Status of Mu2e experiment

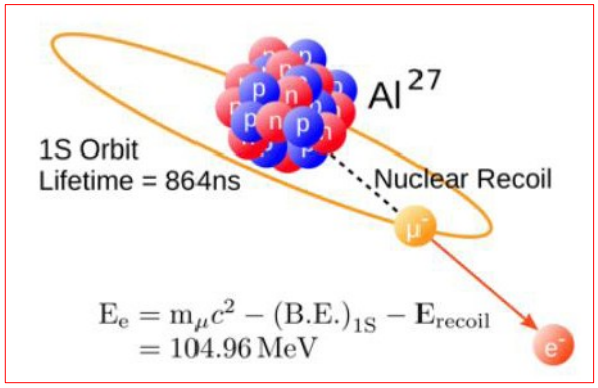
CSN1 meeting, 11 Sep 2023

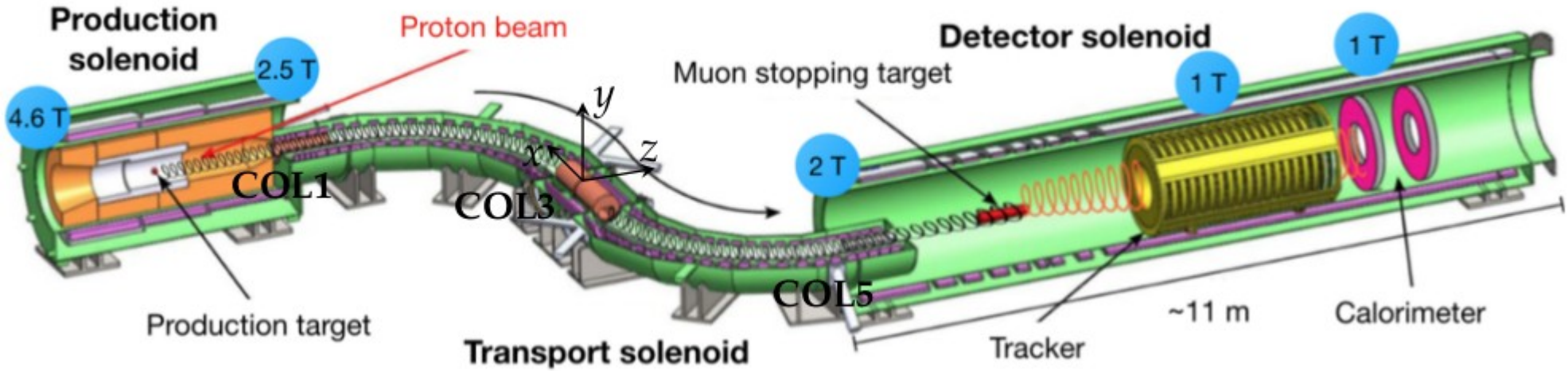
Stefano Di Falco, INFN/Pisa

The Mu2e Experiment at Fermilab

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

$$\mu^- + \mathrm{Al} \rightarrow e^- + \mathrm{Al}$$





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

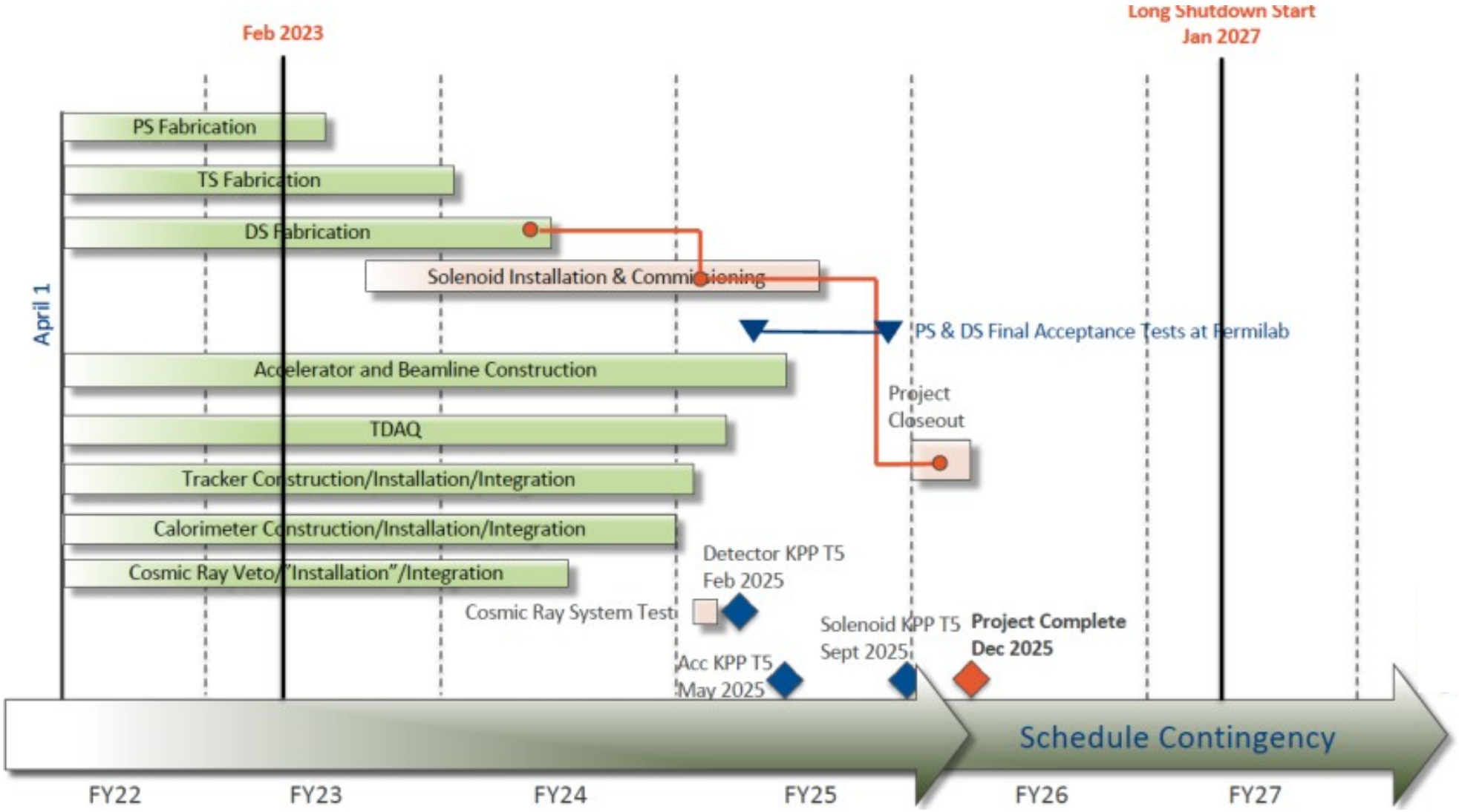
Current 90% CL limit:

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

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

News from Mu2e

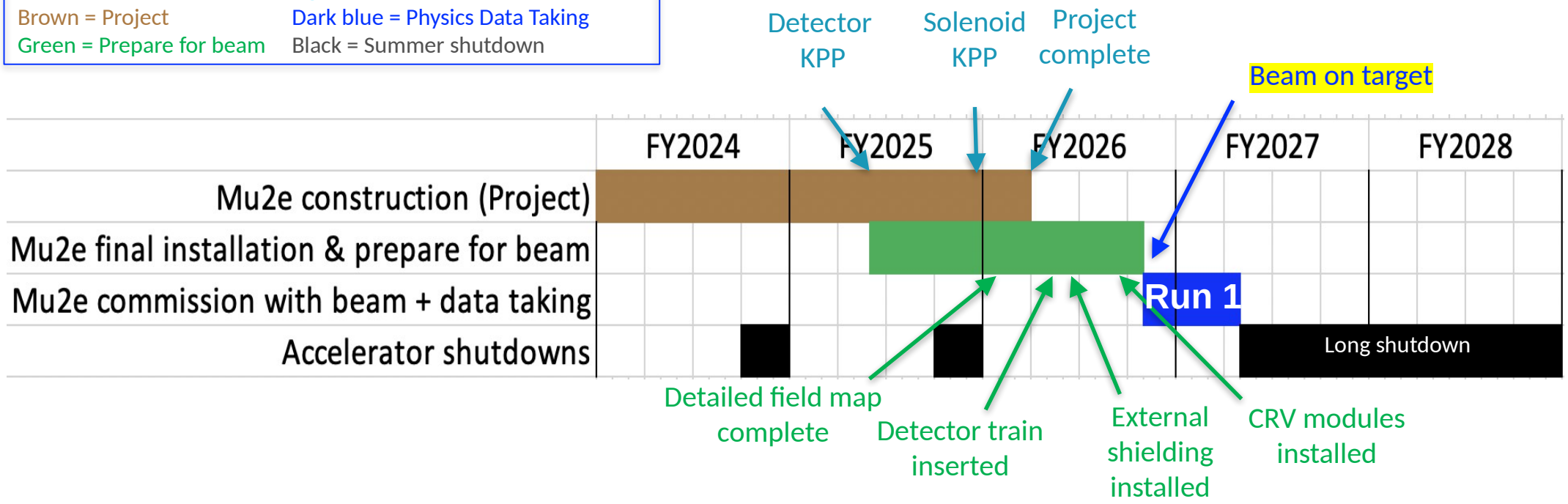
- **Stefano Miscetti** is the new Mu2e co-**spoke person**
- After 2022 rebaseline a new schedule has been released in Feb ‘23:



2024 will be devoted to detector installation in the Mu2e building!

Mu2e Run Plan

Key:
Brown = Project
Green = Prepare for beam
Light blue = Commission with Beam
Dark blue = Physics Data Taking
Black = Summer shutdown



Run 1 goal: get 3×10^{19} POT to improve by $\times 10^{3}$ Sindrum II sensitivity*

Run 2 goal: get 3×10^{20} POT to add an additional factor 10 on sensitivity
(longer run, higher average beam intensity, better shielding and CRV, ...)

** "Mu2e Run I Sensitivity Projections for the Neutrinoless mu- --> e- Conversion Search in Aluminum", Universe 9 (2023) 1, 54 (38 pages) http://arxiv.org/abs/2210.11380*

Some Pictures from Mu2e building

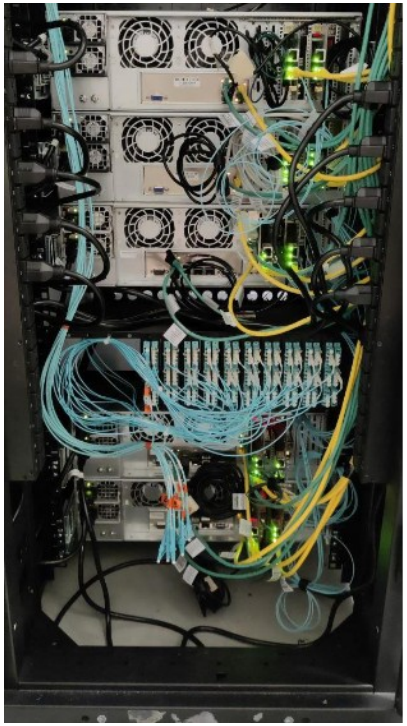
Cryogenic services*

Solenoids power supply

Rails and cable trails

Vacuum pumps

DAQ servers



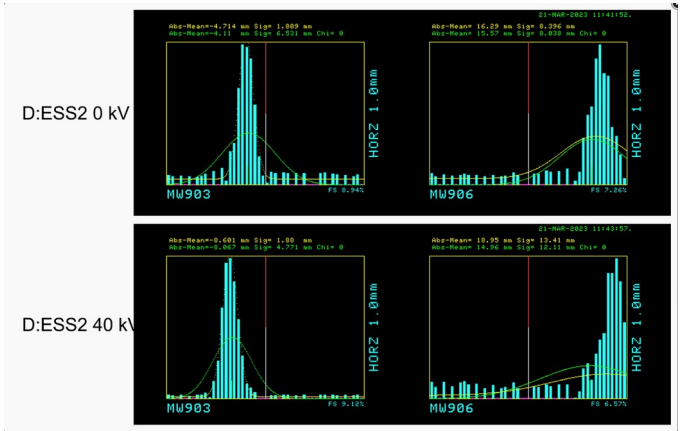
Concrete blocks

Extinction monitor

* First Liquid He produced and stored in Mu2e building in Aug ‘23

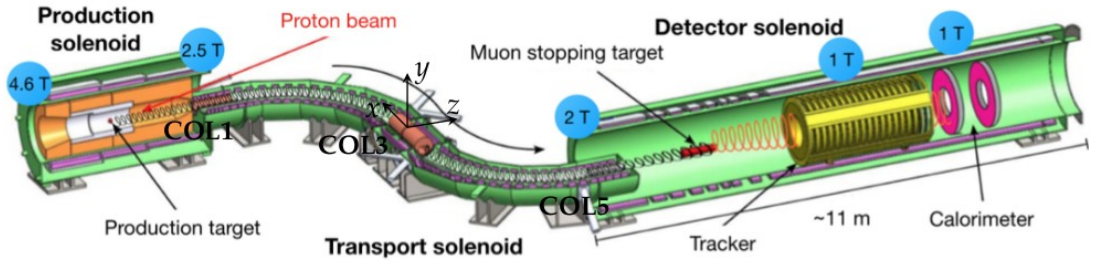
Accelerator

The first of the two Electro Static Septa (ESS) has been installed in the last segment of the beam line that will reach Mu2e



After a succesfull test of the AC dipole needed to extract theproton bunches, the first beam has been succesfully directed to the Mu2e beam dump (July ‘23)

Solenoids

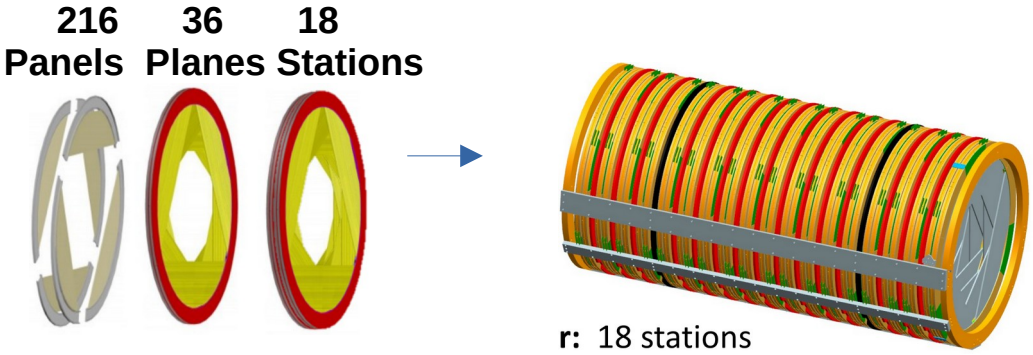


Production Solenoid:
3/3 coils completed
Cold mass assembled and integrated with the Inner thermal shielding
Rough B field map ok
TODO:Outer shield integration and sealing

Transport Solenoid (Nov ‘23):
Upper half completed, lower half almost Ready. Installation end of 2023

Detector Solenoid (on critical path):
11/11 coils built
7/11 coils tested
TODO: - cold mass assembling
- preliminary field map
- final sealing

Tracker status



216/216 panels completed

23/36 planes completed

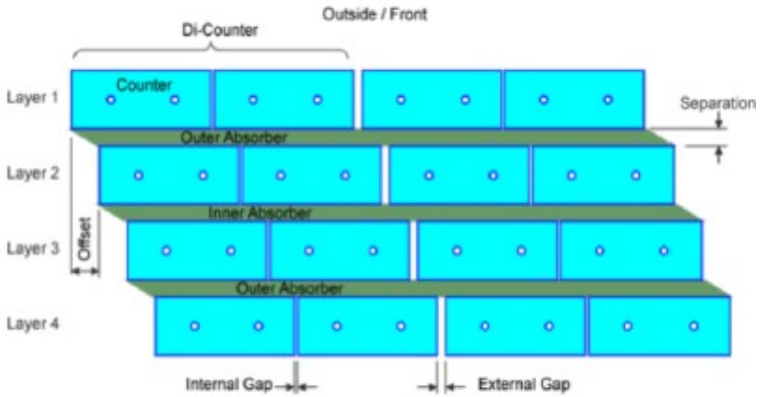
Long term leakage test ongoing

TODO: - FEE test and assembling
- stations sealing

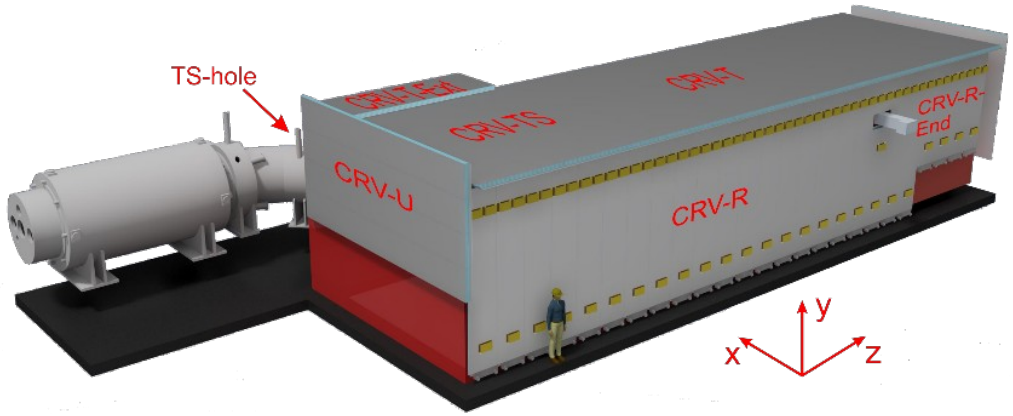
Expected completion: summer 2024

Installation in Mu2e experimental hall:
winter 2024

Cosmic Ray Veto Status



4 scintillator layers with WLS
Efficiency: 99.99%



Coverage: DS and Upper TS

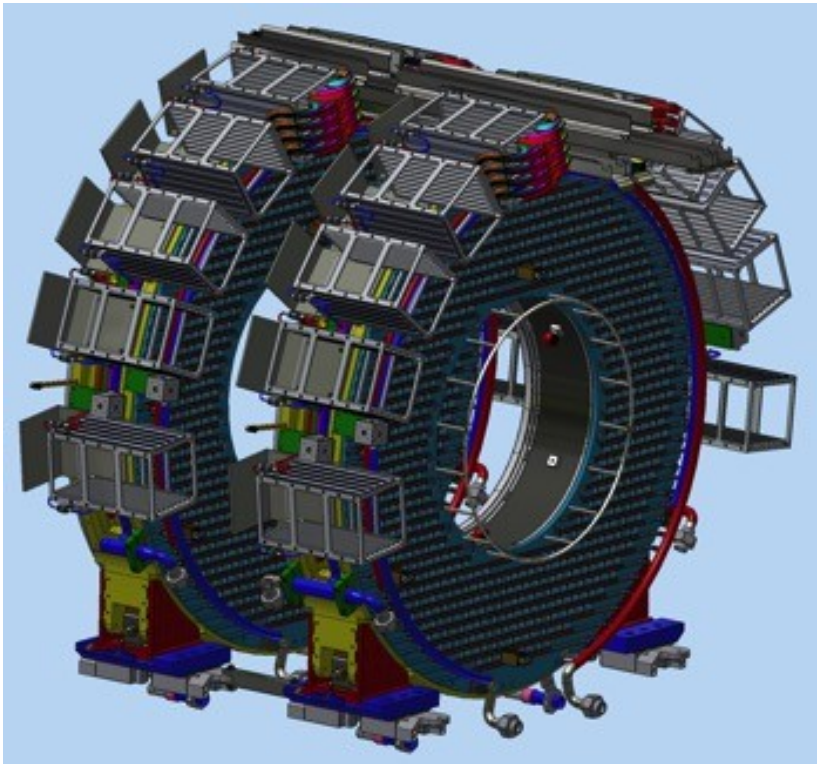
83/83 modules ready

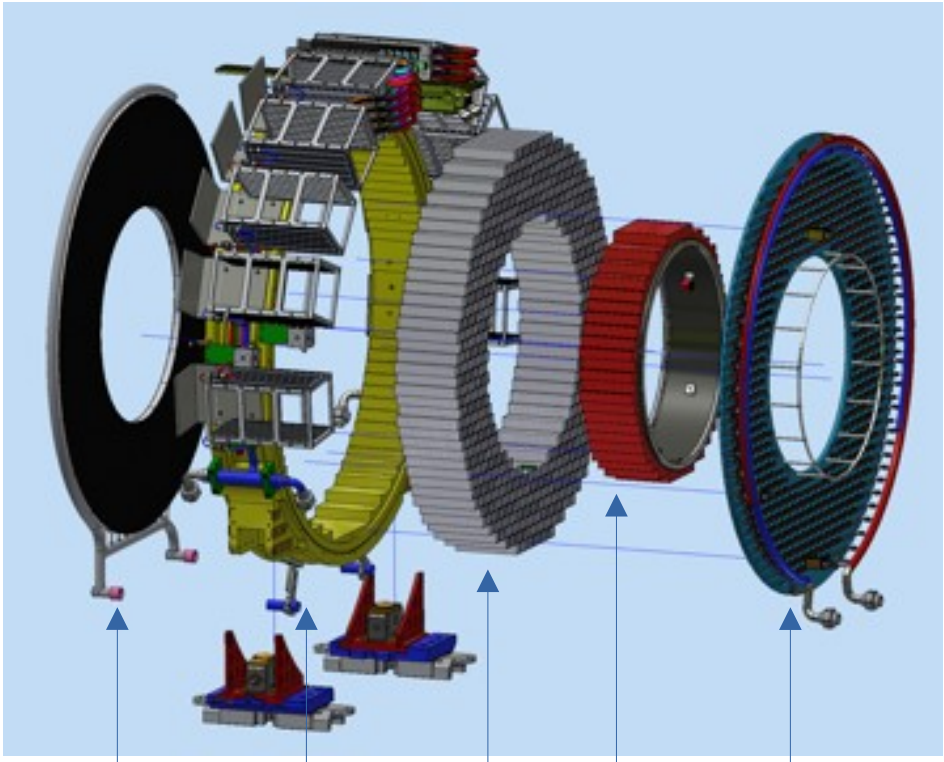
Cosmic ray stand to measure the aging rate

Small delays on electronics procurement (FPGA)

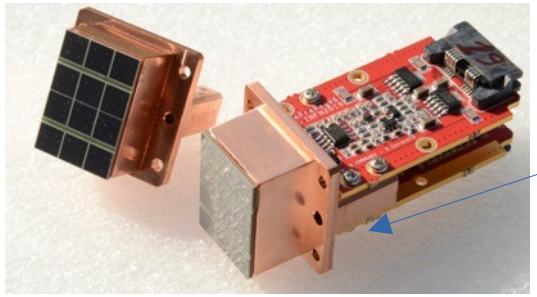
Installation in Mu2e building: 2025
(after concrete blocks placement)

The Mu2e calorimeter

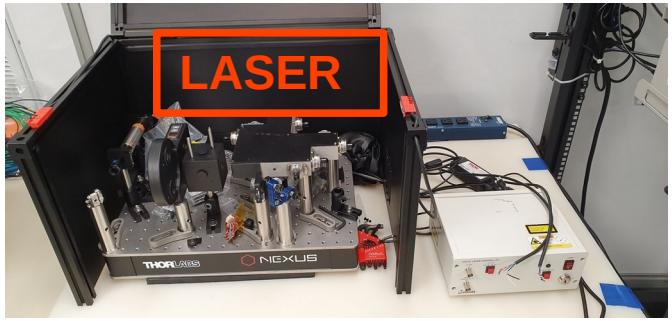




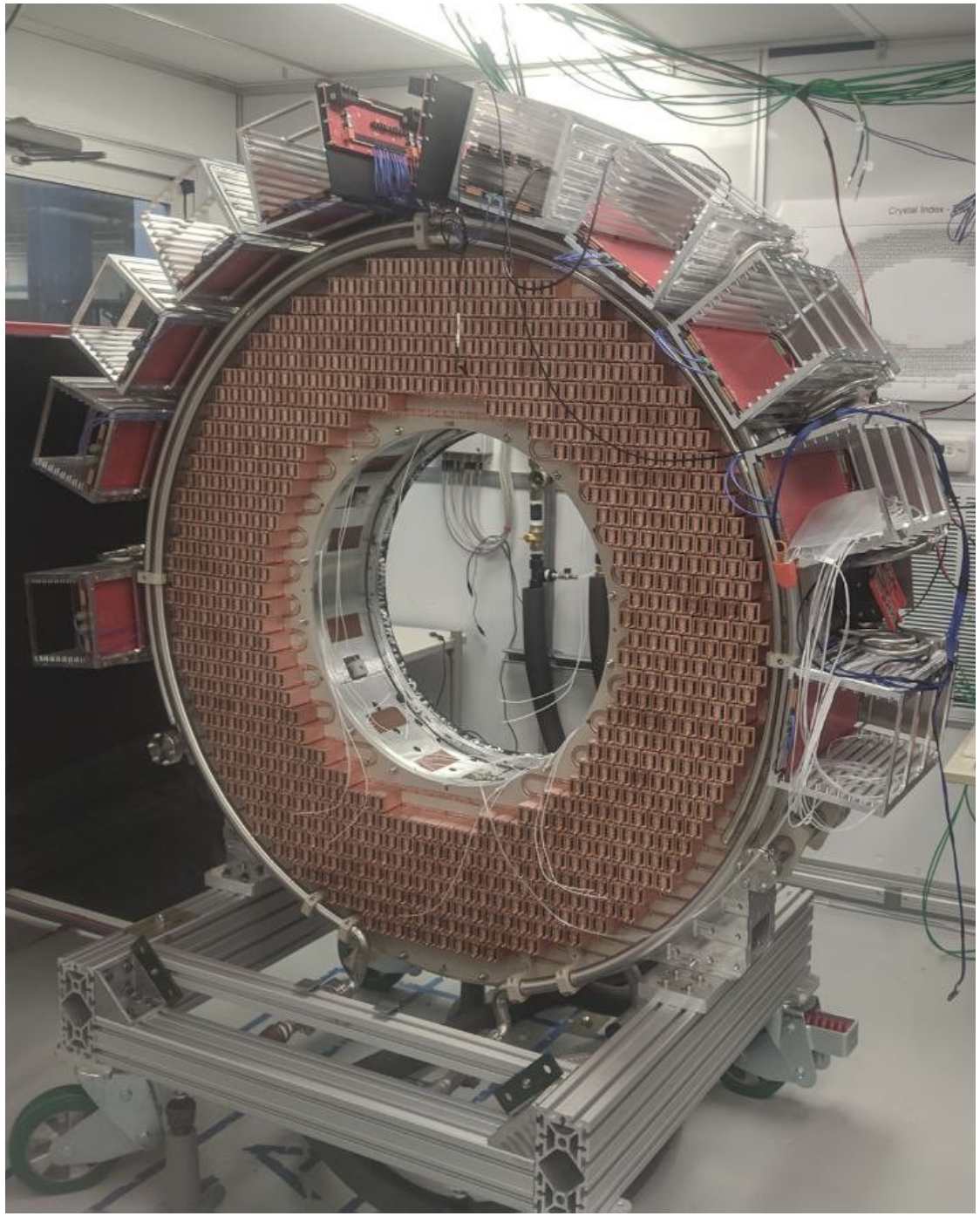
2 disks each consisting of
- 674 pure CsI crystals
- 1248 SiPMs+FEE boards



Hole for laser calibration



Calorimeter Disk 1 status



‘Disk 1’ status:

- mechanical parts assembled

- Crystals and SiPMs+FEE readout units installed

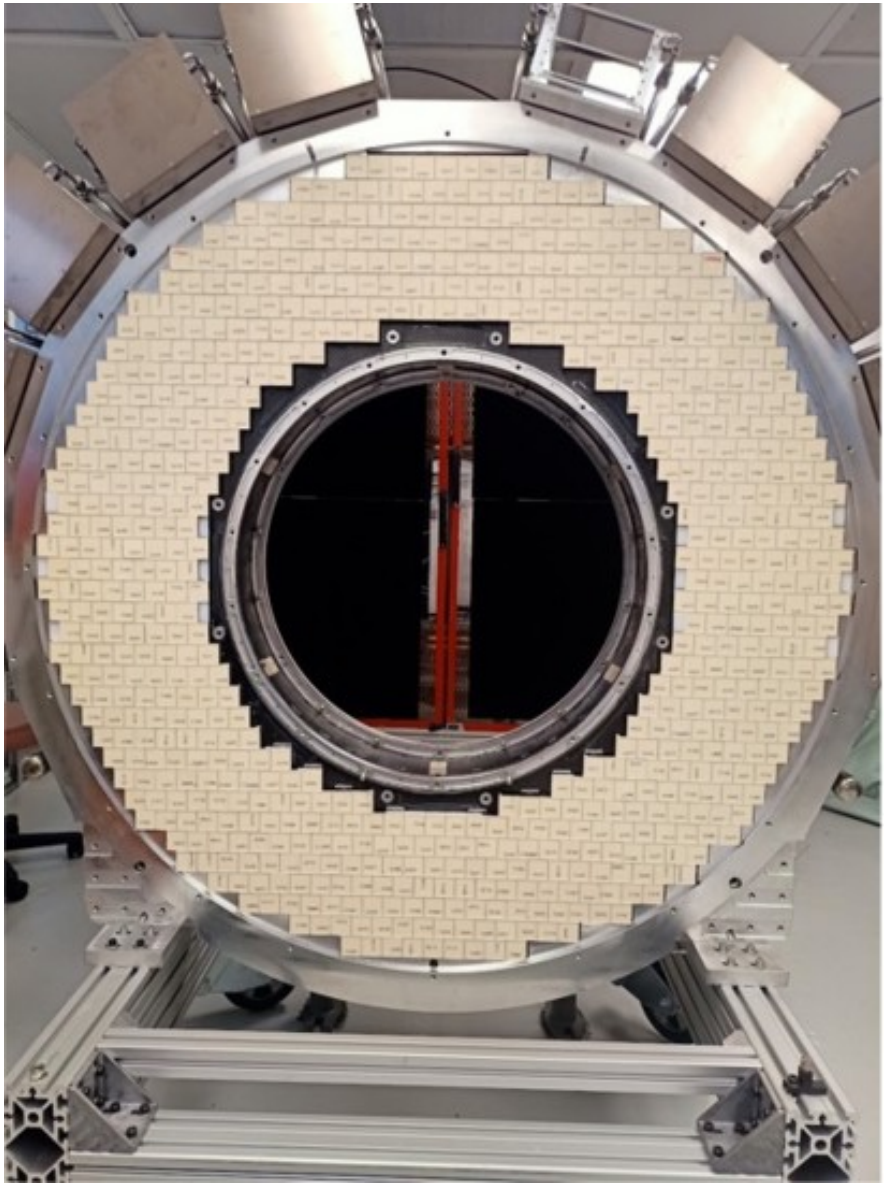
- digital electronic crates installed

- quick leak test of cooling system performed

- all readout units tested with laser pulses

TODO (disk 1):
- digital electronics installation
- TRAD monitors installation
- cabling
- DAQ test
- Long term cooling system test
- complete laser calibration system (diffusive spheres and fibers)

Calorimeter Disk 0 status



‘Disk 0’ status:

- mechanical parts assembled
- Crystals installed
- digital electronic crates installed

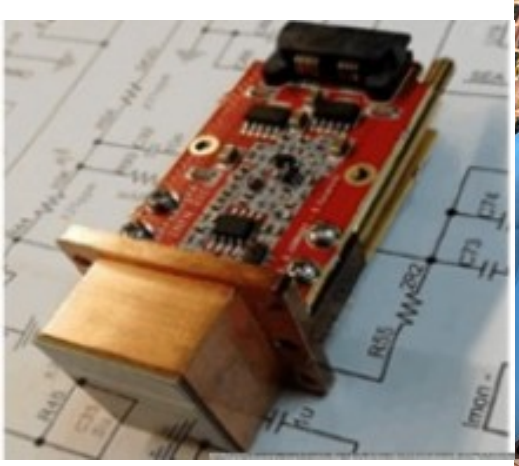
TODO (disk 0):
- install and test readout units
- install and test digital electronics
- install TRAD monitors
- cabling from FEE to crate
- DAQ test
- Long term cooling system test
- complete laser calibration system (diffusive spheres and fibers)

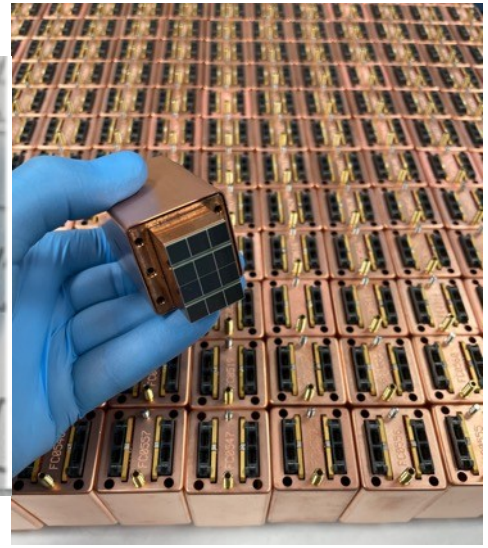
Installation in Mu2e building (both disks):

Autumn 2024

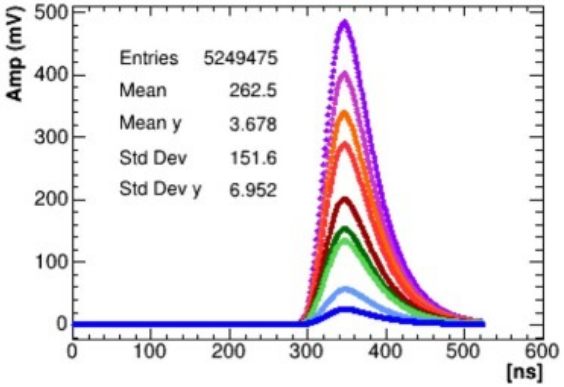
Status of production of basic components

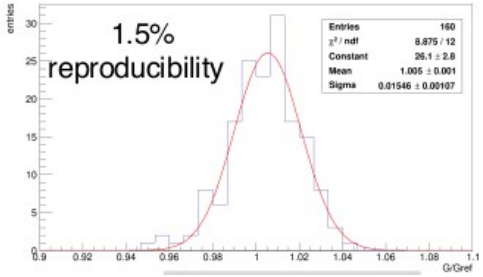
- 1500 crystals produced and tested (best 1348 selected)
- 4000 SiPMs produced and tested
- 3000 SiPM glued to 1500 SiPM holders
- 3300 FEE boards produced
- 400 FEE boards lost due to Russia-Ukraine conflict



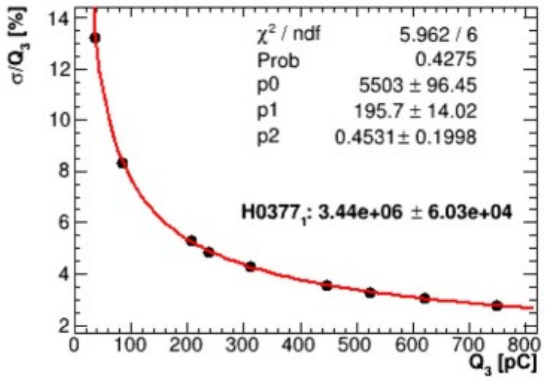


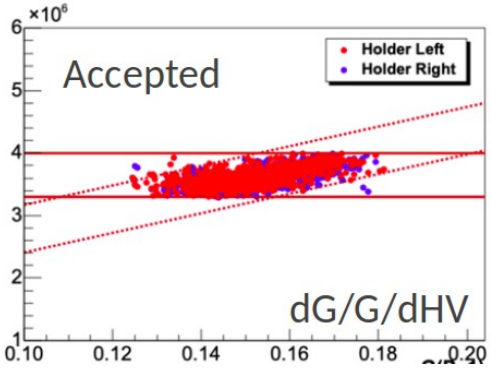
ROU quality assurance





$3.3 \times 10^6 < G_{L,R} < 4 \times 10^6$

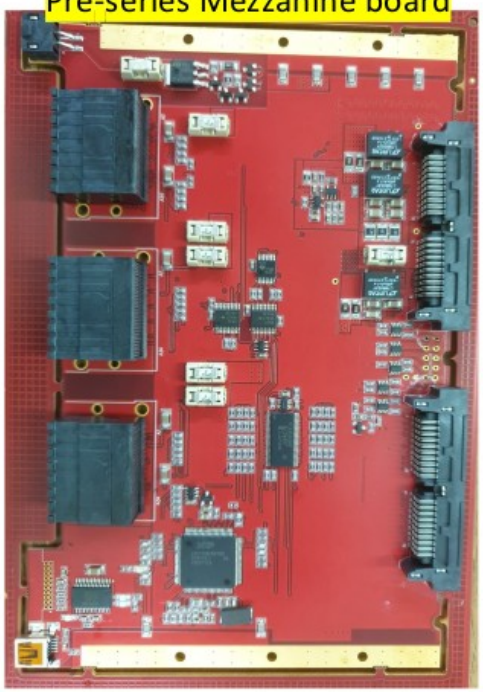




- 1188/1226 ROUs (2 SiPM+2FEE+Faraday cage) passed QA out of a total need of 1348
- remaining 160 ROUs available by Sept 2023

Status of digital electronic production

Pre-series Mezzanine board



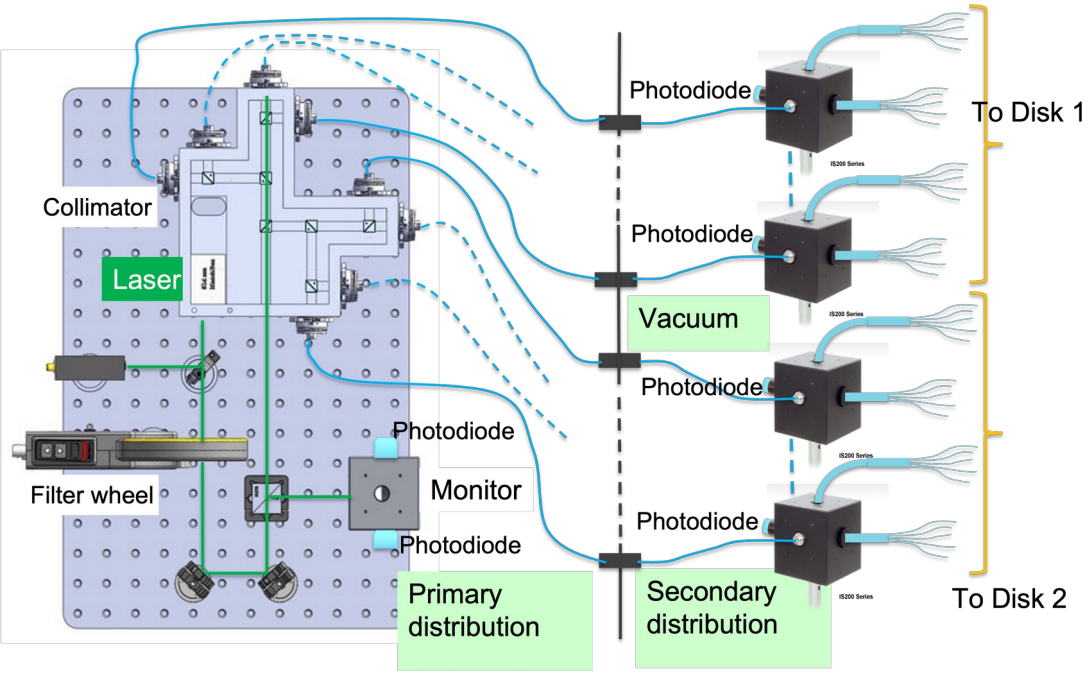
V3 prototype board

Last test at CNAO in April 2023 has finally qualified the Mezzanine Board (MB) and the Digitizer Board (DIRAC) against the expected levels of neutron radiation

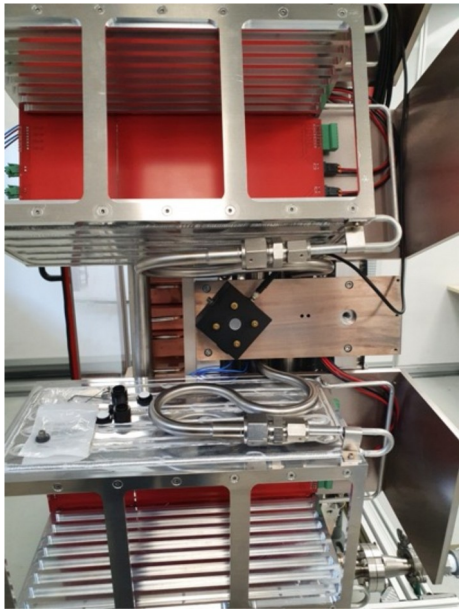
The SEL protection circuit has also been validated

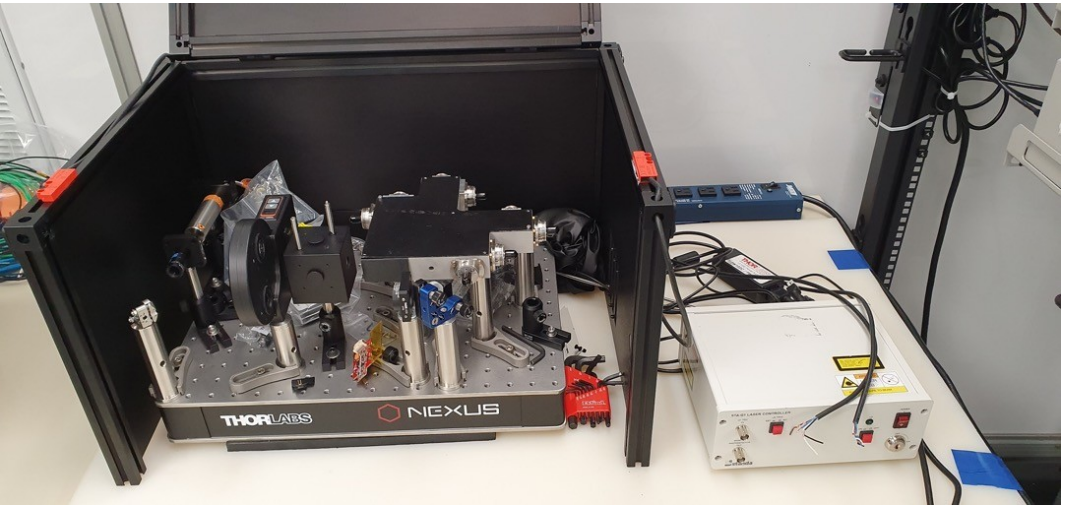
- **Components procurement will be completed by the end of 2023 (with some extracost)**
- **All 160 MB and DIRAC will be available by Spring 2024**

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



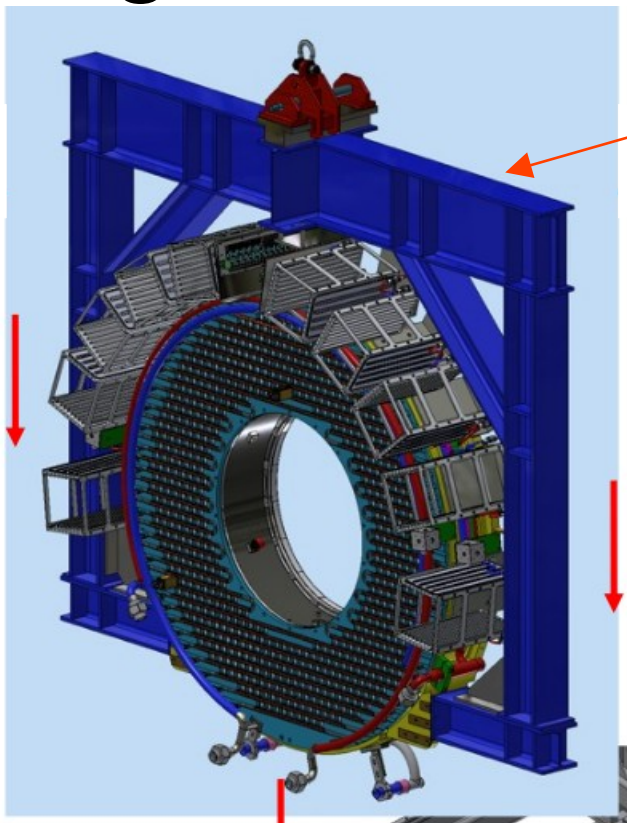


Mu2e Laser primary distribution optical system placed inside a Thorlabs black Enclosure

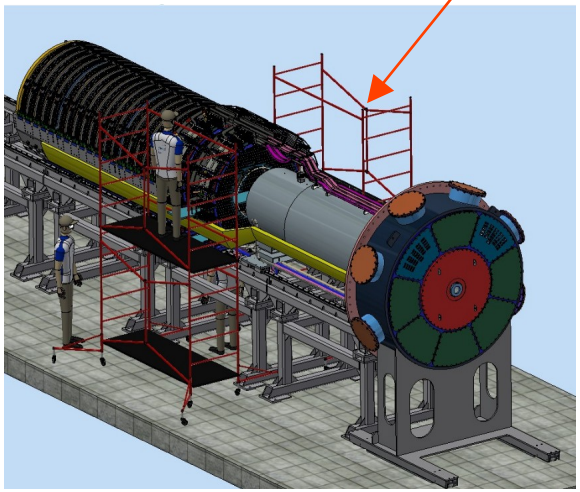
Laser Head # 1 – under test for stability along time.
Interlock system based on two magnetic switches.
Laser Key handling established
Nice results of light distribution losses down to integrating spheres and laser fiber needles in front of each crystal

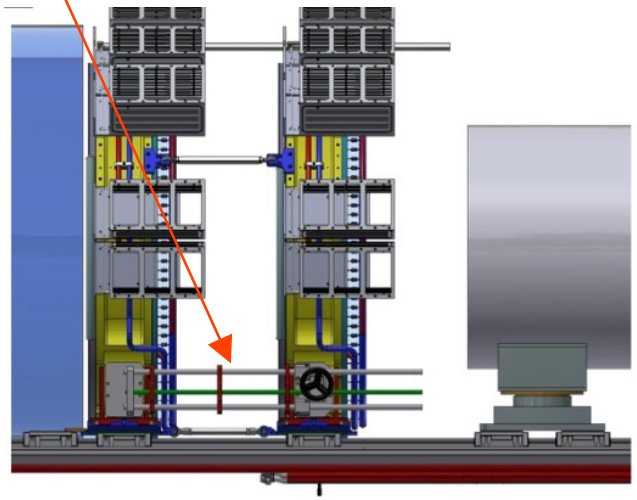
80 % of fiber bundles delivered at SIDET

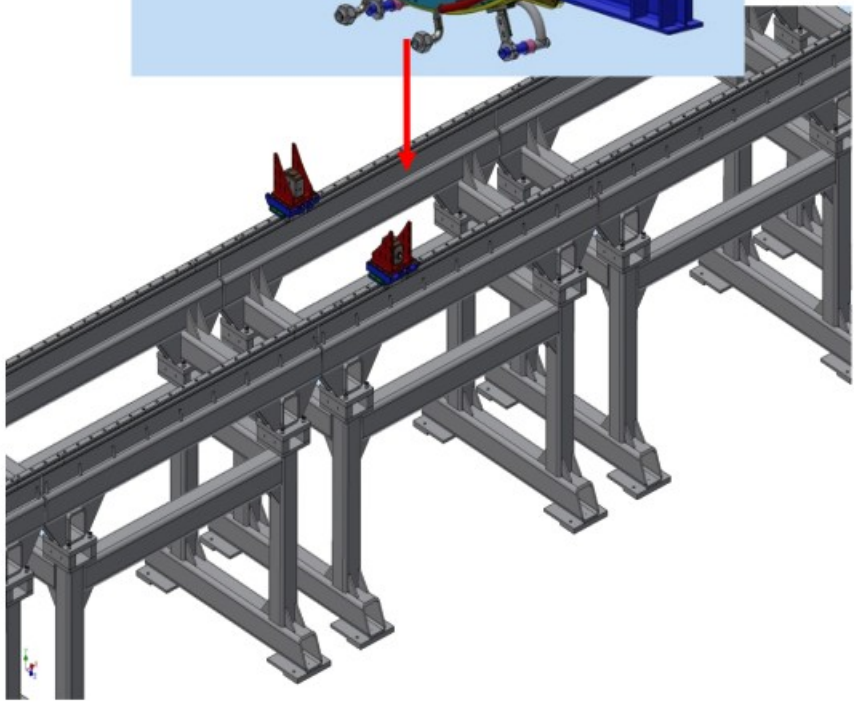
Moving the calorimeter to the Mu2e building

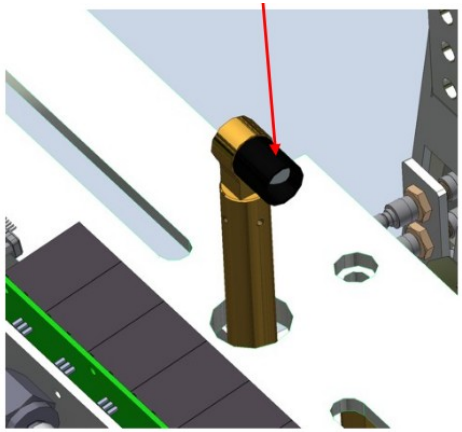


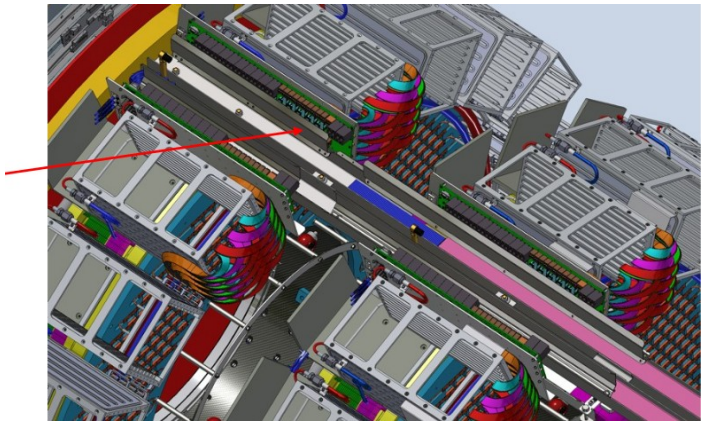
Additional tools are needed and still need to be constructed



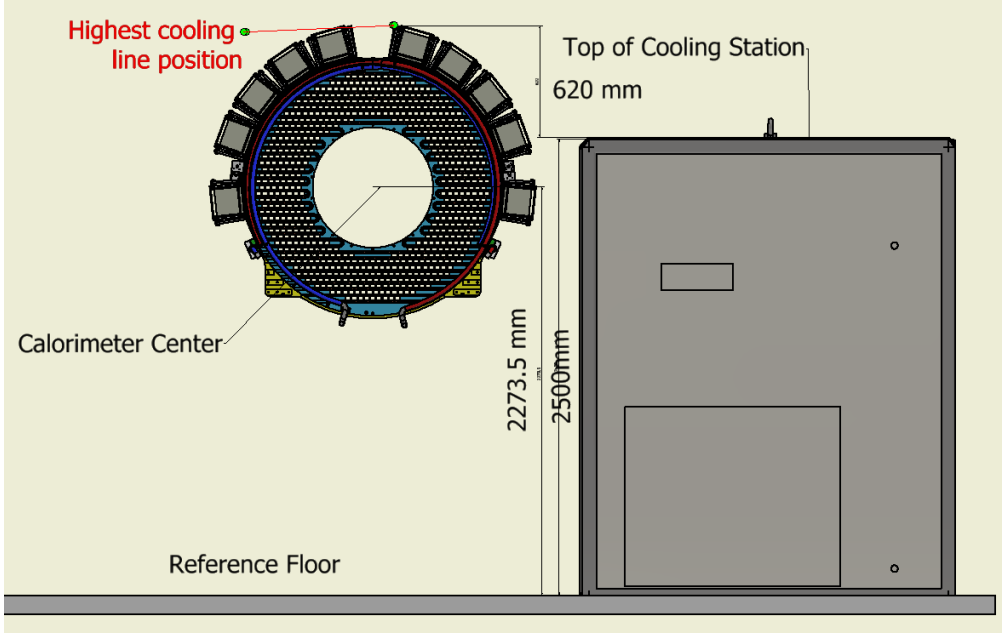








Calorimeter cooling station



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

A coolant liquid at -22° C will circulate in two indipendent cooling lines:

1° to keep SiPMs at -10° C

2° to keep all the electronic boards components below 50° C

The final design is completed

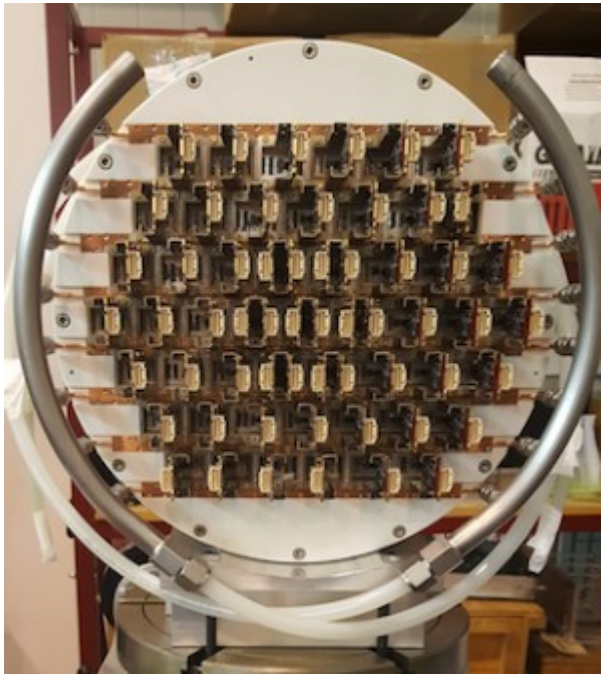
The last details of the tender are being discussed with Fermilab staff

The order is expected to be placed in 2024

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.

Vertical slice test with module 0 at LNF

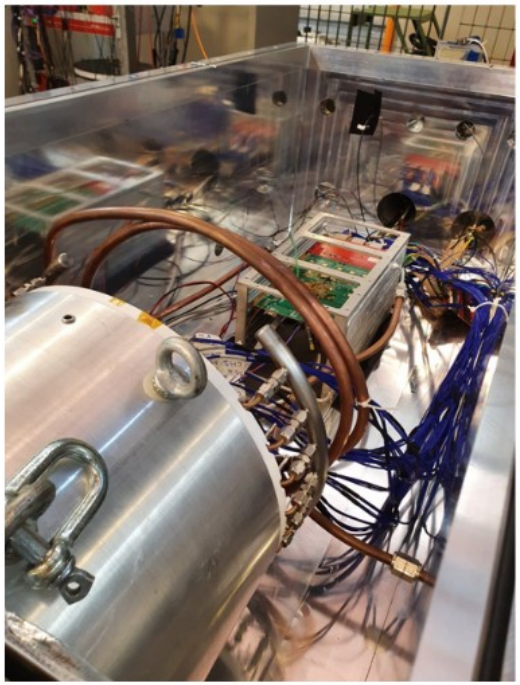


Calorimeter module 0

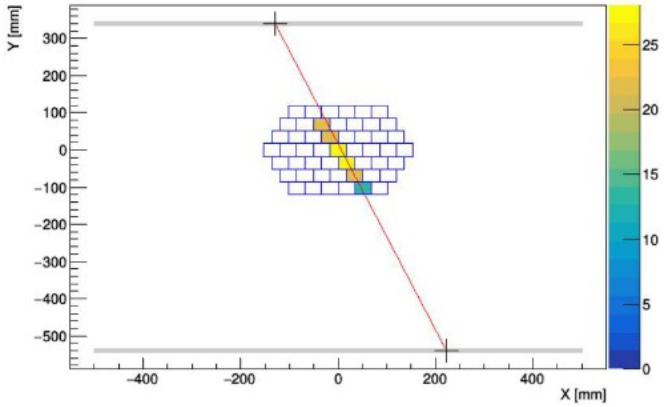
Calorimeter **module 0**, equipped with **51 pure CsI Crystals**, **51 ROUs, cooling lines** can be used to perform a vertical slice test of the full readout chain **under vacuum**

A preliminary test with a commercial digitizer and a serial readout has been succesfully completed

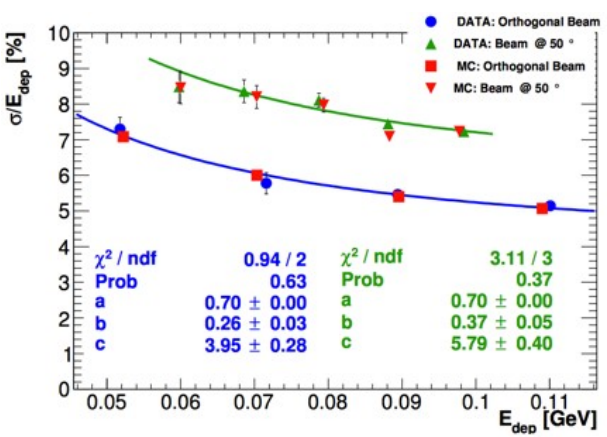
A dedicated Cosmic Ray Tagger has been built to allow a long term test with cosmic rays

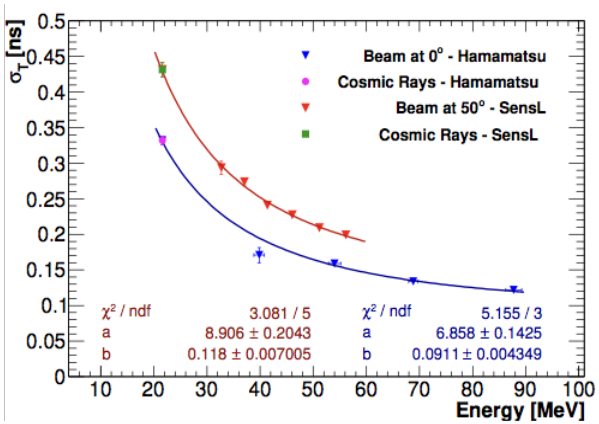


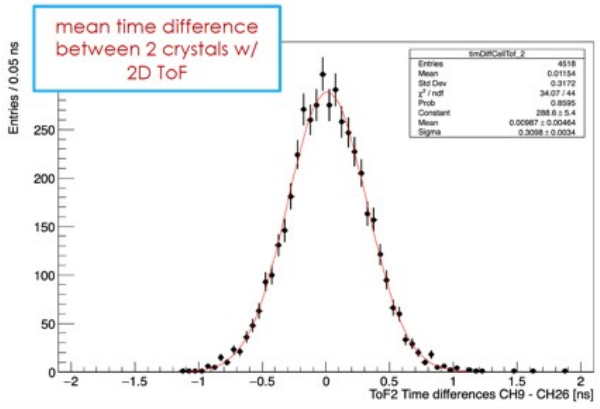
The Cosmic Ray tagger:
2 layers each with 8 scintillator bars read by SiPMs



Module-0 test beam







Calorimeter time and energy performances have been measured in 2017 with an electron beam at LNF BTF (doi:10.1016/j.nima.2018.09.043)

Since then Module-0 has been refurbished with production crystals and SiPMs, and optical cross talk has been mitigated using some black Tedlar between the crystals.

Module-0 will be used to measure the calorimeter performances in the final configuration also including production digital electronics.

Available beams in 2024: BTF@LNF, MAMI@Mainz

MoF status

The FY2024 will see the start of INFN contribution to the Mu2e operation costs.
The contribution requested to INFN is ~220K/year for the first 3 years.
After the subtraction of the in-kind contribution of spares (SIPM, FEE, MB, DIRAC, LV/HV, Laser Head) the amount is ~130K/year.

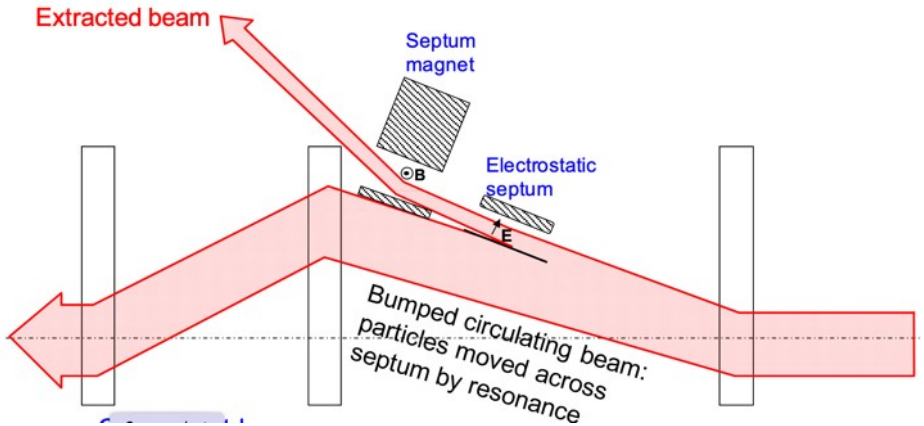
This can be given as in-kind contribution including also man power (+50% of construction costs).

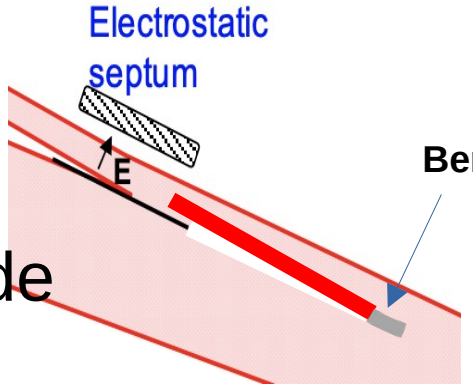
For 2024:

- Bent crystals	60 K + 30 K = 90 K	
- Spill monitor	11 K + 5.5K = 16.5K	(8 LYSO+PMT hodoscope)
- Vacuum flange	5 K + 2.5K = 7.5K	(outgassing tests)
- Contingency*	16K	
Total:	130K	

* This **should be added as an additional request for 2024 as SJ**.
It includes: costs revision, quality controls, in-kind contribution evaluation.

Bent crystals to reduce radiation levels





Beam extraction requires an ElectroStatic Septum(ESS).
The beam impact on the inner electrode produces a large amount of radiation.
The ‘shadow’ of a bent crystal can reduce beam losses by a factor 3, allowing for an higher beam intensity!
Ferrara group is ready to deliver it by Summer 2024.

A win-win in-kind contribution to Common Funds!

Bent crystals: change in sumitted requests

Since inventory item cannot be easily considered as an in-kind contribution, the requests for the Etcher (20K) and the interferometric Lens (8.5 K) will be replaced by a contribution of 28.5 K for the use and maintenace of the clean rooms.

This corresponds to what was initially agreed as cost sharing between INFN and UniFe.

The total request for the bent crystals will still be 60K.

The Mu2e upgrade proposal: Mu2e-2

The PIP-II upgrade of Fermilab accelerator will allow to have an higher intensity muon beam increasing by a factor 10 Mu2e statistical error.

A relatively cheap upgrade of Mu2e apparatus, saving the superconducting solenoids, have been included in the Snow Mass program in March 2022 (arxiv 2203:07569).

A dedicated workshop has been held in Caltech in March 2023 (https://indico.fnal.gov/event/57834)

The proposal has been submitted to the Fermilab Phisycs Advisory Committee in June 2023

The proposal discuss possible improvements of the accelerator, of the target and of the detectors (tracker, CRV e ECAL) to deal with the increased rate of particles and radiation levels.

Our Mu2e collaborators consider natural an involvement of INFN in this upgrade. Can certainly be a good occasion for INFN to keep an important collaboration with Fermilab at a reasonable cost.

Mu2e-2 calorimeter: LYSO proposal

In Mu2e-2, we expect x10 increase in n-fluence up to 10^{13} n/cm^2

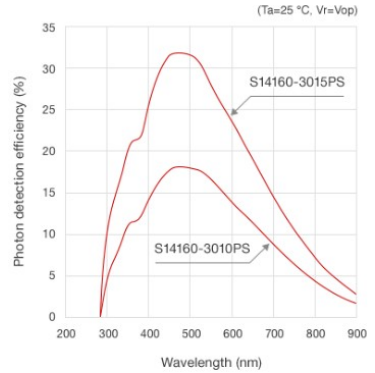
15 μm

Temperature [°C]	V_{br} [V]	I(V_{br}+4V) [mA]	I(V_{br}+6V) [mA]	I(V_{br}+8V) [mA]
-10 ± 1	75.29 ± 0.01	12.56 ± 0.01	30.45 ± 0.01	46.76 ± 0.01
-5 ± 1	75.81 ± 0.01	14.89 ± 0.01	32.12 ± 0.01	46.77 ± 0.01
0 ± 1	76.27 ± 0.01	17.38 ± 0.01	33.93 ± 0.01	47.47 ± 0.01

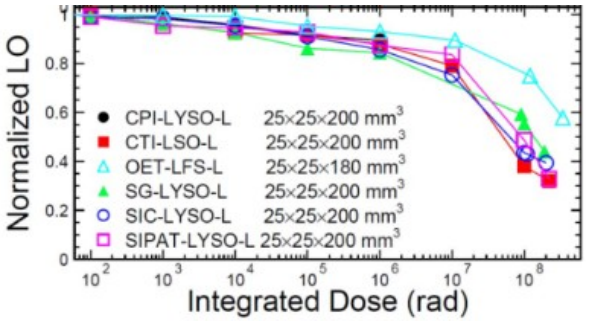
10 μm

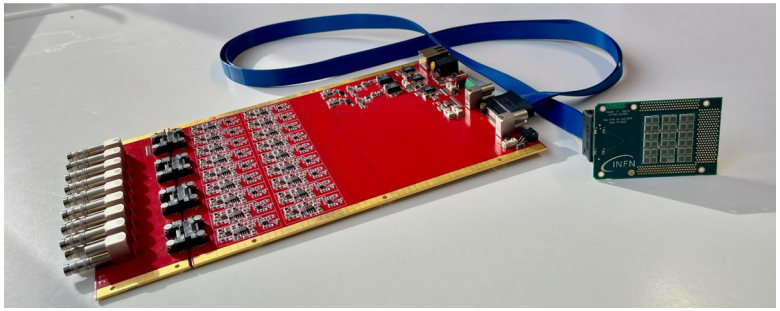
Temperature [°C]	V_{br} [V]	I(V_{br}+4V) [mA]	I(V_{br}+6V) [mA]	I(V_{br}+8V) [mA]
-10 ± 1	76.76 ± 0.01	1.84 ± 0.01	6.82 ± 0.01	29.91 ± 0.01
-5 ± 1	77.23 ± 0.01	2.53 ± 0.01	9.66 ± 0.01	37.51 ± 0.01
0 ± 1	77.49 ± 0.01	2.99 ± 0.01	11.59 ± 0.01	38.48 ± 0.01

SiPMs with pixel 10 or 15 μm can survive but they have a lower PDE
Hamatsu & FBK R&D



Short LYSO crystals (34x34x80 mm^3) can provide a rad hard solution at a reasonable cost (x2 BaF_2)
Emission time: 40 ns



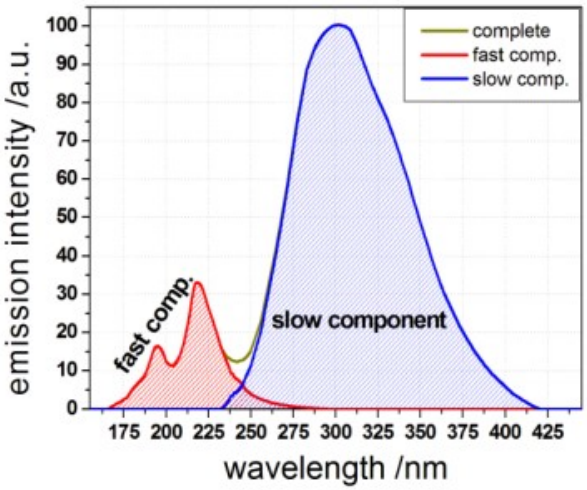


FEE would be connected to SiPMs via a coaxial cable to reduce radiation levels.
A synergic R&D for muon collider (CRILIN and NEXT-100) is already ongoing

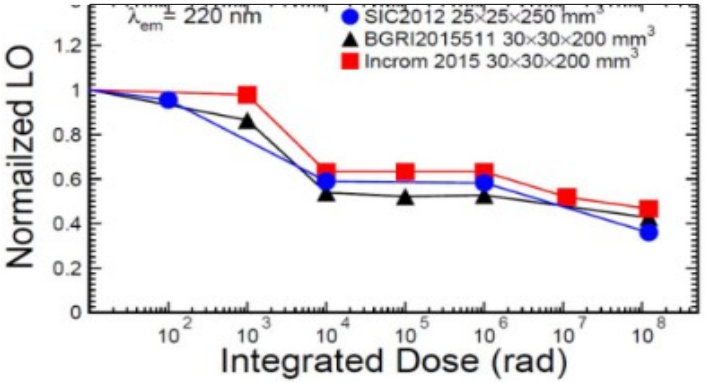
Proposed R&D for 2024:
- support design with simulation (required signal width vs pileup)
- test a 2x2 array of 6x6 mm^2 SiPM with 10 μm pixel
- build a PCB to read 16 3x3 mm^2 SiPMs

Mu2e-2 calorimeter: BaF_2 alternative proposal

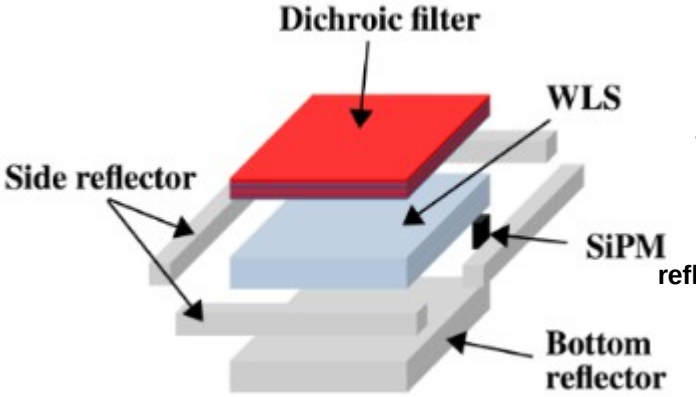
BaF_2 was the baseline also for Mu2e: it has a very fast component (0.6 ns) but an unacceptable dominating slow component (630 ns) that needs to be suppressed.
A long and expensive R&D to incorporate a filter in the sensor is going on (Caltech/JPL/FBK)

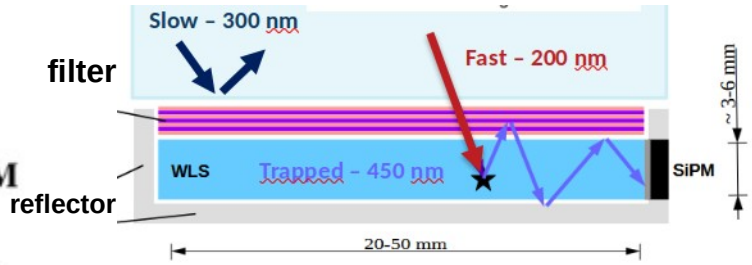


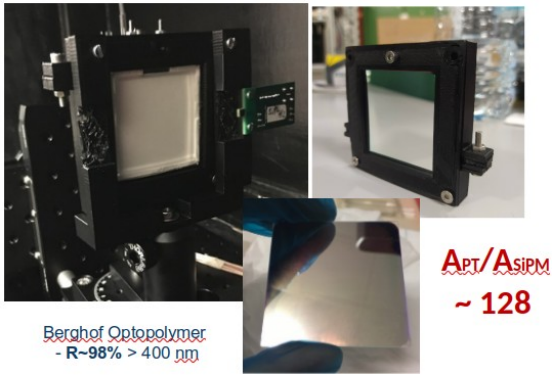
Radiation hardness is ok after an initial loss of ~40%



Alternative R&D proposal: **dichroic filter+ photon trap**







A phototrap prototype with 5% PDE

Proposed R&D for 2024:
- procure and test different combinations of filters and WLS
- build a prototype to evaluate Light Collection and timing
- build a PCB to host SiPMs, shaper and amplifier

European projects: summary of contributions

2022	Returned to CSN1 (k€)	Before 1/9				After 1/9			
		NEWS (from 2021) (k€)	NEWS (k€)	AMUSE (k€)	all (k€)	NEWS (k€)	AMUSE (k€)	INTENSE (k€)	all (k€)
LNF	45,0	9,9	0	19,7	29,6	0	13,4	0	13,4
PI	39,0	1,3	20,2	0	21,5	7,1	0	2,6	9,7
TOTAL	**84,0**	11,2	20,2	19,7	**51,1**	7,1	13,4	2,6	**23,1**

2023	Returned to CSN1 (k€)	After 1/9				
		NEWS (k€)	AMUSE (k€)	INTENSE (k€)	PROBES (k€)	all (k€)
LNF	47,5	0	31,7	0	0	31,7
PI	24,5	17,1	0	8,6	2,2	27,9
TOTAL	**72,0**	17,1	31,7	8,6	2,2	**59,6**

Summary and conclusions

A lot of progresses in the construction of Mu2e at Fermilab

2024 will be a crucial year for the installation of Solenoids, Tracker and Calorimeter in the Mu2e building

Detector key performance should be demonstrated by the end of 2025. Still a lot of work and activity in situ is needed to maximize the results of the Mu2e Run 1 that will start in 2026

Common funds should start in 2024

INFN contribution is visible and much appreciated by the whole collaboration

Important items for a succesfull activity at Fermilab

(also discussed with g-2 and DUNE)

Health insurance:

- Poste Vita requires to anticipate the expenses
- For the first 3 months Blue Cross only covers hospitalizations
- we are collecting experiences of people having troubles with this

Cost of life and travels to USA:

- daily salary is fixed by law, consider to ask for an adjustment
- flight costs increased by more than 50%, monthly reimbersument should reflect this increase

Technician presence at Fermilab:

- consider the possibility of a laboratory allowance (could be cumulated with ‘a piè di lista’ not with ‘a forfait’ refunding)

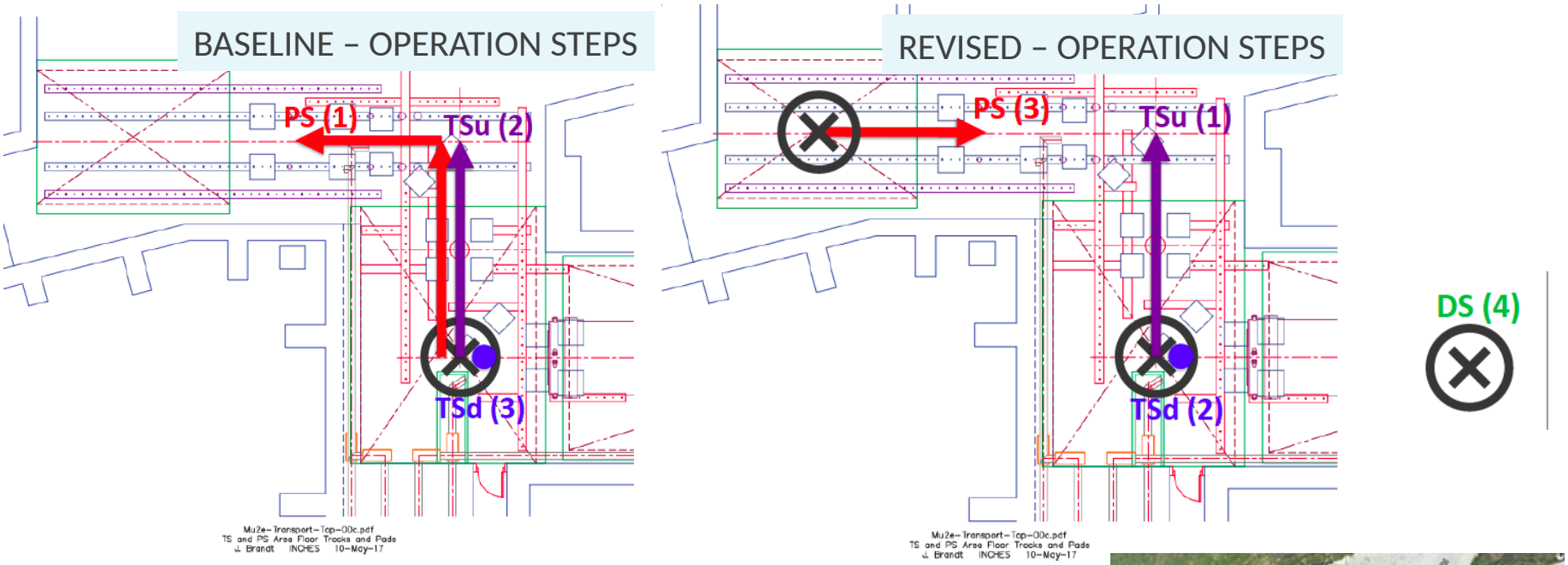
Researcher/technologist presence at Fermilab:

- similfellows/fellows to make long stays more attractive
- overhead and taxation to be discussed with Fermilab
- positive mood from INFN council

BACKUP

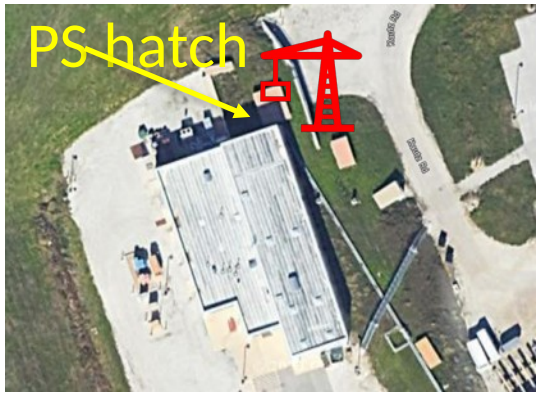
Solenoid installation : revised sequence?

- **PS delivery: October 2023 (Slight Slipping)**
- TSu delivery: October 2023 + TSd delivery: November 2023 (holding)
- DS delivery: May 2024 (holding)
- **It is likely that TSu/TSd will be ready to install before PS**



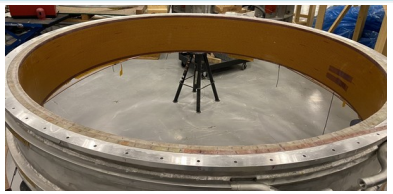
- Do not interrupt installation in Mu2e Hall when magnets are ready
- Need to use a different (PS) hatch + external crane

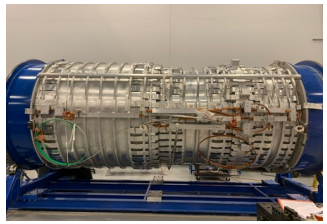
We will have the first magnet in the Mu2 hall in 2023!
It probably will be the one with Italian coils !!!!!



PS/DS fabrication steps

- Make a bunch of coils
- Assemble coils together into a "cold mass"
- Insert shielded inner bore into cold mass
- Insert cold mass/inner bore assembly into outer thermal shield and vacuum vessel
- Close up vacuum vessel





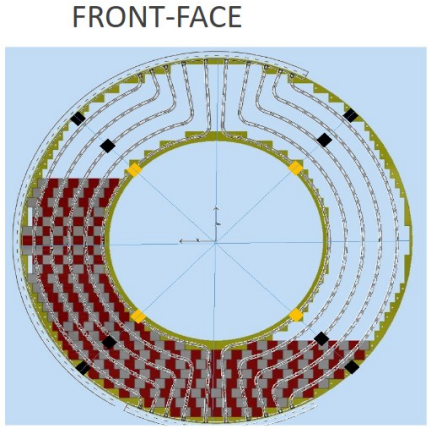
Long term test of cooling system at SIDET (FNAL)

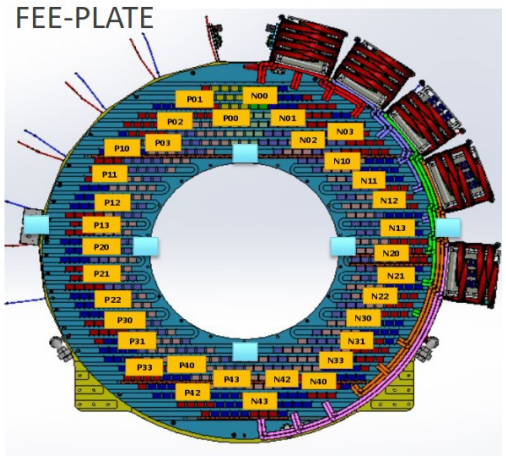
A first test of the cooling lines connected to the ECAL disks has been performed. The components used were too cheap to guarantee a stable performance over a long duration test.

The final coolant selected (ZULU) is slightly more aggressive from the chemical point of view.
leggermente più aggressivo dal punto di vista chimico.

Higher quality pumps, sensors, valves, connectors, pipes ... are needed.

Temperature and Radiation monitor (TRAD-v2)



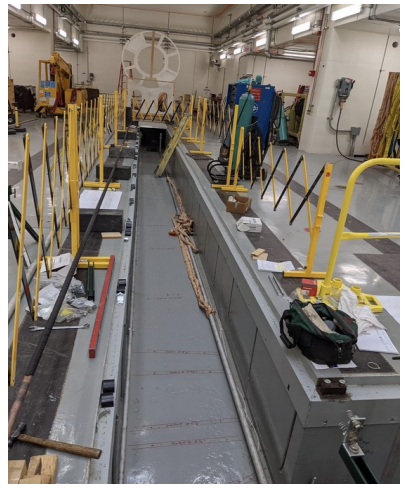


We want to monitor the temperature and radiation in different places on each disk.
A first prototype has been built to validate the tecnology choice
A second prototype (TRAD-v2), including the SEL protection, will be done by the end of 2023.

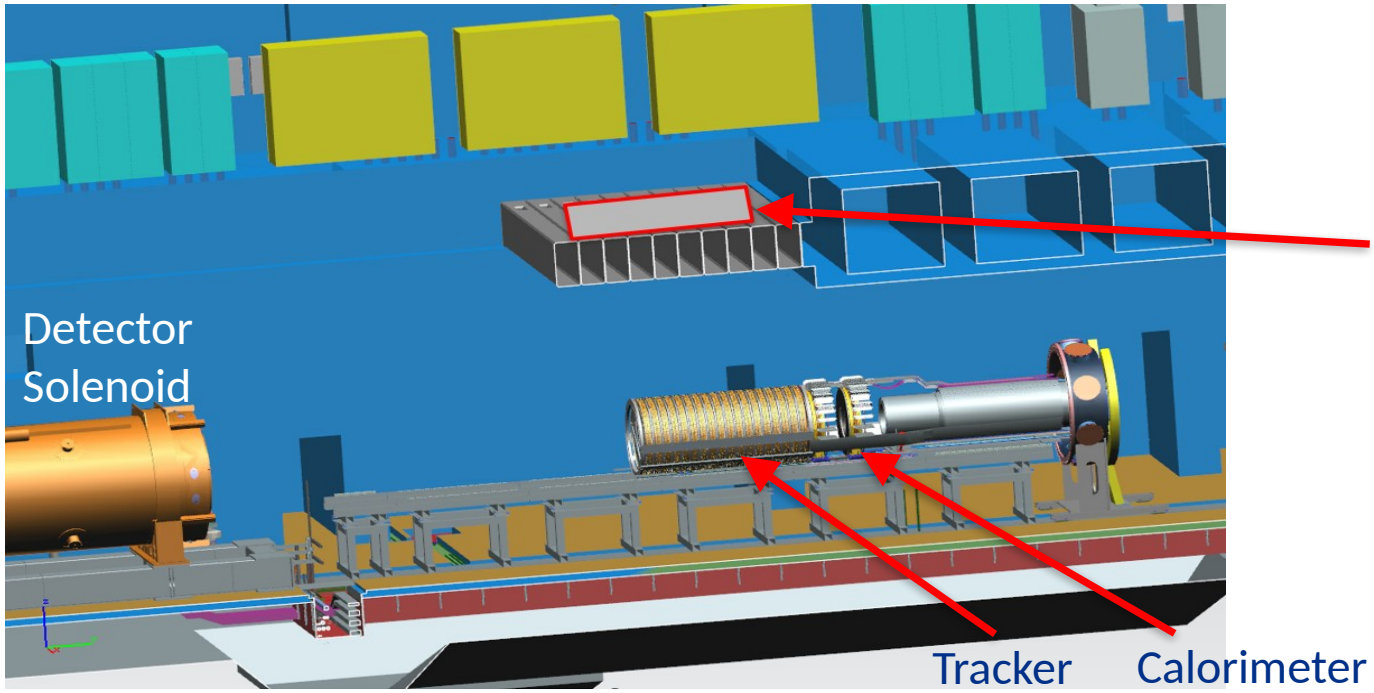
Final production by Spring 2024.

Next steps

- **2024: Test beam of module 0 fully equipped with the final electronics and DAQ**
- **2024: Calorimeter disks installation in Mu2e building**



- **2025: Commissioning with cosmic rays before the insertion in the DS**



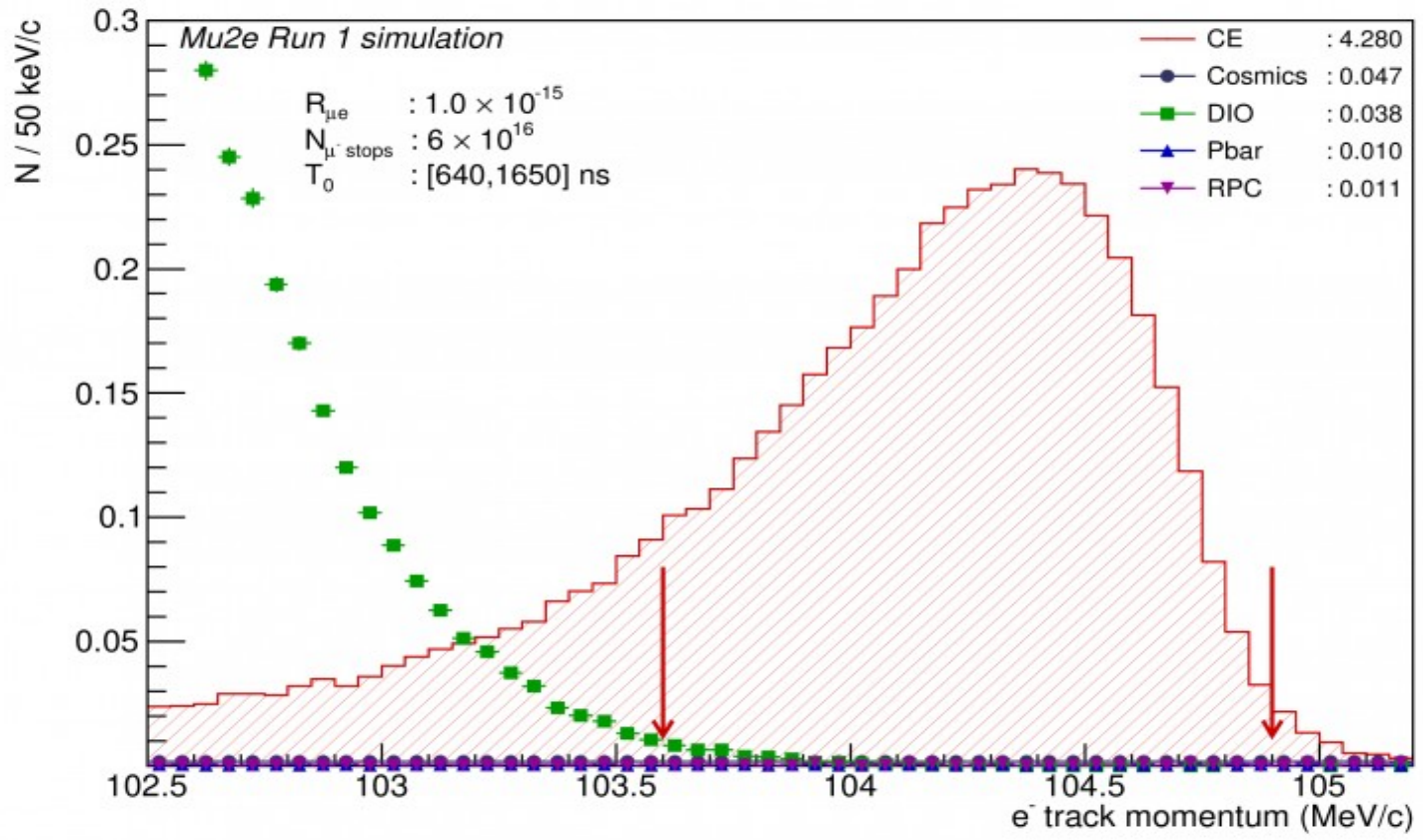
- **2026: First beam!**

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*

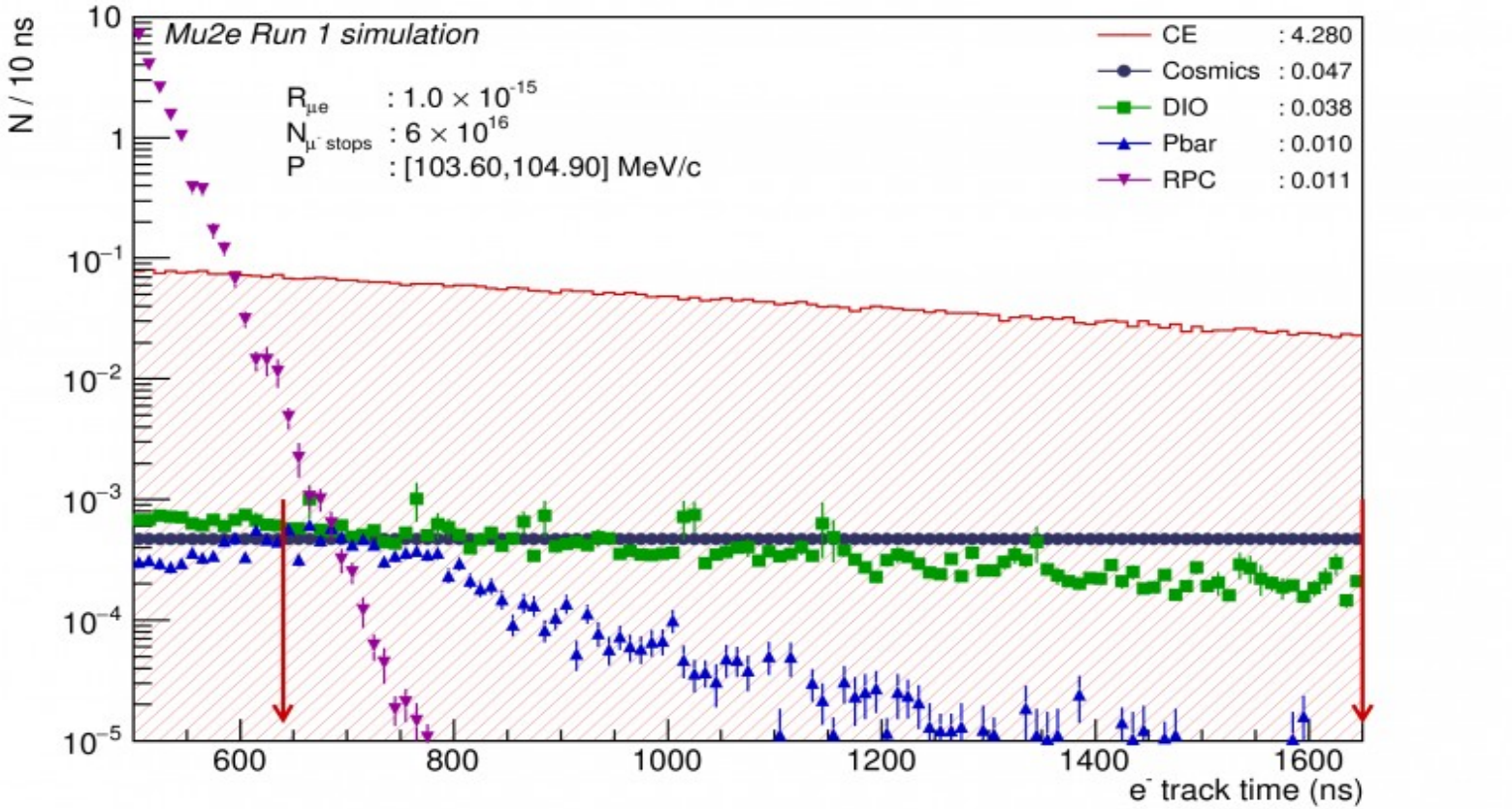
Electron momentum



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!