MQWs
Testing and Corrective Actions

N. Mariani, P. Fessia
TE/MSC/MNC
TRIUMF Visit @ CERN 09/11 March 2016

Outline

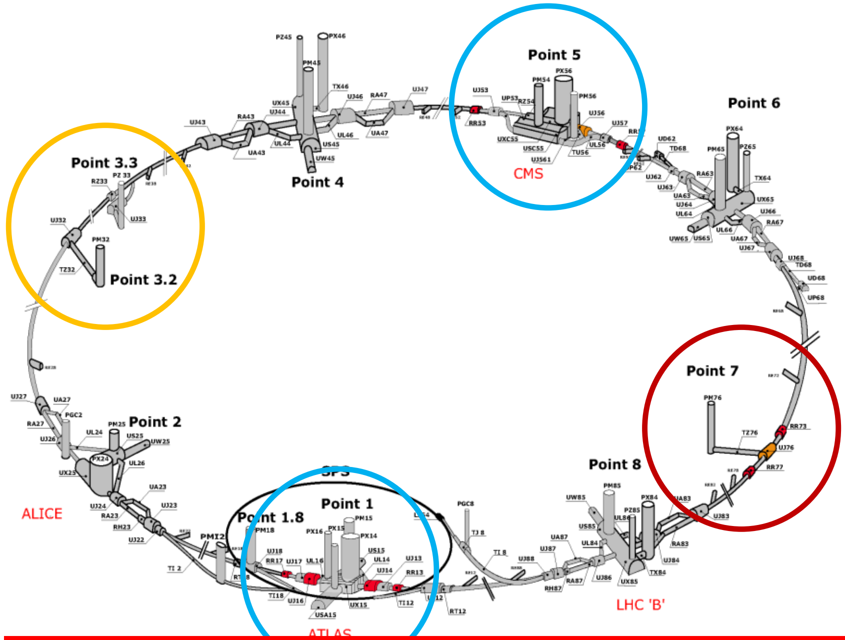
- Wrap-up of MQWs Long Term Strategy
- MQWs Damage Evaluations
  - Mechanical Loads: MQW life Test
  - Radiation induced degradation: Dosimeters Installation, Radiation Hardness Characterization Campaign
  - Thermal loads: MQW Heat Test
- Corrective Actions
  - MQW Brackets Replacement
- Conclusions

MQWs Long Term Strategy

Beam cleaning areas (**IR3 and IR7**) high radiation level ➔ quenches in SC cables.
Use of robust warm magnets (MQWs and MBWs) instead of SCs, however…

- **High activation of equipment, maintenance in next 10 years might become unfeasible!**

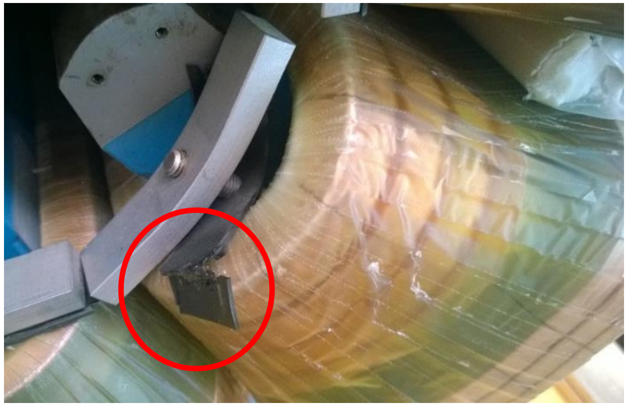
➔ Paramount to predict with large margins eventual mechanical, thermal or radiation induced failures on LHC warm magnets and adopt effective counter measurements…



Long term Strategy already proposed by P. Fessia involves damage prediction, magnets protection and preventive magnet's exchange plan to guarantee smooth operations up to end of HL-LHC era!

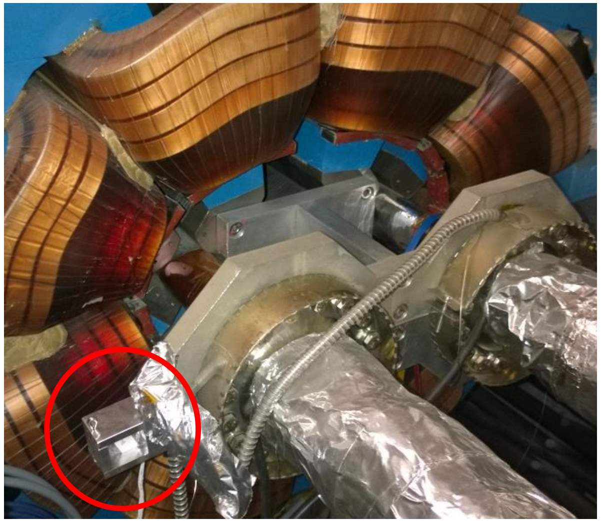
MQWs Damage Evaluations

Prediction of eventual MBWs/MQWs failures on three fronts:



1) Mechanical induced damage:

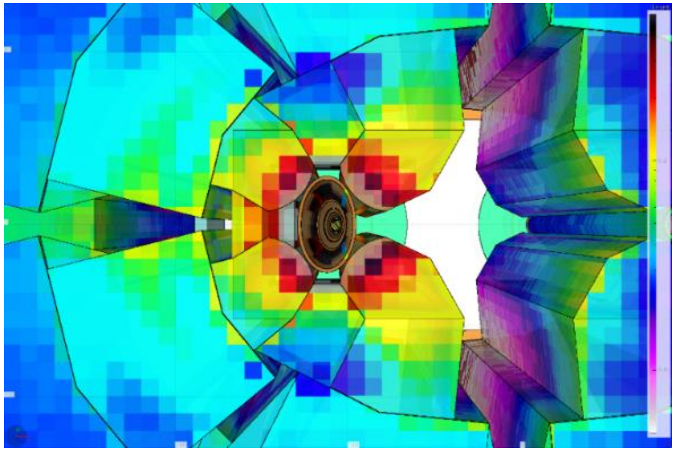
➔ MQW Life Test: Endurance fatigue test on spare MQW to simulate LHC powering cycles (@7 TeV) while acquiring key parameters to verify life span.



2) Radiation induced damage:

➔ Verification of doses received by coils with Dosimetry Campaign: installation of 114 long term dosimeters in meaningful locations and BLMs for long term predictions…

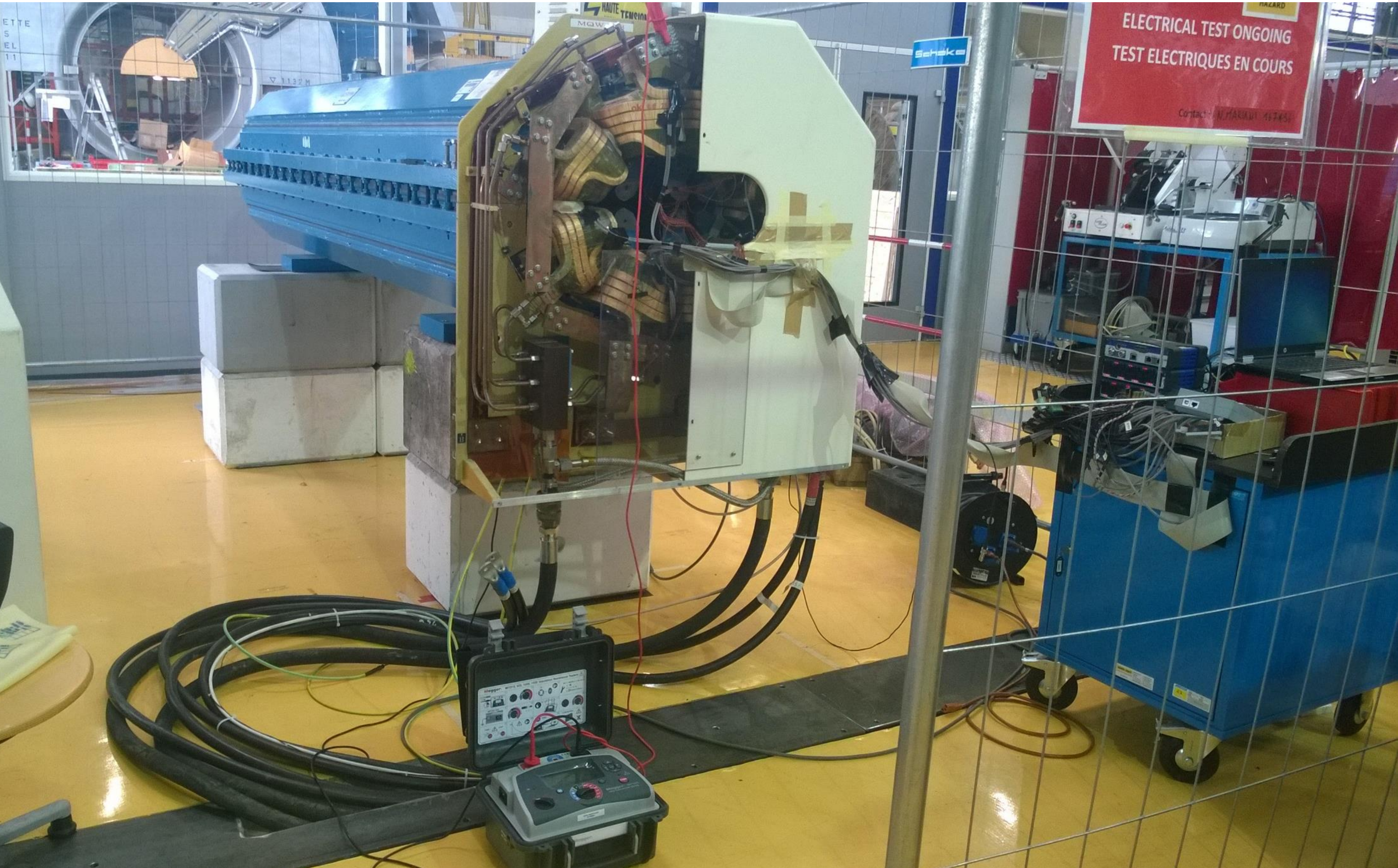
➔ Irradiation and testing of MQWs materials samples to measure the properties loss due to ionizing radiation!



3) Heat induced damage:

➔ Ad hoc Heat Test to simulate Beam Losses Energy Deposition inside tunnel environment and verify absence of hot spots and MQWs cooling capabilities.

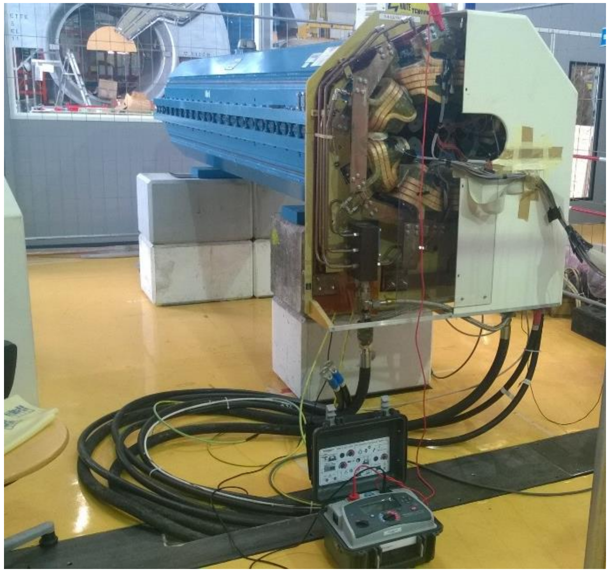
Mechanical Induced Damage: MQW Life Test



MQW Life Test Experiment

Verify the **magnet life time in LHC working conditions:**

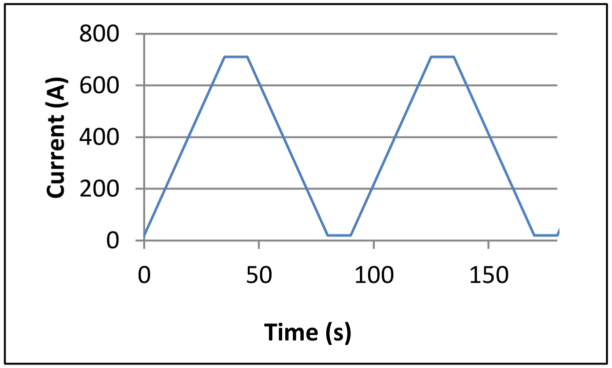
- Cycle number limit for damages on coils and spacers, like loss of insulation, movement of coils, insulation degradation...
- Acquire fundamental parameters (temperatures, electrical behaviour) to evaluate magnets behaviour.
- Test on spare MQW-038 (in new conditions, non irradiated) @ NormaTEF b.180 with LHC operations parameters…



Methods implemented:

1) **Coil-coil displacement** measure through ad-hoc sensors.
2) **Temperature** distribution and time evolution.
3) **Coils strain** through strain gauges to monitor the coil induced deformation.
4) **Electrical verification** of magnet: interruption of cyclic load to perform a High Voltage Test (5 kV) and a Capacitor discharge test (1.5 kV per coil)

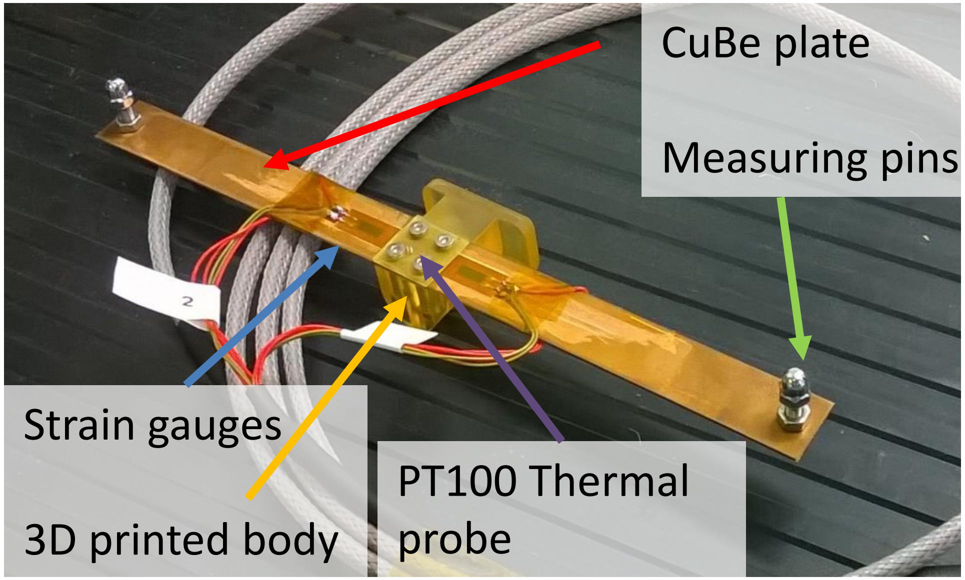
Cyclic Load used for test



Total cycle number until 2036 estimated by HL-LHC latest planning ~60’000 cycles, reduced in 3 months of accelerated Life Test.

Coil-Coil Displacement Sensors (DS) I

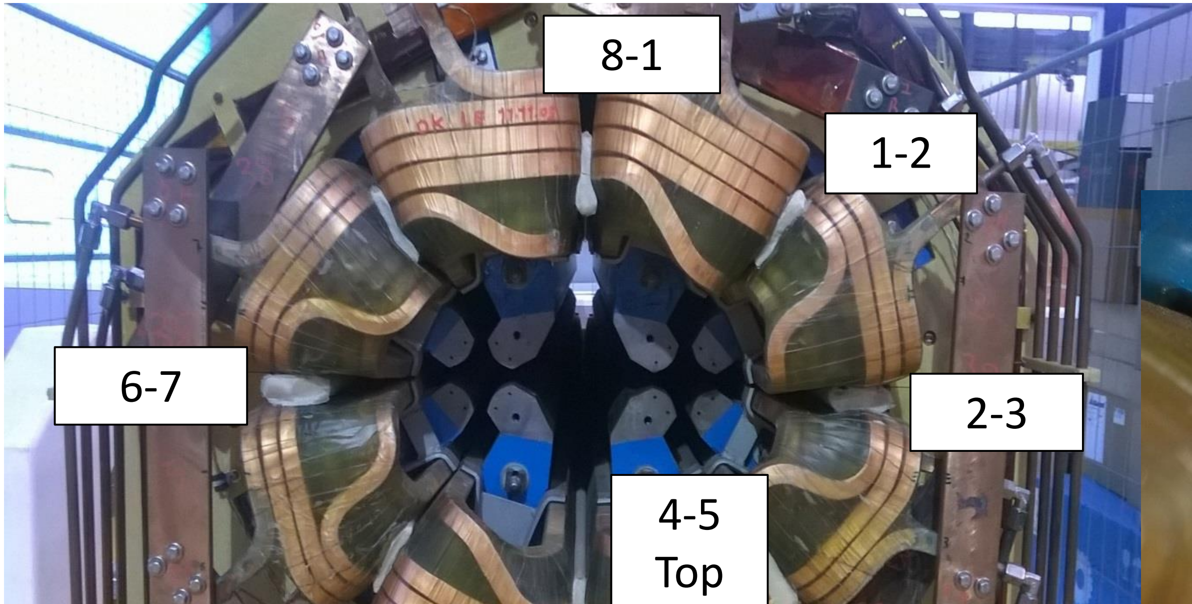
Displacement measured through "Home made CuBe beam based displacement sensors".
R&D in collaboration with: R. Fernandez Gomez (TE/VSC/MDT), E. Gallay, M. Guinchard (EN/MME) and S. Clement and R. Gauthier (TE/MSC, Polymer Lab).



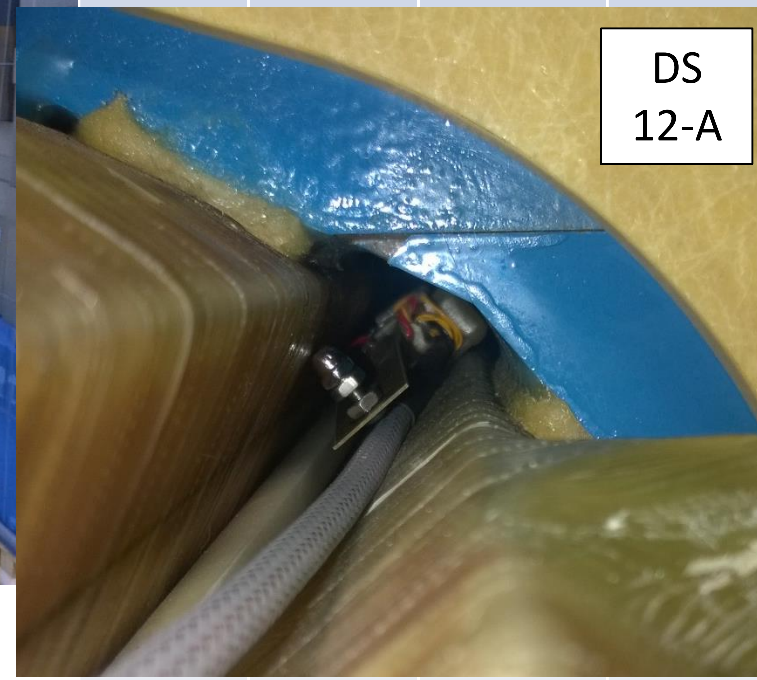
1) Strain gauges calibrated over 10'000 cycles on the final sensor through a LVDT for **µm level accuracy** and **long term reliability!**
2) Sensors inserted (with compressed arms) **at chosen depth inside magnet**.
3) Once installed, the CuBe arms open and their elasticity will keep it forced on the resin walls.

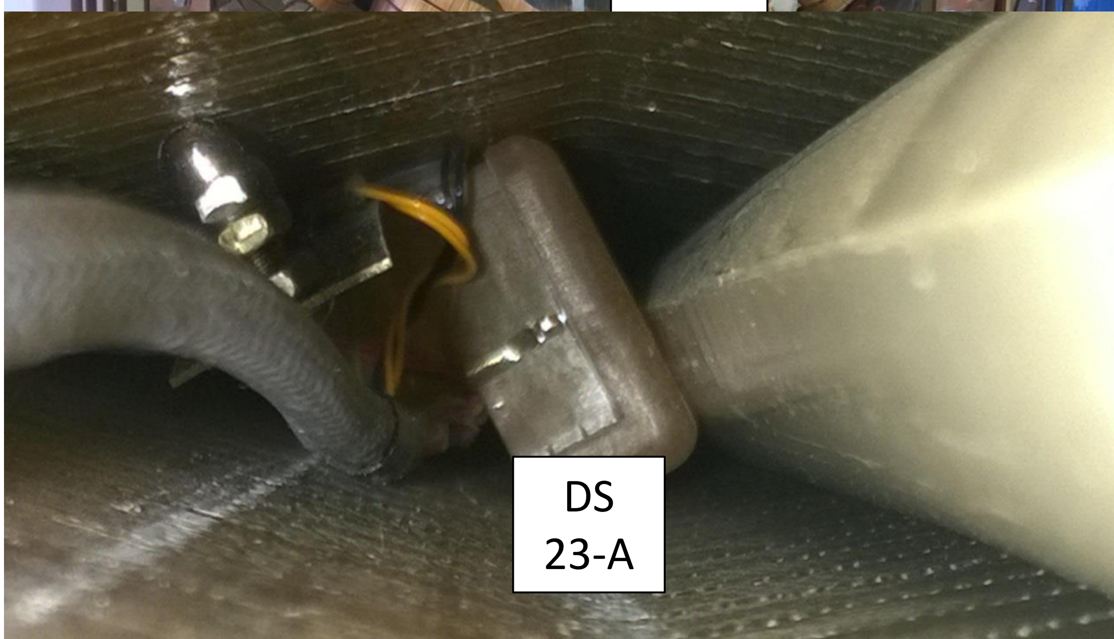
Key points:
- No influence from T or EM fields;
- High accuracy & reliability;
- Sensor shape & dimensions tailored to specific location & loading cond.

Sensors Locations



DSs Id.	Pos.	DSs Body Configuration	Pin Screw length
12-A	1-2	Small body	10 mm



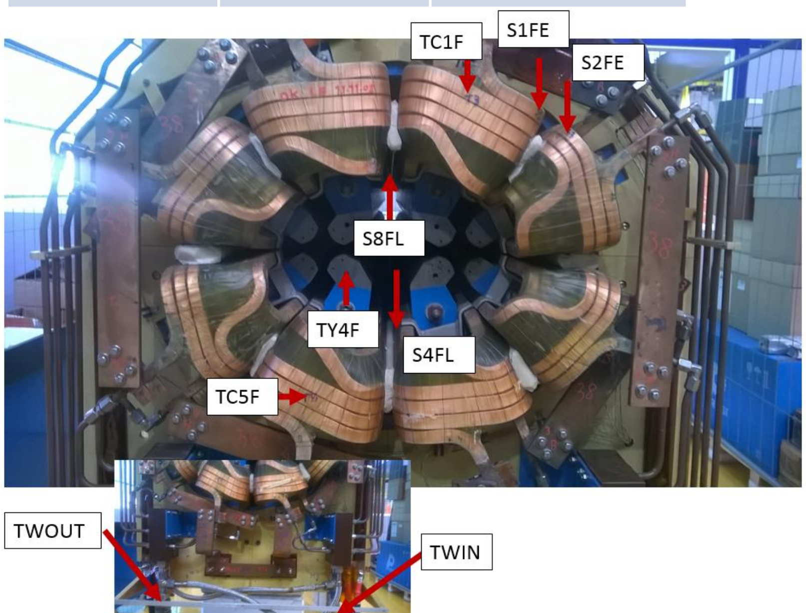


12 Coil-Coil DS produced with different layouts, calibrated and installed at three different depths!

Temperature and Strain Gauges

TSs Id.	Position	Magnet face
TW-IN	H2O IN	Front
TW-OUT	H20 OUT	Front
TC-1F	Coil 1	Front
TC-1B	Coil 1	Back
TY-4F	Yoke 4	Front
TY-4B	Yoke 4	Back
TA	Ambient	Front

TSs Id.	Position	Magnet face
S1-FE	Coil 1 on Edge	Front
S1-BE	Coil 1 on Edge	Back
S2-FE	Coil 2 on Edge	Front
S2-BE	Coil 2 on Edge	Back

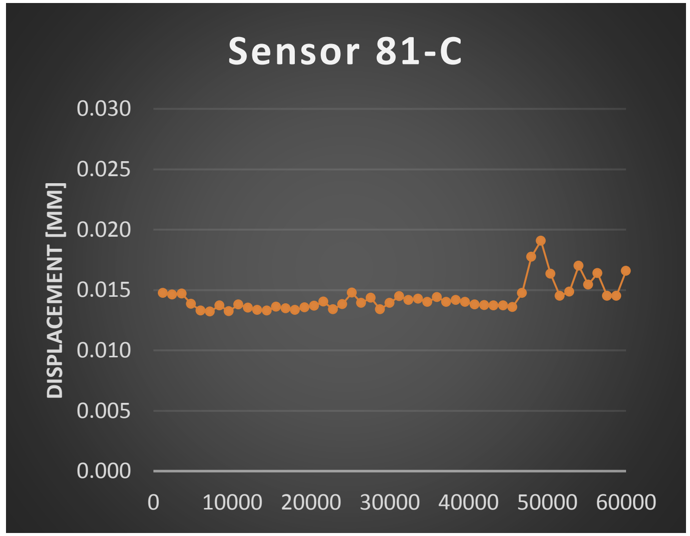


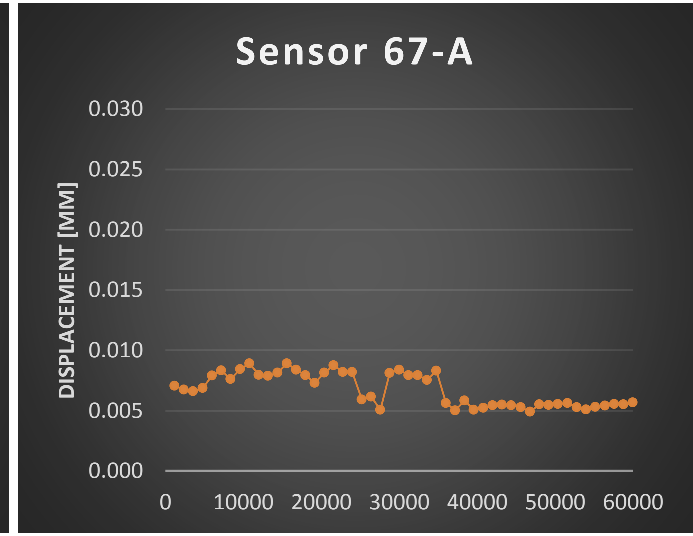
20 T channels (including 12 PT100 on DS) and 16 Strain Gauges (8 positions with 2 gauges at 90° each).

DS Signal Analysis

Analysis:

1) Correction of low frequency T drift
2) Moving average to smooth signal
3) Punctual cycles max-min difference evaluation
4) Sampling of data to reduce point number
5) Daily average.

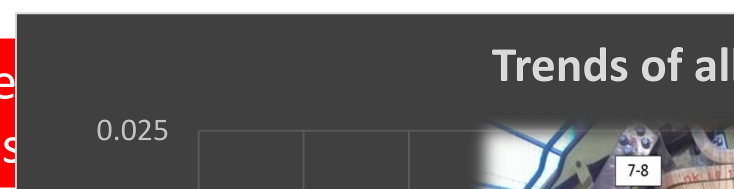




Results:

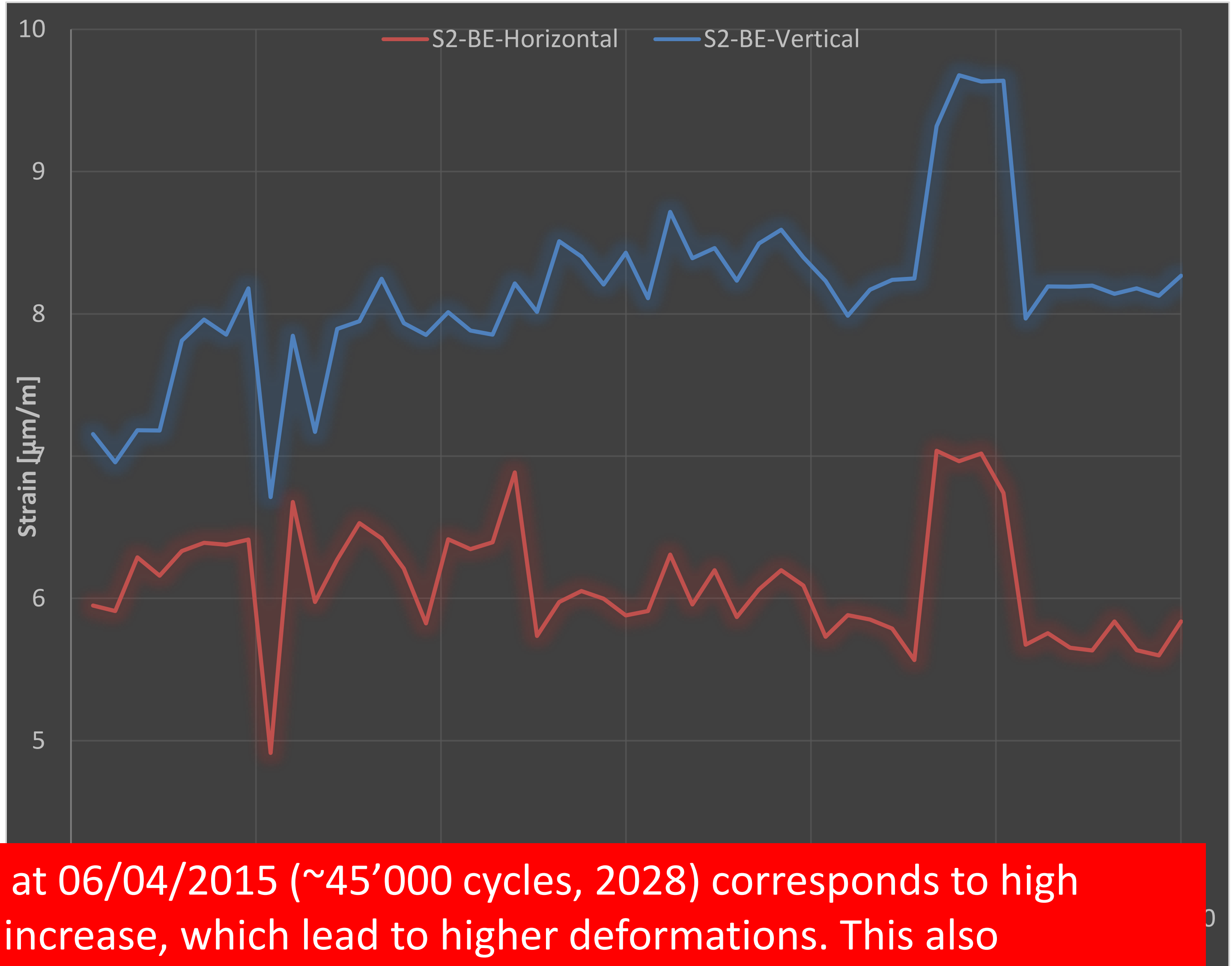
- Very low displacements on all locations
- Small spike at 45000 cycles detected in vertical positions (Pos 8-1 and 1-2), not on horizontal ones
- No great difference between different depths…

No significate variations of signal, observed slight incre
only in few locations (like 81-C). No evidence of increas



Strain gauges Signal Analysis

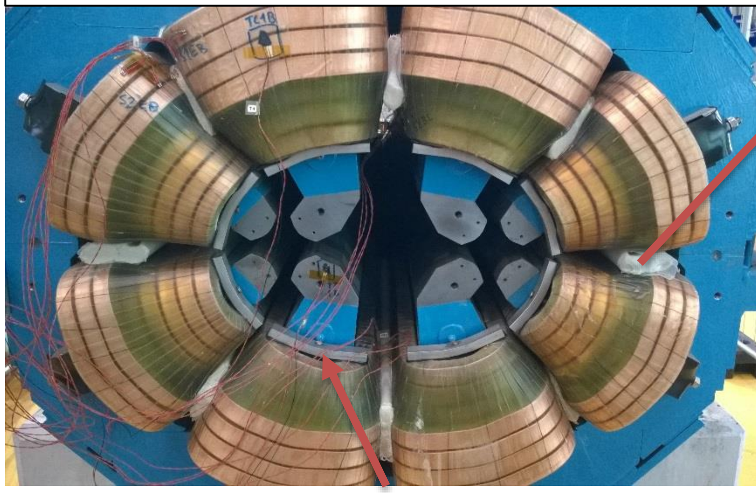
- Same operations as for DS signal;
- Higher time variations due to large Thermal gradients during test campaign,
- Less difference between positions since deformation is driven by thermal expansion
- Extremely low values!



The peak starting at 06/04/2015 (~45’000 cycles, 2028) corresponds to high environmental T increase, which lead to higher deformations. This also corresponds to the first observation of visual damage on coils rubber spacers…

Failure Mechanisms

Back face pristine condition + sensors



MQW Coil Retainers (brackets) inserted between Coils and Coil mainteining blocks

MQW Coil Spacers injected between coils:
Epon 826 + RP1500 + MINSIL 120F Silica

1) Coil spacers ends crack formation and parts detachment due to compressive stresses
   - No increase in coils displacement observed up to test end, not critical for now!
2) Coil Rubber stoppers tear due to compressive stresses: expansion of coils forcing the coils against the maintaining blocks
   - **Critical: reduction of coils-ground insulation!**

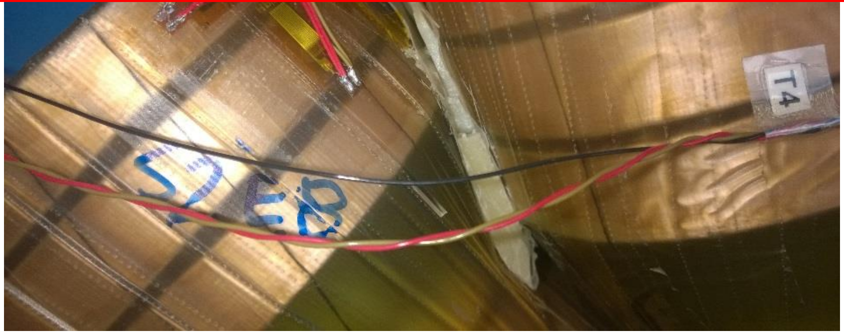
MQW Coils Spacers degradation

Initial detachments (~36000, 2/3 of life span) of parts from spacers edges…
No modification of coil coil displacement signal…
Once all precracked parts detached the degradation stopped…

➔The spacers are well blocked between coils and cannot further move or degrade, since in their middle part they are only loaded in compression.

➔Coil spacers are not critical from a mechanical point of view.

➔Mechanical tests after irradiation are paramount to establish final life span inside the LHC machine!



MQW Coil Stoppers Degradation

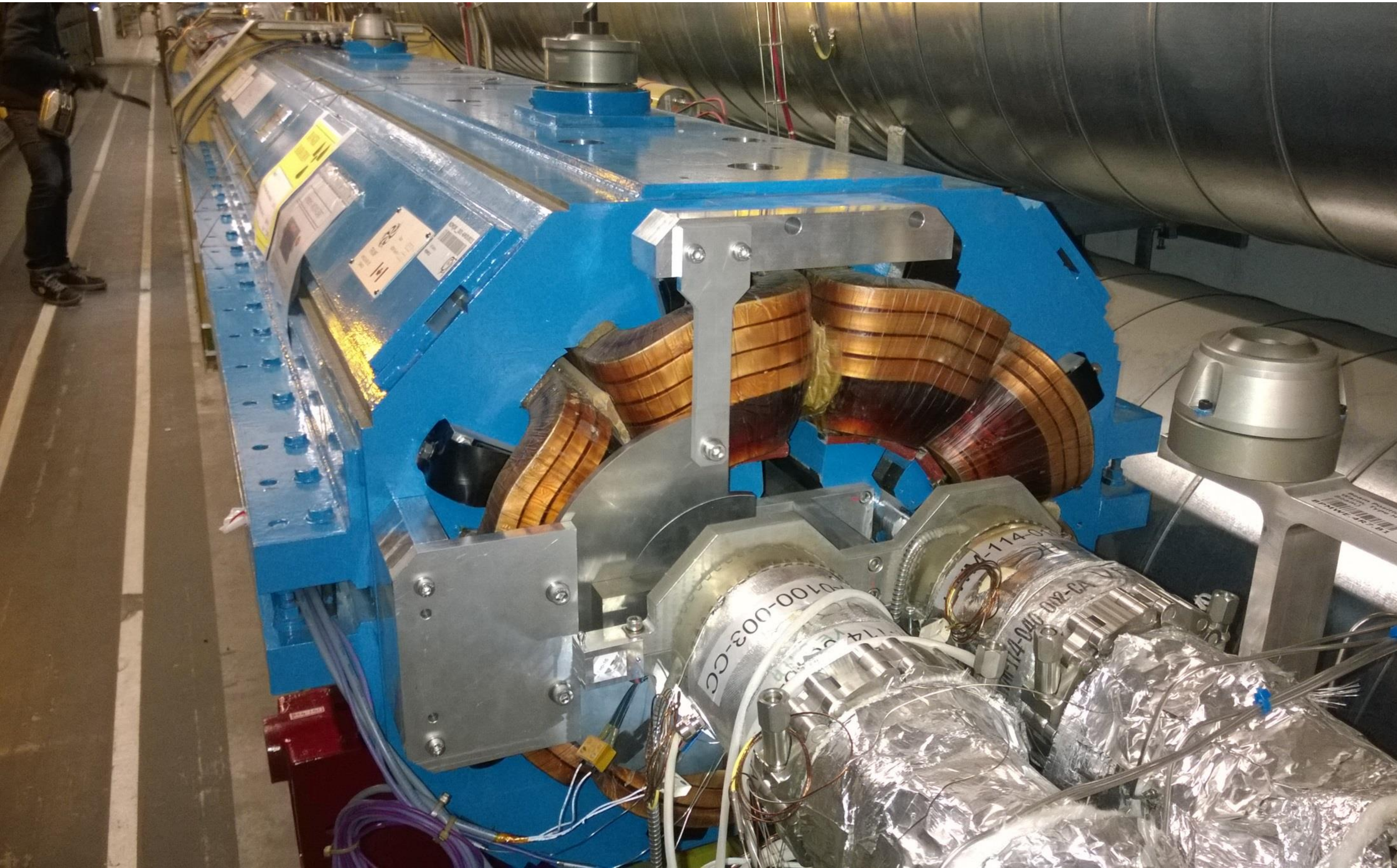
- Final Insulation check at 60’000 cycles showed 50 MOhm of resistivity with magnet completely DRY!
-

→ NOT ACCEPTABLE from electrical point of view, need to replace stoppers after maximum 36000 cycles (2026, replacing during LS3?)

→ Replacing of rubber insulations with Polyimide-Polyurethane sandwich restored magnet’s conditions (insulation at 1 GOhm as specific)

→ Substitution of brackets in tunnel with new, more insulated ones featuring Polyurethane and Polyimide sandwich wrapped in epoxy resin.

Radiation Induced damage:
Dose Monitoring and Materials Testing



Radiation Induced Degradation on MQWs

Radiation induced degradation will affect the Breakdown Voltage, until discharges might happen between coils and/or with the ground

- → Need to replace and dismantle the broken magnet
- → High activation of the magnet itself hampers the dismantling
- → Need to reliably verify lifetime and adopt preventive countermeasures (shielding, magnets replacements, development of rad hard coils, ecc…)

Dosimeters Installation in LHC to monitor doses on critical locations and have a verified forecast of dose on coils

More than 100 dosimeters have been installed on MQWs, MBWs and BLMs in 2014, recording dose on coils during all 2015 activities.

Radiation resistance evaluation of MQW materials (coils insulation and spacers) to find the maximum sustainable dose

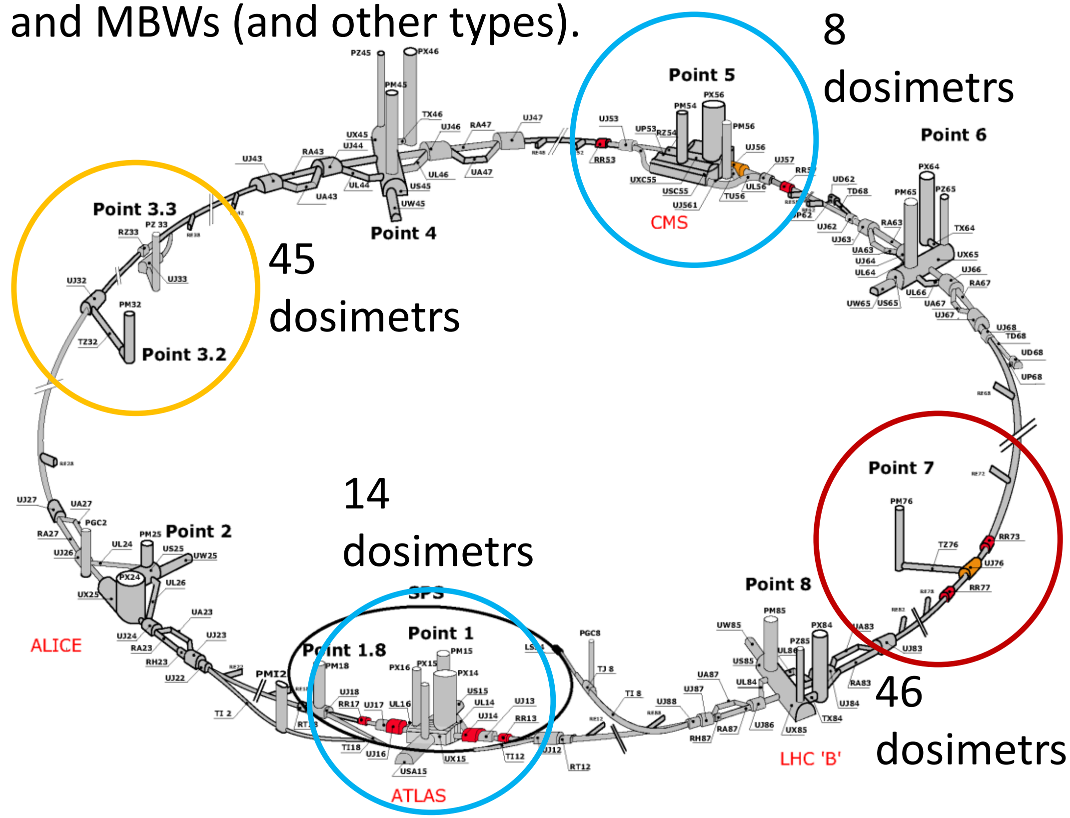
Test campaign launched in collaboration with Fraunhofer Institute (DE) to measure electrical and mechanical properties after irradiation up to 90 MGy.

Dosimeters Installation

In beam cleaning areas (**IR3 and IR7**) and collision points (IR1 and IR5) the radiation generated by the beam might be enough to provoke damage even in robust normal conducting magnets coils, i.e. MQWs and MBWs (and other types).

Objectives of monitoring campaign:

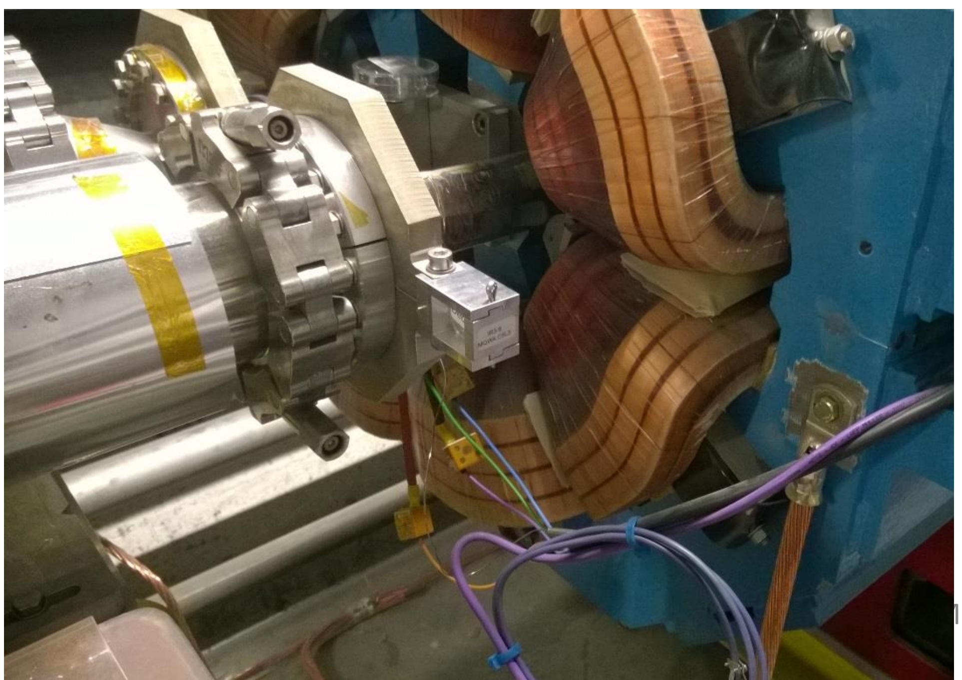
- **Monitor critical locations to prevent radiation damage induced failures on warm magnets;**
- **Establish a correlation between BLM signal and dose received by magnets;**
- Verify the spatial distribution of losses on magnets and on BLMs;
- Extend and maintain the database of critical locations along the ring proposing a reading time-schedule up to LS3;
- **Have fix dosimeters holders for fast and reliable readings in future years, guaranteeing a fair comparison among readings in different stages.**



➔ Long terms strategy to strictly monitor the dose received by magnet’s coils and BLMs in hot LHC locations to allow for precise evaluation of magnet’s lifetime!

Dosimeters on MQWs

- **Dosimeter attached through a support on Magnets flanges**
- Developed with Design Office: AW6082 T6 Al alloy holders fixed to flanges having removable caps for dosimeter exchange.
- **Clear mechanically engraved labels on the supports, printed labels on capsules.**
- **Fast dosimeter exchange procedure, very important for hot locations!**



Key for cap removal

Fixing screw (Allen 1.5)

Cap with Label

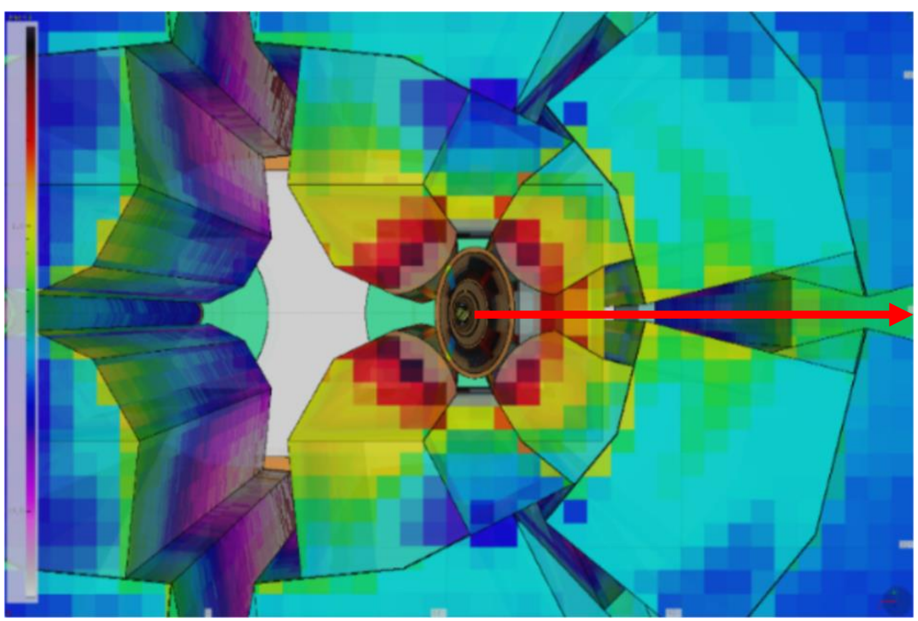
Capsule (with labels)

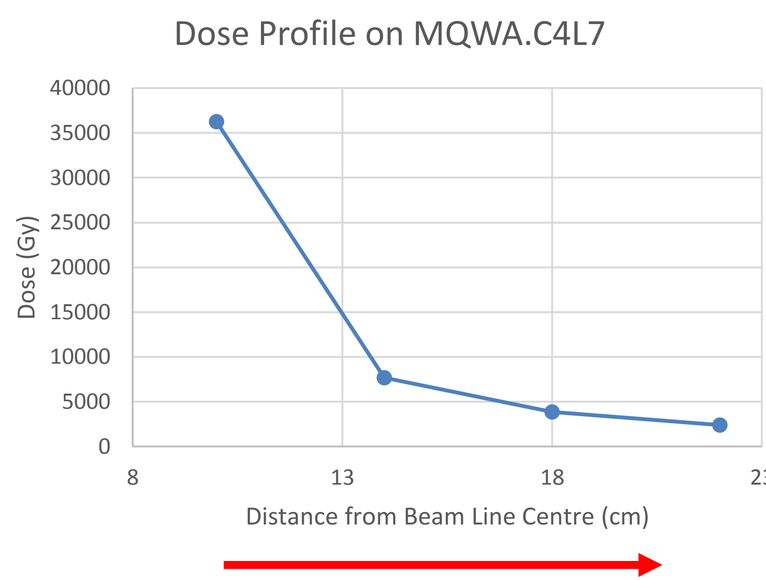
Design of supports by R. Fernandez Gomez, TE/VSC/DLM (ex Design Office)

Dosimeters Preliminary Results

First exchange of dosimeters performed in February 2016, dose recorded during all 2015 LHC Run, results analysis in progress…

- Dosimeters installed on critical magnets gave reasonable results, **confirming the list of highly irradiated magnets already prepared in last years;**
- Dose received by BLMs attached on top of the MQWs were orders of magnitude lower than the dose effectively received by the coils, need to rely on proportion to use values from BLMs in the future.
- Dose gradient measurements along magnets coils and BLMs confirmed FLUKA calculations, therefore having fixed locations for dosimeters is paramount!

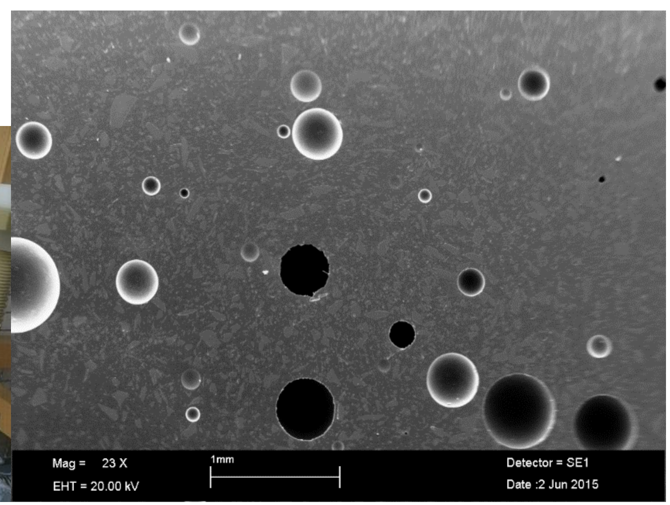


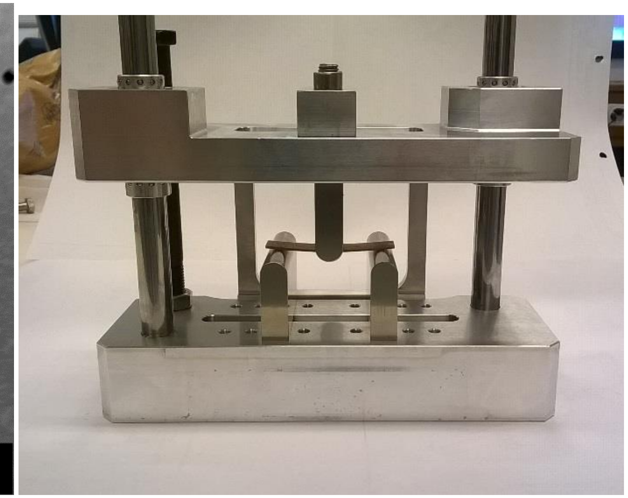


MQW Materials Radiation Hardness

- Campaign to verify effective strength of used materials against radiation induced damage: material samples produced at CERN, irradiation in Fraunhofer Institute (DE) with Co60 source up to 90 MGy, and post irradiation testing back @ CERN.
- Tests performed: Flexural tests (mechanical properties), Breakdown Voltage tests (electrical insulation), microstructural analysis, IR spectroscopy.
- Materials under testing:

1. MQW mix (EPN1138 42% + GY 6004 42% + CY 221 16% Hardener: HY 905 100 %+ Plasticizer 30ml DY 073)
2. MQW Spacers (EPON 826 + RP 1500 Hardener + MIN-SIL 120 F silica particles)

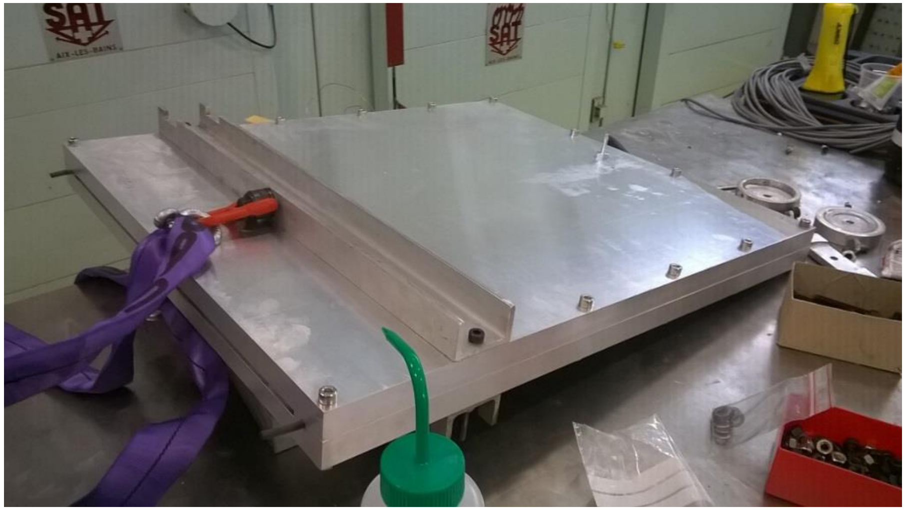





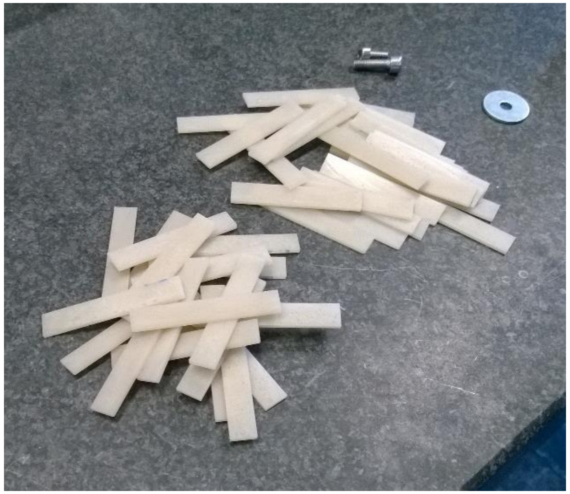
Samples production at CERN Polymer Lab

- Research of raw materials to reproduce at best resins used for MQWs (and MBWs);
- Some components were no more available, equivalent resins have been used instead (GY 6004 no more produced by Huntsmann, substituted by newer GY 776);
- Production of custom moulds & Impregnation
- Water jet cut of samples

MQW samples ready for irradiation



Ad hoc 520x520x1 mm mould to create thin and regular plates of Coils Insulation materials reinforced with Type E Glass Fibres



Flexural tests samples of MQW Spacer Material (MQW-SPA), obtained from mould 310x60x10 mm (similar to spacer geometry)

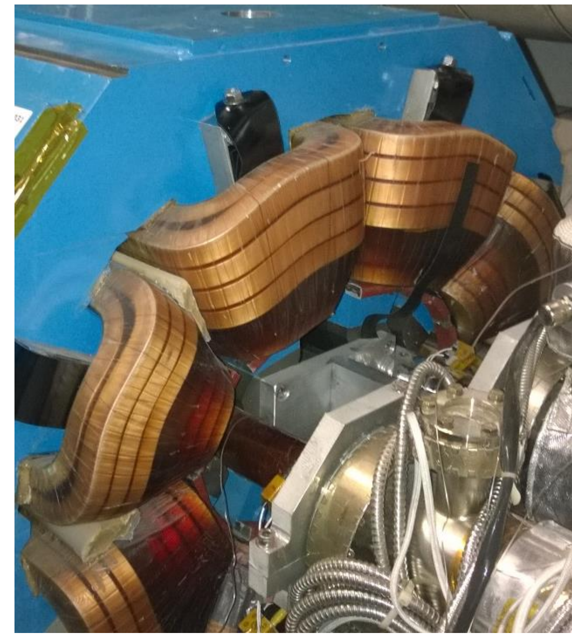
After preliminary characterization at CERN the samples are now being irradiated up tp 25 MGy, final results foreseen by Summer 2016…

MQW Coils Irradiation first results

MQW samples before Irradiation

MQW samples after 10 MGy of Co60 Irradiation

MQW C5R7 coils Feb 2016: left coils already red, right coils still transparent



- Pronounced Colour variation observed on samples, similar to irradiated coils in tunnel;
- Electrical Verification after 10 MGY does not show variations (all samples resisted to 60 KV/mm as non irradiated ones, maximum allowed value by the measuring setup);
- Mechanical tests did not show significant variations
- Microstructural analysis and IR spectroscopy foreseen in next weeks…

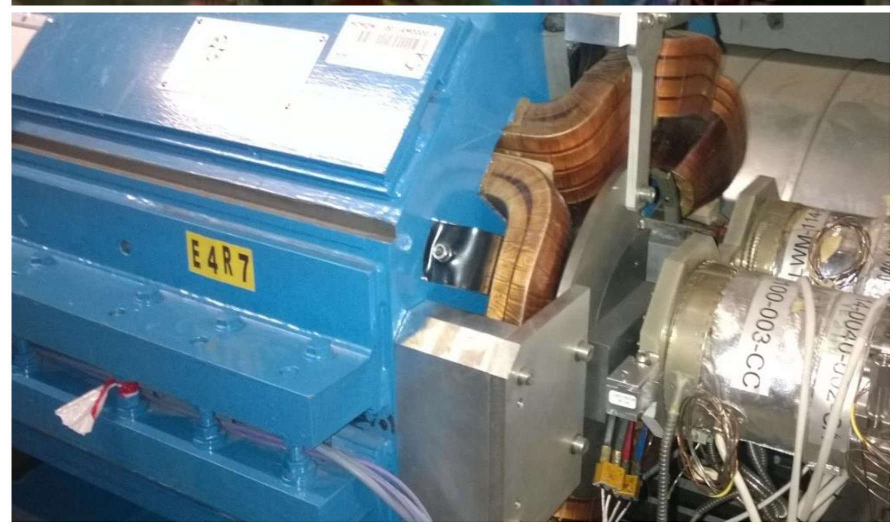
Launched activities will give a detailed picture of MQW radiation damage limits, thus allowing to define in advance eventual design improvements!

Beam Losses Induced damage: MQW Heat Test

Introduction To MQW Heat Test

1) Development and installation during LS1 of Tungsten Heavy Alloy (WHA) shielding to protect coils from radiation, giving a reduction of dose rate by 1/3!
2) Tunnel ventilation in IR7 will be blocked due to high radiation levels…

➔ The high energy deposition on shields, which have limited cooling capability, could lead to dangerous hot spots or too high temperatures on the coils…

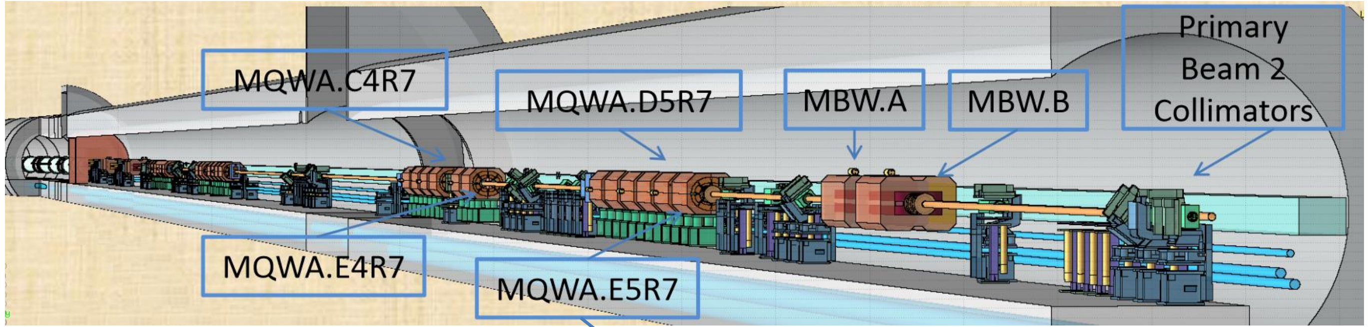


Preparation of ad hoc test:

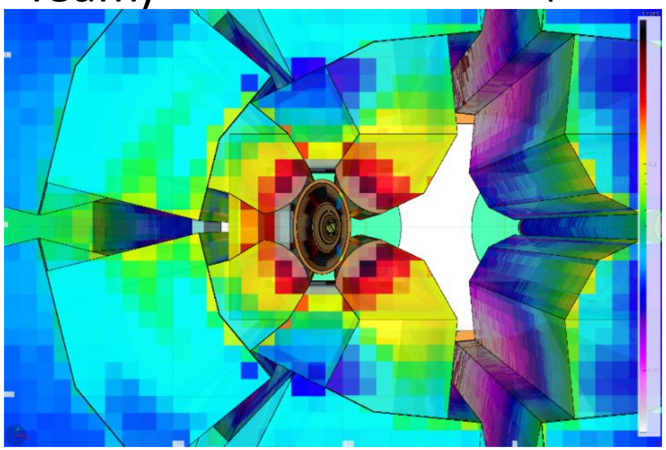
- FLUKA calculations of Power Deposited as a function of LHC parameters (Fast Losses, Continuous Operations)
- Analytical calculation of Temperature increase
- Development of ad hoc setup (heating inserts, thermo-probes, DAQ system, LabVIEW interface)
- Performance of different tests to evaluate any possible dangerous situation…

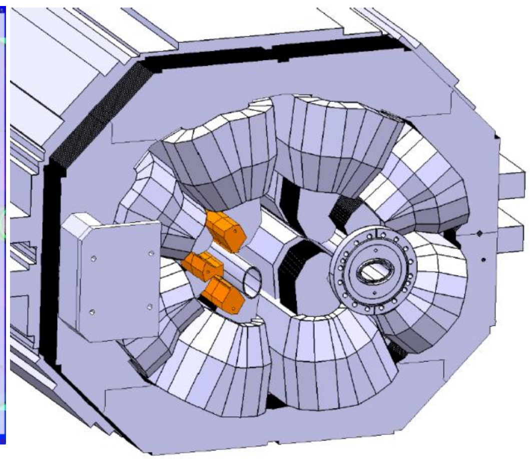
FLUKA Calculations

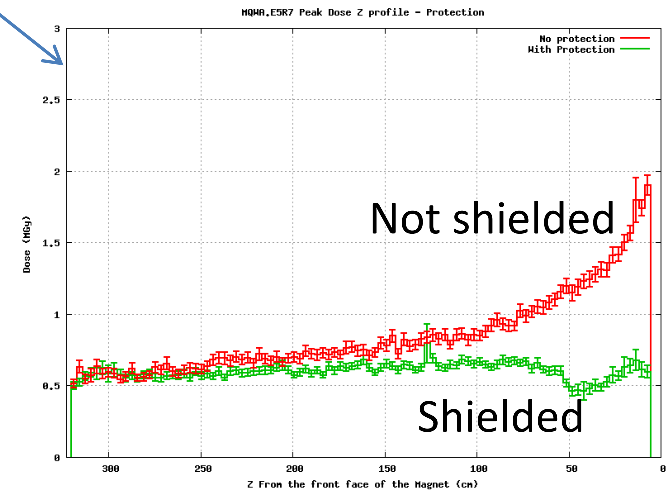
FLUKA calculation of beam losses in LHC Pt. 7 according to LHC Collimation settings (courtesy of E. Skordis and F. Cerutti, FLUKA Team)



FLUKA model of LHC Pt. 7, showing the most exposed MQWs (MQWA.E4R7 and E5R7)







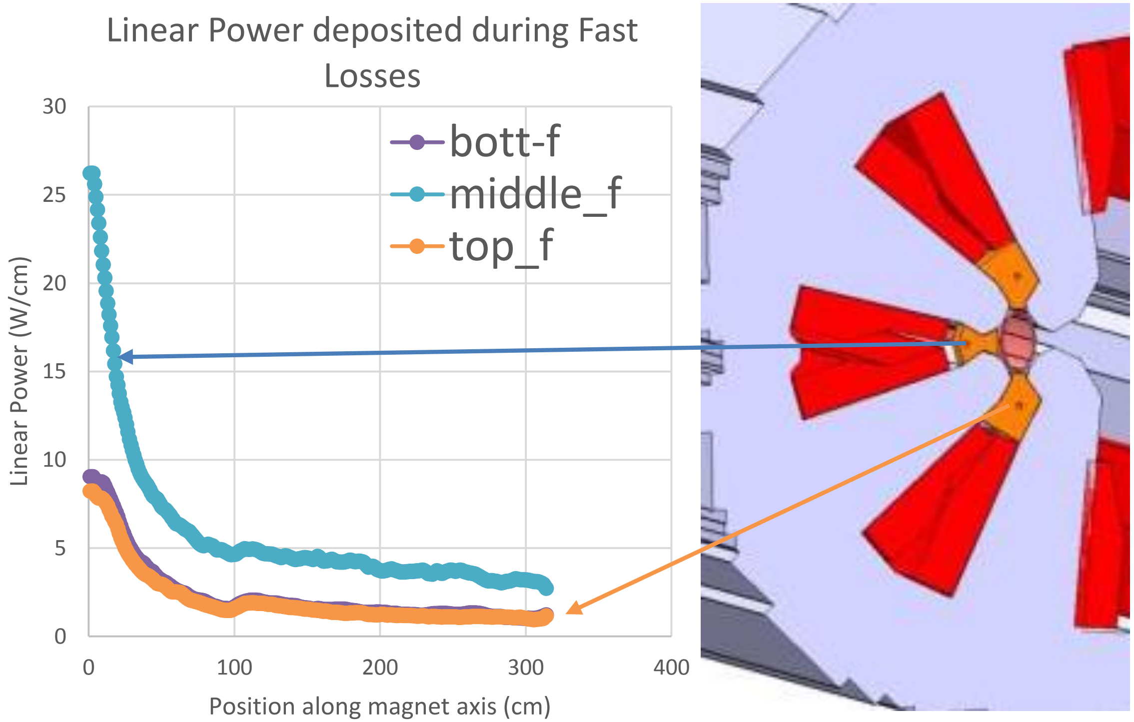
Shields insertion allows for a factor 3 reduction of dose on coils according to simulations!

➔ 4 magnets shielded during LS1 in Pt.7 (MQWA.E4 L and R, MQWA.E5 L and R), more to be shielded during LS2 to assure smooth operations until end of HL-LHC era…

Need to verify that the MQW cooling circuit is capable to evacuate all energy deposited on the inserts without dangerous hot spots on coils!

Power Deposition On Shieldings

- FLUKA Maps of energy deposited along the inserts (GeV/p) (E. Skordis).
- Calculation of power deposited on single inserts to evaluate situation…
- Most loaded inserts: horizontal line (d.n. LHCMQW0119/0120) for first 100 cm (first 20 inserts made in Inermet180, remaining inserts made in Cu).



Beam Losses Temporal Evolution: Beam Losses in Collimators have an exponential decay function ➔

$$N(t) = N_0 e^{\frac{-t}{\tau}}$$

Where N_0 is the initial number of particles lost and τ is the decay constant.

Power deposition is proportional and must follow same temporal function.

Test Goal: equip first 1 m of Middle Line inserts with Heating Resistances and Thermo-probes to verify absence of hot spots in the Yoke and Coil close to equipped inserts.

Power Deposition on Rest of Magnet

MQW 038 equipped **with only 1 m of Middle line heating inserts**;

➔ Other contributions to dT reduced to equivalent adiabatic heating (assuming **average specific heat of the magnet)** taking into account:

- Yoke
- Coils
- Coils insulation (resin + glass fibres)
- Remaining inserts (Cu and WHA)
- Beam lines

Magnet part	Material	Energy (GeV/p)
Total MQW (including beam pipe and yoke)	Cu + Epoxy + Fe + INOX	240
Beam pipe	INOX 316 LN	38
Yoke (close to beam)	Fe	10
Top Shield W (1m)	W	5.13
Middle Shield W (1m)	W	7.44
Bottom Shield W (1m)	W	5.18
Front Shield	W	7.38
Top Shield Cu (2.2m)	Cu	4.84
Middle Shield Cu (2.2m)	Cu	5.82
Bottom Shield Cu (2.2m)	Cu	4.90

Case	Beam Loss rate (p/s)	dt	Heating rate (K/s)	dT (K)
Case 1 Cont. Op.	0.9E11	1 h	0.0009	3.42
Case 2 Fast Losses	4.5E11 p/s	60 s	0.0045	0.27

Hypothesis of Homogeneous distribution of energy :

- Valid for Continuous Operations (enough time to reach thermal equilibrium);
- For Fast Losses negligible dT of the magnet ➔ Conservatively assuming Cont. Op. dT;

Hypothesis of absence of thermal exchange with ambient:

- Valid, absence ventilation in pt.7, RT in tunnel ~40C, **reduced heat exchange**;
- Cover on top of magnet to increase ambient T to ~40C, **very similar situation to tunnel**.

Magnets dT significate only for Continuous Operations!

=> Reduction of water flow to increase magnets T by ~3.5 K…

Experimental Tests Definition

1) Preliminary Verification:
Nominal water flow (28 l/min) and 7 TeV current (610 A) for 1 h (or until equilibrium), inserts inside but not powered.
➔ Measure magnet's base T in ideal conditions

2) Preliminary Verification with Cover:
Same as 1), plus plastic cover placed on top of magnet with fan heater to reach 40C of ambient T.
➔ Measure magnet's base T inside tunnel (RT ~40C)

3) Fast Losses:
Same as 2), once in equilibrium water flow reduced until T magnet increase by 3.5 K, then powering of inserts with Fast Losses parameters for 60 s.
➔ Verify inserts T evolution during fast Losses and final T reached in the magnet.

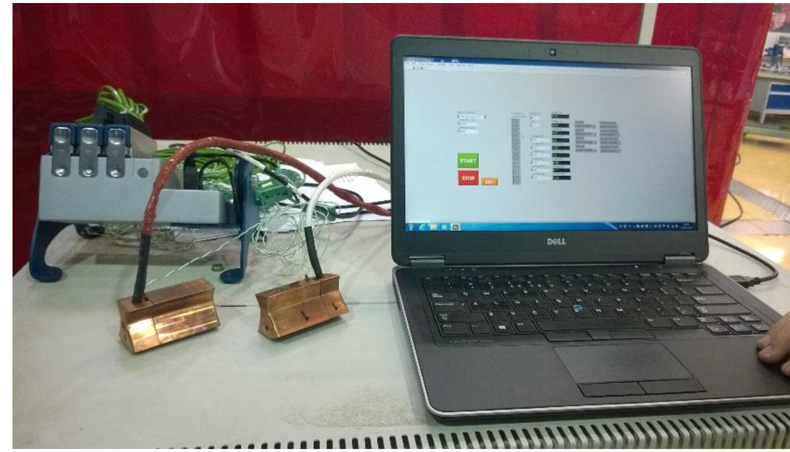
4) Continuous Operations:
Same as 2), once in equilibrium water flow reduced until T magnet increase by 3.5 K, then powering of inserts with Continuous Operations parameters for 1 h (3600 s).
➔ Verify magnet's T evolution and final T reached in the magnet.

5) Maximum Power Evaluation:
Same as 2), once in equilibrium water flow reduced until T magnet increase by 3.5 K, then powering of inserts in steps waiting for equilibrium between steps.
➔ Verify maximum sustainable continuous power on inserts during operations.

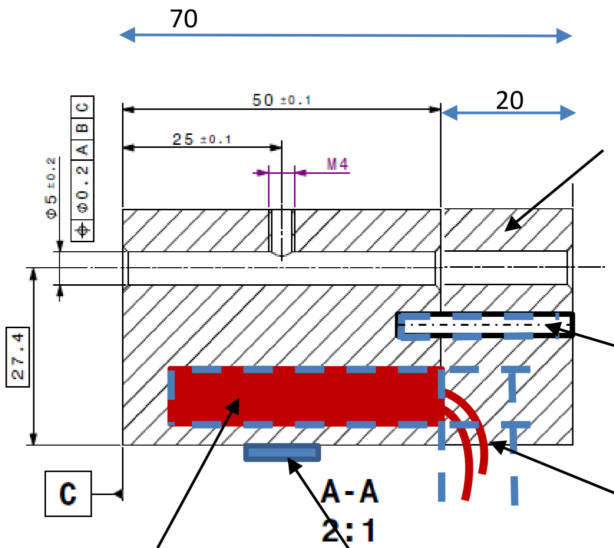
6) Minimum Water Flow Evaluation:
Same as 2), once in equilibrium powering of inserts with Cont. Op. parameters and reduction of water flow in steps waiting for equilibrium between steps.
➔ Verify minimum water flow needed to avoid magnet's overheating in operations.

Experimental Apparatus

- MQW-038 spare magnet: magnet used for MQW Life Test (mechanical fatigue test), certified after simulating the entire HL-LHC life span (60’000 powering cycles, ~2036) ➔ representative of installed units.



Heating Blocks



2nd part obtained by slice 20 mm thick

Screw to bond parts

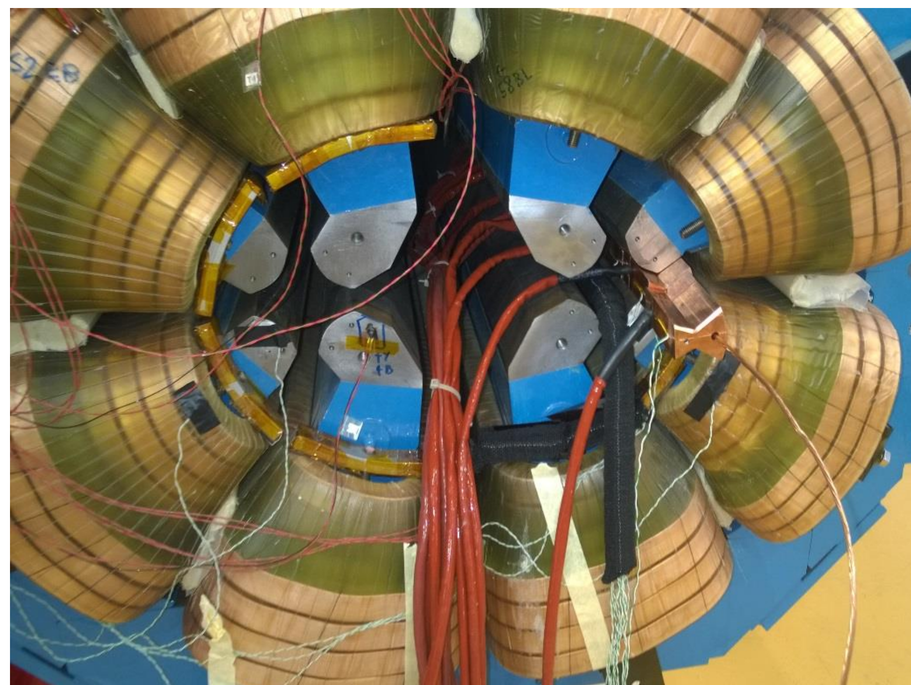
Hole Ø8 mm to accommodate resistance

Thermal probe

Machine aperture for cables on the second block

Design Outlines:

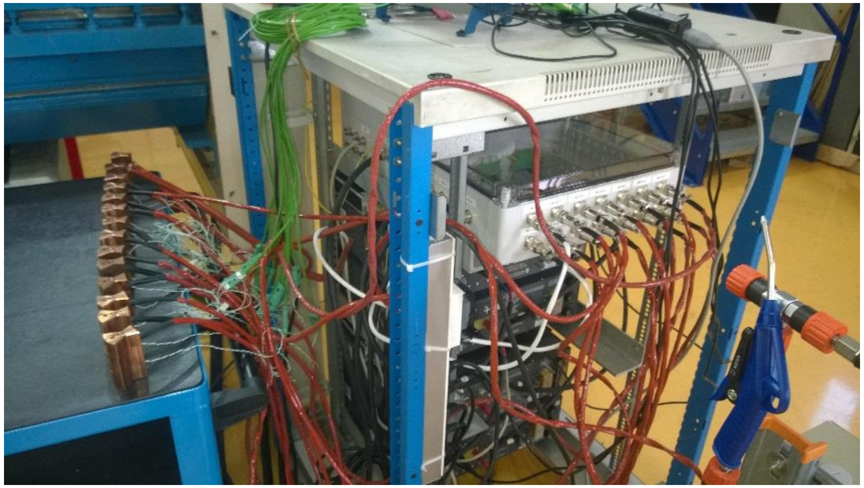
- Blocks to accommodate one Heating Cartridge and one thermal probe;
- Total of 14 blocks needed to equip 1 m of magnet;
- Cables protected with thermal resistant insulation;
- Thermal probes cables separated from power cables;
- Insertion procedure as standard inserts (cables sorting from magnet's central aperture).

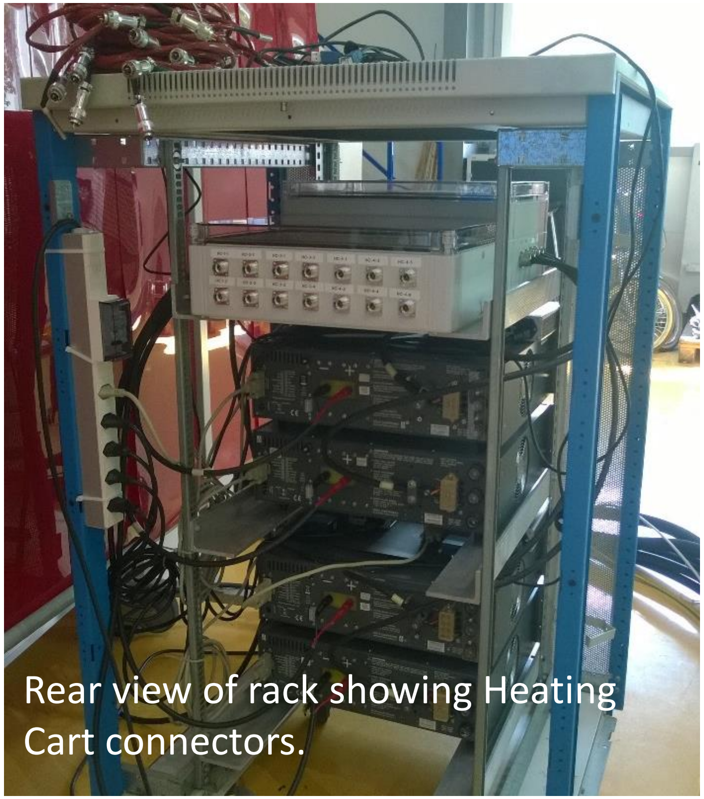


Power Supply Rack & DAQ System

Rack accommodating:

- 4 power supplies (PS) Delta El. SM300/10D;
- 4 control boxes Delta El. (bridge PS with PC);
- Safety Box: provides power to the 4 PS and incorporates the Emergency Stop button;
- Distribution Box: receives power from PS and divides it to the Heating Blocks.





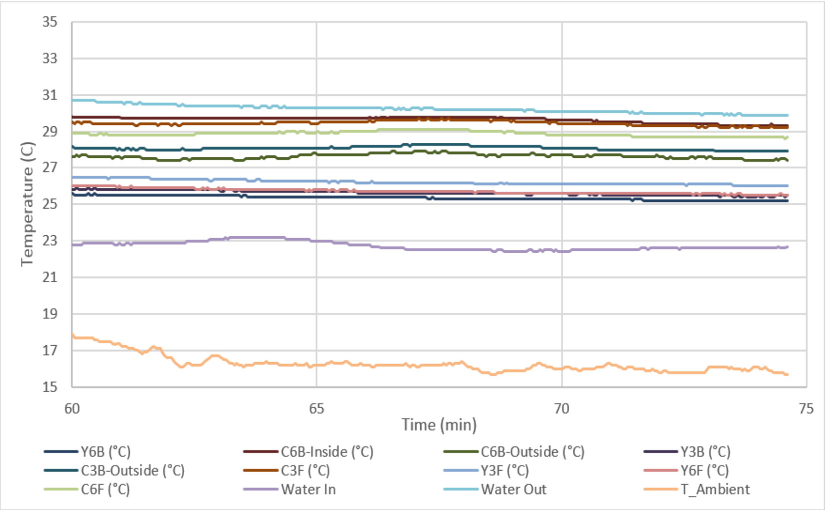
Rear view of rack showing Heating Cart connectors.

LabVIEW DAQ interface: controls 4 PS, receives signals from 25 Thermal probes, can generate time dependent functions and provides a software emergency stop and log file.

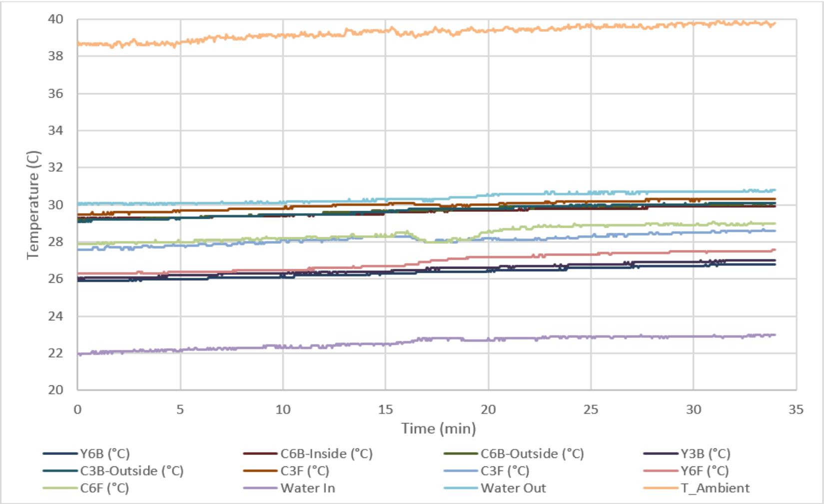
Versatile and customizable system!

Case 1 & 2: Preliminary Verifications

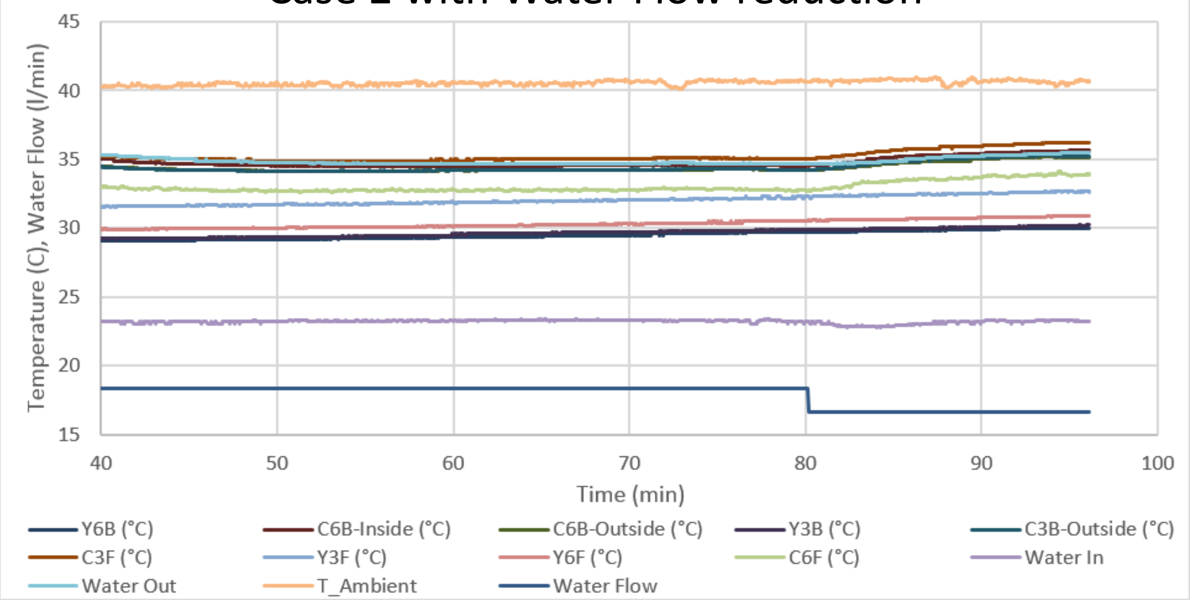
Case 1: No Cover, TA ~16C



Case 2: Cover, TA ~40C

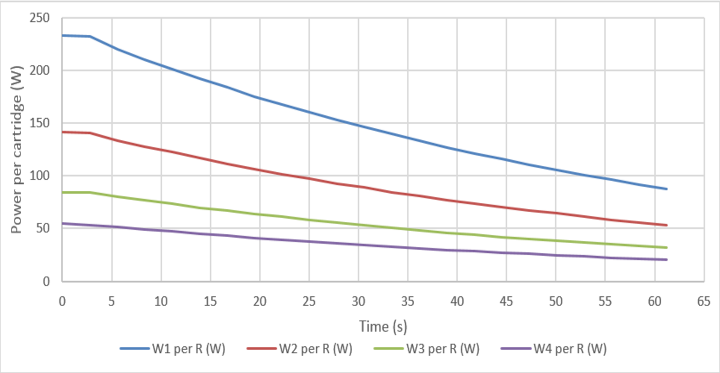


Case 2 with Water Flow reduction

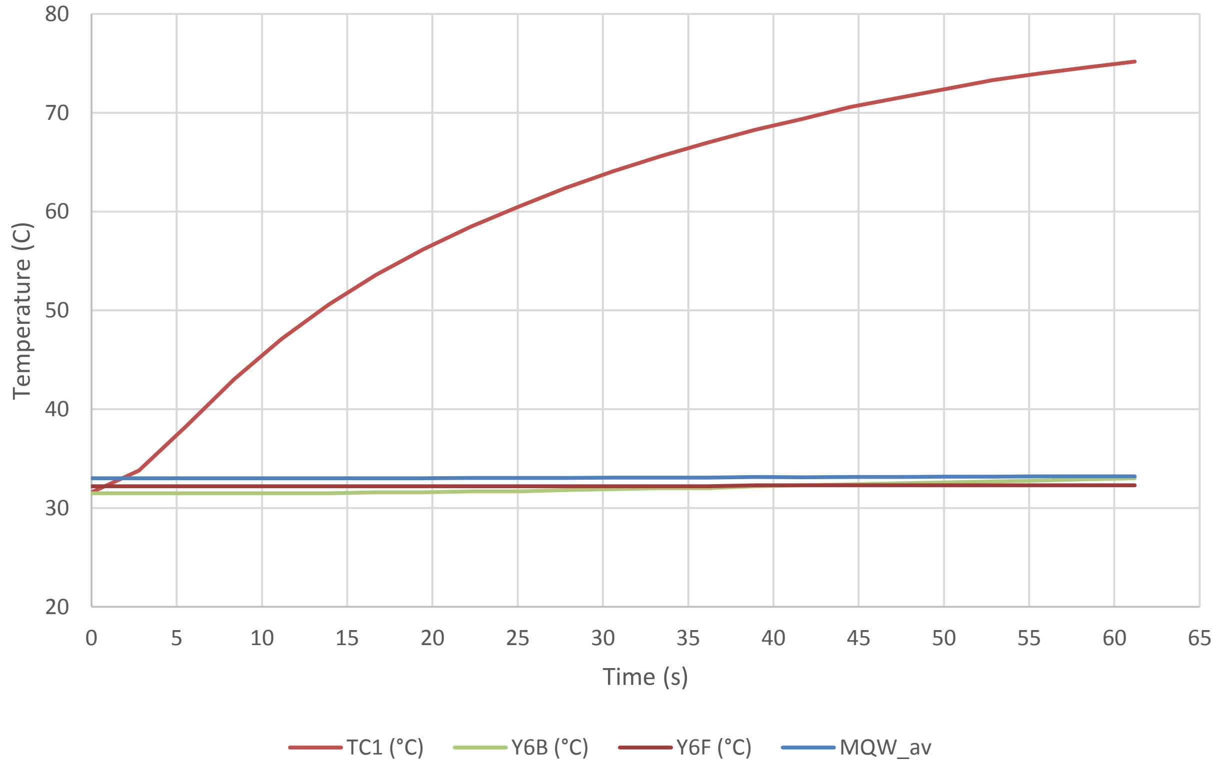


Preliminary cases allowed to take a picture of MQW operating temperatures as a function of Water Flow and Cover (plus heating)

Case 3: Fast Losses

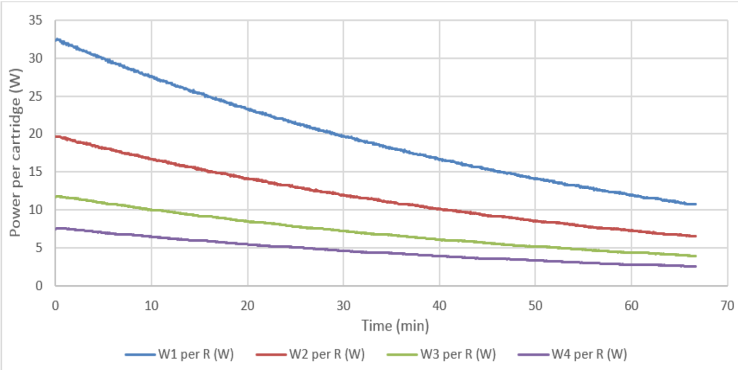


- MQW stable as in Case 2 with reduced waterflow (18 l/min water @23C, Ambient Temperature 40C, 610 A),
- Imposition of exponential decay power curves for the 4 power supplies as in picture with Fast Losses parameters,
- Recording of Temperatures for **60 s.**

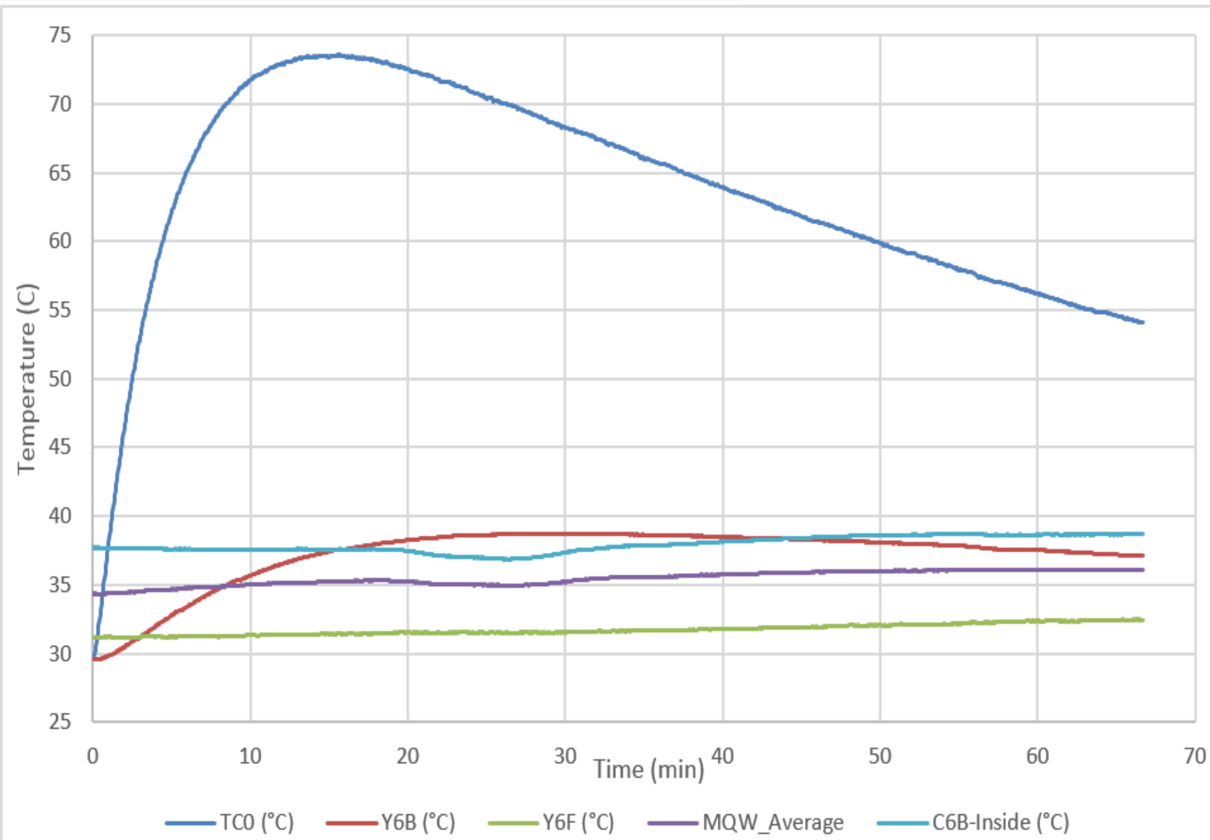


Results show that only the heating cartridges become hot and reach 75C after one minute of Fast Losses, however the rest of the magnet remains perfectly cool with negligible variations.

Case 4: Continuous Operations



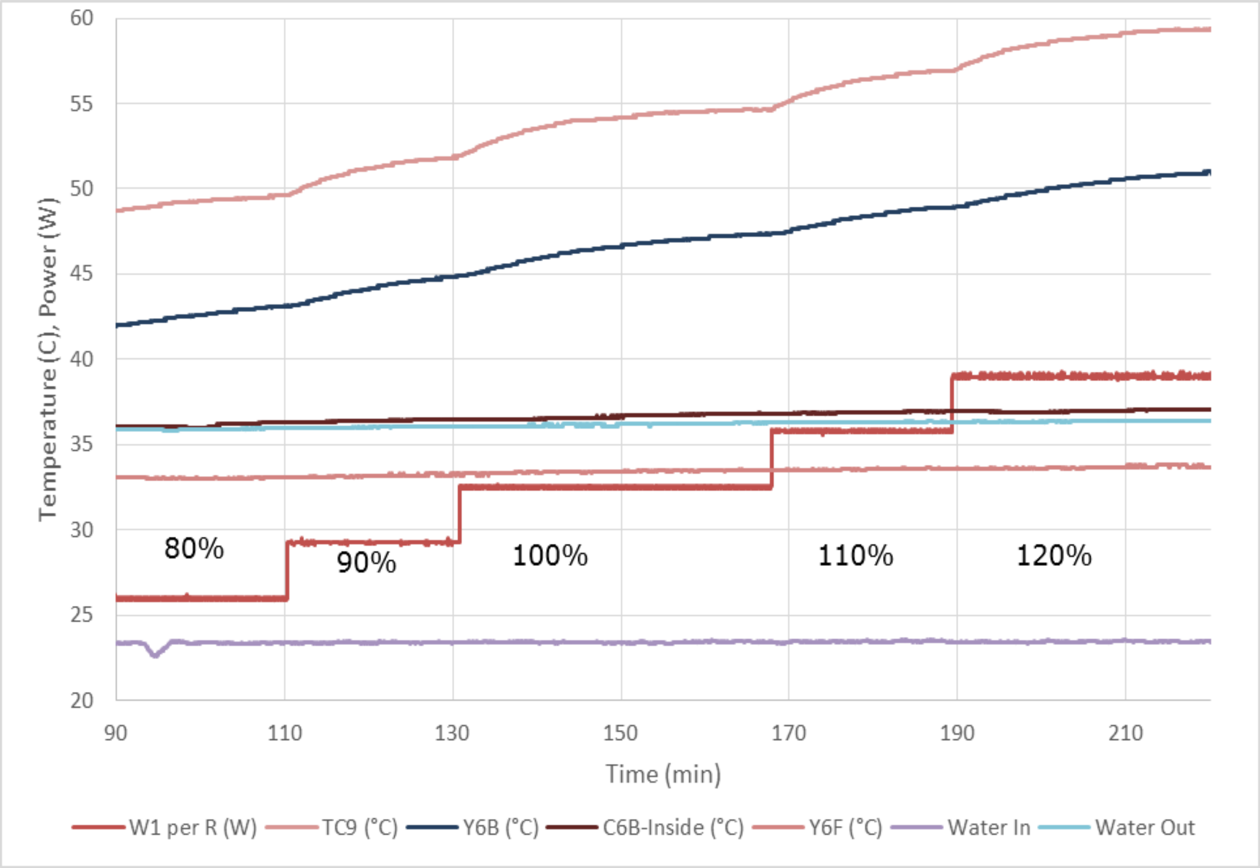
- MQW stable as in Case 2 with reduced waterflow (18 l/min water @23C, Ambient Temperature 40C, 610 A),
- Imposition of exponential decay power curves for the 4 power supplies as in picture with Continuous Operations parameters,
- Recording of Temperatures for **1 hour!**



Results show that after 15 minutes the inserts have a peak at 75C but afterwards the rest of magnet's structure starts to cool down the inserts. The Yoke close to inserts heats up to 40C but after tends to thermalize with the rest of the magnet.

Case 5: Power Limit

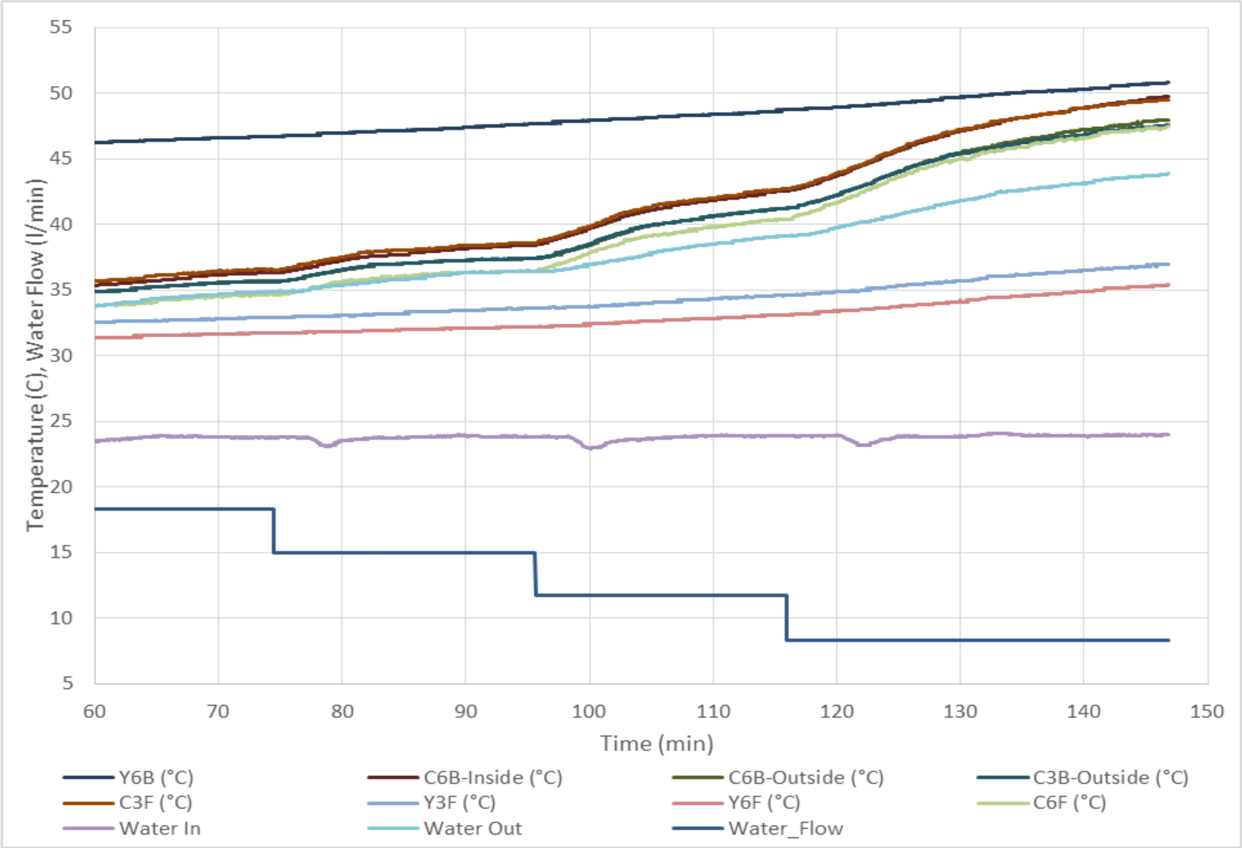
- MQW stable as in Case 2 with reduced waterflow (18 l/min water @23C, Ambient Temperature 40C, 610 A),
- Imposition of power on inserts at increasing steps (10% of nominal power for Continuous Operations)
- When power step reaches equilibrium, increase of power to next level and so on.



Test showed that the MQW cooling system is largely capable to keep the magnet to acceptable temperatures even with constant power equal to 100% of nominal continuous operations values (max T yoke close to inserts 47C, max T on coils 40C)

Case 6: Waterflow Limit

- MQW stable as in Case 2 with nominal waterflow (28.3 l/min water @23C, Ambient Temperature 40C, 610 A),
- Imposition of constant power on inserts at 100% of nominal power for Continuous Operations
- When temperatures reach equilibrium, waterflow is reduced by 3.3 l/min (200 l/h) until the magnet is no more able to keel acceptable temperatures

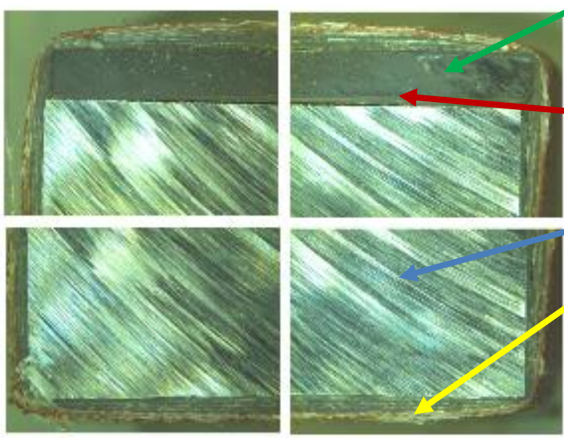


Test showed that the MQW water flow can be reduced in accidental case down to 15 l/min without increasing the coils temperatures to more than 40C, while at 12 l/min the coils will thermalize at around 45C, which could be still acceptable if for very short periods.

Corrective actions:
MQW Brackets Substitution in LHC Tunnel

Corrective Actions: Brackets Substitution

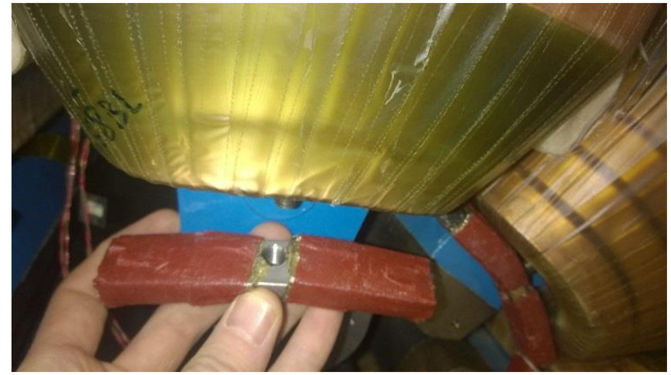
- MQW Life Test showed how the weakest element of the MQWs is the rubber insulation placed between brackets and coils
- A new insulation system made of Polyurethane/Polyimide, epoxy resin and Mica has been developed and tested to improve electrical insulation reliability over next years



Proposed system features extremely high electrical insulation properties, very good mechanical properties and high radiation hardness (thanks to Mica foils and polyimide), plus easiness of installation inside the tunnel

Corrective Actions: Brackets Substitution

New brackets produced at CERN Polymer Lab to equip all installed MQWs and spare magnets, 440 parts produced!



New Brackets installation in LHC IR3 and IR7 performed during February 2016, 46 magnets interested (all MQWs apart from MQWA.E5R7 and E5L7 that will be removed during LS2).
Each magnet required around 25 minutes, depending on vacuum equipment presence or shield presence.

All MQWs are now equipped with new insulated brackets

Conclusions

Present experimental verified in deep the possible damage mechanisms of LHC MQW magnets in the post-LS1 era from a mechanical, radiation hardness and thermal point of view;

- Mechanical damage: first damage appearing on MQW Brackets insulation,
  - corrected with preventive tunnel intervention;
- Radiation Hardness: dose monitoring and materials testing ongoing,
  - results by Summer 2016;
- Beam Losses Heat Deposition: experimental verification showed how the MQW cooling system is capable to evacuate the energy deposited even in very demanding situations,
  - No need for corrective actions…

Thank for your attention

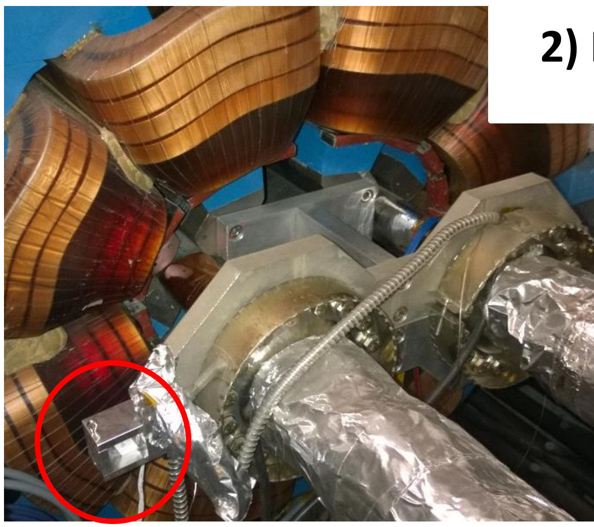
MBWs and MQWs Damage Evaluation

Prediction campaign of eventual MBWs/MQWs failures on three fronts

1) Mechanical induced damage:

- cyclic powering cycles lead to coils deformation, estimation of ~60’000 powering cycles on MQWs before end of HL-LHC…

➔ **MQW Life Test: Endurance fatigue test on spare MQW to simulate LHC powering cycles (@7 TeV) while acquiring key parameters to verify life span.**



2) Radiation induced damage:

- Showers from Collimators in IR3 and IR7 impact directly on MQWs and MBWs coils, materials degradation with insulation loss risk…
- HL-LHC parameters increase foreseen dose by factor 10, used materials to receive doses higher than their literature limits!

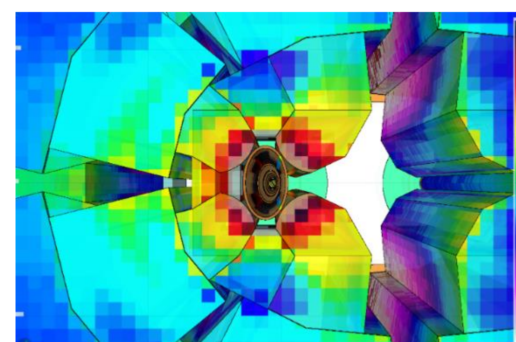
➔ **Verification of doses received by coils with Dosimetry Campaign: installation of 114 long term dosimeters in meaningful locations and BLMs for long term predictions…**

➔ **Irradiation and testing of MQWs and MBWs materials samples to measure the properties loss due to ionizing radiation!**

3) Heat induced damage:

- Energy deposited by beam losses on warm magnets generates thermal loads to be evacuated by cooling circuit, risk of hot areas due to Tungsten shieldings…

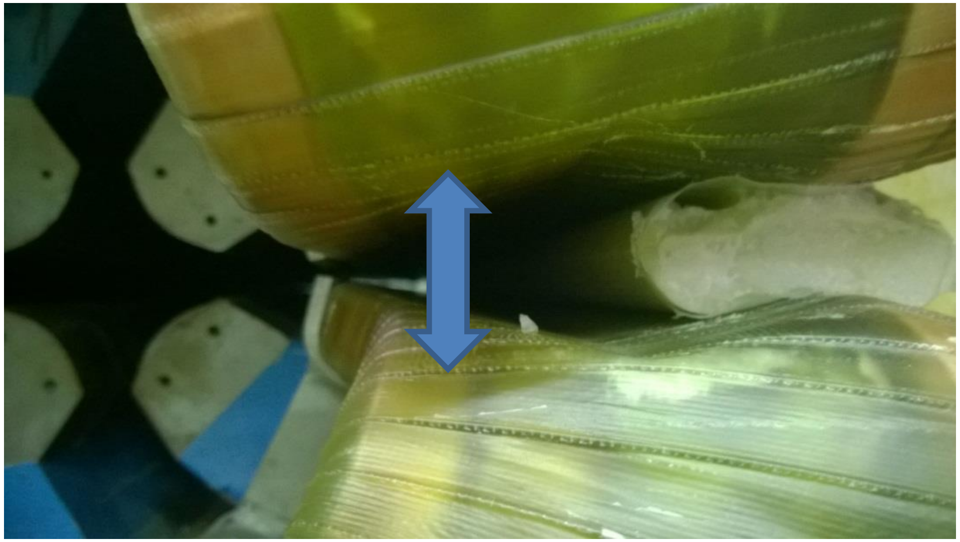
➔ **Ad hoc Heat Test to simulate Beam Losses Energy Deposition inside tunnel environment and verify absence of hot spots and MQWs cooling capabilities.**

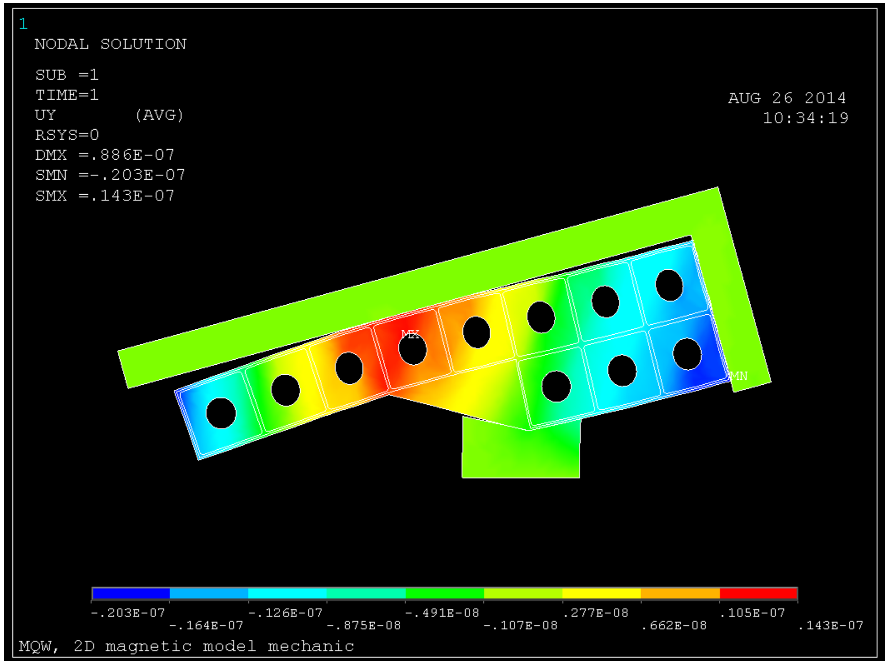


Background of EM Induced Displacement

MQW magnets coils subject to imposed displacement during current applications: Generation of cyclic stresses in coils, spacers and at the coil-joke contact area…

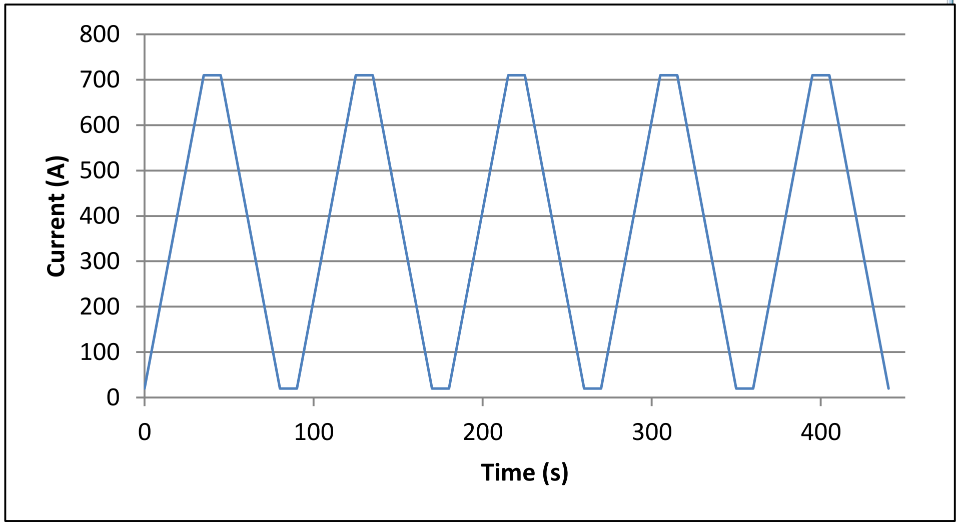
APDL simulations showed limited displacement and stresses, however the **large number of cycles** might lead to the risk of coils movement and/or fatigue induced failures with **electrical insulation degradation that will affect the magnet's performances.**

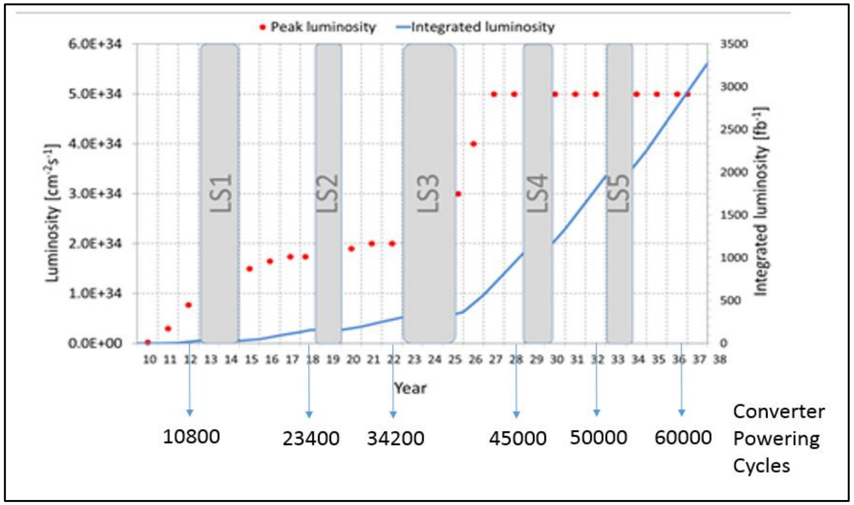




Loading Conditions

- MQW tests made in analogous conditions to LHC tunnel (water, concrete supports)… **apart from radiations!**
- Definition of MQW cyclic load through TIMBER app:
  - Each LHC super-cycle MQWs do 4 complete cycles, 3 of pre-cycle up to 680 A to restore magnetic conditions, 1 of regular operations (340 A @ 4.5 TeV, 610 @ 7 TeV).
  - Conservatively chosen cycle: 20-710 A with 20 A/s ramps, 10 seconds plateau on top and bottom, total cycle duration 90s.





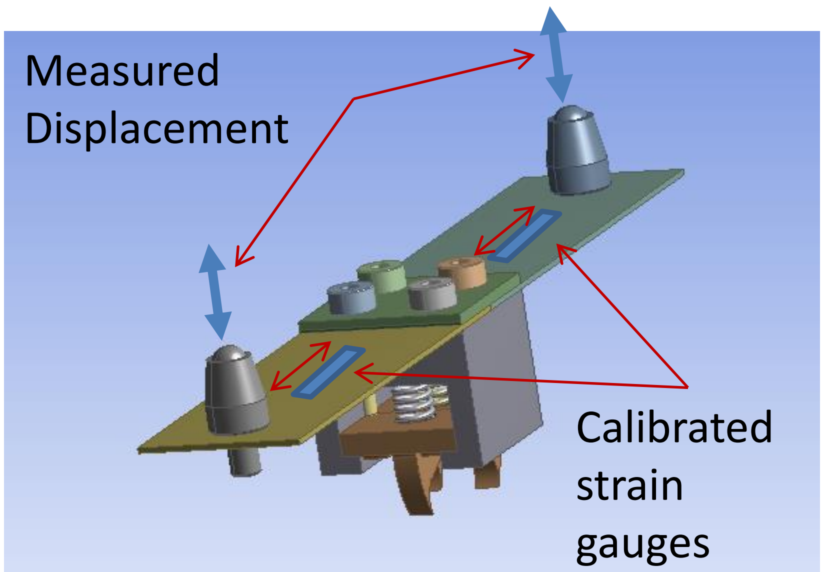
MQW Life Test Duration to allow prediction of entire LHC life:

- Operations from 2010 up to 2036 (end of HL-LHC era)
- 16 years of operation excluding technical stops
- Every year has 10 months of operations…

➔57600 cycles (~60'000) up to the end of HL-LHC era, ~50 days of test!

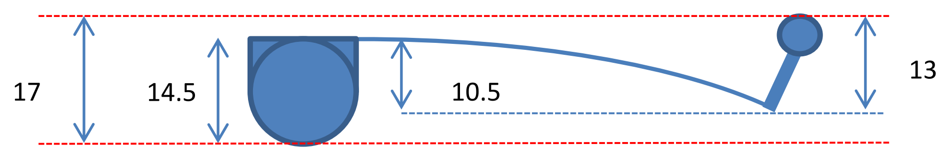
Coil-Coil Displacement Sensor

Displacement measured through “Home made CuBe beam based displacement sensors”.
R&D in collaboration with: R. Fernandez Gomez (EN/MME, Design Office), M. Guinchard (EN/MME, Mechanical Lab.) and R. Gauthier (TE/MSC, Polymer Lab).



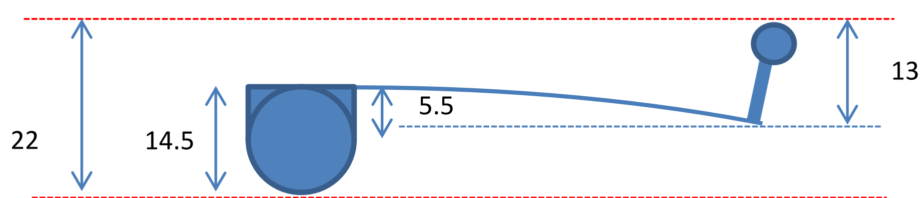
1) Strain gauges calibrated on the final sensor through a LVDT for µm level accuracy!
2) Sensors inserted (with compressed arms) through a pipe at chosen depth inside magnet.
3) Once installed, the CuBe arms open and their elasticity will keep it forced on the resin walls.

Insertion:



22 mm aperture, 20 mm Al pipe, 17 mm available inside pipe

Nominal Condition:

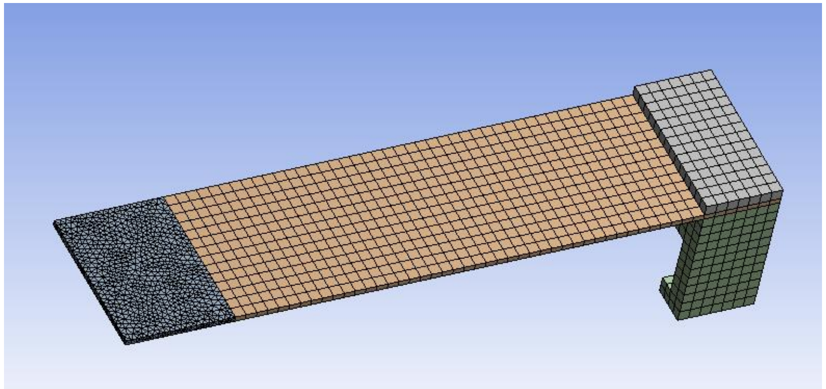


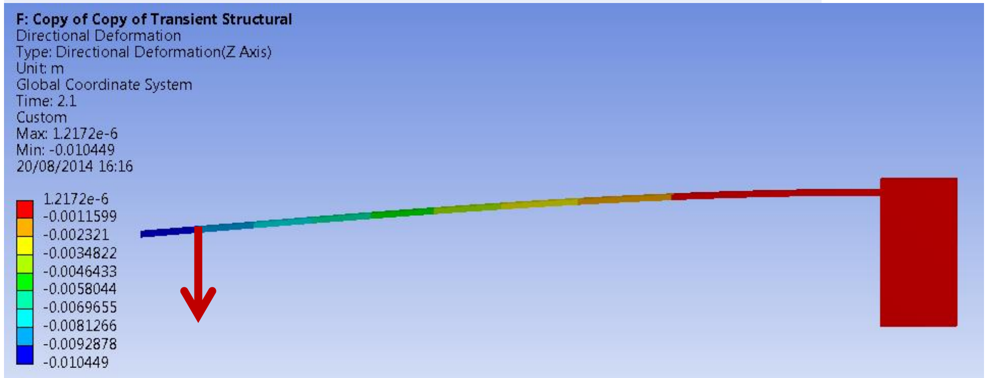
Cycling on a 22 mm aperture

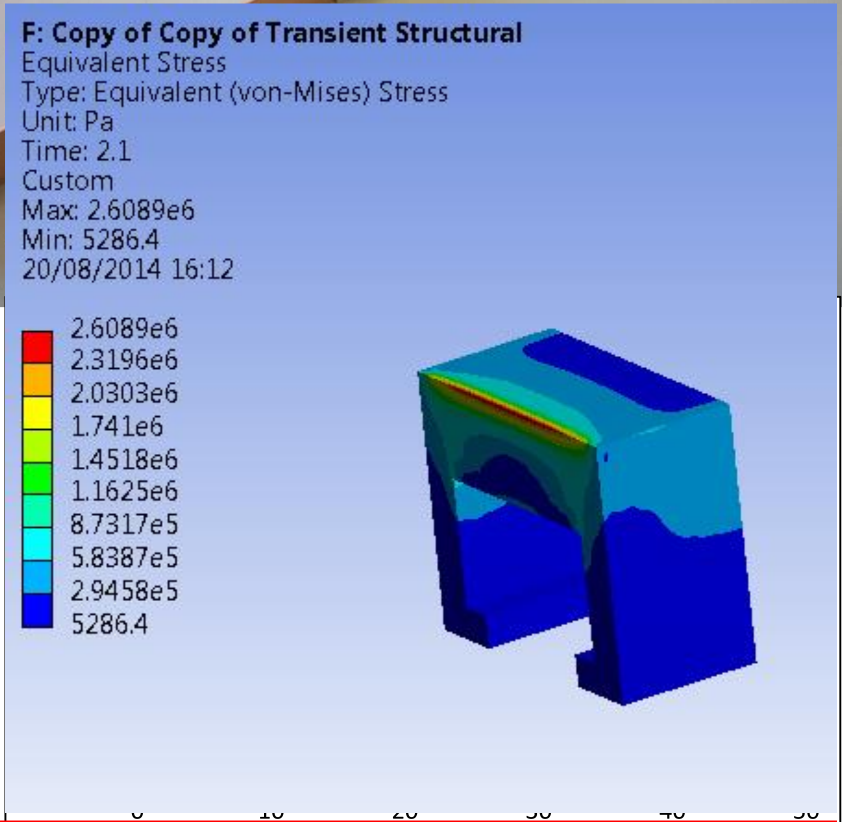
Design, prototyping & production

3D design + Ansys 3D analysis:

1) Verification of polymer sensor support
2) Evaluation of mechanical behaviour with different arms lengths
3) Rapid 3D prototyping







150 mm and 180 mm lengths assure a large measuring range (> +/-5 mm) and an easy insertion without trespassing the materials cyclic strength limit!

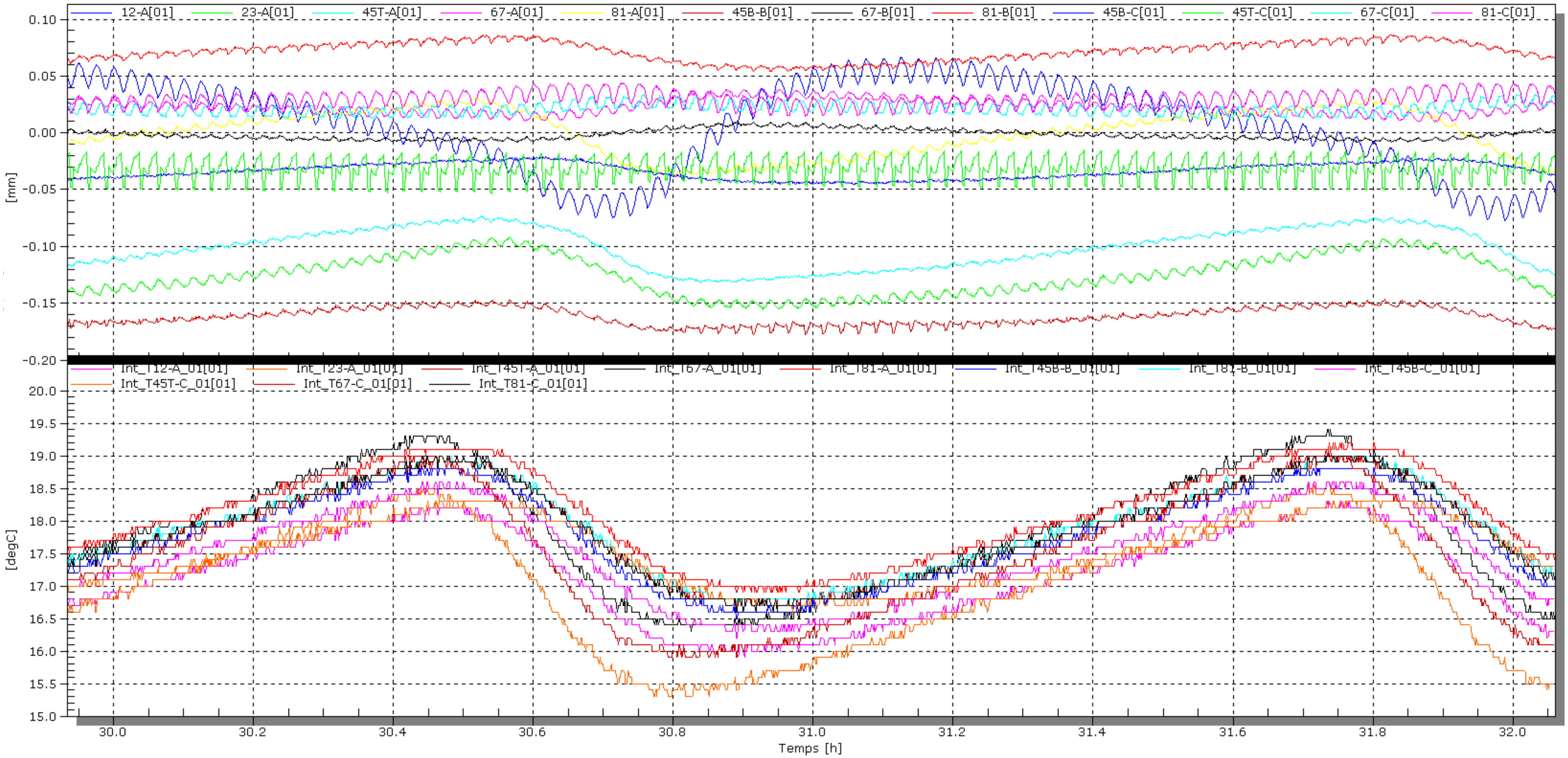
Acquisition system

- 11 Temp probes, 12 LVDTs and 16 (8x2) Strain gauges
- 1 channel from PC at 0-10 V (to acquire current profile)
- ➢ need for a 48 channel acquisition system connected to a controlling laptop (remotely accessible)

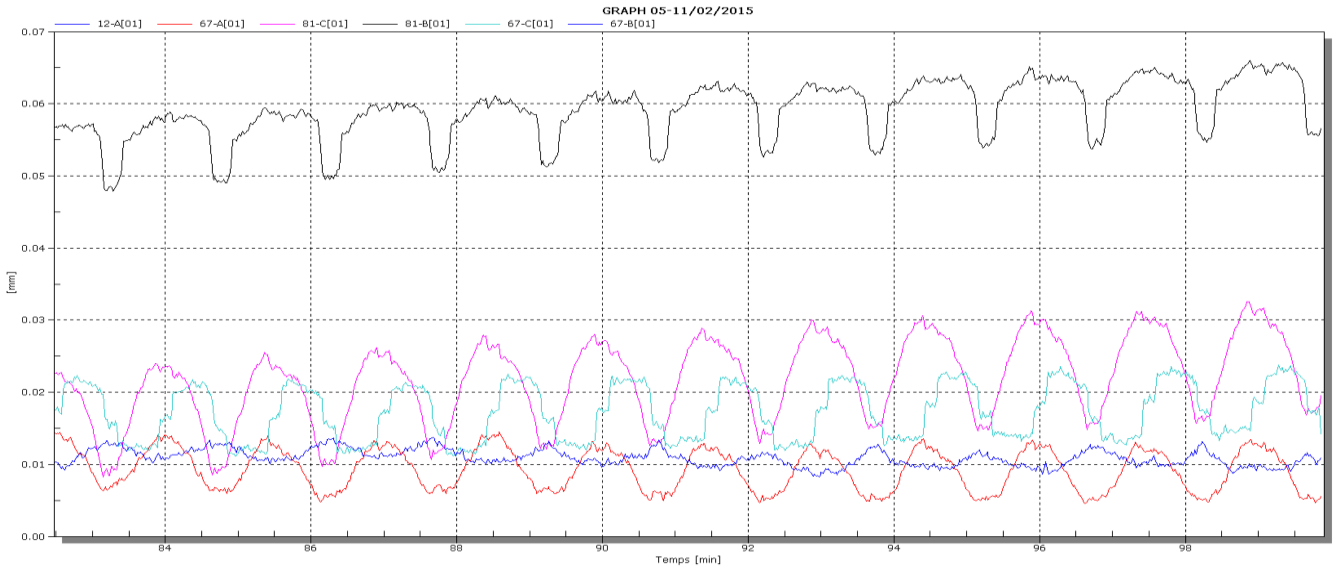
- 2 acquisitions frequencies: base at 1 Hz (slow reference) and fine at 50 Hz (detailed data every 100-1000 cycles)
- Acquisition time ~ 90 days
- Need to be able to access data even during tests → data acquired by connected laptop accessible from internet
- Mechlab Cost ~ 10 KCHF (+/- 5) for: probes + acquisition system installation + data analysis in real time + final lab report + raw data
- Other costs: supports design + production at atelier

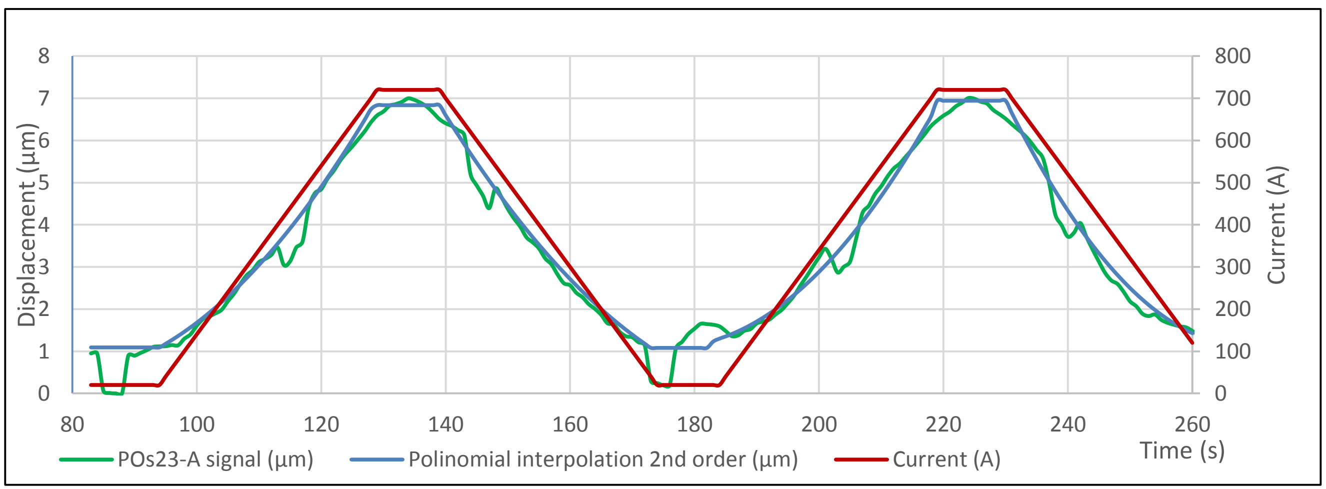
DS & T Signal Analysis I

The EM induced displacements are clearly visible with higher magnification of time scale, however their absolute amplitude is lower than the one due to T variation and the values depend strongly on location



DS Signal Analysis II – Physical





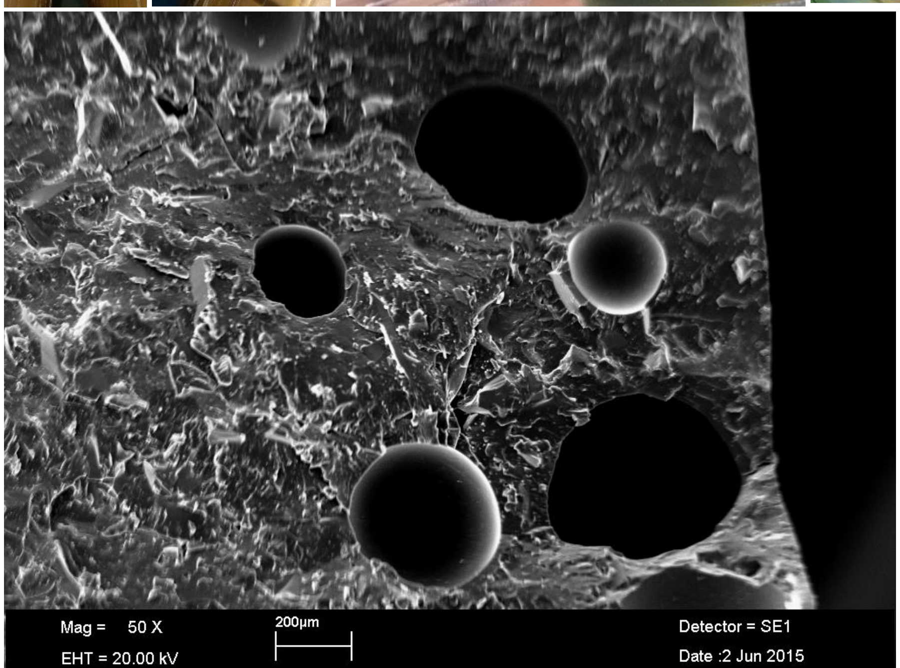
Analysis performed:

- Catman-Matlab acquisition of gauges raw data,
- average between gauges of same sensor,
- smoothing and sampling,
- selection of single cycles for detailed analysis,
- Overlapping of Polynomial fit and Current cycles.

Very good fitting of order 2 polynomial functions ➔ Displacement ∝ current2 ;
Good reproducibility of order 2 polynomial parameters across sequential cycles;

MQW Coils Spacers Degradation - I

Initial Situation of all coils



Pictures show spacers between coils 8-1, 1-2, … in clockwise order.

- Spacers 8-1 and 2-3 showed material detaching right after installation in NormaTEF
- Spacers 4-5, 5-6 and 7-8 had cracks on the surface without detaching

➔ Pre-existing damage due to magnet's ageing and transport.

➔ Extremely porous material with macro-cavities and holes (mm scale)

Heating Blocks Materials Properties Effects

Property	Copper OF	Inermet180 (WHA)
Density (g/cm^3)	8.93	18
Specific Heat (J/KgK)	385	134
Thermal Conductivity (W/mK)	385	90.5
$\rho * c_p$ (J/cm^3K)	**3438**	**2414**

$$dT = \frac{Q}{m * c_p} = \frac{Q}{V * \rho * c_p}$$

With same geometry and amount of Heat the dT obtained depends on the $\rho * c_p$ product of the material…

➔ To have same dT as for WHA inserts Cu requires ~142% of the energy required by WHA inserts

Cases:

1) In Cont. Op. case the inserts dT is limited by the heat exchange with the rest of the magnet, so after the initial transient the dT is governed by the power generated in the inserts and not by their thermal properties;
   - Need to use same power as per WHA inserts

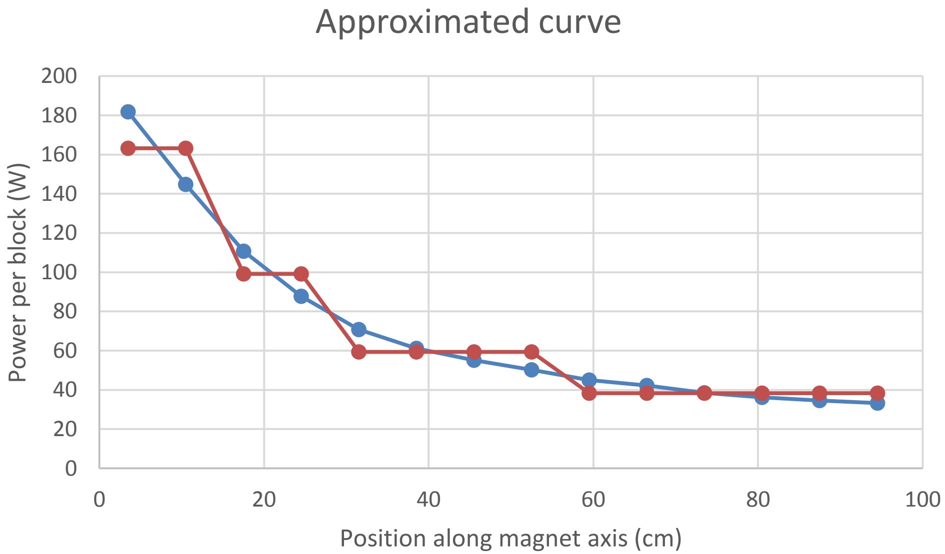
2) In Fast Losses case the inserts have no time to evacuate the heat and therefore the phenomena is governed by the inserts fast Temperature variation
   - Need to increase power of inserts by 42% as shown in table below…

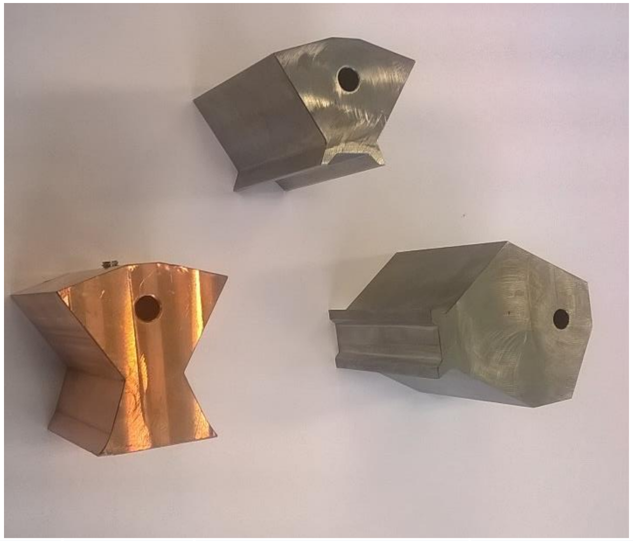
Block	Approx Power per block (W)	dT/dt if WHA inserts (K/s)	dT 60 sec if WHA inserts (K)	dT/dt if Cu inserts (K/s)	dT 60 sec if Cu inserts (K)	Power to have same dT/dT as WHA inserts (W)
1-2	163.23	1.26	75.61	0.88	53.05	232.66
3-4	99.15	0.77	45.93	0.54	32.22	141.32
5-8	59.31	0.46	27.47	0.32	19.27	84.54
9-14	38.29	0.30	17.74	0.21	12.44	54.58

Tests with different loading conditions to better match different scenarios…

Inserts Power Deposition Calculations

1) Input: Energy deposition maps from FLUKA;
2) Definition of case: 4.5E11 p/s for Fast Losses and 0.9E11 p/s for Continuous Operations;
3) Calculation of linear power (with assumption energy constant over area of inserts) by multiplying by block area;
4) Integral power for each 7 cm long block;
5) Approximation of power curve to 4 power levels.





Block	Centre (cm)	Block Power (W)	Approximated Block Power (W)
1	3.5	181.72	163.23
2	10.5	144.73	163.23
3	17.5	110.63	99.15
4	24.5	87.66	99.15
5	31.5	70.73	59.31
6	38.5	61.18	59.31
7	45.5	55.09	59.31
8	52.5	50.23	59.31
9	59.5	44.96	38.29
10	66.5	42.31	38.29
11	73.5	38.45	38.29
12	80.5	36.21	38.29
13	87.5	34.56	38.29
14	94.5	33.24	38.29

Summary MQWA.E5R7 at 7 TeV

Parameter	Test 1	Test 2	Test 3	Test 4
Current (A)	610	610	610	610
Water Flow (l/min)	28	28	Reduced	Reduced
Test duration (s, h)	1 h	1 h	60 s	1 h
Cover to enclose the magnet	No	Yes	Yes	Yes
Temperature increase to match losses on magnet (K)	No	No	3.5	3.5
Block 1 Initial power P_0 (W)	-	-	232.66	32.65
Block 2 Initial power P_0 (W)	-	-	232.66	32.65
Block 3 Initial power P_0 (W)	-	-	141.32	19.83
Block 4 Initial power P_0 (W)	-	-	141.32	19.83
Block 5 Initial power P_0 (W)	-	-	84.54	11.86
Block 6 Initial power P_0 (W)	-	-	84.54	11.86
Block 7 Initial power P_0 (W)	-	-	84.54	11.86
Block 8 Initial power P_0 (W)	-	-	84.54	11.86
Block 9 Initial power P_0 (W)	-	-	54.58	7.66
Block 10 Initial power P_0 (W)	-	-	54.58	7.66
Block 11 Initial power P_0 (W)	-	-	54.58	7.66
Block 12 Initial power P_0 (W)	-	-	54.58	7.66
Block 13 Initial power P_0 (W)	-	-	54.58	7.66
Block 14 Initial power P_0 (W)	-	-	54.58	7.66

Safety Systems

The area and the apparatus have been equipped with the following safety systems:

- Experimental area delimited with white/red bands;
- Flashing panel "High Electrical Current" placed on top of the DAQ close to the magnet;
- Panel "High magnetic field" placed on the white/red bands;
- 2 Fire extinguishers placed close to experimental area;
- 400 V socket and 220 V socket are equipped with independent safety circuit breakers which will shut power off if short circuits are detected;
- The safety box has an emergency fast stop button easily accessible;
- A smoke detector will be placed close to the magnet to monitor absence of fumes/gas generation.

Safety Box. The safety relay stops the PS if the emergency button is pressed (or there is electricity cut).