Magnet Development for the LHC Accelerator Research Program (LARP)

2007 Particle Accelerator Conference
June 29, 2006

Gian Luca Sabbi for the LARP Collaboration

BNL - FNAL - LBNL - SLAC
Goal: Demonstrate \(\text{Nb}_3\text{Sn}\) technology for the LHC Luminosity Upgrade

Three main components (models series) based on \textit{shell-type coils}:

- TQ (Technology Quads, 2005-07) \(D = 90\ \text{mm}, \ L = 1\ \text{m}, \ G_{\text{nom}} > 200 \ \text{T/m}\)
- LQ (Long Quadrupoles, 2008-09) \(D = 90\ \text{mm}, \ L = 4\ \text{m}, \ G_{\text{nom}} > 200 \ \text{T/m}\)
- HQ (High Gradient Quad, 2009-10) \(D = 90\ \text{mm}, \ L = 1\ \text{m}, \ G_{\text{nom}} > 250 \ \text{T/m}\)

\begin{table}[h]
\centering
\begin{tabular}{|c|c|c|c|c|c|c|c|}
\hline
\textbf{MODEL MAGNETS} & \textbf{Type} & \textbf{Length [m]} & \textbf{Gradient [T/m]} & \textbf{Aperture [mm]} & \textbf{FY05} & \textbf{FY06} & \textbf{FY07} & \textbf{FY08} & \textbf{FY09} \\
\hline
Technology Quad (TQ) & \(\cos(2\theta)\) & 1 & > 200 & 90 & \(3\text{N}+1\text{R}\) & \(2\text{N}+1\text{R}\) & \(1\text{N}\) & \(1\text{N}\) & \\
Long Quad (LQ) & \(\cos(2\theta)\) & 4 & > 200 & 90 & & & \(1\text{N}\) & \(1\text{N}\) & \\
High Gradient Quad (HQ) & \(\cos(2\theta)\) & 1 & > 250 & 90 & & & & \(2\text{N}\) & \\
\hline
\textbf{SUPPORTING R&D} & & & & & & & & \(2\text{N}+1\text{R}\) \\
Sub-scale Quad (SQ) & block & 0.3 & 10-11 & 110 & & & & & \\
Short Racetrack (SR) & block & 0.3 & 10-12 & N/A & & & & & \\
Long Racetrack (LR) & block & 4 & 10-12 & N/A & \(1\text{N}+1\text{R}\) & \(1\text{N}+1\text{R}\) & \(1\text{N}+1\text{R}\) & \(1\text{N}\) & \\
\hline
\end{tabular}
\caption{Magnet Development for LARP}
\end{table}
Quadrupole Designs for the LHC IR

- Higher Performance
- NbTi Upgrade
- CERN-HHH [2]
- LBNL & INFN [3]
- FNAL [4]
- HQ-130

Legend:
- KEK & FNAL NbTi LHC IR [1]
- LHC Design Report
- T. Sen et al, PAC-01
- G. Sabbi et al., ASC-02
- R. Ostojic et al., PAC-05
- A. Zlobin et al., EPAC 02
- S. Caspi et al., MT-15
- S. Caspi et al., ASC-06
- G. Ambrosio et al., ASC-06

[5] A. Zlobin et al., EPAC 02
[6] G. Sabbi et al., ASC-02
[8] R. Bossert et al., ASC-06
[9] S. Caspi et al., ASC-06
[10] G. Ambrosio et al., ASC-06
Technology Quadrupoles (TQ)

Objectives:
- Optimize/characterize cable design and heat treatment cycle
- Evaluate conductor/cable performance and stability
- Develop and optimize coil fabrication/handling procedures
- Optimize and finalize the coil design for LQ
- Develop/calibrate FEA models (material properties, friction coefficients)
- Compare mechanical design concepts and support structures
- Compare test data with expected (design) values
- Provide experimental feedback for LQ and HQ structure selection

Implementation: two series of models with same coil design:
- TQS models: aluminum shell over iron yoke; axial pre-load
- TQC models: collar & stainless steel shell; axial support

Main parameters:
- 1 m length, 90 mm aperture, 11-13 T coil peak field
TQ Coil Design and Fabrication

**Design features:**
- Double-layer, shell-type
- One wedge/octant (inner layer)
- TQ01: OST-MJR strand, 0.7 mm
- TQ02: OST-RRP strand, 0.7 mm
- 27-strand, 10.05 mm width
- Insulation: S-2 glass sleeve

**Winding & curing (FNAL - all coils)**

**Reaction & potting (LBNL - all coils)**
TQ Coil Fabrication Experience

- 23 TQ coils have been fabricated (including 5 practice coils & 2 spare coils)
- Producing high quality coils in a reliable and consistent manner, however:
  - Some systematic asymmetries related to “2-in-1” reaction/potting
  - Some de-bonding in TQC instrumentation traces (minor effect in TQS)
- All coils are being wound/cured at FNAL and reacted/impregnated at LBNL
  - Decided based on existing infrastructure and to minimize tooling investment
  - Instrumental in developing and maintaining common procedures
  - Shipping of coils accomplished without damage or significant delays
TQ Performance References & Range

$J_c = 2 \text{ kA/mm}^2$
$(12 \text{ T}, 4.2 \text{ K})$

MJR strand
First models

$J_c = 3 \text{ kA/mm}^2$
$(12 \text{ T}, 4.2 \text{ K})$

RRP strand
Final models

<table>
<thead>
<tr>
<th>Magnet</th>
<th>$T_{\text{op}}$ [K]</th>
<th>$G_{\text{ss}}$ [T/m]</th>
<th>$B_{\text{ss}}^{(\text{body})}$ [T]</th>
<th>$I_{\text{ss}}$ [kA]</th>
</tr>
</thead>
<tbody>
<tr>
<td>TQS</td>
<td>4.2</td>
<td>222</td>
<td>11.4</td>
<td>12.5</td>
</tr>
<tr>
<td></td>
<td>1.9</td>
<td>239</td>
<td>12.3</td>
<td>13.6</td>
</tr>
<tr>
<td>TQC</td>
<td>4.2</td>
<td>215</td>
<td>11.2</td>
<td>13.0</td>
</tr>
<tr>
<td></td>
<td>1.9</td>
<td>233</td>
<td>12.1</td>
<td>14.1</td>
</tr>
</tbody>
</table>

$\cdot$ $I_c$ data from extracted strands determine common performance reference for TQS/TQC

$\cdot$ Issue: relatively wide range of extracted strand $I_c$ (TQ01: 1862-1984 A/mm$^2$ @12T, 4.2K)

$\cdot$ Reference magnet performance limits for a given test run are adjusted for measured $T_{\text{bath}}$

$\cdot$ Actual conductor-limited quench levels may be lower due to other degradation effects
TQS and TQC Design Concepts

TQS
- Aluminum shell over iron yoke
- Assembly with bladders and keys
- Aluminum rods for axial pre-load

TQC
- Stainless steel collars and skin
- Control spacers to limit pre-load
- End support plates, no pre-load
Main differences: warm pre-load, cool-down effect, stress uniformity (pole to mid-plane)

Peak stresses are high & no consensus on degradation limits $\rightarrow$ cable testing required

Peak stress $\sim$20 MPa difference: stress-relief slot, different $G_{ss}$ & pole stress range at $G_{ss}$

Detailed FEA shows that 3D effects have a significant impact on actual coil stresses
• Interfaces for integrated use of CAD, mechanical and electro-magnetic packages
• Studies of the effects of friction among interfaces (coil-pole, coil-pads, yoke-shell)
• Design goal: maintain contact between coil and structure at all steps and locations
TQ Program Status

• **Cable and Coil fabrication:**
  - 23 coils completed, 4 more spares in production
  - Long TQ cable lengths (well above LQ unit length) routinely fabricated

• **Model magnet assembly and test:**
  - TQS01 model assembled (all new coils) and tested (4.5K, LBNL)
  - TQS01b assembled (1 new coil, same pre-load) and tested (4.5K, LBNL)
  - TQS01c assembled (1 new coil, lower pre-load) and tested (1.9K, FNAL)
  - TQS02 model assembled (all new coils) and tested (1.9K, FNAL)
  - TQC01 model assembled (all new coils) and tested (1.9K, FNAL)

• **TQ01 Evaluation Review (TQS01, TQS01b, TQC01) in November 2006**

• **In progress:**
  - TQS02 analysis, TQC01b test preparations
  - Fabrication of spare coils for TQC02 and TQS02b
TQS Measured and Calculated Stresses

- Low coil stress at assembly (5-30 MPa)
- Fine tuning with bladders & key shims
- Large pre-load gain during cool-down
- 3D FEA is critical for cool-down phase
- Interfaces (friction) play significant role
- Transverse and axial effects are coupled
- Measure both transverse & axial strain
- Variations among quadrants need study
TQS(01,01b,01c) Test Results

- TQS01 achieved **87%** of extracted-strand short sample limit (no stress)
- TQS01b, TQS01c: fully trained to an ~80% conductor-limited plateau
- **Plateau quenches occur near gaps** between pole parts; no end quenches

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![Graph showing quench locations and epoxy tearing](image-url)
Coil Stress near Pole Gaps in TQS

- 3D ANSYS calculations and TQS01b measurements indicate high longitudinal tension in coil across gaps, possibly leading to conductor degradation.
- This effect depends on the interfaces between coil, pole (bronze or titanium) and outer support elements.

Differential measurements of coil axial strain in TQS01b:

1. Assembly
2. Cool-down
3. Training
4. Warm-up

• 3D ANSYS calculations and TQS01b measurements indicate high longitudinal tension in coil across gaps, possibly leading to conductor degradation.
• This effect depends on the interfaces between coil, pole (bronze or titanium) and outer support elements.
New design features:

- First TQ test using the LARP baseline conductor (OST RRP 54/61)
- Ti poles: eliminate longitudinal stress near gaps, reduce required axial preload, improve end parts fit after reaction, reduce/eliminate gaps between pole pieces

Test results:

- Performs well above 200 T/m (4.5K & 1.9K) using RRP 54/61 conductor
- Confirms the analysis of the cause of the TQS01 limitation and its cure

### TQS02a Quench History

<table>
<thead>
<tr>
<th>kA</th>
<th>First training cycle at 4.5 K</th>
<th>Ramp Rate</th>
<th>1.9 K</th>
<th>2.2K</th>
<th>4.5 K</th>
</tr>
</thead>
<tbody>
<tr>
<td>200 T/m</td>
<td>160</td>
<td>178</td>
<td>197</td>
<td>215</td>
<td>233</td>
</tr>
</tbody>
</table>

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TQC01 Test Results

- At 1.9K, TQC01 achieved 85% of extracted-strand short sample limit (no stress)
- Highest gradient achieved was 200 T/m
- Limited to 70% of short sample at 4.2K (by different mechanism before/after 1.9K cycle)
- Most quenches before #42 occurred in the pole turn of the inner layer (all coils)
- Straight section quenches occurred in areas where the outer pole pieces were not glued
- Quenches after #42 occurred in the outer layers of coil 9 and 13:
  - Coil 13: mid-plane turn, lead side
  - Coil 9: multi-turn (up to mid-plane)
- Evidence of conductor degradation in mid-plane area
- Reliable results from bullet and skin gauges
- Mixed results from gauges on control spacers and on coils
Analysis of TQC01 Test Results (1/2)

Slow training/plateau observed up to quench #42 can be attributed to:

1. **Low azimuthal pre-load** in the straight section with respect to design targets
   - Overestimation of assembly pre-load (high coil modulus applied to gauge readings)
   - Longitudinal stress-relief cut was filled with epoxy, while the design assumed G10
   - Implementation steps tended toward the low end of the acceptable preload window (due to fears of over-compression causing cable degradation)
   - During cool-down there was some additional decrease of the pre-load

<table>
<thead>
<tr>
<th>TQC01 stress analysis</th>
<th>Baseline</th>
<th>As-built</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pressure at inner pole (MPa)</td>
<td>300K</td>
<td>1.9K</td>
</tr>
<tr>
<td>Max azimuthal stress (MPa)</td>
<td>-100</td>
<td>-95</td>
</tr>
</tbody>
</table>

2. Outer pole pieces in most of the straight section **not bonded to the coil**
   - Due to initial plan to remove outer pole and replace with “tabbed” collar
   - Results in motion of the pole block & increase of bending due to low pre-load

3. **Low collar-to-yoke preload ratio** causing further bending in the collared area
Mid-plane degradation observed after quench #42 can be attributed to:

1. Axial coil motion during excitation (in turn due to low azimuthal pre-load)

2. Bending due to the application of local pressure at the mid-planes

- Rigid metal parts dominate the cross-section near the coil ends
- Ends used stainless steel yoke packs resulting in higher stresses after cool-down
- Combined effects may have resulted in excessive coil pressure at mid-plane
New Mechanical Features in TQC02

- Warm azimuthal preload is increased to **150 MPa**, based on non-linear coil MOE.
- Collared preload is increased to a peak stress of **120 MPa**.
- Added strain gauges on the bronze poles; will be monitored during assembly.
- Preload at the collared coil level is measured based on collar deflection measurements and bronze pole gauges readings, in conjunction with FEA.
- Preload in the final assembly is based on readings from the skin gauges, control spacer gauges and bronze pole gauges, in conjunction with FEA.
- Azimuthal gauges are placed on the coil at both the pole and mid-plane and read during all phases of assembly and testing, but are not used as the “primary” method of determining preload.
- Contact area of yoke upon collars is increased with respect to TQC01, allowing radial support over a greater azimuthal area. This should also result in a rounder final coil shape.
- The pole slot is filled with G-10 (nominal design material) instead of epoxy.
- Yoke laminations will be made of iron over the entire magnet length.
TQC Status and Plans

• TQC02 has been collared: results from strain gauges as well as collar deflection measurements were consistent with analysis.

• However, after collaring one mid-plane shim was found to have been out of place, causing probable permanent damage to 2 coils.

• Two additional coils are being fabricated to replace the damaged ones.

• A new TQC test (TQC01b) was introduced using coils from TQC01 & TQS01. 
  
  **Primary goal:** verify shim system and analysis with respect to preload for TQC during assembly, cool-down and excitation.

• TQC01b has been fabricated and test preparations are underway.

• The completion and test of TQC02 will follow shortly after TQC01b.
TQ Magnetic Measurements

- Field quality measurements of TQC01 and TQS01 show encouraging results
- Normal dodecapole is large but “as built” calculated values are close to measured
- Design/fabrication/assembly need improvements to reduce non-allowed harmonics
- Alignment features and single-coil reaction/potting will be implemented in LQ
- Need AP guidance on requirements for magnetization and eddy current harmonics
- Conductor and cable choices are limited: discuss/understand options and priorities

<table>
<thead>
<tr>
<th>R = 22mm</th>
<th>Normal ($b_n$)</th>
<th>Skew ($a_n$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>n</td>
<td>TQC</td>
<td>TQS</td>
</tr>
<tr>
<td>3</td>
<td>2.01</td>
<td>-1.46</td>
</tr>
<tr>
<td>4</td>
<td>-1.90</td>
<td>-0.52</td>
</tr>
<tr>
<td>5</td>
<td>0.58</td>
<td>3.06</td>
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<tr>
<td>6</td>
<td>1.71</td>
<td>5.40</td>
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<td>7</td>
<td>0.07</td>
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<tr>
<td>8</td>
<td>0.01</td>
<td>-0.11</td>
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<tr>
<td>9</td>
<td>0.04</td>
<td>0.02</td>
</tr>
<tr>
<td>10</td>
<td>-0.06</td>
<td>0.02</td>
</tr>
</tbody>
</table>

Magnetization cycle ($b_n$) in TQC01
Sub-scale Coils and Structures

**Nb3Sn**  
Low field  
Low stress

**SQ**  
High stored energy  
High Axial forces

**NMR**  
4-coil layout  
High field

**Bi-2212**  
High field  
High stress

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Magnet Development for LARP
Sub-scale Quadrupole Series (SQ)

Design:
• 4 racetrack coils in square configuration
• Coil aperture 130 mm (clear bore 110 mm)
• Similar load line as TQ (11.3 T @460 A)
• Similar coil stress as TQ (100-130 MPa)
• Similar axial force as TQ (350 kN @ Iss)

Results:
• 2 magnets, 2 tests each (LBNL/FNAL)
• Cable and MJR conductor evaluation
• Verification of heat treatment for TQ
• Verification of conductor stability
• Evaluation of stress degradation
• Analysis of quench initiation and training
• Study of the effect of axial load
• Improved assembly procedure

Next step (SQ03):
• RRP conductor evaluation, continued studies
Long Racetrack Magnet Design

First step for scale-up, based on LBNL SC/SM coil & structure

- simple coil design → focus on length dependent issues
- well understood SC (SM) baseline: 20+ coils tested
- common coil dipole – lower forces, energy, pre-stress
- coil disassembly/reassembly in different configurations
- **demonstration of bladder & key technology scale-up**
Instrumented dummy coil (6 strain gauge stations along magnet length)

Assembled shell-yoke structure with dummy coil

- LBNL: structure design, procurement & qualification; magnet design & analysis
- BNL: fabrication of short and long coils, magnet assembly, cool-down and test
Long Quadrupole (LQ)

Technical approach and open issues:

- **Baseline strand selected and qualified;** developing improved options and qualification plans for possible use in later phases
- **Present cable and insulation are working well;** further developments desired to facilitate magnet production, improve radiation hardness
- **Key elements of coil technology scale-up:** (1) reaction/potting tooling & fabrication/handling processes; (2) pole/end parts design/materials
- **LQ coil fabrication processes will be derived from TQ, LR, and core programs experience**
- **Alignment becomes more critical** and is also needed for field quality: new features implemented in coil fabrication and magnet assembly
- **Support structure performance** is a key element for success: selection through LQ Design Study
High Gradient Quadrupoles (HQ)

Goals:
- Expand toward higher field/stress
- Feedback to IR optimization

The reference cross-sections were selected taking into account stress considerations:

<table>
<thead>
<tr>
<th>Performance Parameters</th>
<th>Symbol</th>
<th>Unit</th>
<th>HQ1</th>
<th>HQ2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Short sample gradient</td>
<td>$G_{ss}$</td>
<td>T/m</td>
<td>308</td>
<td>317</td>
</tr>
<tr>
<td>Short sample current</td>
<td>$I_{ss}$</td>
<td>kA</td>
<td>10.7</td>
<td>12.6</td>
</tr>
<tr>
<td>Coil peak field</td>
<td>$B_{pk}(I_{ss})$</td>
<td>T</td>
<td>15.6</td>
<td>15.8</td>
</tr>
<tr>
<td>Copper current density</td>
<td>$J_{cu}(I_{ss})$</td>
<td>kA/mm$^2$</td>
<td>2.2/2.2</td>
<td>2.1/2.6</td>
</tr>
<tr>
<td>Inductance</td>
<td>$L(I_{ss})$</td>
<td>mH/m</td>
<td>24.5</td>
<td>18.0</td>
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<tr>
<td>Stored energy</td>
<td>$U(I_{ss})$</td>
<td>MJ/m</td>
<td>1.3</td>
<td>1.4</td>
</tr>
<tr>
<td>Lorentz force/octant (r)</td>
<td>$F_r(I_{ss})$</td>
<td>MN/m</td>
<td>1.7</td>
<td>1.7</td>
</tr>
<tr>
<td>Lorentz force/octant ($\theta$)</td>
<td>$F_\theta(I_{ss})$</td>
<td>MN/m</td>
<td>-6.0</td>
<td>-6.1</td>
</tr>
<tr>
<td>Average coil stress ($\theta$)</td>
<td>$\sigma_\theta(I_{ss})$</td>
<td>MPa</td>
<td>150</td>
<td>152</td>
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<tr>
<td>Dodecapole (22.5 mm)</td>
<td>$b_6$</td>
<td></td>
<td>-0.2</td>
<td>0.0</td>
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<tr>
<td>10-pole (22.5 mm)</td>
<td>$b_{10}$</td>
<td></td>
<td>-0.05</td>
<td>-0.92</td>
</tr>
</tbody>
</table>

(*) Assuming $J_c(12$ T, $4.2$ K) = 3.0 kA/mm$^2$; operating temperature $T_{op}=1.9$K

<table>
<thead>
<tr>
<th>LORENTZ STRESS AT 300 TESLA/METER (MPA)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coil</td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td>HQ1</td>
</tr>
<tr>
<td>HQ2</td>
</tr>
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</table>

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Summary

Phase I (TQ and racetrack coil development)

- TQ01 prototypes fabricated and tested: achieved 200 T/m gradient
- TQ02 models test RRP conductor and optimized designs
- TQS02 performed well above 200 T/m at both 4.5 K and 1.9 K
- TQC02 was delayed due to coils damage during magnet assembly
- TQC02 and TQS02b will be tested in the coming months
- SQ models have provided and will provide key information
- Long shell-based structure fabricated and qualified for use in LR
- LR01 magnet assembly completed; test is starting

Phase II (LQ and HQ models):

- LQ coil design based on TQ; tooling/procedures under development
- LQ structure design and selection process is underway
- Good progress on HQ design, implementation depends on priorities