R&D for High Field Magnets

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9th ICFA Seminar
SLAC, October 28-31, 2008
Conductor Options

Superconductor critical currents for 100 m length capable material (round wires)

- **Nb-Ti**: Example of Best Industrial Scale Heat Treated Composites ~1990 (compilation)
- **Nb-Ti(Fe)**: 1.9 K, Full-scale multifilamentary billet for FNAL/LHC (OS-STG) ASC’98
- **Nb-44wt.%Ti-15wt.%Ta**: at 1.8 K, monofil. high field optimized, unpubl. Lee et al. (UW-ASC) ’96
- **Nb-37Ti-22Ta** at 2.05 K, 2100 fil. strand, 400 h total HT, Chernyi et al. (Kharkov), ASC2000
- **Nb₃Sn**: Bronze route VAC 62000 filament, non-Cu 0.1µW·m⁻¹ 1.8 K J, VAC/NHMFL data courtesy M. Thoener.
- **Nb₃Sn**: Non-Cu J, Internal Sn Oil-ST RRP #6555-A, 0.8mm, LTSW 2002
- **Nb₃Al**: Nb stabilized 2-stage JR process (Hitachi,TML-NRIM,IMR-TU), Fukuda et al. ICMC/ICEC ’96
- **Nb₃Al**: JAERI strand for ITER TF coil
- **Bi-2212**: non-Ag J, 427 fil. round wire, Ag/SC=3 (Hasegawa ASC2000+MT17-2001)
- **Bi 2223**: Rolled 85 Fil. Tape (AmSC) B||, UW’96
- **Bi 2223**: Rolled 85 Fil. Tape (AmSC) B⊥, UW’96

Credit: Peter Lee
Applied Superconductivity Center, FSU/NHMFL
High Field Applications & Challenges

Enabling technology for the highest energy colliders:

LHC: • IR quadrupoles & dipoles – large aperture, high radiation
  • “14→28 TeV is great, 14→42 even better” (SLHC meeting)

MC: • 10-15 T dipoles, very high radiation (collider ring)
  • 30+ T solenoids (final stages of muon cooling)

Main challenges:

• Control of large forces and stresses
• High field superconductors are brittle and strain sensitive

R&D components:

• Development of cable and coil fabrication technology
• New concepts for mechanical support and magnet assembly
• Advances in modeling capabilities and diagnostic techniques
## Infrastructure and Technology Development

<table>
<thead>
<tr>
<th>Organization</th>
<th>Description</th>
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<tbody>
<tr>
<td>BNL</td>
<td>React-and-Wind technology; HTS, special magnets</td>
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<tr>
<td>CEA</td>
<td>Nb₃Sn Quadrupole, sub-scale structure, new insulation</td>
</tr>
<tr>
<td>CERN</td>
<td>Nb₃Sn dipole coils and structures, magnet testing</td>
</tr>
<tr>
<td>FNAL</td>
<td>Cos-θ dipoles, long coil technology, HTS solenoids</td>
</tr>
<tr>
<td>KEK</td>
<td>Nb₃Al coil technology, sub-scale models</td>
</tr>
<tr>
<td>LBNL</td>
<td>Very High Field Dipoles (Nb₃Sn, HTS); advanced cables</td>
</tr>
<tr>
<td>NHMFL</td>
<td>Very High Field Solenoids, HTS coil technology</td>
</tr>
<tr>
<td>TAMU</td>
<td>Stress intercepts for dipoles, new materials/insulation</td>
</tr>
<tr>
<td>UT</td>
<td>Cos-θ dipoles, PIT conductor</td>
</tr>
</tbody>
</table>
A Worldwide Collaboration Network

**LARP (MagSys)**
- Participants: BNL, FNAL, LBNL + CERN
- Goal: **fully qualified quadrupoles for SLHC** (Phase 2 upgrade)

**CARE (NED)**
- Participants: CCLRC, CEA, CERN, CIEMAT, INFN, UT, WTU
- Goal: basic R&D on conductor, insulation, design, quench protection

**EUCARD (HFM)**
- Participants: CERN, CEA, CNRS, COLUMBUS, DESY, EHTS, FZK, INFN, PWR, SOTON, STFC, TUT, UNIGE
- Goal: high field Nb$_3$Sn dipole model & very high field (HTS) insert

**Inter-Laboratory collaborations on specific topics:**
- CERN, RAL, CEA, LBNL on Short Model Coil development
- KEK, NIMS, FNAL on Nb$_3$Al model coils
- LBNL, KEK on Nb$_3$Sn coil, structure and assembly methods
- KEK & CERN on Nb$_3$Al technology for the LHC upgrades
- CERN & CEA, UT, LBNL/LARP on magnet testing
- LBNL & FNAL, BNL, CERN, UT, TAMU on cable development
Quadrupoles for the LHC Phase 2 Upgrade

High field technology provides design options to maximize luminosity

- Higher Field
- Larger Aperture (at same gradient)
- Better beam optics
- More luminosity
- More Design Margin (same gradient / aperture)
- More Operating Margin (at same gradient / aperture)
- Thicker absorbers
- Longer Lifetime
- Lower radiation and heat loads
- Higher T margin
- Easier cooling
- Stable operation
- Higher Gradient (at same aperture)
- Faster development
- Lower risk
- Shorter magnets
- Better IR layout
- Less cost & time for small production
- More Design Margin (same gradient / aperture)
- More luminosity
- More design margin (same gradient / aperture)
- More luminosity
LARP Sub-scale Quadrupoles (2005-06)

Design features:

• Based on LBNL “SM” design
• Four racetrack coils, square bore
• Aperture 130 mm, Length 30 cm

R&D Goals:

• Conductor performance verification
• First shell-based quadrupole structure
• FEA models verification
• Quench propagation analysis

Results:

• Two models tested at LBNL & FNAL
• SQ02: 98% of SSL at 4.5K & 1.9K
LARP Long Racetrack (2006-08)

- Scale up LBNL SM coil and structure: 30 cm to 4 m
- Coil R&D: Cable, handling, reaction, impregnation
- Structure R&D: friction effects, magnet assembly
- BNL: coil fabrication, magnet assembly and test
- LBNL: magnet design, structure fabrication/assembly
- FNAL: contributions to design and coordination
- Fast training: LRS01 first quench at 84% of SSL
- LRS02 achieved 11.5 T, 96% of short sample limit
Fermilab Mirror Dipole (2006-08)

- Three steps were performed: 1m, 2m and 4m models
- First length scale-up of Nb$_3$Sn $\cos \theta$ coil technology
- Experience applied toward LARP models
LARP Technology Quadrupoles (2005-08)

- Double-layer, shell-type coil
- 90 mm aperture, 1 m length
- Two support structures:
  - TQS (shell based)
  - TQC (collar based)
- Target gradient 200 T/m

Winding & curing (FNAL - all coils)  
Reaction & potting (LBNL - all coils)
## TQ Results Summary

<table>
<thead>
<tr>
<th>Model</th>
<th>First Training at 4.4K</th>
<th>First Training at 1.9K</th>
<th>Highest Quench*</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$G_{\text{Start}}$ (T/m)</td>
<td>$G_{\text{Max}}$ (T/m)</td>
<td>$G_{\text{Max}}/G_{\text{ss}}$ (%)</td>
</tr>
<tr>
<td>TQC01a</td>
<td>131</td>
<td>154</td>
<td>72</td>
</tr>
<tr>
<td>TQC01b</td>
<td>142</td>
<td>178</td>
<td>86</td>
</tr>
<tr>
<td>TQC02E</td>
<td>177</td>
<td>201</td>
<td>87</td>
</tr>
<tr>
<td>TQC02a</td>
<td>124</td>
<td>157</td>
<td>68</td>
</tr>
<tr>
<td>TQC02b</td>
<td>141</td>
<td>173</td>
<td>85</td>
</tr>
<tr>
<td>TQS01a</td>
<td>180</td>
<td>193</td>
<td>89</td>
</tr>
<tr>
<td>TQS01b</td>
<td>168</td>
<td>182</td>
<td>84</td>
</tr>
<tr>
<td>TQS01c</td>
<td>159</td>
<td>176</td>
<td>81</td>
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<tr>
<td>TQS02a</td>
<td>182</td>
<td>219</td>
<td>92</td>
</tr>
<tr>
<td>TQS02b</td>
<td>190</td>
<td>200</td>
<td>84</td>
</tr>
<tr>
<td>TQS02c</td>
<td>216</td>
<td>222</td>
<td>93</td>
</tr>
</tbody>
</table>

*Optimized models surpassed the 200 T/m target gradient with good margin*
Present focus: Long Quadrupole (LQ)

Scale up of TQ design from 1 m to 3.6 m

• Coil design and fabrication: FNAL & BNL
• Structure design and fabrication: LBNL
• Magnet assembly: LBNL
• Magnet test: FNAL

Two LQS tests are planned for 2009
**Next Step: 120 mm Quadrupoles**

**Completed:**
- *Cable optimization & test winding (LBNL)*
- *Coil cross-section and end design (FNAL)*
- *Winding/curing tooling design (LBNL)*

**In progress:**
- *Reaction/potting tooling design (BNL)*
- *Coil parts procurements (FNAL)*
- *Support structure design (LBNL)*

**Plans:**
- *Test 1 m models (HQ) in 2009-10, 4 m models (QA) in 2011-12*
- *Aiming at full qualification based on Phase 1 upgrade requirements*
- *Conductor-limited gradient is about twice the Phase 1 requirement*
- *Will provide performance reference for Phase 2 upgrade design*
HFM Developments in Europe and Japan

1. Short Model Coil (SMC) Program
   • CERN, STFC/RAL, CEA and LBNL
   • Demonstrate NED cable and insulation
   • Gain coil manufacturing experience

2. Assembly & Test of TQ models
   • Best results achieved in CERN tests

3. Nb₃Al Magnet Development
   • KEK, NIMS: conductor development
   • FNAL: cable and coil fabrication
   • First model coil reached short sample

Efficient start of new R&D efforts by collaboration with ongoing programs
High Field Dipoles

- Bi-2212 (YBCO)
- Nb$_3$Sn
- NbTi

Graph showing the progress in magnetic field strength over years with key milestones:
- BNL (Sampson)
- CERN (Asner)
- LBNL (D10)
- LBNL (RD3b)
- LBNL (D20)
- LBNL (HD1)
- Twente (MSUT)

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HD2 Design

- Target dipole field: **15 T** (15.8 T coil field)
- Clear bore 36-42 mm
- Coil design: block-dipole with flared ends
- Designed for **accelerator field quality**
- Suitable for 2-in-1 layout
- Can be used for high field **cable testing**
HD2 Components & Assembly
HD2c Peak Field vs. Conductor Limit

\[ I_c \text{ data corrected for self field} \]

\( RW = \text{Round Wire} \)

\( XS = \text{Extracted strand} \)

**Graph Details:**
- **10/25/07 - Brl-R03 - RW**
- **10/16/07 - XS-8**
- **10/17/07 - XS-10**
- **Parameterization RW**
- **Parameterization XS**
- **Parameterization XS at 4.5 K**
- **Parameterization XS at 1.9 K**
- **Loadline layer 2 peak field**

**Legend:**
- **4.2K (RW)**
- **4.2K (XS)**
- **4.5K (XS)**
- **1.9K (XS)**

**Data Points:**
- **T= 1.9 K B= 18.1 T**
- **T= 4.5 K B= 16.4 T**
- **HD2c B=14.5 T**

**Note:**
- Ic data corrected for self field
- RW = Round Wire
- XS = Extracted strand

**Parameters:**
- Magnetic field \([ T ]\)
- Strand critical current \([ A ]\)
Beyond ~18 T: HFS (Bi-2212 & YBCO)

![Graph showing comparison of superconductors at high fields]

- **YBCO B|| Tape Plane**
- **YBCO B⊥ Tape Plane**
- **MgB$_2$**
- **Nb$_3$Sn**
- **RRP Nb$_3$Sn**
- **Bronze Nb$_3$Sn**
- **Nb$_3$Sn High Sn Bronze Cu:Non-Cu 0.3**
- **2212 OI-ST 28% Ceramic Filaments**
- **NbTi LHC Production 38%SC (4.2 K)**
- **MgB$_2$ 19Fil 24% Fill (HyperTech)**

**Key Points**:
- Maximal $J_E$ for entire LHC Nb-Ti strand production
- CERN-T. Boutboul '07, and (- -) <5 T data from Boutboul et al. MT-19, IEEE-TASC’06
- Complied from ASC’02 and ICMC’03 papers (J. Parrell OI-ST)
- 427 filament strand with Ag alloy outer sheath tested at NHMFL
- 18+1 MgB$_2$/Nb/Cu/Monel used in record breaking NHMFL insert coil 2007

**Acknowledgments**:
- Courtesy M. Tomsic, 2007
- 4543 filament High Sn Bronze-16wt.%Sn-0.3wt%Ti (Miyazaki-MT18-IEEE’04)
HTS Challenges

- YBCO: only in tape form, not suitable for high current cables
- Bi-2212 react-and-wind: excessive degradation during winding
- Bi-2212 wind-and-react: reaction temp, materials compatibility

<table>
<thead>
<tr>
<th></th>
<th>NbTi</th>
<th>Nb$_3$Sn</th>
<th>Bi-2212</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dipole Limit</td>
<td>10-11 T</td>
<td>16-17 T</td>
<td>Stress limited</td>
</tr>
<tr>
<td>Reaction</td>
<td>Ductile</td>
<td>~675°C in Air/Vacuum</td>
<td>~890°C in O$_2$ (±2°C)</td>
</tr>
<tr>
<td>Axial compression</td>
<td>N/A</td>
<td>Reversible</td>
<td>Irreversible?</td>
</tr>
<tr>
<td>Transverse stress</td>
<td>N/A</td>
<td>&lt; 200 MPa</td>
<td>60 MPa?</td>
</tr>
<tr>
<td>Insulation</td>
<td>Polymide</td>
<td>S/E Glass</td>
<td>Ceramic</td>
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<tr>
<td>Construction</td>
<td>G-10, stainless...</td>
<td>Bronze, Stainless</td>
<td>Super alloy</td>
</tr>
<tr>
<td>Quench velocity</td>
<td>&gt;20 m/s</td>
<td>~20 m/s</td>
<td>0.1 m/s?</td>
</tr>
</tbody>
</table>
# HTS Coil Technology Development

Dipole coils (MC, DLHC): react & wind at BNL, TAMU; wind & react at LBNL

![Dipole coil images](image)

Solenoid insert coils (MC cooling channel): Record fields obtained at NHMFL

<table>
<thead>
<tr>
<th>Year</th>
<th>Material</th>
<th>$B_{HTS}$ [T]</th>
<th>$B_{Total}$ [T]</th>
<th>$J_e$ [A/mm$^2$]</th>
</tr>
</thead>
<tbody>
<tr>
<td>2003</td>
<td>Bi2212</td>
<td>5</td>
<td>25</td>
<td>100</td>
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<tr>
<td>2007</td>
<td>YBCO</td>
<td><strong>7.8</strong></td>
<td>26.8</td>
<td>259</td>
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<tr>
<td>2008</td>
<td>Bi2212</td>
<td>1.1</td>
<td>32.1</td>
<td>80</td>
</tr>
<tr>
<td>2008</td>
<td>YBCO</td>
<td>2.8</td>
<td><strong>33.8</strong></td>
<td>359</td>
</tr>
</tbody>
</table>

Bi2212 by OST; YBCO by Superpower
Summary

• Strong, efficient collaboration network among magnet programs
• Demonstrated all fundamental aspects of Nb$_3$Sn technology:
  - Conductor & structure performance, length scale-up
• Complete engineering toolbox, fast fabrication turnaround
• On track to fully qualify a Nb$_3$Sn quadrupole for the LHC IR
• Demonstrated a 14 T dipole with accelerator quality features
• Exciting developments for very high field dipoles and solenoids

Acknowledgement

G. De Rijk (CERN), P. Ferracin (LBNL),
D. Larbalestier (NHMFL), L. Rossi (CERN), P. Wanderer (BNL),
A. Yamamoto (KEK), A. Zlobin (FNAL)