TE-MSC Seminar

Design, manufacturing and test of the MQYYM magnet

Damien Simon for the MQYYM team
ACKNOLEDGEMENTS

**CEA core team:** Hélène Felice, Damien Simon, Simon Perraud, Romain Godon, Ricardo Correia-Machado

**CEA design team:** Jean-Michel Rifflet, Michel Segreti, Patrick Graffin, Gilles Minier, Hubert Neyrial, Edouard Pepinter, Sébastien Somson

**CEA test team:** Jean-Marc Gheller, Denis Bouziat, Frédéric Molinie, Philippe de Antoni, Vadim Stepanov, Quentin Guihard, Bertrand Hervieu, Arnaud Madur, Johan Relland, Nicolas Commaux, Pascal Godon

**CERN:** Juan Carlos Perez, Nicolas Bourcey, Michael Guinchard, Salvador Ferradas Troitino, Sohrab Emami Naini, Sylvain Mugnier, Pierre Antoine Contat, Hugues Dupont, Pietro Antonio Rizzo, Arnaud Foussat, Lucio Fiscarelli, Carlos Petrone, Matthias Bonora, Ezio Todesco.
### THE MQYY QUADRUPOLE OPTION IN HL-LHC

<table>
<thead>
<tr>
<th>Characteristics</th>
<th>MQY</th>
<th>MQYY</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aperture diameter</td>
<td>70 mm</td>
<td>90 mm</td>
</tr>
<tr>
<td>Inter beam distance</td>
<td>194 mm</td>
<td>194 mm</td>
</tr>
<tr>
<td>Magnetic length</td>
<td>3.4 m</td>
<td>3.67 m</td>
</tr>
<tr>
<td>Gradient</td>
<td>160 T/m</td>
<td>120 T/m</td>
</tr>
<tr>
<td>Current</td>
<td>3610 A</td>
<td>4590 A</td>
</tr>
<tr>
<td>Peak field at nominal current</td>
<td>6.1 T</td>
<td>6.4 T</td>
</tr>
<tr>
<td>Load line margin</td>
<td>23%</td>
<td>23%</td>
</tr>
<tr>
<td>Temperature</td>
<td>4.5 K</td>
<td>1.9 K</td>
</tr>
<tr>
<td>Mechanical structure</td>
<td>Self supported collars</td>
<td></td>
</tr>
</tbody>
</table>

Removed from baseline in 2016
Decision to continue the R&D on large aperture NbTi quadrupole as an option for HL-LHC
OVERVIEW OF MQYY ACTIVITY

- Single aperture short model of 1.320 m long
- Operating current: 4550 A (23% margin)
- NbTi cable with kapton insulation
- Yoke outer diameter 360 mm

2 full length prototypes

PHASE 1 Concept. Design
PHASE 2 Engineering design
PHASE 3 MQYYP Manufacturing

MSC Seminar - Damien Simon - 6th May 2021
TALK OVERVIEW

DESIGN

MANUFACTURING

COLD TEST

TOWARD QUACO
MAIN GOAL OF THE SEMINAR

- Report on the MQYYM project results
- Report on the lessons learned during all the steps of the project from the design decision to the manufacturing difficulties
MAGNETIC DESIGN

From 2011 to 2015
- Design study (2011-2013)
- Single layer coil
- LHC MB outer layer cable (15 mm wide)

Reasons
- Use available cable
- CEA considerable experience with this cable for the MQ

Characteristics MQYY one layer
- Aperture: 90 mm
- Nominal Gradient: 115 T/m
- Magnetic length at 1.9 K: 3.8 m
- 1st design Nominal Current: 15650 A
- Peak Field: 6.1 T
- Margin on the loadline: 20 %
- Differential inductance: 2 x 2.9 mH
- Cable type: MQ (MB outer layer)

September 2015:
- Two layer coil
- LHC MQM cable (8.8 mm wide)

Reasons
- Saving on power converters and links
- Reduce operational current

Characteristics MQYY two layers
- Aperture: 90 mm
- Nominal Gradient: 120 T/m
- Magnetic length at 1.9 K: 3.7 m
- MQYY Nominal Current: 4590 A
- Peak field: 6.4 T
- Margin on the loadline: 23 %
- Differential inductance: 2 x 37.7 mH
- Cable type: MQM

September 2015:
- Single aperture short model to be manufactured and test by CEA

Reasons
- Prove the feasibility
- Train a new team

Characteristics MQYYM
- Aperture: 90 mm
- Nominal Gradient: 120 T/m
- Magnetic length at 1.9 K: 1.2 m
- MQYYM Nominal Current: 4550 A
- Peak field: 6.4 T
- Margin on the loadline: 23 %
- Differential inductance: 12.4 mH
- Cable type: MQM

### MQM CABLE

<table>
<thead>
<tr>
<th>Conductor Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bare cable width</td>
<td>8.8 mm</td>
</tr>
<tr>
<td>Bare cable thin/thick edge</td>
<td>0.77/0.91 mm</td>
</tr>
<tr>
<td>Insulation thickness at 50 MPa</td>
<td>0.080 mm</td>
</tr>
<tr>
<td>Strand diameter</td>
<td>0.48 mm</td>
</tr>
<tr>
<td>Number of strands</td>
<td>36</td>
</tr>
<tr>
<td>Cu/Superconductor ratio</td>
<td>1.75 ± 0.05</td>
</tr>
<tr>
<td>RRR on extracted strand meas/spec</td>
<td>250/80</td>
</tr>
<tr>
<td>Measured strand Ic at 1.9 K and 8 T</td>
<td>189 A</td>
</tr>
</tbody>
</table>

#### Polyimide film

<table>
<thead>
<tr>
<th>Layer</th>
<th>Thickness</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>4</td>
<td>0.055x8</td>
<td>with adhesive on the outside (220 LCI)</td>
</tr>
<tr>
<td>3</td>
<td>0.025x11</td>
<td>(100 HN)</td>
</tr>
<tr>
<td>2</td>
<td>0.025x11</td>
<td>(100 HN)</td>
</tr>
<tr>
<td>1</td>
<td>Nb3Sn in Cu-matrix</td>
<td></td>
</tr>
</tbody>
</table>
- All the harmonics have been optimized to be below the units including during the imbalance phase
- The coil ends have been optimized to minimize the integrated $b_6$ and $b_{10}$ along the length of the magnet

<table>
<thead>
<tr>
<th>Computed Multipole Components in units</th>
<th>I (kA)</th>
<th>$b_1$</th>
<th>$b_3$</th>
<th>$b_4$</th>
<th>$b_5$</th>
<th>$b_6$</th>
<th>$b_{10}$</th>
<th>$b_{14}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>MQYY 0% imbalance</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Left</td>
<td>4.59</td>
<td>-0.44</td>
<td>-0.17</td>
<td>0.09</td>
<td>0.07</td>
<td>0.00</td>
<td>-0.01</td>
<td>1.32</td>
</tr>
<tr>
<td>Right</td>
<td>4.59</td>
<td>0.44</td>
<td>0.17</td>
<td>0.09</td>
<td>-0.07</td>
<td>0.00</td>
<td>-0.01</td>
<td>1.32</td>
</tr>
<tr>
<td>MQYY 50% imbalance</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Left</td>
<td>4.59</td>
<td>-0.84</td>
<td>-0.56</td>
<td>0.08</td>
<td>-0.02</td>
<td>-0.02</td>
<td>0.00</td>
<td>1.32</td>
</tr>
<tr>
<td>Right</td>
<td>2.29</td>
<td>-0.78</td>
<td>0.34</td>
<td>0.38</td>
<td>-0.09</td>
<td>-0.70</td>
<td>0.01</td>
<td>1.32</td>
</tr>
<tr>
<td>MQYYM single aperture</td>
<td>4.55</td>
<td>0.00</td>
<td>0.00</td>
<td>-0.01</td>
<td>0.00</td>
<td>-0.01</td>
<td>-0.01</td>
<td>1.32</td>
</tr>
</tbody>
</table>

B (T)
## PROTECTION

### Inputs protection

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$V_{\text{threshold}}$</td>
<td>0.1 V</td>
</tr>
<tr>
<td>$T_{\text{detection}}$</td>
<td>10 ms</td>
</tr>
<tr>
<td>$T_{\text{validation}}$</td>
<td>10 ms</td>
</tr>
<tr>
<td>$T_{\text{PHvalidation}}$</td>
<td>10 ms</td>
</tr>
<tr>
<td>QH delay</td>
<td>~ 20 ms</td>
</tr>
<tr>
<td>Dump MQYYM</td>
<td>0.1 $\Omega$</td>
</tr>
</tbody>
</table>

---

### MQYY

- No dump resistor
- Protection heater
- Hotspot estimated with Roxie at 165 K and voltage to ground at 200 V

### MQYYM

- Dump resistor at 0.1 $\Omega$
- Protection heater
- Hotspot estimated with Roxie at 75 K and voltage to ground at 455 V

---

[Diagram showing temperature maximum at 165 K and 75 K]
Design Material Properties

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coils rigidity at warm [4]</td>
<td>5.4 GPa</td>
</tr>
<tr>
<td>Coils rigidity at cold [5]</td>
<td>7.9 GPa</td>
</tr>
<tr>
<td>Coil thermal contraction [5]</td>
<td>5 mm/m</td>
</tr>
</tbody>
</table>

[5] M. Segreti et al, Internal value used for the MQ FEA simulation
**PRE-STRESS REQUIREMENTS**

- **Front collar**
- **Back collar**
- **Keyway**
- **Coil blocks**
- **Collaring key**
- **Ground insulation**
- **Protection sheet**

**CAST3M model**

**Azimuthal stress after collaring (MPa)**

**Design Material Properties**

<table>
<thead>
<tr>
<th>Material Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coils rigidity at warm [4]</td>
<td>5.4 GPa</td>
</tr>
<tr>
<td>Coils rigidity at cold [5]</td>
<td>7.9 GPa</td>
</tr>
<tr>
<td>Coil thermal contraction [5]</td>
<td>5 mm/m</td>
</tr>
</tbody>
</table>

[5] M. Segreti et al, Internal value used for the MQ FEA simulation

MSC Seminar - Damien Simon - 6th May 2021
**PRE-STRESS REQUIREMENTS**

![Cast3M model](image)

**Design Material Properties**

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coils rigidity at warm [4]</td>
<td>5.4 GPa</td>
</tr>
<tr>
<td>Coils rigidity at cold [5]</td>
<td>7.9 GPa</td>
</tr>
<tr>
<td>Coil thermal contraction [5]</td>
<td>5 mm/m</td>
</tr>
</tbody>
</table>

[5] M. Segreti et al, Internal value used for the MQ FEA simulation

**Stress Relaxation**

- Measurement performed at CERN ~17%

---

**MSC Seminar - Damien Simon - 6th May 2021**
PRE-STRESS REQUIREMENTS

Azimuthal stress after collaring:

60 MPa for a minimum compression of 10 MPa on the pole during energization at ultimate current

Lower than 150 MPa to not damage the insulation [6]

Design Material Properties

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coils rigidity at warm [4]</td>
<td>5.4 GPa</td>
</tr>
<tr>
<td>Coils rigidity at cold [5]</td>
<td>7.9 GPa</td>
</tr>
<tr>
<td>Coil thermal contraction [5]</td>
<td>5 mm/m</td>
</tr>
</tbody>
</table>

[5] M. Segreti et al, Internal value used for the MQ FEA simulation
10 COILS FABRICATED AT CEA

Layer jump positioning

Winding of the inner layer

Polymérisation of the inner layer

Vtap soldering

Winding of the outer layer

Polymérisation of the outer layer

Electrical test and shipping
COIL 1
Slit in some of the spacers to give them flexibility, filled with G10 pieces before polymerization

COIL 5
Damage of the interlayer insulation after fabrication during the cutting of the insulation

COIL 7
Issue on insulation encountered after the IL curing sheet removal:

- Imprint of the block on the coil end part and on the wedge
- Missing Kapton matching the weld failure
- Weld failure & pinched Kapton
COIL 1
Slit in some of the spacers to give them flexibility, filled with G10 pieces before polymerization

COIL 5
Damage of the interlayer insulation after fabrication during the cutting of the insulation

COIL 7
Issue on insulation encountered after the IL curing sheet removal:

- Weld failure & pinched Kapton
- Imprint of the block on the coil end part and on the wedge
Check the coils size to adjust the coils preload after collaring (at CERN)

General Procedure [7][8]:

- Define the coil nominal size (using the stainless steel dummy coils)
- Press the coil on the E modulus press until the nominal coil size


E-modulus press in CERN 927
- Both model and Fuji observation show a longer contact zone than expected (due to softness of the coil)
- Thick shims to explore collaring stress for the practice coils
- Real coils tested at lower stress to check consistency and to avoid insulation damage
Coil MECHANICAL MEASUREMENTS

Coil 1 (reference coil)

Corrected curves

Initial collar cavity size (ie dummy coil size)
Preload would be:
\[ \approx 150 \text{ MPa outer} \]
\[ \approx 120 \text{ MPa inner} \]

Nominal collar cavity size
(ie dummy coil size)

The coils are bigger of about 0.2 mm per legs at 60 Mpa (initial target for the prestress)
Fabrication error:
Azimuthal:
- Keys: +20 µm
- Collars nose: -10 µm
- Collars slot for keys: +70 µm
- Protection sheets: -20 µm

Radial:
- Collaring Shoe: +20 µm
- QH: +40 µm

Total azimuthal:
Cavity smaller by +100 µm

Preload would be:
≈160 MPa outer
≈130 MPa inner

Unfavorable components tolerance build-up increase the stress in the coils
=> Need for a mitigation plan
De-Shimming plan proposal by acting on protection sheet to decrease the prestress range to 90 to 120 Mpa

Replace the 316 LN 1 mm thick azimuthal protective plate by 304 L 0.6 mm thick plate with 0.2 mm or 0.3 mm kapton shim

Target preload ≈120 MPa outer ≈90 MPa inner Requires -0.15 mm
Preload will be:
\[ \approx 120 \text{ MPa outer} \]
\[ \approx 90 \text{ MPa inner} \]
Requires -0.1 mm for smaller coils and -0.2 mm for bigger coils.

All the coils behave similarly.
The dispersion between the coils is 0.1 mm.

Priority placed on the prestress rather than on the field quality.
COIL MECHANICAL MEASUREMENTS

Initial decision to not shim the ends

Initial position (@3MPa) and final position (@110MPa) along the coil 1
COIL MEASUREMENTS LESSONS LEARNED

- The calibration of the E-modulus press is a long and painstaking process which need very precise parts
- The coil mechanical measurement has been done too late in the project
- Ideally to be done after the polymerization of the practice coil to adjust the polymerization cavity
- For a first model accept to degrade field quality to insure a proper prestress
**Voltage taps**

- Two different type of voltage taps (wire for the inner layer and copper flag for the outer layer)
- First time that a magnet non-impregnated used PH and Vtaps with trace

**Strain gauges**

- Cancelation of the radial stress on the collar nose ie to have a ratio of -0.3 between the radial and azimuthal strain by adding wire cut
Voltage taps

- Two different type of voltage taps (wire for the inner layer and copper flag for the outer layer)
- **First time that a magnet non-impregnated used PH and Vtaps with trace**

Strain gauges

- Cancelation of the radial stress on the collar nose ie to have a ratio of -0.3 between the radial and azimuthal strain by adding wire cut
- Cancelation of the collar nose bending by gluing strain gauges on the top and on the bottom of the collar nose
- Compensation of the thermal contraction by using bi-axial strain gauges
**Voltage taps**

- Two different type of voltage taps (wire for the inner layer and copper flag for the outer layer)
- **First time that a magnet non-impregnated used PH and Vtaps with trace**

**Strain gauges**

- Cancelation of the radial stress on the collar nose ie to have a ratio of -0.3 between the radial and azimuthal strain by adding wire cut
- Cancelation of the collar nose bending by gluing strain gauges on the top and on the bottom of the collar nose
- Compensation of the thermal contraction by using bi-axial strain gauges
- Strain gages at two positions over the aperture length
ASSEMBLY

Coil instrumentation

Ground plane insulation forming

Electrical test

Coils assembly and half-collars stacking
Collaring press with 16 jacks (4 jacks A, 4 jacks B and 8 jacks C for the collaring keys)

- Step 1: «Massaging» of the aperture by activating jack A in order to position correctly the collars
- Step 2: Activation of the jack A to open the key slot
- Step 3: Activation of the jack B to avoid the ovalization of the collar
- Step 4: Activation of the jack C to insert the collaring keys and limit the stress overshoot during collaring
Collaring press with 16 jacks (4 jacks A, 4 jacks B and 8 jacks C for the collaring keys)

- Step 1: «Massaging» of the aperture by activating jack A in order to position correctly the collars
- Step 2: Activation of the jack A to open the key slot
- Step 3: Activation of the jack B to avoid the ovalization of the collar
- Step 4: Activation of the jack C to insert the collaring keys and limit the stress overshoot during collaring
- Collaring press with 16 jacks (4 jacks A, 4 jacks B and 8 jacks C for the collaring keys)
- Step 1: « Massaging » of the aperture by activating jack A in order to position correctly the collars
- Step 2: Activation of the jack A to open the key slot
- Step 3: Activation of the jack B to avoid the ovalization of the collar
- Step 4: Activation of the jack C to insert the collaring keys and limit the stress overshoot during collaring
- Collaring press with 16 jacks (4 jacks A, 4 jacks B and 8 jacks C for the collaring keys)
- Step 1: « Massaging » of the aperture by activating jack A in order to position correctly the collars
- Step 2: Activation of the jack A to open the key slot
- Step 3: Activation of the jack B to avoid the ovalization of the collar
- Step 4: Activation of the jack C to insert the collaring keys and limit the stress overshoot during collaring
VERTICAL COLLARING PROCESS

- Collaring press with 16 jacks (4 jacks A, 4 jacks B and 8 jacks C for the collaring keys)
- Step 1: «Massaging» of the aperture by activating jack A in order to position correctly the collars
- Step 2: Activation of the jack A to open the key slot
- Step 3: Activation of the jack B to avoid the ovalization of the collar
- Step 4: Activation of the jack C to insert the collaring keys and limit the stress overshoot during collaring
• Collaring press with 16 jacks (4 jacks A, 4 jacks B and 8 jacks C for the collaring keys)

• Step 1: « Massaging » of the aperture by activing jack A in order to position correctly the collars

• Step 2: Activation of the jack A to open the key slot

• Step 3: Activation of the jack B to avoid the ovalization of the collar

• Step 4: Activation of the jack C to insert the collaring keys and limit the stress overshoot during collaring
VERTICAL COLLARING PROCESS

- Collaring press with 16 jacks (4 jacks A, 4 jacks B and 8 jacks C for the collaring keys)
- Step 1: « Massaging » of the aperture by activating jack A in order to position correctly the collars
- Step 2: Activation of the jack A to open the key slot
- Step 3: Activation of the jack B to avoid the ovalization of the collar
- Step 4: Activation of the jack C to insert the collaring keys and limit the stress overshoot during collaring
VERTICAL COLLARING PROCESS

- Collaring press with 16 jacks (4 jacks A, 4 jacks B and 8 jacks C for the collaring keys)
- Step 1: « Massaging » of the aperture by activating jack A in order to position correctly the collars
- Step 2: Activation of the jack A to open the key slot
- Step 3: Activation of the jack B to avoid the ovalization of the collar
- Step 4: Activation of the jack C to insert the collaring keys and limit the stress overshoot during collaring
Collaring press with 16 jacks (4 jacks A, 4 jacks B and 8 jacks C for the collaring keys)

- Step 1: « Massaging » of the aperture by activating jack A in order to position correctly the collars
- Step 2: Activation of the jack A to open the key slot
- Step 3: Activation of the jack B to avoid the ovalization of the collar
- Step 4: Activation of the jack C to insert the collaring keys and limit the stress overshoot during collaring
VERTICAL COLLARING PROCESS

- Collaring press with 16 jacks (4 jacks A, 4 jacks B and 8 jacks C for the collaring keys)

- Step 1: « Massaging » of the aperture by activating jack A in order to position correctly the collars

- Step 2: Activation of the jack A to open the key slot

- Step 3: Activation of the jack B to avoid the ovalization of the collar

- Step 4: Activation of the jack C to insert the collaring keys and limit the stress overshoot during collaring

Vertical press in CERN 927
Collaring press with 16 jacks (4 jacks A, 4 jacks B and 8 jacks C for the collaring keys)

- Step 1: «Massaging» of the aperture by activating jack A in order to position correctly the collars
- Step 2: Activation of the jack A to open the key slot
- Step 3: Activation of the jack B to avoid the ovalization of the collar
- Step 4: Activation of the jack C to insert the collaring keys and limit the stress overshoot during collaring
FIRST COLLARING

- Massaging + Insertion of the keys at 70%
- Factor 2 between the strain read in the collars and the one expected due to the lack of collar nose

Stress in the collars measured by the strain gages
- Massaging + Insertion of the keys at 70%
- Factor 2 between the strain read in the collars and the one expected due to the lack of collar nose

![Stress in the coil diagram]

- Stress in the coil (2 time less than the stress measured in the collar)
FIRST COLLARING

- Misalignment of the collars over the coil ends
- Bigger forces used on the jacks over the coil ends to compensate misalignment => Coils end overloaded
- Electrical tests after the collaring at 70%: **Turn to turn short circuit detected** => decision to decollar
- Short disappears after decollaring of the LE
Localization of the short circuit reproduce with the E modulus press suspected to be between the pole turn and second turn

Crack starts observed in G10 coils ends after polymerisation and worst after collaring
SECOND COLLARING

- Replacement of the coil with a short by a spare coil => New shimming plan
- Creation of a slope in the « stair » part
- Removal of some ground plane insulation in the ends to homogenize the stress
- Special tools manufactured to align the collars in the heads
- Collaring perform with success with good level of stress

Preload between 72 Mpa and 91 Mpa a bit lower than targeted
MANDREL EXTRACTION

DESIGN

CENTRAL PART REMOVAL

BEGINNING OF THE TROUBLE

SOLUTION AND FINAL MANDREL REMOVAL
MANDREL EXTRACTION

DESIGN

CENTRAL PART REMOVAL

BEGINNING OF THE TROUBLE

SOLUTION AND FINAL MANDREL REMOVAL

MSC Seminar - Damien Simon - 6th May 2021
The bars for the alignment of the collar should be very rigid, as long as the magnet ad be kept during the collaring.

The shimming should be homogenous all over the magnet, avoid step and brutal change of preload: particular attention should be paid when shimming is at the pole.

Do not hesitate to make small mock-ups.
End flange welding

Yoking

Connection box

Activities carried out at CERN (927) by the CEA team with the support of the 927 team

The MQYYM magnet arrived at CEA in January 2020 after a warm magnetic measurements campaign on the 927 magnetic test bench

- Preparation of the cryogenic test
- COVID 19 lock down
- Preparation restart end of may 2020
The MQYYM magnet arrived at CEA in January 2020 after a warm magnetic measurements campaign on the 927 magnetic test bench

- Preparation of the cryogenic test
- COVID 19 lock down
- Preparation restart end of may 2020
MQYYM TEST AT CEA

- The MQYYM magnet arrived at CEA in January 2020 after a warm magnetic measurements campaign on the 927 magnetic test bench
- Preparation of the cryogenic test
- COVID 19 lock down
- Preparation restart end of May 2020
MQY YM TEST STATION

TEST STATION AT CEA…

… WITH A LOT OF CERN MATERIAL AND SUPPORT

- Magnetic measurement system coming from CERN
- Mechanical measurement system coming from CERN too

FIRST COOL DOWN

Busbar become resistive at 1295 A
Decision to warm up the magnet and postpone the 1.9K test

Simplification

(P atm at 4.2K and 23 mbar at 1.9K)

Strong support from CERN teams on remote

MSC Seminar - Damien Simon - 6th May 2021
SECOND COOL-DOWN

MQYYM second cool down

Cool-down timeline

MQYYM RRR mesurement

RRR>80
RRR ~ 230

MQYYM mechanical measurements vs simulation

Δσ_{cool-down} estimated vs measured ~ 25 MPa

MQYYM RRR mesurement

Tempertaure (K)

Stress evolution in coils during cooldown

Temperature (K)

MSC Seminar - Damien Simon - 6th May 2021
MQYYM training at 4.2 K

- Operating T°K
- $I_{\text{nominal}}$ (77% $I_{ss}$)
- $I_{\text{ultimate}}$ (83% $I_{ss}$)
- $I_{\text{short\_sample}}$

<table>
<thead>
<tr>
<th>Temperature</th>
<th>Nominal Current</th>
<th>Ultimate Current</th>
<th>Short Sample Current</th>
</tr>
</thead>
<tbody>
<tr>
<td>4.2 K</td>
<td>3585 A</td>
<td>3871 A</td>
<td>4656 A</td>
</tr>
<tr>
<td>1.9 K</td>
<td>4550 A</td>
<td>4914 A</td>
<td>5925 A</td>
</tr>
</tbody>
</table>

- Quench Pole 2
- Quench Pole 3
- $I_{\text{nominal}}$ 1.9 K
- $I_{\text{ultimate}}$ 4.2 K
- $I_{ss}$ 4.2 K
- Reached current without quench

Test at CEA
MQYYM training at 4.2 K

<table>
<thead>
<tr>
<th>Operating $T_0 \text{K}$</th>
<th>$I_{\text{nominal}}$ (77% $I_{ss}$)</th>
<th>$I_{\text{ultimate}}$ (83% $I_{ss}$)</th>
<th>$I_{\text{short}}$</th>
<th>$I_{\text{sample}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>4.2 K</td>
<td>3585 A</td>
<td>3871 A</td>
<td>4656 A</td>
<td></td>
</tr>
<tr>
<td>1.9 K</td>
<td>4550 A</td>
<td>4914 A</td>
<td>5925 A</td>
<td></td>
</tr>
</tbody>
</table>

4420 A is 95% of $I_{ss}$ at 4.2 K

Test at CEA

Quench Pole 2
Quench Pole 3
$I_{\text{nominal}}$ 1.9 K
$I_{\text{ultimate}}$ 4.2 K
$I_{ss}$ 4.2 K
Reached current without quench
We reached at 4.2K the value of the ultimate current at 1.9 K.
TRAINING AT 4,2 K

- Quench n°1: Pole 3 ie coil 6 localized on the inner layer, first turn at the level of the layer jump:

- Quench n°2: Pole 2 ie coil 8 localized on the inner layer, first turn few cm before the layer jump:
Hotspot estimated at 76 K for nominal current with a MIITs analysis apply to the decay current simulated by Roxie

MIITs analysis with measured current decay

- 70 K for 4245 A
- 76 K for 4420 A
WARM MAGNETIC MEASUREMENT

AT CERN 927
- Horizontal translation (scanning probe)
- Radius probe = 30 mm
- Tangential probe
- WMM performed before and after yoking

AT CEA
- Vertical measurements (5 segments)
- Radius probe = 23.5 mm
- Radial probe
- WMM performed before and after pit insertion

COMPARISON
- Good correlation between the WMM performed at CEA and at CERN with ROXIE simulation
COLD MAGNETIC MEASUREMENTS

- The comparison between the magnetic measurements and the ROXIE simulation is still ongoing
- Rather good agreement for the $b_n$

MSC Seminar - Damien Simon - 6th May 2021
Greater loss of preload than expected during cool-down

Position 1

Position 2

Average stress inner layer
Average stress outer layer
Greater loss of preload than expected during cool-down
Pre-stress loss slope during current rise in accordance with simulations
Annotation of the as built drawings that were problematic during assembly

Soon on EDMS
The two magnets will be at CERN for warm magnetic measurements in June.
- Fully new station with lambda plate under construction at CEA-Saclay
- Improved acquisition and protection system
- Test of the MQYYYM and QUACO magnet plan at 1.9 K in 2022
CONCLUSION

- Mechanical assembly validated however some improvements on polymerisation cavity size and initial stress level could be done
- The larger loss of prestress during cool-down still needs to be investigated
- The protection behaviour is conform to design
- Magnetic measurement in agreement with simulation accounting for shimming plan
- The manufacturing and test process have been consolidated at CEA
- 98% of Iss reached at 4,2 K after two quenches, 1.9K results expected in 2022
- The 10 coils were truly needed for the short model
  - 2 practice coils
  - 2 coils with non conformities
  - 1 coil with inter-turn short circuit during collaring
- Some small adjustments on the assembly tooling would be necessary to redo this magnet
- Designing and building a new NbTi quadrupole with a new team is not straightforward
- Success only possible thanks to the strong collaboration between CERN and CEA
THANK FOR YOUR ATTENTION
STACKS MEASUREMENTS AT CEA

- Technical data on MQM cable not fully recovered
- Rigidity measured ~8 Gpa after correction
- Tentative to define the polymerization cavity size
- The set-up used for the stacks measurement did not allow us to measure accurately the insulation size under load for different polymerization cavity size => lead to overestimate the curing cavity size

 Coil bigger than required

RIGIDITY CROSS CHECK AT CERN

- Rigidity set-up more reliable confirm CEA measurements on coils rigidity
- Measurement campaign during coil manufacturing

Compliance Influence on Impregnated and non Impregnated Cables Stiffness Measurements

- 40% stiffness underestimation (CEA Set-up ~80%)
- 7% stiffness underestimation (CEA Set-up ~15%)

Courtesy Michael Guinchard (CERN)
All the coils behave similarly.
The dispersion between the coils is 0.1 mm.

+/- 50μm
AXIAL PRELOAD

Final design

MSC Seminar - Damien Simon - 6th May 2021
- Vertical station with saturated Helium bath (Patm at 4.2K and 23 mbar at 1.9K)
- 4 K pot to reach the 1.9 K
- ADI AMI copper
- Busbar become resistive at 1295 A reached threshold at 1378 A => discharge triggered
- Power dissipated ~9W (not measurable on the 4K pot He bath)
- 5.6 mW => 4.5 m bus resistance (RRR=40) and 12 cm cable resistance
- Decision to warm up the magnet to diagnose and repair the busbar area
BUSBAR CHANGE AND NEW STRATEGY

- Simplification of the test station design by removing the 4K pot
- Same test plan without the 1,9 K training (the 1,9 K test will be done later on the STAARQ station)
- New busbar already used on an other project with CMS cable
- Instrumentation reinforce on each busbar (2 thermal sensors, 12 new Vtaps per busbar) + Improvement of the busbar cool-down
MAGNETIC MEASUREMENTS

Comparison of the b6 evolution in function of time

- b6 in units
  - ROXIE
  - MM

- Current (A)

Transfer function (T/kA at ref. radius)

- Current (kA)

- MM

MSC Seminar - Damien Simon - 6th May 2021
TRAINING AT 4.2 K

Quench sur U3
Coil 6

Les autres tensions sont inversées

Activation des HEATERS
Cde Alimentation

Ouverture du contacteur

Le courant

6 ms 10 ms 8 ms 24 ms
QUENCH PROPAGATION

Quench propagation n°1

<table>
<thead>
<tr>
<th>Time (ms)</th>
<th>Location</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>U56 U45</td>
</tr>
<tr>
<td>5</td>
<td>U23 U34</td>
</tr>
<tr>
<td>16</td>
<td>U67</td>
</tr>
</tbody>
</table>

Propagation velocity ~ 60 m/s

Quench propagation n°2

<table>
<thead>
<tr>
<th>Time (ms)</th>
<th>Location</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>U65</td>
</tr>
<tr>
<td>1</td>
<td>U45 U34</td>
</tr>
<tr>
<td>7</td>
<td>U32</td>
</tr>
<tr>
<td>8</td>
<td>U98</td>
</tr>
<tr>
<td>14</td>
<td>U76</td>
</tr>
</tbody>
</table>

Propagation velocity ~ 65 m/s

MSC Seminar - Damien Simon - 6th May 2021
QUENCH PROPAGATION

QUENCH N°1

QUENCH N°2
Bullets average strain at the different steps of the project

The heads are all the time preloaded
AXIAL PRELOAD

I (A) = f(t(s)) - Stair steps @ 4 K

Bullets strain gages - Raw datas
Bullets with compensation
Bullets with compensation
Bullets with compensation

MSC Seminar - Damien Simon - 6th May 2021