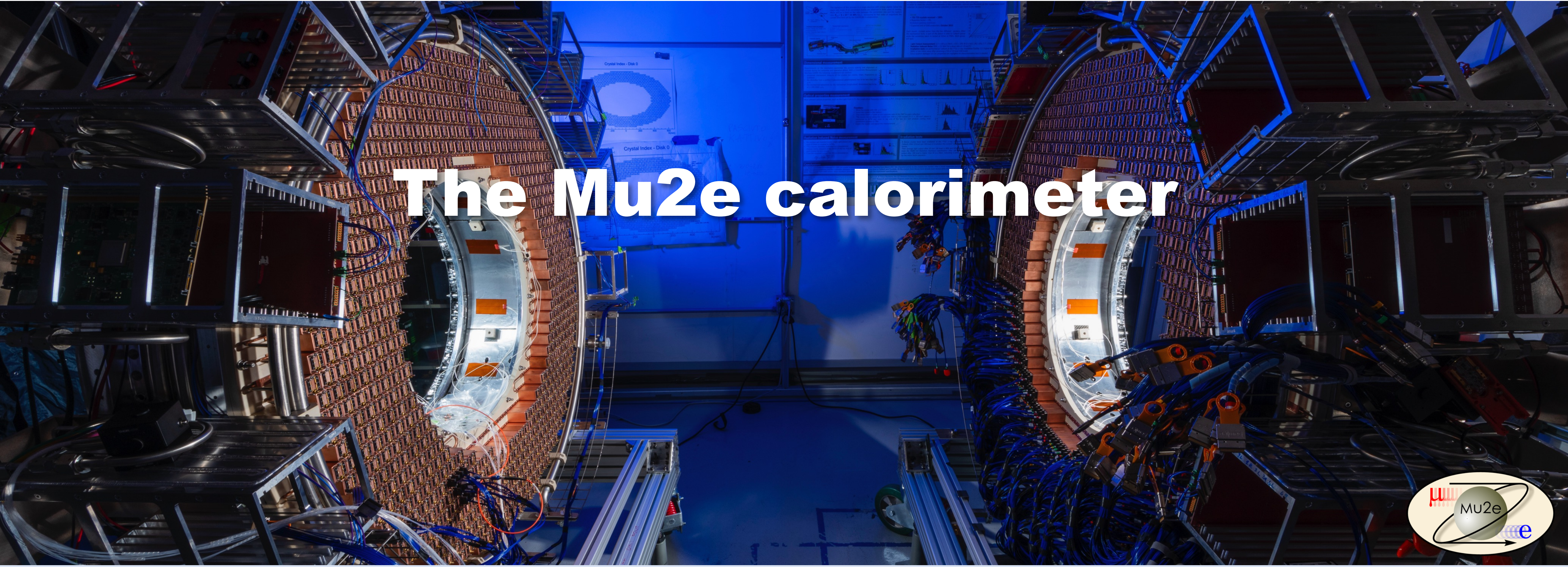
The Mu2e calorimeter



Fabio Happacher (INFN LNF)

on behalf of the Mu2e Calorimeter Group

INFN

Fermilab

42nd International Conference on High Energy Physics

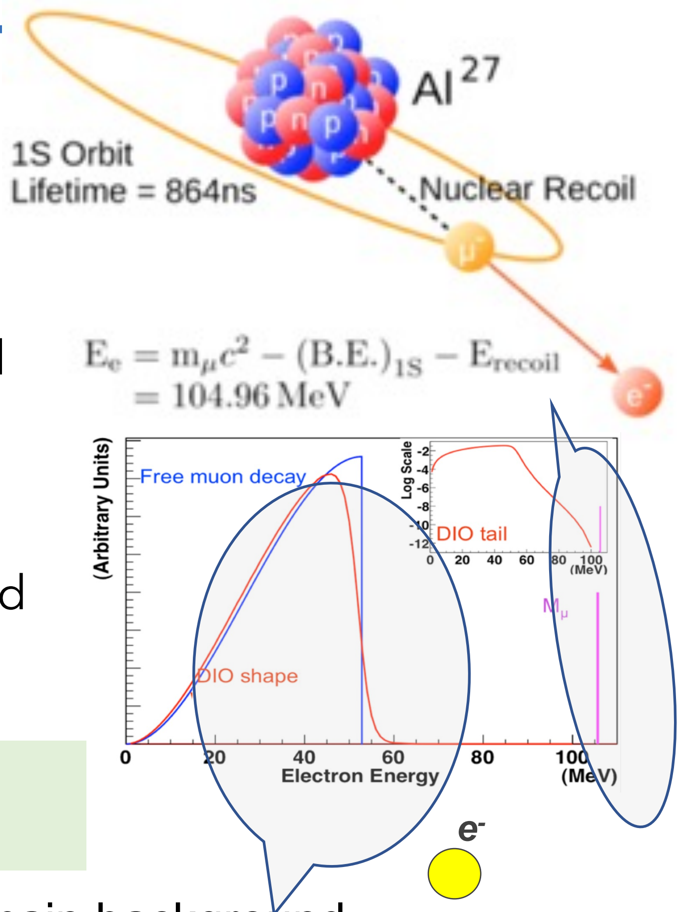
Prague - Jul 17-24, 2024

Outline

- Charged Lepton Flavor Violation and the Mu2e experimental technique
- Calorimeter requirements, technological choices and design
- Calorimeter performances
- Quality Control of production components
- Assembly status
- Commissioning
- Conclusions

The Mu2e Experiment

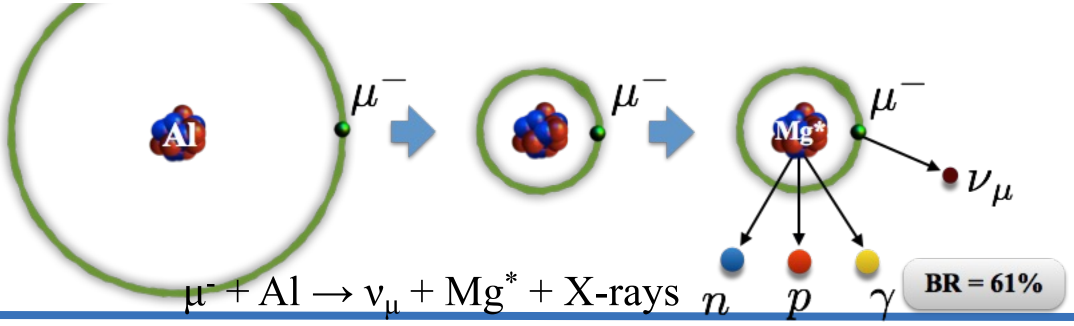
More details from S. Middleton's presentation



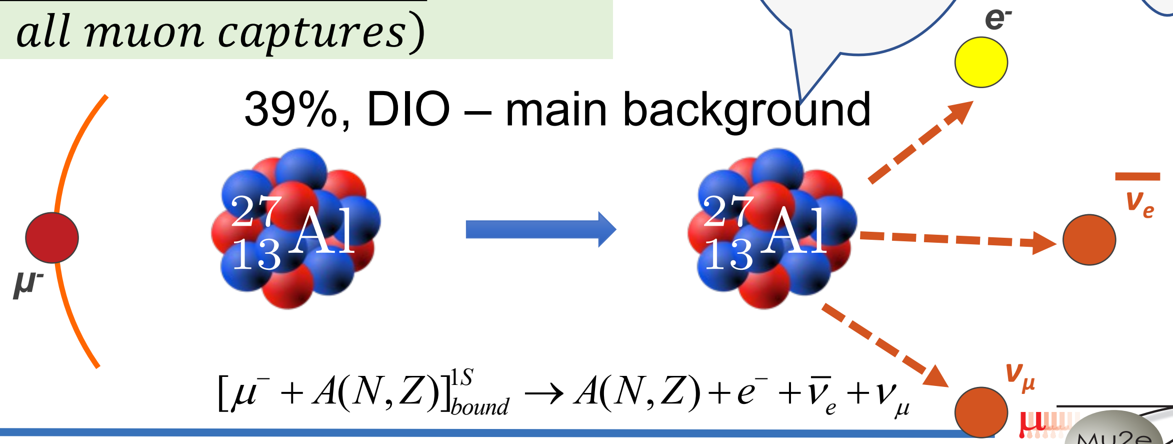
- **Mu2e will search for the CLFV conversion of the muon into an electron** after stopping it on **Al nucleus** $\mu^- Al \to e^- Al$
- Clear signature provided by the **mono-energetic conversion e^- with E ~ M_μ**
- The proton beam of the Fermilab accelerator complex and the Mu2e solenoidal system produce **a high intensity "pulsed" muon beam - 10 GHz of stopped μ**
- Goal is to reach a **single event sensitivity of ~8.4×10^{-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



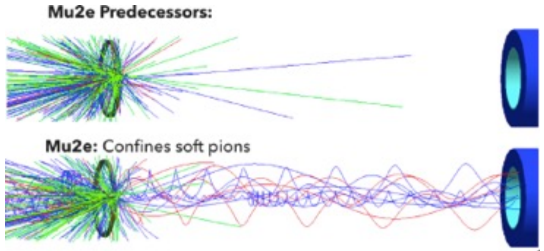
39%, DIO – main background



Mu2e experiment: from cartoons to reality

Production Solenoid

- 10^{12}/s 8 GeV protons on Tungsten target (POT)
- Produced secondaries funneled by the graded magnetic field to TS

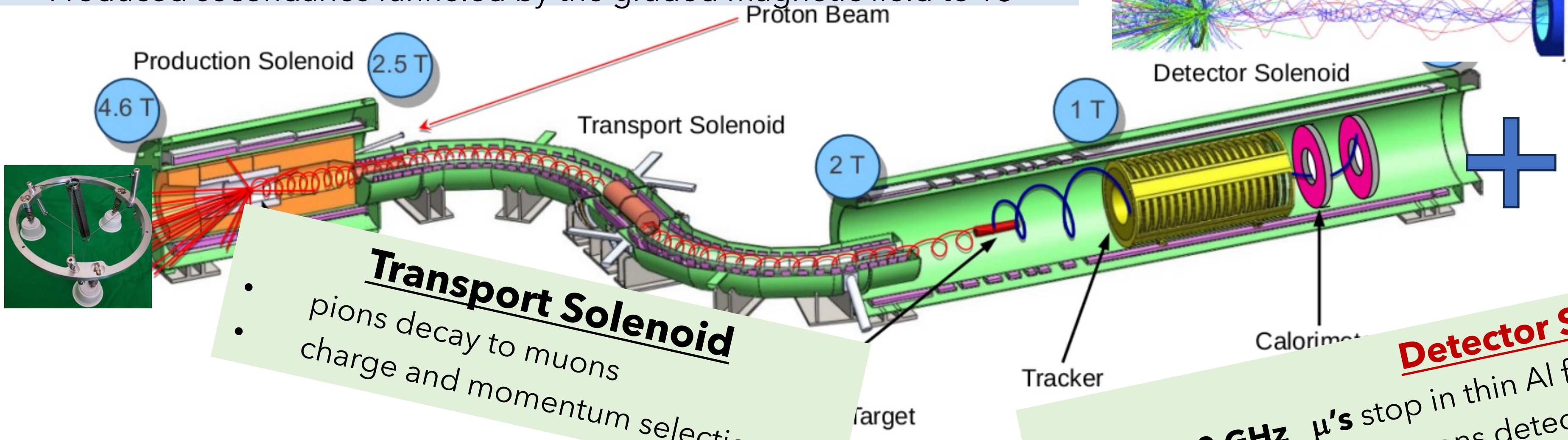


Cosmic Ray Veto

- Covers entire DS and half TS
- Reduces cosmic rays mimicking CLFV signal

Stopping Target Monitor

- Provides normalization factor
- Detects x-rays from muon atomic and nuclear capture procs



Transport Solenoid

- pions decay to muons
- charge and momentum selection

Detector Solenoid

- **10 GHz** **μ's** stop in thin Al foils of stopping target
- Conversion electrons detected by a tracker and a calorimeter
- A sourrounding cosmic ray veto detector tags Cosmic Rays

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

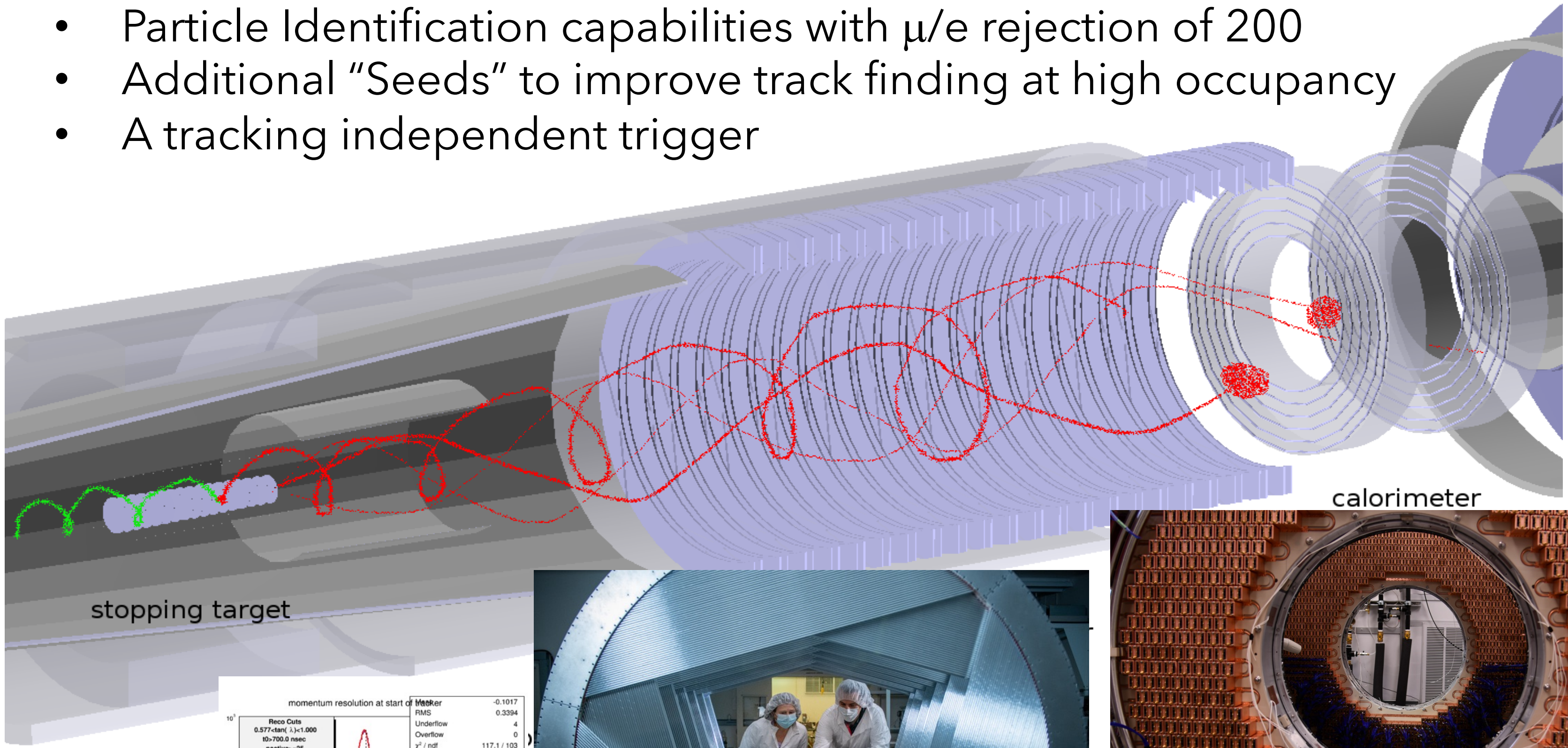
→ Provide energy resolution σ_E/E of O(< 10 %)

→ Provide timing resolution σ(t) < 500 ps

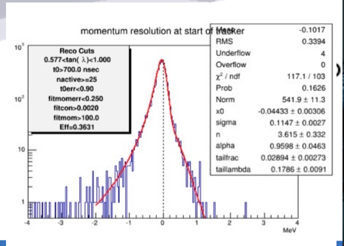
→ Provide position resolution < 1 cm

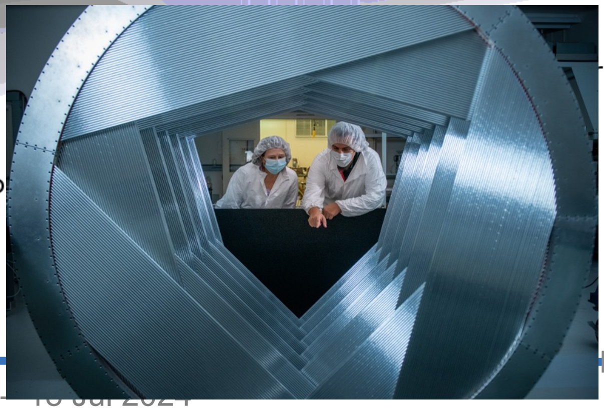
→ Work in vacuum @ 10-4 Torr and 1 T B-Field

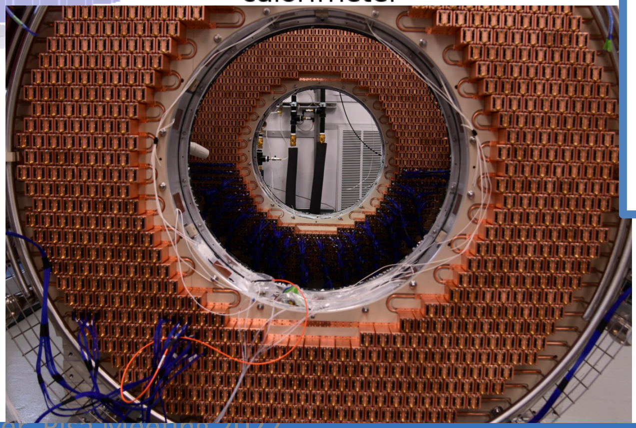
→ stand harsh radiation



115 keV/c momentum resolution







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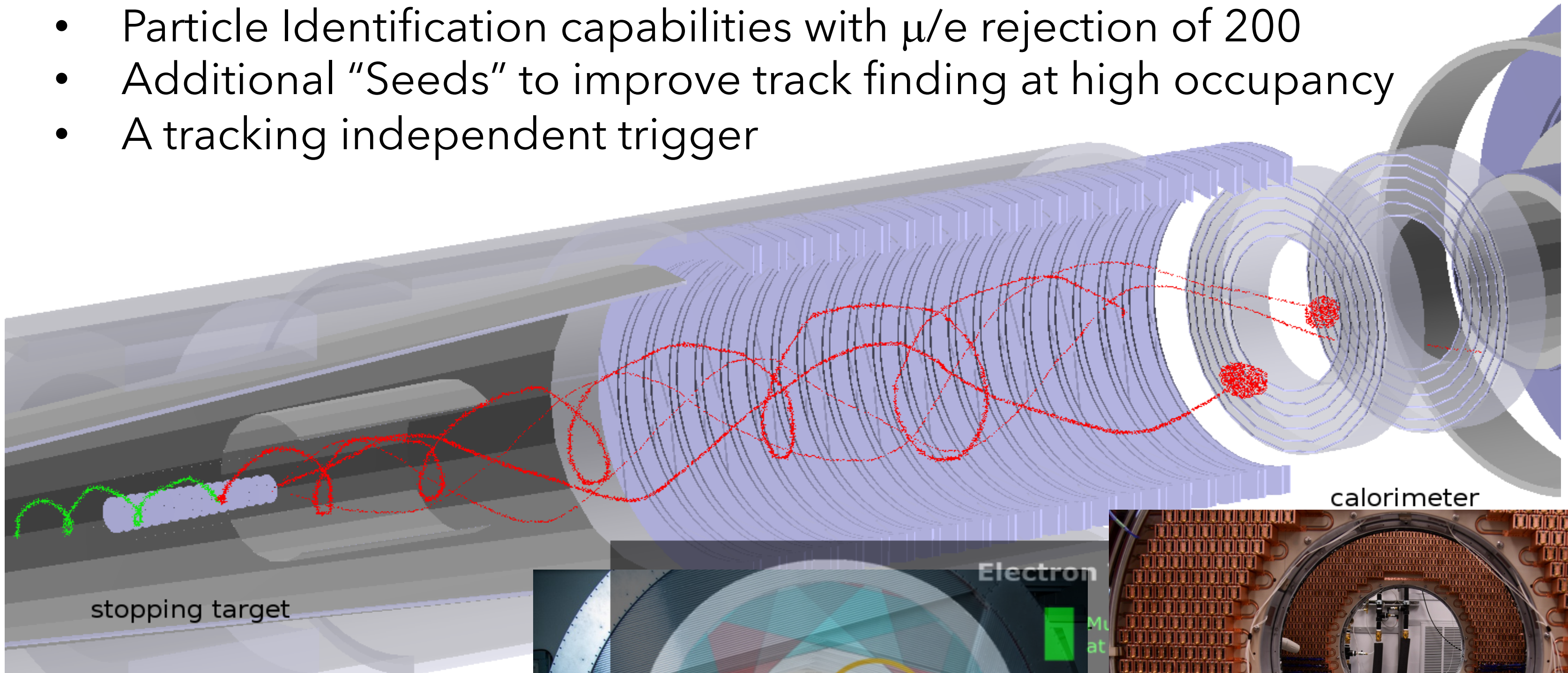

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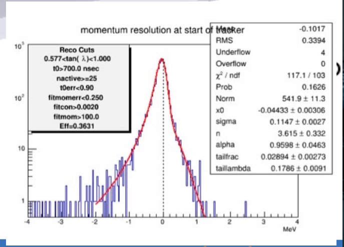
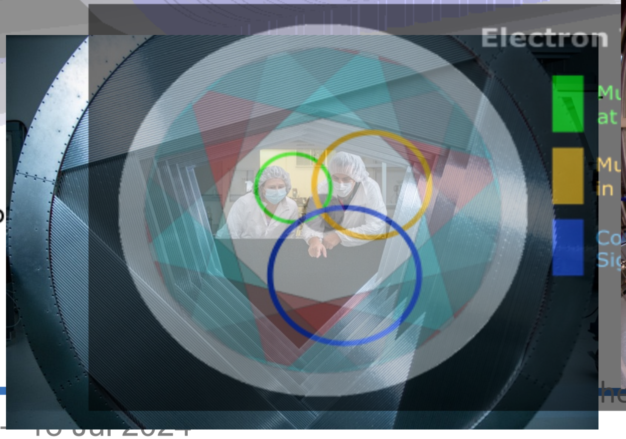
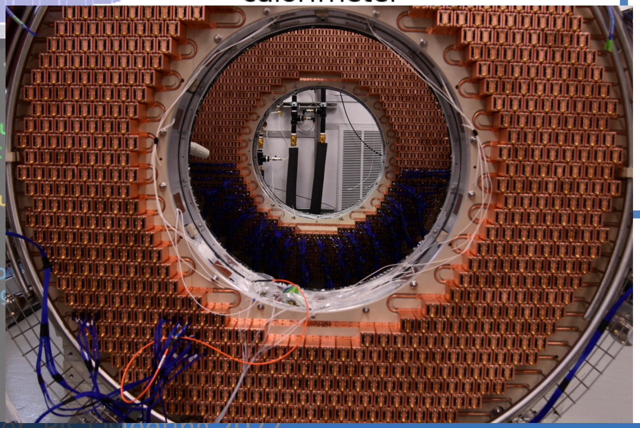
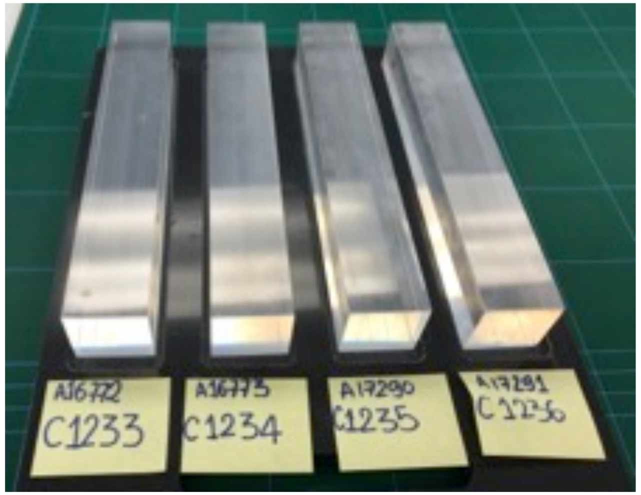


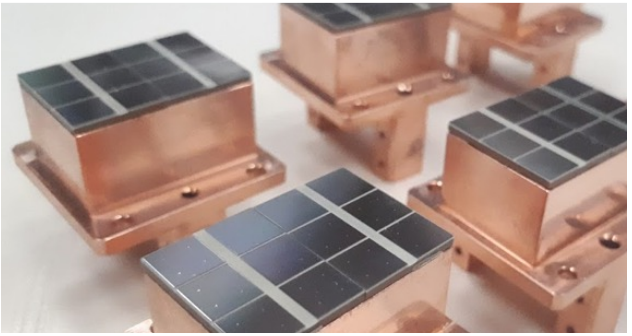




Technological choice

- 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



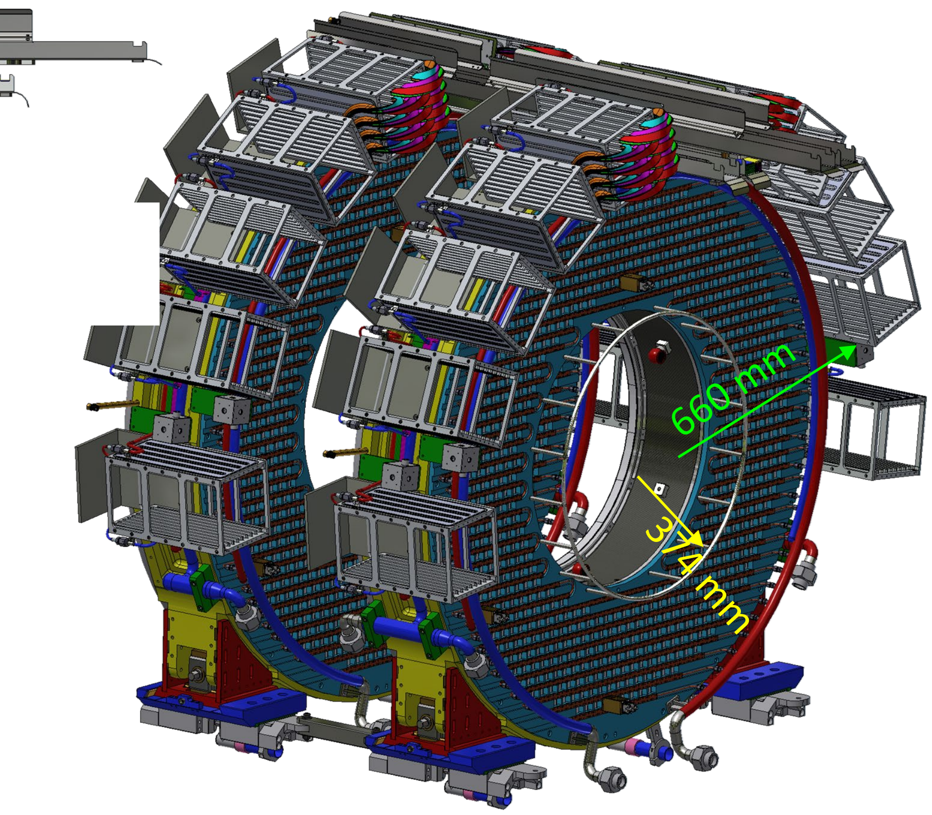


Undoped CsI	+	UV-extended SiPMs	+	Fast electronics
Radiation hard Fast emission time 310 nm emission		New silicon optical window 30 % PDE @ 310 nm TSV readout, Gain = 10^6		FEE: amplifier + shaper Digitizer @ 200 Msps Rad-hard components

To reduce/handle the neutron induced leakage current SiPMs should be cooled down (x2 Idark reduction/10 °C)

SiPM running temperature at –10 °C

The Electromagnetic Calorimeter



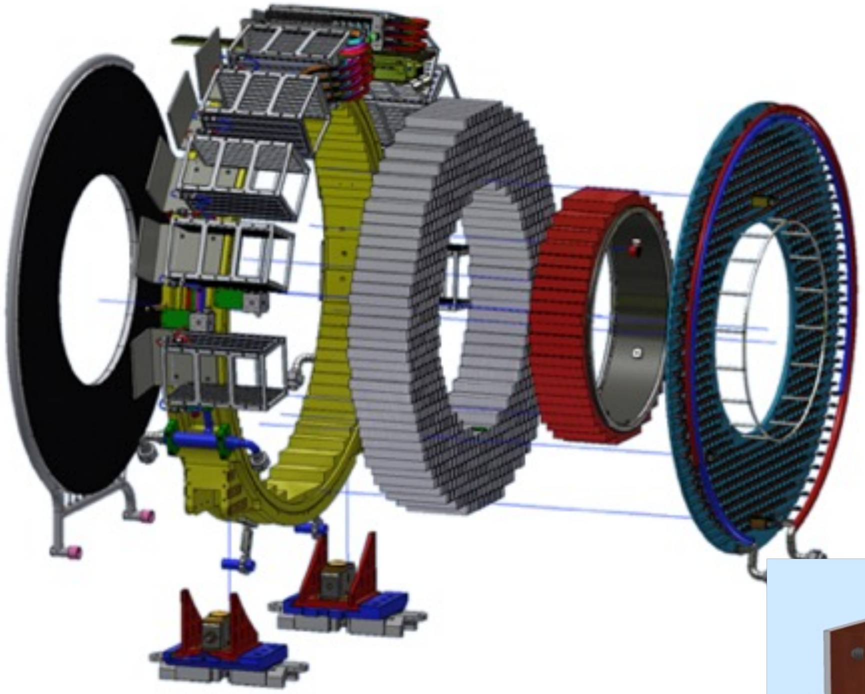
EMC design:

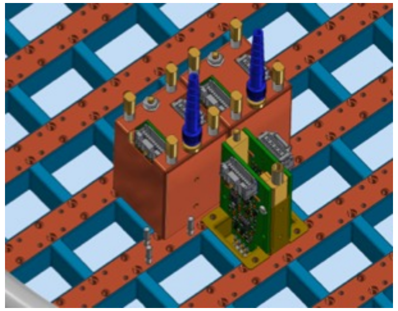
- Two annular disks, R_{in}=374 mm, R_{out}=660 mm, $10X_0$ length, ~ 70 cm separation
- 674+674 square x-sec **pure CsI crystals**, $(34\times34\times200)$ mm^3, Tyvek + Tedlar wrapping
- Redundant readout: For each crystal, two custom arrays (2×3 of 6×6 mm^2 ,50 μm pixel) **large area UV-extended SiPMs**
- 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 crates
- Calibration/Monitoring with 6 MeV radioactive source and a laser system
- Cooling system – power dissipation + Sipm Temperature setting

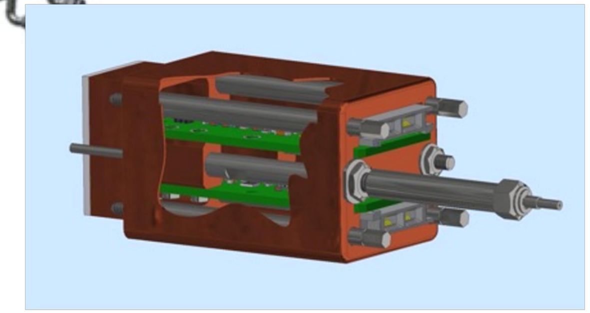
Engineering of the Calorimeter

- 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 Units
  - 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



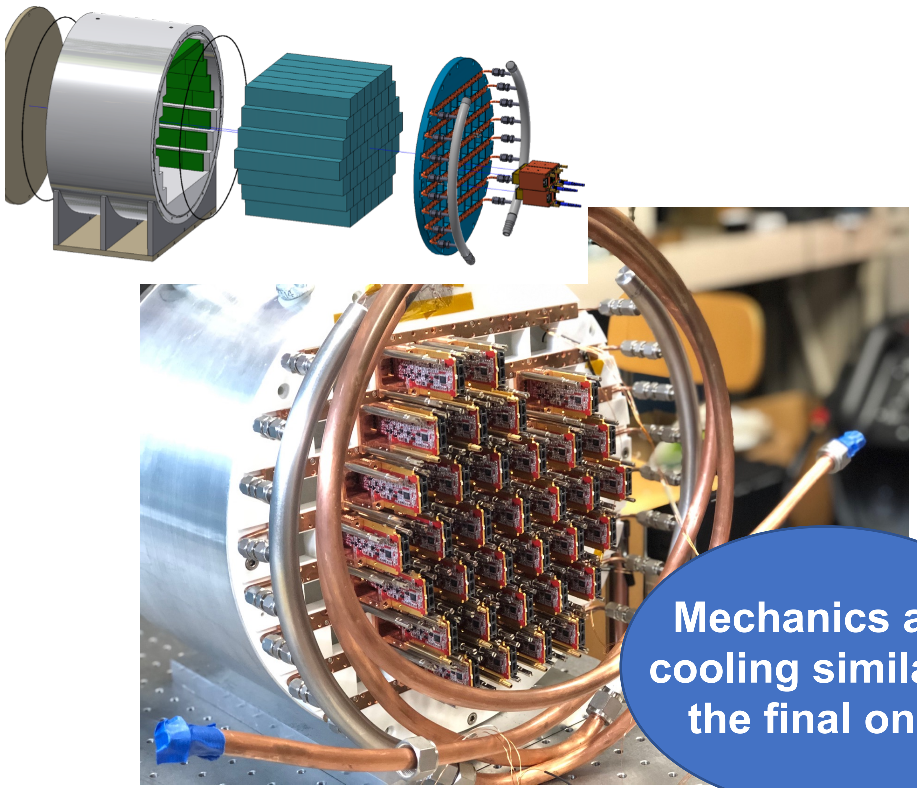




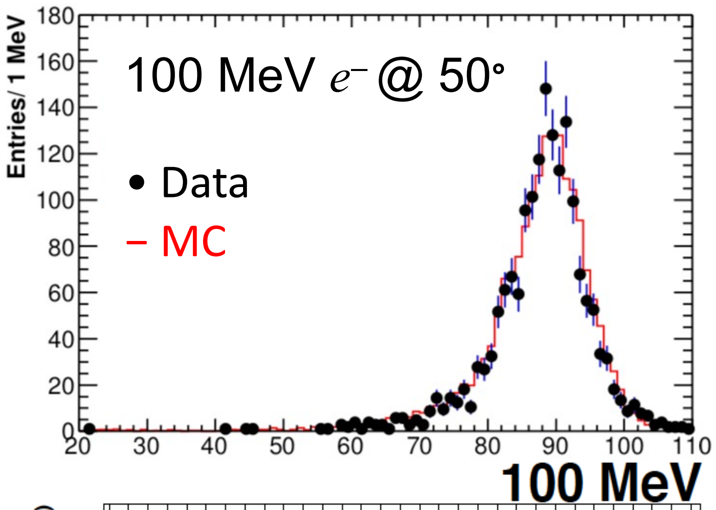
Module 0

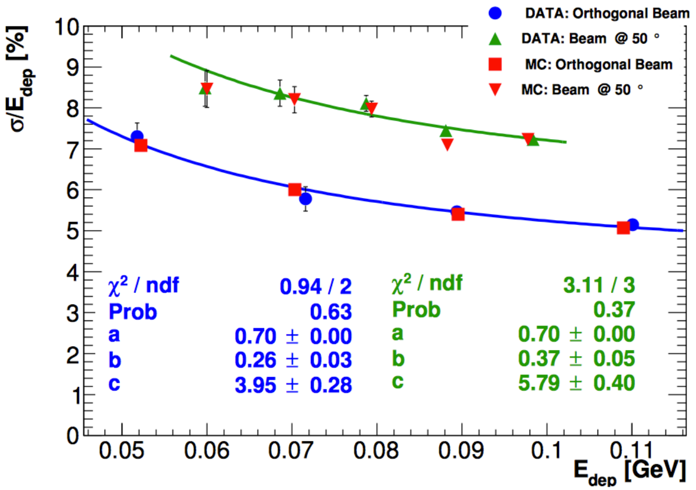
Calorimeter performance validated with Module 0, a large-scale calorimeter prototype (51 crystals, 102 SiPMs/FEE, commercial digitizer) equipped with pre-prod components and tested with e^- beam

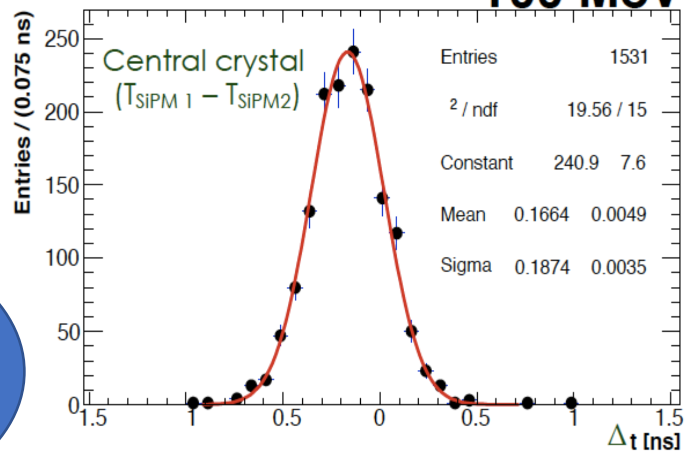
- Mu2e requirements well satisfied
- Green light for components procurement

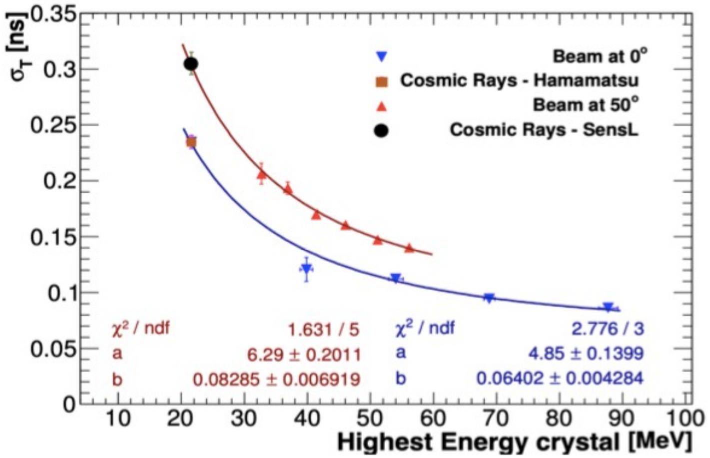


Mechanics and cooling similar to the final ones



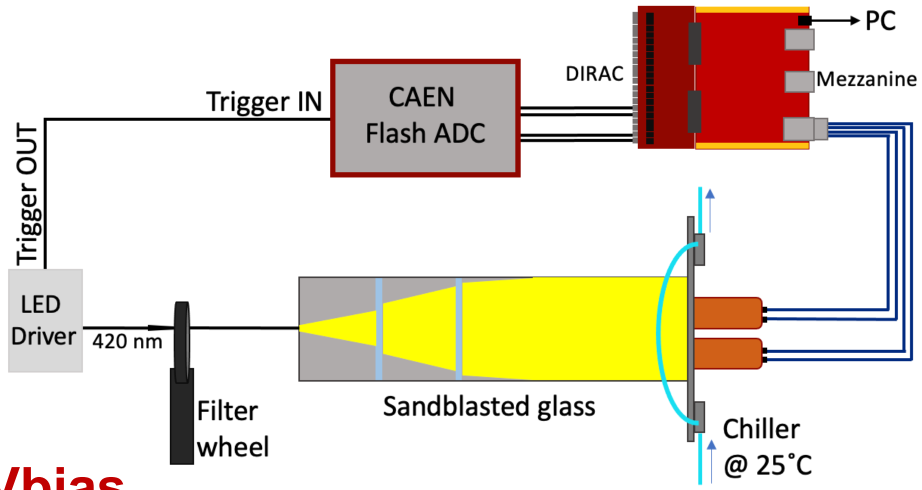


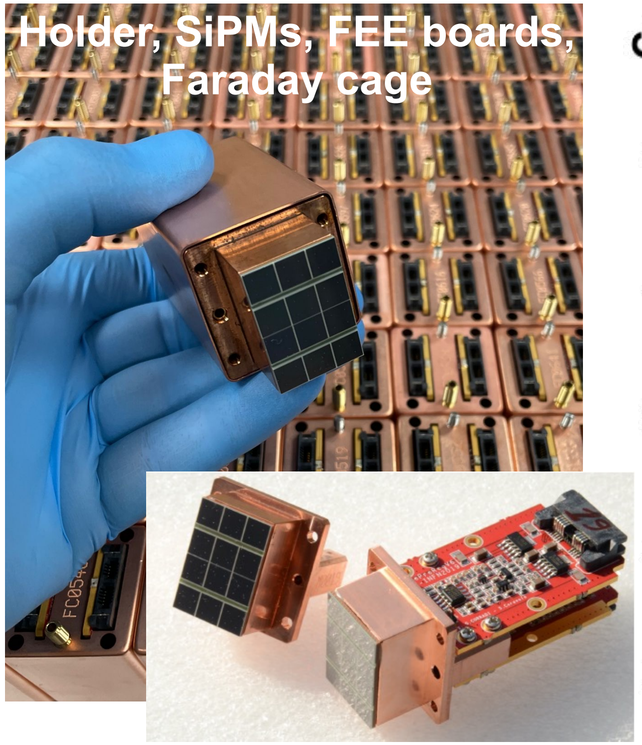


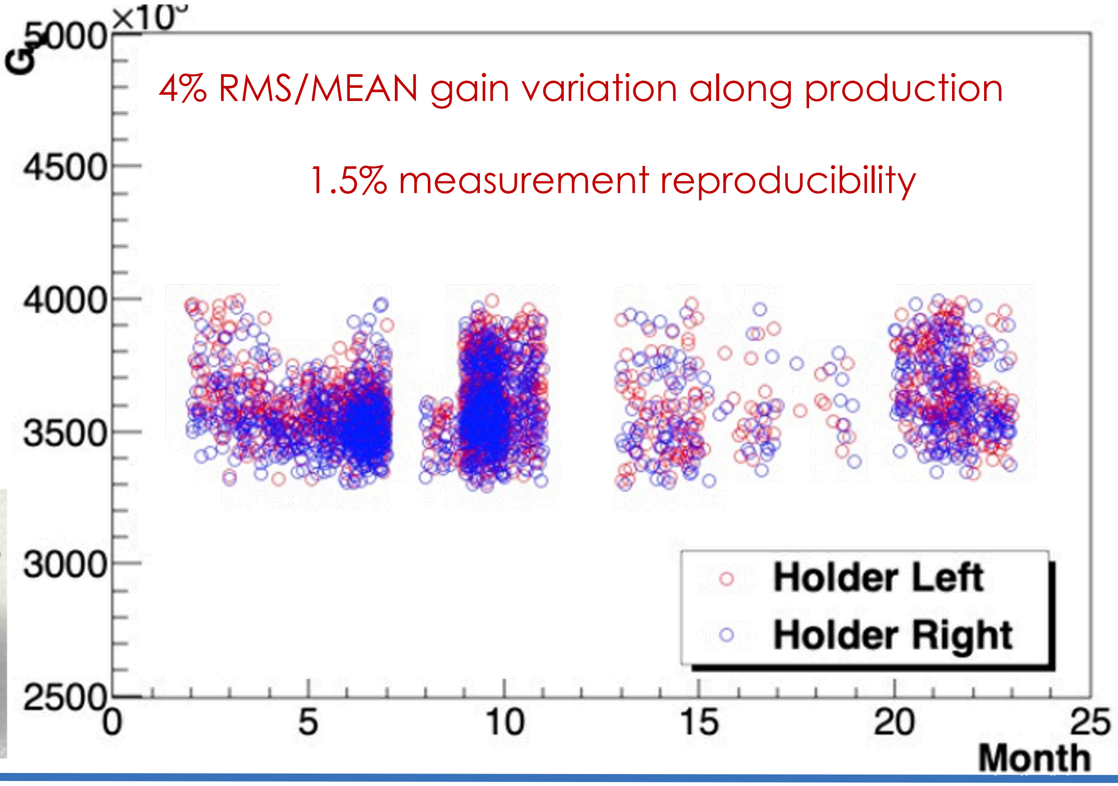


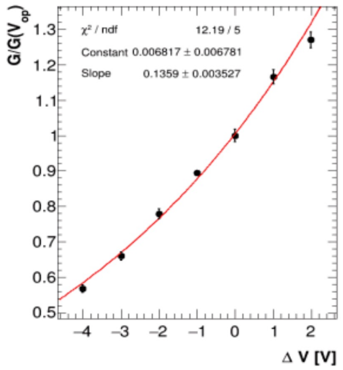
QC of production components

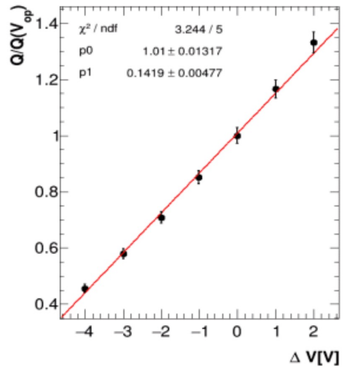
- Crystals/SiPM production tests successfully completed in 2020
- All ~ 1500 Read-Out Units assembled and tested:
  - 7 HV settings in the V_{op}-4V ÷ V_{op}+2V interval
  - 9 positions filter wheel scan per HV value
  - ➢ **Calibration of Gain, response and PDE + dependency on Vbias**

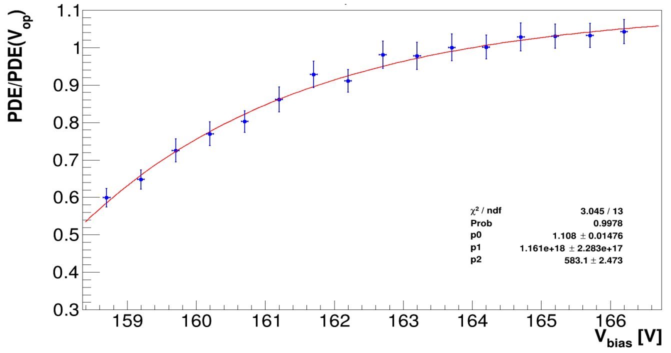






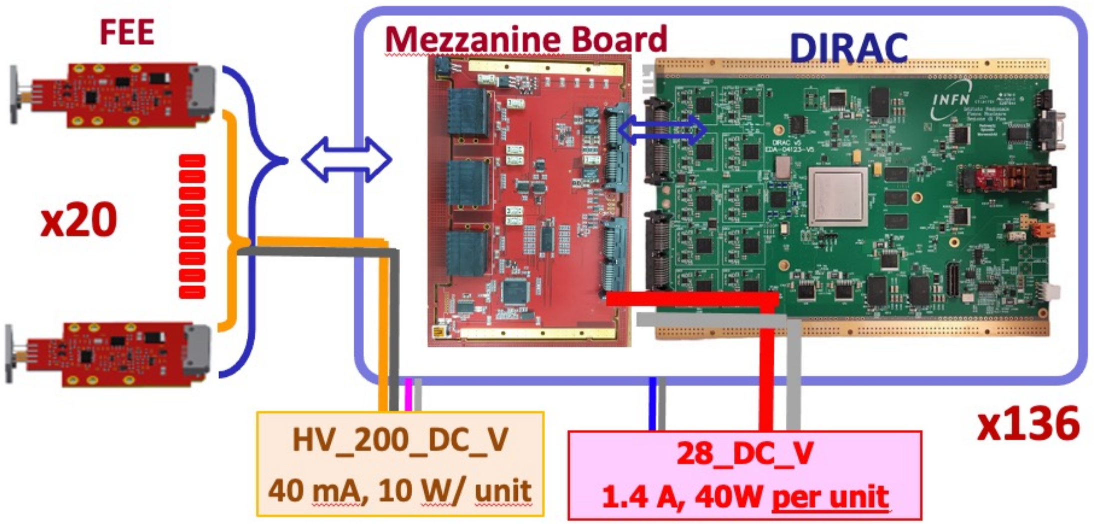


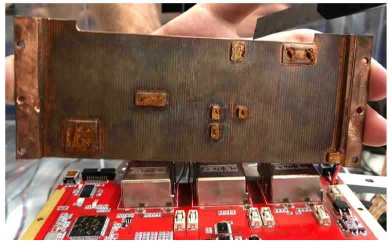


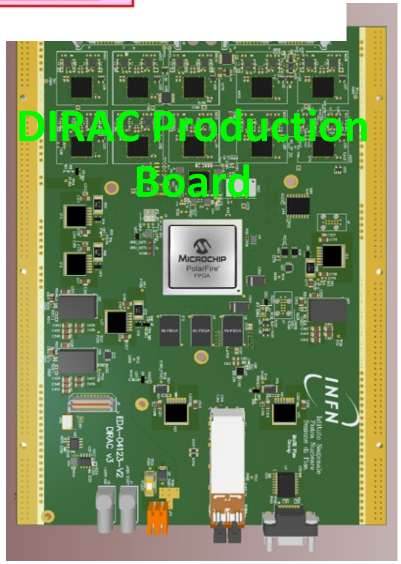


Digital electronics

- Two digital boards:
  - MZB for SiPM/FEE HV settings & readout (HV, I, T)
  - DIRAC for digitization @ 200 Msps, 12 bit ADC
- 2019-2021 B-field test + irradiation tests (TID, neutrons) with single components/boards
- End of 2022: **SEL problem discovered on ARM processor (MZB) and Flash Memory (DIRAC)** when irradiating boards with charged particle (proton, 60–200 MeV/c, 10^{10} p/cm^2)
- 2023: proton irradiation campaigns + engineering effort to understand and solve the problem
  - **new ARM, new Flash memory** production
  - **new layout with recovery circuits**



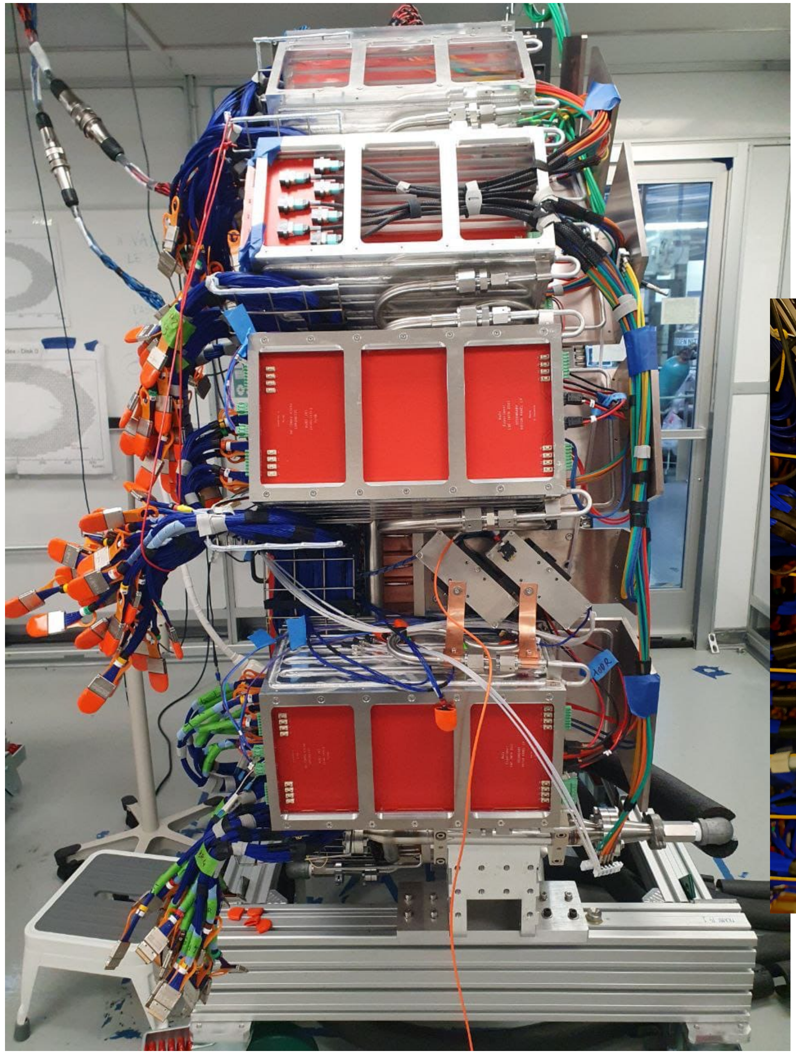


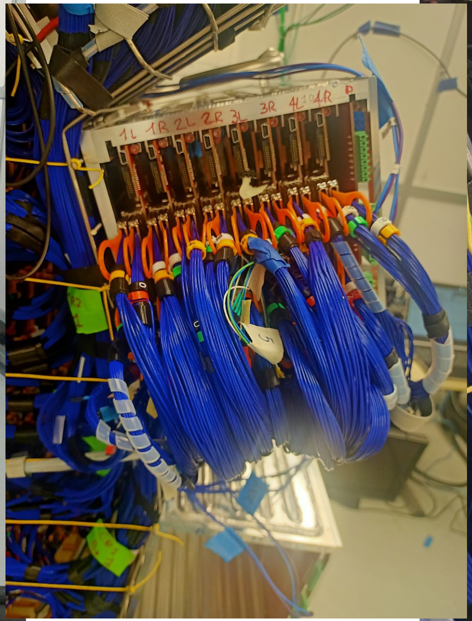


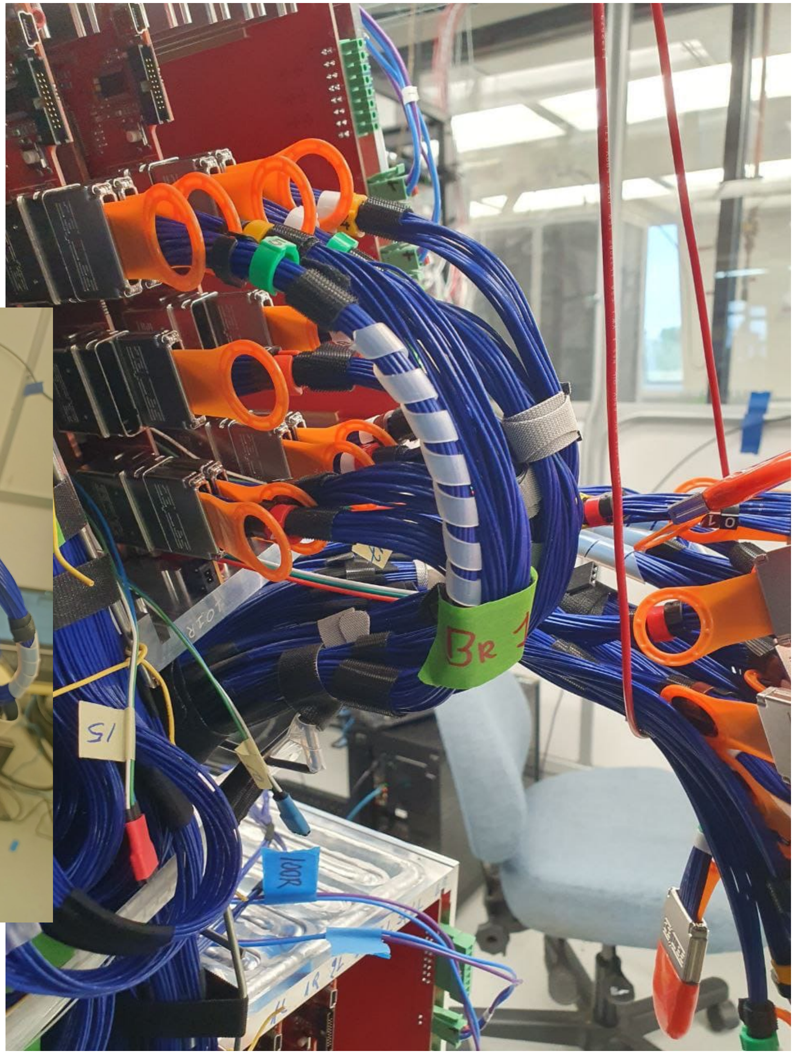
MZB production (140 units) completed
+ Burn-IN + QC tested. **First 80 shipped to FNAL**

1/2 DIRAC production (70 units) completed
Burn-IN + QC test in progress. **Ship to Fermilab in June**

First boards insertion and connection

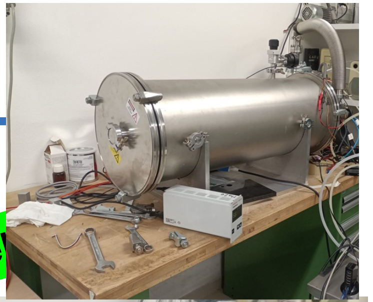


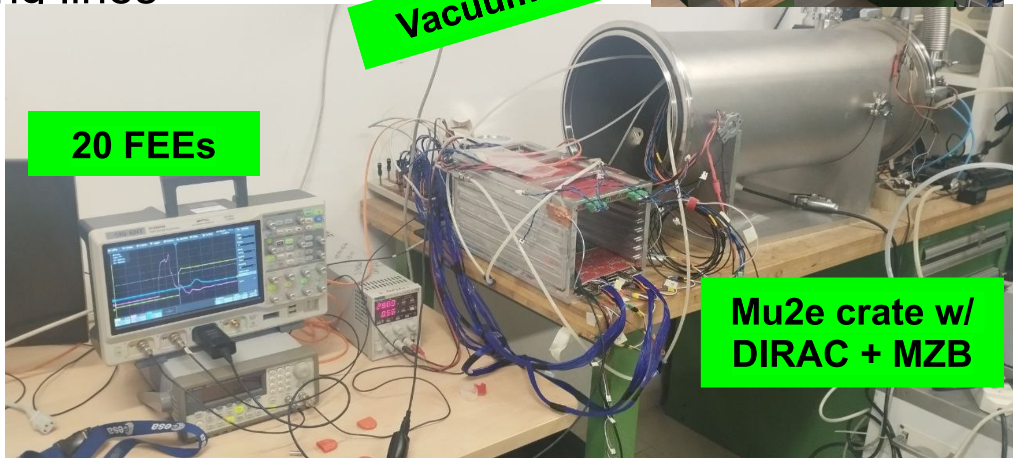




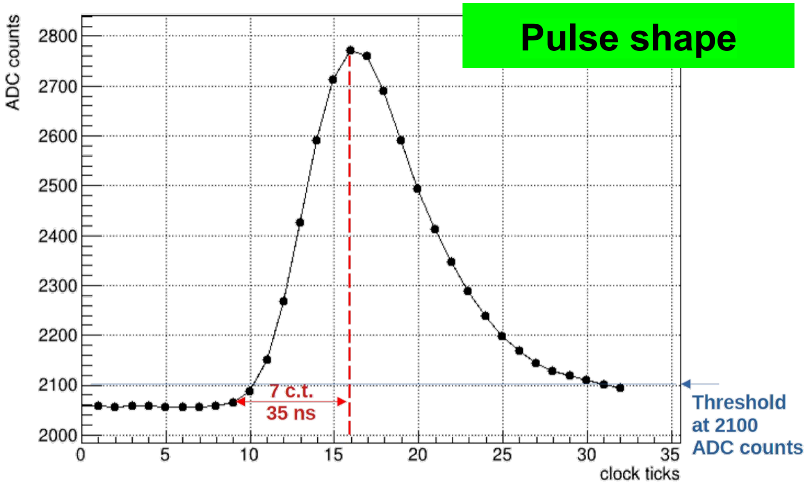
Thermal vacuum test and VST

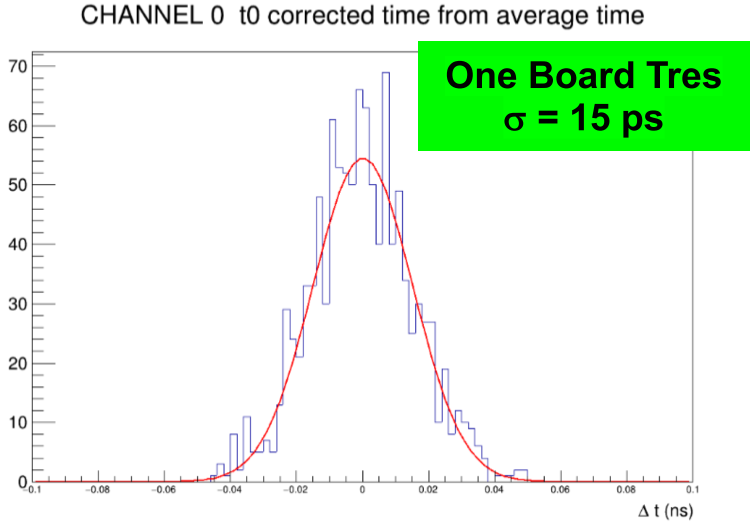
- Setup in Pisa for thermal vacuum test to complete temperature measurements in vacuum
- Vacuum 10E-2 Torr, cooling power similar to mu2e, same cooling fluid at 10 C
- Missing MZB copper plates to dissipate heat through crates' cooling lines
  - 8 DIRACs and 8 MZBs in a final crate
  - More than 20 thermal sensors monitored
  - 20 FEEs modified to provide signals from pulse injection
  - 1 DIRAC is connected to a DTC through an optical flange
  - Mu2e slow control and data acquisition
  - Template fit of signal to evaluate performance

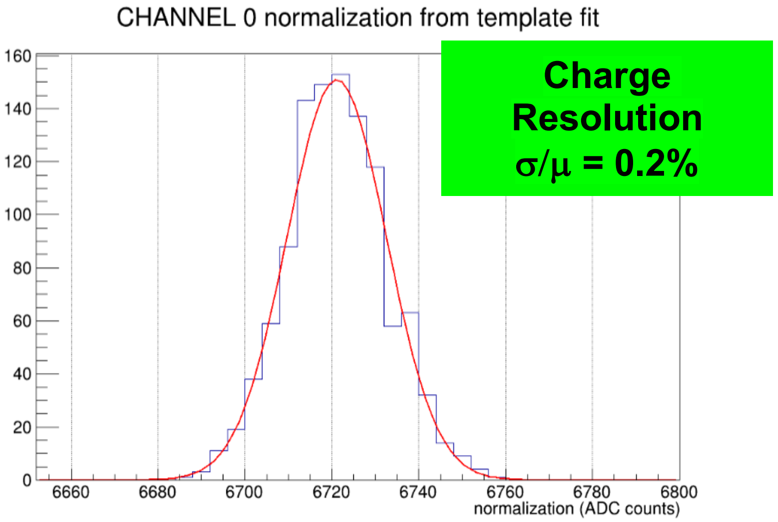




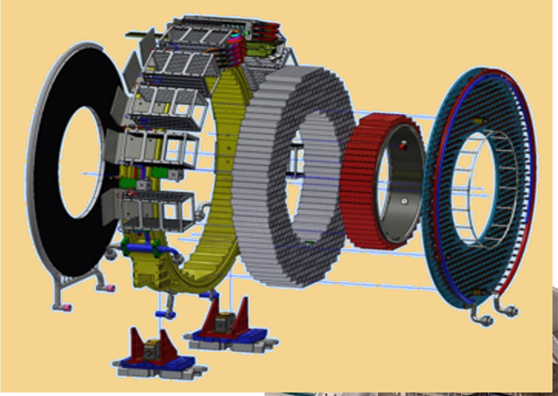
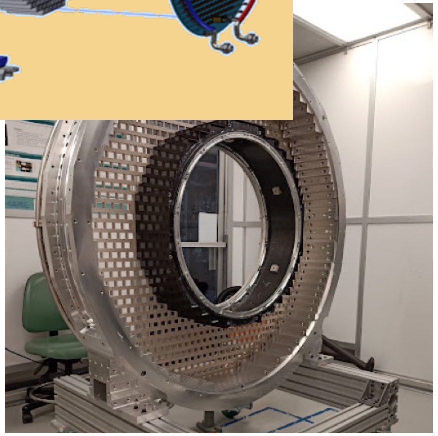
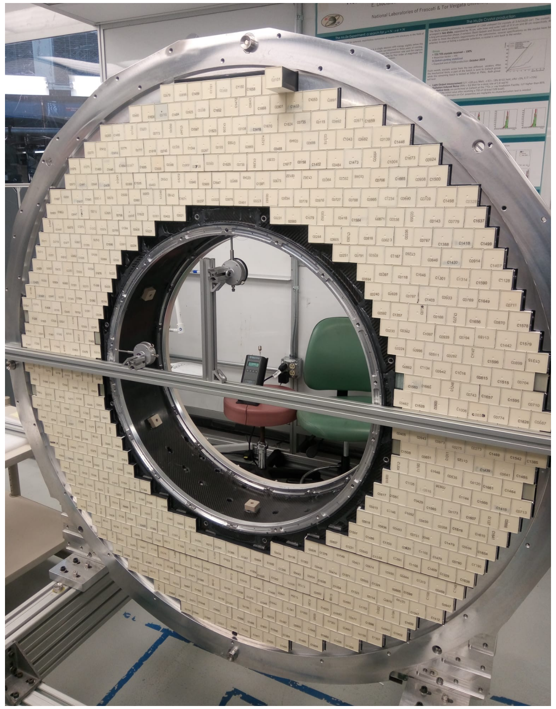
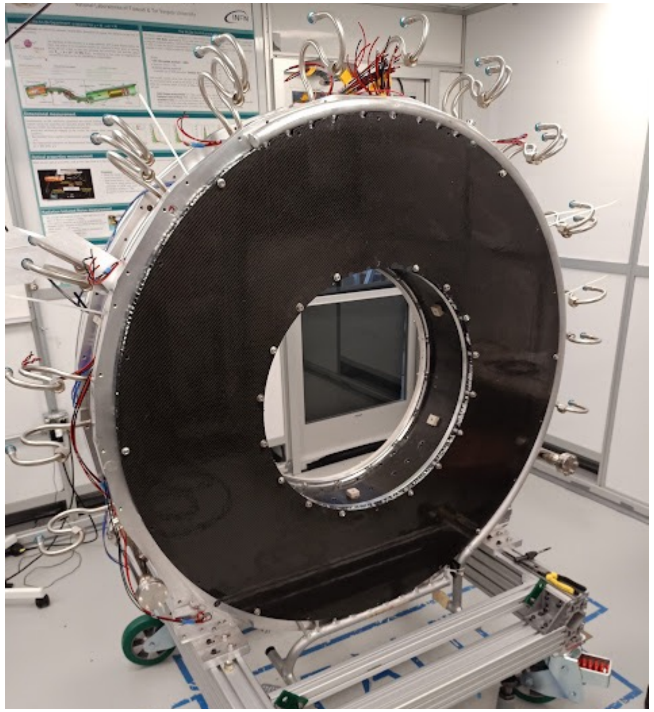
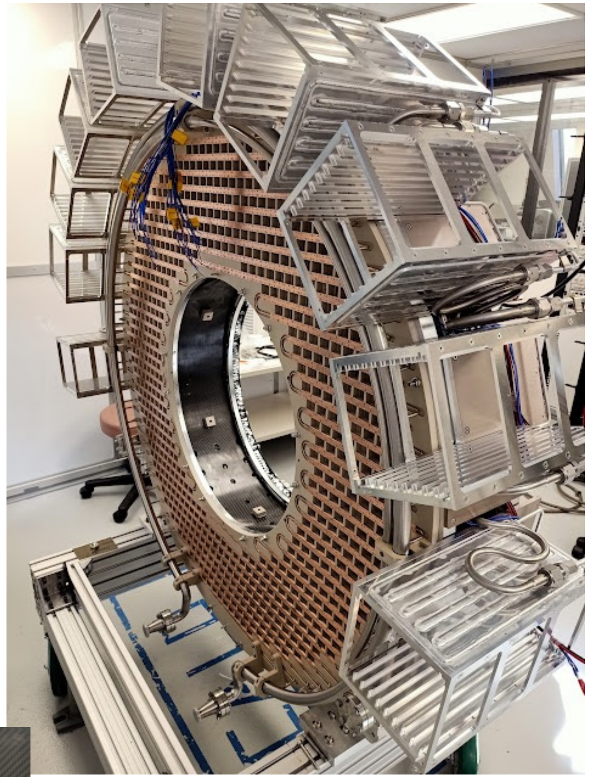
- Preliminary test @ room temperature:





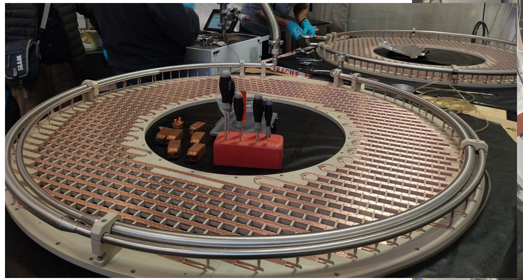


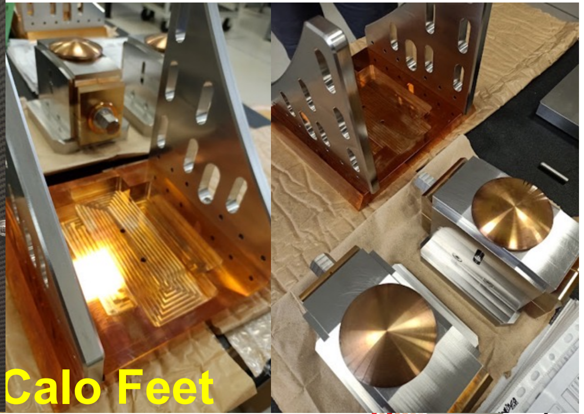
Assembly status: mechanics

All calorimeter mechanical parts built

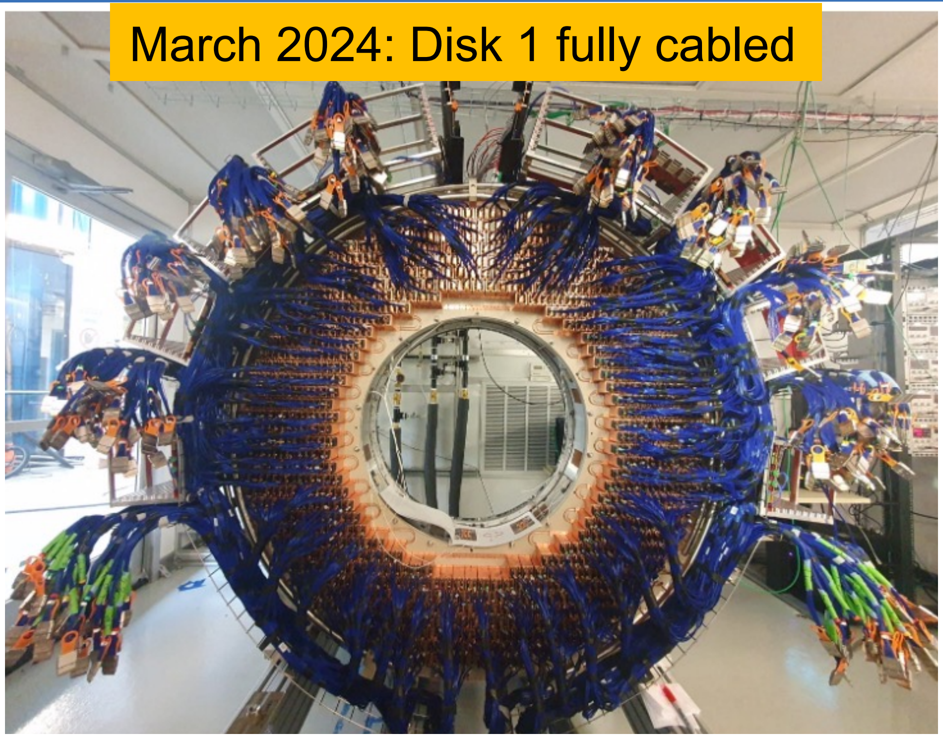
- Disk-1 (Disk-0) mech structure assembled in June 22 (March 23)
- All crystals stacked on both disks
- CF plates with source tubing, Inner Rings installed
- Crates+FEE plates installed and leak checked
- Calorimeter feet for rails at Fermilab (March 2023)

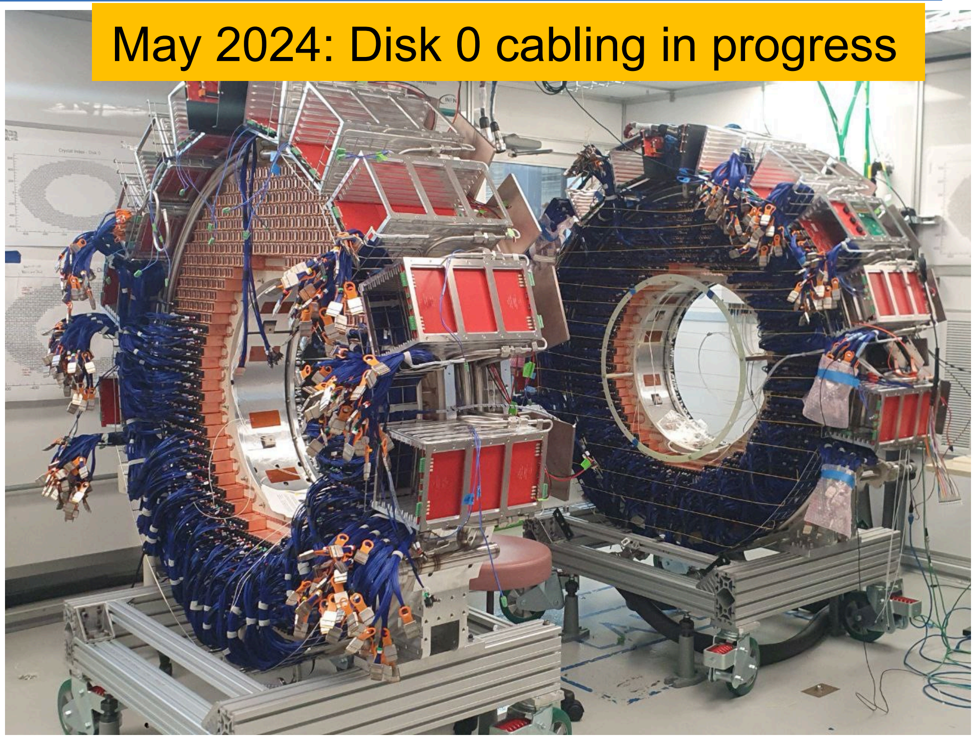




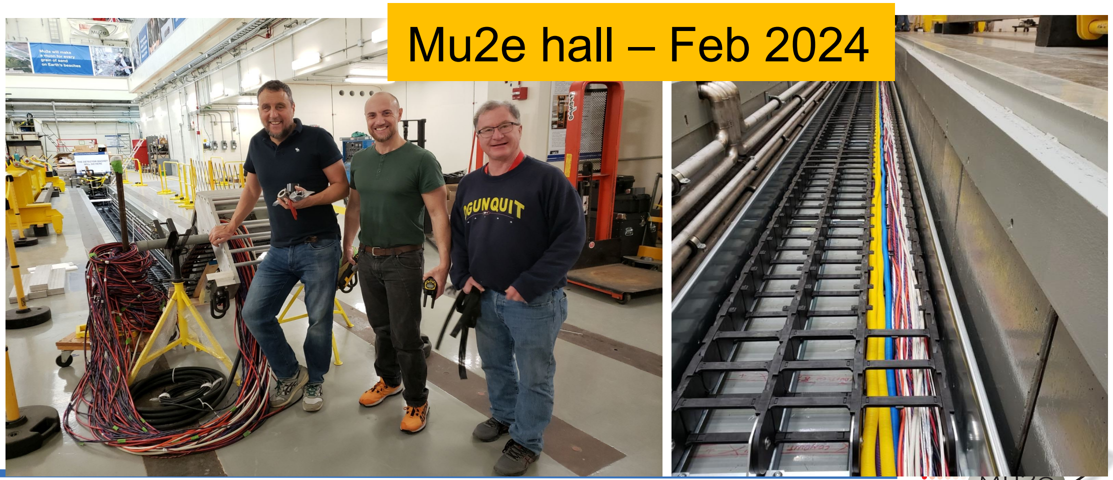
Assembly status


Nov 2023: Read-Out Units, both disks


March 2024: Disk 1 fully cabled


May 2024: Disk 0 cabling in progress

- For both disks, assembly of analog electronics and power distribution is completed
- Cable routing completed for Disk-1 and 2/3 of Disk-0
- At Mu2e Hall:
  - LV/HV power supplies installed
  - Service cables pulled
  - Half DAQ cables and optical fibers installed


Mu2e hall – Feb 2024

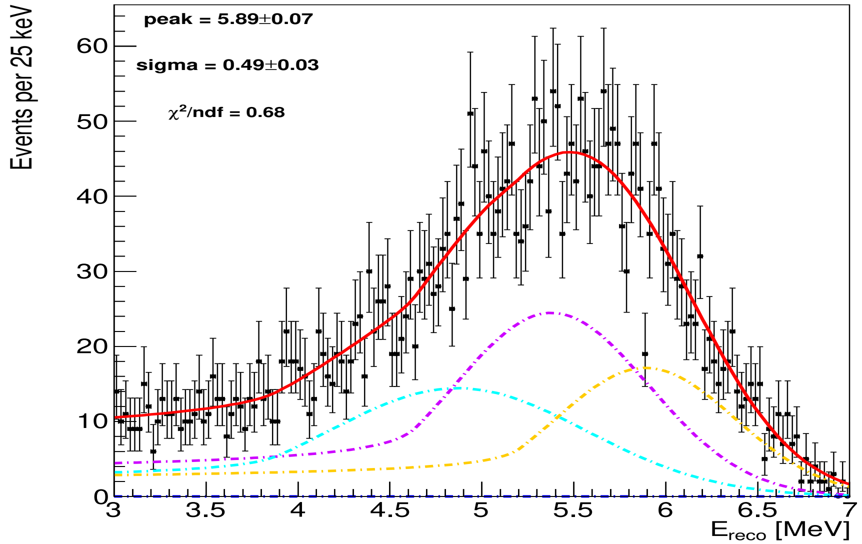
Calorimeter’s heart beating

Source calibration system

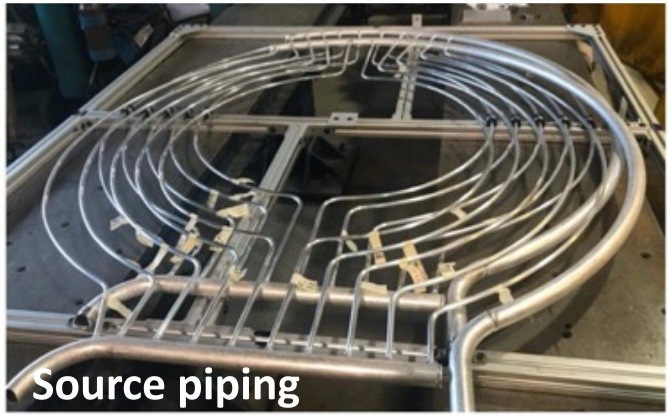
- Neutrons from a DT generator irradiate a fluorine rich fluid (Fluorinert) that is piped to the front face of the disks
- The following reaction chain produces photons at 6.13 MeV

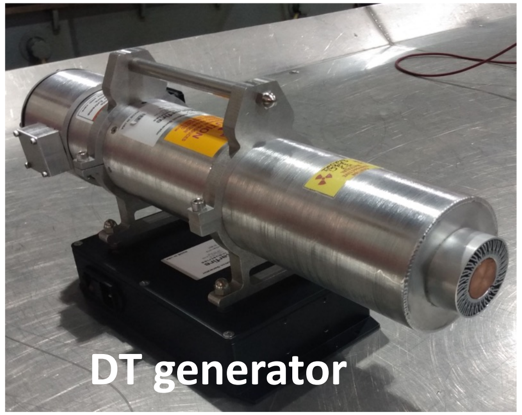
$$^{19}F + n \rightarrow {}^{16}N + \alpha$$
$$^{16}N \rightarrow {}^{16}O^* + \beta \qquad t_{1/2} = 7\ \mathrm{s}$$
$$^{16}O^* \rightarrow {}^{16}O + \gamma(6.13\ \mathrm{MeV})$$

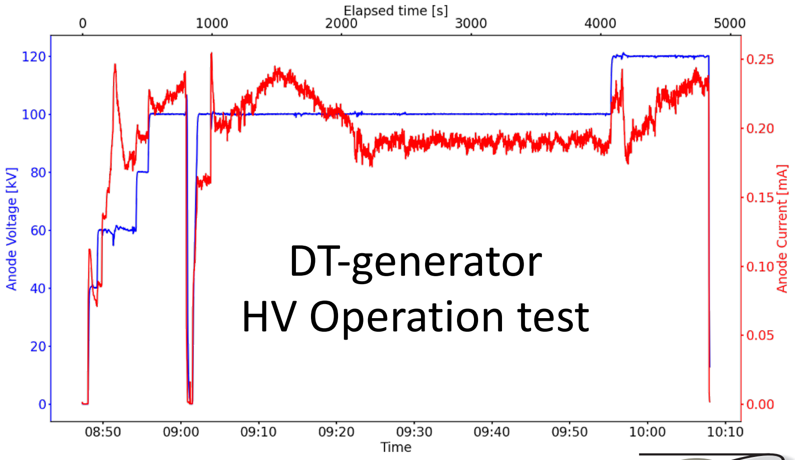
- The gammas illuminate uniformly the crystals
- Few minutes of data taking calibrate each crystal at O(%)



- 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

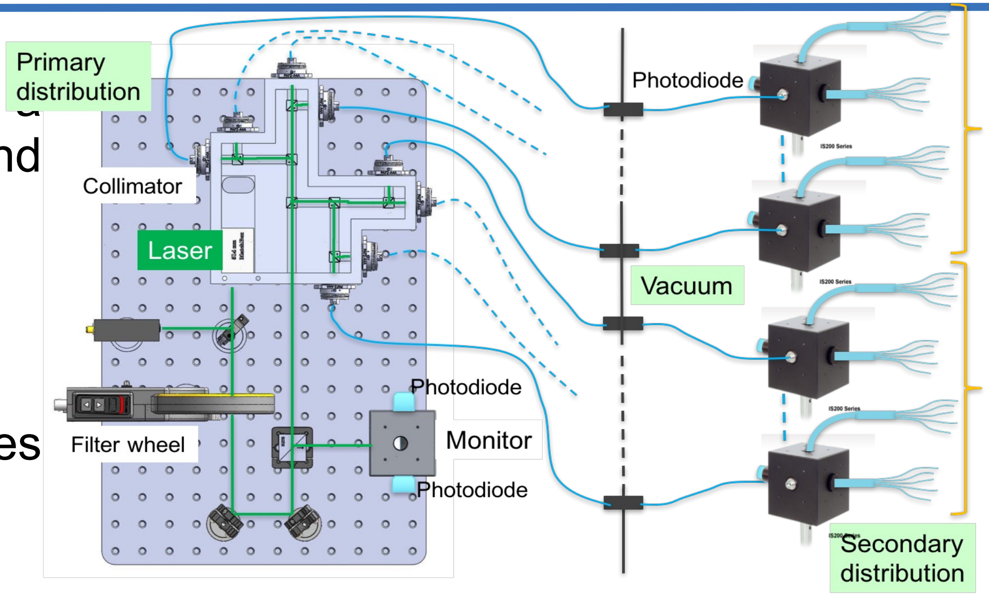


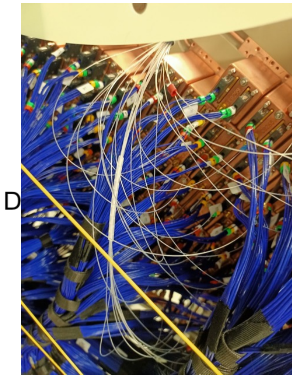


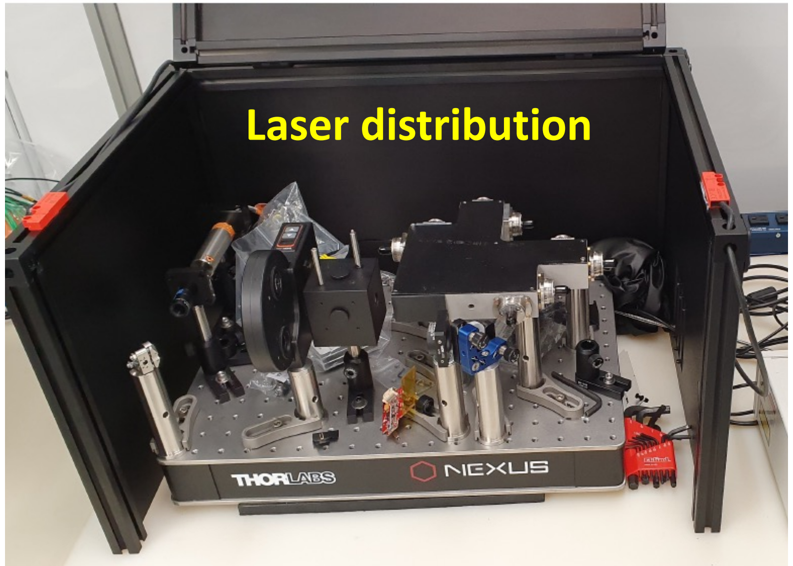


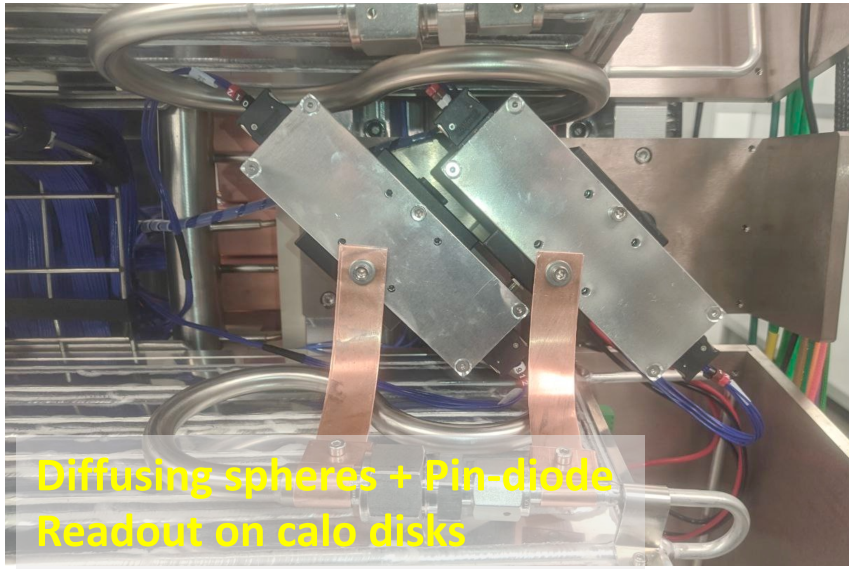
Laser calibration system

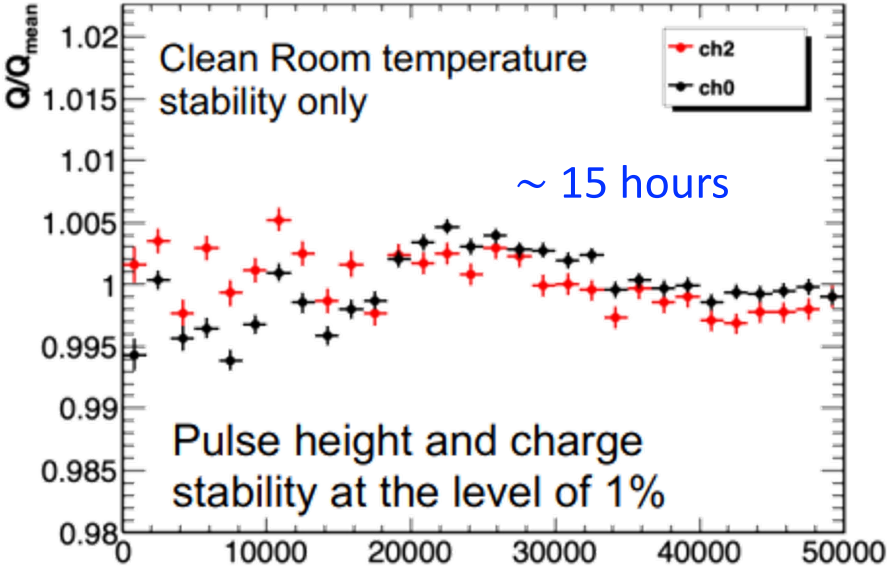
- A pulsed green laser illuminates all crystals through a distribution system based on optical fibers and integrating spheres
- Monitor gain variation at level of 0.5%
- Determine T0's at level of 100 ps
- Stability at a level of few %, monitored with PIN Diodes at laser source. Used at low rate in off-spill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







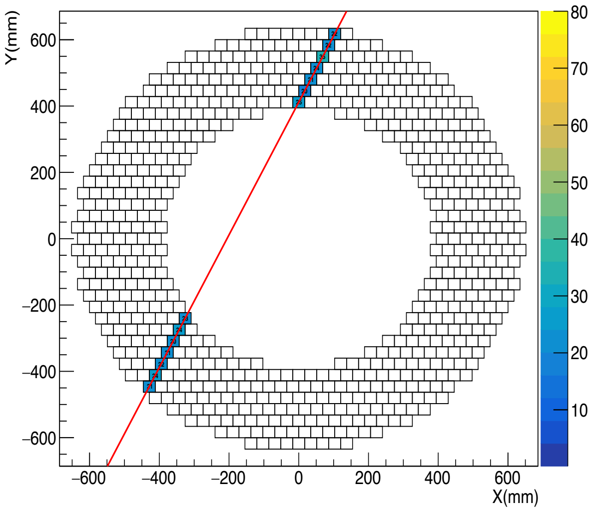


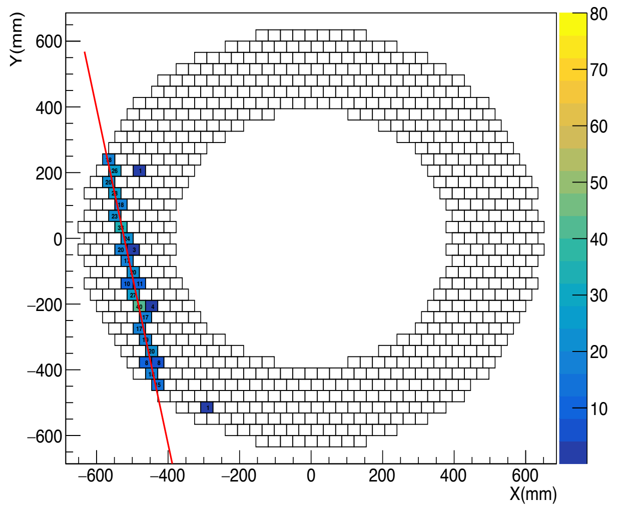


Monte Carlo studies for in-situ calibration

Calibration algorithms developed for in-situ energy and time calibration with 10h cosmic ray MC events:

- Fast calorimeter-based trigger selecting CRs crossing calo disks
- ~ 0.5% spread on energy calibration
- T_0 calibration at 15 ps level
- Npe/MeV evaluated from the response of the two SiPMs connected to the same crystal





Energy

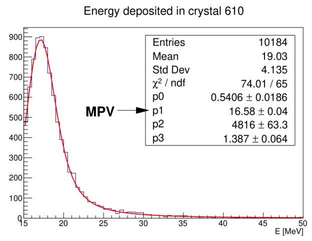
–> Gaussian MPV distribution

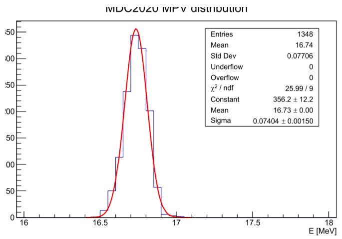
–> MPV mean value: 16.73 MeV

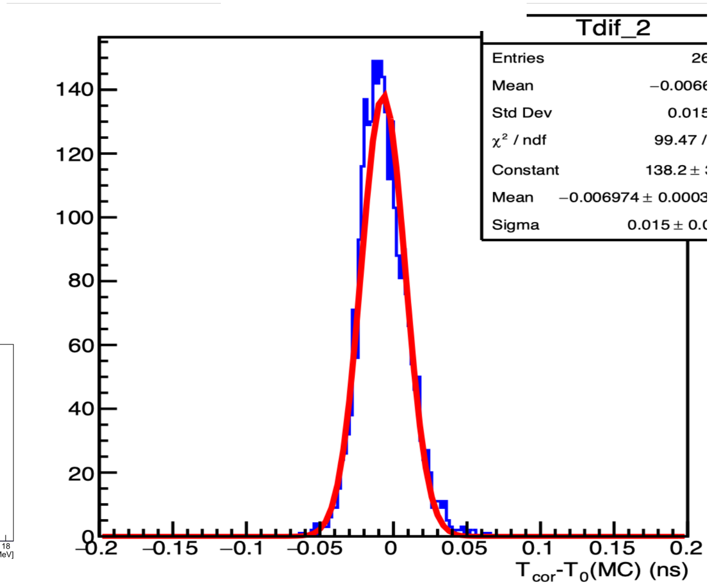
–> σ: 0.07 MeV

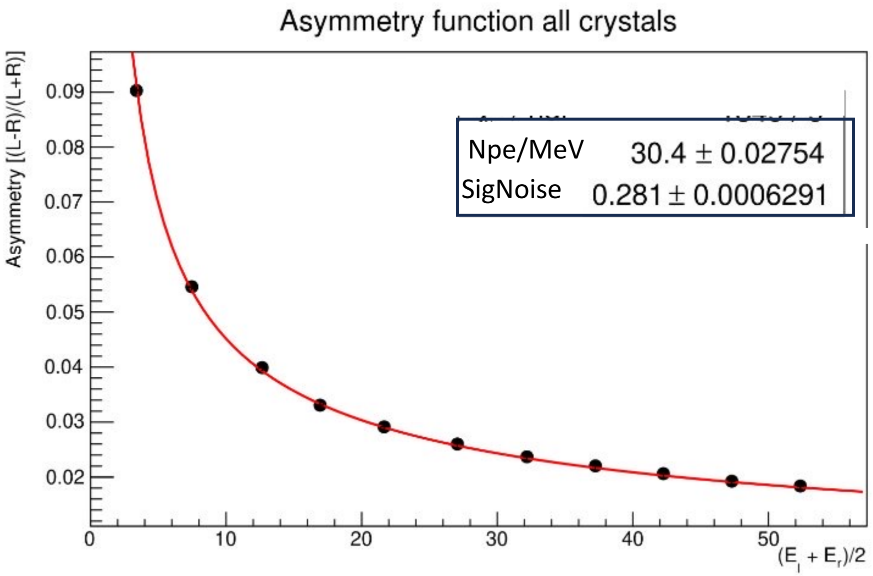
–> σ/MPV ~ 4‰

–> Energy response under investigation



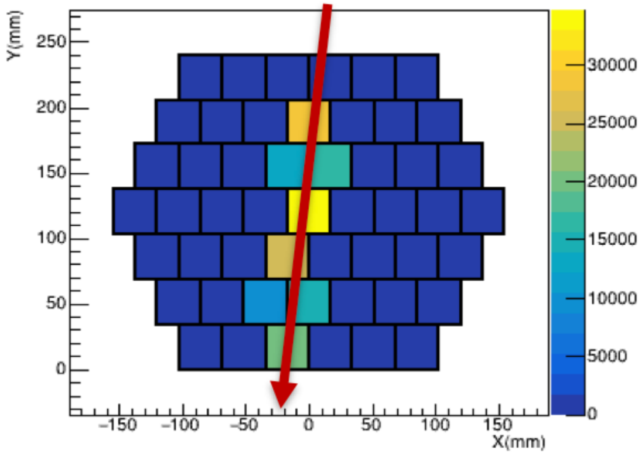


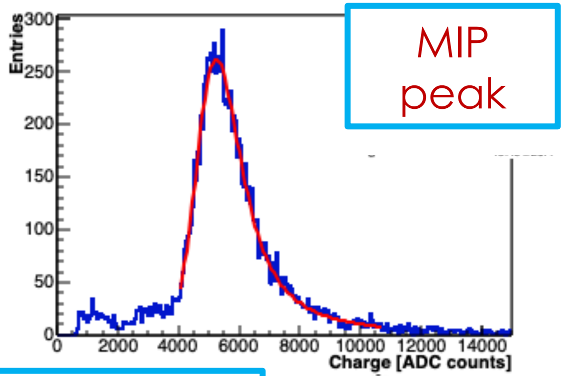


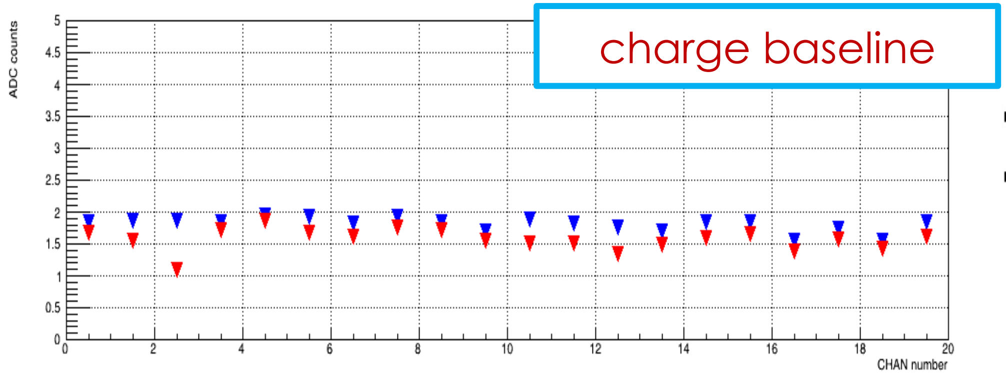


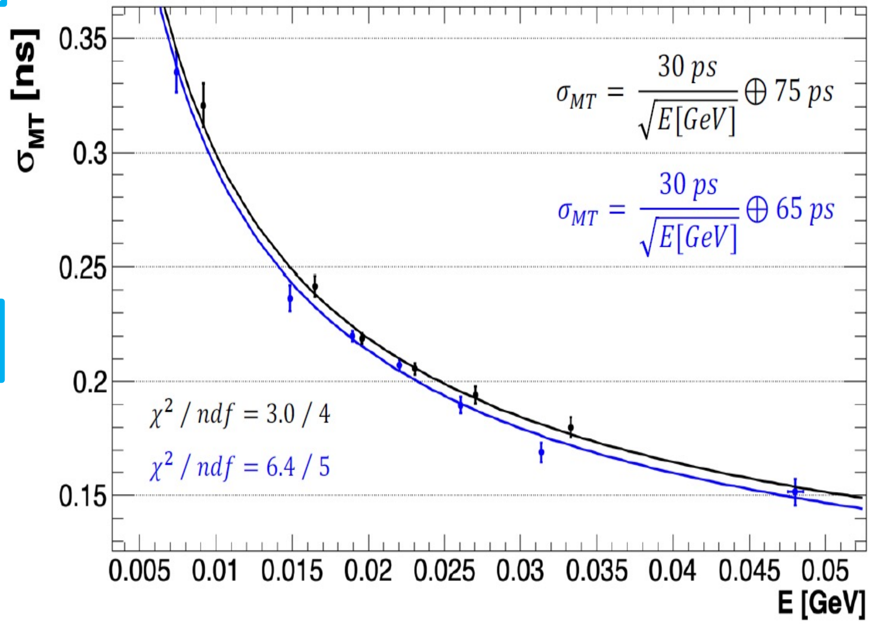
Vertical Slice Test: cosmic ray events

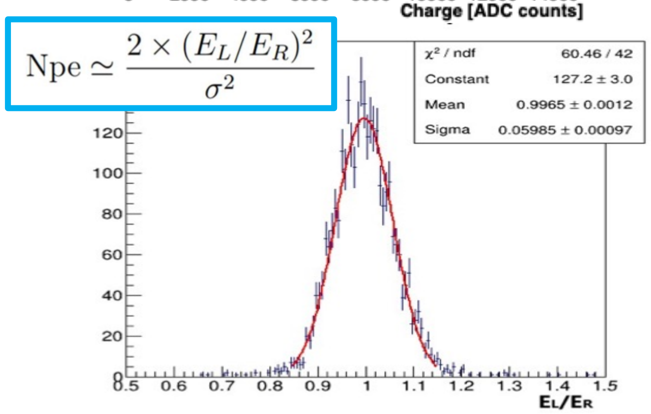
- Module-0 equipped with MZB + DIRAC v2 boards, data collected in vacuum and at low T
- CR events triggered with external scintillators, XY MIP track reconstruction
- Calo calibration & monitoring algorithms finalized with simulation and Module-0 data:
  - Energy equalisation on 21 MeV MIP peak
  - Equivalent noise ≈ 200 KeV
  - Npe and SiPM gain stability check (+1.6 % /°C for SiPM gain)
  - Improved time evaluation + timing alignment @ 15 ps level

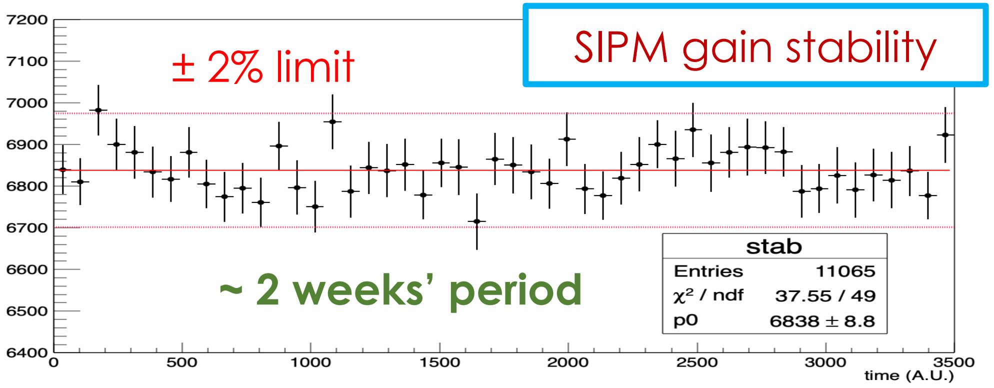








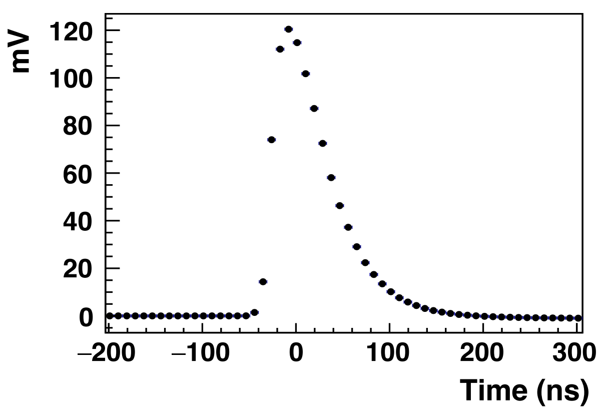


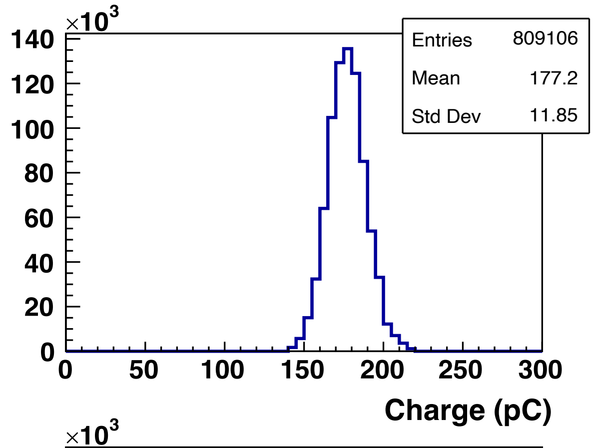


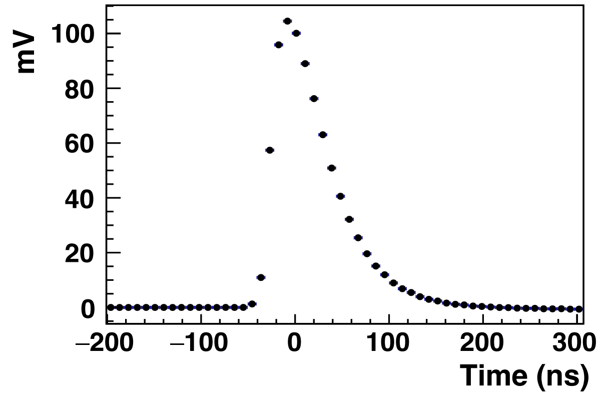
Calorimeter commissioning

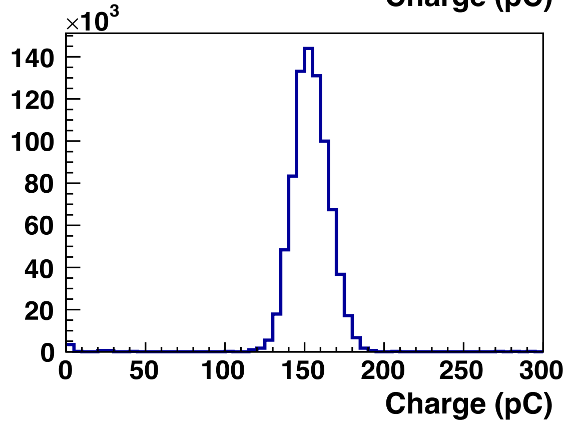
Assembly room @FNAL, commissioning of ½ disk at a time:

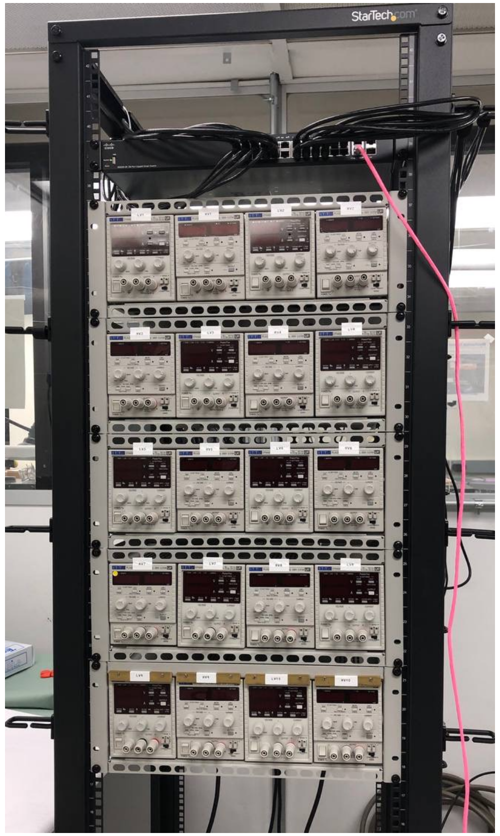
- 4 PC servers, 6 Data Transfer Controllers, TDAQ fibers
- Readout of 36 boards, Event Builder + CR trigger selection
- Calibration/Commissioning with laser + Cosmic Ray events
  Triggered by mean of scintillators taggers







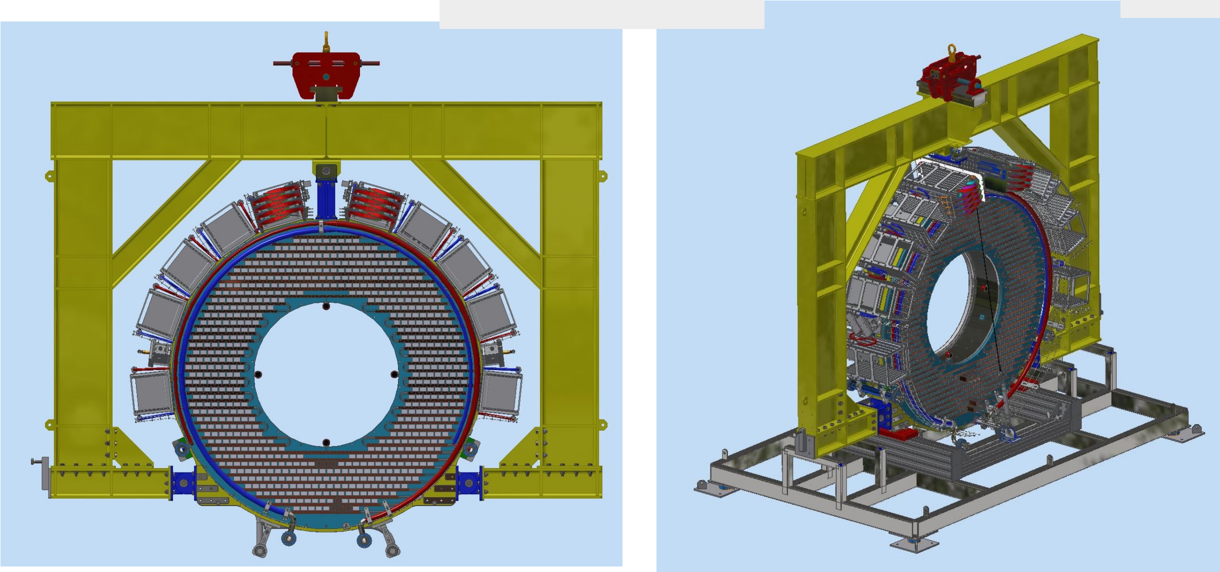




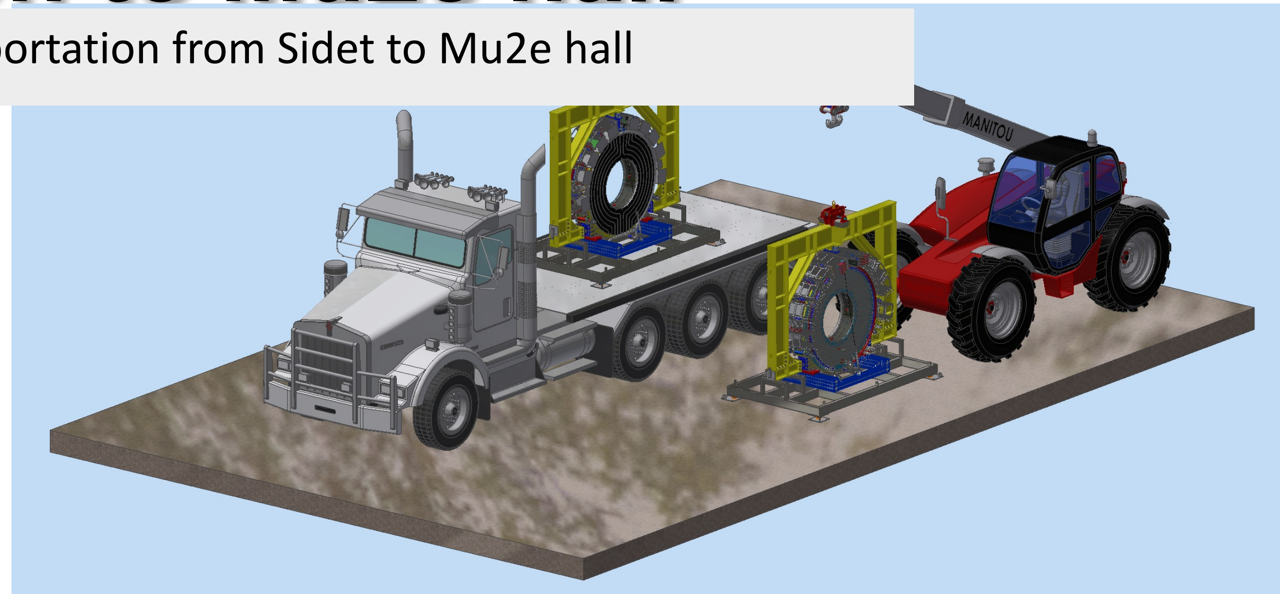
- First laser data from the fully cabled calo disk in one calorimeter sector
- After this final test, the calorimeter will be moved in the Mu2e hall (fall 2024)

Calorimeter transportation to Mu2e hall

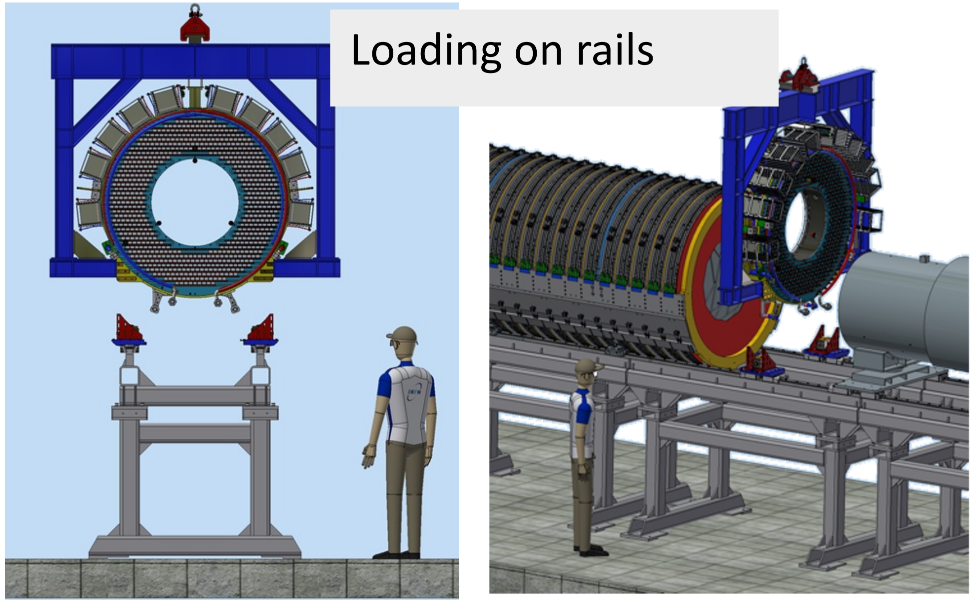
Lifting Tool



Transportation from Sidet to Mu2e hall



Loading on rails



- **Drawing of lifting tool completed**
- Preliminary discussion with Integration team and Transportation Committee carried out
- Procurement of Lifting tool underway

Conclusions

- The Mu2e calorimeter demonstrated excellent energy (<10%) and time (< 500 ps) resolution for 100 MeV electrons for PID, triggering and track seeding purposes
- Production of detector components completed, digital electronics under completion
- Successful VST proved reliable operations and performance in vacuum and at low temperature
- Calibration procedures finalized with Monte Carlo events and verified on prototype
- Calorimeter assembly in an advanced stage, including calibration system
- Final integration of the detector with the TDAQ system is underway
  - Calorimeter commissioning with cosmic ray events with 1/2 disk at a time planned
- Installation and transportation plans are progressing well
  - We expect to move the disks in the Mu2e hall in fall 2024