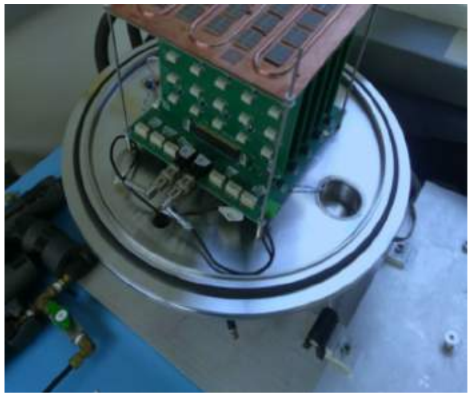
CsI RIN



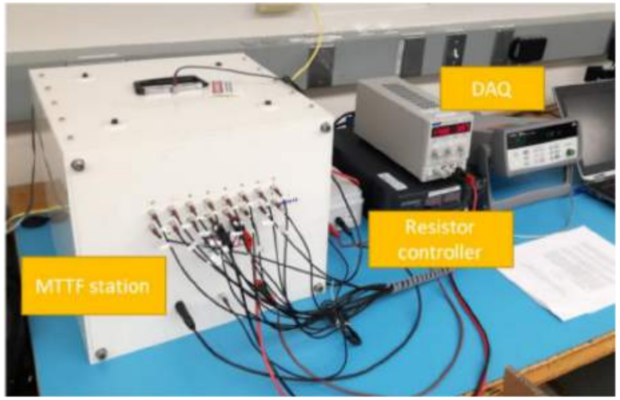
SIPM dimensional test



SiPM QA

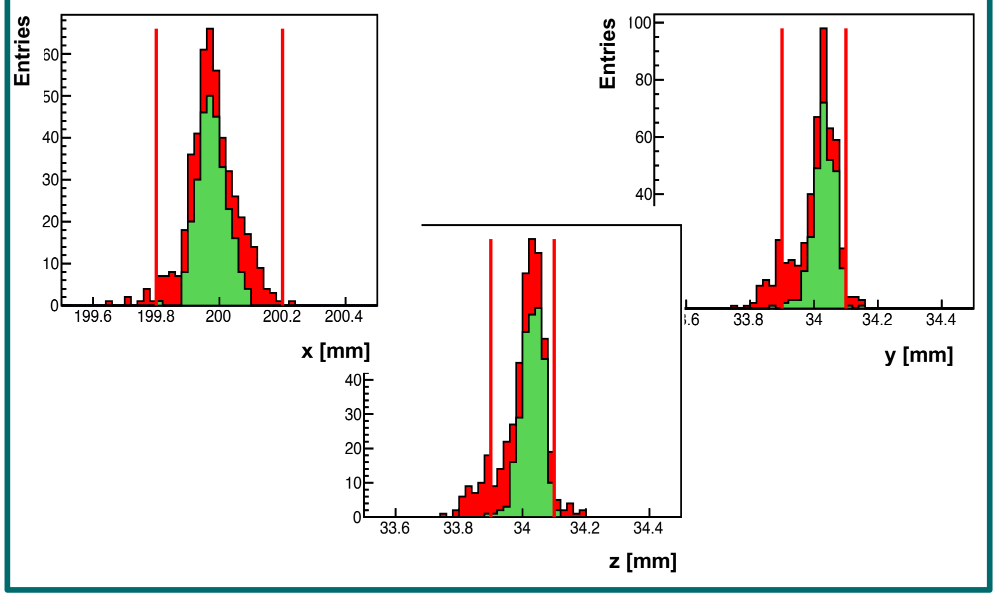


SiPM MTTF

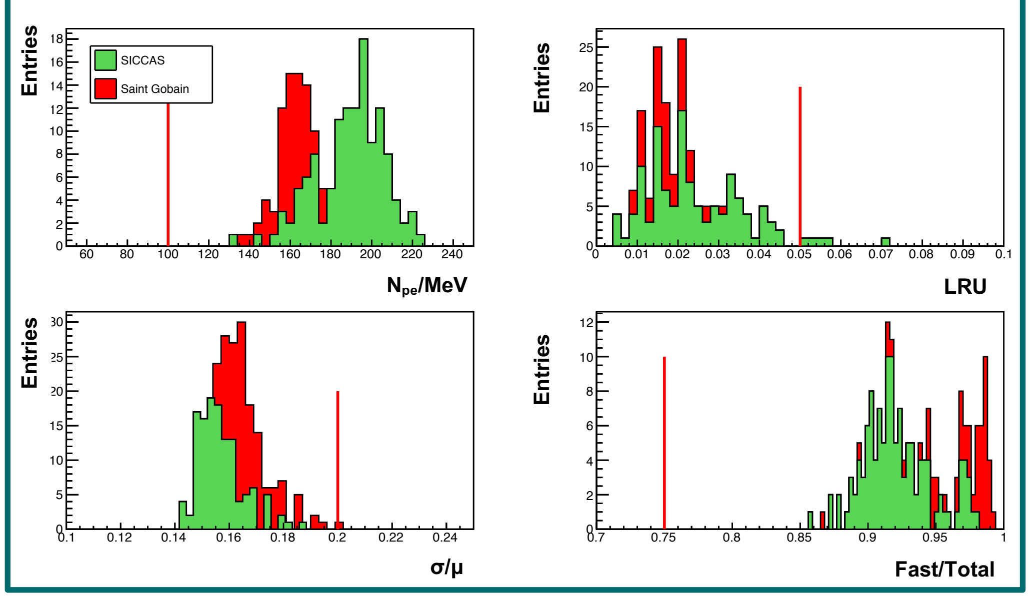


Crystals QC

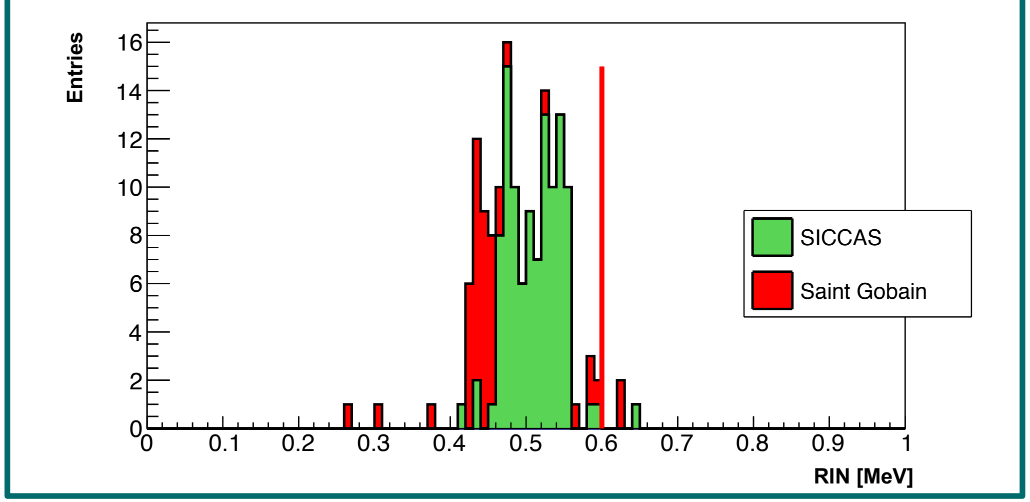
Dimensional test



Optical test

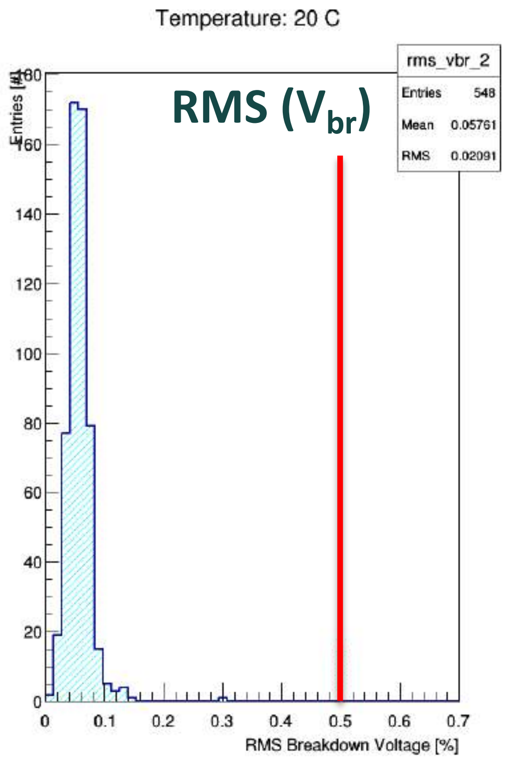


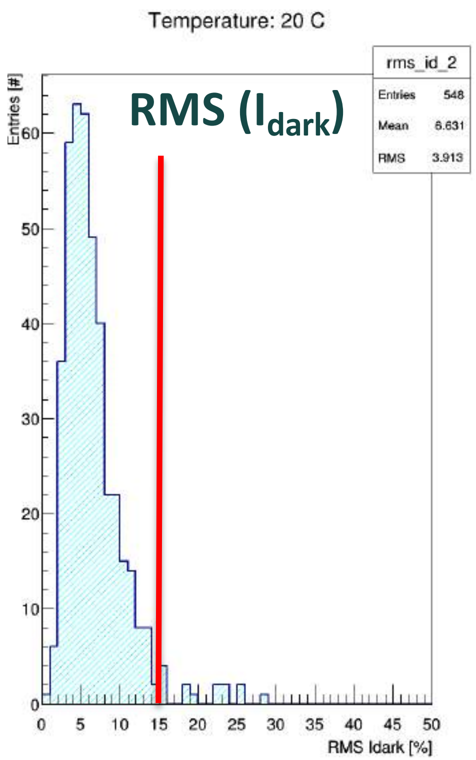
RIN test

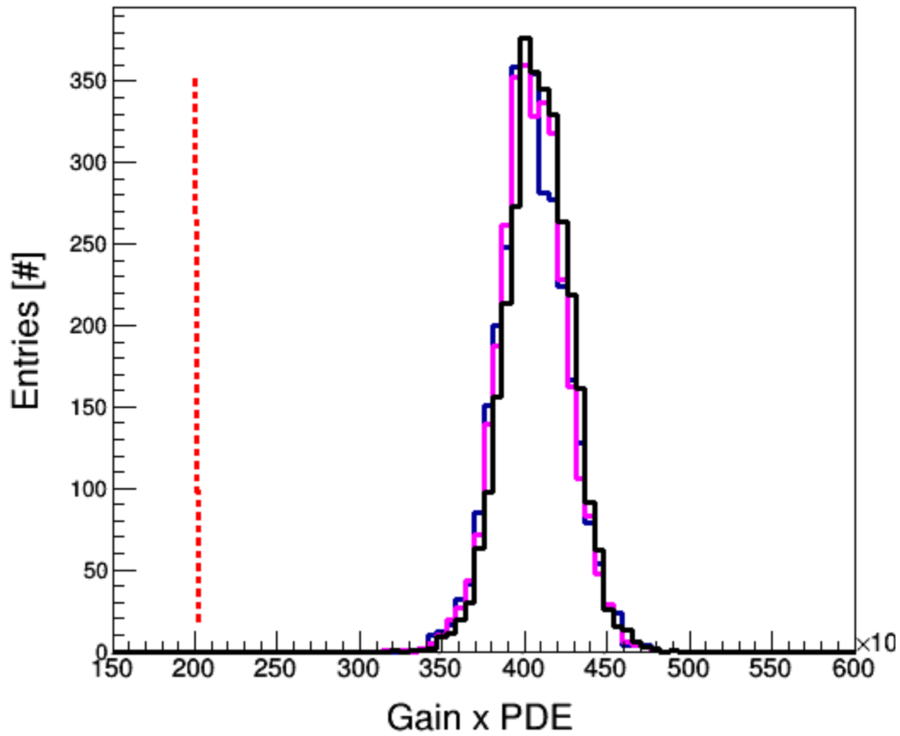


- 99% of crystals satisfy the specifications concerning optical properties
- Some problems to satisfy the mechanical specs for SG but now solved in new production
- End in May 2019

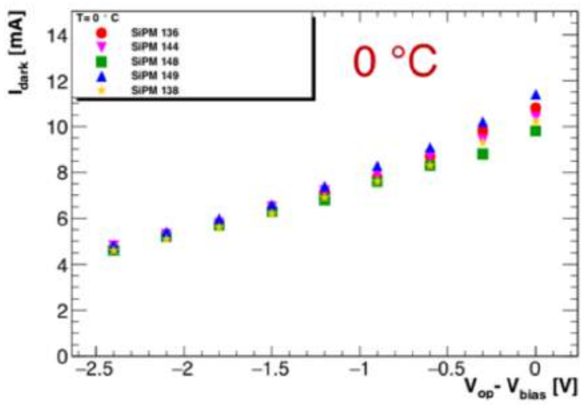
SiPM QC

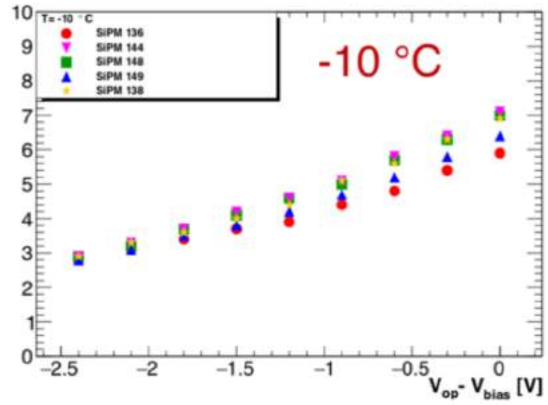






- **Large Scale characterization shows stable results on ~2000 Mu2e SiPMs tested.**
- **Only 0.6% of SiPMs rejected**
- **End in June 2019**





Summary and plans

- **The Mu2e calorimeter has concluded its prototyping phase satisfying the Mu2e requirements:**
  - **Un-doped CsI crystals perform well**
    - **Excellent LRU and LY** 100 pe/MeV (PMT+Tyvek wrapping)
    - τ of 30 ns with negligible slow component
    - **Radiation hardness OK** for our purposes: 40% LY loss at 100 krad
  - **Mu2e SiPMs quality OK**, high gain, high PDE, small I_{dark}, small spread inside array
    - SiPM performance after **irradiation OK**
    - SiPM **MTTF > 3 million hours**
  - **Calorimeter prototypes** tested with e^- beam
    - **Good time and energy resolution achieved @ 100 MeV**

- **Calorimeter production phase started**

Mid 2019: start of calorimeter construction

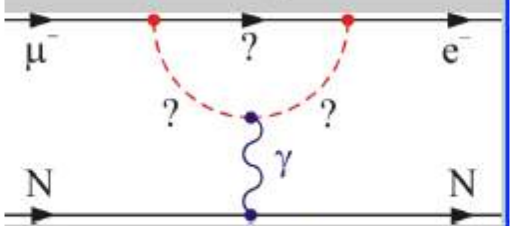
End 2020: installation into experimental hall

Additional material

MU2E sensitivity

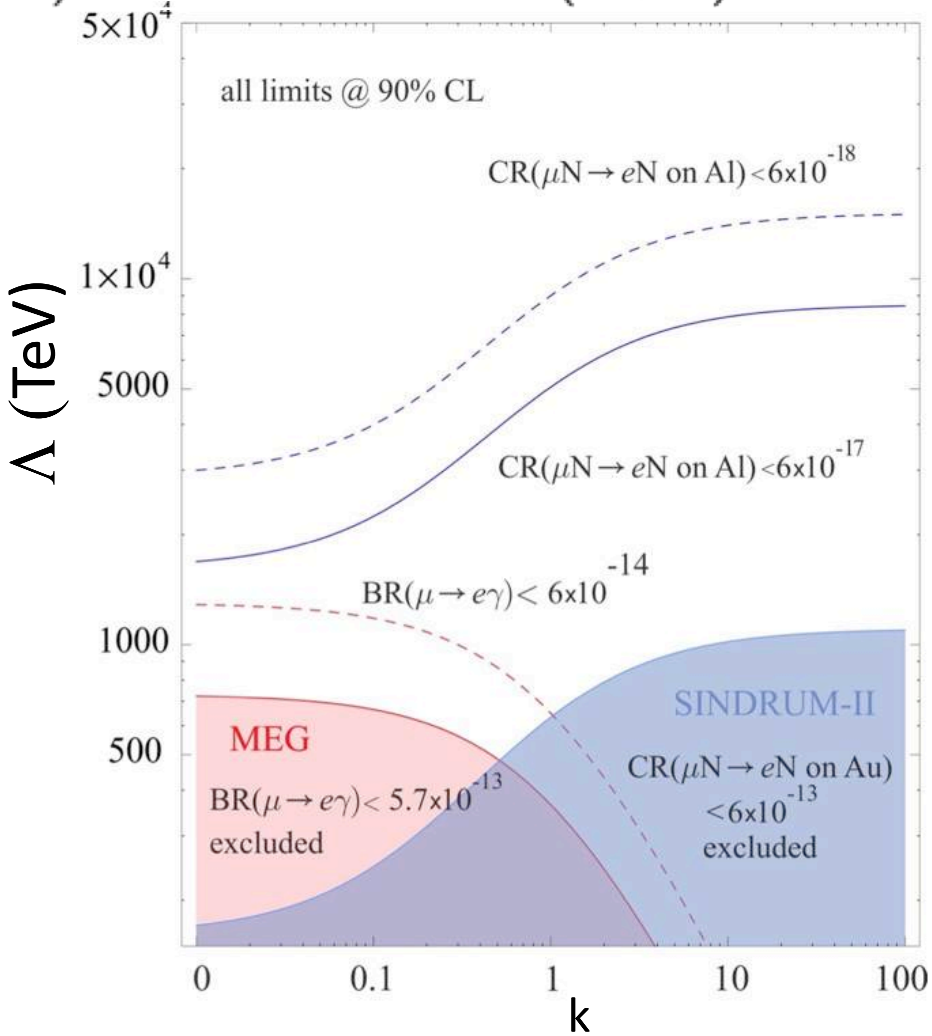
$$L_{CLFV} = \frac{m_\mu}{(\kappa+1)\Lambda^2}\bar{\mu}_R\sigma_{\mu\nu}e_L F^{\mu\nu} + \frac{\kappa}{(1+\kappa)\Lambda^2}\bar{\mu}_L\gamma_\mu e_L(\bar{u}_L\gamma^\mu u_L + \bar{d}_L\gamma^\mu d_L)$$

Loops



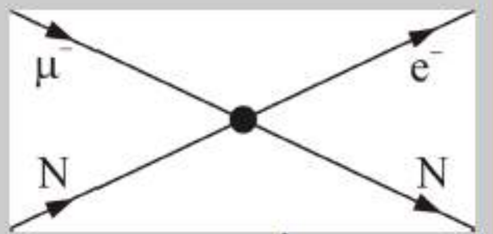
κ<< 1
magnetic moment type operator

μ→ eγ rate ~300X μN → eN rate



Loops contact

Contact Interactions

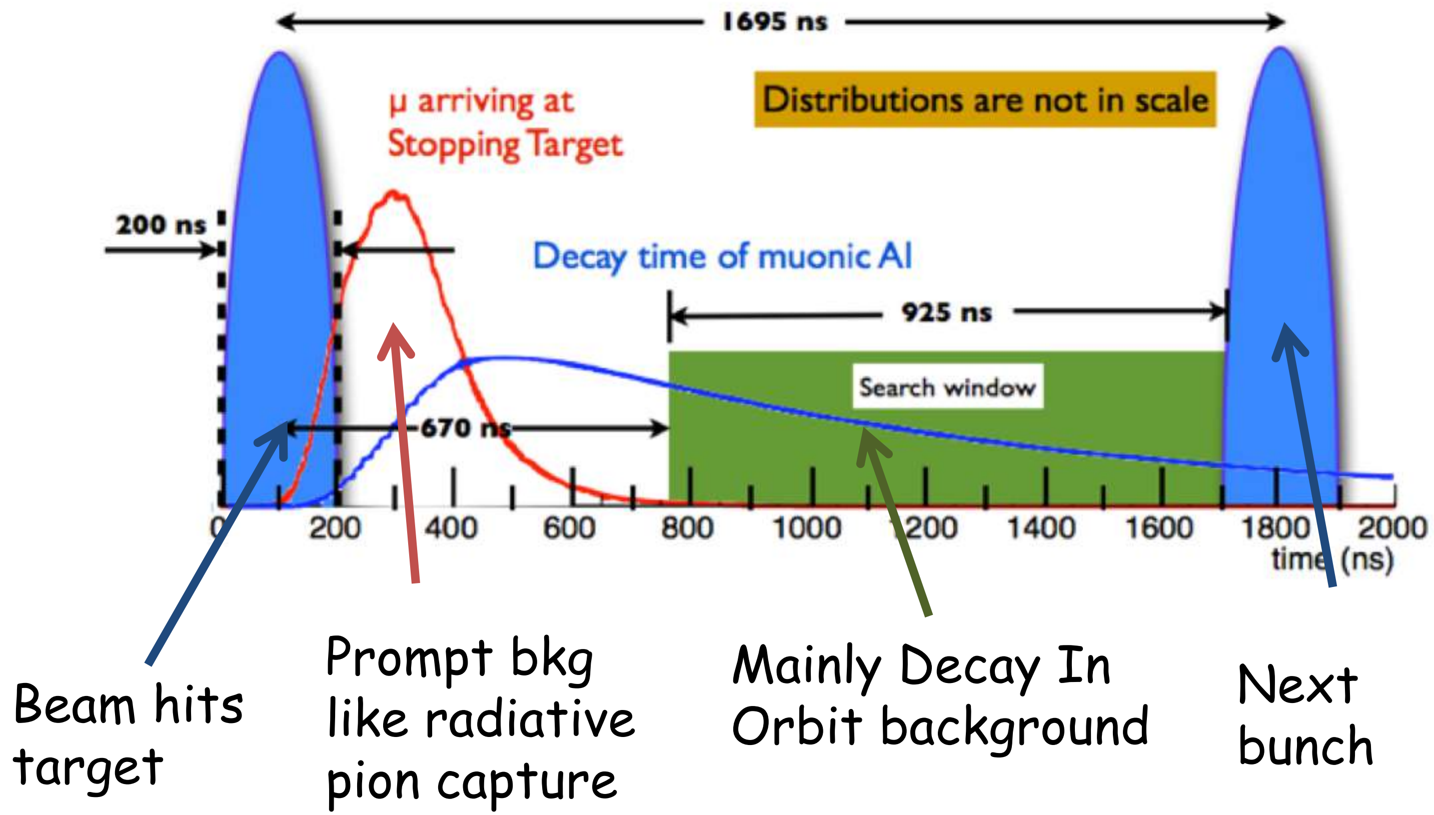


κ>> 1
four-fermion interaction

μN→ eN rate >> μ→ eγ rate

Mu2e Sensitivity best in all scenarios

Beam structure



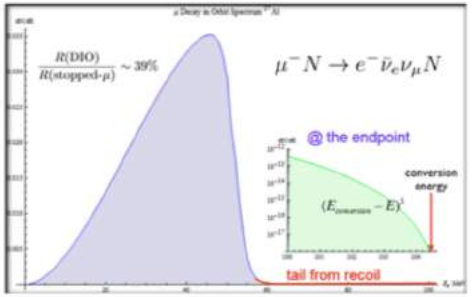
- **Use the fact that muonic atomic lifetime >> prompt background**
  Need a pulsed beam to wait for prompt background to reach acceptable levels
  → Fermilab provides the beam we need !

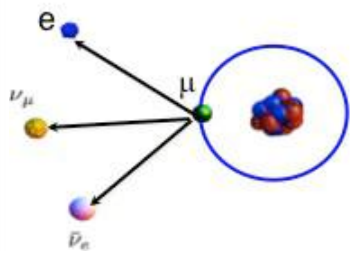
- **OUT of time protons are also a problem->prompt bkg arriving late…**
  To keep associated background low we need proton extinction of 10^{-10} :
  proton extinction (between pulses) → # protons out of beam/# protons in pulse

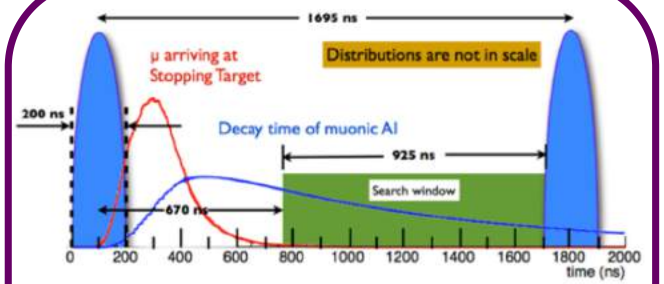
Physics Background

Background	Rejection method
DIO: decay in orbit	Good momentum and energy resolution
Cosmic induced bkg	CRV and PID
Antiproton induced bkg	Antiproton absorber in TS
Radiative pion capture and muon decay-in-flight	Pulsed beam and delayed time signal window

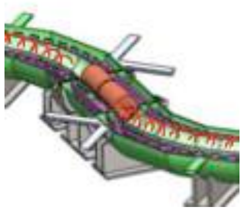
$$[\mu^- + A(N,Z)]^{1S}_{bound} \rightarrow A(N,Z) + e^- + \bar{\nu}_e + \nu_\mu$$



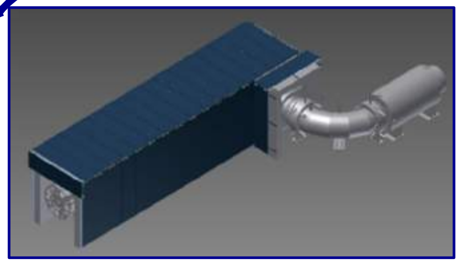


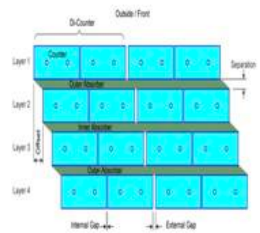


- Narrow proton pulses
- Very few out-of-time protons
- 700 ns delayed time signal window



- P beam just above p-bar production thr
- Absorbedr with mylar thin window





Will use 4 overlapping layers of scintillator. Each bar is 5 x 2 x ~450 cm^3, 2 WLS fibers / bar

Read-out both ends of each fiber with SiPM. Have achieved $\varepsilon > 99.4\%$ (per layer) in test beam

MU2E Background

- Intrinsic – scale with no. stopped muons
  - μ Decay-in-Orbit (DIO)
  - Radiative muon capture (RMC)
- Late arriving – scale with no. late protons
  - Radiative pion capture (RPC)
  - μ and π decay-in-flight (DIF)
- Miscellaneous
  - Anti-proton induced
  - Cosmic-ray induced

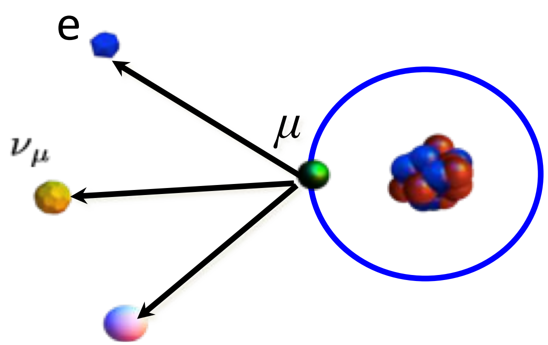
Category	Source	Events
Intrinsic	μ Decay in Orbit	0.20
	Radiative μ Capture	<0.01
Late Arriving	Radiative π Capture	0.02
	Beam electrons	<0.01
	μ Decay in Flight	<0.01
	π Decay in Flight	<0.01
Miscellaneous	Anti-proton induced	0.05
	Cosmic Ray induced	0.10
Total Background		0.37

(assuming 6.8E17 stopped muons in 6E7 s of beam time)

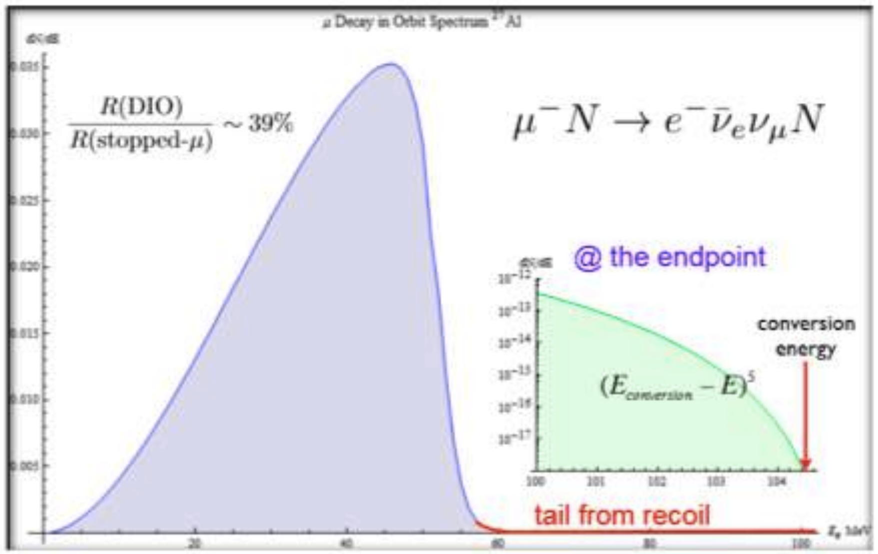
Decay in orbit

- The most sneaky source of background comes from Stopped Muons

$$[\mu^- + A(N,Z)]^{1S}_{bound} \rightarrow A(N,Z) + e^- + \bar{\nu}_e + \nu_\mu$$

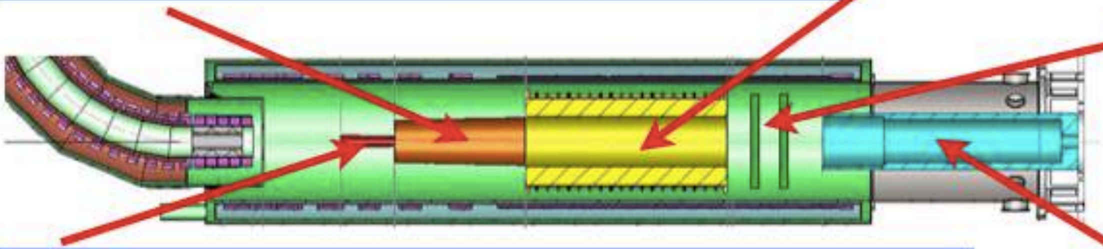


- For decay-in-orbit muons, the maximum energy of the electron is equal to the energy of a conversion electron
- The high energy tail falls as **(Ece–Ee)^5**
- 10**-17** of the spectrum is within 1 MeV from the endpoint
- An excellent momentum resolution is needed to beat this background

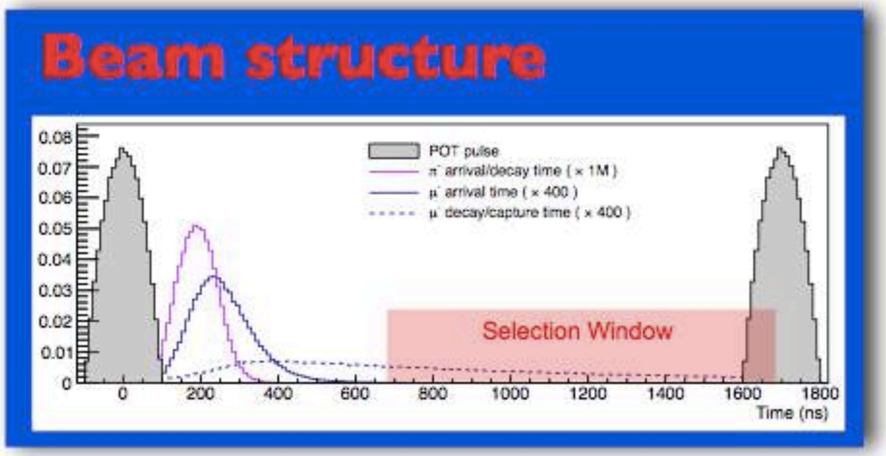


Experiment setup

- *Proton absorber:*
  ❖ made of high-density polyethylene
  ❖ designed in order to reduce proton flux on the tracker and minimize energy loss



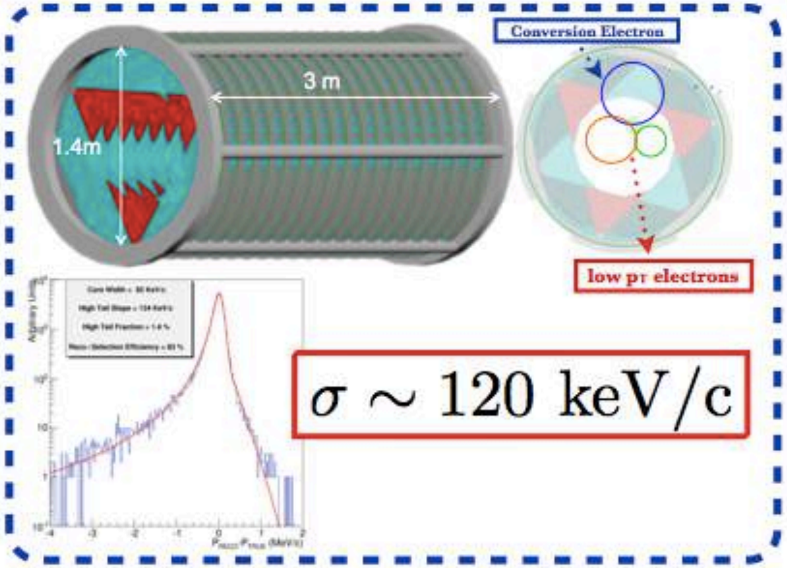
- *Targets:*
  ❖ 17 Al foils; Aluminum was selected mainly for the muon lifetime in capture events (**864 ns**) that matches nicely the need of prompt separation in the Mu2e beam structure.



- *Tracker:*
  ❖ 21600 tubes arranged in planes on stations, the tracker has 18 stations
  ❖ Expected momentum resolution ~ 120 keV/c

- *Calorimeter:*
  ❖ 2 disks composed of CsI crystals and separated by 1/2 wavelength

- *Muon beam stop:*
  ❖ made of several cylinders of different materials: stainless steel, lead and high density polyethylene

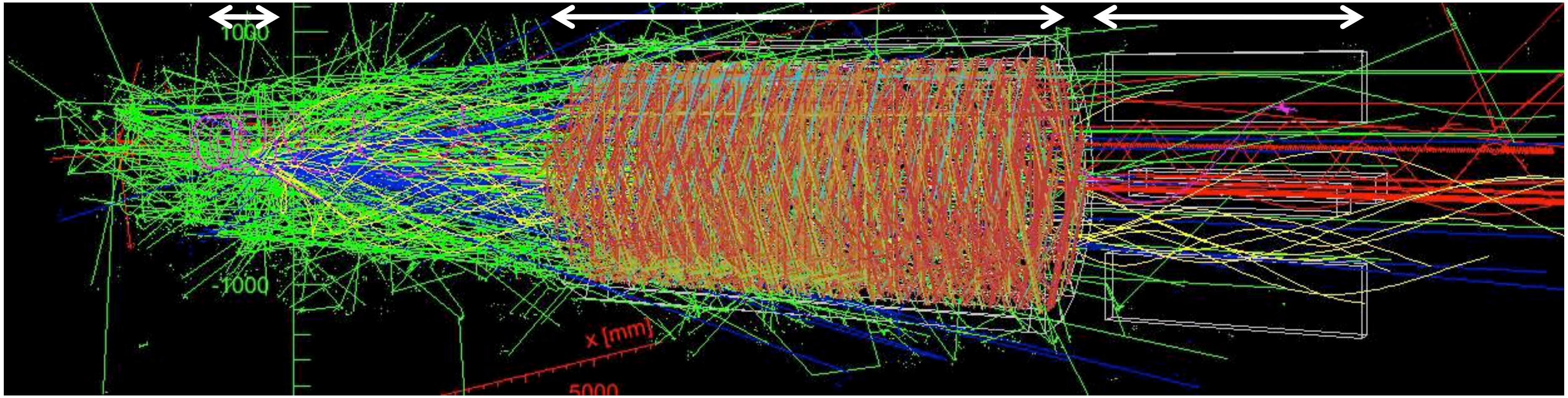


Pattern recognition

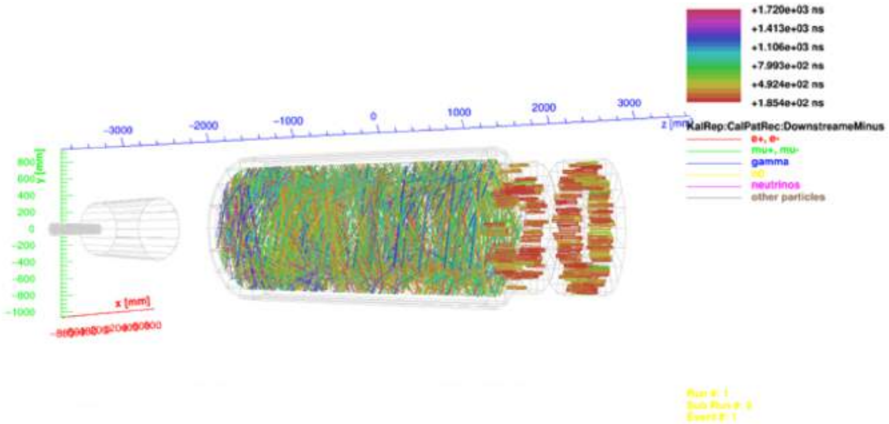
Stopping Target

Straw Tracker

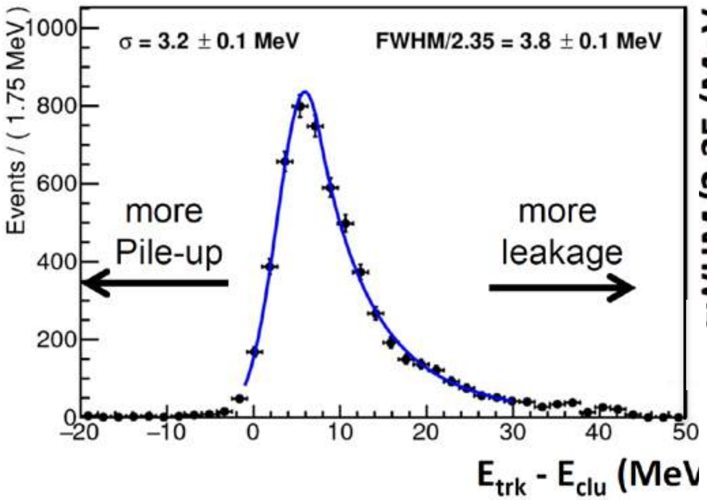
Crystal Calorimeter



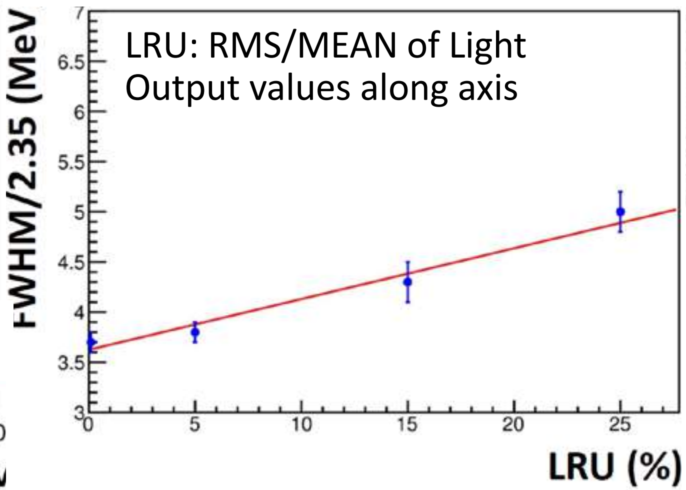
- A signal electron, together with all the other "stuff" occurring simultaneously, integrated over 500-1695 ns window

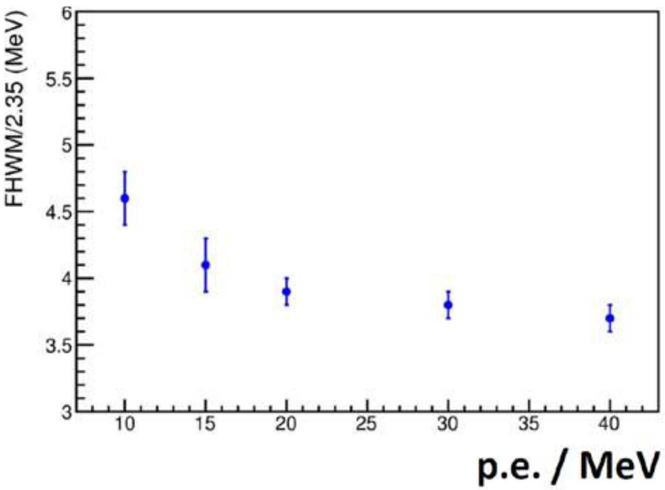


Simulation



FWHM / 2.35 = 3.8 ± 0.1 MeV

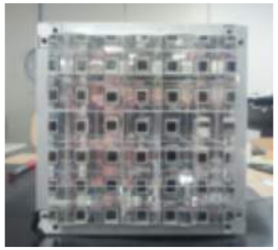


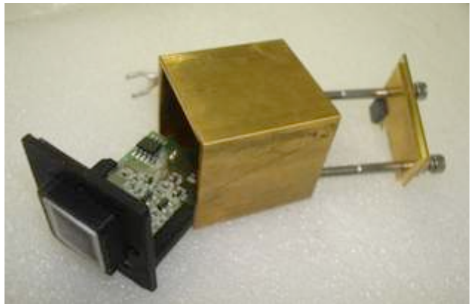


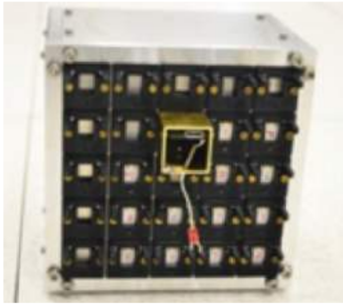
- **Simulation includes full background and digitization and cluster-finding, with split-off and pileup recovery**
- The overall resolution depends on crystals features
  - Several crystals considered

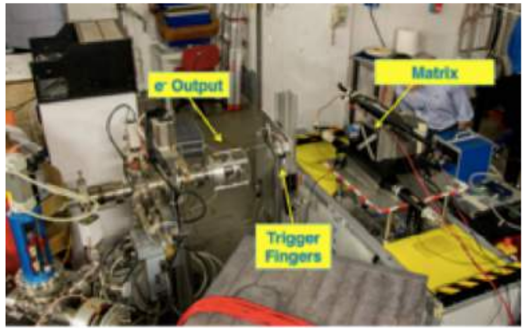
	$ ~~**LYSO**~~	~~**BaF_2**~~	**CsI**
Radiation Length X_0 [cm]	1.14	2.03	1.86
Light Yield [% NaI(Tl)]	75	**4**/36	3.6
Decay Time[ns]	40	**0.9**/650	20
Photosensor	APD	**RMD APD**	SiPM
Wavelength [nm]	402	**220**/300	310

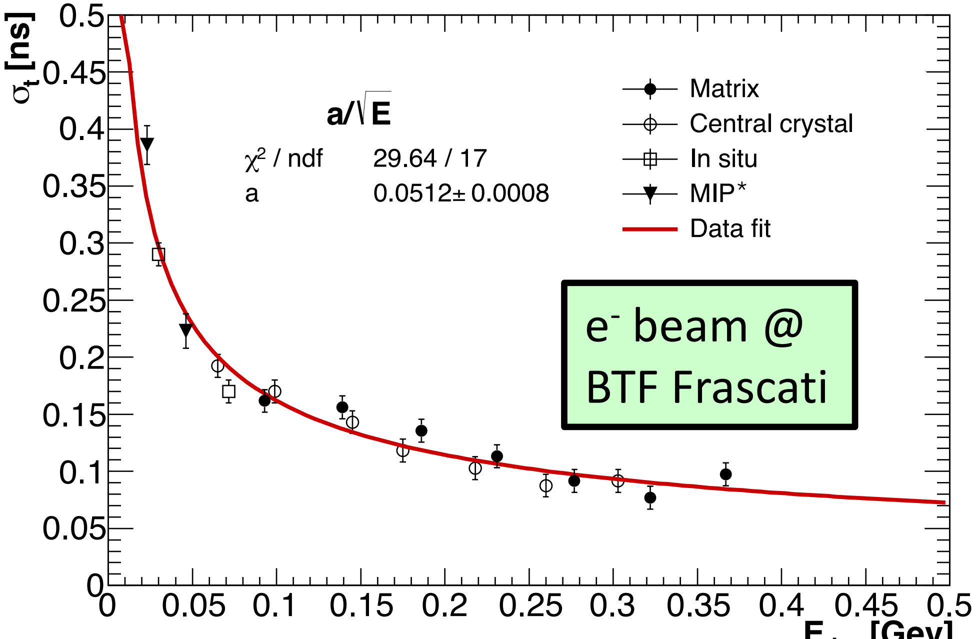
LYSO legacy



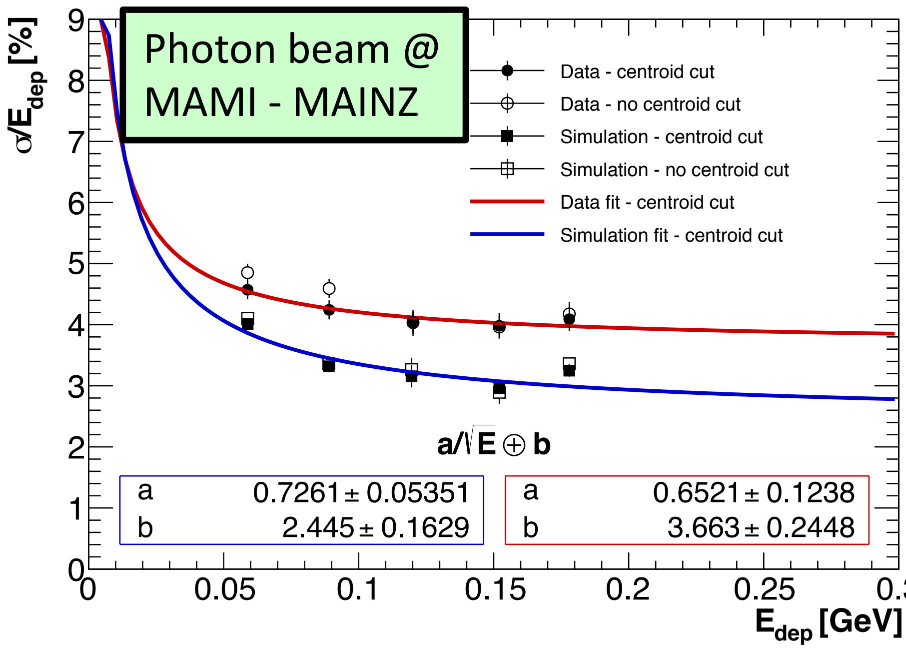








*Time resolution with MIPs from Mu2e DocDB 4409



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).

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Crystal irradiation

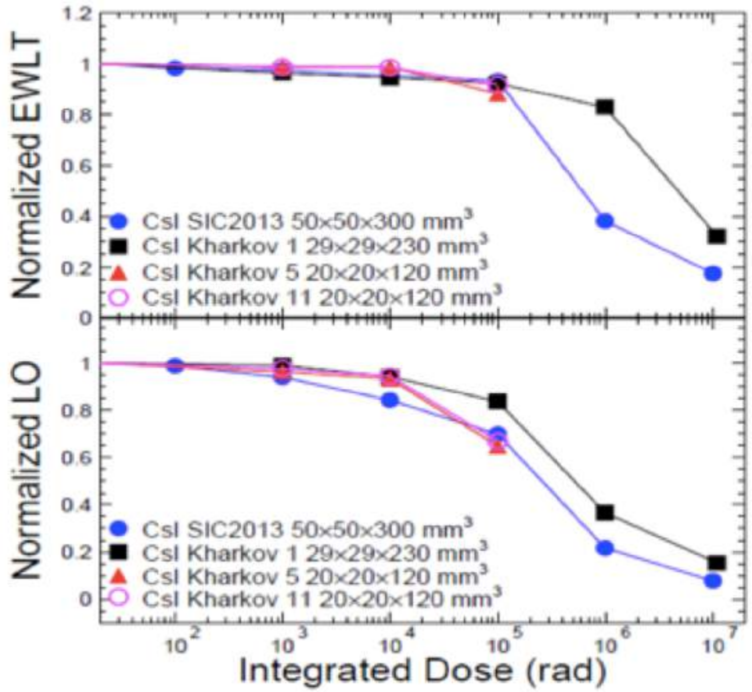
Test on different vendors performed:

- ISMA (Ukraine)
- SICCAS (China)
- OptoMaterial (Italy)

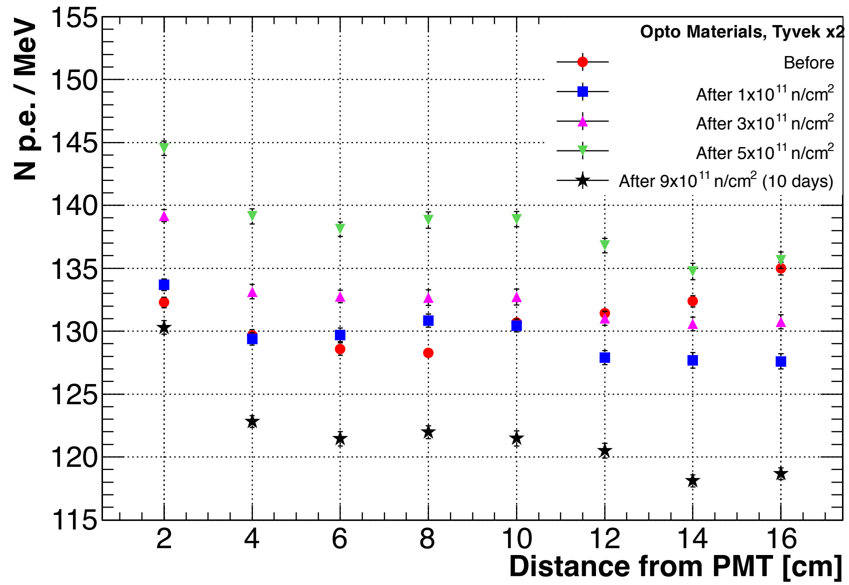
- CsI crystals irradiated up to 900 Gy and to a neutron fluency up to 9×10^{11} n_{1MeV}/cm^2 @Caltech (USA) and CALLIOPE and FNG in ENEA(Italy)

- The ionization dose does not modify LRU while a 20% reduction in LY is observed at 900 Gy.

- Similarly, the neutron flux causes an acceptable LY deterioration (< 15%).



FNG



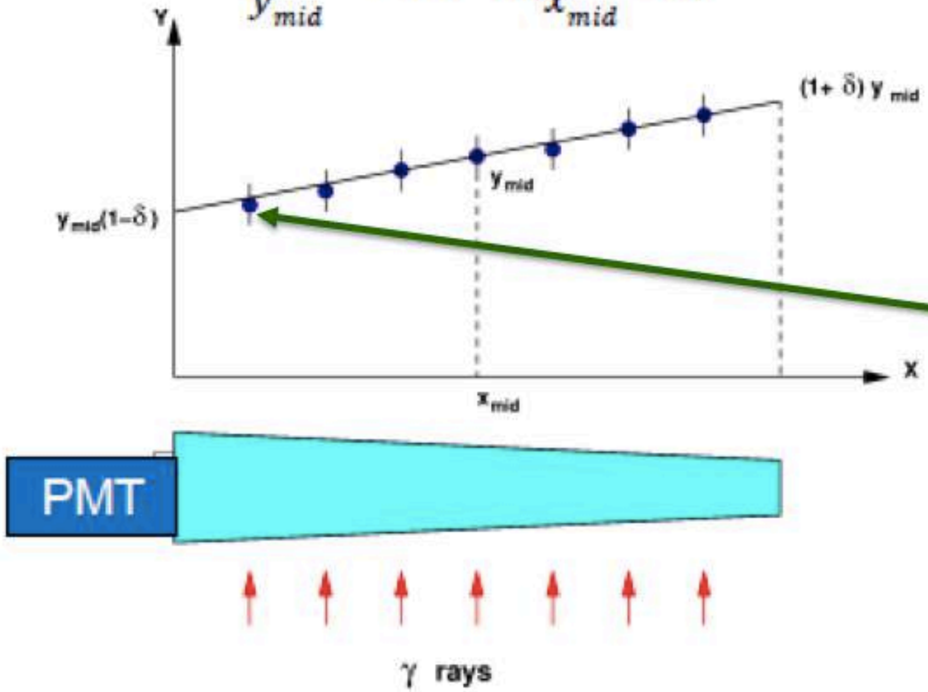
CsI crystal requirements

- Longitudinal transmittance (LT) was measured by using a Perkin-Elmer Lambda 950 spectrophotometer. (0.15%)
- Pulse height spectrum (PHS), FWHM energy resolution of 511KeV gamma-rays (ER), light output (LO), light response uniformity(LRU) and decay kinetics were measured by a Hamamatsu R2059 PMT with coincidence triggers from a 22Na source. All samples were wrapped with two layers of Tyvek paper with precision and reproducibility of <1%.
- PHS/ER/LO/LRU were measured with air gap for pure CsI because of the soft and hygroscopic surface.

LO, LRU and decay kinetics

LRU, *Light Response Uniformity*, is defined as follow:

$$\frac{y}{y_{mid}} = 1 + \delta(\frac{x}{x_{mid}} - 1)$$



LO is defined as the average of LO values measured at seven points with rms spread as LRU

Decay kinetics was measured at the point closest to the PMT with F/T ratio specified

Radiation induced noise

Assuming 230 days' run (2×10^{7} sec) each year, the hottest crystals would have the following radiation environment:

- Ionization dose: 10 krad/year ⟶ 1.8 rad/h,
- Neutron fluence: 2×10^{11} n/cm²/year ⟶ 1.0×10^{4} n/cm²/s.

The energy equivalent noise (σ) is derived as the standard deviation of photoelectron number (Q) in the readout gate:

$$\sigma = \frac{\sqrt{Q}}{LO} \qquad \text{(MeV)}$$

Standard SiPM array

We have tested arrays of 16 3x3 mm² Hamamatsu TSV MPPCs (12x12 mm²)

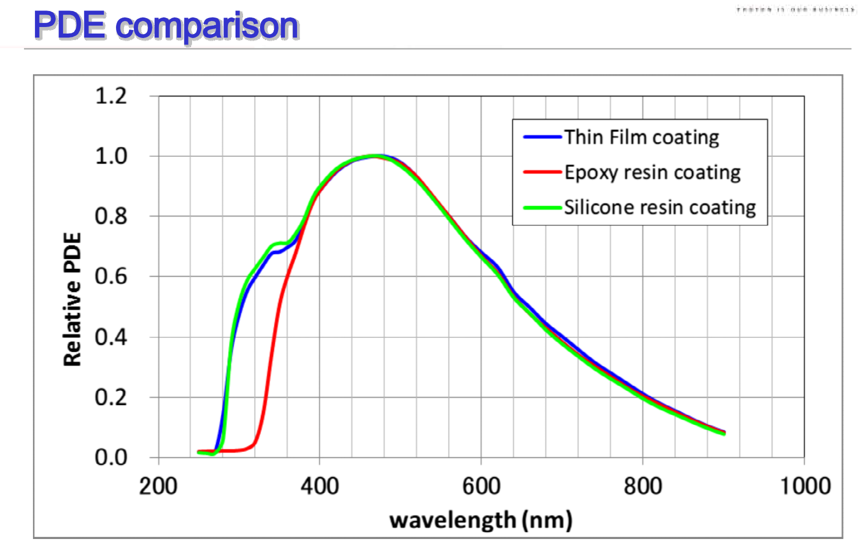
- These have silicon and thin film protection layers
- SiPMs are coupled to pure CsI crystals (30x30x200) mm³

→ ~ 30 (20) p.e./MeV with (without) optical grease with Tyvek-wrapped crystals

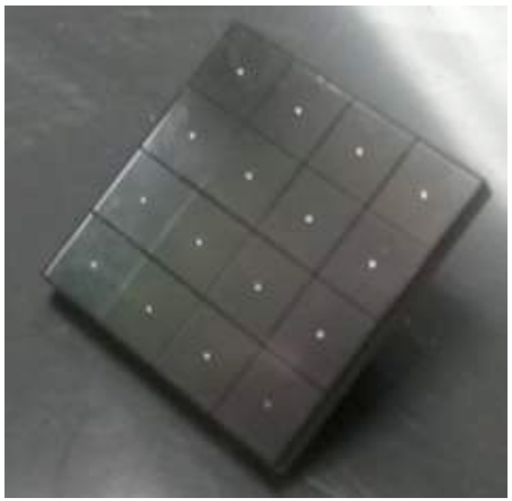
→ Time resolution < 150 ps @ 100 MeV with 45° e^- impact angle

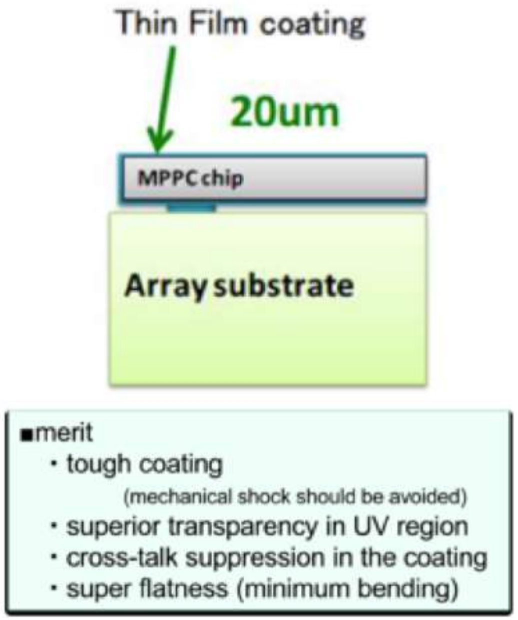
→ Energy resolution better than 7% at 100 MeV (leakage dominated)

→ Equivalent noise ~ 100 keV

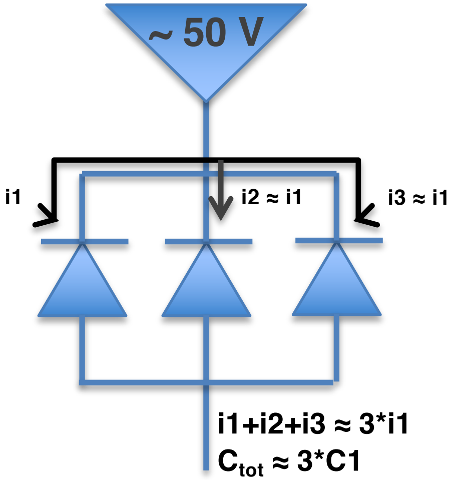


Thin Film coating and Silicon resin coating has PDE advantage in UV region.



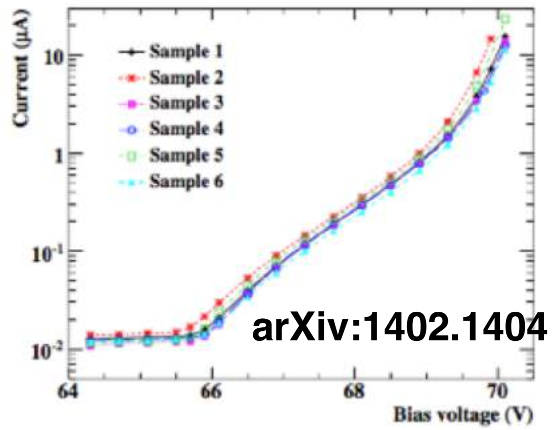


Series vs Parallel configuration

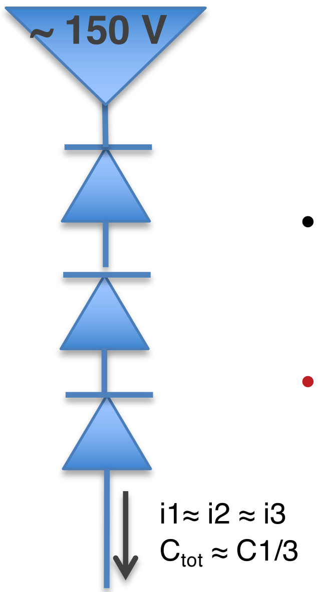


	Parallel	Series
Total Bias (Volt)	☺	☹
Total Current (A)	☹	☺
Power (Watt)	😐	😐
Total Capacitance	☹	☺
Decay Time	☹	☺

While the individual breakdown voltages differ by a few hundred millivolts, the shapes of the I-V curves are quite similar.



I-V characteristics of individual SiPMs



- Decay time can be regulated at the shaping level, but a high detector capacitance increases noise (worsens the signal-to-noise ratio)
- **When SiPMs are connected in series, the voltage applied to each SiPM is determined by the common leakage current. Then, the difference in breakdown voltages is absorbed, and the over-voltages are approximately aligned. It depends on "how much the I-V curve are similar"**

Cooling requirements

Starting point: after 6 years of Running

We have measured, for a 3x3 mm^2 MPPC, a leakage current of 2.3 mA after a flux of 2.2×10^{11} n_14MeV/cm^2 (4×10^{11} n_1MeV/cm^2) @ 25°C

→ This corresponds to 9 mA for a 6x6 mm^2 MPPC @ 25°C

1) Assuming a factor 2 for annealing

→ 4.5 mA per a MPPC of 6x6 mm^2 @ 25°C (Vop)

for the proposed SiPM (matrix 2x3 of 6x6 mm^2) we expect:

→ 9 mA for the parallel of two series @ 25°C

2) We have measured a leakage current reduction of a factor 5 operating at 0°C

→ 9/5 = 1.8 mA for the device @ 0°C

3) we can take advantage of an additional factor of 2 if needed by lowering of 0.5 V the Vbias with respect to Vop (@ 0°C)

→ 1.8/2 = 1 mA @ 0°C

at the experiment end, we will get 1 mA with 200 V of bias, 200 mW @ 0°C , Vop-0.5 V for the innermost Layer of Disk 1→ 120 crystals → 240 photosensors