Superconducting accelerator magnets

Daniel Schoerling
daniel.schoerling@cern.ch
10th of October 2019
CAS@EAS

Thanks to many colleagues, in particular Paolo Ferracin for the material they have given to me
Why colliders?

Accelerators are the finest microscopes: *atto-scope* or *zepto-scope*

\[ \lambda = \frac{h}{p} ; \quad \text{@LHC: } p = 1 \text{ TeV} \Rightarrow \lambda \approx 10^{-18} \text{ m} \]

\(\lambda\): wavelength

\(h\): Planck constant

\(p\): momentum
COLLIDERS (LEP, Tevatron, Hera, RHIC, LHC, etc.)

- One of the most important parameter of colliders is the beam energy, as it determines the physics discovery potential.
The energy $E$ in GeV of particles in a circular accelerator is limited by the strength of the bending dipole magnets $B$ in Tesla and the machine radius $r$ in m:

$$E \approx 0.3 \times B \times r$$
Dipoles

- The magnetic field $B$ steers the particles in a circular orbit:
  \[ F = qE + qv \times B \]

- First term ($qE$) negligible: 300 MV/m corresponds to 1 T

$NI$: Ampere turns in A
$J$: Current density in A/m$^2$
$B$: Magnetic flux density in T = N/Am
$v$: velocity in m/s
$F$: Force in N
$\rho$: particle path radius in m
Why SC magnets?

Normal-conducting iron-dominated magnets:
- \( B \approx \mu_0 NI / g \)
- Limited by the iron saturation: \( B \lesssim 2 \text{ T} \)
- Ohmic losses, cooling, power converters, etc.

- \( g = 100 \text{ mm (gap)} \)
- \( NI = 160 \text{ kA (Ampere turns)} \)
- \( B = 2 \text{ T (Magnetic flux density, limit)} \)

Superconducting magnets:
- \( B \approx \mu_0 NI / \pi r \)
- Limited only by SC material properties and cost
- Cooling, power converters, busbars

- \( r = 1/2g = 45 \text{ mm (aperture radius)} \)
- \( NI = 1 \text{ MA (Ampere turns)} \)
- \( B = 8.84 \text{ T (magnetic flux density)} \)
50 000 tons of normal conducting magnets
50 000 tons of superconducting magnets
The LHC dipole magnet

- 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
- 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)
In which domains do we need to work?

Multidisciplinary field:
• Chemistry and material science: superconducting materials
• Quantum physics: the key mechanisms of superconductivity
• Classical electrodynamics: magnet design
• Mechanical engineering: support structures
• Electrical engineering: powering of the magnets
• Cryogenics: keep them cool …
• Industrialization & large and complex project management
• Cost modelling
• Impact on society

Very different fields and multi-disciplinary field not limited to physics and engineering
What do we need to do to get a good design?

Let’s focus on the main (technical) points:
• Conductor and cable design, which superconducting material, strand and cable to choose?
• How to do the electromagnetic and structural design of the coil (field and field quality load line margin, quench)?

**AIM OF LECTURE:** Understand the main technical concepts relevant in superconducting accelerator magnets!
Superconducting material

- Superconductivity discovered in 1911 by Kammerlingh-Onnes: ZERO resistance of mercury wire at 4.2 K
- Temperature at which the transition takes place: critical temperature $T_c$
- Observed in many materials: but not in the typical best conductors (Cu, Ag, Au)

Kammerlingh-Onnes proposed 1913 a 10 T solenoid, but it took 50 years (!) of hard work to make this dream come true
Superconductivity – Type I superconductors

Meissner-Ochsenfeld effect (1933):
• Perfect diamagnetism: With $T < T_c$ magnetic field is expelled
• No magnetic field inside the superconductor $\rightarrow$ no transport current inside a round conductor

<table>
<thead>
<tr>
<th>Material</th>
<th>$T_c$ (K)</th>
<th>$\mu_0 H_c$ (mT)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aluminum</td>
<td>1.2</td>
<td>9.9</td>
</tr>
<tr>
<td>Cadmium</td>
<td>0.52</td>
<td>3.0</td>
</tr>
<tr>
<td>Gallium</td>
<td>1.1</td>
<td>5.1</td>
</tr>
<tr>
<td>Indium</td>
<td>3.4</td>
<td>27.6</td>
</tr>
<tr>
<td>Iridium</td>
<td>0.11</td>
<td>1.6</td>
</tr>
<tr>
<td>Lanthanum $\alpha$</td>
<td>4.8</td>
<td>4.9</td>
</tr>
<tr>
<td>Lanthanum $\beta$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Lead</td>
<td>7.2</td>
<td>80.3</td>
</tr>
<tr>
<td>Lutecium</td>
<td>0.1</td>
<td>35.0</td>
</tr>
<tr>
<td>Mercury $\alpha$</td>
<td>4.2</td>
<td>41.3</td>
</tr>
<tr>
<td>Mercury $\beta$</td>
<td>4.0</td>
<td>34.0</td>
</tr>
<tr>
<td>Molybdenum</td>
<td>0.9</td>
<td></td>
</tr>
<tr>
<td>Osmium</td>
<td>0.7</td>
<td>~6.3</td>
</tr>
<tr>
<td>Rhenium</td>
<td>1.7</td>
<td>20.1</td>
</tr>
<tr>
<td>Rhodium</td>
<td>0.0003</td>
<td>4.9</td>
</tr>
<tr>
<td>Ruthenium</td>
<td>0.5</td>
<td>6.6</td>
</tr>
<tr>
<td>Tantalum</td>
<td>4.5</td>
<td>83.0</td>
</tr>
<tr>
<td>Thallium</td>
<td>2.4</td>
<td>17.1</td>
</tr>
<tr>
<td>Thorium</td>
<td>1.4</td>
<td>16.2</td>
</tr>
<tr>
<td>Tin</td>
<td>3.7</td>
<td>30.6</td>
</tr>
<tr>
<td>Titanium</td>
<td>0.4</td>
<td></td>
</tr>
<tr>
<td>Tungsten</td>
<td>0.016</td>
<td>0.12</td>
</tr>
<tr>
<td>Uranium $\alpha$</td>
<td>0.6</td>
<td>1.8</td>
</tr>
<tr>
<td>Uranium $\beta$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Zinc</td>
<td>0.9</td>
<td>5.3</td>
</tr>
<tr>
<td>Zirconium</td>
<td>0.8</td>
<td>4.7</td>
</tr>
</tbody>
</table>
Superconductivity – Type II superconductors

• So, for 40-50 years, superconductivity was a research activity
• Then, in the 50’s, type II superconductors were discovered:
  • Between $B_{c1}$ and $B_{c2}$: mixed phase
  • $B$ penetrates as flux tubes: fluxoids with a flux of $\phi_0 = \hbar/2e = 2 \cdot 10^{-15}$ Wb
• Much higher fields and link between $T_c$ and $B_{c2}$

\[ B_{c1} < B < B_{c2} \]

by L. Bottura
Superconductivity – Hard superconductors

- ...but, if a current passes through the tubes
  - Lorentz force on the fluxoids: \( f = J \times B \)
- The force causes a motion of tubes
  - Flux motion \( (dB/dt) \) → energy dissipation
- Fluxoids must be locked by pinning centres
  - Defects or impurities in the structure

- The pinning centres exert a pinning force as long as \( f \leq J \times B \):
  - No flux motions → no dissipation
  - \( J_c \) is the current density at which, for a given \( B \) and at a given \( T \) the pinning force is exceeded by the Lorentz force
A type II material is superconductor below the critical surface defined by

- Critical temperature $T_c$ (property of the material)
- Upper critical field $B_{c2}$ (property of the material)
- Critical current density $J_c$ (property of the material but in practice hard work by the producer)
Technical superconductors: Nb-Ti (1961) and Nb$_3$Sn (1954)

- Nb and Ti: ductile alloy
- Production route: Extrusion + drawing
- $T_c$ is ~9.2 K at 0 T
- $B_{c2}$ is ~14.5 T at 0 K
- Firstly in Tevatron (80s), then in HERA, RHIC and LHC
- ~50-200 US$ per kg of wire (1 euro per m)

- Nb and Sn → intermetallic compound
- Brittle, strain sensitive, formed at ~650-700°C
- $T_c$ is ~18 K at 0 T
- $B_{c2}$ is ~28 T at 0 K
- Used in NMR, ITER, HL-LHC and baseline for FCC
- ~700-1500 US$ per kg of wire (target price for FCC: 500 US$ per kg of wire)
Conductors: from Cu to Nb₃Sn

- **Cu**:
  - $J_c \sim 5 \text{ A/mm}^2$
  - $I \sim 3 \text{ A}$
  - $B = 2 \text{ T}$

- **Nb-Ti**:
  - $J_c \sim 600-700 \text{ A/mm}^2$
  - $I \sim 300-400 \text{ A}$
  - $B = 8-9 \text{ T}$

- **Nb₃Sn**:
  - $J_c \sim 600-700 \text{ A/mm}^2$
  - $I \sim 300-400 \text{ A}$
  - $B = 12-16 \text{ T}$

0.85 mm diameter strand
Conductors: from Cu to Nb$_3$Sn

Cu

0.85 mm diameter strand

$J_c \sim 5 \text{ A/mm}^2$

$I \sim 3 \text{ A}$

$B = 2 \text{ T}$

Nb-Ti

$J_c \sim 600-700 \text{ A/mm}^2$

$I \sim 300-400 \text{ A}$

$B = 8-9 \text{ T}$

Nb$_3$Sn

$J_c \sim 600-700 \text{ A/mm}^2$

$I \sim 300-400 \text{ A}$

$B = 12-16 \text{ T}$
Why small filaments? Stability!

- Simple model: SC carries either $J_c$ or no current $\rightarrow$ If field is changed, eddy currents are resistively damped
- The conductor is stable as long as temperature stays below the critical temperature $T_c$

One large filament | Several ($N \gg 1$) small filaments
---|---
same SC area, i.e. $a_L^2 = Na_S^2$ | total volumetric heat $[\text{J/m}^3]$

$Q_L \approx \frac{8\Delta B}{3\pi} Jc a_L$ | $Q_S \approx \frac{8\Delta B}{3\pi} Jc a_S$

$\frac{Q_S}{Q_L} = \frac{a_S}{a_L} = \frac{a_S}{a_S \sqrt{N}}$ for $N = 100$ $\frac{Q_S}{Q_L} = \frac{1}{10}$

$\alpha \leq \sqrt{\frac{3\gamma C (\theta_c - \theta_0)}{\mu_0 J_c^2}}$
Why Cu? Stability & Protection!

Quench protection
• Superconductors have a very high normal state resistivity
• If quenched, could reach very high temperatures in few ms
• If embedded in a high-purity copper matrix, when a quench occurs, current redistributes in the low-resistivity matrix yielding to a lower peak temperature

by L. Bottura
Twisting

- When a multi-filamentary wire is subjected to a time varying magnetic field, current loops are generated between filaments.
- If filaments are straight, large loops with large currents → AC losses
- If the strands are magnetically coupled the effective filament size is larger → flux jumps

To reduce these effects, filaments are twisted, the twist pitch is of the order of 20-30 times of the wire diameter.
And magnetization

**Superconductor magnetization**
- A hard superconducting filament shows a magnetization curve, as the one shown on the right.
- The magnetization stays constant (if no flux jumps occur) at constant field: persistent current.
- Field persistent currents produce field errors proportional to $J_c$ and filament diameter:
  - HERA filament diameter 14 μm
  - LHC filament diameter 6-7 μm
  - HL-LHC filament diameter 50 μm
  - FCC target filament diameter 20 μm
Practical superconductors: Fabrication of Nb-Ti multifilament wires

- Nb-Ti ingots
- 200 mm Ø, 750 mm long
- Monofilament rods are stacked to form a multifilament billet, then extruded and drawn down
- Can be re-stacked: double-stacking process
Practical superconductors: Fabrication of Nb$_3$Sn multifilament wires

- Since Nb$_3$Sn is brittle it cannot be extruded and drawn like Nb-Ti.

- Process in several steps
  - Assembly multifilament billets from with Nb and Sn separated
  - Fabrication of the wire through extrusion-drawing
  - Fabrication of the cable
  - Fabrication of the coil

- Reaction
  - Sn and Nb are heated to 600-700°C
  - Sn diffuses in Nb and reacts to form Nb$_3$Sn
Conductors: Strand and cables

• Now, we know we need conductors composed out of small filaments and surrounded by a stabilizer (typically copper) to form a multi-filament wire or strand.

• To keep voltages reasonable small, the inductance of the magnet has to be small $\rightarrow L \propto 1/I^2$ $\rightarrow$ we need large currents!

• Large wires are excluded due to self-field instabilities yielding to flux jumps (same argument as for small filaments) $\rightarrow$ practical limit 1-2 mm

Solution: Superconducting cable composed of several wires: multi-strand cable!

Courtesy of GL Sabbi
What else do we need? Insulation!

Rule in accelerator magnets: never sacrifice the insulation!

Courtesy of A. Siemko, CERN
Typical insulation schemes for Nb-Ti and Nb$_3$Sn

Typically the insulation thicknesses: 100 and 200 µm
- The cable insulation must feature good electrical properties to withstand turn-to-turn V after a quench
- Good mechanical properties to withstand high pressure conditions
- Porosity to allow penetration of helium (or epoxy)
- Radiation hardness

In Nb-Ti magnets overlapped layers of polyimide

In Nb$_3$Sn magnets, fibre-glass braided or as tape/sleeve.
Let’s take the cable and do an electromagnetic design!

- How do we express field and its “imperfections”?
- How do we create a perfect field?
- How do we design a coil to minimize field errors?
- How do we select the current density in the coil?
How do we generate a perfect dipole?

- How to generate a dipolar field:
  - Two infinite slabs
  - Two intersection cylinders
  - Cos-theta current distribution
- Many different winding schemes typically classified as
  - Block type magnets (block, common-coil)
  - Cos-theta/shell type magnets (traditional cos-theta, canted cos-theta)
Magnetic design: Harmonics

The field can be expressed as (simple) series of coefficients.

So, each coefficient corresponds to a “pure” multipolar field:

\[ B_y(x, y) + iB_x(x, y) = \sum_{n=1}^{\infty} C_n(x + iy) = \sum_{n=1}^{\infty} (B_n + iA_n)(x + iy) \]

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

Dipole

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

\[
B_n = \frac{2\mu_0}{\pi} J \left( \frac{R_{\text{out}}^{2-n} - R_{\text{in}}^{2-n}}{n(2-n)} \right) r_{\text{ref}}^{n-1} \sin(n\varphi), \quad n = 3, 5, 7, \ldots
\]
Magnetic design: Optimization of one layer designs

- We compute the central field given by a sector dipole with 2 blocks
- Equations to set to zero $B_3$, $B_5$ and $B_7$

\[
\begin{align*}
\sin(3\alpha_3) - \sin(3\alpha_2) + \sin(3\alpha_1) &= 0 \\
\sin(5\alpha_3) - \sin(5\alpha_2) + \sin(5\alpha_1) &= 0
\end{align*}
\]

- And with 3 blocks
- Equations to set to zero $B_3$, $B_5$, $B_7$, $B_9$ and $B_{11}$

\[
\begin{align*}
\sin(3\alpha_5) - \sin(3\alpha_4) + \sin(3\alpha_3) - \sin(3\alpha_2) + \sin(3\alpha_1) &= 0 \\
\sin(5\alpha_5) - \sin(5\alpha_4) + \sin(5\alpha_3) - \sin(5\alpha_2) + \sin(5\alpha_1) &= 0 \\
\sin(7\alpha_5) - \sin(7\alpha_4) + \sin(7\alpha_3) - \sin(7\alpha_2) + \sin(7\alpha_1) &= 0 \\
\sin(9\alpha_5) - \sin(9\alpha_4) + \sin(9\alpha_3) - \sin(9\alpha_2) + \sin(9\alpha_1) &= 0 \\
\sin(11\alpha_5) - \sin(11\alpha_4) + \sin(11\alpha_3) - \sin(11\alpha_2) + \sin(11\alpha_1) &= 0
\end{align*}
\]

Two wedges, $b_5=b_3=b_7=0$  
[0°−33.3°, 37.1°−53.1°, 63.4°−71.8°]
A review of coil layouts: Existing

TEVATRON
USA, 1983-2011

HERA
Germany, 1991-2007

RHIC
USA, since 2000

LHC
CERN, since 2008
Winding of Fresca2

Winding machine with dedicated tooling
The Winding House at CERN (bld. 180)
Reaction furnace(s)

Dedicated ovens with controlled atmosphere
- Ramp at 25°C/h, held during 72 h at 210°C
- Ramp at 50°C/h, held during 48 h at 400°C
- Ramp at 50°C/h, held during 50 h at 650°C
Impregnation tank

Dedicated autoclave for vacuum impregnation with epoxy
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: $B_{op} = 8.33$ T, $I_{op} = 11,850$ A, $J_{eng} = \sim 450$ 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

Margin to quench (%)

- 89.40
- 85.47
- 81.54
- 77.60
- 73.67
- 69.73
- 65.80
- 61.87
- 57.93
- 54.00
- 50.06
- 46.13
- 42.2
- 38.26
- 34.33
- 30.39
- 26.46
- 22.52
- 18.59
- 14.66

LHC
Temperature margin
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
  \[ U = L \frac{dI}{dt} \] (LHC MB: \( L = 98.7 \text{ mH/magnet}, \ I = 11.85 \text{ kA} \))
  \[ \rightarrow \text{A discharge in 0.1 s would yield a voltage of } \sim 12 \text{ kV} \]

• **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.
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!
The e.m. forces in a dipole/quadrupole magnet tend to push the coil
• Towards the mid plane in the vertical-azimuthal direction \((F_y, F_\theta < 0)\)
• Outwards in the radial-horizontal direction \((F_x, F_r > 0)\)
**Mechanical structure: Examples**

**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 μm
- \( F_z = 27 \text{ t: } \sim \text{weight of the cold mass} \)

**\( \text{Nb}_3\text{Sn dipole (Fresca-2)} \)**
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 objet 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.
Cold mass
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!

MQXFS01 test
First test of HiLumi Nb₃Sn IR quadrupole
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!
Memory
The LHC dipole magnet
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
LHC what next? CLIC?
# Magnet Design Options: Future Circular Collider

<table>
<thead>
<tr>
<th>Timeline</th>
<th>~ 5</th>
<th>~ 10</th>
<th>~ 15</th>
<th>~ 20</th>
<th>~ 25</th>
<th>~ 30</th>
<th>~ 35</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Lepton Colliders – Linear and Circular:</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SRF-LC/CC</td>
<td>Proto/pre-series</td>
<td>Construction</td>
<td>Operation</td>
<td>Upgrade</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>NRF–LC</td>
<td>Proto/pre-series</td>
<td>Construction</td>
<td>Operation</td>
<td>Upgrade</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Hadron Collier – Circular:</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>14~16T Nb₃Sn</td>
<td>Short-model R&amp;D</td>
<td>Prototype/Pre-series</td>
<td>Construction</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>12~14T Nb₃Sn</td>
<td>Short-model R&amp;D</td>
<td>Proto/Pre-series</td>
<td>Construction</td>
<td>Operation</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>9~12T Nb₃Sn</td>
<td>Model/Proto/Pre-series</td>
<td>Construction</td>
<td>Operation</td>
<td>Upgrade</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>6~8T NbTi</td>
<td>Proto/Pre-series</td>
<td>Construction</td>
<td>Operation</td>
<td>Upgrade</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Note:** LHC experience: NbTi, 10 T R&D started in 1980’s and 8.3 T Production started in late 1990’s, after ~ 15 years

A. Yamamoto, 190513b/updated:190628a
Superconducting magnets
High-Temperature Superconductors

- High-temperature superconductor promise much higher fields
- Technology is currently being developed
- Main challenge: Reduce cost!
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, an accelerator type magnet reached ~14 T with margin and after few quenches, other 14 T magnets for FCC to be manufactured from now on, first HTS dipole to be tested in background field, HTS undulator to be built, …

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

Daniel Schoerling and Alexander V. Zlobin, Nb$_3$Sn accelerator magnets: Designs, technologies, and performance, 2019, link: Review of all so far built Nb$_3$Sn dipole magnets.