H2020-MSCA-RISE-2020 – Grant Agreement N° 101006726

Mu2e Status

Fabio Happacher – LNF-INFN

aMuse General Meeting

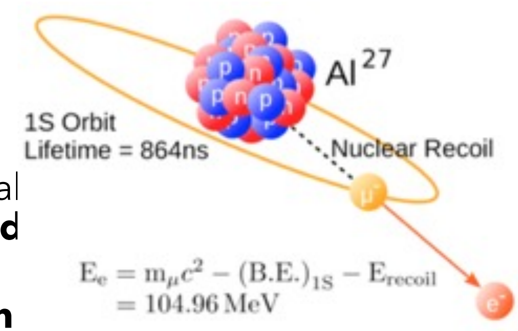
Padova 17-19 Sep, 2024

Outline

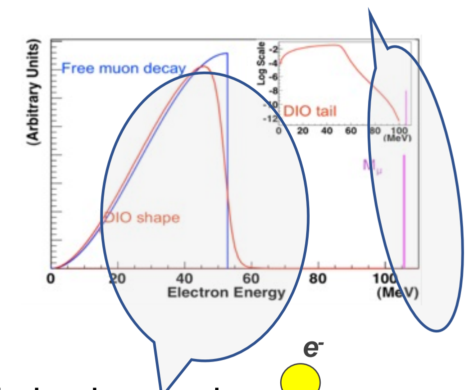
- Mu2e Experiment: a recap
- Experimental apparatus construction status
- Calorimeter requirements, technological choices and design
- Calorimeter performances
- Assembly status
- Moving and Commissioning
- Conclusions

Mu2e experiment concept

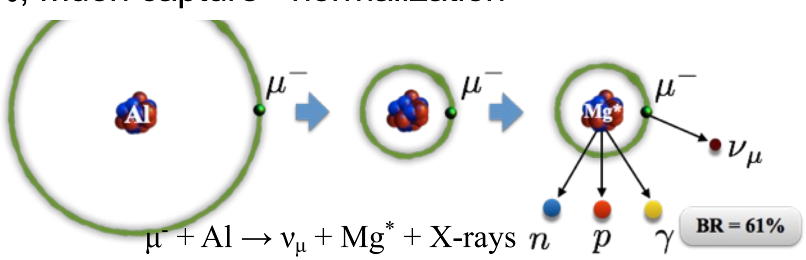
- **Mu2e will search for the CLFV conversion of the muon into an electron** after stopping it on **Al nucleus** **μ^-Al → e^-Al**
- Clear signature provided by the **mono-energetic conversion e^- with E ~ M_μ**
- The proton beam of the Fermilab accelerator complex and the Mu2e solenoidal system produce **a high intensity "pulsed" muon beam - 10 GHz of stopped μ**
- Goal is to reach a **single event sensitivity of ~8.4 x10^{-17} i.e. 10^4 better than Sindrum II** → This requires 10^{20} protons on target, 10^{18} stopped muons
- Mu2e will detect and count the conversion electrons with respect to the standard muon capture on the nucleus.
- **Main background is SM μ^- decay in orbit (DIO) – softer p_T spectrum**



$$R_{\mu e} = \frac{\Gamma\left(\mu^- + N(A,Z) \to e^- + N(A,Z)\right)}{\Gamma\left(\mu^- + N(A,Z) \to all\ muon\ captures\right)}$$

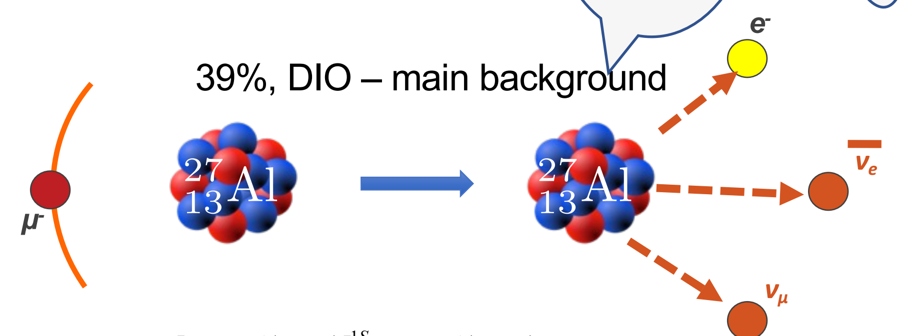


61%, Muon capture - normalization



- 347 keV X-ray emitted – **candidate for normalization**

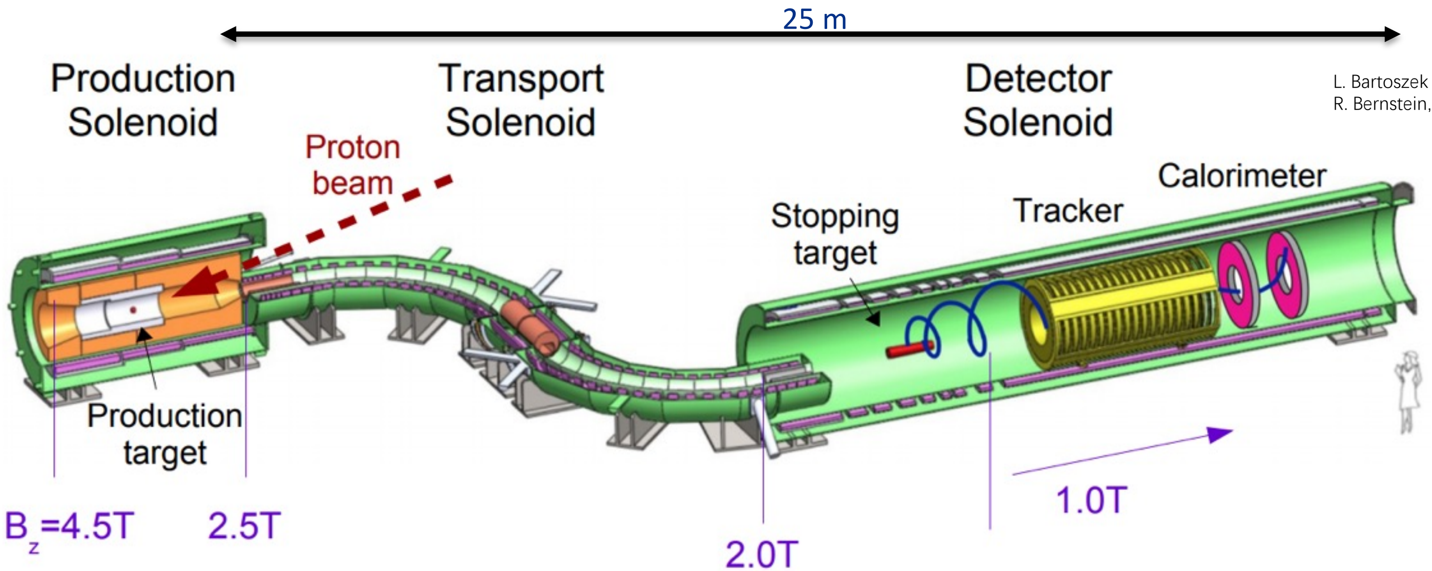
39%, DIO – main background



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

Mu2e experiment layout

- **Production solenoid (PS)**
  – Contains tungsten production target
  – Gradient magnetic field sweeps pions/muons to transport solenoid
- **Transport solenoid (TS)**
  – S-shaped; collimator in the middle selects sign and momentum
  – Absorbers to remove antiprotons at center of S
- **Detector solenoid (DS)**
  – Al muon stopping target
  – Proton absorber to reduce accidental events
  – Straw tube tracker provides momentum measurement, electromagnetic calorimeter differentiates particles through energy deposition
- Searching for 105 MeV electrons, with a 180 keV/c momentum resolution

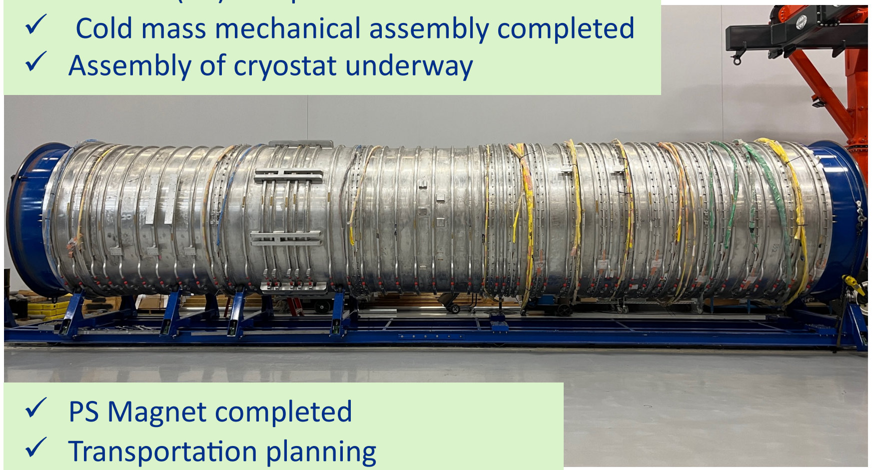


L. Bartoszek et al., arXic:1501.05241;
R. Bernstein, Front. Phyis. 7, 1 (2019)

A schematic view of the Mu2e experiment (not including the Cosmic Ray Veto)

Solenoids status

- ✓ DS coils (11) completed
- ✓ Cold mass mechanical assembly completed
- ✓ Assembly of cryostat underway

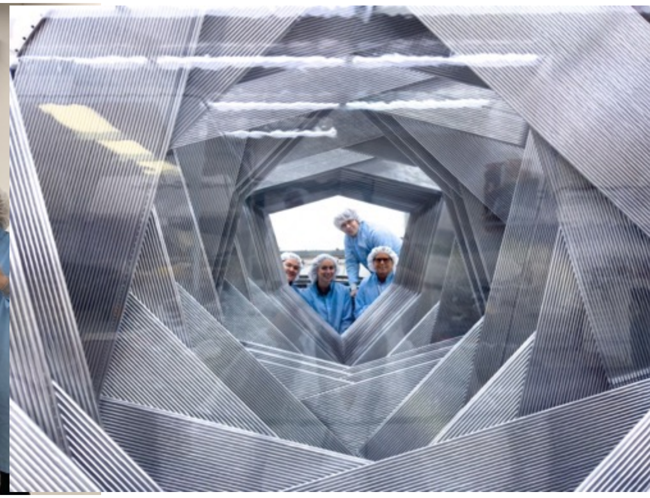


- ✓ PS Magnet completed
- ✓ Transportation planning
- ✓ Delivery is foreseen in September

Transport solenoids delivered: 12/23 (TSU) 2/24 (TSD) & installed in Mu2e hall

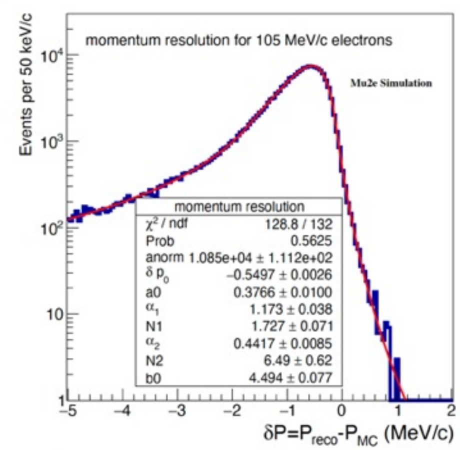
- DS delivery slippage still drives the project schedule. Delivery is foreseen for beginning of 2025

Detectors: tracker



- Very high precision detector (~ 180 keV for CE) with 20 k mylar straws 5 mm ϕ, 15 um thick
- Organized in 18 station. Each station 2 planes, each plane 6 panels

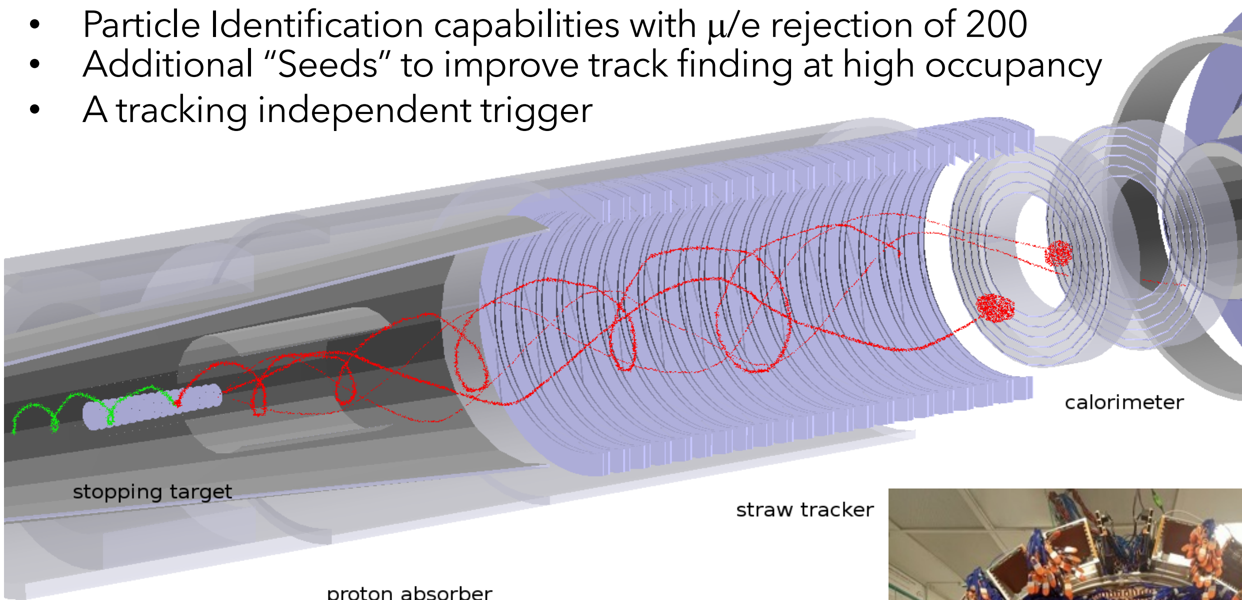
✓ 100 % of panels (216) completed.
✓ Planes preparation almost done (33/36)
✓ All electronics delivered. Installation of electronics in progress
✓ Assembly of stations in progress
✓ Advanced status for services and infrastructure
→ Expect to land in Detector Hall in extracted position – Spring 2025



Calorimeter scope and 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 μ/e rejection of 200
- Additional "Seeds" to improve track finding at high occupancy
- A tracking independent trigger



For 100 MeV electrons @ 50 degrees impact angle

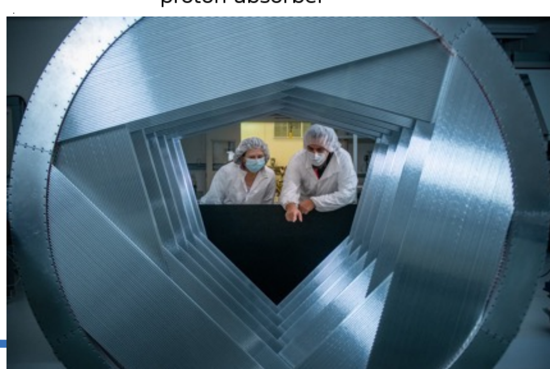
→ Provide energy resolution σ_E/E of O(< 10 %)

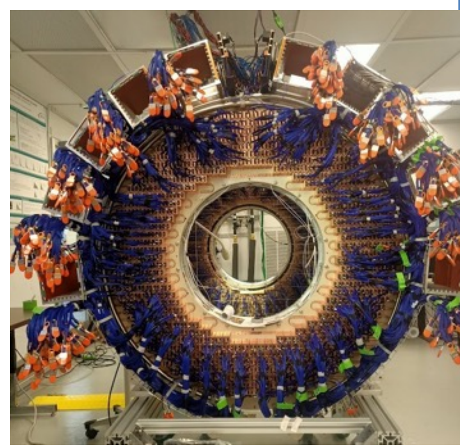
→ Provide timing resolution σ(t) < 500 ps

→ Provide position resolution < 1 cm

→ Work in vacuum @ 10-4 Torr and 1 T B-Field

→ stand harsh radiation





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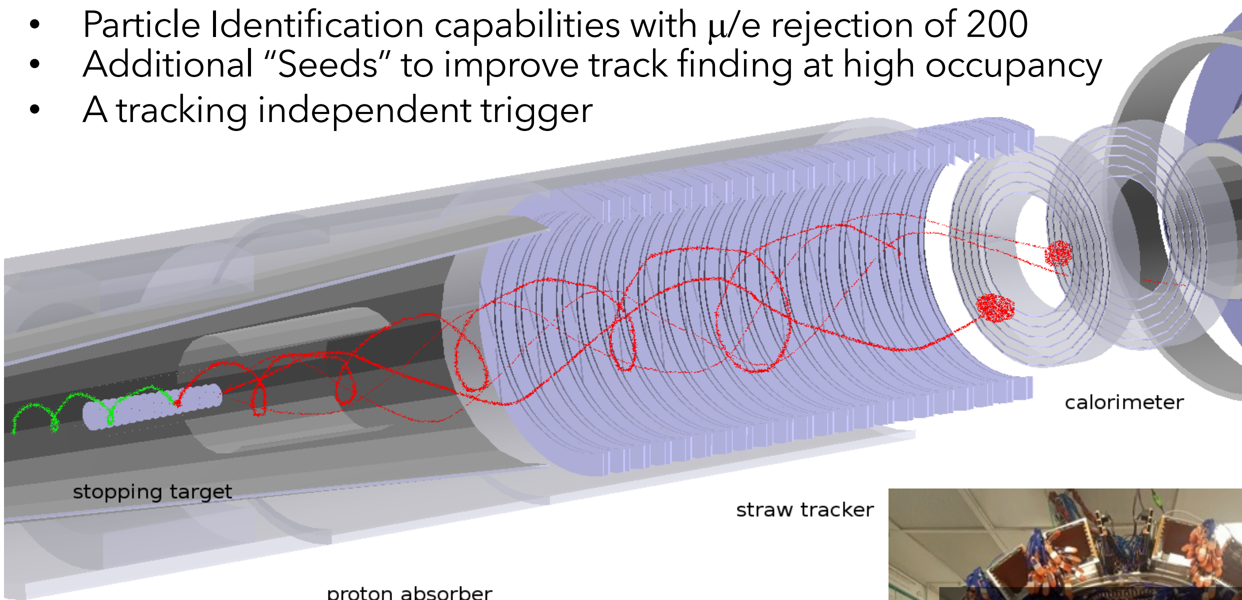

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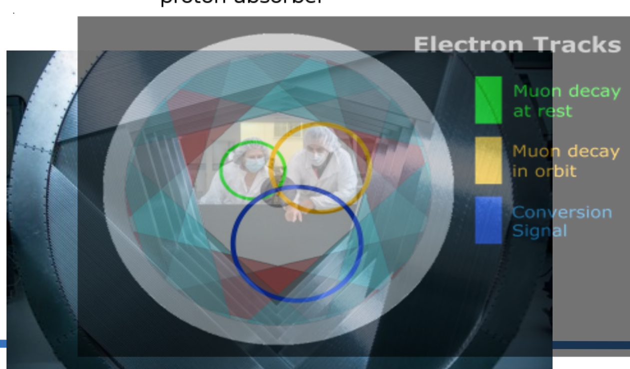
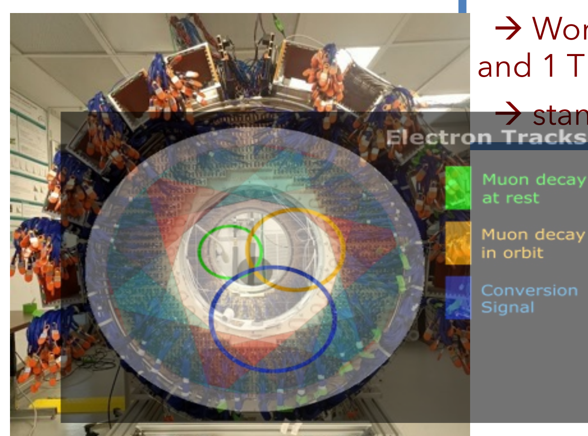
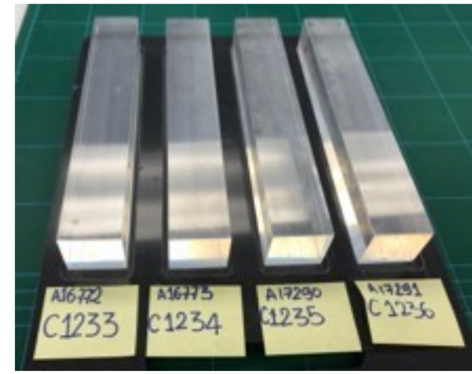




Technological choice

- Crystals with high Light Yield for timing/energy resolution
  - **LY(photosensors) > 20 pe/MeV**
- Fast signal for Pileup and Timing:
  - **τ of emission < 40 ns**
  - Fast readout chain
- Redundancy in the readout chain
  - **Two fully independent readout channels per crystal**
- 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**
- **1 T magnetic field** operation



Undoped CsI + **UV-extended SiPMs** + **Fast electronics**

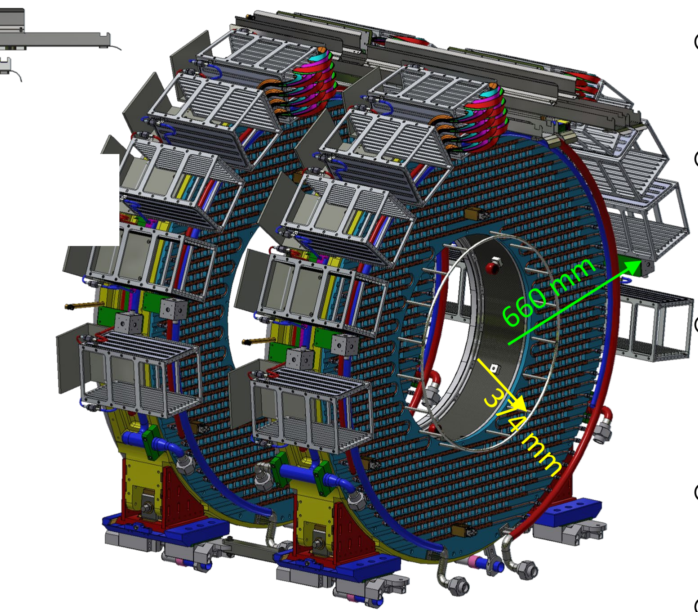
Undoped CsI:
- Radiation hard
- Fast emission time
- 310 nm emission

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

Fast electronics:
- FEE: amplifier + shaper
- Digitizer @ 200 Msps
- Rad-hard components

To reduce/handle the neutron induced leakage current SiPMs should be cooled down (factor of 3 ↘ every 10 °C 30mA ->3mA, 25–>5 °C) **SiPM running temperature at –10 ° C**

The Electromagnetic Calorimeter



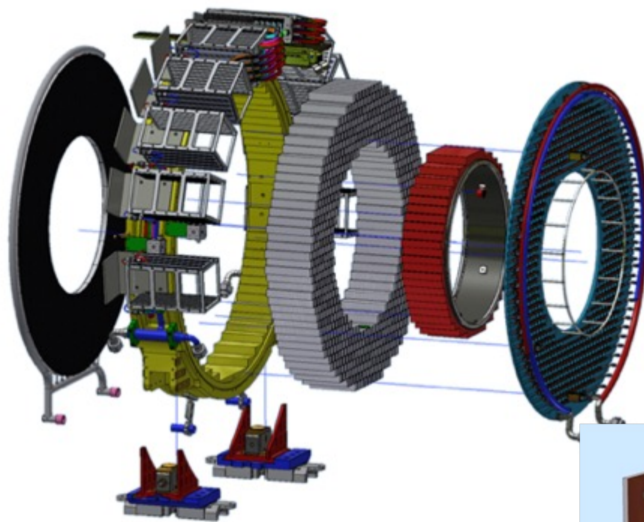
EMC design:

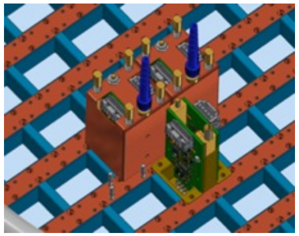
- Two annular disks, R_{in}=374 mm, R_{out}=660 mm, $10X_0$ length, ~ 70 cm separation
- 674+674 square x-sec **pure CsI crystals**, (34×34×200) mm^3, Tyvek + Tedlar wrapping
- Redundant readout: For each crystal, two custom arrays (2×3 of 6×6 mm^2 ,50 μm pixel) **large area UV-extended SiPMs**
- SiPM thermally controlled down to -10℃ to reduce radiation induced leakage current (factor of ~ *3* every 10 °C : 30mA → 3mA, 25 → -5 °C)
- Analog FEE directly mounted on SiPM + digital electronics in on-board custom built crates
- Calibration/Monitoring with 6 MeV radioactive source and a laser system
- Cooling system – power dissipation + Sipm Temperature setting

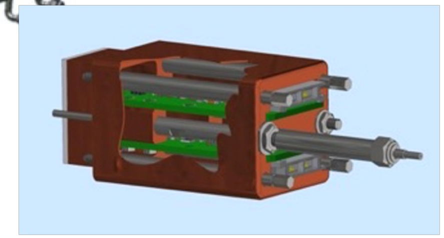
Engineering of the Calorimeter

- Outer monolithic stepped Al supporting cylinder with integrated cradle and stands
- X-Y adj feet
- Inner carbon fiber stepped cylinder
- PEEK back plate, housing Read Out Unit
  - Embedded copper cooling lines
- Read Out Units, ROU's, composed of
  - Copper holders
  - Glued SiPm
  - FEE cards
  - Faraday cages
  - Fibers needle
- Carbon fiber front plate integrating the source calibration pipes
- Array of 674 Tyvek wrapped crystals
- 10 Read out/service electronics crates (6-8 boards each)
- Cabling and pipes

Exploded view of the components



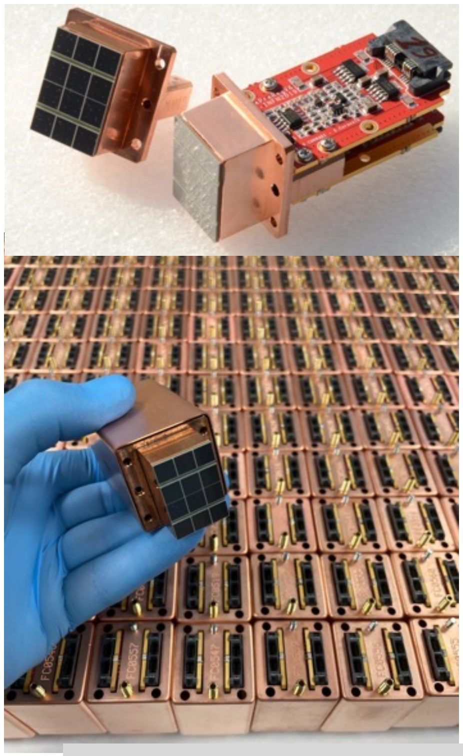


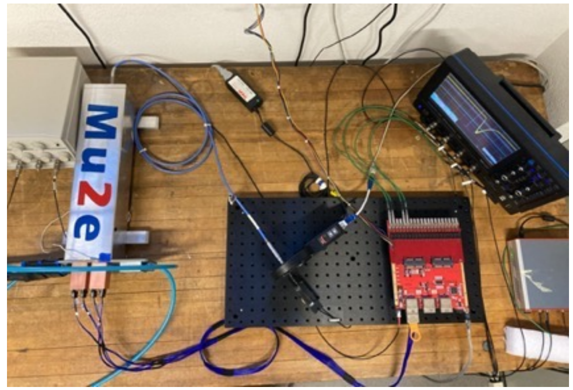


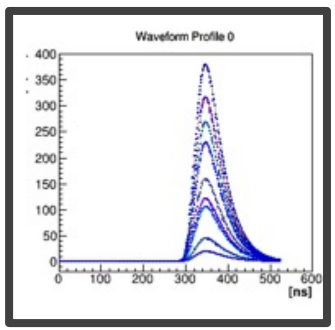
Mu2e Calo Activities

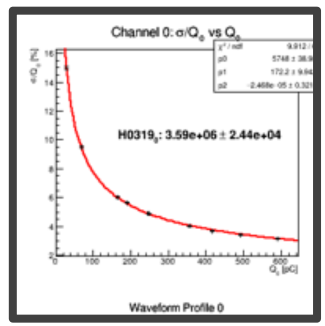
- We have assembled both Disks with crystals, plates and ROU
- crates assembled
- Cooling pipes connected and checked
- FEE cabling completed
- MB production completed
- Dirac boards production under way, first boards at FNAL and being tested
- Assembled Laser fibers distributors on Disk 1
- Fiber cabling under way
- Outgassing/washing Electronics copper Cooling plates to be assembled on MB+Dirac
- HV/LV cabling at Mu2e building done
- Channel debugging
- Started Review for Calo lifting and transportation

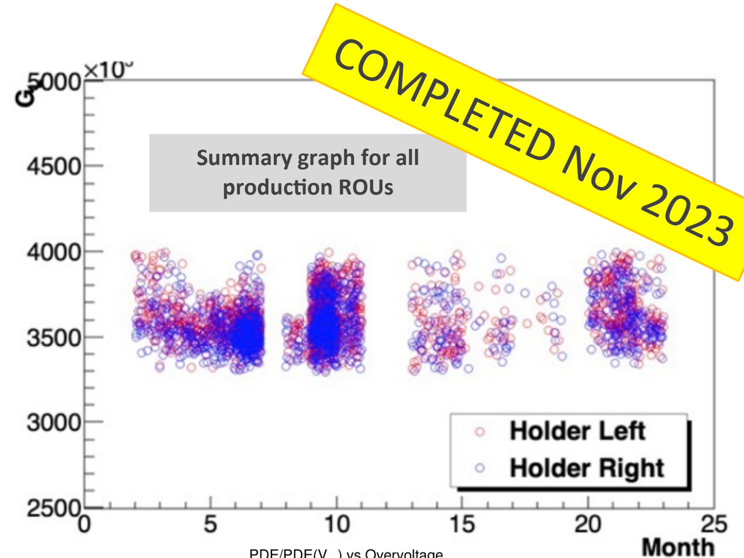
Technical progress: ROU = photosensors and FEE

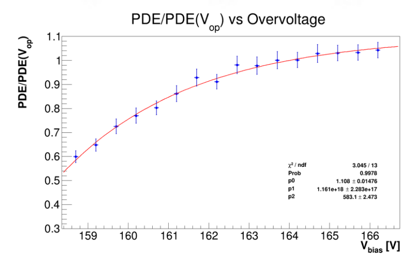










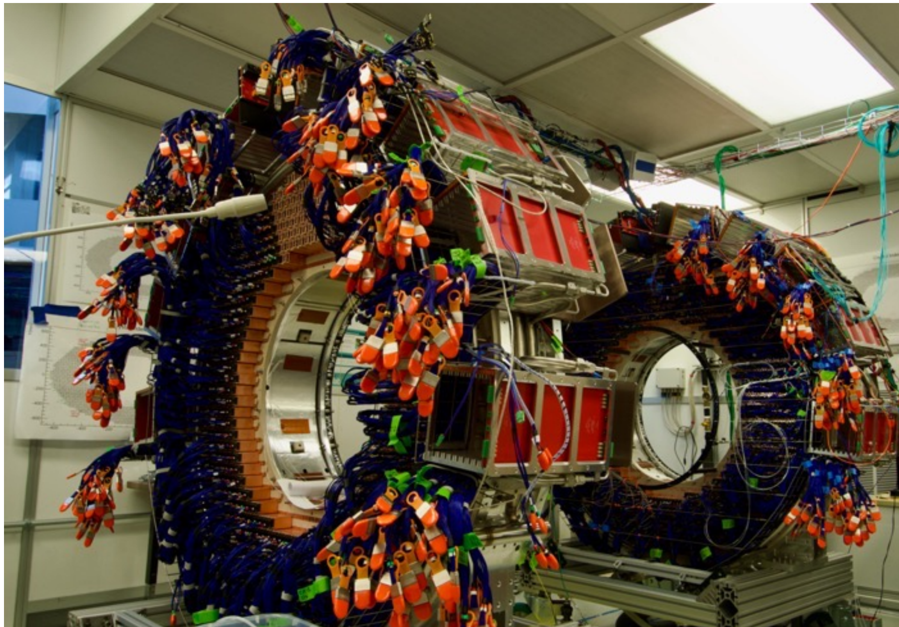
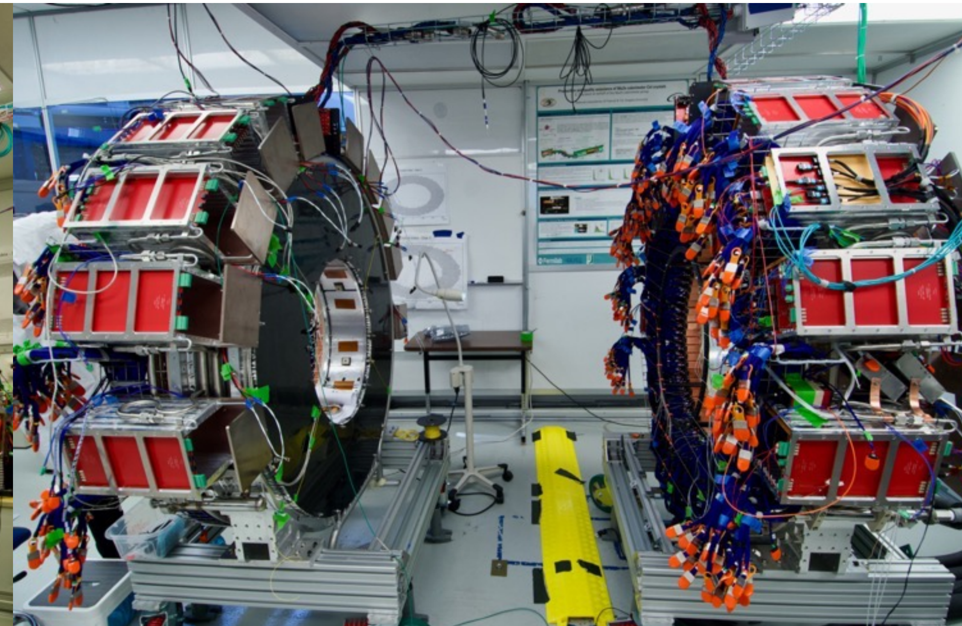
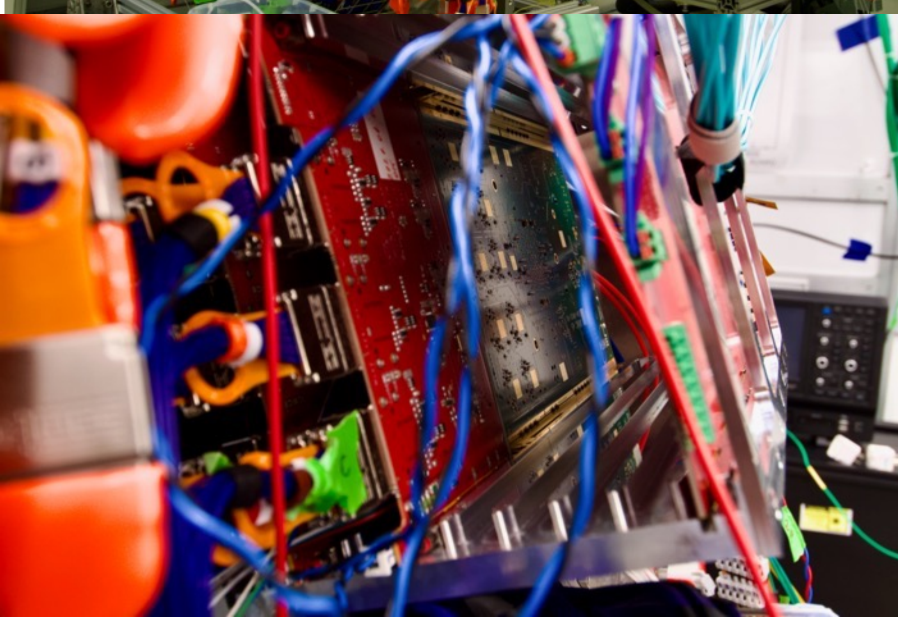


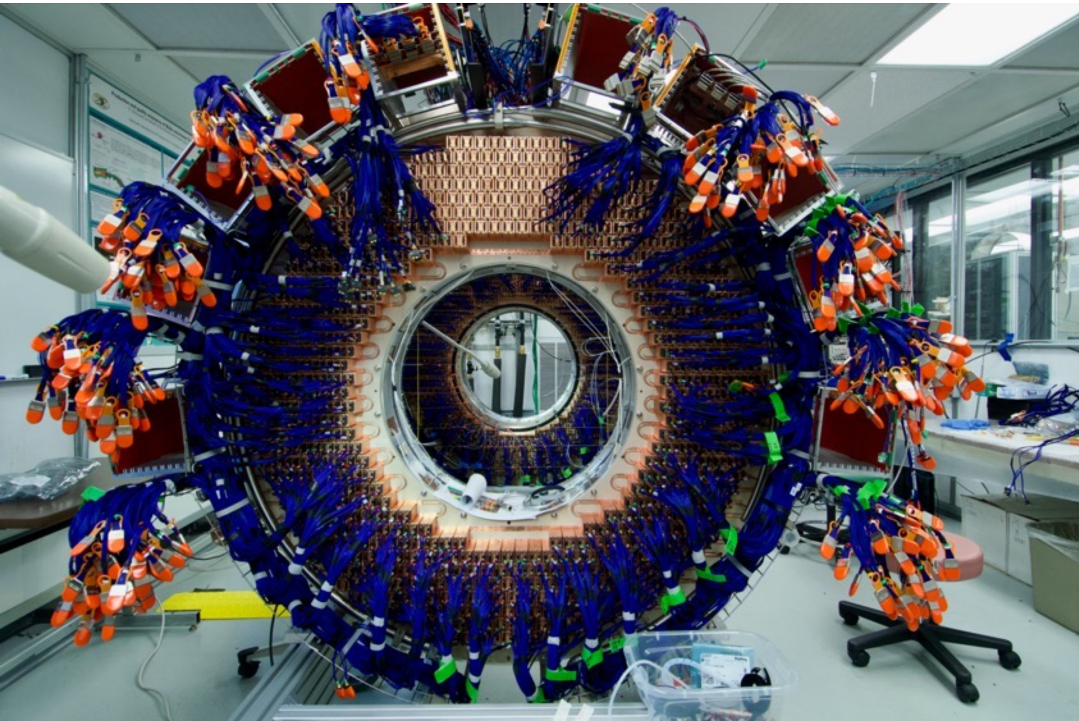
- 4000 SiPMs produced in 2019 ➔ 3000 shipped 2020/2021 to INFN and glued to Copper holders (mitigation of Covid)
- 3300 rad-hard FEE produced (2021/2022) : **800 lost due to Ukraine Russia war ➔ realized anew during 2023**
- 1500 Readout Units assembled (2022-2024) ➔ All QC tested. 20 failing QC, 1348 assembled – 130 spares

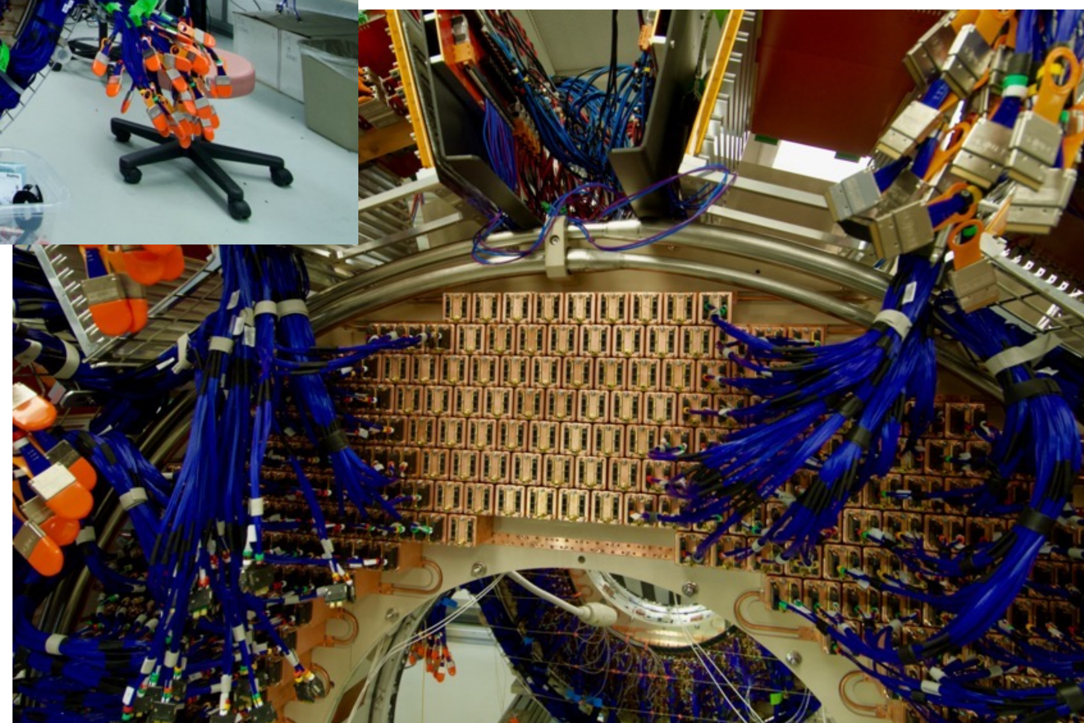
Calorimeter's heart beating

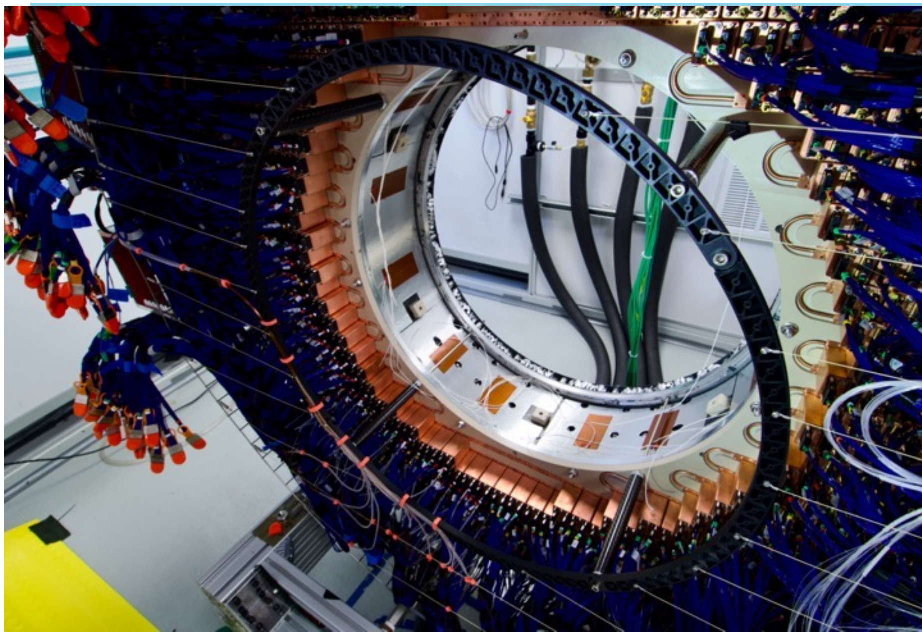
Mu2e

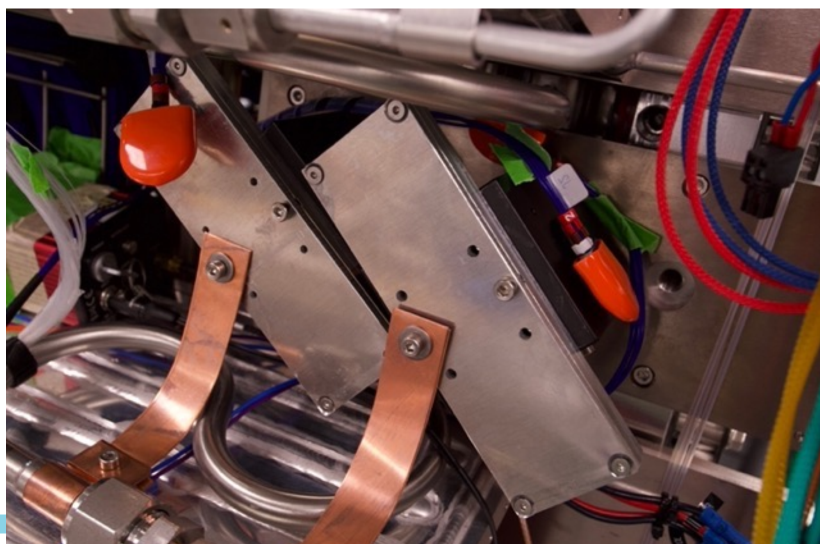
Calorimeter as of few days ago

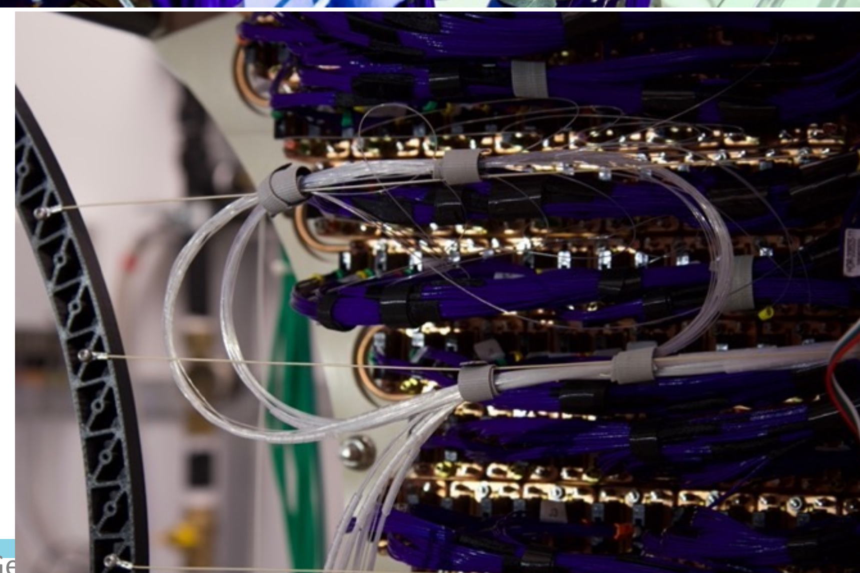




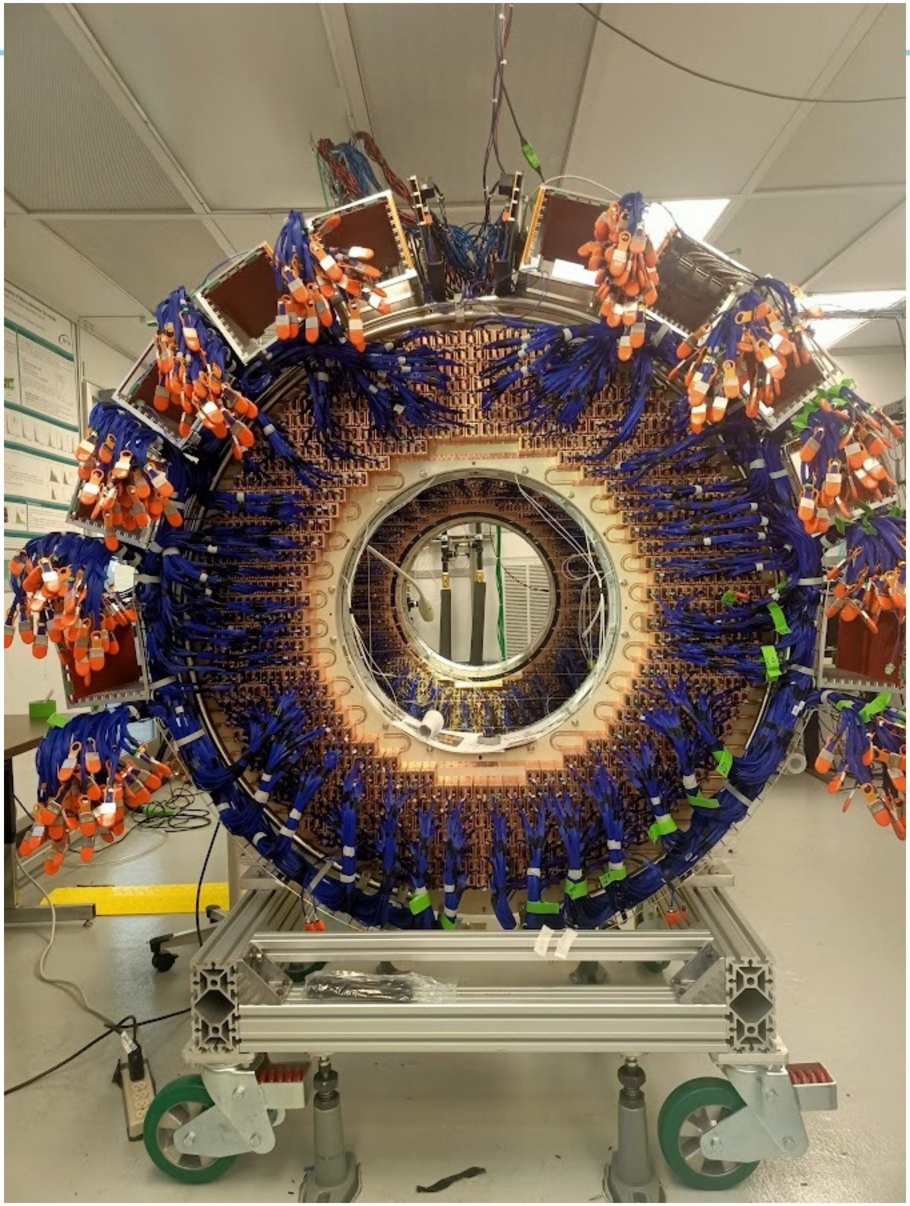








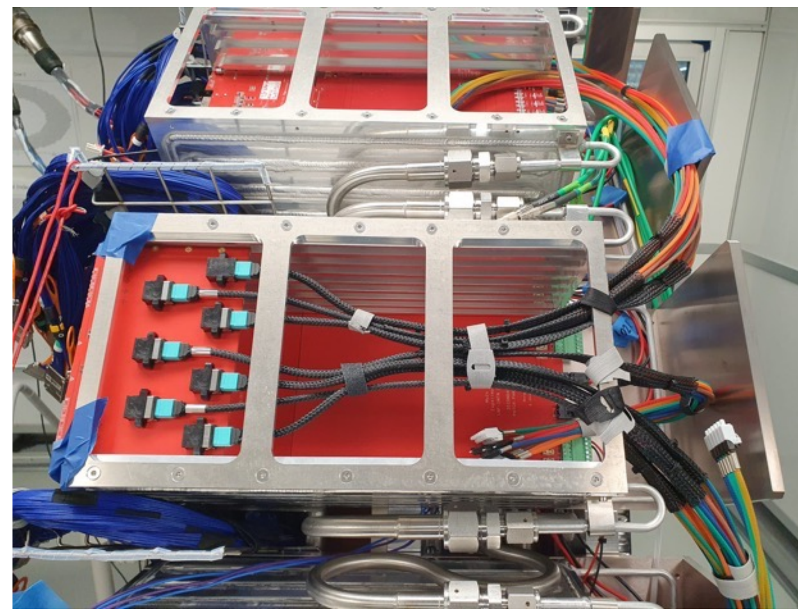
Calorimeter as of today



Calorimeter assembly status - details

- Disk-1, Disk-0 fully cabled + Service cables OK for both disks.
  completed FEE/MZB cabling last week.

- Currently – 90 MZB + 70 DIRAC at SIDET + 40+40 copper plates (1 DISK 68 boards)
- Integrated and outgassed: 40 MZB + 40 DIRAC →
  Diracs were outgassed but with a broken manometer.
  To be fixed.
- Next round of shipments:
  - 50+50 copper plates at SIDET last week
  - 80 MZB middle of September
  - 70 DIRAC middle/end of October
- Laser fibers – 8 bundles outgassed, support mounted
  1/8 mounted.
  →Modification of Laser PIN diode FEE in progress.
- Disk1 test. All channels tested with scope.
  Few cables, few ROU's fixed.
  Same test done on Disk-0
- TDAQ fiber breakout. **Approved.**
  → Adding cable tag on TX/RX
- TRAD cables and sensors .. Approved and delivered.



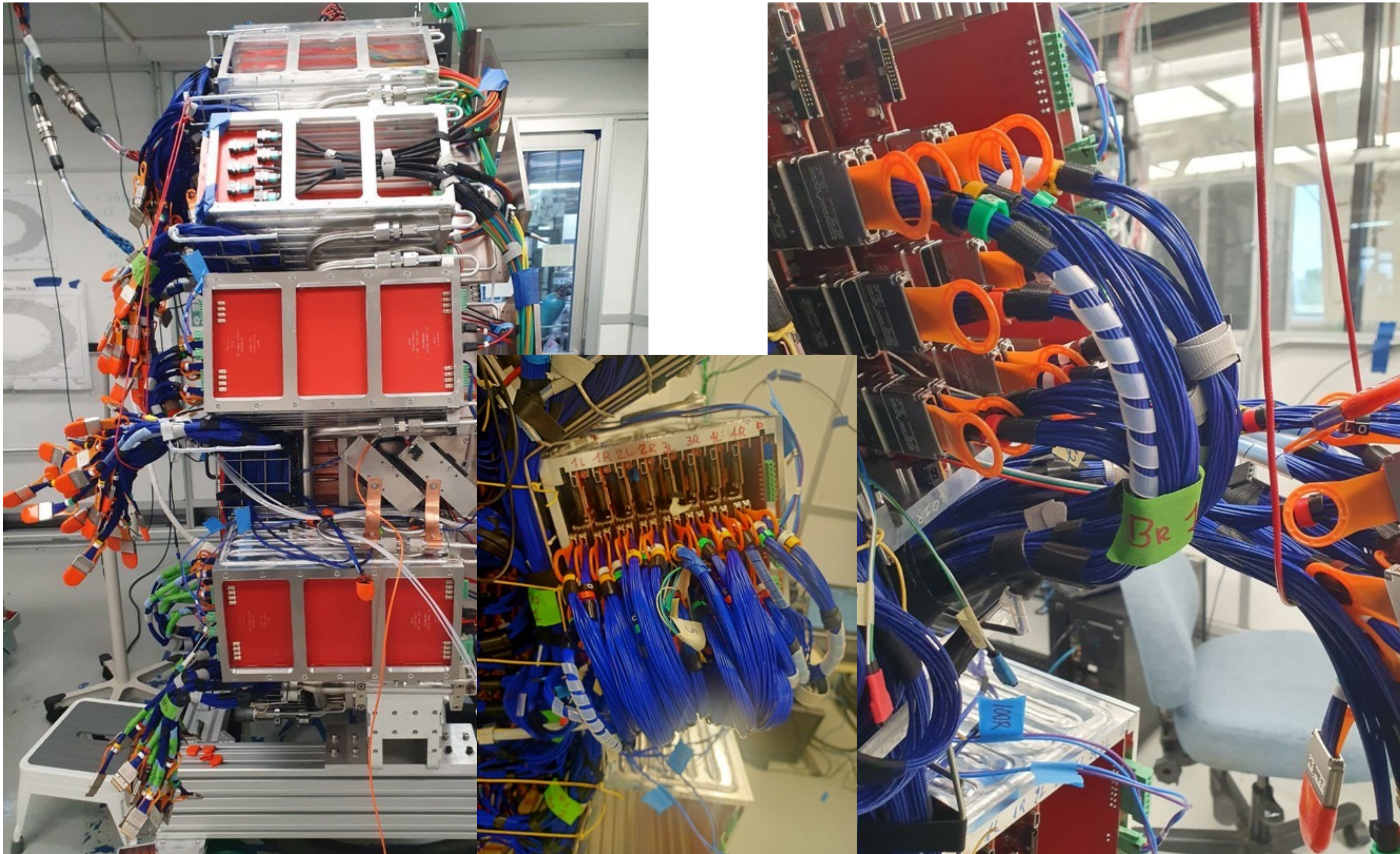
Calorimeter assembly Status: Procurements of parts

- ✓ **MZB production completed.**
  90 at FNAL, 80 at LNF. Shipping will be completed in the middle of September
- ✓ **DIRAC production ½**
  70 at FNAL, 70 boards production in progress

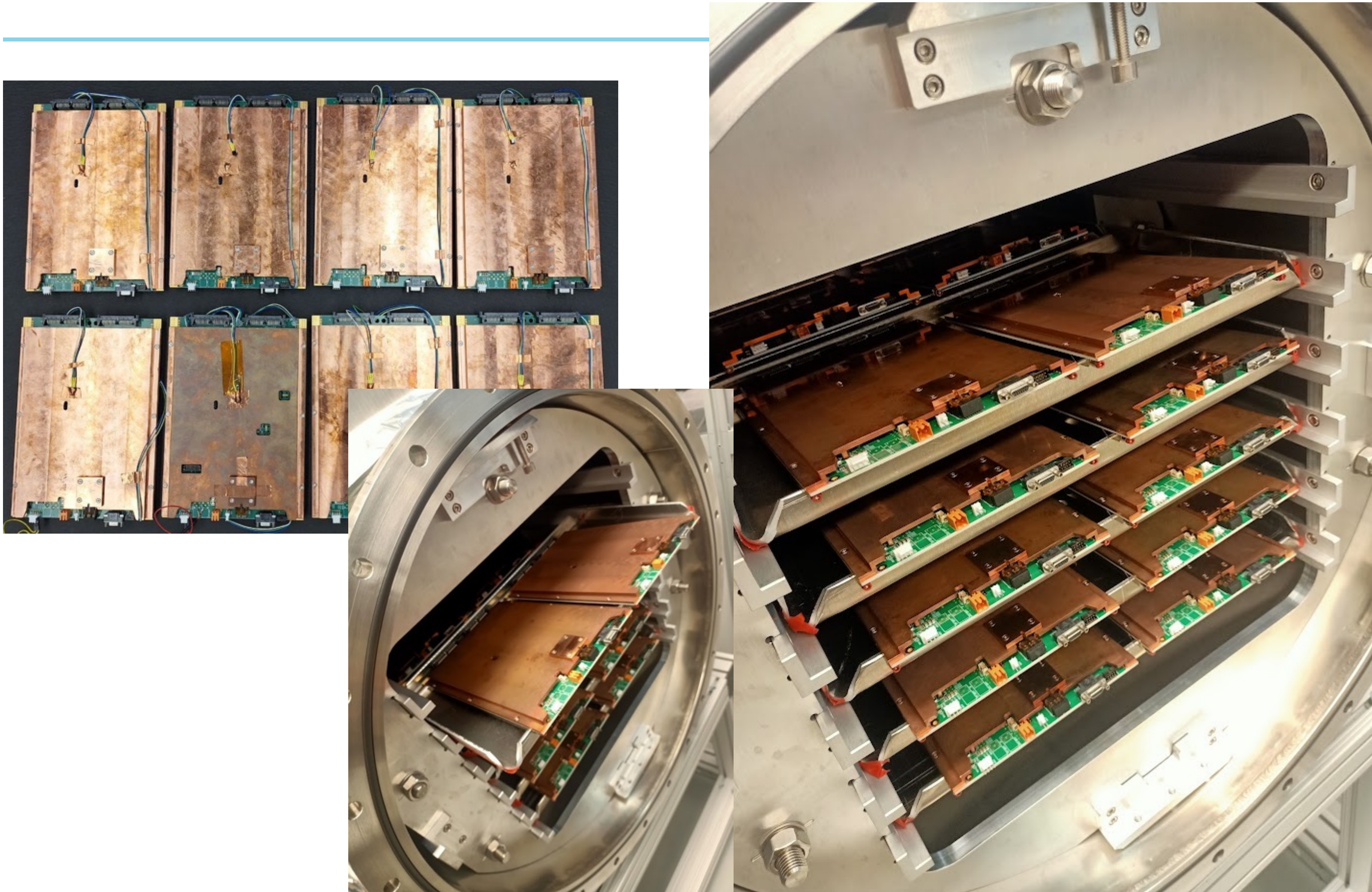
- ✓ **TRAD production 4+4 boards → in progress**
  TRAD sensors → produced
  TRAD cables → produced
- **Upcoming procurements:**
  → Flanges (rear/radial)+ Flexible tubes.
  Discussions with George and the integration team are ongoing
  → still working on modifications of the Measurement Vessel at SIDET

- Procurement for TDAQ breakout started
- 40 cardloc missing from our pool
- Vacuum grease Apizon-h to complete boards integration

first boards insertion and connection



DIRAC Outgassing

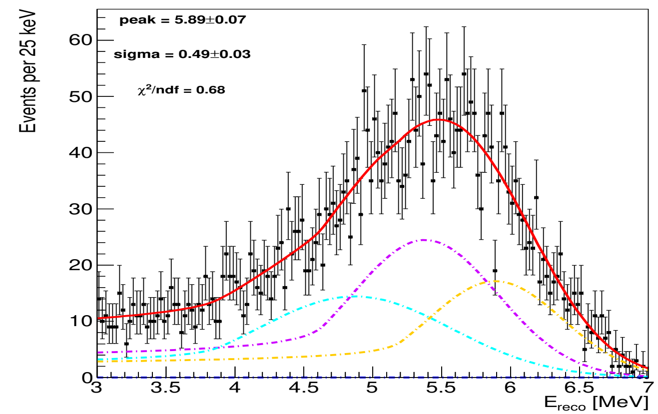


Source calibration system

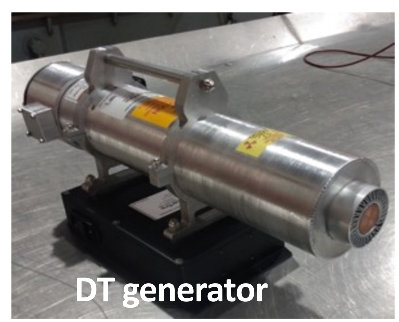
- Neutrons from a DT generator irradiate a fluorine rich fluid (Fluorinert) that is piped to the front face of the disks
- The following reaction chain produces photons at 6.13 MeV

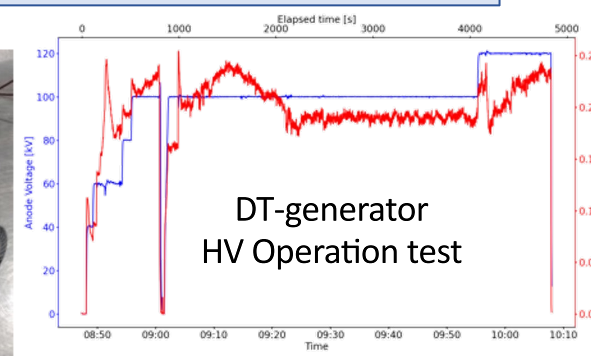
$$^{19}F + n \rightarrow \; ^{16}N \; + \alpha$$
$$^{16}N \; \rightarrow \; ^{16}O^{*} + \beta \quad t_{1/2} = 7\ s$$
$$^{16}O^{*} \rightarrow \, ^{16}O + \gamma(6.13\ \mathrm{MeV})$$

- The gammas illuminate uniformly the crystals
- Few minutes of data taking calibrate each crystal at O(%)



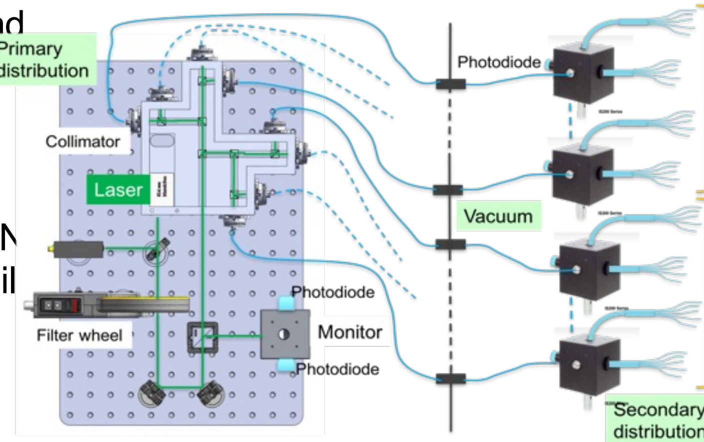
- Source DT generator installed in Mu2e hall in its ”cave“ in 2022, final shielding completed in 2023
- DT-generator HV operated up to 120 kV. ESH radiation survey performed in 2023 /2024 well within limits

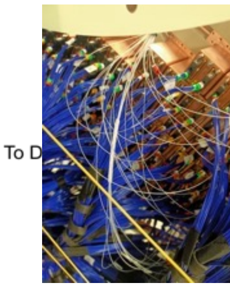


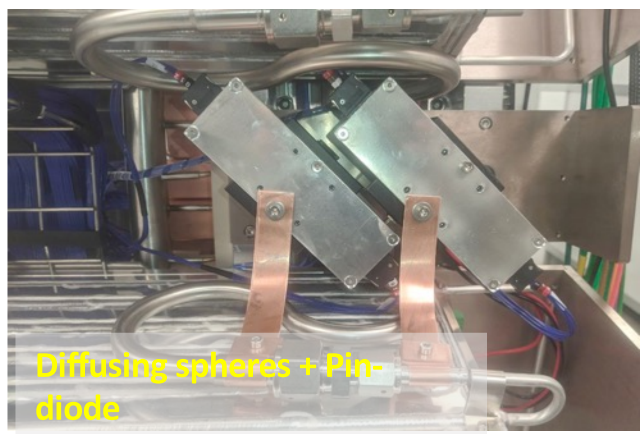


Laser calibration system

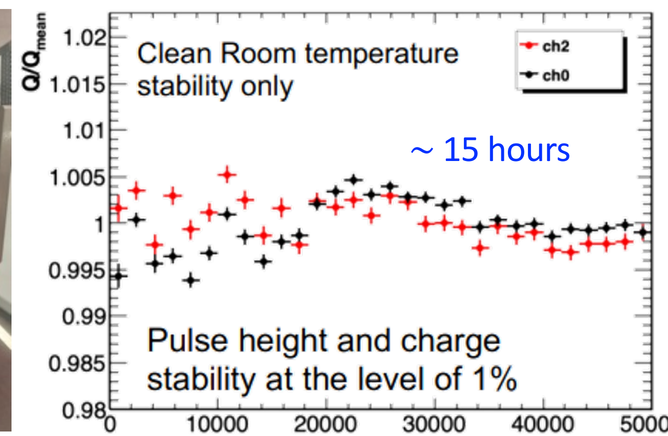
- A pulsed green laser illuminates all crystals through a distribution system based on optical fibers and integrating spheres
- Monitor gain variation at level of 0.5%
- Determine T0's at level of 100 ps
- Stability at a level of few %, monitored with PIN Diodes at laser source. Used at low rate in off-spill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





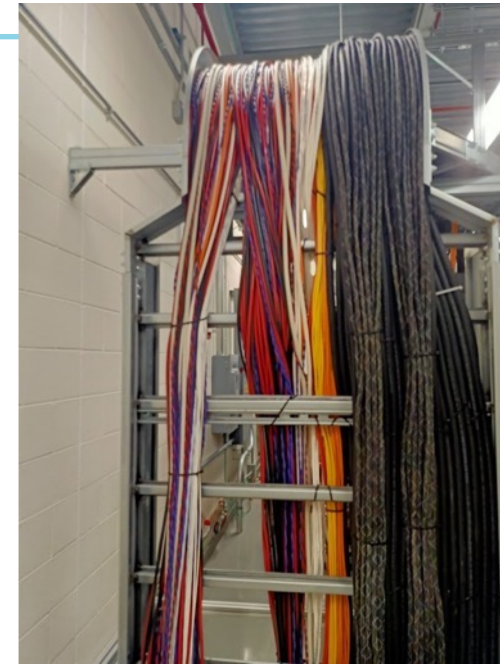
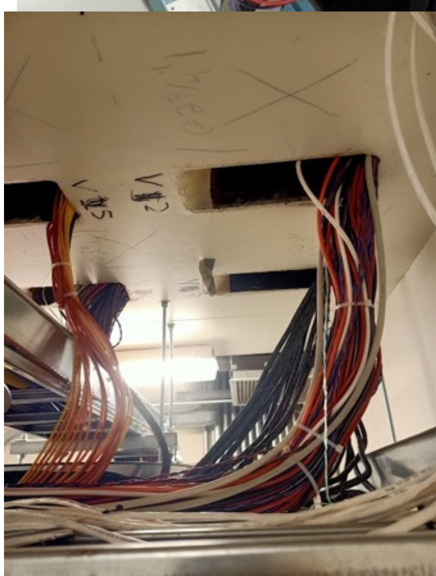
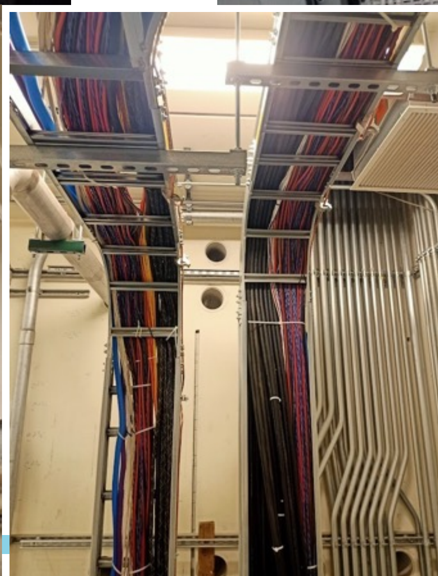
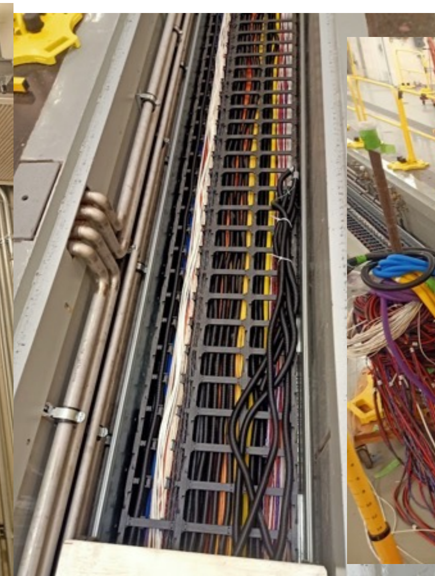


Diffusing spheres + Pin-diode
Readout on calo disks



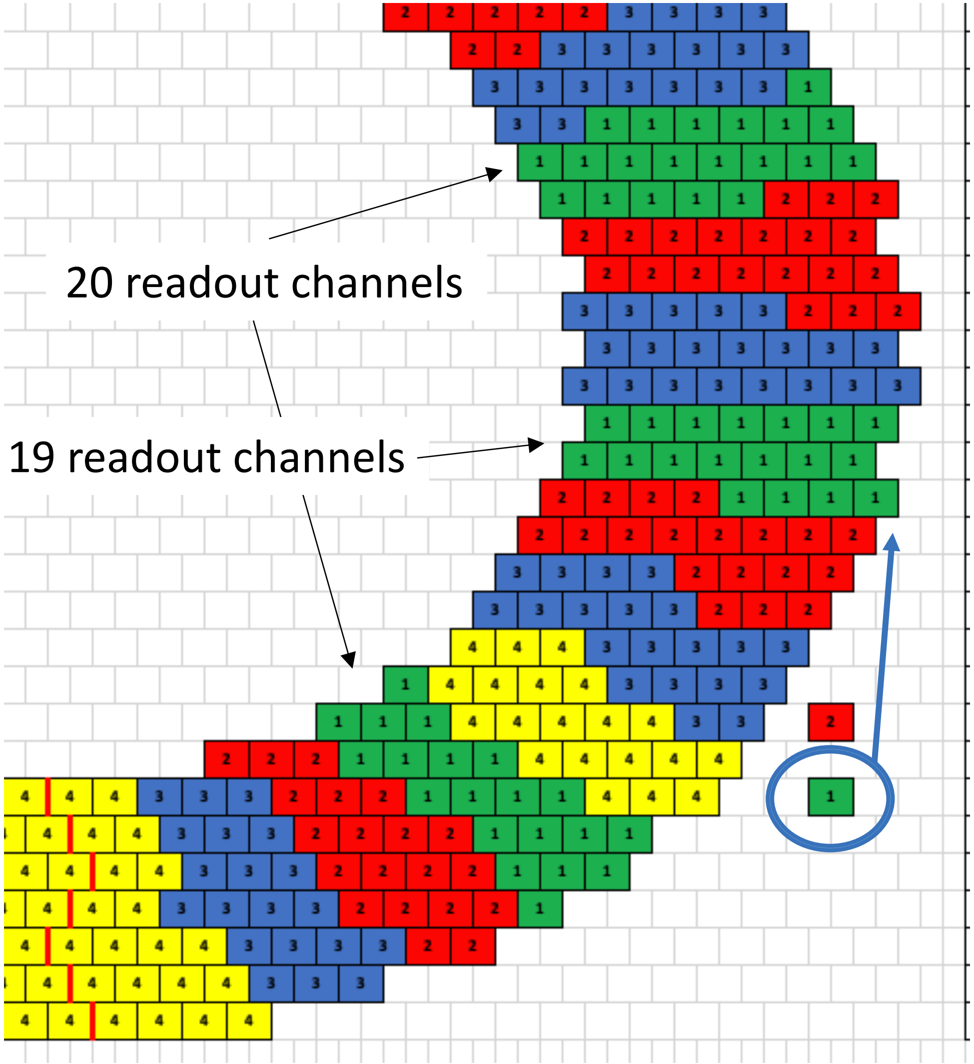
Service HV/LV cables installation



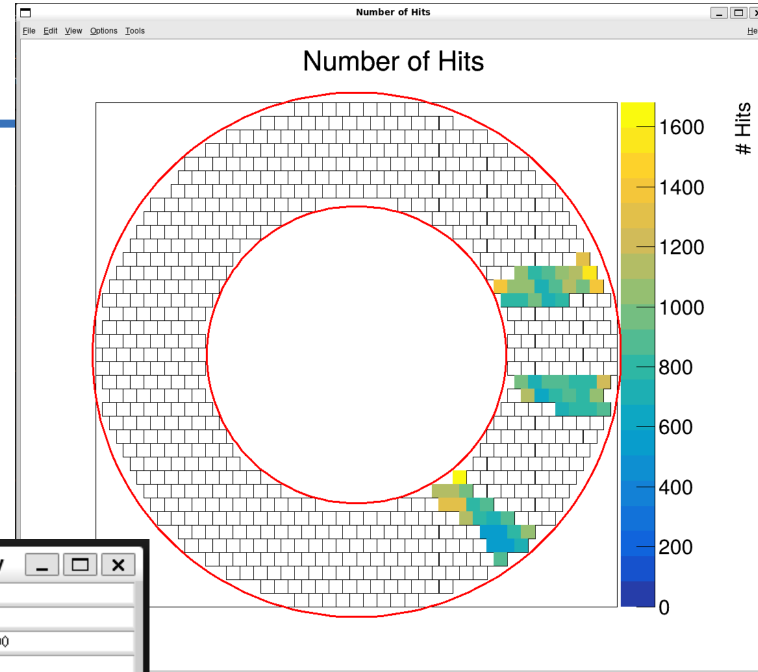

First calorimeter VST @ SiDet

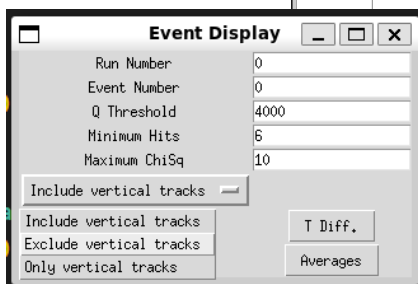
- First data from six boards:
  - Disk 1, phi=1
  - Board 1 of Crates 0/1/2
  - Both SiPMs
- Few hours of running
- Nominal V_{op} setting loaded through configuration files
- Most of the data acquired with average FEE calibration
- Three V_{bias} configurations
- Cosmics, laser and noise runs

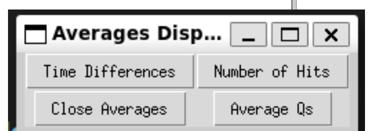


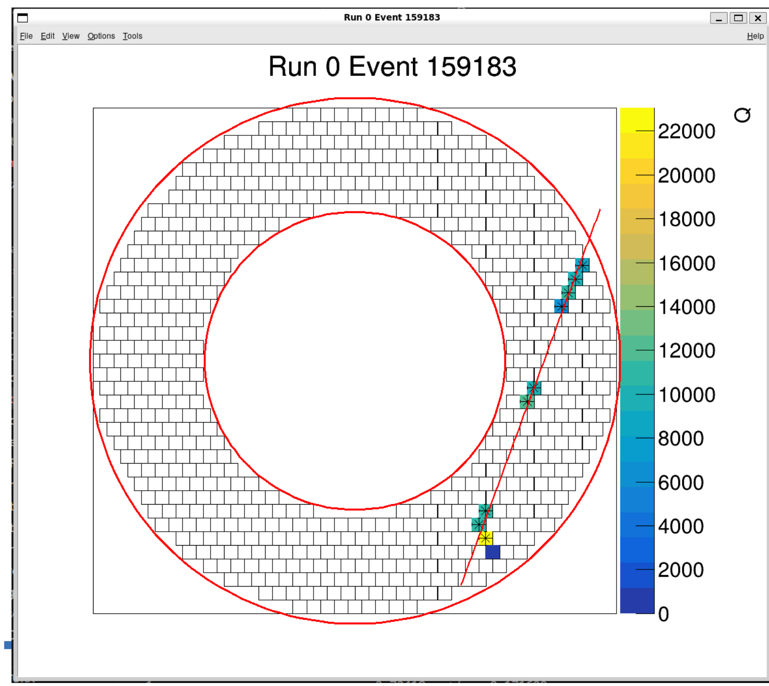
New event display

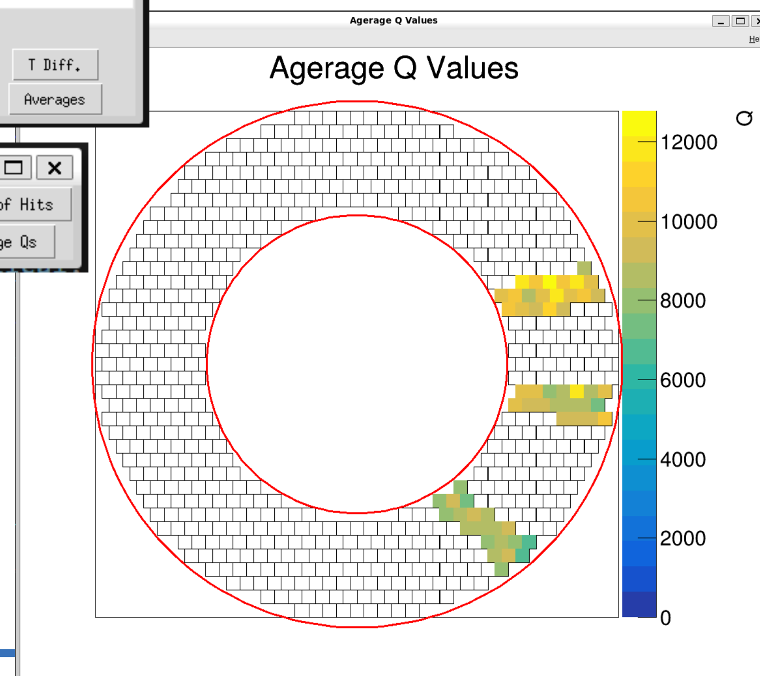
- PyROOT script working on reconstructed ntuples starting from SDF code
- Fitting hits above a threshold with a linear function
- Menus to select events, their topology and to display different quantities





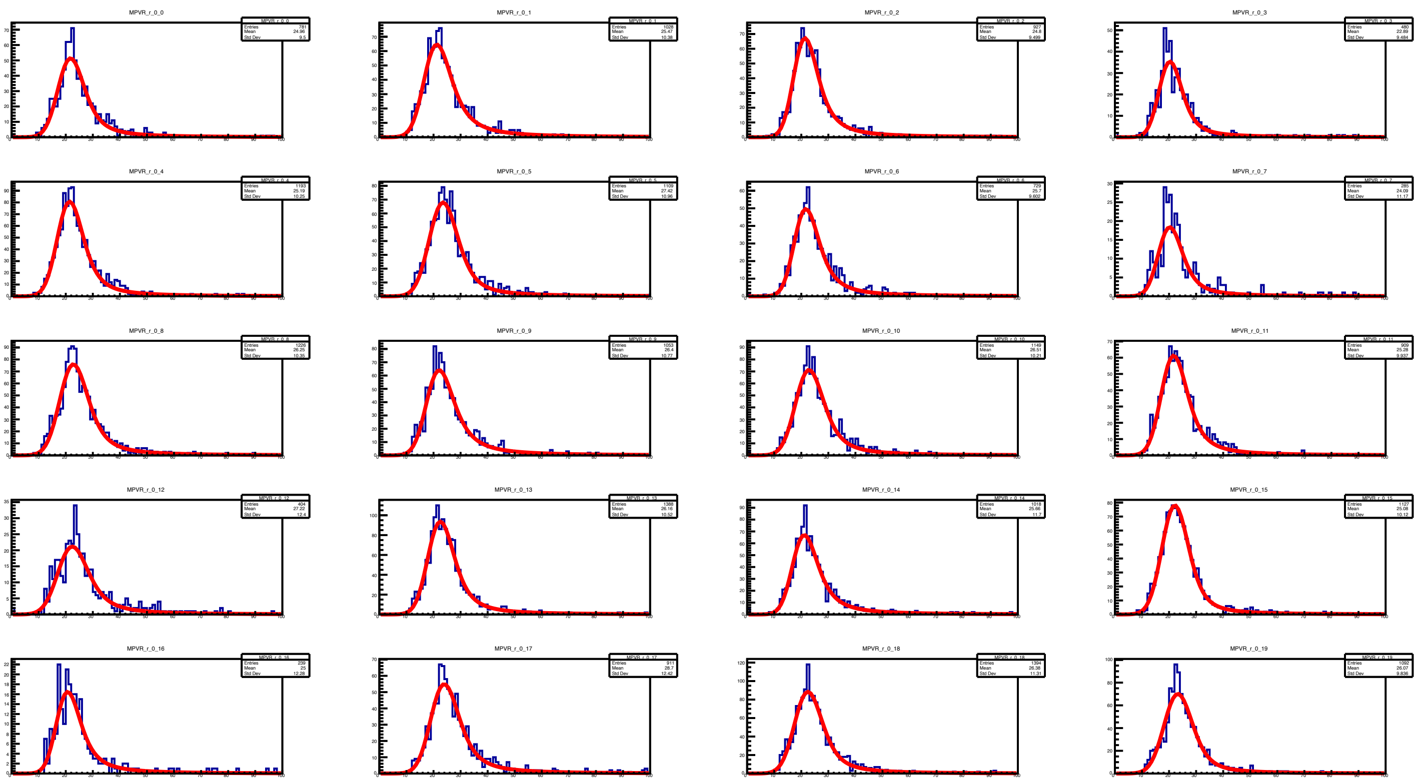






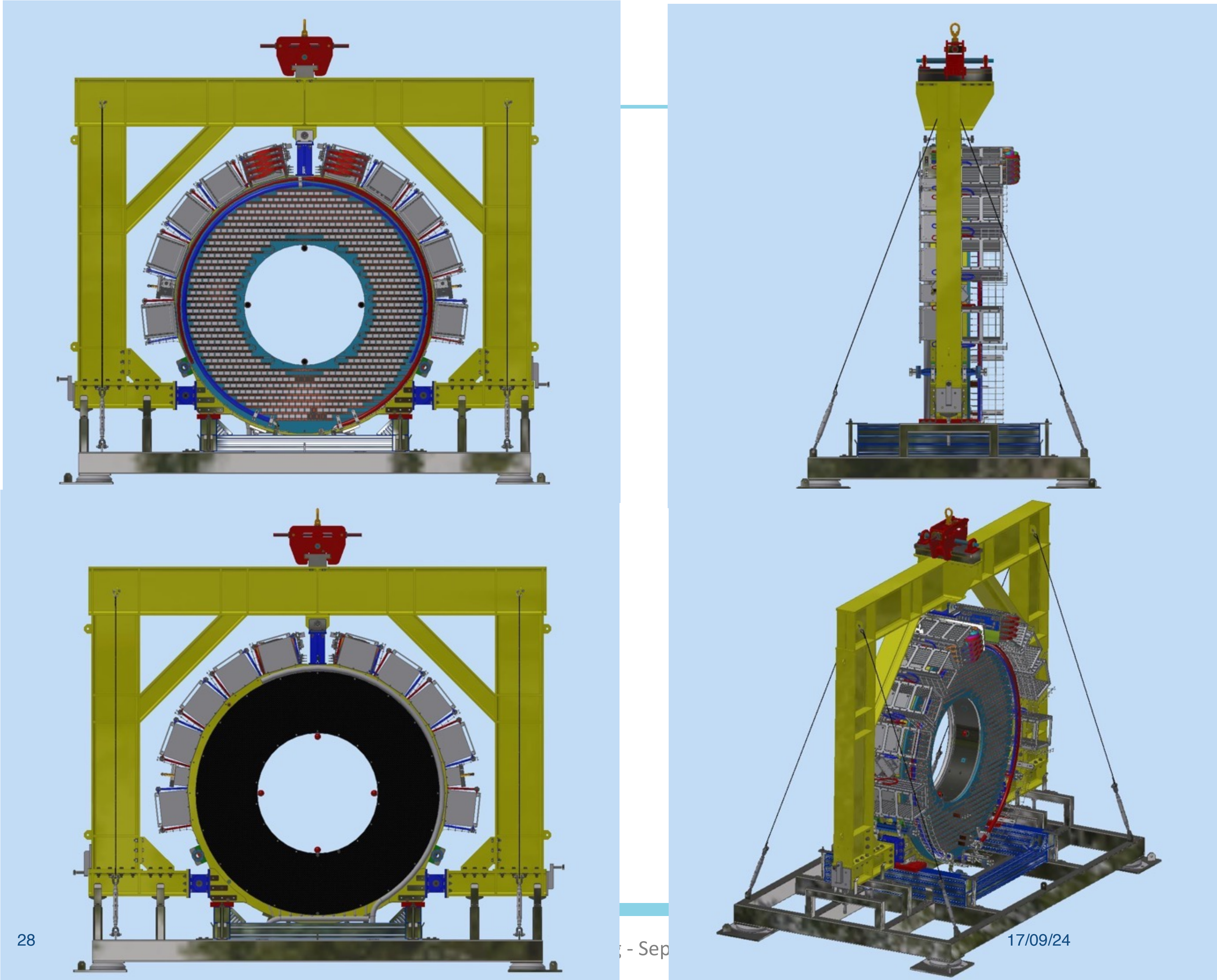
Energy calibration

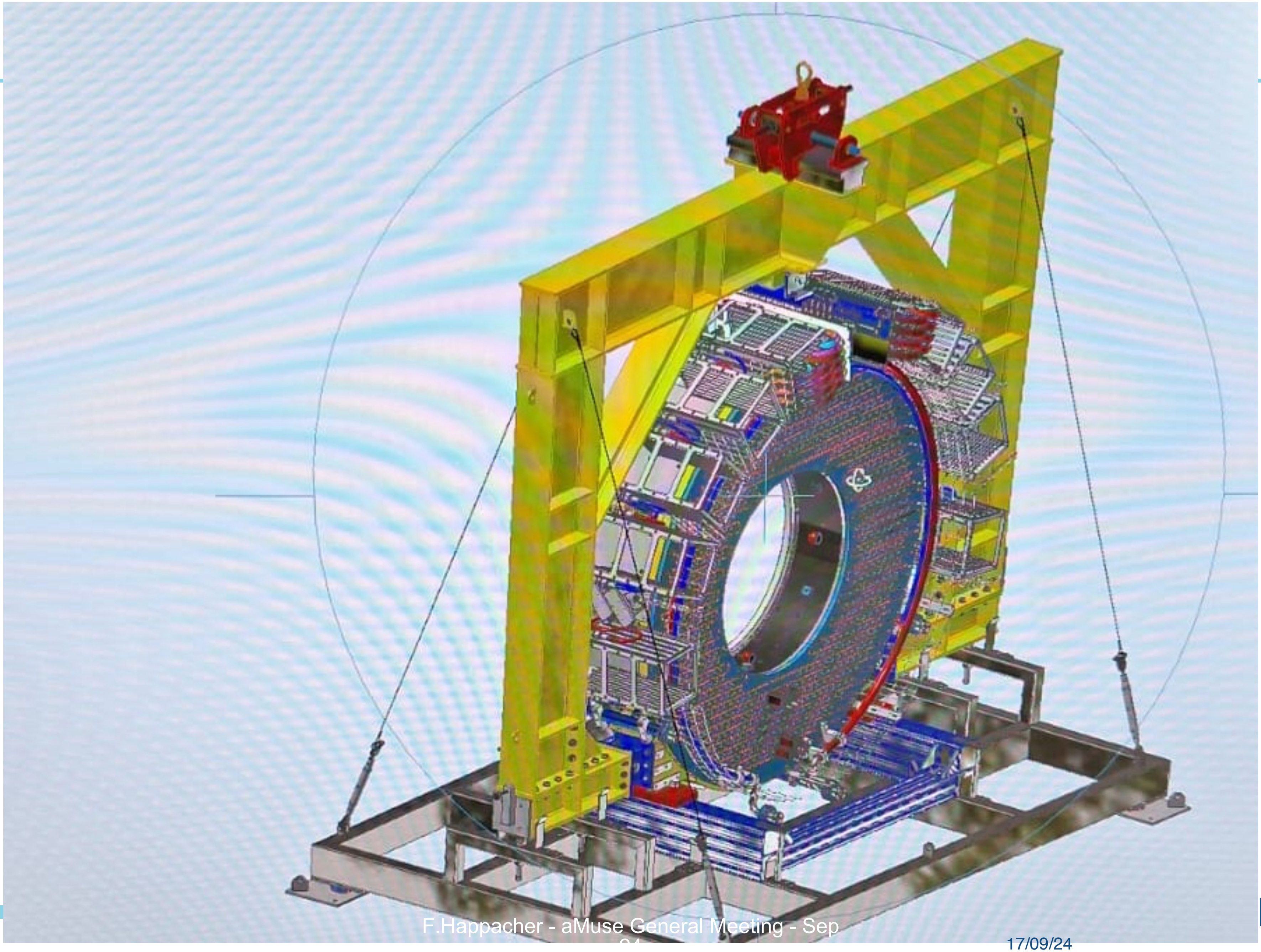
- Q = Vmax (max of the waveform)
- At least three crystals with Q > 2300 ADC counts
- Langauss fit to each readout chann → MPV peak to equalize the response
- Calibrated energy response: E_{calib} = Q/MPV*21 MeV



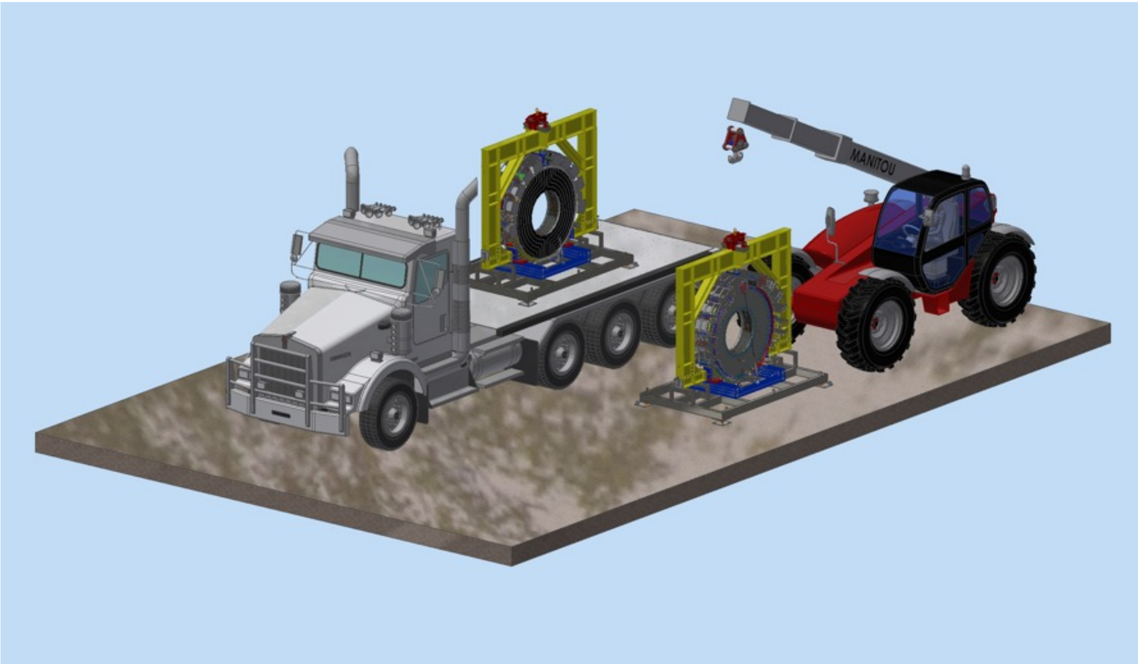
Refined sample:

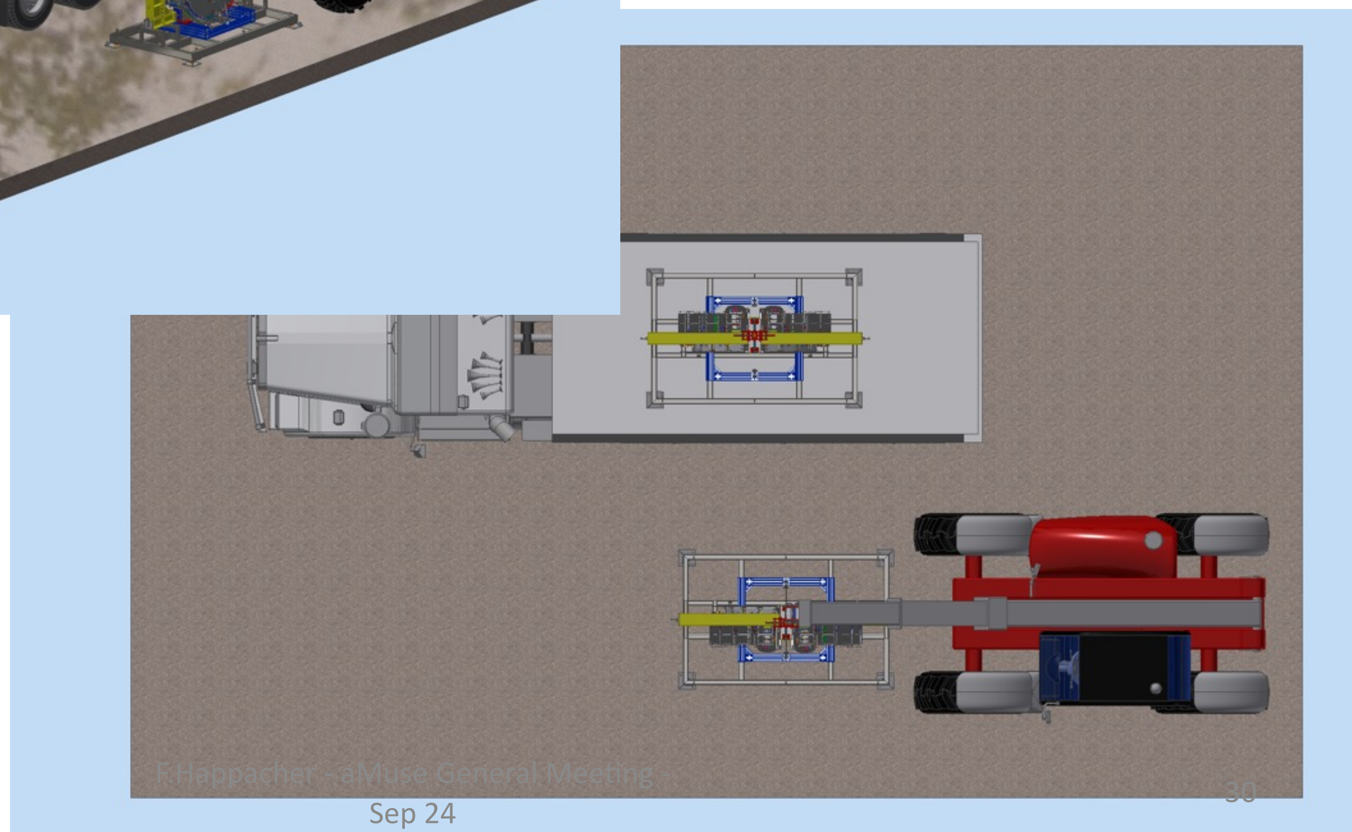
- Track selection
- Track length correction





On board of Transportation Truck





Conclusions

- We plan to complete the Disks assembly by fall 2024
- ongoing steps: MB+Dirac insertion and cabling + laser Fibers routing
- Soon after we will transport the calo to Mu2e hall
- Still to build some supports for cabling, like the trays between the disks and the ones going over the MBS toward the IFB penetrations. This will take place in the Mu2e hall
- Keep working on the Cooling plant design and manufacturing – Outsourced