FRONTIER DETECTORS FOR FRONTIER PHYSICS
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R&D on High Field Magnets for Accelerators at Fermilab

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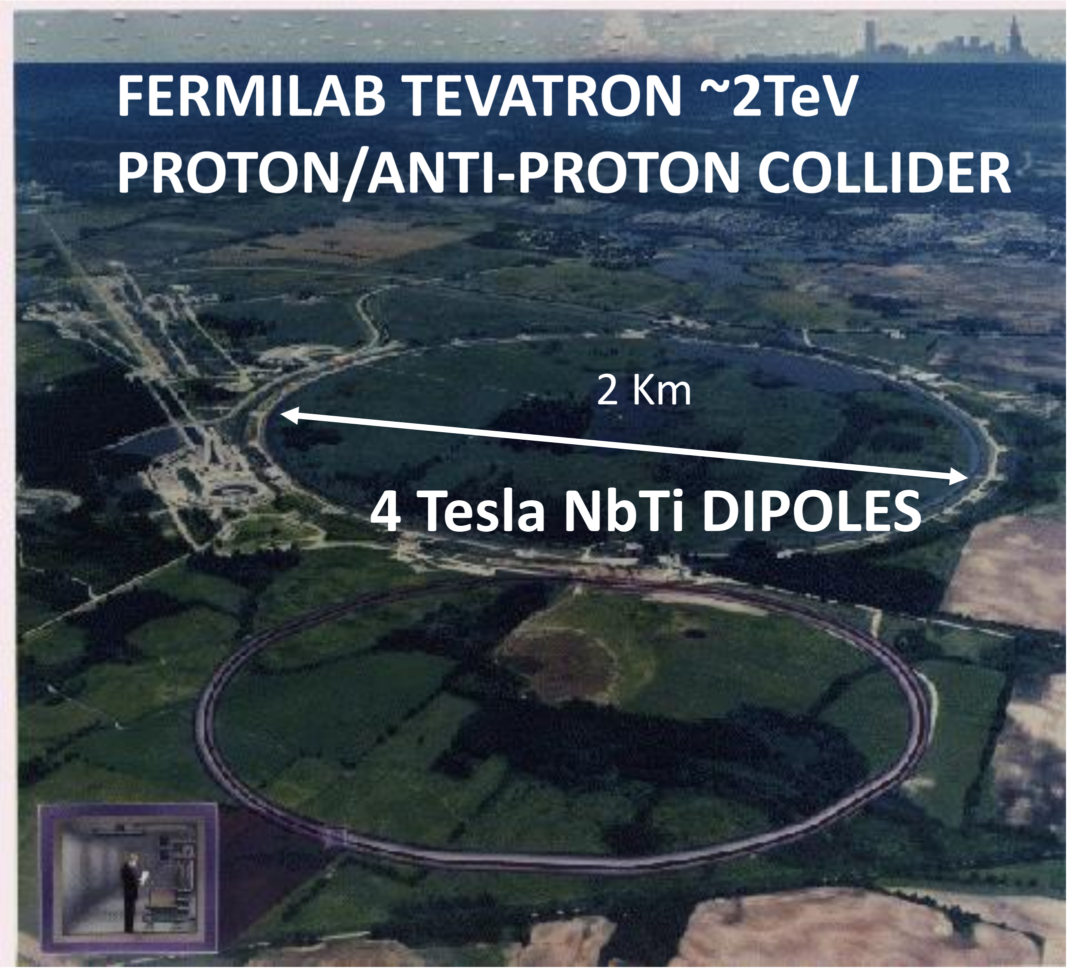
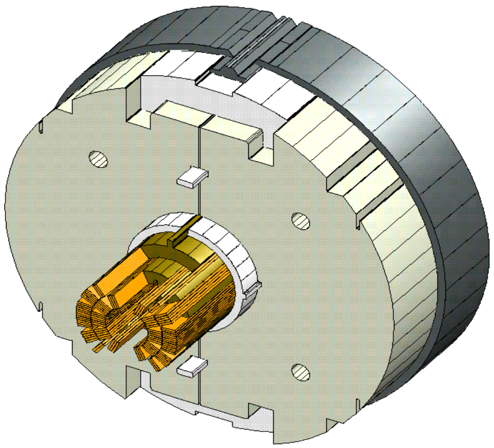
The Past vs. the Future

- The most recent P5 strategic plan for U.S. High Energy Physics (HEP) endorses a continued world leadership role in superconducting magnet technology for future very high-energy p-p colliders, focusing on increasing performance and decreasing costs.
- This includes 10 to 15 T Nb_3Sn accelerator magnets for LHC upgrades and a future 100 TeV scale *pp* collider.
- The ultimate goal is developing magnet technologies for accelerators above 20 T based on both High Temperature Superconductors (HTS) and Low Temperature Superconductors (LTS).
- This program is intended to be conducted in close collaboration with U.S. and International labs, Universities and Industry.

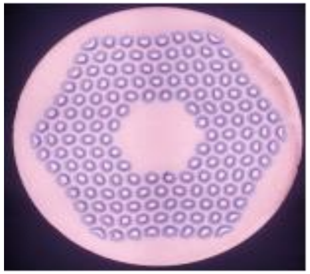


FNAL High Field Magnet Program Mission

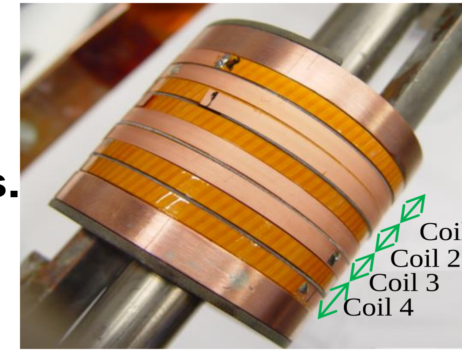


- **Development of advanced SC high-field magnets, materials and technologies for particle accelerators is one of Fermilab's core competencies**
  - **The program supported the development of magnet design and analysis methods and tools, fabrication and test infrastructure, instrumentation, and provided a platform for training of young magnet scientists and engineers**
- **During the past 15 years the FNAL HFM program demonstrated the first series of 10-12 T Nb_3Sn accelerator-quality dipoles and quadrupoles, and Nb_3Sn technology scale up, forming a strong foundation for the future LHC luminosity upgrades.**

Mission of Superconducting R&D



The Mission of the Superconductor R&D is to understand and improve scientific and engineering aspects of superconducting strands and cables for accelerator magnets. A most pressing goal of this program now is to reach production level for the best possible Nb_3Sn conductor for the 15 T Dipoles and HTS for the 5 T inserts.

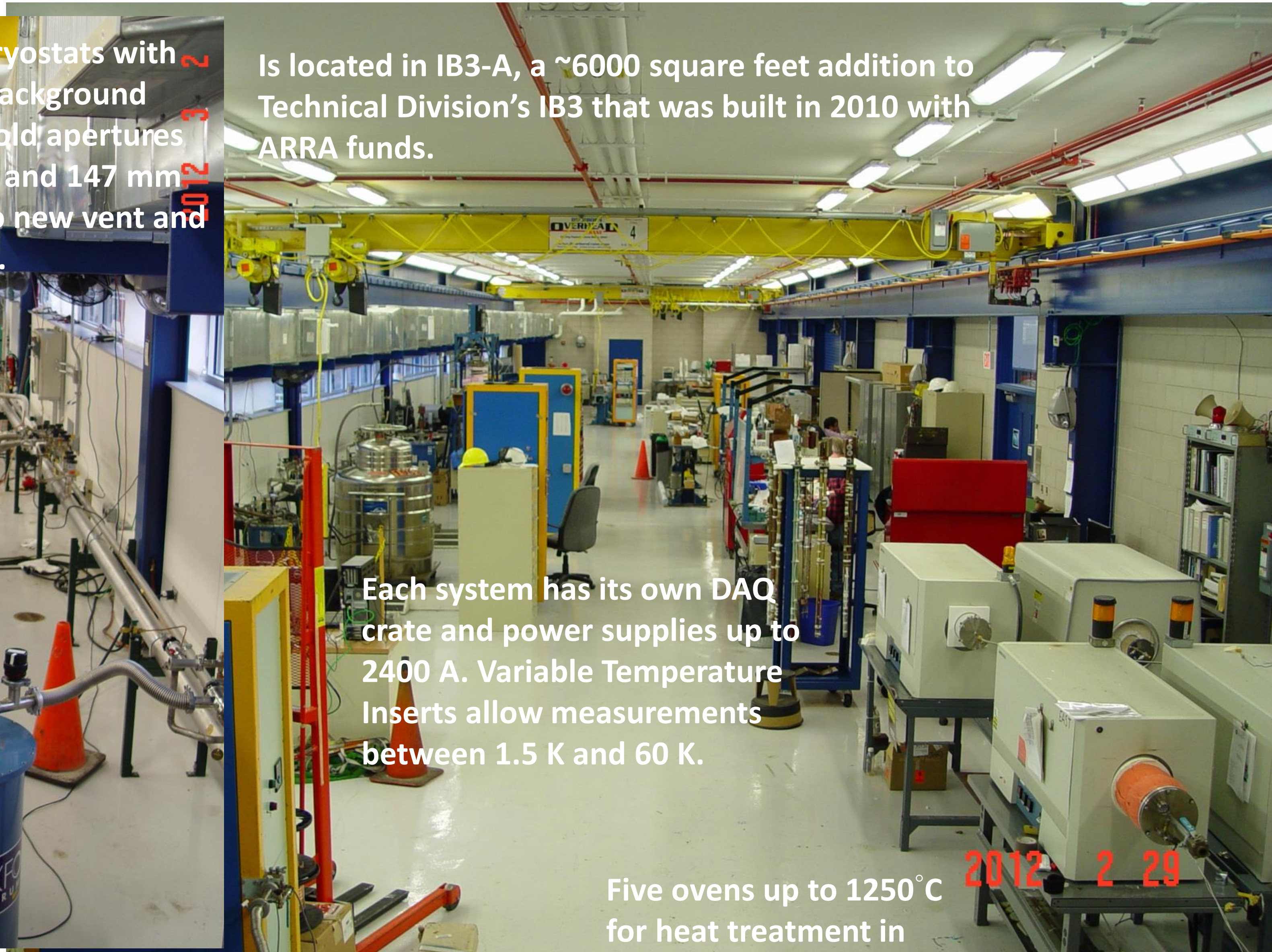


Milestones

- The development with industry of Nb_3Sn superconductors that solved the magnet instability problem and are now adopted by CERN and by the LHC Accelerator Research Program.
- The development with Japanese colleagues of a Nb_3Al cable that established the use of this conductor in magnets for the first time.
- The development of an YBCO solenoid that produced a record field at FNAL of 21.5 Tesla.
- The development of a unique 14 T/16 Tesla accelerator cable test facility with ~30,000 Ampere current.
- Since 1998, the Superconducting R&D lab has served as platform for 34 graduate students in physics and engineering for hands-on training during summer internships or Masters and PhD theses.

Superconducting R&D Lab

Four magnetic cryostats with up to 15T/17 T background field, and with cold apertures between 64 mm and 147 mm are connected to new vent and vacuum systems.



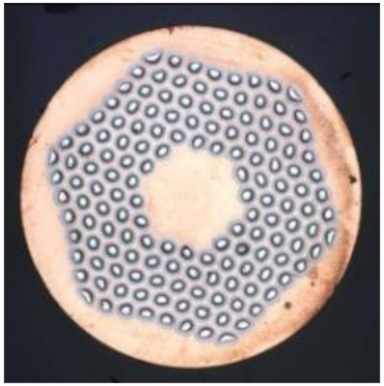
Is located in IB3-A, a ~6000 square feet addition to Technical Division’s IB3 that was built in 2010 with ARRA funds.

Each system has its own DAQ crate and power supplies up to 2400 A. Variable Temperature Inserts allow measurements between 1.5 K and 60 K.

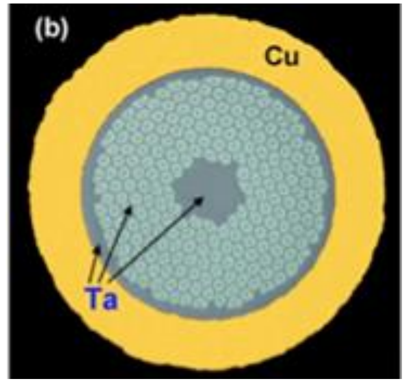
Five ovens up to 1250°C for heat treatment in

Superconducting Materials

Strands



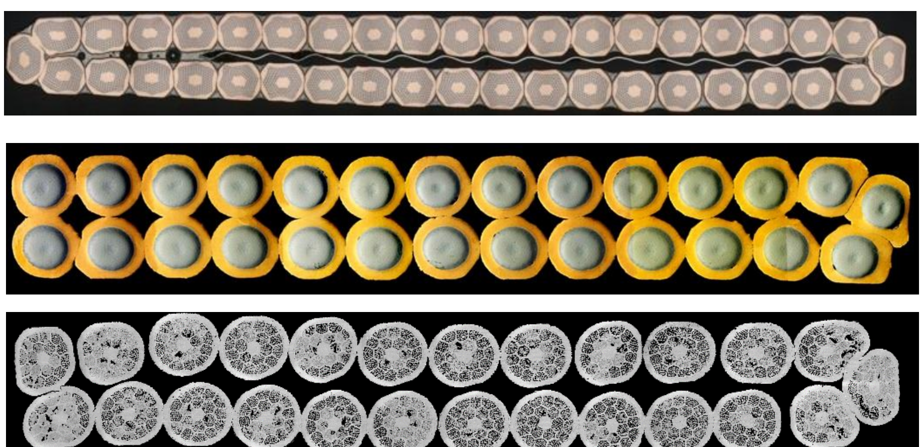
Nb_3Sn

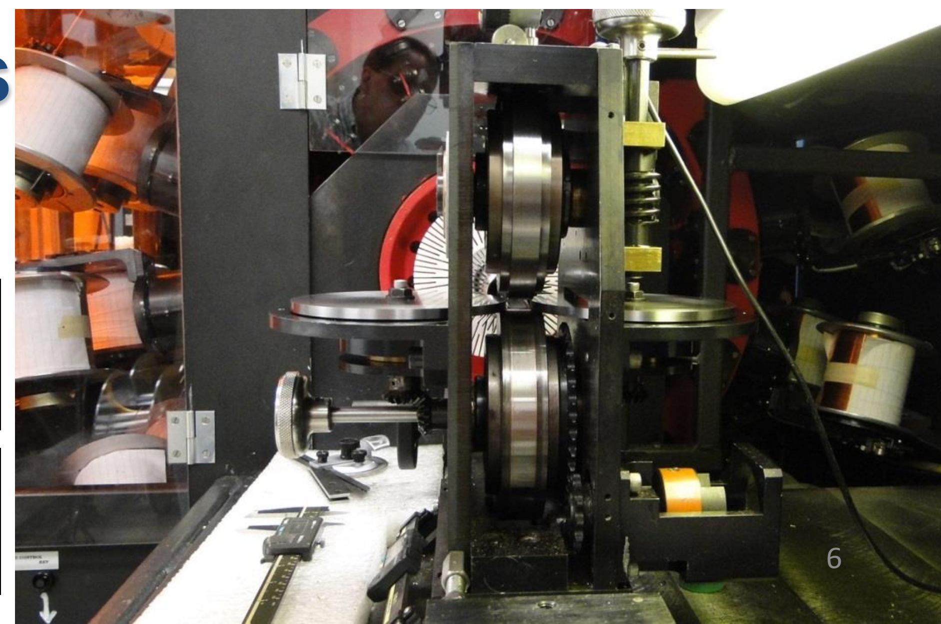


Nb_3Al

Bi-2212

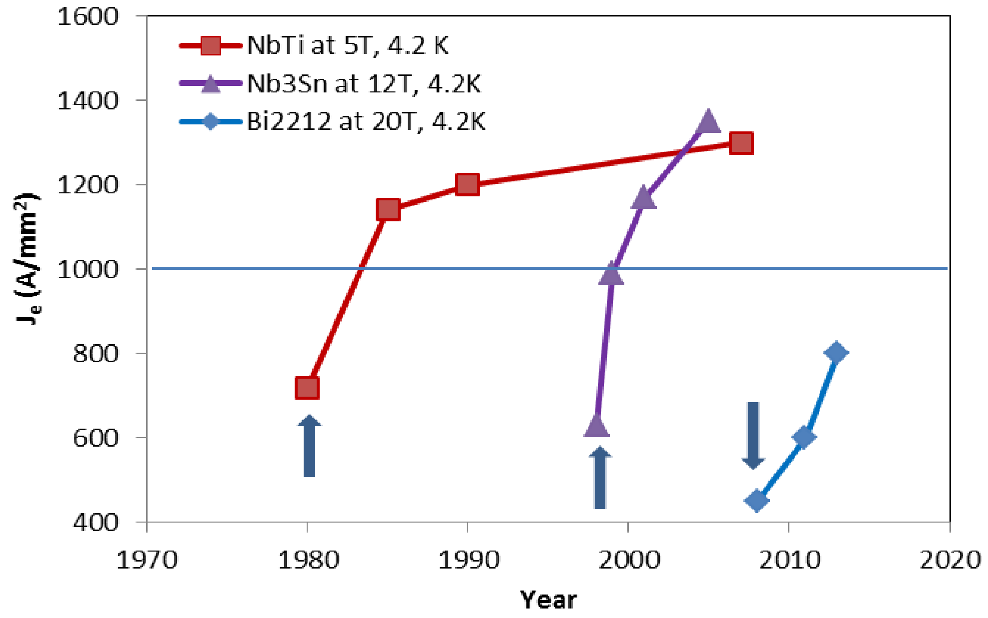
Rutherford-type Cables



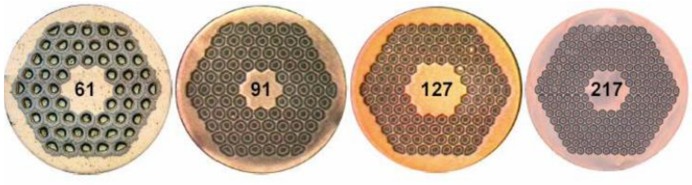


Superconductor R&D programs

- Nb_3Sn strand and cable
  - Internal tin (within the U.S. Conductor Development Program and at FNAL)
  - Powder-in-tube (NED, EU)
  - Nb_3Sn Rutherford-type cable development

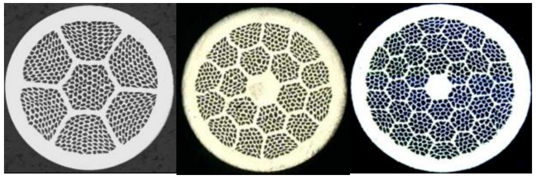


- HTS conductor and cable
  - Bi-2212 R&D (U.S.)
  - YBCO (EU)



RRP strand, Oxford SC Technologies

- Objective: improve J_e and other parameters for accelerator magnets

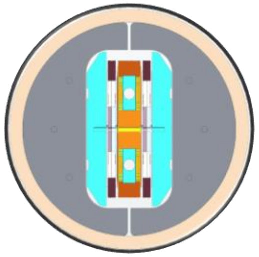


Bi2212 PIT strand, Oxford SC Technologies

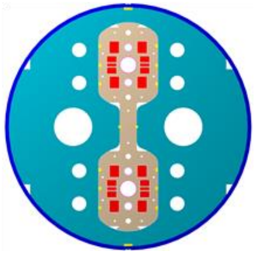
Magnet Design Choice from VLHC Studies

- Coil design:
  - cos-theta
  - block-type
  - common coil
- Technology: W&R, R&W
- Mechanical structure:
  - with and w/o collar
  - Stainless Steel or Al shell
  - stress management
- Field range: 10-13.8 T
  - 13.8 T - record since 2008

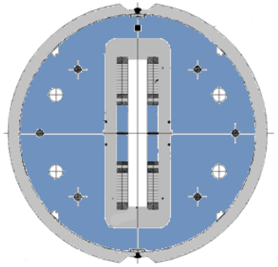
- **Based on data, FNAL decided to focus on the cos-theta (shell-type) design w/o collar**



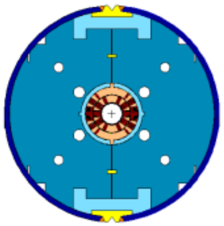
RD3c (LBNL), 10 T, W&R, 2003



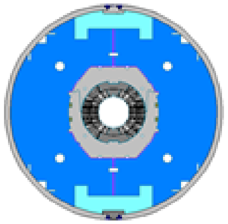
HFDC (FNAL), ~6 T, R&W, 2004



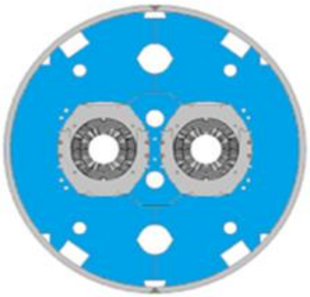
DCC017 (BNL), 10 T, R&W, 2007



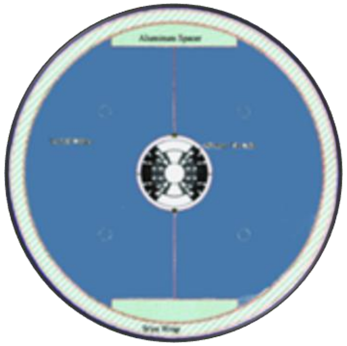
HFDA (FNAL) 10 T, 2003-2006



MBHSP (FNAL) 11.6 T, 2012-2014



MBHDP (FNAL) 11.5 T, 2015



D20 (LBNL), 13.4 T, 1997

HD2 (LBNL), 13.8 T, 2008

11 T Magnet R&D

Magnet design – Fabrication - Test - Analysis

Cable fabrication

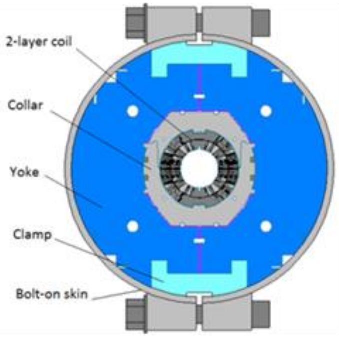
Coil fabrication

Collared coil assembly

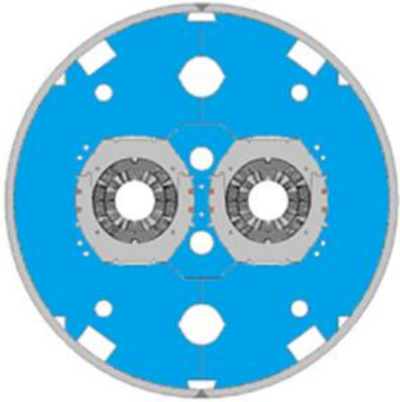
Cold mass assembly

11 T Magnet Test Results

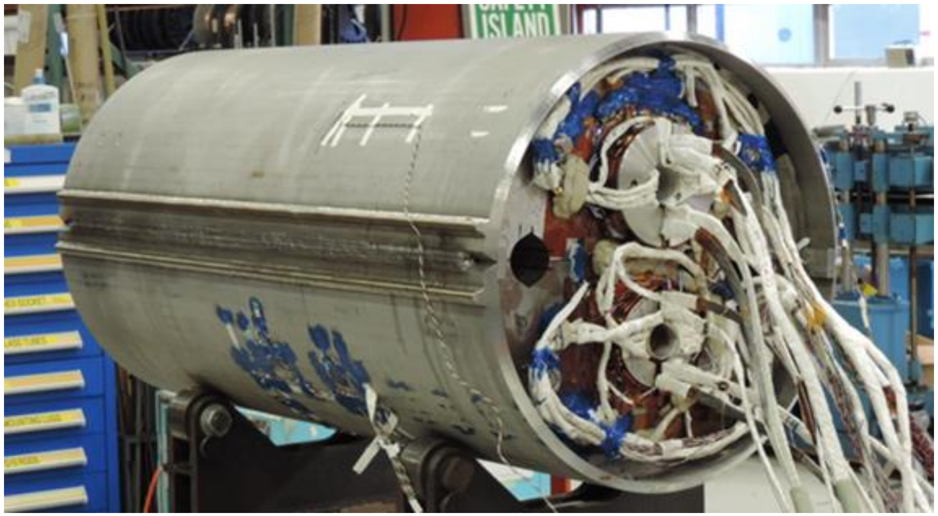
- Recent progress in R&D of 11 T Dipoles for LHC Upgrades
  - **Twin-aperture model MBHDP01:**
    - **B_{max}=11.5 T (2D calculated TF)**
  - Single-aperture models MBHSP02, MBHSP03:
    - **B_{max}=11.6 T (measured TF)**

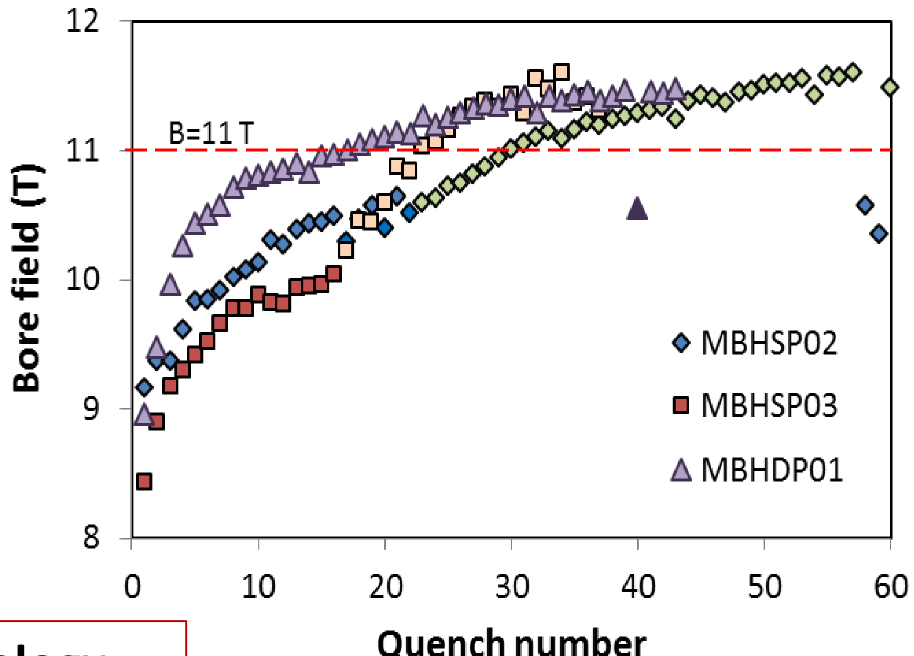


MBHSP02, MBHSP03



MBHDP01



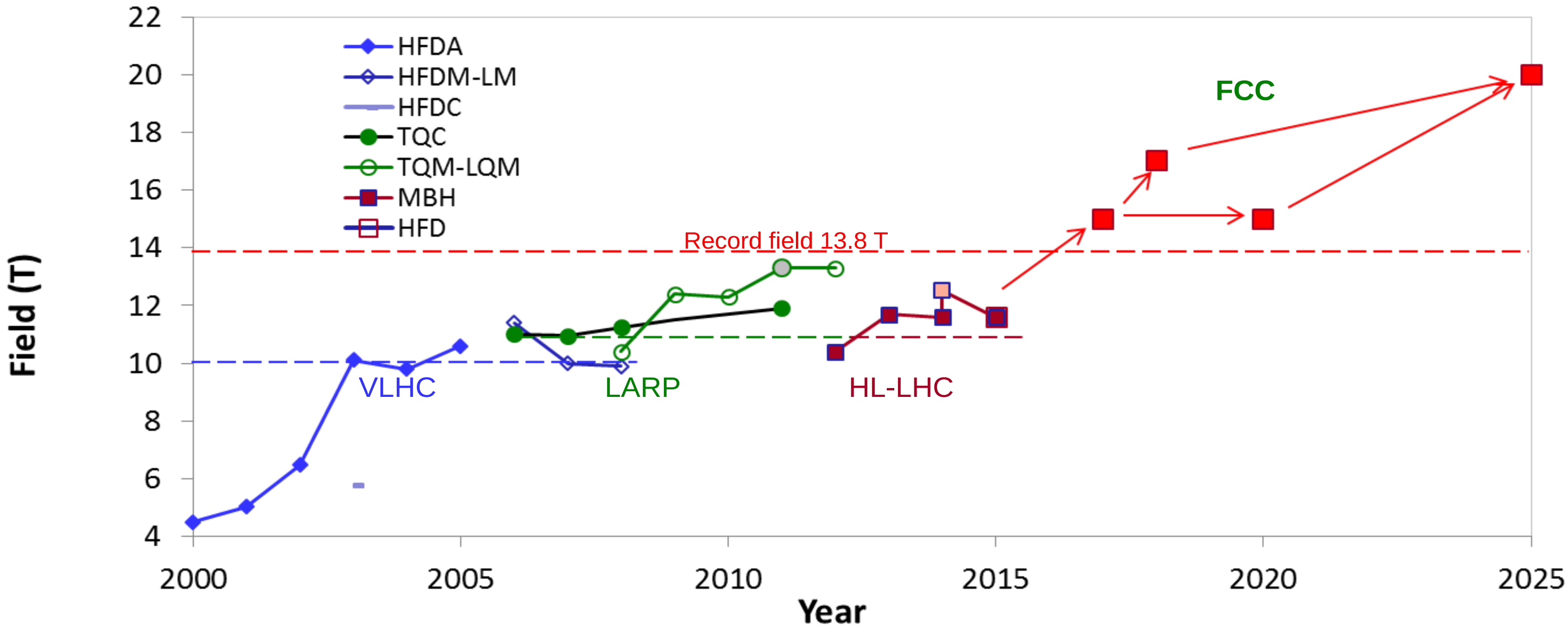


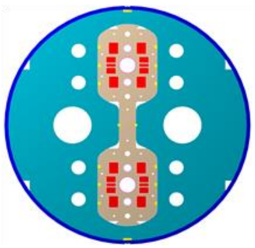
One of the goals of this program was technology transfer to CERN, which has been successful.

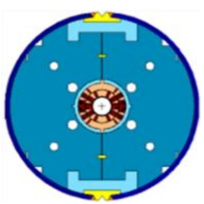
FNAL HFM Program Plan 2015-2025

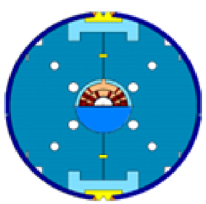
- **FNAL HFM R&D plan was coordinated with the recent P5 recommendations and updated DOE-HEP General Accelerator R&D (GARD) program:**
  - **Recommendation 24: "Participate in global conceptual design studies and critical path R&D for future very high-energy proton-proton colliders. Continue to play a leadership role in superconducting magnet technology focused on the dual goals of increasing performance and decreasing costs."**
- **In collaboration with the U.S. National laboratories, universities and industry:**
  - ***Develop 15-16 T SC dipole magnets*, suitable for the future 100 TeV scale pp collider, based on Nb_3Sn superconductor and innovative approaches which would lead to a *substantial reduction of magnet production, installation and operation costs.***
  - ***Explore very high field, 20-25 T*, accelerator magnets beyond the limits of Nb_3Sn technology based on combination of LTS (Nb_3Sn) and HTS (Bi-2212 or YBCO) coils.**
  - **Develop suitable SC materials (strands, cables, structural materials, etc.) for 15-25 T accelerator magnets.**

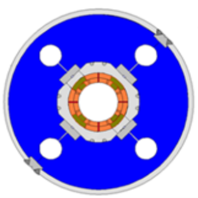
Magnet R&D Summary and Plans

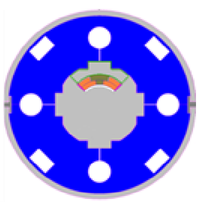


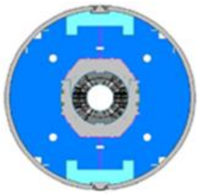

HFDC (R&W)
40 mm 10 T dipole

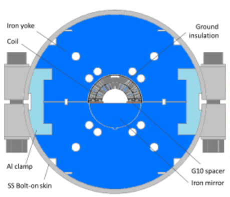

HFDA 43.5 mm
10 T dipole

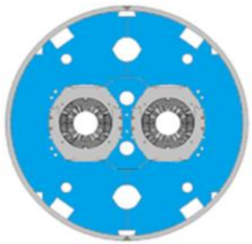

HFDM-LM
Dipole mirror


TQC
90 mm 200 T/m
quadrupole


TQM-LQM
Quadrupole
mirror

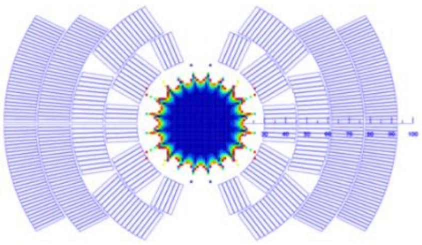

MBHSP
60 mm 11 T dipole


MBHSM
Dipole mirror

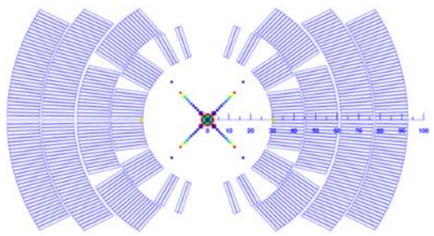

MBHDP
60 mm 11 T dipole

15 T Dipole Demonstrator

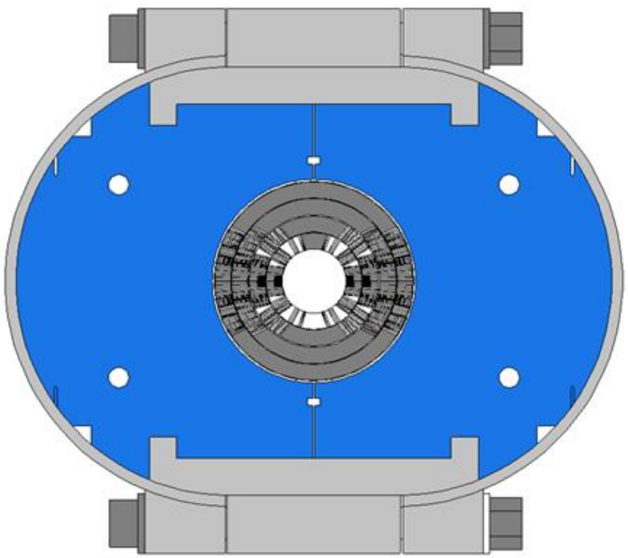
- **Design concept:**
  - Coil bore: 60-mm
  - Final design: 4-layers, graded
  - Interim design: 11 T coil
  - Cold iron yoke
  - Bore B_{max}=15.6/14.6 T @4.3 K
  - +10% at 1.9K
- **Structure:**
  - Thin coil-yoke spacer
  - Stainless steel clamps
  - Bolted skin (from 11 T dipole)
  - Cold mass length: 1 m
  - Cold mass OD<610 mm
- **Protection heaters:**
  - Up to 80% of coil volume



Optimized graded coil



Interim coil design



First Technique for Thin Films of Nb_3Sn on Nb substrate

XRD and GDOES analysis of Cu/Sn/Cu/Nb Samples after Thermal Treatment

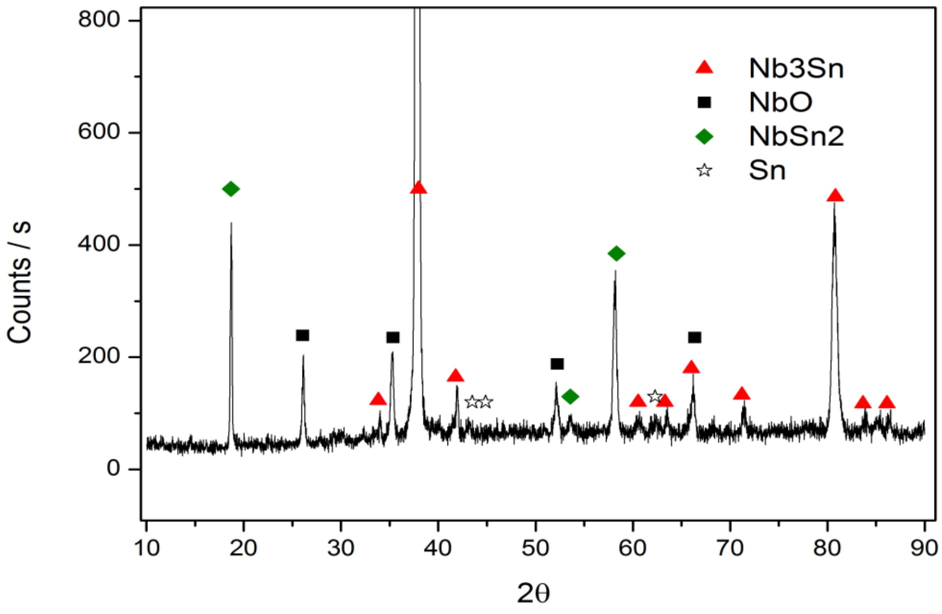
Sample 1

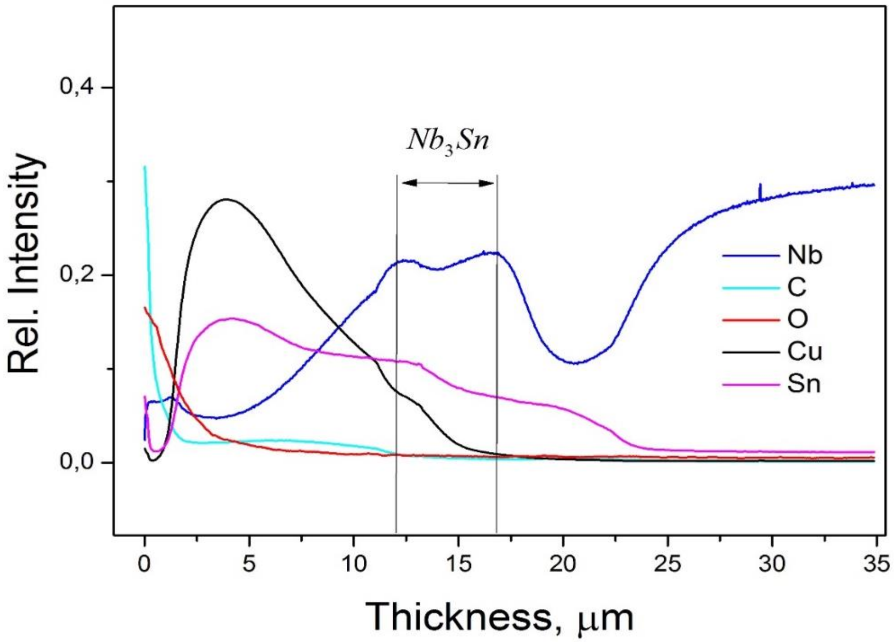
XRD Analysis

- **Superconductive Nb_3Sn**
- Non superconductive **$NbSn_2$**
- Niobium **oxides** are present on the surface

GDOES Analysis

- Sn and Nb **overlapping** is observed, Nb_3Sn phase thickness: ≈ **5 μm**
- **Oxygen** detected close to the surface.





[Barzi, Bestetti, Franz, "Synthesis of Superconductive Nb_3Sn Coatings onto Nb Substrates", under submission to APS Journal]

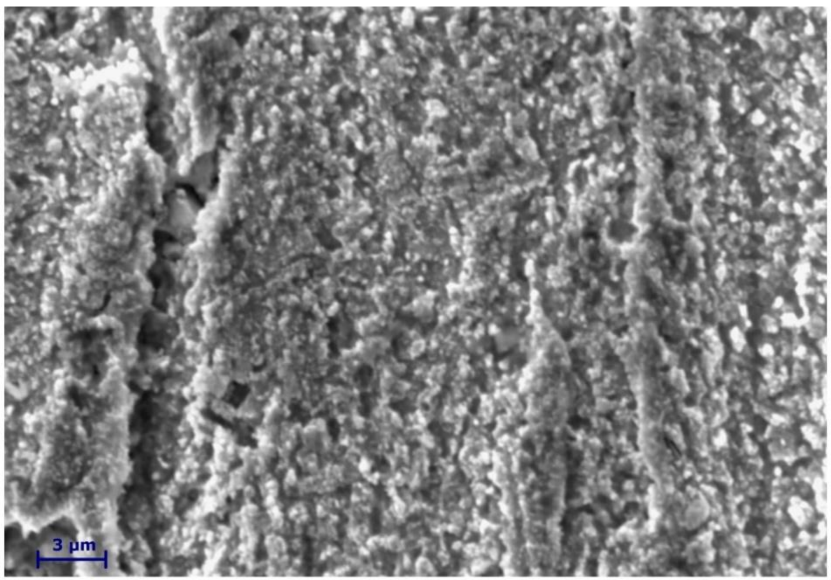
Second Technique for Thin Films of Nb_3Sn on Cu substrate

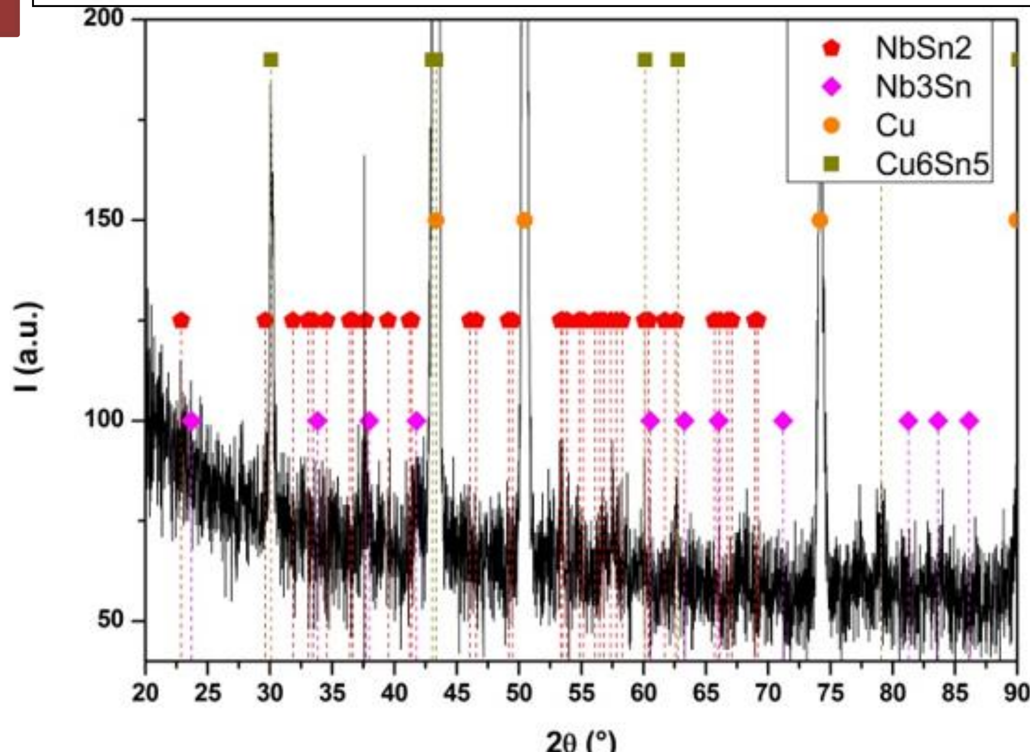
This is the first time that Nb_3Sn is reproducibly formed directly in molecular form on any material, and at much lower temperatures (100°-130°C), than in any other state-of-the-art method, which is by solid diffusion at very high temperature (650°C+).

Direct Electrodeposition of Nb-Sn films

- **Film thickness: 500 nm**

Constant Current Mode at 40 mA/cm^2 and Temperature of 130°C.





[Barzi, Bestetti, Franz, “Electrodeposition of Nb-Sn coatings from EMIC and BMIC Ionic Liquids”, under submission to APS journal]

Conclusions

- FCC needs:
  - Cost-effective main dipole magnets with nominal operation fields of 10 to 15 T based on Nb_3Sn technology
  - Special magnets with operation fields up to 20+ T based on HTS/LTS coils
- The explored range for Nb_3Sn magnets is 10 to 13.5 T:
  - 11-12 T Nb_3Sn magnets – Dipoles and Quadrupoles – are planned for the LHC upgrades
- Problems to be understood and resolved for FCC:
  - Nb_3Sn magnets: demonstration of 15-16 T nominal field, improvement of magnet training, reduction of conductor degradation, magnet cost optimization
  - HTS magnets: feasibility, technology, HTS cable
- Fermilab has a sound realistic program to address these challenges, and a National SC magnet collaboration is being formed with Fermilab taking a leadership role
- This consistent 15-year Nb_3Sn magnet R&D has produced a by-product with strong potential for applications in high performance SRF cavities and magnetic shields