HFM Program Overview

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Outline

Program goals and strategies

HFM technology development

Contribution to LARP

Strand, cable and component R&D

Plans

Introduction

Fermilab has a strong superconducting magnet R&D program focused on addressing magnet issues important to Fermilab and to U.S. High Energy Physics

- **Support of Tevatron Collider operations**
  - **Study of present Tevatron magnets in order to improve machine performance**
  - **Development of special purpose magnets as required (e.g. short high strength dipoles, possible new C0 IR, etc.)**
- **Support of US participation in the LHC**
  - **Construction of 1st Generation IR Quads development and construction,**
  - **Development of 2nd generation IR magnets (LARP)**
  - **Participation in possible R&D for LHC energy upgrade**
- **Development of high field SC accelerator magnets and technologies for a future HEP facilities (VLHC, LC, etc.)**

High Field Magnet R&D Program Goals

Future HEP facilities will require high-field, high-performance SC magnets with parameters exceeding present SC magnets based on NbTi superconductor.

A HFM R&D program was started at FNAL in 1998.

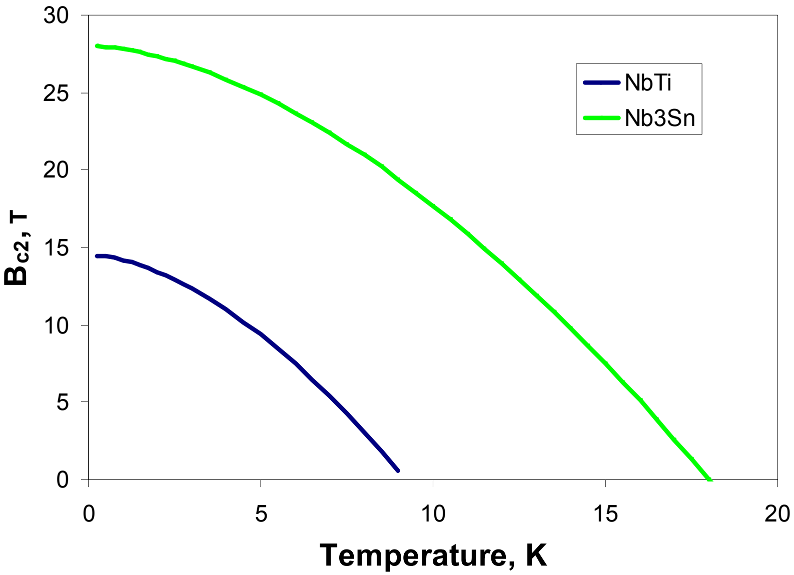
Fermilab's HFM Program is focused on the development of next generation SC accelerator magnets with high operating fields (>10T at 4.5 K) and high operating margins for different applications.

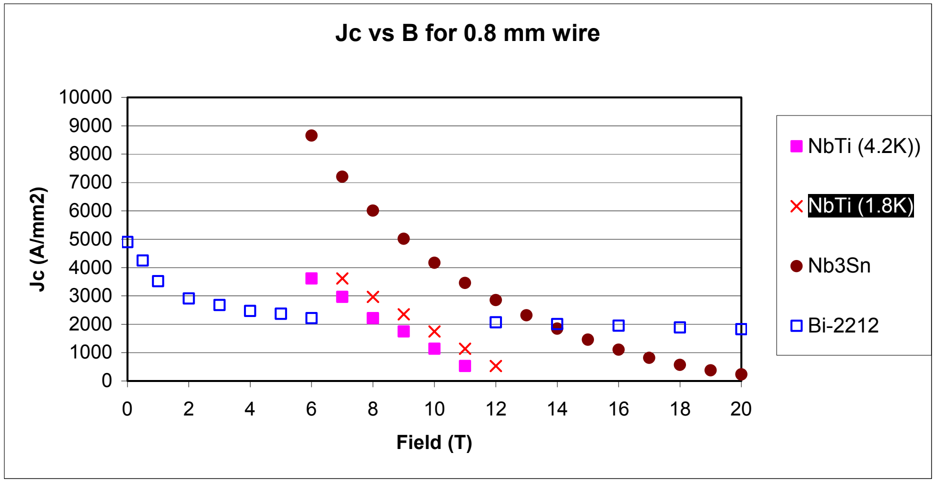
Practical designs ⇒ **worry about field quality, length, protection, manufacturability, cost, reproducibility, etc… not just peak field**

Superconductor

At present time we develop accelerator magnets based on Nb_3Sn superconductor.

- **Critical parameters of Nb3Sn (Bc2, Tc and Jc) are much higher than NbTi**
- **Nb_3Sn conductor is commercially available in long lengths**





Technologies

Nb3Sn is very difficult material because it is brittle. Ic of Nb_3Sn conductor is very sensitive to strain and stress

- o **25% Ic degradation at 0.5% strain whereas NbTi loses 25% of Ic at 4% strain when it mechanically breaks**
- o **Permanent irreversible Ic degradation of Nb3Sn conductor starts at stresses ~150 MPa**

We explore two basic technologies for brittle superconductors:

Wind-and-React and React-and-Wind

Challenges:

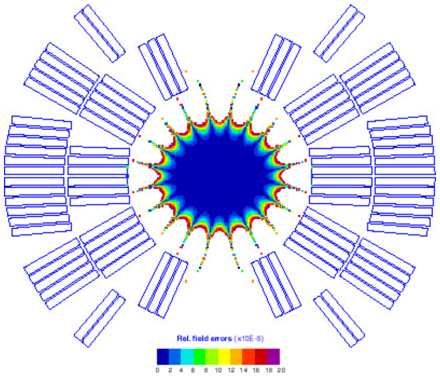
- ❖ **Pre-reacted Nb3Sn conductor requires controlling the strain on the conductor → large bending radii**
- ❖ **Heat treatment after the magnet is wound is also an engineering challenge**
  - o **high temperatures (650-750 C)**
  - o **long durations (100-600 hrs)**
- ❖ **In both cases magnet mechanical structure and assembly technology must prevent the coil from excessive stress**

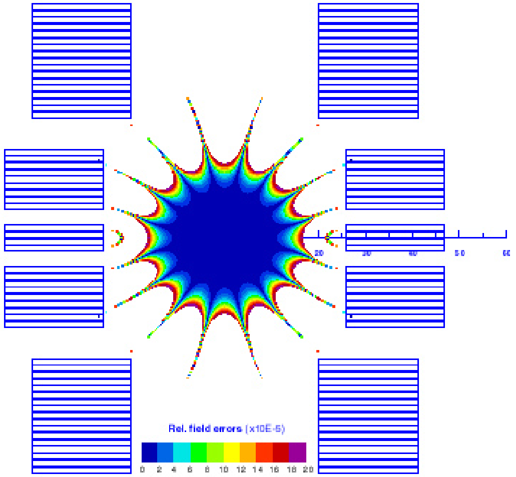
Design Approaches

Two basic high-field dipole coils:

- **shell-type coils with a cos-theta azimuthal current distribution**
  - **Traditional coil design for SC accelerator magnets**
- **block-type coils arranged in the common coil configuration**
  - **Innovative approach**
  - **friendly to brittle conductors such as Nb_3Sn and HTS.**

Both designs have advantages and disadvantages in different applications and both need to be studied and optimized for High Field Magnets based on brittle superconductors





Magnet R&D Infrastructure

Fermilab has the necessary infrastructure to perform successful magnet R&D including:

- **Cable insulating machine**
- **Winding tables (<2m,<15m)**
- **Coil HT oven and retorts (<1m)**
- **Epoxy impregnation facility (<6m)**
- **Collaring/yoking presses (<15m)**
- **Magnet test facilities (vertical <4m,horizontal <15m)**

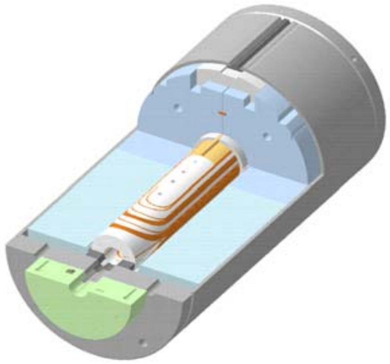
The unique feature of Fermilab’s infrastructure is the possibility for performing both short and long magnets fabrication and tests

SC Magnets at Fermilab

W&R Cos-Theta Dipole Models

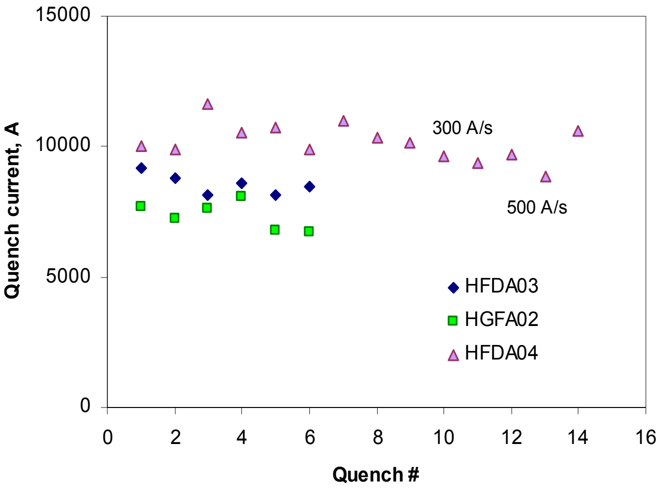
A series of 1-m long cos-theta Nb3Sn dipole models (HFDA) is being fabricated and tested

- High-Jc 1-mm Nb3Sn strand
- 28 strand cable
- 2-layer coil with cold iron yoke
- Nominal field of 12 T at 4.5 K
- 43.5-mm diameter bore



Four short models were fabricated and three of them were tested in FY2001-2002

- All three magnets achieved good field quality
- Quench current was only 50-60% of expected short sample limit



Quench Performance Issues

Now we focused on the magnet quench performance.

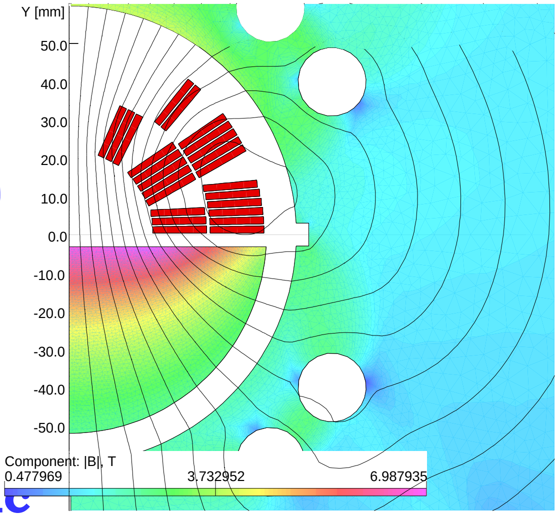
We studied possible splice effects (heating, mechanical damage) and did not find any problems with them.

We continue studying

- **BICC**
- **Strand stability**
  - Filament size and flux jumps
- **Cable stability**
  - current sharing due to cable inner-strand resistance
- **Coil fabrication and magnet assembly technology**
  - Coil mechanical damage during assembly and/or preload (unplanned strain ?)

Magnetic Mirror

SC Magnets at Fermilab

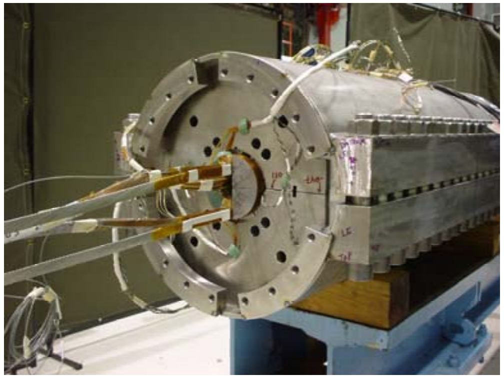


We continue study and optimization of the W&R technology and quench performance issues using half-coils and a magnetic mirror (HFDM)

- **The same mechanical structure and assembly procedure**
- **Advanced instrumentation**
- **Short turnaround time, cost effective**

The objectives of the half-coil tests with magnetic mirror

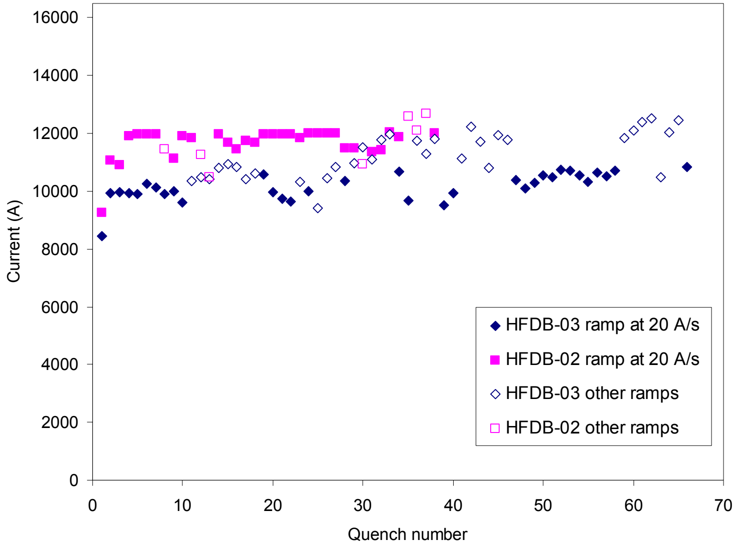
- **Splice tests using an old half-coil**
- **Cable testing in self-field**
- **Technology verification using the new half-coils**



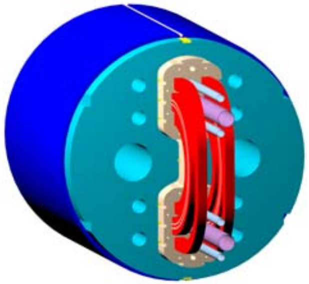
Next cos-theta models will be fabricated after reaching progress with mirror configuration.

React & Wind Technology

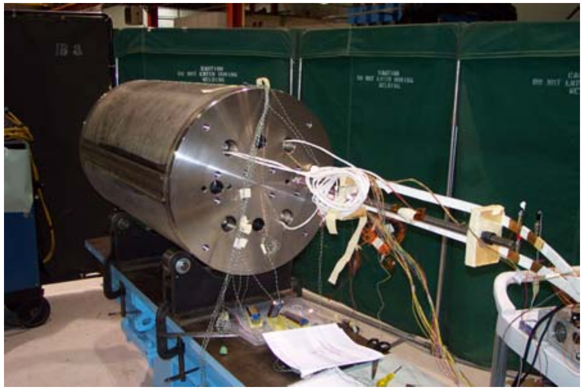
- Experimental studies and optimization of R&W techniques are performed using sub-sized cable and flat 1-m long racetrack coils (HFDB)
- Three R&W racetracks have been fabricated and tested in FY2001-2003
  - o 2nd and 3rd racetracks reached 75-78% of their short sample limit (world record for the R&W technology, good reproducibility)
- We will continue studies and improve the R&W technology using modified (simple, cost-effective) racetracks.



R&W Common Coil Dipole

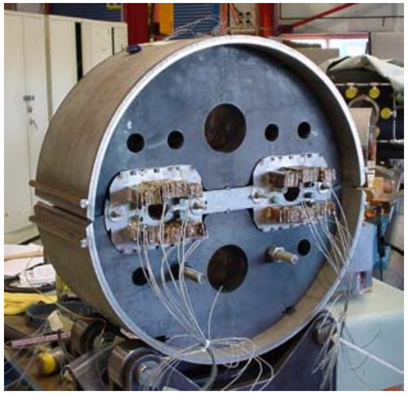


Encouraged by 2nd racetrack we started fabrication of 1-m long common coil dipole model (HFDC):



- High-Jc 0.7 mm Nb3Sn strand
- Wide pre-reacted 59-strand cable
- Single-layer coil with cold iron yoke
- Advanced mechanical structure
- Nominal field of 11 T at 4.5 K
- Accelerator quality field
- Magnet bore of 40 mm
- Different mechanical design vs. the racetrack

Mechanical model was fabricated and tested in FY2002



The 1st common coil short model has been fabricated and will be tested this summer

Participation in LARP

We are participating in the U.S. LHC Accelerator Research Program (LARP). The Program has been reviewed and approved by DOE last week.

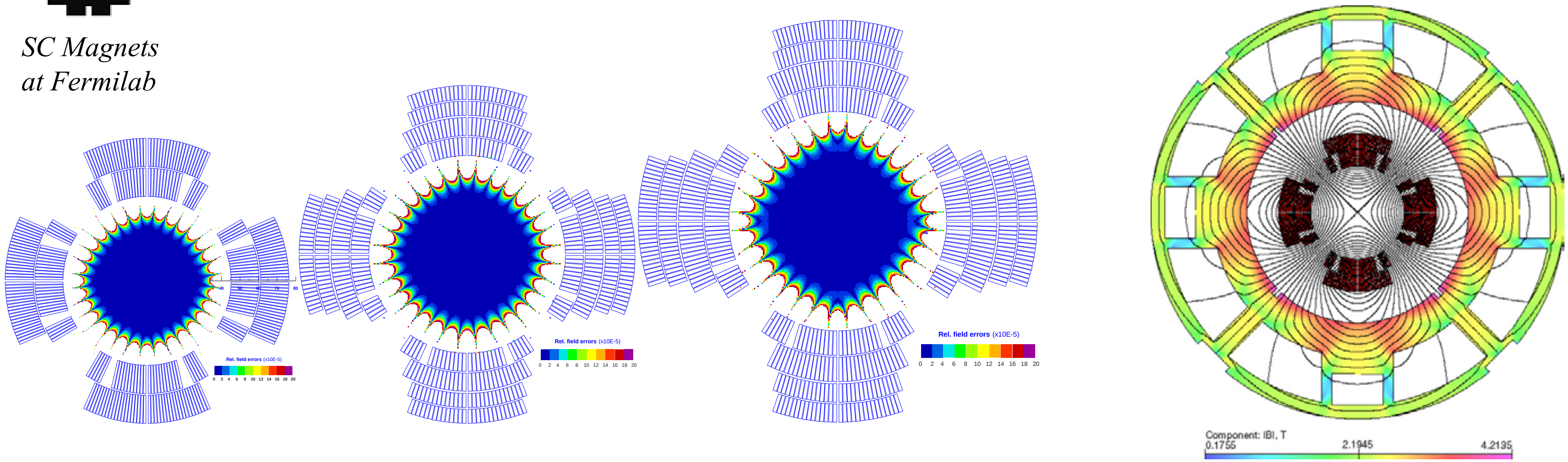
One of the LARP goals is to develop 2nd generation IR magnets for LHC luminosity upgrade.

- **1st generation magnets have radiation-limited lifetime**
- **New IR design based on large-aperture high-field Nb3Sn magnets will allow reaching the highest possible luminosity**
- **This will be first use of high field Nb_3Sn magnets in an accelerator.**

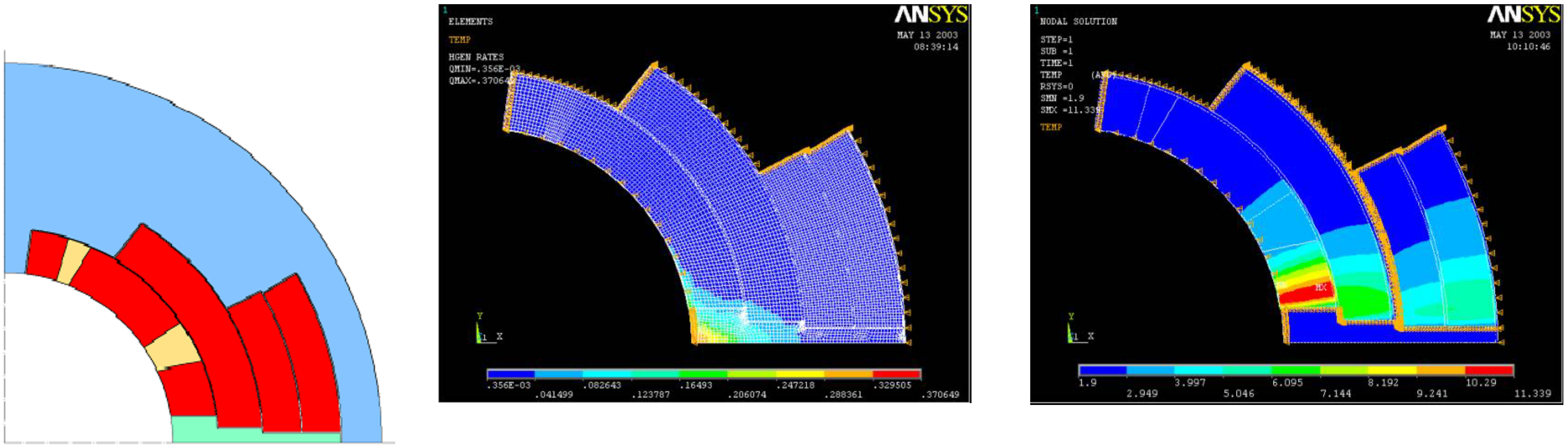
Contributions of Fermilab to LARP Magnet R&D include:

- **Conceptual design studies of various magnet types for 2nd generation LHC IRs**
  - IRQ conceptual design studies
  - D1 conceptual design with the mid-plane spacer
  - Radiation heat deposition and margin analysis
- **Fermilab will also participate in short and long model magnet R&D as well as in the development and test of full-scale prototypes of the LHC IR magnets**

IRQ and D1 Design Studies



IRQ coils with 90, 100 and 110 mm aperture and cold mass x-section



D1 with increased operation margin and preliminary thermal analysis

Material and Component R&D

SC Magnets at Fermilab

- New generation accelerator magnets requires advanced superconductors, structural materials and components.
- Fermilab developed unique infrastructure to perform extensive material R&D in support of the magnet R&D
  - Small ovens for NB3Sn strand and cable Heat Treatment
  - Compact 28-strand cabling machine
  - Sample compression fixtures (4.2-300K)
  - Ic and magnetization sample holders
  - compact 25 kA SC transformer
  - SEM and optical microscopes
  - Short Sample Test Facility
    - 15-17 T solenoid,
    - 1.5-100 K temperature insert,
    - 2 kA power supply

- Fermilab is participating in national programs sponsored by DOE to encourage the development of advanced high-field superconductors and materials in U.S. industry

Nb3Sn Strand R&D

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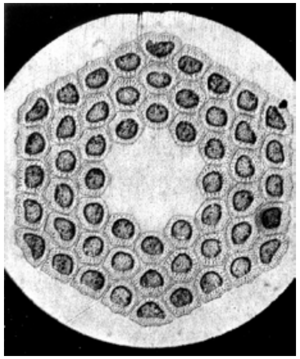
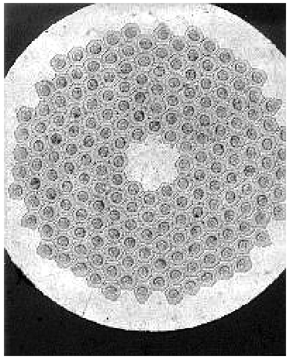
at Fermilab

We study Nb_3Sn strands (0.3-1.0 mm) produced using different methods:

- **"Internal Tin" (IT)**
- **"Distributed Tin" (DT)**
- **"Modified Jelly Roll" (MJR)**
- **"Powder in Tube" (PIT)**





Strand studies include:

- **$I_c(B)/J_c(B)$ ⇒ magnet short sample limit**
- **RRR ⇒ quench protection**
- **M(B) ⇒ field quality @ low fields**
- **current and magnetic instabilities ⇒ quench current limits**
- **SEM studies and chemical analysis**
- **Strand expansion after reaction ⇒ technology**
- **Heat treatment optimization**

Cable R&D

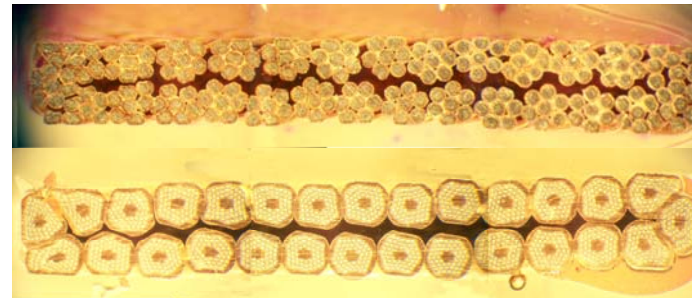
SC Magnets
at Fermilab

We are studying Rutherford-type cables:

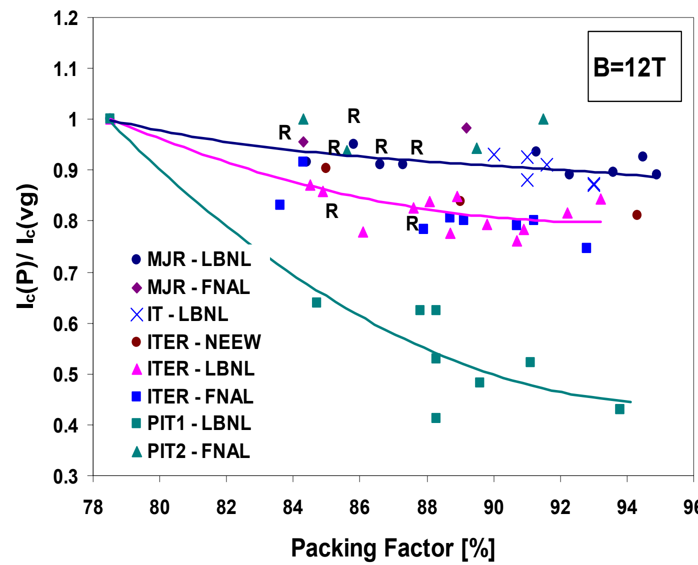
- Different Nb_3Sn strand types
- Rectangular and keystone x-section
- With and w/o SS core
- Different packing factor
- One and two stage cables
- copper stabilizer (Cu tape wrapped on the cable)

Major studies:

- ❖ I_c degradation due to cabling
- ❖ cable bending and compression effects
- ❖ cable inter-strand resistance

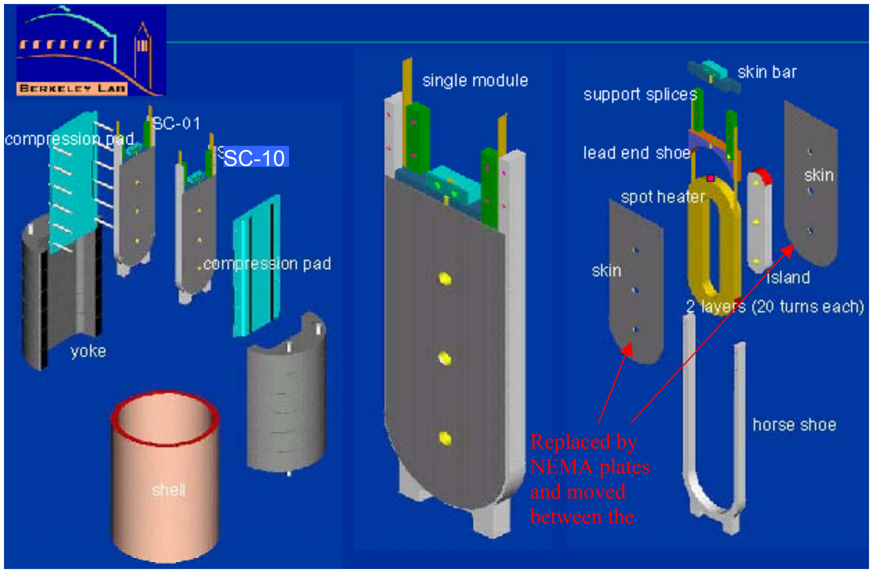


Nb3Sn strand Ic degradation database.



Cable Testing

SC Magnets at Fermilab

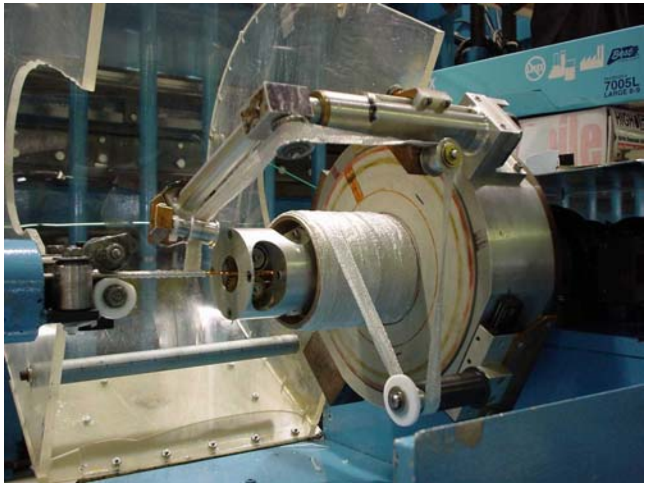


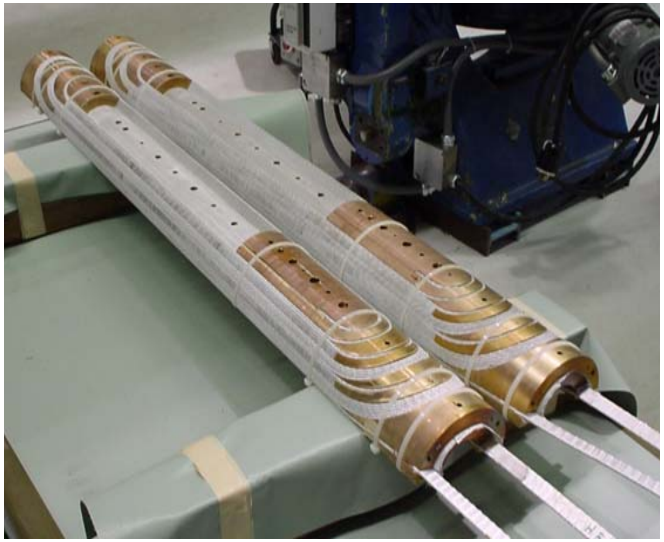
We are planning cable testing using the technique developed at LBNL. The goals are:

- **Test and optimize real full-size cables before using in magnets**
- **Use well understood mechanical structure to avoid effects related to test setup**

Insulation for W&R

- **We developed ceramic insulation for W&R technology in collaboration with industry:**
  - **Ceramic fiber tape or cloth with liquid ceramic binder (no organics)**
  - **Pre-preg tape is made by CTD Inc. (SBIR)**
  - **Cable insulation using regular insulating machine**
  - **Cures at 150 C but survives HT @ 800C**
  - **Handle cured coils during assembly, prior to heat-treatment**



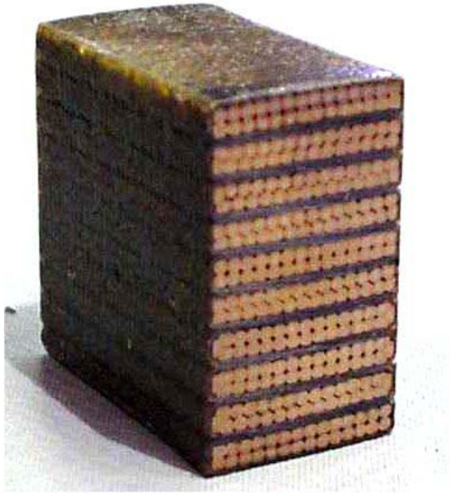


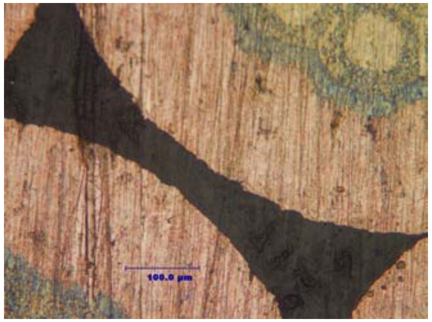
Coil Impregnation Materials

We investigate various commercially available polyimide solutions in order to replace epoxy as an impregnation material for Nb_3Sn coils.

The mechanical, thermal and electrical properties of "ten-stack" samples impregnated with Matrimid® 5292 were studied

⇒ **The results are very encouraging**

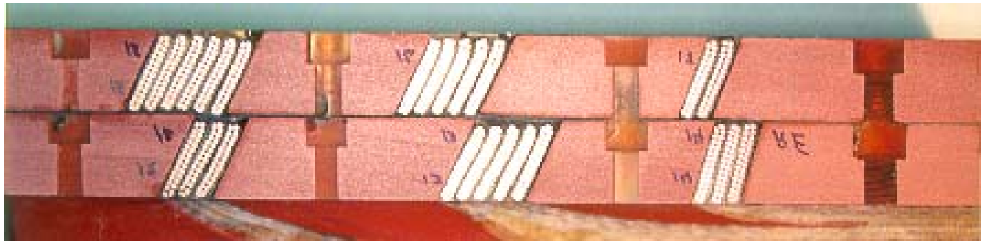




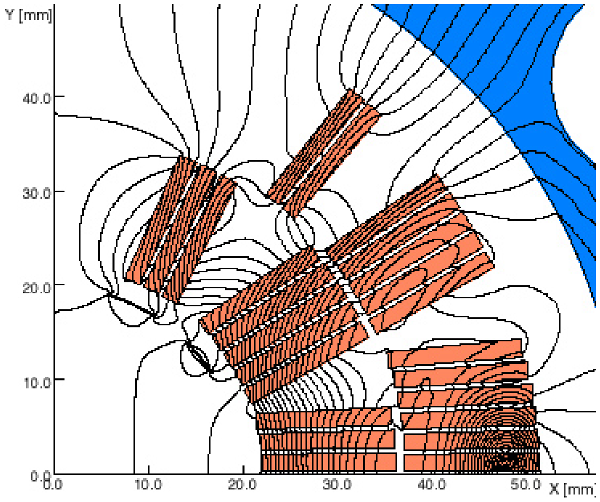
These studies will be continued on practice coils and then tested in model magnets in the frame of LARP magnet R&D

End Parts

- **We developed a method for metallic end parts designing and used it together with the rapid prototyping techniques**
  - **Reduction of the time and the cost of end part development processes.**
- **Water jet machining was used for end part fabrication**
  - **reduction of part costs by a factor of 3 (even more in the future) and manufacturing time by a factor of 10**



Passive correction technique

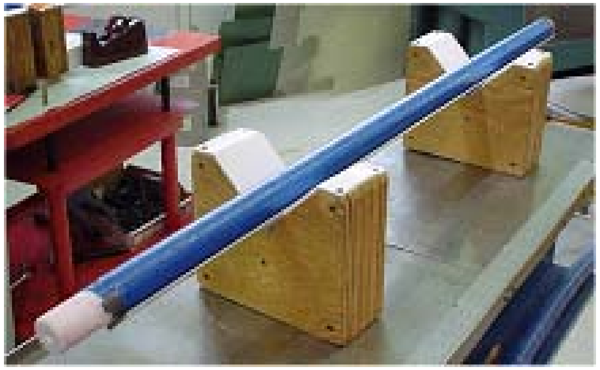


We developed and tested a simple passive correction technique based on thin iron strips installed in the magnet bore or inside the magnet coil in order to reduce large coil magnetization effect in Nb3Sn magnets.

- **3 tested corrector models confirmed the design parameters**

This approach offers:

- **significant increase in the dynamic range of accelerator magnets,**
- **relaxation of the requirements on the effective filament size in Nb_3Sn strands.**



Collaboration

We developing and strengthening our collaboration with U.S. and European groups working in HFM R&D. Some examples of our collaboration activities :

- **Cable development and fabrication with LBNL**
- **Binder tests with LBNL**
- **Thermal shock test with NHFML and LBNL**
- **Small racetrack test facility development and cable tests with LBNL**
- **R&W technology development with BNL**
- **Interstrand resistance measurement technique with CERN and BNL**
- **Thermal conductivity measurements with LASA**

We are participating in LTS and AAM Workshops and collaboration meetings.

SC Magnets
at Fermilab

Staff

HFM development staff:

- **3 physicists**
- **5 full-time engineers**
- **2 (1 term) engineers in superconductor R&D**
- **5 full-time techs in the model magnet program**
- **1.5 techs in superconductor R&D**

We continue involving students in magnet and conductor R&D:

Laurea students (Italy):

- C. Boffo – 1999-2000
- M. Fratini – 2000-2001
- S. Mattafirri – 2001-2002
- L. Del Frate – 2002-2003

Ph.D. students

- V. Kashikhin (Russia) – 1998-2002
- L. Imbasciati (Italy) – 1999-2003
- B. Bordini (Italy) – 2003-2006

Base HFM R&D plans

- **We plan fabricating and testing of 2-3 short Nb_3Sn model magnets per year. Goals:**
  - **Understand and improve magnet quench performance (FY2003-2004)**
  - **Optimize field quality and reproducibility (FY2005-2006)**
- **When the basic problems of Nb_3Sn technology are under control we will select a design based on our model magnet experience**
- **We will develop the required infrastructure to start fabrication of long prototypes in FY2007-FY2008.**

LARP Model Magnets

- LARP IRQ model R&D starts in FY2006 with simplified 1-m long models (2-layer design) in order to develop basic tooling and infrastructure and start basic technology development.
- A series of short models will address the issues of magnet quench performance, field quality, mechanics, quench protection, reproducibility, long term performance, etc. (FY2007-FY2010)
- Study of length dependent effects with 4-m long coils starts as soon as we achieve acceptable quench performance (FY2009-FY2011).
- Model R&D will be followed by the construction of one or more prototypes containing all of the features required for use in the LHC (FY2011-2012).

LARP and Base Magnet R&D

The base HFM and LARP magnet R&D programs are extremely challenging.

LARP has finite time for magnet R&D.

Strong connection between the LARP magnet R&D program and the base High Field Magnet R&D programs is critical, in order to reduce risks and increase the probability of LARP success.

Base magnet R&D programs for Nb_3Sn HFM have to demonstrate the possibilities and limitations for this technology during next couple of years.

Designs and technologies developed for LARP are similar to that required for a high field VLHC.

Conclusions

- Fermilab has a strong and healthy SC accelerator magnet R&D program. Success of this program is very important for the future of HEP.
- Several innovative high field accelerator magnet design approaches and fabrication techniques are being developed and studied.
- Unique experimental data related to the magnet and component performances are being collected and analyzed.
- Fermilab SC Magnet R&D program will continue to be focused on the development of SC accelerator magnets for
  - Tevatron needs
  - Participation in LHC construction and luminosity upgrades
  - future Very Large Hadron Collider, LC, etc.