Nb$_3$Sn Magnets for the LHC Upgrades

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Upgrade components

- Linac2
- PSB
- Linac4
- LPSPL
- PS
- PS2
- SPS
- SPS+
- LHC / SLHC
- DLHC

Proton flux / Beam power

Output energy:
- 50 MeV
- 160 MeV
- 1.4 GeV
- 4 GeV
- 26 GeV
- 50 GeV
- 450 GeV
- 1 TeV
- 7 TeV
- ~ 14 TeV

LPSPL: Low Power
Superconducting Proton Linac (4 GeV)

PS2: High Energy PS
(~ 5 to 50 GeV – 0.3 Hz)

SPS+: Superconducting SPS
(50 to 1000 GeV)

SLHC: “Superluminosity” LHC
(up to $10^{35}$ cm$^2$s$^{-1}$)

DLHC: “Double energy” LHC
(1 to ~14 TeV)

L. Evans – EDMS Document 974861

9th ICFA Seminar
SLAC, Oct. 2008
**Technology 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, 210 fil. strand, 400 h total HT, Chernyi et al. (Kharkov), ASC2000
- **Nb3Sn**: Bronze route VAC 62000 filament, non-Cu 0.1µW·m⁻¹ K⁻¹, VAC/NHMFL data courtesy M. Thoener.
- **Nb3Sn**: Non-Cu Jc, Internal Sn OI-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 Jc, 427 fil. round wire, Ag/SC=3 (Hasegawa ASC2000+MT17-2001)
- **Bi 2223**: Rolled 85 Fil. Tape (AmSC) B||, UW’6/96
- **Credit**: Peter Lee Applied Superconductivity Center, FSU/NHMFL
Magnet R&D Collaboration Network

LARP (MagSys)  • Participants: BNL, FNAL, LBNL + CERN
  • Goal: fully qualified Nb$_3$Sn quadrupoles for SLHC

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
Physics goals:

- Improve measurements of new phenomena seen at the LHC
- Detect/search low rate phenomena inaccessible at nominal LHC
- Increase mass range for limits/discovery by ~30%

Implementation in 2 phases:

- Phase 1 ($L = 2 \cdot 10^{34} \text{ cm}^{-2}\text{sec}^{-1}$): ~2014
- Phase 2 ($L = 10 \cdot 10^{34} \text{ cm}^{-2}\text{sec}^{-1}$): ~2017

Required accelerator upgrades include new IR magnets:

- Directly increase luminosity through stronger focusing
  ⇒ decrease $\beta^*$
- Provide design options for overall system optimization/integration
  ⇒ collimation, optics, vacuum, cryogenics
- Be compatible with high luminosity operation
  ⇒ Radiation lifetime, thermal margins

Major detector upgrades are also required to take full advantage of SLHC
Quadrupole Upgrade Roadmap

High field technology provides design options to maximize luminosity

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

PAC 2009, Vancouver, May 2009
Gb3Sn Magnets for the LHC Upgrades
GianLuca Sabbi, LBNL
LARP Magnet Program Components

1. Materials R&D:
   - *Strand specification and procurement*
   - *Cable fabrication, insulation and qualification*
   - *Heat treatment optimization*

2. Technology development with Racetrack Coils:
   - *Subscale Quadrupole (SQ)*
   - *Long Racetrack (LR)*

3. Cos $2\theta$ Quadrupoles with 90 mm aperture:
   - *Technology Quadrupole (TQ)*
   - *Long Quadrupole (LQ)*

4. Cos $2\theta$ Quadrupoles with 120 mm aperture:
   - *High-Field Quadrupole (HQ)*
   - *Accelerator Quadrupole (QA)*

   - **Ongoing**
   - **Completed**
   - ~80%
   - ~10%
Sub-scale Quadrupole (SQ)

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
Long Racetrack (LR)

- 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

- Fast training: LRS01 first quench at 84% of SSL
- LRS02 achieved 11.5 T, 96% of short sample limit
Mirror Dipoles and Quadrupoles

- Fermilab dipole models: 1m, 2m and 4m
- First length scale-up of Nb$_3$Sn cosθ coil technology
- Experience applied toward LARP models
- Quadrupole version to test single LARP coils
LARP Technology Quadrupole (TQ)

- 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

<table>
<thead>
<tr>
<th>Model</th>
<th>First Training at 4.4K</th>
<th>First Training at 1.9K</th>
<th>Highest Quench*</th>
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<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>
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<tr>
<td>TQC01b</td>
<td>142</td>
<td>178</td>
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<td>TQC02E</td>
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<tr>
<td>TQS02b</td>
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</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 >10% margin**
TQ Summary and Next Steps

Achievements:

- Three coil series using different wire design
- A total of 12 quadrupole models were tested
- More than 30 coils fabricated
- Distributed coil production (FNAL, LBNL)
- Two models assembled and tested at CERN
- Magnetic, mechanical, quench studies
- Optimized models surpassed 220 T/m
- First quench >200 T/m in optimized models

Issues and Next Steps:

- Coil variability resulting in local degradation
- Coil selection required to achieve best results
- Local degradation leads to instability at 1.9K
- Need to improve coil fabrication, wire design
Present focus: Long Quadrupole (LQ)

Scale up of TQ design from 1 m to 3.6 m length

- **Coil parts, winding and curing**: FNAL
- **Coil reaction and potting**: FNAL & BNL
- **Instrumentation traces, strain gauges**: LBNL
- **Collar structure fabrication/assembly**: FNAL
- **Shell structure fabrication/assembly**: LBNL
- **Magnet test**: FNAL
LQSD Mechanical Model

- LQS assembly w/instrumented Dummy coils
- Verify design calculations, qualify structure
- *Practice transport, test setup, cool-down*

![LQSD Mechanical Model Diagram]

- S1 (2)
- D1 (1)
- S2 (4)
- D2 (4)
- S3 (2)
- D3 (1)
- S4 (2)

![Graph showing data points for coils at temperatures 77 K and 293 K]

- Comp. 77K
- Comp. 293K
- Data point

θ
Z
LQ Status and Plans

• April 2009 review following cool-down test confirmed LQS Structure Readiness
• Four coils received (2 practice coils); last 2 LQS01 coils to be received in May
• Coil instrumentation & LQS01 assembly in June-July; test in September-October
• Additional coil fabrication and magnet tests are planned for FY10
Next Phase: 120 mm Quadrupoles

- IR Studies show *large aperture quads required* for $L=10^{35}$ cm$^{-2}$ sec$^{-1}$
- Phase 1 ($L=2 \times 10^{34}$ cm$^{-2}$sec$^{-1}$) will use NbTi Quads with *120 mm aperture*
- The *same aperture* was chosen for the next series of Nb$_3$Sn models (HQ)

Aiming at:
- **Full qualification** based on Phase 1 upgrade specifications
- Providing **performance reference** for Phase 2 upgrade design

**Expected range**

$L=10^{35}$ cm$^{-2}$ s$^{-1}$
HQ Design Features and Parameters

- Coil peak field of **15.2 T at 219 T/m** (1.9K un-degraded short sample)
- **190 MPa coil stress** at SSL (**150 MPa if preloaded for 180 T/m**)
- Stress minimization is **primary goal at all design steps** (from x-section)
- Coil and yoke designed for small **geometric and saturation harmonics**
- **Full alignment** during coil fabrication, magnet assembly and powering
HQ Status and Plans

**Status:**
- Developed **15 mm wide cable**, test windings w/RP parts (LBNL)
- Designed and procured stainless steel **coil parts** (FNAL)
- Designed and procured **winding/curing tooling** (LBNL)
- Designed **reaction tooling** (BNL); procurement underway (LBNL)
- Design and procurement of **support structure** is underway (LBNL)
- **Winding of the first (practice) coil has started** (LBNL)

![Test winding w/RP parts](image1)
![First coil winding - layer 1 pole turn](image2)

**Plans:**
- **First HQ magnet test expected in early 2010**
- Several 1 meter models will be needed to optimize the design
- **Next:** 2 meter models (QA) for **field quality study/optimization**
Energy Upgrade (DLHC)

Motivation for a 14 TeV → 28 TeV upgrade:

- Direct enhancement of physics reach by a factor of two in mass
- No major detector upgrades required

The better upgrade path depends on where and what the new physics is:

- Low mass: 10xLum better than 2xE_{beam}
- High mass: increase of E_{beam} is essential

Strong physics interest in energy upgrade:

“14→28 TeV is great, 14→28 is even better”

(M. Mangano, SLHC kick-off meeting)

However, energy upgrade is extremely difficult from the accelerator standpoint
Many issues, but key R&D challenge is developing the high field dipoles
HD2 Design

- Target dipole field: 15 T
- Target aperture: 40-43 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 Field and Aperture

Ic data corrected for self field
RW = Round Wire
XS = Extracted strand

Parameterization RW
Parameterization XS
Parameterization XS at 4.5 K
Parameterization XS at 1.9 K
Loadline layer 2 peak field

HD2d2 (43 mm) B=14 T
HD2c (36 mm) T= 4.5 K B=14.5 T
HD2c (36 mm) B= 16.4 T

10/25/07 - Brl-R03 - RW
10/16/07 - XS-8
10/17/07 - XS-10
HD2 Training & Ramp Rate Quenches

Quench locations w/o bore tube (HD2-d2)

![Graph showing training quenches and ramp rates](image)

- SSL 4.5K (based on virgin strand Ic)
- HD2c
- HD2d2

- Quencher locations without bore tube (HD2-d2)

Conductor peak field (T) vs. Training quench #

- HD2c
- HD2d2

Quench current (kA) vs. Ramp-rate (A/s)
Next Steps in Dipole Development

**HD2 optimization:** 15 T & field quality

- Eliminate localized quenches in L1 pole turn
- Determine stress limits, optimal pre-load
- Test at 1.9K (requires facility upgrades)
- Field quality optimization:
  - geometric harmonics (tolerances)
  - persistent currents (magnetic shims)
  - end region design (axial shift L1/L2)

Fabrication of new coils planned for next year

**16 T and beyond:** HTS technology

- Conductor options: Bi-2212 and YBCO
- Technology development with sub-scale coils
- Fabrication of hybrid \( \text{Nb}_3\text{Sn}/\text{HTS} \) dipoles
Magnet Programs 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. Hybrid (Nb$_3$Al) Sub-scale Magnet

- NIMS, KEK: Nb$_3$Al conductor R&D
- FNAL: Nb$_3$Al coil fabrication and test
- KEK, LBNL: Mech. structure, Nb$_3$Sn coil
- KEK: radiation and thermal studies

Efficient start of new R&D efforts by collaboration with ongoing programs
EuCard-WP8 Program

- Work Package 8: Superconducting High Field Magnets for higher luminosities and energies
- Comprises the following Tasks:
  - Task 1: Coordination and Communication.
  - Task 2: Support studies
  - Task 3: High field model
  - Task 4: Very high field dipole insert
  - Task 5: High Tc superconducting link
  - Task 6: Superconducting wiggler for ANKA
  - Task 7: Short period helical superconducting undulator
- WP8 is a CERN, CEA, CNRS, COLUMBUS, DESY, EHTS, FZK, INFN, PWR, SOTON, STFC, TUT, UNIGE collaboration
- Project time span: 2009-2012
- Coordinated with individual Lab programs
Summary

• Strong, efficient collaboration network among magnet programs
• Demonstrated the fundamental aspects of Nb$_3$Sn technology:
  - Conductor & structure performance, length scale-up
• Complete engineering toolbox and fabrication capabilities
• On track to qualify a 120 mm Nb$_3$Sn quadrupole for the LHC IR
• Developing 15 T dipoles with accelerator quality features
• Started HTS material & technology development for dipoles >16 T

Acknowledgement