



Rad-hard warm magnets

P. Fessia, N. Mariani, A. Sanz Ull, D. Tommasini and the whole TE-MS-C-MNC section

Presented by P. Fessia

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MNC team: Paolo Fessia, N. Mariani, Pierre Alexandre Thonet, D. Tommasini

Power Converter: Hugues Thiesen

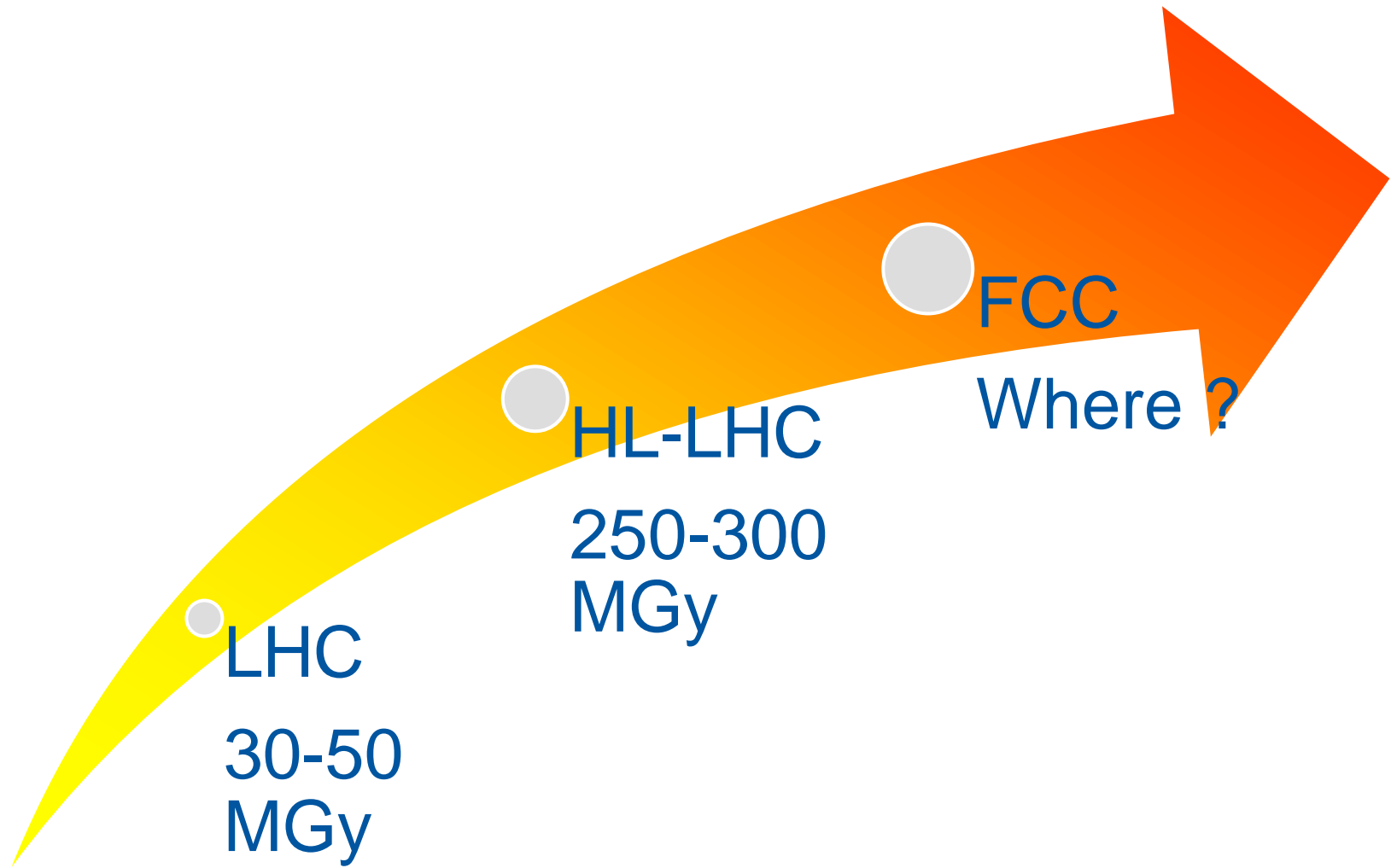
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MME design office: L. Favre, T. Sahner

VSC: E. Page, N. Zelko

Magnetic Measurement team: M. Buzio

LHC → HL-LHC → FCC



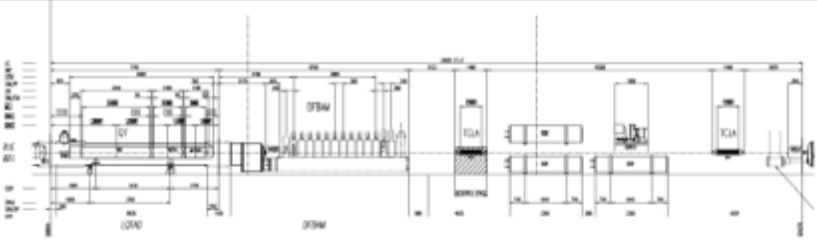
LHC or re-acting

MQW: Magnet Quadrupole Warm

MBW: Magnet Bending Warm

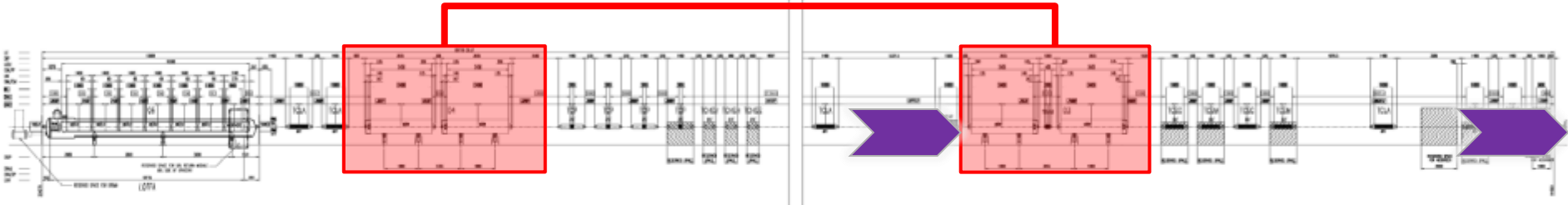
(1:250)

| | |
|--|-------|
| LENGTH OF CELL | LC |
| DISTANCE BETWEEN INTERCONNECT VIRTUAL PLANES | DP |
| LENGTH OF COIL WIRE | LQW |
| DISTANCE COIL WIRE/INTERCONNECT VIRTUAL PLANE | QW/P |
| LENGTH OF WIRE | W |
| DISTANCE WIRE/COIL WIRE | W/LQW |
| WIRE | W |
| DISTANCE BETWEEN MAGNETIC LENSING, OR BETWEEN MAGNETIC LENSING AND INTERCONNECT VIRTUAL PLANE (OPENING CONDITIONS) | QW |
| DISTANCE BETWEEN MAGNETIC LENSING/ OR INTERCONNECT VIRTUAL PLANE (OPENING CONDITIONS) | QW |
| DISTANCE BETWEEN SUPPORT POSTS | SP |
| DISTANCE BETWEEN VACUUM VESSEL JACKS | DAJ |
| DISTANCE BETWEEN VESSEL/INTERCONNECT VIRTUAL PLANE | DAJ/P |
| LENGTH OF VACUUM VESSEL | LV |



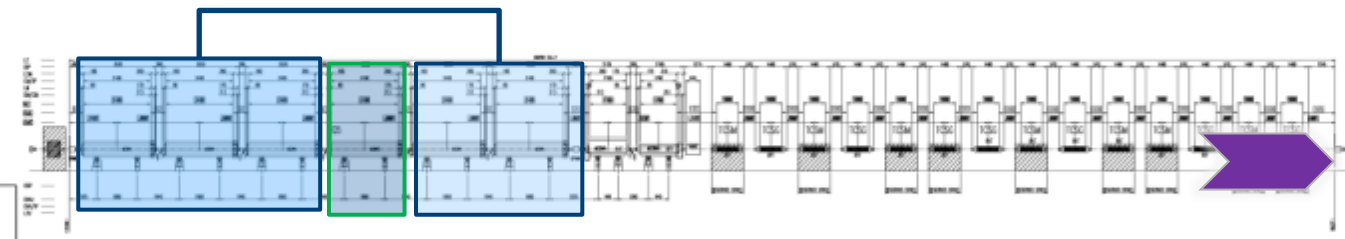
C7.L7

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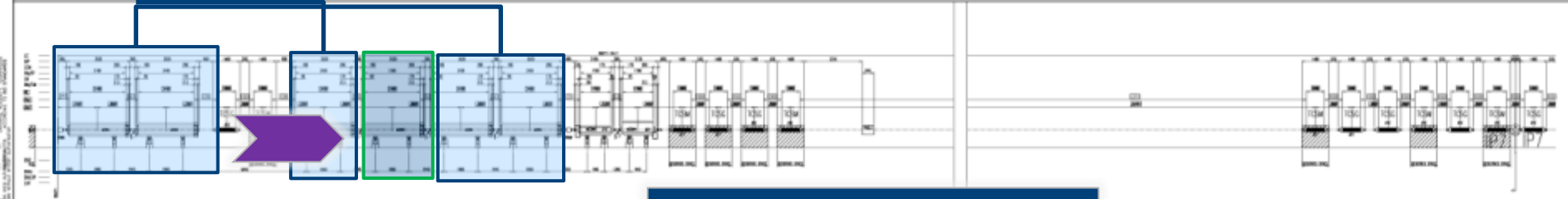
C6.L7

(1:75)



C5.L7

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C4.L7

(1:75)

Point 7

| | | | | |
|-----|-------------------------|------------|-----|-------------|
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DO: REAM J EXTENSION
 BY: REAM J EXTENSION
 ALL DIMENSIONS ARE IN INCH, EXCEPT THE MAGNETIC LENSING
 AND DISTANCES BETWEEN THEM WHICH ARE AT OPENING CONDITIONS
 * DIMENSIONS TO BE DEFINED

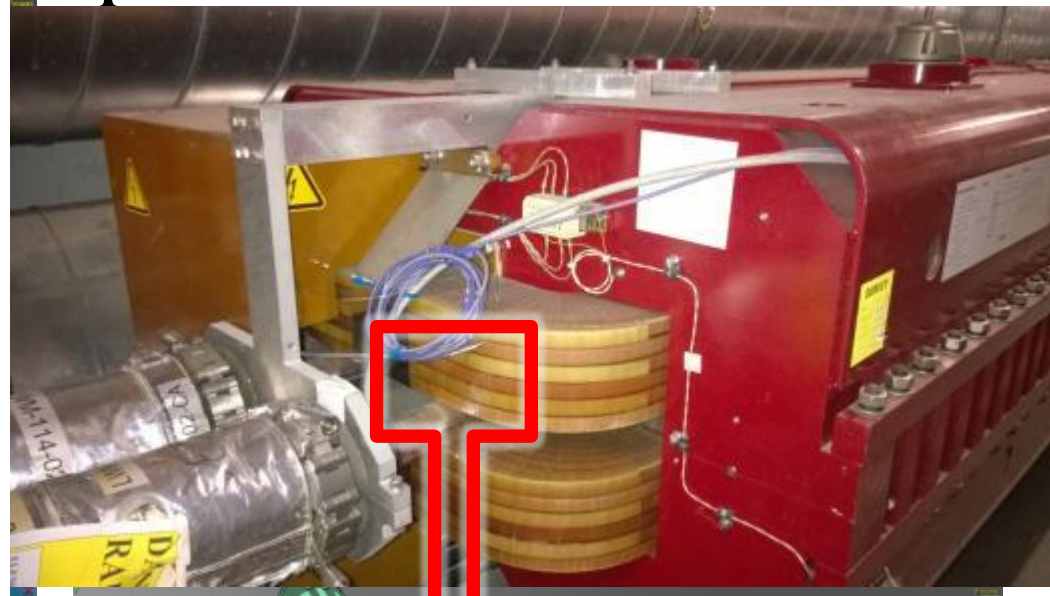
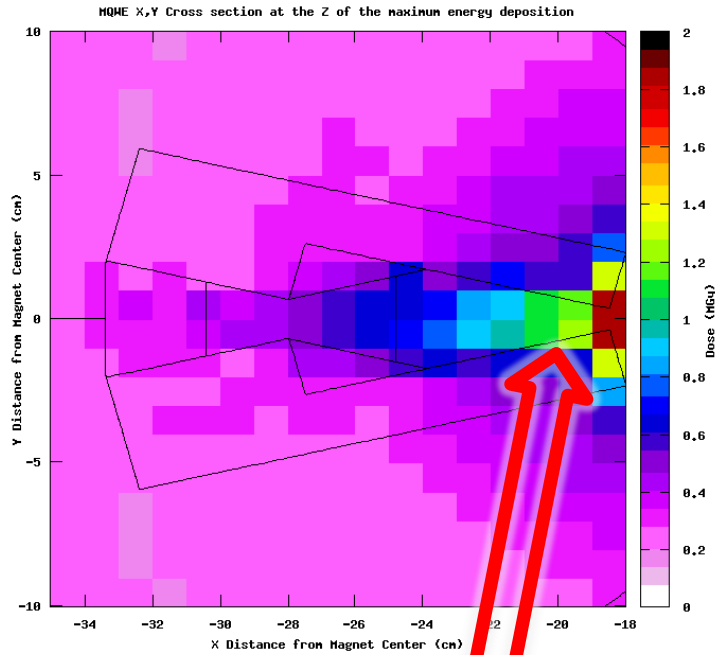
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| 97 | 97 | 97 | 97 |
| 98 | 98 | 98 | 98 |
| 99 | 99 | 99 | 99 |
| 100 | 100 | 100 | 100 |

Identified Failure modes



- Degradation of the insulation system due to radiation leading to inter turn short or shorts to ground
- Degradation of the mechanical shimming performed with ambient temperature cured resins
- Degradation of the insulation system due to radiation leading to inter turn short or shorts to ground
- Remark magnet build with no coil on the mid plane and therefore out from the expected zone of highest losses

nap



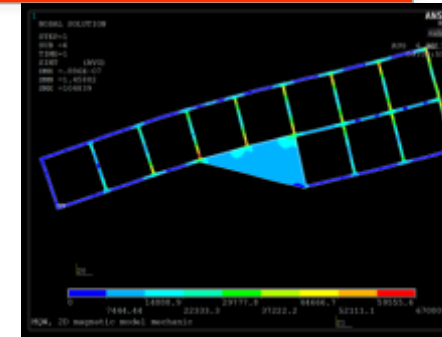
1.15 10^{-4} p ($30-30 \text{ } 10^{-4}$)
5 TeV relaxed collimator settings

Radiation resistance dose estimation

Degradation of mechanical properties appears and it can be measured before degradation of electrical properties

Actions of the fillers on the radiation resistance

Results mechanical test of the irradiated used resin or similar one



Value of mechanical load in the insulation

Estimation of the level of resistance of the insulation system to radiation

| Resins | Hardeners | Additives | Filler | Composition (p-p) | Fig | Dose for 50% Rec. (MGy) | Dose Range (MGy) |
|--------|-----------|-----------|---------------------------|-------------------|------|-------------------------|------------------|
| DEBA | MDI | | Filler | 100-27-200 | 5,14 | 1,3 | 1-2 |
| DEBA | MDI | | Silice | 100-27-200 | 5,14 | 30 | |
| DEBA | MDI | | Silice | 100-27-200 | 5,18 | 31,4 | |
| DEBA | MDI | | Silice (5 micron) | 100-27-20 | 5,16 | 14,8 | 10-15 |
| DEBA | MDI | | Silice (20micron) | 100-27-20 | 5,16 | 14,8 | |
| DEBA | MDI | | Silice (40micron) | 100-27-20 | 5,16 | 14,8 | |
| DEBA | MDI | | Silice (60micron) | 100-27-200 | 5,17 | 12,1 | |
| DEBA | MDI | BMA | Silice (60micron) | 100-80-2-200 | 5,17 | <30 | <10 |
| DEBA | MDI | | Nirol + Sulfure de Baryum | 100-27-2-100 | 5,14 | 15,8 | 15 |
| DEBA | MDI | | Magnésie | 100-27-120 | 5,14 | 18 | 18 |
| DEBA | MDI | | Graphite | 100-27-60 | 4,6 | 26,8 | 25-30 |
| DEBA | MDI | | Graphite | 100-27-60 | 5,13 | 85,5 | |
| DEBA | MDI | | Alumine | 100-27-220 | 4,7 | 23,50 | |
| DEBA | MDI | | Alumine | 100-27-220 | 5,14 | 55,7 | 20-80 |
| DEBA | MDI | | Alumine | 100-27-100 | 5,15 | 39,0 | |
| DEBA | MDI | | Alumine | 100-27-220 | 5,15 | 42,5 | |
| DEBA | MDI | | Fibre de verre | 100-27-90 | 5,18 | 81 | 80-100 |
| DEBA | MDI | | Fibre de verre | 100-27-60 | 5,18 | 100 | |
| EPH | MDI | | Fibre de verre | 100-28-60 | 5,18 | >100 | >100 |
| TGMD | MDI | | Fibre de silice | 100-41-50 | 5,20 | >100 | >100 |
| TGMD | MDI | | Fibre de silice | 100-43-50 | 5,20 | >100 | >100 |

But ...

- 1) What is the effect of the insulation thickness on the degradation ?
- 2) We know that exposure to air during irradiation should make the larger the damage. How much ?

1) Worth re-evaluating the correlation between electrical and mechanical properties degradation

IP 3

Dose [MGy] for
integrated luminosity
150 fb⁻¹

Dose [MGy] for
integrated luminosity
350 fb⁻¹

| | R | L | R | L |
|---------|---|----|----|----|
| MQWA.A4 | 0 | 0 | 0 | 0 |
| MQWA.B4 | 0 | 0 | 0 | 0 |
| MQWB.4 | 0 | 0 | 0 | 1 |
| MQWA.C4 | 0 | 0 | 0 | 1 |
| MQWA.D4 | 0 | 1 | 1 | 2 |
| MQWA.E4 | 2 | 3 | 4 | 8 |
| MQWA.A5 | 1 | 2 | 3 | 5 |
| MQWA.B5 | 1 | 3 | 3 | 6 |
| MQWB.5 | 3 | 7 | 8 | 15 |
| MQWA.C5 | 8 | 15 | 18 | 36 |
| MQWA.D5 | 2 | 4 | 4 | 9 |
| MQWA.E5 | 3 | 7 | 8 | 16 |
| MBW.A6 | 2 | 4 | 5 | 9 |
| MBW.B6 | 2 | 5 | 5 | 11 |
| MBW.C6 | 3 | 7 | 8 | 15 |

Point 3 and 7 coil
magnet damage
estimation

IP 7

Dose [MGy] for
integrated luminosity
150 fb⁻¹

Dose [MGy] for
integrated luminosity
350 fb⁻¹

R L R L

| | R | L | R | L |
|---------|----|----|----|----|
| MQWA.A4 | 1 | 1 | 1 | 2 |
| MQWA.B4 | 0 | 1 | 1 | 3 |
| MQWB.4 | 1 | 2 | 2 | 5 |
| MQWA.C4 | 6 | 6 | 14 | 14 |
| MQWA.D4 | 4 | 4 | 9 | 9 |
| MQWA.E4 | 7 | 14 | 16 | 32 |
| MQWA.A5 | 3 | 3 | 6 | 6 |
| MQWA.B5 | 4 | 4 | 10 | 10 |
| MQWB.5 | 4 | 4 | 10 | 10 |
| MQWA.C5 | 2 | 5 | 5 | 12 |
| MQWA.D5 | 5 | 7 | 11 | 16 |
| MQWA.E5 | 41 | 14 | 95 | 32 |
| MBW.A6 | 22 | 16 | 52 | 37 |
| MBW.B6 | 37 | 19 | 86 | 43 |

MQW

MBW

From 10 to 20 MGy

From 40 to 60 MGy

From 20 to 50 MGy

From 60 to 80 Mgy

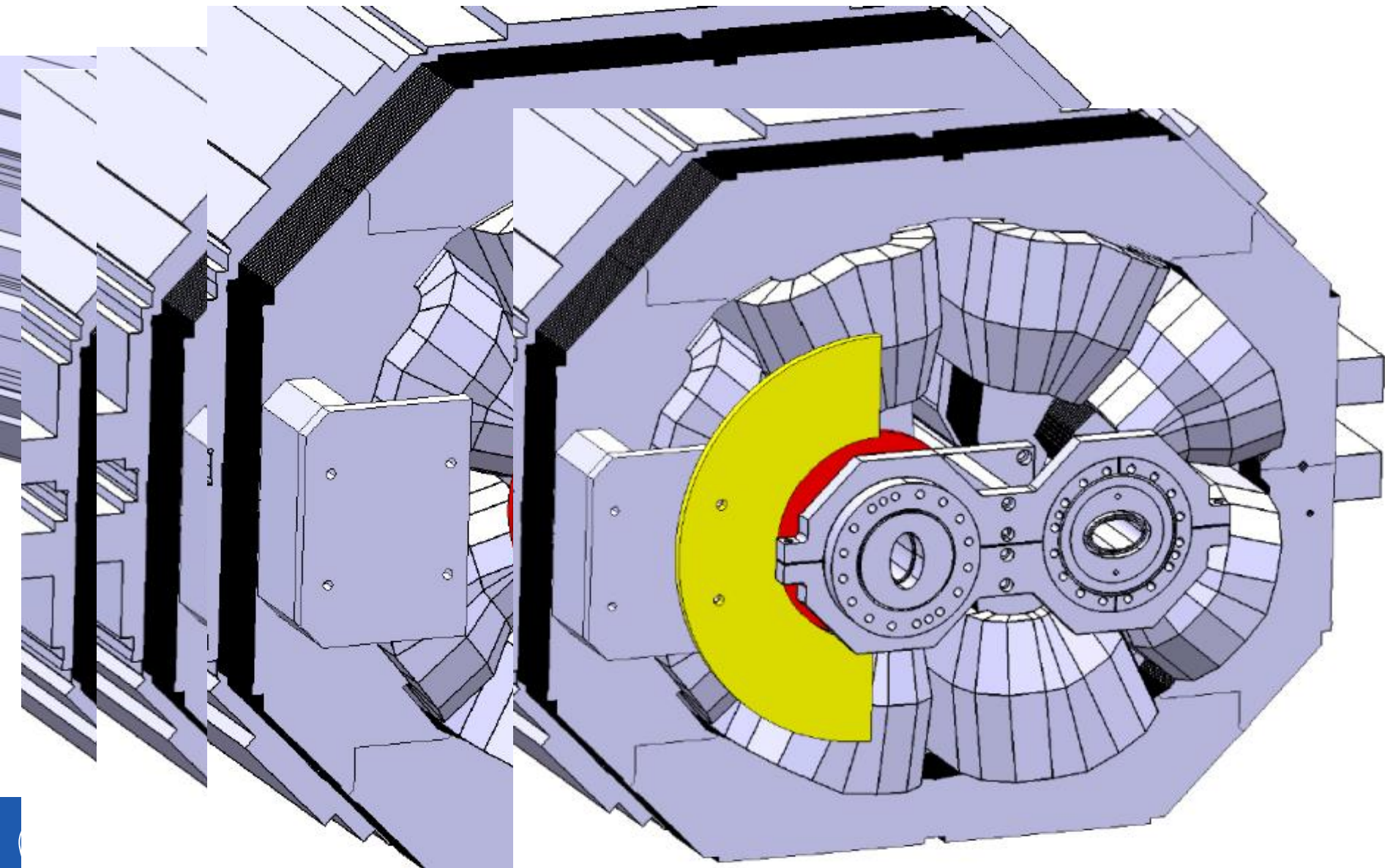
Larger than 50 MGy

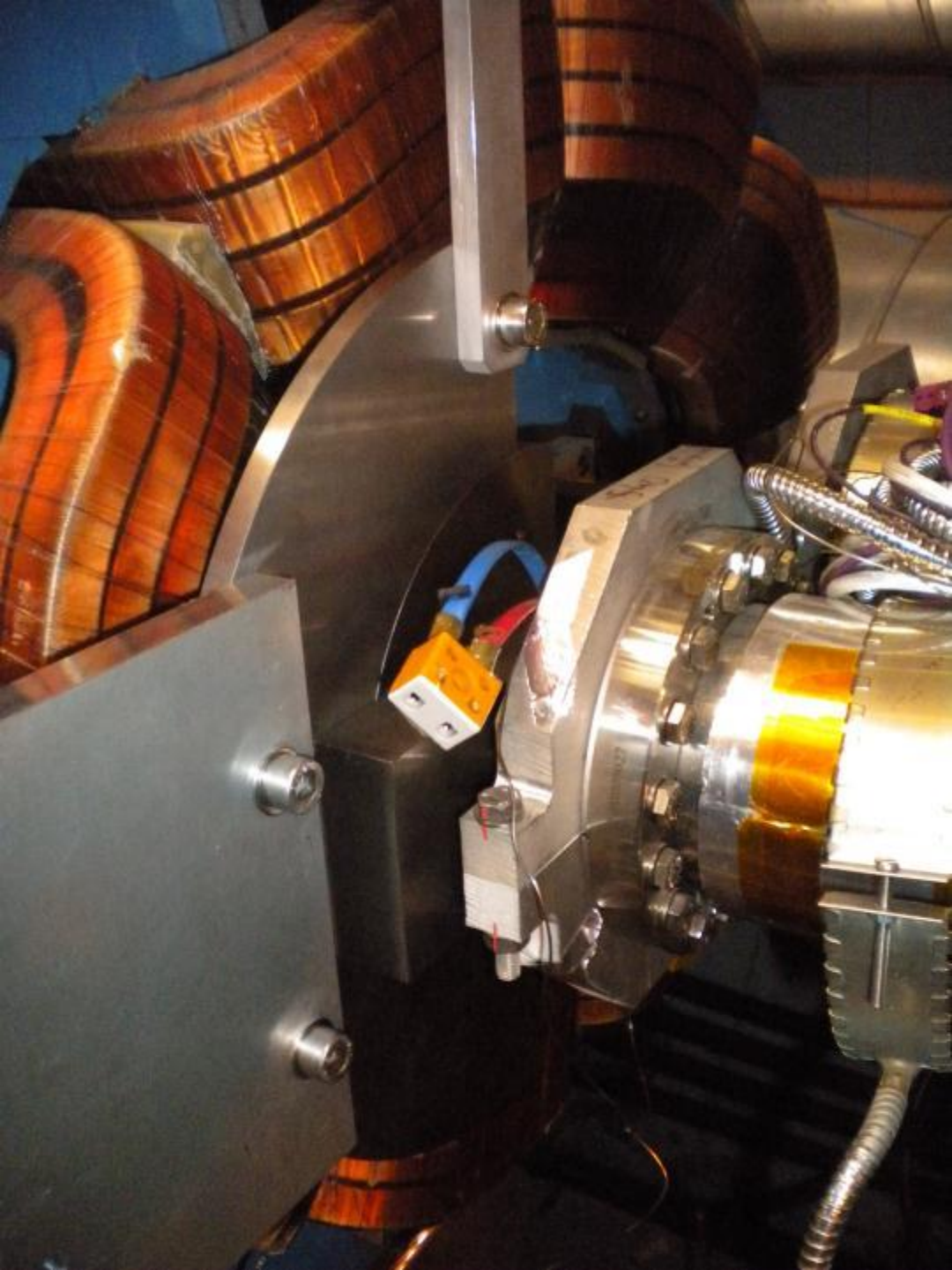
Larger than 80 MGy



Preparing HL-LHC or acting

MQW shielding

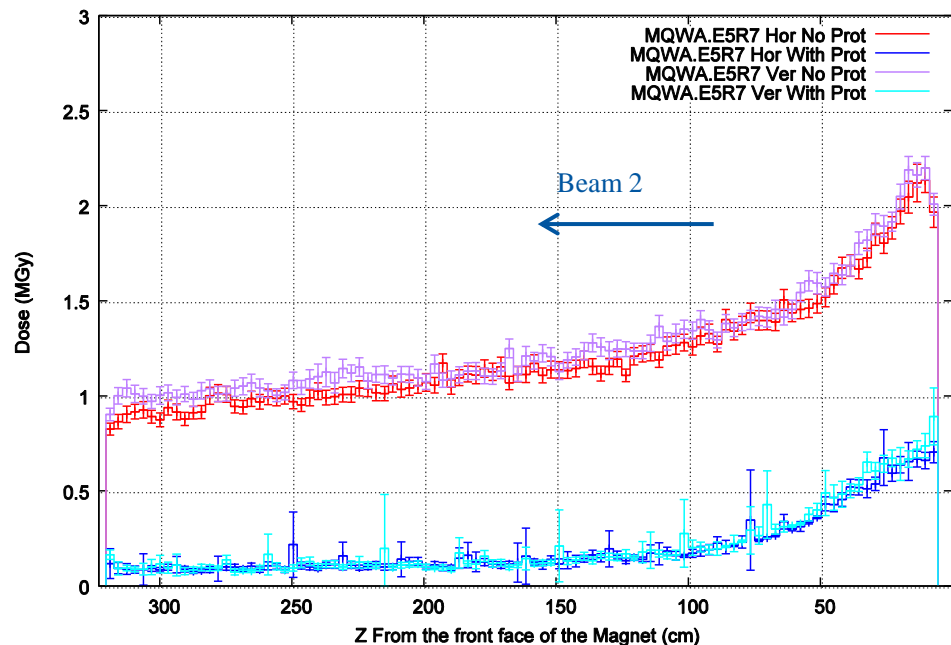




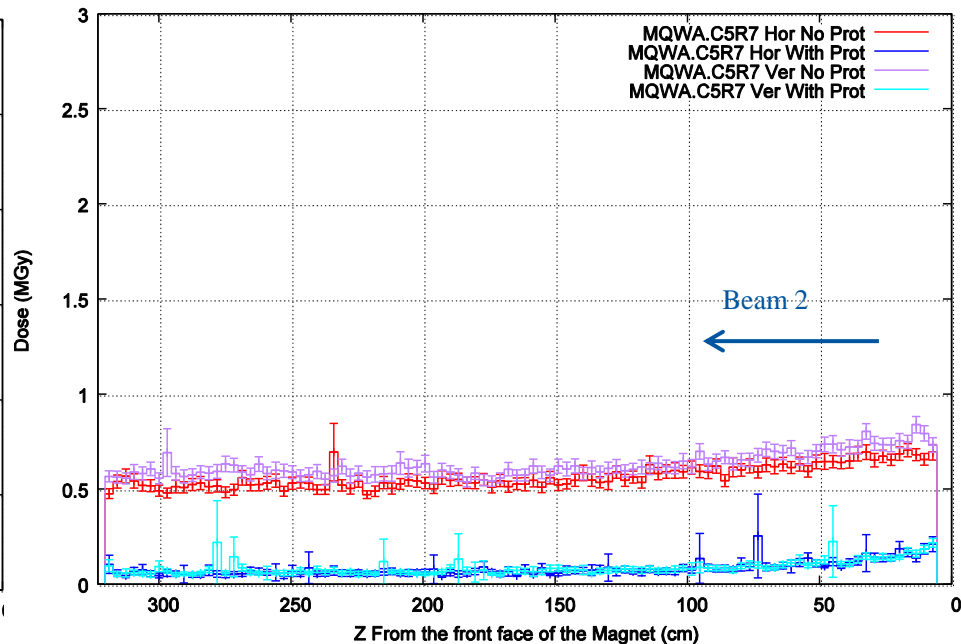
MQW shielding effect on the coil

Normalization: $1.15 \cdot 10^{16} \text{ p (50 fb}^{-1}\text{)}$

MQWA.E5R7 Peak Dose Z profile - Comparison



MQWA.C5R7 Peak Dose Z profile - Comparison



Reduction Factor 3 on most exposed magnet with the hardest spectra. It shadows 20 % the radiation on the following magnet

Reduction Factor 4 on less exposed magnet with the softer spectra.

IP 3

Dose [MGy] for integrated luminosity 150 fb⁻¹ Dose [MGy] for integrated luminosity 350 fb⁻¹ Dose [MGy] for integrated luminosity 3000 fb⁻¹

| | R | L | R | L | R | L |
|---------|---|----|-----------|-----------|-----------|------------|
| MQWA.A4 | 0 | 0 | 0 | 0 | 2 | 4 |
| MQWA.B4 | 0 | 0 | 0 | 0 | 2 | 4 |
| MQWB.4 | 0 | 0 | 0 | 1 | 2 | 4 |
| MQWA.C4 | 0 | 0 | 0 | 1 | 3 | 6 |
| MQWA.D4 | 0 | 1 | 1 | 2 | 7 | 14 |
| MQWA.E4 | ← | 3 | <u>2</u> | <u>5</u> | <u>13</u> | <u>24</u> |
| MQWA.A5 | ← | 2 | <u>2</u> | <u>3</u> | <u>8</u> | <u>15</u> |
| MQWA.B5 | ← | 3 | <u>2</u> | <u>4</u> | <u>10</u> | <u>19</u> |
| MQWB.5 | ← | 7 | <u>5</u> | <u>10</u> | <u>24</u> | <u>45</u> |
| MQWA.C5 | ← | 15 | <u>11</u> | <u>22</u> | <u>57</u> | <u>106</u> |
| MQWA.D5 | ← | 4 | <u>3</u> | <u>5</u> | <u>14</u> | <u>25</u> |
| MQWA.E5 | ← | 7 | <u>5</u> | <u>10</u> | <u>25</u> | <u>47</u> |
| MBW.A6 | ← | 4 | <u>3</u> | <u>6</u> | <u>15</u> | <u>27</u> |
| MBW.B6 | ← | 5 | <u>3</u> | <u>7</u> | <u>17</u> | <u>31</u> |
| MBW.C6 | ← | 7 | <u>5</u> | <u>9</u> | <u>24</u> | <u>44</u> |

Point 3 and 7 coil magnet damage estimation with shielding

green arrow installed LS1
yellow arrow foreseen for LS2

MQW

MBW

From 10 to 20 MGy

From 40 to 60 MGy

From 20 to 50 MGy

From 60 to 80 MGy

Larger than 50 MGy

Larger than 80 MGy



IP 7

Dose [MGy] for integrated luminosity 150 fb⁻¹

Dose [MGy] for integrated luminosity 350 fb⁻¹

Dose [MGy] for integrated luminosity 3000 fb⁻¹

| | R | L | R | L | R | L |
|---------|-----------|----------|-----------|-----------|------------|------------|
| MQWA.A4 | 1 | 1 | 1 | 2 | 10 | 15 |
| MQWA.B4 | 0 | 1 | 1 | 3 | 9 | 22 |
| MQWB.4 | 1 | 2 | <u>1</u> | <u>3</u> | <u>6</u> | <u>14</u> |
| MQWA.C4 | 6 | 6 | <u>9</u> | <u>9</u> | <u>41</u> | <u>41</u> |
| MQWA.D4 | 2 | 2 | <u>4</u> | <u>4</u> | <u>24</u> | <u>24</u> |
| MQWA.E4 | <u>1</u> | <u>2</u> | <u>2</u> | <u>5</u> | <u>19</u> | <u>39</u> |
| MQWA.A5 | 3 | 3 | <u>4</u> | <u>4</u> | <u>20</u> | <u>20</u> |
| MQWA.B5 | 4 | 4 | <u>6</u> | <u>6</u> | <u>29</u> | <u>29</u> |
| MQWB.5 | 4 | 4 | <u>6</u> | <u>6</u> | <u>29</u> | <u>29</u> |
| MQWA.C5 | 2 | 5 | <u>3</u> | <u>7</u> | <u>11</u> | <u>28</u> |
| MQWA.D5 | 3 | 5 | <u>6</u> | <u>8</u> | <u>34</u> | <u>49</u> |
| MQWA.E5 | <u>14</u> | <u>5</u> | <u>32</u> | <u>11</u> | <u>278</u> | <u>93</u> |
| MBW.A6 | <u>7</u> | <u>5</u> | <u>16</u> | <u>12</u> | <u>138</u> | <u>99</u> |
| MBW.B6 | <u>12</u> | <u>6</u> | <u>29</u> | <u>14</u> | <u>247</u> | <u>123</u> |

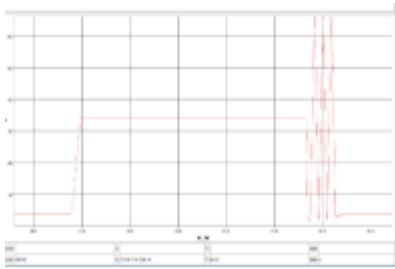


MQW Life Test to the HL-LHC era

Estimation of mechanical induced damage on LHC Warm

Quadrupoles

Reproduction of electromagnetic induced stresses on coils, spacers and magnet's frame to assess life expectation of installed magnets with respect to cyclic loads during LHC operations.



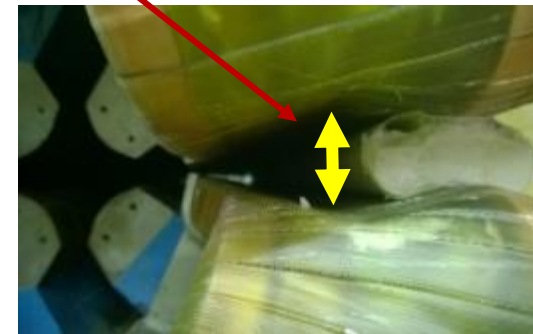
Imposed load: **4 power cycles every LHC physics run, ~47'000 cycles expected up to HL-LHC era end.**

Experimental activities:

- Measure of **coil-coil displacement** to identify eventual mechanical degradation (12 positions)
- Measure of **Temperature evolution** (20 positions)
- Measure of **coils longitudinal and transversal deformation** (8 positions)
- **Electrical verification of the magnet** at regular intervals with **two complete certifications** (at 50% and 100% of foreseen life cycle)



Temperature probes and strain gauges



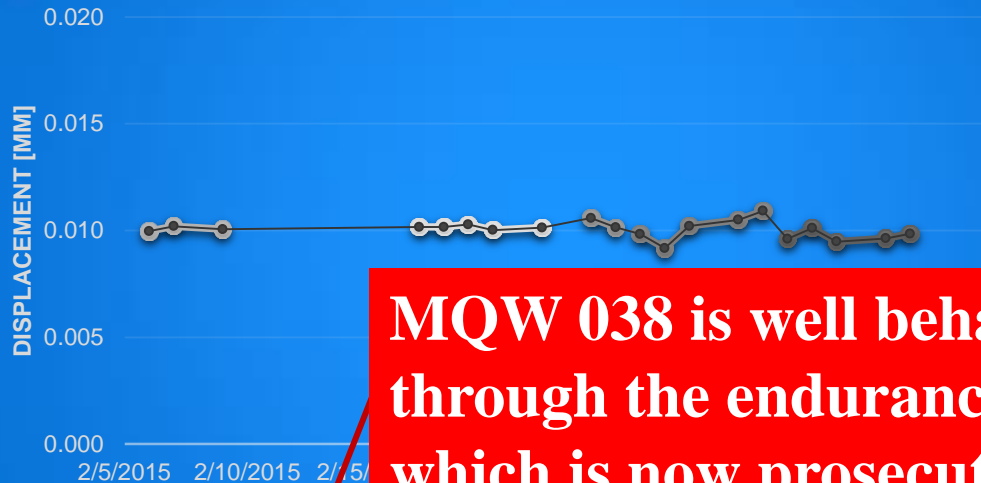
Coil-coil relative displacement

Work performed in collaboration with: CERN Mechanical Laboratory, CERN Polymer Laboratory and CERN Design Office.

MQW Life Test: first results

Preliminary results up to 25'000 cycles (half of foreseen magnet's life)

Displacement Sensor 67-C

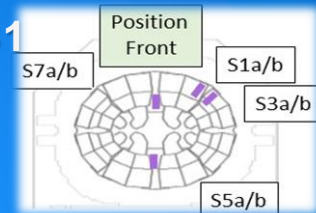


MQW 038 is well behaving through the endurance test, which is now prosecuting the road to 50'000 cycles (end of HL-LHC era)!

- Very stable signal with few oscillations mostly due to T effect.
- No influence of em fields or hysteresis effects.
- Displacements constant since beginning of test.
- Coils Strains giving regular and strong signal.



S1a and S1b



- S1a - Longitudinal Deformation
- S1b Transversal Deformation

MQW/MBW Coils Insulation Resins

Characterization

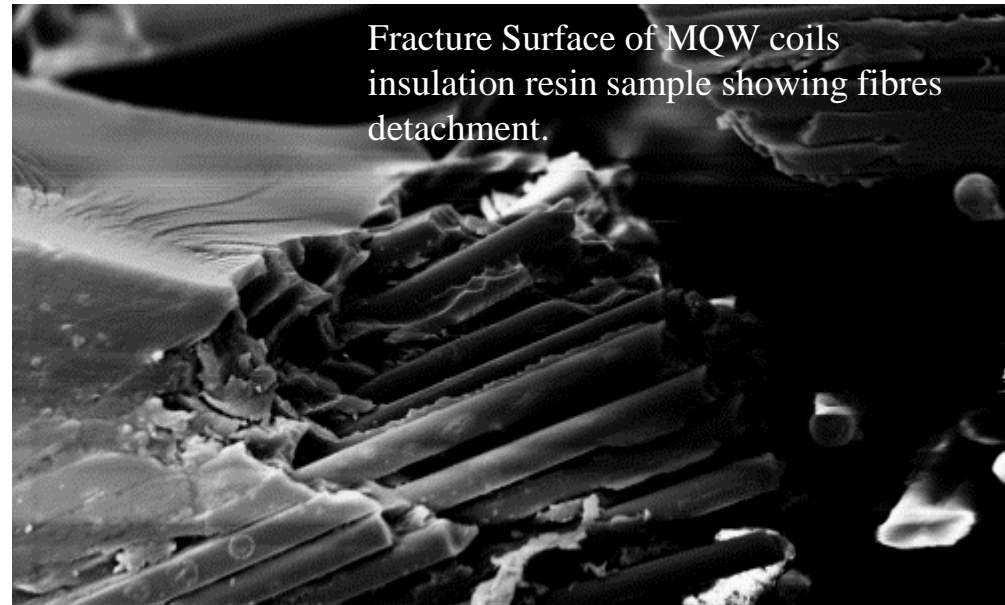
Additional activities to predict the long term behaviour of the materials used for MQW (and MBW) magnets, including:

Mechanical tests,

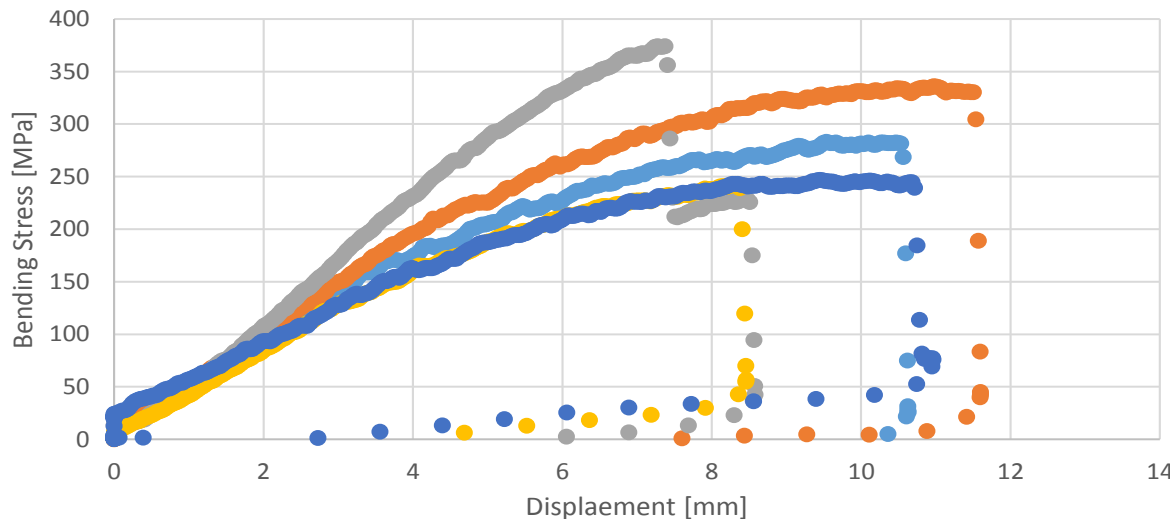
Electrical tests,

Microstructural analysis...

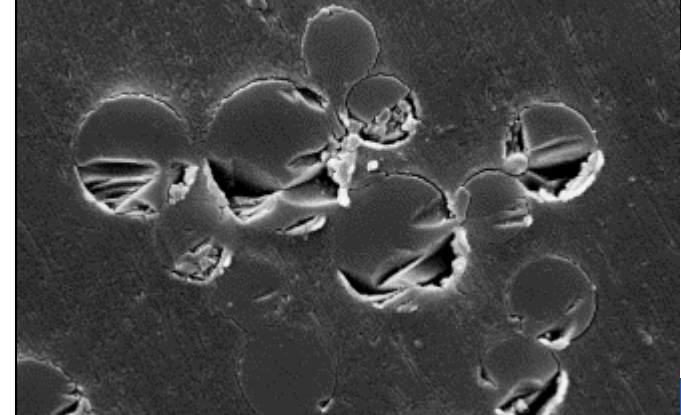
All evaluated as a function of received dose (irradiation campaign under preparation)!



MQW Coils Insulation Flexural Strength



Metallographic sample of type E glass fibres embedded in MQW epoxy resin.



Flexural Tests plots courtesy of O. Sacristan De Frutos (CERN Mechanical Laboratory).

FCC and HL-LHC development or pro-acting

Know better

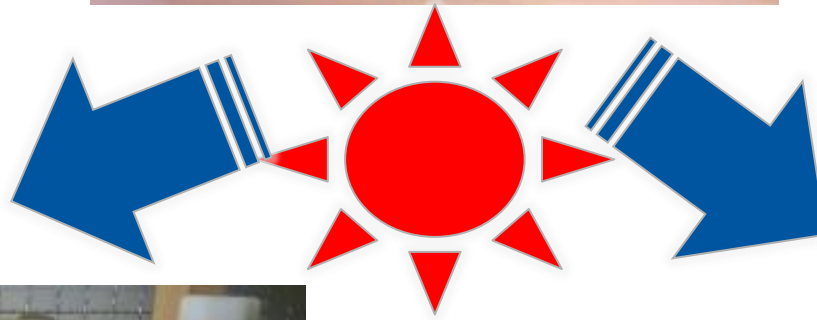
for HL-LHC and
FCC

Known margin

Know before

Know better: resin testing from present to future

Presently used insulations systems and new insulation systems



Monitoring the health of the magnet:

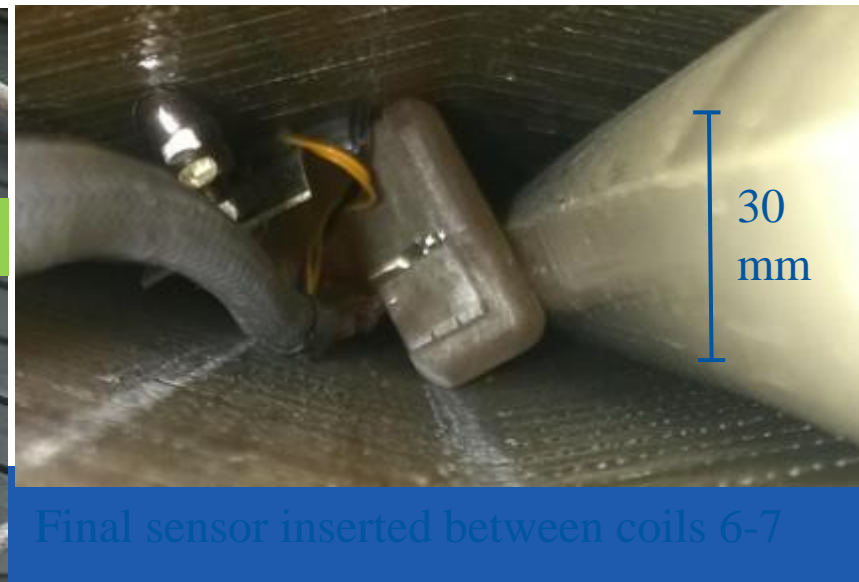
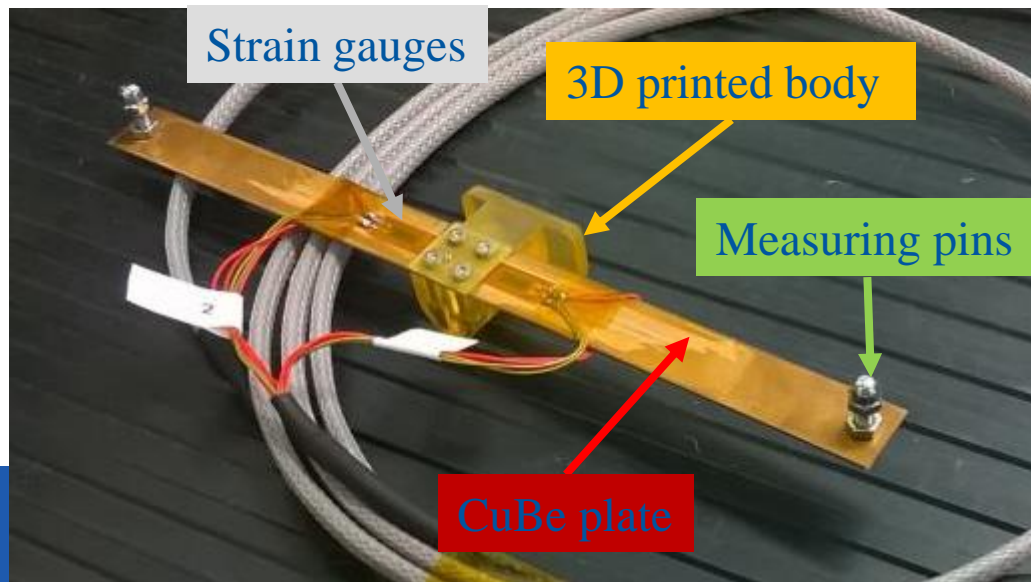
DS R&D

High demanding requirements:

- High precision and reproducibility over a long number of cycles;
- No influence from Temperature and EM fields;
- Capable to slide in the small interstitial between MQW coils, adapting to irregular surfaces and locations...

- Displacement measured through “**Home made CuBe beam based displacement sensors**”, in the following DS.
- DS are made of a CuBe plate, instrumented with strain gauges and mounted on a support structure in **3D printed polymer**.
- The DS is then calibrated and inserted inside the magnet along the interstitials between coils **up to 1.5 m depth**.
- Final accuracy achieved **~0.5 microns for excursions of ~4 mm**.

→ The technology can be implemented in different situations by ad hoc designs of the main body and of the CuBe plate geometry...



Know margin: rad hard insulation schemes

Organic insulations

Possible schemes

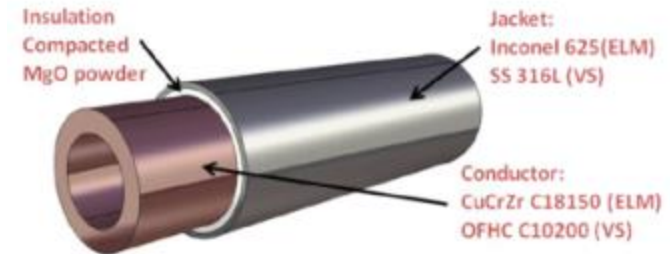
Non organic insulations

Cyanate Esther compounds

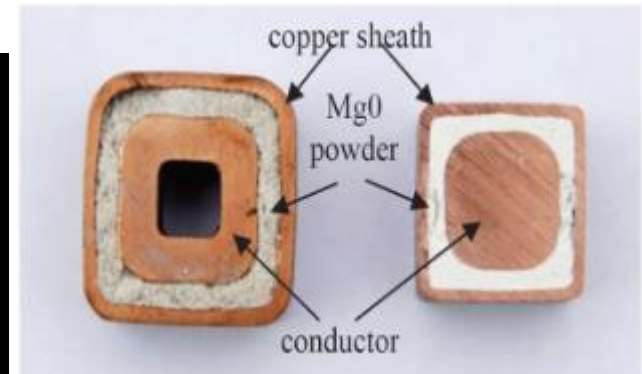
High radiation hard epoxy with mica

S glass fibre

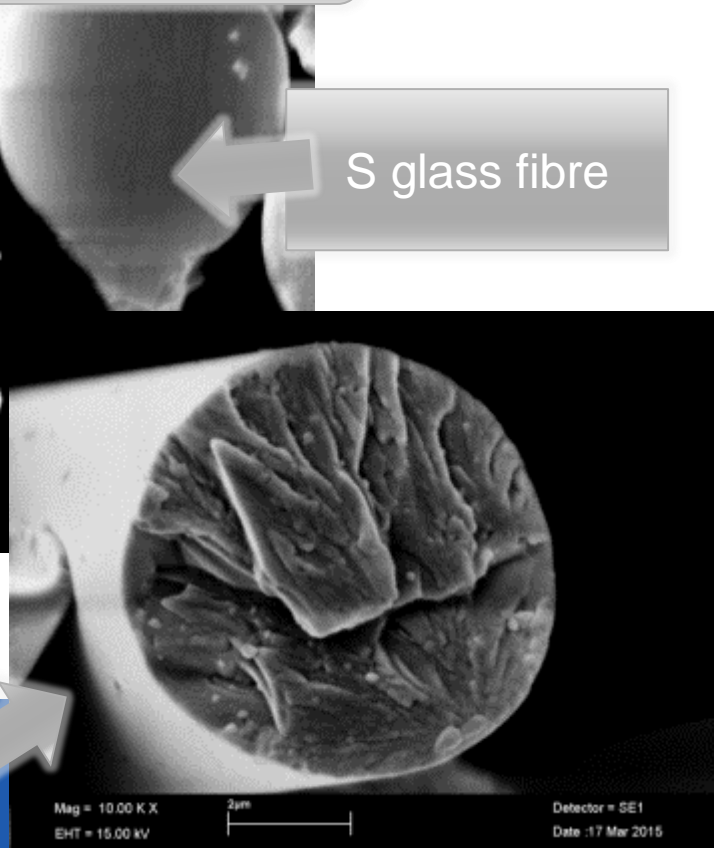
E glass fibre



ITER cables: round shape, tailored design for different machine areas.^[2]

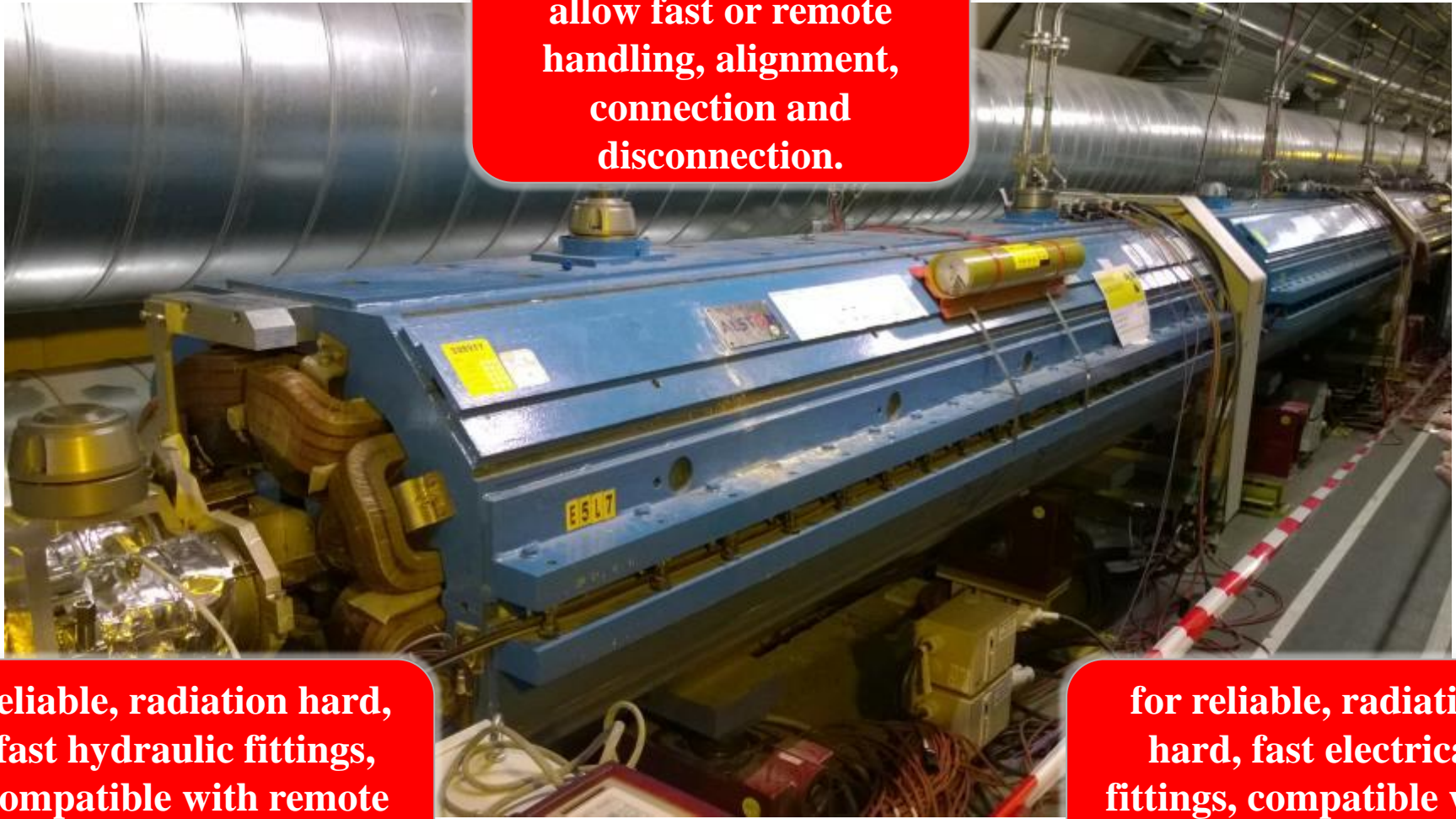


Hitachi cables used in KEK & PSI: square shape, Cu cladding, different dimensions available. ^[1]



Known margin: the whole magnet

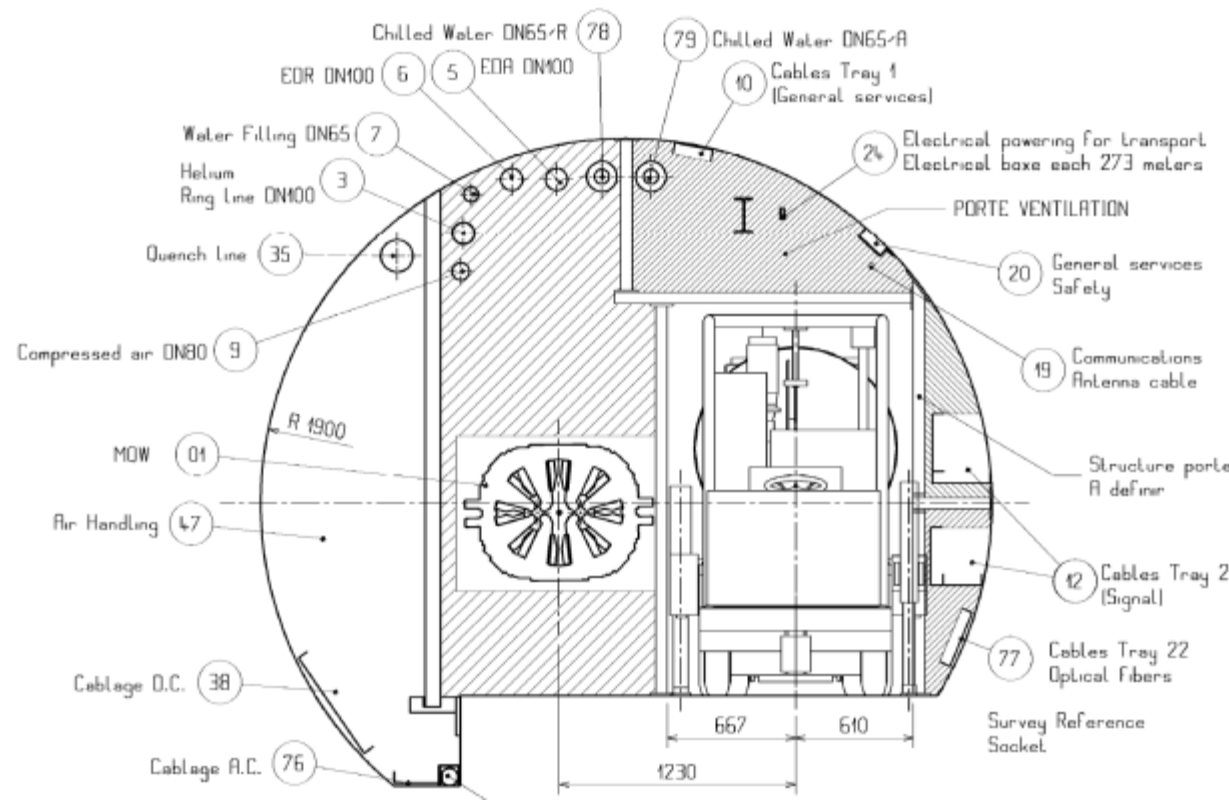
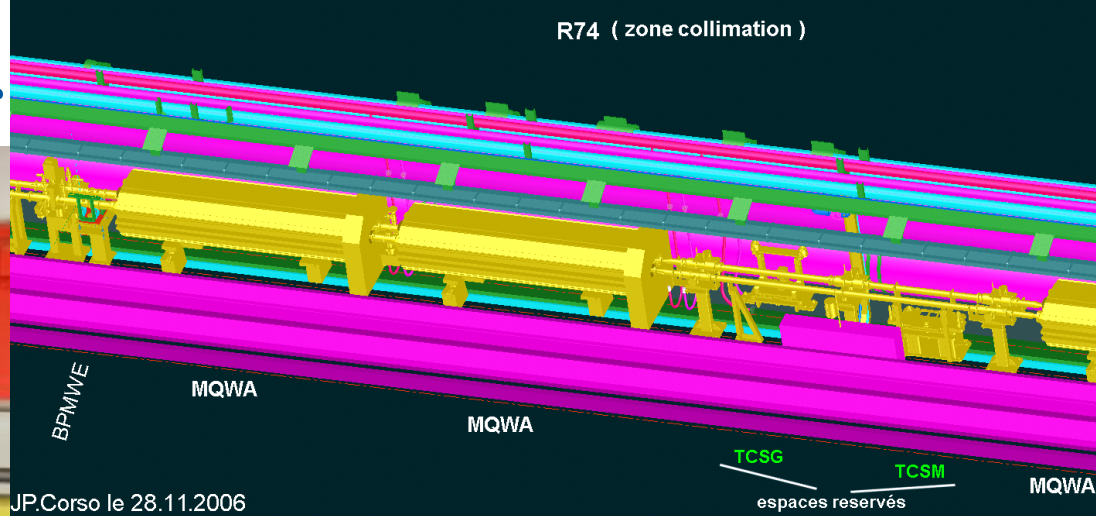
mechanical systems to allow fast or remote handling, alignment, connection and disconnection.



reliable, radiation hard, fast hydraulic fittings, compatible with remote handling

for reliable, radiation hard, fast electrical fittings, compatible with remote handling

Plug in magnet for



Conclusion

- The development of rad-hard magnets for FCC is a continuum of the LHC Consolidation program and of the HL-LHC development program. The Three projects are synergic and build one on the other
- A rad hard coils does not mean a rad hard magnet: electrical connection, hydraulic connections and manipulation have to be intimately integrated to provide an homogenous product. CERN needs partners in order to develop the adequate answers in the different fields