Technical Division R&D Retreat
January 26, 2016

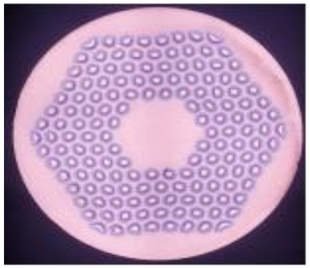
Superconducting Materials R&D

Emanuela Barzi, Fermilab

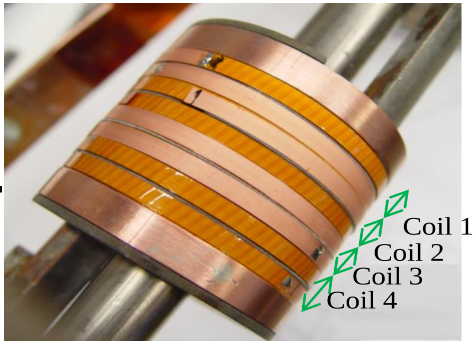
Outline

- Mission of superconducting R&D
- Experimental setups
- Examples of results
- Examples of innovative contributions
- Latest wire R&D for 15 T dipole
- Cable R&D for 15 T dipole
- SBIR's
- US and International Collaborations
- Conference Organization/Outreach
- IMPACT
- Next steps

Mission of Superconducting R&D



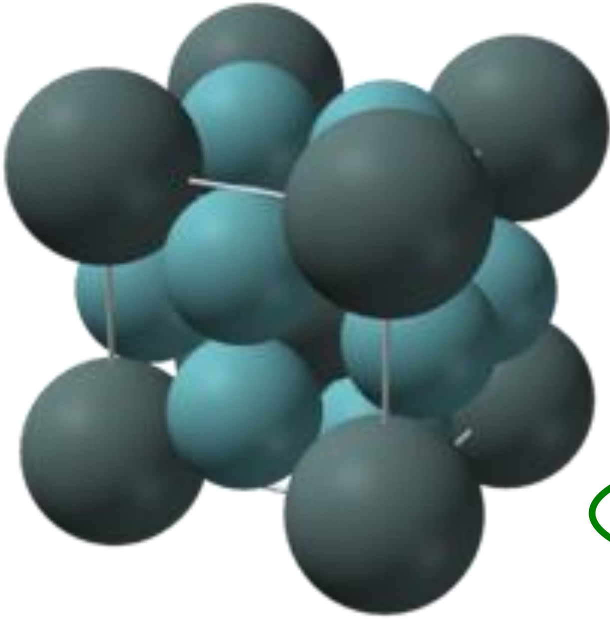
The Mission of the Superconductor R&D is to understand and improve scientific and engineering aspects of superconducting strands and cables for accelerator magnets. A most pressing goal of this program now is to reach production level for the best possible Nb_3Sn conductor for the 15 T Dipoles and HTS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

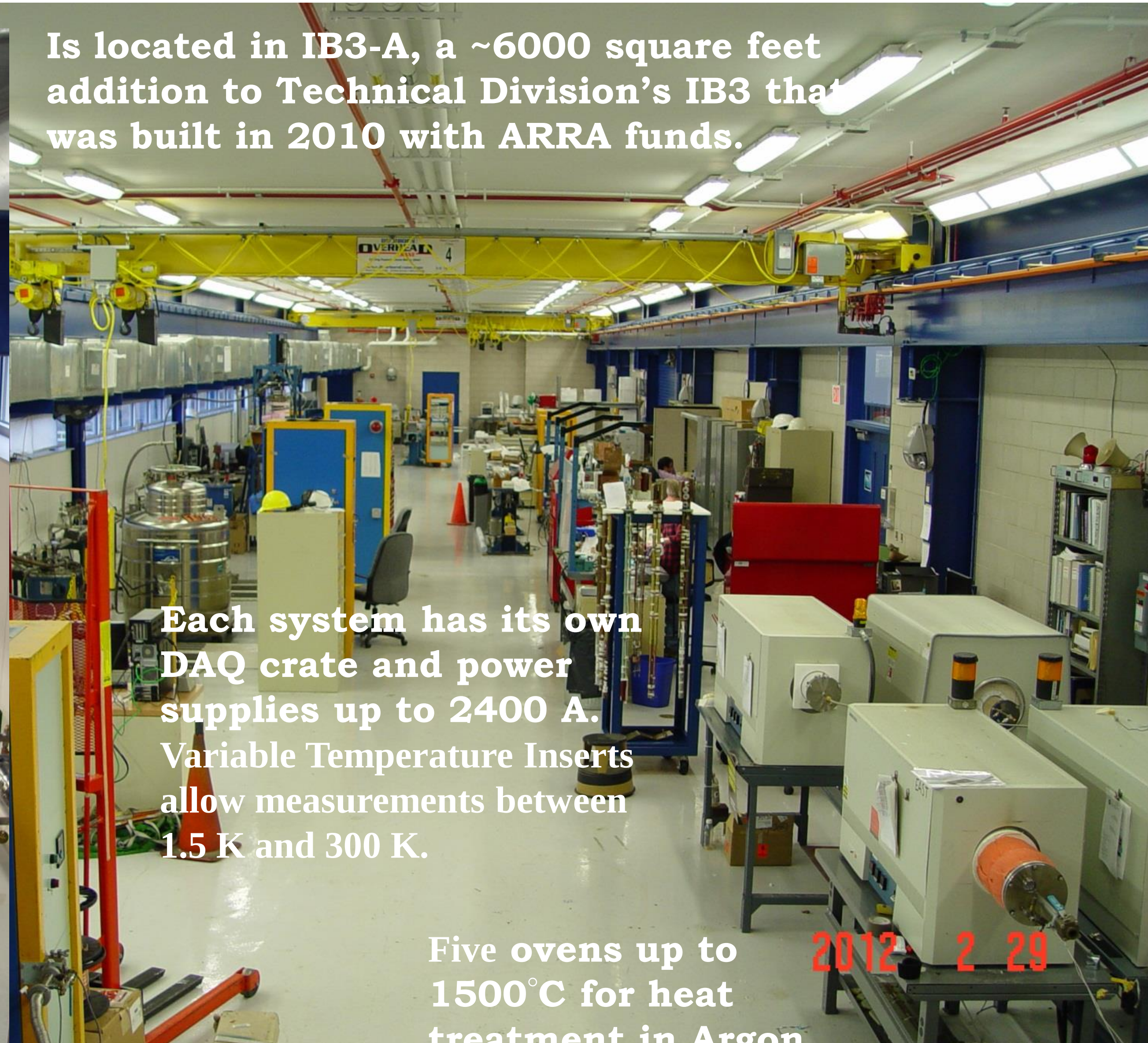
Target Specifications for HEP Conductor



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

Strand&Cable R&D Lab in IB3A



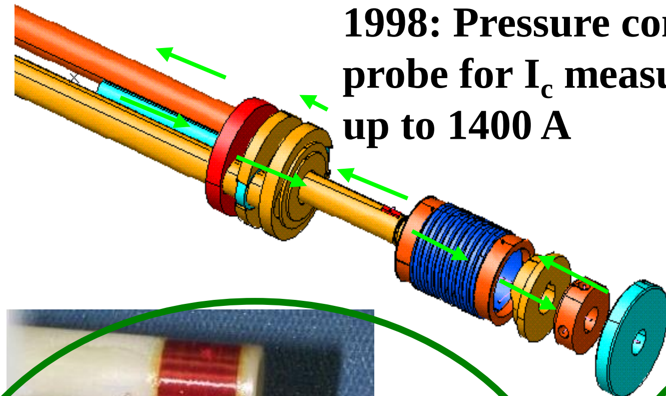
Four magnetic cryostats with up to 15T/17 T background field, and with cold apertures between 64 mm and 147 mm are connected to new vent and vacuum systems.

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 300 K.

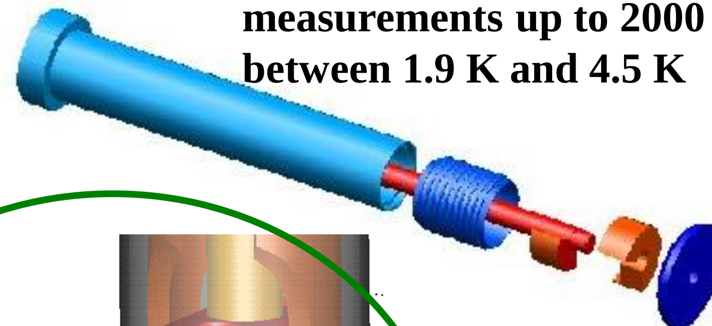
Five ovens up to 1500°C for heat treatment in Argon

Experimental Setups

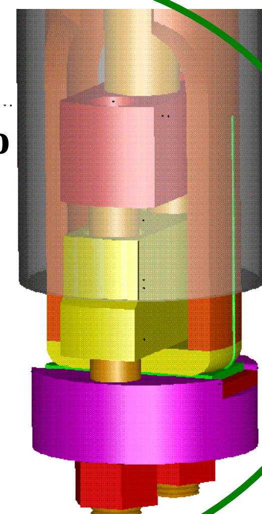


1998: Pressure contact probe for I_c measurements up to 1400 A

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

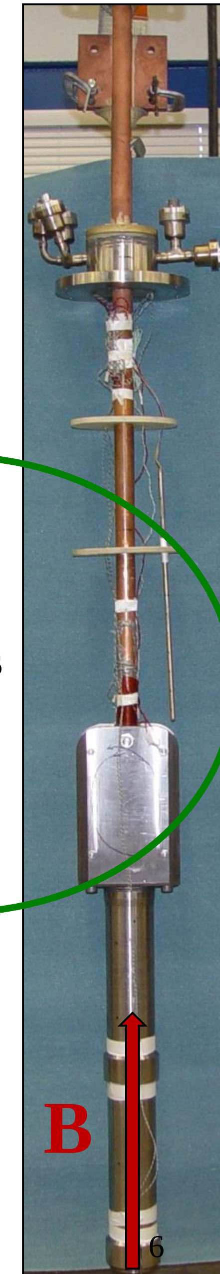


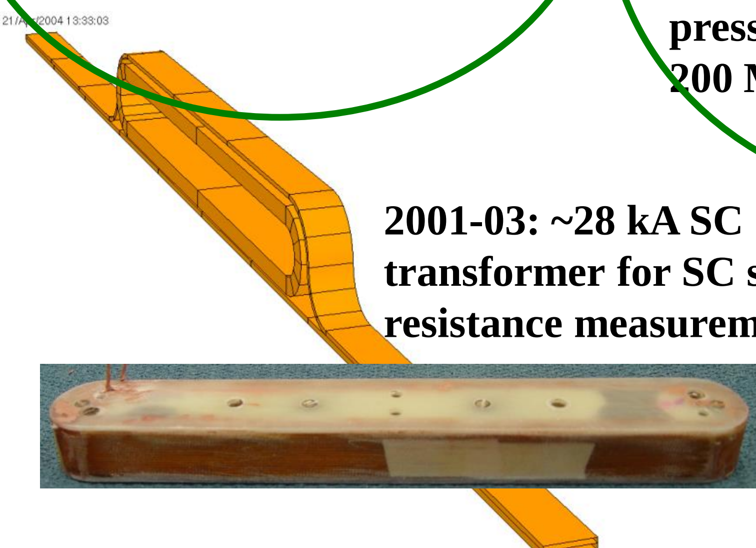
1999: Balanced coil magnetometer for magnetization measurements



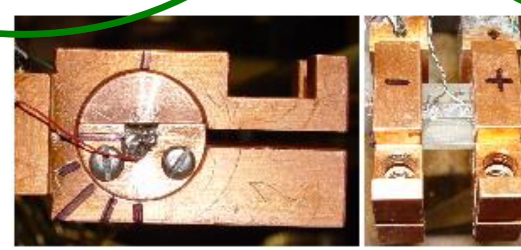
2001: Device to test I_c sensitivity to uniaxial transverse pressure up to 200 MPa

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



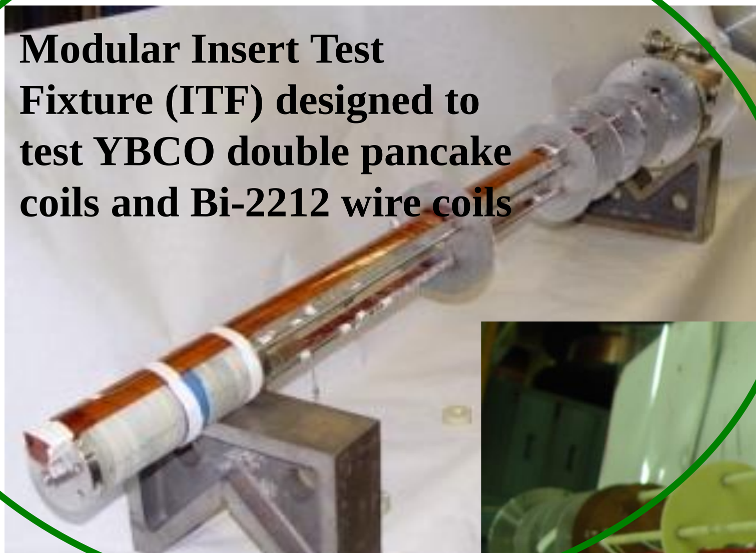


2001-03: ~28 kA SC transformer for SC splice resistance measurements

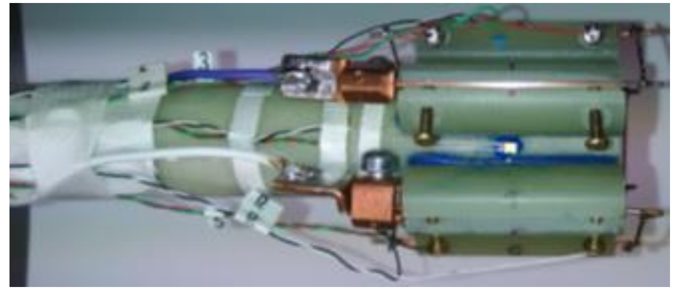


2007: Probe to measure I_c dependence on field orientation for anisotropic HTS wires.

Experimental Setups (cont.)

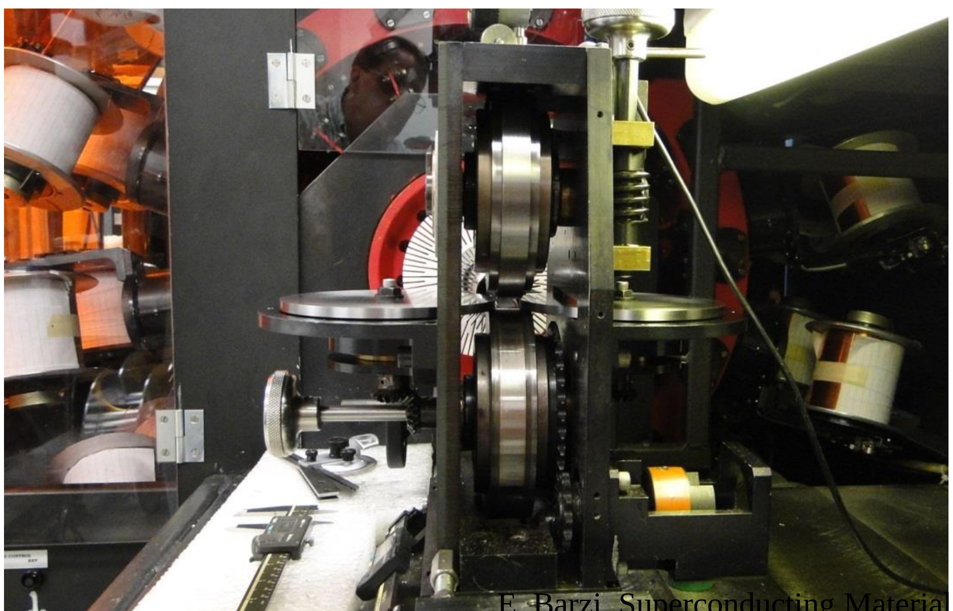


Modular Insert Test Fixture (ITF) designed to test YBCO double pancake coils and Bi-2212 wire coils

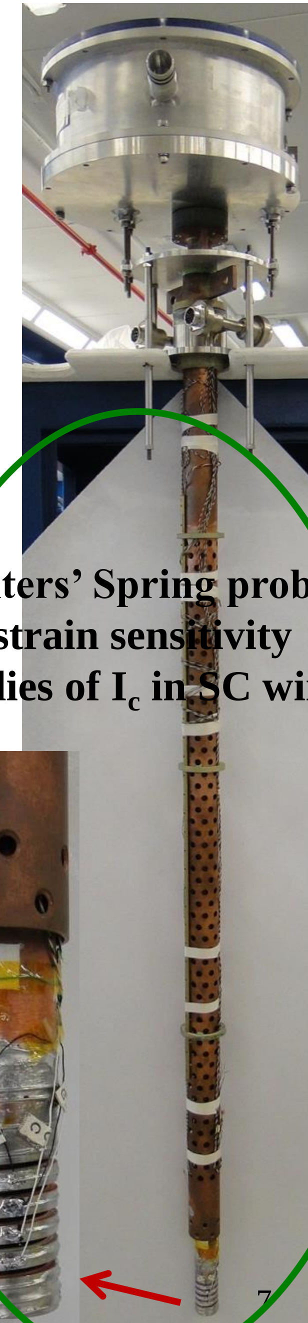


New RRR probe for wire and bulk

New Hall probe system to measure shielding of bulk MgB_2 tubes



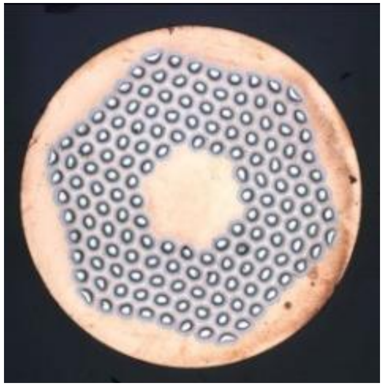
New keystoned turkhead for Rutherford cable fabrication in 1 step



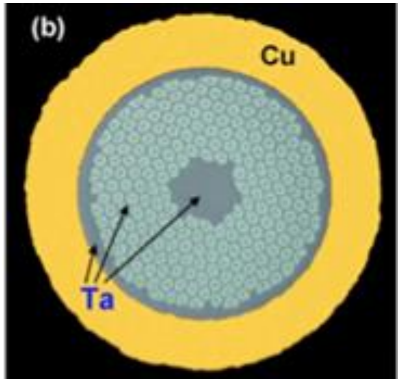
Walters' Spring probe for strain sensitivity studies of I_c in SC wir

Superconducting Materials

Round Wires



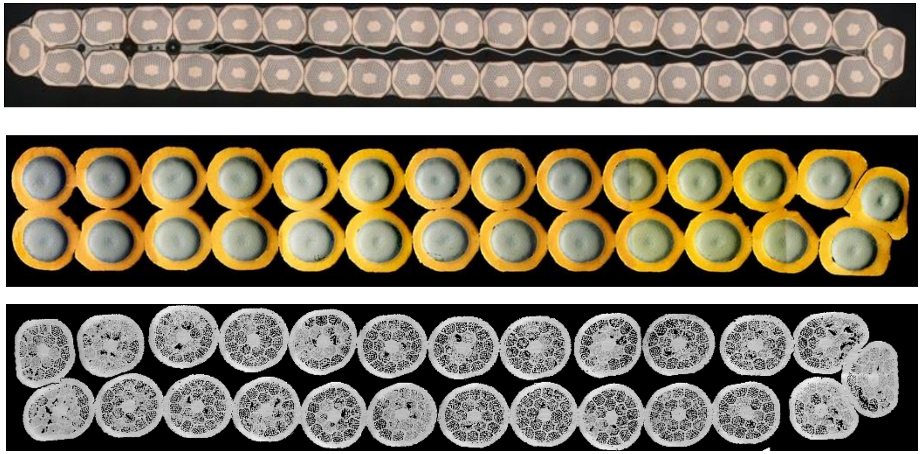
Nb_3Sn

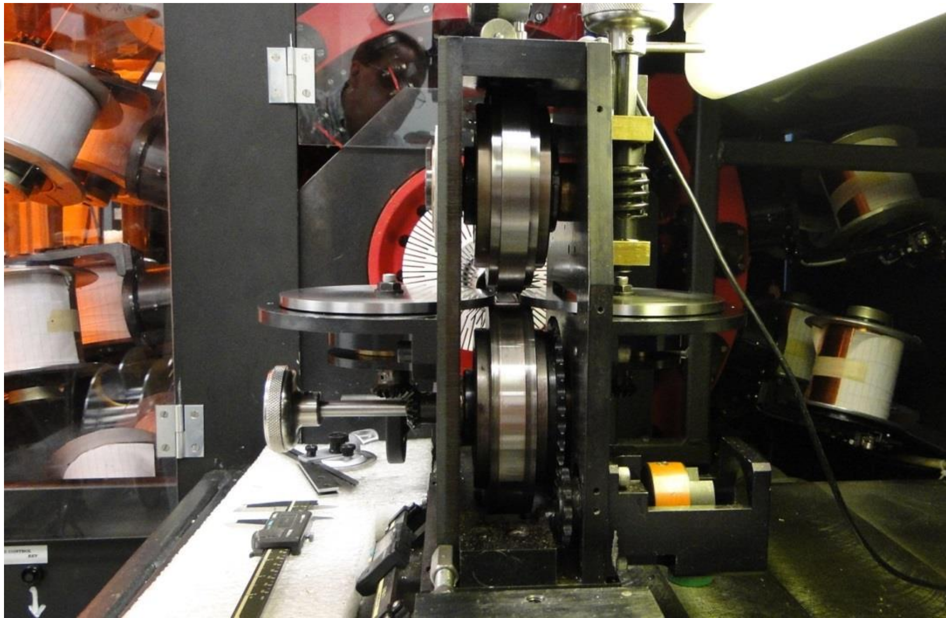


Nb_3Al

Bi-2212

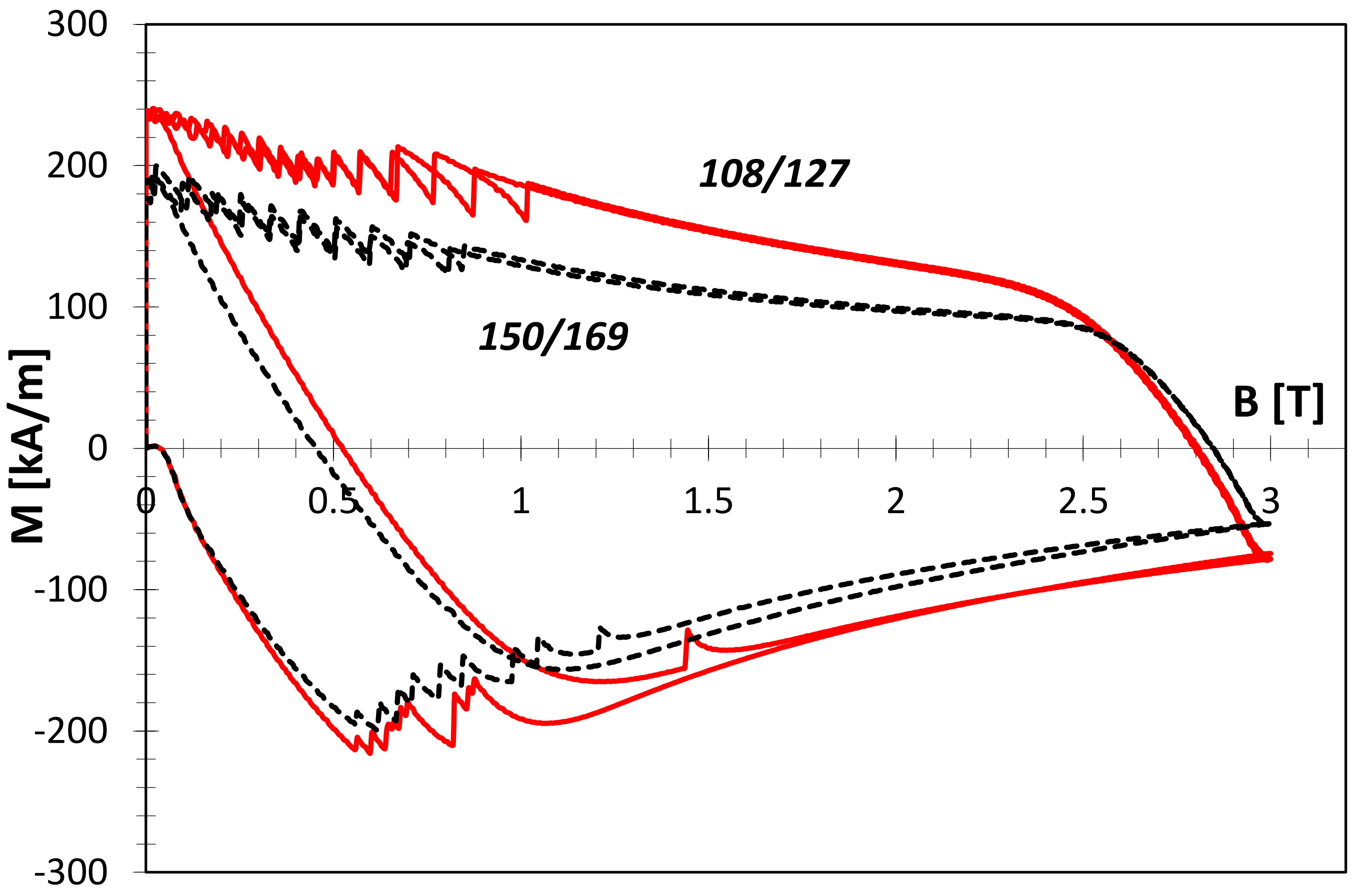
Rutherford-type Cables





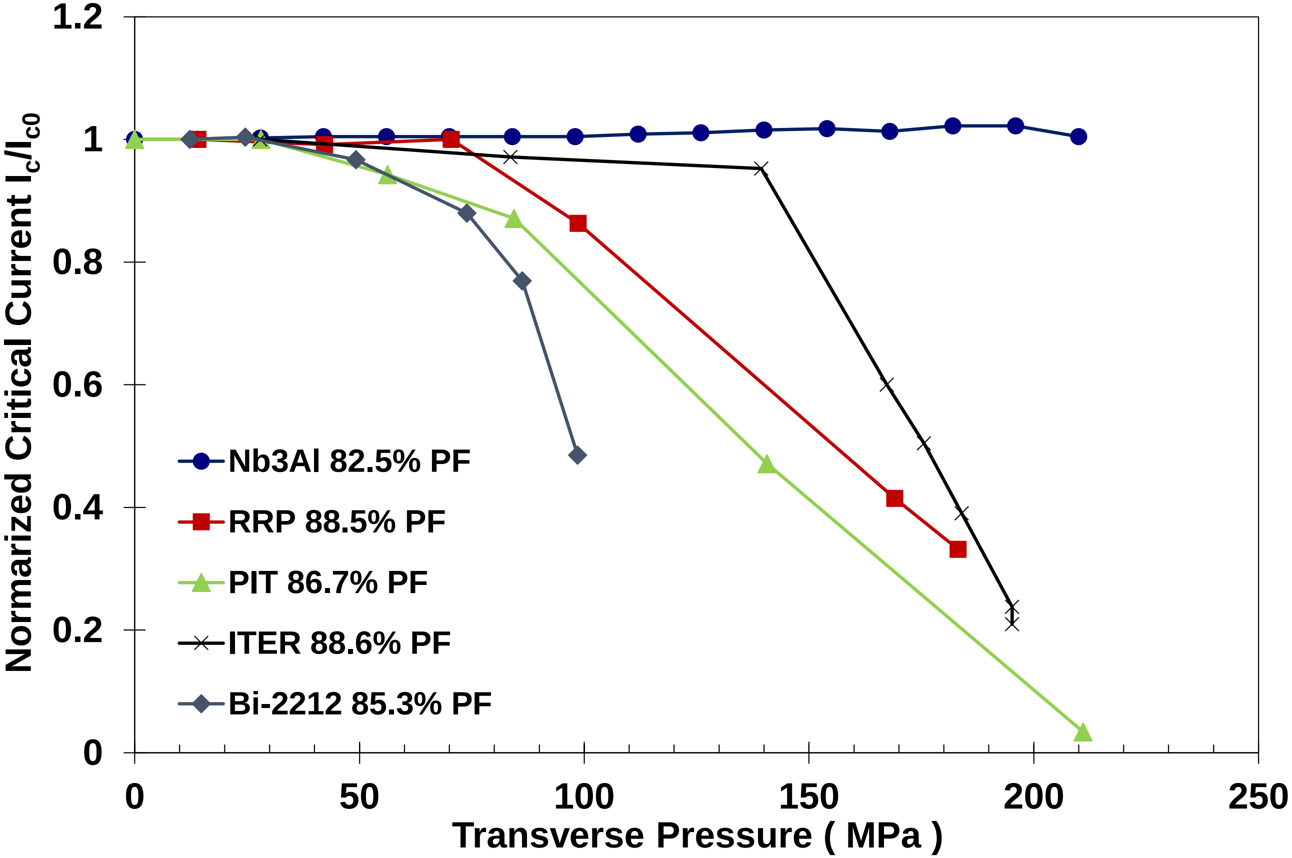
Magnetization

1999: Balanced coil magnetometer for magnetization measurements



Magnetization at 4.2 K per total strand volume for two 0.7 mm RRP® wires between 0 and 3 T

Uni-axial Transverse Pressure



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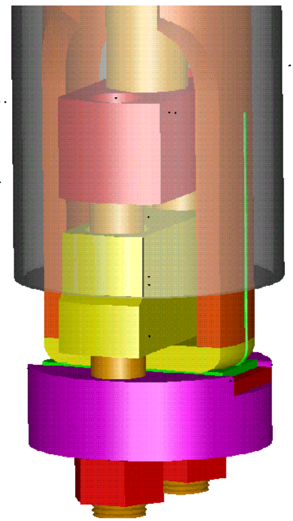
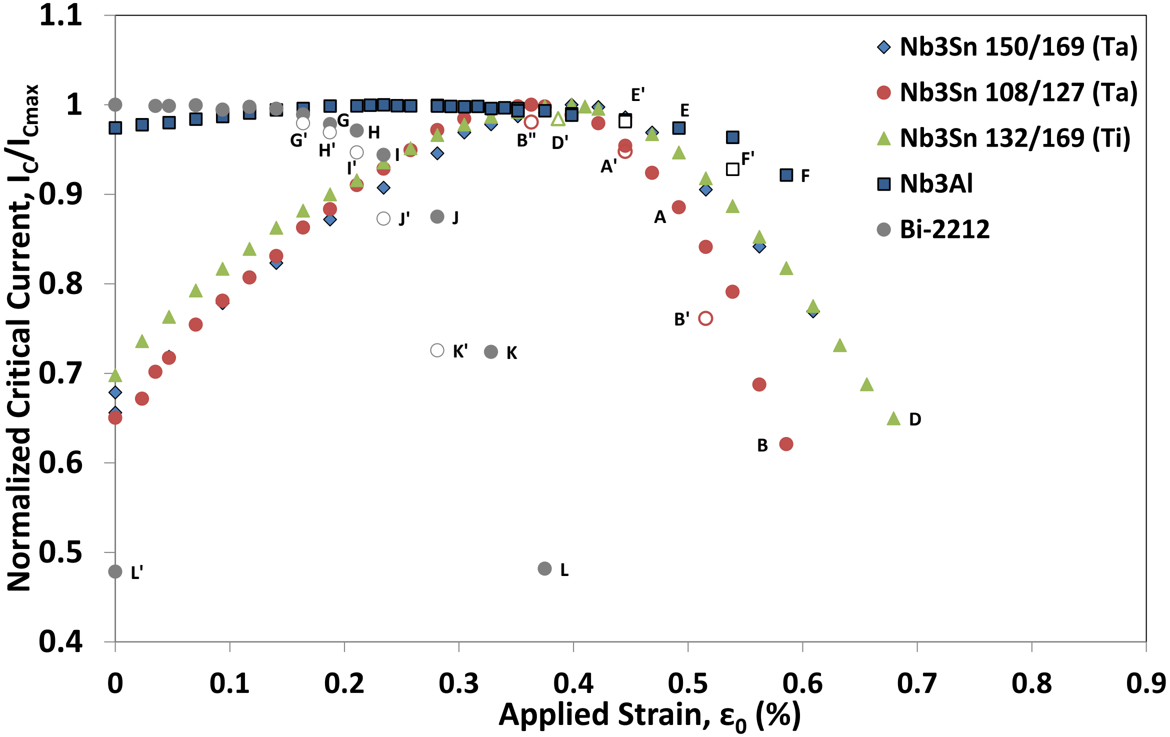
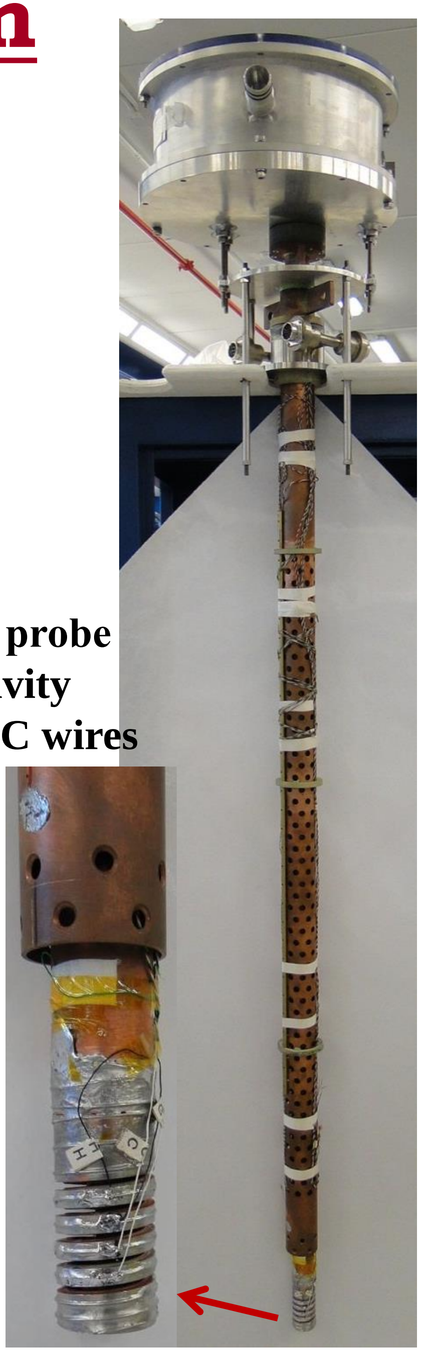


Normalized I_c(4.2K,12T) vs. uni-axial transverse pressure on Rutherford cable face for a number of superconductors

I_c Sensitivity to Axial Strain

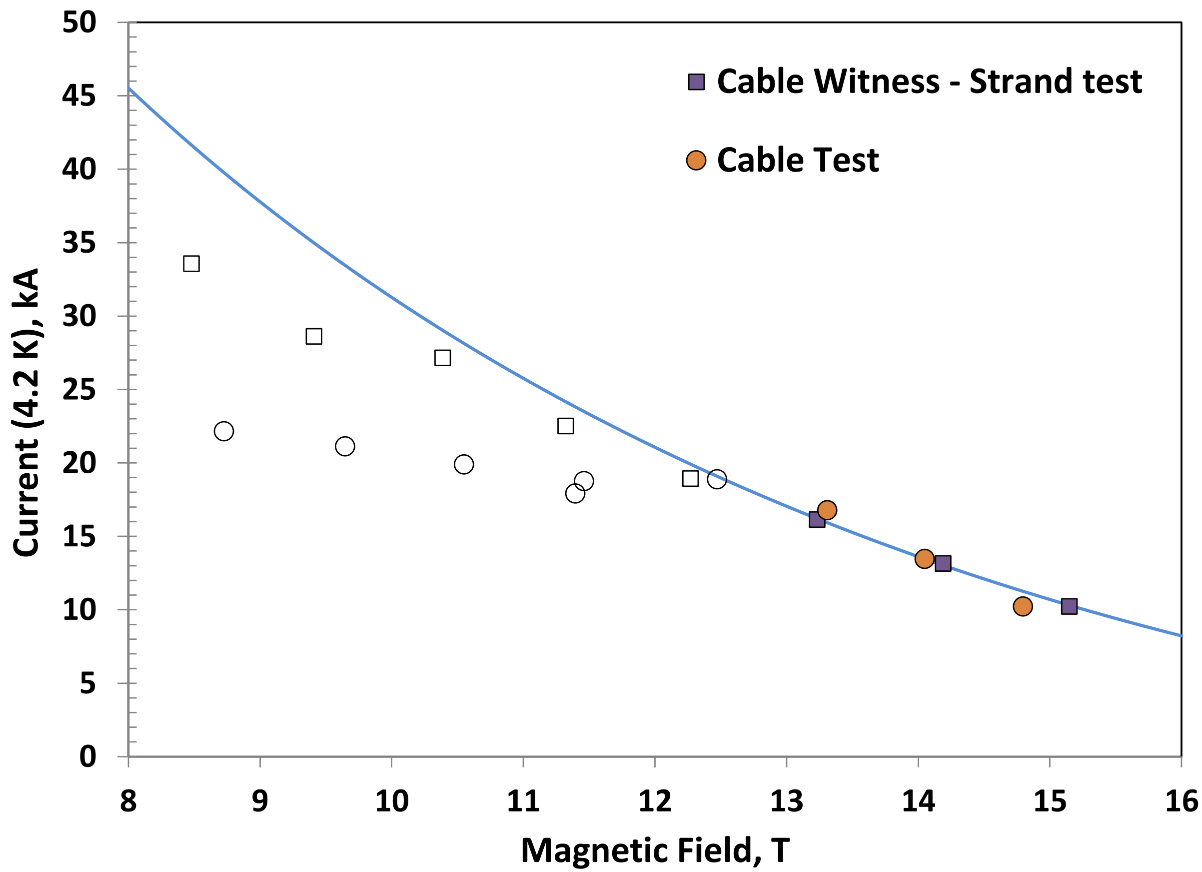


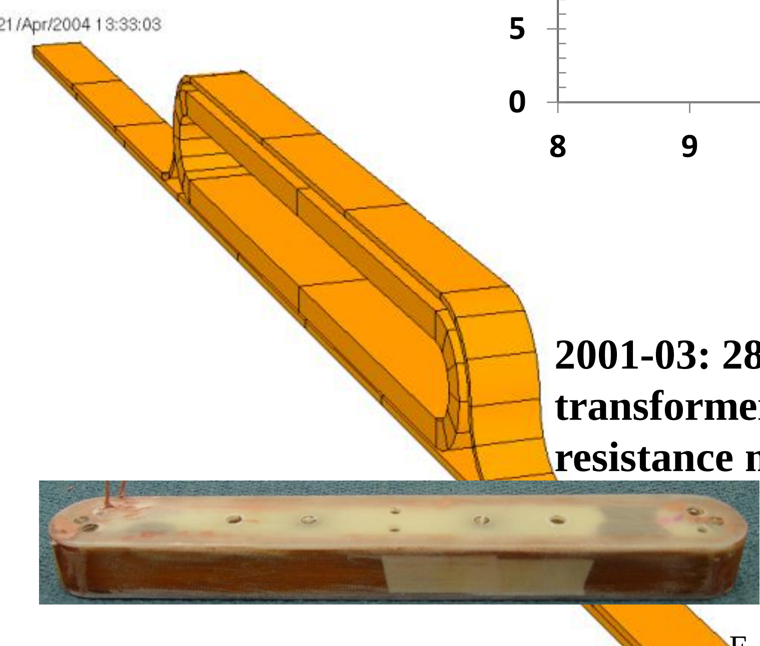
Normalized I_c(4.2 K, 15 T) as function of longitudinal intrinsic strain for a number of superconductors



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

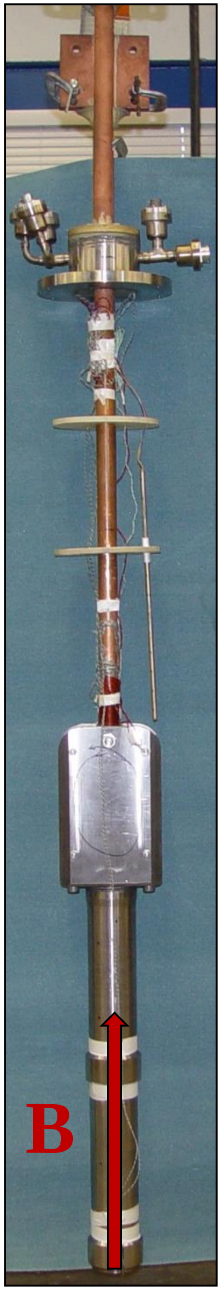
Cable Current Test



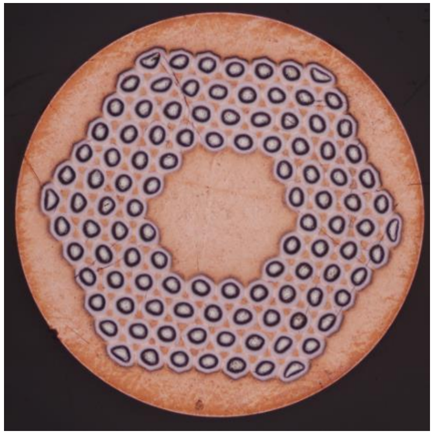


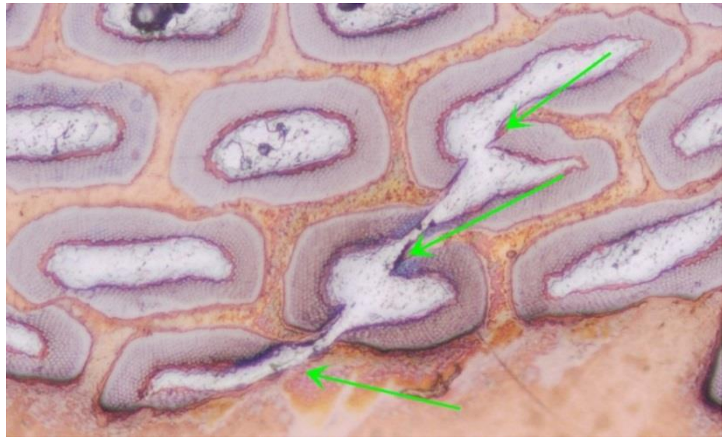
2001-03: 28 kA SC transformer for SC splice resistance measurements

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



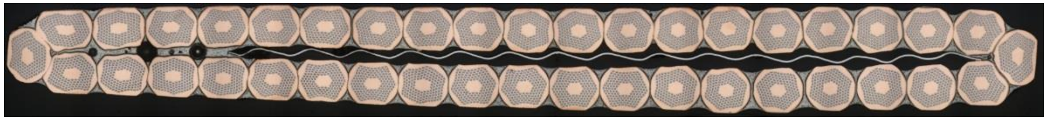
Example of Innovation for Nb_3Sn

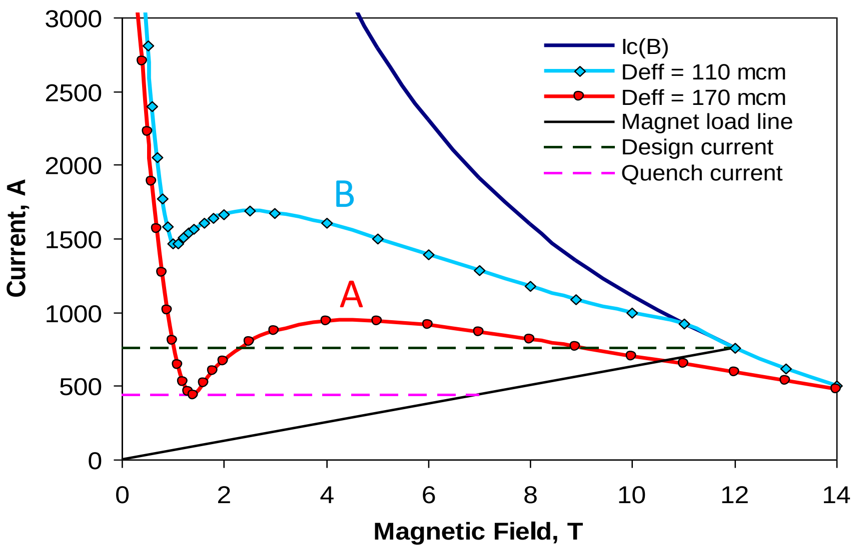




Only 10 years ago, none of the existing Nb_3Sn technologies met all of the specifications for high quality magnets. When plastically strained during the cabling process, the filaments deformed and merged together, creating even larger flux jumps instabilities in magnets.

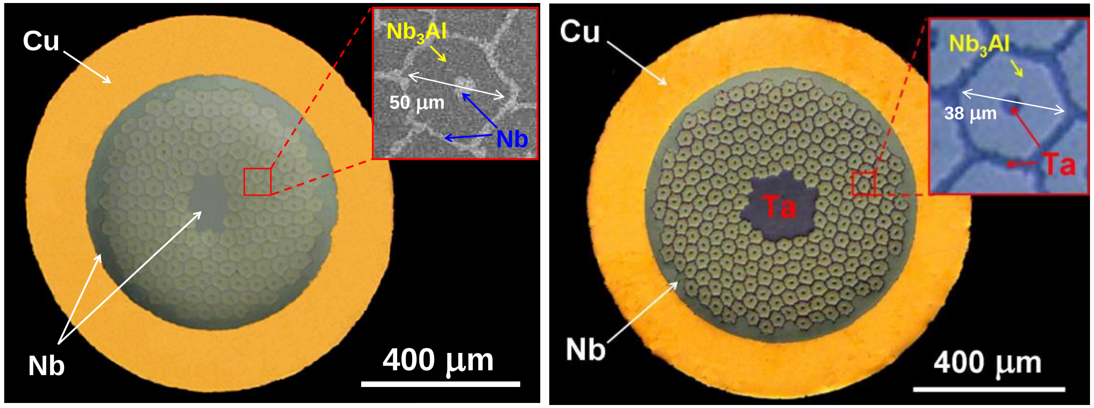
Cross section of a 0.7 mm wire of the Restacked Rod Process (RRP) type with108 hexagons of Nb_3Sn (top), and Rutherford-type cable made of 40 wires and a central stainless steel core (bottom).





This kind of damage in the superconductor makes the magnet quench before reaching its operation current. In collaboration with Oxford Superconducting Technology, new and better Nb_3Sn wires were developed and produced. Eventually 10T small racetracks and dipoles were able to reach their nominal current both at 4.2 K and at 1.9K, where stability is further challenged by higher critical currents.

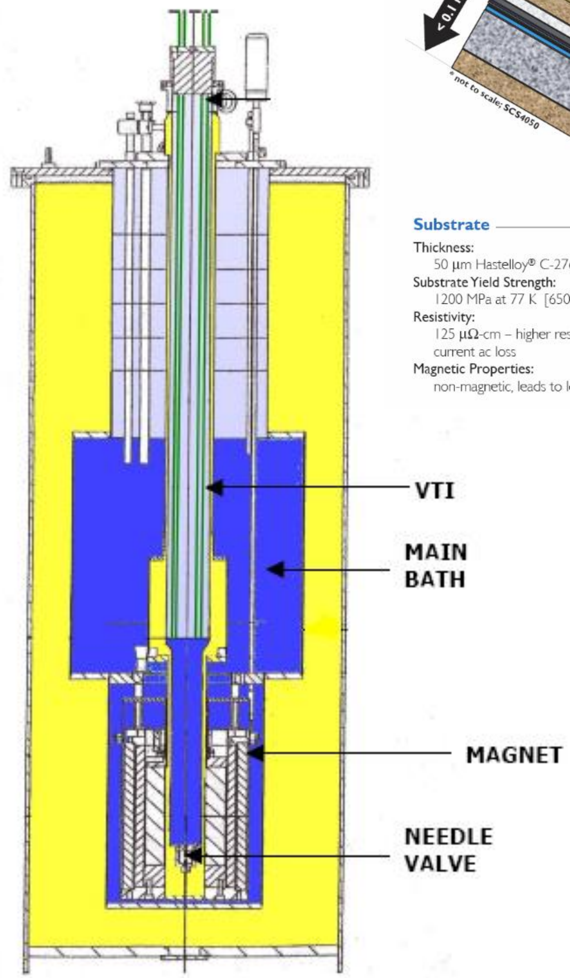
Innovations for Nb_3Al

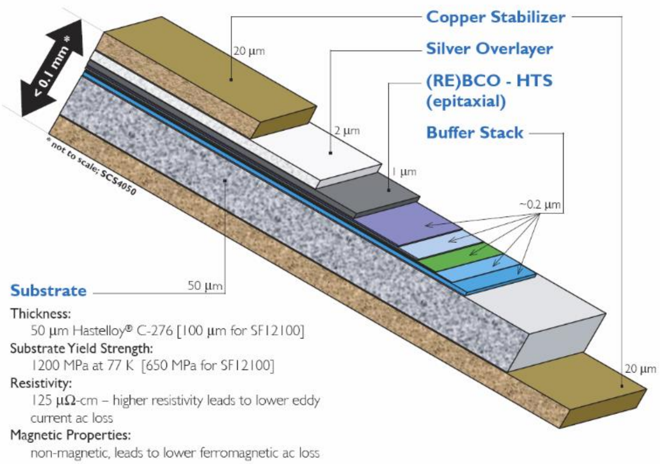


Cross section of a 1 mm wire of Nb_3Al with 144 superconducting hexagons within a Nb matrix (left), and with 222 superconducting hexagons in a Ta matrix (center).

Nb_3Al requires heat treatment at very high temperatures (1900°C) to become superconducting, and this had prevented coating it with Cu as stabilizer. This obstacle had slowed down progress in the US. Then in 2005 in Japan, Dr. Akihiro Kikuchi developed a method to coat the superconducting precursors with Cu. This stimulated new research and, in collaboration with a Japanese team, we were able to produce Rutherford cables and small magnet coils (see right) in excess of 10 Tesla. This was the first time that the Nb_3Al conductor was shown to work in a magnet. Now this technology is available, for instance for fusion magnets. This achievement was recognized by the Japanese "Superconductor Science and Technology Prize".

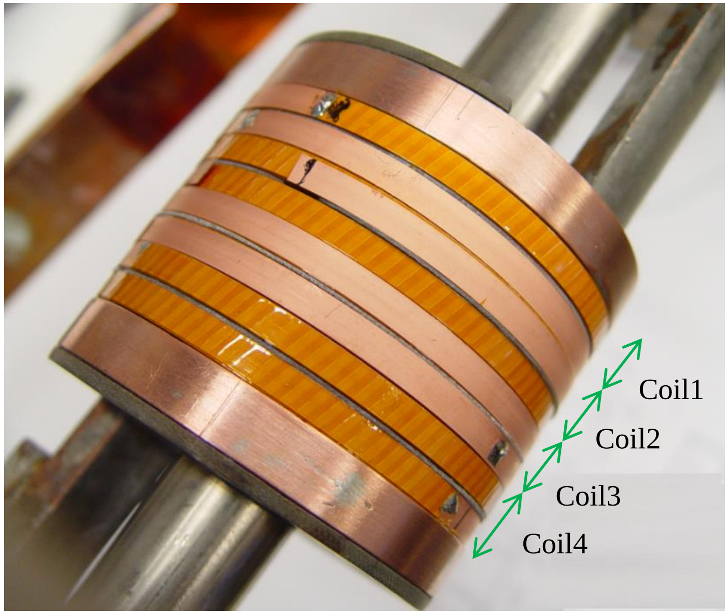
Record Field at FNAL with YBCO Coil





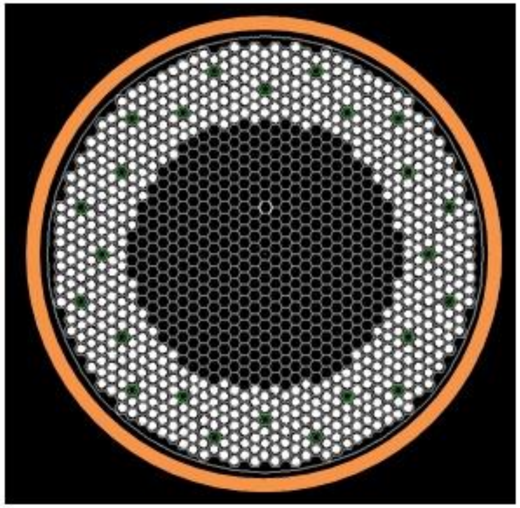
14 T solenoid with 77 mm bore

B_{max}(single pancake)=18.2 T



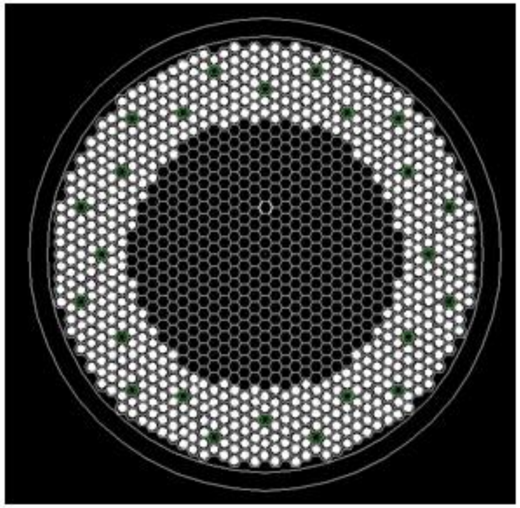
B_{max}=21.5 T (7.5 T in a 14 T background)

RRP Strand R&D



Ta diffusion barrier for Ti doped strand

Ti doped strand reacts faster at lower temperatures than Ta doped – if diffusion barrier is Ta doped and the filaments are Ti doped, will it be possible to react at a low temperature and obtain a more effective (slower reacting) diffusion barrier?



LAR adjustment for smaller Ds strand

Present LAR (~0.2) works well for D_s>50 microns. For D_s<50 microns, it is possible that a slightly larger LAR will be more effective in terms of J_c?

OXFORD INSTRUMENTS

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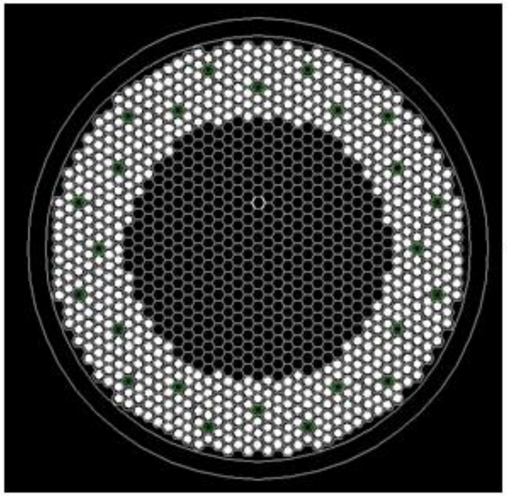
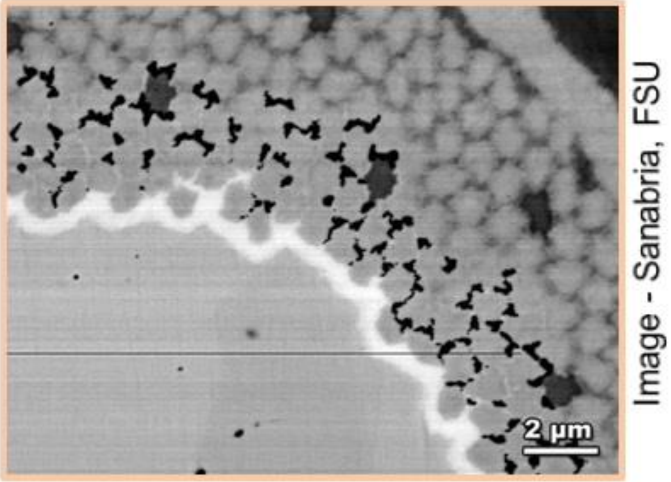
RRP Strand R&D (cont.)





Graded LAR in a Subelement

Standard subelement – There is a complex interaction between the nausite layer and effect on tin diffusion and large Nb_3Sn grain formation on inner ring. For small D_s strand, we are trying a new subelement with graded LAR to alter nausite formation on inner ring and add additional effective barrier thickness to OD.

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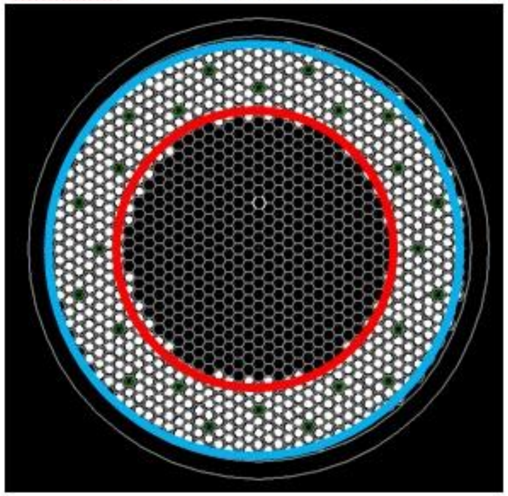

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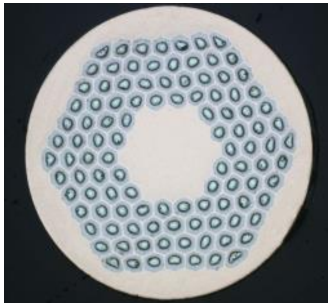
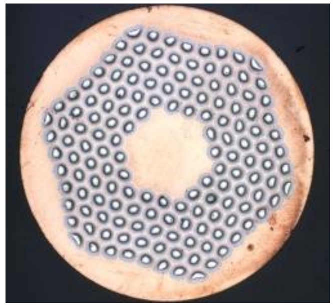
15 T Dipole Cable R&D





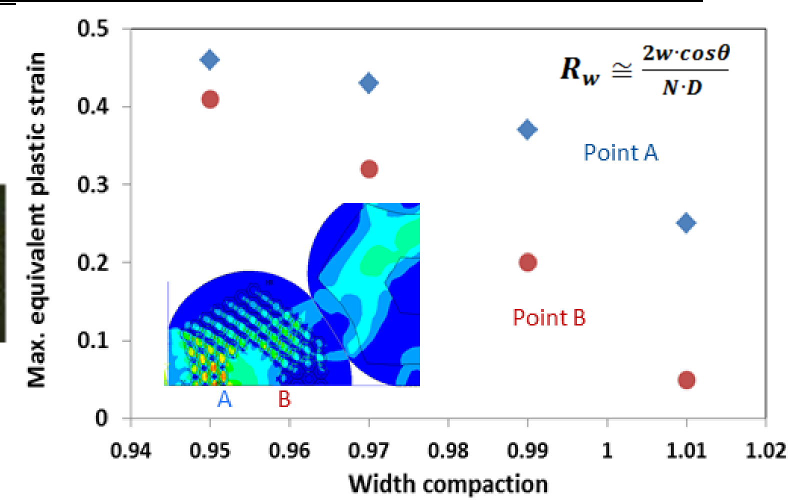
CABLES FOR DEVELOPMENT OF 15 T DIPOLE

Cable ID	RRP® wire design	Width (mm)	Mid-thickness (mm)	Lay angle, (deg)	*PF* (%)
1	RRP1, RRP2	14.84	1.804	16	86.7
2	"	14.87	1.759	16	88.7
3	"	14.82	1.737	16	90.2
4	"	14.85	1.707	16	91.6
5	"	14.89	1.689	16	92.3
6	RRP3	14.89	1.835	17.5	85.4
7	"	14.89	1.812	17.5	86.5
8	"	14.93	1.786	17.5	87.6
9	"	14.94	1.762	17.5	88.7
10	"	14.94	1.736	17.2	89.9
11	"	14.94	1.710	17.4	91.4
12	"	14.94	1.685	17.6	92.8
13	RRP3, pre-treated	14.90	1.836	16.9	85.0
14	"	14.89	1.813	17.0	86.2
15	"	14.92	1.787	17.0	87.3
16	"	14.91	1.766	17.0	88.4
17	"	14.91	1.734	17.3	90.2
18	"	14.94	1.710	17.3	91.3
19	"	14.90	1.684	17.0	92.8

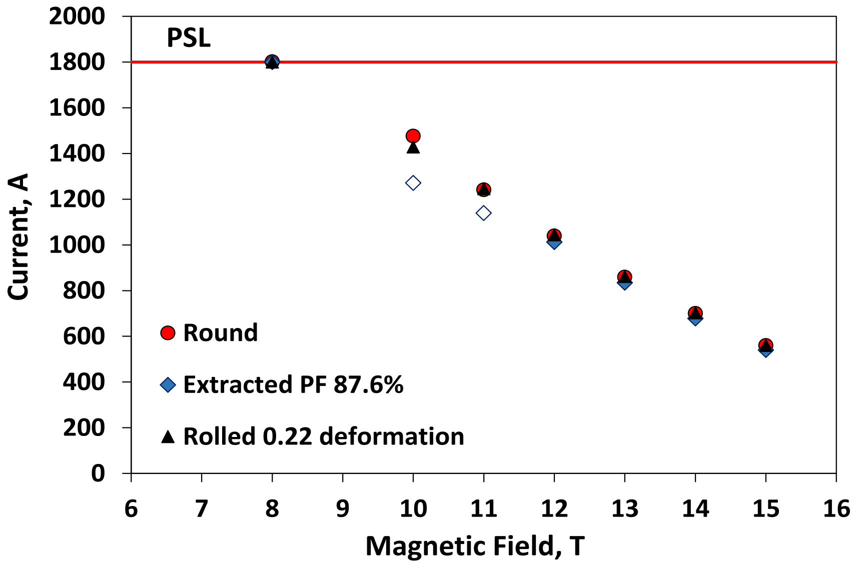
STRAND PARAMETERS – OST DATA

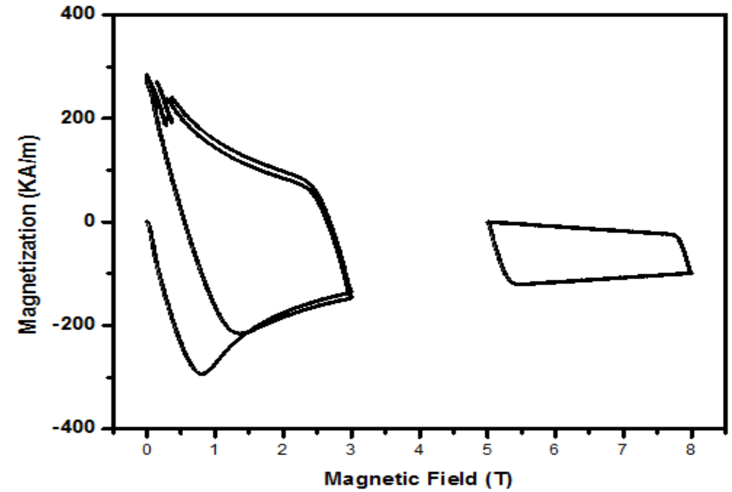
Strand ID	RRP1	RRP2	RRP3
Stack design	108/127	108/127	150/169
Ternary element	Ti	Ta	Ti
Production year	2006	2006	2014
Diameter *d*, mm	1.0	1.0	1.0
I_c (4.2K, 12 T), A	854	1103	1077
J_c (4.2K, 12 T), A/mm^2	2,323	3,066	2,650
I_c (4.2K, 15 T), A	437	570	578
J_c (4.2K, 15 T), A/mm^2	1,188	1,582	1,424
D_S, μm	65	65	58
Twist pitch, mm	43	26	23
Cu fraction λ, %	53	54.0-54.3	48.1-48.4
RRR	153	264	369
Final HT step	650°C/40h	665°C/50h	665°C/50h

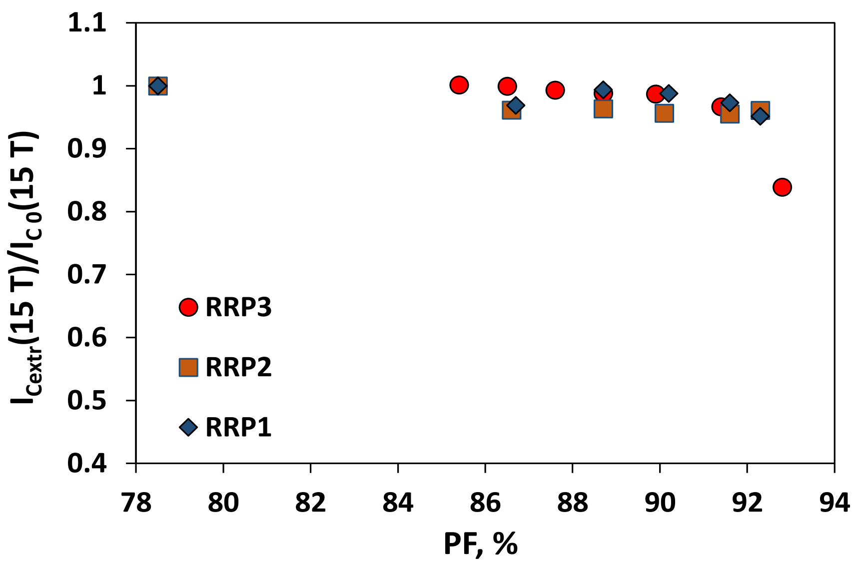
Cable width w

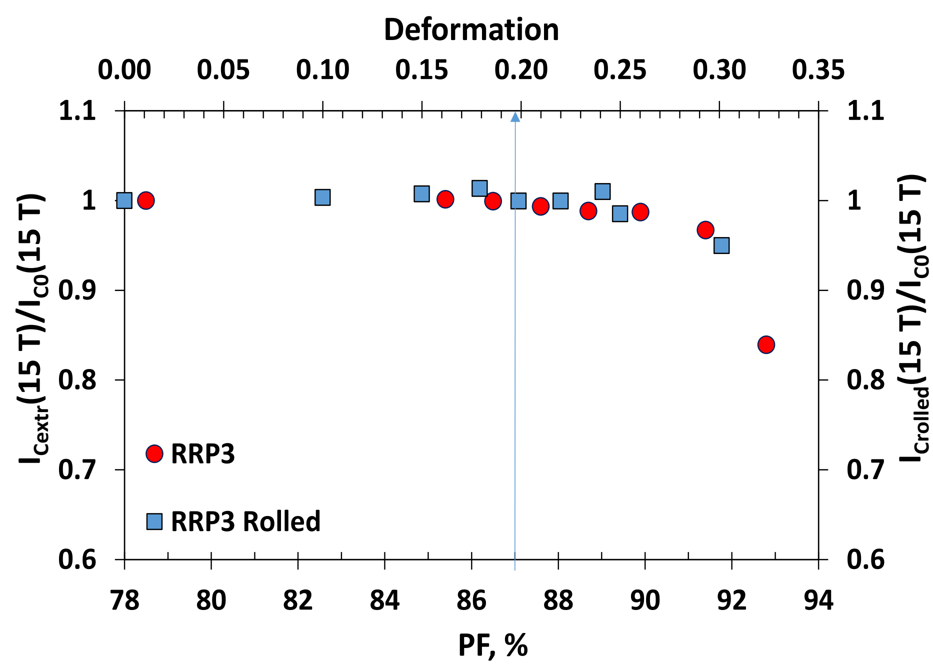


Cable R&D – SC Properties

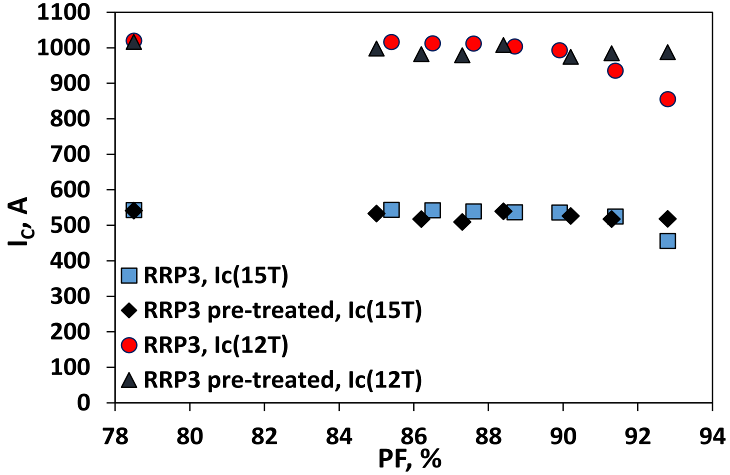


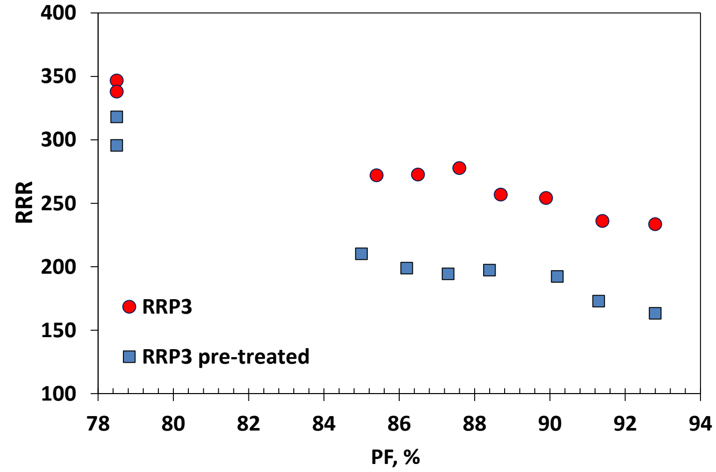






Cable R&D – Effects of Wire Pre-treating and Magnetoresistivity



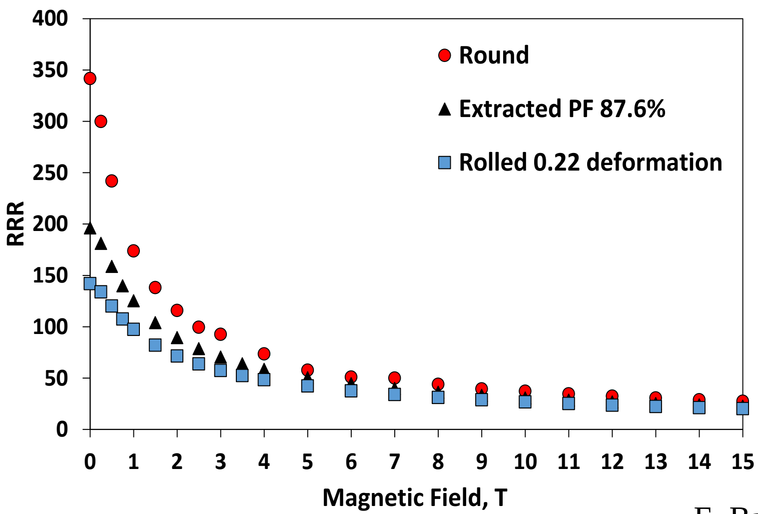


Heat Treatment Parameters

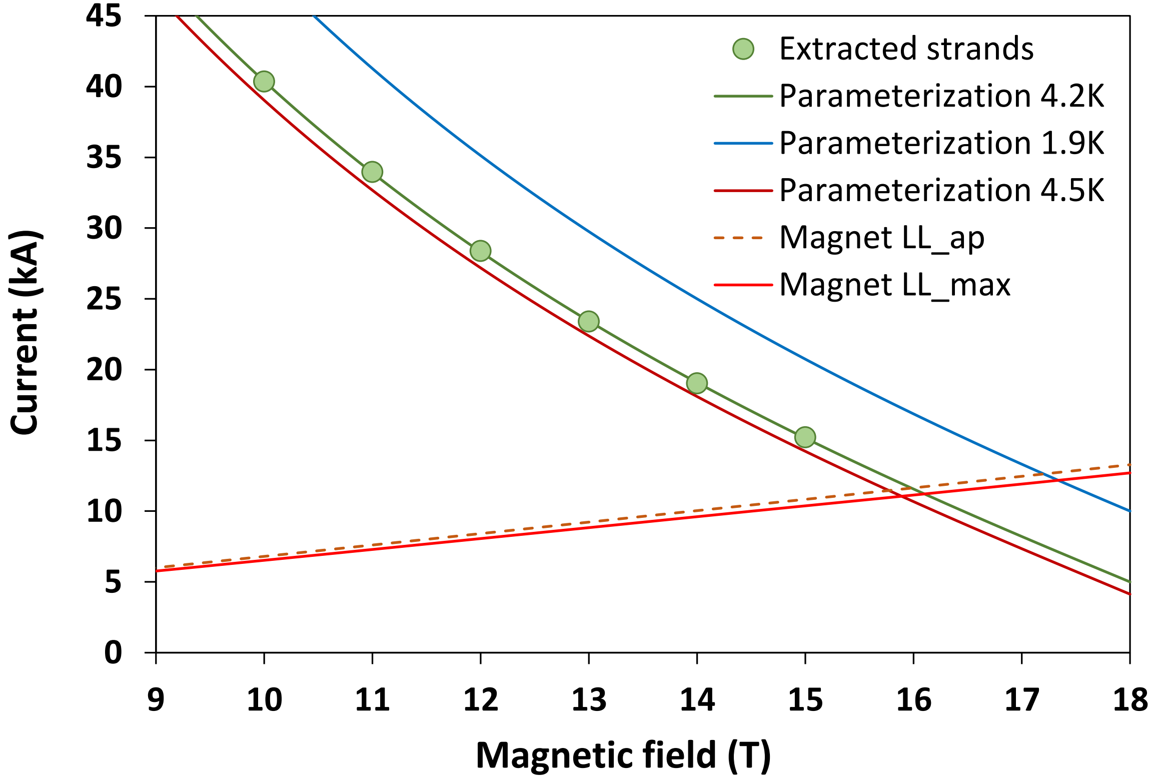
RRP1, RRP2			RRP3		
TC1, °C	TC2, °C	t, h	TC1, °C	TC2, °C	t, h
209.5	214.0	72	204.8	209.9	48
397.7	403.2	48	396.9	400.9	48
649.9	651.8	50	663.7	665.9	50

Heat Treatment Parameters for RRP3 Pre-Processed Wire

RRP3 - Pre treated			RRP3 - Post treated		
TC1, °C	TC2, °C	t, h	TC1, °C	TC2, °C	t, h
209.5	211.5	72	205.6	208.7	12
-	-	-	397.8	400.9	48
-	-	-	663.9	666.3	50



15 T Dipole Short Sample Limits



- **Based on the cable R&D, the nominal mid-thickness of the inner-coil unreacted cable that was chosen for the 15 T dipole is 1.80 mm.**
- **The magnet short sample limits estimated based on data are 11.05 kA (B_0=15.25 T) at 4.5 K and 12.2 kA (B_0=16.65 T) at 1.9 K.**

SBIR's under discussion

- **Hyper Tech: YBCO magnet designs with a CORC type cable design, with and without encapsulating a CORC cable in an additional small diameter outer tube (could be any material, Cu for more stability, SS or CuNi for more strength, etc.).**

Phase I – Determine if magnet design is favorable, Hyper Tech would make 1-2 meter encapsulated CORC cable, OSU would test the short cable for damage.

- **SupraMagnetics: Construct a billet for the monofilament of alternating layers of Nb/Ta. Build first rod with tapes, which would probably reduce the number of restacks. Ta not as ductile but barriers process and Ta is more compatible with copper. Grain size presumably would be controlled by Ta spacing once dimensions are below typical Nb_3Sn grain size. Proceed with multiple restacks.**

Collaborations

INTERLAB PROGRAMS:

- FNAL/CERN (2011-2015) for Leading Conductor Development for the 11 T Dipole Program - Developing and producing 40-strand cables for the demonstrator magnets of this program.
- The multi-Lab Very High Field Superconducting Magnet Collaboration (VHFSMC), with included BNL, FNAL, FSU-NHMFL, LANL, LBNL, NIST, and Texas A&M University, Level 2 Superconducting Cable Task Leadership (2008 to 2011) - Development of Bi-2212 cable technology.
- The LHC Accelerator Research Program (LARP), with BNL, FNAL, LBNL and SLAC, Level 3 Strand Task Leadership (2004 to 2010) – Coordination of Nb_3Sn billet characterization.
- FNAL/KEK (2005 to date) for originally leading the Small Magnet Program at Fermilab, whose first Nb_3Sn racetrack coil made of Powder-in-Tube conductor achieved 100% of short sample limit in 2005, and presently coordinating a KEK-FNAL collaboration on a 13 T hybrid Nb_3Al/Nb_3Sn subscale model.
- FNAL/ANL as P.I. of a User Program proposal titled “Implementation of nano-scale formations in A15 brittle superconductors” at the ANL Center for Nanoscale Materials (2012). This work has continued with the Polytechnics of Milan, with which electrochemical deposition in aqueous solutions of copper and tin layers, followed by thermal treatment to form a Nb_3Sn film on a niobium surface, was developed.

Collaborations (cont.)

INDUSTRY:

- Jan Lindenhovius at ShapeMetal Innovations, the Netherlands, on development of Powder-in-Tube Nb_3Sn conductor (2000-2005).
- N. Long and R. Badcock at Industrial Research Limited, Lower Hutt, New Zealand, on HTS conductor development (2010).
- Jeff Parrell and Mike Field at Oxford Instrument Superconducting Technology (OST) on Nb_3Sn wire research and development (2000 to date).
- Ken Marken and Dr. Hanping Miao and their team at OST on Bi-2212 strands and cables (2005-2007).
- C. Thieme at American Superconductors (2007) and D. Hazelton at SuperPower (2005-2011) on HTS research.
- D. Hazelton at SuperPower (2005-2011) on HTS research and development.
- Eric Gregory on Internal Tin Nb_3Sn development (1999-2004).
- Principal Investigator of CRADAs for SBIRs on superconductor development with a number of Small Businesses, including Supergenics (2003), SupraMagnetics (2007-2010) and Hyper Tech (2011).

ACADEMIA:

- Prof. Costantino Carmignani at University of Pisa, Italy, on the design of a cable test facility by means of a superconducting voltage transformer (2008-2010).
- A. Polyanskii, P. Lee and Prof. David Larbalestier at FSU-NHMFL on magneto-optical and electromagnetic studies in Nb3Sn (2008-2009).
- Profs. M. Sumption and T. Collings at Ohio State University (OSU) on AC losses in Nb3Sn cables (2006-2010).
- John Miller, Nicolai Martovetsky and Joel Schultz, the latter of MIT's Plasma Science and Fusion Center, on measuring the effects of damage on ITER strands (2006).
- Profs. M. Bestetti and S. Franz at Polytechnics of Milan on electro-chemical deposition of Nb3Sn (2012 to date).

European Programs

FNAL, including TD, is participating as a partner to a M$3.9 Marie Sklodowska-Curie *Research and Innovative Training Networks* call proposal "ITE-MUONS" for future Intensity Frontier HEP facilities at Fermilab, as well as future high energy colliders, with the following institutions:

- INFN – Italy
- University of Pisa
- Politecnico di Milano
- Scuola Superiore Sant'Anna
- Helmoltz-Zentrum Dresden-Rossedndorf EV
- University College London
- The University of Liverpool
- Technische Universitaet Dresden
- Prisma Electronics ABEE
- Faraday Technology Inc., US

This proposal is focused on the Muon Campus detectors at FNAL for Muon g-2 and Mu2e, and will also include an "Advanced Superconducting Technologies for Future Accelerators" topic for the development of future colliders at the 100 TeV-scale. It requests funding for 15 early researchers for 3 years each with the purpose of strengthening the partnership between European and US institutions, and training a new generation of researchers through participation <u>for a third of their time at FNAL and other innovative entities</u>. The next European Project in preparation is a *Research and Innovation Staff Exchange* to support US training of PhD students and researchers.

Conference Organization/ Outreach

Conference Organization

1. A Special Session on "Superconducting Sensors and Instrumentation" was organized and co-chaired with Dr. Marcel Demarteau at the IEEE International Instrumentation and Technology Conference – I2MTC in Pisa, Italy, May 11-14, 2015, where FNAL Director gave the keynote speech.

2. A new Plenary Special Session on "Applied Superconductivity in HEP" was founded, organized and co-chaired with Dr. Flavio Gatti at the "Frontier Detectors for Frontier Physics" (FDFP) Pisa Meeting, 24-30 May 2015, at La Biodola, Isola d'Elba (Italy). ➔ A 2-page editorial titled "Frontier detectors for the future" has appeared on this Conference, which takes place only every three years, on the July/August 2015 CERN COURIER.

3. TD employees were members of the International Advisory Committee (IAC) of an ICFA Mini-Workshop on High Field Magnets for Future pp Colliders (endorsed by the ICFA Beam Dynamics Panel), Shanghai JiaoTong University, June 15-17, 2015, Shanghai (China).

Outreach

1. A PLENARY talk ,"*15 Years of R&D on Superconducting Accelerator Magnets at Fermilab OR An Example of Education and Innovation in Global Science*", was given at the CAM GRADUATE STUDENT PHYSICS CONFERENCE, 9-12 September 2015, Oaxaca, Oaxaca, Mexico.
2. An Editorial, titled "*Education and Innovation in Global Science*", was published in the APS FIP Spring 2015 Newsletter.

IMPACT

- **Since 1998, ~200 peer-reviewed publications in Materials Letters, Superconductor Science and Technology, IEEE Transactions on Applied Superconductivity and on Nuclear Science, Advances in Cryogenic Engineering, Nuclear Instruments and Methods in Physics Research, as well as one book chapter.**
- **3000+ citations**
- **h-index up to 27**
- **Two APS Fellowships**
- **Memberships in prestigious committees (APS Fellowship Committee, Lehman's Reviews, etc.)**

Next Steps

- **Keep working on optimizing wire architecture to improve Nb_3Sn Critical Current Density up to ~2 kA/mm^2 at 15 T (~3.8 kA/mm^2 at 12 T).**
- **However, since J_c has a clear dependence on the Nb content in the wire, independently of the wire technology, there are no first order cost reductions in sight. More substantial improvements of J_c at high fields, by a factor of 2 or more, would be important to reduce magnet cost. This will require significant enhancement of pinning in Nb_3Sn commercial wires.**

See presentation in New Ideas.