Brookhaven National Laboratory

U.S. DEPARTMENT OF ENERGY

Research and Developments in the US towards the FCC IR magnets and MDI systems

Maria Chamizo Llatas (BNL), Kathleen Amm (BNL), Brett Parker (BNL), Mark Palmer (BNL), Lance Cooley (FSU), Giorgio Apollinari (FNAL), Steve Gourlay, Soren Prestemon (LBNL)

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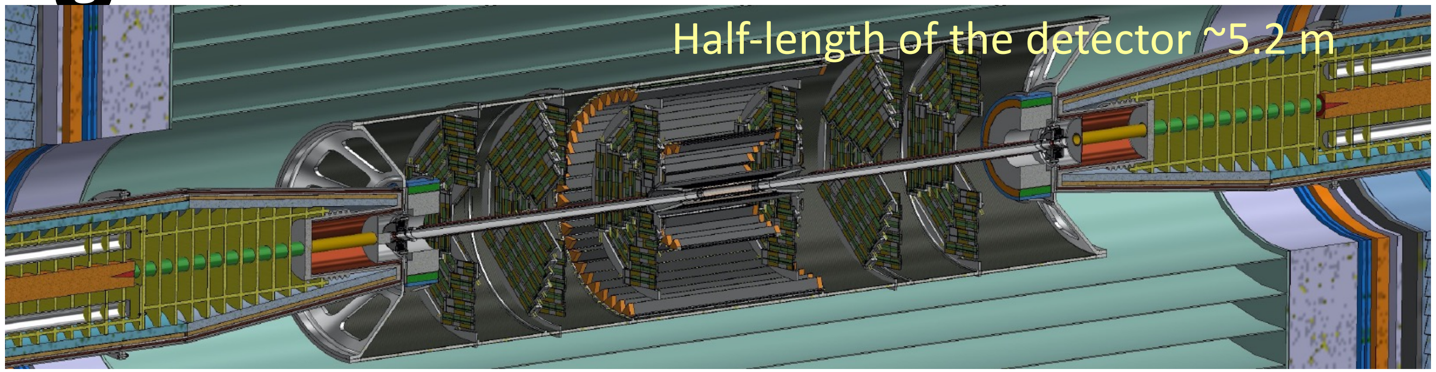
Outline

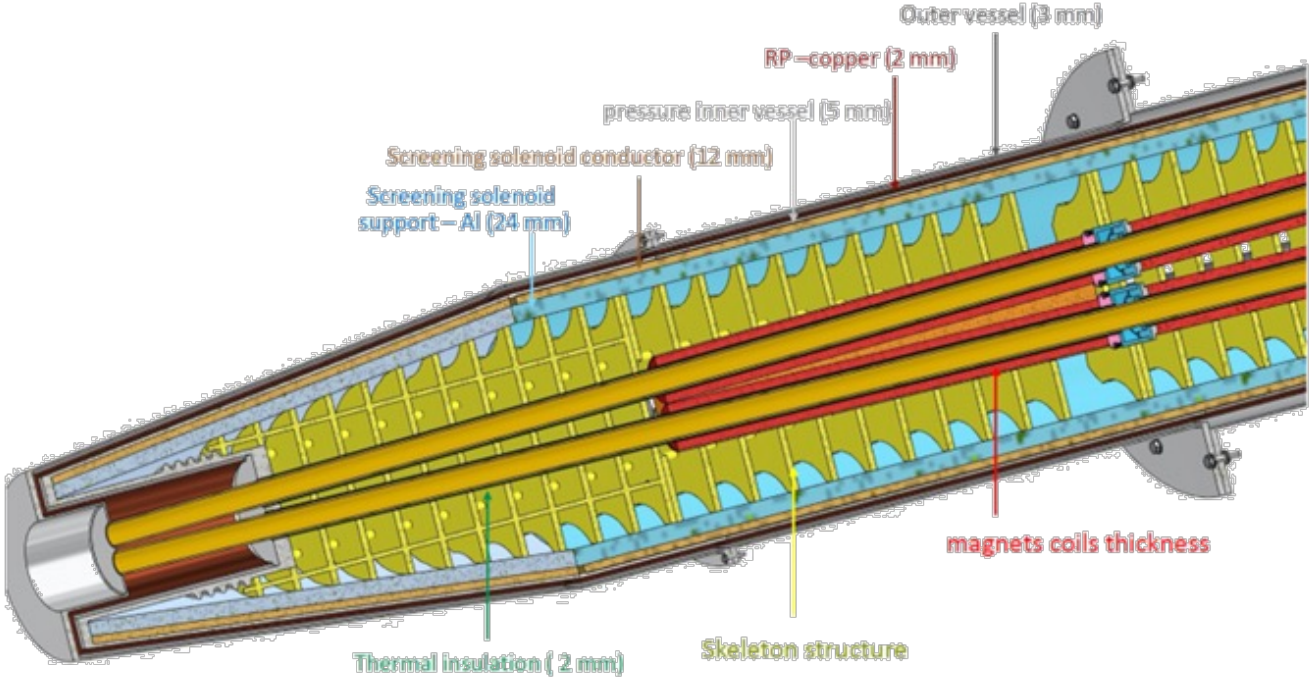
FCC IR key challenges
US capabilities
  IR design – EIC example
  Direct wind
  Magnet alignment
  Magnet testing
  Magnetic measurement
Potential US contributions

FCC IR Key Challenges

FCC-ee IR challenges



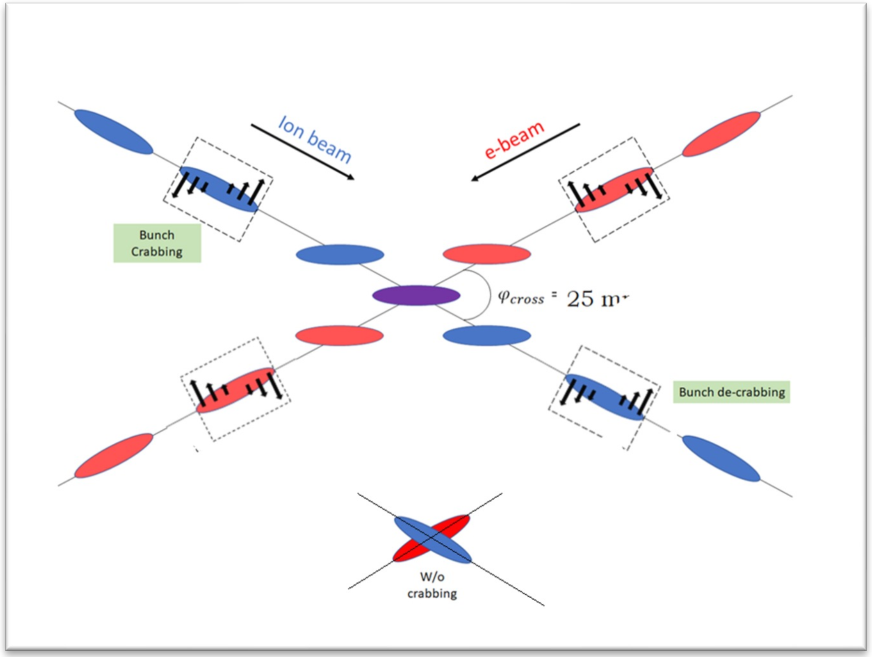
- Very tight MDI requirements
- Strong anti-solenoid field 300kN (30Ton) → large forces, no space for support
- Warm beam pipe inside cold magnet (1.9K)
- Cross-talk field compensation between beam lines
- Warm BPMs embedded in LHe
- Cryostat support (from detector or external)
- Utility interface (cryogenics, leads etc.),
- Detector installation
- Stray field, radiation shielding requirements.



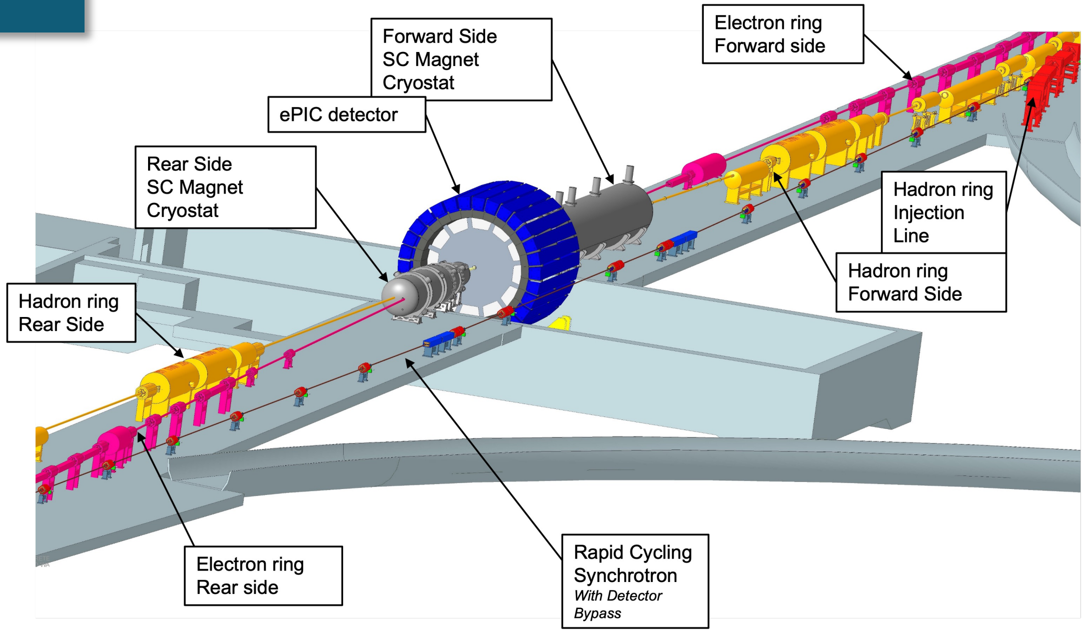
US capabilities

EIC Interaction Region

- 25 mrad crossing angle,
- 10 ns bunch spacing
- Variable CM energy 20-140 √(Z/A) GeV
- Hadron beam species from protons up to Uranium
- Small β* to reach luminosity $10^{34} cm^{-2} s^{-1}$ requires crab cavities and large final focus quadrupole aperture



Machine Detector Interface
- Large detector acceptance
- Forward spectrometer
- No magnets within - 4.5 / +5 m from IP
- Space for luminosity detector, neutron detector, "Roman Pots"

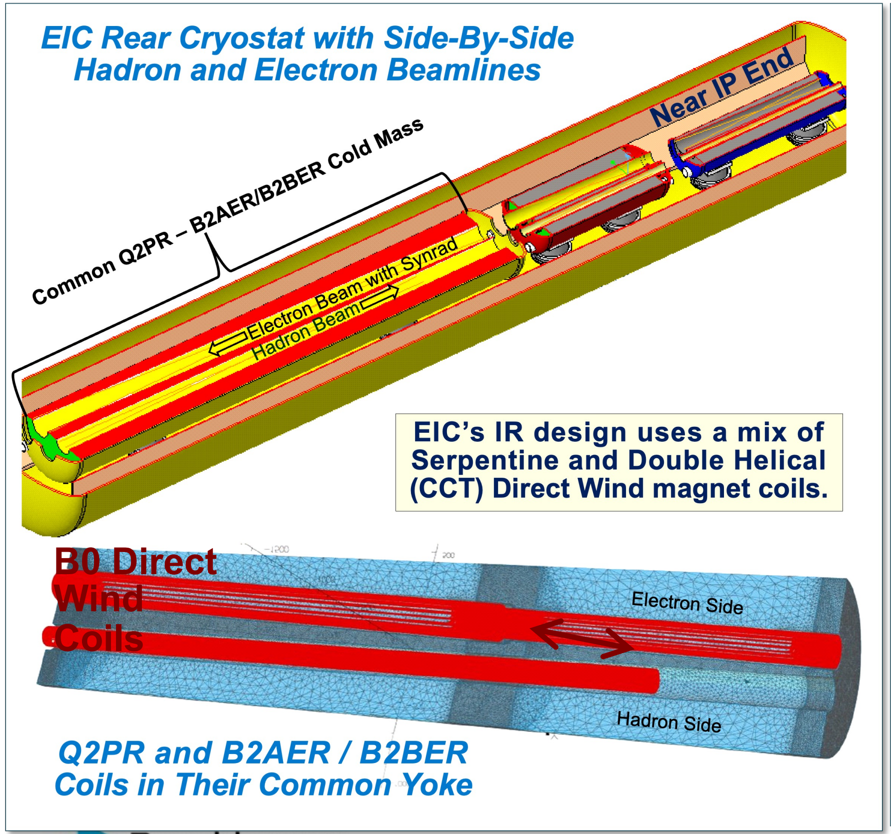


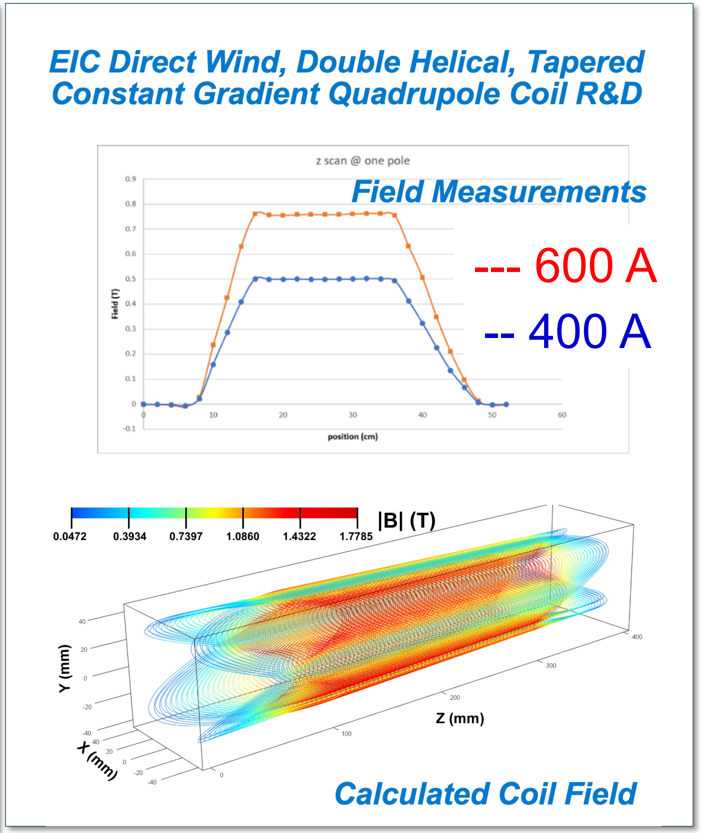
EIC IR Superconducting magnets

EIC IR Magnet Challenges:
Highly integrated superconducting electron and hadron magnets (NbTi).
Need to prototype, manufacture and test multiple one of a kind magnets.

The customized tooling for collared coils is expensive

Most magnets done using Direct Wind technique (use collared coil technology only for highest fields / gradients).



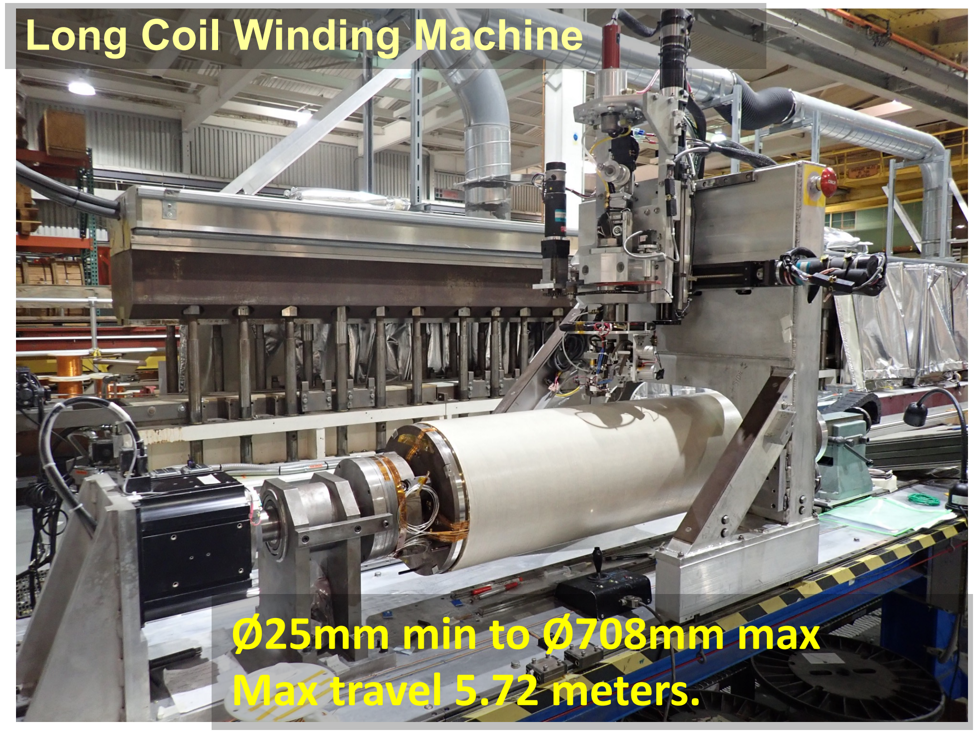


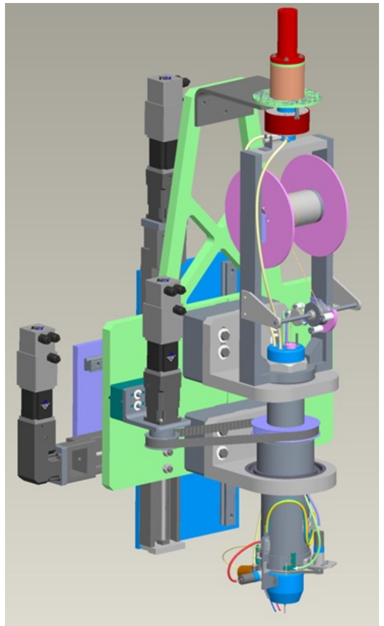
The FCC-ee IR magnets intrinsically require very carefully tailored field profiles to enable variable CM energy strong focusing while handling magnetic crosstalk and local optics correction (dipole, skew-dipole and skew-quadrupole coils).

Direct Wind coil fabrication enables flexible implementation of radially thin, compact correctors to adapt to demanding IR space and magnetic field configuration requirements.

Direct Wind Coil Fabrication (NbTi)

- Unique BNL Direct Wind capability for high precision, specialty and IR magnets
- FCC-ee can benefit from EIC upgrades to two existing capabilities:
  - Modernized computer control hardware / software for increased precision
  - Enhanced reliability capable of winding longer / larger-diameter coils.
- **This is the only practical technology foreseen for making the FCC-ee IR magnet correction coils on very tight spaces.**





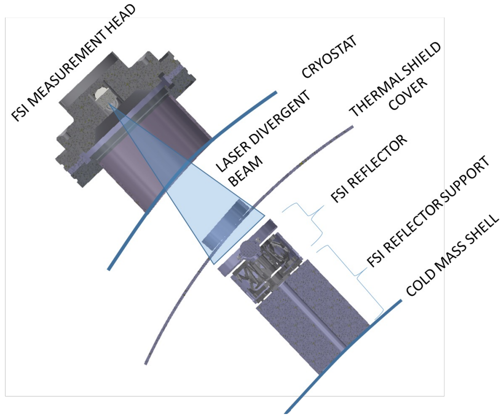
New winding heads providing greater speed, extended wire lengths for longer / larger diameter patterns.

Magnet alignment

- The AUP/Hi Lumi projects are using a Frequency Scanning Interferometry (FSI) monitoring system and surveying to achieve high accuracy magnet alignment
- There are 2 key aspect of magnet alignment

1. Survey effort to understand where the magnetic axis is relative to outside fiducials (single strand wire) – 100 µm accuracy
2. Actual effort to align the magnet to be in the desired location. This usually happens in the accelerator tunnel – 10-20 µm accuracy

- These very precise alignment technologies developed for Hi Lumi can also be utilized in FCCee



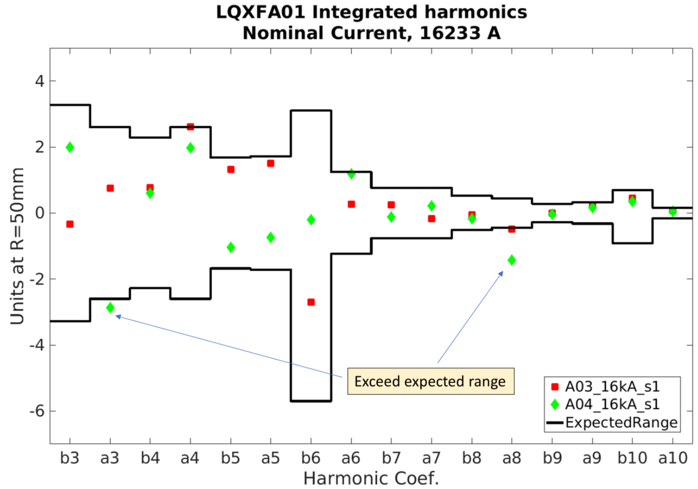
SSW system used for alignment/strength measurements (shown here during fabrication)

Magnetic measurements

FNAL has successfully utilized both a single stretched wire system and a PCB based rotating coil probe for AUP magnet measurements

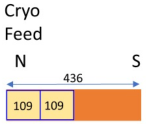
These capabilities are critical for magnetic alignment and verification during the installation of the magnets at CERN

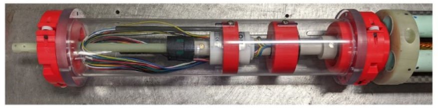
The measurements also verified the integrated harmonics for the magnets



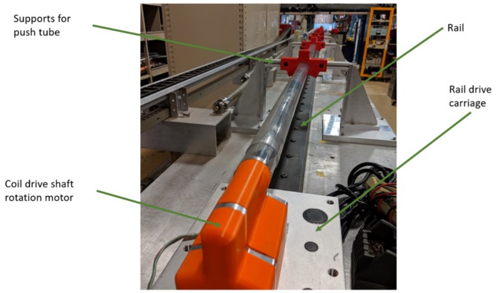
Rotating coil 'FERRET' probe

Probe has 436mm-long winding and two 'back-to-back' 109mm-long windings.





Local encoder and slipring

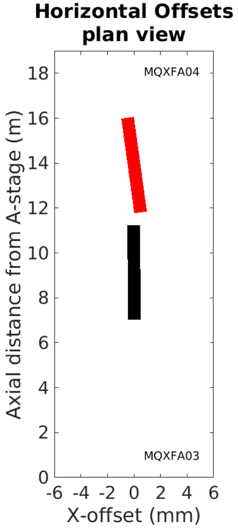


22m-long, 6mm diameter carbon fiber rotating drive shaft and polycarbonate push-tube

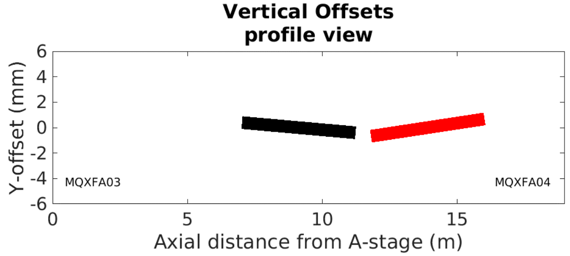
PCB probes stiffened with carbon fiber or G10

Laser tracker targets visible from non-drive end

MQXFA03/MQXFA04 Alignment
After move to average axis
23Aug2023 - cold TC2, 2K



MQXFA03 Lead End: X= 0.042, Y= 0.394 mm
MQXFA03 Interface End: X= -0.030, Y= -0.402 mm
MQXFA04 Interface End: X= 0.498, Y= -0.676 mm
MQXFA04 Lead End: X= -0.482, Y= 0.681 mm



SSW_R_20230823_181305_AC_PitchYaw, SSW_R_20230823_180625_AC_PitchYaw

BNL Magnet Division – Capabilities and Priorities

Vision: To be a world class superconducting and electromagnetics team creating the future of superconducting magnet technology.

Magnet Division staff deliver leadership in:

- Superconducting magnet technology
- Magnet development, manufacturing and testing with application to accelerator, science, fusion and industry

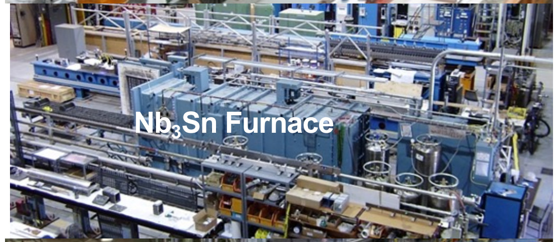
Capabilities:

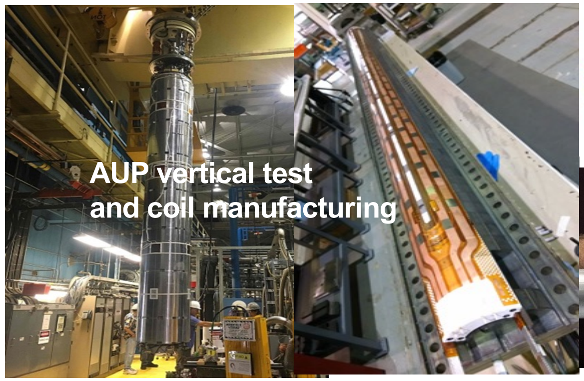
- LTS and HTS superconducting magnets - 10m Coil Winding Capability, Nb_3Sn furnace 4.2 m
- Direct wind magnets and facility -IR and Specialty Magnets, Precision Field Quality, 2.5m Coil Winding Capability
- Magnet Test facility - 1.9K, 22KA, 6.1m deep, 71cm dia.

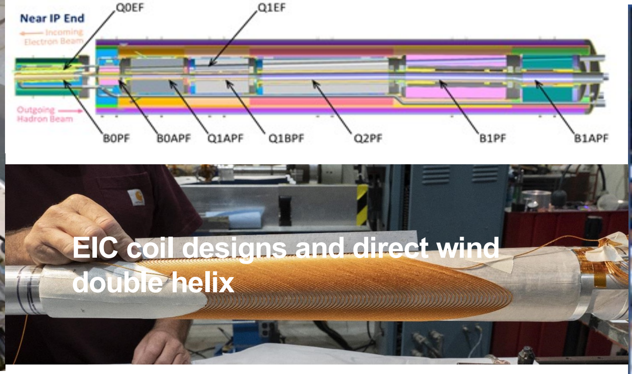
Current priorities:

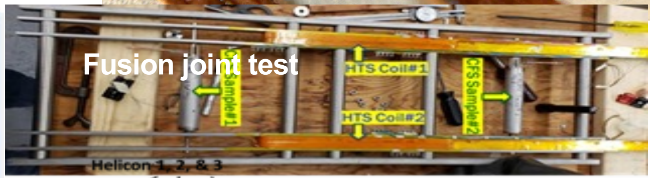
- Accelerator Upgrade project – coil construction, vertical magnet test
- EIC magnets – IR, magnet measurement, RHIC magnet re-use
- Magnet Development Project – HTS/LTS hybrid, Diagnostics
- Fusion – INFUSE, ARPA-E (CFS), MPEX

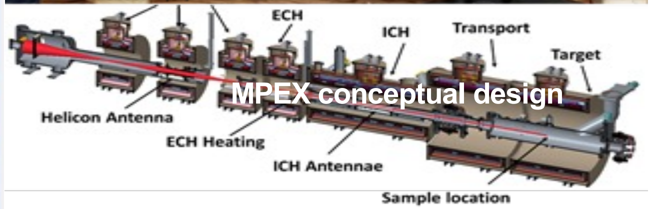
Deliver superconducting applications for DOE (SC, ARPA-E, ...) and SPP (Power, Fusion,...)







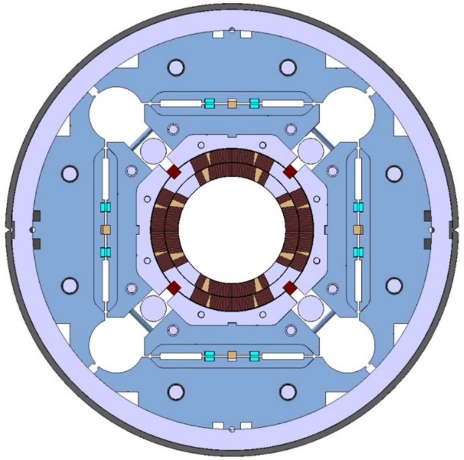


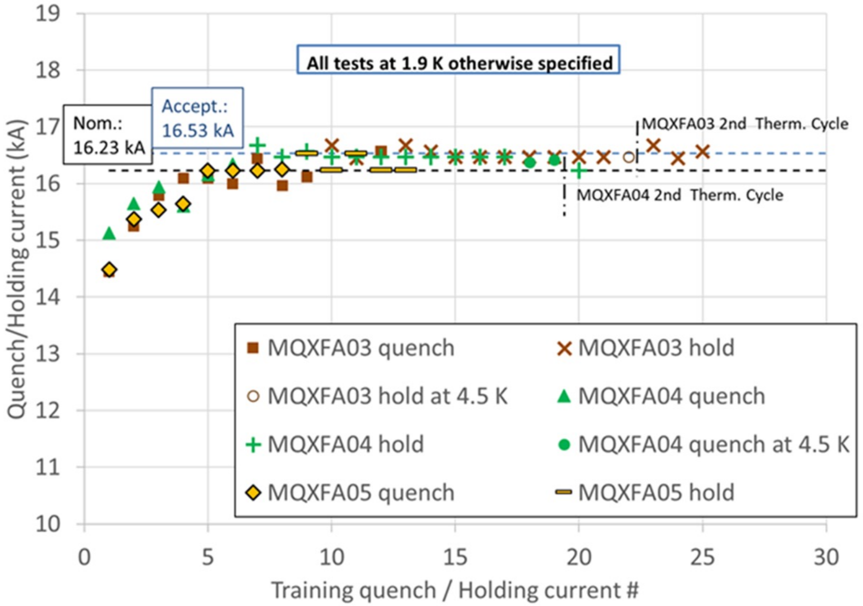


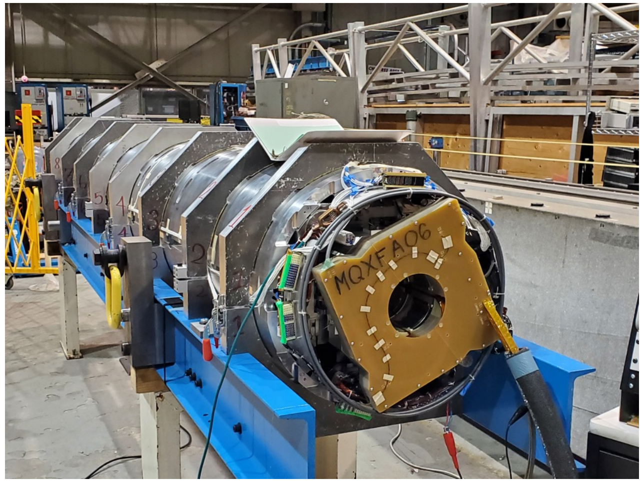
Accelerator Upgrade Project

BNL Scope

- Manufacture 47 4.2m quad coils
- Test 27 4.2 magnet cold masses





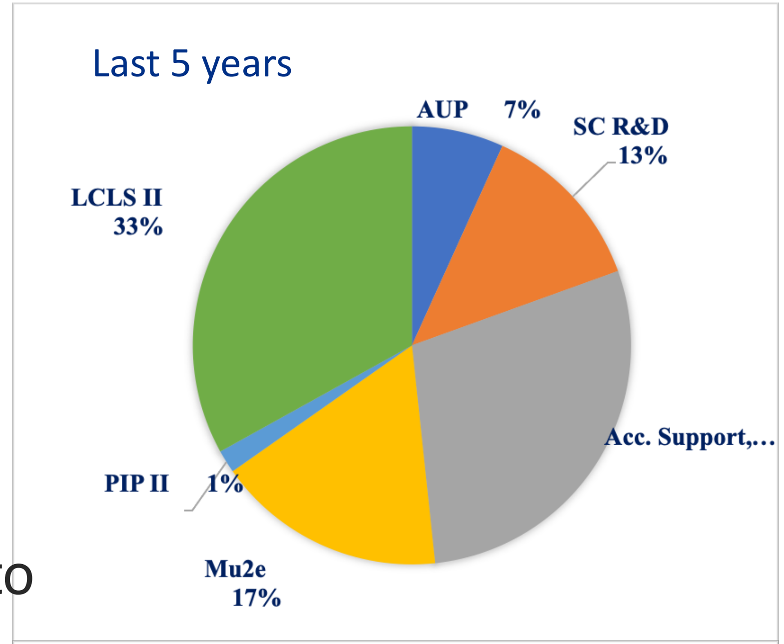


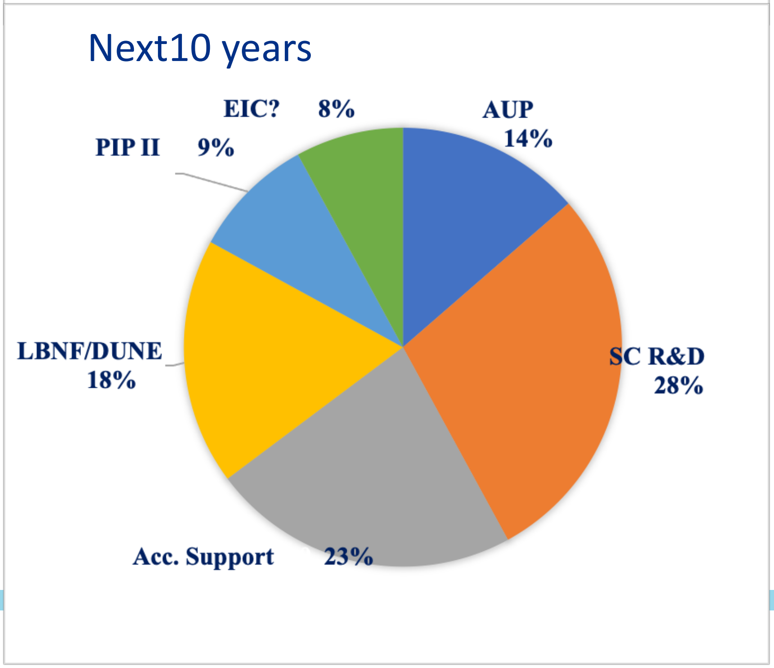
Magnet fabrication and test facilities at Fermilab

- Mission: to support developing and maintaining magnet fabrication and test facilities for GARD, other R&D programs (MDP, LDRD, ECA, …), and projects (PIP-II, LBNF/Dune, HL-LHC, Mu2e, High Field Vertical Magnet Test Facility (HFVMTF))
- To support this mission, our state-of-the-art facilities must be maintained and updated to fulfill demands of current and future research programs and projects
- World-class capabilities include
    - ❑ SC Strand and Cable Testing Lab - projects and R&D
    - ❑ Superconducting Magnet Fabrication Facility – AUP coil production, MDP
    - ❑ Magnet Testing Facilities
        - Room Temperature Magnet Measurements – Accelerator Complex (MI, spares), WFO (ORNL PPU)
        - Superconducting Magnet Testing
            - Vertical Magnet Test Facility (cold masses, AUP, and R&D)
            - Stand 4 Horizontal Test Stand (AUP)
            - Stand 3 (Mu2e HTS leads, small R&D magnets)
            - Stand 7 cryostat for small cryo-cooled magnets - PIPII, undulators

SC Magnet Test Facility

- MTF is an ensemble of comprehensive capabilities and facilities that enable Magnet Science and Technology R&D and support projects at Fermilab
- For the last 5 years MTF performed 79 tests for different projects and R&D
- For the next 10 years we expect throughput to increase serving:
  - HEP projects for next decade (LBNL, PIPII)
  - Support complex R&D for the future lepton and hadron colliders
  - Support testing of LTS and HTS conductor for fusion and HEP
  - Develop cutting-edge test systems and stands





Fermilab

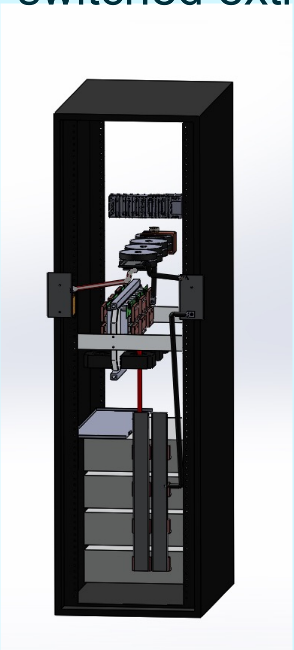
The Magnet Test Facility (MTF) at LBNL

- **Mission**: testing and characterizing prototype high field superconducting magnets at 77K and 4.2K;
- Several magnet parameters, such as current, training behavior, and field quality are tested and characterized at MTF;
- The facility can adapt to a wide variety of magnets and provide unique instrumentation capabilities;
- Several upgrades are current ongoing at LBNL to further improve the Magnet Test Facility capabilities.

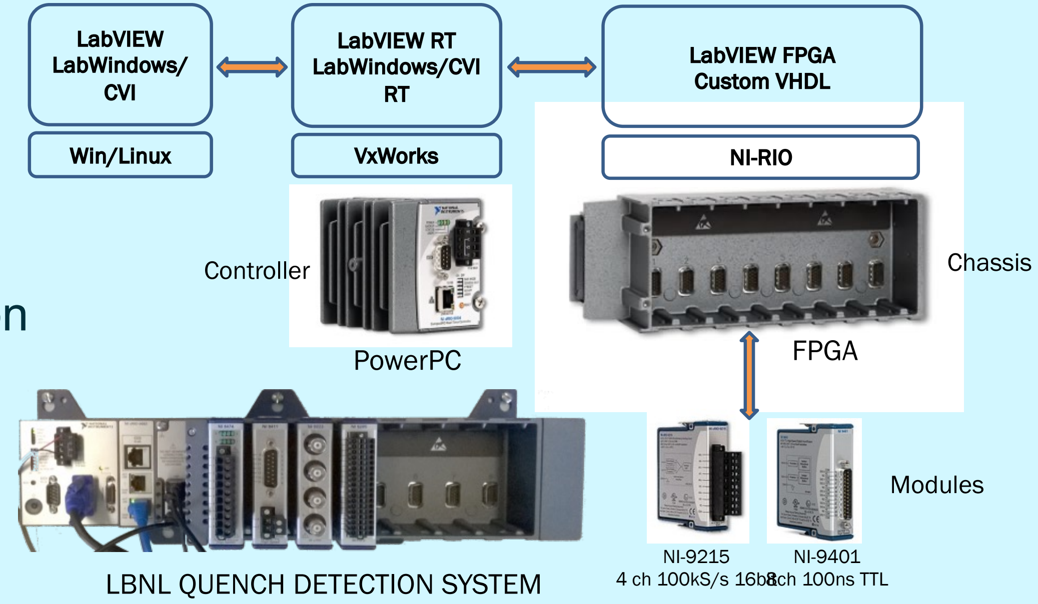
- Two power supplies (25 kA, 4.8kA) and protection circuits with fast IGBT switches; *upgrade to 7.2 kA coming soon*
- Dual FPGA quench detection systems and FPGA IGBT Timing controller
- Hybrid header for dual powering (13 kA, 10 kA)
  - *Will be upgraded to 20 kA*

25kA Power Supply

IGBT-switched extraction

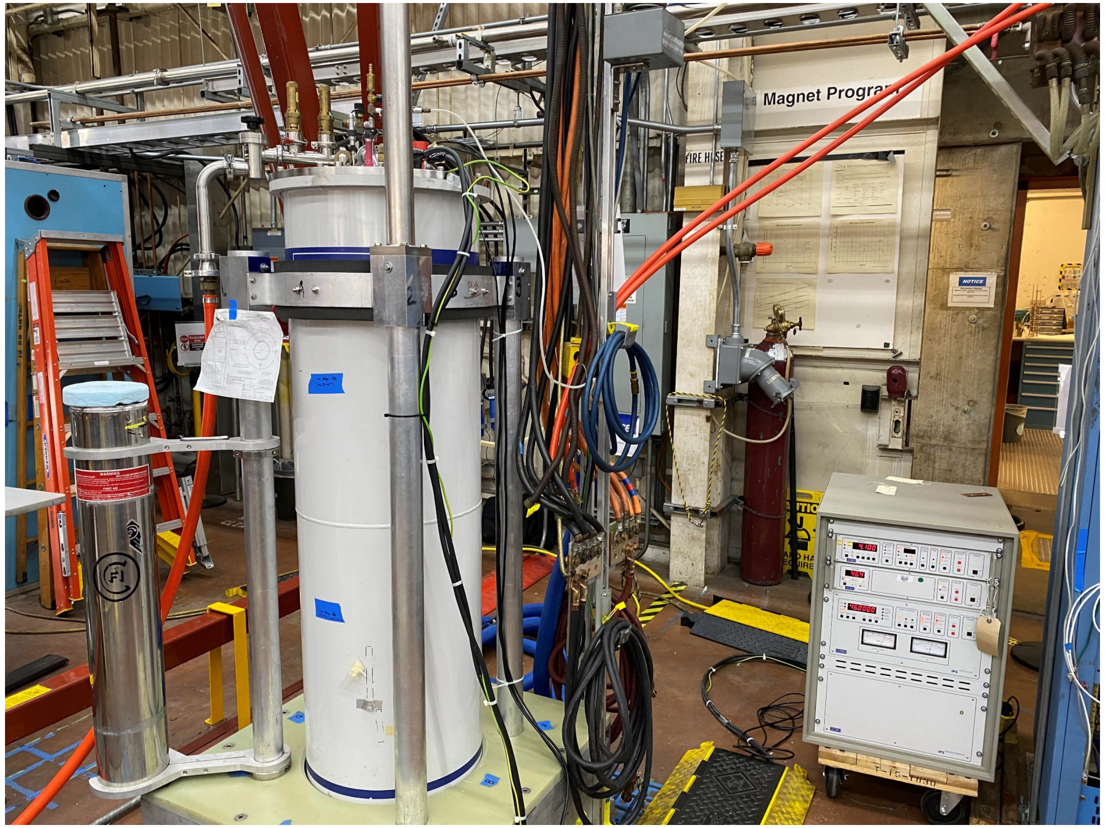


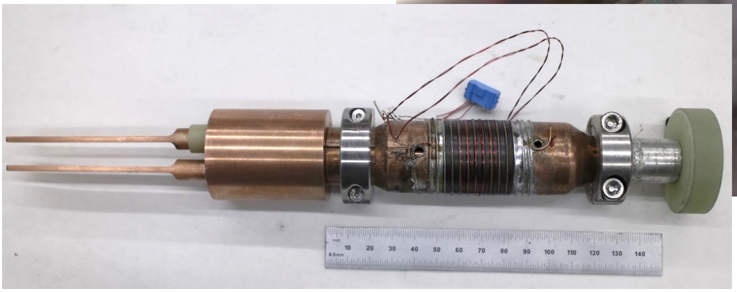
FPGA-based quench detection system



Short Sample Test Facility

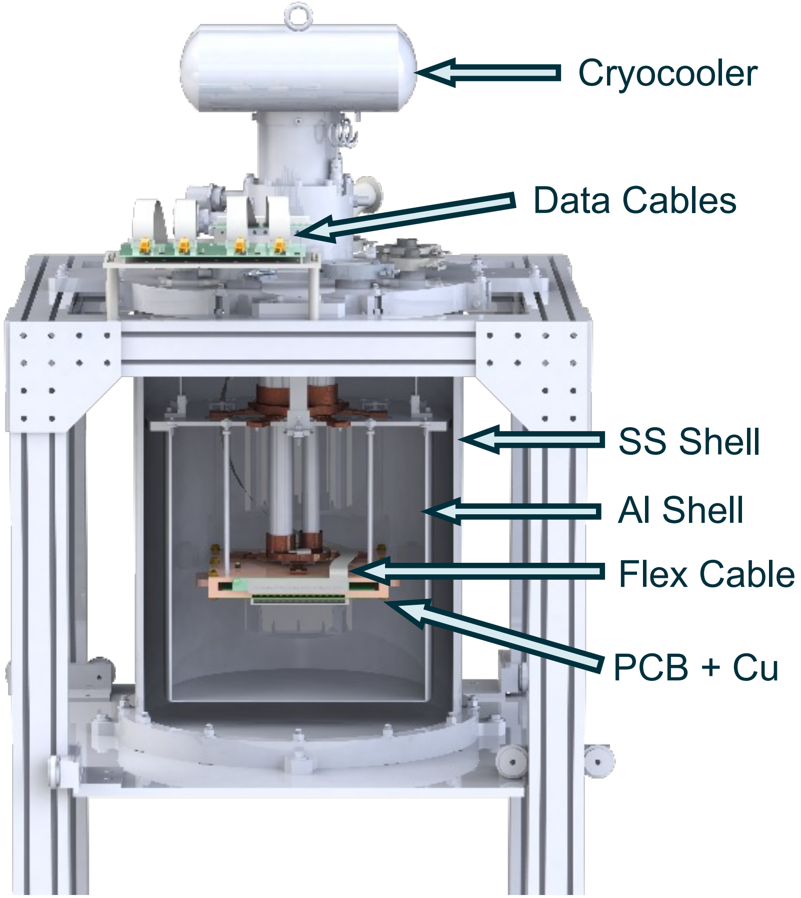
- 16 T solenoid magnet for short sample measurements
- Current up to 2 kA for the samples

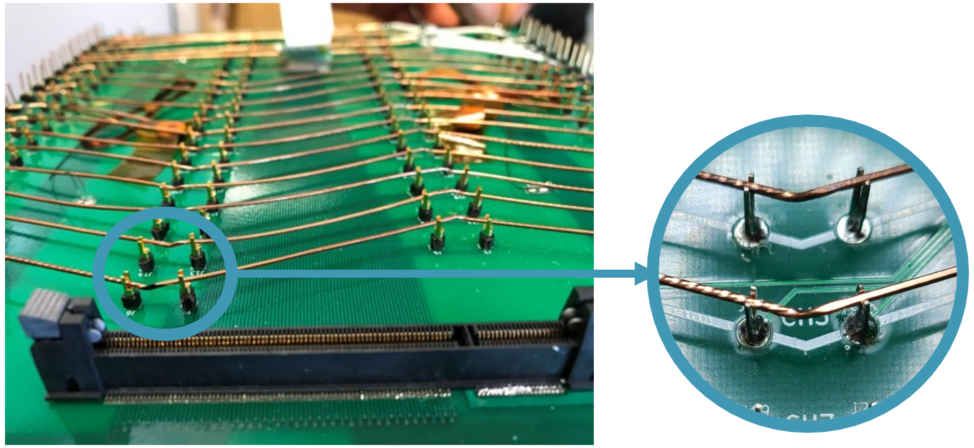


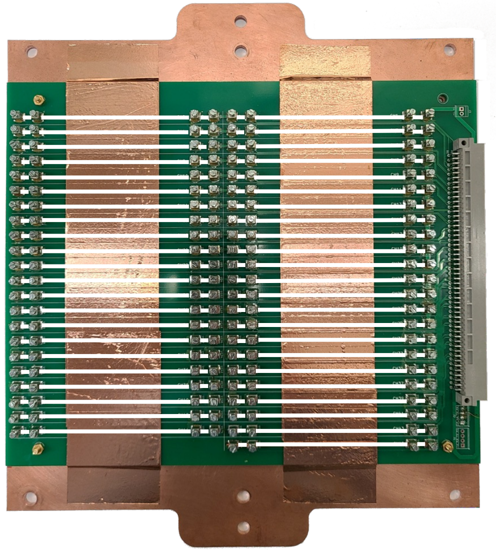


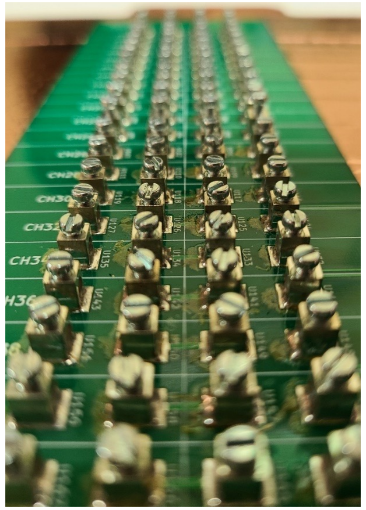
Cryogen-Free RRR Measurements

Cryogen-free measurements of RRR with a high reproducibility and a low cost.





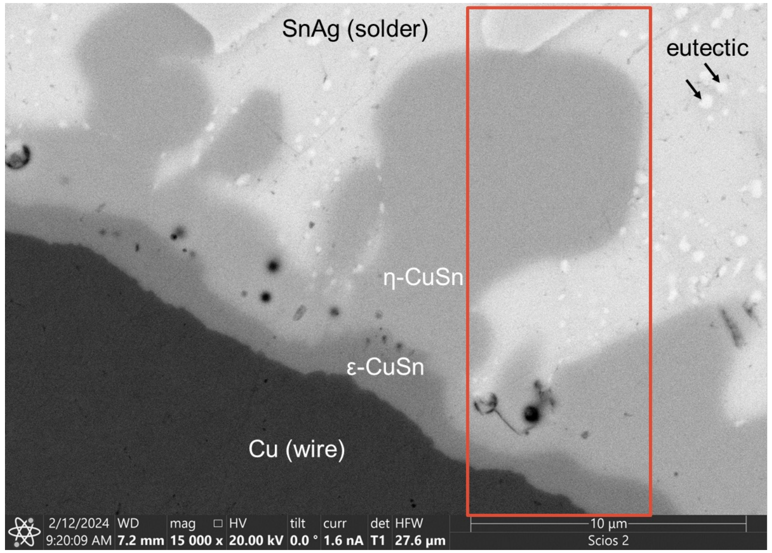


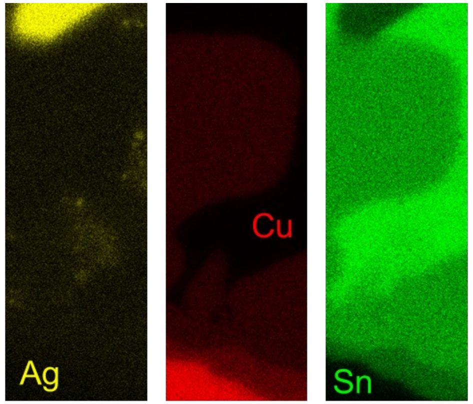


Custom designed PCBs to measure RRR of strands extracted after cabling (top) and straight wires (bottom).

Material Characterization

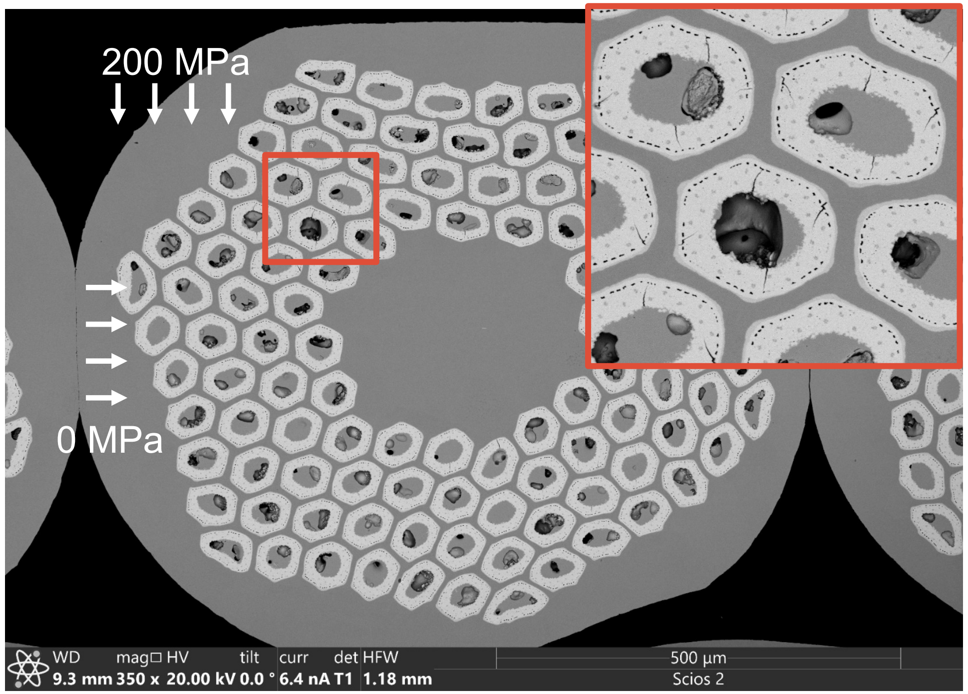
- Extensive SEM capabilities for phase and crack analysis, coupled with advanced image analysis
- Experience characterizing Nb_3Sn, REBCO, NbTi, Bi2212, Bi2223





Elemental composition maps

Phase analysis for Nb_3Sn



Crack analysis in reacted Nb_3Sn

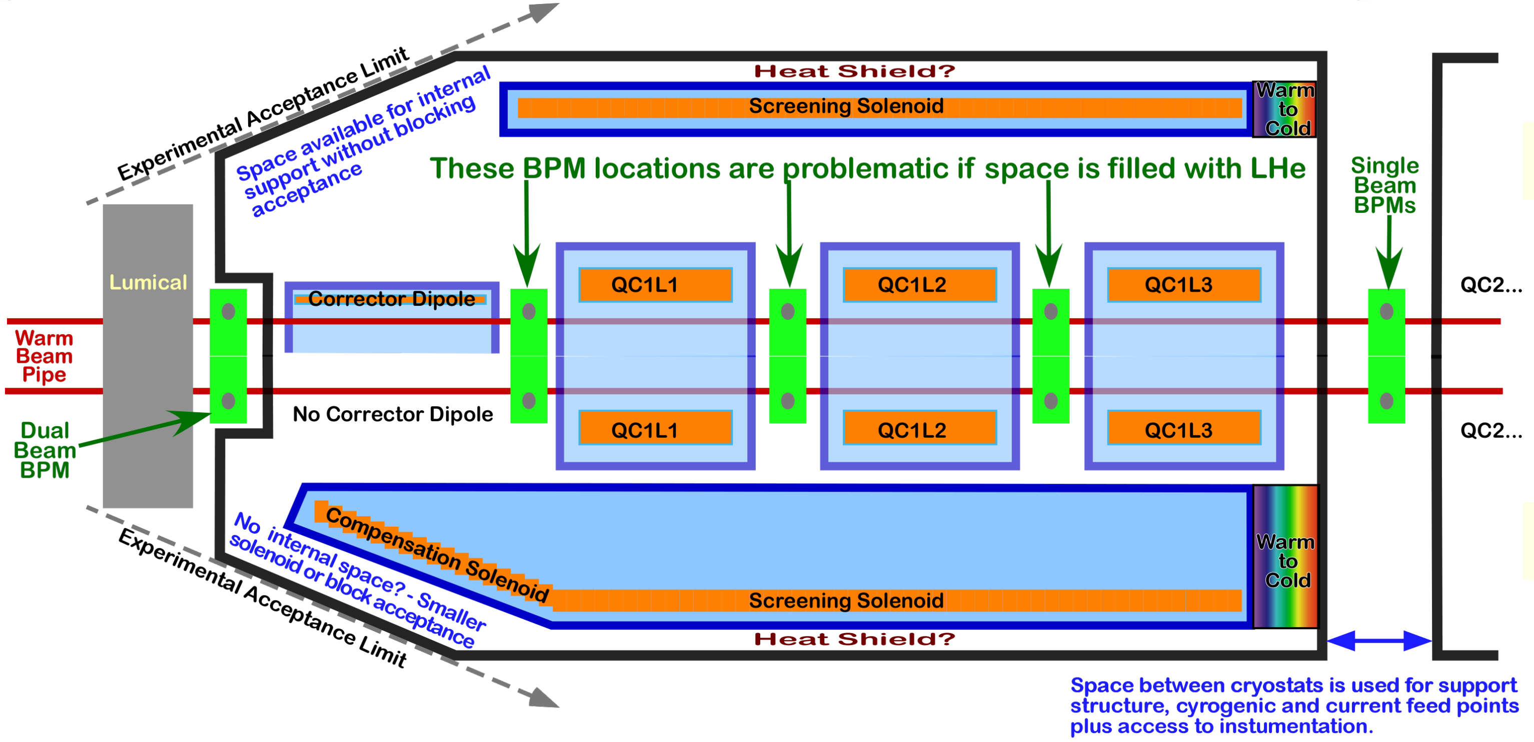
Potential US contributions

Magnet Systems

IR Magnet Design
- Anti-solenoid optimization
- IR quadrupole design
- IR corrector design
- Prototype and testing

IR Magnet Design
- Quadrupole strengths for different CM energies
- Detector solenoid compensation implementation
- Optics tunning and necessary correctors
- Dealing with energy deposition in cold mass

Experiment



Accelerator

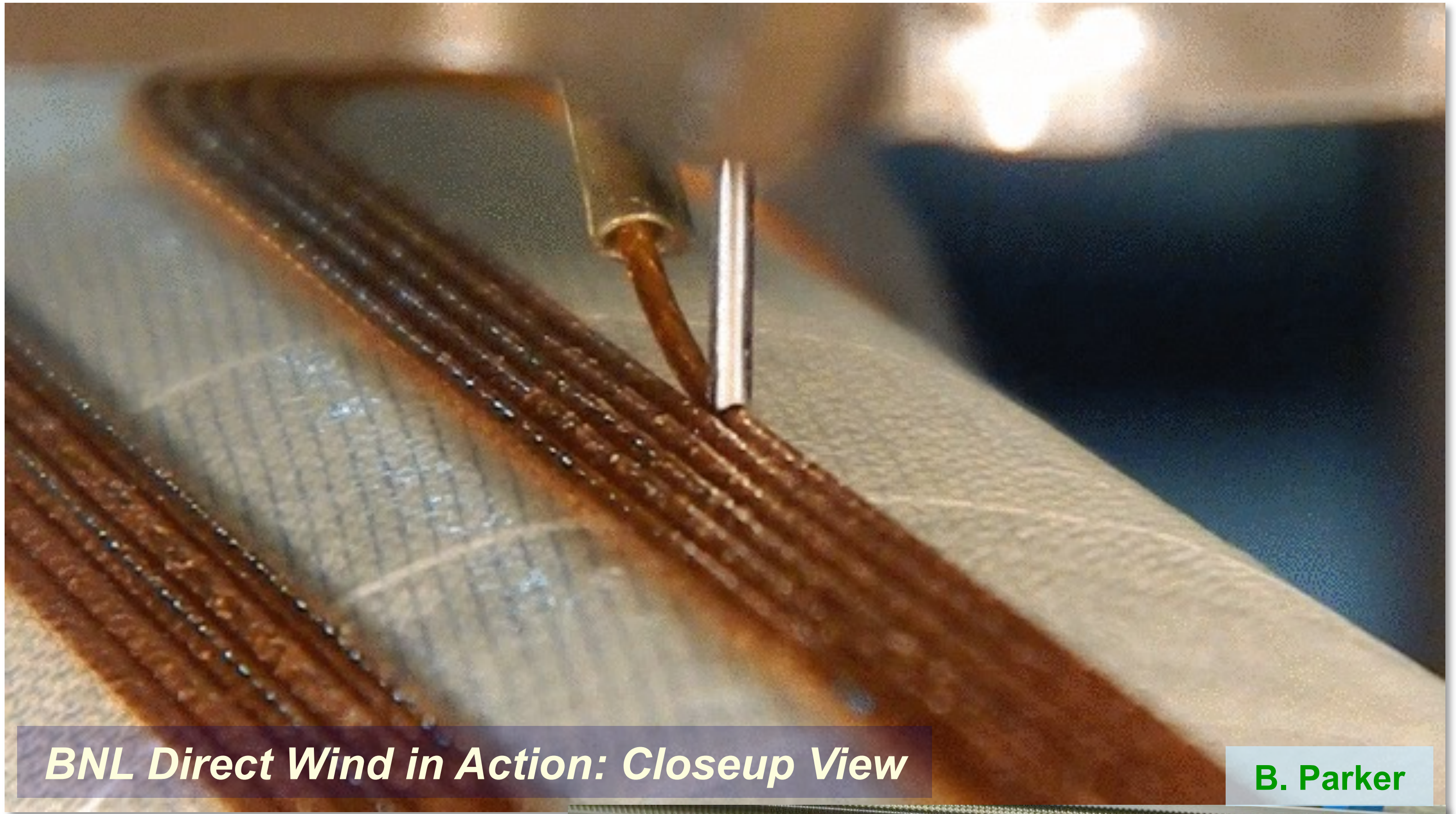
PR Optics Scheme

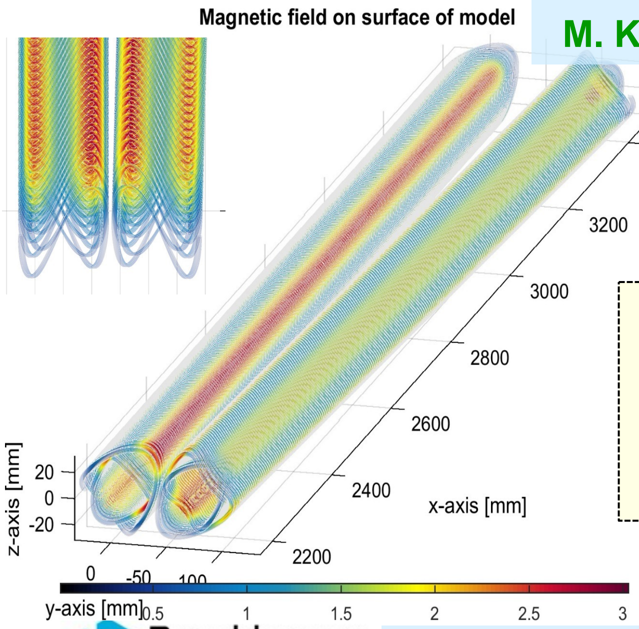
KO Optics Scheme

IR Cryostat Design
- Cold mass optimization
- Internal support structure
- Thermal management
- Internal BPM interface

IR Cryostat Design
- Installation, support and alignment
- Vibration stability studies (for nanobeams!)
- Utility access requirements (cryogenics, current leads, instrumentation etc.)
- Experimental detector interface (with experimental access)

Topics for Possible Contributions for FCC-ee IR Magnets with MDI

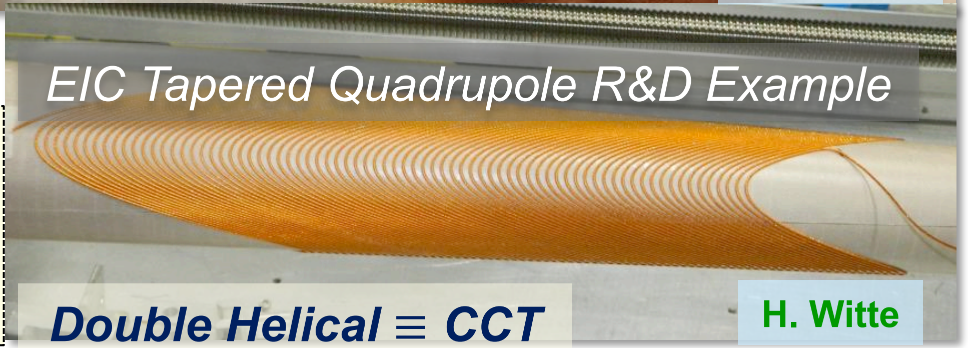




M. Koratzinos

In addition to main quad coils, FCC-ee needs a slew of correctors (b_1, a_1, a_2...).

BNL Direct Wind process is natural for making the necessary correctors.



Direct Wind Tapered Double Helical Coil

Some FCC-ee IR Magnet Coil Production Technology Possibilities

Brookhaven National Laboratory

M. Koratzinos

Summary

US national labs have significant capabilities that they can utilize to make the FCC ee IR successful

The labs can provide extensive MDI/IR design capabilities

These capabilities include design, fabrication, alignment, magnet testing and measurement capabilities

The BNL direct wind capability can provide an excellent means to address the tight spacing required for the correctors.