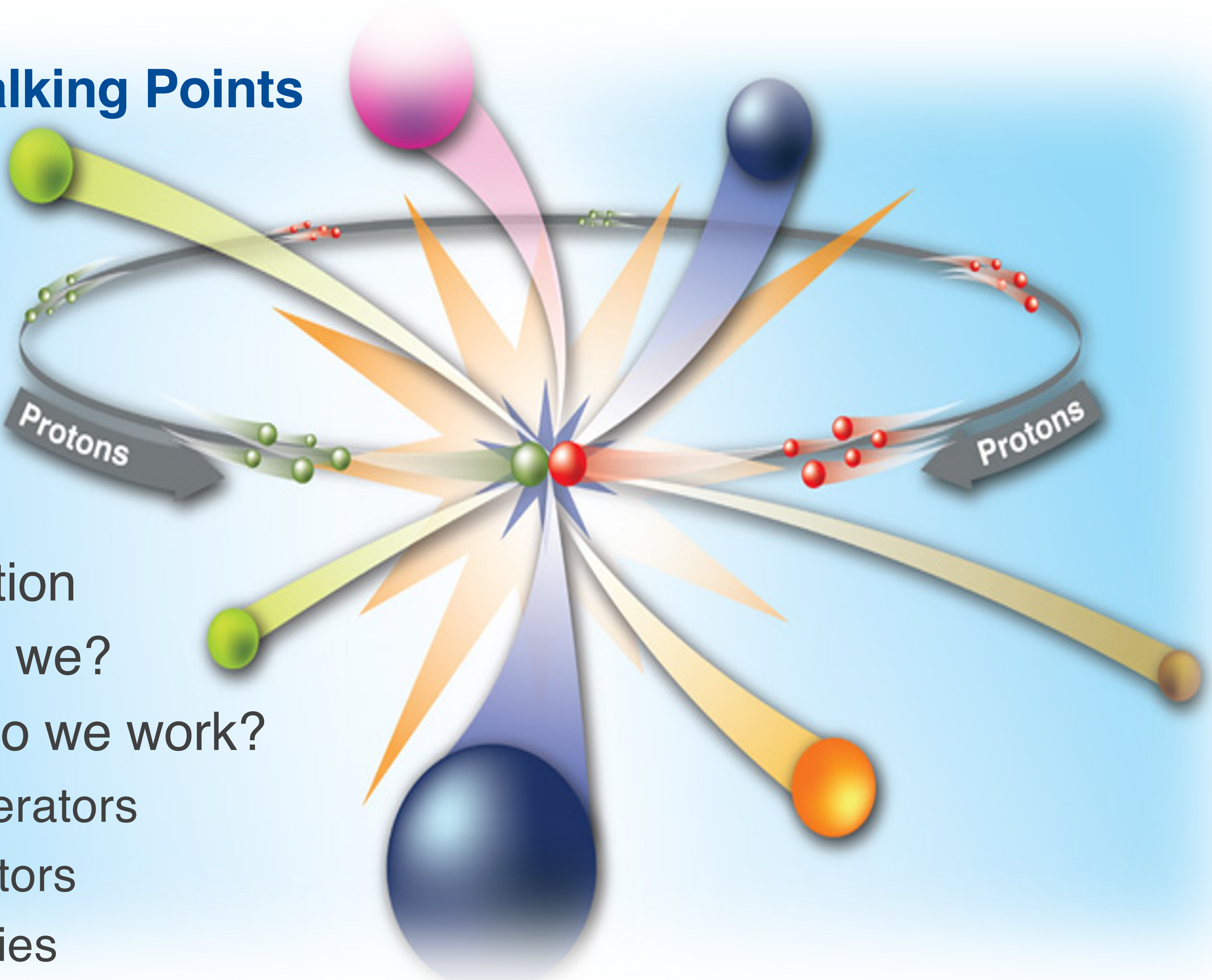
Engineering at Fermilab

Mayling Wong-Squires

Summer Lecture Series

6 July 2023

Today's Talking Points

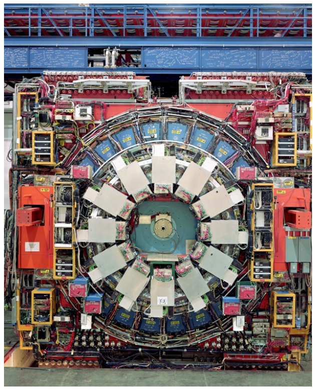


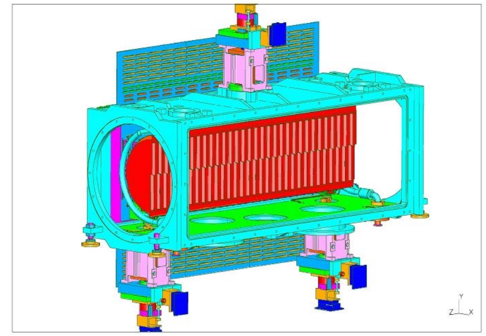
- Introduction
- Who are we?
- Where do we work?
  - Accelerators
  - Detectors
  - Facilities
  - Projects

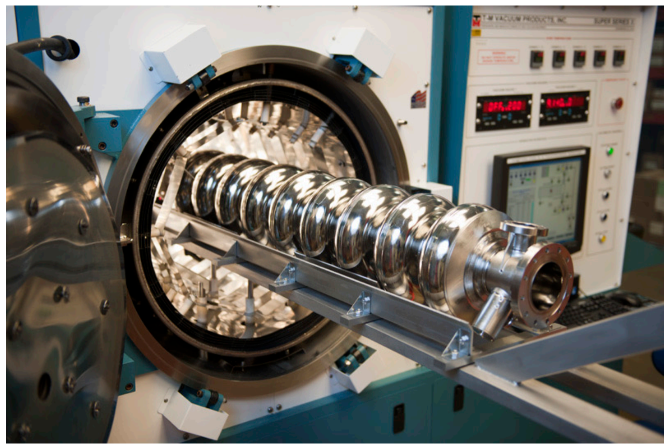
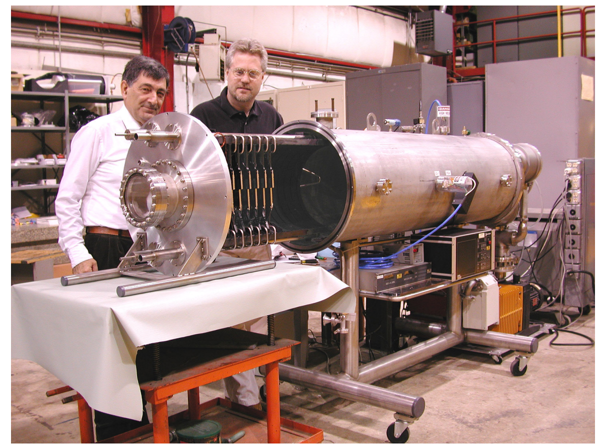
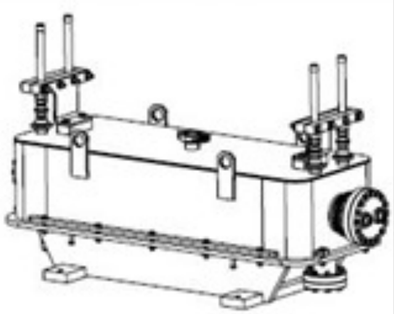
About me

- 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

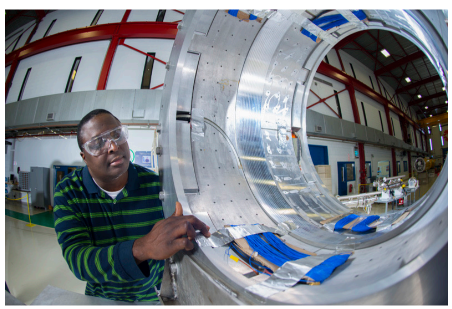
Introduction to Engineers at Fermilab

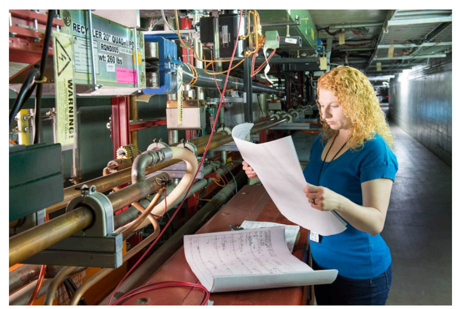
Engineers at Fermilab are essential to its vision, which is to solve the mysteries of matter, space and time for the benefit of all.

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

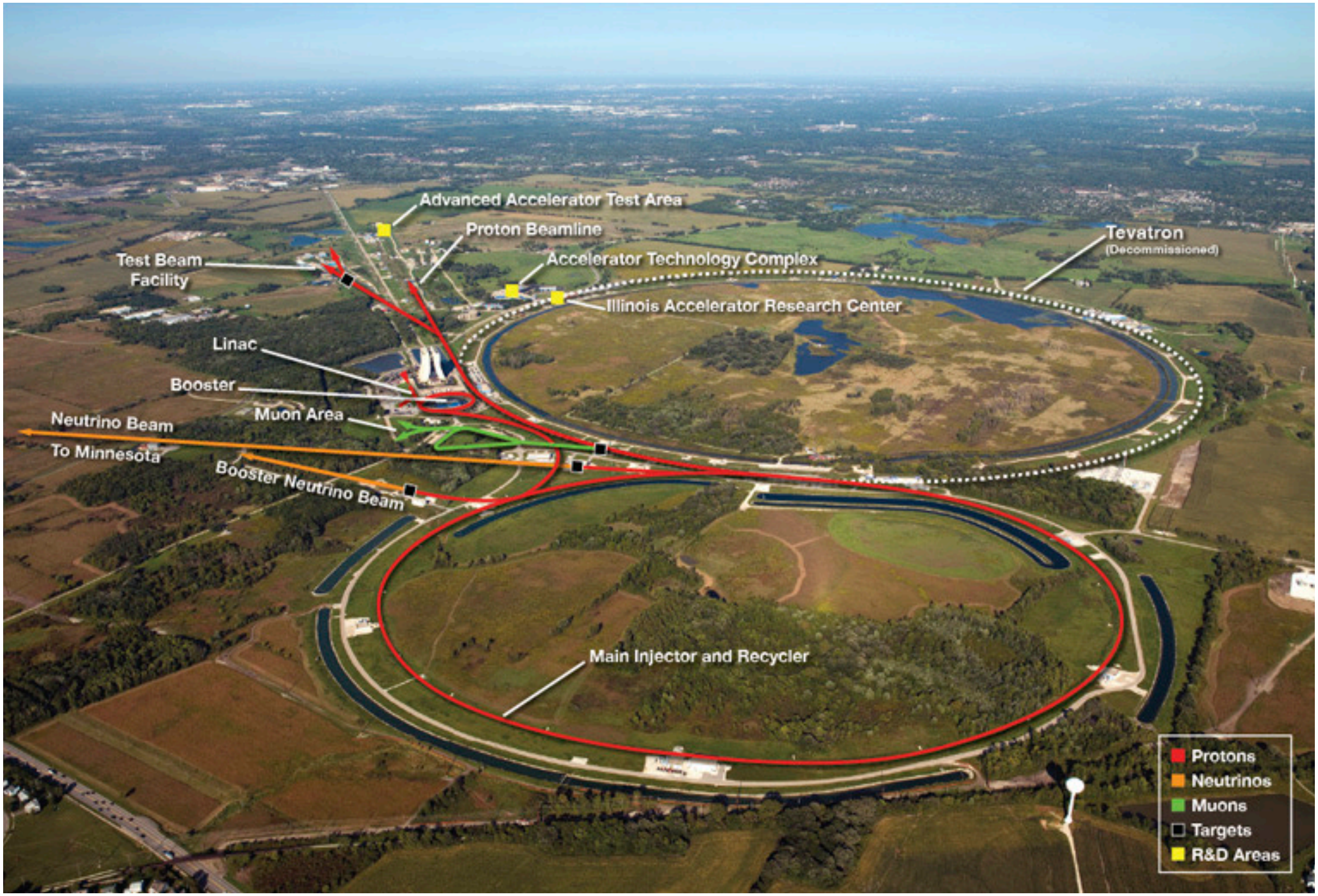
Who are we?

- Part of a team that also includes scientists, technicians, drafters, contractors, project managers
- 280 engineers (~15% of lab employees)
  - Civil Engineers
  - Electrical Engineers
  - Mechanical Engineers
- Computer engineers / professionals

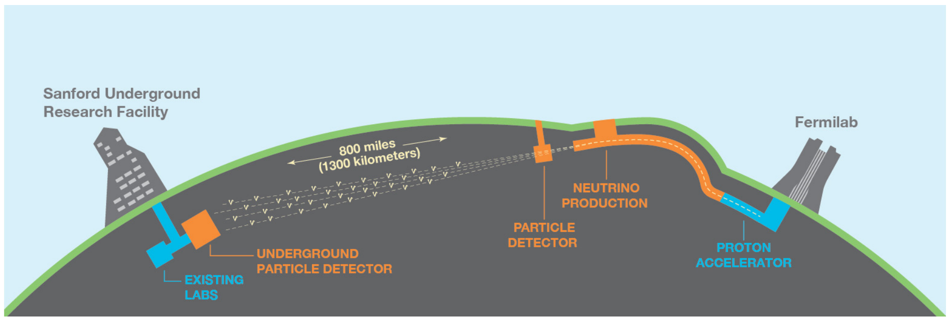




Where do we work? Main Campus – Batavia, IL



Remote sites: Lead, SD and Ash River, MN

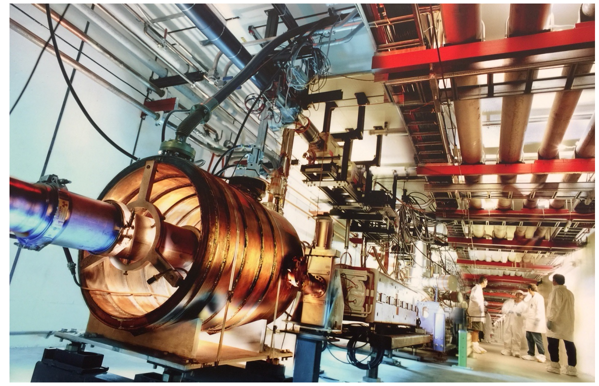


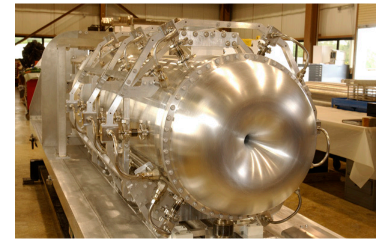
Deep Underground Neutrino Experiment (DUNE)

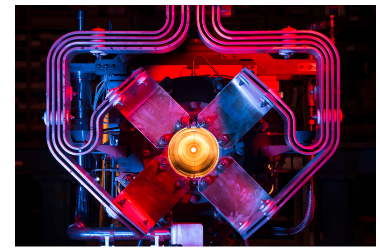
NoVA Experiment

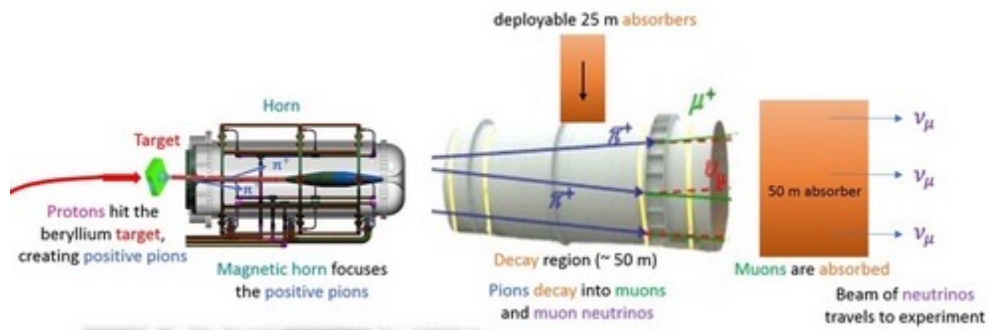
What does it take to study sub-atomic particles?

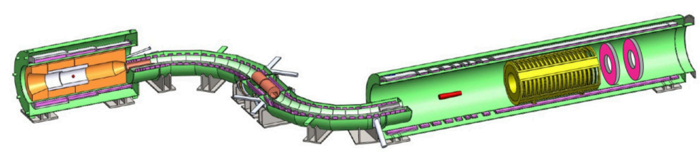
- Accelerate a beam of protons
  - Electromagnets and radio-frequency cavities to accelerate and position the beam
  - Instrumentation to “see” the beam
- Create new particles
  - Neutrino or muon beam
  - Target, horn, decay region and absorber
- Send particles to detector to study
  - Neutrino detectors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





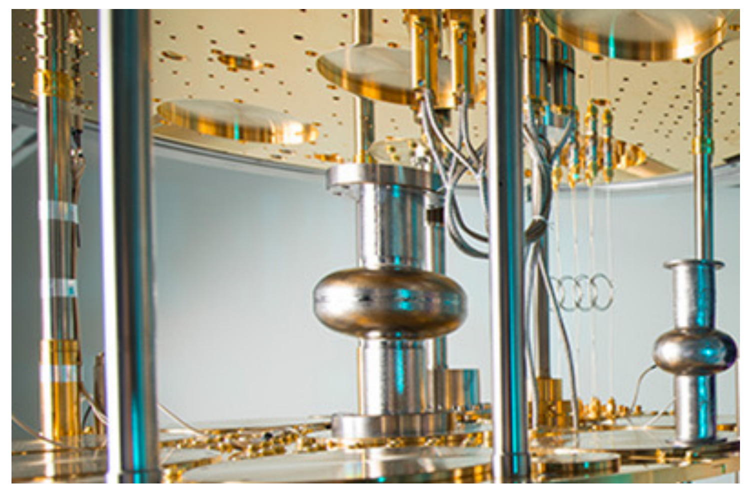




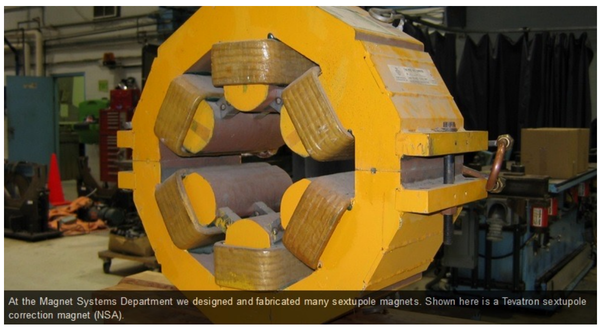


What does it take to study sub-atomic particles?

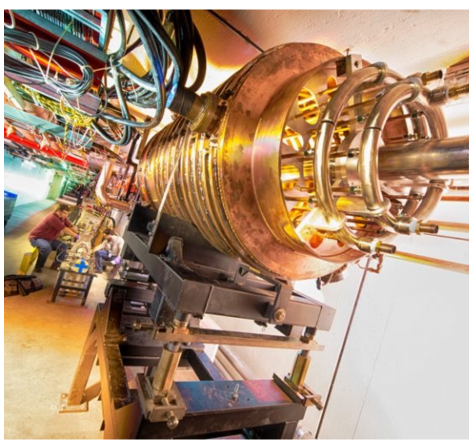
- Scientific Computing
  - Process and analyze experimental data
  - Compare experimental data with simulations
  - Requires home-grown high-performance computing systems
- Quantum Computing
  - Potential to tackle calculations that can currently take years
  - Hardware
  - Software



Accelerator Components



Sextupole magnet during assembly and completed

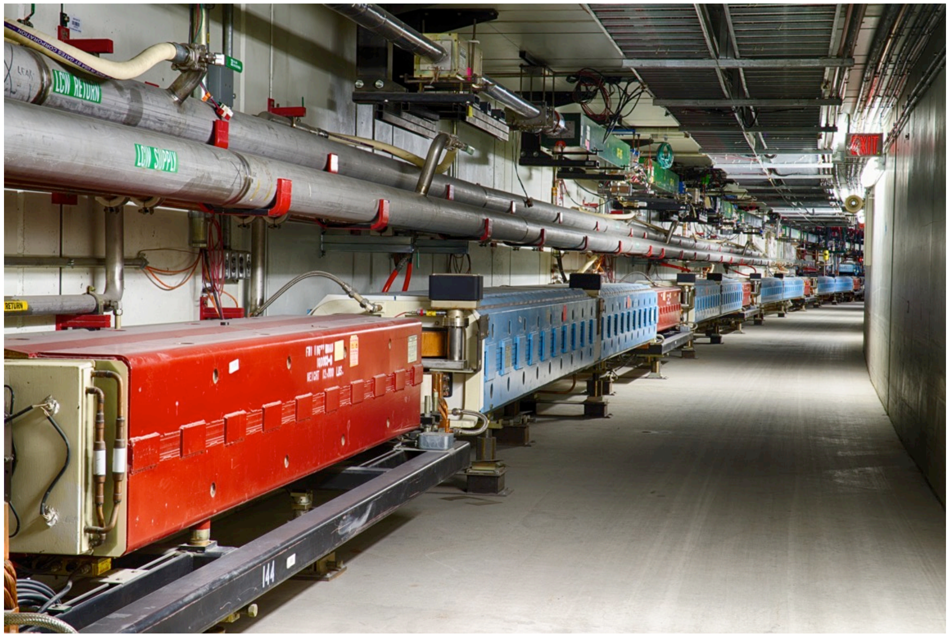


High powered
radio frequency cavity
2.5MHz to 1.3 GHz
(cell phone systems 2 GHz)

- 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 $1x10^{-8}$ 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

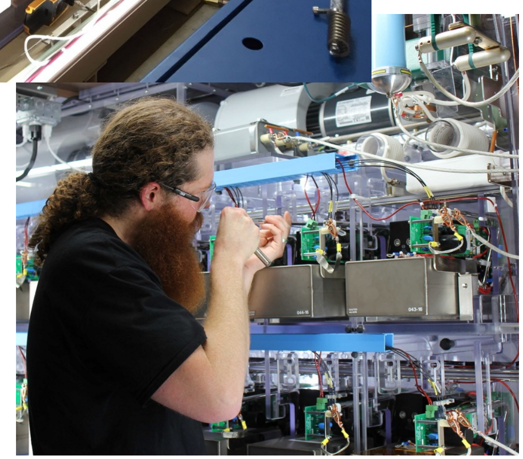
- 800-V AC
- 4000-A AC

Rectifier inside a service building

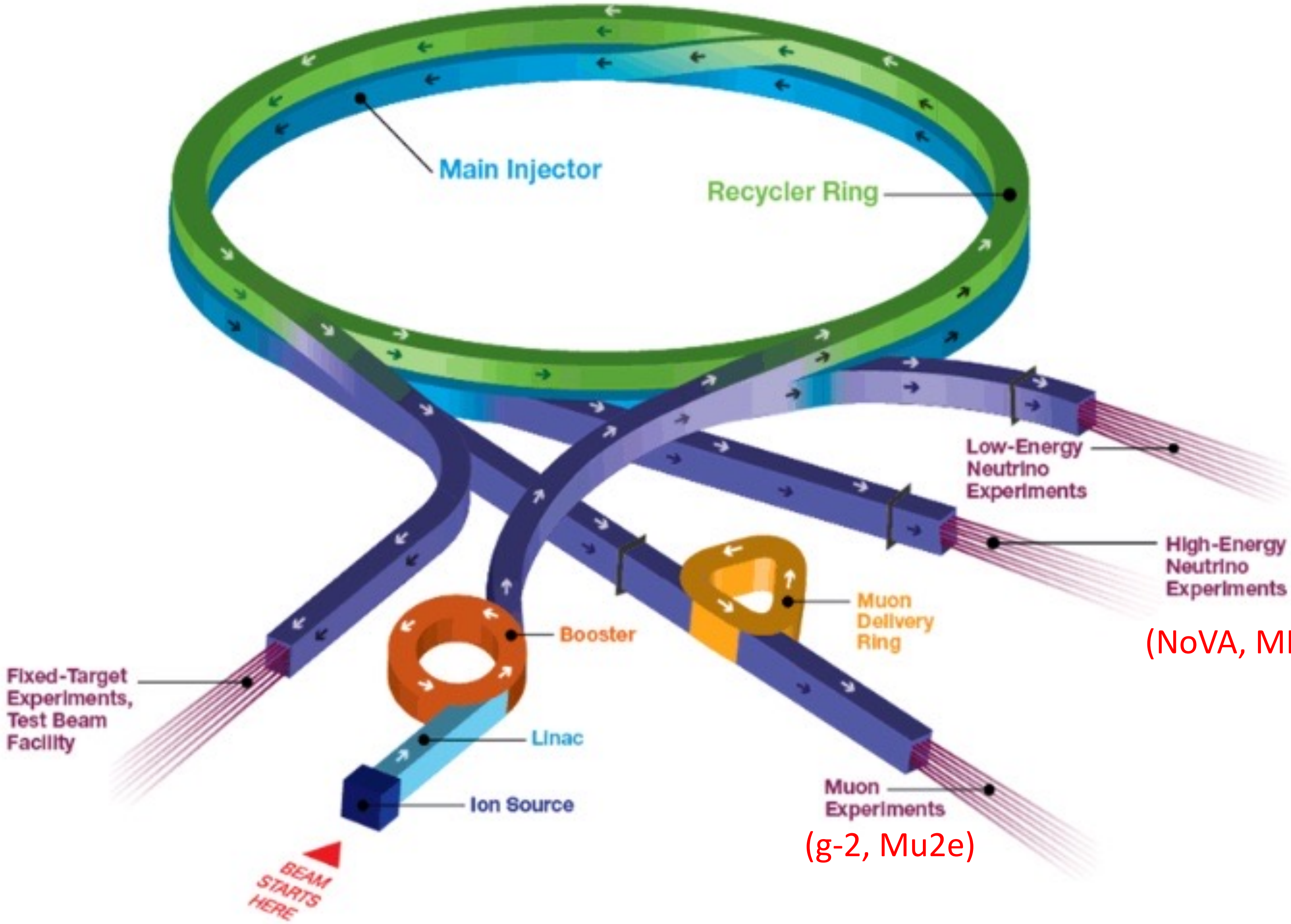
- Converts AC to 1000-V DC
- 10,000-A DC
- Total capacity per building 10 MVA

Marx Modulators for Linac RF Cavities

- Custom-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

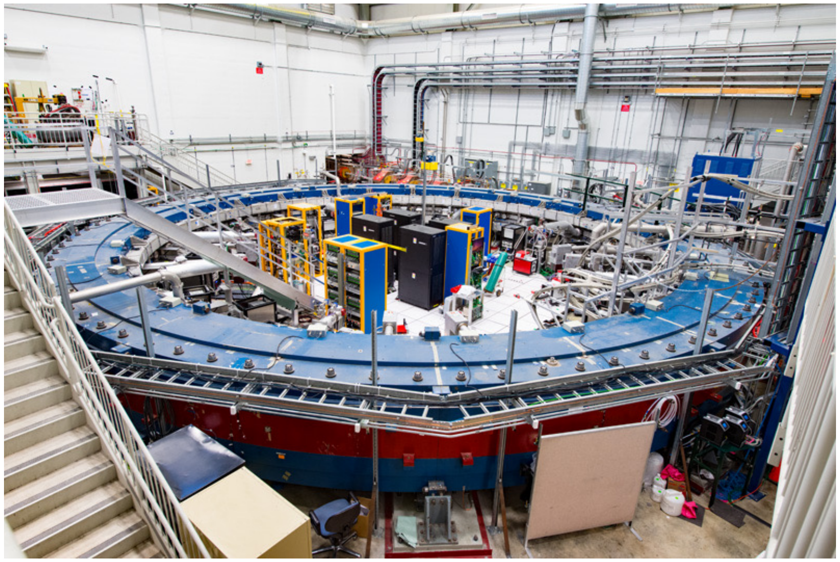


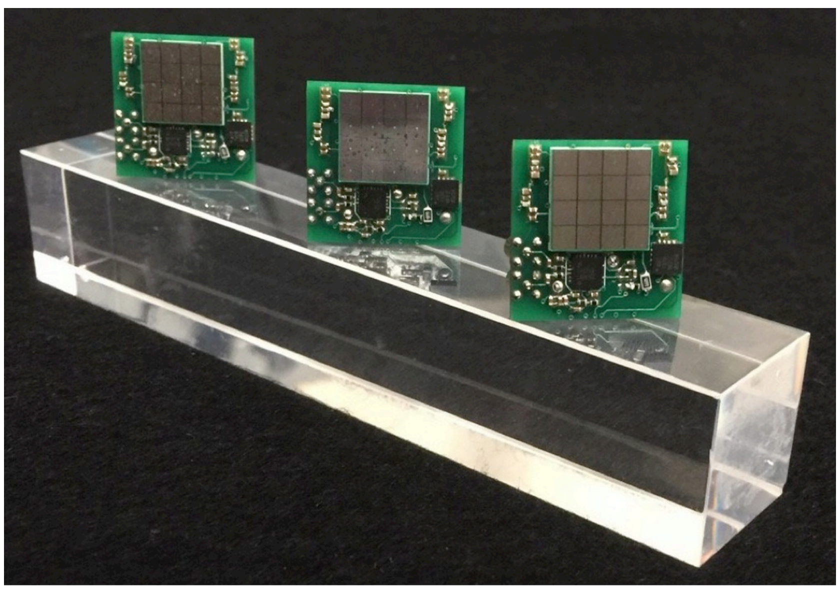
(Short-Baseline Neutrino Program: ICARUS)

(NoVA, MINOS)

(g-2, Mu2e)

Send beam to a muon experiment

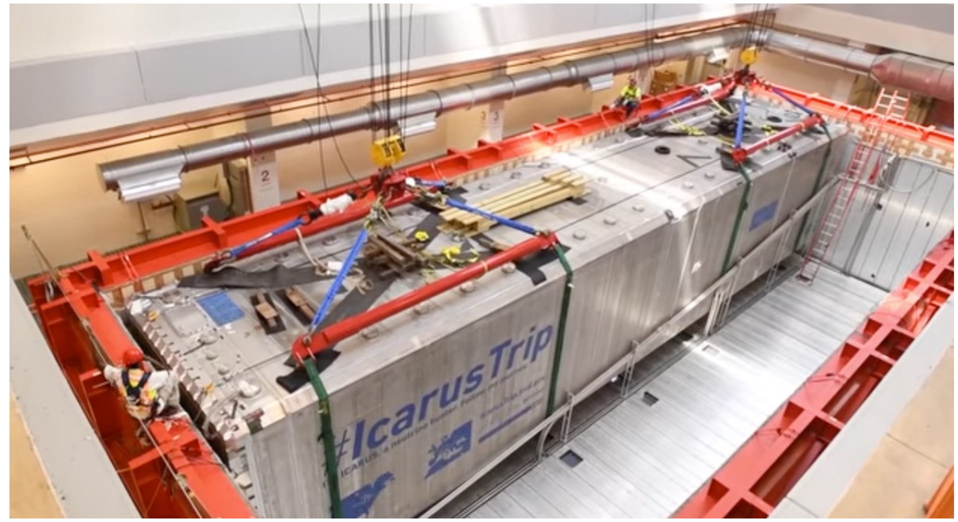




- Muon g-2
  - 50-foot diameter superconducting electromagnet
  - Study the “wobble” of the muon beam when placed in the magnetic field
  - Detectors to measure muon energy and decay time (calorimeter)
- Electrical engineers
  - Design, manufacture, install detectors
  - Control system
- Mechanical engineers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

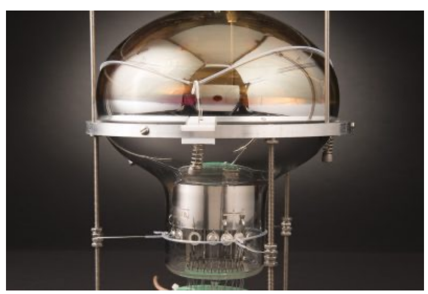
Send beam to an on-site neutrino experiment

- ICARUS
  - 760-ton 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



One of two cryostats during installation, 3.6-m x 3.9-m x 19.9-m, that will hold 170,000-gallons of LAr

PLC Based Process Controls



PMT

View of one of the ICARUS detector's inner time projection chamber (TPC): Cathode plane on the left, wire plane and PMT array on the right

Send beam to an off-site experiment

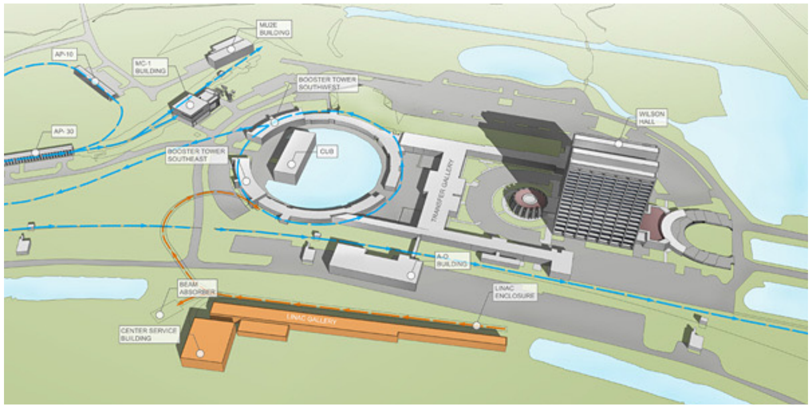
NoVA 14-kiloton far detector comprised of liquid scintillator

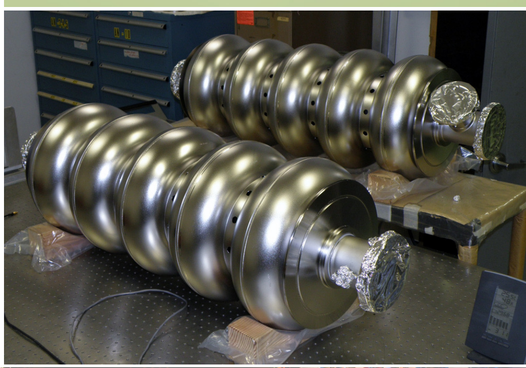
Highly reflective plastic extruded tubing 15.5-m long. Inside the detector, the tubing will be filled 2.7-million gallons scintillating oil

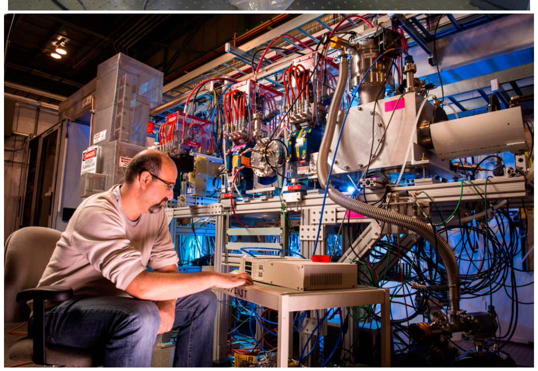
- Study of neutrino interaction
- NuMI
  - Create neutrino beam here at the main campus
  - “Near” detector to characterize the neutrinos at Fermilab
- NoVA and MINOS
  - Ash River, MN
  - Bottom of a former iron mine (Soudan mine) located 2341-ft below the surface
  - “Far” detector to characterize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

Future Accelerator and Detector

Proton Improvement Plan II (PIP-II)

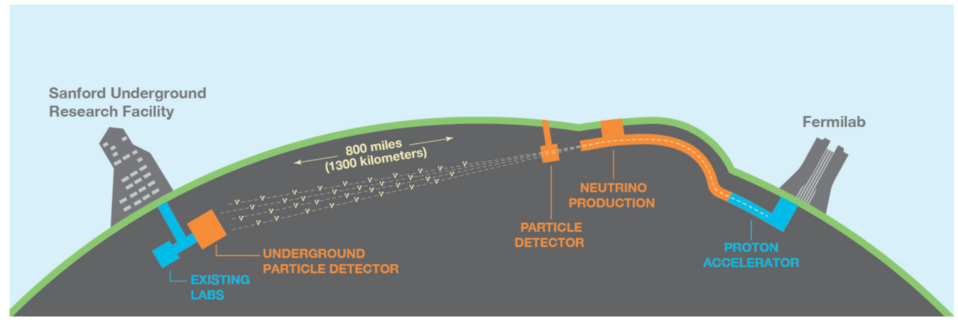


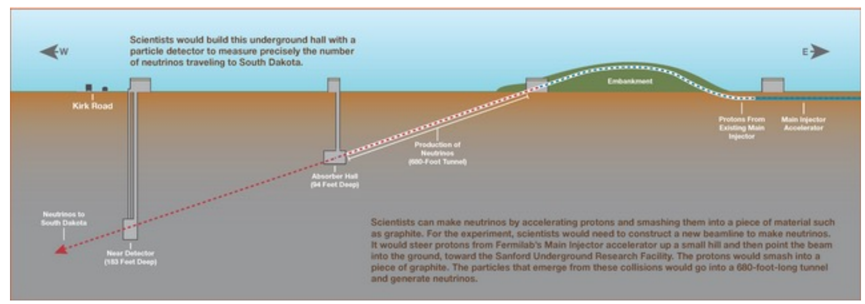


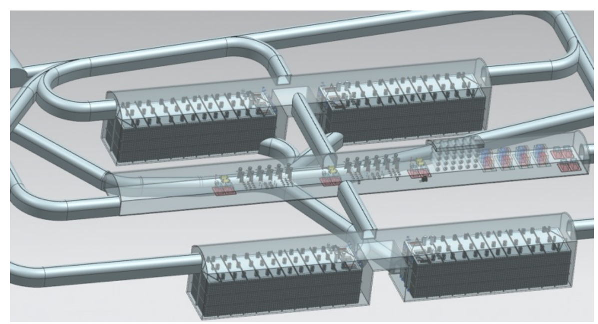


PIP-II will supply a 800-MeV proton beam accelerated at 8-GeV. The beamline will use the next generation superconducting radio frequency cavities. This provides the protons that will create the most intense neutrino beam for LBNF. Construction is not scheduled until 2026. A test beam was built and completed 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)

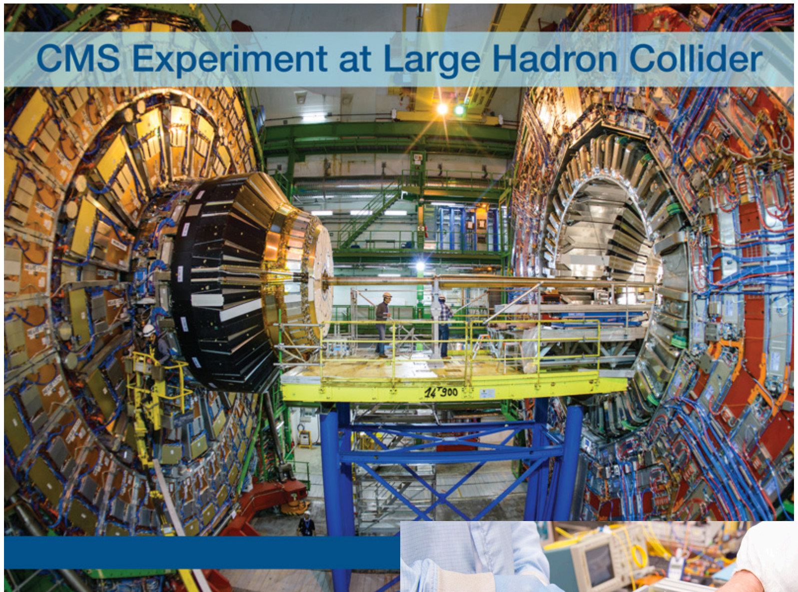




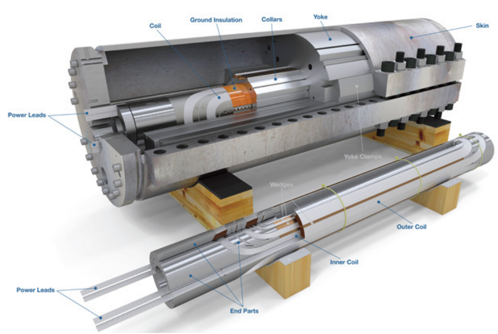


Neutrino research from the LBNF/ DUNE project will make use of the most intense neutrino beam. At DUNE, there will be 4 detector modules, each filled with 17,000-tons of LAr. The detectors will sit at 4850-ft below the earth's surface.

Support experiments and projects at other organizations



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

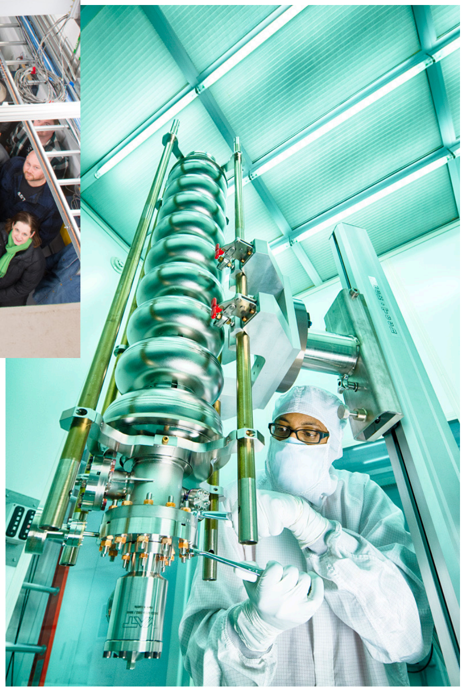


11-Tesla dipole test magnet for the LHC High Lumi upgrade at CERN

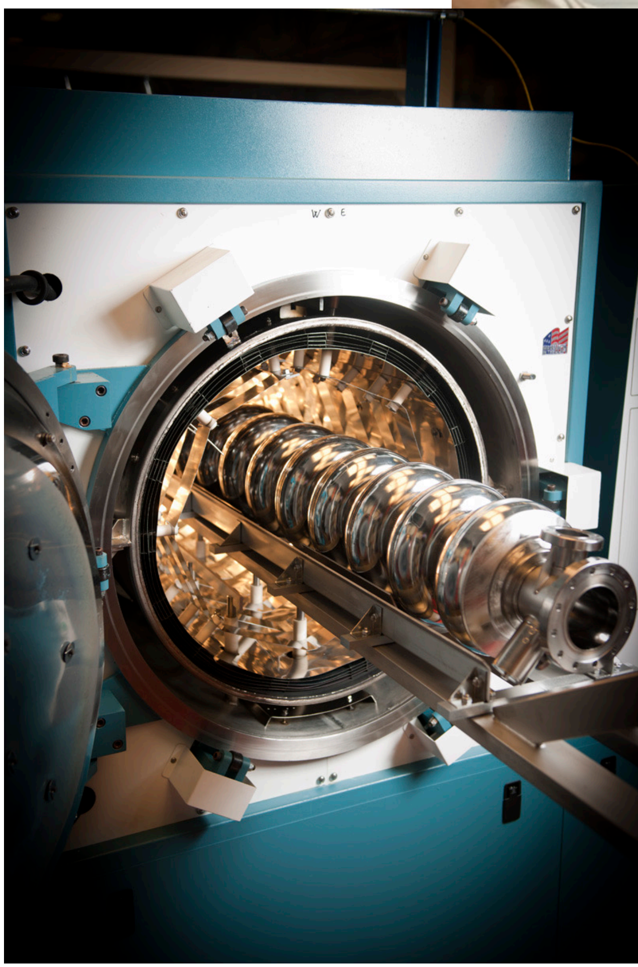
- CERN – particle physics laboratory in Geneva, Switzerland
  - Particle / particle collisions
- Forward Pixel Detector upgrade for Compact Muon Solenoid
  - Silicon detectors located near the collision location
  - Carbon fiber provides mechanical support to minimize particle interaction
- Large Hadron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

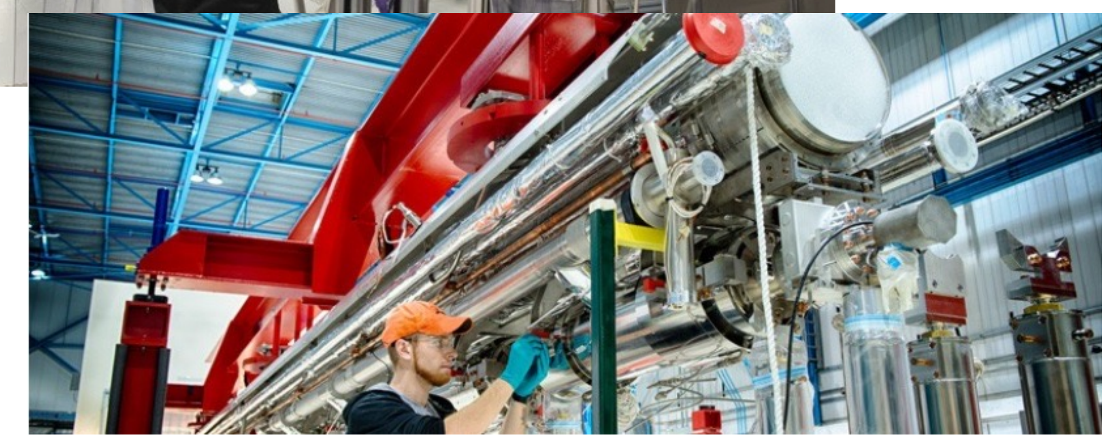
Support for other projects – LCLS-II

- 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) 2.7x10^{10}

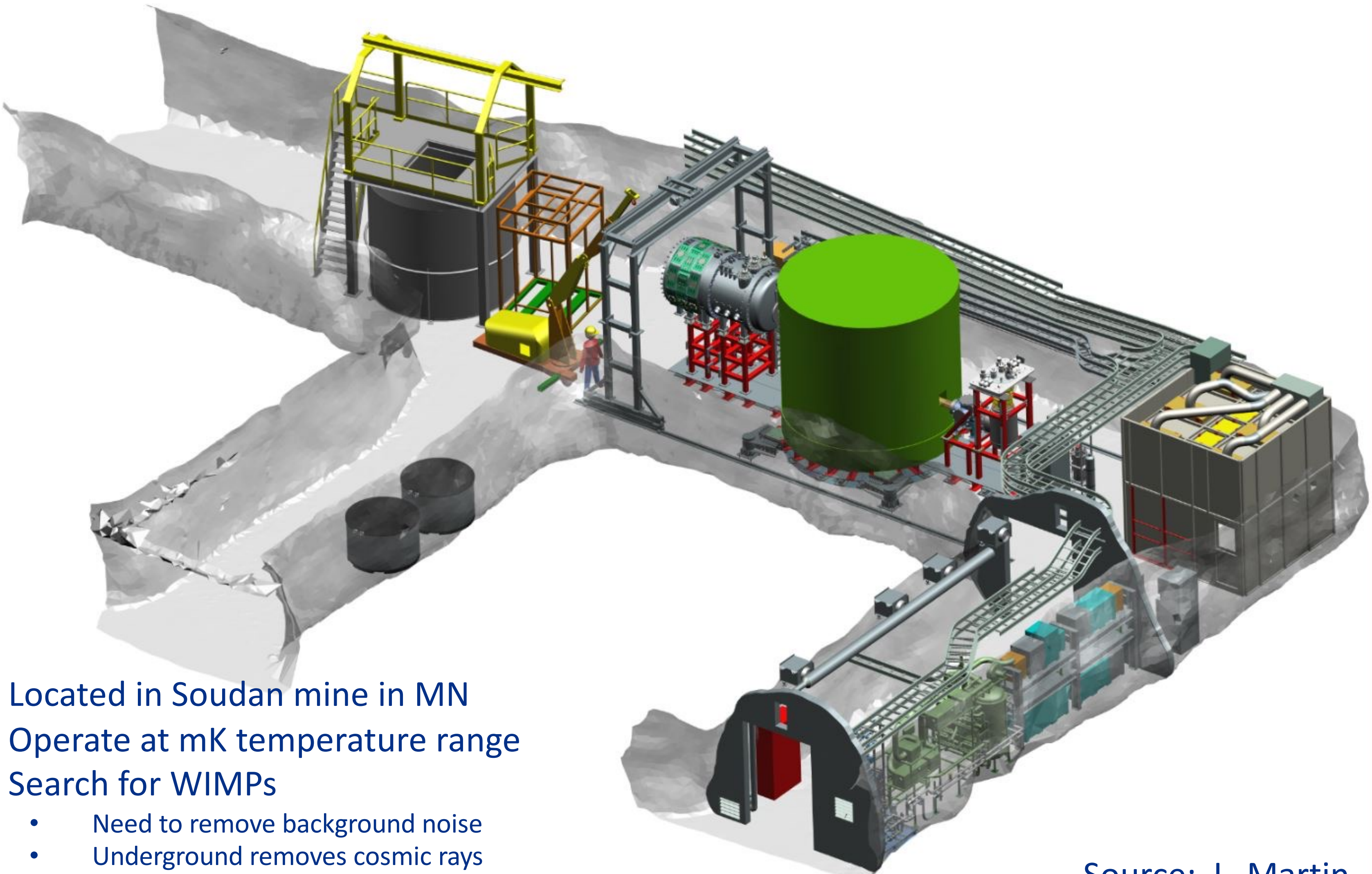


Design, manufacturing, and testing cryomodule and its components





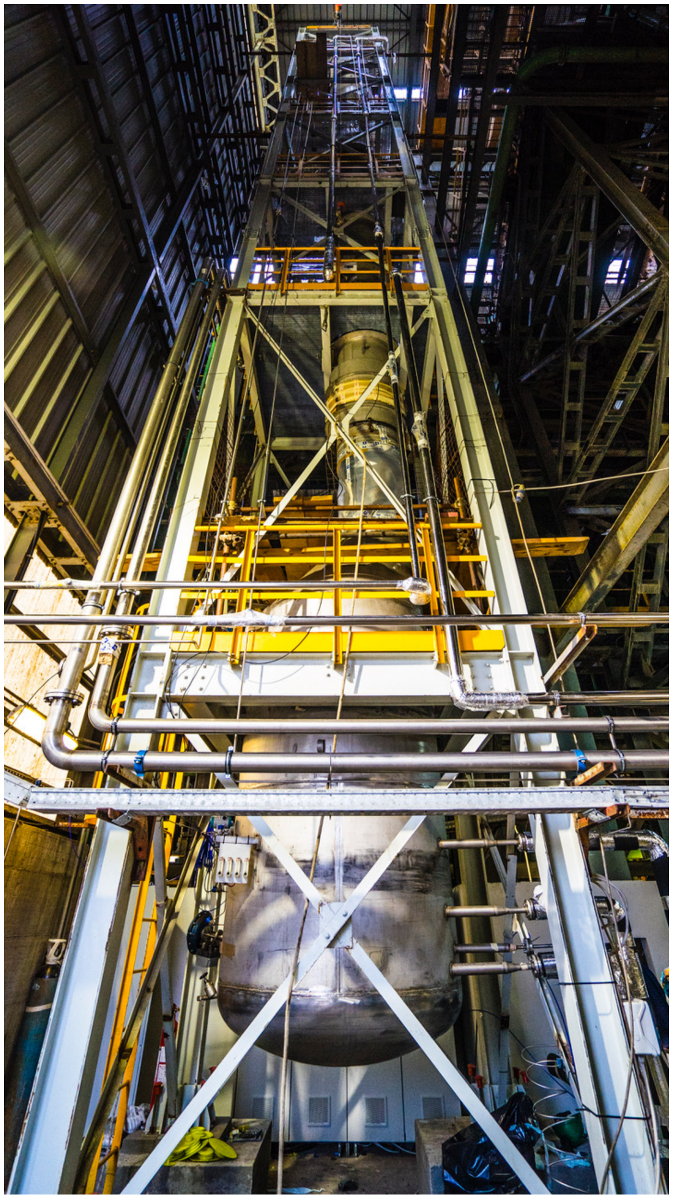
Other projects: Super Cryogenic Dark Matter Search experiment



- 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: L. Martin

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

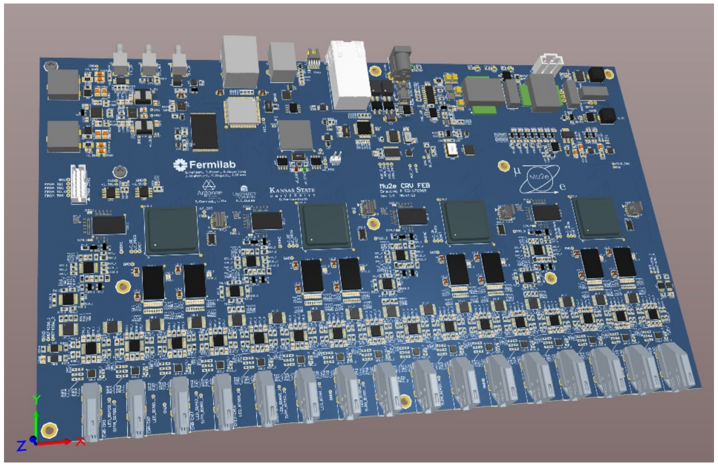


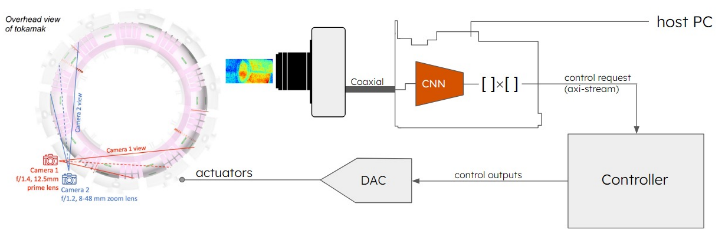
- installation of Seruci 0 (distillation column phase 0)

Source: Cary Kendziora

Fermilab

CSAID - Data-Intensive Systems Department



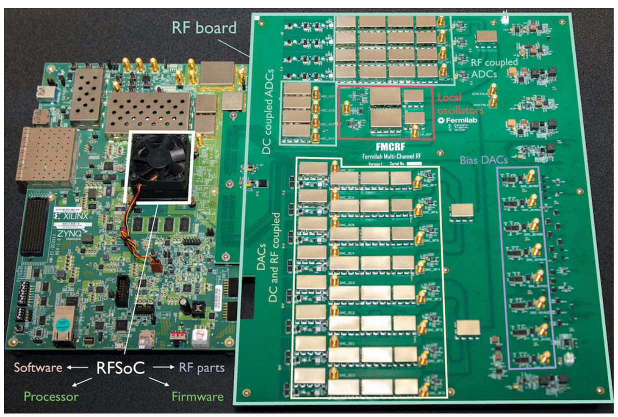


- Accelerator Controls Operations Research Network (ACORN):
  - Leading Accelerator Data Acquisition and Controls hardware modernization effort.
- DUNE:
  - Photon Detection System readout hardware: DAPHNE for FD-1 and Analog and Digital signal over fiber R&D for FD-2.
- PIP-II:
  - High-speed digitization 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

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.



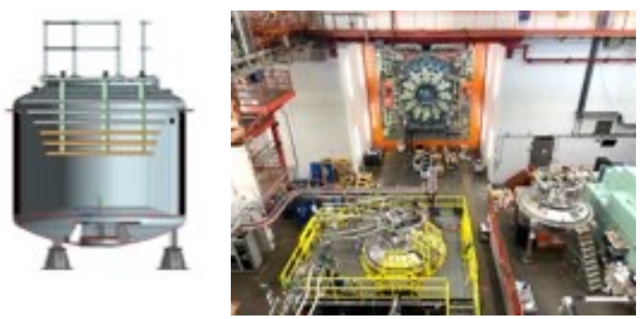
- QICK (Quantum Instrumentation Control Kit.
- A comprehensive, control and readout system for QIS (Quantum Information Science), including quantum computing (QC), quantum networks (QN) and quantum sensors (QS).
- Adopted by and supporting a growing community of over 200 institutions (Labs, academia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

SQMS Research Center

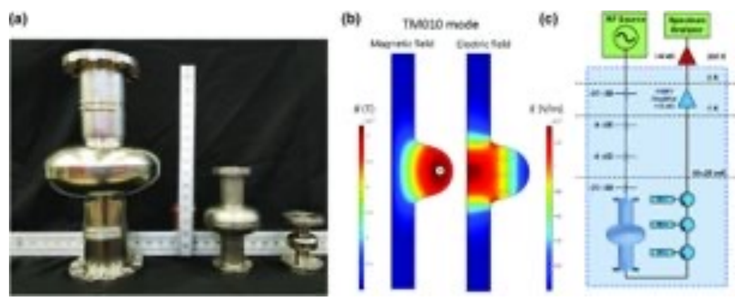
The Superconducting Quantum Materials and Systems Center, led by Fermi National Accelerator Laboratory, is one of five research centers funded by the U.S. Department of Energy as part of a national initiative to develop and deploy the world's most powerful quantum computers and sensors.

The SQMS Center capitalizes on Capitalize on DOE investments and leverages state-of-the-art facilities and expertise for quantum computing and sensing

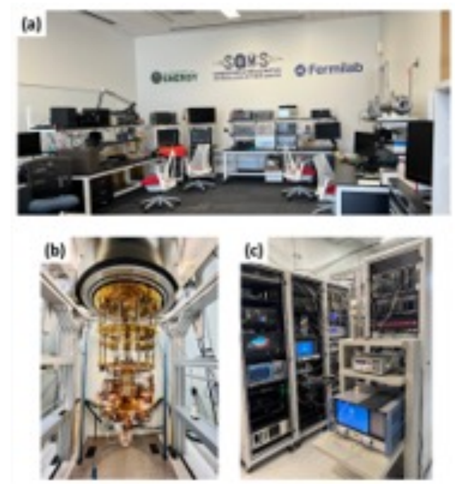
- SQMS engineers are designing novel superconducting cavities and equipment for dark matter searches and quantum computing
- The Ultralow Temperature Cryogenics team supports the SQMS dilution refrigerator systems and several other millikelvin platforms throughout the lab.
- SQMS is designing innovative 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

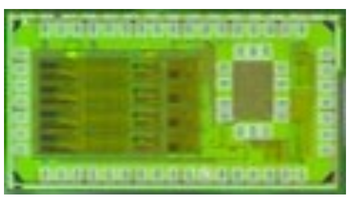


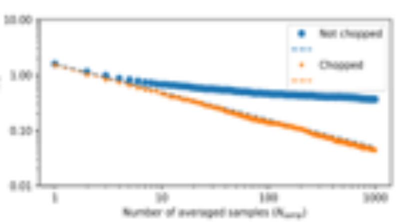
Equipment and control instrumentation

ETD - Microelectronics Department

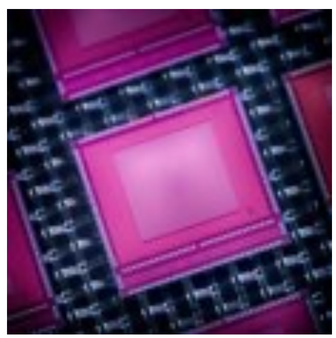
Next generation, custom microelectronics with complex in-pixel process and reconfigurable data-driven architectures, enabling edge computing and the ability to dramatically winnow particle events to the most important data.

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



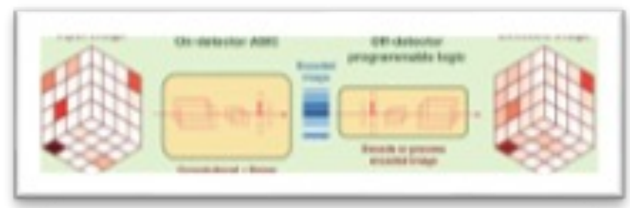


Ultra-Low Noise Sensing (Dark matter detectors)

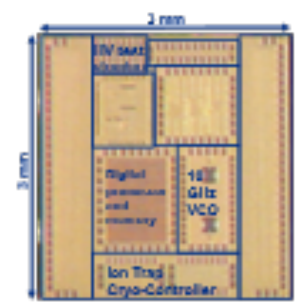


Ultra-High Frame Rates (X-ray detectors)

High speed cryogenic data converters (with Microsoft)



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



Quantum support chips

Engineers for the Facility

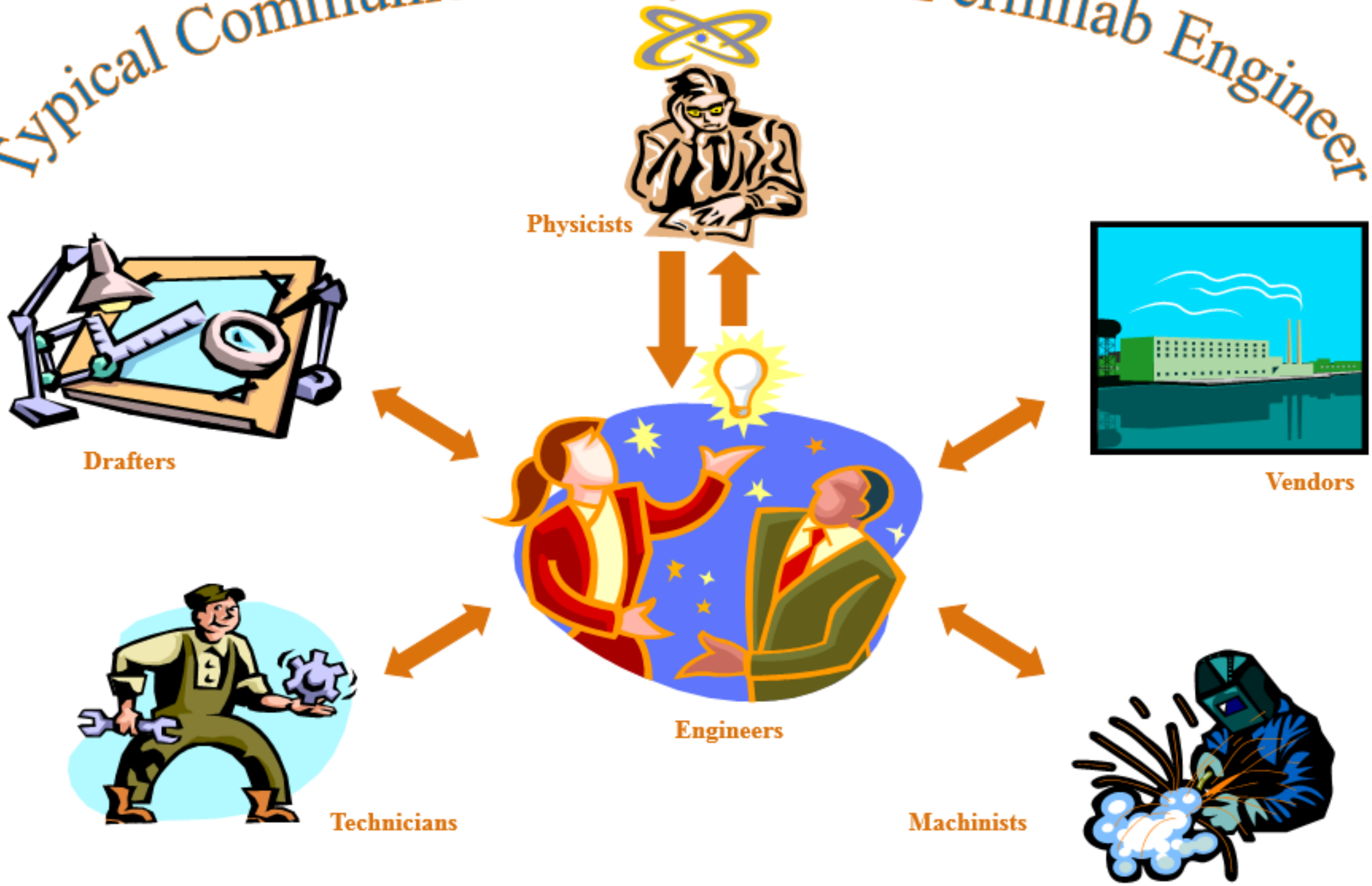
Civil, mechanical and electrical engineers for maintenance, upgrades, and new projects

- 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

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

Typical Communication Cycle of a Fermilab Engineer



Thank you to the contributors

- Martin Bentivengo – ISD
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