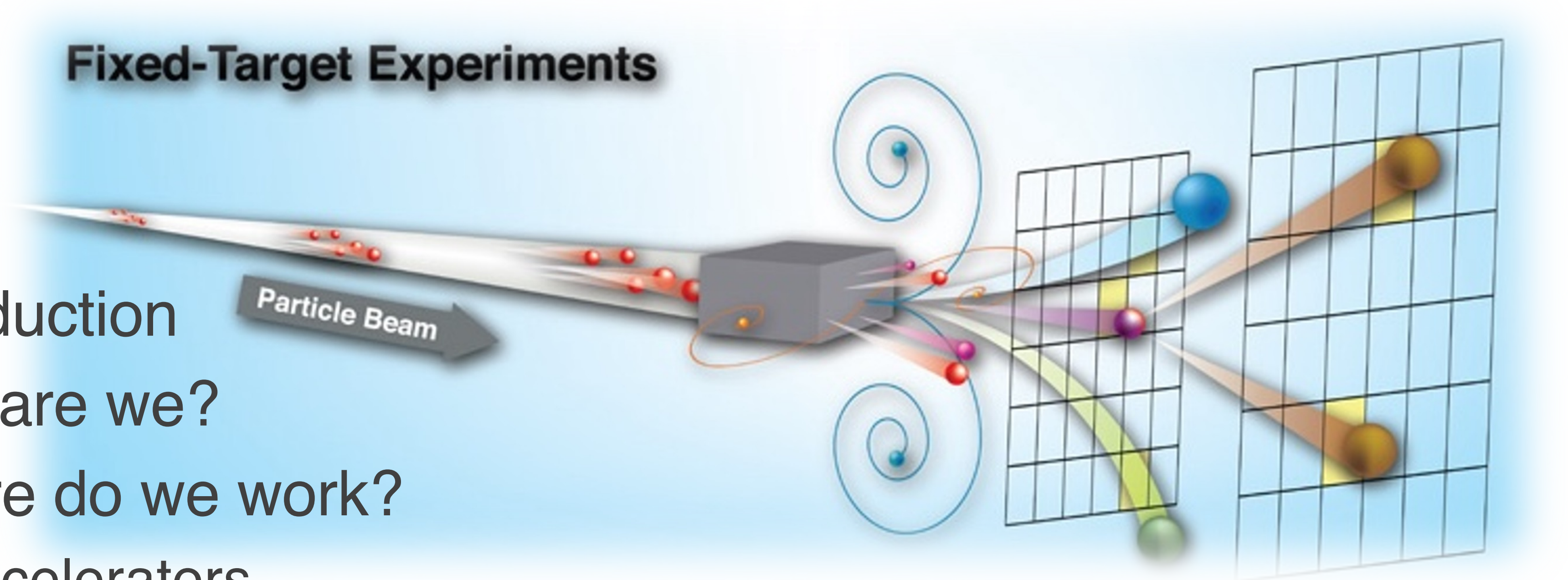
Engineering at Fermilab

Mayling Wong-Squires
2024 Summer Lecture Series
9 July 2024

Today's Talking Points

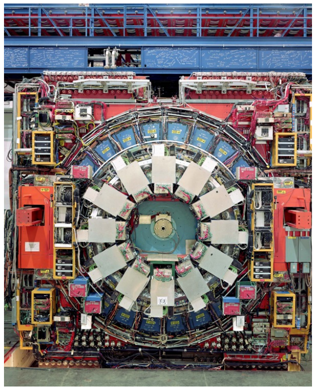


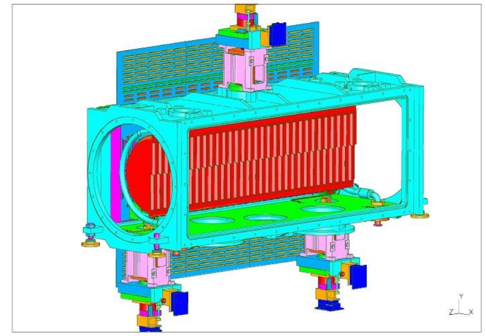
- Introduction
- Who are we?
- Where do we work?
  - Accelerators
  - Detectors
  - Facilities
  - Projects
- Engineering at work
  - Mu2e Straw Tracker's Front-End Electronics
  - SBND in-situ electronics repair

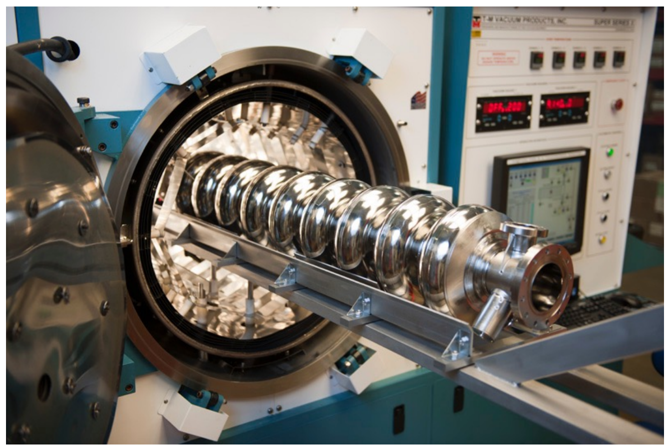
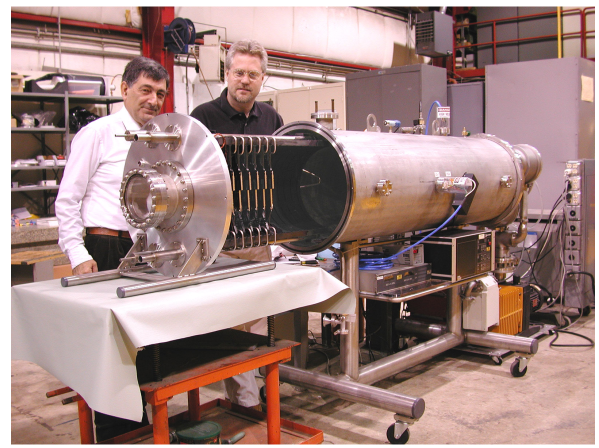
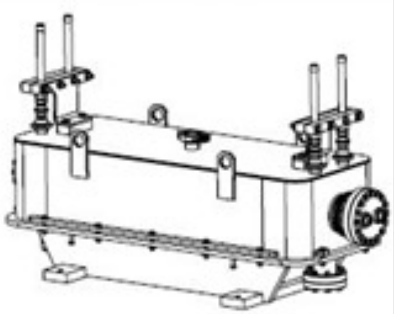
About me

- Mechanical Engineer at the lab for 20+ years
- My roles
  - Lab's Chief Engineer
  - Head of AD/Mechanical Support Department
    - 70+ personnel
    - Mechanical engineers, design/drafters, technicians
    - Provide vacuum, structural and fluids support to accelerator complex

Some projects from the past 20+ years




- Flammable gas system for a detector
- Installation of 5-ton to 20-ton magnets on a sloped surface without a crane
- Optimizing the vacuum pumping for a pixel detector
- Vacuum furnace heat treatment to degas SRF cavities
- Vacuum vessel design of a cryomodule
- Vacuum design of a dipole magnet containing ferrites

Introduction to Engineers at Fermilab

Engineers at Fermilab are essential to its vision, which is to solve the mysteries of matter, space and time for the benefit of all.

- Unique and challenging projects
- Work in extremes
- Diverse set of design problems
- Special solutions

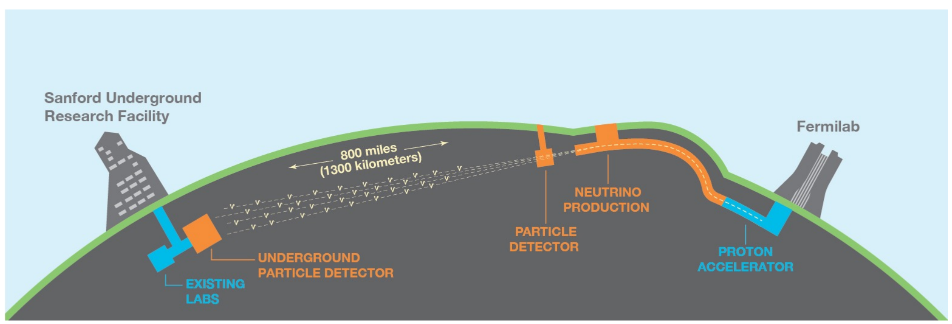
Who are we?

- 300 engineers (~17% of lab employees)
  - Chemical Engineers
  - Civil Engineers
  - Electrical Engineers
  - Mechanical Engineers
- Computer engineers / professionals
- Engineering physicists

Where do we work? Main Campus – Batavia, IL

Fermilab

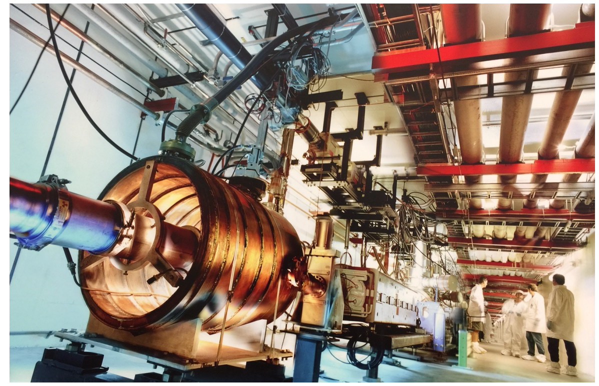
Remote site: Lead, SD

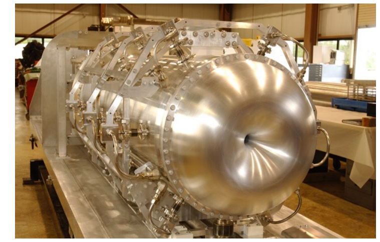


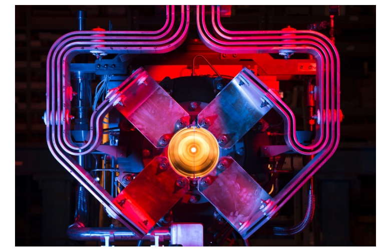
Deep Underground Neutrino Experiment (DUNE)

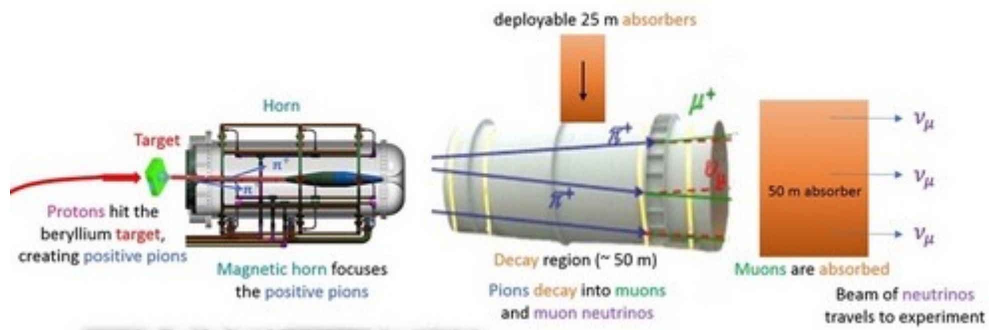
What does it take to study sub-atomic particles?

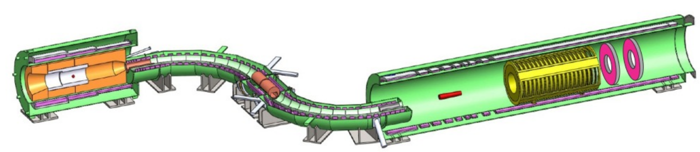
- Accelerate a beam of protons
  - Electromagnets and radio-frequency cavities to accelerate and position the beam
  - Instrumentation to “see” the beam
- Create new particles
  - Neutrino or muon beam
  - Target, horn, decay region and absorber
- Send particles to detector to study
  - Neutrino detectors using liquid argon
  - Muon experiments
    - Study muons in a high magnetic field (g-2)
    - Do muons convert to electrons? (Mu2e)





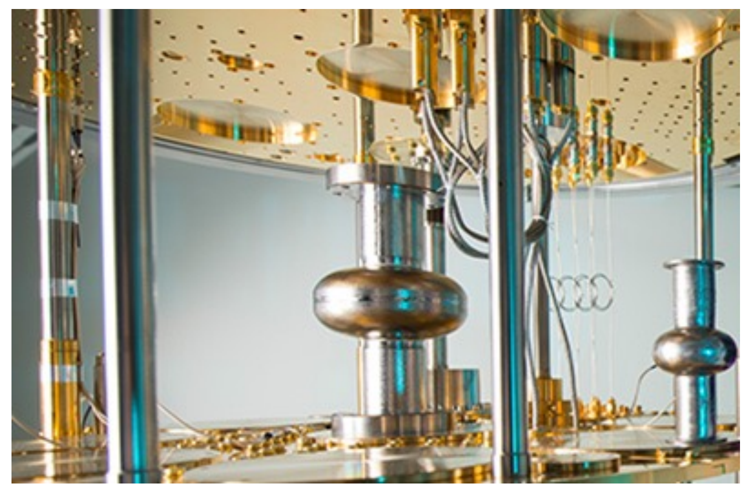






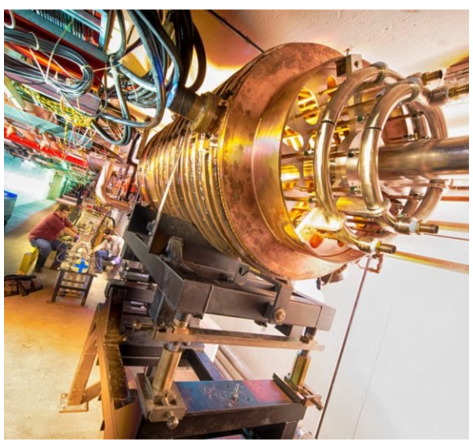
What does it take to study sub-atomic particles?

- Scientific Computing
  - Process and analyze experimental data
  - Compare experimental data with simulations
  - Requires home-grown high-performance computing systems
- Quantum Computing
  - Potential to tackle calculations that can currently take years
  - Hardware
  - Software



Accelerator Components

Sextupole magnet during assembly and completed

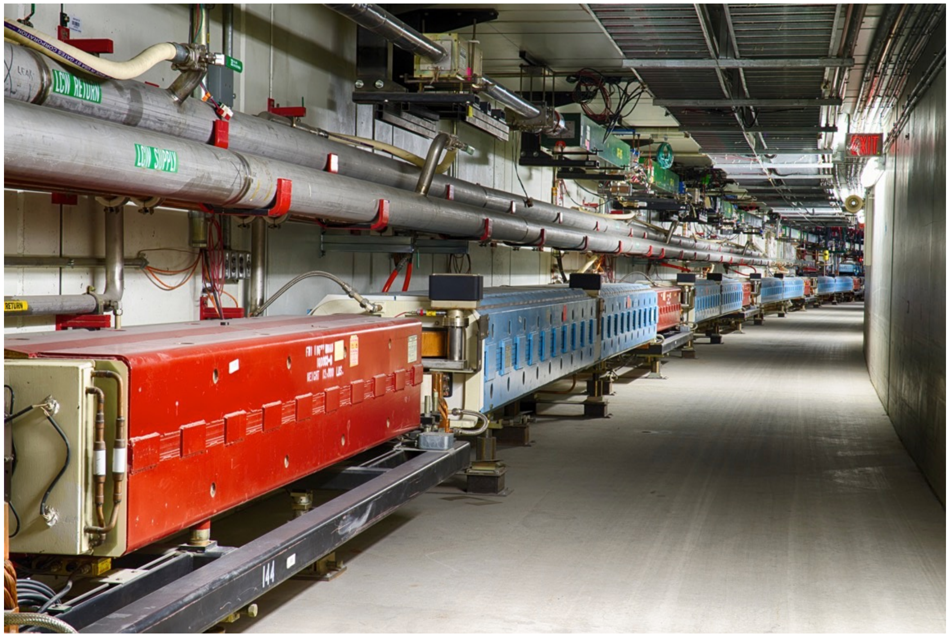


High powered radio frequency cavity 2.5MHz to 1.3 GHz (cell phone systems 2 GHz)

- Conventional electromagnets
  - Copper conductor
  - Water cooled
- Superconducting magnets
  - Niobium-tin or niobium-titanium coils
  - Cooled to 4°K with liquid helium
- Radio frequency cavities
  - Water cooled, copper
  - Superconducting, niobium (future)
- Areas of expertise
  - Electrical engineering
    - Magnet power
    - Magnetic measurements
    - High power radio frequency systems
    - Electrical controls
  - Mechanical engineering
    - Materials study
    - Thermal analysis
    - Mechanical design
    - Vacuum design
    - Cryogenics

Accelerator Complex

Engineering in an Accelerator



Main Injector / Recycler Accelerator

Mechanical engineer

- Fluid and process engineering
- Thermal analysis
- Structural design
  - 3D printing
- Vacuum engineer

Electrical engineer

- Power
- Radio frequency (RF)
- Instrumentation

- Cooling fluid
  - Low conductivity water
  - Cooling capacity in the megawatts
  - Operating temperature 90°F
  - Compare to a typical residential AC unit 10-kW
- Vacuum beampipe
  - Pipe diameter 6-inches
  - Vacuum pressure 1×10^{-8} torr
  - Comparisons
    - 730 torr at atmospheric pressure
    - 10^{-12} torr in outer space
- Mechanical support
  - Magnet weight 100 to 40,000 pounds
  - Align to position 0.005-inches
  - Consider position
    - Support off the ground
    - Hang from ceiling
    - Hang from the wall
- Power supplies
  - 2000 power supplies for the entire accelerator
  - Total capacity of over 240 MVA
  - Comparison: typical computer power supply 0.0001 MVA

Main Injector Power Supply - 6 sets

Transformer outside of a service building

- 800-V AC
- 4000-A AC

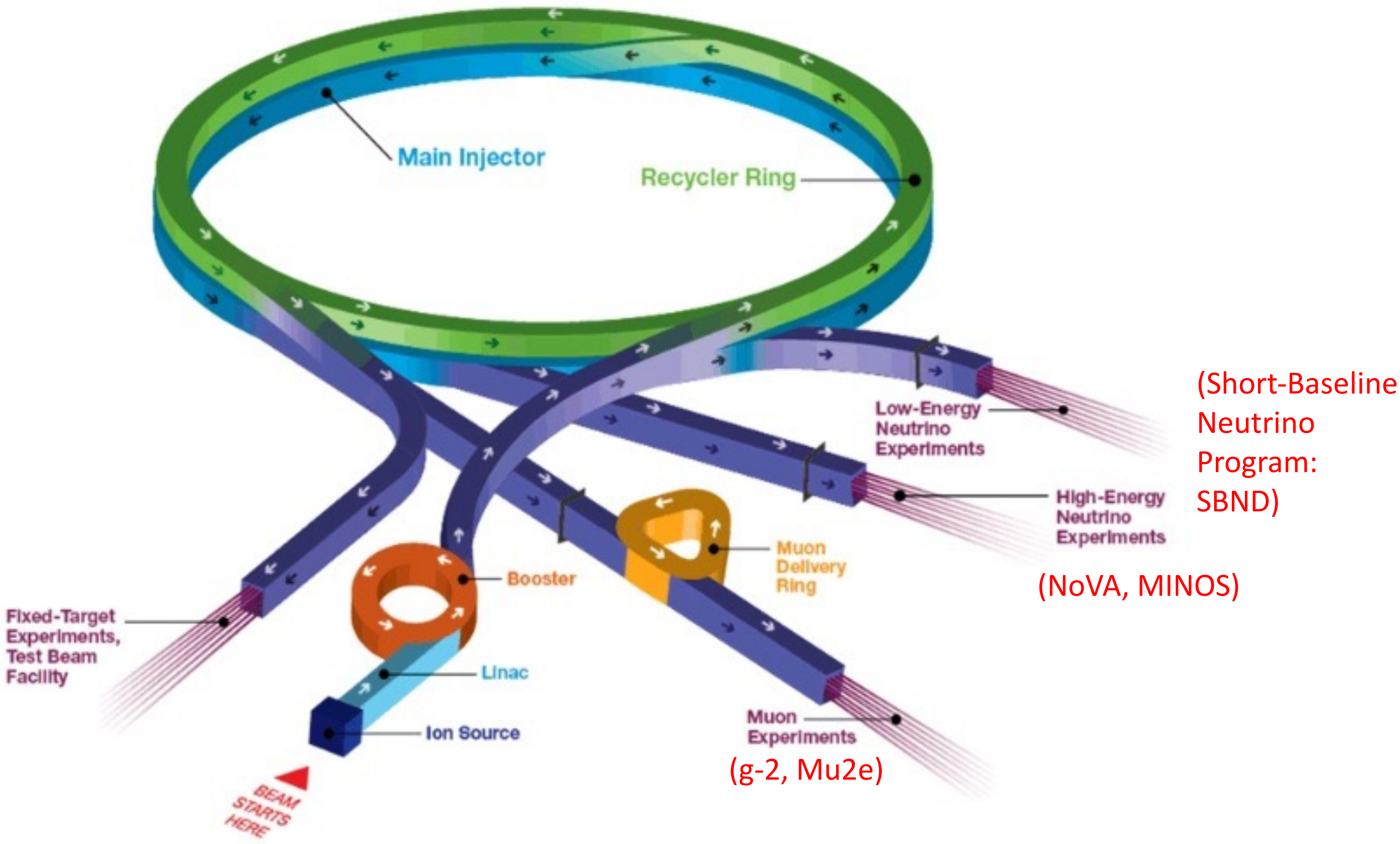
Rectifier inside a service building

- Converts AC to 1000-V DC
- 10,000-A DC
- Total capacity per building 10 MVA

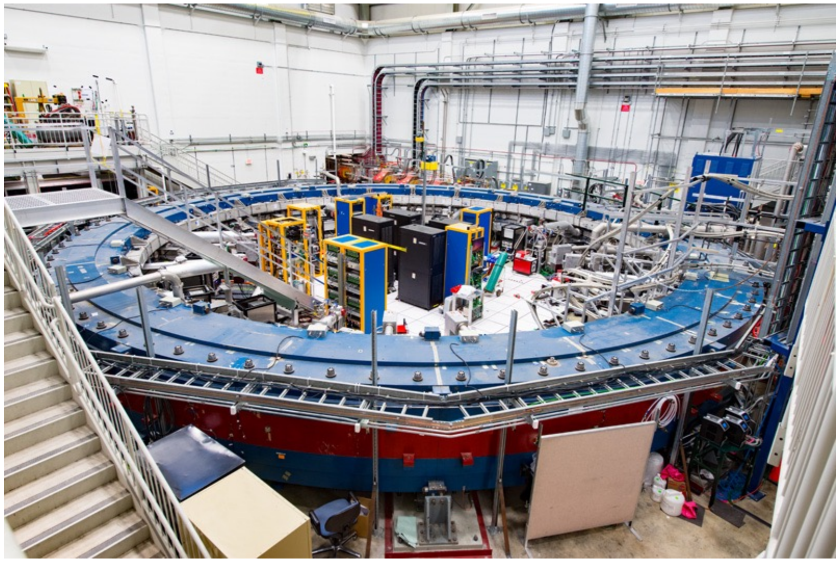
Marx Modulators for Linac RF Cavities

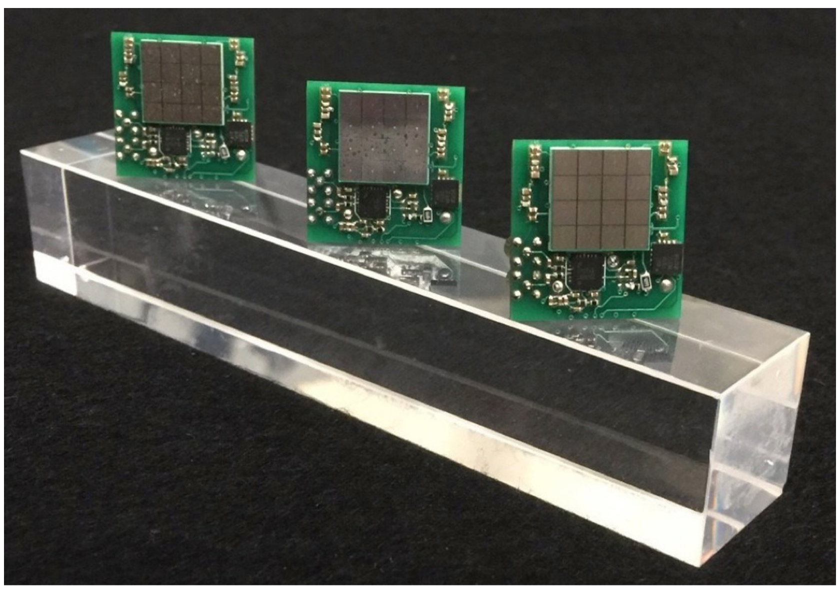
- Custom- and in-house-built system that provides 30-kV, 300-A to the power amplifier
  - Power amplifier supplies power to the RF cavities to accelerate beam
- Charges capacitors to give a large voltage drop
  - The more capacitors, the larger the voltage drop
  - An analogy: the more battery power, the brighter the flashlight

Provide Beam to Experiments On-Site and Off-Site

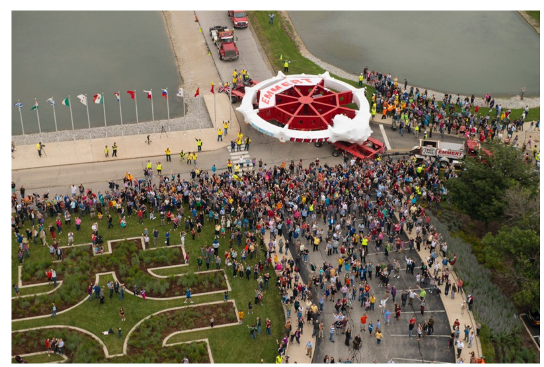


Send beam to a muon experiment



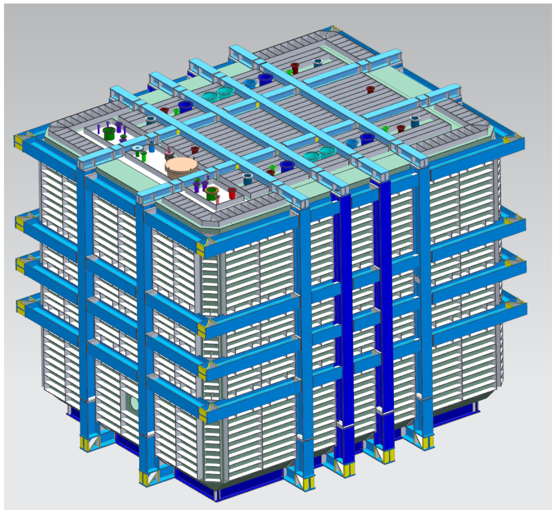


- Muon g-2
  - 50-foot diameter superconducting electromagnet
  - Study the “wobble” of the muon beam when placed in the magnetic field
  - Detectors to measure muon energy and decay time (calorimeter)
- Electrical engineers
  - Design, manufacture, install detectors
  - Control system
- Mechanical engineers
  - Cryogenic system – liquid helium
  - Transport and install electromagnet that from Brookhaven National Laboratory (NY)

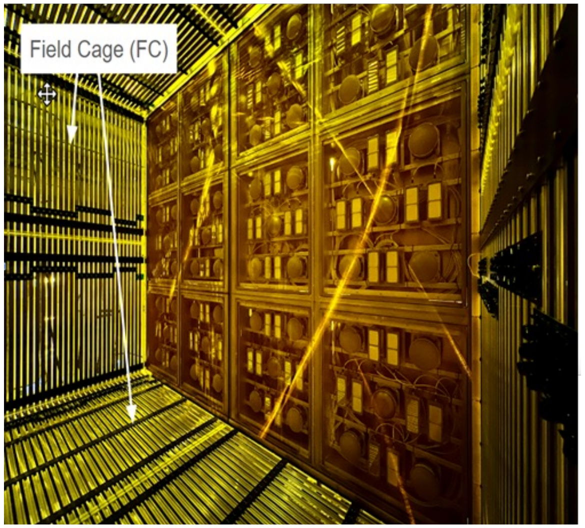


Send beam to an on-site neutrino experiment

- Short Baseline Near Detector
  - Send neutrino beam to a target made of liquid argon (LAr)
  - Detector made of wire planes to record ionized electrons that emerge from LAr
  - Array of photomultiplier tubes (PMT) measure the scintillating light of the ionized particles
  - Auxiliary systems
    - LAr cryogenic system
    - PLC-based process controls



5-m x 5-m x 5-m, that holds ~200,000-gallons (112-tons) of LAr



View of inside the time projection chamber of the detector, which holds an array of wire planes

PLC Based Process Controls

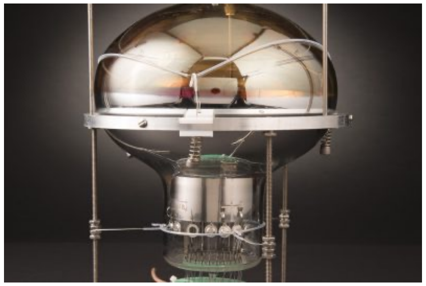
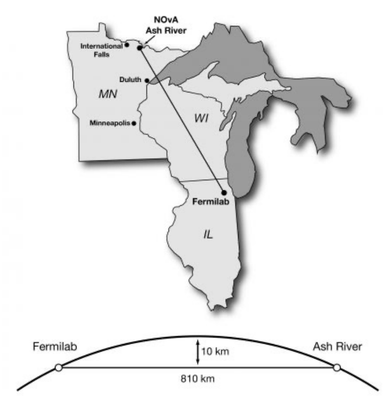


Photo Multiplier Tube (PMT)

Fermilab

Send beam to an off-site experiment

NoVA 14-kiloton far detector comprised of liquid scintillator

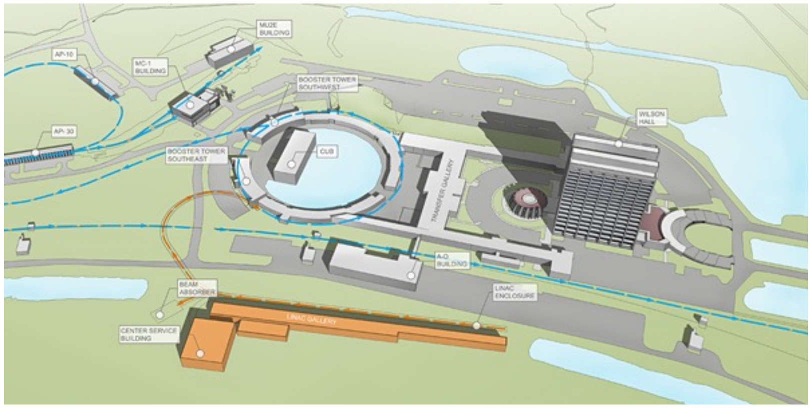


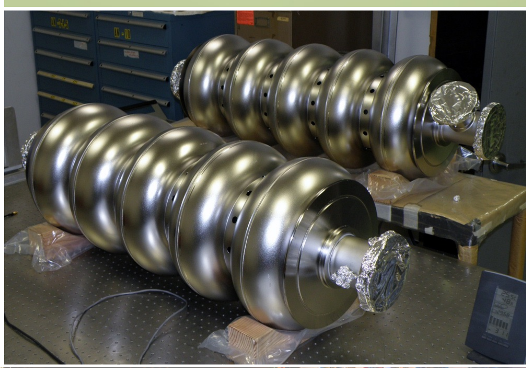
Highly reflective plastic extruded tubing 15.5-m long. Inside the detector, the tubing will be filled 2.7-million gallons scintillating oil

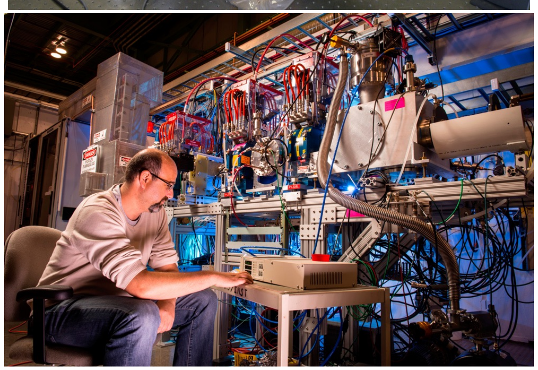
- Study of neutrino interaction
- NuMI
  - Create neutrino beam here at the main campus
  - “Near” detector to characterize the neutrinos at Fermilab
- NoVA and MINOS
  - Ash River, MN
  - Bottom of a former iron mine (Soudan mine) located 2341-ft below the surface
  - “Far” detector to characterize neutrinos after 810-km travel

Future Accelerator and Detector

Proton Improvement Plan II (PIP-II)

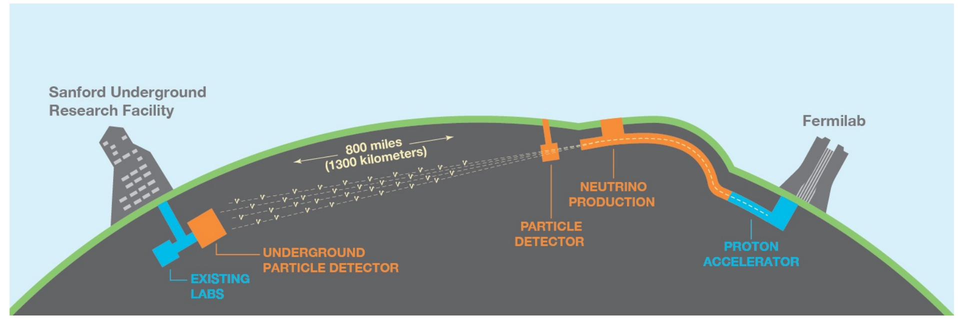


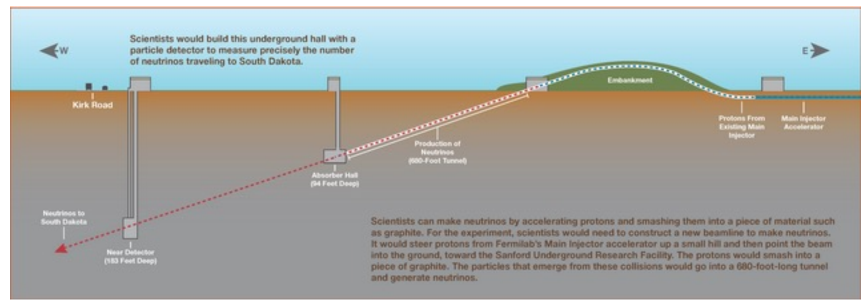


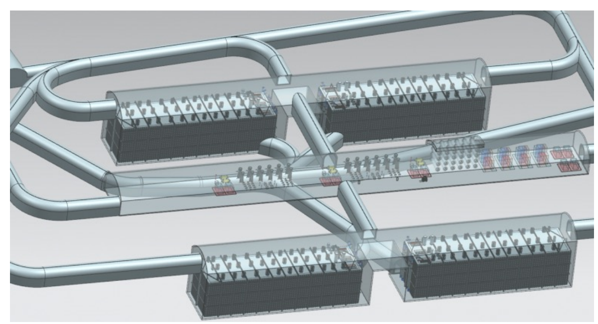


PIP-II will supply a 800-MeV proton beam accelerated at 8-GeV. The beamline will use the next generation superconducting radio frequency cavities. This provides the protons that will create the most intense neutrino beam for LBNF. Construction is not scheduled until 2028. A test beam was built and completed its run to prove the cryomodule operation. The test beam will become part of the new beamline.

Long Baseline Neutrino Facility (LBNF) / Deep Underground Neutrino Experiment (DUNE)

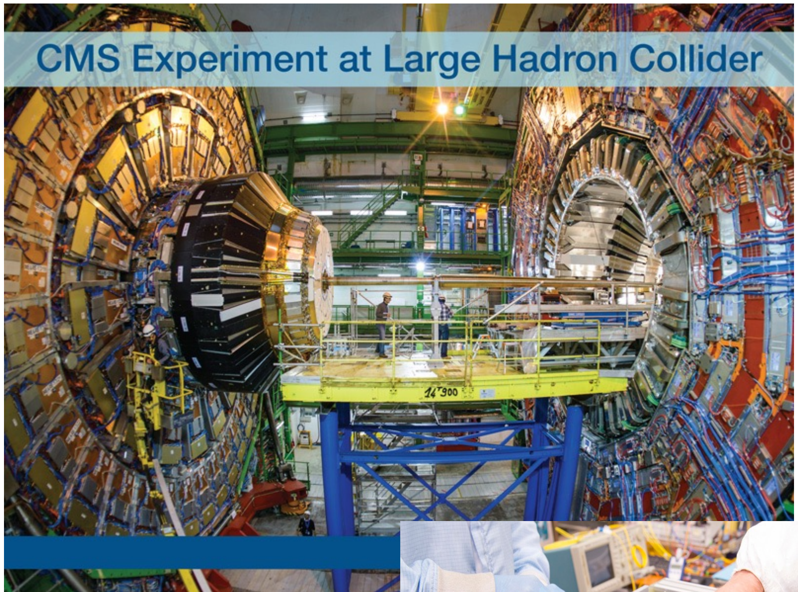




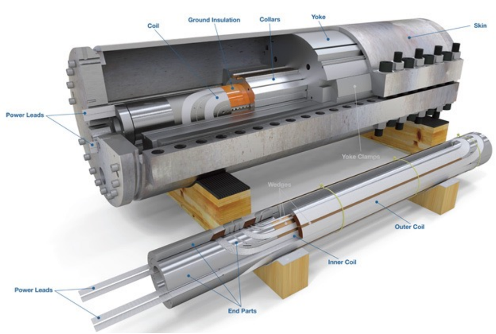


Neutrino research from the LBNF/ DUNE project will make use of the most intense neutrino beam. At DUNE, there will be 4 detector modules, each filled with 17,000-tons of LAr. The detectors will sit at 4850-ft below the earth's surface.

Support experiments and projects at other organizations



Quarter-section of the CMS Forward Pixel (FPIX) Detector Upgrade, part of LHC at CERN

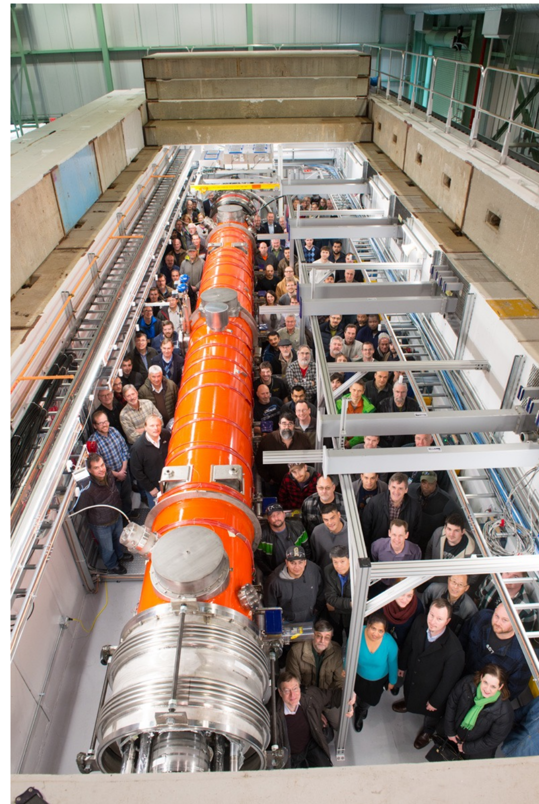


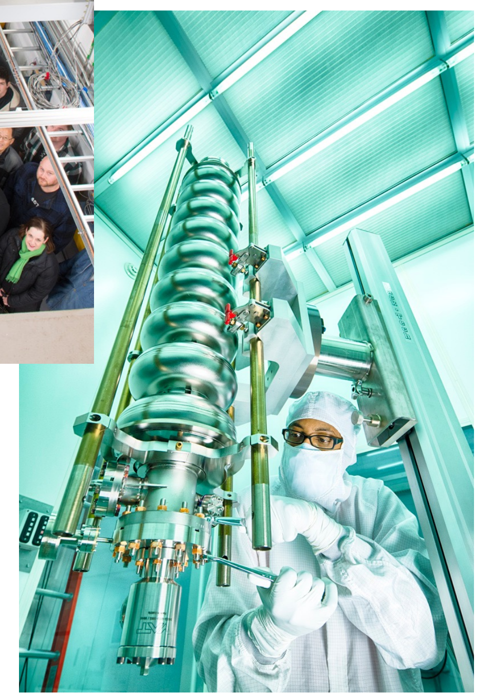
11-Tesla dipole test magnet for the LHC High Lumi upgrade at CERN

- CERN – particle physics laboratory in Geneva, Switzerland
  - Particle / particle collisions
- Forward Pixel Detector upgrade for Compact Muon Solenoid
  - Silicon detectors located near the collision location
  - Carbon fiber provides mechanical support to minimize particle interaction
- Large Hadron Collider (LHC) High Luminosity Upgrade
  - Design and fabricate 11-Tesla dipole magnet
  - Superconducting coils made of niobium-tin

Support for other projects – LCLS-II

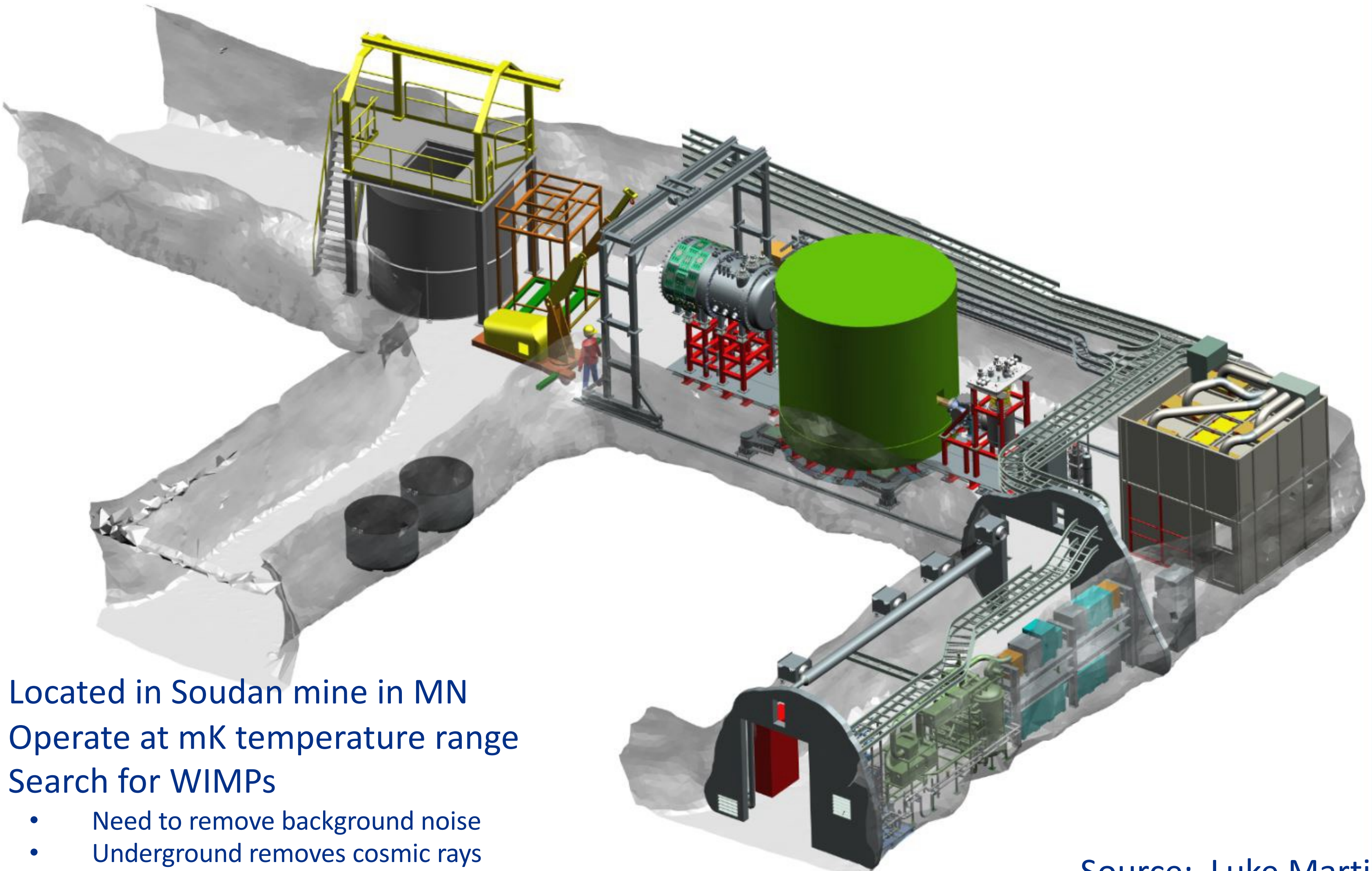
- Linac Coherent Light Source II at Stanford Linear Accelerator Laboratory (SLAC)
- Cryomodule
  - Next generation accelerator component
  - Superconducting radio frequency cavities
    - Niobium and niobium-titanium
    - Operate at 1.8°K
    - Cavity frequencies of 1.3-GHz and 3.9-GHz
    - Record breaking quality factor (Q_0) 2.7×10^{10}





Design, manufacturing, and testing cryomodule and its components

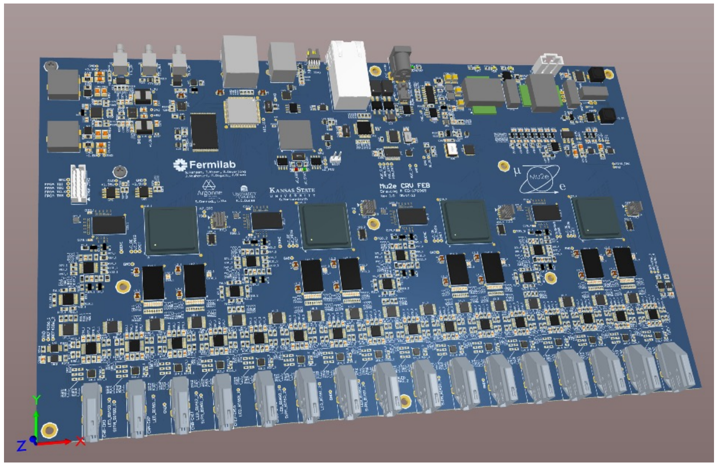
Other projects: Super Cryogenic Dark Matter Search experiment

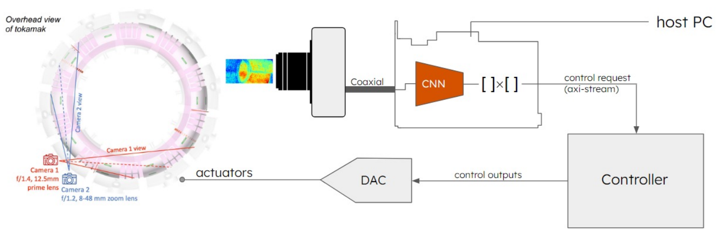


- Located in Soudan mine in MN
- Operate at mK temperature range
- Search for WIMPs
  - Need to remove background noise
  - Underground removes cosmic rays
  - Cold temps remove electronic noise

Source: Luke Martin

CSAID - Data-Intensive Systems Department





- Accelerator Controls Operations Research Network (ACORN):
  - Leading Accelerator Data Acquisition and Controls hardware modernization effort.
- DUNE:
  - Photon Detection System readout hardware: DAPHNE for FD-1 and Analog and Digital signal over fiber R&D for FD-2.
- PIP-II:
  - High-speed digitization and low-latency processing system for machine protection.
- Mu2e:
  - Data acquisition system hardware, firmware and software development, teststands and installation.
- CMS:
  - Outer Tracker production testing and correlator trigger firmware.
- Test Beam:
  - Particle tracking support for multiple users.
- AI/ML
  - Presented a real-time, FPGA-based, image identification demo at DEFCON in Las Vegas
  - Major contributions to HLS4ML low-latency ML software.
  - Leading research on ML architectures optimized for low-power FPGA applications.
  - Enabled real-time inference on frame grabber FPGA for optical instability tracking and suppression in Fusion experiments.
- Physics Research Equipment Pool (PREP)

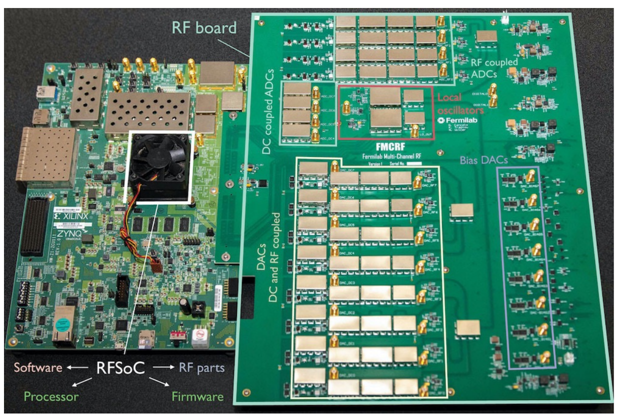
CSAID – Computational Science and Artificial Intelligence Directorate

Source: Ryan Rivera

CSAID - Quantum & Astrophysics Systems Dept.

The LTA (Low Threshold Architecture) controller supports all charge-coupled devices (CCD) and skipper-CCD instrumentation at Fermilab and collaborators in astrophysics.

- Dark matter experiments such as DAMIC, SENSEI and Oscura 10Kg.
- Space-LTA for future space mission.
- Used for readout of quantum imaging with skippers.
- Used for CNNS (Coherent Neutrino Nucleus Scattering) experiments.



QICK (Quantum Instrumentation Control Kit)

- A comprehensive, control and readout system for QIS (Quantum Information Science), including quantum computing (QC), quantum networks (QN) and quantum sensors (QS).
- Adopted by and supporting a growing community of over 200 institutions (Labs, academia and industry).
- All types of qubits: superconducting, AMO, NV-centers, trapped ions, spin.
- Sensors such as MKIDs, RF broadband, SNSPDs, quantum capacitor, etc.

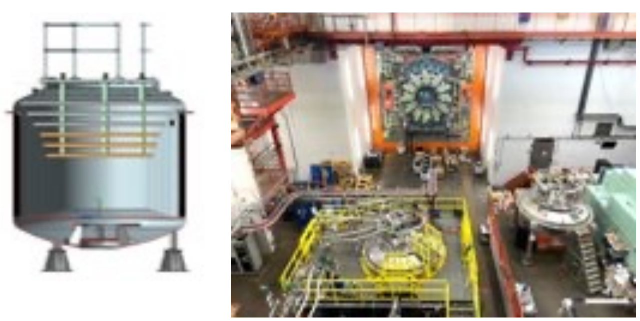
Source: Gustavo Cancelo

SQMS Research Center

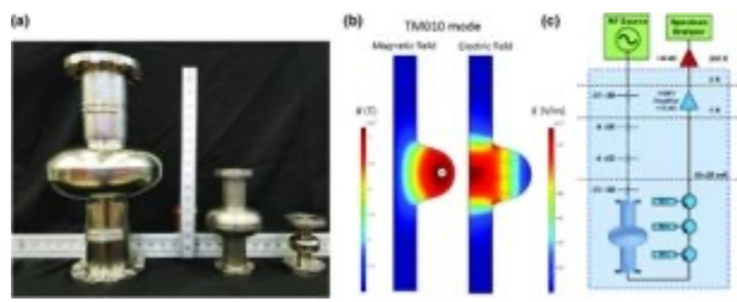
The Superconducting Quantum Materials and Systems Center, led by Fermi National Accelerator Laboratory, is one of five research centers funded by the U.S. Department of Energy as part of a national initiative to develop and deploy the world's most powerful quantum computers and sensors.

The SQMS Center capitalizes on Fermilab technical expertise and leverages state-of-the-art facilities and expertise for quantum computing and sensing

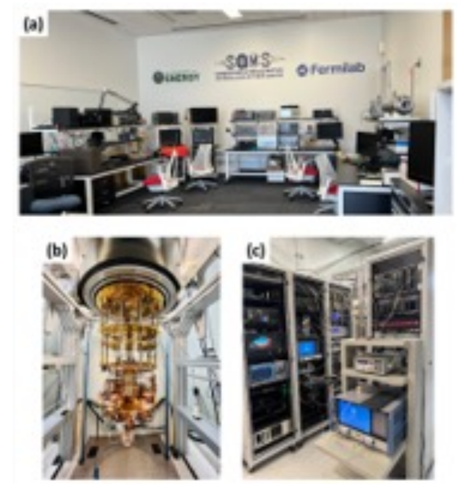
- SQMS engineers are designing novel superconducting cavities and equipment for dark matter searches and quantum computing
- The Ultralow Temperature Cryogenics team supports the SQMS dilution refrigerator systems and several other millikelvin platforms throughout the lab.
- SQMS is designing innovative millikelvin platforms to achieve increased efficacy and capacity of millikelvin systems compared to what is commercially available today.



COLOSSUS - creating the world's largest dilution refrigerator, operating at millikelvin degrees



Single-cell TESLA-shape superconducting cavities with record-high coherence time. Developed for particle accelerators and used to enhance the coherence time in quantum computing

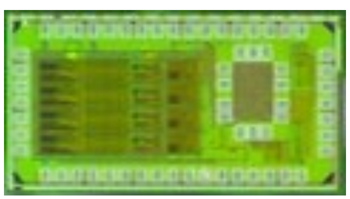


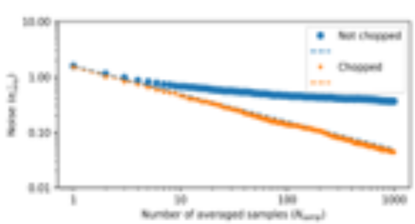
Equipment and control instrumentation

Emerging Technologies Directorate - Microelectronics Department

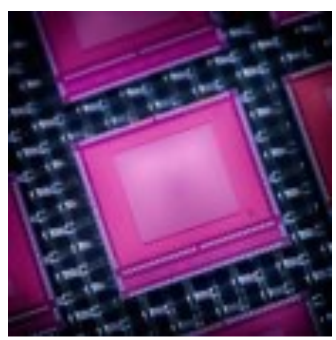
Next generation, custom microelectronics with complex in-pixel process and reconfigurable data-driven architectures, enabling edge computing and the ability to dramatically winnow particle events to the most important data.

- Deep cryogenic electronics for quantum systems
- On-chip machine learning for data processing



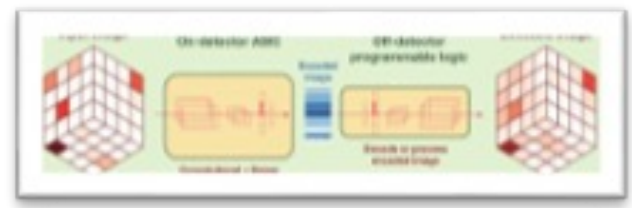


Ultra-Low Noise Sensing (Dark matter detectors)

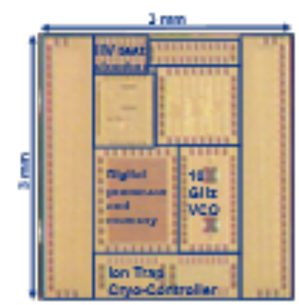


Ultra-High Frame Rates (X-ray detectors)

High speed cryogenic data converters (with Microsoft)



AI-on-chip (ultra-fast data processing)



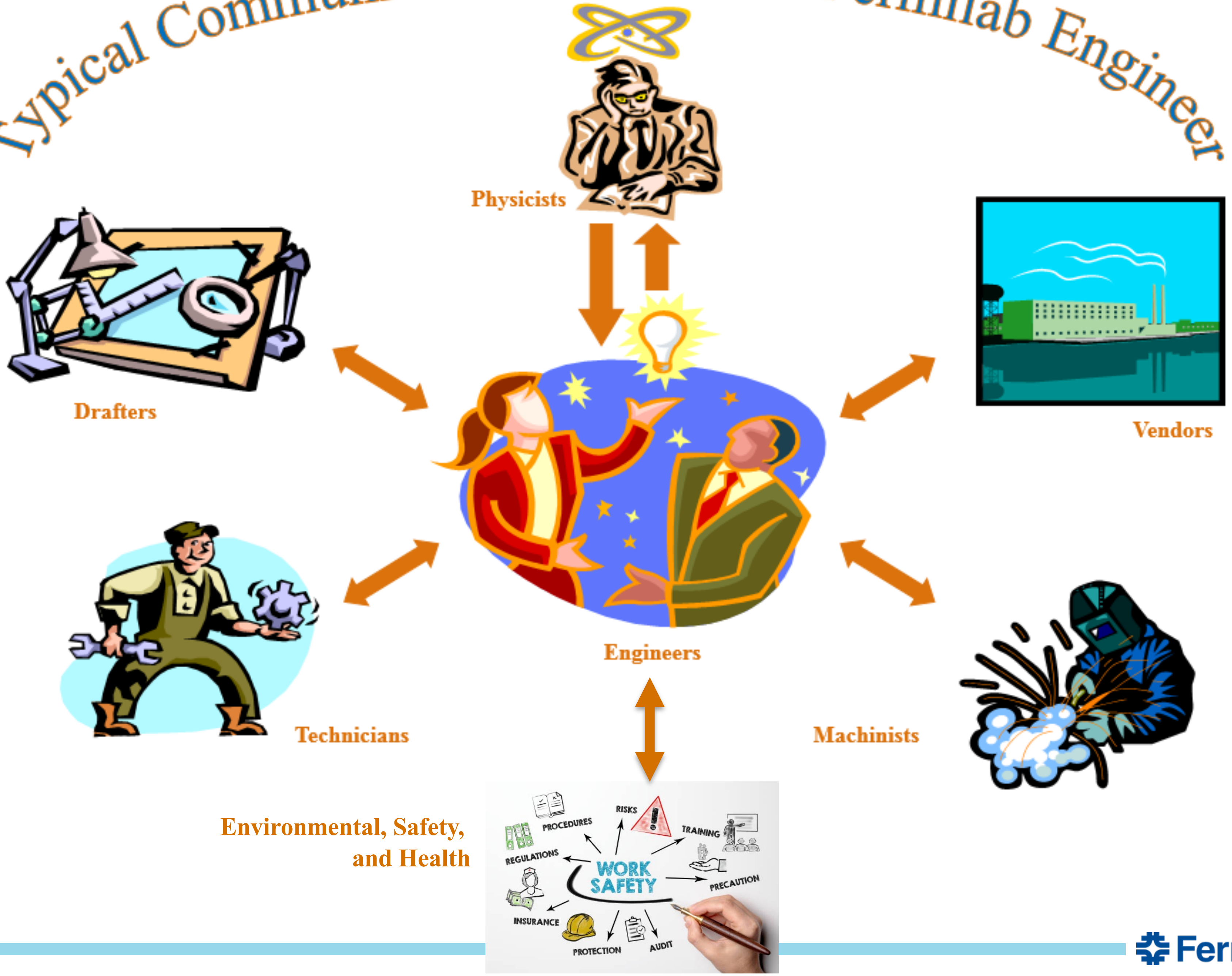
Quantum support chips

Engineers for the Facility

Civil, mechanical and electrical engineers for maintenance, upgrades, and new projects

- 6800 acres
  - Same size as O'Hare Airport
- 36 miles of roads
- 112 acres of parking lots
- 366 buildings
  - 2.4 million gross square feet
  - New buildings: IERC, PIP-II
- 101 miles of electric cable energized through
  - 2 primary electric substations
  - 241 secondary electric substations
- 20 miles of natural gas pipe
- 44 miles of water pipe

Typical Communication Cycle of a Fermilab Engineer

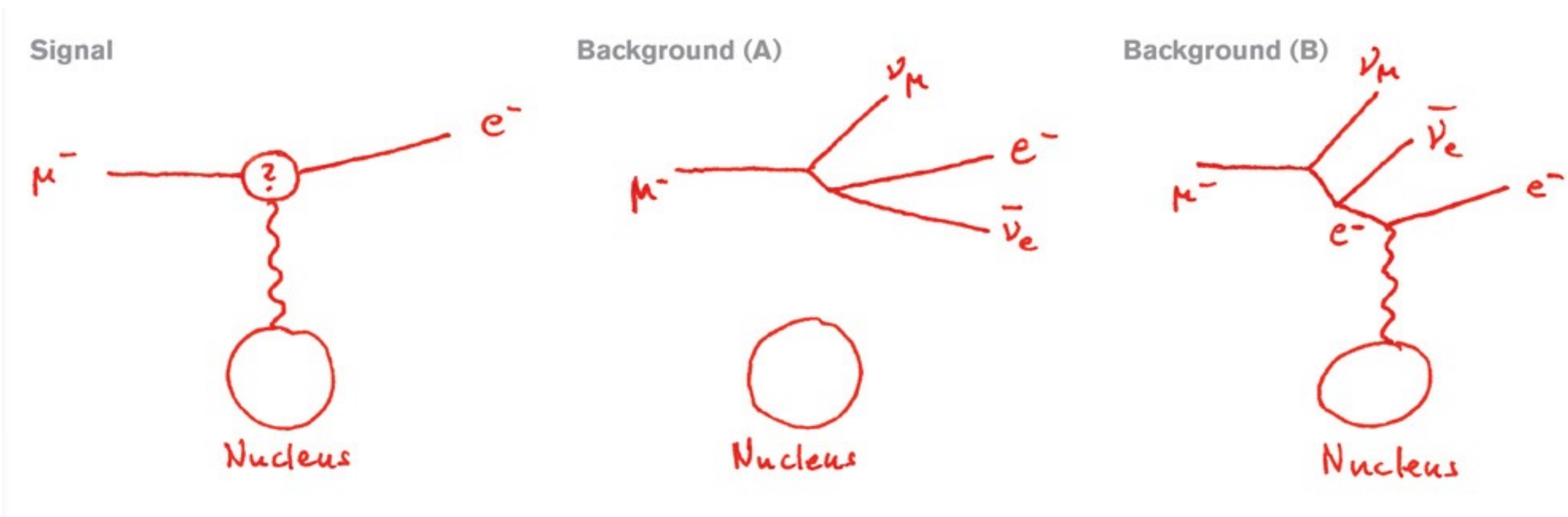


Mu2e Straw Tracker's Front End Electronics

Scientists: "The Mu2e experiment is looking for evidence that a muon can change into an electron and nothing else. Observing muon-to-electron conversion would be a major discovery and would signal the existence of new particles or new forces of nature."

Engineers: OK, but what does that *look like*?

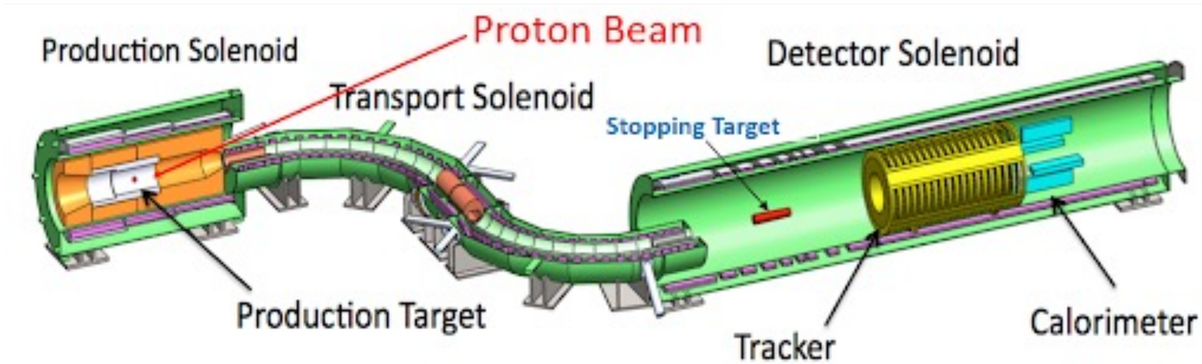
Scientists: Like this:



Source: Jamieson Olson for the Mu2e slides

Engineers: No, I mean, what does that **look like**?

Scientists: We build this experiment, with several different sub-detectors:

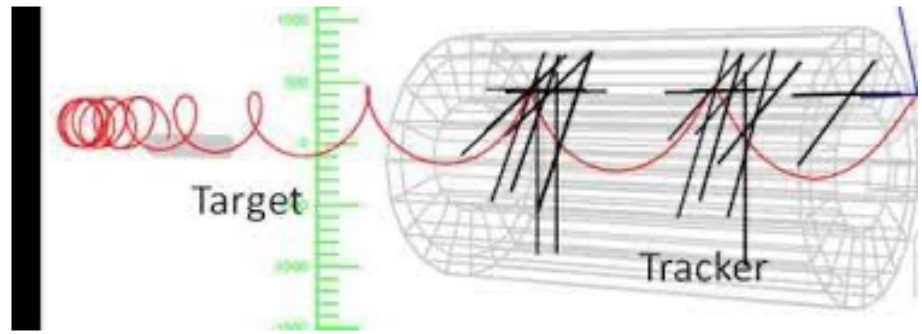


Transport Solenoid

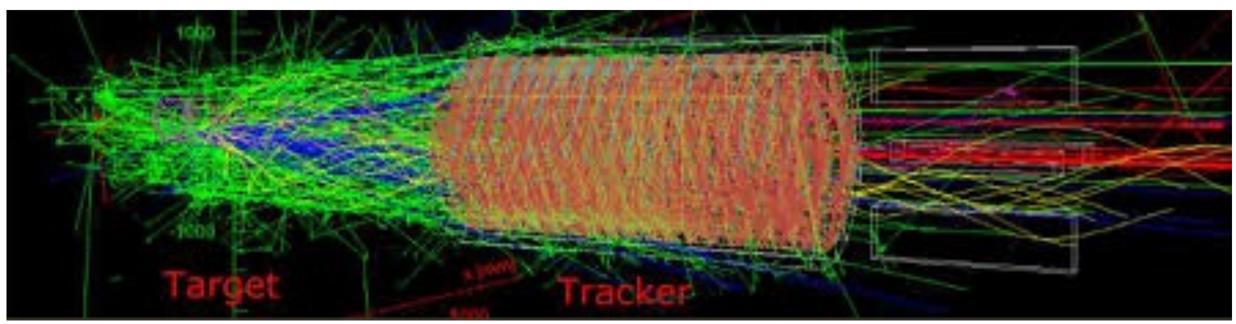
Stations of the Straw Tracker. The completed tracker will have 20 stations that will hold a total of 23,040 straws.

Engineers: OK, what signature or pattern should the electronics look for?

Scientists: We're looking for this needle…



In this haystack…

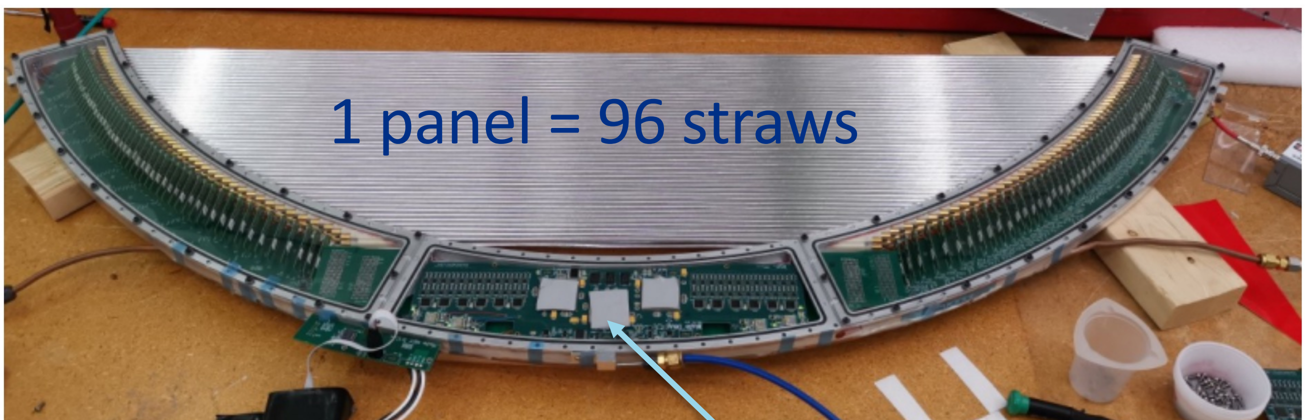


Engineers: So how much of the detector does the electronics need to “see”?

Scientists: All of it!

Engineers: Well, that’s too many signals to route into one place!

How can we break it up into smaller parts…?

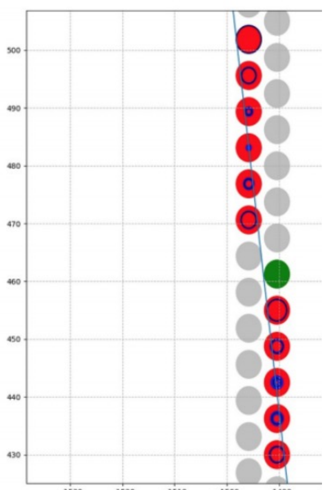


Straw = 25-µm gold plated tungsten wire immersed in argon-carbon dioxide gas and running through a 5-mm diameter mylar tube

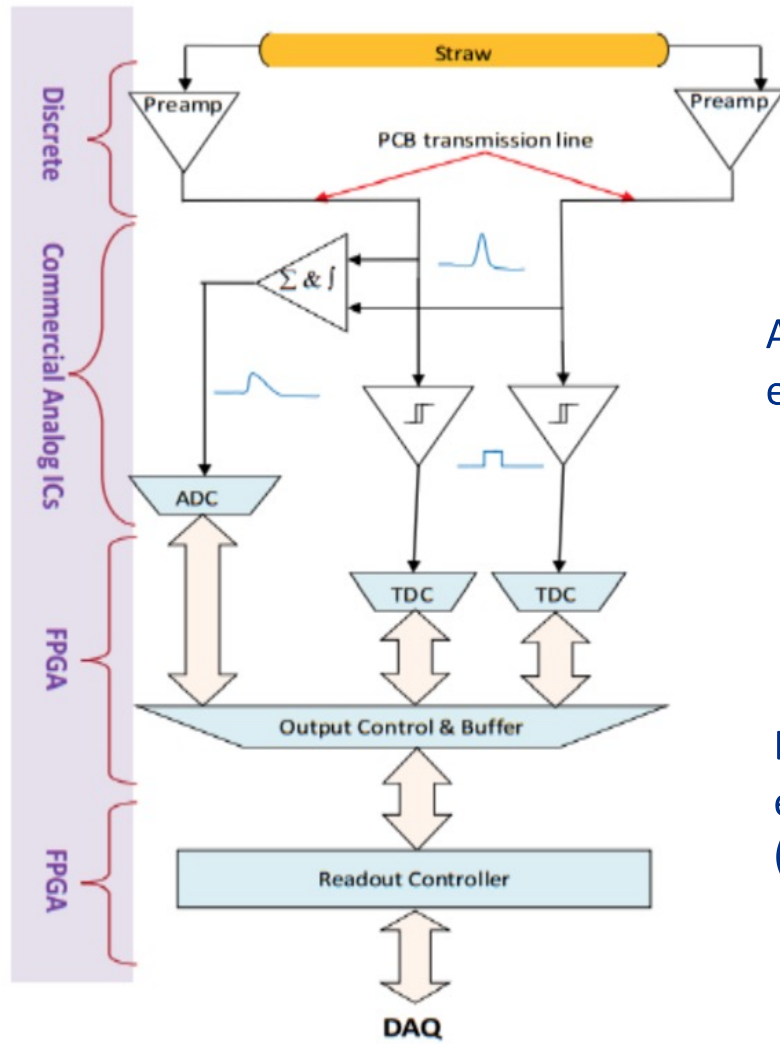
FPGAs
(Field Programmable Gate Arrays)

Engineers: Now we're getting to something manageable! What does the FPGA have to do?

Scientists: Identify which straws are hit, time stamp the hits, package the data, send data downstream to the data acquisition system (DAQ).



Particle track passing through straws



Analog electronics

Digital electronics (FPGAs)

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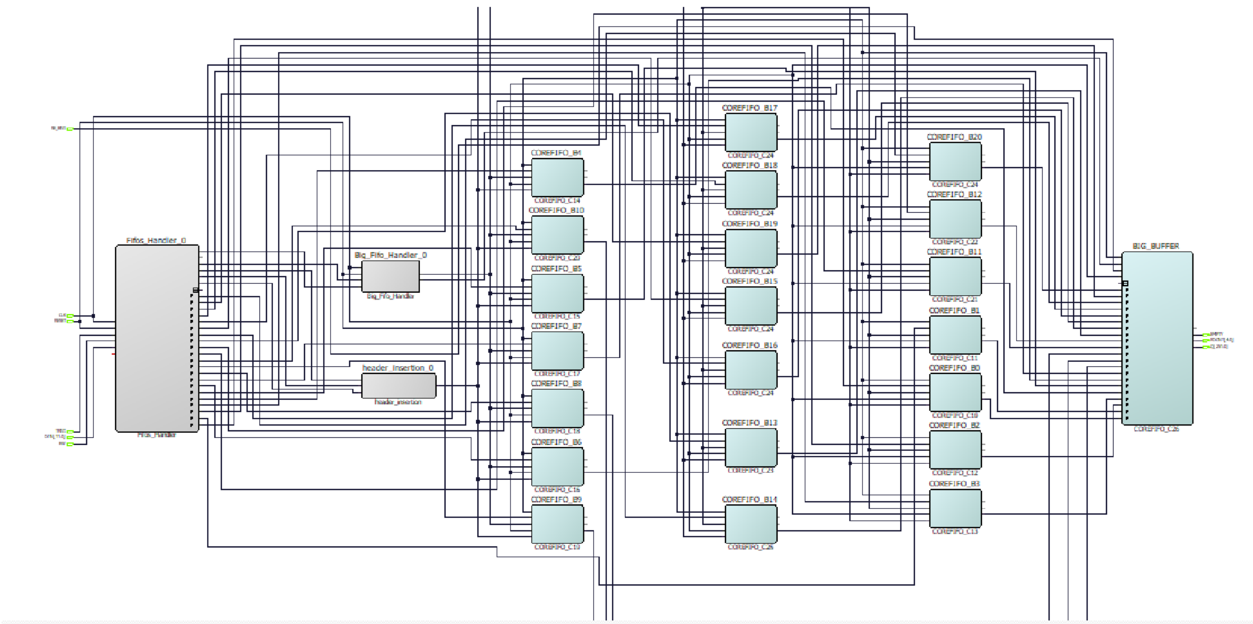
Engineers: Got it! Now to start writing firmware for those FPGAs!



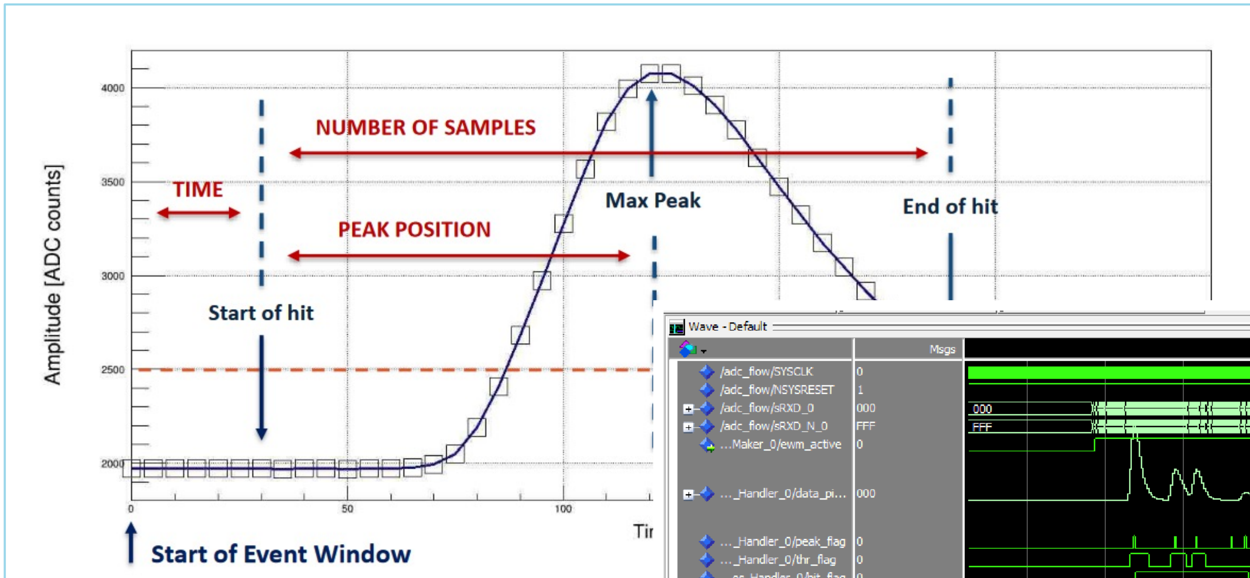
```
if (peak_flag = '1' and thr_flag = '1') then
  PIL_STATE <= BLIND_TH;
  pileup_counter := nBPEAKs;
else
  if (pileup_counter = 0) then
    pileup_counter := nBPEAKs;
    PIL_STATE <= WAIT_PEAK;
    continue_hit <= '0';
  else
    pileup_counter := pileup_counter - 1;
    PIL_STATE <= BLIND_TH;
  end if;
end if;
```

Firmware is very different from a conventional programming language.

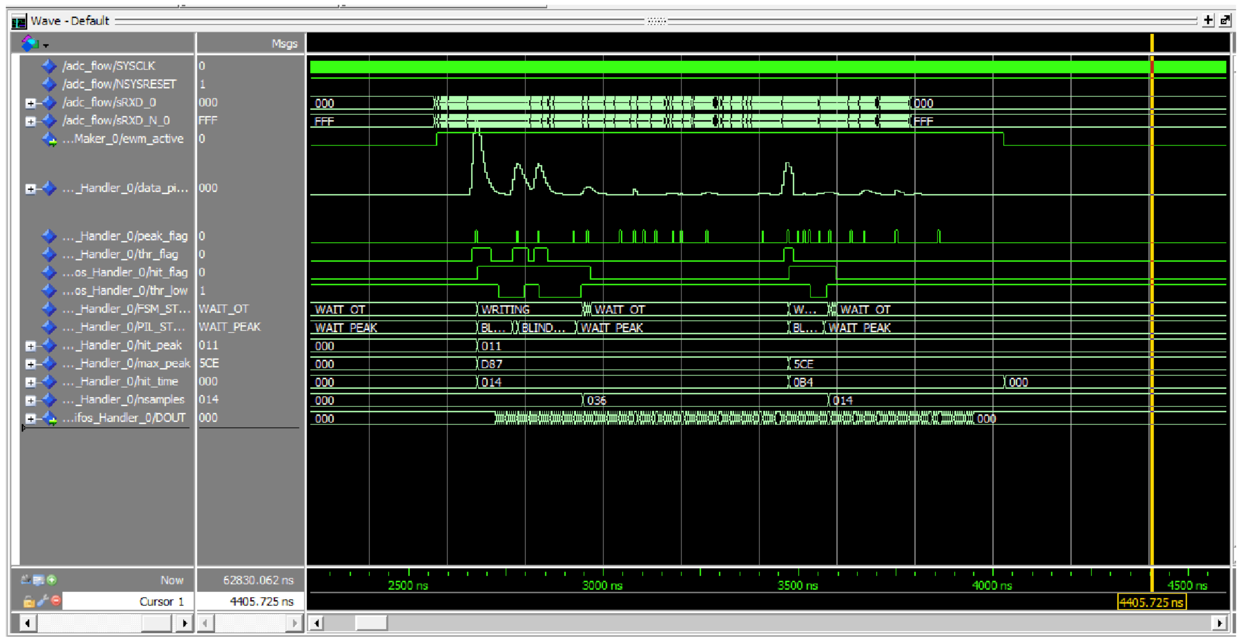
Firmware (VHDL or Verilog) describes very small steps happening concurrently, in parallel.

Firmware is then tested in a simulator, in software, before testing in hardware.

Scientists supply simulated event data…



Engineers run these “test vectors” through the simulator…



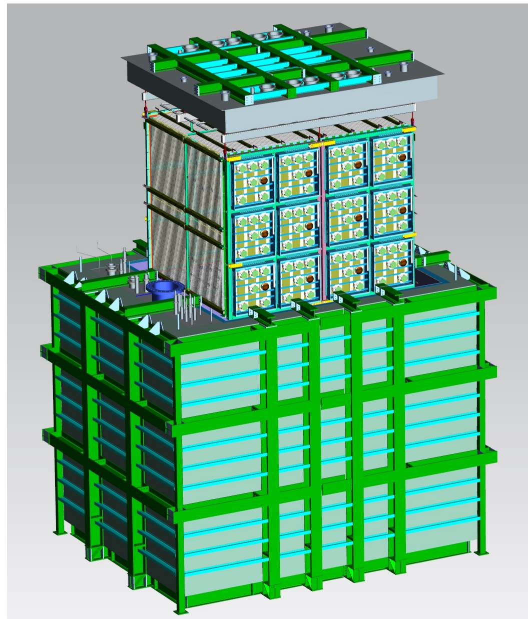
Check the simulator output. Does the firmware work as expected?
Does the design fit into the chosen FPGA?
Does the design meet the timing requirements?

SBND – In-Situ Electronics Repair

Short Baseline Near Detector

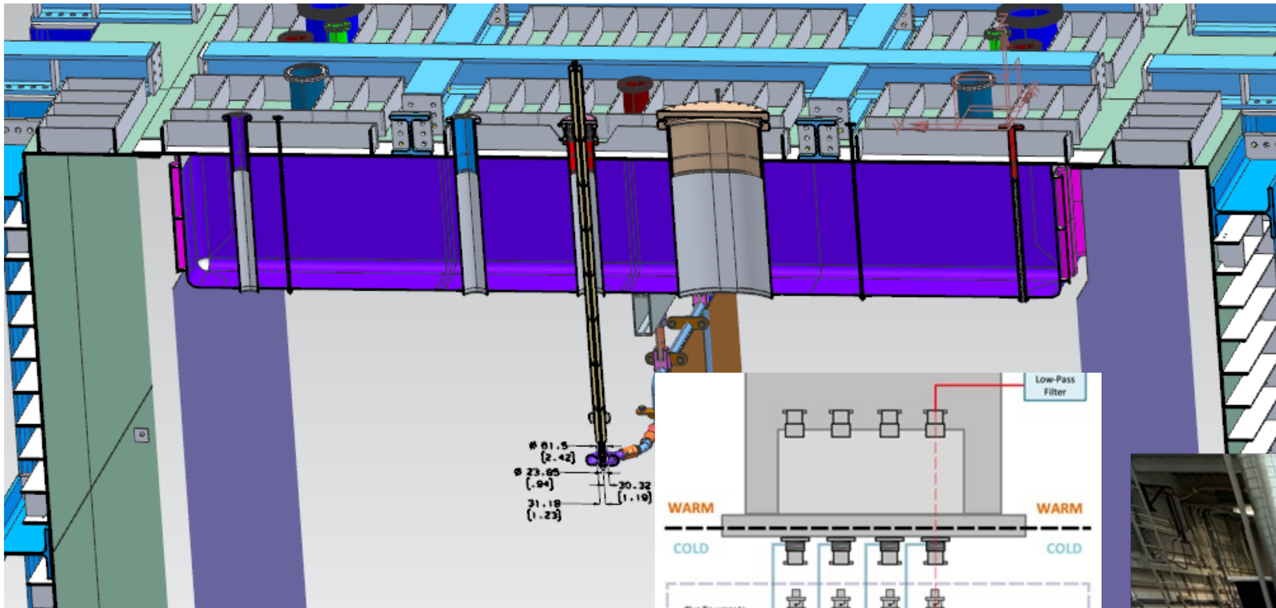
- **Designed to record a million neutrinos interactions a year**
- **Construction and physics prototypes the future LBNF/DUNE experiment in South Dakota**
- **Filling with highly pure liquid argon to 1.1-bara took months**
- **Commissioned and start of operation in July, 2024**

Source: Michael Geynisman and Roza Doubnik for the SBND slides

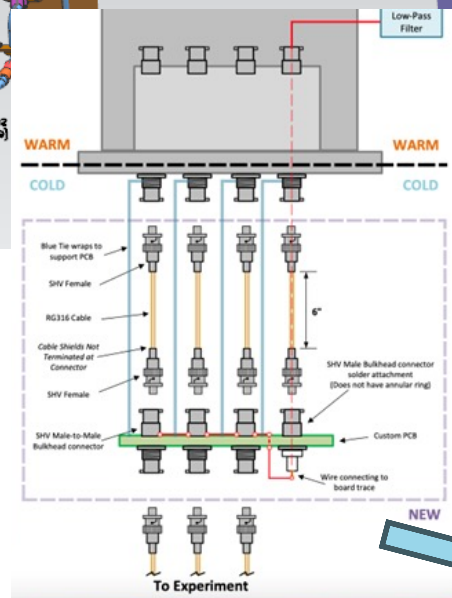


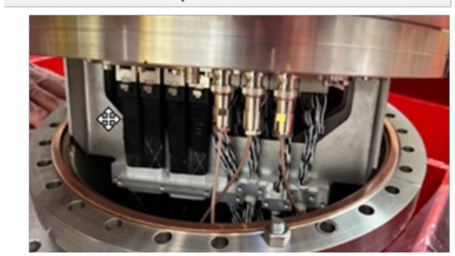
SBND detector's time projection chamber (left: modelled above the membrane cryostat; below: being lowered into final place)

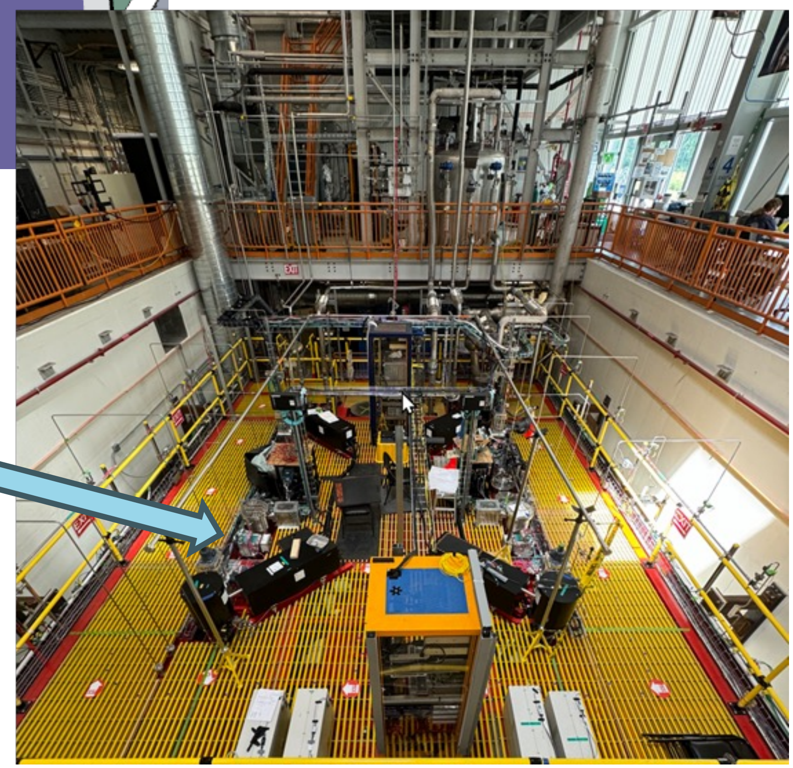
SBND – Chimneys and Electrical Feedthroughs



Chimneys: vertical access through top insulation to TPC volume







Some chimneys used for electrical feedthroughs- 14-inch flange (left);

View of top of the detector (right)

During commissioning, a malfunction in the electrical system was discovered

Planning for the repair

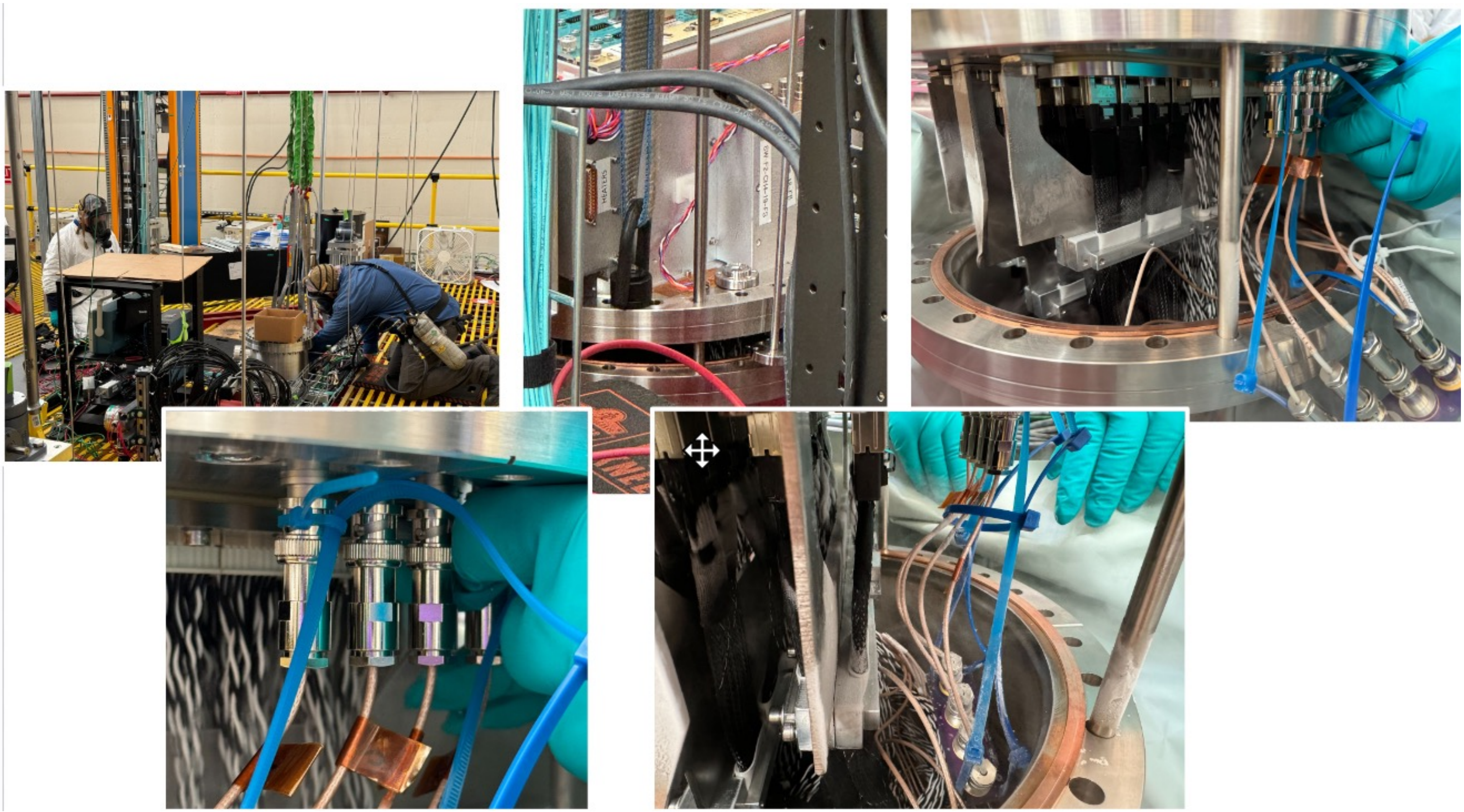
- Repair: Open the electrical feedthrough to replace parts
- Challenge: Open the feedthrough and repair the electronics in a safe way while the liquid argon remained in the detector
- Hazards:
  - Release of cold argon gas
  - Oxygen deficiency for personnel
  - Rigging of equipment above cryo equipment
  - Potential for back diffusion of air to the cryostat and spoiling argon purity
- Collaboration of scientists, engineers, and safety personnel
  - Months of evaluating hazards, work planning and setting up safety controls
  - Team included personnel from Fermilab Neutrino Division, Fermilab Environmental Safety and Hazard, and CERN

Collaboration of scientists, engineers, technicians, and safety personnel

- Reliance on personnel who designed and who operate the detector and its associated argon refrigeration system
  - Calculated projected cold argon release rates
  - Calculated impact on local oxygen concentrations
  - Developed procedures for depressurizing the cryostat and opening of the flange
- Work planning included:
  - Developing procedures for rigging
  - Identifying specialized safety equipment to purchased
  - Trained two teams (3 people each) on prototypes to do work coordinated by cryo engineers.
  - Multiple in-situ meetings of the team with management and safety personnel led to review and approval of the procedures.

Opening of the flange and cold argon gas release (video)

Coordinated work of team replacing the electronics



Coordinated work of team replacing the electronics (details)

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Results of the procedure

- It took 5 days of cryo operations to de-pressurize of the cryostat and cool down of more than 200 ton of liquid argon at 87.9K by additional 0.4K.
  - 112-ton of liquid argon in the detector + additional liquid argon in the refrigeration system and piping
- On June 20, the teams were dressed in protective gear, positioned at the cryostat, and the pressure was dropped almost to atmospheric without loss of cryo operations.
- The flange was opened and rigged up to allow scientists and technician to reach into cold space below and replace the electronics components.
- The whole operation took less than 30 min and was completed successfully without any safety incidents.

Thank you to the contributors

- Martin Bentivengo – ISD
- Gustavo Cancelo - CSAID
- Paul Czarapata – AD
- Abhishek Deshpande – AD
- Roza Doubnik – PPD / ND
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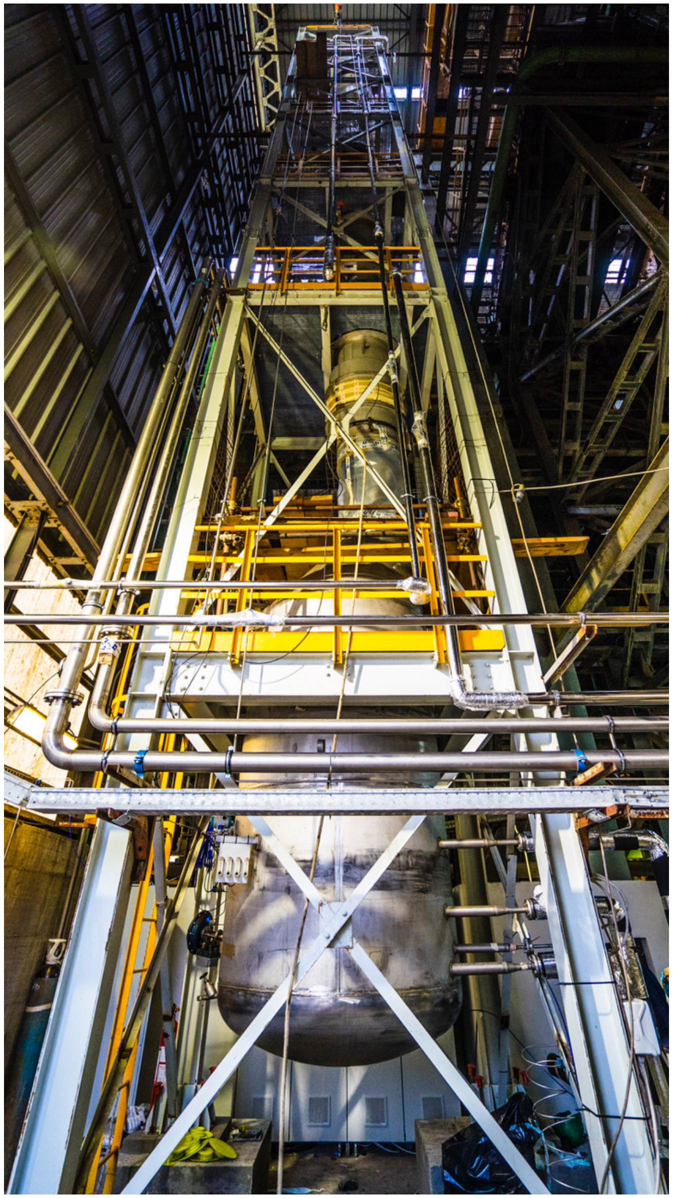
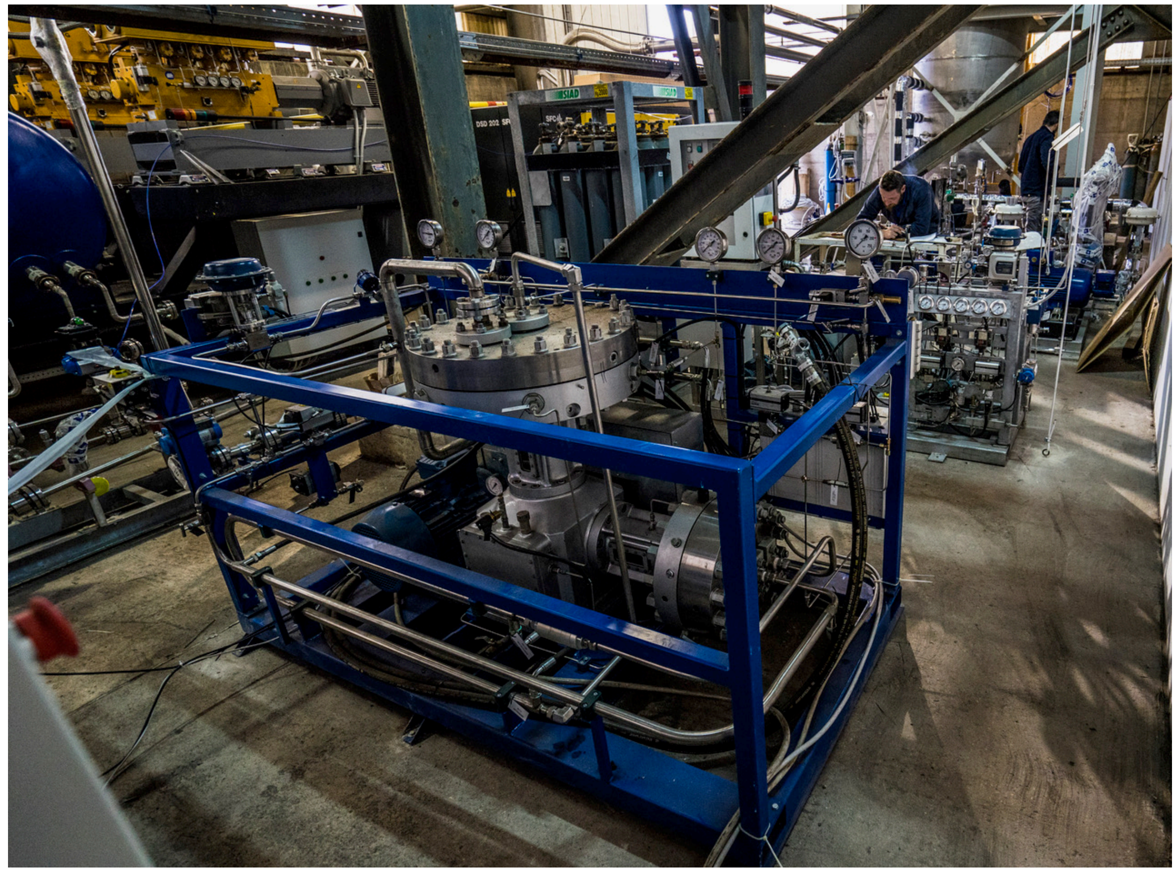
- Michael Geynisman – PPD / ND
- Greg Gilbert - ISD
- Dave Harding – APS-TD
- Chris James - SQMS
- Chris Jensen - AD
- Barry Norris – PPD / ND
- Jamieson Olson - PPD
- Ryan Rivera - CSAID
- Russ Rucinski – PPD
- Silvia Zoretti - SQMS

Back-Up Slides

Other projects: DarkSide LAr Distillation Column installation in Sardinia, Italy



- installation of Seruci 0 (distillation column phase 0)



Source: Cary Kendziora

Water at Fermilab

- 24 miles of Industrial Cooling Water pipe and conveyances
  - Provide water for cooling systems of accelerators and detectors
  - Fire protection
  - HVAC cooling
  - 97 million gallons annually
    - Recovered from NuMI/MINOS underground halls
    - Warrenville (well water)
    - Deep well water
- 20 miles of domestic (drinking) water pipe
  - 20 million gallons annually
- Compare: City of Batavia pumped 1.2 billion gallons of water to its users in 2007