IAAM Webinar on Composite & Ceramic Materials, February 15, 2021

Research and Development of Nb_3Sn Wires and Cables for High-Field Accelerator Magnets

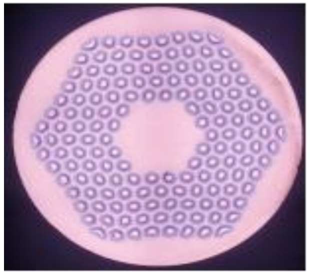
Emanuela Barzi, Fermilab & Ohio State University

THE OHIO STATE UNIVERSITY

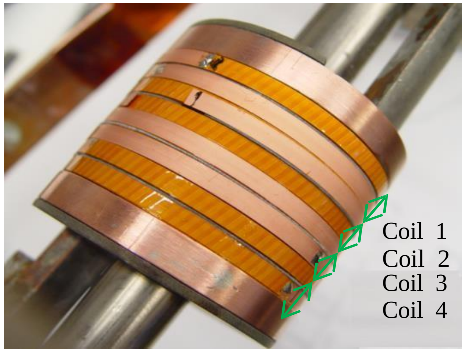
Outline

- Mission of Superconducting R&D
- Basic concepts on Superconducting Magnets and how they impose specific requirements on the superconductor
- Overview of experimental setups for strand and cable characterization
- Example of innovation for Nb_3Sn wire
- Example of side product from research
- Conclusion

Mission of Superconducting R&D



The Mission of Fermilab's 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 15-16 T Dipoles and HTS for 5 T inserts for future High Energy Physics (HEP) colliders.



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 Tesla /16 Tesla accelerator cable test facility with ~30,000 Ampere current.
- Since 1998, the Superconducting R&D lab has served as platform for more than 30 graduate students in physics and engineering for hands-on training during summer internships or Masters and PhD theses.

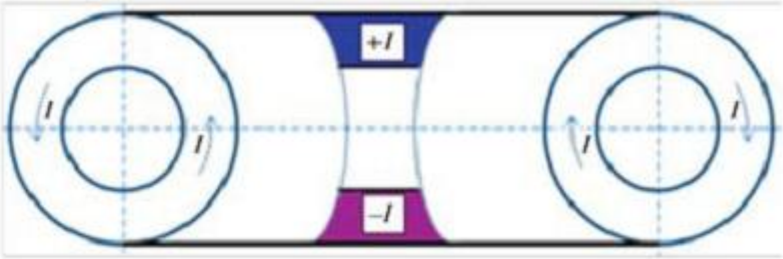
Main Field Configurations

$$\vec{B} = \frac{\mu_0}{4\pi}\int_C \frac{I d\vec{l} \times \vec{r}}{r^3}$$ **Biot-Savart**

AXIAL-SOLENOID

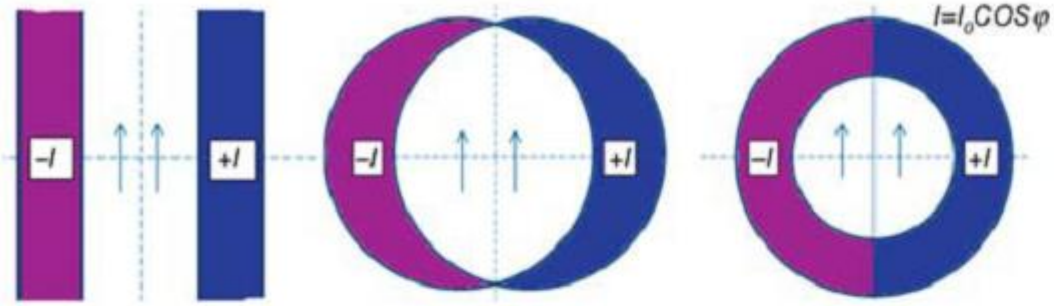
AXIAL-TOROID

$$B_z = \mu_0 J (R_{out} - R_{in})$$



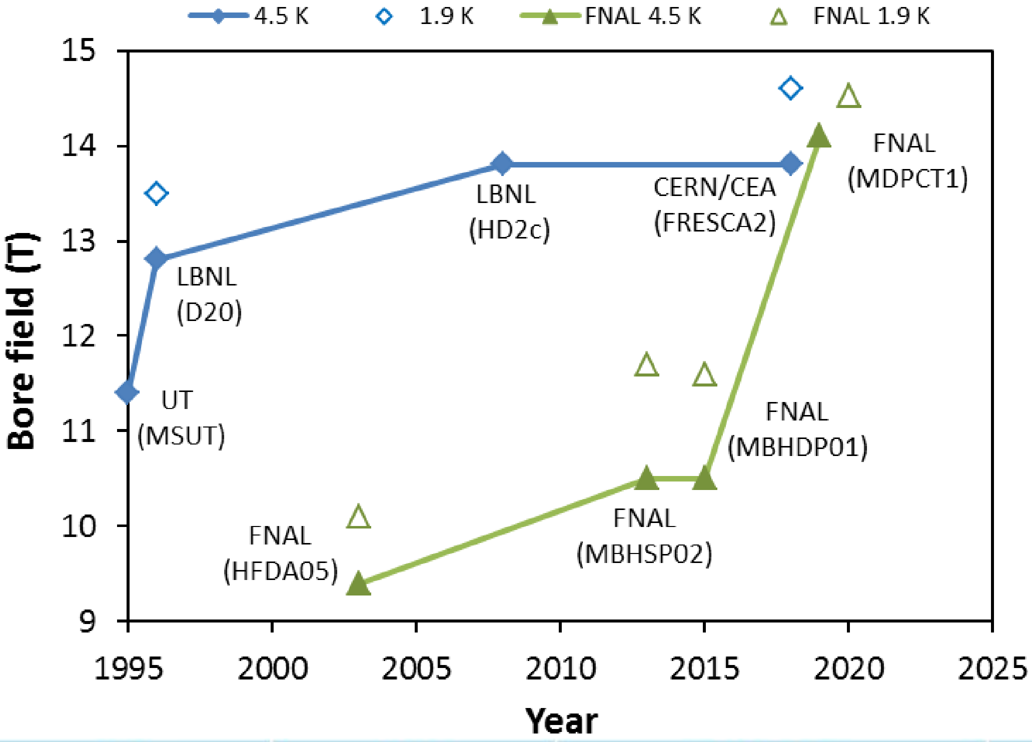
$$B_\varphi = \frac{\mu_0 N I}{2\pi r}$$

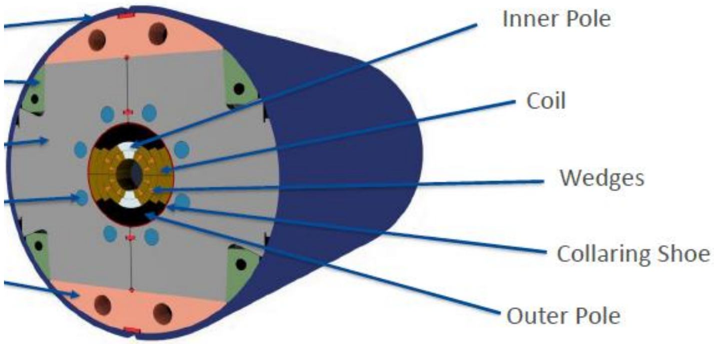
TRANSVERSE - DIPOLE

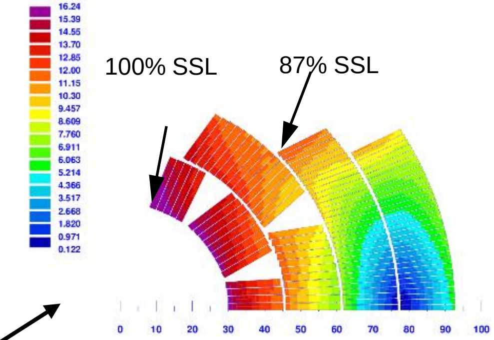


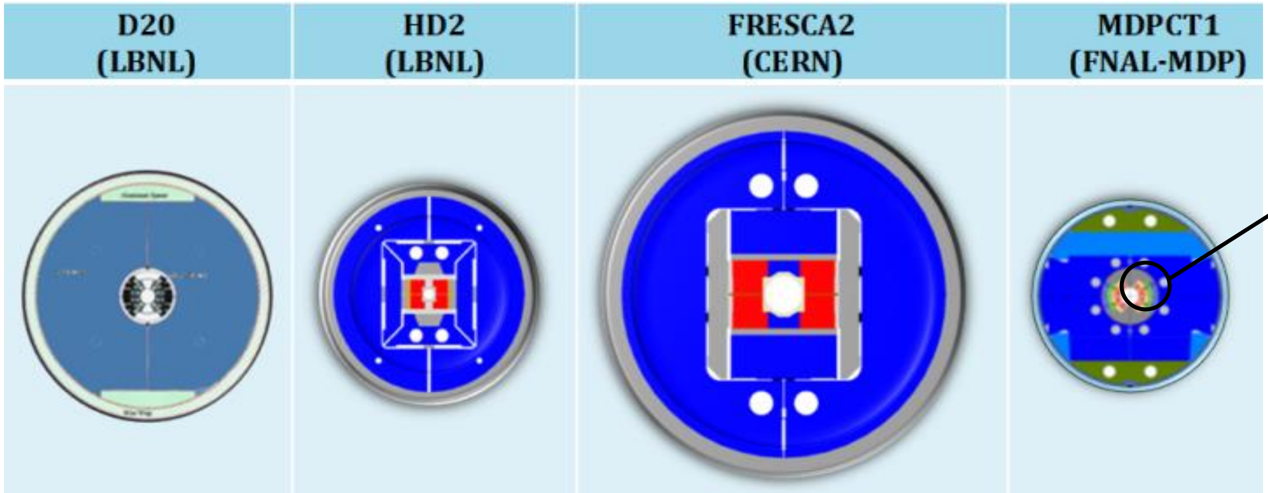
$$B = \frac{\mu_0 J w}{2}$$

Progress in Maximum Field in Accelerator Magnets

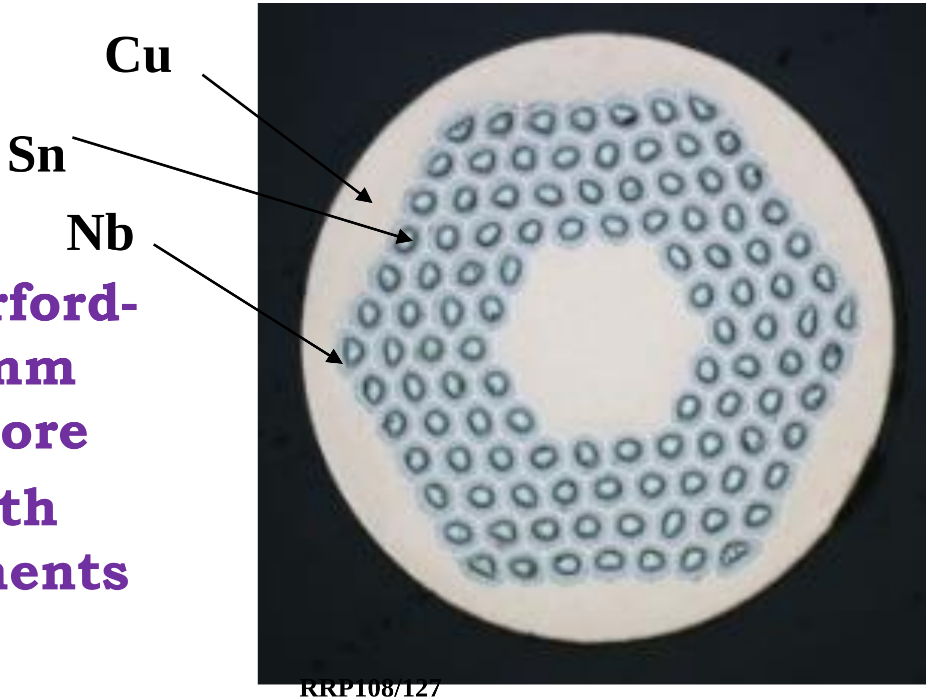








Strand and Rutherford Cable



- ❖ **Conductor**
  - Cable: 15 mm wide Rutherford-type, 40-strands, with 11mm wide 0.025 mm thick SS core
  - Strand: 0.7 mm Nb_3Sn with 108 superconducting elements

- ❖ **Cable insulation**
  - E-glass tape
  - 12.7mm wide 0.075 mm thick
  - 2 layers with ~50% overlap

Important Factors in Magnet Design

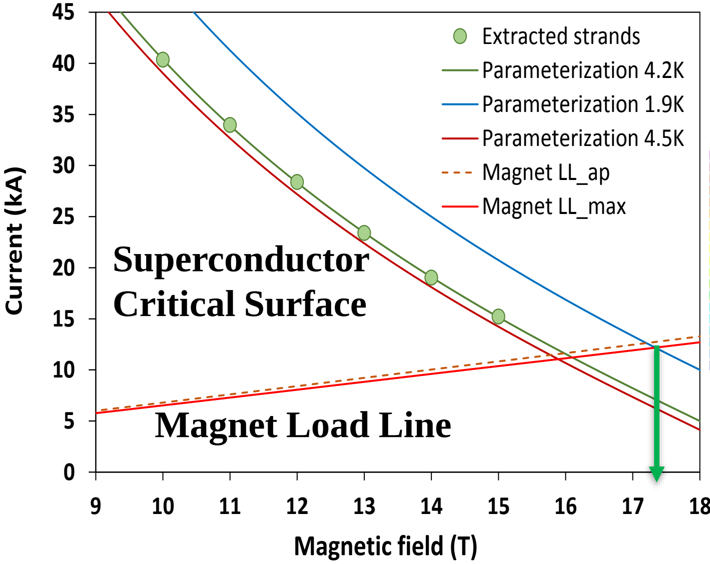
- **OPERATION MARGINS**
- **LORENTZ FORCES AND SUPPORT STRUCTURE**
- **FIELD QUALITY**
- **MAGNETIC STABILITY**
- **MAGNET COOLING AND CRYOSTAT - vacuum vessel, thermal shields, superinsulation, support system, current leads, cryogenic feedthroughs and instrumentation**
- **CRYOGENIC STABILIZATION AND/OR ADIABATIC STABILIZATION**
- **MAGNET QUENCH DETECTION AND QUENCH PROTECTION**

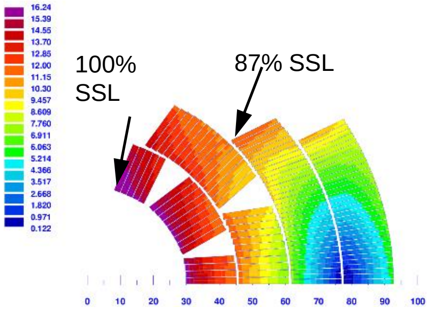
Target Specifications for High Energy Physics Conductor

Parameter	Value
Strand diameter, mm	1.000 / 0.700
J_c(4.2K,12T), A/mm^2	> 3000
d_{eff}, μm	< 40 / 30
Cu, %	50-60
RRR	> 100
Piece length, km	> 10
Cabling degradation	< 10 %
Cost, $/kA-m (12T, 4.2K)	< 1.5

Plus stress requirements ≥ 150 MPa

Requirement on Critical Current Density

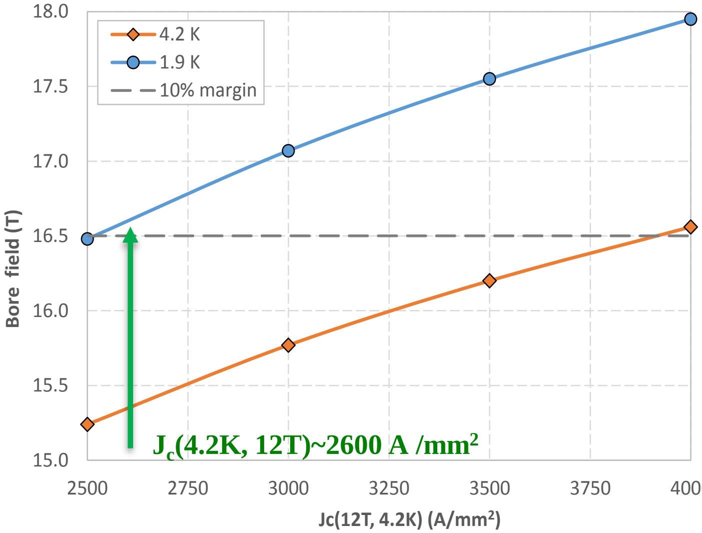




Magnet SSL:

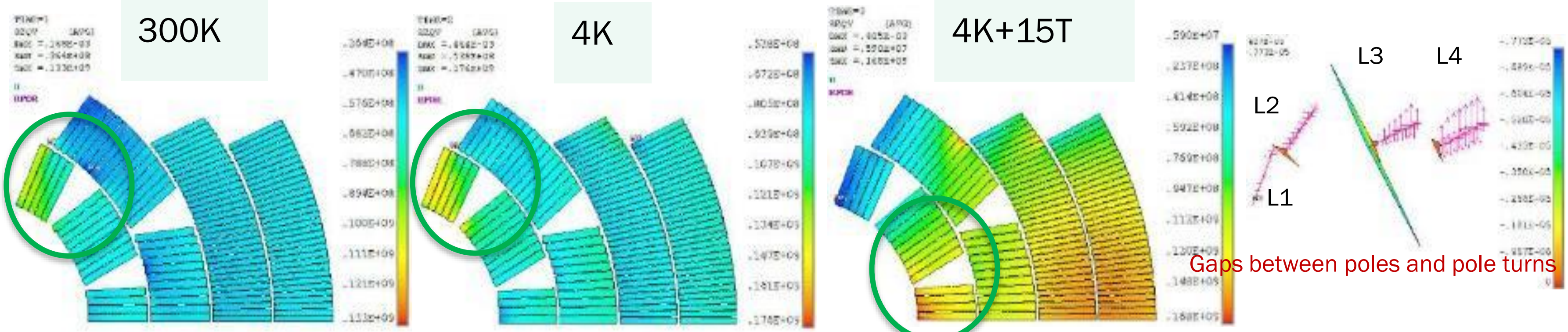
- B_{ap}=15.3T @4.5K
- B_{ap}=16.7T @1.9K

Magnetic Field, Tesla



Jc (12 T), A/mm^2

Magnet design limit is determined by the mechanical constraints and it is 15 T.



S_{eqv}=133 MPa

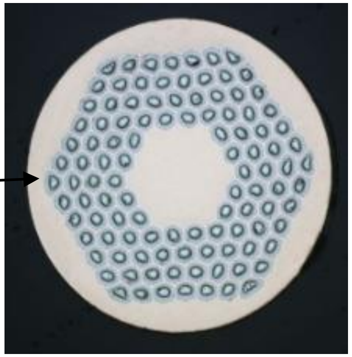
S_{eqv}=176 MPa

S_{eqv}=168 MPa

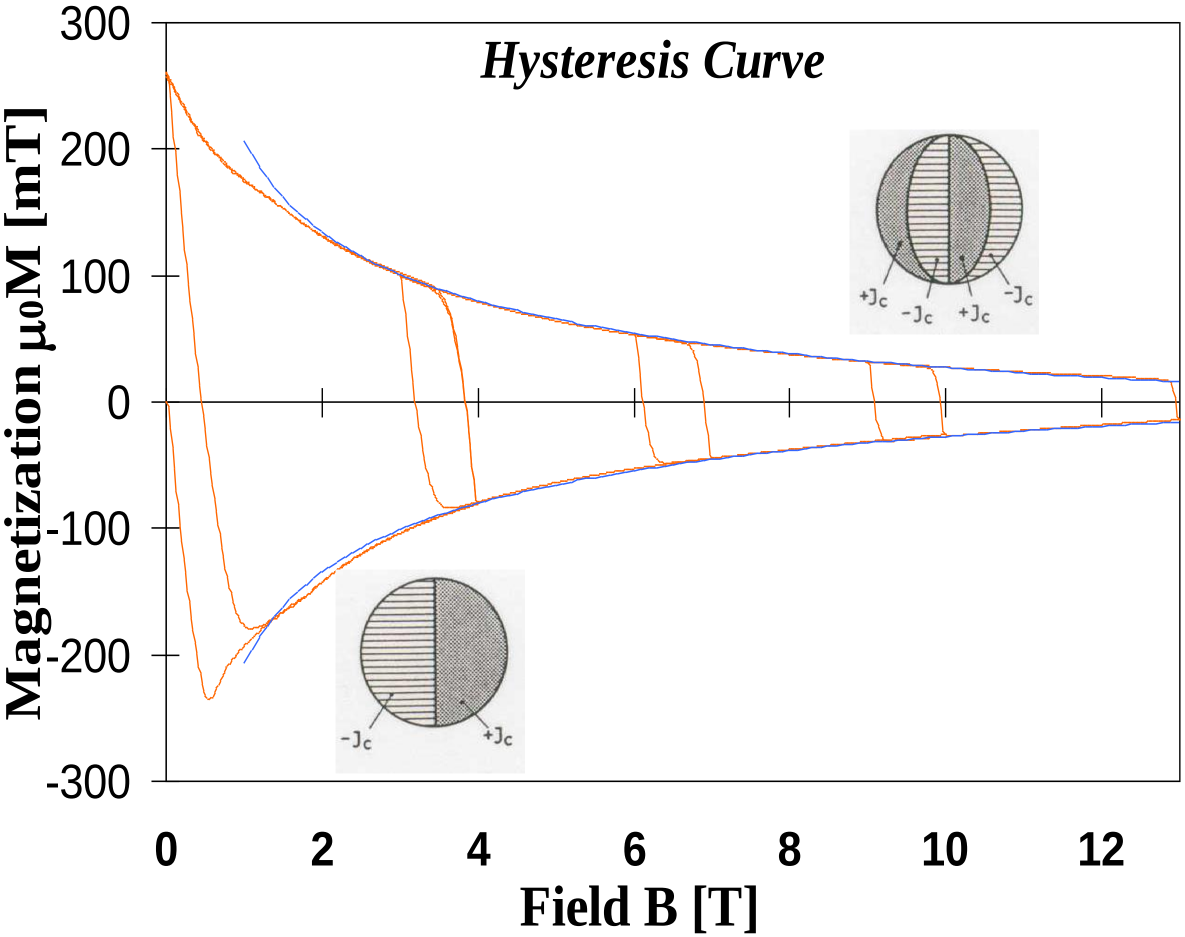
Requirement on Magnetization

- $\Delta M \propto J_c \cdot \boxed{d_{eff}}$

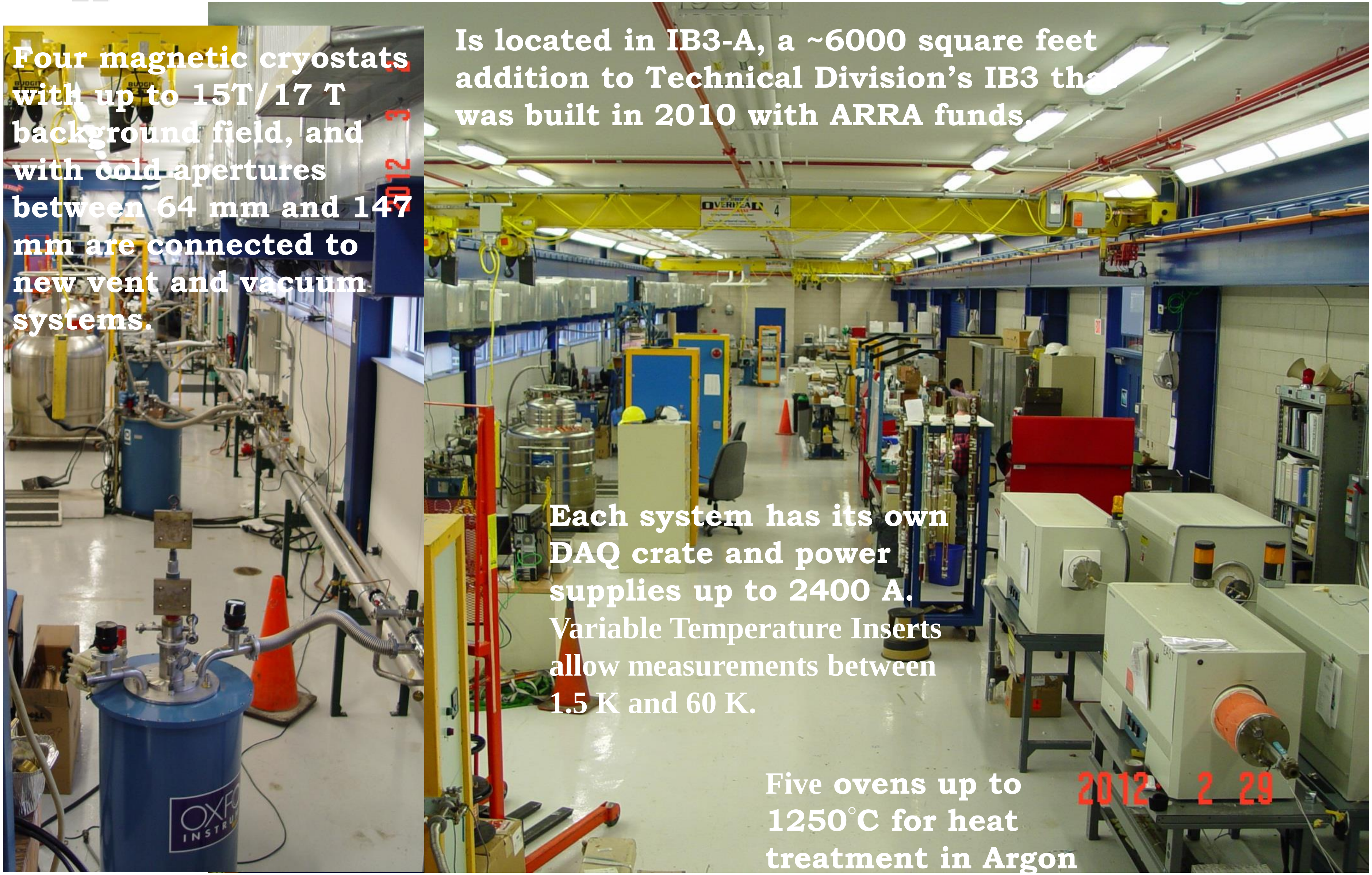
Size of Superconducting element in wire



Persistent currents are induced in a type II superconductor when the field is changed. These bipolar currents are the source of severe field distortions at low excitation. They generate all multipoles allowed by the coil symmetry.



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.

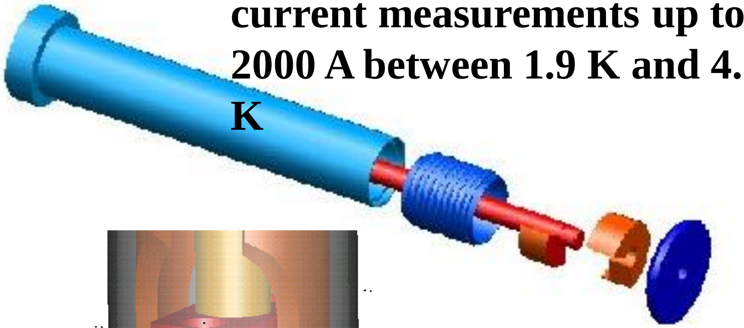
Is located in IB3-A, a ~6000 square feet addition to Technical Division's IB3 tha was built in 2010 with ARRA funds.

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 Argon

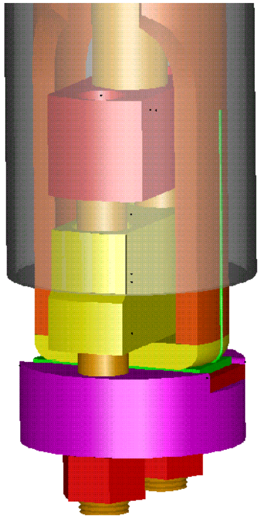
Experimental Setups

1998: Pressure contact probe for I_c measurements up to 1400 A



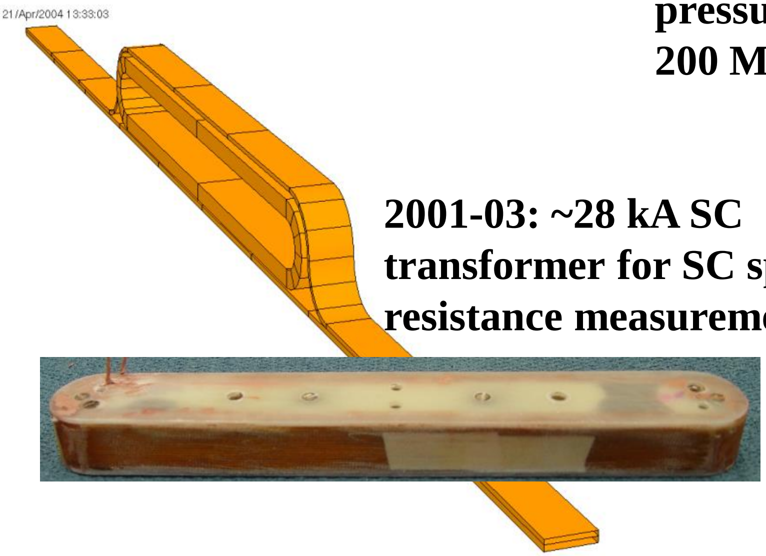
2003-2009: Five low resistance probes for stable current measurements up to 2000 A between 1.9 K and 4.5 K

1999: Balanced coil magnetometer for magnetization measurements

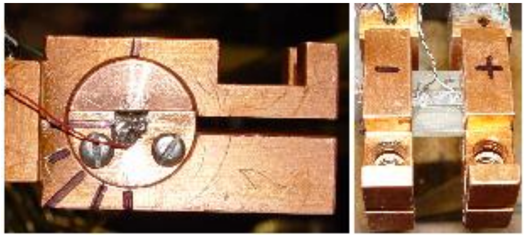


2001: Device to test I_c sensitivity to uniaxial transverse pressure up to 200 MPa

2009-13: SC transformer for cable tests in fields up to 14T/16T and ~30 kA



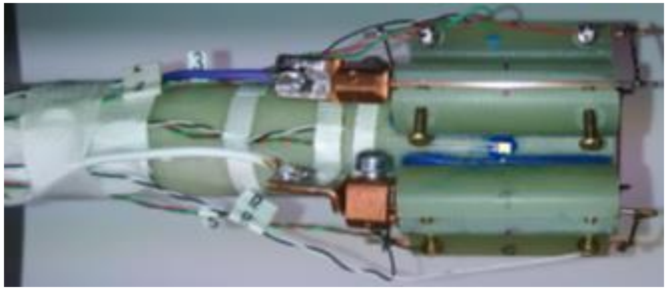
2001-03: ~28 kA SC transformer for SC splice resistance measurements



2007: Probe to measure I_c dependence on field orientation for anisotropic HTS wires.

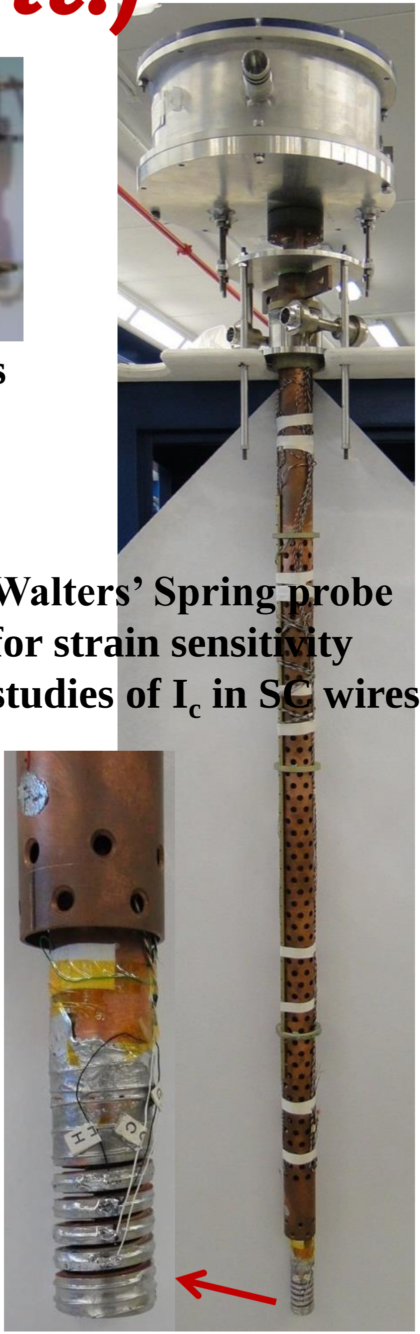
Experimental Setups (cont.)

Modular Insert Test Fixture (ITF) designed to test YBCO double pancake coils and Bi-2212 wire coils

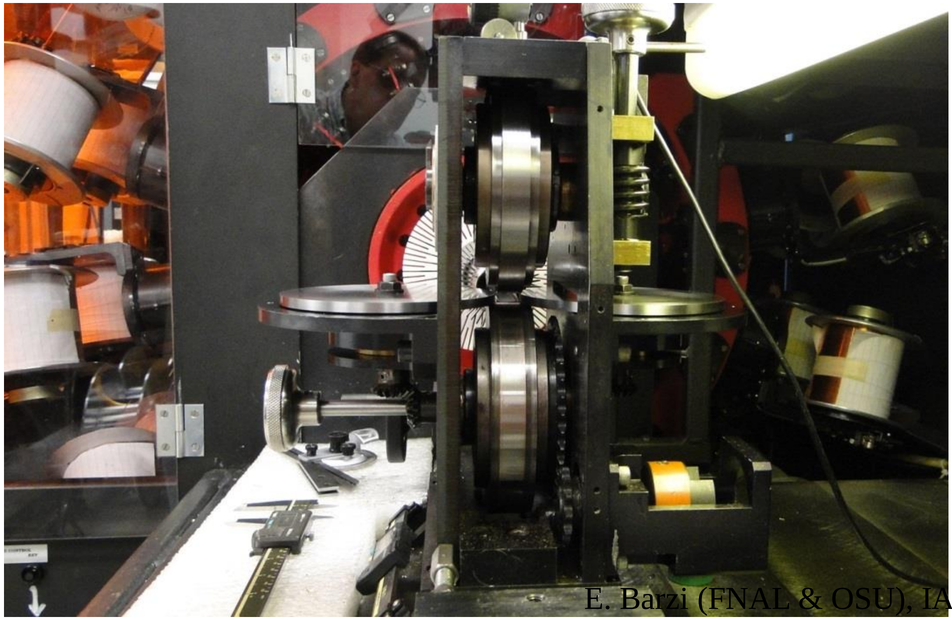


RRR probe for wire and bulk samples

Hall probe system to measure shielding of bulk MgB_2 tubes

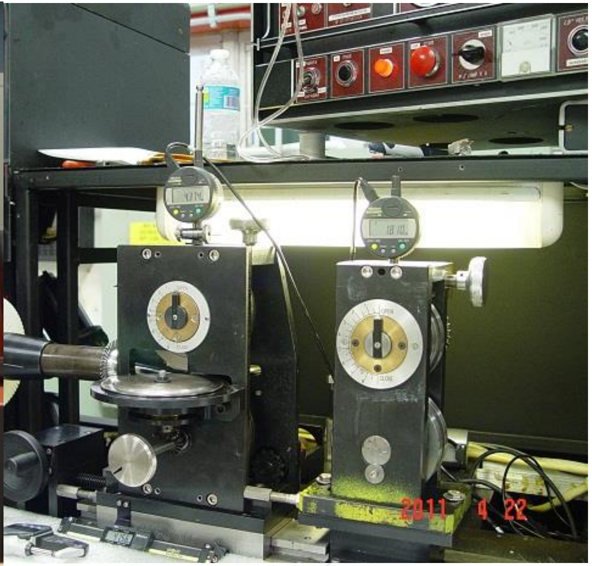


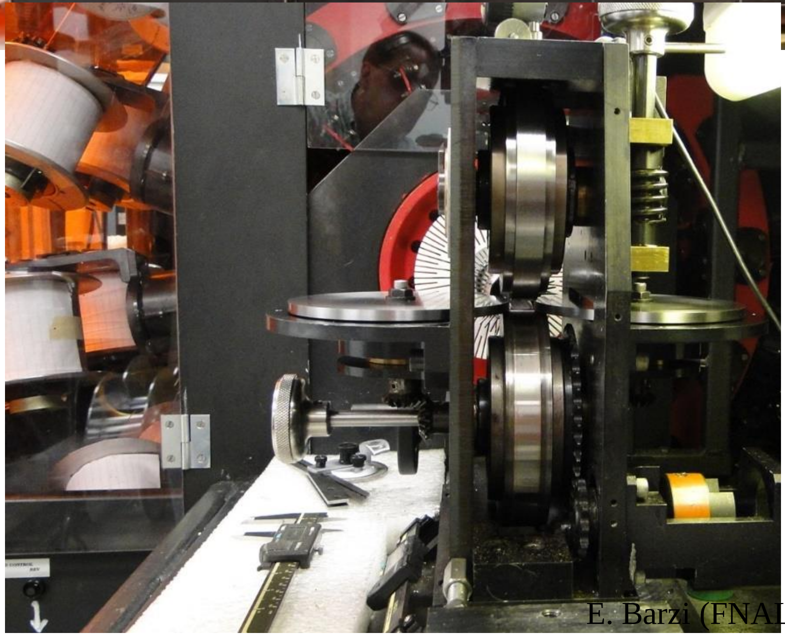
Walters' Spring probe for strain sensitivity studies of I_c in SC wires



Keystoned turkhead for Rutherford cable fabrication in 1 step

42-spool Cabling Machine





- **Cabling machine with 42 spools.**

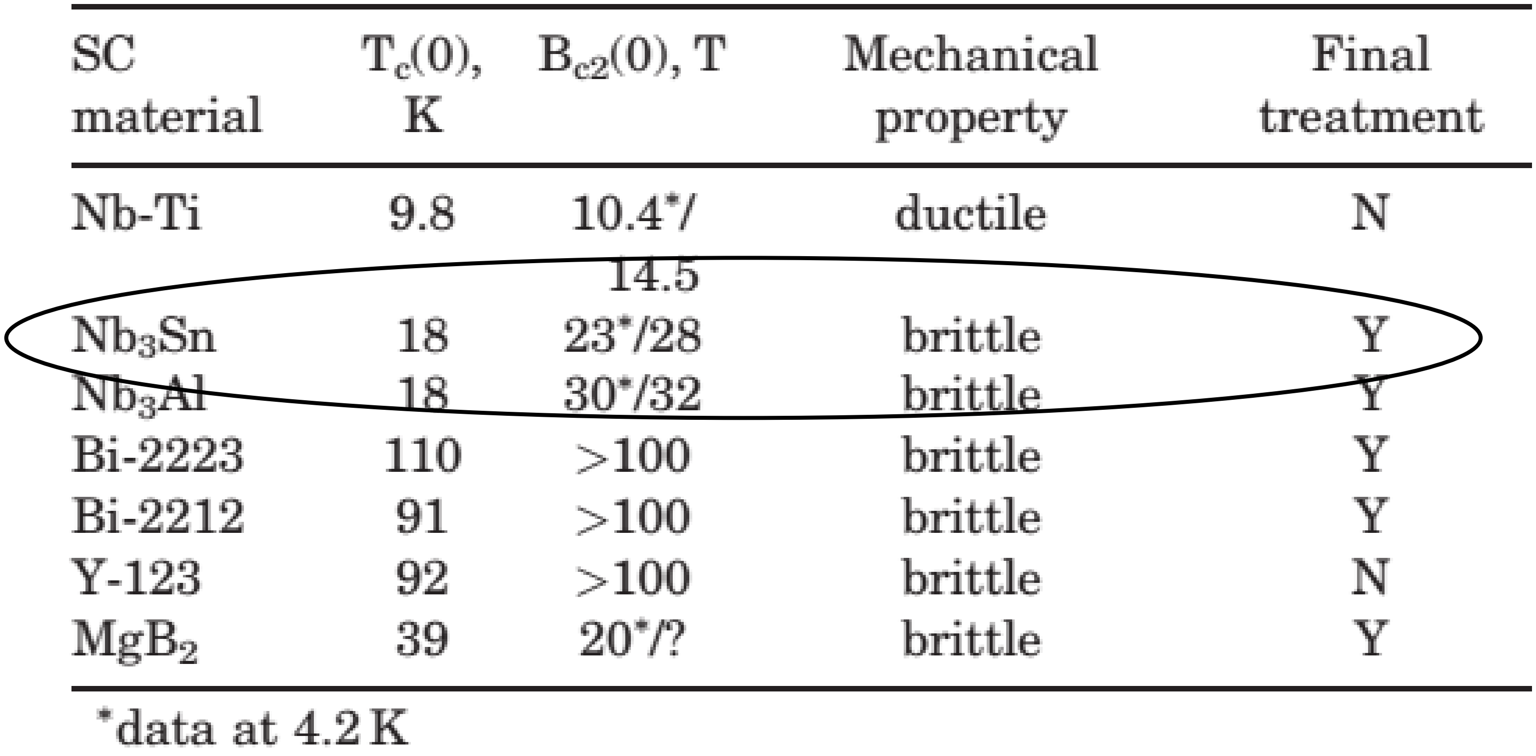
Mandrels

Rutherford cable

Superconductor Equipment List at FNAL, IB3A

- Teslatron 1 (T1) Cryostat with 15T/17T 64 mm cold aperture solenoid, 1875 A Power Supply w/ 49 mm Variable Temperature Insert (VTI) for testing between 1.5 K to 300 K
- Teslatron 2 (T2) Cryostat with 14T/16T and 77 mm cold aperture solenoid, 2000 A PS w/VTI
- Teslatron 3 (T3) Cryostat with 8.5T/10T and 147 mm cold aperture solenoid, 2400 A PS
- Telslatron 4 (T4) Cryostat with 253 mm neck, 2400 A PS
- Low temperature loader for cryogenic strain gauge calibration
- 4 tube furnaces 6'' diameter for heat treatment in Argon and Oxygen to 1500°C
- 2 m long furnace up to 1250°C for heat treatment in air and in argon
- Metrology well calibrator for thermocouples calibration up to 700°C
- Motorized flat-rolling system for wires
- Probes and sample holders for SC strand critical current tests up to 2000 A in T1 and T2
- Devoted probes to test RRR of up to 6 wire samples in T1,T2 and T3
- Sample holders to measure angular dependence of current with field for HTS wires in T1 and T2
- Balanced coil magnetometer to measure magnetization in T1 and T2
- Device to test critical current sensitivity of impregnated cables to uniaxial transverse pressure in T2
- Walters' spring-type device for tensile/compressive strain sensitivity studies of critical current density in T1
- SC transformer for Rutherford cable tests and splice studies up to 28 kA in self-field in T1 and T2
- 14T/16T Rutherford cable test facility for cable tests up to 30 kA in T2
- Modular Insert Test fixture for testing HTS YBCO pancake coils in T2
- Hall probe system for magnetic measurements in T4, eg shielding capabilities of bulk MgB_2 tubes
- Instrons for mechanical properties
- Optical and electron microscopes
- Respooler and 42-spool cabling machine with turkheads for 1-step and 2-step cables

Summary of Superconductor Properties



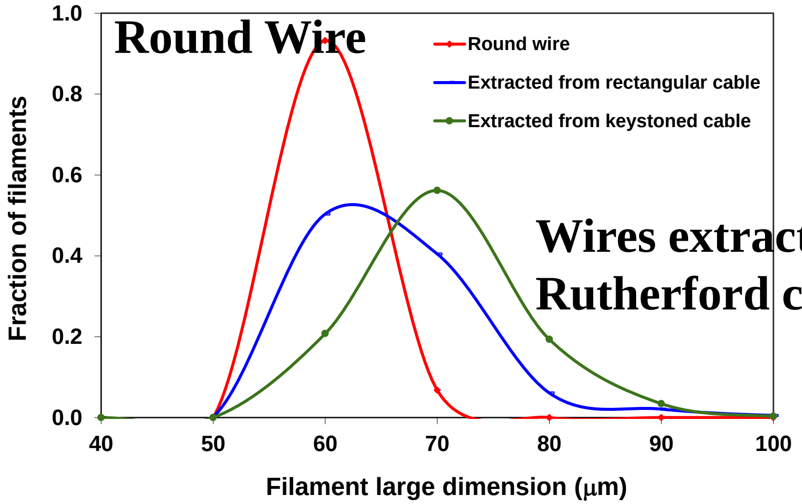
SC material	$T_c(0)$, K	$B_{c2}(0)$, T	Mechanical property	Final treatment
Nb-Ti	9.8	10.4*/ 14.5	ductile	N
Nb_3Sn	18	23*/28	brittle	Y
Nb_3Al	18	30*/32	brittle	Y
Bi-2223	110	>100	brittle	Y
Bi-2212	91	>100	brittle	Y
Y-123	92	>100	brittle	N
MgB_2	39	20*/?	brittle	Y

*data at 4.2 K

Effect of Cabling on Round Strand Layout

Subelement Deformation

$$\varepsilon_{SE} = \frac{d_{max}-d_{min}}{d_0}$$



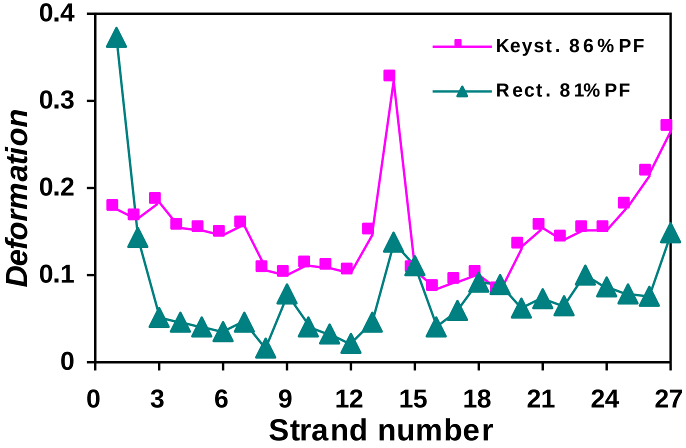
Wires extracted from Rutherford cables

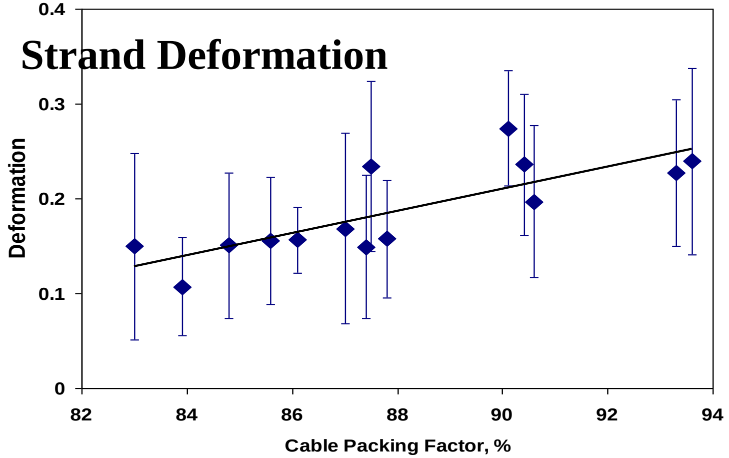
thin

thick

Strand Deformation

$$\varepsilon_{str} = \frac{d_{max}-d_{min}}{d_0}$$



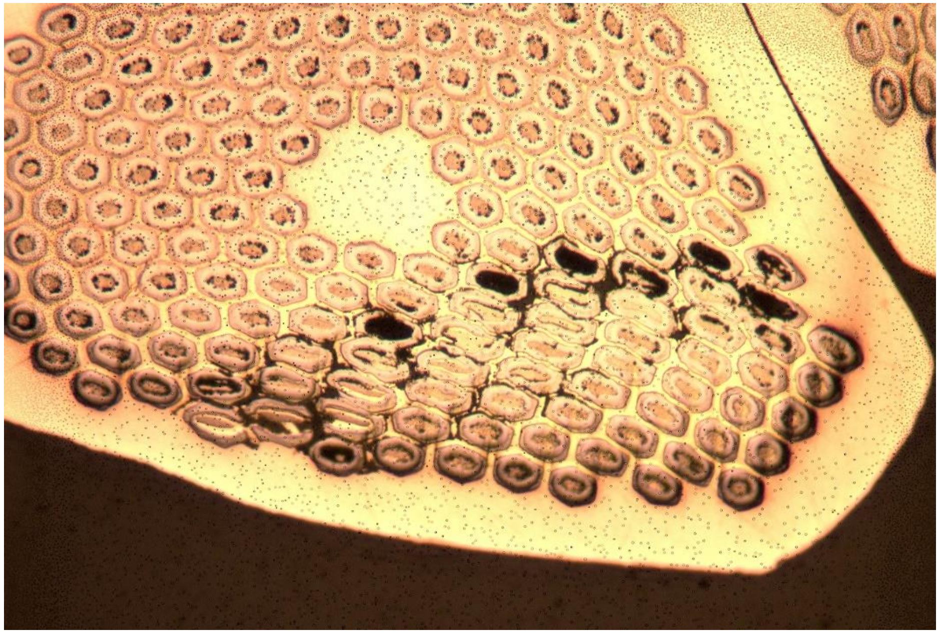


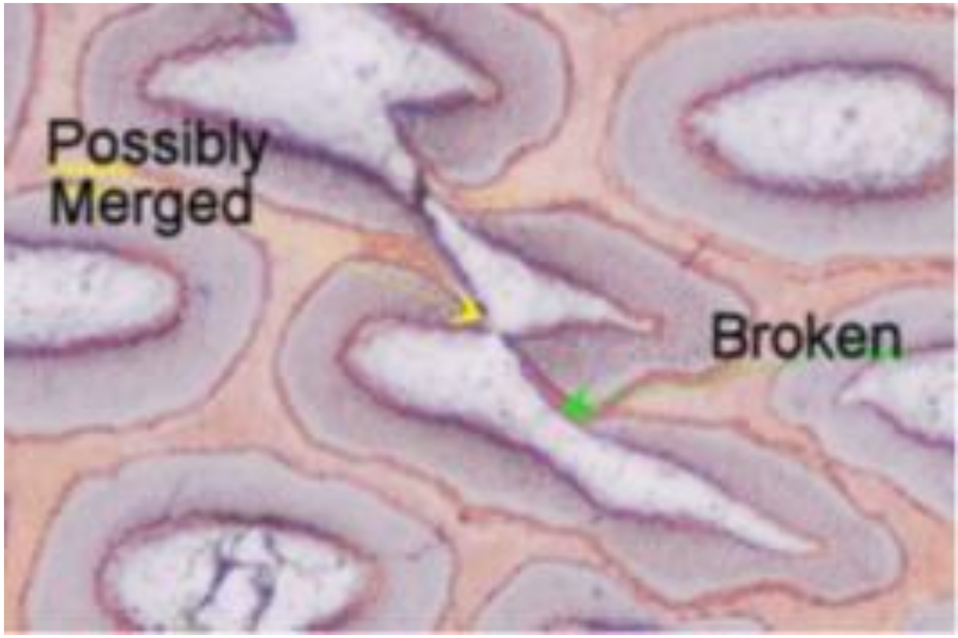
Cable Compaction

Mechanisms of plastic deformation on PIT and RRP wires

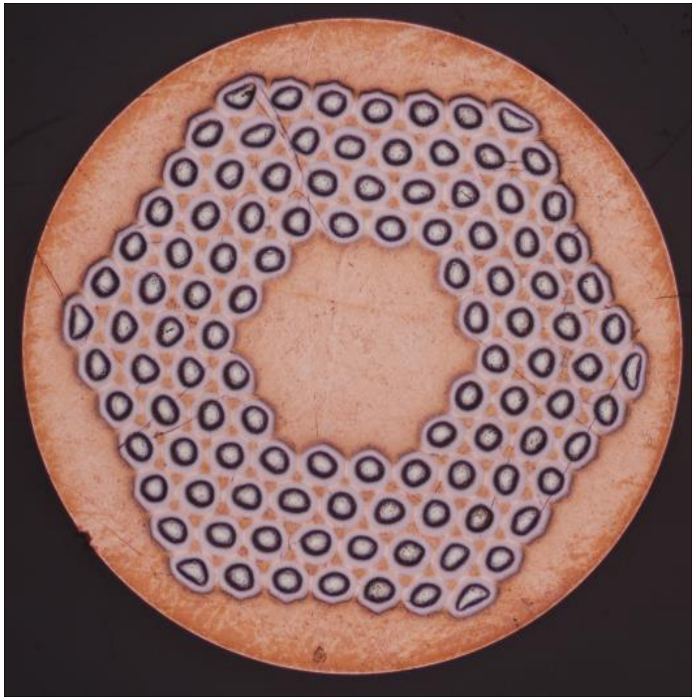
Powder-In-Tube Nb_3Sn

Restacked-Rod Process Nb_3Sn





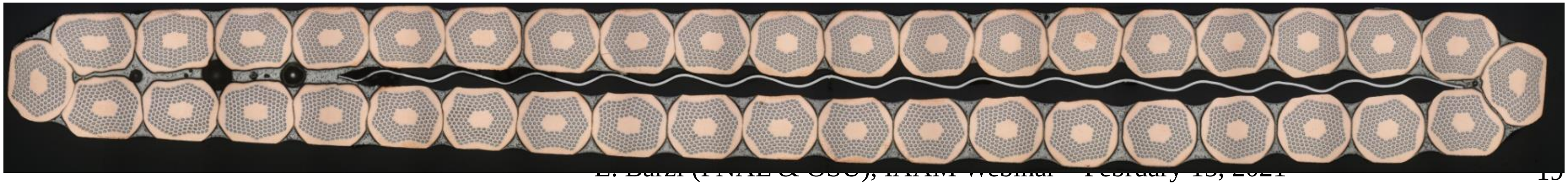
Example of Innovation for Nb_3Sn




Courtesy M. Bossert

Only 10 years ago, none of the existing Nb_3Sn technologies met all of the specifications for high quality magnets. When plastically strained during the cabling process, the filaments deformed and merged together, creating flux jumps instabilities in magnets (see above).

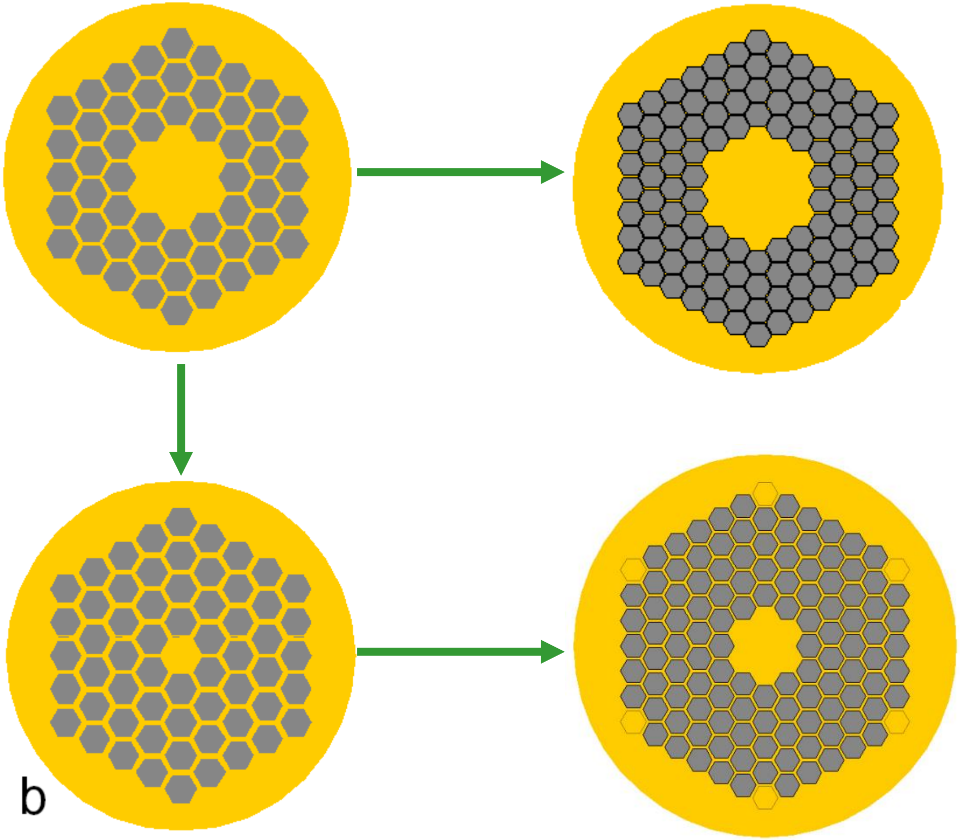
Cross section of a 0.7 mm wire of the Restacked-Rod Process (RRP) type with108 hexagons of Nb_3Sn (top), and Rutherford-type cable made of 40 wires and a central stainless stee ribbon (bottom).



RRP Strand Development with Bruker-OST

Increase Subelement Number

Increase Subelement Spacing



54/61 restack
Jcmax~3000 A/mm^2

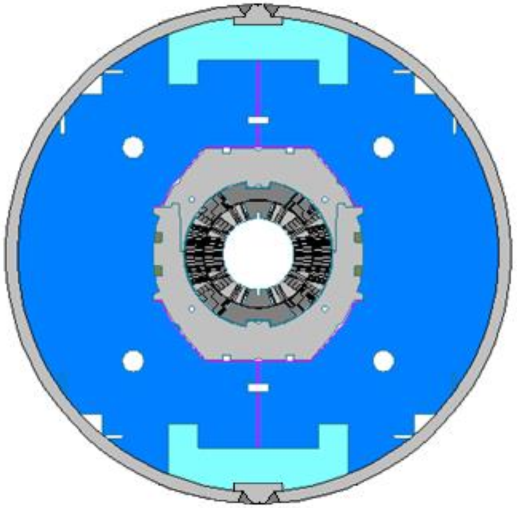
108/127 restack
Jcmax~2400 A/mm^2

60/61 restack with spaced SE's
Jcmax≥3000 A/mm^2

114/127 restack with spaced SE's
Jcmax~3000 A/mm^2

Example of Innovation for Nb_3Sn (cont.)

This kind of damage in the superconductor makes the magnet magnetically unstable, which favors flux jump quenches that prevent reaching the nominal operation current. A few years were invested in understanding the parameters into play and, in collaboration with Oxford Superconducting Technology, new and better Nb_3Sn wires were developed and produced. Eventually prototypes of 11 T Nb_3Sn magnets were able to reach their nominal current both in liquid helium at 4.2 K and also in superfluid helium at 1.9 K, where stability is further challenged by higher critical currents. The technology that was developed at FNAL was transferred to CERN for implementation of these dipoles in the upgraded LHC in 2020. WITH THESE ADVANCED WIRED WE MADE 14.5 T IN A FNAL DIPOLE, i.e. WORLD RECORD FIELD FOR ACCELERATOR MAGNETS.

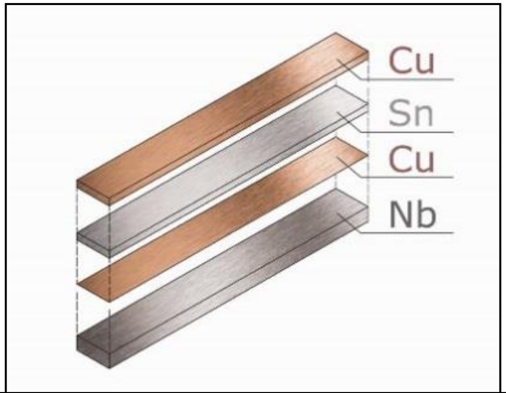


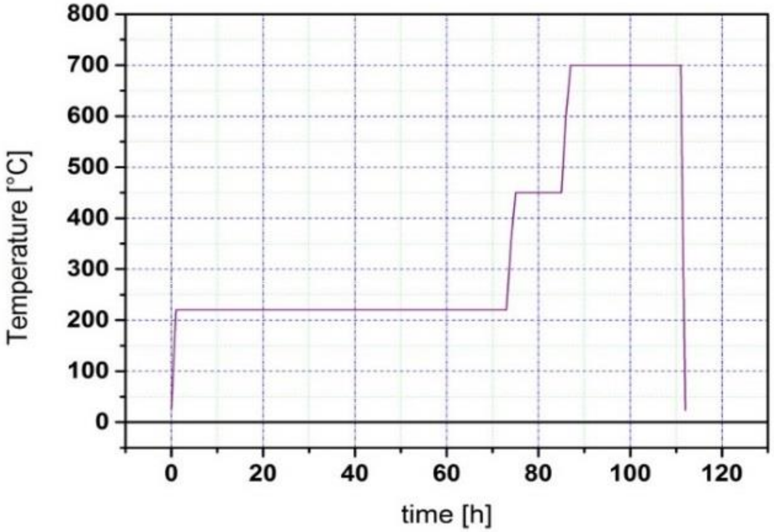
Schematic of a cross section for an 11 T dipole for accelerators (left), and 2 m long prototype (right).

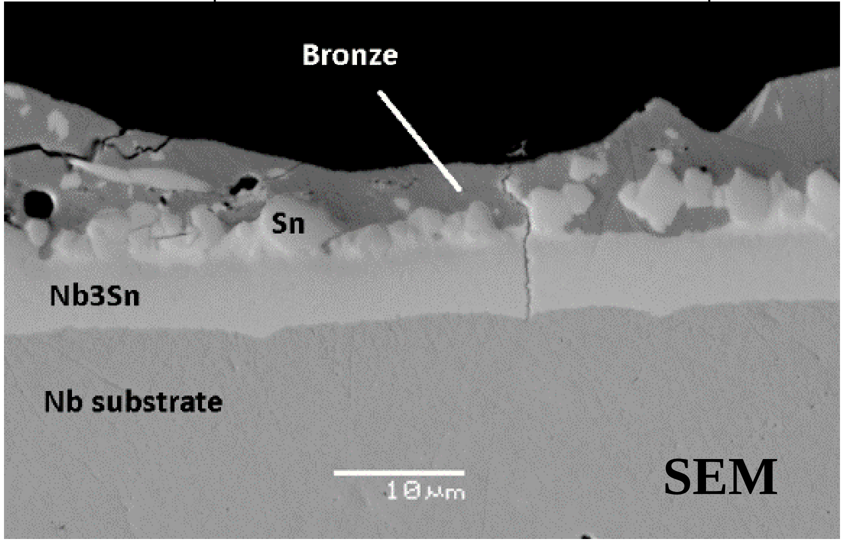
Nb_3Sn Thin Films on Nb

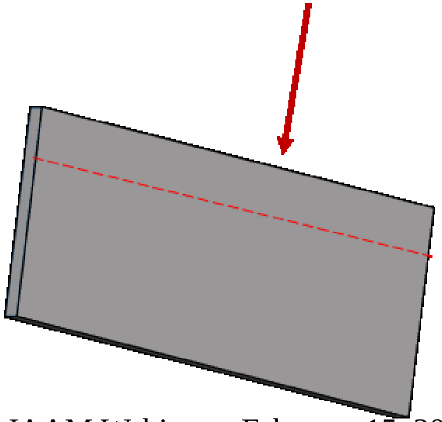
* An electro-chemical deposition technique to produce Nb_3Sn coatings was developed in the last few years by FNAL and the Politecnico di Milano.

* The Nb_3Sn phase is obtained by electrodeposition of Sn layers and Cu intermediate layers onto Nb substrates, followed by high temperature diffusion in inert atmosphere. In 2014, Nb_3Sn superconducting samples between 5.7 and 8.0 μm in thickness were produced with a maximum obtained T_c of 17.68 K and B_{c20} ranging between 22.5 T and 23.8 T.



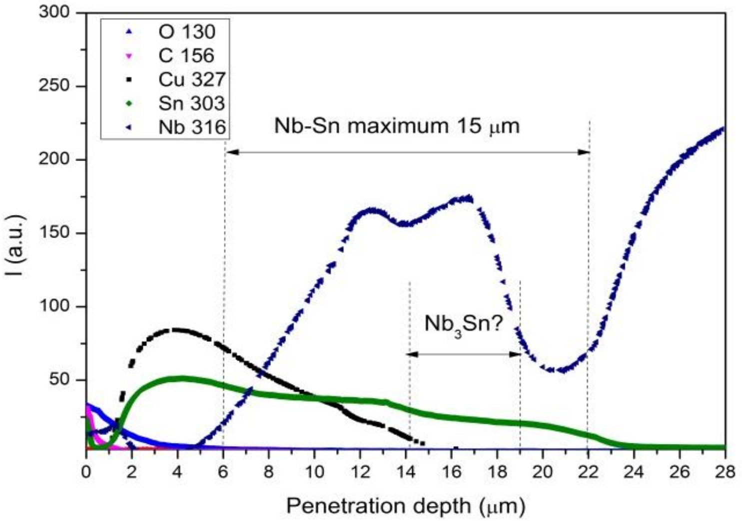




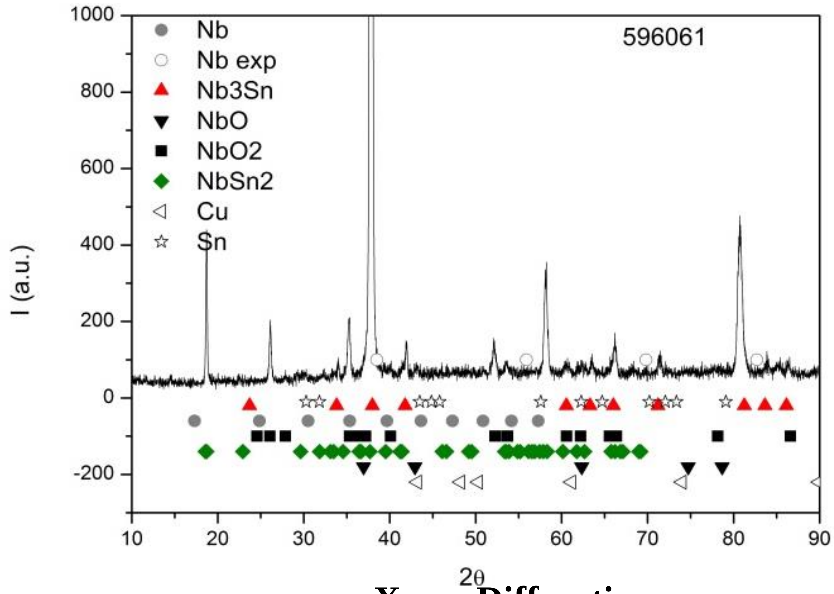


[1] "Synthesis of Superconducting Nb_3Sn Coatings on Nb Substrates", E. Barzi, M. Bestetti, F. Reginato, D. Turrioni and S. Franz, Supercond. Sci. Technol. 29 015009.

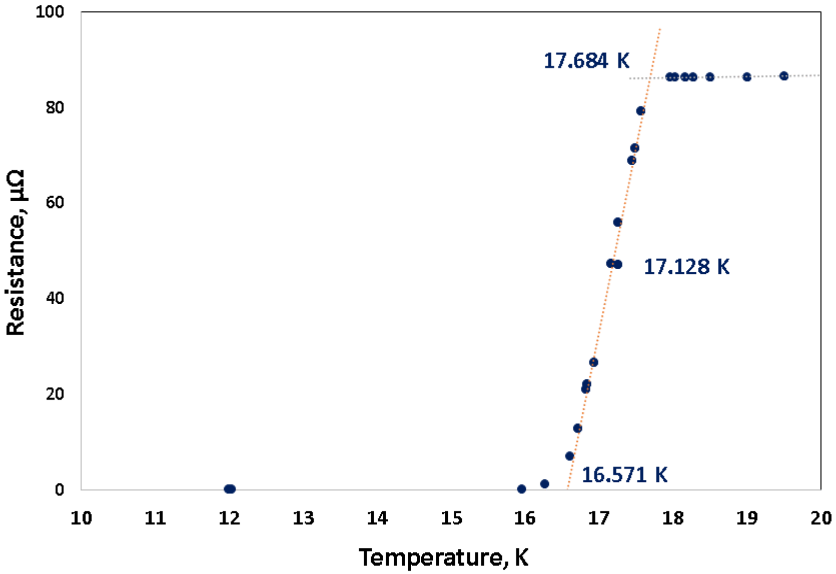
Nb_3Sn Thin Films on Nb –Past Results

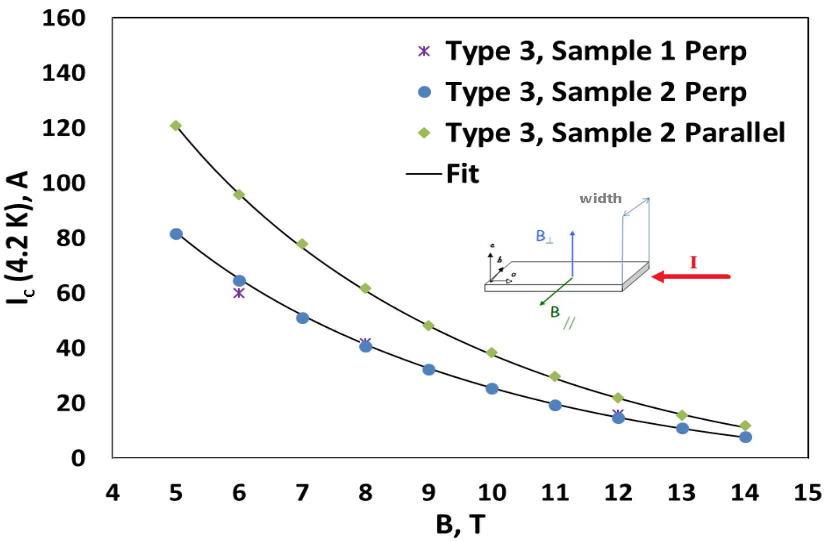


Glow Discharge Optical Emission Spectrometry



X-ray Diffraction

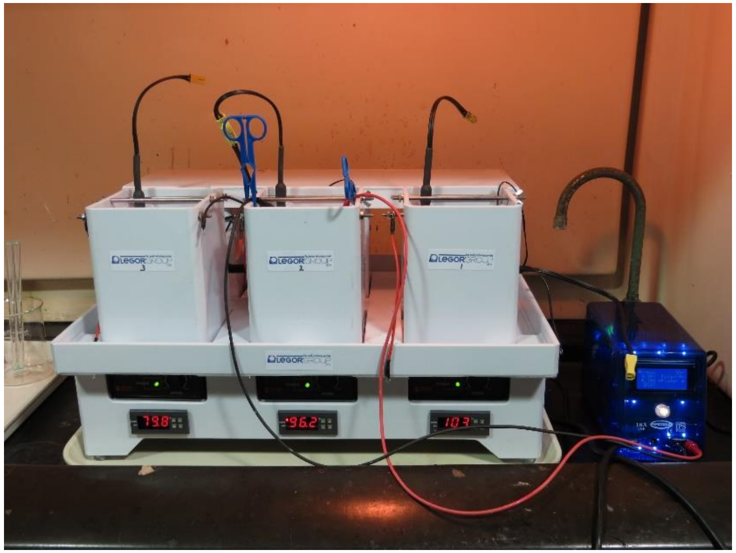




The maximum obtained T_c was 17.68 K and the B_{c20} ranged between 22.5 T and 23.8 T

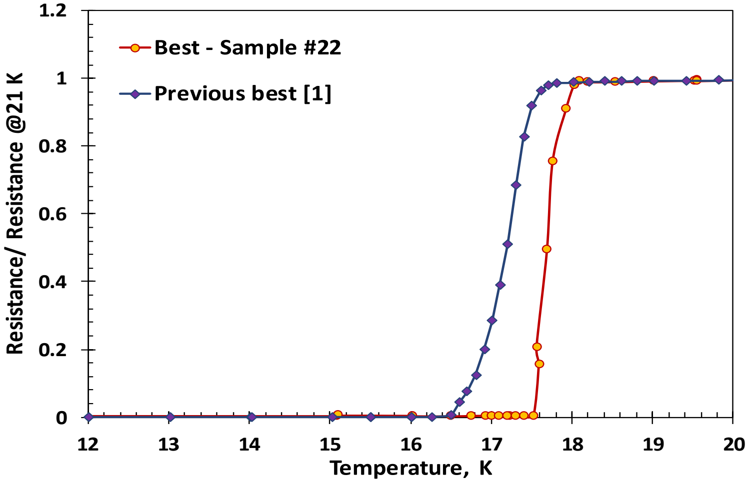
Results & Status of Nb$_3$Sn Thin Films on Nb

Dozens of Nb$_3$Sn film samples were produced on Nb substrate and characterized for SC properties at FNAL.

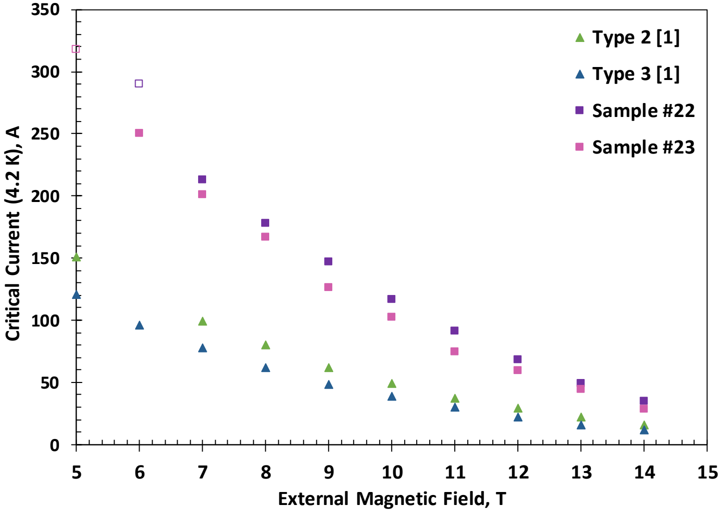


New electrochemical plating setup at FNAL

T_c compared with old [1] samples →



$I_{c\parallel}$(4.2K, B) compared with old [1] samples →



SC Properties of best new and old [1] Nb$_3$Sn films

	$I_{c\parallel}$(4.2K, 12T), A	T_{c0}, K	B_{c2o}, T
Type 2 [1]	29	17.1	23.2
Sample #22	51^{*}	17.7	23.2

Conclusions

- **The work on optimization of Nb_3Sn wires for 15-16 T accelerator magnets continues in collaboration with industry and universities:**
  - **To produce further J_c increase at 15 T through Artificial Pinning Centers**
  - **For larger heat capacity through insertion of high-Cp elements either in the wire or in the Rutherford cable**

- **In addition to the 14.5 Tesla record field in an accelerator dipole at Fermilab, the Nb_3Sn wire that was developed for High Energy Physics was also recently used for Nb_3Sn undulators for the Argonne National Lab Advanced Photon Source, within Basic Energy Sciences (BES), achieving the best performance ever in these planar undulator magnets.**

Acknowledgments

- **Funding: Work is funded by Fermi Research Alliance, LLC, under contract No. DE-AC02-07CH11359 with the U.S. Department of Energy and supported by the U.S. Magnet Development Program (US-MDP).**