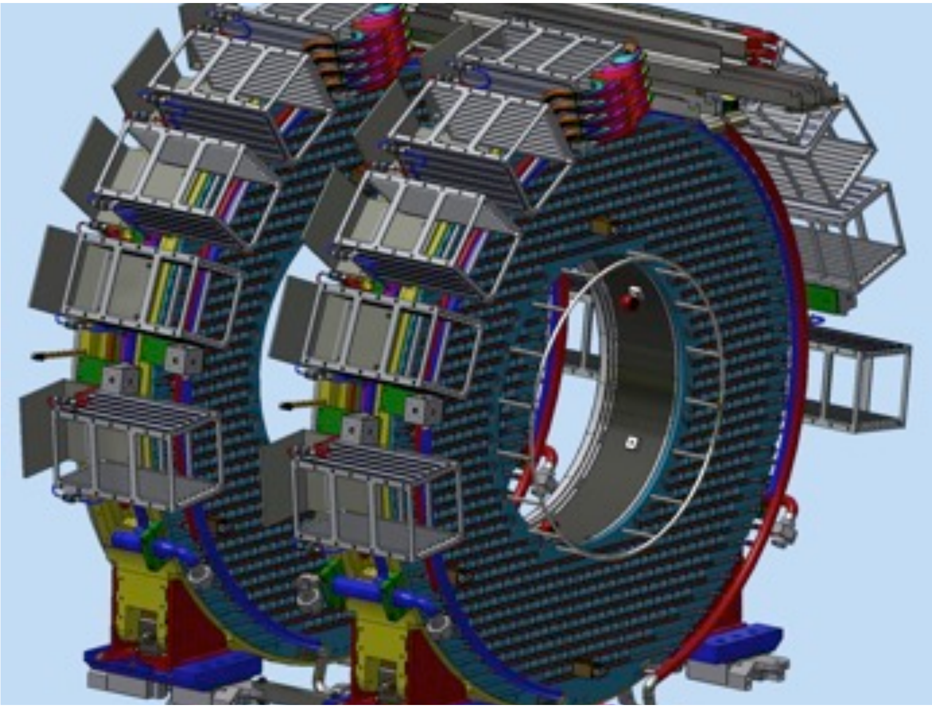
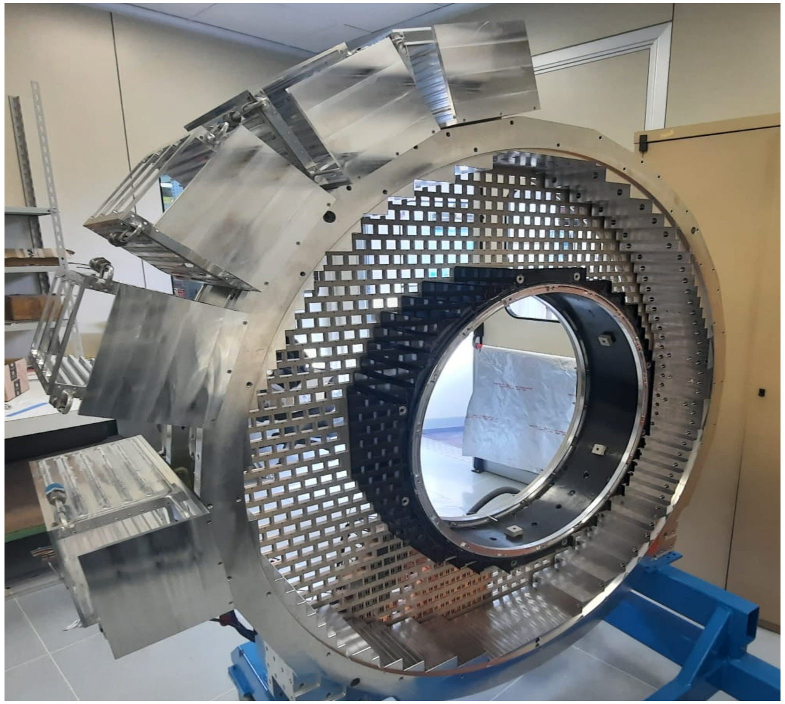
The Mu2e Electromagnetic Calorimeter





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On behalf of the Mu2e calorimeter group

16-May-2022

CALOR 2020 – 19th International Conference on Calorimetry
in Particle Physics
University of Sussex, UK, 16-20 May, 2022

Talk layout

- The Mu2e experiment
- Calorimeter requirements and design considerations
- Technical choice: un-doped CsI + Mu2e SiPMs
- Calorimeter engineering Layout
- Performance test with Module-0
- Production of crystals , Mu2e SiPMs and FEE
- Status of Readout units
- Status of Digital electronics and VST
- Status of mechanics
- Assembly plan

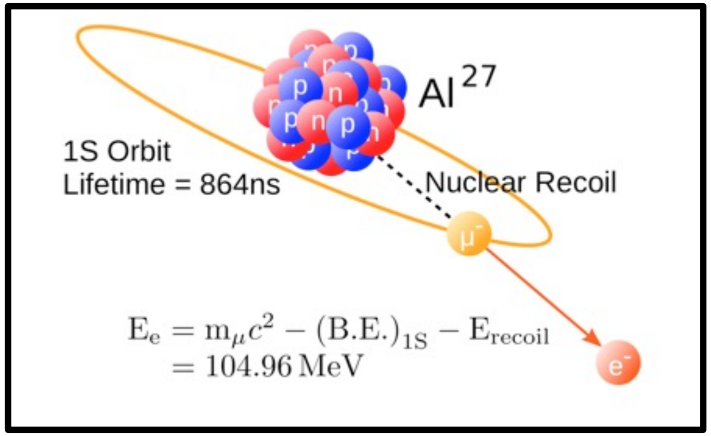
The Mu2e experiment @ Fermilab

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

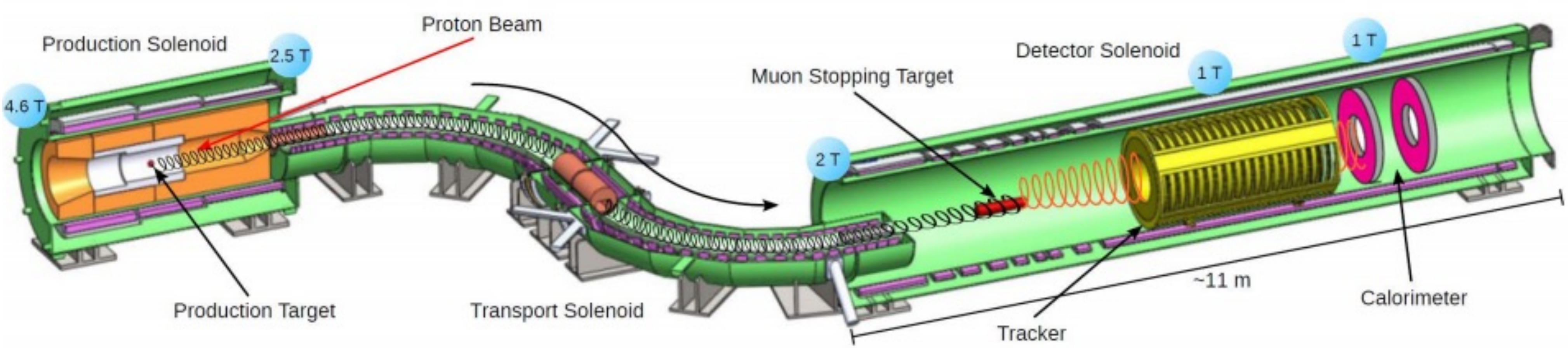
$$R_{\mu e} = \frac{\mu^- + N(A,Z) \rightarrow e^- + N(A,Z)}{\mu^- + N(A,Z) \rightarrow \nu_\mu + N(A,Z-1)} < 8.4 \times 10^{-17}$$

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→*e*N signature → **mono-energetic electron @ 105 MeV**

Production & Transport Solenoids

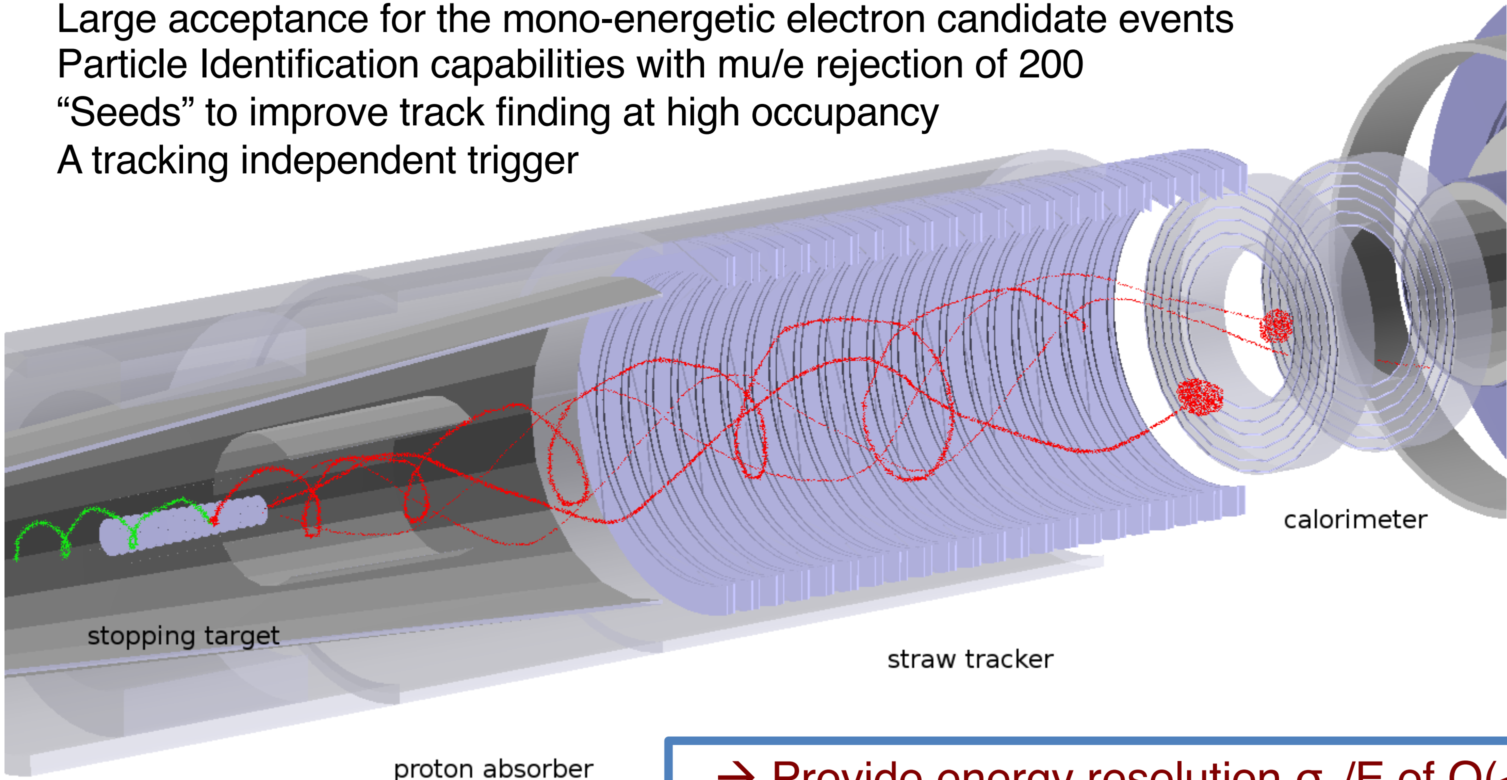


Detector Solenoid

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**

Technical specifications

- Chosen Technical Solution → **Crystal calorimeter with SiPMs**
- 2 Disks (Annuli) geometry to improve acceptance
- Crystals with high Light Yield for time/energy resolution → **LY(SiPM) > 20 pe/MeV**
- **2 SiPMs/preamps/crystal** for redundancy and MTTF requirement → **1 million hours/SIPM**
- Fast signal for Pileup and Timing → **τ of emission < 40 ns + Fast preamps**
- **Fast Digitization to disentangle signals in pileup**
- **Crystals should withstand a TID of 90 krad and a fluence of $3x10^{12}$ n/cm^2**
- **Photo-sensors/FEE should withstand 45 krad and $1.2x10^{12}$ n_1MeV/cm^2**
- **Digital electronics should withstand :**
  - → a TID of 15 krad
  - → a neutron fluence of $3x10^{11}$ n/cm^2.
  - → Charged Hadron (>20MeV) 10^{10}/cm^2

Safety Factor = 3
5 years of run

Mu2e calorimeter design

- ✓ Two annular disks, each one with 674 un-doped CsI parallelepiped crystals with square faces:

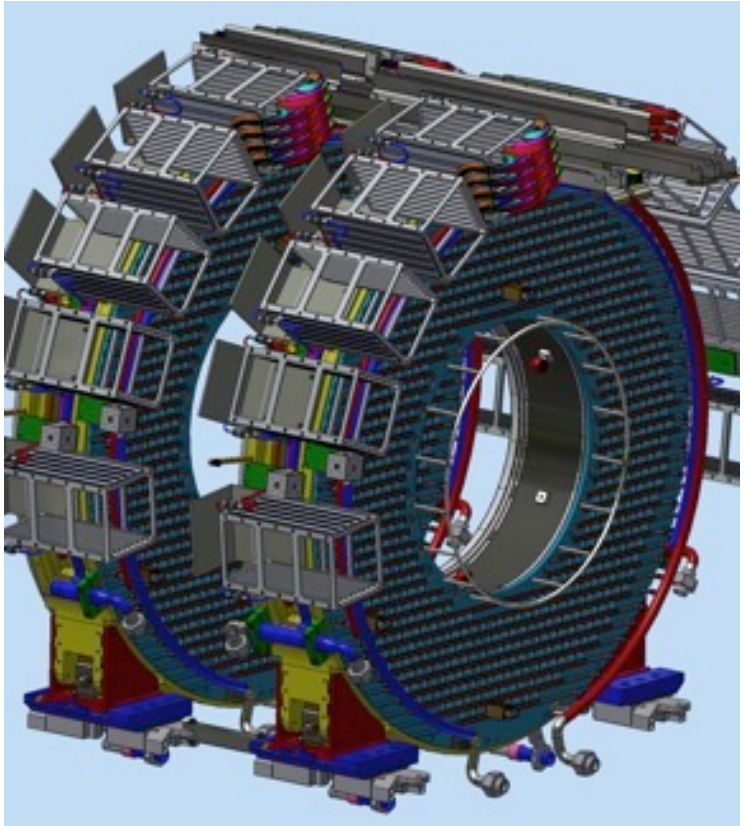
  ➔ Crystal dimensions (34 x 34 x 200 mm^3) ~ 10 X_0
  ➔ Inner/Outer Radius = 374/660 mm

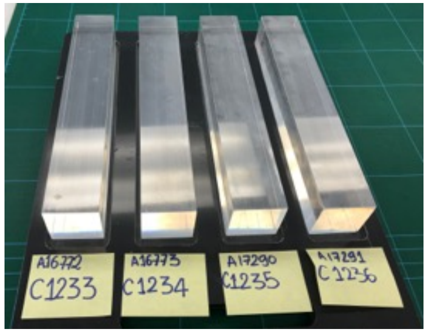
- ✓ Each crystal is read out by two large area UV extended Mu2e SiPM's (14x20 mm^2) through a 2mm air gap

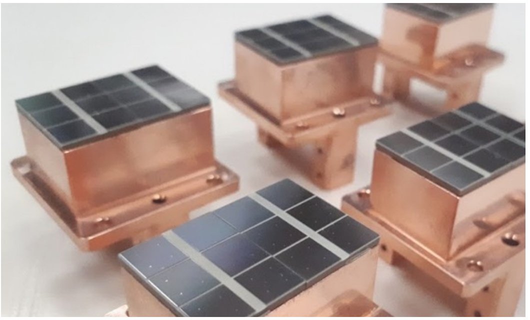
- ✓ SiPM glued on copper holders with FEE mounted on SiPM pins

- ✓ Digital electronics at 200 Msps located in near-by electronics crates

- ✓ Radioactive source (ala Babar) and laser system provide absolute calibration and monitoring capability







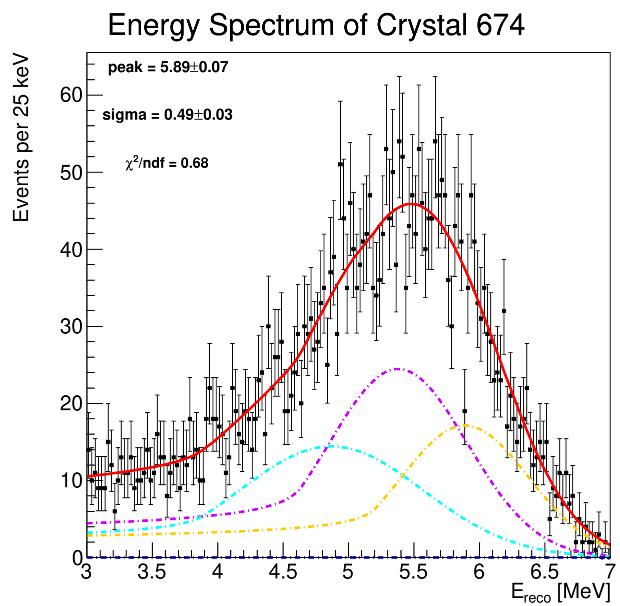
Operate with very high reliability in vacuum and radiation hard environment → -10 °C for SiPMs

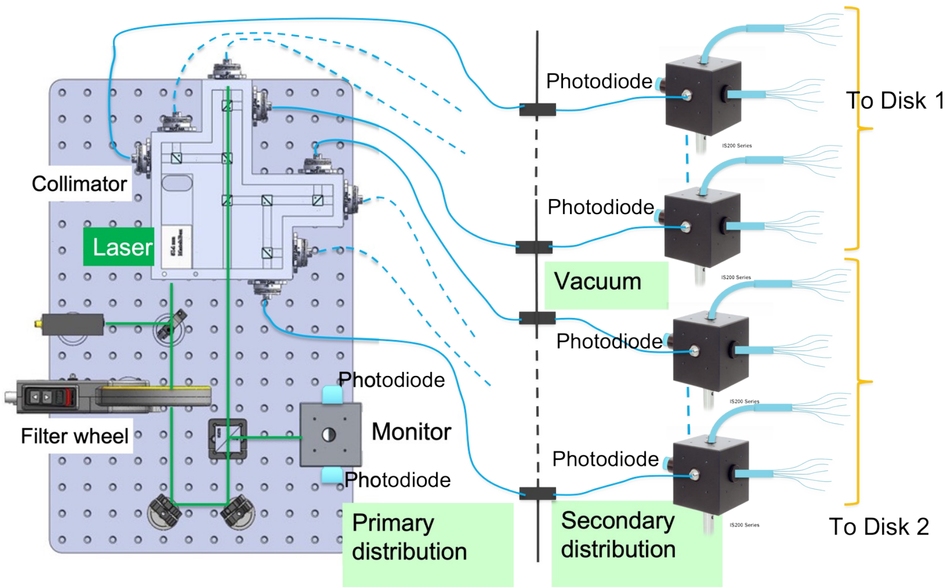
Calibration Tools

- ✓ 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

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

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

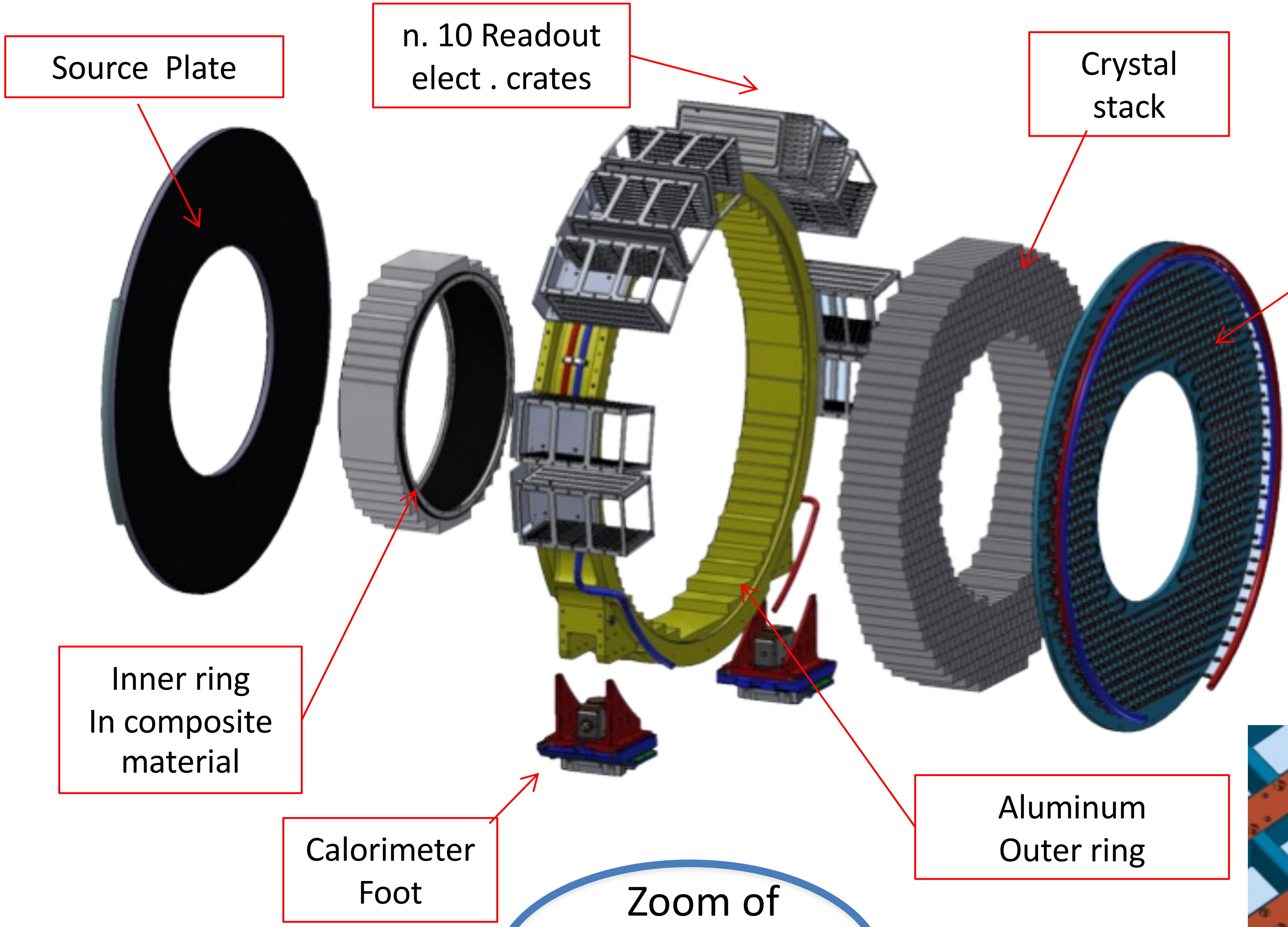




- ✓ A pulsed green laser illuminates all crystals through a distribution system based on optical fibers and integration spheres
- ✓ Monitor gain variation at level of 0.5%
- ✓ Determine T0's at level of 100 ps
- ✓ Stability at level of few %, monitored with PIN Diodes at laser source. Used at low rate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

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

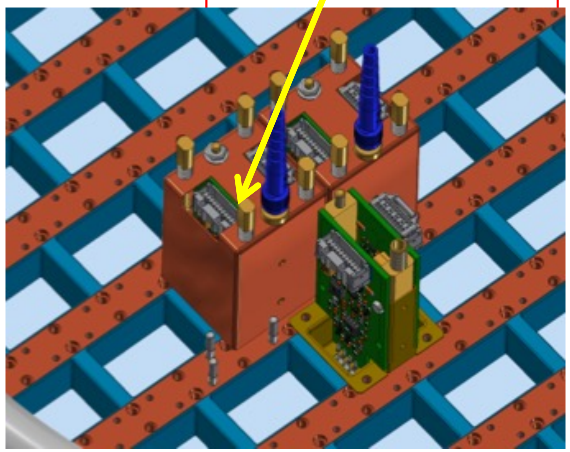
Mu2e calorimeter engineering



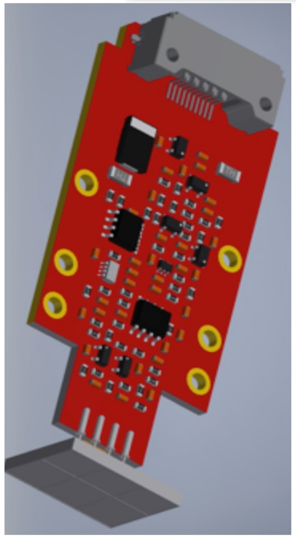
To reduce/handle the neutron induced leakage current,Id, SiPMs should be cooled down
(x 2 Id reduction/10 °C)
➔ **SiPM running temperature at -10 °C, Coolant at -20°C**

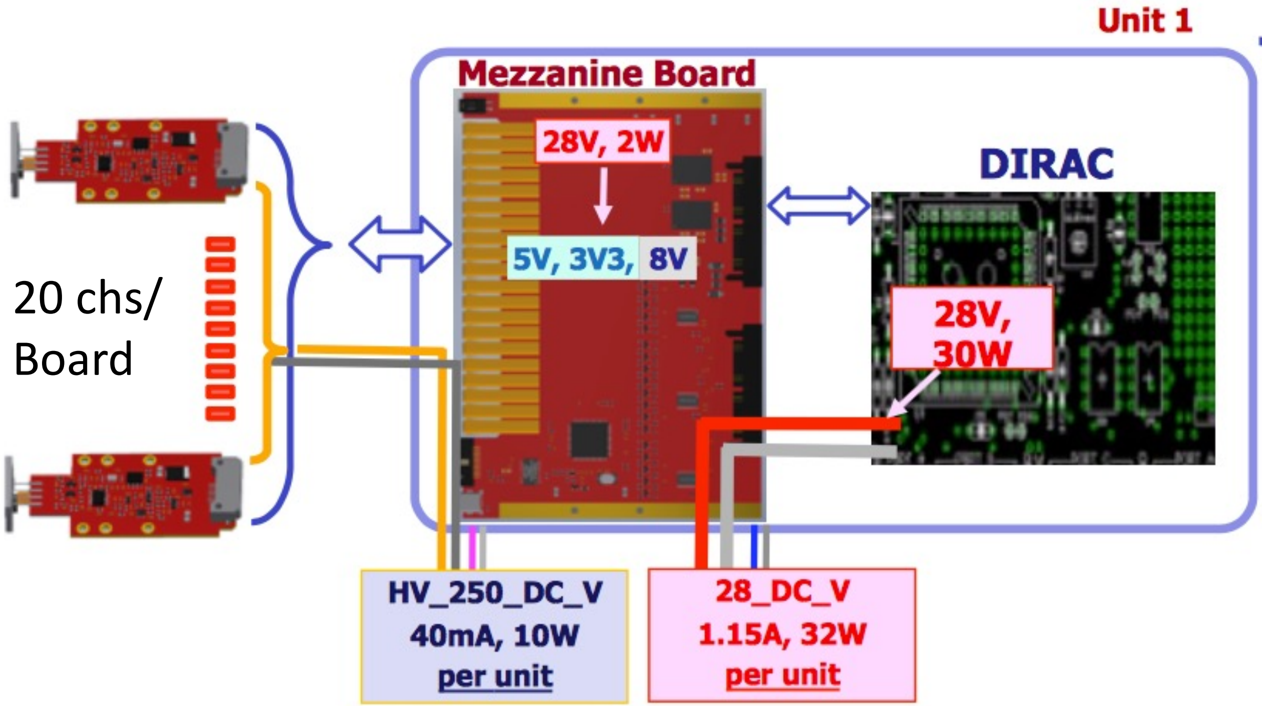
Zoom of SiPM/FEE/Holders on support disk

Readout Units = SiPM+FEE holder



FEE and Digitization scheme





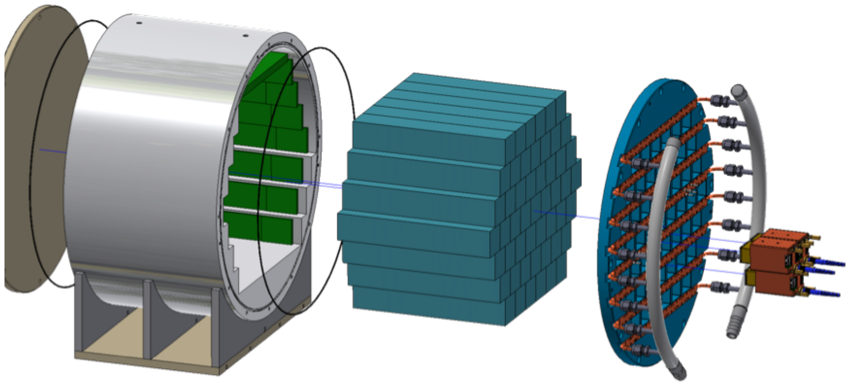
More details about electronics
+ rad-hardness development
D. Paesani's talk

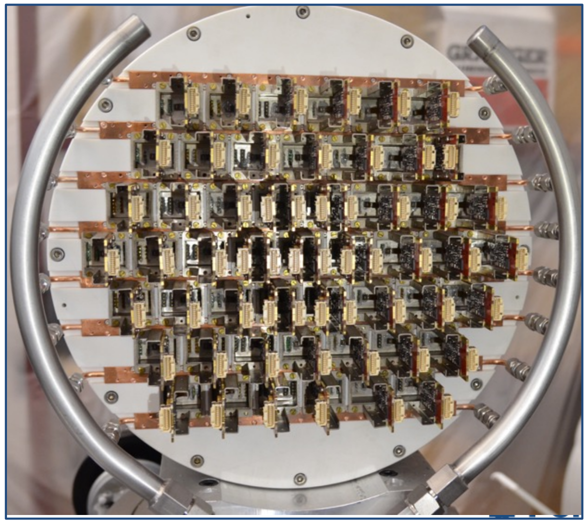
- ✓ **1 FEE chip (amplification and HV regulation) locally on the SiPM pins**
  - → Independent amplification, HV & readout for Left/Right SiPMs
  - → radiation hardness up to 100 krad, 10^{12} n/cm^2
- ✓ **6-8 (Digitizer + Mezzanine) boards in 10 crates → 20 chs format.**

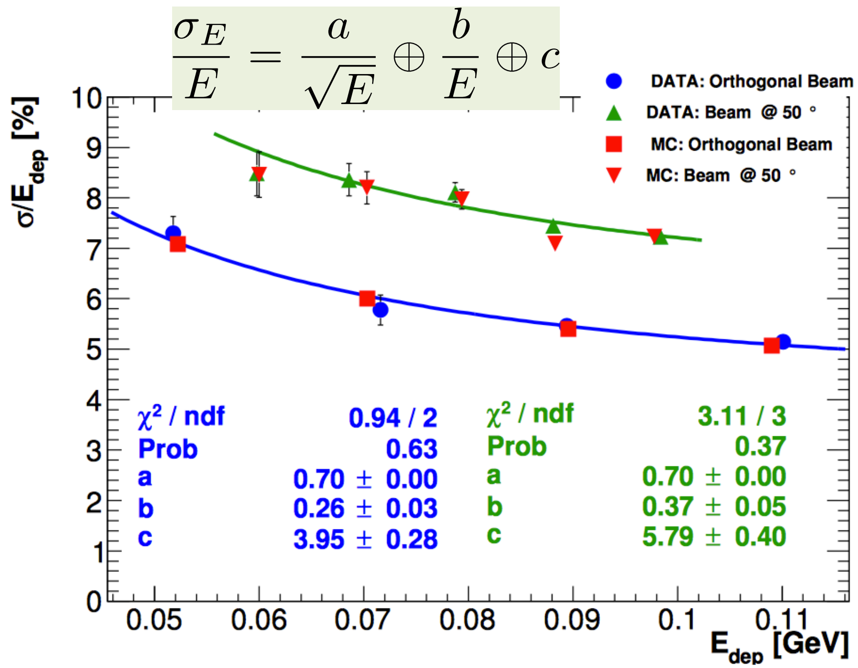
Digitizer @ 200 Msps (5 ns binning), Mezzanine to set/read HV of each SiPM
→ radiation hardness up to 15 krad + 10^{10} p/cm^2

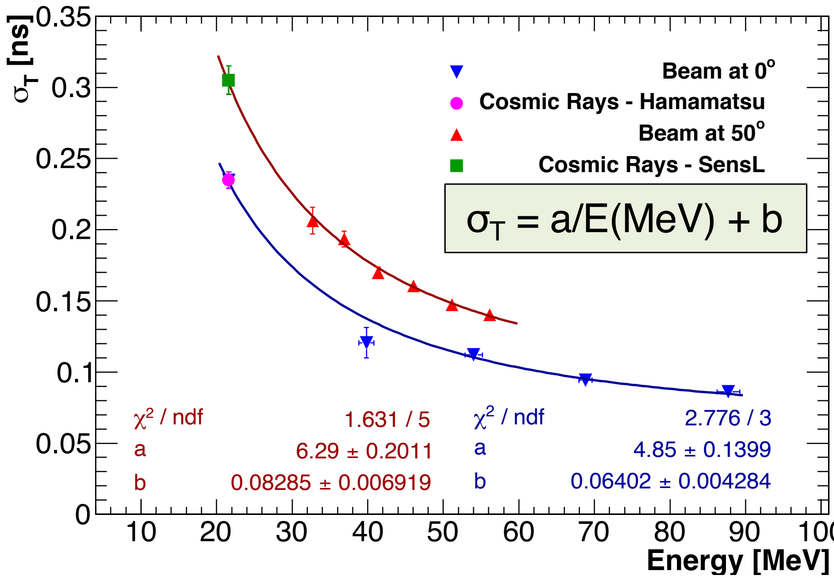
Module-0 test beam results (2017)

- ✓ 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**









Production of Crystals and SiPMs

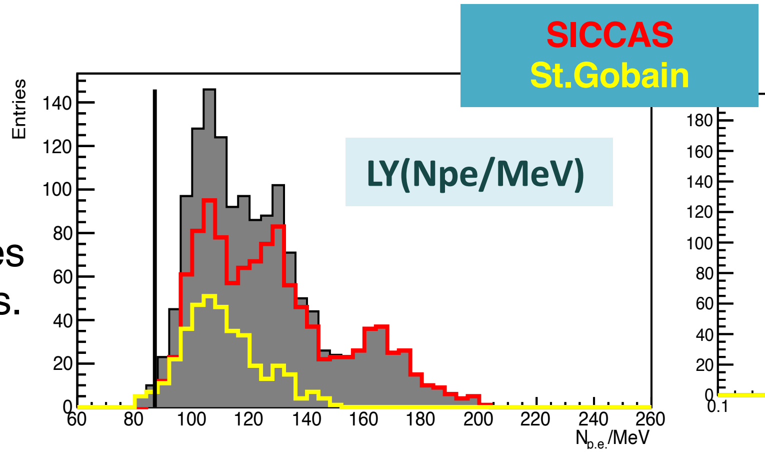
- ❑ Production of 1500 CsI crystals and 4000 Mu2e SiPMs started in 2018
- ❑ QA test at SIDET (FNAL) + irradiation tests at Caltech, HZDR, FNG, Calliope

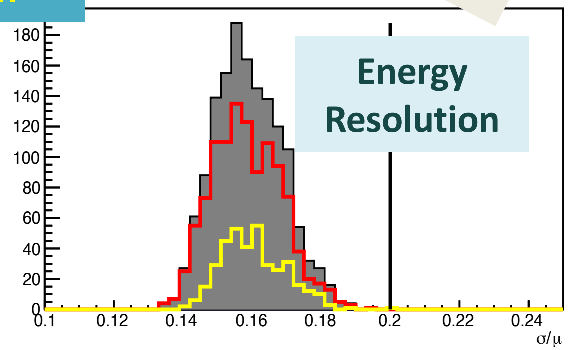
Production Completed

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

Completed end of 2020

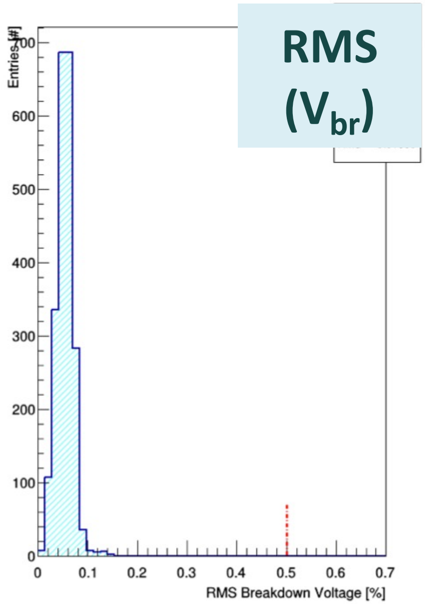


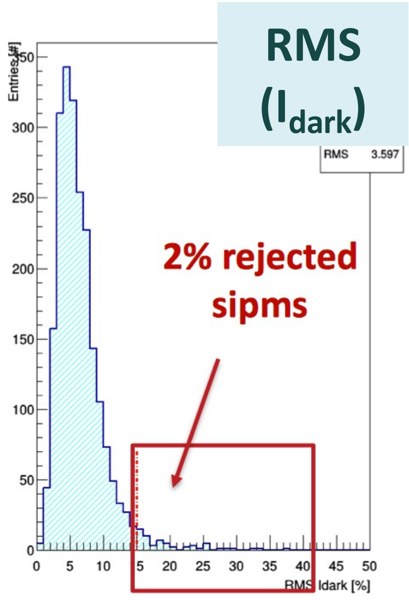


SiPMs

- ❑ 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

Completed end of 2019

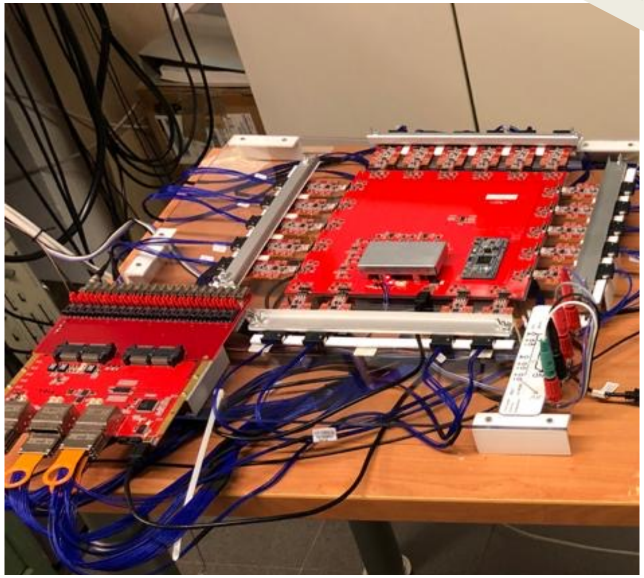


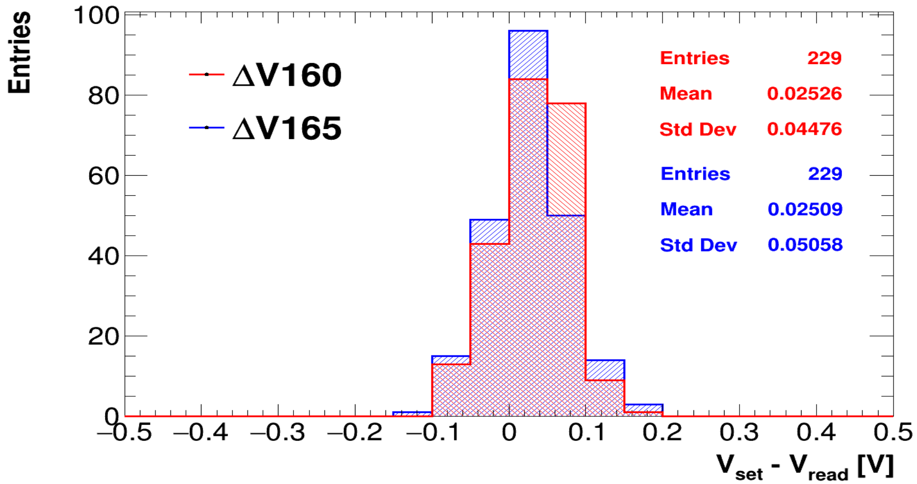


FEE production

- ✓ **3510 FEE boards produced, 2500 calibrated at JINR**
- ✓ Two levels QC : Burn-IN + Calibration of HV, amplification and signal shape.

Production completed end of 2021





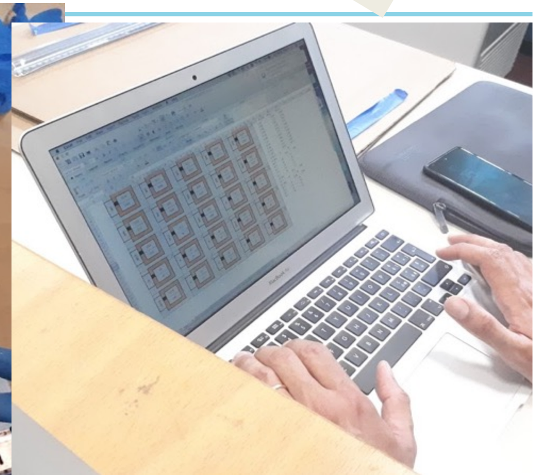
SiPM gluing operation

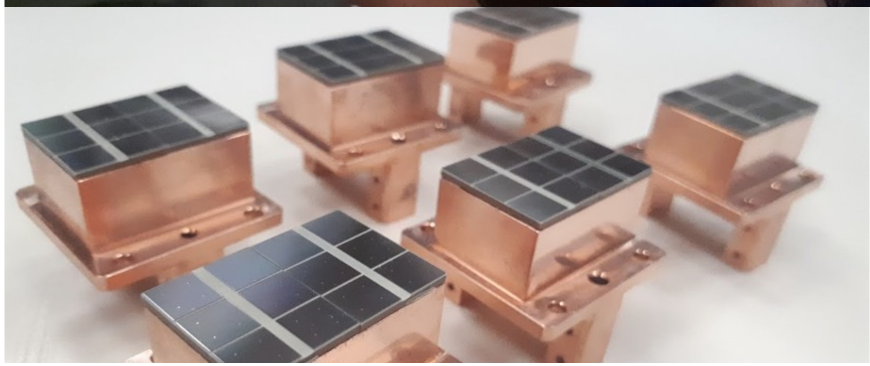
Due to the pandemics, we moved the gluing operation from FNAL to INFN (+ 1 year delay)

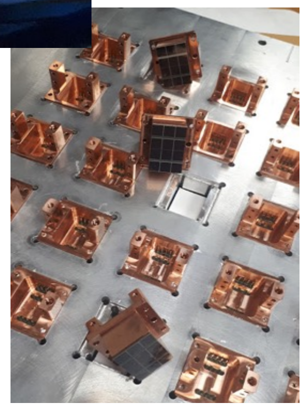
- ❑ All copper holders produced (1500 pieces)
- ❑ 2 SiPMs glued per Holders

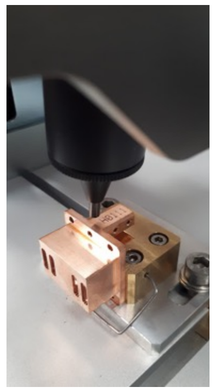
2800 SiPMs glued on 1400 Holders

Completed end of 2021



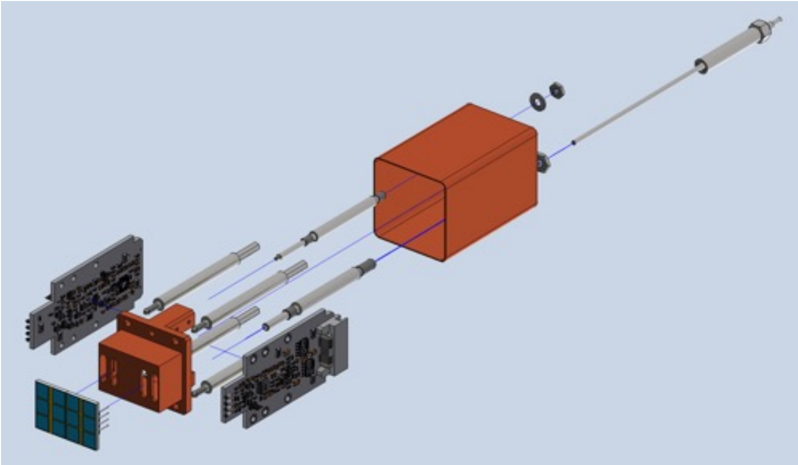


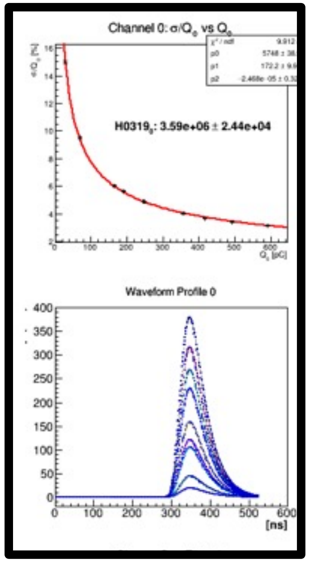


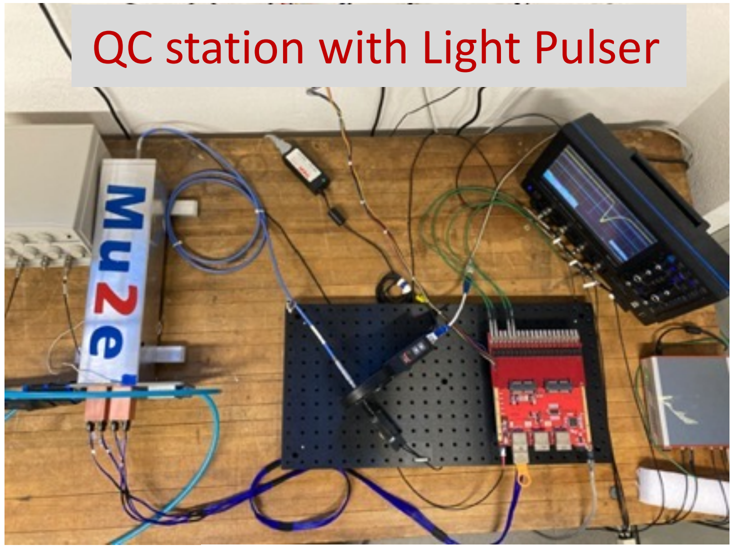


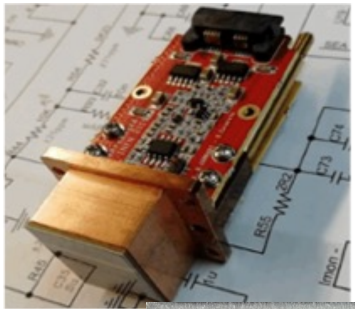
Preparation of Readout Units

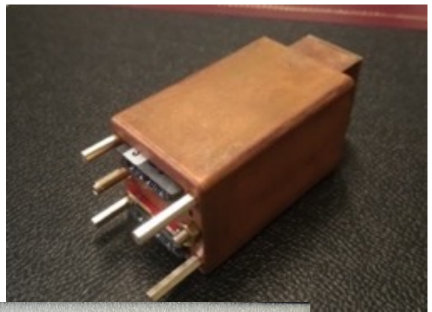
- **300/1400** Holders + Faraday Cage **(RO)** assembled and tested
- Progressing well with 100 pieces/week → Expected to complete for end of summer 2022

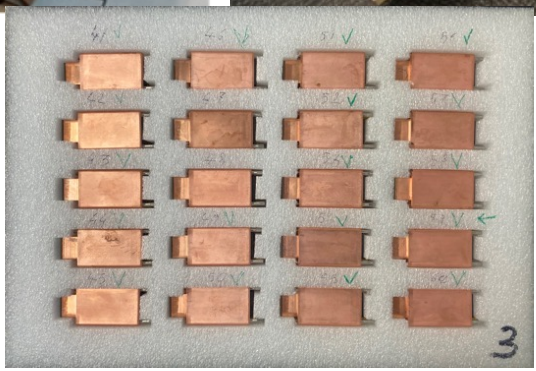


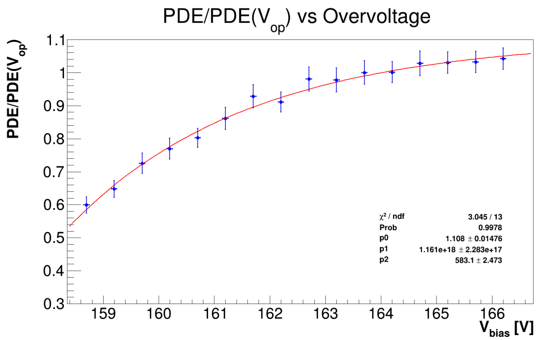


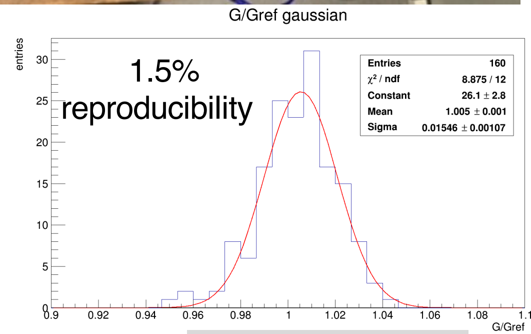


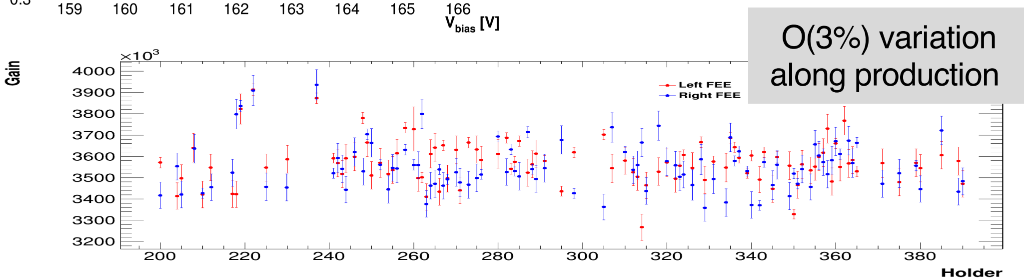








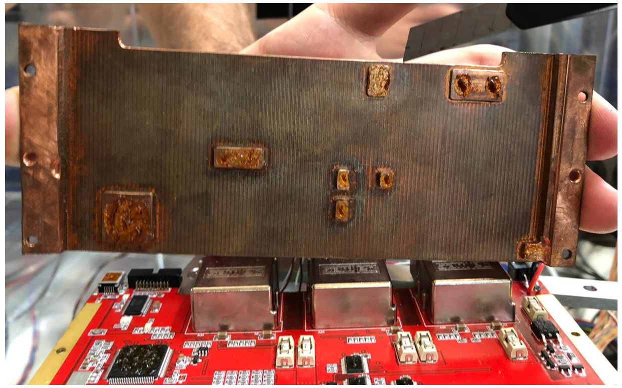




Status of digital electronics

Final QA/QC tests performed:

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



✓ **frozen design for V3 version of Mezzanine and DIRAC boards**

✓ 10 pre-series Mezzanine boards produced on March 2022

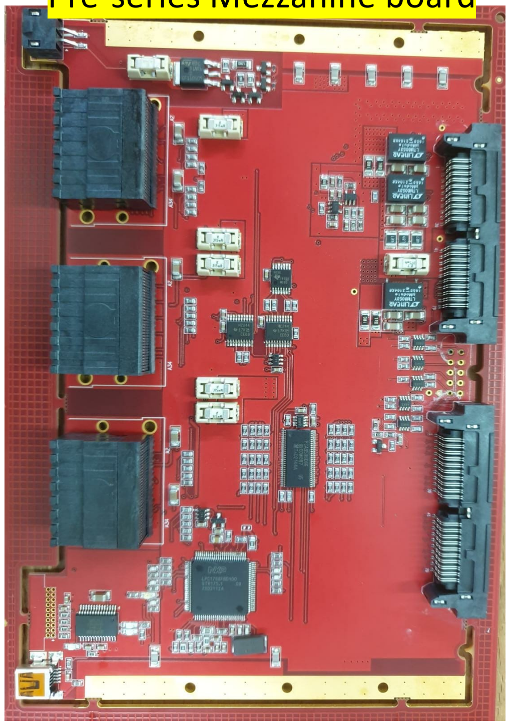
✓ After pre-series tests, **production of 150 MB boards expected for July 2022**

✓ **5 V3 DIRAC prototypes in hands**

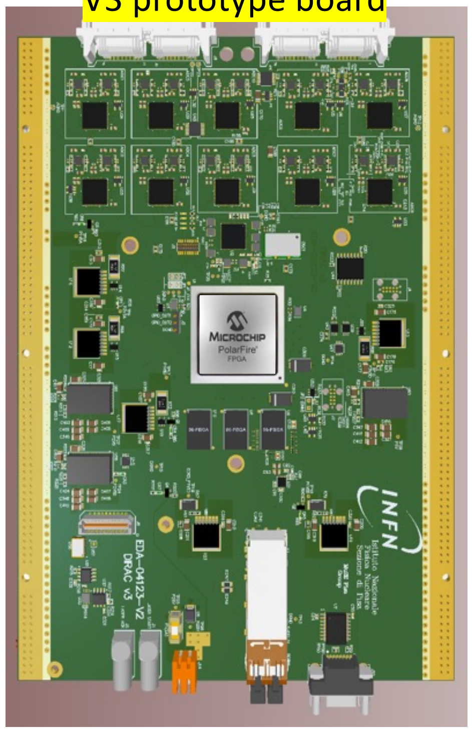
- 5 ns sampling, zero suppression
- New rad-hard FPGA "POLARFIRE"
- VTRX for optical link readout

✓ All componentes ready for DIRAC production apart FPGA due to **Covid supply chain** delay issues → ***delivery expected for spring 2023***

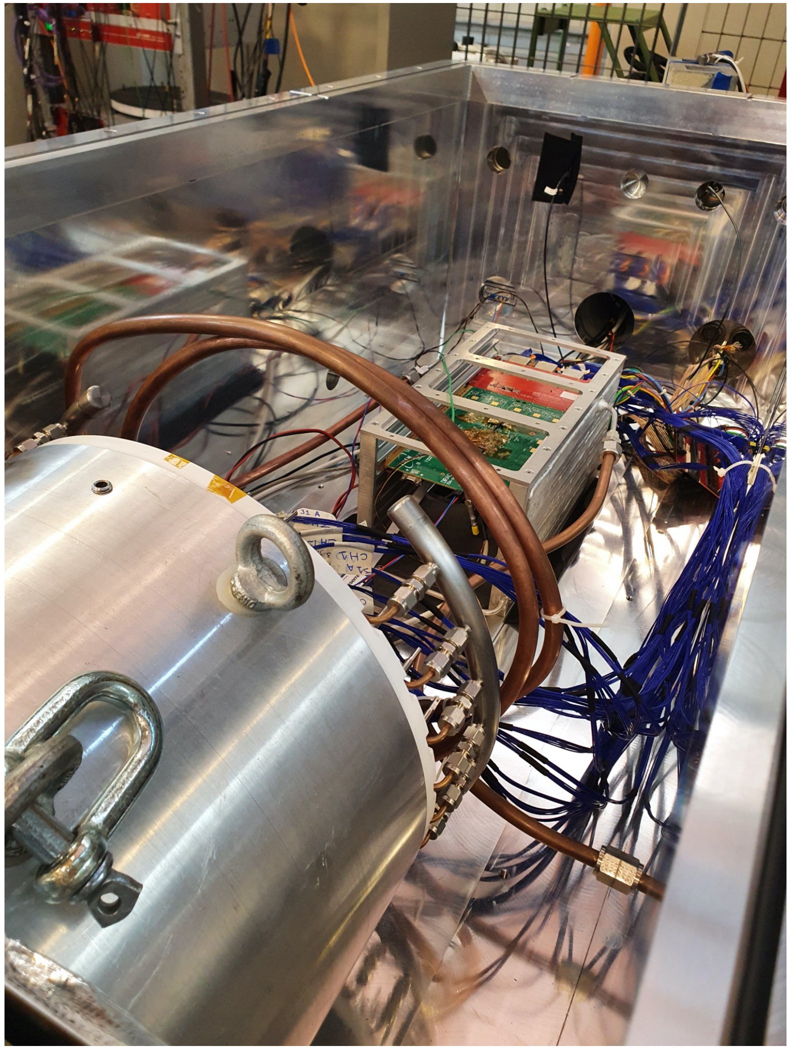
Pre-series Mezzanine board

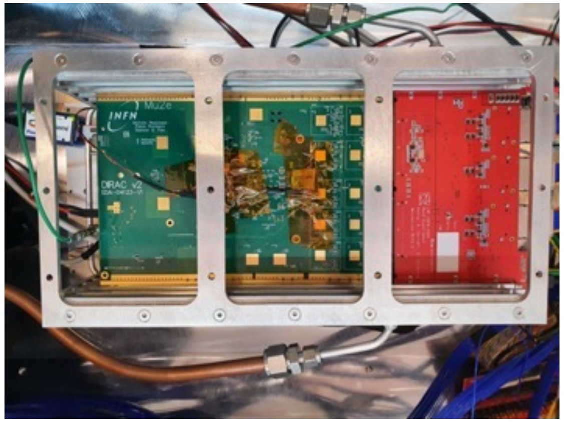


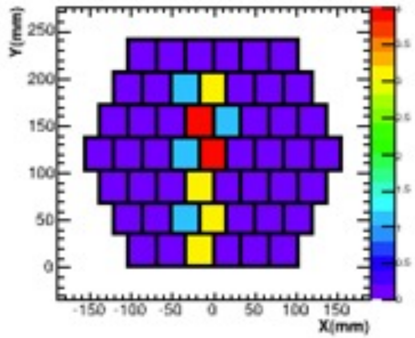
V3 prototype board



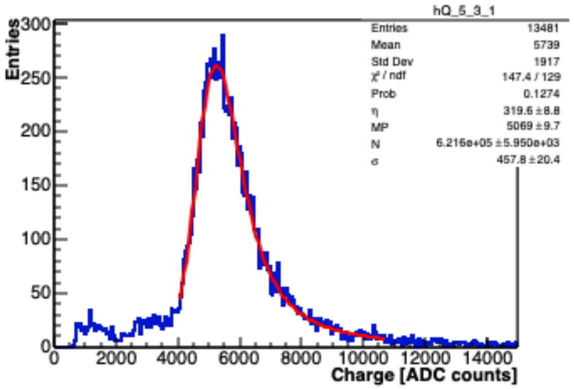
Calorimeter Vertical Slice Test



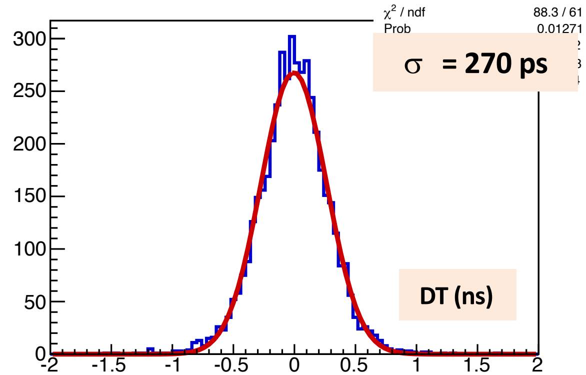




- MB+ DIRAC V2 boards used for full Vertical Slice Test (VST)
- **Data collected in vacuum, at low T and with irradiated sensors for the last 10 months**
- Stable operation and reconstruction
- Data taking of CR events triggered with external scintillators

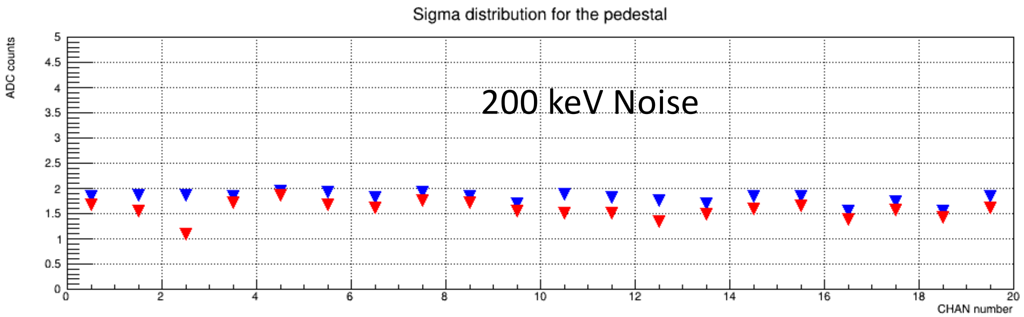


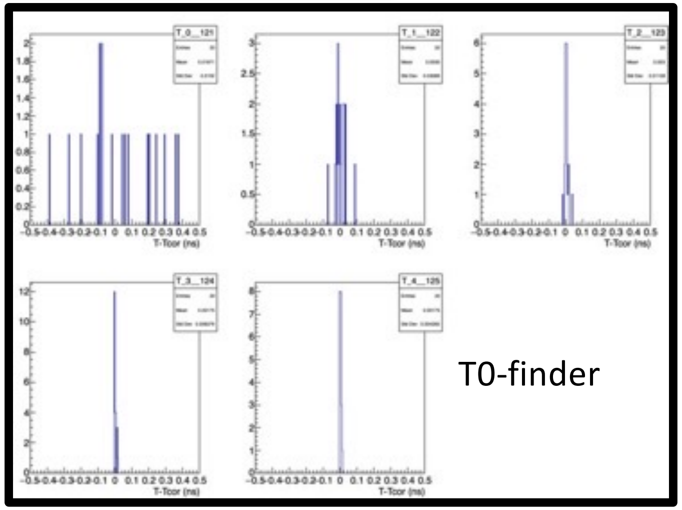
MIP charge distributions



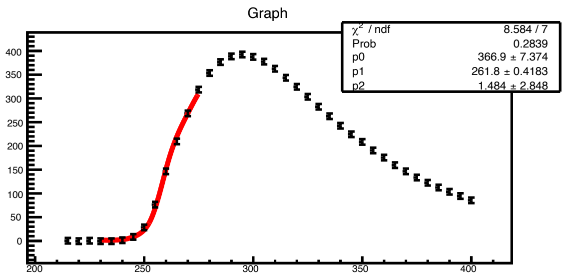
Time difference of two SiPMs/Crystal

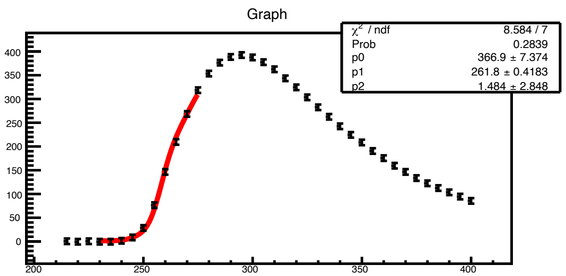
VST: summary of results

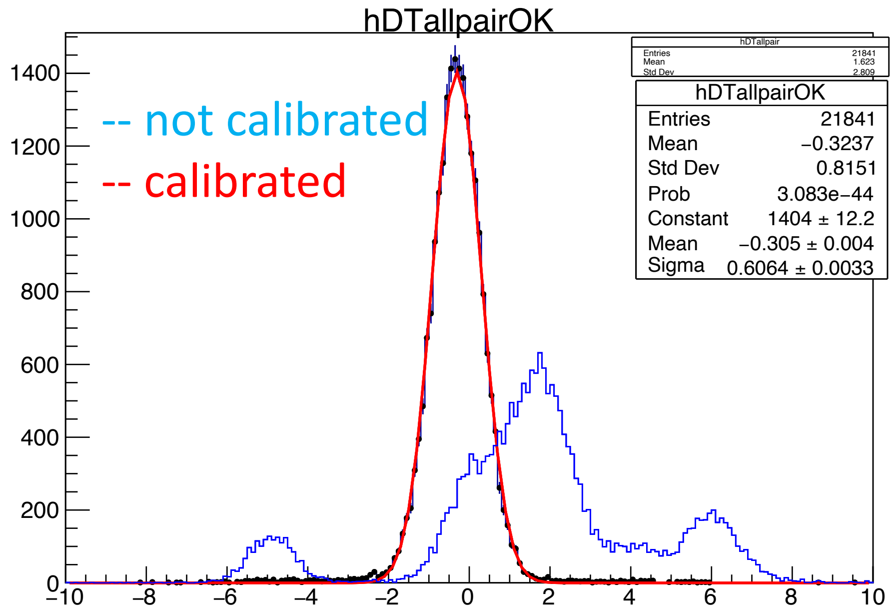


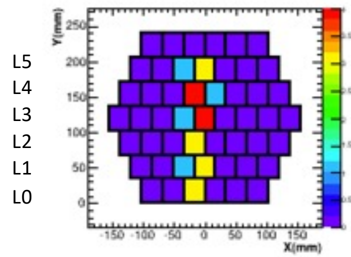


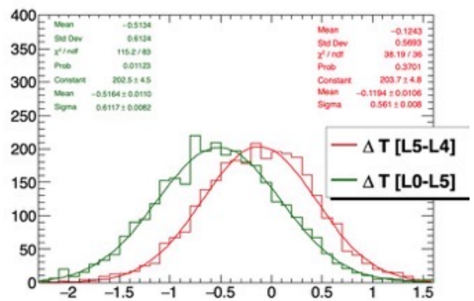
400 mV/MIP







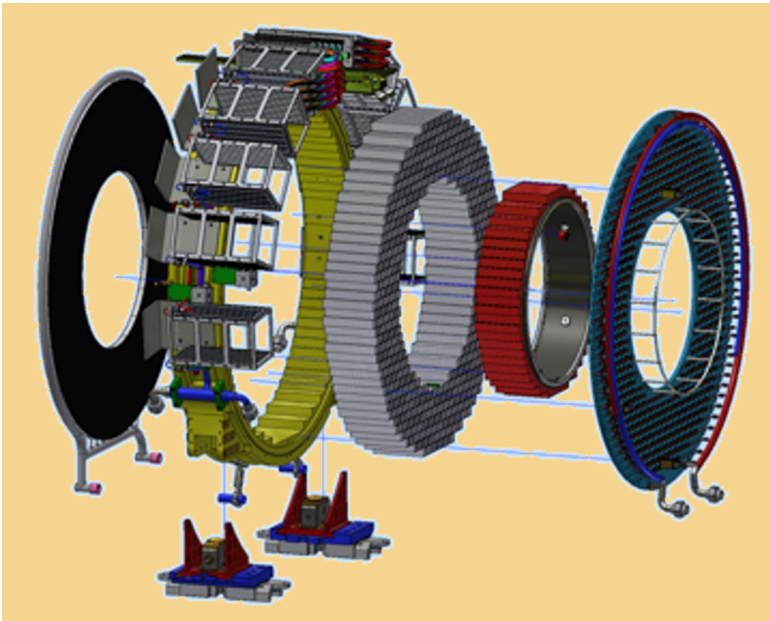


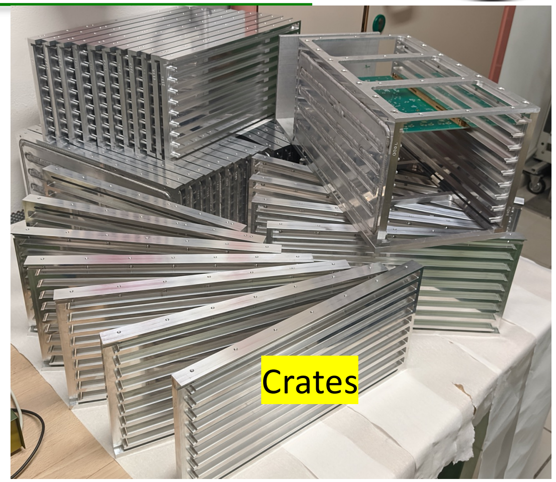


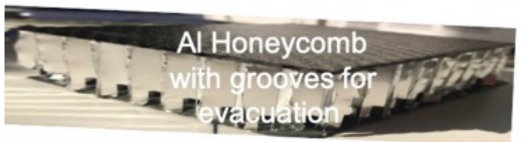
- T0-calibration done with iterative ”alignment” method (residual better than 10 ps)
- **Results of timing btw all pairs really excellent (< 300 ps)**

Production of mechanical parts

Front Panel in CF
with embedded source
Al tubing

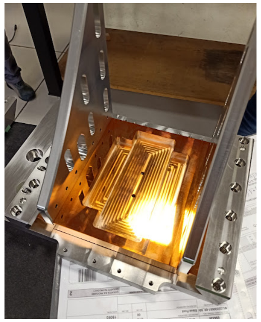


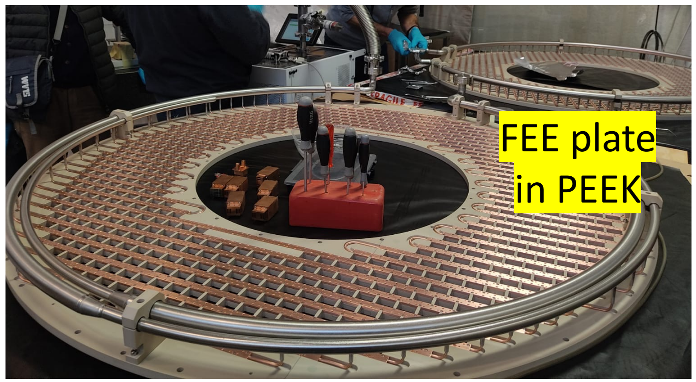




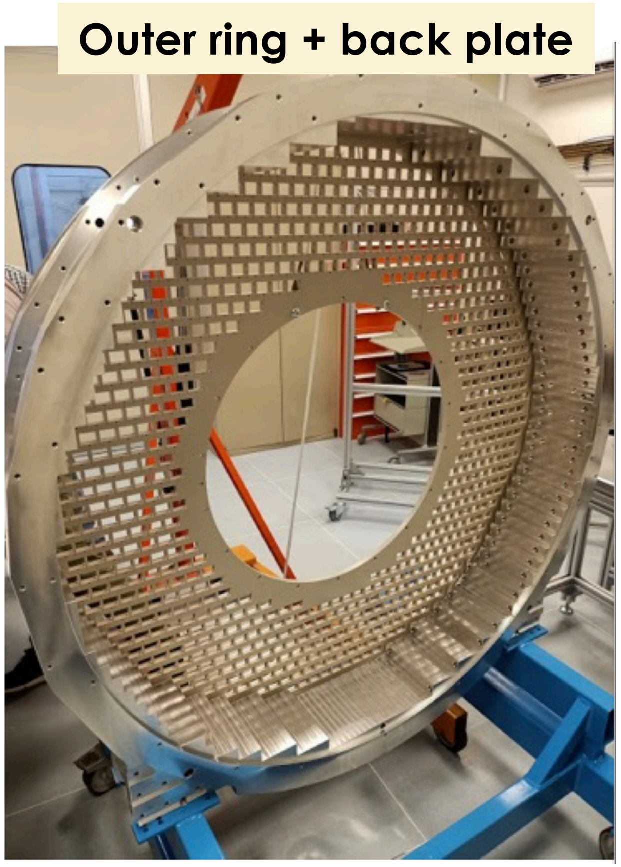
Front Plate: CF+Al Honeycomb+
Source Al Tubing

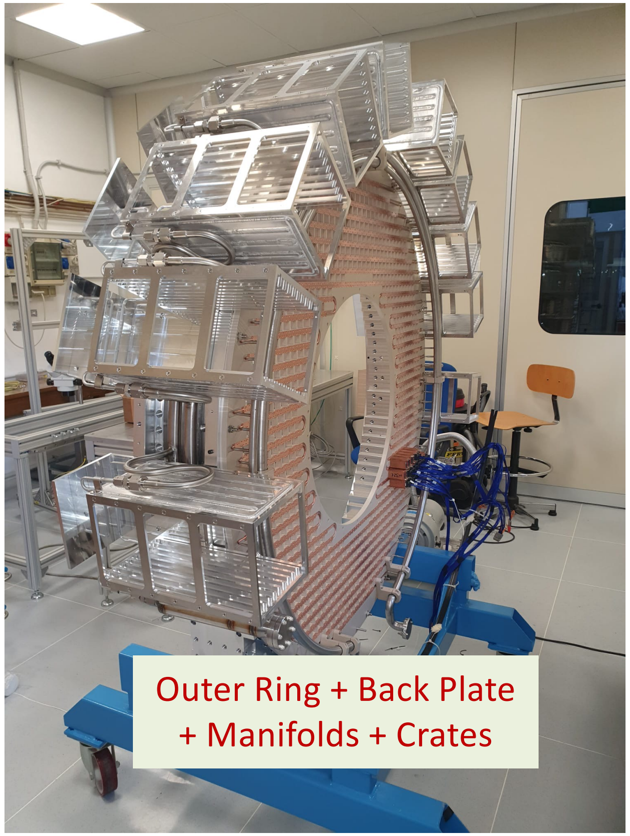
Calorimeter
Feet

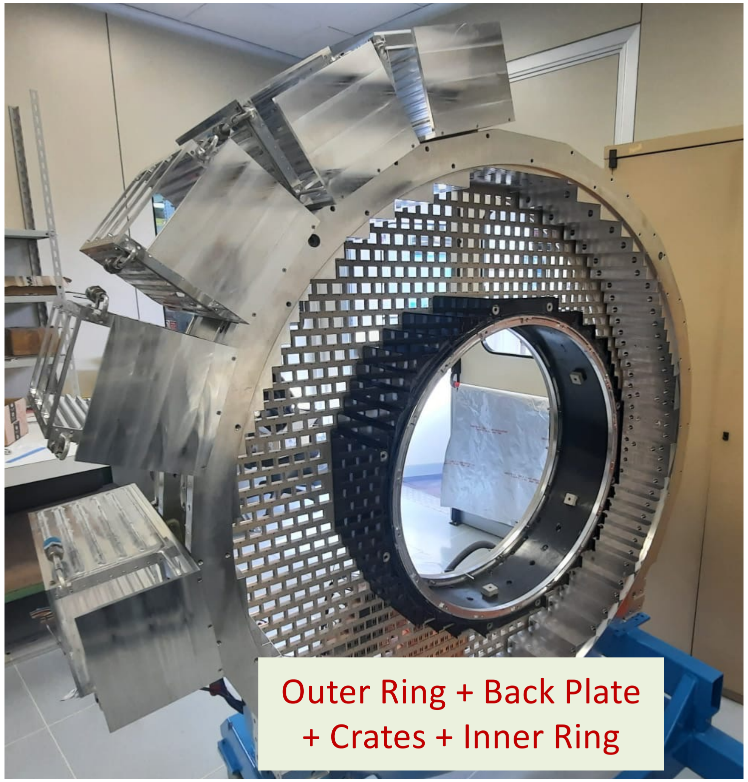




Dry fit run at INFN

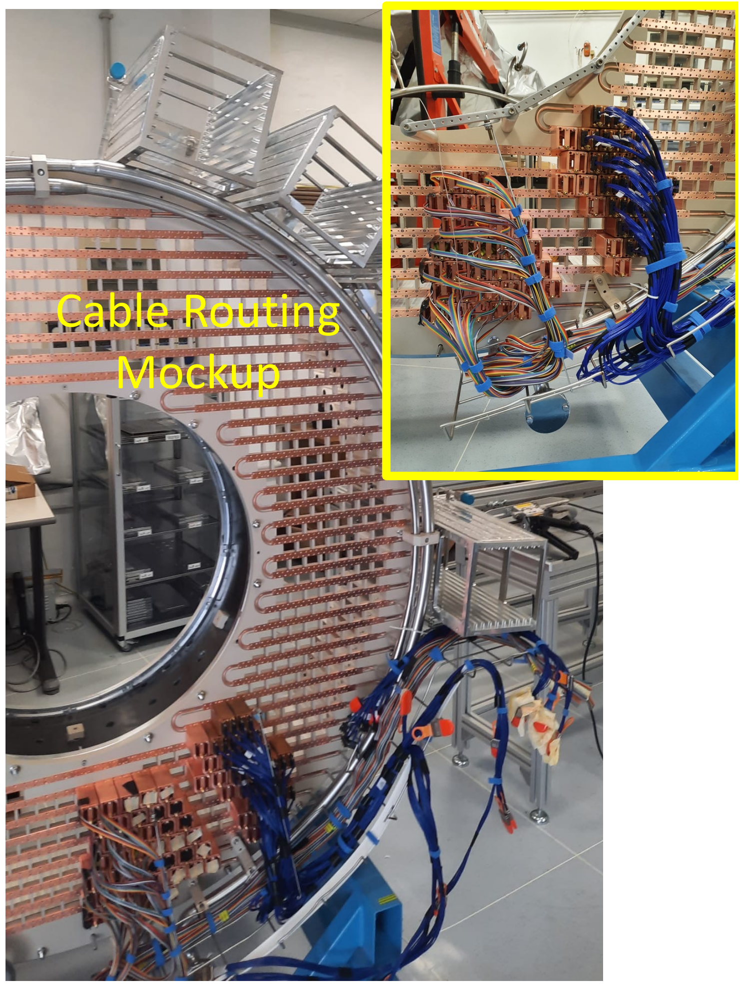


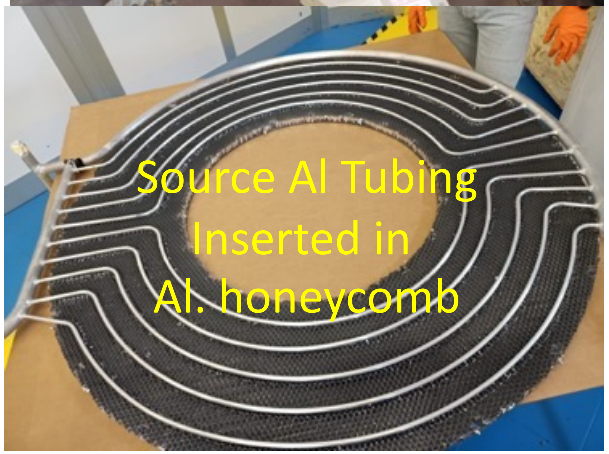




- ❑ Apart from the source tubing integration on the front plate **all calorimeter mechanical parts produced**
- ❑ In progress: routing test of FEE-MB cables from FEE plate to the crates
- ❑ Shipment to FNAL of all large mechanical parts in progress for the downstream disk

QC tests, mockup, assembly





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 presence of 1 T field, in vacuum and in a rad-hard environment:*

  → SiPMs work under neutron irradiation but need to be cooled down to -10 °C
  → Engineering of cooling and calorimeter mechanics is crucial

- **Production of crystals, SiPMs and FEE completed**

- **Production of mechanical parts well under way + dry FIT completed**

- **Successful VST carried out** with excellent results on timing and energy calibration
  → Production of Digital electronics underway or planned

- Shipments of material from INFN to FNAL is beginning

- **Assembly room at FNAL being completed**
  → We plan to begin crystal stacking this summer + to be ready to move in the Mu2e building in summer 2023