New Magnets for the IR

How far are we from the HL-LHC Target?

GianLuca Sabbi

for the US LHC Accelerator Research Program

LHC Performance Workshop – Chamonix 2012
New Magnets for the IR

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Topics/guidelines:

1. Summary of LARP magnet program components and achievements
2. Focus on remaining challenges, both technical and programmatic
   • Selecting a conductor design and developing it for production
   • Managing stress/strain in the final design and during production
   • Incorporating design elements for accelerator integration
   • Project organization and timelines for prototyping/production
   ➢ ...and wait, how far from what? Converging on targets for HL-LHC
3. Build on collaboration meeting discussion, minimize repetitions
   • LARP program goals and organization
   • Details of conductor development, magnet designs, test results

https://indico.cern.ch/conferenceDisplay.py?confId=150474
US LHC Accelerator Research Program

- 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

General 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

Major focus: development of Nb$_3$Sn IR Quadrupoles for HL-LHC
**Nb$_3$Sn Technology Challenges**

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

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

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<table>
<thead>
<tr>
<th>Material</th>
<th>NbTi</th>
<th>Nb$_3$Sn</th>
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</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>
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<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>
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</table>
LARP Magnet Development Chart

- **Subscale Quadrupole (SQ)**
  - 0.3 m long
  - 110 mm bore

- **Technology Quadrupoles (TQS, TQC)**
  - 1 m long
  - 90 mm bore

- **Subscale Magnet (SM)**
  - 0.3 m long
  - No bore

- **Long Racetrack (LRS)**
  - 3.6 m long
  - No bore

- **High Field Quadrupole (HQ)**
  - 1 m long
  - 120 mm bore

- **Long Quadrupole (LQS)**
  - 3.7 m long
  - 90 mm bore

- **Long High-Field Quadrupole (LHQ)**
  - 3.7 m long - 120 mm bore

**Completed**

**Ongoing**
LARP Magnets

SM  SQ  TQS  LQS-4m

LR  TQC  HQ
Program Achievements - Timeline (1/2)

Mar. 2006    SQ02 reaches 97% of SSL at both 4.5K and 1.9K  
• Demonstrates MJR 54/61 conductor performance for TQ

Jun. 2007    TQS02a surpasses 220 T/m at both 4.5K and 1.9K  (*)
• Achieved 200 T/m goal with RRP 54/61 conductor

Jan. 2008    LRS02 reaches 96% of SSL at 4.5K with RRP 54/61  
• Coil & shell structure scale-up from 0.3 m to 4 m

July 2009    TQS03a achieves 240 T/m (1.9K) with RRP 108/127  (*)
• Increased stability with smaller filament size

Dec. 2009    TQS03b operates at 200 MPa (average) coil stress  (*)
• Widens Nb$_3$Sn design space (as required...)

(*) Tests performed at CERN
Program Achievements - Timeline (2/2)

Dec. 2009  LQS01a reaches 200 T/m at both 4.5K and 1.9K
• *LARP meets its “defining” milestone*

Feb. 2010  TQS03d shows no degradation after 1000 cycles  
(*)
• *Comparable to operational lifetime in HL-LHC*

July 2010  LQS01b achieves 220 T/m with RRP 54/61
• *Same TQS02 level at 4.5K, but no degradation at 1.9K*

Apr. 2011  HQ01d achieves 170 T/m in 120 mm aperture at 4.5 K
• *At HL-LHC operational level with good field quality*

Oct. 2011  HQM02 achieves ~90% of SSL at both 4.6 K and 2.2 K
• *Reduced compaction results in best HQ coil to date*

(*) Test performed at CERN
TQ Studies: Stress Limits

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
TQS03d Cycling Test

- Reduced coil stress to TQS03b levels (160 MPa average)
  - Pre-loading operation and test performed at CERN
- Did not recover TQS03b quench current (permanent degradation)
- Performed 1000 cycles with control quenches every ~150 cycles
- No change in mechanical parameters or quench levels
Long Quadrupole (LQ)

- TQ length scale-up from 1 m to 4 m
- Coil Fabrication: FNAL+BNL+LBNL
- Mechanical structure and assembly: LBNL
- Test: FNAL
- Target gradient **200 T/m**

LQS01 assembly at LBNL

LQSD test at FNAL
LQS01 & LQS01b Quench Performance

- LQS01a
- LQS01b

Quench number

Current (kA)

200 T/m

4.5 K

~3 K

1.9 K

0 10 20 30 40 50

LQS01 & LQS01b Quench Performance Graph

- Blue diamonds represent LQS01a performance.
- Black diamonds represent LQS01b performance.

Temperature and magnetic field levels indicated at various quench numbers.

LHC Performance Workshop 2012

Nb₃Sn IR Magnets – G. Sabbi
Conductor – Technical Issues

Two leading processes:

- **Internal tin (US-OST-RRP) and powder in tube (EU-Bruker-PIT)**
- A quasi-continuous range of “stacks” using fewer or more sub-elements
- **Mainly exercised for RRP, for programmatic and historical reasons**

Low range: 😊 Better developed (high/controlled Jc/RRR; long pieces
😊 Larger filament size (magnetization effects, flux-jumps)

High range: 😊 Smaller magnetization effects and in principle more stable
(only if tolerance to cabling and reaction can be preserved)
😊 Less developed: control of properties, piece length
Conductor – Programmatic Issues

- Multiple applications with different requirements, priorities, time scales
  - IR Quads, 11 T dipoles, cable testing and HE-LHC dipoles

- Developing a single conductor suitable for all applications is difficult
- Pursuing parallel routes & incremental improvements is inefficient

- Need to define a clear strategy for the HL-LHC IR Quads. Examples:
  I. Focus on “middle range” 108/127 (moderate improvement from 54/61, close to production readiness)
  II. Select/push a more ambitious target (RRP 217 and/or PIT 192) and analyze/qualify a fall back option using RRP 54/61

- Perform cost/benefits analysis for accelerator, materials, magnet
- Move from R&D approach to project-type organization
- Engage the DOE-HEP materials R&D community, which appears to be primarily focused on very long term developments (HTS)
The best performing HQ coil to date was built with RRP 54/61 a production-ready conductor.
Handling High Stress in Magnet Coils

1. Understand limits
   - **TQ** (90 mm, ~12 T)

2. Optimize structure and coil for minimum stress
   - **LQ** (90 mm, ~12 T)
   - **HQ** (120 mm, ~15 T)

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**Titanium pole**

**Key location**

**Coil geometry**
Pole quenches and strain gauge data indicate insufficient pre-load

Mid-plane quenches indicate excessive pre-load

Narrow design and assembly window: ok for an R&D model designed to explore stress limits, may require optimization for production, in particular if the aperture is further increased.
HQ design assumed less space for inter-turn insulation than TQ/LQ
• Based on measurements, but limits expansion during reaction
• As a result, coils were over sized and over compressed
• Also, insufficient pole gaps led to excessive longitudinal strain

😊 Analyzed, understood and fixed in second generation coils
😢 We do not yet control this technology sufficiently well to scale to a larger aperture or full length coils without experimental verification
Accelerator Integration Issues

- Pre-load optimization for high gradient with minimal training
- Alignment, quench protection, radiation hardness, cooling system
- Field quality: cross-section iteration; cored cable for eddy current control
- Structure and assembly features for magnet production and installation
## Accelerator Quality in LARP Models

<table>
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<tr>
<th>Design Features</th>
<th>LR</th>
<th>SQ</th>
<th>TQS/LQS</th>
<th>TQC</th>
<th>HQ</th>
<th>LHQ (Goals)</th>
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<tr>
<td>Geometric field quality</td>
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Coil Aperture and Length

Two design choices will have significant implications on the project:

- **Quadrupole aperture** (120 mm vs. 140-150 mm)
- **Production coil length**: full (8-10 m) or half (4-5 m)

*If* the final design uses 120 mm aperture *and* half length coils:

- LHQ can be considered as a pre-prototype
- The coil fabrication infrastructure is (mostly) available
- Simple transition from technology demonstration to production

*Otherwise*, experimental verification of the final design will be required:

- Larger aperture will require *short model development*
- Full length coils will require **infrastructure and a prototype**
- Change of aperture and full length coils will require both *in series*
Significant contributions from CERN will be required to implement this plan, in particular if the larger aperture and/or the full length coil option is selected.
Summary

- A large knowledge base is available after 7 years of fully integrated effort involving three US Labs and CERN
- Demonstrated all fundamental aspects of Nb$_3$Sn technology:
  - Steady progress in understanding and addressing R&D issues
- The remaining challenges have an increasingly programmatic flavor: design integration, production organization and processes
- HL-LHC IR Quads are a key step for future high-field applications
- Next few years will be critical and much work is still left to do
  - Integrate effort with CERN, EuCARD, KEK, US core programs

Acknowledgement