Rutherford Cables for Accelerator Magnets

J. Fleiter and A. Ballarino

Cryogenic Cluster Day,
Rutherford Appleton Laboratory, 20/09/2016
Outline

• Superconductors for accelerator magnets
• Rutherford cable
• Nb-Ti cables for the Large Hadron Collider
• Nb$_3$Sn cables for High Luminosity LHC (HL-LHC)
• HL-LHC and beyond
CERN

- CERN: European Organization for Nuclear Research
- Founded in 1954, 22 member states
- LHC accelerator (14 TeV, 27 km, 2010)
- LHC relies on Nb-Ti Rutherford cables
- Discover of Higgs Boson in 2012
- In 2019 Nb$_3$Sn magnet in LHC (HL-LHC)
- Future Circular Collider (FCC) study (100 TeV, Nb$_3$Sn)
Superconducting strands for acc. magnets

Relevant parameters for accelerator magnets (Nb-Ti, Nb$_3$Sn..)

- Large overall current density $\sim$400–500 A/mm$^2$
- Cu fraction of about 50% with RRR >100
- Small filaments to reduce magnetization and flux jumps
- Twist of filaments
- Sufficient mechanical properties (axial and transverse)
- Long piece lengths (~1 km)
- Good uniformity of electrical performances
- …

Practical superconductors

- Nb-Ti $B_{\text{0 max}} = 9$ T
- Nb$_3$Sn $B_{\text{0 max}} = 16$ T
- BSCCO $B_{\text{0 max}} > 20$T
- YBCO (but tape geometry)

Beam energy: $E$ [TeV] $\sim$ 0.3 $B$[Tesla] $R$[km]
Superconducting devices in LHC

Magnets

- **LHC ring magnets (Nb-Ti): Rutherford cables**
- **1232 main dipoles**: 8.3 T x 15 m
- **392 Main quadrupoles**: 223 T/m (7 T) x 4 m
- **7600 other SC magnets (cable or wire)**

- **RF cavities (Nb coating)**

➢ **Rutherford Nb-Ti cable: a key technology for LHC**
Rutherford cables

• Why cables:
  • Need for high current
  • Reduce piece length of conductor (~1 km)
  • Improve stability
  • Make easier the winding

• The use of large current cables implies also
  • Dealing with dynamic effects
  • Less freedom for magnetic optimization

• Advantages of Rutherford cables vs other cables
  • High packing factor
  • Transposition of strands
  • Good control of dimensions (+/- 6 µm on thickness)
  • Good windability

\[ E = \frac{1}{2} LI^2 \]
\[ V = \frac{LI}{t} = \frac{2E}{It} \]
Specification of Rutherford cables

A balance between limited wire deformation and desired cable compaction

• **Geometry**
  - Nb. of strands (N) determined by current
  - Pitch angle (PA) ~ 12-18 Degree
  - Width ~ N d/(2cos(PA))+0.72d
  - Thickness ~ 10-15% compaction
  - Typical unit length ~ 500-1000 m

• **Strong control of geometry** (+/- 6 µm in thickness)
• **Good windability**
• **Small $I_c$ degradation** (<5%)
• **Controlled inter-strand resistance**
Rutherford Cabling process

- Planetary machine with regulation of strand tension (~50N)
- Single stage process: cable dimensions given at Turk head
- CERN machine: up to 40 strands, and up to ~5 m/min
- Online QC tests to control dimensions and of possible defects (crossover, inclusions, facet size…)

Spools  Rolling  Caterpillar
**LHC Rutherford cables**

7500 km of Nb-Ti Rutherford cables in LHC accelerator

**Nb-Ti is ductile: Strands already superconducting when cabled.**

<table>
<thead>
<tr>
<th>Type</th>
<th>Number of strands</th>
<th>Width (mm)</th>
<th>Mid Thickness (50MPa)</th>
<th>Keystone Angle</th>
<th>Transposition pitch</th>
<th>Cable Ic</th>
<th>Cabling degradation (%)</th>
<th>Unit length (m)</th>
<th>Produced length (km)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type 01</td>
<td>28</td>
<td>15.09 +/- 0.01</td>
<td>1.90 +/- 0.006</td>
<td>1.25 +/- 0.05</td>
<td>115</td>
<td>13750 A</td>
<td>&lt;5</td>
<td>460</td>
<td>2370</td>
</tr>
<tr>
<td>Type 02/03</td>
<td>36</td>
<td>15.09 +/- 0.01</td>
<td>1.48 +/- 0.006</td>
<td>0.90 +/- 0.05</td>
<td>100</td>
<td>12960 A</td>
<td>&lt;5</td>
<td>750</td>
<td>4600</td>
</tr>
<tr>
<td>Type 04</td>
<td>36</td>
<td>8.80 +/- 0.02</td>
<td>0.840 +/- 0.005</td>
<td>0.91 +/- 0.05</td>
<td>66</td>
<td>6768 A</td>
<td>&lt;5</td>
<td>530 / 760</td>
<td>246</td>
</tr>
<tr>
<td>Type 05</td>
<td>34</td>
<td>8.30 +/- 0.02</td>
<td>0.845 +/- 0.005</td>
<td>0.90 +/- 0.05</td>
<td>66</td>
<td>6392 A</td>
<td>&lt;5</td>
<td>760</td>
<td>71</td>
</tr>
<tr>
<td>Type 06</td>
<td>22</td>
<td>8.30 +/- 0.02</td>
<td>1.275 +/- 0.005</td>
<td>1.72 +/- 0.05</td>
<td>66</td>
<td>11308 A</td>
<td>&lt;5</td>
<td>660</td>
<td>46</td>
</tr>
</tbody>
</table>

**Nb-Ti Rutherford cable, a mature technology, mastered by industry**
Nb$_3$Sn cables for High Field Magnets

- Dipolar fields of up to 16 T with Nb$_3$Sn
- Nb$_3$Sn is Strain sensitive
  - Wind and React technology
  - Coils have to be impregnated
  - Rutherford cabling should manage I$_c$ and RRR degradations
- HL-LHC: boost of luminosity thanks to Nb$_3$Sn
  - 2019: dual aperture 11 T dipole Nb$_3$Sn magnets
  - 2024: large aperture 132 T/m quadrupole magnets
- FCC study: 100 TeV with 16 T Nb$_3$Sn dipoles
Nb$_3$Sn Conductor for Hi-Lumi LHC

- **Internal Sn (RRP, OST)**
- **Powder in Tube (PIT, Bruker EAS)**

Both technologies are based on solid state diffusion to transport Sn from the source to the Nb and both require a diffusion barrier.
The HL-LHC Nb$_3$Sn magnets

**11.2 T Dipole, 12 kA, 5.5 m long, 60 mm aperture (2019)**

Insertion of collimators at IP7 by replacing LHC Nb-Ti dipole (8.3 T, 15 m) with shorter Nb$_3$Sn dipole (11 T, 2×5.5 m)

**Quadrupole 133 T/m, 16 kA, 4-7 m long, 150 mm aperture (2024)**

Increase of Luminosity with higher aperture quads

HL-LHC magnets based on Rutherford cables
HL-LHC Rutherford Nb$_3$Sn cables

Nb$_3$Sn cables prone to $I_c$ and RRR degradation:

- Optimization of cable geometry to limit degradation to less than 5 % and RRR > 100
- Same cable geometry for RRP and PIT strands
- Unit lengths of 650 m and 750 m

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Unit</th>
<th>11 T</th>
<th>QXF</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of strands</td>
<td>(-)</td>
<td>40</td>
<td>40</td>
</tr>
<tr>
<td>Strands diameter</td>
<td>mm</td>
<td>0.7</td>
<td>0.85</td>
</tr>
<tr>
<td>Cable bare width</td>
<td>mm</td>
<td>14.7</td>
<td>18.15</td>
</tr>
<tr>
<td>Cable bare thickness</td>
<td>mm</td>
<td>1.25</td>
<td>1.525</td>
</tr>
<tr>
<td>Keystone angle</td>
<td>°</td>
<td>0.79</td>
<td>0.4</td>
</tr>
<tr>
<td>Thin edge compaction*</td>
<td>%</td>
<td>17.95</td>
<td>14.02</td>
</tr>
<tr>
<td>Thick edge compaction*</td>
<td>%</td>
<td>3.48</td>
<td>6.57</td>
</tr>
<tr>
<td>Transposition pitch</td>
<td>mm</td>
<td>100</td>
<td>109</td>
</tr>
<tr>
<td>SS Core width (thickness)</td>
<td>mm</td>
<td>12 (0.0025)</td>
<td></td>
</tr>
</tbody>
</table>

11T cables entering into series production
Inter-strand resistance in Nb$_3$Sn cables

- Need to control inter-strand resistance to allow current sharing (stability) and avoid large eddy currents (field quality and losses)
- Sintering of strands during final reaction (650 °C for 2 weeks) $\Rightarrow$ low $R_c$
- A stainless steel core (25 µm thick) inserted in the cable to increase the crossing resistance

The core is effective to reduce field distortions and ramp rate dependencies

Control of inter-strand crossing resistance by stainless steel core
Quench in Nb$_3$Sn Rutherford cables

- Nb$_3$Sn magnets are challenging for protection => good understanding of dominating physics required
- Many experiments and modelling performed on strand, cable and coils
- Turn-to-turn delay time of propagation also measured on cables and coils
- Design of protection system based on quench propagation velocity
The FCC study

- hh-100 TeV collider
- based on 16 T Nb$_3$Sn dipole magnets made from Rutherford cables
- ~10000 tons of Nb$_3$Sn (LHC used 1300 tons of Nb-Ti)
- Dipole magnet design is on-going, followed by cable design
Performances of Nb$_3$Sn strands

- **HL-LHC:**
  - High J$_c$ $\sim$2500 A/mm$^2$ @ 12 T
  - Sub elements $\sim$50 µm
  - RRR$>$150

- **Target of FCC:**
  - Very High J$_c$ $\sim$1500 A/mm$^2$ @ 16 T
  - Sub elements $\sim$20 µm
  - RRR$>$150

Main challenge for Nb$_3$Sn: Much Higher J$_c$ than state of the art
High current cables for $B_0 > 16$ T

**Rutherford BSCCO (2212)**
- Wire
- Weak mechanical properties
- Delicate heat treatment ($O_2/900^\circ C$)
- High $J_{ce}$ (HT @100 bar)
- Cable performances so far:
  - $5$ kA @ $4.3$ K and $\sim 2$ T

**Roebel cable (REBCO tape)**
- Tape
- Strong mechanical properties
- No reaction after coil winding
- High $J_{ce}$ in $\parallel$ field, medium in perp.
- Cable performances so far:
  - $12$ kA @ $4.3$ K and $12$ T

Protection is a key issue for HTS coils
Conclusions

• Nb-Ti Rutherford cable: a mastered technology
• About 7500 km of Rutherford cable in LHC
• Field >10 T thanks to the use of Nb$_3$Sn cable
• Lot of effort over last decade to develop the Nb$_3$Sn conductor and cables
• Nb$_3$Sn cables are now mature for accelerator magnets
• Not to forget: “A magnet cannot perform better than the conductor it is made of”
Thank you for your attention