Design and assembling status of the Mu2e electromagnetic calorimeter mechanical structures

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1. The Mu2e Experiment: a Search for $\mu + N \rightarrow e + N$

The **Mu2e Experiment** will search for coherent, neutrinoless conversion of muons into electrons in the field of a nucleus. **Such a charged lepton flavor-violating reaction allows to probe energy scales up to thousands TeV**, far above the highest energy reachable at the most powerful colliders. If no conversion events are observed in three years of running, Mu2e will set a limit on the ratio between the conversion rate and the capture rate: **$R_{\mu e}$<6 x 10^{-17} (@ 90% C.L.).**

Production Solenoid (PS)

An **8 GeV proton beam** hits a tungsten target

A graded magnetic field reflects muons to the TS

Cosmic Ray Veto (CRV)

4 layers of plastic scintillator bars

Covers the entire DS and half of the TS

Straw Tracker (TRK)

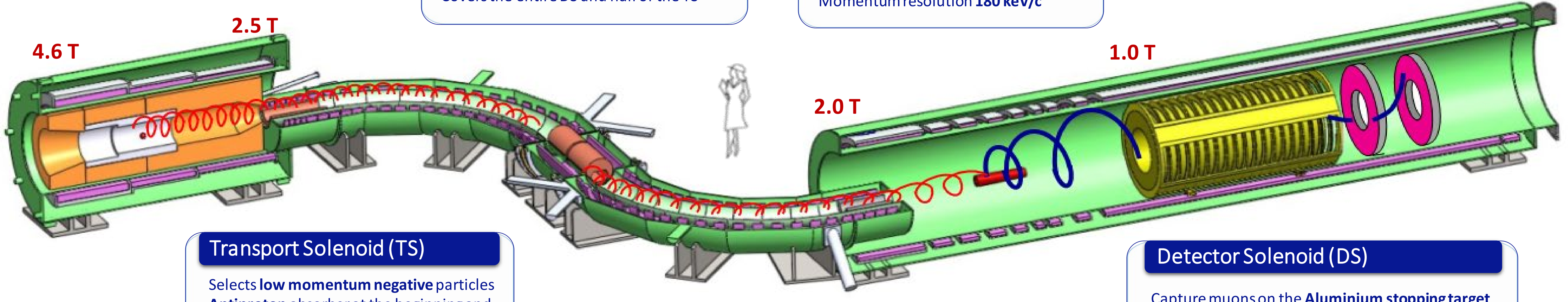
20000 low mass straw drift tubes

Momentum resolution **180 keV/c**

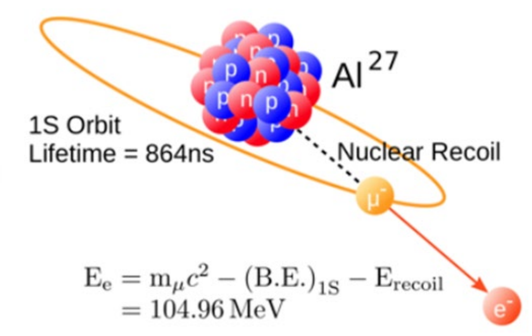
Electromagnetic Calorimeter (ECAL)

Two annular disks

Energy, Time and Position measurements



Schematic view of the Mu2e beamline



Experimental Technique

Stop muons in Aluminium

Muons quickly get to 1S orbit

Lifetime of muonic atom is 864 ns

Look for the 105 MeV conversion electron

Transport Solenoid (TS)

Selects **low momentum negative** particles

Antiproton absorber at the beginning and in the mid-section

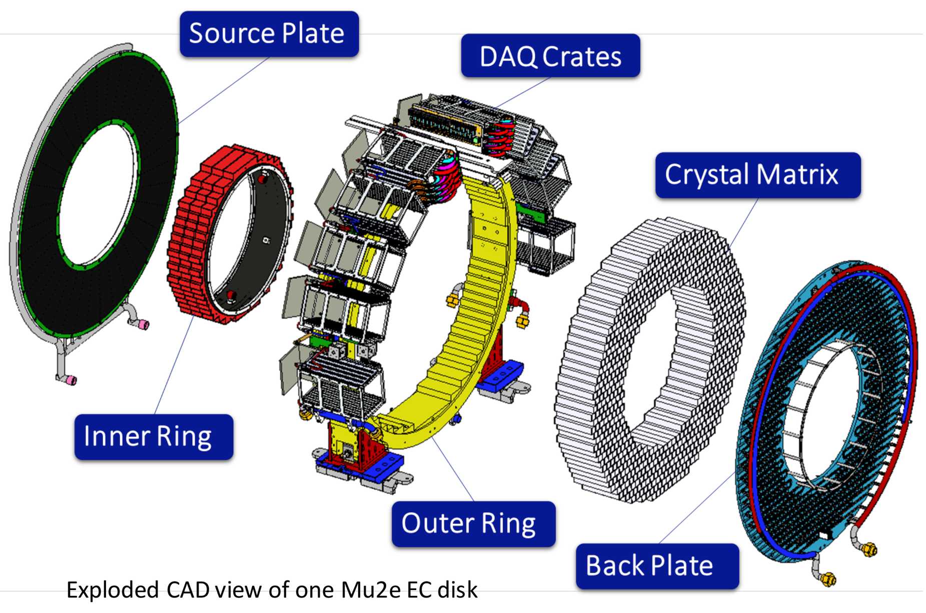
Detector Solenoid (DS)

Capture muons on the **Aluminium stopping target**

1 T B field and **10^{-4} Torr** vacuum in the detector zone

2. The Electromagnetic Calorimeter

The Electromagnetic Calorimeter is a high granularity crystal calorimeter consisting of two disks, each made of 674 **undoped CsI crystals.** Each crystal is coupled to two 14x20 mm² **large area UV-extended SiPM,** fastened to the Backplate for thermalization. 10 custom crates, with integrated cooling, host power distribution and DAQ boards.



Exploded CAD view of one Mu2e EC disk

The whole Calorimeter is supported by an external aluminum ring, with adjustable positioning feet for detector alignment.

From the inside, the crystal matrix is held by the carbon fiber inner ring.

A source calibration system closes frontally the crystals.

Calorimeter Requirements:

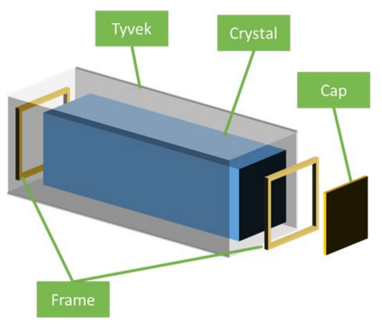
- Particle identification μ/e
- Seed for track pattern recognition
- Independent trigger

⇒ **$\Delta E/E$ < 10% and Δt < 500 ps**

⇒ **Position resolution of O(1 cm)**

Operational conditions: • 1 T B-field • 10^{-4} torr • 90 krad, 10^{12} n cm^{-2} year^{-1} • 25°C

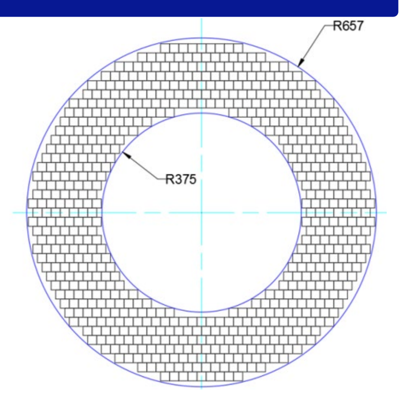
3. Cesium Iodide Crystal Matrix



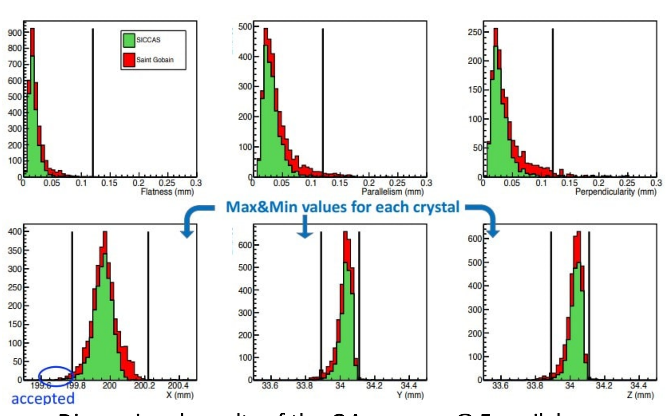
Schematic view of a crystal module

Crystals are placed in a 'donut'-shape staggered matrix, with an inner diameter of 650 mm and an external diameter of 1314mm. Each crystal is a brick of 34x34x200 mm³, wrapped with Tyvek foils of 150 µm for light reflection and separated with a 50 µm thick Tedlar foil to avoid cross talk effect.

Crystals have been finely checked both for physical and dimensional properties. They all satisfy a linear dimensional tolerance below 0.1 (short side)/0.2 (long side) mm and a planarity and perpendicularity below 0.1.



EC crystals matrix



Dimensional results of the QA process @ Fermilab

Both vertical and horizontal crystal stacking have been measured to obtain a model of crystals true position.

Inner and outer cylinders have been designed to minimize SiPM-Crystal alignment errors.

100% crystals have been purchased, tested and stored at Fermilab in nitrogen fluxed cabinets ready for assembling.

Crystal vertical piling up measurement test

4. Inner Ring and Source Plate

Inner Ring CAD model

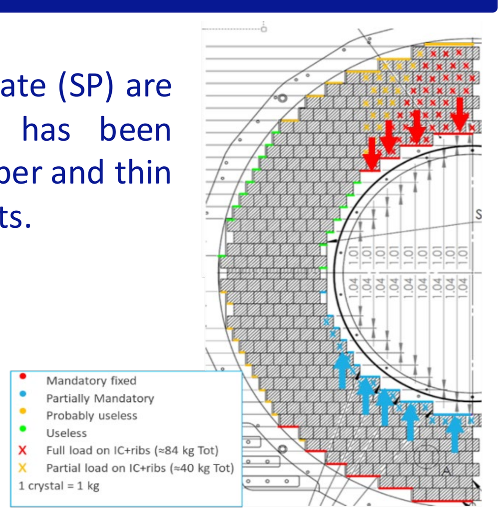
a) **One cylinder**: ID of 672 mm, 4.2 mm thick, F°...220/193/50 CF fabric (0/90) with cyanate ester resin

b) **Two rings**: ID of 672 mm, OD of 712 mm, 13 mm thick, 5083 H111 Al alloy

c) **Three ribs**: Sandwich with 1.4 mm CF skins (same as a)) and a core of aluminum honeycomb (series 3003) 22mm thick, 3/8"

Because both the Inner Ring (IR) and the Source Plate (SP) are on the particle's trajectories, material budget has been optimized to reduce particles energy loss. Carbon fiber and thin wall aluminum have been used for these components.

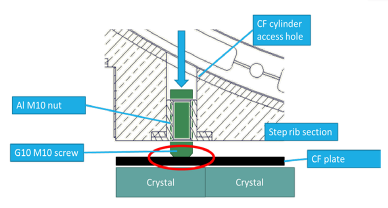
The IR must support the crystal matrix load without excessive displacement. It is made of two aluminum rings to stiff the structure, three honeycomb structure ribs, to create crystal vertical and horizontal references and a CF cylinder skin to bound everything together



Vertical load scheme for the IR

CF+Al honeycomb sandwich sample

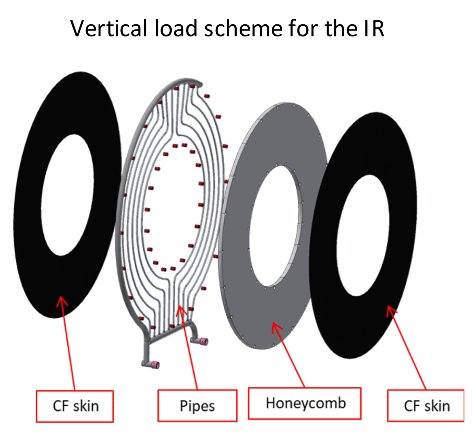
To avoid damaging crystals beneath, and to regulate IC position, several adjusting feet will be installed on the bottom layers. Compression tests have been performed.



SP thin wall pipes

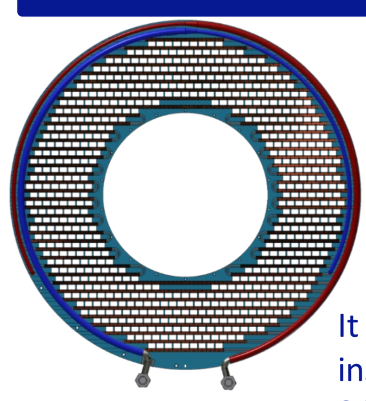
SP is made of a CF and Al honeycomb sandwich with a thin wall aluminum pipe embedded. Fluid CF-770 will flow in it for energy calibration.

It will also support a frontal enclosure for crystals protection.



Exploded CAD view of one SP

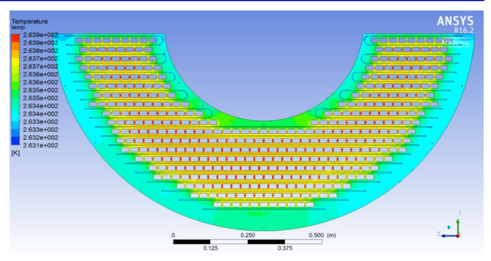
5. Back Plate and Front End Electronics



BP CAD Model

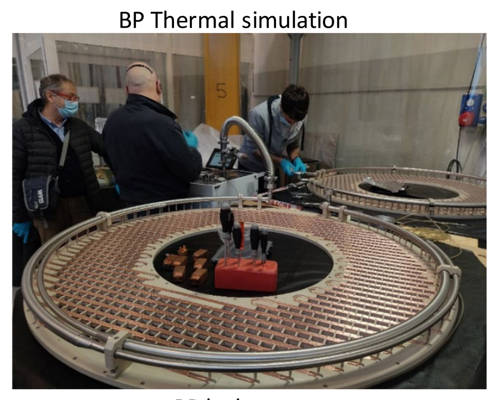
- ΔT < 1°C between inlet and outlet
- Head loss <0.6 bar
- $h_c \geq 2000\ W/m^2K$

As the name suggests, the Back Plate (BP) is the rear side of each EC disk. It will give a physical positioning reference for both crystals and SiPMs. It will also refrigerate FEE boards and keep SiPM thermalized to -10°C to keep dark current low and keep stable SiPM readout signal over time.

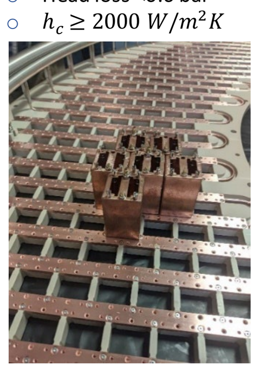


BP Thermal simulation

It has been made of a PEEK support plate, for its thermal insulation and outgassing properties. A stainless steel (AISI 316L) I/O manifolds have been placed at the outer diameter and will distribute homogenously refrigerant fluid (3M™ Novec™ 649) between the 38 parallel copper cooling lines embedded in the plate. Both BPs have been manufactured and we are making a geometrical, thermal and integration survey before final installation



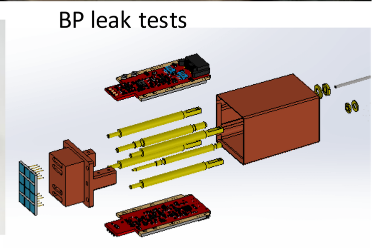
BP leak tests



FEE Modules mounted on the BP

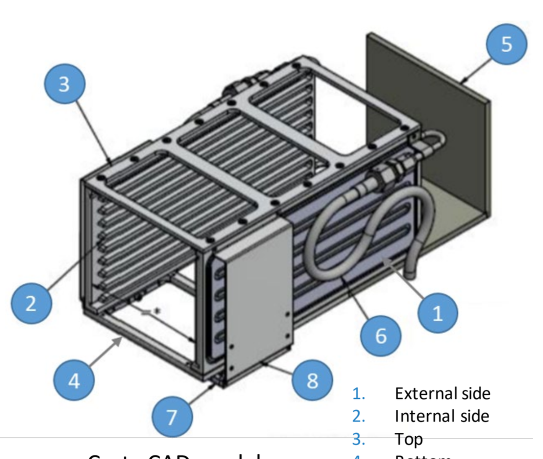
On the BP, 674 FEE modules will be installed. Each of them is composed by 2 read-out boards, 2 SiPMs glued on a copper mounting holder, a copper protecting Faraday cage and a fiber guide. They will be fasted on the BP cooling lines to reduce thermal resistance. Modules will be prepared and tested apart before installation on the calorimeter

FEE holders with glued SiPMs



FEE Module exploded view

6. Crates and DAQ boards



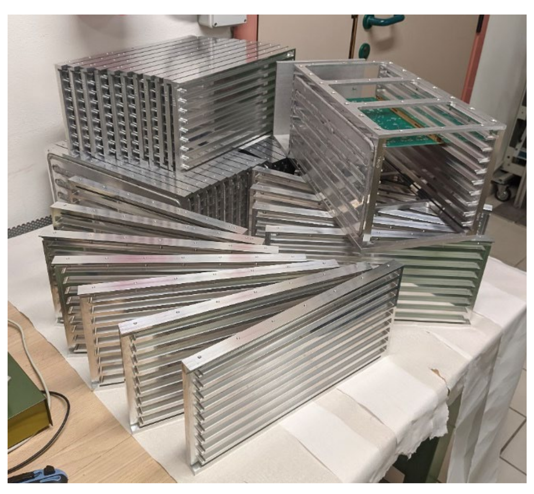
Crate CAD model

1. External side
2. Internal side
3. Top
4. Bottom
5. Tungsten shield
6. Inlet/Outlet pipe
7. Cable holder
8. Cable containment wall

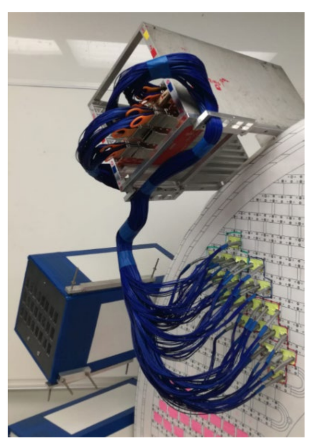
Crates are placed around the calorimeter disks, inside the cryostat. Each of them hosts up to 8 Mezzanine and Dirac boards which will acquire data from the FEE boards, digitalize and send them out of the cryostat through optical fibers.

The crate will give mechanical support for the DAQ boards and cool them at the same time.

Crates are connected in parallel with two main manifolds and they can remove up to 320W of power each.

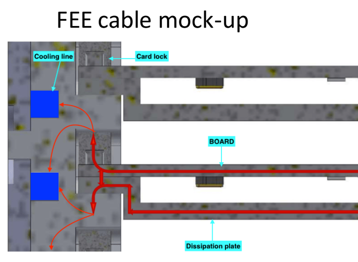


Crate sides during leak test



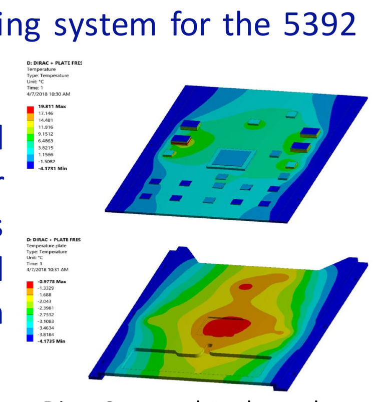
FEE cable mock-up

To improve heat removal, a copper plate has been designed to be in thermal contact with the most powerful components and vacuum proof thermal grease (Apiezon) will be applied on those components. To reduce envelopes and optimize thermal performance, crates have embedded cooling lines on their sides. A tungsten plate as the frontal and bottom side will protect boards from radiation exposure. Moreover, crates will furnish a primary holding system for the 5392 FEE cables.



Board heat flux path schematic

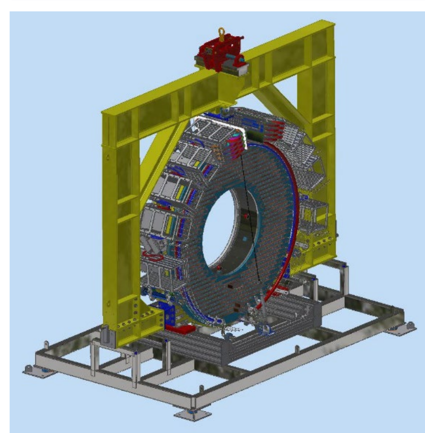
Thermal simulations and experimental tests have been performed both in air and vacuum. Crate production is ongoing and QA tests have been and will be performed during production to assure required performances.



Dirac Copper plate thermal simulation

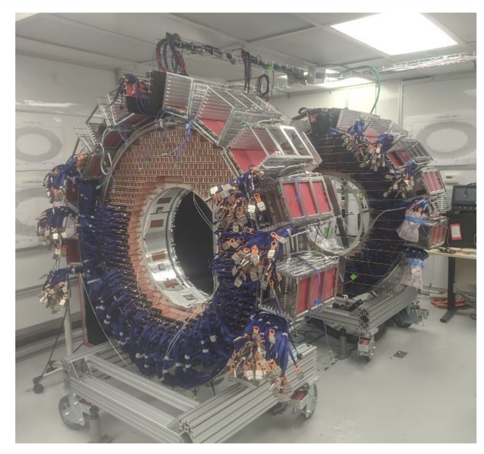
MB and Dirac coupled with copper plates

7. Detector Assembly



Calorimeter transportation system from SiDet Lab to MC-2

- The calorimeter is being assembled in the SiDet Laboratory at Fermilab, in a 10000-class cleanroom.
- Two mounting stations have been set up to simultaneously test one disk while building another.
- Outgassing of most components, including cables and crystals, has been completed in a dedicated station before their installation.
- Cooling performance and electronic tests have been conducted prior to assembling the calorimeter.
- The transportation system is currently under construction, and the organization of its procedures is being reviewed.



Calorimeter assembling @ SiDet Lab

8. 'Final' steps

- The mechanical design of the Mu2e EM calorimeter has been finalized.
- The mechanical structure is now complete.
- Production of the crystals, SiPMs, FEE, cables, and fibers has been concluded; DAQ boards are currently under production and testing.
- The installation of the DAQ board, calibration laser fibers, and FEE cables is being finalized.
- Expected completion date: December 2024
- **We look forward to deploying the calorimeter in the experimental room and letting it do its job!**

MC-2 experimental hall @ Fermilab

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