Superconducting Magnet R&D at Fermilab

R.D. Kephart

DOE Annual Program Review

March 19, 2003

Introduction

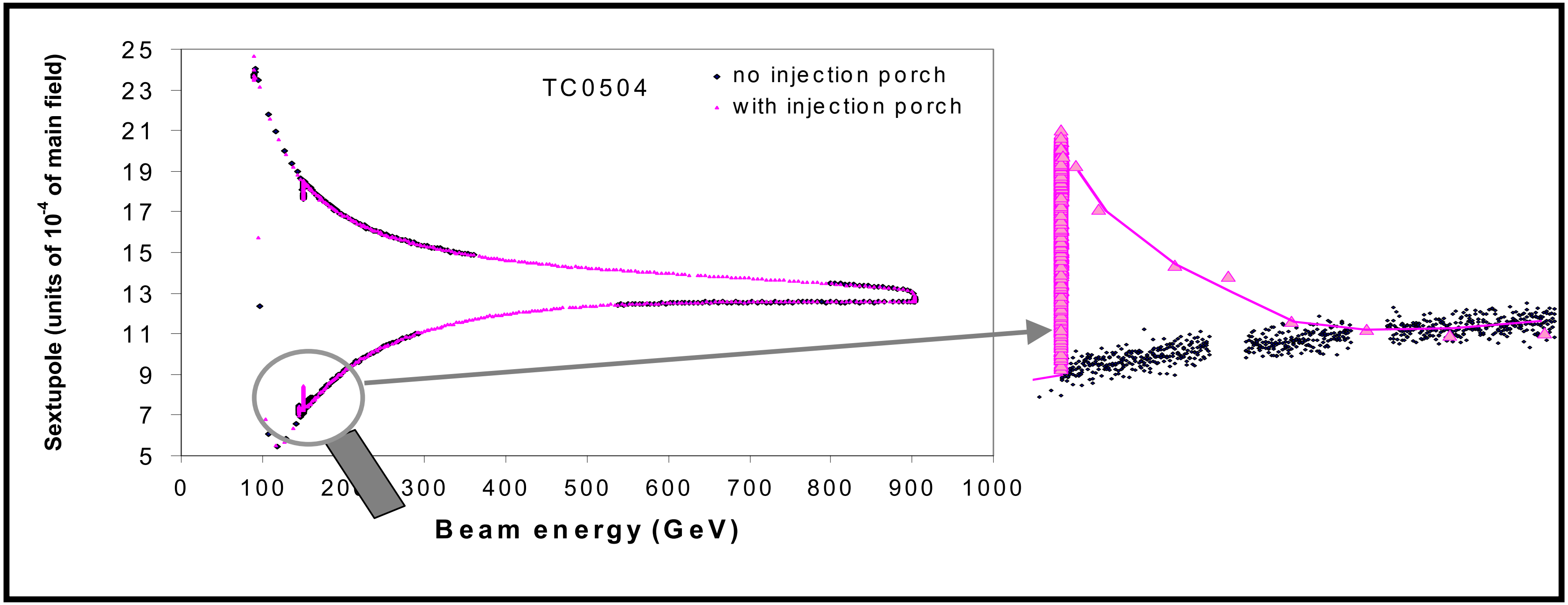
- **Superconducting Magnet Technology is one of the enabling technologies required by FNAL both to maintain the Tevatron and to design and build components for future accelerators**
- **At FNAL Superconducting Magnet R&D is done in the Technical Division**

Magnet R&D: Tevatron

Tevatron is 20 yrs old why are you doing magnet R&D ?

- **Long range beam-beam interactions in the Tevatron Collider require helical orbits with large separation.**
  - **This and the larger beam intensities in Run II require careful control of the machine tune to limit emittance growth/losses**
  - **➔Tevatron is now more sensitive to magnet errors**
- **Persistent current effects in the superconducting cable result in multipole contributions with:**
  - **non-linear time dependent drifts**
  - **non-linear hysteretic effects (e.g. snapback)**
  - **dependence on the excitation history of the magnet**
  - **variations from magnet to magnet because of construction differences (e.g. superconductor from different vendors)**

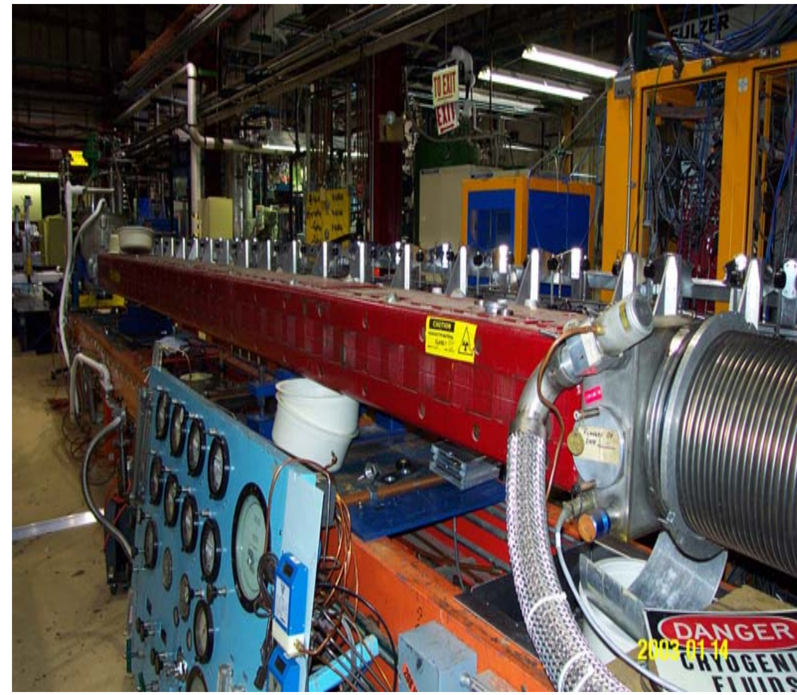
b_2 drift and snapback



- Sextupole drifts while machine is at 150 GeV injection energy
- Snaps back to hysteric value at start of ramp
- Excitation history dependent. Magnets behave differently.
- Multipole drift and snapback effects also exist in LHC magnets (in fact the effects are worse) and our measurements and compensation techniques are of great interest to CERN

Magnet R&D: Tevatron (cont)

- **Many of these effects were known to exist in the mid to late 80's but they are complex.**
- **Improved measurement capability and theoretical understanding is allowing BD & TD to develop better methods to compensate for these magnetic effects during collider operations.**



We hope that improved understanding of Tevatron magnets will lead to increased Collider Luminosity

Magnet R&D: Tevatron (cont)

- **Studying aging effects in Tevatron magnets**
  - **Recently discovered that some Tevatron dipole cold masses have moved downwards 50 microns WRT the magnet iron.**
  - **Suspect this is due to creep in G-11 magnet supports**
  - **Results in skew quad → strong H-V coupling in the Tevatron**
  - **Investigating the problem and exploring possible fixes**

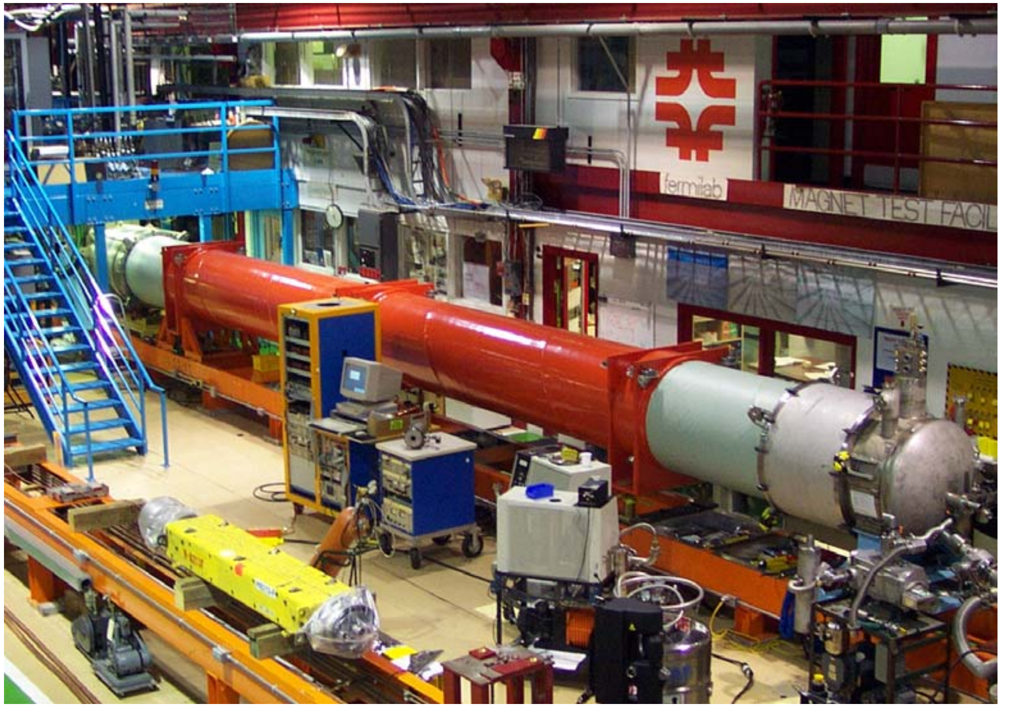
- **Investigating new higher field Tevatron dipoles**
  - **Goal is to make warm space for more electrostatic separators**
  - **Reduce beam-beam effects at high intensity**
  - **BD requested paper study of 6.6 T NbTi dipole (50% stronger)**
  - **If approved, magnets needed for 2006 shutdown**
  - **Use technology developed for LHC quad**
  - **Bonus = frees up Tev dipoles to increase spares**

Magnet R&D: LHC

- Part of Fermilab's responsibilities to the US-LHC Accelerator Project is the development and production of high gradient quadrupole magnets for the LHC IR's
- State-of-the-art NbTi based SC quadrupoles (70mm bore, very high gradient = 205 T/M, 1.9K)
- Pushs NbTi SC about as far as it can reasonably go
- 1996-2002 Fermilab built a series of model magnets and a full size prototype that lead to a successful design
- The first production quad assembly (2 quad cold masses + a corrector) is now complete and was tested Jan-Feb
- Obtained excellent test results ! (next slides)

LQXB01 Performance

- **Excellent quench performance**
- **Field harmonic consistent with design expectations**
- **Alignment meets specs**
- **No retraining w/thermal cycle**
- **Excellent Magnet !**
  - **Production is in full swing**
  - **9/18 cold mass assemblies are complete**



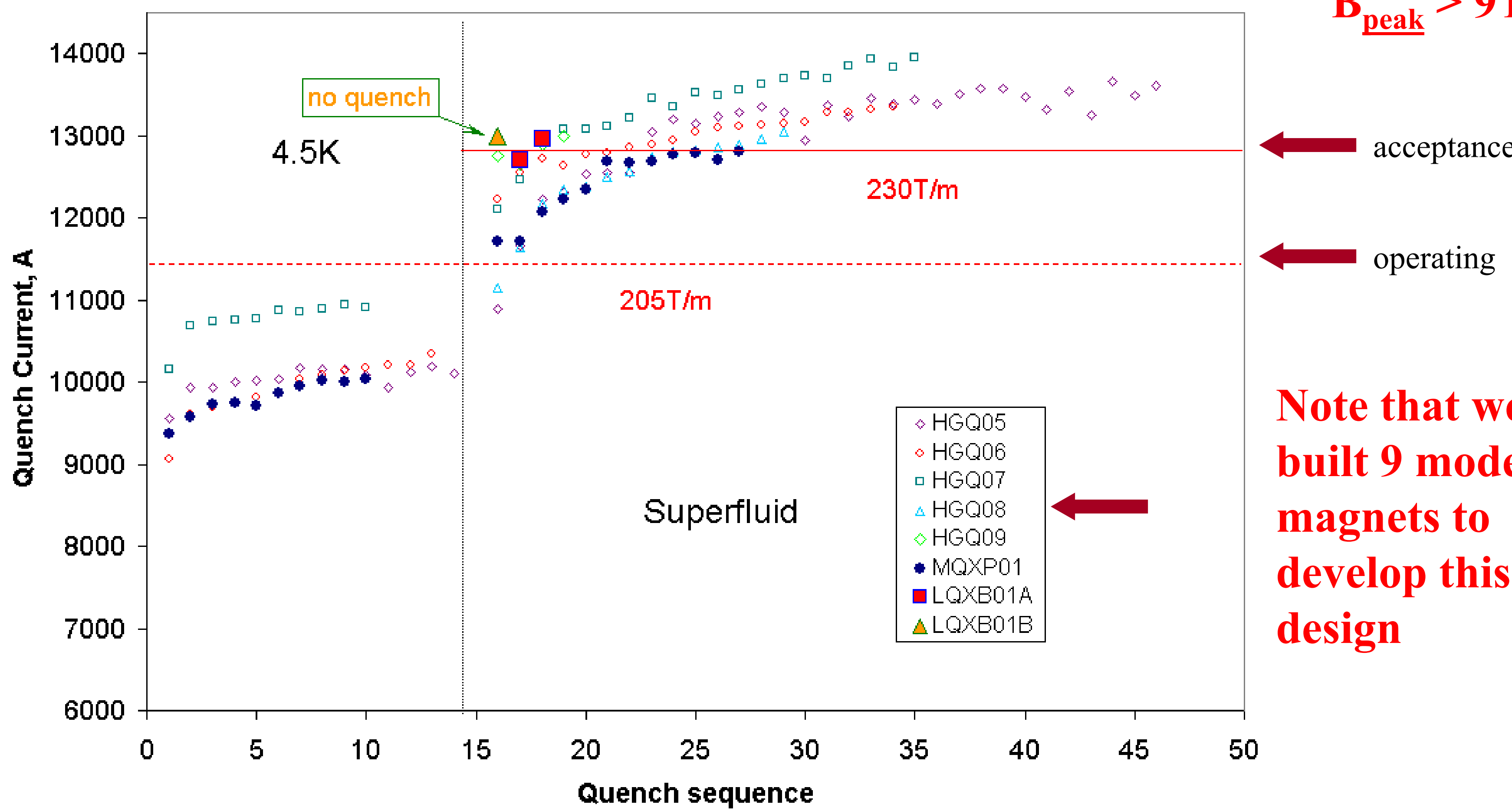
1st LHC "Production" Quad in MTF

FNAL Technical Division

SC Magnet R&D at Fermilab

1st LHC Quad Quench Performance

B_{peak} > 9T



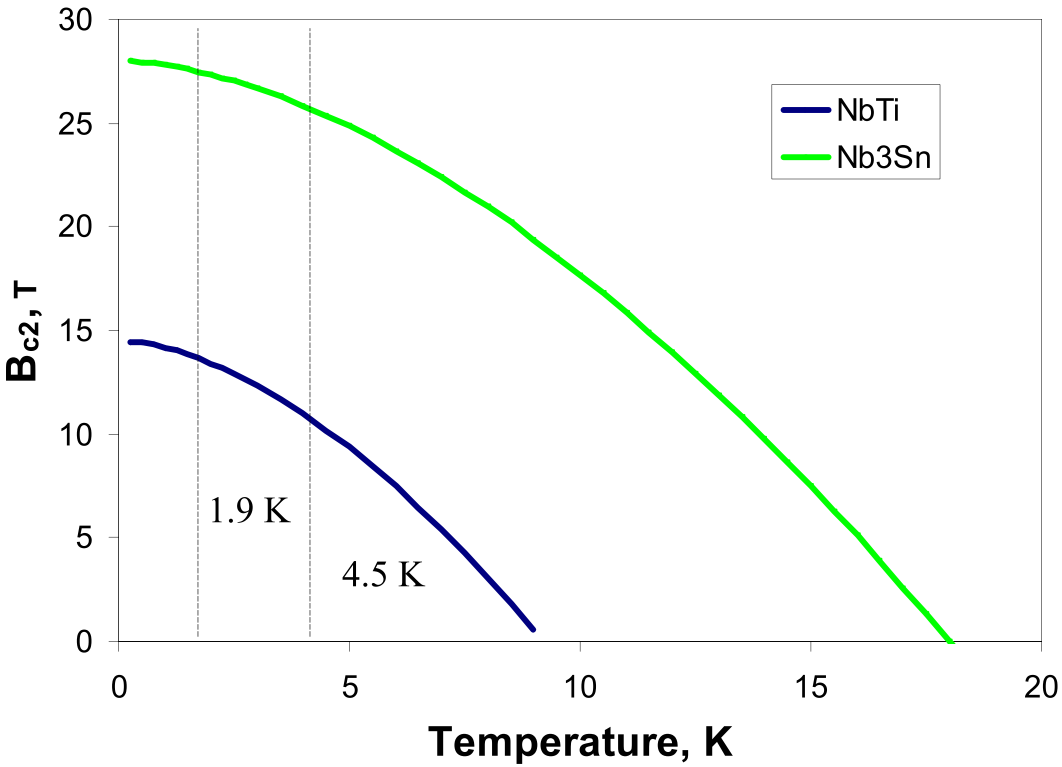
Note that we built 9 model magnets to develop this design

High Field Magnet Program

- **Future accelerators will require higher performance magnets than present NbTi based Superconducting magnet technology allows**
- **A HFM R&D program was started at FNAL in 1998. This program focuses on the development of next generation of accelerator magnets to upgrade existing machines or to build new ones.**
- **Design goals:**
  - **Operating fields above 10 T at 4.5 K**
  - **Large operating margins and apertures (high radiation loads)**
  - **Designs based on Nb_3Sn superconductor**
  - **Practical designs suitable for 2nd generation quads for the LHC, magnets for a future VLHC, etc.**
  - **→worry about manufacturability, cost, control of field harmonics, etc… not just peak field**

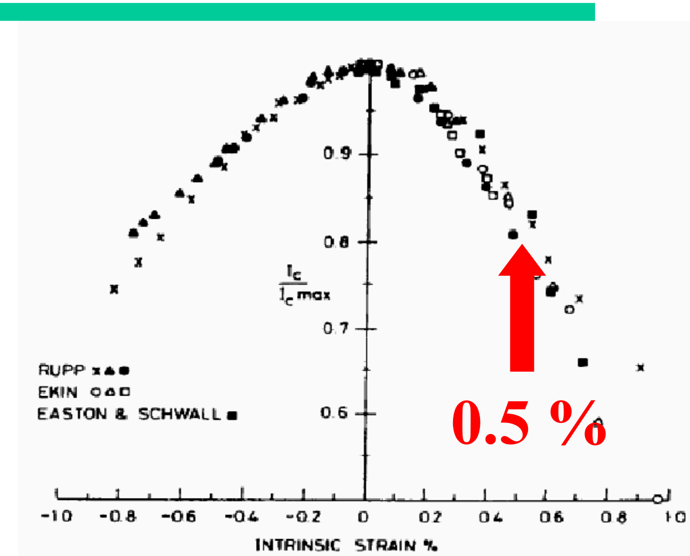
Why Nb_3Sn ?

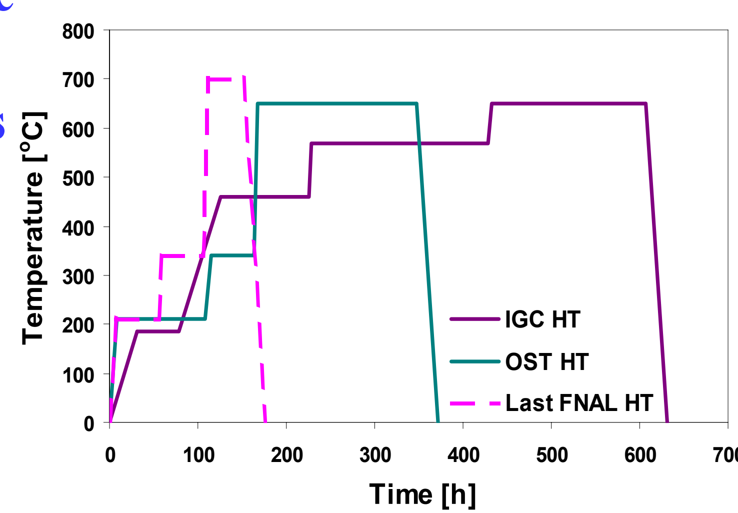
- Critical field is much higher than NbTi
- High current density Nb_3Sn conductor is commercially available in long lengths
- But…very difficult engineering material because it is brittle.



Nb_3Sn Challenges

- After heat treatment Nb_3Sn conductor is very sensitive to permanent strain degradation of Ic
  - 25% Loss of Ic at 0.5% strain
  - NbTi loses 25% in Ic at 4% strain when it breaks
- If conductor is heat treated before winding winding one must carefully control the strain strain on the conductor for its entire lifetime lifetime ➔ large bending radii
- Heat treatment after the magnet is wound is is also an engineering challenge
  - requires high temperatures (> 600 C)
  - long durations
  - special insulation schemes

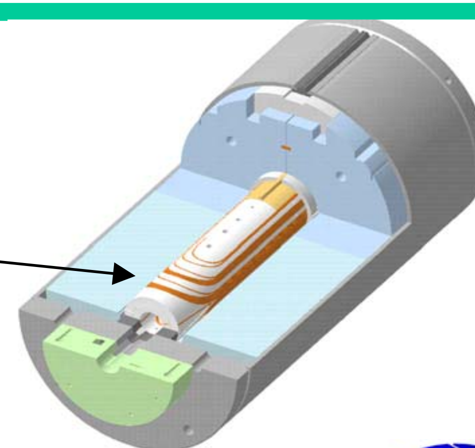




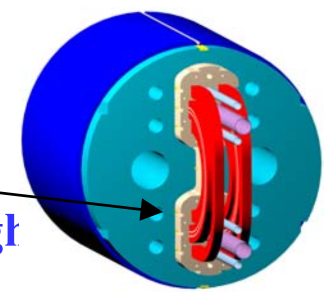
High Field Magnet Program

These features of Nb_3Sn lead to two approaches:

- **Wind-and-React:**
  - **Familiar cos θ shell-type coils**
  - **New high temp insulation schemes**
  - **Carefully engineered strain limits**

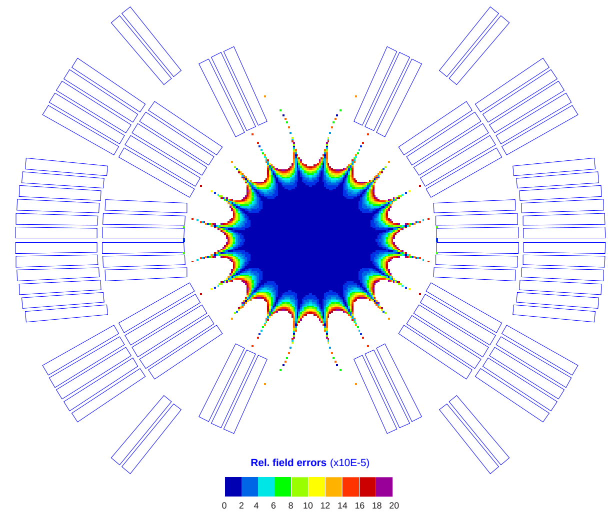


- **React-and-Wind:**
  - **Large bend radius block-type coils**
  - **Friendly to brittle conductors such as Nb_3Sn and other HTS.**
  - **Arranged in a twin aperture common-coil configuration**

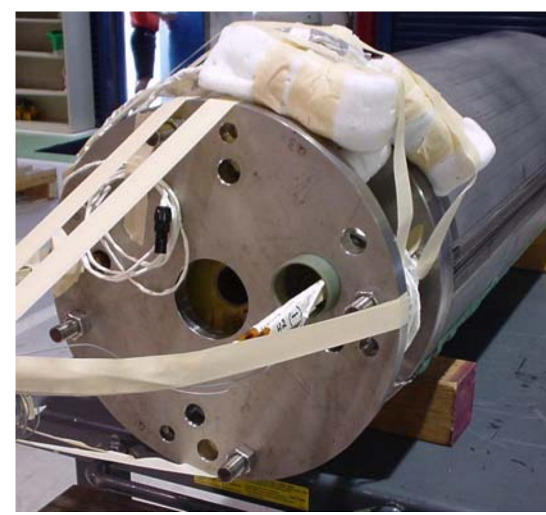


- **Fermilab is investigating both approaches with the goal to develop high high-field dipole design suitable for use with Nb_3Sn :**
  - **Each approach has its challenges ⇒ significant development time**
  - **e.g. LHC quad design took 4 yrs but was based on NbTi accelerator accelerator magnet development started in early 1970's, Tevatron, HERA, RHIC, etc.**
  - **Practical accelerator magnets based on Nb_3Sn will take a longer**

Cos θ Wind-&-React Model Magnets

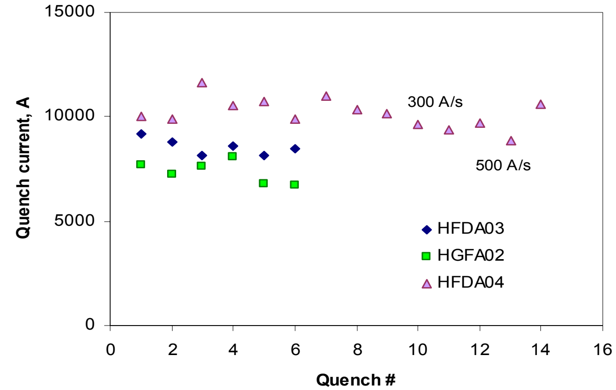


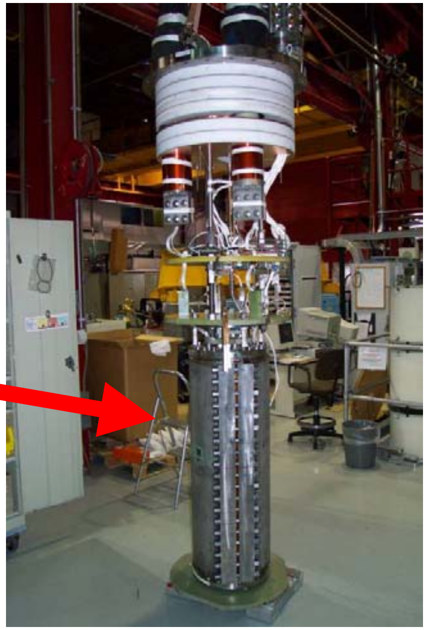
- **We have started building 1 m long models of a cos θ dipole**
  - **Magnet bore diameter: 43.5 mm**
  - **Bore Field, B = 11- 12 T**
  - **Strand: Nb_3Sn, ϕ 1.00 mm**
  - **Jc(12T;4.2K) = 1.8 - 1.9 kA/mm²**
  - **Wind-and-react**
  - **48 turns of 28 strand cable**
- **In 2001-2002 we built and tested three cos θ model magnets**



Cos θ Wind-&-React Model Magnet: Test Results

- **All three magnets achieved good field quality**
- **However, the quench performance was only 50-60% of that obtained with short samples**
- **Possible causes**
  - **Conductor damage at the splices** ✗
  - **Conductor Stability**
    - Filament size and flux jumps
    - Problems with current sharing due to cable inner-strand resistance
  - **Coil mechanical damage during assembly and/or preload (unplanned strain ?)**
- **Investigating these issues with extracted half coils using a mirror magnet setup**
  - **Fast turn-around, added instrumentation**
  - **Expect results from several tests by May**
- **Using this information we will construct and test next cos θ dipole model by ~ Sept**

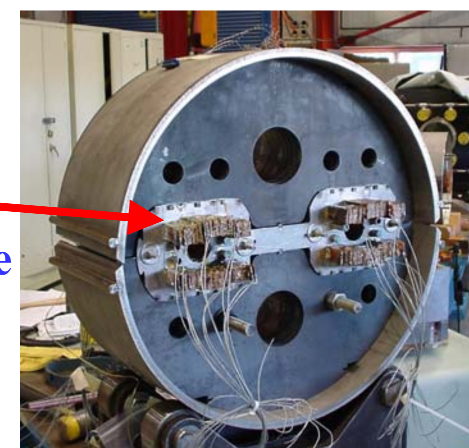




React-and-Wind Model Magnets

- React-and-wind techniques are being developed with 1-m long long racetrack coils using sub-sized cable
  - 2 react&wind Nb_3Sn racetracks were tested in FY01-02
  - 2nd racetrack tested reached 78% of short sample
  - This is a world record for react-and-wind
  - 3rd racetrack is almost complete, test in April

- Encouraged by the promising performance of the 2nd racetrack we began design and fabrication of 1-m long common coil dipole using using pre-reacted Nb_3Sn
  - Goal: 11 T of accelerator quality field in twin 40 mm bores
  - Conductor bending radius set by aperture separation
  - Different mechanical issues in this design vs. the racetrack
  - Mechanical model was fabricated and studied in FY2002



- 1st model magnet is being fabricated now, we expect it will be will be ready for test this summer

LHC Accelerator Research Program (LARP) Magnet R&D

One goal of LARP is to develop 2nd generation IR magnets for LHC

- 1st generation magnets have limited radiation lifetime
- Plan is to replace 1st generation quads after ~ 5 years @ design ☹
- First use of high field Nb_3Sn magnets in an accelerator.

❖ Fermilab to LARP activities include:

- Preparing the proposal to DOE (with LBNL, BNL)
- Conceptual designs studies for 2nd generation quad FY03-04
- ~ FY05, when sufficient LARP funds are available, Fermilab will begin constructing short model magnets
- That will lead to fabrication and tests of full-scale prototypes of the 2nd generation LHC IR magnets.

❖ There exists a strong connection between the existing FNAL High Field Magnet program and the planned LHC Accelerator Research program

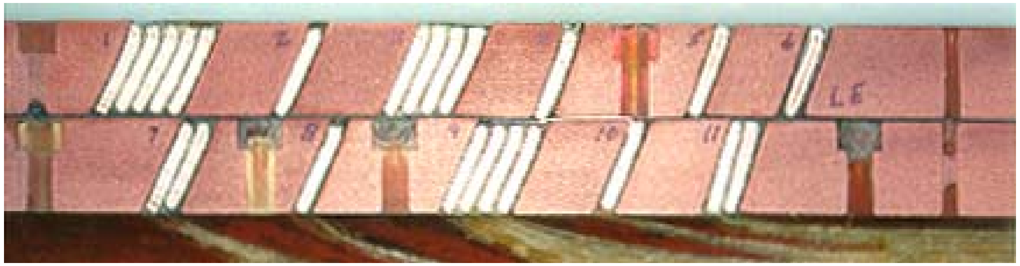
Superconductor R&D and infrastructure

- Fermilab is participating in national programs sponsored by DOE to encourage the development of improved high-field superconductor and and other magnet components in industry
  - e.g. developing faster conductor heat treatments
  - Improved insulation schemes
- Fermilab also has developed extensive infrastructure in support of materials and magnet development:
  - Vertical Dewar test facility in MTF & 20 KA→30 KA power supply
  - Instrumentation and field mapping systems
  - Ovens for superconductor heat treatment
  - Cabling machine for fast turn-around
  - Short Sample test facility
  - Electron microscope, etc….

Technology improvements

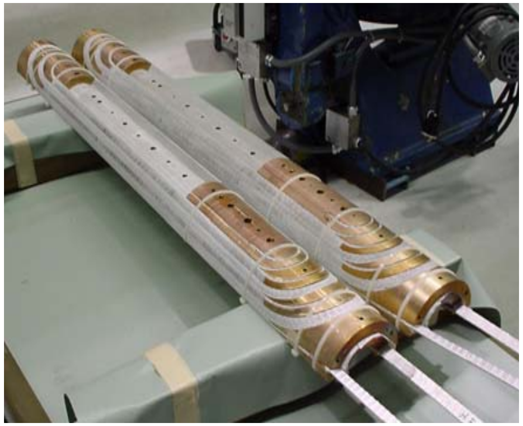
- **To reduce the fabrication cost of the fabrication of end-parts**
  - **Fermilab worked with industry to use Five Axis <u>Water Jet Machining</u>**
  - **Used for all our model magnets**

Second Generation End-Parts



Cable Insulation

- **New Insulation scheme developed by FNAL**
  - **Ceramic Fiber Tape with Ceramic Binder**
  - **Pre-preg tape is made by CTD Inc. (SBIR)**
  - **Cures at 150 C but survives HT @ 700C**
  - **High temperature insulation (<u>no organics</u>)**
  - **Handle cured coils during assembly, prior to heat-treatment**



The Future

- We plan production of 2-3 Nb_3Sn model magnets per year. This will increase to 5-6 models per year when LARP is in full swing
- 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 we will select a design based on our model magnet experience
- We will then develop the required infrastructure to start fabrication of of full length prototypes in FY2006.
- Goal is to insure that a viable 2nd generation quad design exists when it when it is needed for LHC. (~ 2009-2010)
- Technology is very similar to that required for a high field VLHC

Conclusions

- 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, 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, 1st Generation IR Quads development and construction, LARP (2nd generation IR Quads, possible LHC energy upgrade)
- Development of high field SC magnets for a VLHC

  Although a LC is 1st priority, the 2002 HEPAP sub panel recommendation is that SC magnet development is important, should continue to be well supported, and that a VLHC remains a long range goal of the field