Rutherford cables for HL-LHC magnets

J. Fleiter

Acknowledgements to A. Bonasia, A. Ballarino and the colleagues in buildings 103-163
Outline

- Genesis and main parameters of Rutherford cables
- HL-LHC Rutherford cables’ technical specification
- Production of Rutherford cables at CERN
  - Cabling plan
  - Cabling machine
  - Quality Control tests
- Overview of produced cables
- Conclusions
Genesis and main parameters of Rutherford cables
Genesis of Rutherford cables

- The **Concept of Rutherford cable** was developed at the **Rutherford High Energy Laboratory** (RHEL, UK) in the early 1970’s, and is attributed to G. Gallagher-Daggit.

- Accelerator magnets, where the superconducting coils need large current density and controlled geometrical dimensions, rely on Rutherford cables.

- Rutherford cables have been used in all large scale colliders (RHIC, Tevatron, HERA), including the LHC.

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<table>
<thead>
<tr>
<th></th>
<th>Tevatron</th>
<th>HERA</th>
<th>RHIC</th>
<th>LHC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dipole field</td>
<td>4.4 T</td>
<td>5.3 T</td>
<td>3.5 T</td>
<td>8.3 T</td>
</tr>
<tr>
<td>Number of strands</td>
<td>23</td>
<td>24</td>
<td>30</td>
<td>28-36</td>
</tr>
<tr>
<td>Cable current</td>
<td>4 kA</td>
<td>5.5 kA</td>
<td>5 kA</td>
<td>11.8 kA</td>
</tr>
</tbody>
</table>

Rutherford cables

The final cross section of a Rutherford cable can be:

- **rectangular** for block coils or bus-bar,
- **trapezoidal** for cos-theta coils or bus-bar

Made from ~10-60 round multi-filamentary twisted strands

Strands are arranged in a two-layer structure.

The main parameters are:

- Number of wires $N_{\text{wire}}$
- Strand diameter $d_{\text{wire}}$
- Cable mid-thickness $t_c$
- Cable outer thickness $t_o$
- Cable inner thickness $t_i$
- Cable width $w_c$
- Keystone angle $\varphi$
- Transposition pitch and direction

![Diagram of Rutherford cable parameters](image)
Rutherford cable topology: pro and cons

With respect to other types of high current cables, the Rutherford-type cable has the advantages of:

- Low void fraction and high engineering current density (~500-700 A/mm$^2$)
- Improved flexibility for easy bending around the ends of small aperture magnets
- Easy stacking of cable in the coil straight parts
- Small thickness that allow fine tuning of field quality
- Well controlled geometry over long lengths (~km) for precise winding
- Reduced losses thanks to transposition of the strands
- Good mechanical stability, coupled with a minimum amount of degradation of the strands following compaction
- Reproducible low resistance splices promoting good current distribution.

The main challenges of Rutherford cable are:

- Large transverse Lorentz stress accumulation towards the coils that can become detrimental when dealing with brittle conductors
- Full impregnation (mechanics, insulation) resulting in modest heat transfer
- Mechanical stability of the cable in narrow coil heads
- Stability versus external perturbations (energy releases) inducing training.
Rutherford cables production

- Rutherford cables are fabricated by a planetary cabling machine (to allow for torsion free cabling)
- Strands are wound on spools mounted on a rotating drum
- Strands are twisted around a mandrel into an assembly of rollers (Turk’s head) – the rollers compact the cable and provide the final shape of the cable (window)

- **Typical control parameters during production**: Width, Thickness, Twist pitch, Wire tension

- **More details on production in next slides**

Cabling machine in Building 163
Cable compaction and strand deformation

- Compaction of a Rutherford cable is a delicate balance between cabling deformation, electrical performance, and cable mechanical stability.

- Cable compaction quantified via three parameters:
  - With compaction ($C_w$)
  - Thickness compaction ($C_t$)
  - Packing factor (PF)

- The cable compaction is chosen to provide:
  - Good mechanical stability (to prevent from popping strands and collapse),
  - High current capability, leaving enough space for helium cooling or epoxy impregnation
  - Non excessive deformation of the conductor that results in $I_c$, RRR degradation and strand stability limitations (best results obtained when strands are supported in all directions).

- For HL-LHC Nb$_3$Sn cables the maximum tolerable $I_c$ degradation is 5%, with RRR > 100.

- Cable design parameters should not exceed the superconducting material limitations.

\[
c_t = \frac{t}{2d} - 1
\]

\[
c_w = \frac{N}{2 \cos(\theta) + 0.732} d^{-1}
\]

40 strands of 1 mm, 20.4 mm cable width

40 strands of 1 mm, 20.9 mm cable width
Several numerical cabling model developed for studying strand deformation in cable and their strain state

- Cable design parameters should not exceed the superconducting material limitations => Conductor limitation shall be known with accuracy
- A cable design could suit to one strand layout but not to another one more sensitive to strain/deformation.


Cocascope, CEA Saclay P. Manil, F. Nuno
Rutherford cable facets

- At cable sides, the strand deformation determines:
  - Reduction of the filament cross-sectional area (Nb-Ti)
  - Distortion of sub elements and breakage of reaction barrier with incomplete tin reaction (Nb$_3$Sn)
  - Reduction of RRR, instabilities

- General rule to minimize deformation and associated electrical degradations in Nb$_3$Sn cables: no overlapping of consecutive facets $x/y<1$

D.R. Dietderich et al., Cryogenics 48 (2008) 331–340
Control of inter-strand resistance

- Control of resistance at cross over (Rc) of strands is mandatory in Rutherford cables:
  - **Excessive** resistance at strand’s cross over is limiting cable stability against thermal excitation and current redistribution
  - **Too low** resistance at strand’s cross over allows for coupling currents, resulting in field distortion and energy losses (reducing operating margins).
- Typical Rc resistance of about 20-40 µΩ for NbTi cables is provided by oxidation of the coating of strands.
- In Nb₃Sn cables, a stainless-steel core inserted between the strands and covering the ~2/3 of the width of the cable is providing Rc of about 0.1-0.5 mΩ.

Picture from G. Willering PhD thesis
Winding of Rutherford cables

- To minimize degradation of electrical performance, Nb$_3$Sn cables are less compacted than Nb-Ti and therefore are more prone to popping/roping during winding stage.
- The plastic deformation of the strands provides a locking force.
- Diameter of strand plays a major role in locking force.
- The mechanical loading of the cable during winding may exceed this locking force.
- Popped strands in coils result in magnet performance limitation.

Picture from D. Pulikowski, Windability of the Rutherford cable.
HL LHC Rutherford cables
Technical specifications
**LHC Rutherford cables**

~7500 km of Nb-Ti Rutherford cables in the LHC

Nb-Ti is ductile: strands 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 (deg)</th>
<th>Transposition pitch (mm)</th>
<th>Cable Ic (kA)</th>
<th>Cabling degradation (%)</th>
<th>Unit Length (m)</th>
<th>Produced length (km)</th>
</tr>
</thead>
<tbody>
<tr>
<td>01</td>
<td>28</td>
<td>15.09 +/- 0.01</td>
<td>1.900 +/- 0.006</td>
<td>1.250 +/- 0.05</td>
<td>115</td>
<td>13.8 (1.9K,10T)</td>
<td>&lt;5</td>
<td>460</td>
<td>2370</td>
</tr>
<tr>
<td>02/03</td>
<td>36</td>
<td>15.09 +/- 0.01</td>
<td>1.480 +/- 0.006</td>
<td>0.900 +/- 0.05</td>
<td>100</td>
<td>12.9 (1.9K,9T)</td>
<td>&lt;5</td>
<td>750</td>
<td>4100</td>
</tr>
<tr>
<td>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>6.8 (4.2K,5T)</td>
<td>&lt;5</td>
<td>530 / 760</td>
<td>246</td>
</tr>
<tr>
<td>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>6.4 (4.2K,5T)</td>
<td>&lt;5</td>
<td>760</td>
<td>71</td>
</tr>
<tr>
<td>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>11.3 (4.2K,5T)</td>
<td>&lt;5</td>
<td>660</td>
<td>32</td>
</tr>
</tbody>
</table>

Nb-Ti Rutherford cable, a mature technology mastered also by industry
HL-LHC Magnets

- Rutherford cables “inside”
HL-LHC Rutherford cables

- **Nb-Ti cables:**
  - **D1 and D2, Type 02 LHC** (outer layer of MB)
  - **MCBXFA(B), new cable** 18 strands, Ø= 0.48 mm,
  - **MQXF bus bar, new cable** 34 strands, Ø= 1.07 mm

- **Nb\textsubscript{3}Sn cables:**
  - **11 T**, 40 strands Ø=0.7 mm
  - **MQXF**, 40 strands Ø= 0.85 mm

<table>
<thead>
<tr>
<th></th>
<th>Nb-Ti HL LHC cables</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>LHC type 02</td>
</tr>
<tr>
<td>Number of strands (-)</td>
<td>36</td>
</tr>
<tr>
<td>Diameter of strands (mm)</td>
<td>0.825</td>
</tr>
<tr>
<td>Mid thickness (mm)</td>
<td>1.48</td>
</tr>
<tr>
<td>width (mm)</td>
<td>15.1</td>
</tr>
<tr>
<td>Keystone angle (deg)</td>
<td>0.9</td>
</tr>
<tr>
<td>Transposition pitch</td>
<td>100</td>
</tr>
</tbody>
</table>

\textbullet\textsuperscript{NB}: Nb-Ti cables, Nb\textsubscript{3}Sn HL-LHC cables
### HL-LHC Nb-Ti strands’ specifications

<table>
<thead>
<tr>
<th></th>
<th>MQXF LEADS</th>
<th>D1 &amp; D2</th>
<th>MCBXFA/B</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Strand ID</strong></td>
<td>Type 01 LHC</td>
<td>Type 02 LHC</td>
<td>NEW Type 05 LHC</td>
</tr>
<tr>
<td><strong>Quantity of strand required (km)</strong></td>
<td>~100</td>
<td>~1500</td>
<td>~1500</td>
</tr>
<tr>
<td><strong>Wire diameter after coating</strong></td>
<td>1.065 ± 0.0025 mm</td>
<td>0.825 ± 0.0025 mm</td>
<td>0.4800 ± 0.0025 mm</td>
</tr>
<tr>
<td><strong>Filament diameter</strong></td>
<td>7.0±0.1 µm</td>
<td>6.0±0.1 µm</td>
<td>6.3 ± 0.1 µm</td>
</tr>
<tr>
<td><strong>Cu to Sc volume ratio</strong></td>
<td>1.65 ±0.05</td>
<td>1.95 ±0.05</td>
<td>1.75 ±0.05</td>
</tr>
<tr>
<td><strong>Twist pitch after annealing</strong></td>
<td>18.0 ± 1.5 mm</td>
<td>15.0 ± 1.5 mm</td>
<td>15.0 ± 2 mm</td>
</tr>
<tr>
<td><strong>Twist direction</strong></td>
<td>[Image]</td>
<td>Right handed screw</td>
<td></td>
</tr>
<tr>
<td><strong>Minimum Ic at 4.2 K</strong></td>
<td>532 A at 7 T</td>
<td>387 A at 6 T</td>
<td>194 A at 5 T</td>
</tr>
<tr>
<td><strong>Minimum Ic 1.9 K</strong></td>
<td>515 A at 10 T</td>
<td>390 A at 9 T</td>
<td>189 A at 8 T</td>
</tr>
</tbody>
</table>

Type 05 Nb-Ti conductor procured in 2017, being electroplated (control of inter-strand resistance), EDMS 2393180
HL-LHC D1 and D2 Rutherford cable

- Type 02 LHC cable (outer layer MB)
  - 36 strands, 0.825 mm diameter
  - 15.1 mm x 1.48 mm
- Quantity of cables for HL-LHC magnets
  - D1: **35 UL** of 600 m
  - D2: **22 UL** of 740 m
- Bare cables delivered in 2019 from LHC stock

### D1 and D2 Cable Parameters (LHC MB outer layer)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>D1</th>
<th>D2</th>
</tr>
</thead>
<tbody>
<tr>
<td>No. of strands</td>
<td>36</td>
<td>36</td>
</tr>
<tr>
<td>Strand diameter (mm)</td>
<td>0.825 +/-0.0025</td>
<td>0.825 +/-0.0025</td>
</tr>
<tr>
<td>Cable mid-thickness (mm)</td>
<td>1.48 +/-0.006</td>
<td>1.48 +/-0.006</td>
</tr>
<tr>
<td>Cable width (mm)</td>
<td>15.10 +/-0.02</td>
<td>15.10 +/-0.02</td>
</tr>
<tr>
<td>Key-stone angle (º)</td>
<td>0.9 +/-0.05</td>
<td>0.9 +/-0.05</td>
</tr>
<tr>
<td>Pitch (mm)</td>
<td>100 +/-5</td>
<td>100 +/-5</td>
</tr>
</tbody>
</table>


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**Diagram:**
- Iron yoke
- Iron stack tube
- Protection heater, insulation, brass shoe
- SS collar
- GFRP wedge
- HX hole
- Protection heater, insulation, brass shoe
- SS collar
- Al sleeve
- SS shell
- Coils
**HL-LHC MCBXF Rutherford cable**

- **New cable** based on Type 05 LHC strands
- Conductor procured in 2017, being electroplated
- 18 strands, 0.48 mm diameter
- **Quantity of cables for series**
  - **MCBXFB:**
    - Inner coils: 30 UL of 390 m
    - Outer coils: 30 UL of 510 m
  - **MCBXFA:**
    - Inner coils: 18 UL of 670 m
    - Outer coils: 18 UL of 910 m

<table>
<thead>
<tr>
<th>MCBXF Cable Parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>No. of strands</strong></td>
</tr>
<tr>
<td><strong>Strand diameter (mm)</strong></td>
</tr>
<tr>
<td><strong>Cable thickness (mm)</strong></td>
</tr>
<tr>
<td><strong>Cable width (mm)</strong></td>
</tr>
<tr>
<td><strong>Key-stone angle (º)</strong></td>
</tr>
<tr>
<td><strong>Pitch (mm)</strong></td>
</tr>
</tbody>
</table>

Virgin MCBXF Strand
0.48 mm OD
Nb-Ti Cable heat treatment

All HL-LHC Nb-Ti cables (except MQXF bus bar) are heat treated in air @200 °C for 8 hrs after production:

- Releasing residual strain on the conductor
- Increasing RRR of the strands (>150) that was reduced to ~80 during cabling (Cu plastic strain)
- Forming the oxide layer at surface of strand that is governing the inter-strand resistance

![Graph showing RRR of MCBXF EXTRACTED STRANDS]
HL-LHC MQXF bus bar Rutherford cable

- **New cable** based on Type 01 LHC strands, 34 strands, OD of 1.065 mm
- Cable with same width as MQXF Nb$_3$Sn cable
- Use for “magnet leads” and bus-bars.
- ~5 km required for HL-LHC
  - 0.5 km produced in 2017
  - 1.8 km produced in 2019
  - 2.4 km produced in Jan 2021
- Cable is not heat treated after cabling

**MQXF Leads Cable Parameters**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>No. of strands</td>
<td>34</td>
</tr>
<tr>
<td>Strand diameter (mm)</td>
<td>1.065 +/-0.0025</td>
</tr>
<tr>
<td>Cable mid-thickness (mm)</td>
<td>1.92 +/-0.01</td>
</tr>
<tr>
<td>Cable width (mm)</td>
<td>18.15 +/-0.05</td>
</tr>
<tr>
<td>Key-stone angle (º)</td>
<td>0.0 +/-0.1</td>
</tr>
<tr>
<td>Pitch (mm)</td>
<td>125 +/-3</td>
</tr>
</tbody>
</table>

E. Todesco, WP3 BUSBARS, EDMS 2029211
# HL-LHC Nb$_3$Sn strands’ specification

<table>
<thead>
<tr>
<th></th>
<th>11 T dipole RRP</th>
<th>MQXF Quad. RRP</th>
<th>MQXF Quad. PIT</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wire diameter $\Phi$</td>
<td>0.700 ± 0.003 mm</td>
<td>0.850 ± 0.003 mm</td>
<td>0.850 ± 0.005 mm</td>
</tr>
<tr>
<td>Nominal sub-element diameter</td>
<td>&lt; 50 $\mu$m</td>
<td>&lt; 55 $\mu$m</td>
<td>&lt; 55 $\mu$m</td>
</tr>
<tr>
<td>Copper to non-copper ratio</td>
<td>1.15 ± 0.1</td>
<td>1.2 ± 0.1</td>
<td>1.2 ± 0.1</td>
</tr>
<tr>
<td>Wire twist pitch</td>
<td>14 ± 2 mm</td>
<td>19 ± 3 mm</td>
<td>19 ± 3 mm</td>
</tr>
<tr>
<td>Wire twist direction</td>
<td>Right-handed screw</td>
<td>Right-handed screw</td>
<td>Right-handed screw</td>
</tr>
<tr>
<td>Minimum Ic @ 4.22K, 12T</td>
<td>438 A</td>
<td>632 A</td>
<td>590 A</td>
</tr>
<tr>
<td>Minimum Ic @ 4.22K, 15T</td>
<td>-</td>
<td>331 A</td>
<td>331 A</td>
</tr>
<tr>
<td>RRR (after full heat treatment)</td>
<td>&gt; 150</td>
<td>&gt; 150</td>
<td>&gt; 150</td>
</tr>
<tr>
<td>n-value @ 4.22K, 12T</td>
<td>&gt; 30</td>
<td>&gt; 30</td>
<td>&gt; 30</td>
</tr>
<tr>
<td>$J_C(4.22 \text{ K, } 12 \text{ T})$</td>
<td>2450 A/mm$^2$</td>
<td>2450 A/mm$^2$</td>
<td>2290 A/mm$^2$</td>
</tr>
<tr>
<td>$J_C(4.22 \text{ K, } 15 \text{ T})$</td>
<td>1280 A/mm$^2$</td>
<td>1280 A/mm$^2$</td>
<td>1280 A/mm$^2$</td>
</tr>
</tbody>
</table>

- Procured **PIT conductor will not be used** for the series
- **Series conductor RRP 108/127**
- **11 T**  RRP 108/127 ~1000 km
- **MQXF**  RRP 108/127 ~1500 km

Technical specification EDMS No.: 1419926, 1419924
HL-LHC Nb₃Sn cables’ specification

- MQXF Q2 and 11 T cables produced at CERN
- MQXF Q1 and Q3 cables produced in US
- Series conductor: RRP 108/127

<table>
<thead>
<tr>
<th></th>
<th>11 T</th>
<th>MQXF</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of strands</td>
<td>40</td>
<td>40</td>
</tr>
<tr>
<td>Pitch direction</td>
<td>Left</td>
<td>Left</td>
</tr>
<tr>
<td>Cable mid thickness (mm)</td>
<td>1.25 ±0.01</td>
<td>1.525±0.01</td>
</tr>
<tr>
<td>Cable width (mm)</td>
<td>14.70 ±0.05</td>
<td>18.15±0.05</td>
</tr>
<tr>
<td>Cable Keystone (deg)</td>
<td>0.79 ±0.1</td>
<td>0.40±0.1</td>
</tr>
<tr>
<td>Continuous Cable length without cross over or inclusions (m)</td>
<td>&gt;655</td>
<td>&gt;760</td>
</tr>
<tr>
<td>Pitch (mm)</td>
<td>100 ±3</td>
<td>109±3</td>
</tr>
<tr>
<td>Core Material</td>
<td>EN 1.4404</td>
<td>EN 1.4404</td>
</tr>
<tr>
<td>Core width (mm)</td>
<td>12 ±0.1</td>
<td>12±0.1</td>
</tr>
<tr>
<td>Core thickness (µm)</td>
<td>25 ±1.5</td>
<td>25±1.5</td>
</tr>
<tr>
<td>Facets length at thin edge (mm)</td>
<td>2.4±0.5</td>
<td>2.4±0.5</td>
</tr>
<tr>
<td>Facets length thick edge (mm)</td>
<td>1.9 ±0.5</td>
<td>2.1±0.5</td>
</tr>
<tr>
<td>Sharpness at thin edges (mm)</td>
<td>&gt;0.1</td>
<td>&gt;0.1 mm</td>
</tr>
<tr>
<td>Cabling $I_c$ degradation (measured on strands @ 4.3 K and 12 T)</td>
<td>&lt;5%</td>
<td>&lt;5%</td>
</tr>
<tr>
<td>RRR extracted strands</td>
<td>&gt;100</td>
<td>&gt;100</td>
</tr>
</tbody>
</table>
HL-LHC Nb₃Sn cables
strand $I_c$ degradation vs. cable compaction

- $I_c$ degradation vs cable compaction investigated at the beginning of the project
  - PIT Cable $I_c$ degradation less than 5%, if thin edge compaction less than 16%
  - RRP cables are not sensitive to thin edge compaction (in the range 14-18%)
- Reduction of thin edge compaction is beneficial to the RRR of RRP and PIT cables
- Cable $I_c$ degradation also depends on width compaction and pitch angle (shear stress)
- Cable MQXF geometry was modified 2016 (reduction of keystone angle) in order to reduce compaction at thin edge (cable specs. in next slides)
Fabrication of HL-LHC cables
- Cable production plan
- CERN Rutherford cabling machine
- Cable production QC
Cable production plan

- **Cable production plan** established in accordance with strand delivery and requirements for coils winding EDMS 2002194.
- **Cabling of multiple unit lengths** during the same cabling run:
  - Long piece lengths of conductors (e.g. 2 UL for 11 T up to 10 for Nb-Ti)
  - Cold welds (Nb-Ti) or mechanical junction (Nb$_3$Sn) removed after cabling
- First cable series production performed at CERN, completed in 2022
- Status of series production:
  - 11T completed in July 2020 (35 UL)
  - MQXF bus bars, D1 and D2 all cables delivered
  - MQXF 29 UL over 50 produced
  - MCBXF 37 UL over 96 produced

![Cable production vs time](image)

(markers: production, full line: cable due dates, dashed line: strand stock)
CERN Rutherford cabling machine

- Machine installed since 2006 at CERN
- Used previously in industry for LHC cabling
- All the CERN HL-LHC production performed at CERN
- 40 spools planetary cabling machine:
  - Active regulation of strand mechanical tension (~20-70 N)
  - Used for HL-LHC production but also for R&D and other projects.
- Throughput in operation ~1.5 m/min (Nb$_3$Sn), and up to 5 m/min for LHC cables
- Final shape given at the Turkshead with appropriate rollers and mandrel
CERN Rutherford cabling machine
Upgrade of the cabling machine in 2016

- Before start of HL-LHC production, major upgrade of the machine in building 103 was performed
- Replacement of all spool motors and their drivers (controllers)
- New machine supervision
- Machine reliability and regulation of strand tension were improved
- New features implemented for detail monitoring and recording of cabling parameters
Rutherford cable production : QC tests

- All QC tests listed in production flowchart EDMS 1863797

- Cable Geometry
  - Dimensions:
    - Ten-stack (point of UL, thickness)
    - CMM all along production: thickness, keystone angle and width
    - Length
  - Cross section (point and tail of UL)
  - Sharpness of edges (point and tail of UL)
  - Cross over (detection system run during production)
  - Facets (1 pitch long samples: point and tail of UL) and on-line with production
  - Integrity and shape of SS core (point and tail of UL) – visual inspection
  - Scratch on strands facing the core (point and tail of UL) – visual inspection
  - Pitch measurements (point of UL)

- Strand $I_c$ measurements (@ 4.3 K and 12 T)
  - Extracted strand
  - Virgin strands adjacent to extracted
    - 1 pair per billet in the cable (4 to 5 per UL)

- RRR measurements
  - 1 pair per billet in the cable (4 to 5 per UL)
Control of cable geometry along a unit length is crucial. Cable dimensions are monitored on line during production:

- **Cable dimensions**: thickness, width and Keystone measured and monitored online with the Cable Measuring Machine (CMM) *(see next slides)*

- **Strand Tension Monitoring System**: monitoring and recording of mechanical tension applied on each individual strand. *New system as from 2016* *(see next slides)*

- **Cable Facets Inspection System (CFIS)**: detect crossovers, abnormal flattening of wires or deviation from its nominal shape and inclusions. *Same system as for LHC*

- **Cable Edges Inspection System (CEIS)**: measure facets dimension, *New system*, implemented on production line in 2016. *(see next slides)*
Measurement of cable’s dimensions

- Cable thickness, width and keystone angle measured online with the CMM: stringent control on cable dimensions
- Same system used as for LHC
- A 10 stack measurement is performed at the beginning of each cabling run, to determine the absolute value of the cable mid-thickness
Mechanical tension on single strands

- Good strand regulation is crucial to produce good quality cables.

- Loose or tight strand for less than a second may induce strands crossover, resulting in major non conformity, cable could not be use in coil.

- A new system recording at 50 Hz the mechanical tension applied on each single strands in operation since 2016.

- Used for the commissioning of the machine and for cable production (log of production).

![Graph showing mechanical tension over time.](image)
Inspection system of cable’s facets

- Inspect in real time the cable on its wide faces
- Detect cable defects and recognise the gravity of the defect (minor or major defect)
- Warn the operator when anomalies occur, and display the defects
- Record all incidents
- Edit a status report at the end of inspection
Inspection system of cable’s edges

- Dimensions of each facets (at thin and thick edges) over the full cable length are measured since mid 2016

- Measurement performed by Keyence CV-X vision system equipped with cameras

- Threshold of acceptable facet dimensions

- Save photograph of facets with non-conformity for off line analysis
Fabrication of HL-LHC cables
- Overview of produced cables
**Nb-Ti cables**

- **All D1 and D2 cables approved at the time of LHC 2004-2006**
  - For all cables, homogeneous width over cable length, no drifting, tiny fluctuations within spec, cable $I_c$ and all other parameters in spec

- **All produced MCBXF cables approved all parameters within spec**
  - Homogeneous cable dimensions over cable length with no drifting
  - Tiny fluctuations from cable to cable,
  - Extracted strand $I_c$ and RRR OK

- **All MQXF bus bar cables approved all parameters within spec**

**Nb-Ti cable production is under control**
Nb$_3$Sn cables thickness (@ 50 MPa)

- All cables to date are in spec, stable STDEV over production (~2 µm)
- For all cables, small drift (< 1-5 µm) at the beginning of the production
- The cable thickness is under control
Width of Nb$_3$Sn cables

- All cables to date are in spec, STDEV of 2-3 μm over production
- For all cables, homogeneous width over cable length, no drifting, tiny fluctuations within spec
- The cable width is under control
Keystone angle of Nb₃Sn cables

- All cables to date are in spec, STDEV of 0.01 deg for full production
- For all cables, homogeneous keystone angle over cable length, no drifting, tiny fluctuations within spec
- The cable keystone is under control
**Nb\textsubscript{3}Sn cables sharpness of edges and facets**

- **Facet length @ thin and thick edge:**
  - All cables to date are in spec
  - For all cables, homogeneous facet length over production run
  - No drifting of facet length with production
- **Cable sharpness:**
  - All cables to date are in spec
  - For all cables, homogeneous sharpness between point and tail of UL
  - Both edges behave the same
  - No drifting of sharpness with production
- **The cable sharpness and facets are under control**

![Facet length at thin edge](chart)

![Facet length at thick edge](chart)
**Nb₃Sn cables Iᶜ of extracted strands**

- **All RRP cables are in spec**
  - Average Iᶜ degradation of 2.6% QXF and 2.7% for 11T
  - Limited spread: except for few cases

- The Iᶜ degradation of RRP cables (11 T Dipole and QXF) is **under control**

- All proto QXF PIT cables have average Iᶜ larger than 5% with n-value of about 30-35

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[Graphs and diagrams are shown, but descriptions are not transcribed into natural text.]
**Nb$_3$Sn cables: RRR of extracted strands**

- **Extracted strands’ RRR**
  - All cables to date are in spec
  - RRP: typically ~ 24% reduction of integrated RRR with cabling
  - PIT: no reduction of integrated RRR with cabling
  - Reduction of RRR is stable over production

- Regarding the extracted strands’ RRR, the production process is under control for both PIT and RRP cables
NON CONFORMITIES –11T Cables

- 43 units produced, **42 units fully conform to technical specification**
- One non conformity on the last cabling run
- Sudden strand breakage cable H15OC0333A EDMS 2573936
  - At 165 m from start, strand 20 broke suddenly with no precursor
  - Cause was identified to be strand local mechanical weakness
NON CONFORMITIES – MQXF RRP CABLES

- 37 Units produced, two major non-conformities
  - Strand cross over Cable H16OC0215A (expected to be first proto cable)
    - Cable too short for proto coil. It was regraded to 4 short models plus archived length (now used for other projects)
    - Preventive action: The procedure of strand spooling before cabling was reviewed (EDMS 1863706 Rev.0.2)

- Strand breakage Cable H16OC0370A  EDMS 2573936
  - At 115 m from start, excessive tension on strands results in breakage
    - Cable too short for series coil. Remaining non cabled length of strands were archived
    - 11 preventive actions implemented as reported in NCR EDMS 2573936
Insulation of HL-LHC Rutherford cables

- The cable insulation must feature:
  - Good electrical properties to withstand high turn-to-turn voltage during a quench.
  - Good mechanical properties to withstand high pressure conditions
  - Porosity to allow penetration of helium (or epoxy)
  - Radiation hardness
- For D1 and D2 magnets it is a series of overlapped layers of polyimide tapes
- For 11T, MQXF and MCBXF magnets there is a fiber glass braided around the cable (with inclusion of 80-µm-thick C-shaped Mica for 11T cable). The coil are then impregnated with low viscosity epoxy.
Conclusions

- Rutherford cables have ~50 years history
- Core technology for all high energy superconducting colliders, including LHC
- Five types of cables in HL-LHC magnets:
  - Three Nb-Ti cables (D1 and D2, MCBXF, and MQXF bus bar)
  - Two Nb$_3$Sn cables (MQXF and 11 T)
- The cables produced are systematically controlled according to QA plan
- All Nb-Ti and Nb$_3$Sn cables produced (except few cases) are conform to technical specification
- The Nb-Ti and Nb$_3$Sn Rutherford cable production at CERN is under control
- Production of D1, D2, MQXF bus bar and 11 T completed
- Production of MQXF (58%) and MCBXF (39%) on going planned to be completed by Q4 and Q2 2022
- Not to forget: “A Rutherford cable cannot perform better than the conductor it is made of”
THANKS FOR YOUR ATTENTION
Rutherford cables
Cross section of LHC strands with NbTi filaments

<table>
<thead>
<tr>
<th>Type 01</th>
<th>Type 02</th>
<th>Type 04/05</th>
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<tbody>
<tr>
<td><img src="image" alt="Type 01" /></td>
<td><img src="image" alt="Type 02" /></td>
<td><img src="image" alt="Type 04/05" /></td>
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 specifications:
All PIT proto cables have a NCR related to average Ic degradation > 5%.

- H16EC0235A: EDMS 1976468, Ic degradation of 8.0%
- H16EC0236A: EDMS 1976604, Ic degradation of 7.3%
- H16EC0248A EDMS 2038726, Ic degradation of 8.2%
- H16EC0252A EDMS 2038737, Ic degradation of 9.3%
- H16EC0253A EDMS 2068560, Ic degradation of 13.6%

All above listed cables were accepted by WPE as concession.