Nb$_3$Sn Quadrupoles for the LHC Luminosity Upgrade

GianLuca Sabbi

for the LARP collaboration

CERN, January 12, 2010
LARP Program Goals

Coordinate US LHC Accelerator Research:

• Started by DOE in 2003, expected to be completed around 2014
• Progression from the US LHC Accelerator Research Project
• Collaboration of four national Labs: BNL, FNAL, LBNL, SLAC
• Funding level: $12-13M/year (FY06-FY10)

Goals:

• Extend and improve the performance of LHC
  ➢ Maximize scientific output in support of the experiments
• Maintain and develop US Labs capabilities
  ➢ Prepare for a leadership role in future projects
• Research and training for US accelerator physicists and engineers
• Advance international collaboration on large accelerator projects
### Overview of LARP Activities

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<td>• Tune tracker, AC dipole</td>
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<td>• Schottky monitor</td>
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<td>Accelerator Physics</td>
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<td>• Crab crossing</td>
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<td>Model Quadrupoles</td>
<td>• Cable development</td>
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<td>• Long Term Visitors</td>
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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
Luminosity Upgrade (SLHC)

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 up to 30%

Implementation:

• Phase 1 (2-3 times increase from nominal $L=10^{34}$ cm$^{-2}$sec$^{-1}$)
• Phase 2 (up to a factor of 10 increase from nominal)

Required accelerator upgrades include new IR magnets:

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

Major detector upgrades are also required to take full advantage of SLHC
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 1.8 K J, VAC/NHMFL data courtesy M. Thoener.
- **Nb3Sn**: Non-Cu J, 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
- **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
- **Bi-2223**: Rolled 85 Fil. Tape (AmSC) B|_, UW’6/96

At 4.2 K Unless Otherwise Stated

**NbTi**: 11 T @ 1.9K
**Nb3Sn (Nb3Al)** 17 T @ 4.2 K
**Bi-2212** (YBCO)

**Applied Field, T**

**A/mm²**
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 luminosity
    - Longer Lifetime
    - Lower radiation and heat loads
  - More Operating Margin (at same gradient / aperture)
    - Higher T margin
    - Easier cooling
    - Stable operation
    - Faster development
    - Less cost & time for small production
  - More Design Margin (same gradient / aperture)
    - Lower risk
    - Shorter magnets
    - Better IR layout
  - Higher Gradient (at same aperture)
# Nb$_3$Sn Challenges

**Brittleness:**
- React coils after winding
- Epoxy impregnation

**Strain sensitivity:**
- Mechanical design and analysis to prevent degradation under high stress

<table>
<thead>
<tr>
<th>Material</th>
<th>NbTi</th>
<th>Nb$_3$Sn</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dipole Limit</td>
<td>~ 10 T</td>
<td>~ 17 T</td>
</tr>
<tr>
<td>Reaction</td>
<td>Ductile</td>
<td>~ 675°C</td>
</tr>
<tr>
<td>Insulation</td>
<td>Polymide</td>
<td>S/E Glass</td>
</tr>
<tr>
<td>Coil parts</td>
<td>G-10</td>
<td>Stainless</td>
</tr>
<tr>
<td>Axial Strain</td>
<td>N/A</td>
<td>~ 0.3 %</td>
</tr>
<tr>
<td>Transverse stress</td>
<td>N/A</td>
<td>~ 200 MPa</td>
</tr>
</tbody>
</table>
Magnet R&D 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)

Ongoing

Completed

~75%

~25%
Magnet Development Chart

Subscale Quadrupole
SQ
0.3 m long
110 mm bore

Technology Quadrupoles
TQS, TQC
1 m long
90 mm bore

Long Quadrupole
LQS
3.7 m long
90 mm bore

High Field Quadrupole
HQ
1 m long
120 mm bore

Subscale Magnet
SM
0.3 m long
No bore

Long Racetrack
LRS
3.6 m long
No bore
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 (2004-2006):
- Two models tested at LBNL & FNAL
- SQ02: 97% of SSL at 4.5K & 1.9K
SQ vs. TQ (LQ) Parameters

SQ and TQ (LQ) closely match in terms of operating point, forces and stresses.

<table>
<thead>
<tr>
<th></th>
<th>$D_{\text{strand}}$ (mm)</th>
<th>$I_{\text{strand}}$ (A)</th>
<th>$B_{\text{peak}}$ (T)</th>
<th>$\sigma_\perp$ (MPa)</th>
<th>$F_z$ (kN)</th>
<th>$S_z$ (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SQ</td>
<td>0.7</td>
<td>490</td>
<td>11.1</td>
<td>100-150</td>
<td>340</td>
<td>87</td>
</tr>
<tr>
<td>TQ (LQ)</td>
<td>0.7</td>
<td>460</td>
<td>11.3</td>
<td>100-150</td>
<td>350</td>
<td>81</td>
</tr>
</tbody>
</table>
SQ Findings

• Achieved 97% of short sample at both 4.5 K and 1.9K (SQ02b test)
  - **Validated conductor used in the TQ01 Models (MJR 54/61)**
  - **Minimal/no degradation due to transverse or axial stress**
• Showed critical role of axial coil support at high field (SQ02c test)
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 and 96% of short sample limit
- No fundamental issues with coil/structure scale-up
Longitudinal Strain in LRS01 Shell

- FEA models predicted strong dependence of axial strain on shell-yoke friction
- Six strain gauge stations were included to measure axial strain dependence
- Measurements during initial cool-down and excitation show $\mu = 0.2$
- Slippage occurred during the test, after which measurements show $\mu = 0.05$
Segmented Shell in LRS02

- Shell was divided in 4 segments
- No axial strain accumulation
- Required for very long shells
- Factor of 2 improved homogeneity
- Increased field and no slippage
- 96% SSL with minimal training

Structure re-assembly with segmented shell
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)
Conductor design:
- TQ01: OST MJR 54/61
- TQ02: OST RRP 54/61
- TQ03: OST RRP 108/127

Cable:
- 27 strands, 0.7 mm diameter
- Width: 10.05 mm
- Mid-thickness: 1.26 mm
- Keystone angle: 1.0 deg
- Insulation: S-2 glass sleeve

Coil:
- double-layer, shell-type
- one wedge/octant (inner layer)
TQ Tests: Quench Training at 20 A/s

Model: S01a S01b S01c S02a S02b S02c S02d S03a S03b C01a C01b C02E C02a C02b
Tested by: LBNL LBNL LBNL FNAL CERN CERN CERN CERN FNAL FNAL FNAL FNAL FNAL FNAL

CERN, 1/12/2010
GianLuca Sabbi

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TQ Studies: Axial Tension at Pole Gaps

- **Bronze pole** (TQS01/b/c)
  - Spikes in coil axial strain (cool-down & excitation)

- **Titanium pole** (TQS02)
  - Spikes in coil axial strain are reduced/eliminated

All limiting quenches in pole gaps

- \( I_{\text{ref}} = 12.3 \text{ kA} \)
- \( G_{\text{ref}} = 218 \text{ T/m} \)
TQ Studies: Conductor Stability

TQS02c test (CERN)

SSL 4.4K

SSL 1.9K

TQS03a test (CERN)

SSL 4.4K

SSL 1.9K

TQS02c limit at 1.9K: conductor instability, enhanced by local degradation:

- Limiting quenches in the same coil & location (c23 ramp) at 4.5K and 1.9K
- 1.9K stability limit in magnet is lower than expected from strand data

TQS03a with RRP 108/127 shows expected increase at 1.9K

- Qualifies RRP 108/127 as new baseline conductor for LARP
- CDP is funding R&D on RRP conductor with 217 sub-elements
Systematic investigation in TQS03:

- TQS03a: 120 MPa at pole, 93% SSL
- TQS03b: 160 MPa at pole, 91% SSL
- TQS03c: 200 MPa at pole, 88% SSL

Peak stresses are considerably higher → Considerably widens design window
Long Quadrupole (LQ)

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

• **Cable fabrication** (w/ RRP 54/61 wire): LBNL
• **Coil parts, winding and curing**: FNAL
• **Coil reaction and potting**: BNL & FNAL
• **Instrumentation traces, strain gauges**: LBNL
• **Structure fabrication/assembly**: LBNL
• **Magnet test**: FNAL

Winding/curing (FNAL)

Reaction/Potting (BNL and FNAL)

Instrumentation and heater traces (LBNL)
LQSD Mechanical Model

• LQ Shell structure assembly w/ Dummy coils
• Verify design calculations, qualify structure
• Practice transport, test setup, cool-down

![Graph showing coil azimuthal and axial microstrain](image)

- Comp. 77 K
- Comp. 293 K

![Image of LQSD mechanical model](image)
LQS01 Test: Strain Gauge Measurements

**SHELL COOL-DOWN**
- Design target, 4.5K
- Design target, 293K

**AXIAL RODS COOL-DOWN**
- Design target, 4.5K
- Design target, 293K

**COIL (Ti POLE) COOL-DOWN**
- Design target, 4.5K
- Design target, 293K

**COIL (Ti POLE) EXCITATION**
- Unloading
LQS01 & TQS Quench Performance

Comparison of first training sequences at each temperature with all new coils

- **TQS01a**
- **TQS02a**
- **TQS03a**
- **LQS01a**

Note: LQS01 & TQS02 use same strand design (RRP 54/61)
Achieved 200 T/m target at first attempt, no major issues discovered

**Further optimization work is needed:**

**2010**: using current coil series (RRP 54/61)
- Improve coil pre-load distribution
- SG data consistent with coil-pad mismatch
- Conductor performance at 1.9K
- Quench protection studies

**2011 (2012)**: With a new series of coils (RRP 108/127)
- Fully reproduce best TQ performance
- Faster training, increased stability and stress tolerance
• IR Studies show *large aperture quads required* for $L=10^{35} \text{ cm}^{-2} \text{ sec}^{-1}$
• Phase 1 ($L=2 \times 10^{34} \text{ cm}^{-2} \text{ sec}^{-1}$) 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:
• Nb$_3$Sn qualification based on Phase 1 upgrade specifications
• Providing performance reference for Phase 2 upgrade design

![Graph showing coil aperture vs. short sample gradient for different materials and phases.]

- **Nb$_3$Sn** expected range $L=10^{35} \text{ cm}^{-2} \text{ s}^{-1}$
HQ Design Features and Parameters

- Coil peak field of **15.1 T at 219 T/m** (1.9K un-degraded SSL: 19.5 kA)
- **193 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
Coil and Cable Design

Coil parameters:
- 120 mm aperture, 2 layer
- One wedge in each layer
- 46 turns/quadrant

Cable parameters:
- 35 strands, 0.8 mm diam.
- Width: 15.15 mm
- Mid-thickness: 1.44 mm
- Keystone angle: 0.75°

Cable insulation:
- Glass sleeve, 0.1 mm thick

Test windings
Sub-element deformation
Edge facets
Magnetic Design and Field Quality

- Reference radius 40 mm (2/3 aperture)
- Small geometric harmonics (2 wedges)
- Saturation $b_6$ 1 unit from 0 to 20 kA
- Optimized for 120 T/m gradient
- End design optimized for minimum field
- No additional spacers in the ends
Mechanical Design

Main structural components:

- **Aluminum shell**: 25 mm thick, OD = 570 mm (same as LHC dipole)
- **4-split iron yoke**
- **Iron pads** provide space for axial rods and cooling channels
- **Iron masters** house 50 mm wide bladders, loading and alignment keys
- **Aluminum collars** align poles while transferring pre-load to the coils
**Mechanical Analysis**

**Pre-loading for 219 T/m**

**Pole contact pressure:**
- 140 MPa compression at 0 T/m
- 20 MPa max. tension at 219 T/m

**Axial forces:**
- E.m. force: 1372 kN
- 620 kN applied at 4.2 K

**Mid-plane stress:**
- 193 MPa at 219 T/m

![Graph showing contact pressure vs. temperature](image)

193 MPa @ 219 T/m
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<td><strong>Reaction and potting tooling design</strong></td>
</tr>
<tr>
<td><strong>Coil winding and curing</strong></td>
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<tr>
<td><strong>Coil reaction and potting</strong></td>
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<tr>
<td><strong>Coil handling and shipping tooling</strong></td>
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<td><strong>Structure fabrication and test</strong></td>
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<td><strong>Magnet assembly</strong></td>
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<td><strong>Magnet test</strong></td>
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<td><strong>Structure Optimization</strong></td>
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### HQ Timeline

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<th>Month</th>
<th>Event</th>
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<tr>
<td>2008</td>
<td>June</td>
<td>Presented conceptual designs for 114 and 134 mm bore</td>
</tr>
<tr>
<td></td>
<td>July</td>
<td>Selection of <strong>120 mm quadrupole aperture</strong> for Phase 1</td>
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<td></td>
<td>Aug.</td>
<td>Practice cables fabricated, test windings completed</td>
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<td></td>
<td>Sept.</td>
<td><strong>Cable and coil cross-section geometry finalized</strong></td>
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<tr>
<td></td>
<td>Oct.</td>
<td>3D magnetic and coil design completed</td>
</tr>
<tr>
<td></td>
<td>Dec.</td>
<td>All coil fabrication tooling in <strong>procurement</strong></td>
</tr>
<tr>
<td>2009</td>
<td>Jan.</td>
<td>Mechanical analysis completed</td>
</tr>
<tr>
<td></td>
<td>Mar.</td>
<td>All coil and structure components in <strong>procurement</strong></td>
</tr>
<tr>
<td></td>
<td>Apr.</td>
<td>Cables for ~10 coils fabricated (54/61 and 108/127)</td>
</tr>
<tr>
<td></td>
<td>June</td>
<td>Practice <strong>coil 1 winding/curing completed</strong></td>
</tr>
<tr>
<td></td>
<td>Aug.</td>
<td>All structure components received</td>
</tr>
<tr>
<td></td>
<td>Sept.</td>
<td><strong>Coil 1 completed and coil 2 wound</strong></td>
</tr>
<tr>
<td></td>
<td>Dec.</td>
<td><strong>Coil 2 completed, coil 3-4 reacted, coil 5 wound</strong></td>
</tr>
<tr>
<td>2010</td>
<td>Jan.</td>
<td><strong>Structure pre-assembly completed</strong></td>
</tr>
</tbody>
</table>

Design and fabrication timeline is comparable to NbTi technology
Coil and Structure Fabrication

Layer 1 Winding

Layer 2 Winding

Structure assembly

Instrumentation trace

Practice coil 1

Quench heater

Alignment slot
Accelerator Integration

- Pre-load optimization for high gradient with minimal training
- Alignment, quench protection, radiation hardness, cooling system
- Field quality: length extension to 2m; cored cable eddy current effects
- Structure and assembly features for magnet production and installation
Future Plans

2010-2012: complete technology demonstration - LARP original goal

• LQ to address all length-related issues:
• HQ to address field/energy limits and accelerator quality
  - Use Phase 1 specifications as reference
• No HQ extension to 4 m in this phase

2013-2015: fabricate full scale prototypes for Phase 2 upgrade

Preparations (2010-2012):

• Converge on main specifications by the end of 2012
• Optimize HQ strand/cable for use in prototype
• Upgrade infrastructure as needed

Could be managed by LARP or APUL
Summary

• Strong, efficient collaboration among magnet programs
• Demonstrated all fundamental aspects of Nb$_3$Sn technology:
  - Conductor & structure performance, length scale-up
• Steady progress in understanding and addressing R&D issues
• Complete engineering toolbox and fabrication capabilities
• On track to qualify a 120 mm Quadrupole for the LHC IR

Acknowledgement