Technology challenges: Superconducting accelerator magnets
PART II/II

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Thanks to many colleagues, in particular Paolo Ferracin for the material they have given to me
Part I

- Superconductivity
- Electromagnetic coil design
- Coil manufacture

Part II

- Margins and quench protection
- Structural design and assembly
- Testing
- Outlook, what brings the future?
Recap from last lecture

- Technical low-temperature superconductors (Nb-Ti, Nb$_3$Sn) are multifilamentary wires
- Rutherford cables are made of typically out of ~30-40 wires
- Insulation: polyimide (Nb-Ti), S2-glass/mica (Nb$_3$Sn)
- Electromagnetic coil design to optimize the field quality
Recap Magnet design

The field can be expressed as (simple) series of coefficients. So, each coefficient corresponds to a "pure" multipolar field.

Dipole

\[ B_1 = \frac{2\mu_0}{\pi} J(R_{\text{out}} - R_{\text{in}}) \sin \varphi = \frac{2\mu_0}{\pi} Jw \sin \varphi \]

\[ B_n = \frac{2\mu_0}{\pi} J \left( \frac{R_{\text{out}}^{2-n} - R_{\text{in}}^{2-n}}{n(2-n)} \right) r_{\text{ref}}^{n-1} \sin(n\varphi), \ n = 3, 5, 7, ... \]
How much superconductor is in the cable?

Filling ratio: 0.25-0.3
How to select the \( J \) in the coil?

- LHC main dipole at nominal operation: 
  \[ B_{op} = 8.33 \text{ T}, \ I_{op} = 11850 \text{ A}, \ J_{\text{eng}} = \sim 450 \text{ A/mm}^2 \]
How to select the $J$ in the coil?

Why margins?
- Reach design field
- Limit number of training quenches
- Avoid quenches during operation

Margins:
- Load line margin
- Temperature margin
- Current margin

How to select the margins? Typically, designs are done for load line margin (LHC & FCC: 14%)

How is it selected? Empirically: long discussions and many prototypes!
Margin on the load line
Temperature margin
Question: A magnet shall reach a bore field of 16 T with a load line margin of 14% (example of FCC). What is the field this magnet could potentially reach?
Circuit protection

- LHC MBs are powered in 8 sectors, each with 154 MBs
- The stored energy is 1.1 GJ:
  →Corresponds to the kinetic energy of a fully loaded jumbo jet at start

\[ E_m = \frac{B^2}{2} \int_0^\nu dv = \frac{1}{2} LI^2 \]
Magnet quench protection

- In case a quench occurs, the stored energy does not allow to be extracted within the required time (few tens of ms): too large voltages (several kV-MV, depending on the circuit) would be required
  \[ U = LdI/dt \] (LHC MB: \( L = 98.7 \) mH/magnet, \( I = 11.85 \) kA)
  \[ \rightarrow \] A discharge in 0.1 s would yield a voltage of \(~12\) kV

- **Alternative:** stored energy is damped into the entire magnet by quenching it: upper theoretical limit can be calculated with adiabatic model
Quench heater

- In case a quench is detected, the magnet will be quenched (brought to normal conducting) within ~40 ms everywhere.
- The final peak temperature for a given magnet depends on the time span to quench the magnet and the stored energy density.
How to protect the magnets?

Which parameters determine the final temperature after quench of a magnet connected in series and operated at nominal field?
What is around the coils?

• How do keep the coils in place despite the large forces?
• How do we keep them cool?
• How we ensure that they perform well in the tunnel: testing!
Mechanical structure

The e.m. forces in a dipole/quadrupole magnet tend to push the coil
• Towards the mid plane in the vertical-azimuthal direction ($F_y, F_0 < 0$)
• Outwards in the radial-horizontal direction ($F_x, F_r > 0$)

$F \propto B^2 a$
What to do to avoid movement and tensile stress?

Effect of e.m forces
- change in coil shape: effect on field quality
- a displacement of the conductor: potential release of frictional energy
- Nb-Ti magnets: possible damage of polyimide insulation at ~150-200 MPa.
- Nb$_3$Sn magnets: possible conductor degradation at about 150-200 MPa.
- All the components must be below stress limits.
**Nb-Ti LHC MB**
Values for a central field of 8.33 T
- \( F_x = 340 \, \text{t per meter} \): \( \sim 300 \, \text{compact cars/m} \)
- Precision of coil positioning: 20-50 \( \mu \text{m} \)
- \( F_z = 27 \, \text{t} \): \( \sim \) weight of the cold mass

**\( \text{Nb}_3\text{Sn} \) dipole (Fresca-2)**
Values for a central field of 13 T
- \( F_x = 770 \, \text{t per meter and quadrant} \)
- \( F_z = 72 \, \text{t/octant} \)

These forces are applied to an object with a cross-section of 150x100 mm and by the way, it is brittle.
How to do to avoid movement and tensile stress?
How to do to avoid movement and tensile stress?

No pre-stress
No e.m. force

No pre-stress
With e.m. force

Pre-stress
No e.m. force

Pre-stress
with e.m. force
Mechanics of superconducting magnets: Collars

- Implemented for the first time in Tevatron, since then, almost always used

- Composed by stainless-steel or aluminium laminations few mm thick.

- By clamping the coils, the collars provide
  - coil pre-stressing;
  - rigid support against e.m. forces
  - precise cavity
Mechanics of superconducting magnets: Collars

Collaring of a dipole magnet

Collaring of a quadrupole magnet
Mechanics of superconducting magnets: Shell structure

Alternative structure, principle is based on different contraction coefficients:
• No large scale infrastructure required
• Only part of pre-stress is applied at ambient temperature

<table>
<thead>
<tr>
<th>Material</th>
<th>$\alpha$ in mm/m</th>
</tr>
</thead>
<tbody>
<tr>
<td>293 K $\rightarrow$ 4.2 K</td>
<td></td>
</tr>
<tr>
<td>Coil</td>
<td>3.88</td>
</tr>
<tr>
<td>Austenitic steel 316LN</td>
<td>2.8</td>
</tr>
<tr>
<td>Al 7075</td>
<td>4.2</td>
</tr>
<tr>
<td>Ferromagnetic iron</td>
<td>2.0</td>
</tr>
<tr>
<td>Pole (Ti6Al4V)</td>
<td>1.7</td>
</tr>
</tbody>
</table>
Mechanics of superconducting magnets: Iron yoke

- Iron yoke are also made in laminations (several mm thick)

Magnetic function:
- contains and enhances the magnetic field.

Structural function
- tight contact with the collar
- it contributes to increase the rigidity of the coil support structure and limit radial displacement.

Holes are included in the yoke design for
- Correction of saturation effect
- Cooling channel
- Assembly features
- Electrical bus
Cold mass

- The shell constitutes a containment structure for the liquid Helium.
- It is composed by two half shells of stainless steel welded around the yoke with high tension (about 150 MPa for the LHC dipole).
- With the iron yoke, it contributes to create a rigid boundary to the collared coil.
- If necessary, during the welding process, the welding press can impose the desired curvature on the cold mass.
- In the LHC dipole the nominal sagitta is of 9.14 mm over ~14.3 m
An overview of the infrastructure (bldg. 180)
Cryo-magnets!

<table>
<thead>
<tr>
<th></th>
<th>Tevatron</th>
<th>HERA</th>
<th>RHIC</th>
<th>LHC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aperture (mm)</td>
<td>76</td>
<td>75</td>
<td>80</td>
<td>56</td>
</tr>
<tr>
<td>Magnetic length (m)</td>
<td>6.1</td>
<td>8.8</td>
<td>9.45</td>
<td>14.3</td>
</tr>
<tr>
<td>Nominal bore field (T)</td>
<td>4.3</td>
<td>5.3</td>
<td>3.5</td>
<td>8.3</td>
</tr>
<tr>
<td>Nominal current (kA)</td>
<td>4.3</td>
<td>5.7</td>
<td>5.1</td>
<td>11.9</td>
</tr>
<tr>
<td>Stored energy at $I_{\text{nom}}$ (MJ)</td>
<td>0.30</td>
<td>0.94</td>
<td>0.35</td>
<td>6.93</td>
</tr>
<tr>
<td>Operation temperature (K)</td>
<td>4.6</td>
<td>4.5</td>
<td>4.3-4.6</td>
<td>1.9</td>
</tr>
</tbody>
</table>
All magnets to be installed in a machine have to go through testing. A detailed test plan is elaborated. Main points:

- Electrical integrity (test voltage 1-2 kV)
- Performance (field, field quality): Reduce training!
- Memory after thermal cycle: Keep memory!
**Main causes**

- Frictional motion
  - E.m. forces → motion → quench
  - Coil locked by friction in a secure state
- Epoxy failure
  - E.m. forces → epoxy cracking → quench
  - Once epoxy locally fractured, further cracking appears only when the e.m. stress is increased.
- Magnets operate with margin: Nominal current reached with few quenches.

In general, very emotional process!
Testing of magnets: Horizontal test station
Testing of magnets: Vertical test station
Testing of magnets: Vertical test station
Memory

![Graph showing quench current versus quench number with different curves for different energies: 5.5 TeV, 6.0 TeV, and 6.5 TeV. The curves are labeled S12, S23, S34, S45, S56, S67, S78, and S81. Each curve represents a different quench number, ranging from 0 to 60.]

- 5.5 TeV
- 6.0 TeV
- 6.5 TeV
The LHC dipole magnet

- Vacuum vessel
- Thermal shield
- Superinsulation
- Shrinking cylinder / Helium vessel
- Main quadrupole bus-bar
- Magnetic insert
- Iron yoke
- Non-Magnetic collars
- Superconducting coils
- Main dipole bus-bar
- Thermal shield
- CryoLine (QRL)
- Heat exchanger tube
- Beam pipe
- Auxiliary bus-bar
- Bunch of $10^{11}$ protons
  - Beam 1, anti-clockwise
- Bunch of $10^{11}$ protons
  - Beam 2, clockwise
Hi-Lumi LHC at CERN

- Achieve instantaneous luminosities a factor of five larger than the LHC nominal value
- Enable the experiments to enlarge their data sample by one order of magnitude compared with the LHC baseline programme
LHC, what next? FCC!

International FCC collaboration (CERN as host lab) to study:

- 80-100 km tunnel infrastructure
  - $pp$-collider ($FCC-hh$)
  - $e^+e^-$ collider ($FCC-ee$) as potential first step
  - $p-e$ ($FCC-he$) option

HE-LHC with $FCC-hh$ technology
FCC versus LHC dipole

Twice the magnetic field $\rightarrow$
- 2 x more Ampere turns
- 4 x higher forces/m
- $\sim$6 x more stored energy/m
- 4 x more magnets

Prototypes will be built.
Magnet Design Options: Future Circular Collider

Cosine-theta (baseline)

Block-type coils

Common-coils

CCT (PSI with LBNL and CERN)

- Magnet length: 14.3 m
- Free physical aperture: 50 mm
- Inter-beam distance: 204 mm
- Field amplitude: 16 T
- Margin on the load-line @ 1.9K: 14 %
High-Temperature Superconductors

- High-temperature superconductor promise much higher fields
- Technology is currently being developed
- Main challenge: Reduce cost!
Other superconducting magnets in accelerators

- Experimental magnets (large solenoids)
- Insertion devices for reducing the beam emittance and creating synchrotron radiation: Very active field of R&D for storage rings and FELs (ESRF, Soleil, etc.... and European XFEL, SwissFEL,...)

D. Schoerling et al.

David Attwood, Soft X-Rays and Extreme Ultraviolet Radiation: Principles and Applications
Concluding remarks

• Superconducting magnet design and manufacture is a very diverse field. It starts with superconductors (materials, wires, cables, and their electric and thermal properties), continues with electromagnetic design, thermal calculations, mechanics, protection, stability, etc…

• Cooling requires cryogenic, a field of applied science by its own

• The manufacture requires cost modelling, industrialization, complex project management, etc.

• First Nb$_3$Sn magnets to be installed in HL-LHC soon, first 14-15 T magnet tested at FNAL, and further prototype of similar field range under construction in Europe, first HTS dipole to be tested in background field, HTS undulator to be build, …
Literature


Stephan Russenschuck, Field computation, 2010: The book for all questions related to electromagnetic calculations!
Werner Buckel and Reinhold Kleiner, Superconductivity, 2015: Very accessible and comprehensive introduction to superconductivity!

Daniel Schoerling and Alexander Zlobin, Nb$_3$Sn accelerator magnets: Designs, technologies, and performance, August 29, 2019, Review of all so far built Nb$_3$Sn dipole magnets.
Oliver Bruning, Lucio Rossi (editors), High Luminosity Large Hadron Collider, The New Machine For Illuminating The Mysteries Of Universe: Introduction to HL-LHC