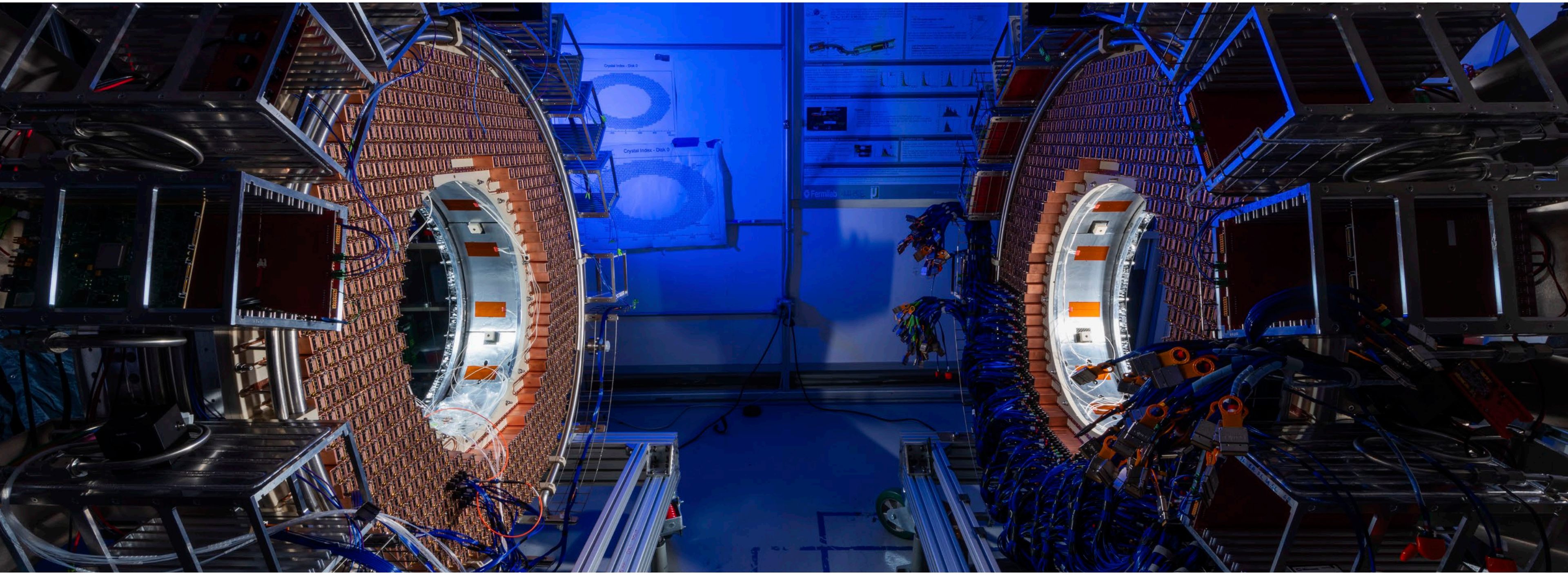
The Mu2e Electromagnetic Calorimeter



L. Morescalchi
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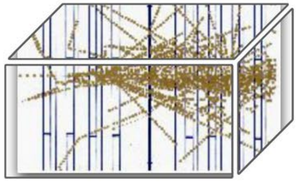
On behalf of the Mu2e calorimeter group



CALOR 2024
Tsukuba

The Mu2e experiment @ Fermilab

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

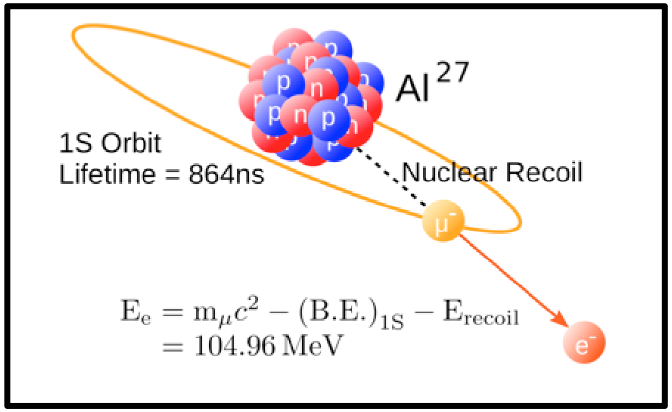
➔ CLFV process strongly suppressed in Standard Model: BR $\leq 10^{-52}$

➔ 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

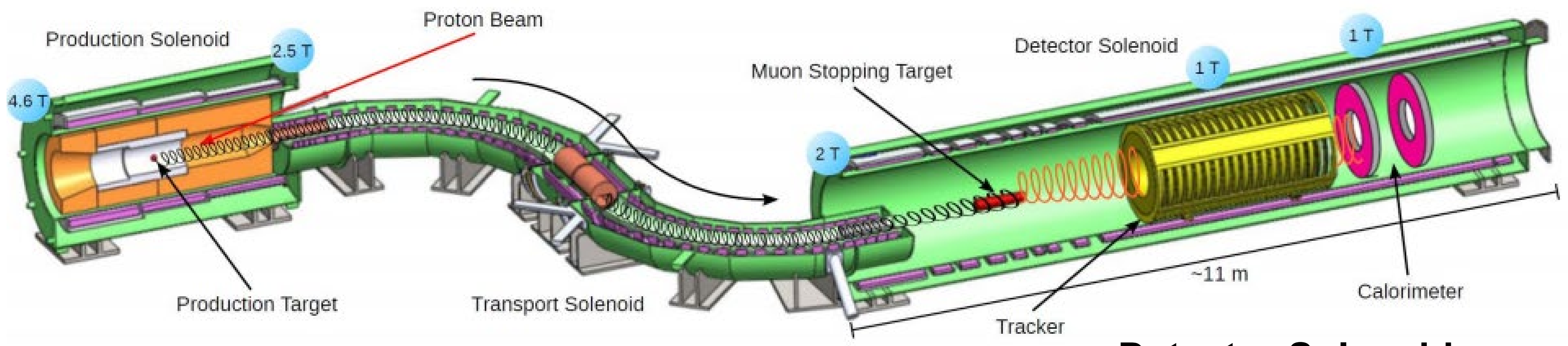
$$R_{\mu e} = \frac{\mu^- + N(A,Z) \rightarrow e^- + N(A,Z)}{\mu^- + N(A,Z) \rightarrow \nu_\mu + N(A,Z-1)} < 8.4 \times 10^{-17}$$

Nuclear captures of muonic Al atoms



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

Production & Transport Solenoids

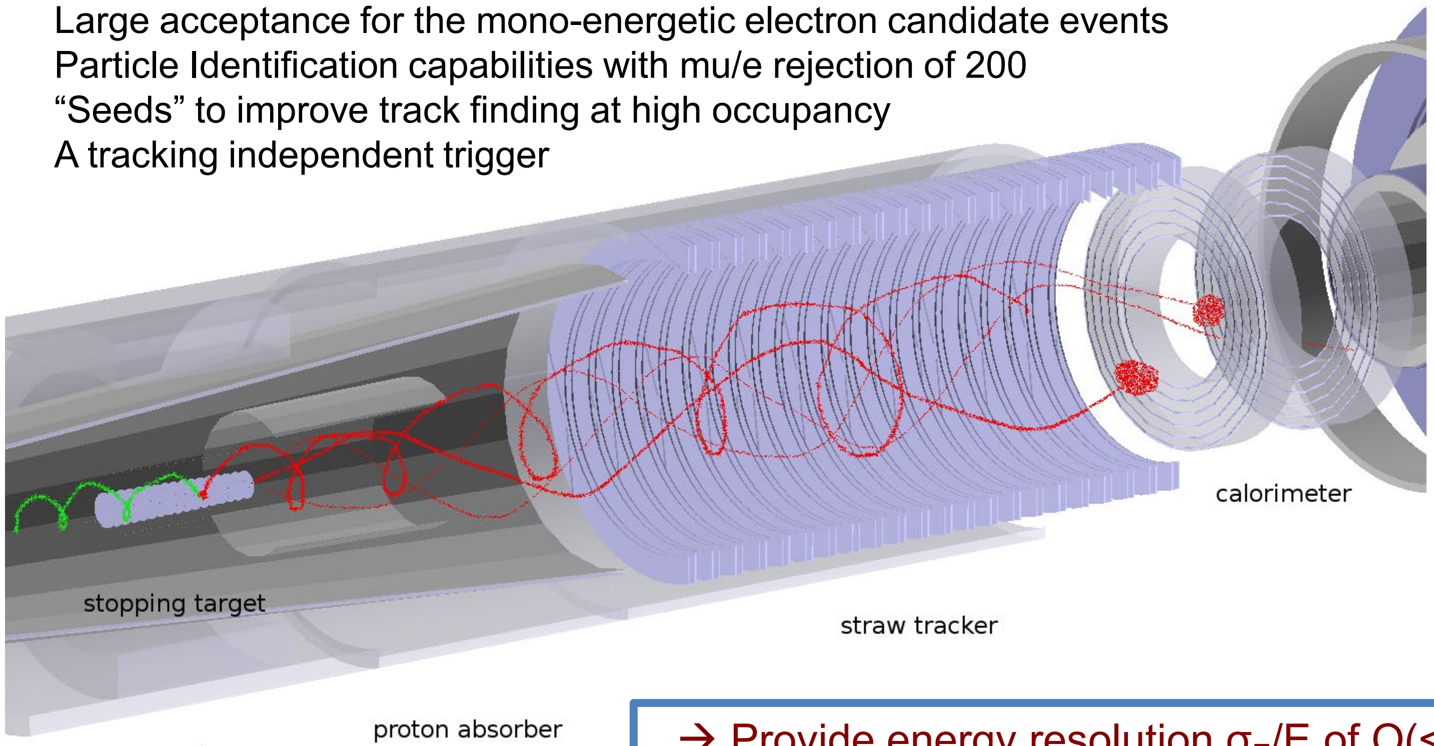


Detector Solenoid

Calorimeter Requirements

For the μ → e conversion search, the calorimeter adds redundancy and complementary qualities with respect to the high precision tracking system

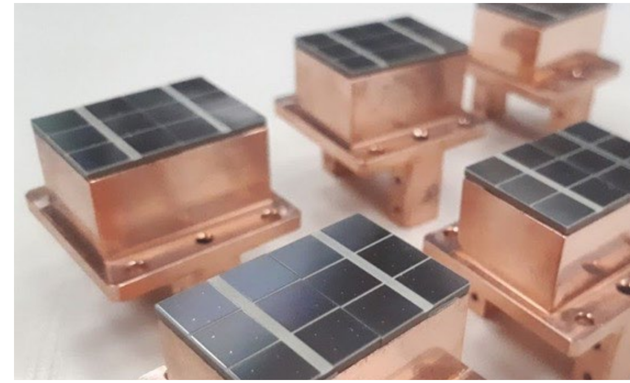
- Large acceptance for the mono-energetic electron candidate events
- Particle Identification capabilities with mu/e rejection of 200
- "Seeds" to improve track finding at high occupancy
- A tracking independent trigger



For 100 MeV electrons @ 50 degrees impact angle

→ 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**

Technological Choice



- Fast signal for Pileup and Timing:
  - **τ of emission < 40 ns**
  - Fast Digitization (WD) to disentangle signals in pileup
- Crystals with high Light Yield for timing/energy:
  - resolution → **LY(photosensors) > 20 pe/MeV**
- 2 photo-sensors/preamps/crystal for redundancy:
  - reduce MTTF requirement → **1 million hours/SIPM**
- Radiation Hardness (5 years of running with a safety factor 3):
  - Crystals should survive a TID of **90 krad** and a fluence of **3×10^{12} n/cm^2**
  - Photo-sensors should survive **45 krad** and a fluence of **1.2×10^{12} n_1MeV/cm^2**
- The 1 T magnetic field + the small space suggests → SiPMs

best compromise

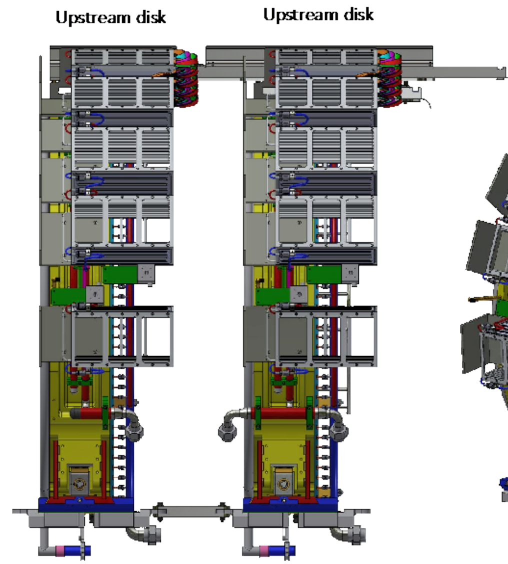
Undoped CsI + UV-extended SiPMs

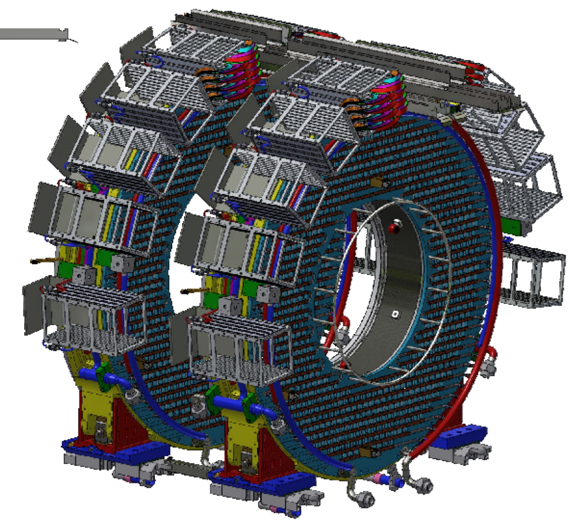
Undoped CsI
- → It is radiation hard
- → It has a fast emission time
- → Emits at 310 nm

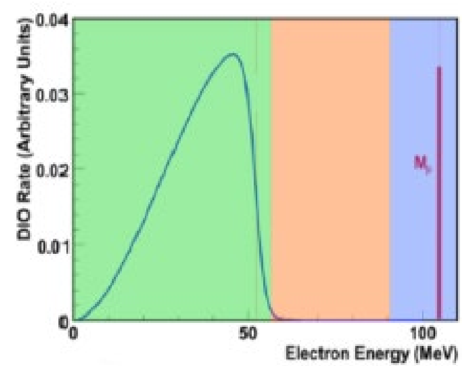
UV-extended SiPMs
- → 30 % PDE @ 310 nm
- → New silicon resin window
- → TSV readout, Gain = 10^6

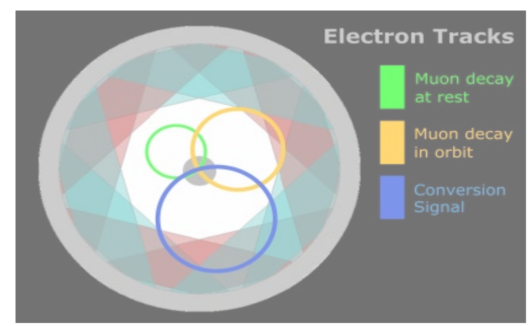
Mu2e calorimeter design

- ✓ Two annular disks, each one with 674 un-doped CsI parallelepiped crystals with square faces:
  - ➔ Crystal dim (34 x 34 x 200 mm^3) ~ 10 X_0
  - ➔ Inner/Outer Radius = 374/660 mm
- ✓ Each crystal is read out by two large area UV extended Mu2e SiPM's (14x20 mm^2) through a 2mm air gap
- ✓ SiPM glued on copper holders with FEE mounted on SiPM pins
- ✓ Digital electronics at 200 Msps located in near-by electronics crates
- ✓ Radioactive source (ala Babar) and laser system provide absolute calibration and monitoring capability



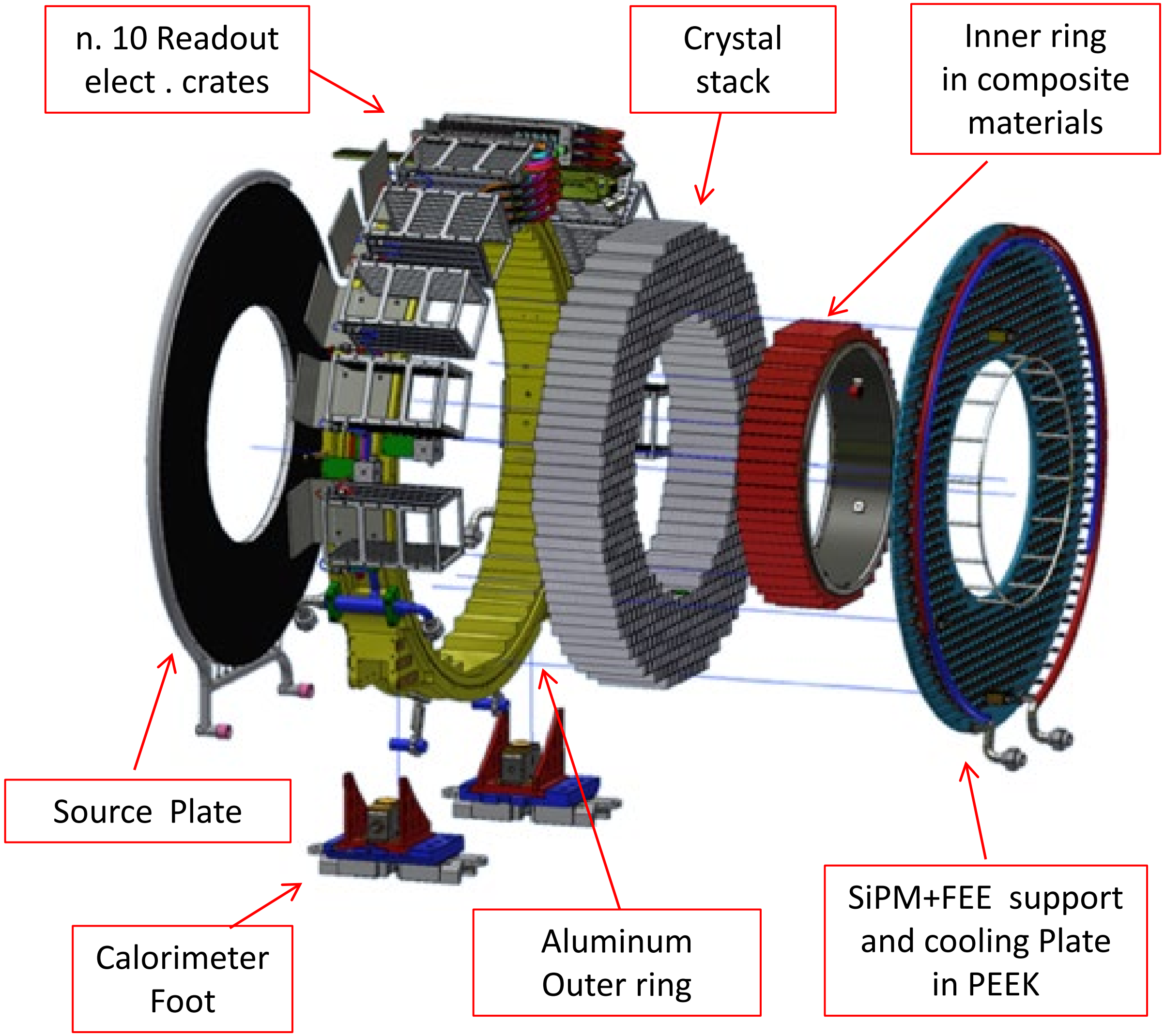




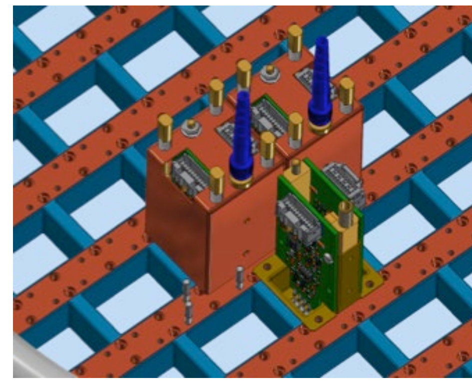


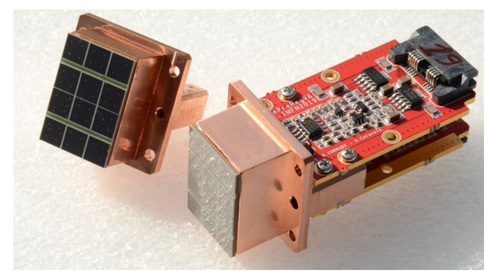
Operate with very high reliability in vacuum and radiation hard environment → -10 °C for SiPMs

Mu2e calorimeter engineering



To reduce/handle the neutron induced leakage current,Id, SiPMs should be cooled down (x 2 Id reduction/10 °C)
➔ **SiPM running temperature at -10 °C, Coolant at -20°C**

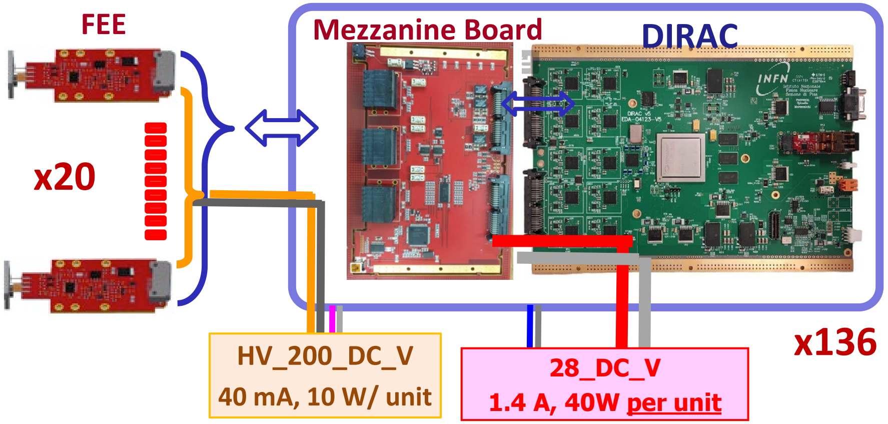




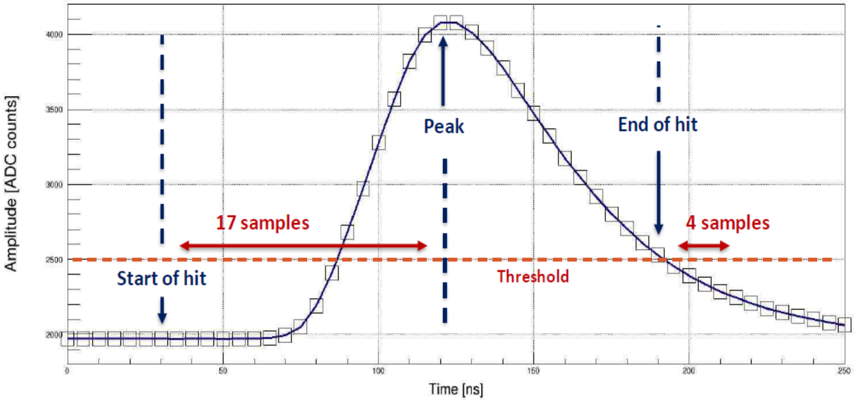
Readout Units = SiPM+FEE holder

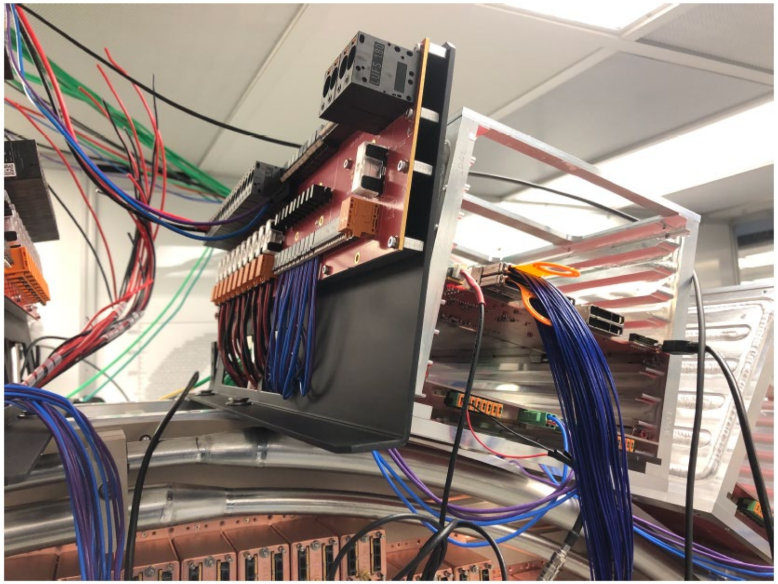
FEE and Digitization scheme

- MZB → Control and set 20 channels HV, monitor current and temperature of photosensors
- A fast digitizer system is needed due to the high expected pileup and time resolution requirements
  - About **2700 channels**, **136 boards**
  - Sampling frequency of **200 MHz**
  - ADC with **12 bits** resolution over 2 V
- Mechanical constraints → DAQ crates inside cryostat:
  - Limited space → **20 channels/board**
  - Limited access for maintenance → **Reliable design**
  - Close to stopping target → **Radiation hard electronics**
  - Vacuum → **Copper plate cooling**



- Polarfire Rad-tolerant FPGA from Microchip
- CERN VTRX for optical link readout



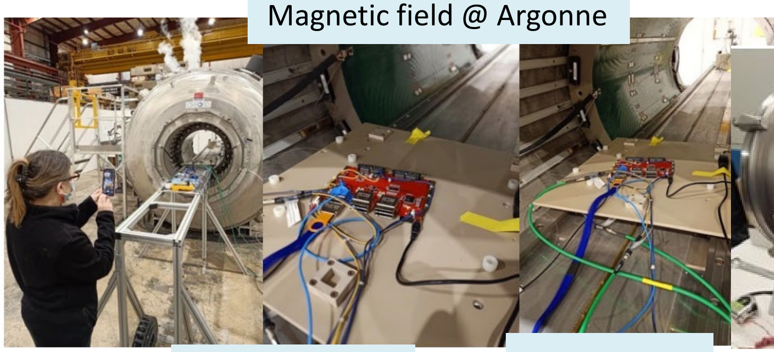


Qualification test of electronics

Final QA/QC tests performed:

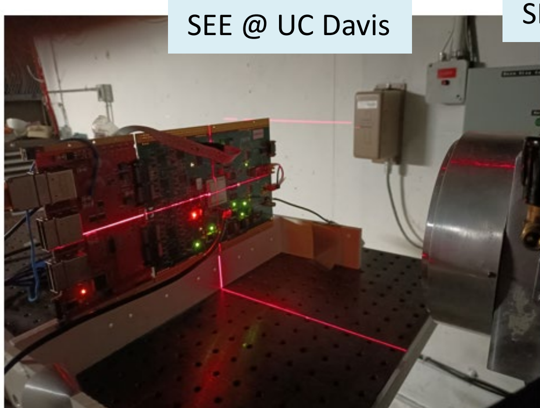
- Dose Test of components and boards OK
- B-Field test of DC-DC converters and boards OK
- Neutrons test for DD OK
- Proton test for SEL OK
- Thermal tests in vacuum with copper plate OK


TID @ ENEA Calliope


Magnetic field @ Argonne


Thermalvaccum


TID @ HZDR gELBE


SEE @ UC Davis


SEE @ CNAO

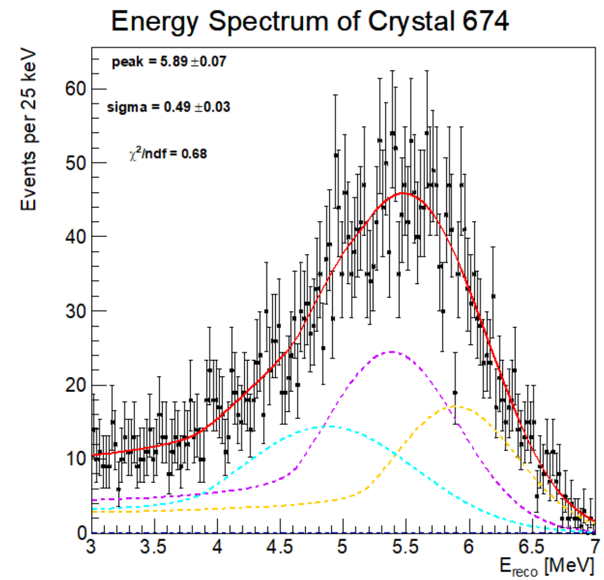

neutrons @ FNG

Calibration Source

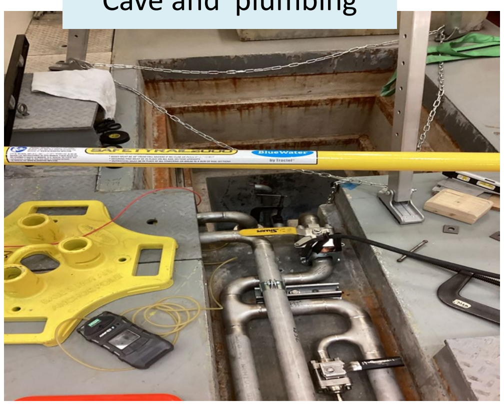
- ✓ Neutrons from a DT generator irradiate a fluorine rich fluid (Fluorinert) that is piped to the front face of the disks
- ✓ The following reaction chain grants photons at 6.13 MeV

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

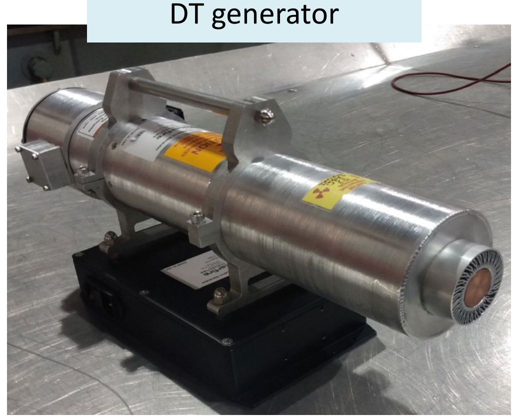
- ✓ The produced gamma's illuminate uniformly the crystals
- ✓ Few minutes of data taking calibrate each crystal at O(%)



Cave and plumbing



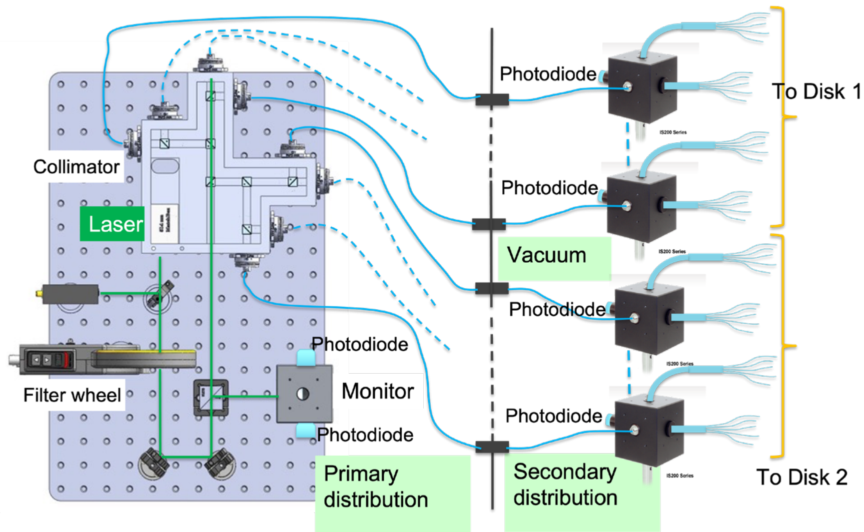
DT generator



Front face pipes

Source DT generator installed in Mu2e hall in its "cave" and final shielding completed

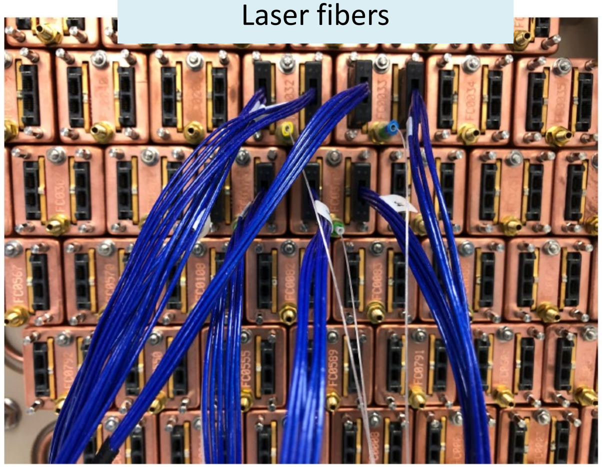
Laser System



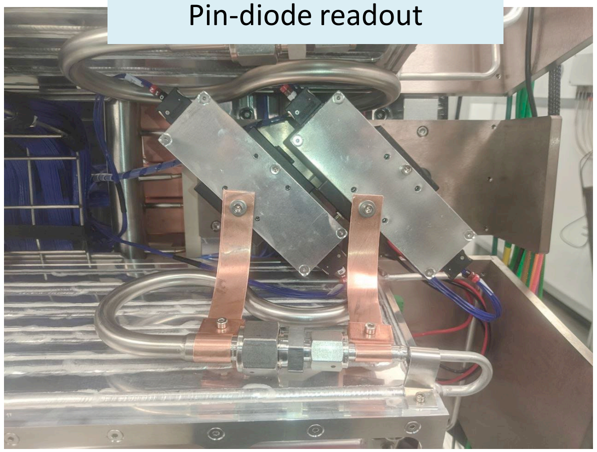
- ✓ A pulsed green laser illuminates all crystals through a distribution system based on optical fibers and integration spheres
- ✓ Monitor gain variation at level of 0.5%
- ✓ Determine T0's at level of 100 ps
- ✓ Stability at level of few %, monitored with PIN Diodes at laser source. Used at low rate in off-spill gates

Laser distribution

Laser fibers



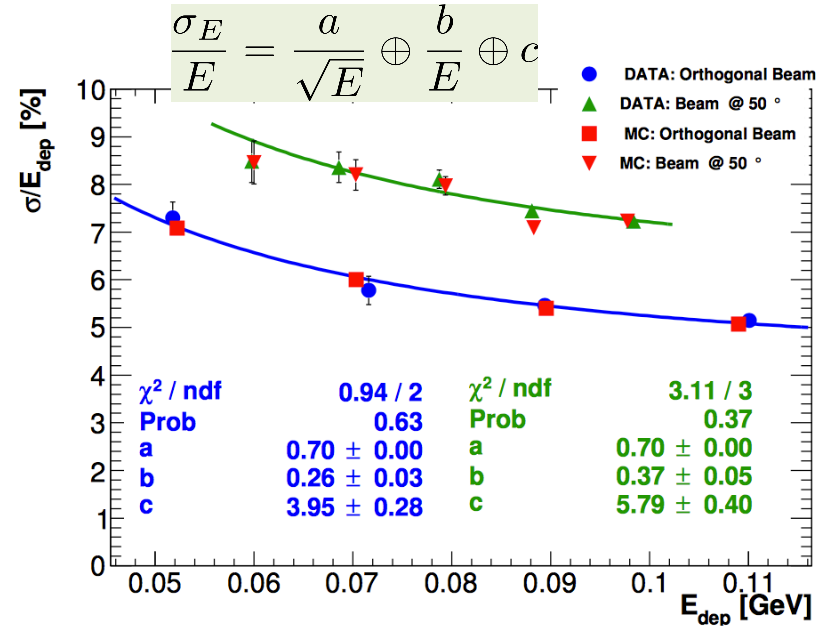
Laser - Diffusing spheres + Pin-diode readout

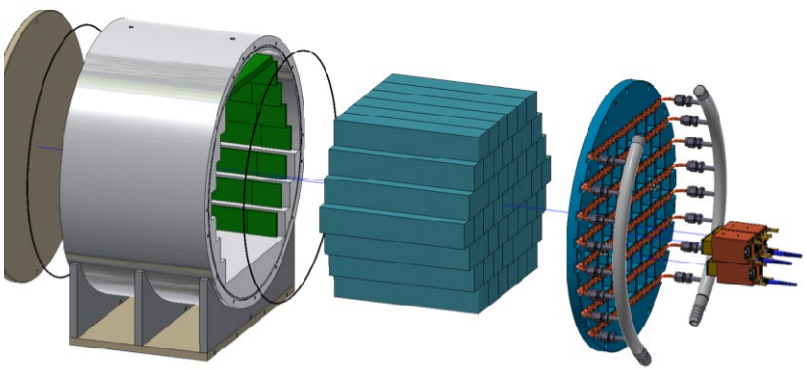


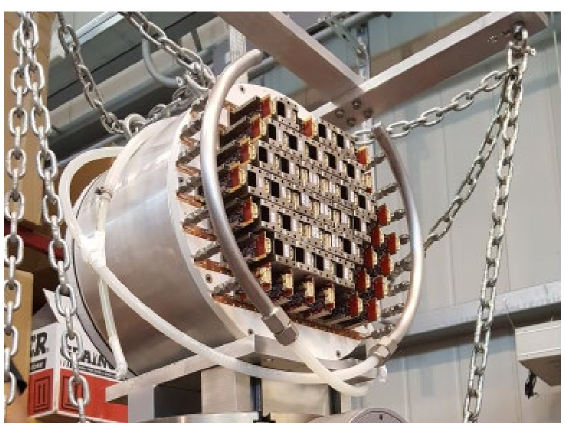
In-situ calibration with crossing MIPs, DIO's and other physics processes

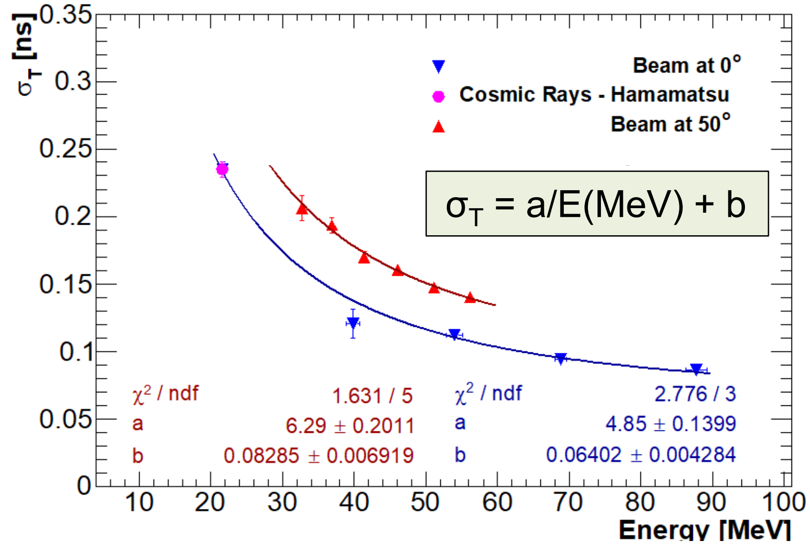
Module-0 test beam results

- ✓ Large size calorimeter prototype , 51 CsI crystals, 102 SiPMs, tested with electron beam (50-110 MeV) and v2 version of electronics to measure energy and time resolutions.
- ✓ **Results fully satisfied our requirements**
- ✓ **Green light for Production of components**

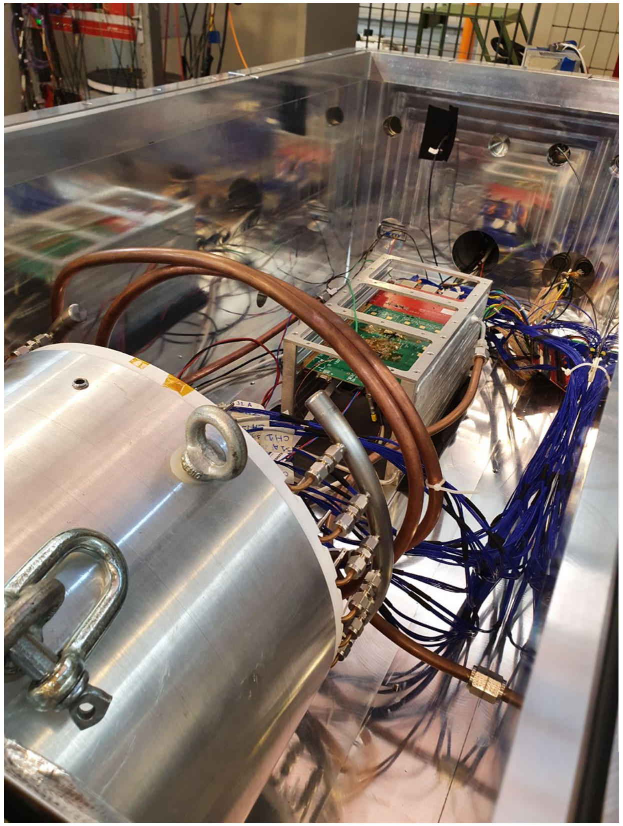




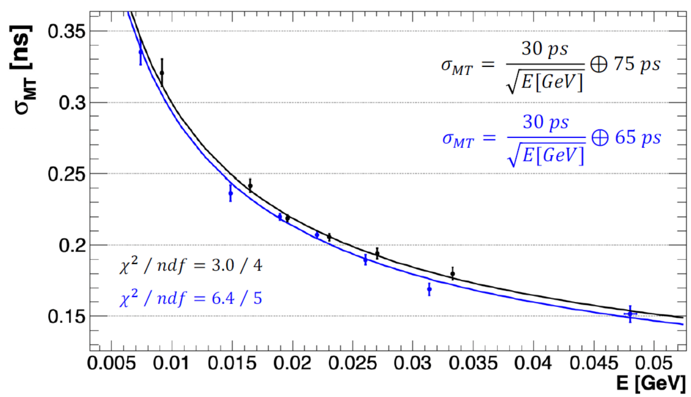


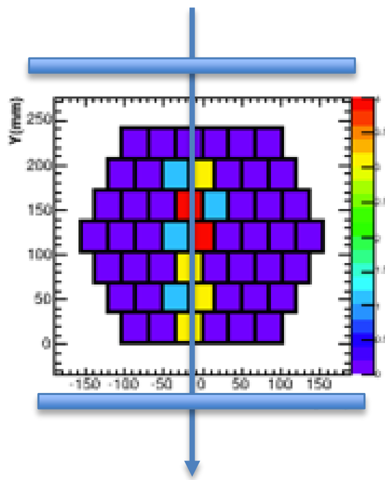


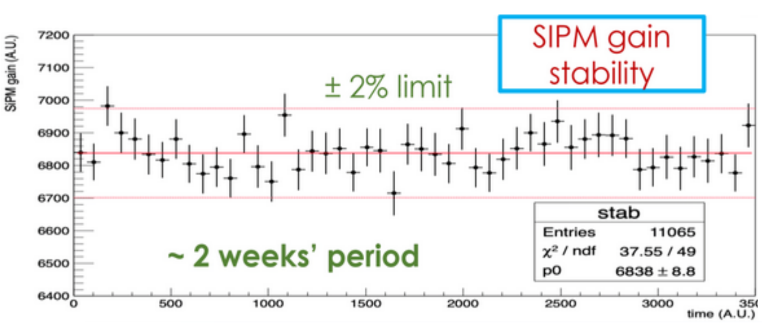
Calorimeter Vertical Slice Test

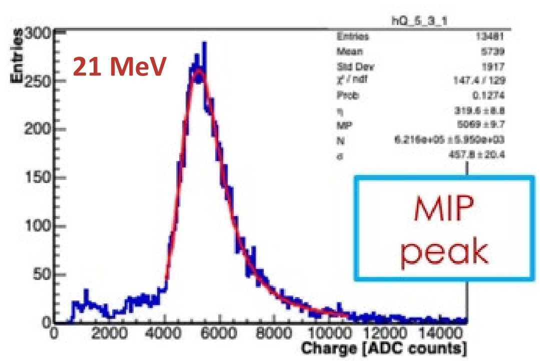


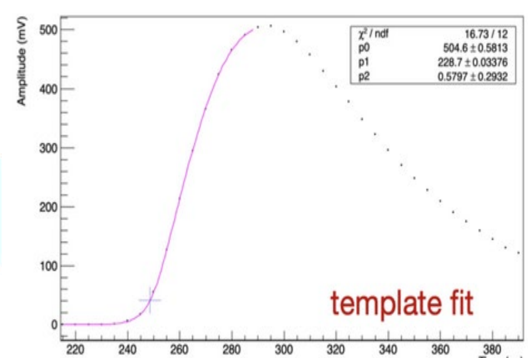
- MB+ DIRAC V2 boards used for full Vertical Slice Test (VST)
- **Data collected in vacuum, at low T and with irradiated sensors for 10 months**
- Stable operation and reconstruction: template + CFD
- Data taking of CR events triggered with external scintillators











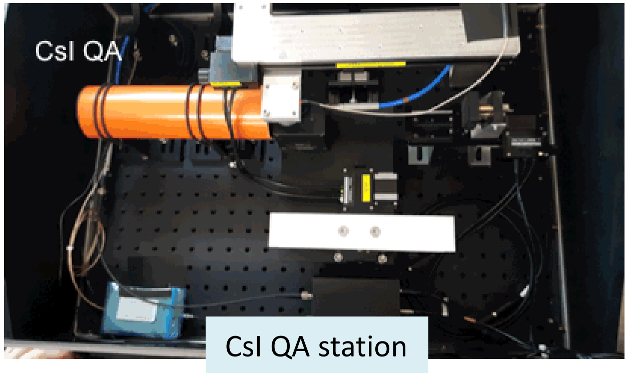
Procurement and QA/QC Status

- ✓ **1500 Pure CsI Crystals** (SICCAS) all procured, optical response and dimensionally tested and Tyvek wrapped
- ✓ **4000 Hamamatsu SiPMs** all procured and tested (24k cells) for gain, Vb spread, Id spread, MTTF and irradiation
- ✓ **3300 rad-hard FEE** (800 lost due to Ukraine Russia war) and calibrated + integrated to SiPM
- ✓ Laser system parts produced

- ❑ 70 final Dirac and Mezzanine boards produced in April 2024, **production of the other 80 expected for June 2024**
  - boards are being tested for burn-in, thermal cycles and functional readout test


SiPMs QA station


FEE burn-in

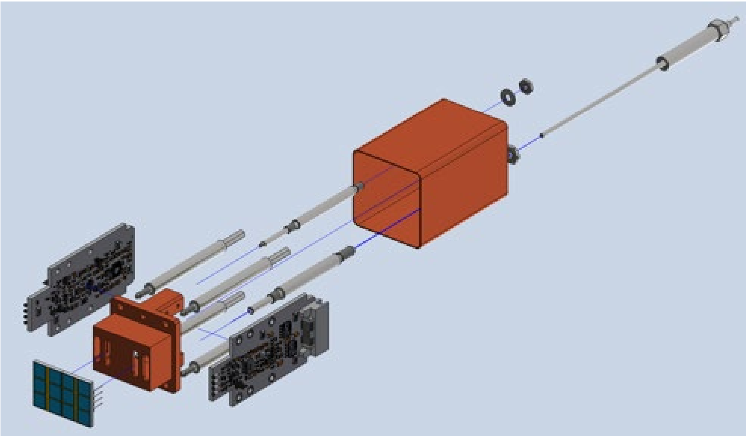


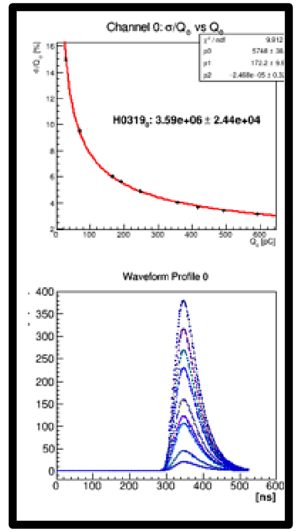
CsI QA station

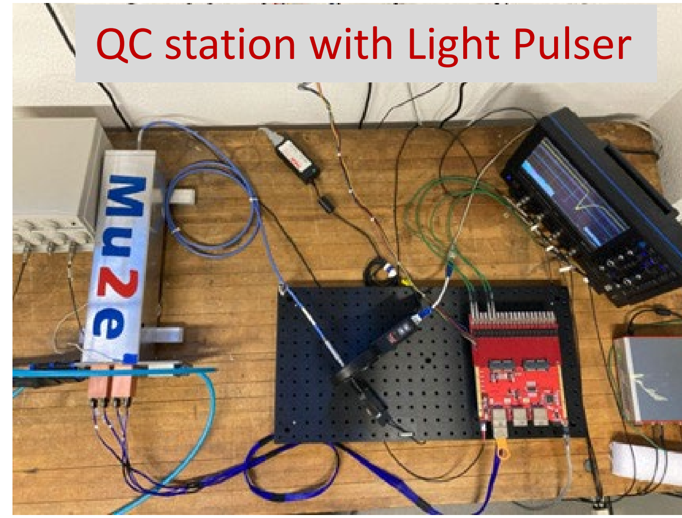

SiPMs gluing

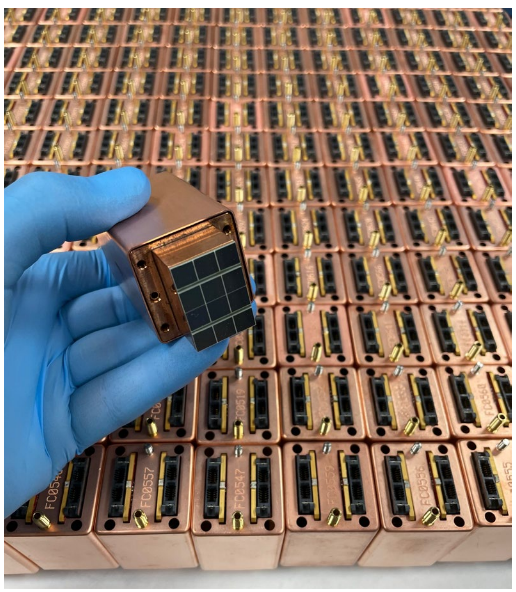
Preparation of Readout Units

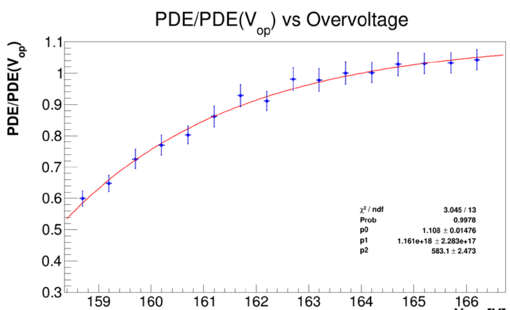
- **All** Holders + Faraday Cage **(RO)** assembled and tested



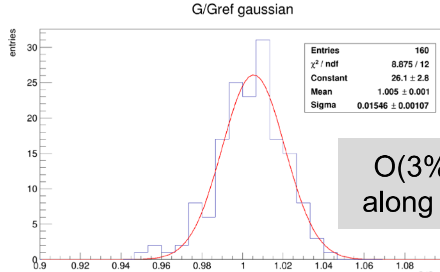




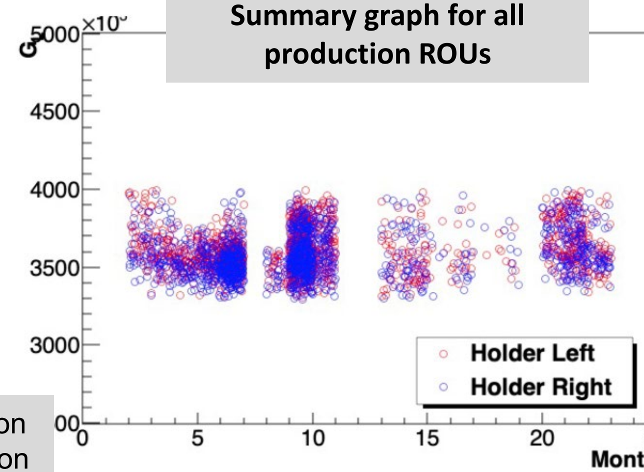




G/Gref gaussian



O(3%) variation along production



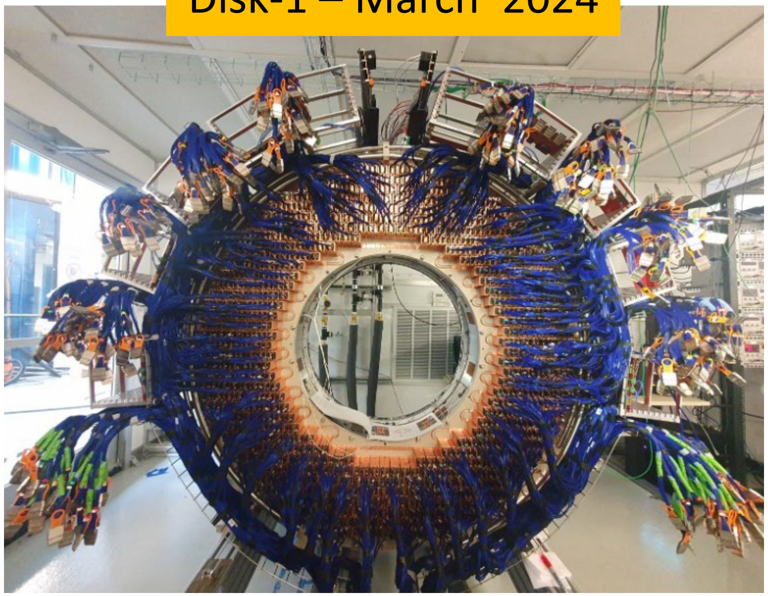
Disks Assembly status

All calorimeter mechanical parts built

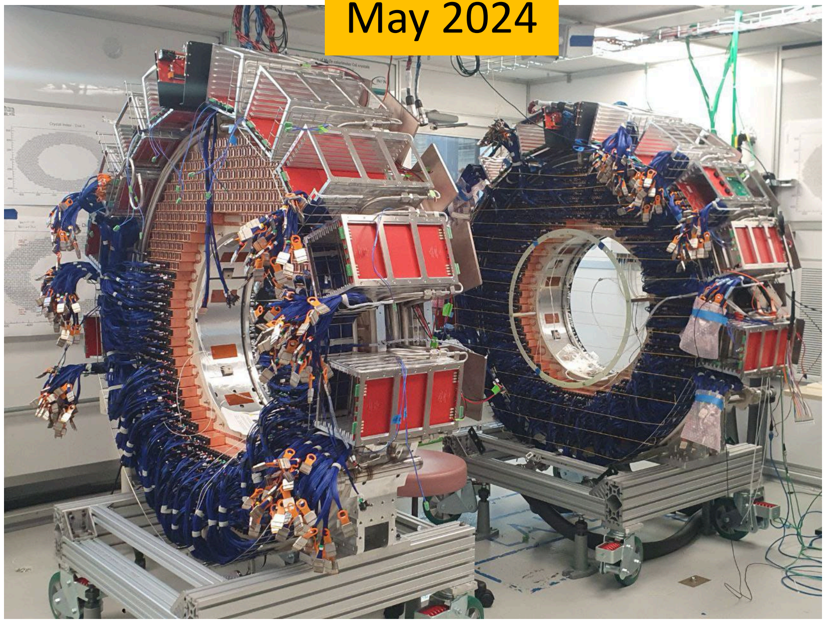
- Disk-1 (Disk-0) mech structure assembled in June 22 (March 23)
- All crystals stacked on both disks
- CF plates with source tubing, Inner Rings installed
- Crates+FEE plates *installed and leak checked*
- Installation feet for rails at Fermilab (March 2023)

Disks Assembly status

Disk-1 – March 2024



May 2024



Mu2e hall – Feb 2024

For both disks, mechanics, analog electronics and power distribution is completed.
Cable routing completed for Disk-1 and 2/3 for Disk-0

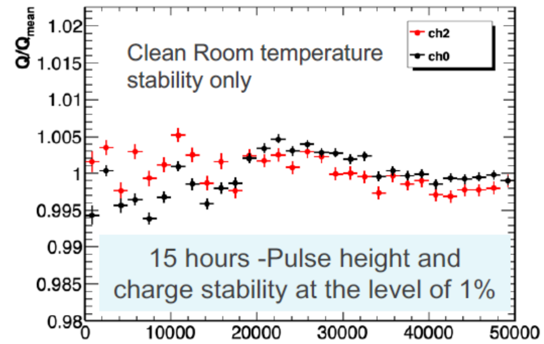
At Mu2e Hall:

- ✓ LV/HV power supplies installed
- ✓ Service cables in the south-side done
- ✓ Service cables in the north side in progress

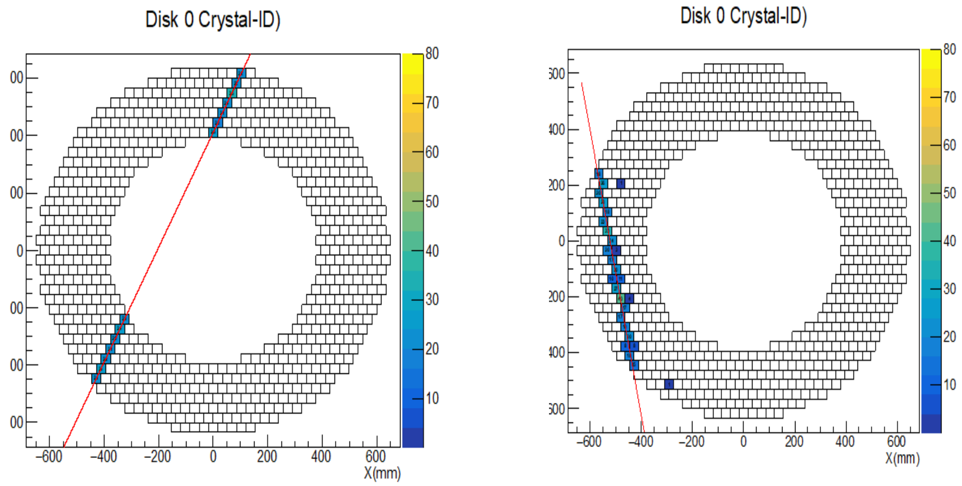
Calorimeter Commissioning @ Sidet

Commissioning ½ disk at a time:

- 4 PC servers, 6 DTCs, MTP fibers and breakout fibers
- Readout of 36 boards, EVB + CR selection trigger
- Calibration with Laser + Cosmic Rays



- Cosmic-rays calibration can provide in 2-4 hours **energy calibration at 1%** level **and time alignment at 10 ps level**



- **Repeat simulation exercise and prove calo mapping and resolution**

Conclusions

- The Mu2e CsI+SiPM Calorimeter demonstrated excellent energy (< 10 %) and timing (< 500 ps) resolution @ 100 MeV as proven with electron beams

- *The most demanding request is to do all of the above in an evacuated region with 1 T axia field and in a rad-hard environment:*
  → SiPMs work well under neutron irradiation but need to be cooled down to -10 °C
  → Engineering of cooling and calorimeter mechanics is crucial

- **Production of mechanics, crystals, SiPMs , FEE and FEE-MZB cabling completed**

- **Successful VST carried out** with excellent results on timing and energy calibration
  → Production of Digital electronics advanced (1/2 MZB and DIRAC boards)

- **Final integration of the detector readout with the TDAQ system** underway to allow calorimeter commissioning by collecting CR data from ½ disk/time.

- Calibration source and laser system well advanced.

- **Installation and transportation plans are progressing well**
  → We plan to move the disks in the Mu2e building in fall 2024

Backup Slides

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

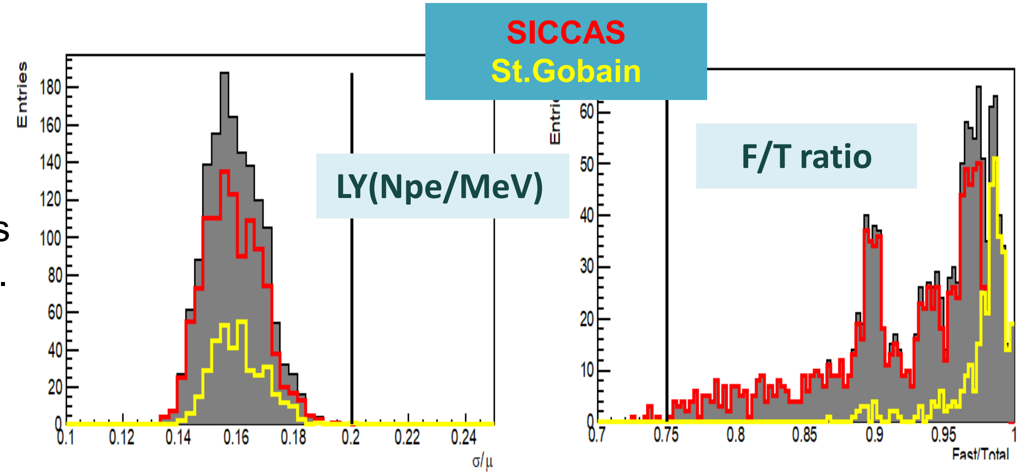
- Not too radiation hard
- Slightly hygroscopic
- 15-20 ns emission time
- Emits @ 320 nm.
- Comparable LY of fast component of BaF_2.
- Cheap (6-8 $/cc)

Production of Crystals and SiPMs

- ❑ Production of 1500 CsI crystals and 4000 Mu2e SiPMs started in 2018
- ❑ QA test at SIDET (FNAL) + irradiation tests at Caltech, HZDR, FNG, Calliope

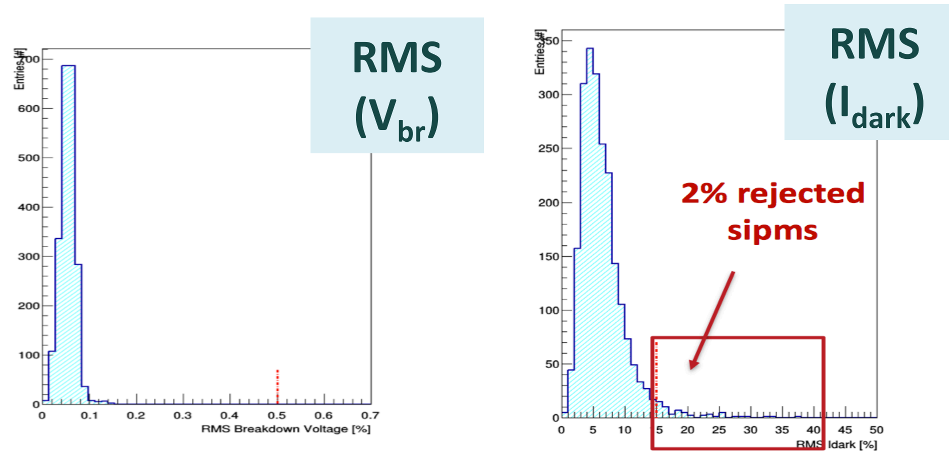
Crystals

- ❑ Two producers **(SICCAS, St. Gobain)**
- ❑ QA of optical (**LY, LRU, F/T, RIN)** and mechanical (**thickness, shape**) properties
  - ✓ St.Gobain failed to match our specs.
  - ✓ Final production back to SICCAS
- ❑ OK with irradiation tests
- ❑ 8 % specification failure

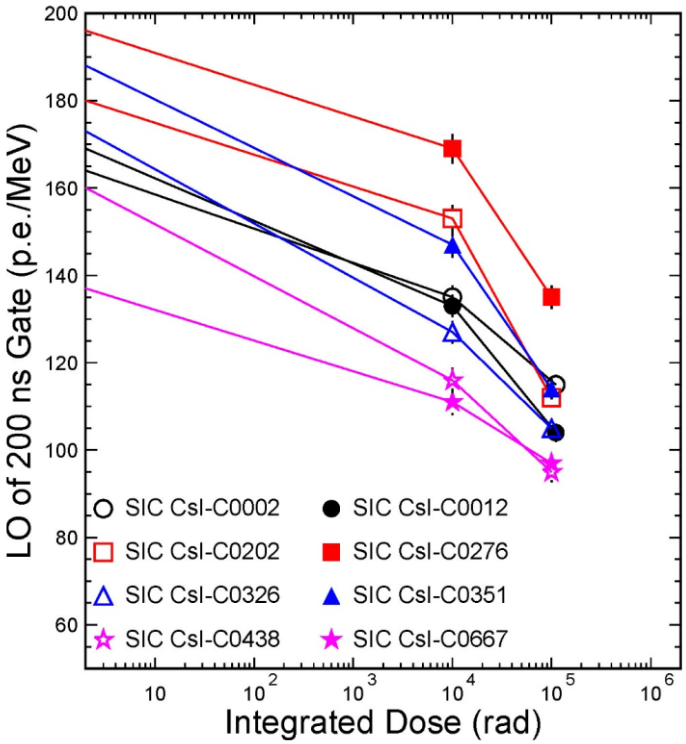


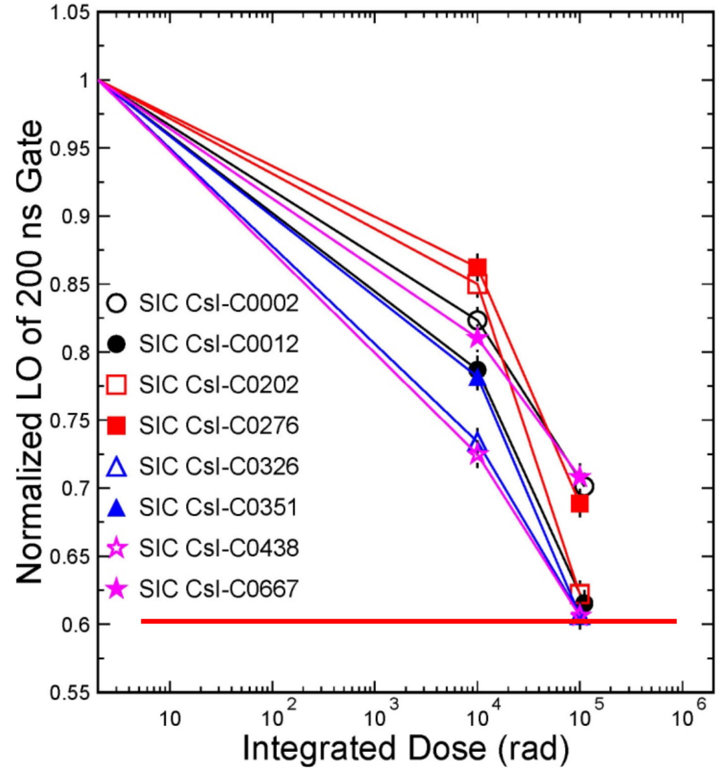
SiPMs

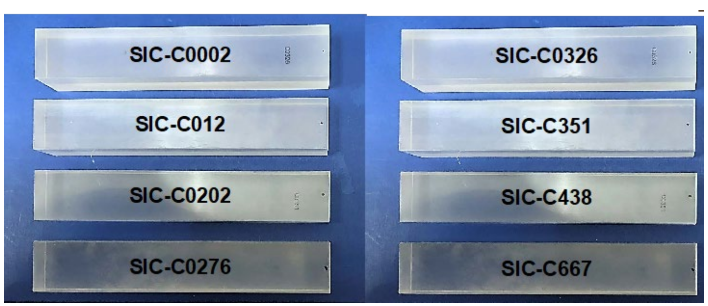
- ❑ Producer: **HAMAMATSU**
- ❑ All 6 cells/SiPM tested, measuring
  V_{br}, I_{dark}, Gain x PDE
- ❑ **Irradiation with ~1x10^{12} neutrons/cm^{2} and (MTTF)** test on 5 SiPMs/batch



Irradiation of production crystals



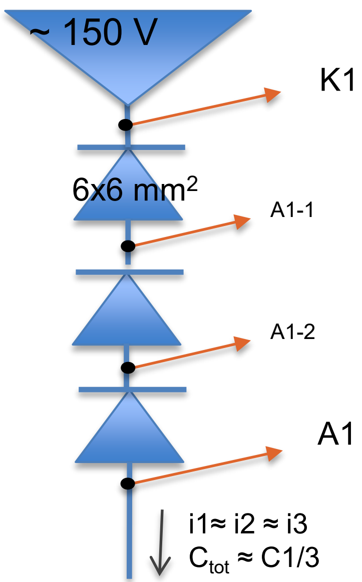


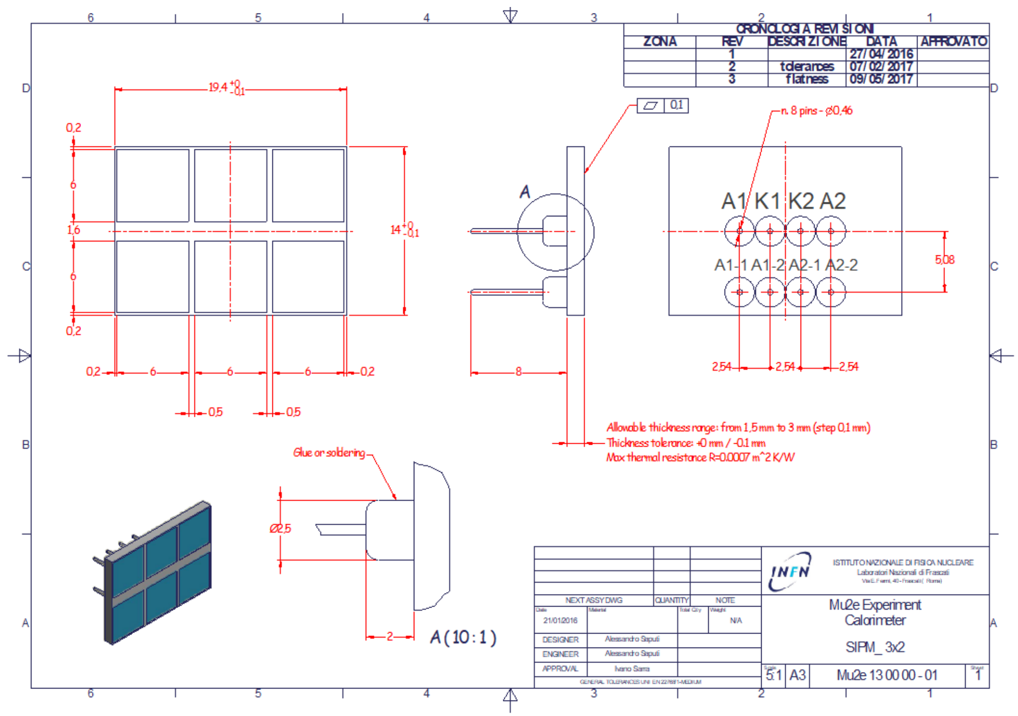


- 8 crystals measured;
- LY OK with requirements
- LRU,FT,Eres in specs
- No recovery observed with time

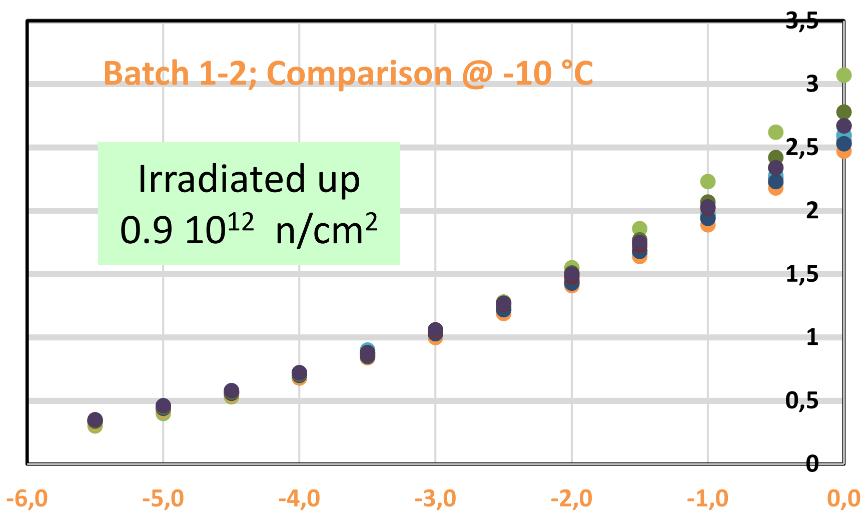
Mu2e custom SiPMs design

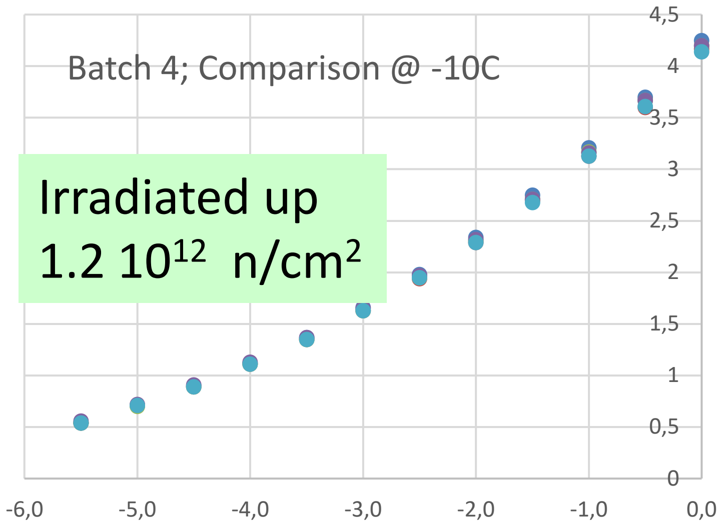
- **2 arrays of 3 6 x 6 mm² UV-extended SiPMs for a total active area of (12x18) mm²**
- The series configuration reduces the overall capacity and allows to generate narrower signals

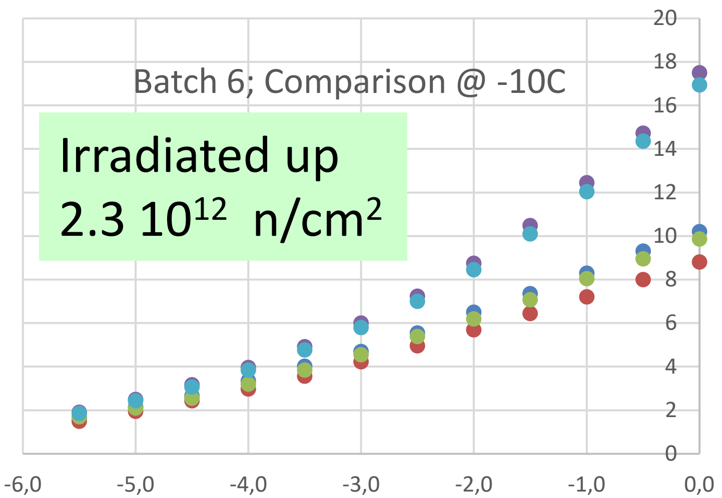




SiPM irradiation with neutron





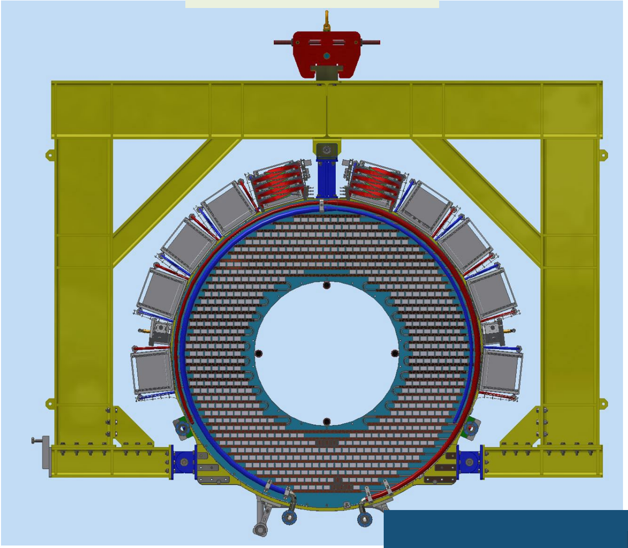


- 5 SiPMs/batch "passively" neutron irradiated @ Dresden
- For Mu2e, the max n-flux in SiPM area is of around 4×10^{10} n/cm^2
- Safety Factor 3(MC)x5(Years)x2(Prod) = 1.2 10^{12} n/cm^2
- Max I-dark current for operation of 2 mA

➔ Requires cooling of -10 C, Lower operation overvoltage to Vop-3V (for the MU2E series) , 20% of PDE relative loss

Calorimeter Installation

Lifting Tool



Transportation from Sidet to Mu2e hall