Challenges in Mechanical and Electrical Design of EuCARD2 HTS Insert Magnet's.

TALK OVERVIEW

- EuCARD2 HTS Project
- Material ReBCO
- Cables
- Magnet designs and optimization
- Calculating current distribution the multi-physics program
- Quench detection in ReBCO tape cables
- Magnet development
INTRODUCTION TO THE EuCARD2 WP 10 PROJECT

- 5 Tesla stand alone, (18 Tesla to 20+ Tesla in 13 Tesla background or other)
- 40 mm aperture
- 10 kA class cable
- Accelerator Field quality
- @ 4.5K

- WP 10 Magnets
  - 10.1 Communication
  - 10.2 Cable 10kA 20T
  - 10.3 Magnet
  - 10.4 Test

http://eucard2.web.cern.ch/
ReBCO Coated Conductor Tape
LONG LENGTHS

- 500-2000 m available
## Cable Options REBCO

<table>
<thead>
<tr>
<th></th>
<th>Stacks</th>
<th>Twisted Stacks (TST)</th>
<th>Helically Twisted Stacks (HTST)</th>
<th>Conductor on Round Core (CORC)</th>
<th>Roebel</th>
</tr>
</thead>
<tbody>
<tr>
<td>$J_E$ (A/mm²)</td>
<td>600</td>
<td>273 (@16 T)</td>
<td>100 (@12 T)</td>
<td>250 (@17 T)</td>
<td>400 (@10T)</td>
</tr>
<tr>
<td>$I_{OP}$ (kA)</td>
<td>3...5</td>
<td>4 (@19 T)</td>
<td>10...20</td>
<td>7 (@17 T)</td>
<td>10 (@10T)</td>
</tr>
<tr>
<td>$\varepsilon$ (%)</td>
<td>as for tape</td>
<td>unknown</td>
<td>unknown</td>
<td>+0.6...0.7</td>
<td>unknown</td>
</tr>
<tr>
<td>$\sigma$ (MPa)</td>
<td>as for tape</td>
<td>unknown</td>
<td>unknown</td>
<td>&gt; 300</td>
<td>&gt; 170(*)</td>
</tr>
</tbody>
</table>
PUNCH-AND-COAT

- Standard Roebel production sequence
  - Produce Cu-coated tape
  - Punch meanders
  - Assemble cable

- Modified Roebel production sequence
  - Produce Ag-capped tape
  - Punch meanders (less than 5% $I_C$ degradation)
  - Cu-coat (dog-boning)
  - Assemble cable
# Comparing the Designs

**Table VII**

Overview comparing the aligned block layout to other available options.

<table>
<thead>
<tr>
<th>Parameter Name</th>
<th>1 - Aligned block</th>
<th>2 - Normal block</th>
<th>3 - Cosine Theta</th>
<th>4 - Cosine Theta</th>
<th>5 - Canted (CCT)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Optimization</td>
<td>medium field quality</td>
<td>medium field quality</td>
<td>CEA single layer</td>
<td>CEA dual layer</td>
<td>$\alpha = 20^\circ$, $f_s = 0.7$</td>
</tr>
<tr>
<td>Standalone Coil Layout</td>
<td>yoke</td>
<td>yoke</td>
<td>yoke</td>
<td>yoke</td>
<td>yoke</td>
</tr>
<tr>
<td>Aperture Diameter</td>
<td>40 mm (2 mm)</td>
<td>40 mm (2 mm)</td>
<td>40 mm (2 mm)</td>
<td>40 mm (2 mm)</td>
<td>40 mm (2 mm)</td>
</tr>
<tr>
<td>Cable Width / Thickness</td>
<td>12 mm / 0.8 mm</td>
<td>12 mm / 0.8 mm</td>
<td>12 mm / 1.2 mm</td>
<td>10 mm / 1.2 mm</td>
<td>4 mm / 0.8 mm</td>
</tr>
<tr>
<td>Nonlinear Poles</td>
<td>yes</td>
<td>yes</td>
<td>no</td>
<td>no</td>
<td>no</td>
</tr>
<tr>
<td>Required Bend Radius</td>
<td>16 mm</td>
<td>16 mm</td>
<td>8 mm</td>
<td>8 mm</td>
<td>const. perimeter req.</td>
</tr>
<tr>
<td>Number of Turns</td>
<td>12/6 (18)</td>
<td>12/7 (19)</td>
<td>5/4/3/2 (14)</td>
<td>4/5/3 - 6/10/4/32</td>
<td>n.a.</td>
</tr>
<tr>
<td>Block Area</td>
<td>885 mm$^2$</td>
<td>908 mm$^2$</td>
<td>965 mm$^2$</td>
<td>1827 mm$^2$</td>
<td>1557 mm$^2$ (real)</td>
</tr>
</tbody>
</table>

**General Geometric**

- Percentage on Loadline: 70%
- Current Density (Block): 649 A/mm$^2$
- Critical Current Density: 1216 A/mm$^2$
- Dipole $B_1$: 5.0 T
- Harmonic $b_3 / b_5 / b_7$: 16 / 1 / 0 units
- Maximum Pressure: 17.3 MPa

**Standalone in Yoke**

- Percentage on Loadline: 70%
- Current Density (Block): 635 A/mm$^2$
- Critical Current Density: 1164 A/mm$^2$
- Dipole $B_1$: 5.0 T
- Harmonic $b_3 / b_5 / b_7$: 0 / 0 / 0 units
- Maximum Pressure: 20 MPa

**In 13 T Background Field**

- Percentage on Loadline: 70%
- Current Density (Block): 530 A/mm$^2$
- Critical Current Density: 1068 A/mm$^2$
- Dipole $B_1$: 16.2 T
- Harmonic $b_3 / b_5 / b_7$: 4 / 0 / 0 units
- Maximum Pressure: 87 MPa

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*Diagram showing 13T background field with pole and yoke details.*
Angular dependence changes the picture may help with field quality?

Assumed homogeneous current distribution
Two main unknowns for ReBCO coated conductor:

- **Magnetization** – wide tapes act as mono-filaments allowing for large magnetization currents and uncertainty in the position of the current. What is the effect on field quality?
- **Quench** – High Minimal Quench Energies (MQE) but slow normal zone propagation velocity. Challenge for quench protection.
matrix differential algebraic equation (DAE)
A transient evolution of the currents, voltages and temperatures is found by solving the following system of equations. The first row is Kirchhoff's current law, the second is Kirchhoff's voltage law and the third is the discretized heat equation.

\[
\begin{bmatrix}
G & M_{kvl} & 0 \\
M_{kv} & R & 0 \\
I_G & V_R & K - K_c
\end{bmatrix}
\begin{bmatrix}
V \\
I \\
T
\end{bmatrix}
+ 
\begin{bmatrix}
0 & 0 & 0 \\
0 & L + M_{S2T} & -C_p \\
0 & 0 & 0
\end{bmatrix}
\begin{bmatrix}
\frac{\partial V}{\partial t} \\
\frac{\partial I}{\partial t} \\
\frac{\partial T}{\partial t}
\end{bmatrix}
+ 
\begin{bmatrix}
I_s \\
V_s \\
P_s
\end{bmatrix}
+ 
\begin{bmatrix}
V_{nl}(I, T, B, \alpha) + V_{fm}(\frac{\partial I}{\partial t}) + V_{bg}(\frac{\partial B}{\partial t}) \\
P_{nl}(I, T, B, \alpha) + M_{kc}T_{bath}
\end{bmatrix}
= 0,
\]

current sharing
The superconducting elements are modeled as a superconductor in parallel with the matrix:

\[
I_0 - \frac{E_0}{\rho(B, T)} \left[ \frac{I_{sc}}{I_c(B, T, \alpha)} \right]^N - I_{sc} = 0,
\]

self inductance

\[
L_{ribbon} = 0.002 \left[ \log \left( \frac{2 \ell}{w + t} \right) + 0.5 + 0.235 \left( \frac{w + t}{\ell} \right) \right],
\]

\[
L_{wire} = 2\ell \left[ \log \left( \frac{2\ell}{d} \left( 1 + \sqrt{1 + \left[ \frac{d}{2\ell} \right]^2} \right) \right) - \sqrt{1 + \left[ \frac{d}{2\ell} \right]^2} + \frac{\mu}{4} + \frac{d}{2\ell} \right],
\]

contact Elements
Voronoi cells are used to calculate the contact areas which determine electrical and thermal contact resistance.
CURRENT FLOW IN CABLE TYPES

Figure 4.7: Current flow in magnetized Roebel cable.

Figure 4.8: Current flow in magnetized CorC cable.

Figure 4.9: Current flow in magnetized Stacked cable.
QUENCH DETECTION SENSORS

- Voltage taps
- Pick-up coils
- Temperature sensors (CCS, Fibre)
- Acoustics
QUENCH ANALYSIS

1D model predicted 35 ms to 300 K

Temperature sensors

very different from LTS
COIL VOLTAGES

in drift and pre-quench the voltages are well below the detection threshold.

significant current changes occur.

Mr. voltage tap
PICKUP COILS

signals calculated directly from current elements

pick-up coil voltage [mV]

time [s]

signals calculated directly from current elements

pick-up coil voltage [mV]

time [s]
**MINIMUM QUENCH ENERGY IN HTS CABLE (MQE)**

- MQE for cables with 1, 2, 3, 4, ..... Tapes in cables.
- HTS MQE is 3 orders of magnitude higher than low temperature superconductor.
- What will induce a Quench.
CURRENT REDISTRIBUTION IN TAPES

- Can we detect the current distribution anywhere along the cable?
- Use High pass filter to get rid of slow redistribution
**COSINE THETA FIELD QUALITY**

Cosine theta geometry (design by CEA Saclay)

1 month of computing time
ALIGNED BLOCK FIELD QUALITY

1 month of computing time
HYSTERESIS/MAGNETIZATION LOSS

- Losses are two orders of magnitude more for Cosine Theta than for Aligned Block
CLIQ – COUPLING-LOSS INDUCED QUENCH SYSTEM & HTS

- Current change
- Magnetic field change
- Transitory losses (Heat)
- Temperature rise

QUENCH
Temperature profile in two adjacent HTS tapes

Study jointly performed by E. Ravaioli and J. Van Nugteren
IMPREGNATION

- Impregnation is obligatory
- Looked at different resins
  - CTD101G, CTD101K, etc.
- With glass sleeve insulation

UNIVERSITY OF TWENTE.
COPPER RINGS
30% reduction in cost
Hollow parts

Material 316L stainless steel

CERN laser welding

Laser welding section
max length 218 mm

Test weld
SOLDERING TOOLING

Soldering profile graph

Front view, A-A, B-B: 1:1

Top view: 1:1

Isometric view: 1:1
We like!
- The thin layer of solder [solder thermal contraction 6 mm/m].
- Fully soldered surface between the tapes.
- Very low 3 Mpa pressure during soldering
- Low temperature if possible.
LAP JOINT INTERNAL TAPE RESISTANCE

- Electrical resistance of REBCO lap joints characterized at 4.2 K versus field and at 77 K
- Three topologies of lap joint investigated: no substrates (Type 1), one substrate (Type 2) or two substrates (Type 3) interleaved in between the HTS layers.

- Lowest resistances measured for Type 0 at 4.2 K:
  - 11.6 nΩ·cm² for Bruker,
  - 36 nΩ·cm² for SuperPower and SuperOx tapes
  - 151 nΩ·cm² for AMSC tapes.
  - 825 nΩ·cm² for SUNAM (excessive value, could be smaller)
- Type 0 resistance almost unchanged (<20%) vs. field and temperature

- Type 1 joints: 7-16 times more resistive compare to Type 0 (except SuNAM*)
- Type 2 joints 10-25 times more resistive compare to Type 0 (except SuNAM*)

- On-going work:
  - RRR measurement of Cu stabilizer
  - Characterization of 12 mm wide splices

* measured excessive internal resistance on this batch

J. Fleiter and A. Ballarino, "In-Field Resistance of REBCO Electrical Joints at 4.2 K", CERN internal note 2015-10, EDMS Nr: 1562549.
IMPREGNATION TOOLING.
Left: soldered cable to seal resin
Right: silicon over seal. We see the tube that is protecting the Fibre
ADJUSTING THE NUMBER OF TURNS SO THAT THE CABLE FITS THE SPACE AVAILABLE IN THE COIL CAVITY

3 turns 0.2mm tape
15 strand cable  higher winding tension

5 turns , 0.1 mm tape
15 strand cable
MOULD RELEASE ON COIL FORMER
COLD TESTING IN GAS!

Connecting magnet to current leads?
Test temp 80 He Gas to 5 K!
Current lead heat exchanger

Feather zero
In Iron yoke

F2 in Freacs2
F-Zero

HTS link
SM18, INFN, AND FRESCA2 CRYOSTATS.

SM18 Super critical helium supplied at a wide range of temperature

Planned Testing 70K to 4K,

INFN test station

Fresca 2 test station due 2016
SUMMARY

- PhD student Jeroen Van Nugteren has developed a multi-physics program that can predict: current distribution, quench, and much more! (Thesis due this year with full details).
- We have a multi-strand 10 kA cable.
- We are about to test several very promising quench detection and protection systems.
- Accelerator Field quality looks to be achievable.
- Cable must be impregnated.
- Joint design is a challenge.
- We are taking advantage of the angular dependence.
- I haven’t presented any FEA but extensive studies have been performed.
THANK YOU
FOR YOUR ATTENTION
Evidence of current redistribution between the 15 tapes.
Magnetisation in cable displayed only one tape
But all tapes are powered.
Voltage tapes aside spot heater
FEATHER ZERO WINDING
We have selected a low melting point solder with tin – bismuth alloy. It comes in a liquid form, so a thin layer can be applied to the tape. The flux is incorporated in the liquid so a very thin, we
"MAGIC MAGNET" SEXTUPLE DYNAMIC PASSIVE CORRECTION

Diameter 100 mm
Wire 0.8 mm
Thickness of assembly 2mm
Turn Spacing 1 mm
With 10 units of sextipole to correct at 2.6 Tesla
18A are induced to shield out errors
Persistent joint,
QUENCH ANALYSIS

1D model predicted 35 ms to 300 K

Temperature sensors
#3 repeat of #2 to fix electrical short at cable exit

#1 StSt dummy ctd101K

#2 test instrumentation tests, electrical short

#4 stst dummy filled resin CTD101G test

#5 HTS, 1st real test coil
SQUARE WAVE SPOT HEATER AND POWER SUPPLY
LabVIEW PROGRAMMABLE CURRENT PROFILE.