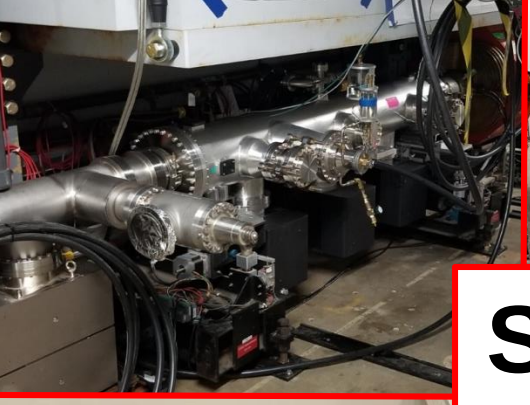
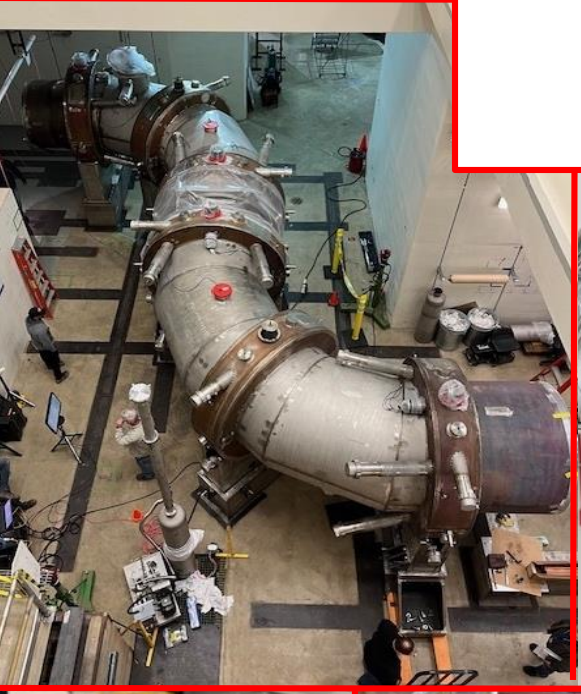


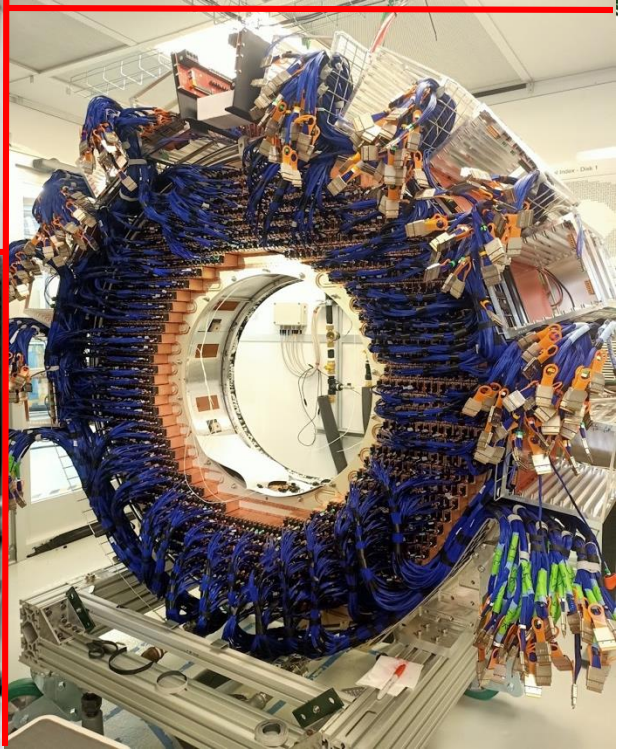

Status of Mu2e experiment

and focus on the CALORIMETER

CSN1 LNF, Sept. 25, 2024



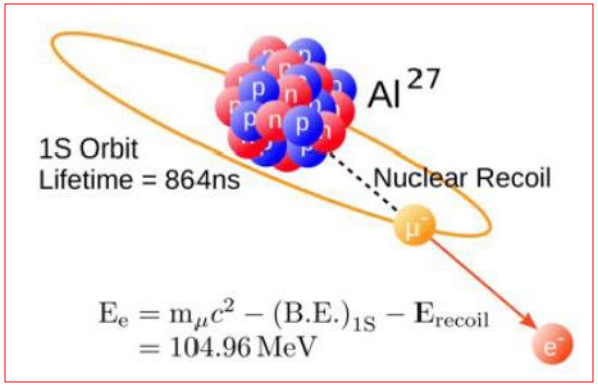


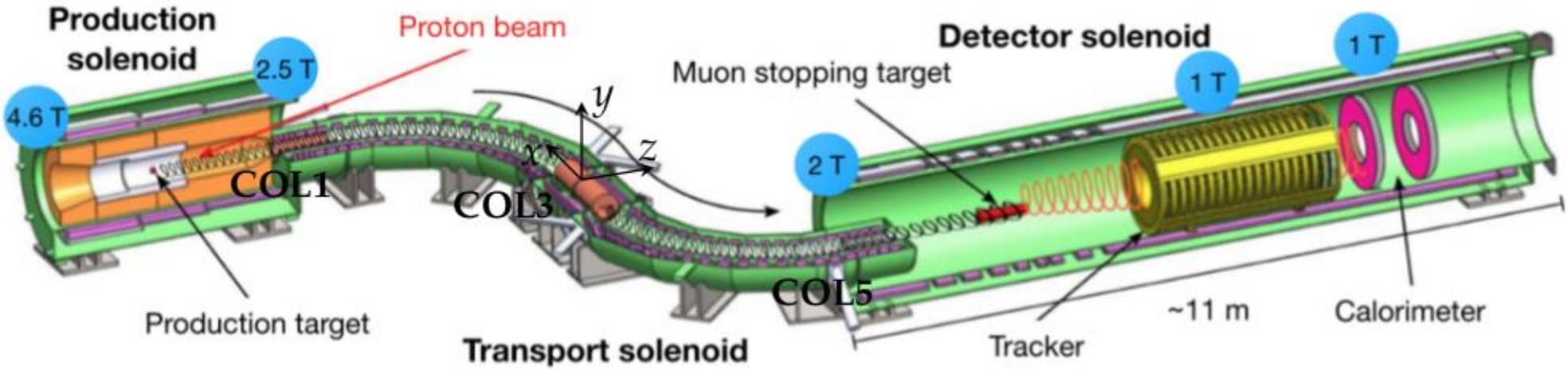



The Mu2e Experiment at Fermilab

Mu2e searches for **Charged Lepton Flavor Violation (CLFV)** via the coherent conversion:

$$m^- + Al \rightarrow e^- + Al$$





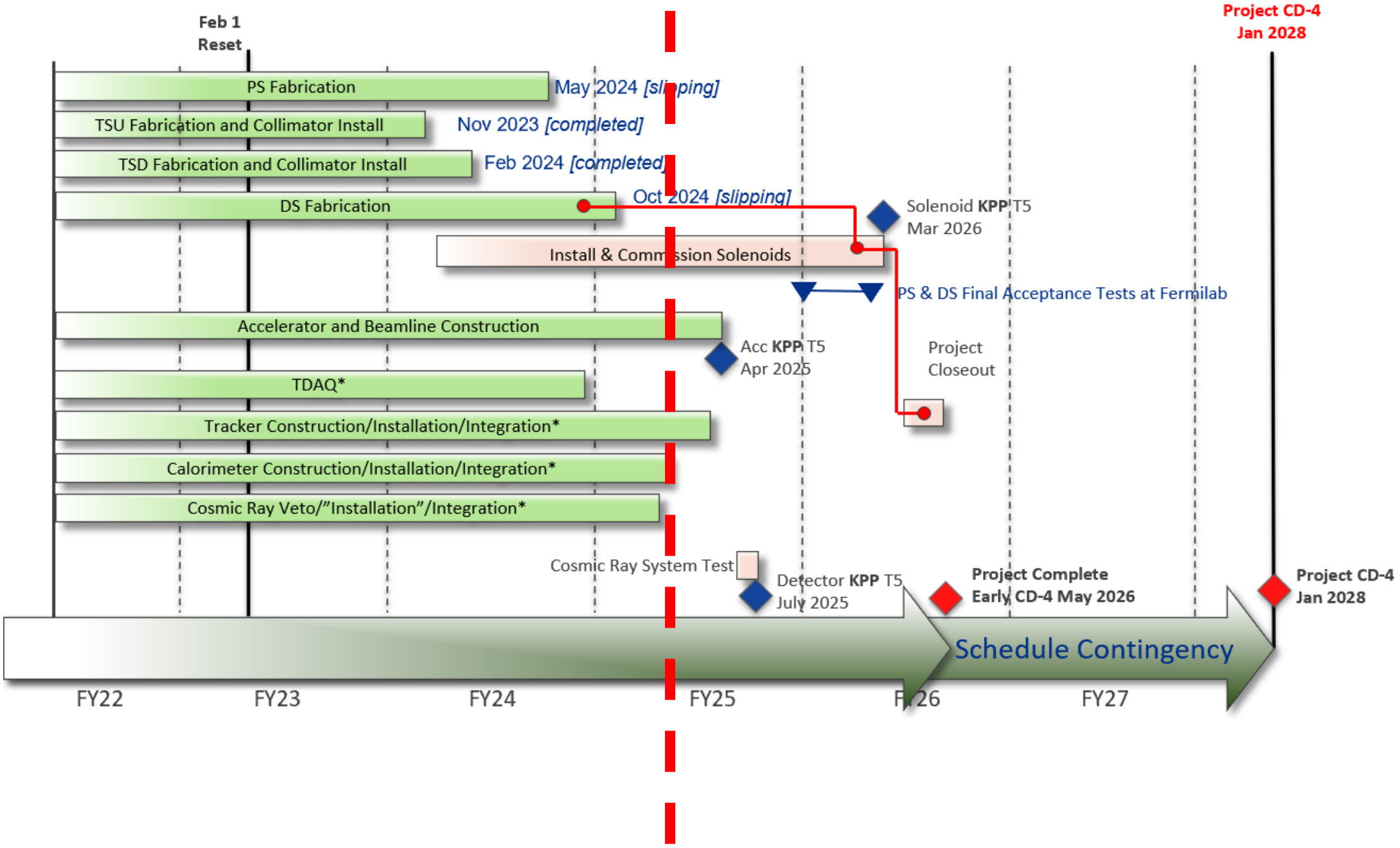
$$R_{\mu e} = \frac{\Gamma(\mu^- + N \rightarrow e^- + N)}{\Gamma(\mu^- + N \rightarrow \text{all captures})}$$

Current 90% CL limit:

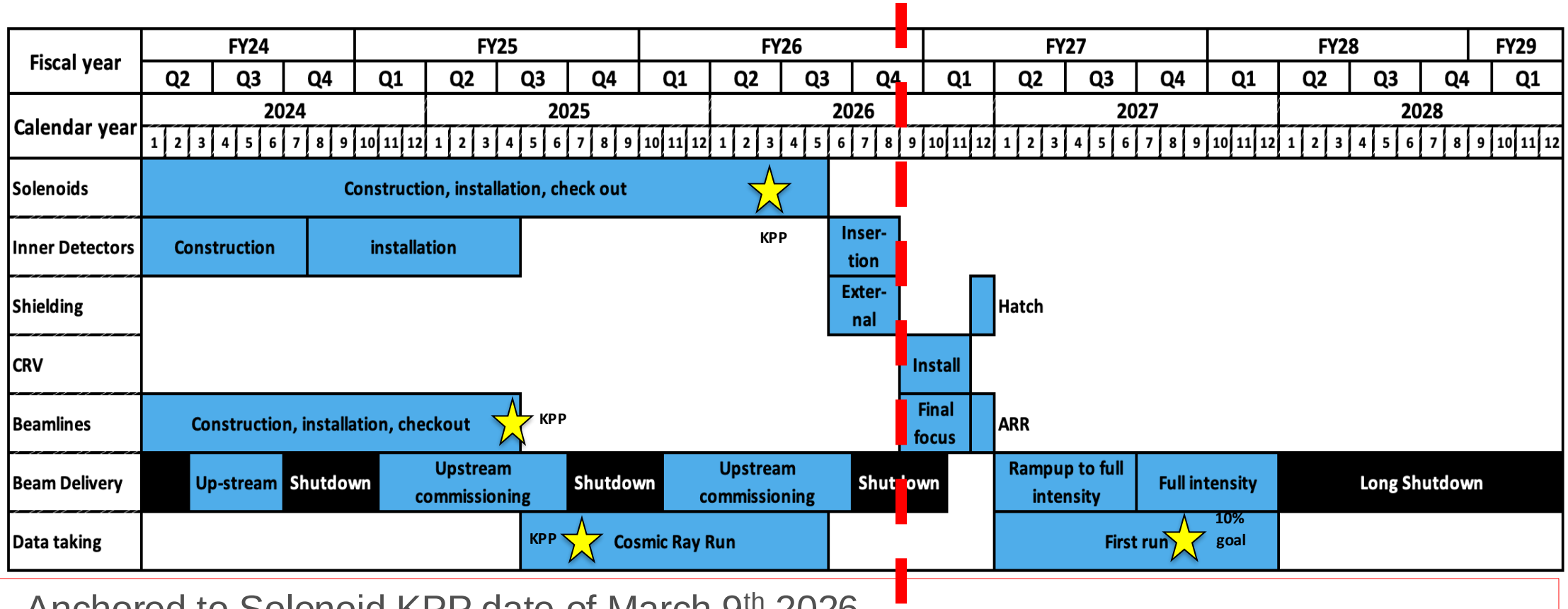
$R_{\mu e} < 7 \cdot 10^{-13}$ SINDRUM II (2006)
Bertl et al.
Eur.Phys.J.,C47,337

Mu2e goal: 5σ discovery or x10^4 limit improvement

Mu2e schedule (updated to June 2024)

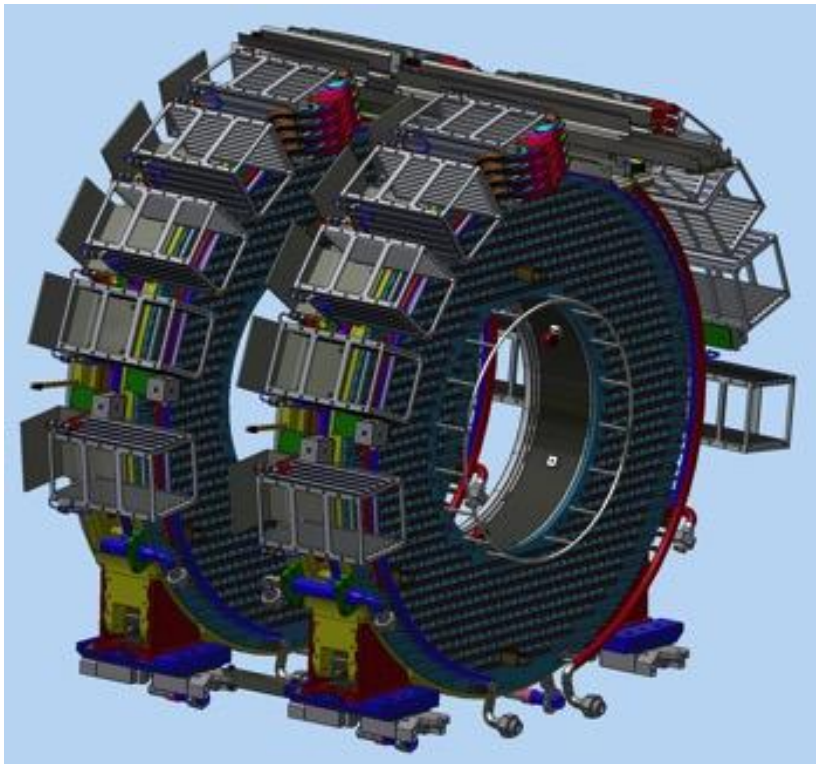


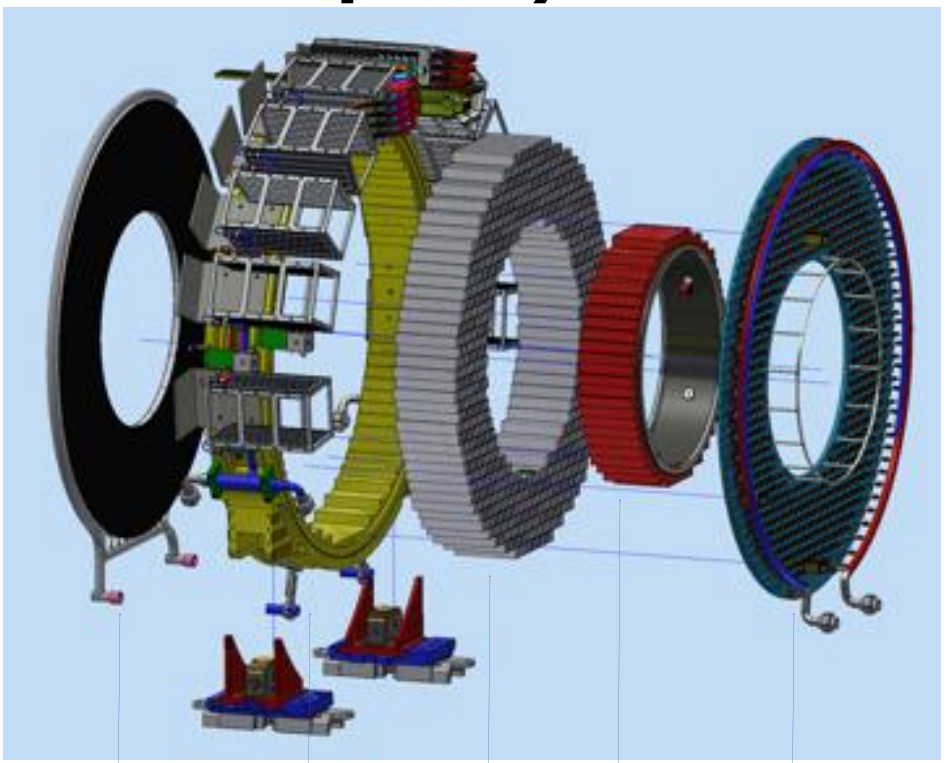
Mu2e Run Plan



- Anchored to Solenoid KPP date of March 9th 2026
- Need ~7 months after solenoids are checked out before we are ready for beam
- Dominated by installation tasks, not commissioning tasks
- **Run 1**: **need ~7 months** of beam time to commission and **get first 10% of data on tape**
- Currently have 5 months contingency to Long Shutdown based on March 2024 status
- **Run 2** after Long Shutdown to reach the final sensitivity goal

Calorimeter (91% complete)





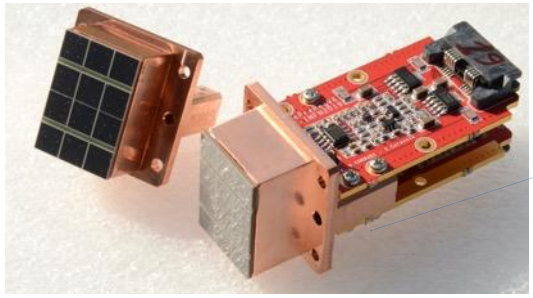
2 disks each consisting of
- 674 pure CsI crystals
- 1248 SiPMs+FEE boards

6 MeV Calibration source

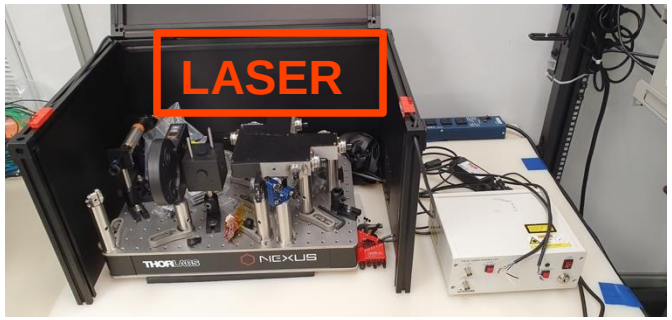
External crystals ring

Inner ring

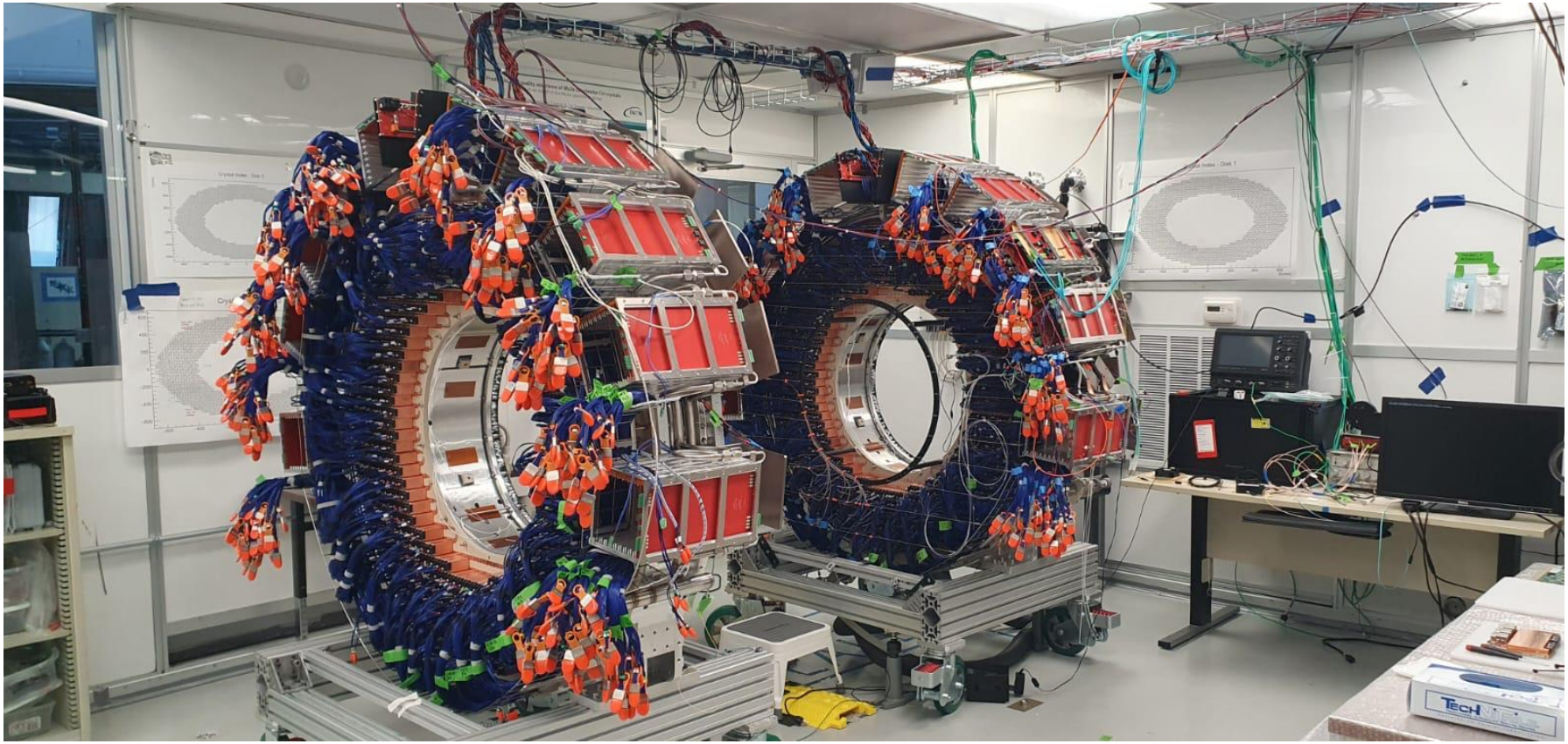
Back plane with SiPM housing and cooling lines



Hole for laser calibration



Calorimeter Disks status



- **Crystals and SiPMs+FEE readout units and electronics crates installed**
- **A quick leak test of the cooling system done**
- **Cable routing from FFE to crates completed**
- **All readout units tested with laser pulses**

Next activities in 2024:

- July: install electronics in crates

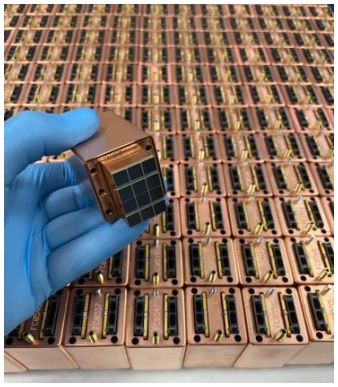
- Jul-Sep: run with cosmics (DAQ test)

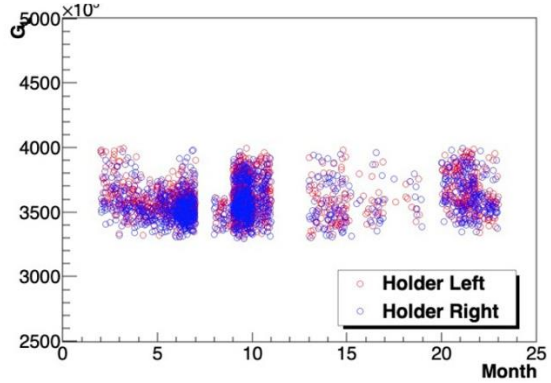
- Sep: complete laser system

- Dec: move Disk 1 to Mu2e Hall

Procurement and installation: ROU and MZB

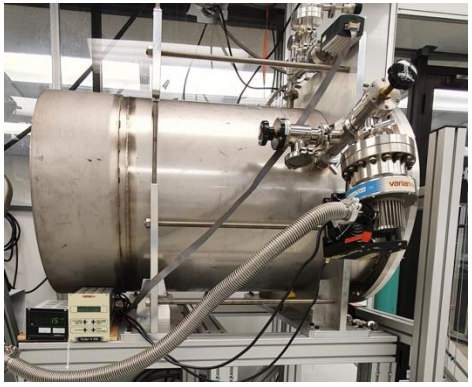
- All crystals, SIPMs and FEE boards procured
- All ROU (SIPM+FEE) tested and installed





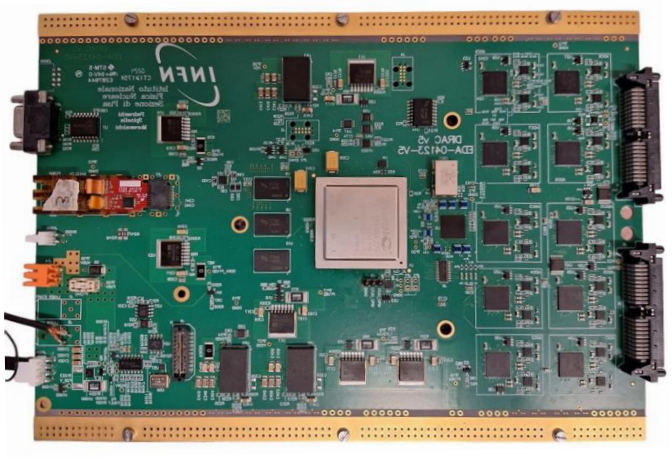
- All Mezzanine Boards (HV and slow control) procured
- Burn in + QC successfully tested
- 90 MZB already at FNAL + 80 shipped last week to FNAL

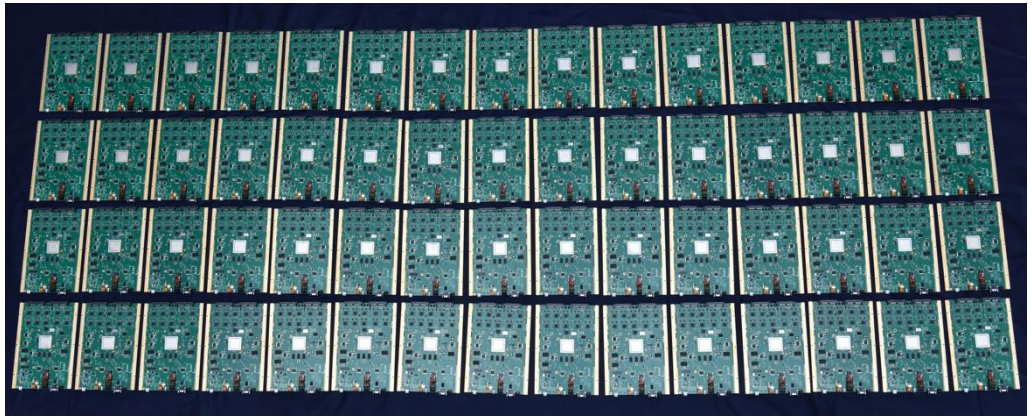
- Radiative shields integration with thermal grease and outgassing (Jul-Sep 24)
- Installation in crates completed by mid Oct 24

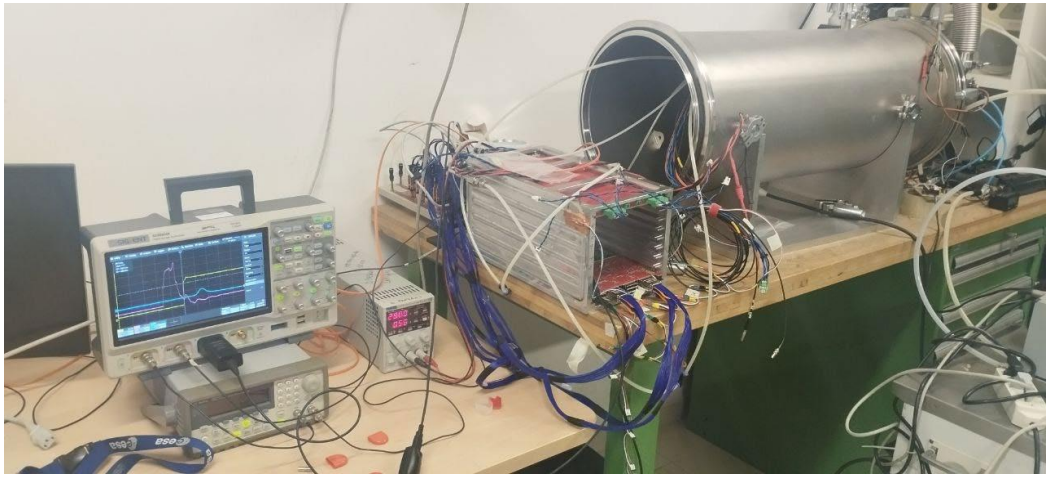


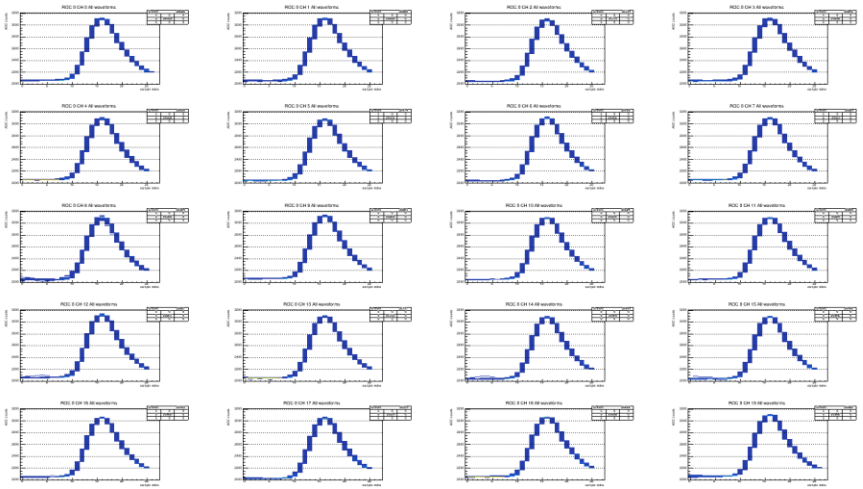
Procurement and installation: DIRAC boards

- 70 DIRAC boards already tested and sent to FNAL
- Remaining 60 at FNAL in Sep 24
- Radiative shields integration with thermal grease and outgassing (Jul-Sep 24)
- Installation in crates completed by mid Oct 24
- Successful vertical slice test in a vacuum vessel with 20 channels

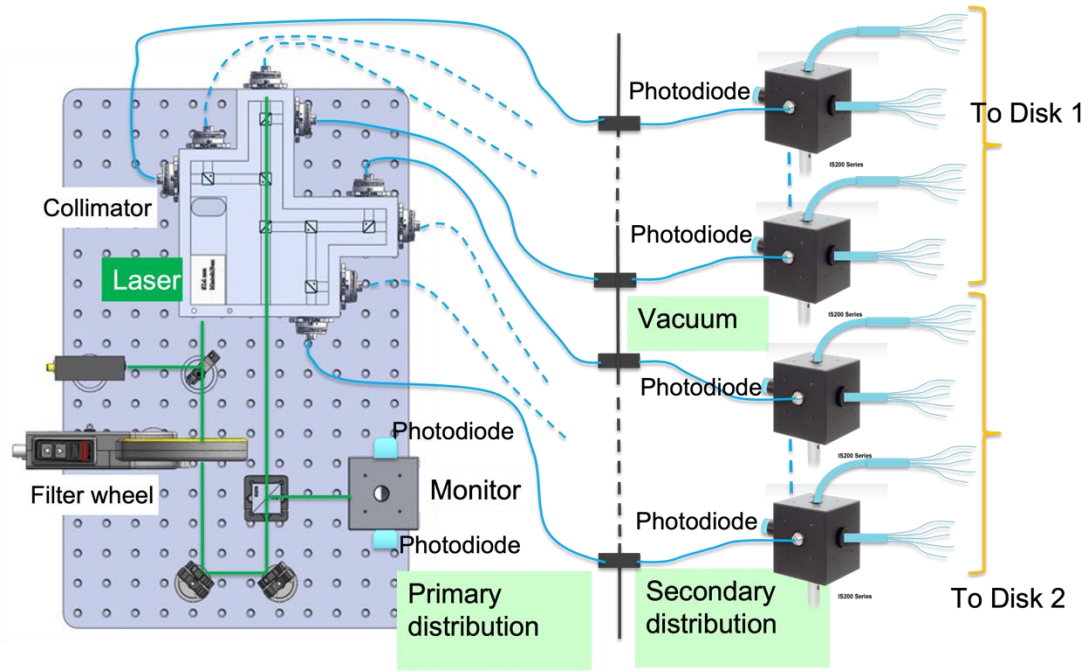




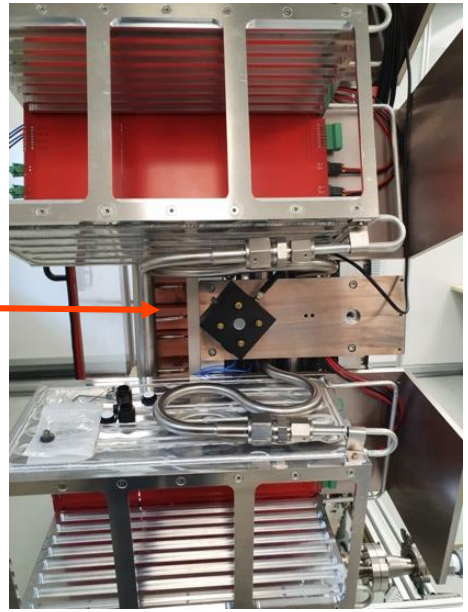




Procurement and installation: Laser System



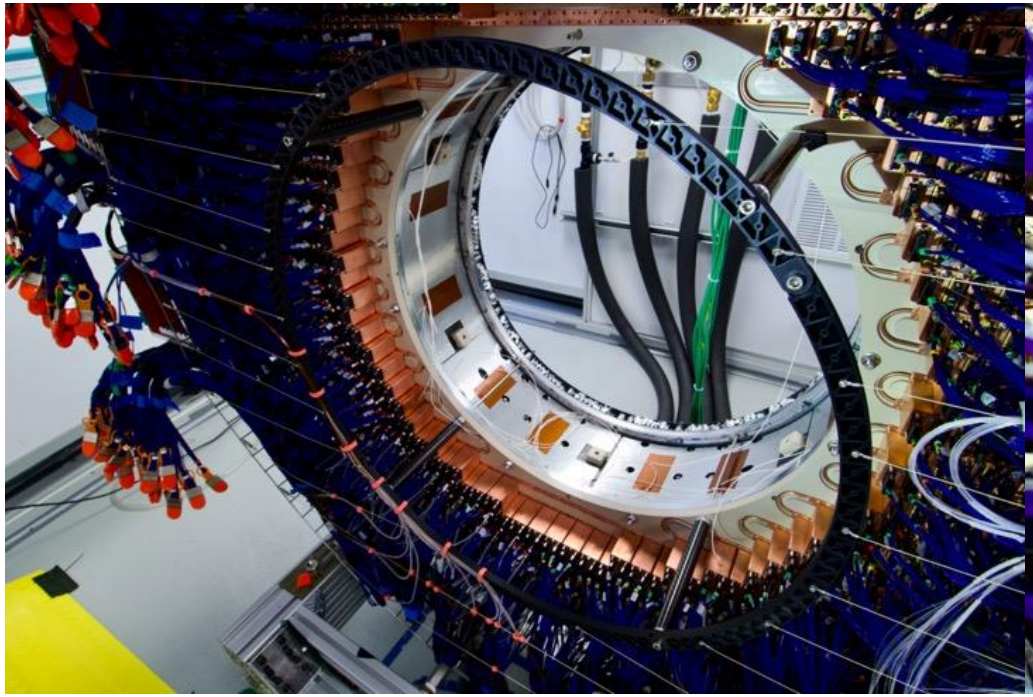
A pulsed green **laser** will be sent to each crystal through a system of diffusive spheres and optical fibers. PIN diodes will check the system stability

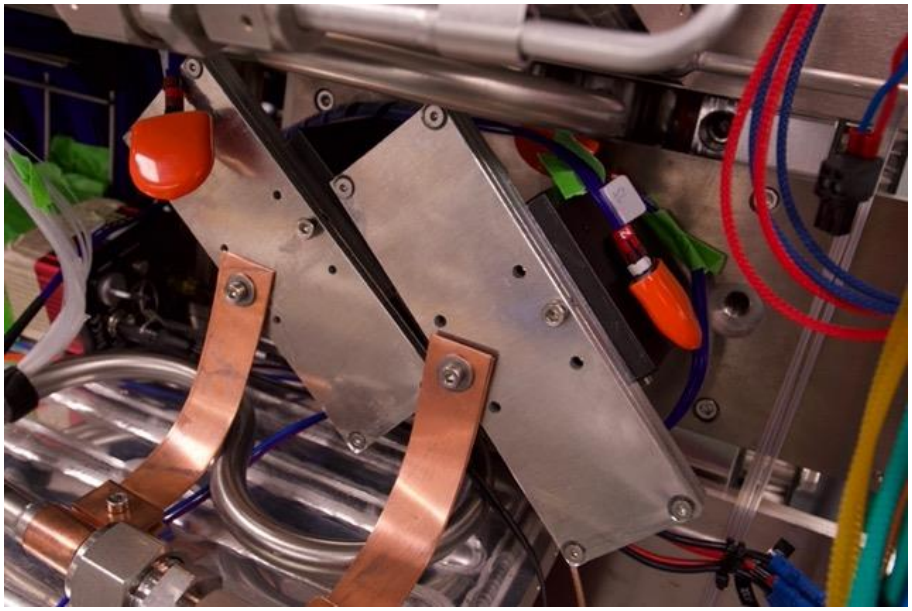


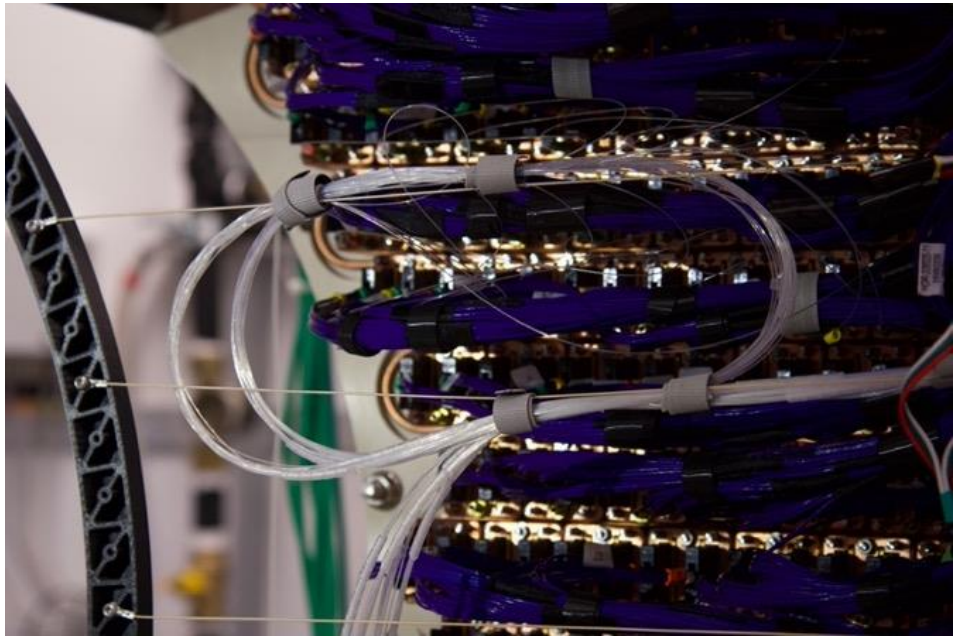
Innolas picolo Laser

Laser Head used for tests died.
Repaired using spare parts.

More reliable Laser Head identified.
Procurement should be postponed to ensure the guarantee to be valid during Run 1.
A spare should be used to check the final system



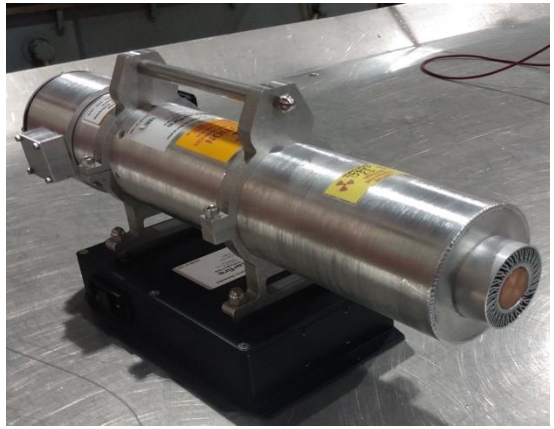




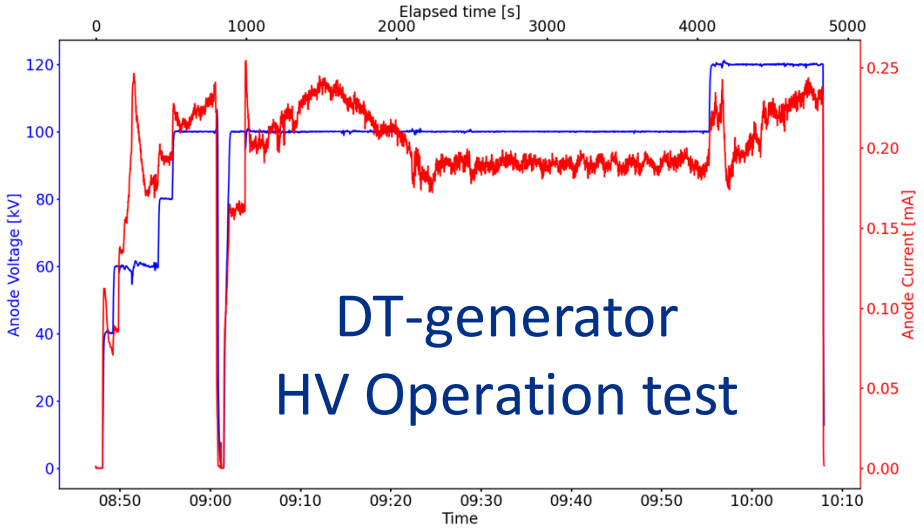
Additional calibration: radioactive source

n from DT-generator irradiating Fluorinert liquid provide absolute calibration at 6.1 MeV

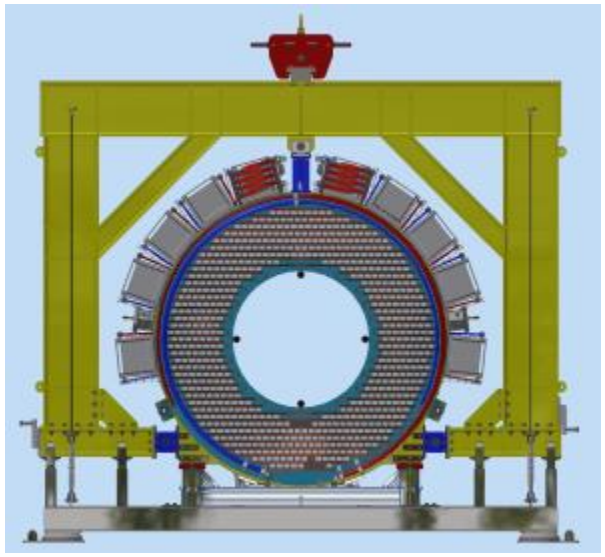
$$^{19}F + n \rightarrow {}^{16}N + \alpha$$
$$^{16}N \rightarrow {}^{16}O^{*} + \beta \quad t_{1/2} = 7\ s$$
$$^{16}O^{*} \rightarrow {}^{16}O + \gamma(6.13\ MeV)$$

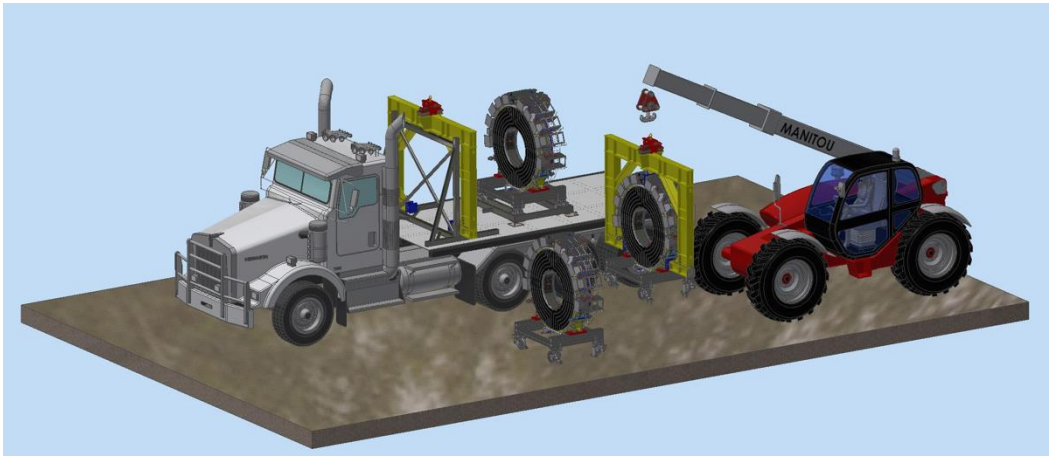


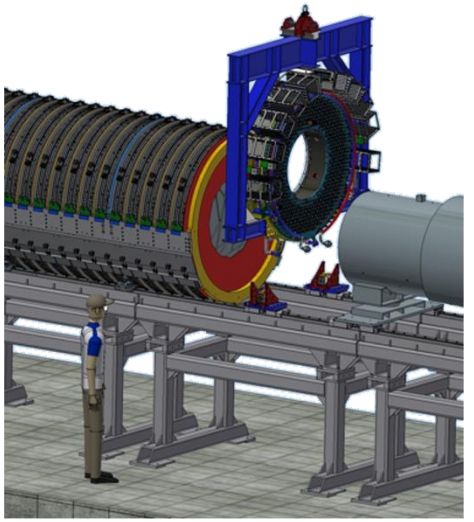
- Source DT generator installed in Mu2e hall in its ”cave“ in 2022
- Plumbing inside the cave completed
- Final shielding completed in 2023.
- DT-generator HV operated up to 120 kV confirming expected neutron yield
- ESH radiation survey performed in 2023 /2024 well within limits



Moving the calorimeter to the Mu2e building



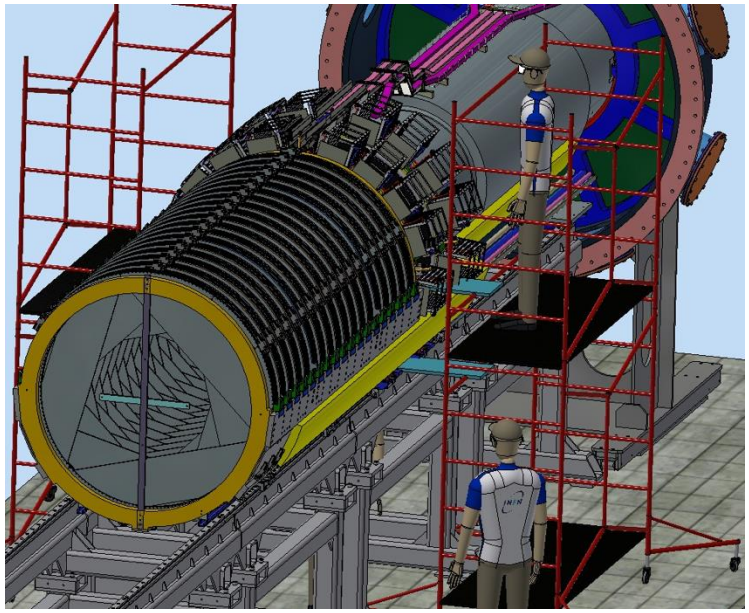


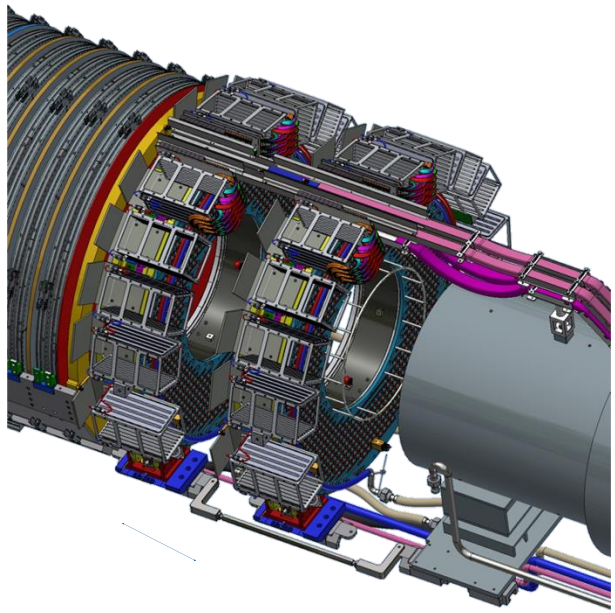


Transportation plan judged robust by the Independent Project Review of Last June

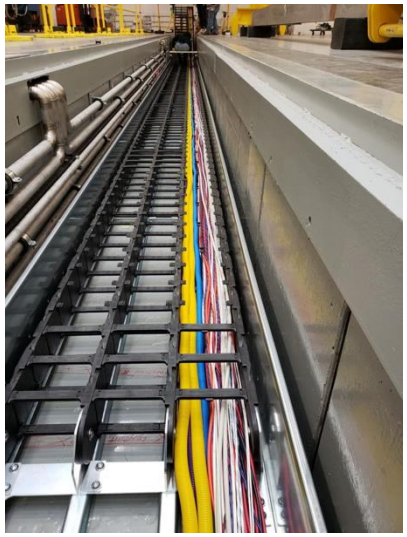
Coldest winter months should be avoided for moving (no Dec or Jan)

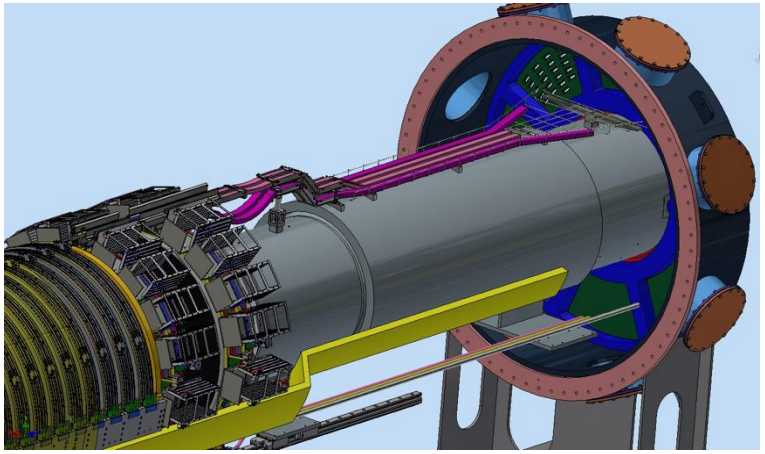
Additional tools needed to work on the calorimeter in Mu2e Hall and to move the first disk with respect to the second





Calorimeter services in Mu2e building



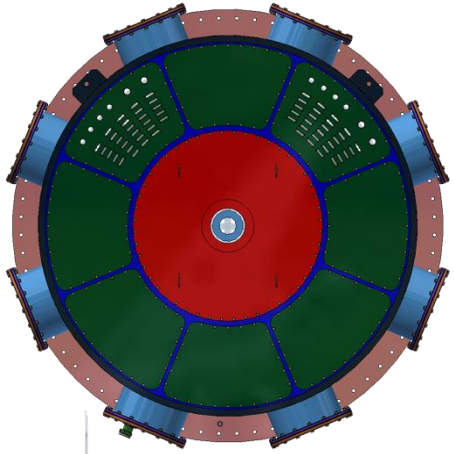


All LV/HV power supplies installed in TDAQ room

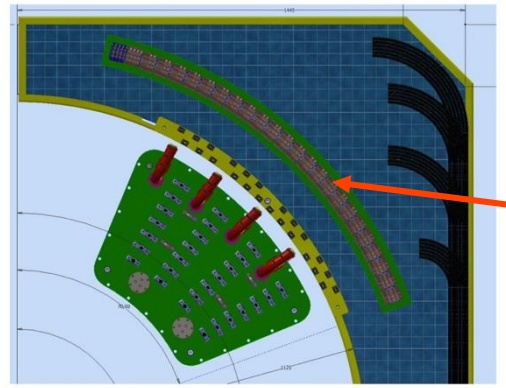
All services cables routed

Cable tray to be installed after Muon Beam Stop (beginning of 2025)

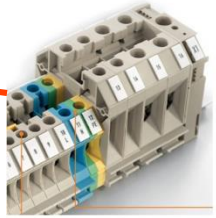
Important contribution to cabling from italian technicians



Instrumented Feedthrough Bulkhead (IFB)

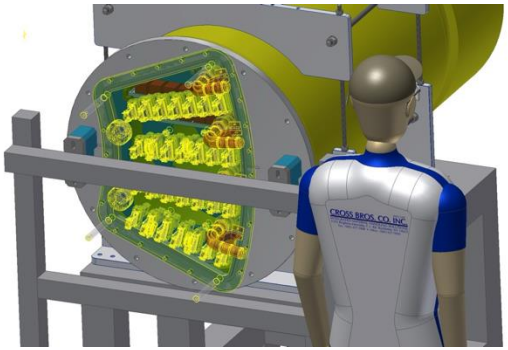


Terminal blocks



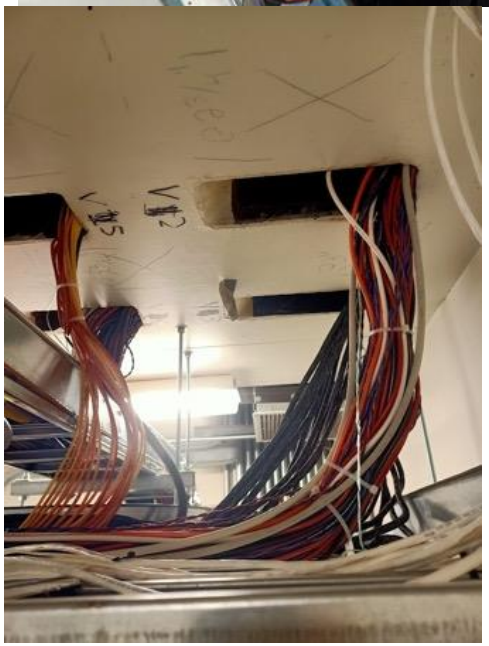
Design of IFB calorimeter flange completed

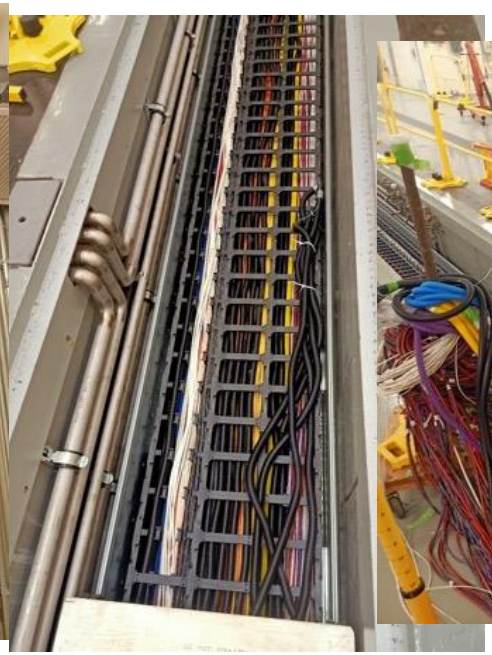
Terminal blocks on Transition Box procurement underway

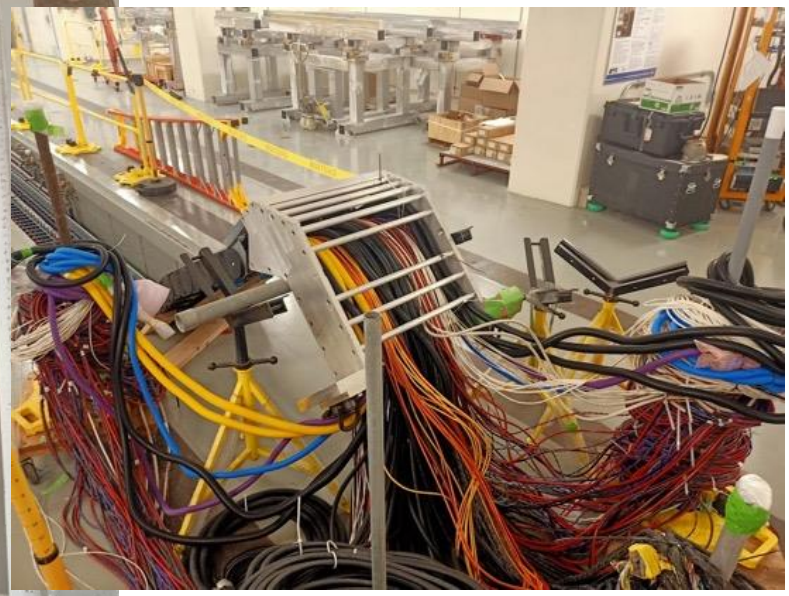


Interlock and PLC control for cooling, power, vacuum, and Inner Ring temperature control to be completed

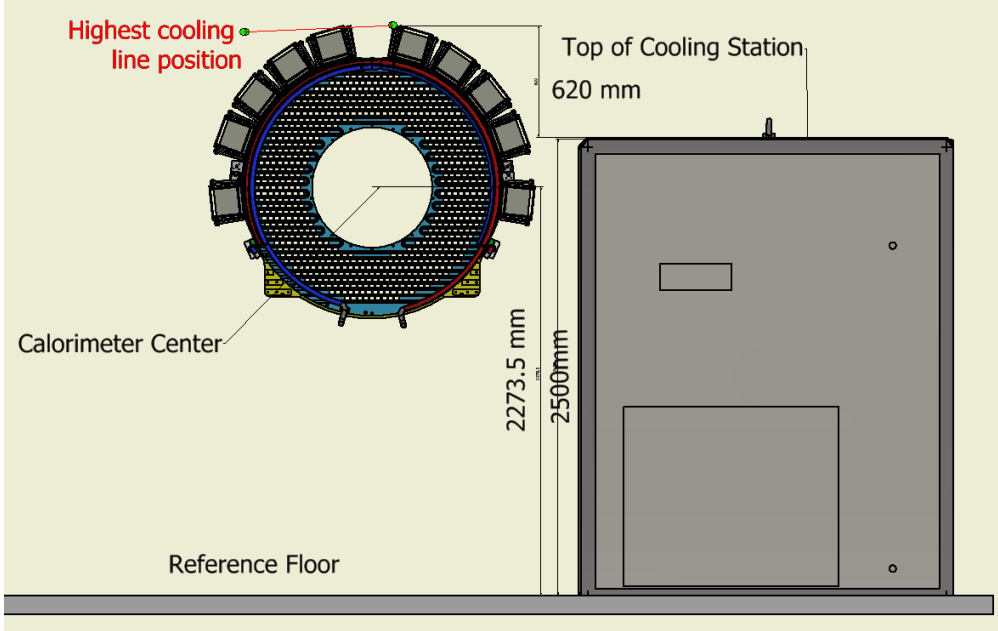
Service HV/LV cables installation





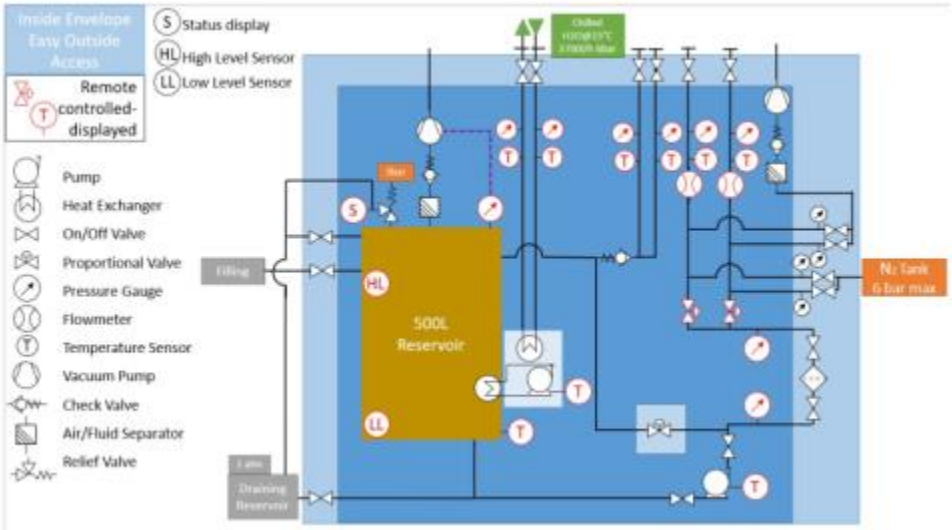


Calorimeter cooling station



A cooling station dedicated to the calorimeter will be located in the Mu2e building

A coolant liquid at -22º C will circulate in two indipendent cooling lines:
- to keep SiPMs at -10º C
- to keep all the electronic boards components below 50º C



Technical design and procurement plan completed. Engineering design procured.

Order to be placed in 2024

Common effort INFN-Mu2e Project:

Significant extra-cost: O(100k€)

Can partly be mitigated using in-kind contribution to Common Funds

Requirements:

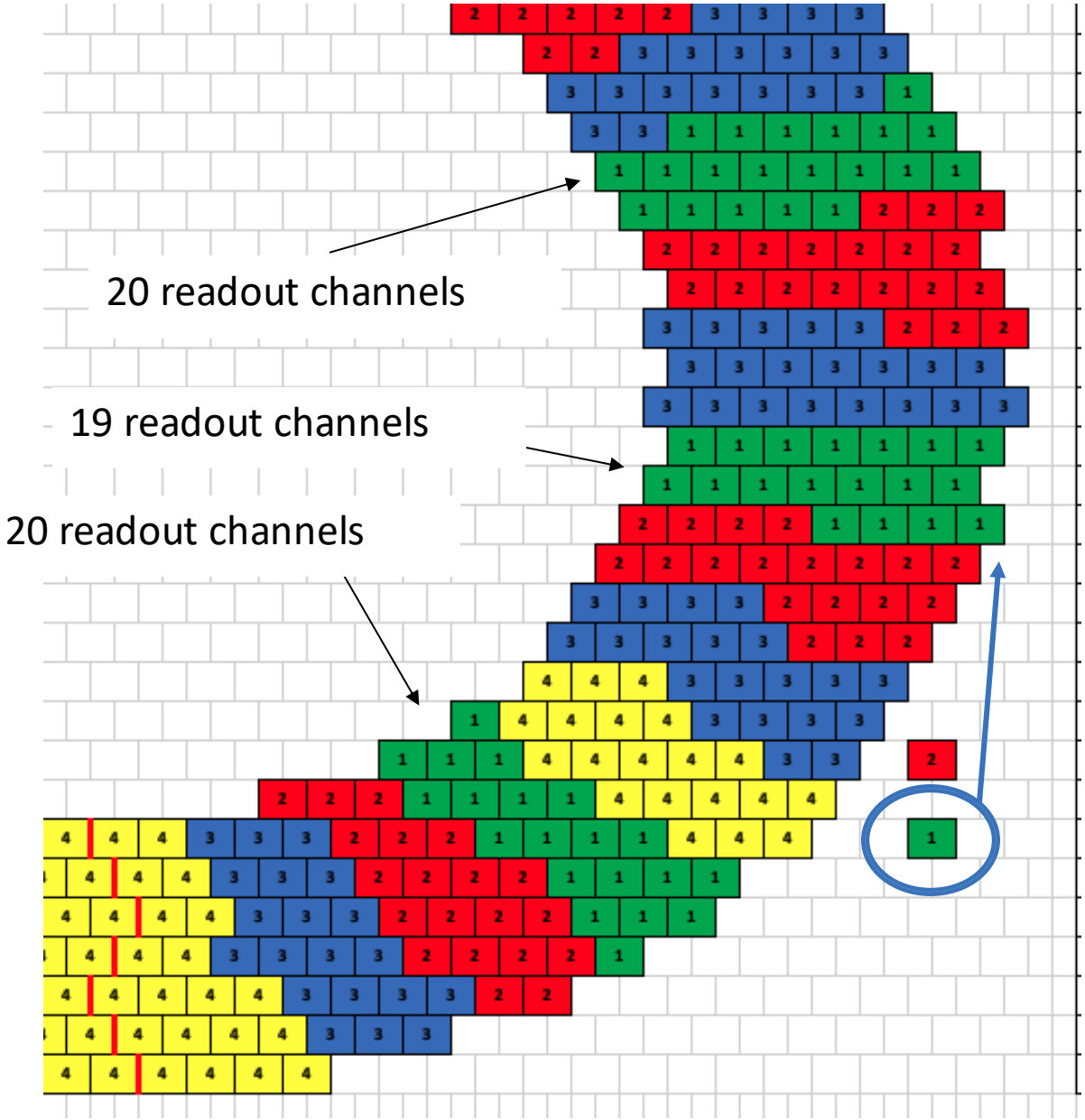
1. Operation during commissioning, at 15 °C, total power (TP) of 5.4 kW;
2. Operation at low power at standard low temperature, -12 °C, TP=5.4 kW;
3. Operation at high power and lowest possible temperature, -22 °C, TP=6.6 kW.

Installation in second half of 2025:

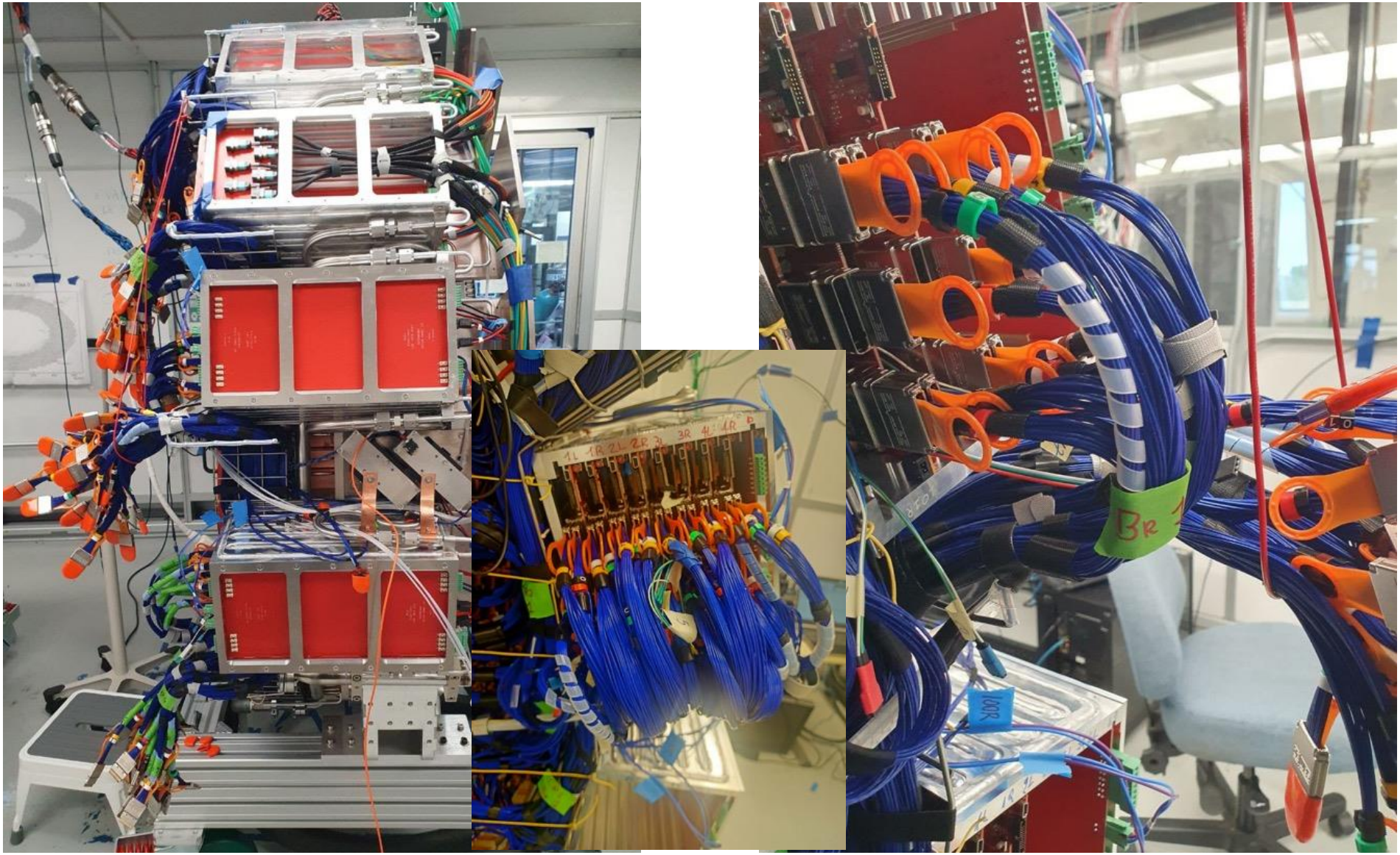
Backup solution needed to operate the calorimeter before that

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

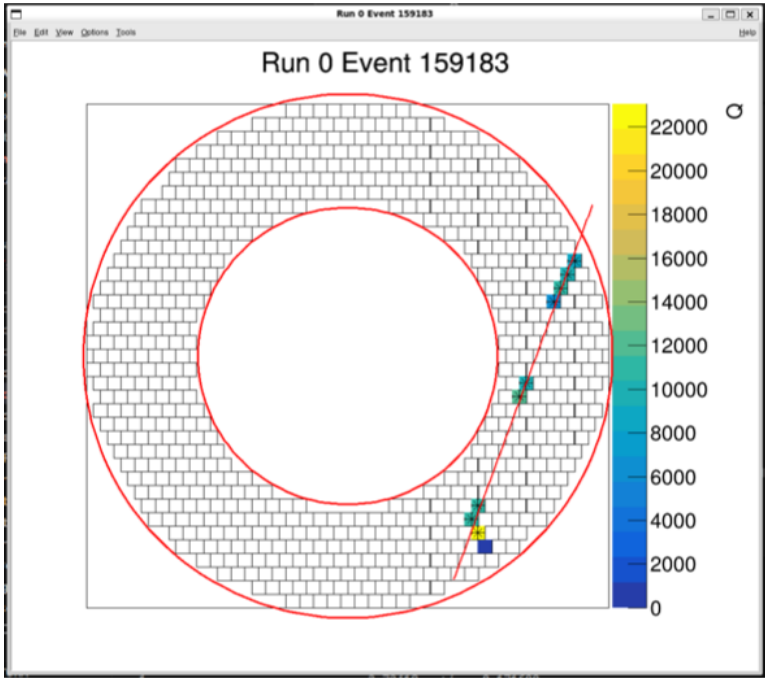


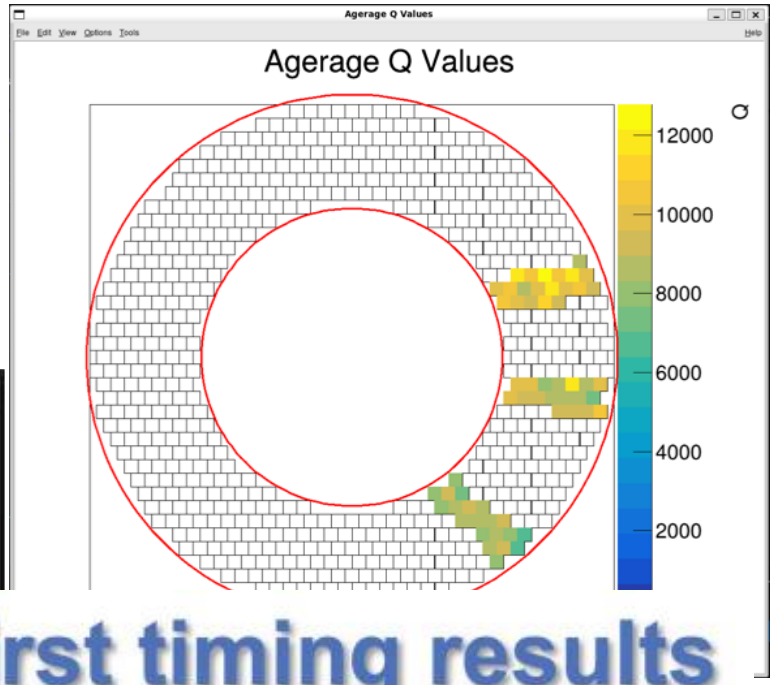
first boards insertion and connection



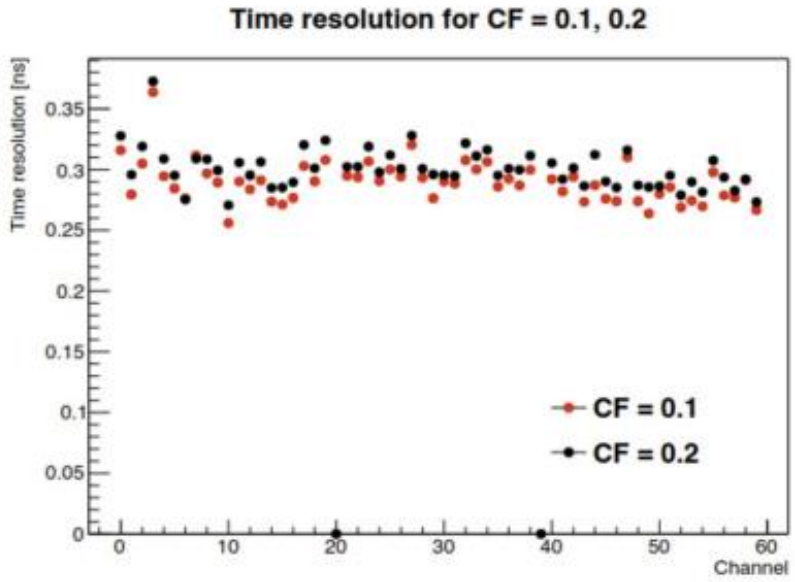
First Results: amazing

- 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

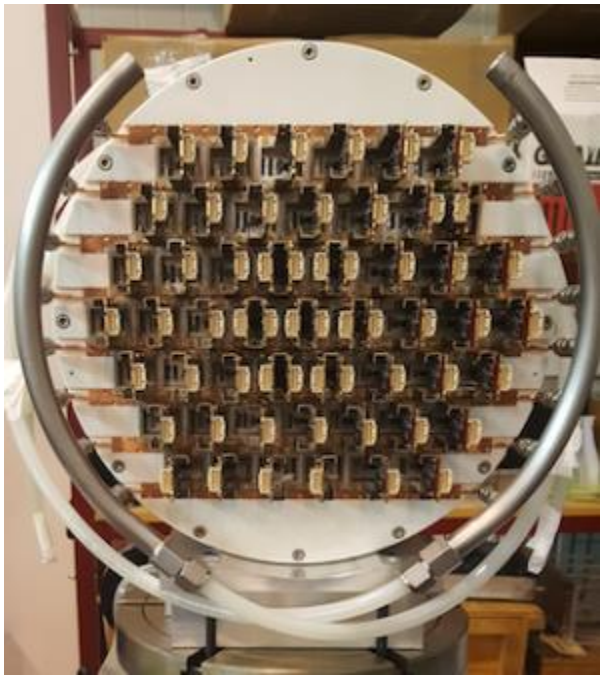




First timing results

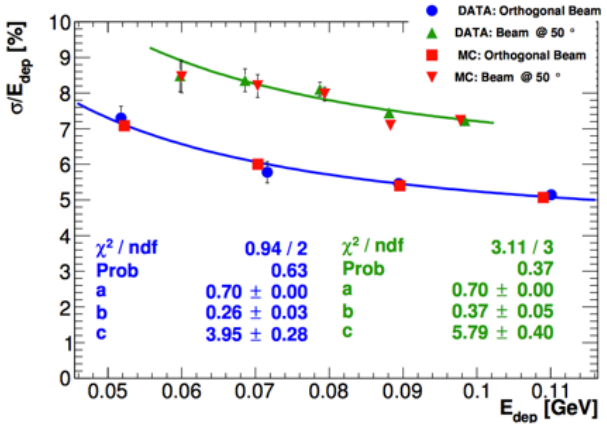


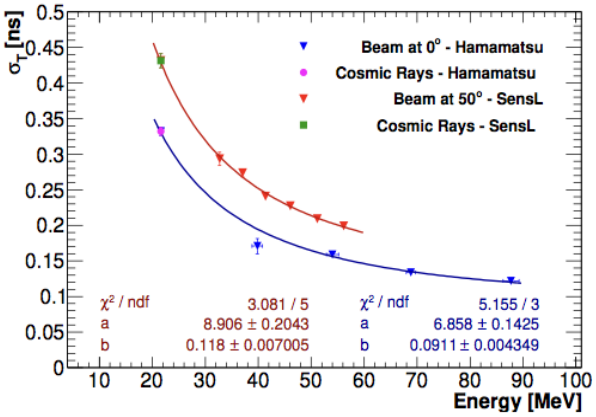
2025 Activities: module 0 test beam



2017 Test beam results

(doi:10.1016/j.nima.2018.09.043)





Calorimeter module 0 contains 51 production crystals and is equipped with final SiPMs, FEE boards, electronic crate and cooling lines.

It’s important to update the results of 2017 test beam (with non final components) to establish the response to electron and photons in the energy range relevant to Mu2e.

No time to do it in 2024. First choice for 2025 would be MAMI@Mainz

Italian (LNF) responsibilities in Mu2e

L1 Stefano Miscetti: Mu2e **spoke person**

Executive Board members : Stefano Miscetti (ex officio), Caterina Bloise

Mu2e Project

L2 Stefano Miscetti: **calorimeter project**

L2 deputy Fabio Happacher: **calorimeter project**

L3 Simona Giovannella: calorimeter crystals

L3 Fabio Happacher: calorimeter mechanics

L3 Fabrizio Raffaelli: calorimeter mechanics

L3 Luca Morescalchi: calorimeter photosensors

L3 Eleonora Diociaiuti: calorimeter photosensos

L3 Franco Spinella: calorimeter digitizer

L3 Elena Pedreschi: calorimeter digitizer

L3 Carlo Ferrari: calorimeter calibration

L3 Sergio Ceravolo: calorimeter front end electronics and power supply

L3 Alessandro Saputi: calorimeter assembly and installation

L3 Ivano Sarra: calorimeter assembly and installation

Transition to operations

L3 Simona Giovannella: **calorimeter operations**

L3 Luca Morescalchi: **calorimeter operations**

L3 Stefano Di Falco: **Mu2e simulation convener**

Summary and conclusions

A lot of progresses in construction and installation of Mu2e at Fermilab: things look more and more real!

2025 will be devoted to detector integration and Calorimeter and Tracker commissioning with cosmic rays

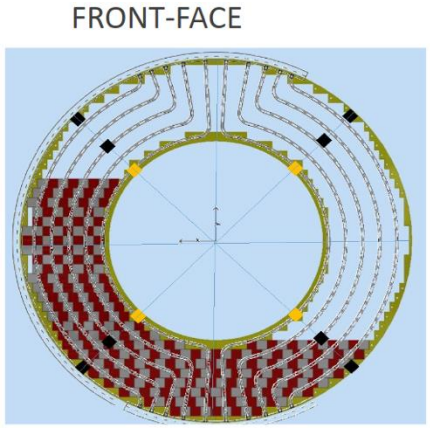
New accelerator schedule now provides 1 year of beam for Mu2e Run 1 starting from Jan 2027

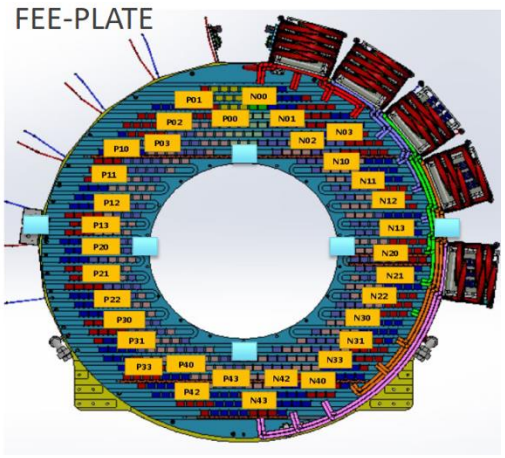
Common funds, started in 2024, provide good opportunities for inkind contributions.

INFN contribution continue to be crucial and much appreciated by the whole collaboration

BACKUP

Temperature and Radiation monitor (TRAD-v2)





We want to monitor the temperature and radiation in different places on each disk.
A first prototype has been built to validate the tecnology choice
A second prototype (TRAD-v2), including the SEL protection, will be done by the end of 2023.

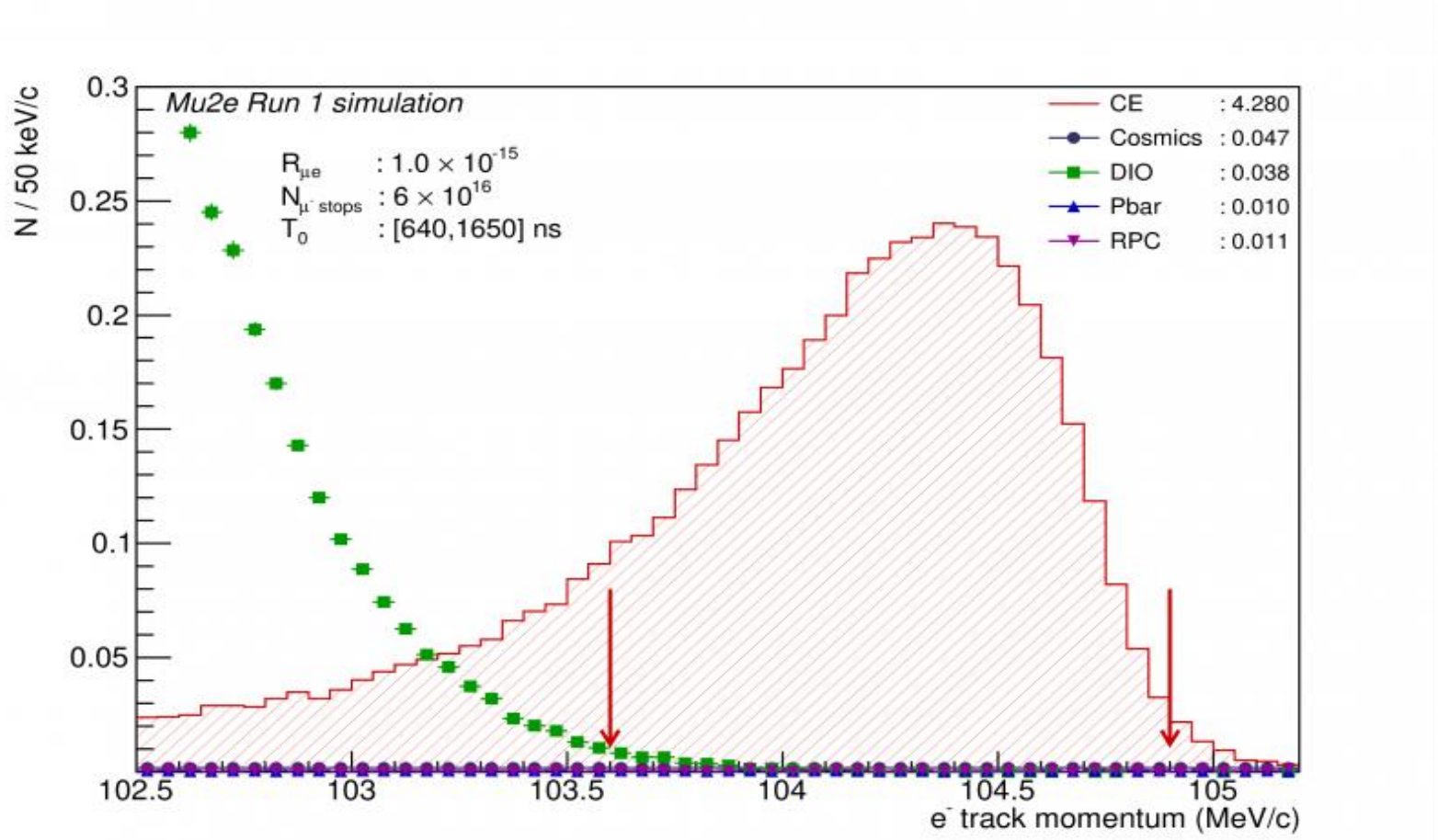
Final production by Spring 2024.

Mu2e expected backgrounds for Run 1 (assuming $6 \cdot 10^{16}$ stopped muons, mostly at half proton beam intensity*)

Channel	Mu2e Run I
SES	2.4×10^{-16}
Cosmic rays	$0.046 \pm 0.010\ (\text{stat}) \pm 0.009\ (\text{syst})$
DIO	$0.038 \pm 0.002\ (\text{stat})\ ^{+0.025}_{-0.015}\ (\text{syst})$
Antiprotons	$0.010 \pm 0.003\ (\text{stat}) \pm 0.010\ (\text{syst})$
RPC in-time	$0.010 \pm 0.002\ (\text{stat})\ ^{+0.001}_{-0.003}\ (\text{syst})$
RPC out-of-time ($\zeta = 10^{-10}$)	$(1.2 \pm 0.1\ (\text{stat})\ ^{+0.1}_{-0.3}\ (\text{syst})) \times 10^{-3}$
RMC	$< 2.4 \times 10^{-3}$
Decays in flight	$< 2 \times 10^{-3}$
Beam electrons	$< 1 \times 10^{-3}$
Total	0.105 ± 0.032

** More details in "Mu2e Run I Sensitivity Projections for the Neutrinoless mu- --> e- Conversion Search in Aluminum", submitted to MDPI Universe in October 2022 (38 pages) http://arxiv.org/abs/2210.11380*

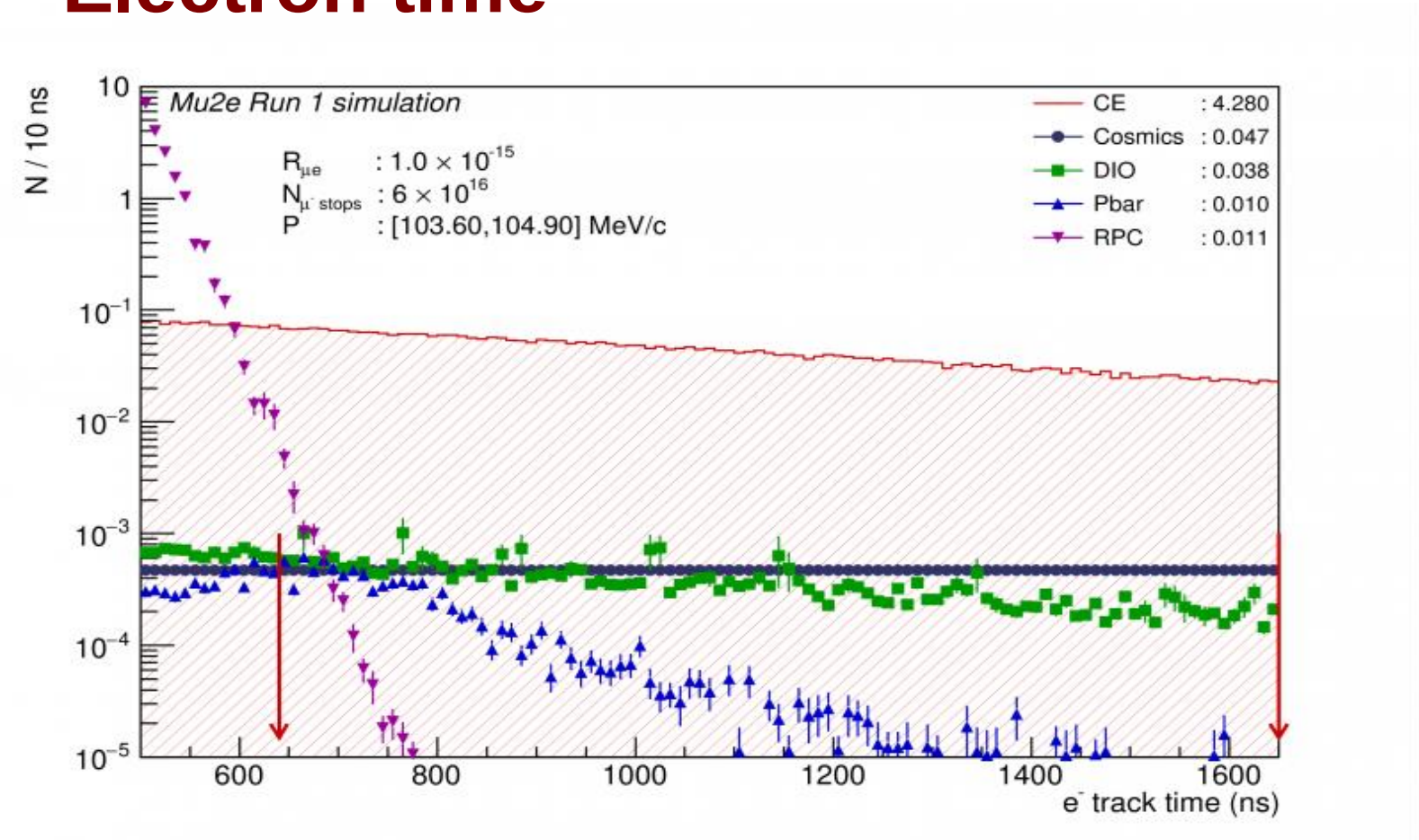
Electron momentum



The **DIO** spectrum falls as $(E_{max}\text{-}E)^5$ close to the end point

Can be suppressed by the momentum window cut

Electron time



Radiative Pion Captures (RPC) in the Al target producing photons converting in e^+e pairs can be suppressed by a time window cut
Also delayed pions coming from **antiproton** annihilation can be suppressed

Time and momentum windows **optimized** to get the best **discovery sensitivity**

Mu2e expected sensitivity for Run 1

Given the very low background level a **5σ discovery** will require Mu2e to observe just **5 events** of muon conversion

The $R_{\mu e}$ corresponding to a **5σ discovery** in Run 1 is:

$$R_{\mu e} = 1.1 \cdot 10^{-15}$$

Mu2e Run 1
5σ Discovery reach

If no events will be observed the **90% CL limit** will be:

$$R_{\mu e} = 6.2 \cdot 10^{-16}$$

Mu2e Run 1
90% CL limit

that is more than **x1000** better than current best limit!