Development of High Field Superconducting Accelerator Magnets

Helene Felice
Lawrence Berkeley National Laboratory
Berkeley, USA
High Energy Physics requires powerful linear or circular machines to collide e+/e- and proton beams and explore fundamental laws of the universe.

The LHC is the biggest proton collider ever built.

- Why do we need High field Superconducting Magnets in colliders such as LHC?
- A specific challenge: the mechanical preload
- Beyond LHC: what kind of magnets?
- How the high field accelerator dipole for colliders finds its way to everyday application: gantry for ion beam cancer therapy
Magnets for Colliders

- The **colliders** are a sub-species of circular accelerators

**Arc**

- **Dipole**: constant field to bend the beam: $F = e \mathbf{v} \times \mathbf{B}$
  (No change of momentum)

- **Quadrupole**: gradient of field to focus the beam

**Long Straight section**

Interaction Regions where collisions occur:
- **Quadrupoles** to focus the beam
- **Dipole** for beam crossing in two-ring machines
- Other functionalities not addressed here
Beyond the critical surface, the superconductor **quenches** = transition to a normal conducting state

- The beam energy:
  \[ E [\text{GeV}] = 0.3 \times B[\text{T}] \times \rho[\text{m}] \]

- Beyond 2 T => use of **superconducting material**
  - zero electrical resistance at cryogenic temperature
  - operate below a **critical surface** defined with 3 parameters: field, current and temperature.

---

**High Field reachable but high complexity**

4/22/2015  
H. Felice
A (not so) large variety of superconductors

~250$/kg

P. Lee et al., Applied Superconductivity Center

April 2014
A (not so) large variety of superconductors

\[ \text{Nb}_3\text{Sn} \]

- Strain sensitive
- To be implemented in HiLumi LHC (2023)

250$/kg \times 10$

\[ 10^4 \rightarrow 10^3 \rightarrow 10^2 \rightarrow 10 \]

Applied Magnetic Field (T)

Whole Wire Critical Current Density (A/mm$^2$, 4.2 K)

- \(\text{Nb}_3\text{Sn}: \) Internal Sn RRP$^\text{®}$
- \(\text{Nb}_3\text{Sn}: \) High Sn Bronze
- \(\text{Nb}_3\text{Sn}: \) High J$_c$
- \(\text{High-J}_c\) \(\text{Nb}_3\text{Sn}\)
- \(\text{Bronze Nb}_3\text{Sn}\)
- \(4543\) filament High Sn Bronze-16wt.\%Sn-0.3wt.%Ti (Miyazaki-MT18-IEEE’04)
- Compiled from ASC’02 and ICMC’03 papers (J. Parrell CI-ST)
- \(\text{Nb}-\text{Ti}: \) LHC 1.9 K
- \(\text{Nb}-\text{Ti}: \) LHC 4.2 K
- \(\text{Nb}-\text{Ti}: \) LHC 4.2 K
- \(\text{Nb}-\text{Ti}: \) Iselut/INUMAC MRI 4.22 K


P. Lee et al., Applied Superconductivity Center

4/22/2015

H. Felice
A (not so) large variety of superconductors

Cost
Complexity
(anisotropy, strain sensitivity, reaction temperature...)

P. Lee et al., Applied Superconductivity Center
High Field Superconducting Magnets for Colliders

The example of the LHC Main Dipole

- Cable made out of wire
- Cable is wound in coil
- 2 coils per beam pipe
- Assembly in the support structure
- Assembly in cryostat

Wire cross-section

Rutherford Cable

Lucio Rossi (CERN)
The example of the LHC Main Dipole
A few numbers

- 15 m long magnet
- 27.5 ton
- 0.5 MCHF

- Nominal: 14 TeV c.o.m.
- $B_{\text{nom}} = 8.33$ T
- $I_{\text{nom}} = 11.8$ kA

- $E_{\text{stored}}$ at nominal = 7.1 MJ

- Forces at $B_{\text{nom}}$
  - $F_x = 1.7$ MN/m
  - $F_y = -0.8$ MN/m
  - $F_z = 370$ kN

LHC Project Report 623, Lucio Rossi (CERN)
Magnet Design and Fabrication
what kind of engineering?

Material Science: conductor, insulation

Electrical Engineering
• Magnetic FEM analysis
• Field quality requirements = field purity
• Magnet testing
  • Magnetic measurements
  • Diagnostics...

Mechanical Engineering
• Coil fabrication tooling
• Coil and magnet handling tooling
• **Support structure**
• LHe containment...

Thermal analysis and Cryogenics
• Protection in case of quench
• Cryostating

Integrated design approach required
Broad Engineering from design to fabrication
The concept of pre-stress

- **Lorentz forces: JxB**

- **Requirements for the support structure**
  - Preserve the superconductor in operating condition by **minimizing motion**
  - **Control the position** of each conductor
    - Conductor position = field quality in the aperture => 10-100 ppm

- The **pre-stress** consists in applying before excitation and via the support structure a force equivalent to the Lorentz force in order to pre-compress the coil and minimize motion during excitation

- **Challenges toward high fields**: large forces and strain sensitive material
Pre-stress in the LHC Dipole

- Support structure using collaring process
  - Same kind of concept used in quadrupoles

Lorentz forces increasing

Colling press ➔ Before cool-down ➔ After cool-down ➔ 20% Fm
8 ➔ 40% Fm ➔ 60% Fm ➔ 80% Fm ➔ 100% Fm

Preload required

Overshoot

Courtesy of Paolo Ferracin (CERN)
Shell-based support structure
Concept

Case study
Prototype Nb$_3$Sn **quadrupole** for the Hi-Luminosity LHC upgrade => interaction region quad
- Strain sensitive material
- 12 T peak field in the conductor
- Large Lorentz forces
  - 2.7MN/m horiz, -3.8 MN/m vert
Case study

Prototype Nb$_3$Sn **quadrupole** for the Hi-Luminosity LHC upgrade => interaction region quad

- Strain sensitive material
- 12 T peak field in the conductor
- Large Lorentz forces

Displacement scaling 30
Shell-based support structure

Concept

Case study

Prototype Nb$_3$Sn *quadrupole* for the Hi-Luminosity LHC upgrade => interaction region quad

- Strain sensitive material
- 12 T peak field in the conductor
- Large Lorentz forces

![Diagram of a shell-based support structure](image_url)

Displacement scaling 30

**Bladder**

**Keys**
Case study
Prototype Nb₃Sn quadrupole for the Hi-Luminosity LHC upgrade => interaction region quad

- Strain sensitive material
- 12 T peak field in the conductor
- Large Lorentz forces
Innovative support structure
- Gradual application of the preload
- Tunable preload
- Reversible assembly process
- Implemented in the HL-LHC upgrade (2023)

Displacement scaling 30
Challenges for the future: the post-LHC era

Future Circular Collider

More beam energy...
=> More field, more forces
=> More magnets
In LHC, 18km out of 27km are dipoles!

Example of questions among the magnet community:

Is there a “stress wall”? Making high field magnets out of reach?

How can we reduce the cost?

⇒ Need for a change of approach?
⇒ Innovative design?
The Canted Cosine Theta
An example of new paradigm

Two superimposed coils, oppositely skewed, achieve a pure dipole field and eliminate axial field.

\[ J_\vartheta \sim \text{const} \]
\[ J_z \sim \cos \vartheta \]

Structure “embedded” in the coil
\[ \Rightarrow \text{Avoid azimuthal force accumulation} \]
\[ \Rightarrow \text{Minimize number of components} \]
Ongoing development program at LBNL

LHC dipole for comparison
18 T Design using CCT concept

8 layers Nb$_3$Sn

4 layers Bi2212 insert

Clear bore ID=40mm, OD=274.3mm

Courtesy of Lucas Brouwer and Shlomo Caspi (LBNL)

Courtesy of Xiaorong Wang (LBNL)
From Fundamental use to medical application:
Cancer Ion beam therapy

Heidelberg Carbon Ion Therapy Gantry – Germany – unique Carbon therapy facility
A gantry is a beam line that directs and focuses the beam onto the patient at whatever angle is required for the treatment plan optimization

Interest
Sparing healthy tissues
Bragg peak

4/22/2015

H. Felice
From Fundamental use to medical application: Cancer Ion beam therapy (II)

- Unique Carbon gantry in the world
- Rotating device
- 600 tons => final dipole ~100 tons

Superconducting final dipole would allow compactness and weight reduction

Courtesy of David Robin (LBNL)
Concept of curved CCT for carbon gantry

- Concept of curved CCT
- Allows combined function magnet

Ongoing stewardship program at LBNL

Uniform dipole field
Uniform quadrupole field
Uniform sextupole field

Combined function

Courtesy of Shlomo Caspi (LBNL)
Summary and Next steps

• Superconducting Accelerator Magnets are multi-disciplinary objects requiring an integrated design approach

• Dipoles and Quadrupoles are key components of high energy colliders

• Producing higher field requires the use of more challenging superconducting materials
  • Innovative “shell-based” support structure was demonstrated

• **Beyond LHC**: Superconducting Magnets for accelerator are in an interesting phase, looking for new concepts and designs
  • CCT is one of them and require demonstration: ongoing program at LBNL

• Pushing the limits for fundamental application opens possibility for everyday applications
  • Curved CCT could be a major asset for carbon therapy

**We need to keep probing the limits of magnet technology!**
Acknowledgment

LBNL:
Lucas Brouwer, Shlomo Caspi, Dan Dietderich, Soren Prestemon, David Robin, Xiaorong Wang

CERN:
Paolo Ferracin, Ezio Todesco

Funding Agency: US Department of Energy