Status and Plans for the Fermilab Test Beam Facility

Evan Niner

HEPAP Meeting

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Introduction

- Fermilab Test Beam Facility (FTBF) – Supports a wide program of research and detector R&D
  - Operating since 2005 and serving over 1000 users from more than 30 counties conducting research in all P5 thrusts and beyond.

- Irradiation Test Area (ITA) –
  - Low energy (400 MeV protons), high rate (~2.5e15 protons/hr)
  - Unique in the US to have irradiation and test beam co-located (P. Merkel talk)

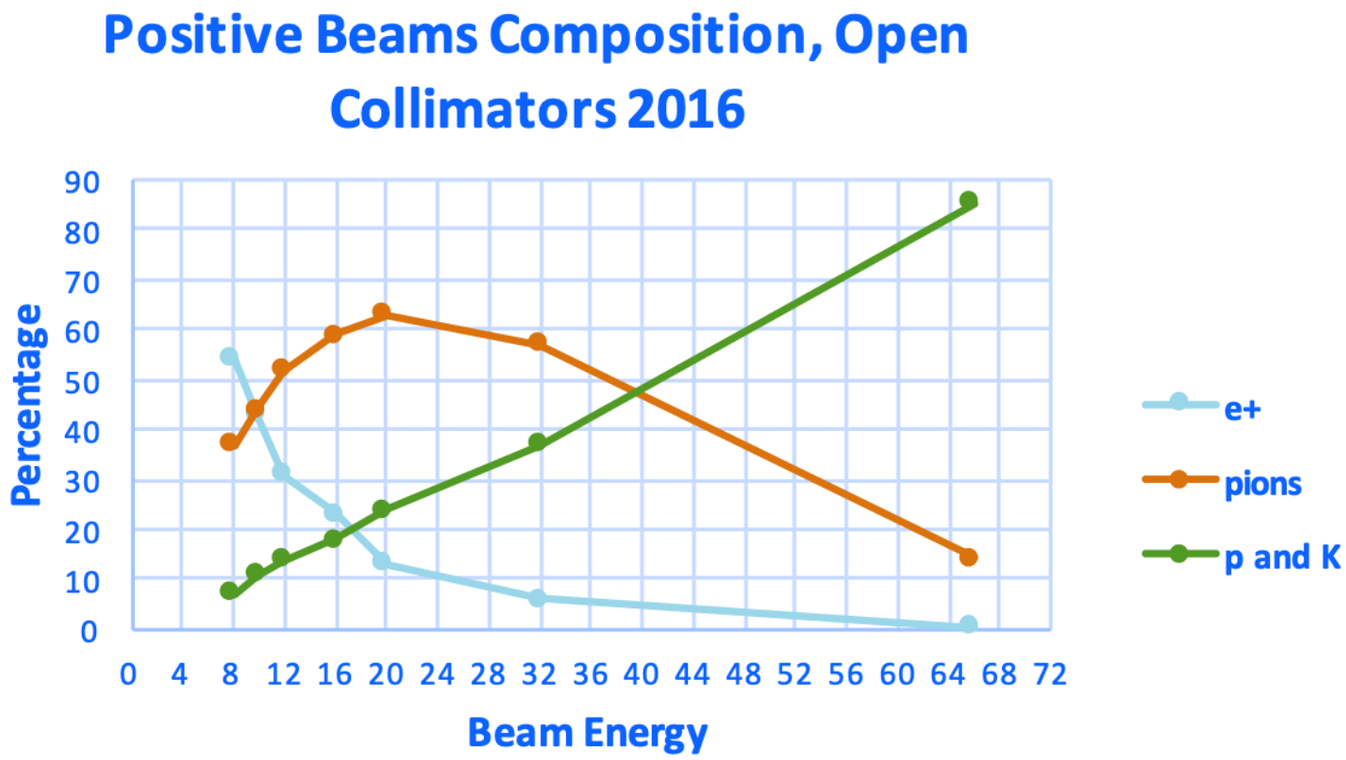
- Beam traditionally available ~8 months a year (roughly November through June)

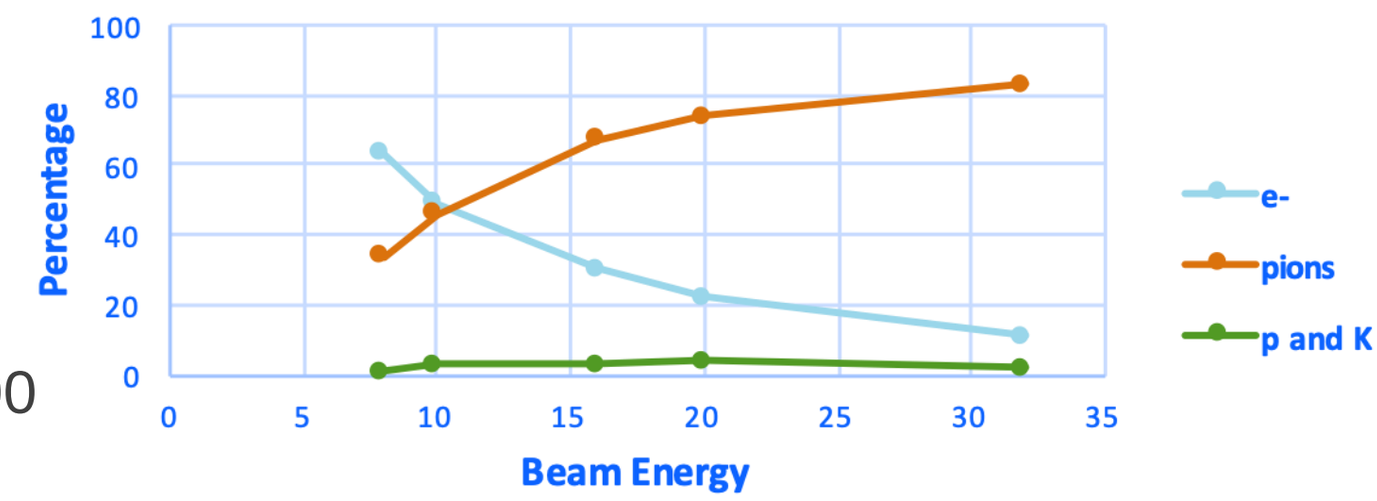
Beam Details

- 4.2 second slow extraction beam spill every super cycle from Main Injector
- ~1000 to 900,000 particles per spill

- MTest
  - 120 GeV protons
  - 1-66 GeV mixed secondary beam
  - ~2cm spot size
  - typically 1-4 week experiments

- MCenter
  - Secondary beam, 8-90 GeV pions
  - Two tertiary beam stations down to 200 MeV
  - Longer term experiments





https://ftbf.fnal.gov/beam-overview/

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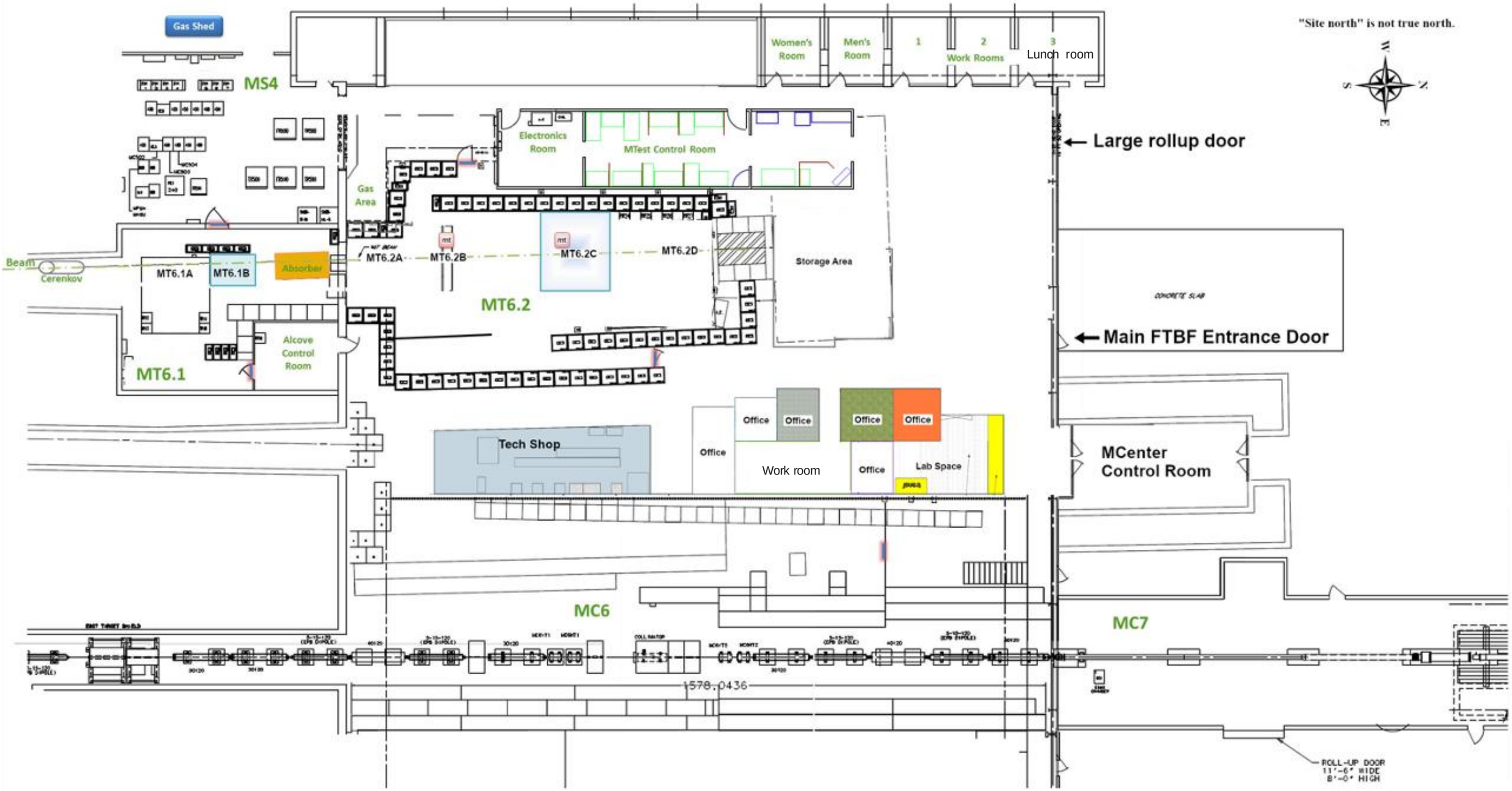
FTBF Layout

Onsite technical and scientific staff coordinate experiments from planning through execution safely and efficiently.



FTBF Layout - MTest

- Maintain plug-and-play infrastructure to minimize installation overhead and maximize beam efficiency
- FTBF provides beamline instrumentation and DAQ, tools, cabling and patch panels, motion tables, common equipment pools, gas delivery systems, control room and computing, access to other lab resources
- One experiment changeover day per week, six days beam delivery



FTBF Layout - MCenter

- Beam instrumentation and target configuration varies significantly between experiments where installation efforts commonly take months.

- Facility provides equipment pool and technical expertise, but experiments are expected to manage their own installation and provide specialized instrumentation and DAQ systems.

Tracking Telescopes

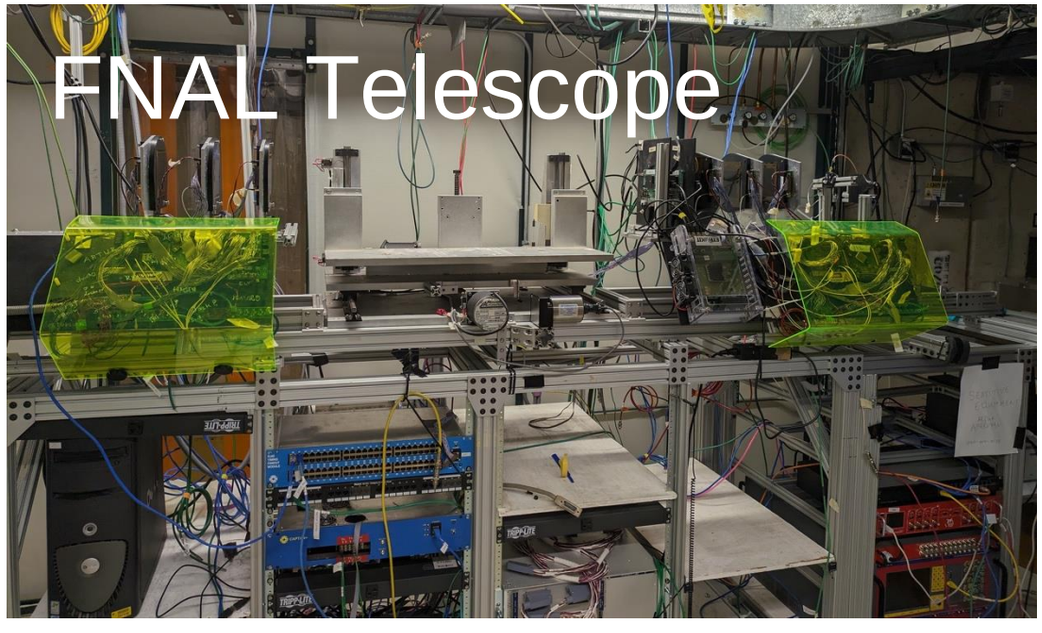
- 2 silicon telescopes are in the MTest beam line
  - One built and operated by FNAL
  - One built and operated by ANL

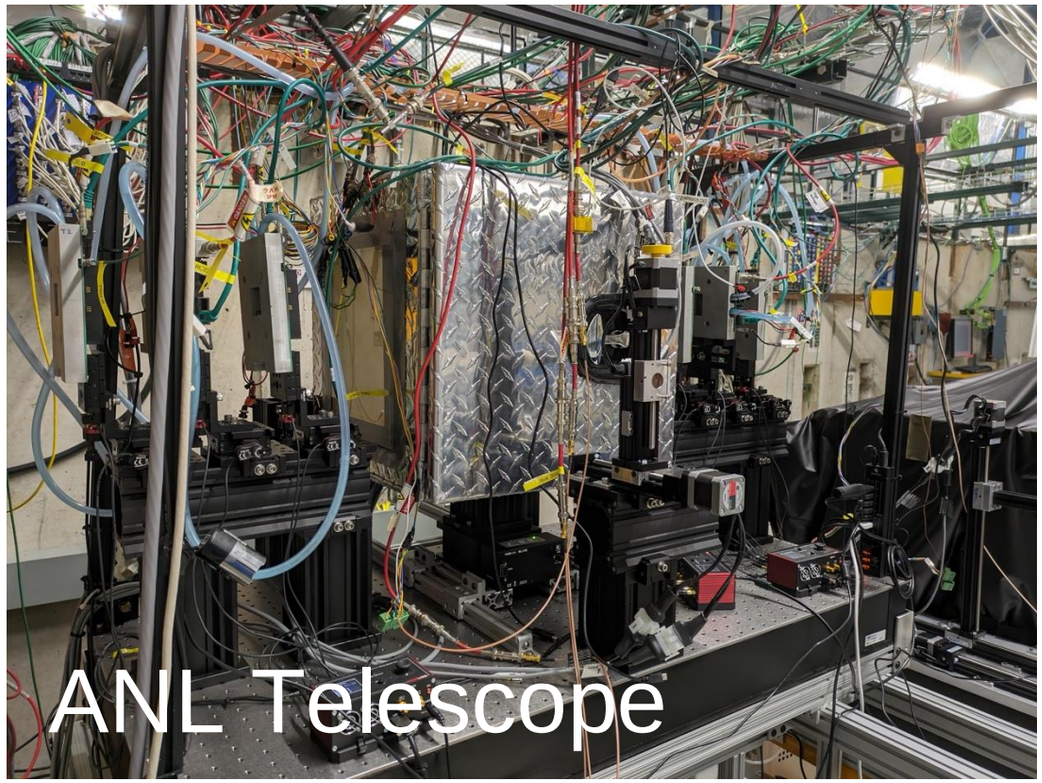
- Allow precision tracking of particles to ~5μm

- Motion tables allow scanning location of devices under test

- Used largely for CMS and ATLAS tracker tests, but available to all users

- Crucial infrastructure for a test beam facility

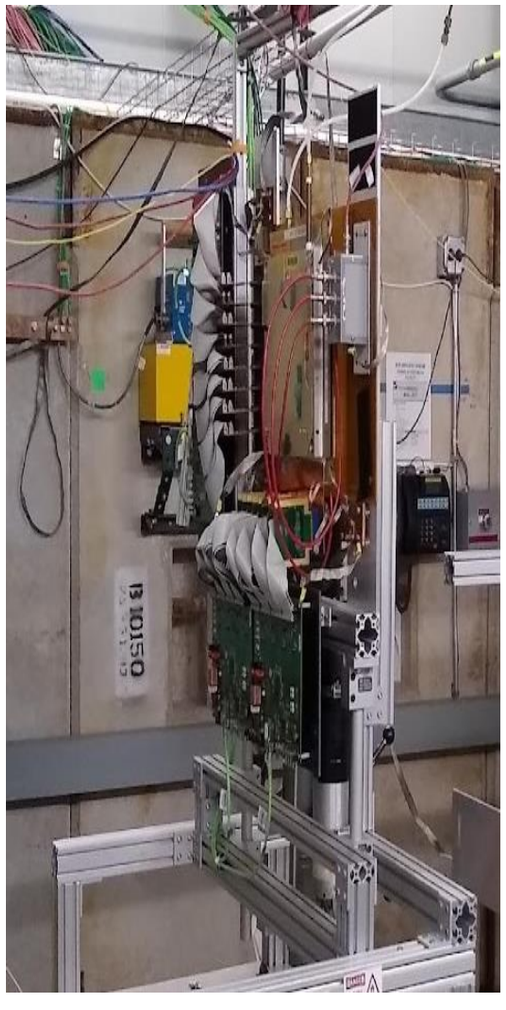




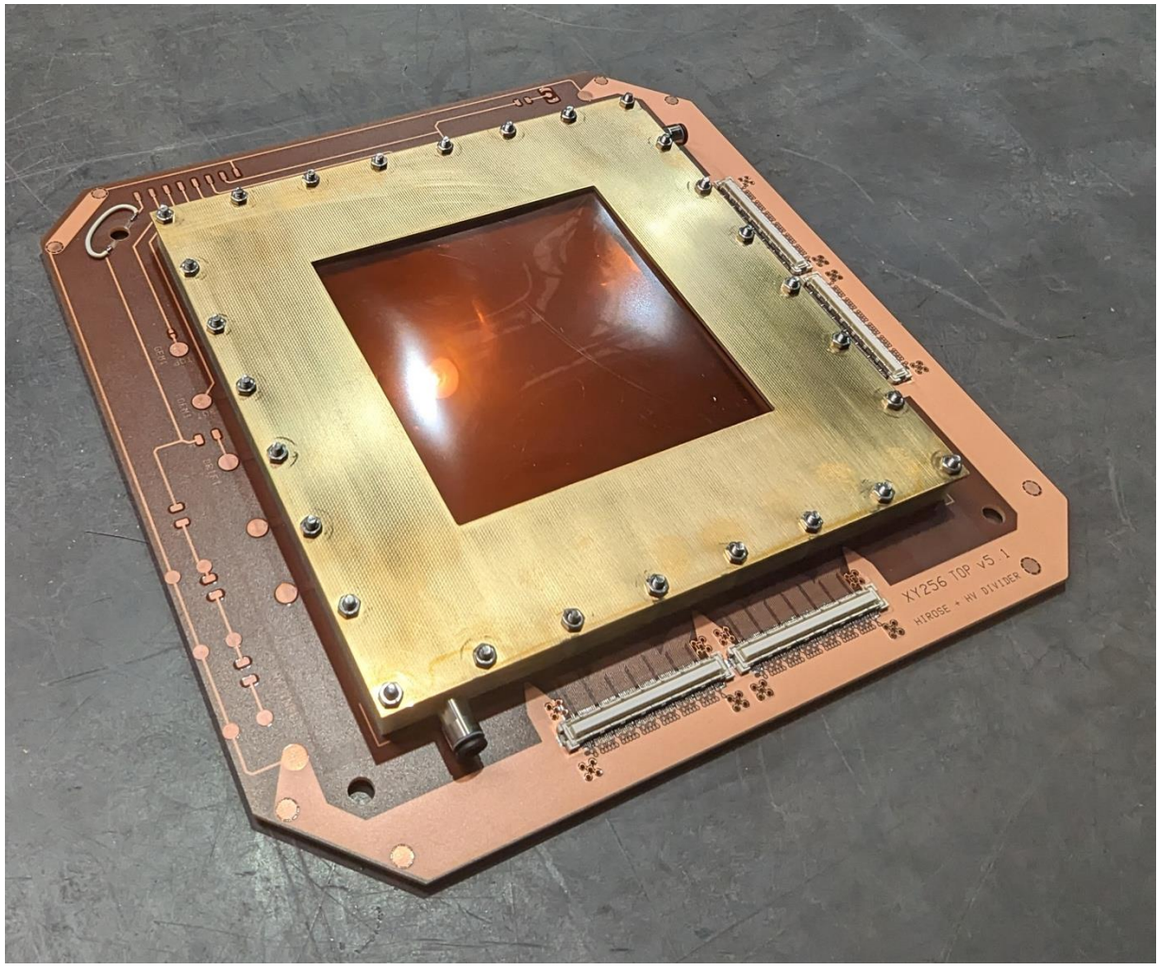
Instrumentation upgrades – Particle tracking

- Replacing Fenker chambers for particle tracking in MT6.2 with CERN GEM chambers
- GEM chambers have arrived at FNAL in March
- Scalable Readout System DAQ solution, developed by RD52 collaboration, has been ordered (Arrival by end of 2024)

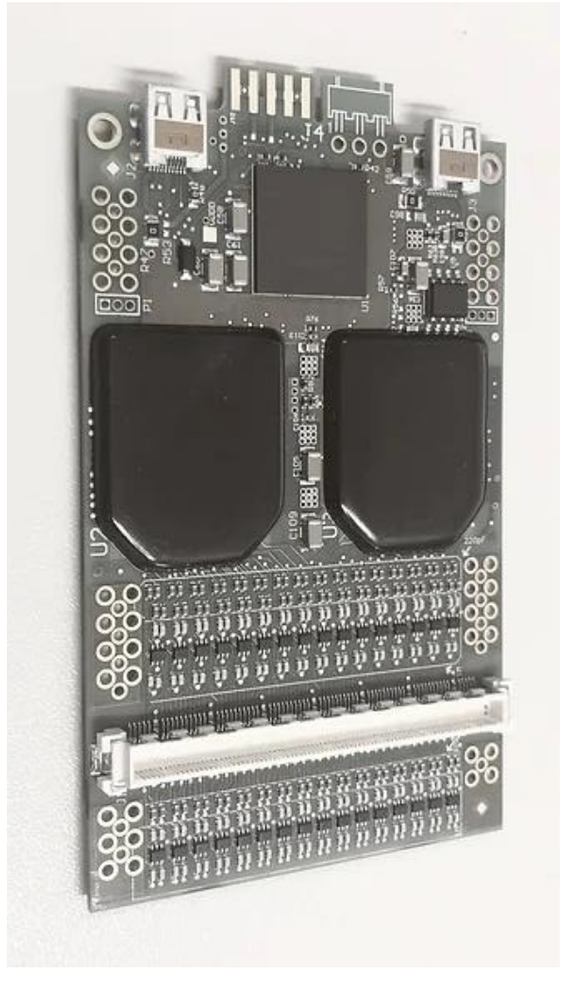
Fenker Chamber



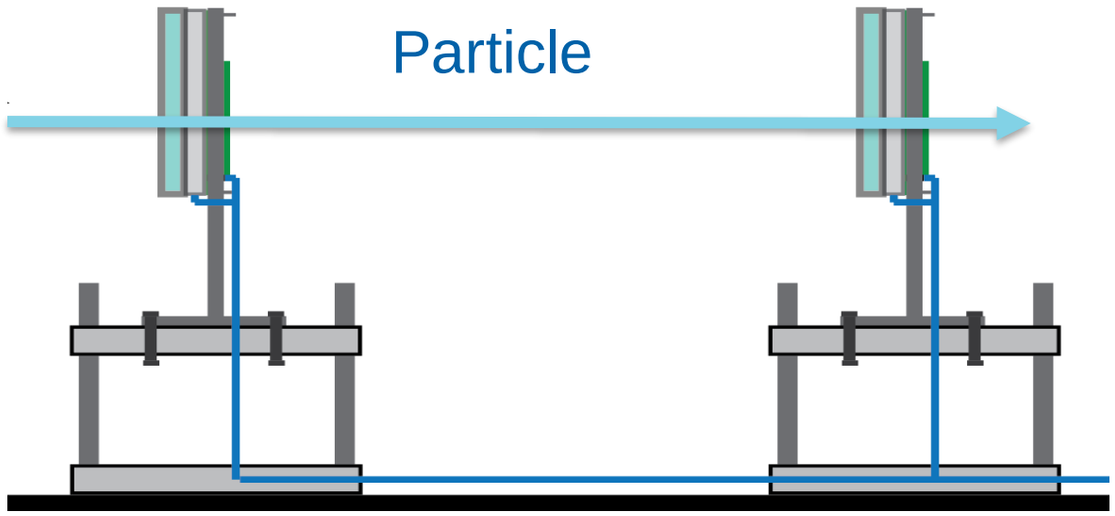
GEM Chamber



SRS VMM3a card

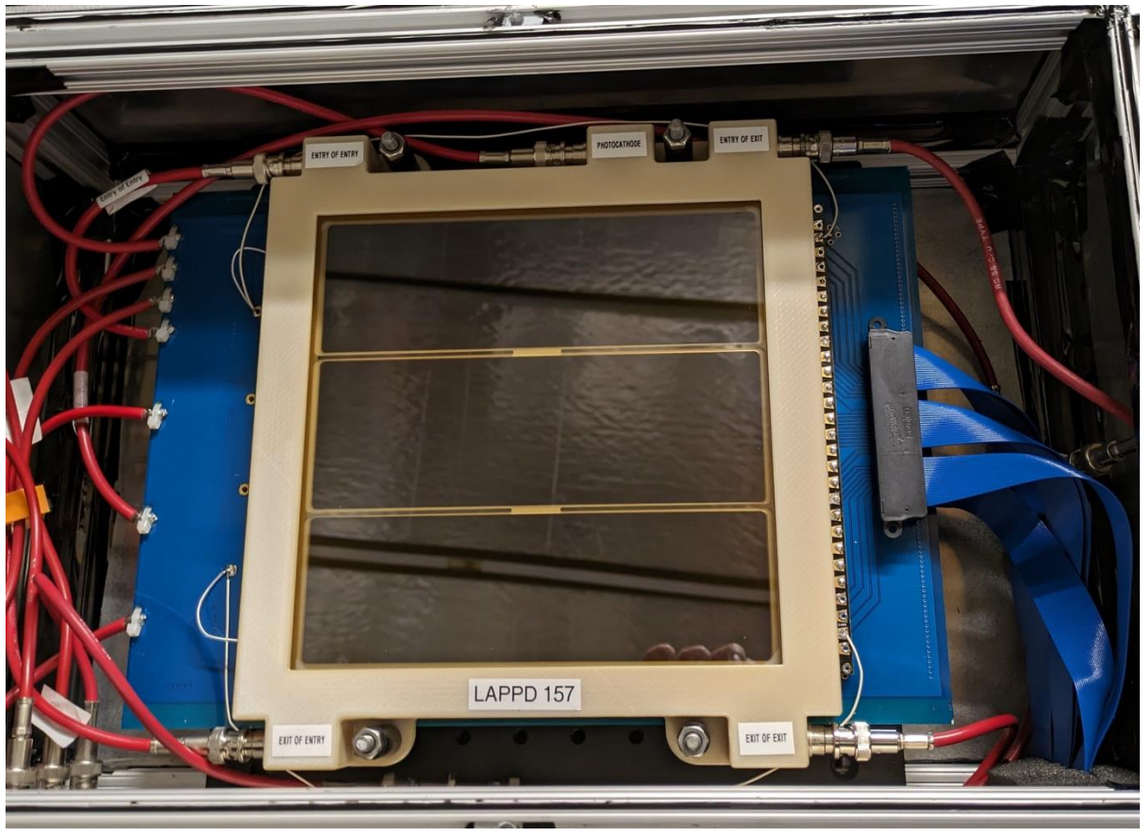


Instrumentation upgrades – LAPPD based TOF



E. Angelico

- Use pairs of Large Area Picosecond PhotoDetectors (LAPPD) to measure time of flight (TOF) of particles at FTBF. Allows for particle ID



- With 50 m distance allows
  - e/π separation to 7 GeV
  - π/K separation to 25 GeV
- Hope to install system in FY25
- Initial work piloted by U. Chicago

Angelico, Evan. doi:10.2172/1637600	$\sigma_L/\sqrt{N_{\text{pe}}}$	σ_{pulse}	σ_{WR}	σ_{tof}	Maximum π/K momentum at 5 m / 45 m
Use of fused silica window	55 ps / $\sqrt{200}$	7 ps	5 ps	14 ps	8.2 / 25 GeV/c

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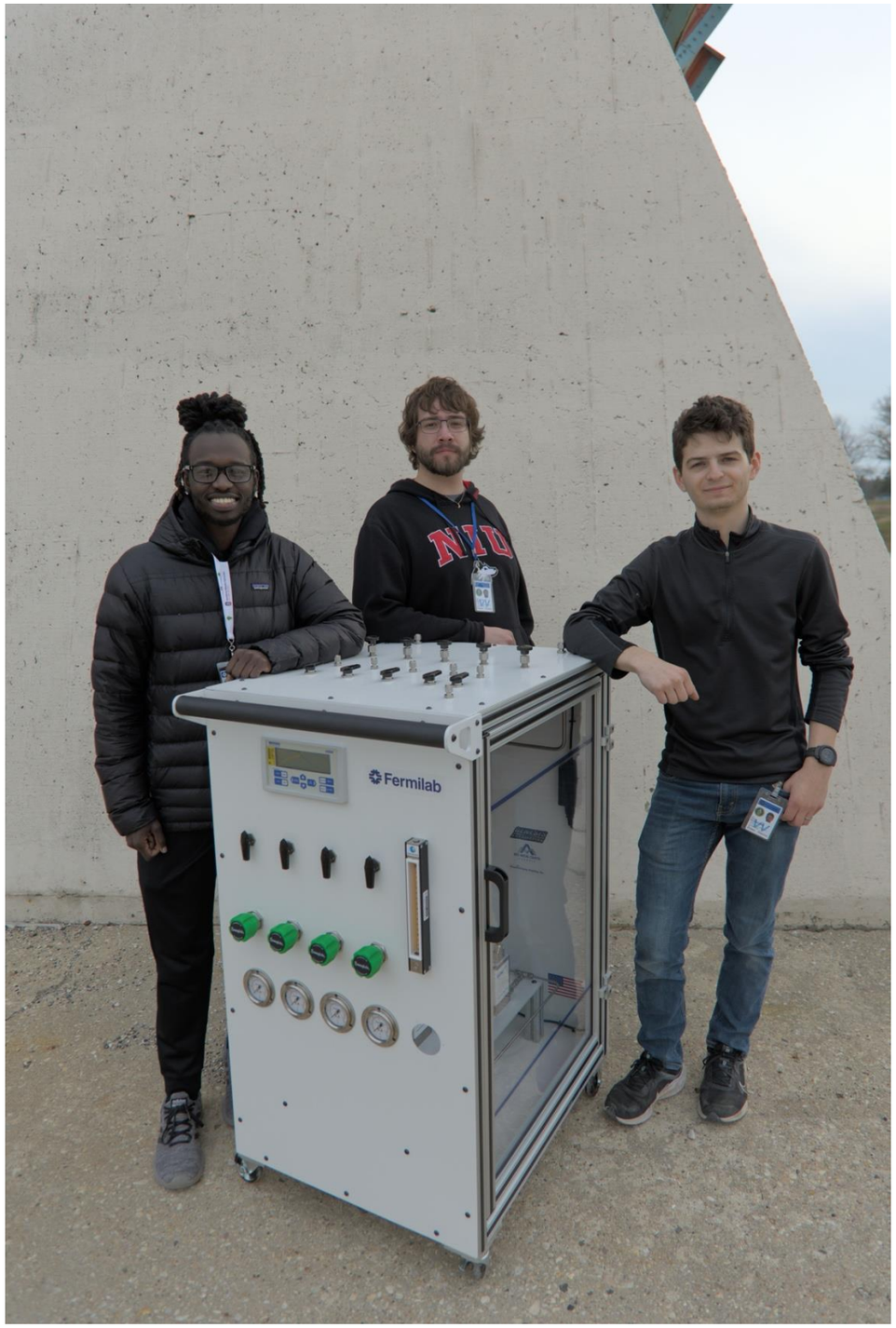
Instrumentation upgrades – Gas mixer system

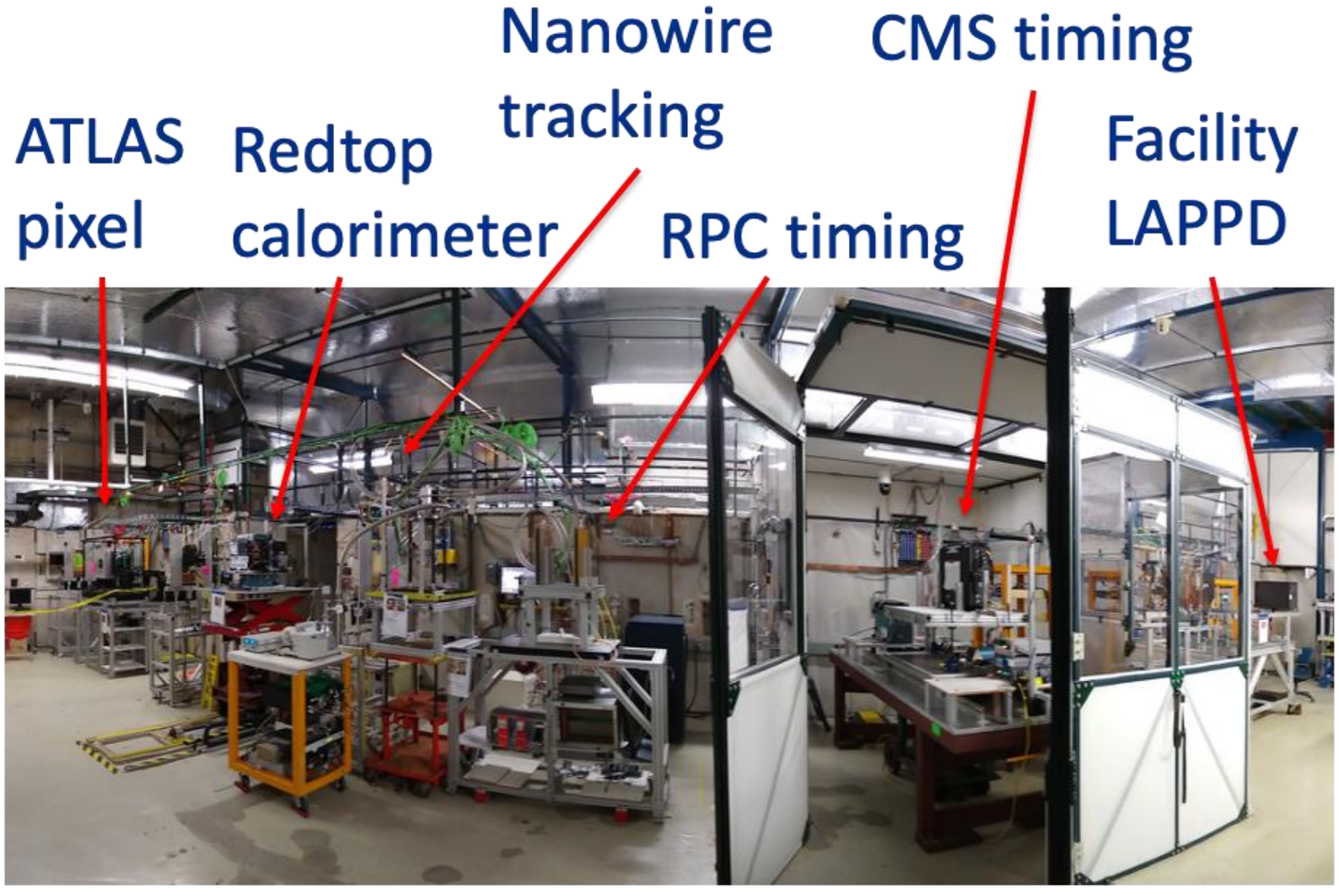
- Over the 2023-24 school year we had a group of senior engineering students from Northern Illinois University design and built a gas mixing system which will be used in MTest
  - Allows mixing of up to 4 different gasses in precise ratios
  - Reduces need for users to bring their own mixers which require significant cost and lead time in engineering and safety approval
  - Mixer complete and ready for use



Experiments at MTest

- FY23, MTest users have included experiments from the CMS, ATLAS, EIC, neutrino, and general R&D communities.
- Established regular users transitioning expertise from CMS/ATLAS to continued general R&D and FCC and EIC applications.

MT6.1



MT6.2

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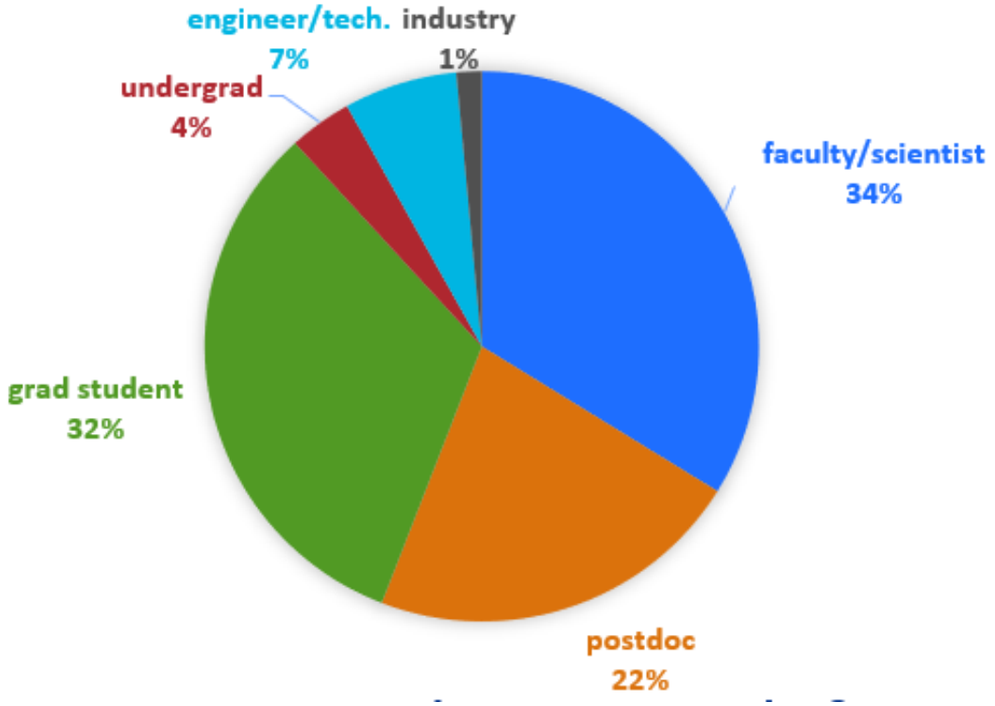
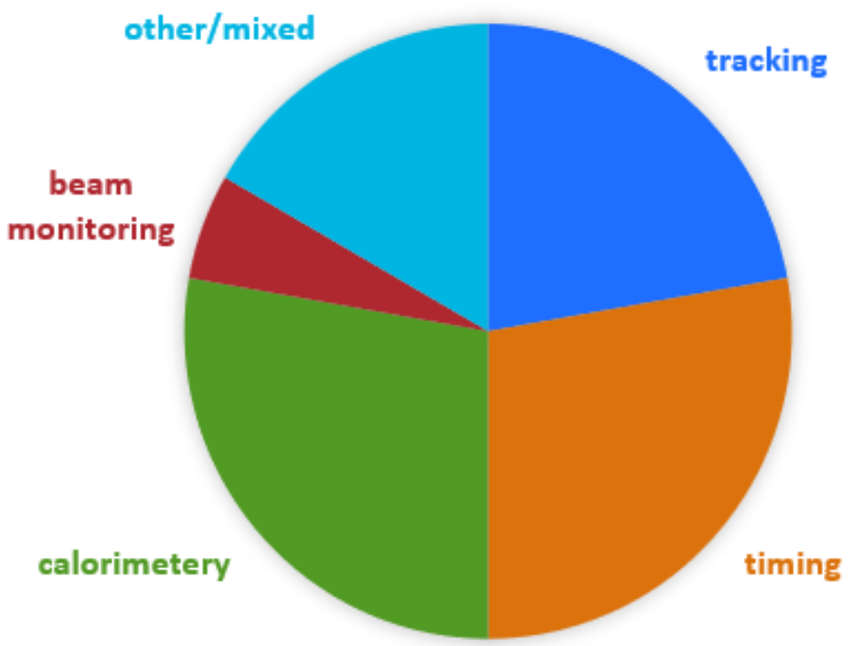
Who Uses FTBF?

- 223 users in FY23
- Users from 53 Universities/Labs (18 international)
- 20 Experimental efforts, 4 new efforts

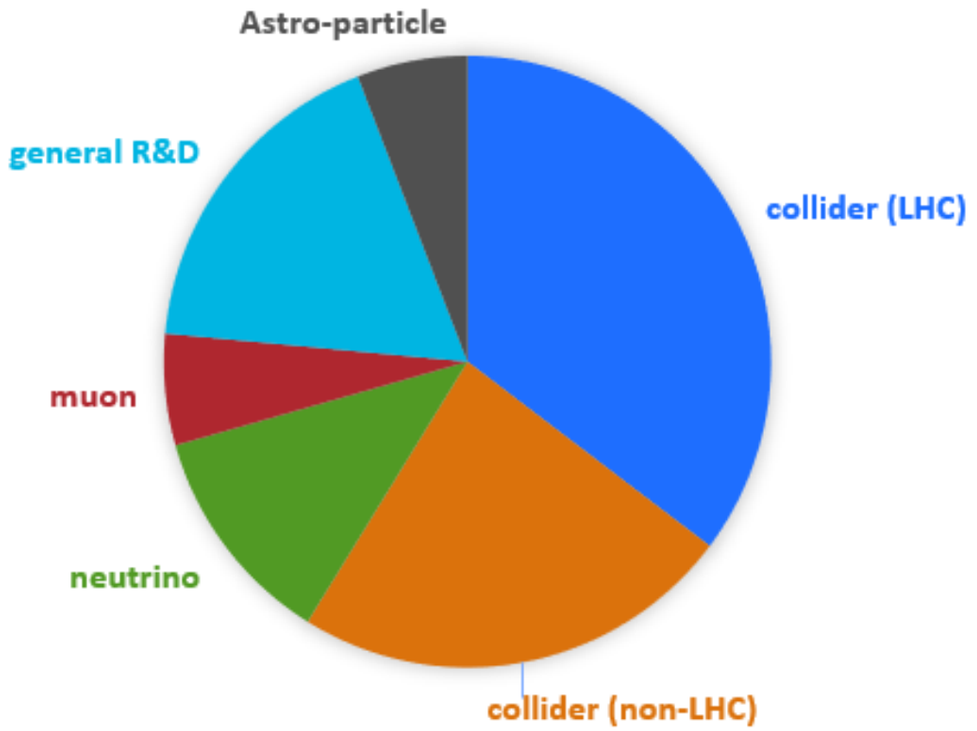
Users by professional category



Experiment by detector



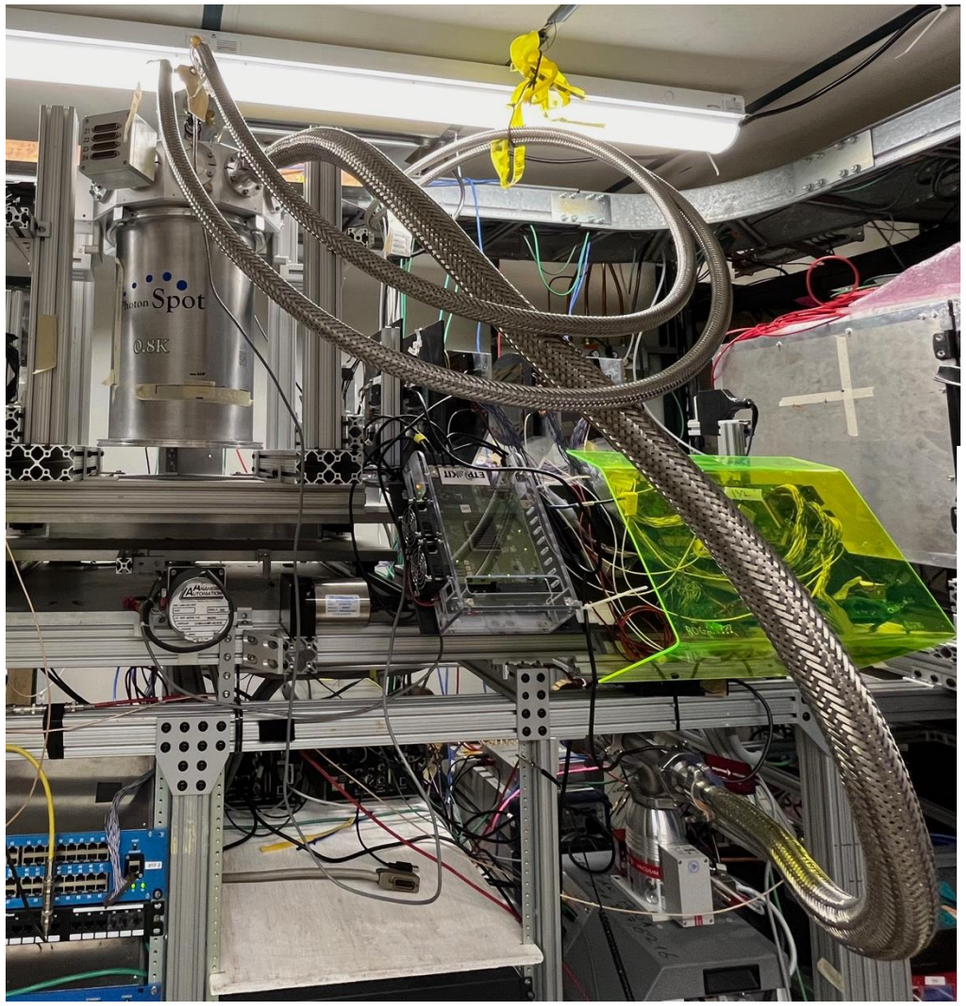
Experiment by research focus

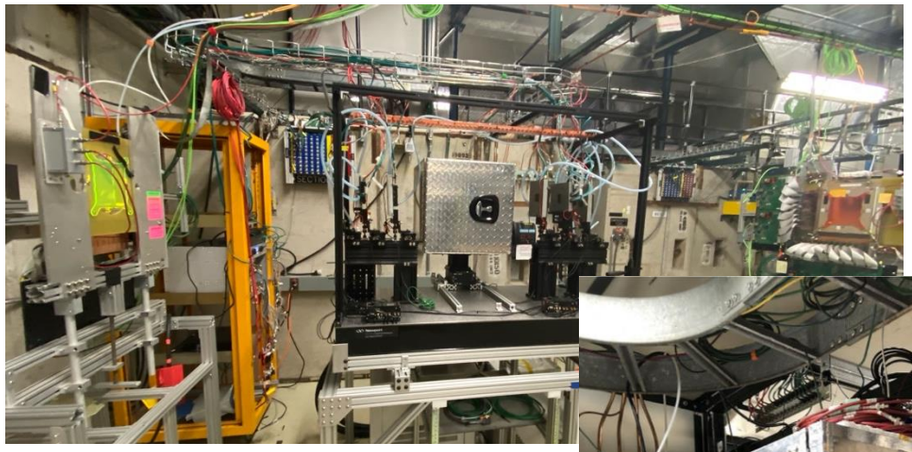


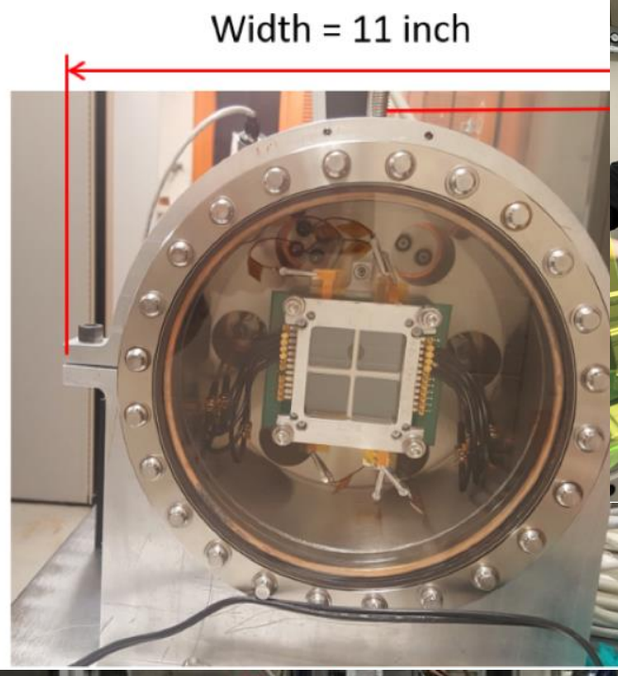
FTBF Users

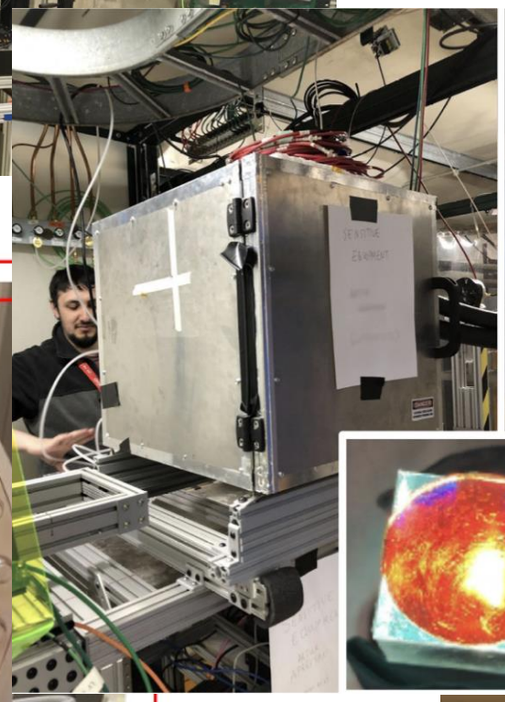
- Support general R&D in developing new technologies across all research thrusts
- Projects
  - LBNF/DUNE, HL-LHC (CMS/ATLAS), Mu2e have all had critical tests that depended on FTBF in order to make design decisions.
  - Muon g-2 and sPHENIX/EIC have also used the Test Beam when designing components for projects.
- Students use the Test Beam to develop critical skills
  - FTBF supports 2-5 student interns every year.
  - FTBF is an essential part when FNAL hosts the EDIT school
- Student Theses
  - FTBF allows students to experience a full lifecycle of an experiment, writing their theses using detectors they built and tested.
  - Typically 1-2 theses per year
- Early Career
  - FTBF is a vital component for several successful early career and LDRD proposals
  - Students and postdocs have returned to FTBF as PIs

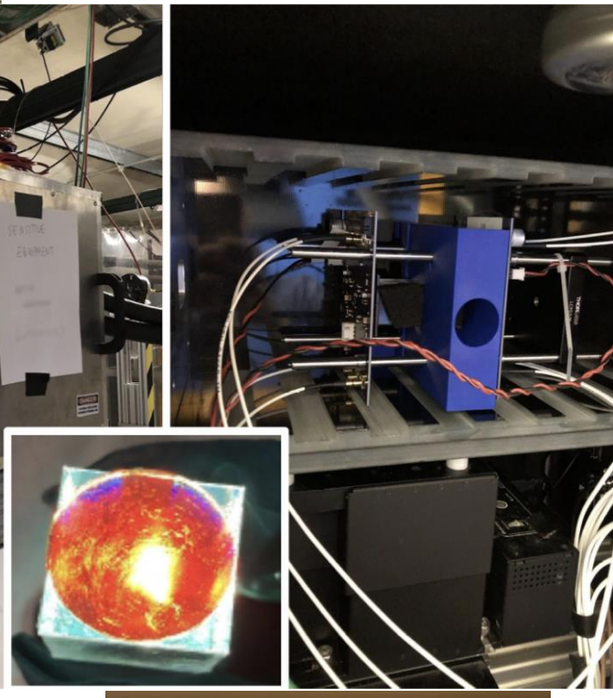
Users from many different experiments use the Test Beam

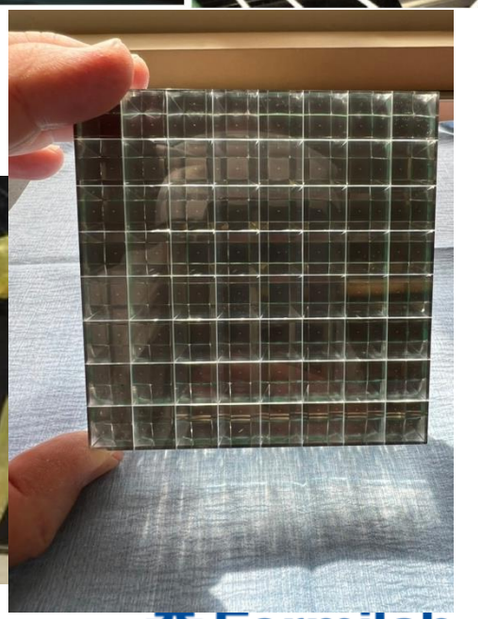












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MCenter Activities

- “Jolly Green Giant” magnet has been refurbished in 2022
  - 0.7 T magnet field
  - Large Bore (> 1m diameter)
- Three new experiments in progress in MCenter for neutrino program in support of P5
  - TOAD: High pressure argon gas TPC with MCPs
  - ArCS: liquid argon TPC will be operated in the Jolly Green Giant magnet (LDRD effort from Marco Del Tutto)
  - EMPHATIC: Measuring hadron production with replica targets from NuMI and LBNF/DUNE (DOE Early Career Award from Laura Fields)

Beam Use in FY24 and FY25 at FTBF

- In FY24 FTBF received 7 weeks of beam after sitewide downtime to update the Accelerator Safety Envelope and technical delays in preparing the switchyard beamline.
  - Beam to 13 user groups including CMS, ATLAS, and EIC work. 25% of FY25 requests were deferred from FY24.

- For FY25, 24 user groups requested 75 beam time slots (beyond nominal capacity)
  - EIC, CMS, ATLAS, LBNF, DUNE, CalVision, DAMSA, AstroPix, superconducting nanowires, etc
  - Determined on 11/27 there will be no operations of the Main Injector 120 GeV beam in FY25 due to infrastructure issues impacting the accelerator complex (power transformers and heat exchangers) and thus no beam delivery to FTBF.

Future of FTBF/ITA

- Beam to FTBF scheduled to turn off in January 2027 for long LBNF/PIP-II shutdown for ~3.5 years.
  - Overlap of shutdown with CERN and DESY puts increased test beam community demand on FY26

- Switchyard beam line will require maintenance and refurbishment for operations after the shutdown
  - ~2.4 kilometers of beamline with many components beyond end of life with little or no remaining spares and limited expertise
  - Cooling systems insufficient for summer running
  - Efforts needed to operate Switchyard beam line are unsustainable

- **Our users express strong support for FTBF but find the significant beam reductions over several years burdensome.**

- **ITA operations will end with the shutdown of the original LINAC in 2028**

Recent Recommendations

- Fermilab PAC July 2024 excerpts
  - Access **to an irradiation facility in the US is essential to the global energy frontier community** and the support to detector innovation and the US leadership in HEP instrumentation. **The facility would be most impactful if it had the irradiation and test beam capabilities in the same location**, allowing irradiated detector components to be tested in situ.
  - **"The PAC encourages the lab to consider a future planning exercise on the long-term evolution of the FTBF/ITA.** Broad community input would facilitate the identification of synergistic uses with the proposed PIP-II beam dump facility (F2D2) for dark matter searches and the proposed 120 GeV dark matter program as part of the "Fixed Target Campus."

Recent Recommendations

- FCC-ee PED Task Force excerpts
  - **Facilities, and their specialized technical personnel, that are critical to the FCC-ee R&D phase are**: Sidet and IERC, the scintillator detector production facility, the thin film facility, the **Fermilab Test Beam Facility (FTBF),** and the laboratory's computing facilities (including *e.g.* the CMS Tier 1, the largest CMS computing facility in the U.S).
  - **Apart from the availability of a broad spectrum of world class facilities, capabilities and competencies, their co-location and synergy is what makes Fermilab a leader in the field**. For example, the expertise from the theory division, the Computational Science and AI Directorate (CSAID), home of the CMS software framework and a unique Geant4 group, combined with a strong CMS calorimeter group and the availability of test beams for simulation model improvement and validation, puts Fermilab in an ideal position to enable an integrated design and development of the experimental program.
  - **Success of this program hinges on maintaining and expanding current support to SiDet and IERC silicon detector development facilities and the Test Beam Facility**.

Community Input

- Snowmass white paper based on community survey and input on long term needs of FTBF and ITA

- Irradiation Area Needs
  - Deliver (O) 10^18 protons/cm^2 in a few days to meet future collider needs
  - Ability to adjust beam size, intensity and energy
  - In-house sample storage and radionuclide analysis facility
  - Post irradiation bench top testing room

- Test Beam Needs
  - 4-6 low intensity beam spigots
    - 120 GeV proton running with tracking stations to support silicon sensor testing
    - Lower energy secondary particles to test calorimeters
    - Dedicated support for clean electron and muon beams
    - Ability to stage medium term experiments in addition to short term users
      - Hadron production measurements like EMPHATIC, neutrino detector test stands, dark matter searches, ASTAE program
      - Leverages built in support staff from test beams and infrastructure
  - Control rooms, staging areas, crane coverage

One Concept of a Future

- **One way to address evolving experimental needs of the test beam community in alignment with P5 and restore irradiation capabilities in the PIP-II era is through a new facility.**
  - New location within the main accelerator complex security footprint
  - Substantially shorter beam path and new components to reduce maintenance
- Combine test beam and irradiation facility under one roof with access to PIP-II, Booster, and Main Injector beam as a potential Fixed Target Campus

Summary

- FTBF is a user-oriented facility with a 20 year history in providing high energy/intensity particle beams in support of all aspects of the HEP program and beyond.

- FTBF is modernizing its instrumentation to improve functionality.

- Upcoming long shutdowns at FNAL, CERN, and DESY place increased demand on test beam facilities over the remaining 2020s across all major projects.

- **FTBF and ITA play an essential role to the Office of Science. To meet test beam community needs into the 2030s and restore irradiation capabilities, Fermilab is initiating a long-term planning exercise with community input.**

Backup

Recent Publications

- Optimization of LYSO crystals and SiPM parameters for the CMS MIP timing detector (https://arxiv.org/abs/2410.08738)
- Results for pixel and strip centimeter-scale AC-LGAD sensors with a 120 GeV proton beam (https://arxiv.org/abs/2407.09928)
- High Energy Particle Detection with Large Area Superconducting Microwire Array (https://arxiv.org/abs/2410.00251)
- First Observation of Antiproton Annihilation At Rest on Argon in the LArIAT Experiment (https://arxiv.org/abs/2409.13596)
- Dual-readout calorimetry with homogeneous crystals (https://arxiv.org/abs/2408.11973)
- Novel indium phosphide charged particle detector characterization with a 120 GeV proton beam (https://arxiv.org/pdf/2404.12497)
- Beam Test Results of the RADiCAL -- a Radiation Hard Innovative EM Calorimeter (https://arxiv.org/pdf/2303.05580)
- First survey of centimeter-scale AC-LGAD strip sensors with a 120 GeV proton beam (arXiv:2211.09698)
- Argonne Pixel Tracking Telescope at the Fermilab Test Beam Facility (https://arxiv.org/pdf/2202.05316)
- Characterization of BNL and HPK AC-LGAD sensors with a 120 GeV proton beam (https://arxiv.org/abs/2201.07772)
- Test beam characterization of sensor prototypes for the CMS Barrel MIP Timing Detector (https://arxiv.org/abs/2104.07786)
- Test Beam Study of SiPM-on-Tile Configurations (https://arxiv.org/abs/2102.08499)
- Resistive AC-Coupled Silicon Detectors: principles of operation and first results from a combined analysis of beam test and laser data (https://arxiv.org/pdf/2007.09528)

A selection of recent theses (not exhaustive)

- FERMILAB-MASTERS-2023-02, Performance Before and After Irradiation of Pixelated 3D Silicon Sensors for the HL-LHC CMS Tracker, https://doi.org/10.25417/uic.21516741.v1.

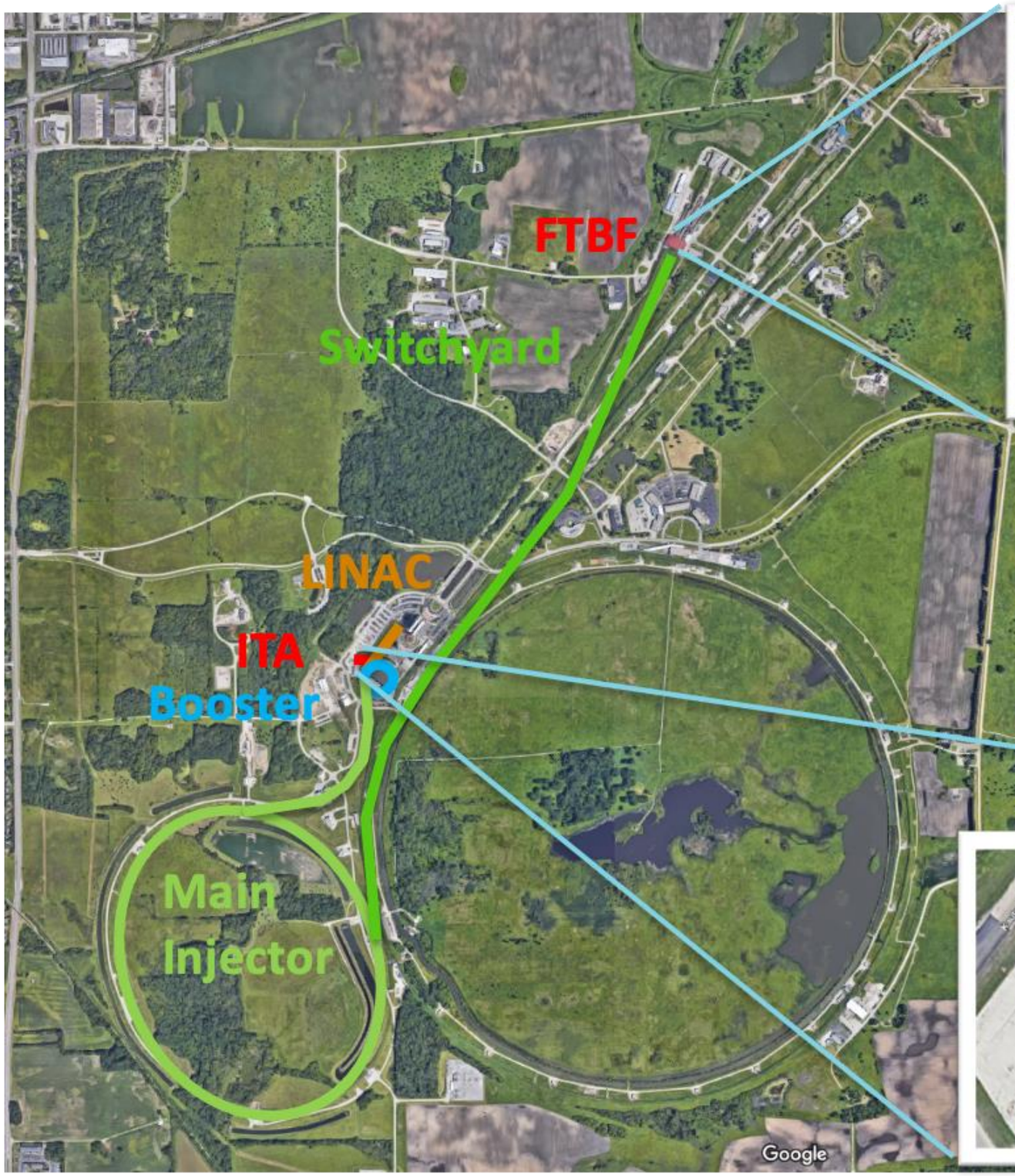
- FERMILAB-THESIS-2022-13, Proton Scattering in NOvA Test Beam, Lackey, Teresa Megan

- FERMILAB-THESIS-2018-24, Measurement of the Negative Pion and Positive Kaon Total Hadronic Cross Sections on Argon at the LArIAT Experiment, (https://www.osti.gov/biblio/1489387/)

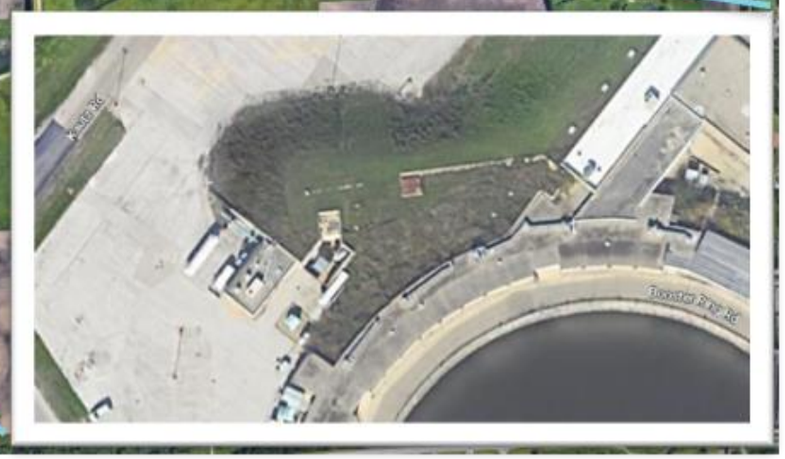
- Constraining Beam Backgrounds and Analyzing the Detector Response in a Test Beam With the Nova Experiment

- FERMILAB-THESIS-2019-01, A Demonstration of Light-Augmented Calorimetry For Low-Energy Electrons in Liquid Argon. (DOI: 10.2172/1495330)

Where are FTBF and ITA?



FTBF – Meson Detector Building



ITA – Irradiation Test Area

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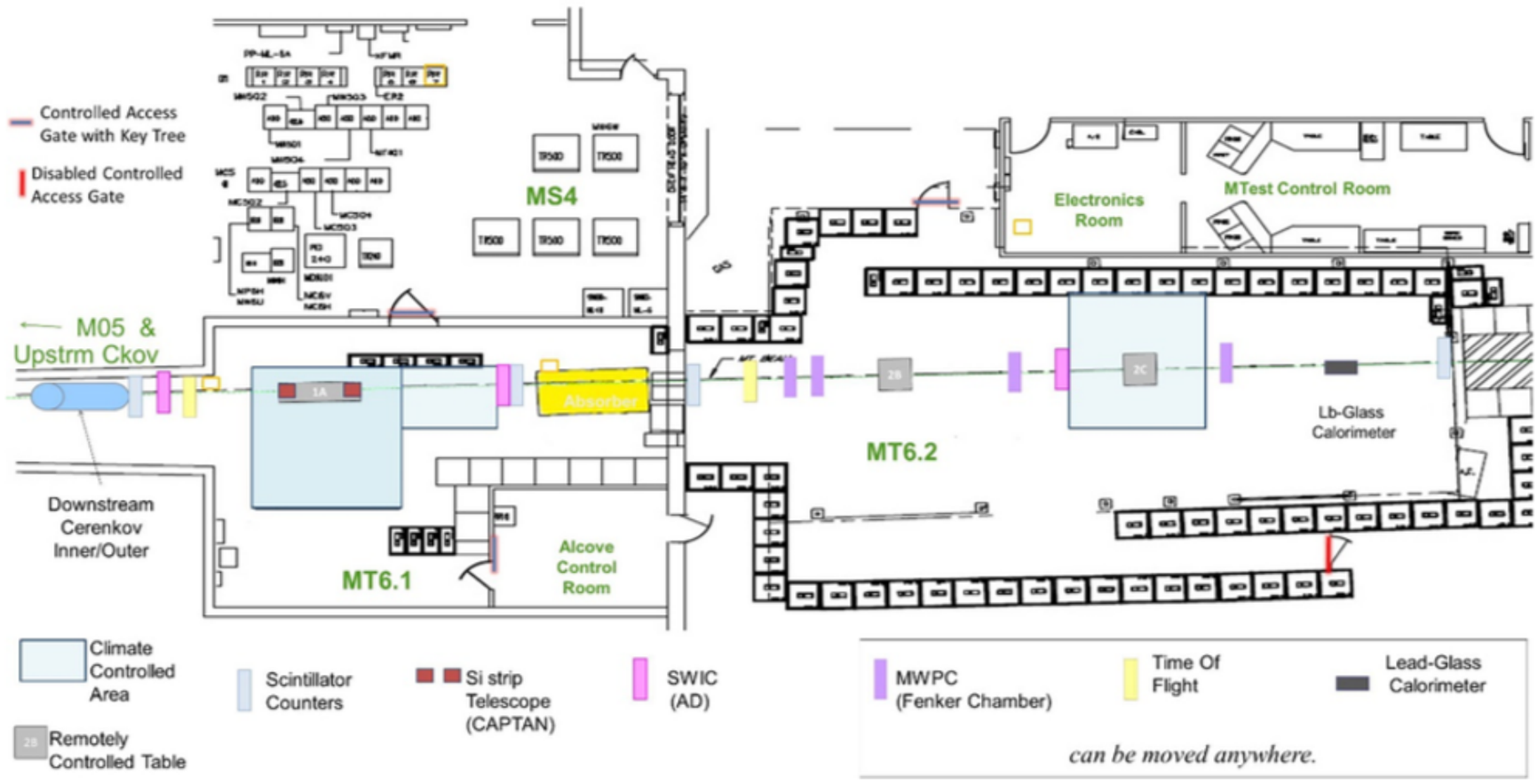
Instrumentation Layout - MTest



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Irradiation Facility

- Counting house in service building next to beam enclosure.
  - Set of ~50’ penetrations connect the two spaces for cabling.

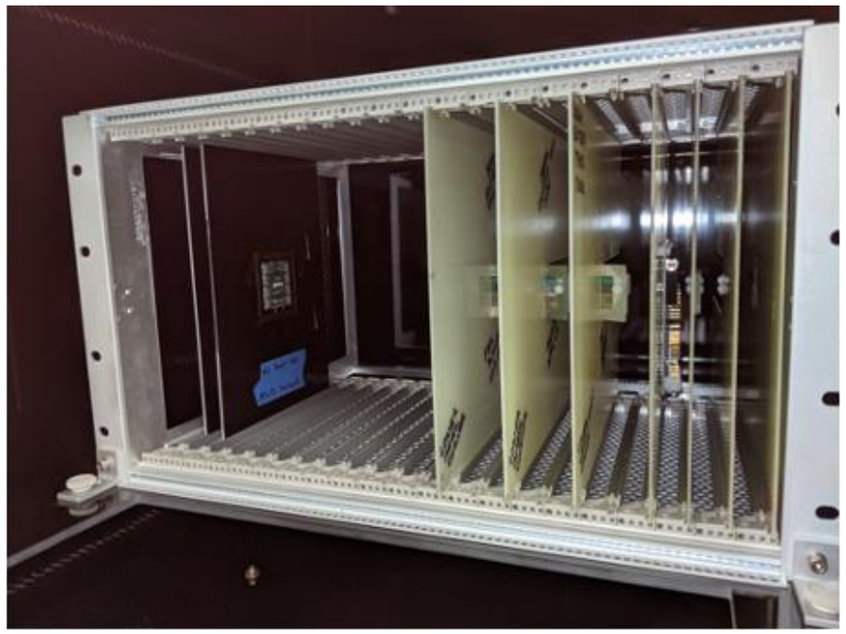
- Beam line is approved for a maximum intensity of 2.7e15 particles per hour per the current shielding.
  - Typical rates are around 2.2e15 particles per hour

- Unique in the US to have an irradiation facility and test beam onsite together
  - Ongoing work with radiation safety on process to bring potentially contaminated sensors at ITA to FTBF.

Experimental Hall

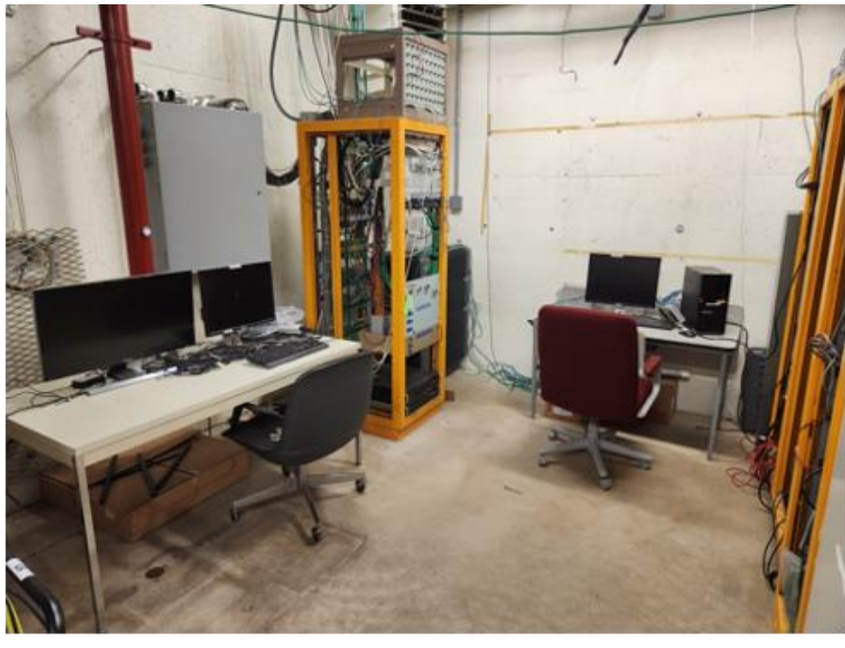
Irradiation Infrastructure

Photo courtesy Abhishek Bakshi



Very first samples from CMS and ATLAS ready for irradiation. Photo courtesy Corrinne Mills

Photo courtesy Todd Nebel



Electronics Testing for TID and NIEL

- For 400 MeV proton beam:
  - Achieve 1 Grad total ionizing dose (TID) in silicon ~= 2.6e16 protons/cm^2
  - Achieve 2e16 neq/cm^2 displacement damage from non-ionizing energy loss (NIEL) ~= 2.4e16 protons/cm^2
- Able to reach TID and NIEL levels expected at the HL-LHC inner trackers simultaneously.
- Reach these doses in ~2-3 days of continuous beam depending on Linac conditions.

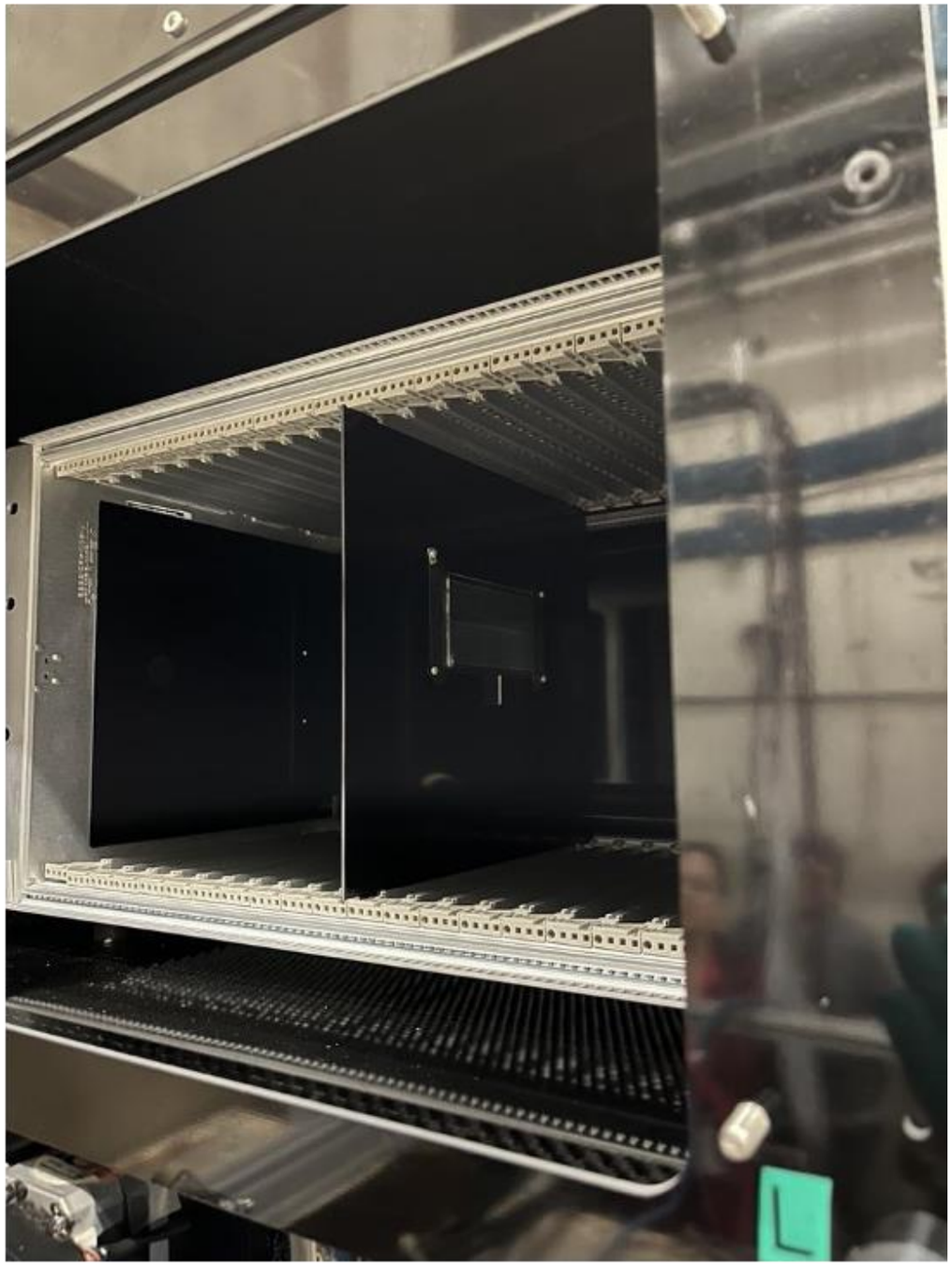
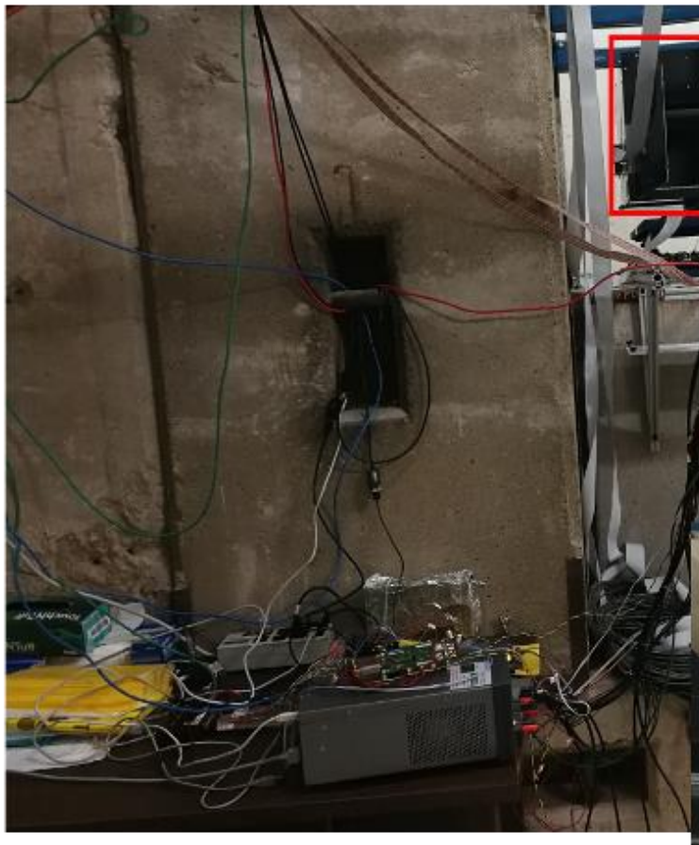
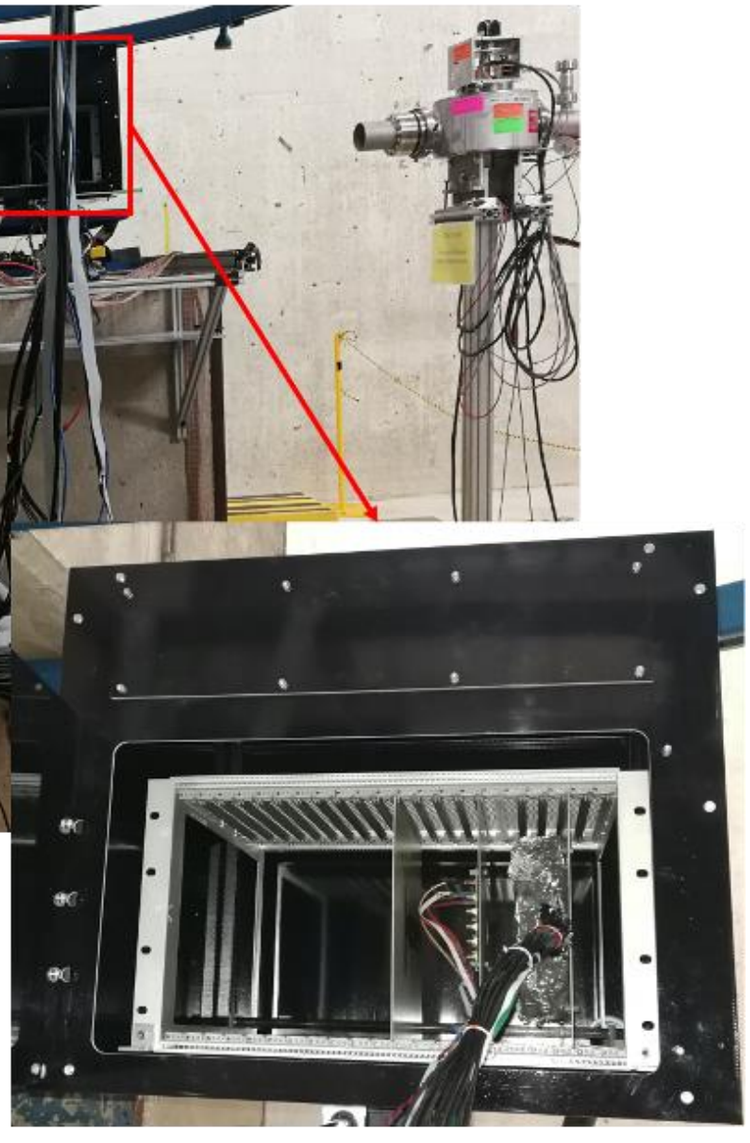


Photo by Jennet Dickinson

Single Event Upset/Effect (SEU/SEE) Electronics Testing

CMS ECON-T ASIC irradiation. Photo courtesy D. Noonan (FNAL).

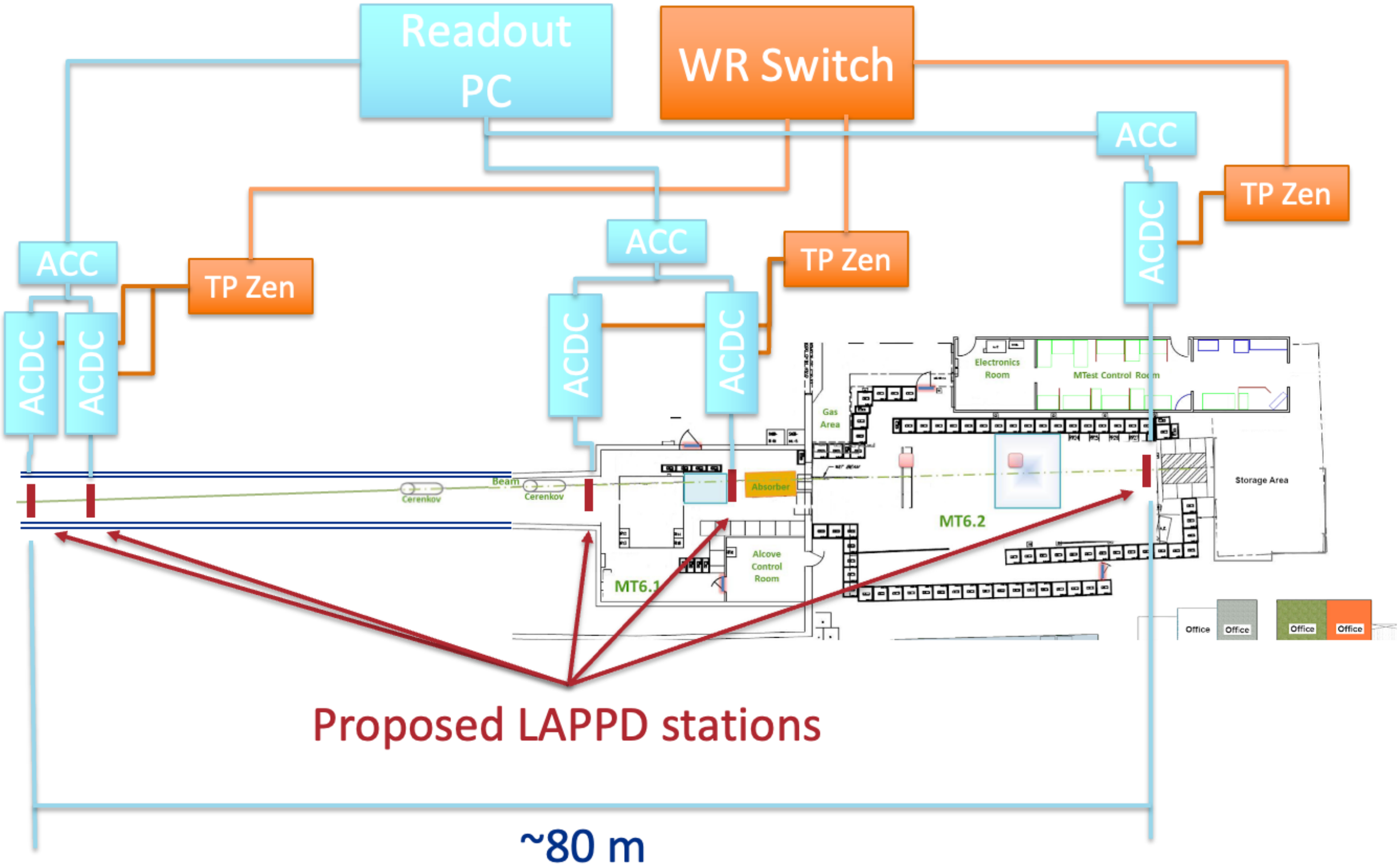




ATLAS GBCR2 ASIC irradiation. Photo courtesy T. Liu (SMU).

- Linac beam is fixed intensity, leaving an intense beam for electronics testing.
- Some success has been had locating samples off-axis and with shielding.

Proposed TOF system layout in MTest



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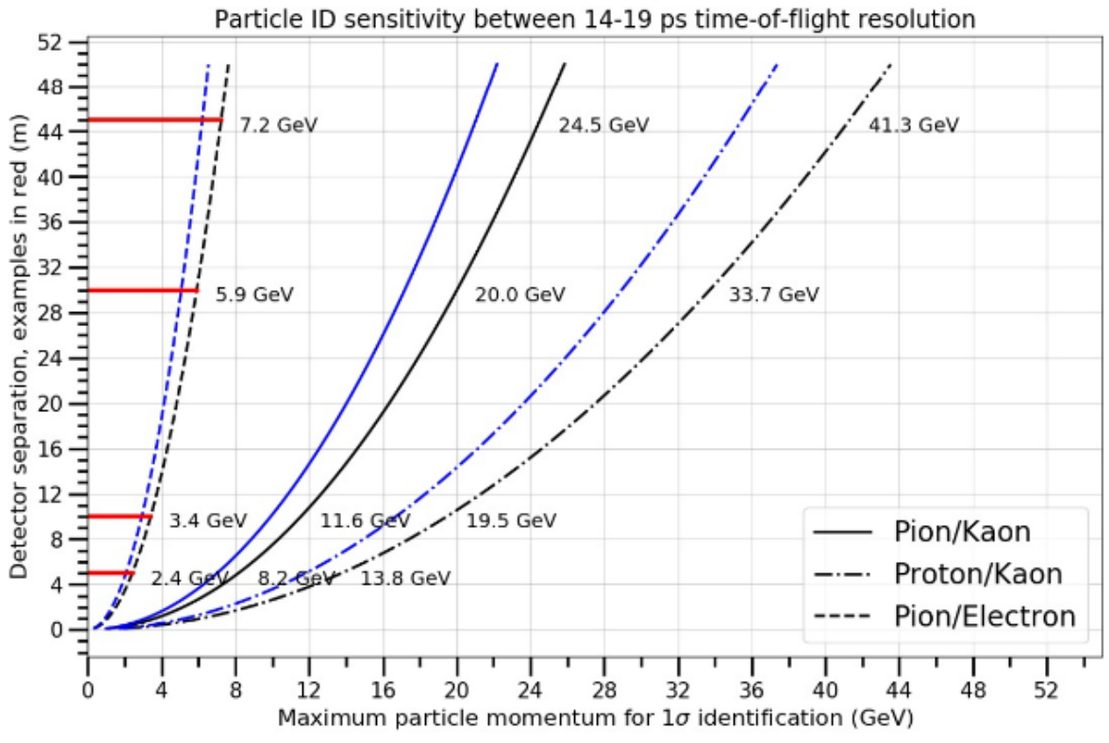
Expected sensitivity

- Projected sensitivity based on calculations and measurements by E. Angelico
- Informs we want at least 40 m separation



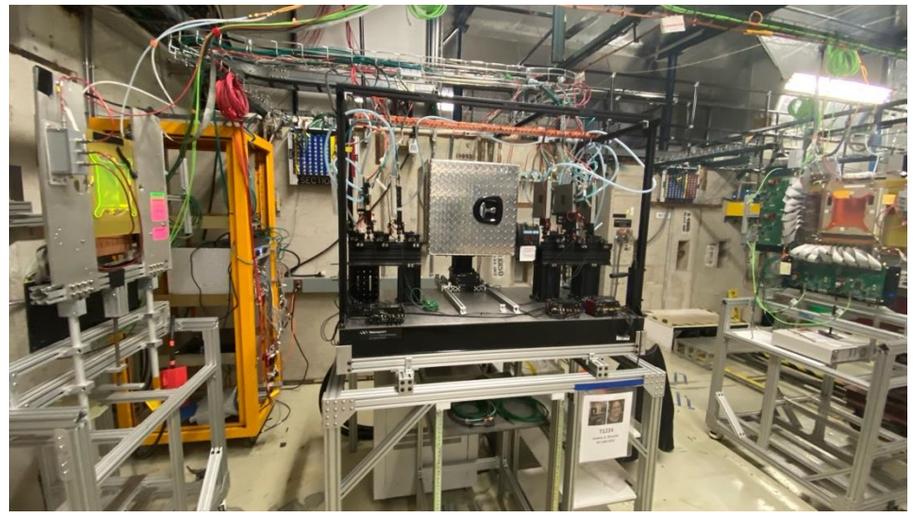
Angelico, Evan. doi:10.2172/1637600

	$\sigma_L/\sqrt{N_{\text{pe}}}$ PE spread	σ_{pulse} readout	σ_{WR} Inter station timing	σ_{tof}	Maximum π/K momentum at 5 m / 45 m
Gen 1 LAPPD	55 ps / $\sqrt{30}$	7 ps	5 ps	19 ps	7.0 / 21 GeV/c
Use of fused silica window	55 ps / $\sqrt{200}$	7 ps	5 ps	14 ps	8.2 / 25 GeV/c
Low-jitter WR-ZEN	55 ps / $\sqrt{200}$	7 ps	< 0.5 ps	13 ps	8.5 / 25 GeV/c
10 μm pores and higher cathode voltages	10 ps / $\sqrt{200}$	7 ps	< 0.5 ps	11 ps	9.2 / 28 GeV/c
PSEC4 chip development	10 ps / $\sqrt{200}$	1 ps	< 0.5 ps	1.7 ps	24 / 70 GeV/c

5

Recent Highlights from CMS and ATLAS

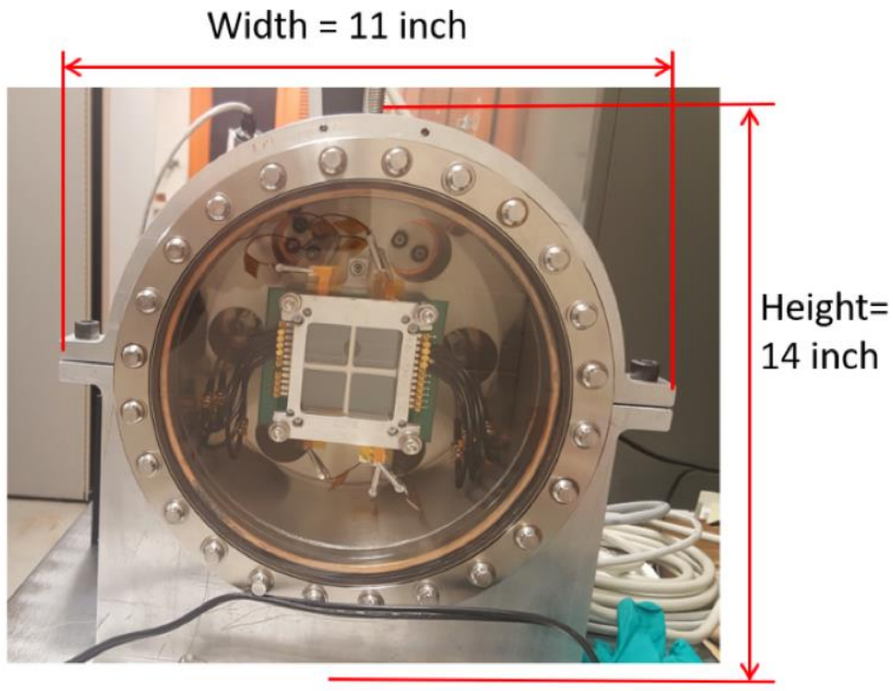
- ATLAS
  - The ATLAS pixel telescope established by Argonne as a test bed for a variety of sensors and chips.
  - Results used in final design for HL-LHC upgrades
  - Test stand transitioning to EIC and AstroPix work



- CMS
  - Completed critical testing of various sensors and ASIC chips, which will be installed in the HL-LHC
    - Barrel and Endcap Timing Layers, Inner and Outer trackers, calorimetry
  - LGAD Timing layer achieved picosecond timing resolution.

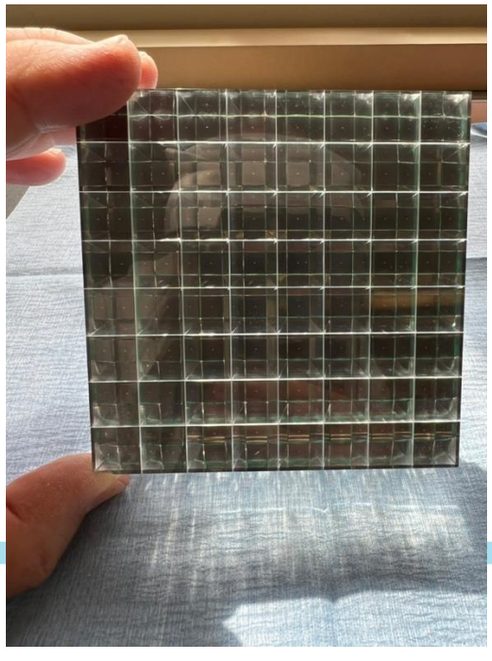
Recent Highlights from EIC

- The highest priority for a new facility in the U.S. Nuclear Physics community is an electron-Ion Collider (EIC), capable of colliding electrons on Ions or polarized protons at center of mass energies that will be roughly about a third of HERA, but with luminosities 100 times higher.
  - 40% of FY25 requests were EIC related



  - Testing of LGADs for EIC
    - (https://arxiv.org/abs/2407.09928

- Testing of GEMs and Micromegas detectors



- Calorimetry

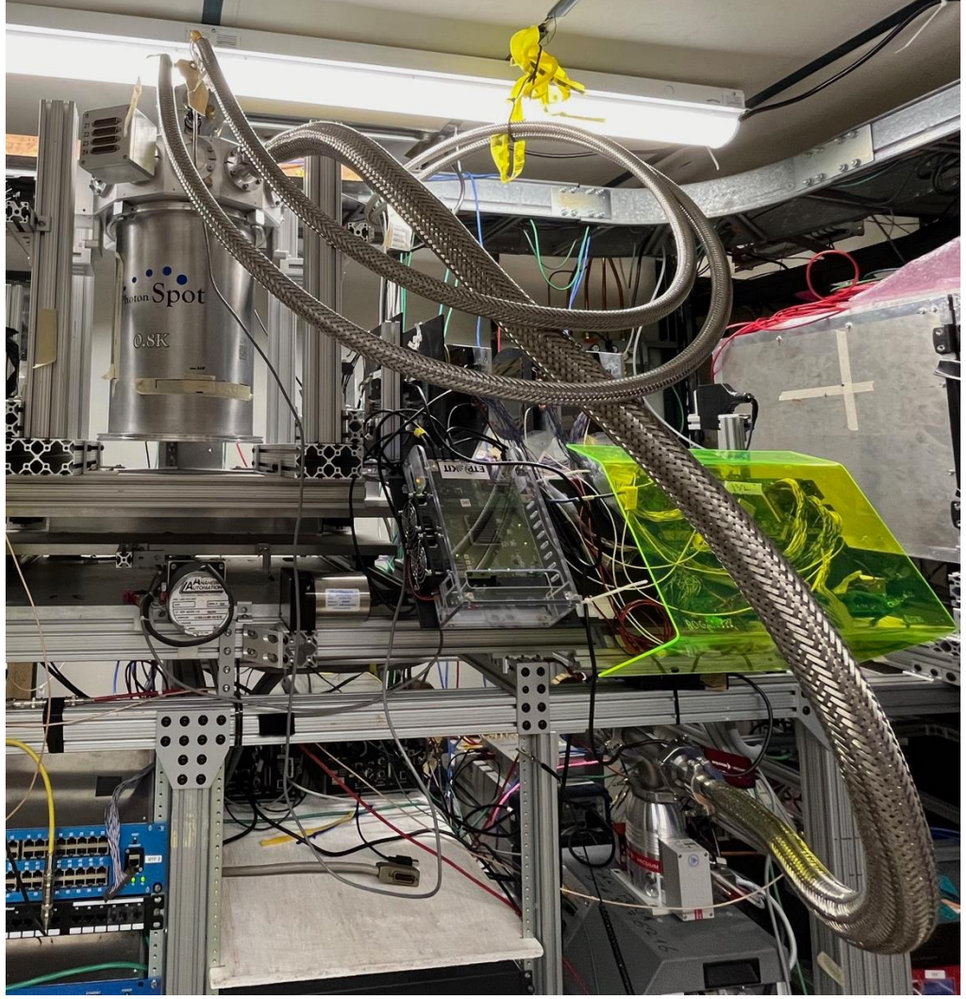
Other Recent MTest Highlights

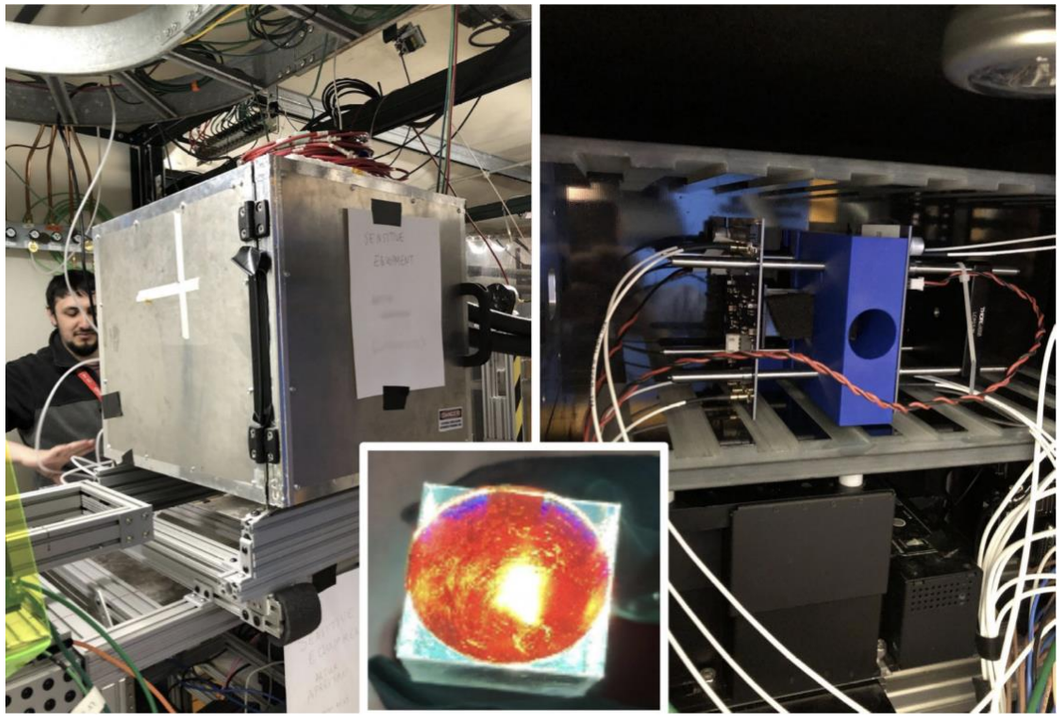
- Superconducting nanowires single photon detectors (https://arxiv.org/pdf/2312.13405)
  - Used to detect single photons in the EIC
  - Tests happen over multiple years

- Tests of High Energy Particle Detection with Large Area Superconducting Microwire Array (https://arxiv.org/abs/2410.00251)
  - Used in quantum communication protocols

- CalVision R&D (https://arxiv.org/abs/2408.11973)

- NASA mission concept APT (Advanced Particle-astrophysics Telescope)
  - Studies to test a new gamma ray detector, looking at position resolution and calibration data.





Fermilab