# MCBXF status update

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M. Bajko, S. Emami, L. Fiscarelli, M. Guinchard, S. Izquierdo Bermúdez, F. J. Mangiarotti, J.C. Perez, E. Todesco, G. Willering (CERN).

9th HL-LHC Collaboration Meeting – 15th October 2019

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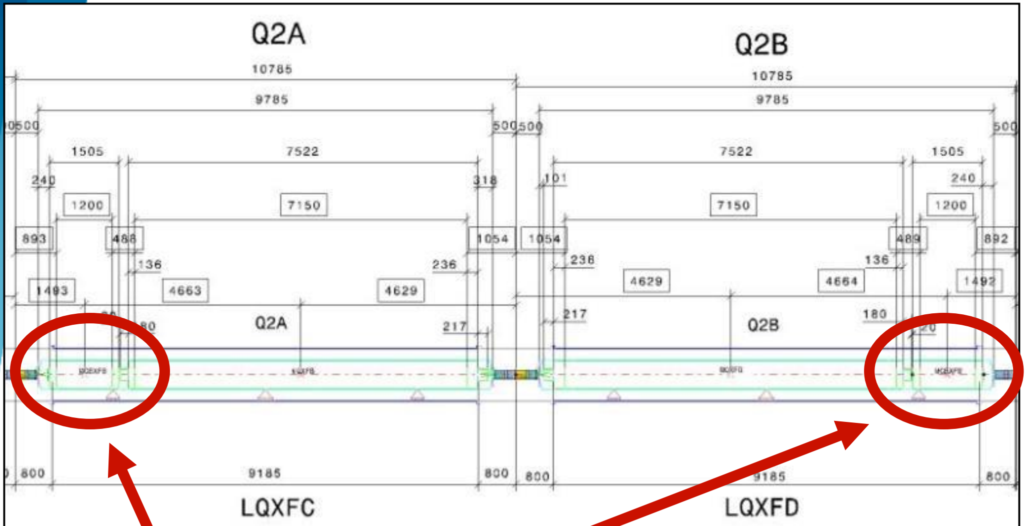
- Conclusions.




# MCBXF Orbit Correctors

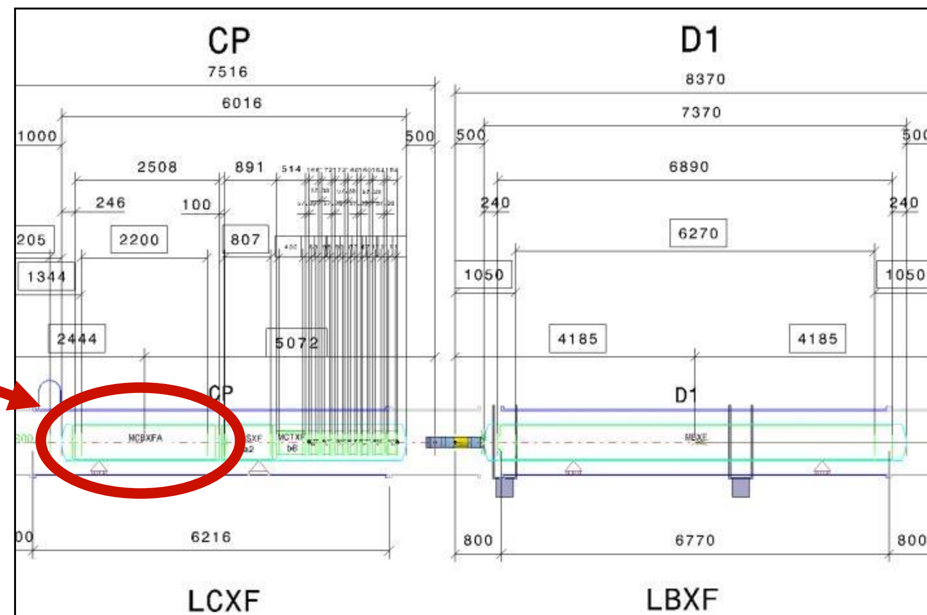
- Installed at each side of the interaction point in the LHC upgrade.
- Same cross section: type A is 2.5 m long while type B is 1.5 m long.

**MCBXFB (2.5 T·m)**

Ciemat Centro de Investigaciones Energéticas, Medioambientales y Tecnológicas

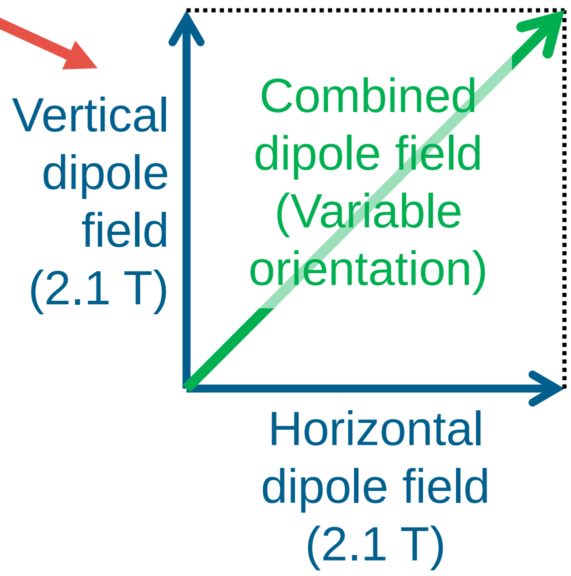
**MCBXFA (4.5 T·m)**

Ciemat Centro de Investigaciones Energéticas, Medioambientales y Tecnológicas



# Magnet and cable specifications

| MCBXF Technical specifications | |
|---|---|
| **Magnet configuration** | Combined dipole (Operation in X-Y square) |
| **Integrated field** | 4.5 (A) / 2.5 (B) Tm |
| **Minimum free aperture** | 150 mm |
| **Nominal current** | < 2000 A |
| **Radiation resistance** | 35 MGy |
| **Physical length** | < 2.5 (A) / 1.505 (B) m |
| **Working temperature** | 1.9 K |
| **Iron geometry** | D1 (A) / MQXF (B) iron holes |
| **Field quality** | < 10 units (1E-4) |
| **Fringe field** | < 40 mT (Out of the Cryostat) |




| Cable Parameters | |
|---|---|
| **No. of strands** | 18 |
| **Strand diameter** | 0.48 mm |
| **Cable thickness** | 0.845 mm |
| **Cable width** | 4.37 mm |
| **Key-stone angle** | 0.67º |
| **Cu:Sc** | 1.75 |

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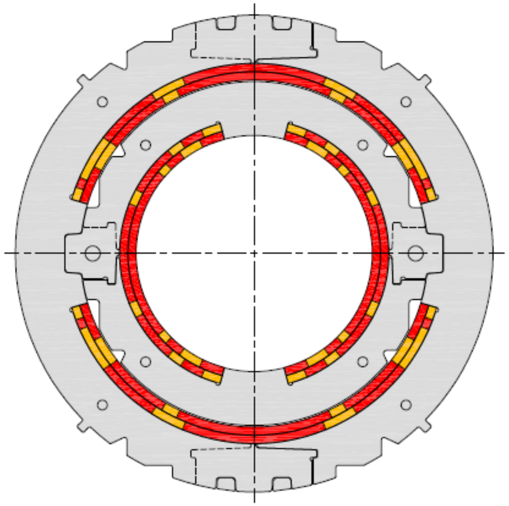
**Radiation resistance requires mechanical clamping**



**Working point < 65%**

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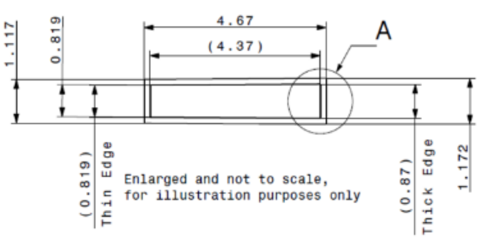
| **Cable width** | 4.37 mm |
| **Key-stone angle** | 0.67º |
| **Cu:Sc** | 1.75 |

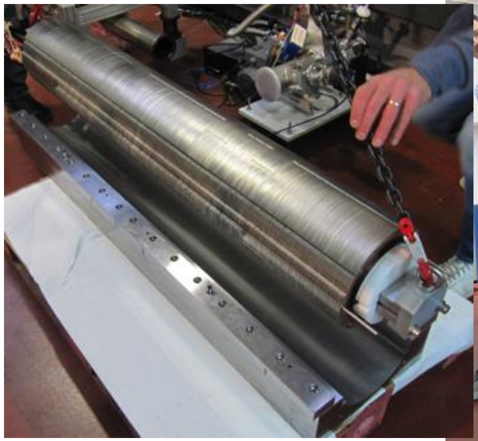
**Coil fabrication techniques not previously used** due to the high number of turns:

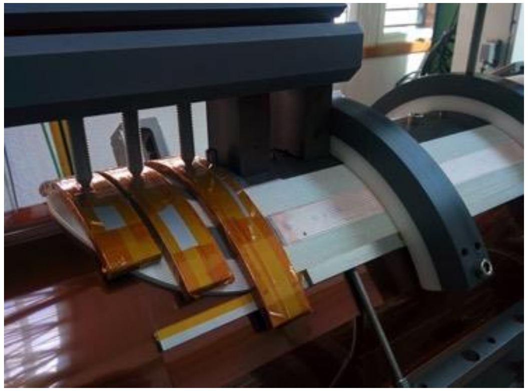
- Insulated NbTi Rutherford cable with braided glass fibre
- Each layer is fixed with a binder after winding
- Coils are fully impregnated with epoxy resin CTD 101-K

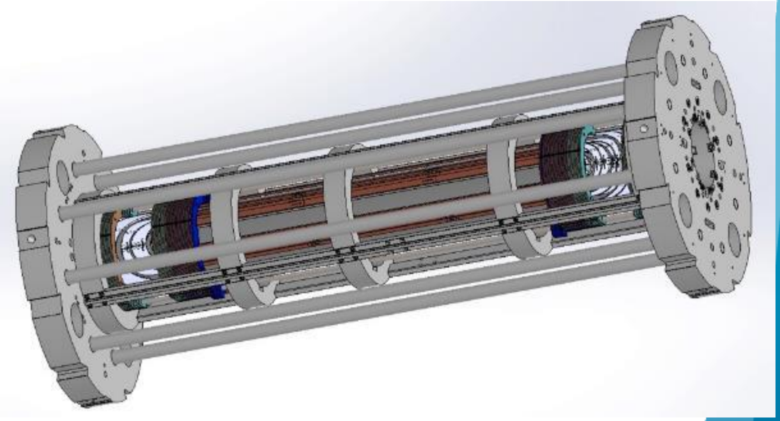


# Last HL-LHC Collaboration Meeting reminder

- ID coils were finished and the inner dipole had been successfully assembled and pre-collared.
- Inner dipole power test was foreseen for Dec’18 in order to validate the coil fabrication techniques. All the parts required were under fabrication or finished.
- The production of the OD coils had started.







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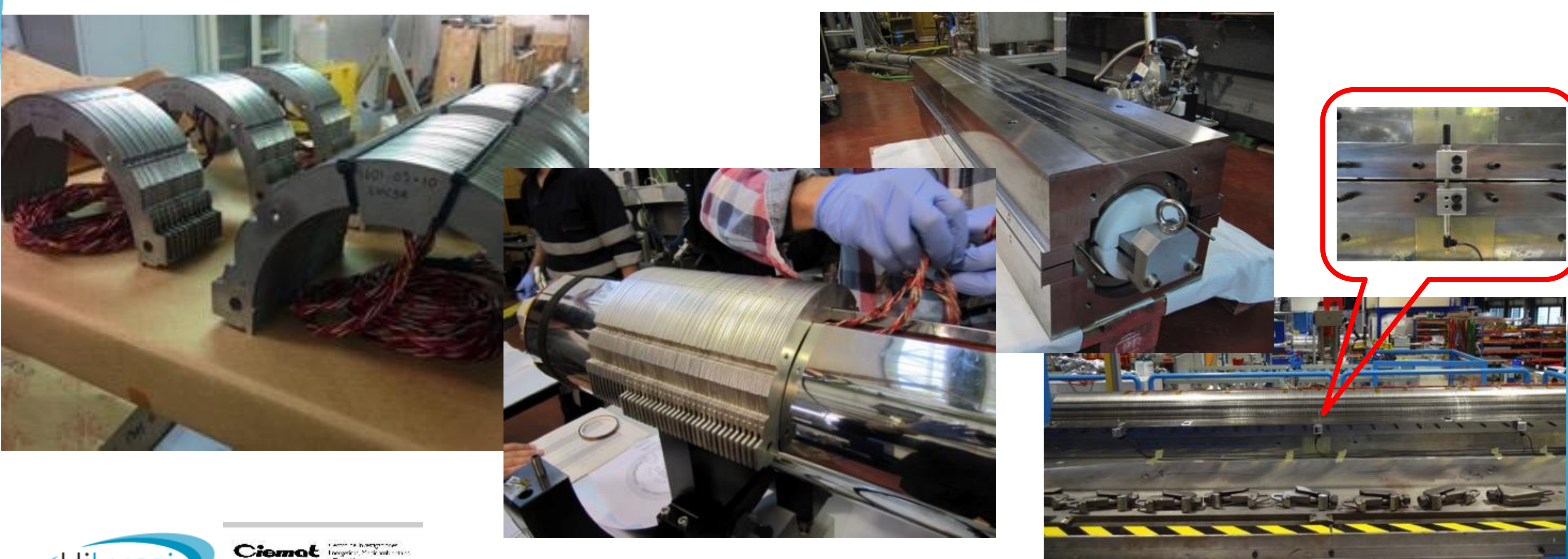
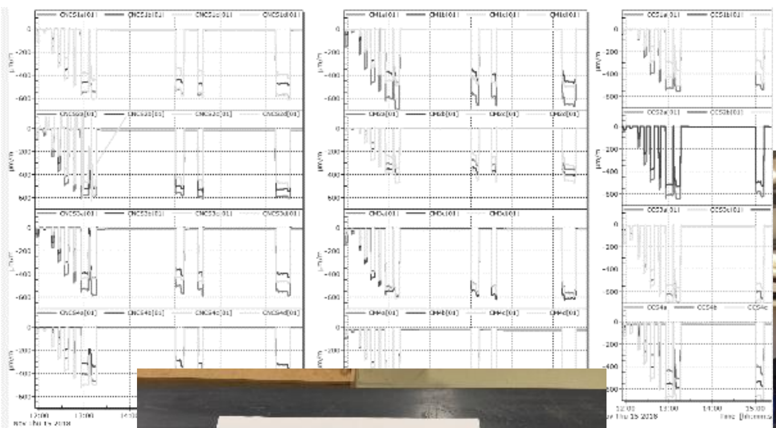
# Inner dipole collaring at CERN (1/2)

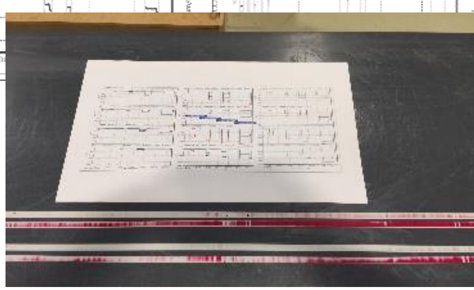
- The collaring procedure used during the short mechanical model assembly was applied (control of the cavity size using different shim thickness as mechanical stoppers on the collaring tool)
- The collaring tool displacement is monitored with 6 LVDTs.
- Six cross sections (12 collars equipped with 2 strain-gauges per side in ½ bridge configuration) are instrumented: two at each pole end extremity and two in the middle of the straight section).

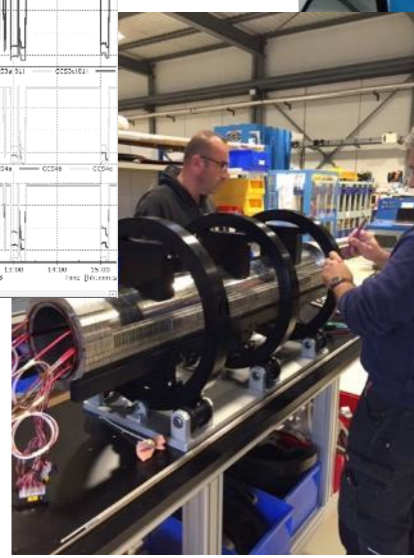


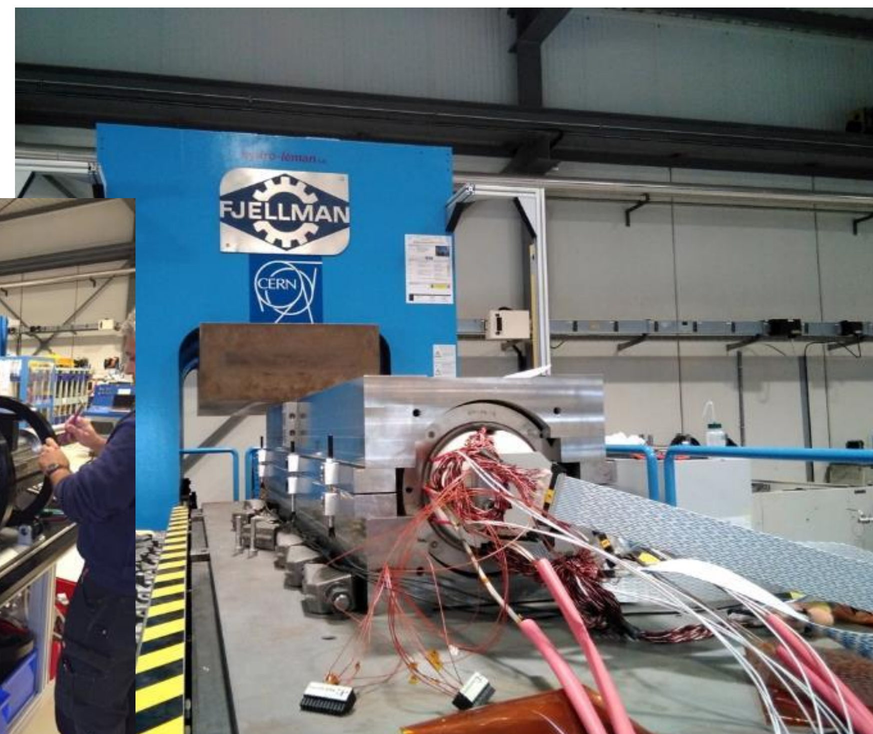
# Inner dipole collaring at CERN (2/2)

- Several shimming iterations were necessary to obtain the targeted pre-compression on the coils.
- The preload loss due to spring-back was too high: from 100 MPa under the press down to 50 instead of computed 70 MPa.
- Still under investigation, but likely due to the excessive play of the pin holes.



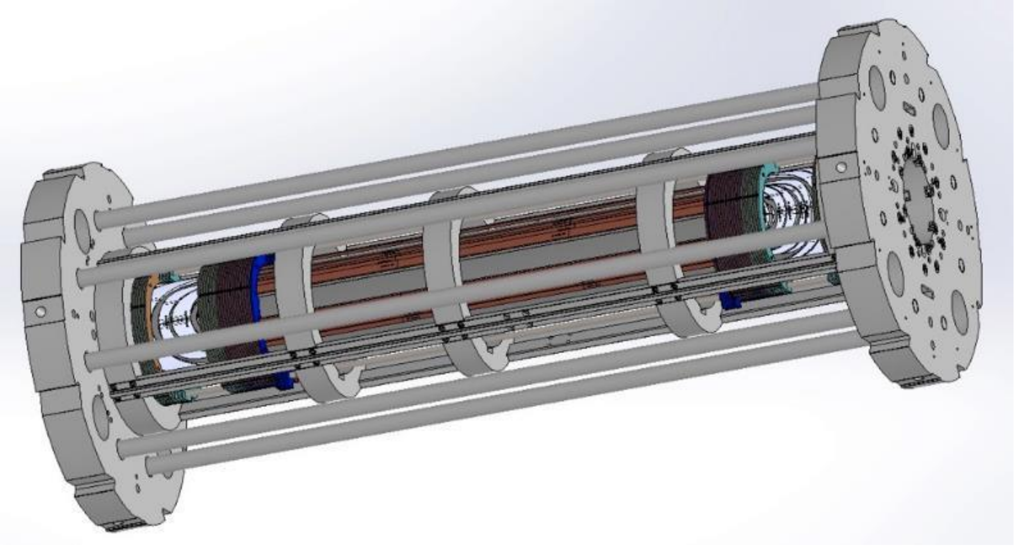






# Inner dipole assembly

- In order to get earlier information on the magnet performance and validate de coil fabrication techniques, it was decided to test the magnet without the outer dipole.
- The assembly techniques of the final magnet can be also validated.
- As the outer dipole coils were not ready yet, they were replaced inside the iron yoke by 316 L stainless steel spacers.
- The end-plates with rods hold the coil axial preload and compress the iron laminations.



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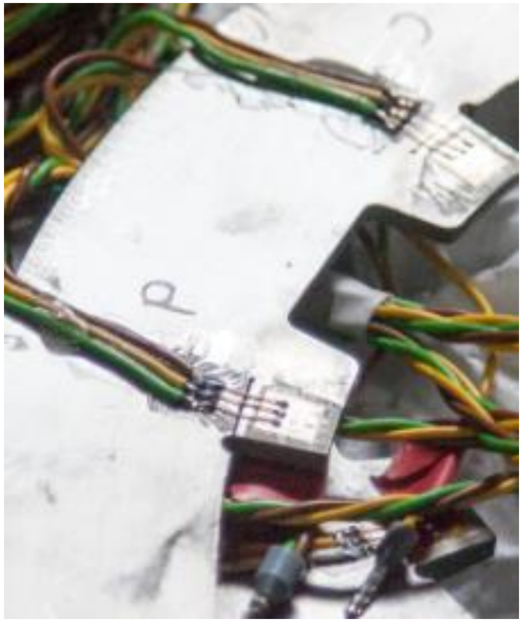
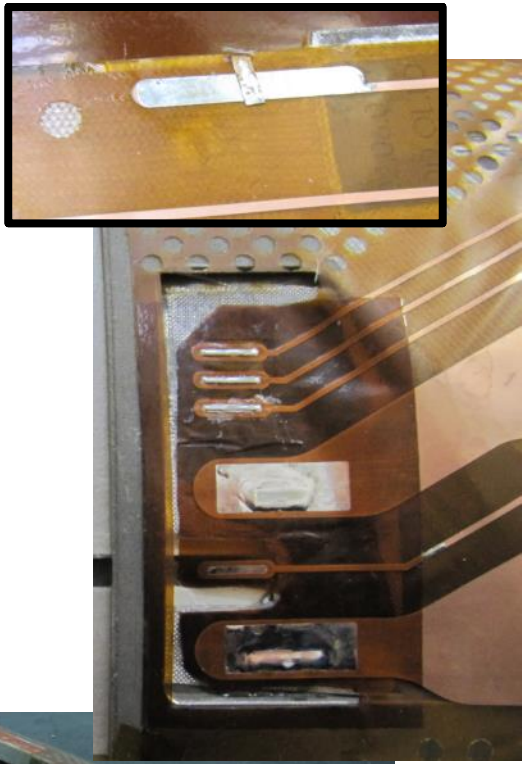
# Instrumentation & Protection (both dipoles)

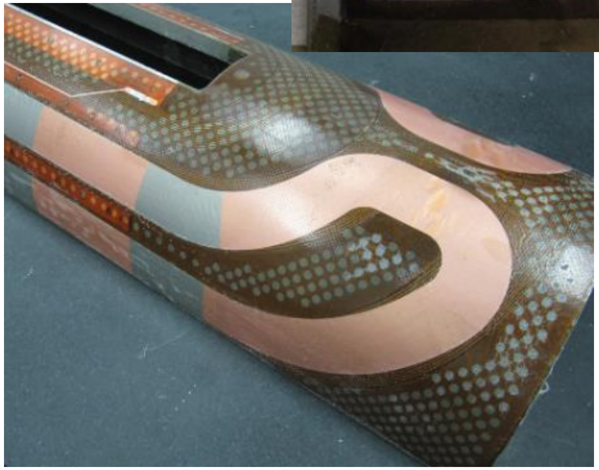
- Strain gauges: Six cross sections per collared dipole, two at each pole end and two in the middle of the straight section.



# Instrumentation & Protection (both dipoles)

- Strain gauges: Six cross sections per collared dipole, two at each pole end and two in the middle of the straight section.
- Quench heaters: Outer layer equipped with a trace including the QH circuit and Vtaps in order to validate the integration of the QH for the long orbit corrector.
- Voltage taps: 8 taps per coil. External Vtaps were installed in the coil leads to monitor/protect the inter-coil splices and the main powering leads.





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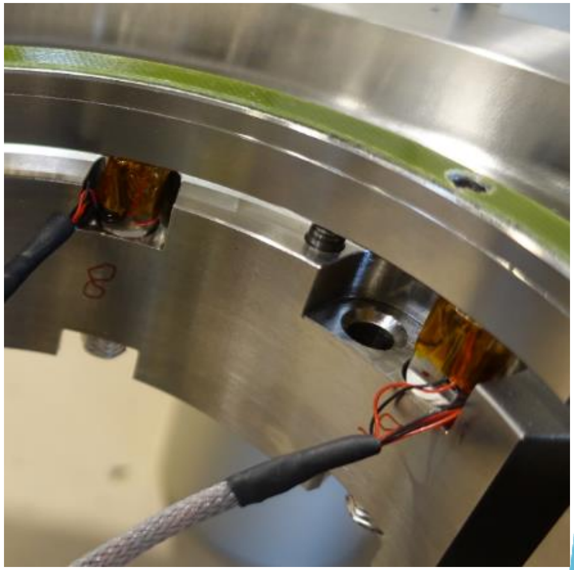
- Quench heaters: Outer layer equipped with a trace including the QH circuit and Vtaps in order to validate the integration of the QH for the long orbit corrector.
- Voltage taps: 8 taps per coil. External Vtaps were installed in the coil leads to monitor/protect the inter-coil splices and the main powering leads.
- Bullet gauges: One coil per dipole was instrumented with bullet gauges. The inner dipole was equipped with 8 bullet gauges (4 on each side of the coil) and 10 for the external dipole.



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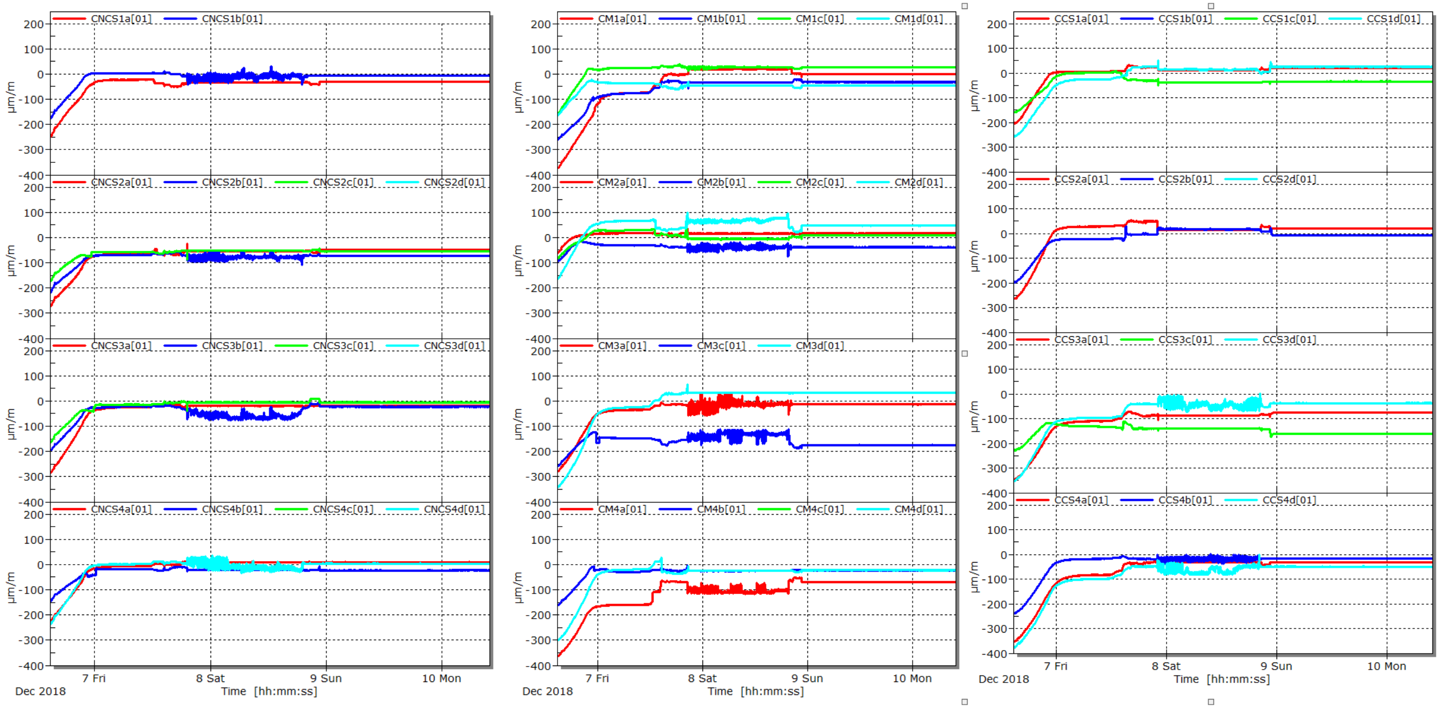
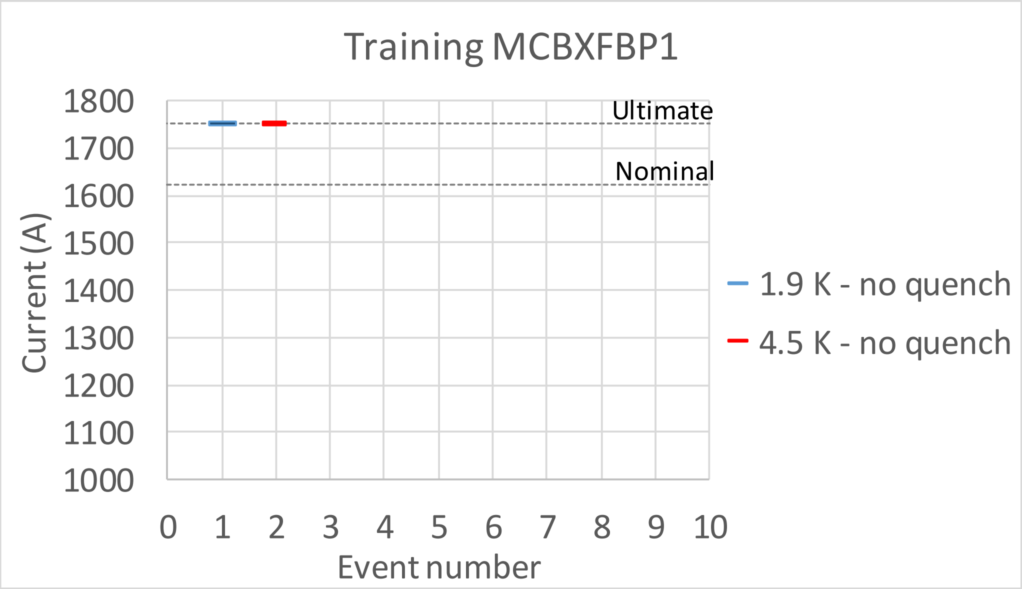
# Strain gauges cool-down overview




- We lost the coil pre-compression during cool-down.
- We took the decision to power the inner dipole.

# Inner dipole power test




- Ultimate current reached without any quench throughout the tests
- The magnet has not been stressed due to thermal gradients due to quench.
- Field quality: b3 of 22.2 units instead of 9.2 units because of shimming. Higher order multipoles below 5 units.

# Conclusions & Actions for assembly MCBXFP1b

- Azimuthal preload loss due to wrong assumption of thermal contraction coefficient (3.2 per mil):
  - MQXF is using a cable with similar insulation. Integrated thermal contraction coefficient is 4.2 per mil, which can be explained as a composition of 3.2 for metal and 9.6 for insulation. Using the same figures, the MCBXF cable would contract with 4.7 per mil (1.5 per mil more than previously assumed).
- Assuming 50 GPa as coil smeared-out Young's modulus, MCBXF azimuthal pre-load of 46 MPa yield a compression about 100 micron,
- 1.5 per mil of differential thermal contraction means about 150 microns. It makes sense that the coils would just lose the preload.

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- It is decided to increase the shimming by **150 micron all along the straight section.**
- Same axial preload of 6 kN per bullet will be applied on this new assembly.

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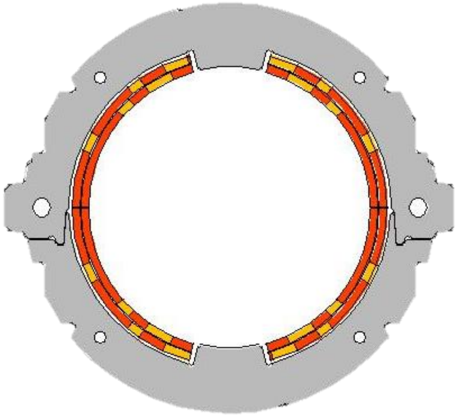
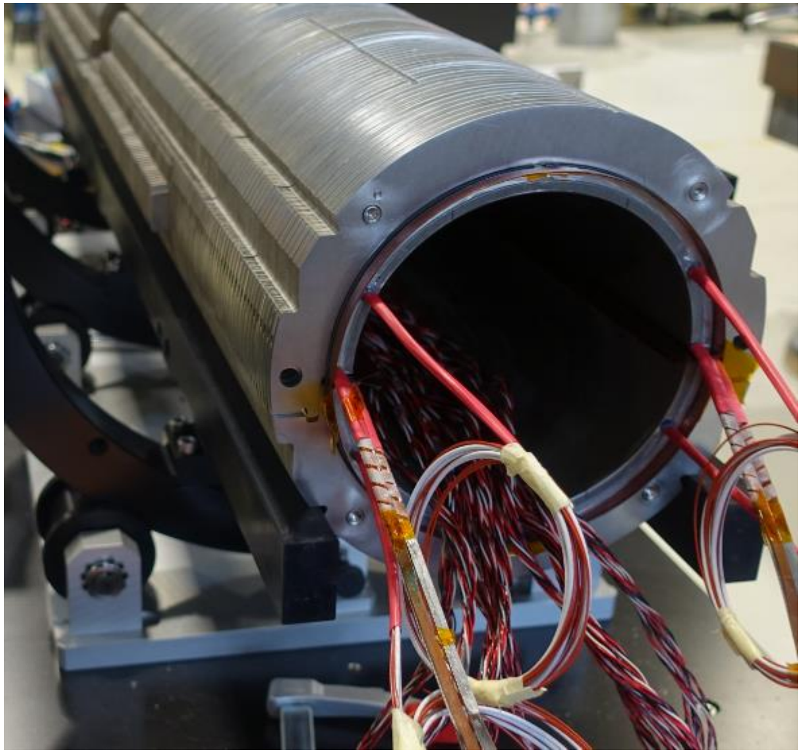
# MCBXF assembly sequence





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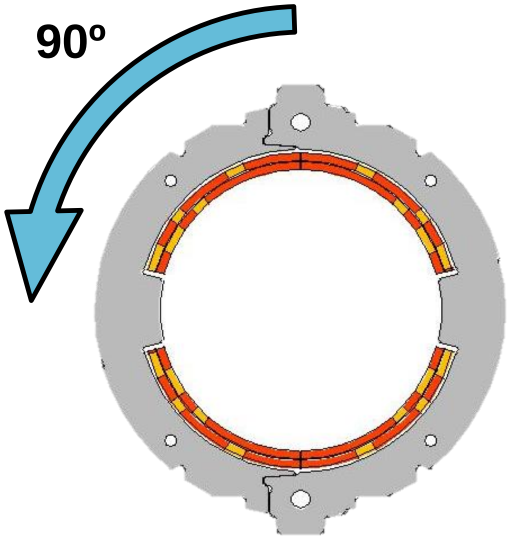


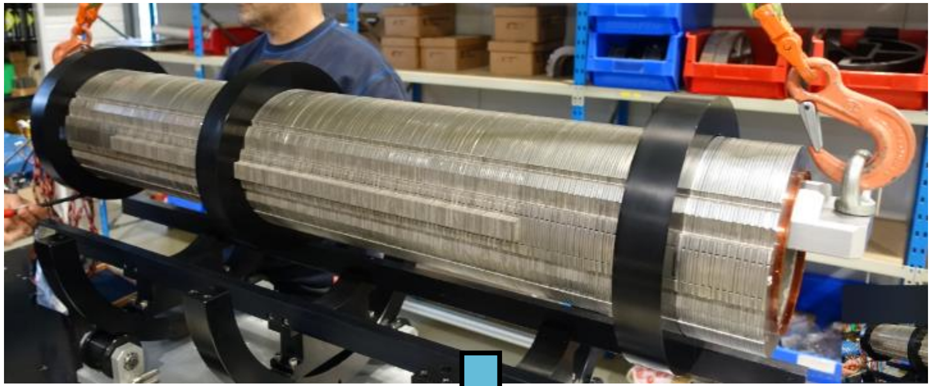

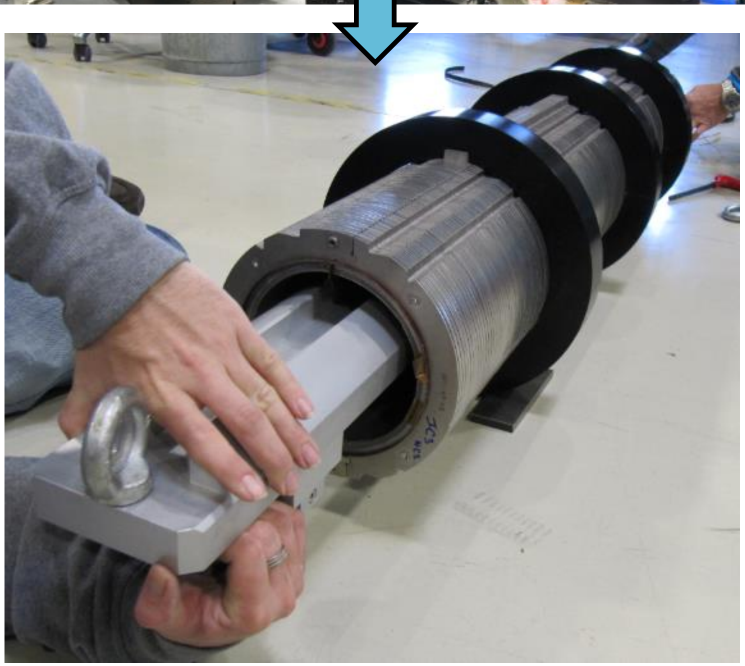

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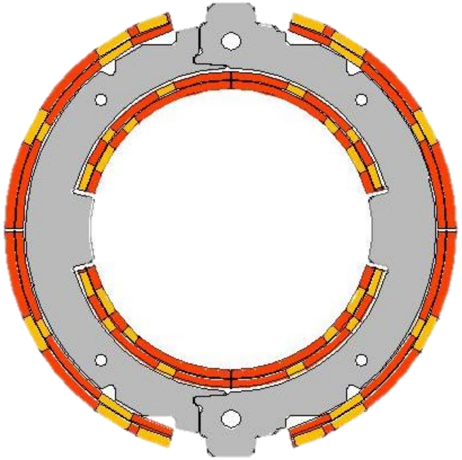

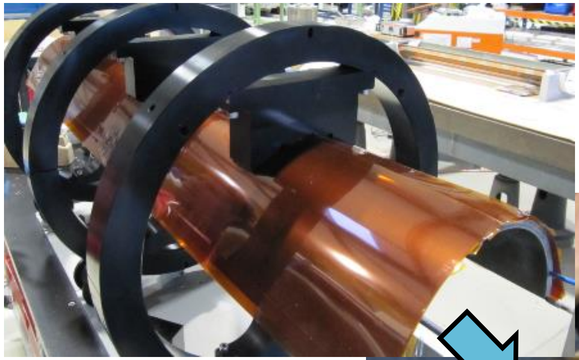

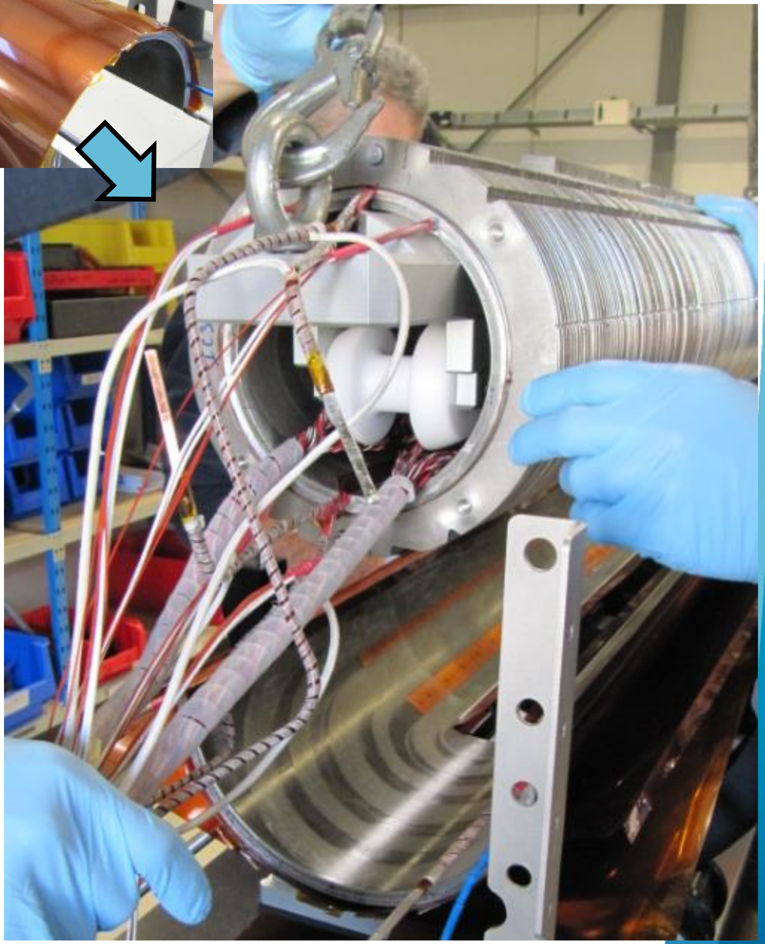

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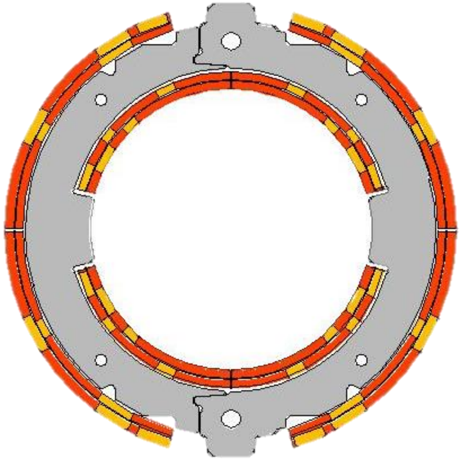

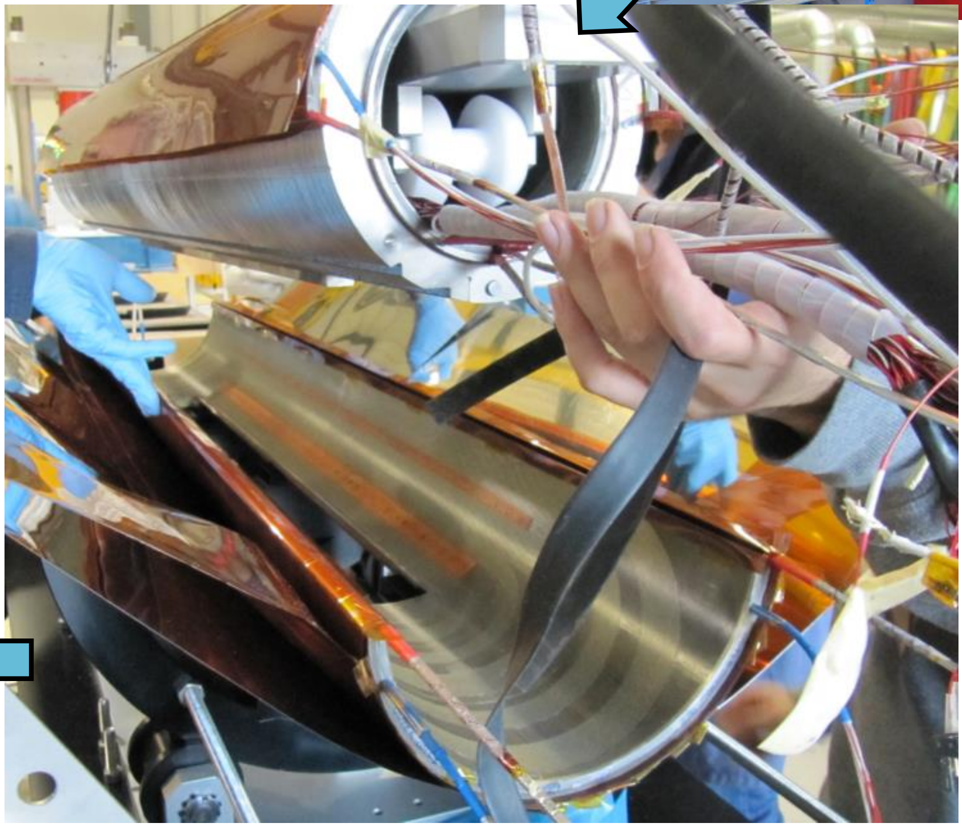

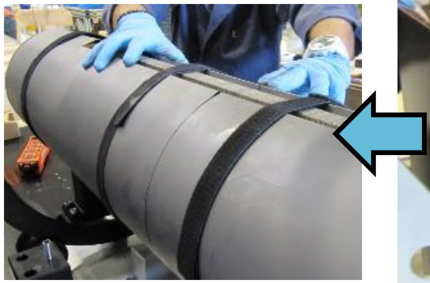

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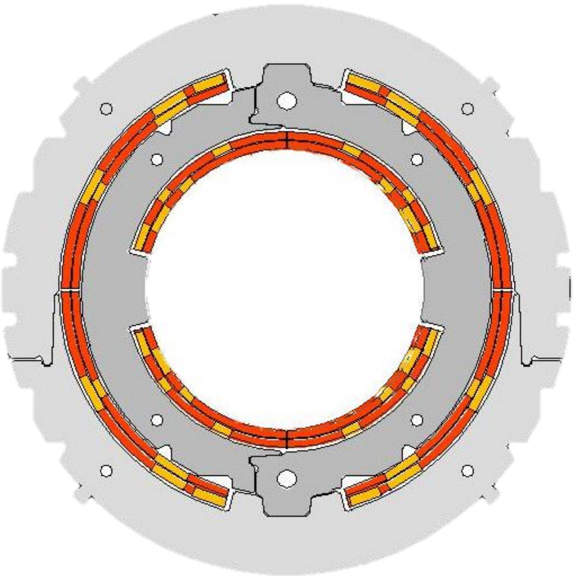

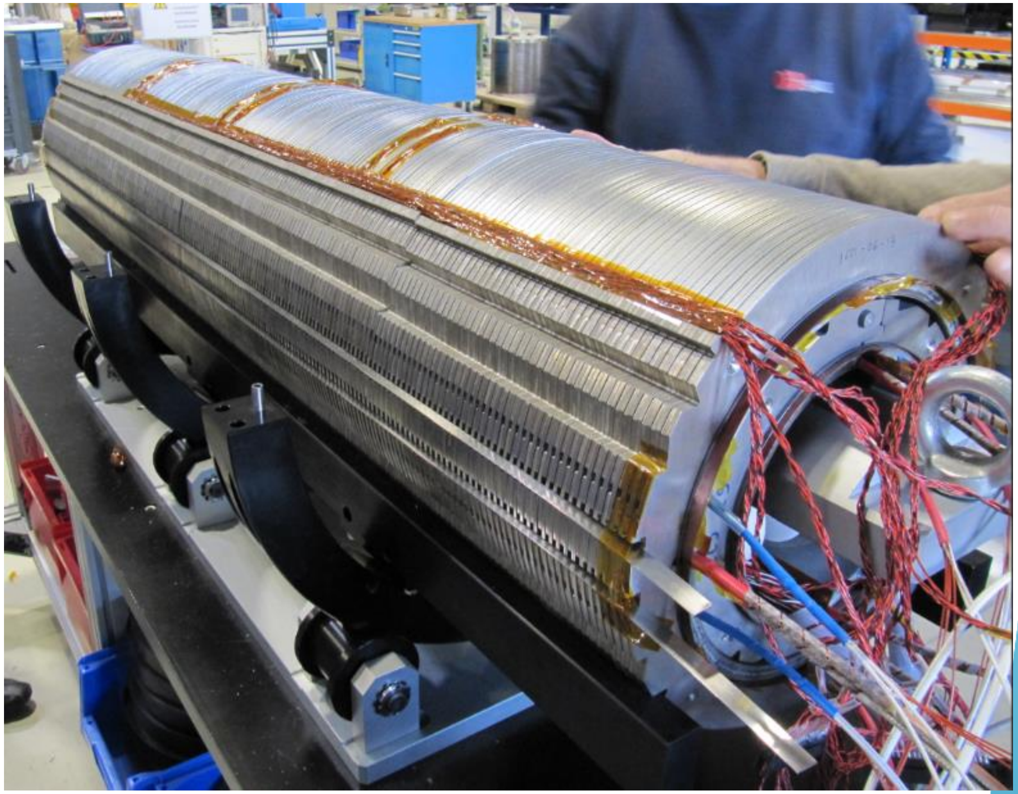

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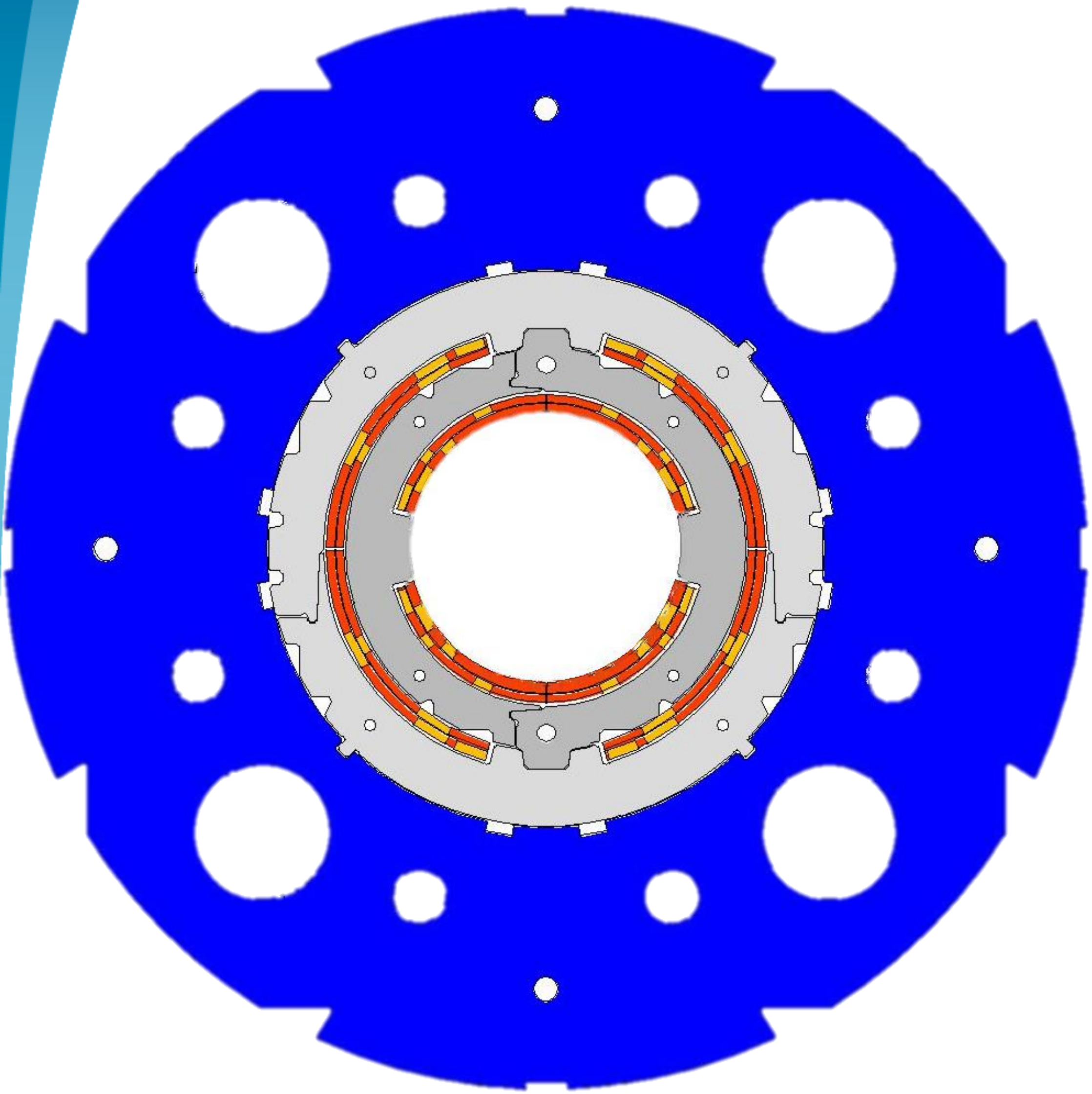

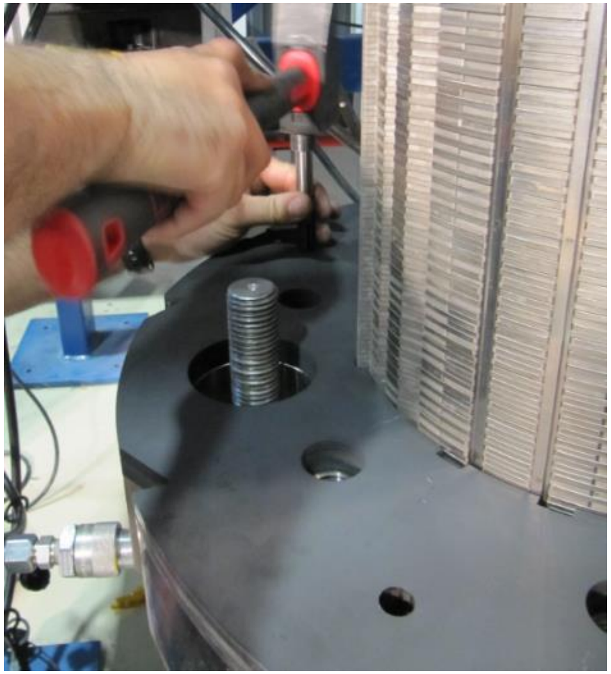

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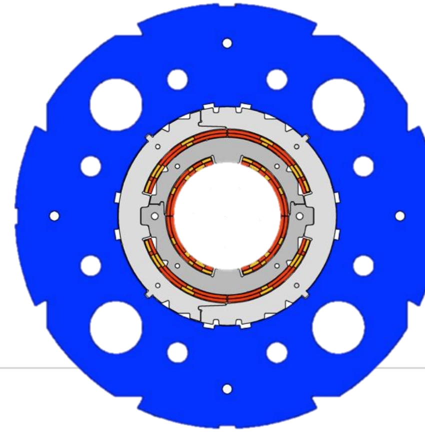
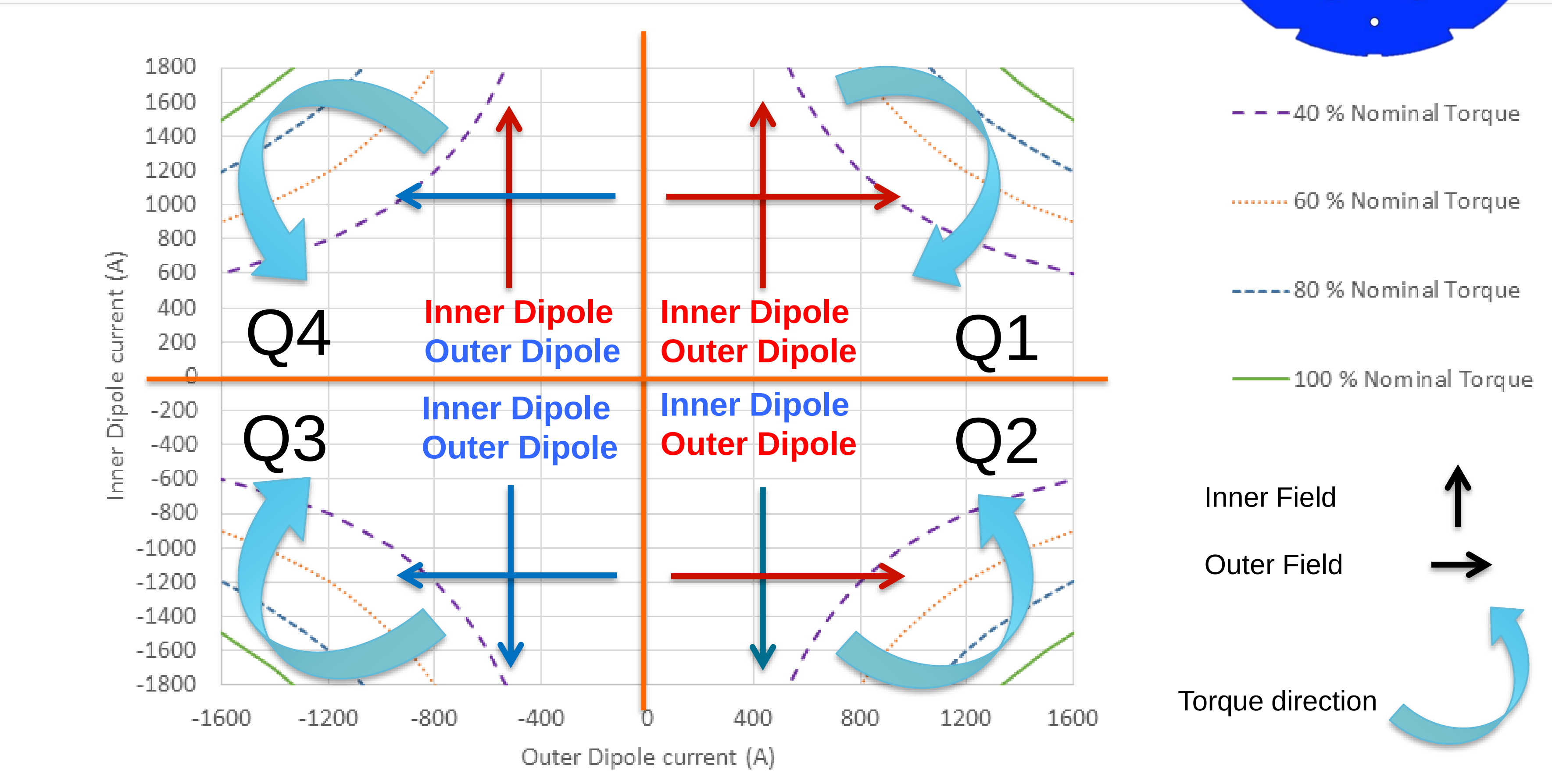
# MCBXFBP1b Powering

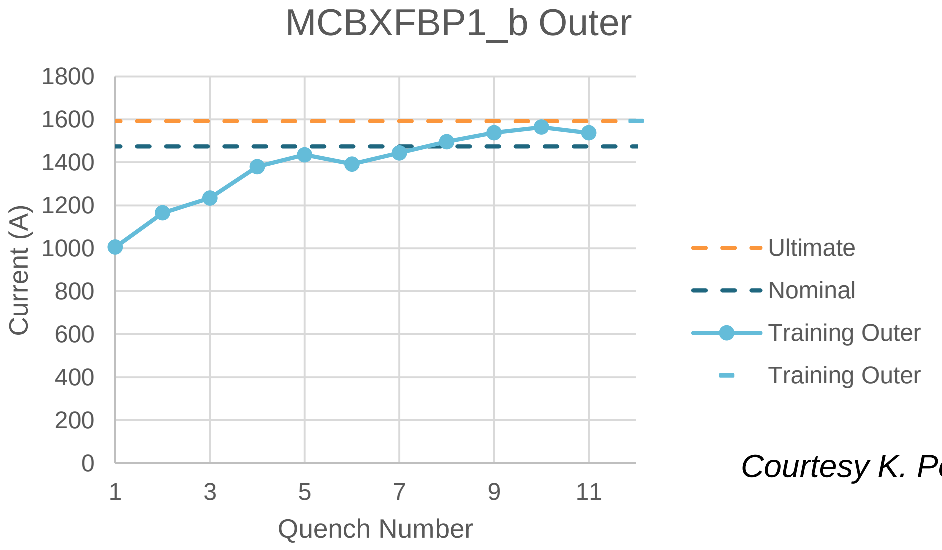


**Two independently powered nested dipoles.**



# Full magnet: Individual powering

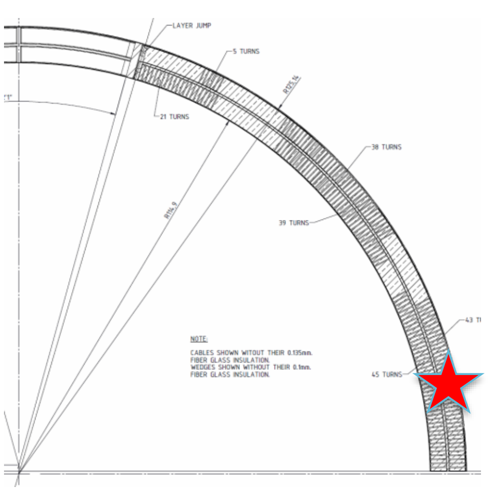
- The inner dipole was powered till ultimate current without quench.
- The outer dipole experienced a slower training:
  - 7 quenches till reaching nominal current (1474 A)
  - 11 quenches till reaching ultimate current (1592 A)
- The resin content at the pole turns of the outer dipole coil could be higher (because of curing mould assembly procedure and thinner insulation thickness than nominal) and may have an impact for the different coil behaviour.

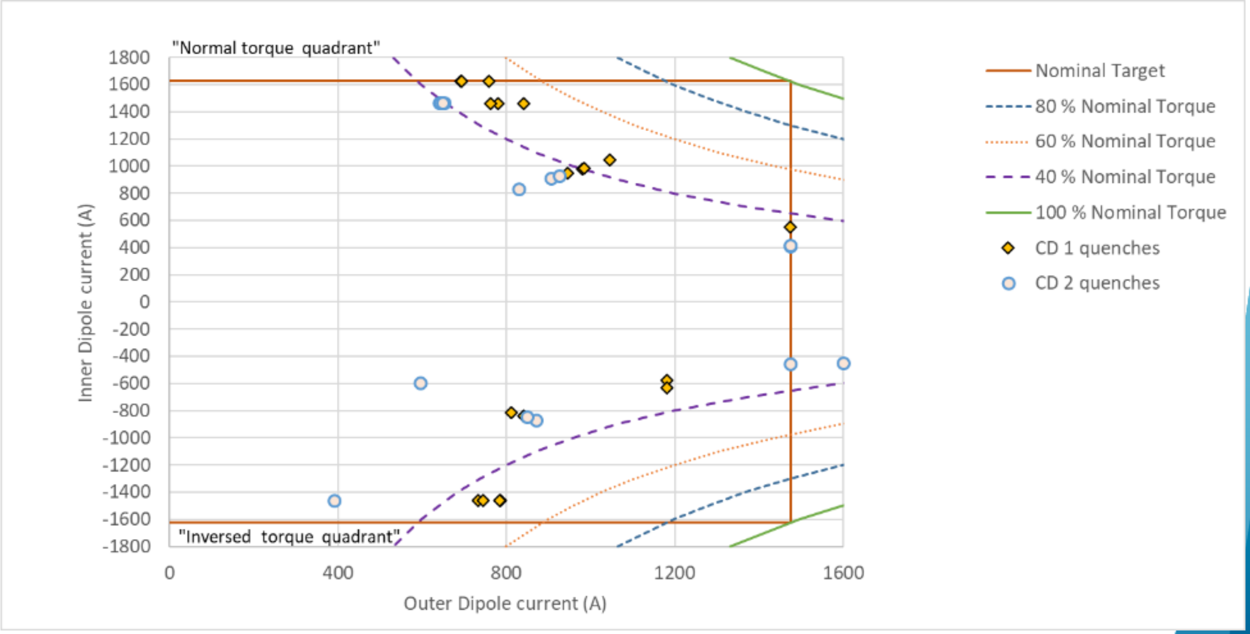



*Courtesy K. Pepitone*

# Full magnet: Combined powering

- Different powering strategies, but torque always below 50% of nominal.
- Quench origin at inner dipole coils: outer layer, mid-plane block.
- No significant detraining.
- No noticeable difference between inverse and direct torque.
- Strain gauges and collars behaviour as expected.
- After thermal cycle, with reduced axial preload for diagnosis, the performance was worse.
- No degradation of the performance of the coils individually powered.



# Conclusions & Actions for assembly MCBXFP1c

- Inner dipole is still not enough pre-compressed.
- After several campaigns of power tests, both dipoles performed successfully when individually powered.
- When powered simultaneously, the performance was limited by the torque (around 50% of nominal torque).
- We supposed this torque limitation was likely due to stick/slip effect due to low friction at the coil ends.

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- The magnet was disassembled and the azimuthal preload of the inner dipole corrected in the pole slot (+ 200 µm per side).
- The friction between coil end-spacers and the bullets was increased by changing the surface roughness of spacers and ½ moon pushers.

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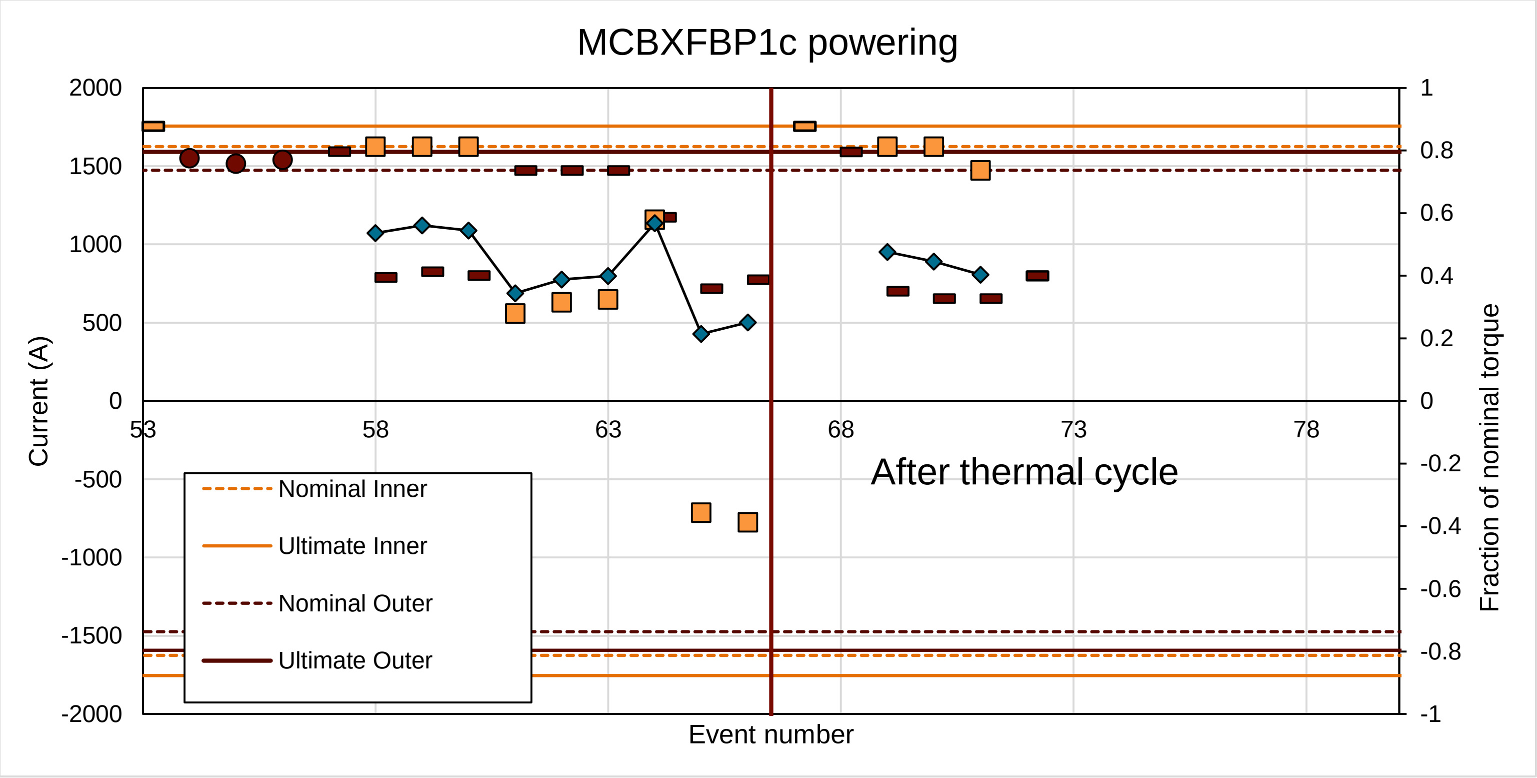
# Powering tests of MCBXFBP1c

- The magnet performance did not increase significantly (+ 8% on torque) while applying the friction configuration changes at coil extremities.
- The initial longitudinal force applied by the bullet gauges to the inner coils was increased by 50% (from 6 to 9 kN/bullet) during thermal cycle to 300 K.
- The magnet performance did not improve after the thermal cycle.
- **… What now?**



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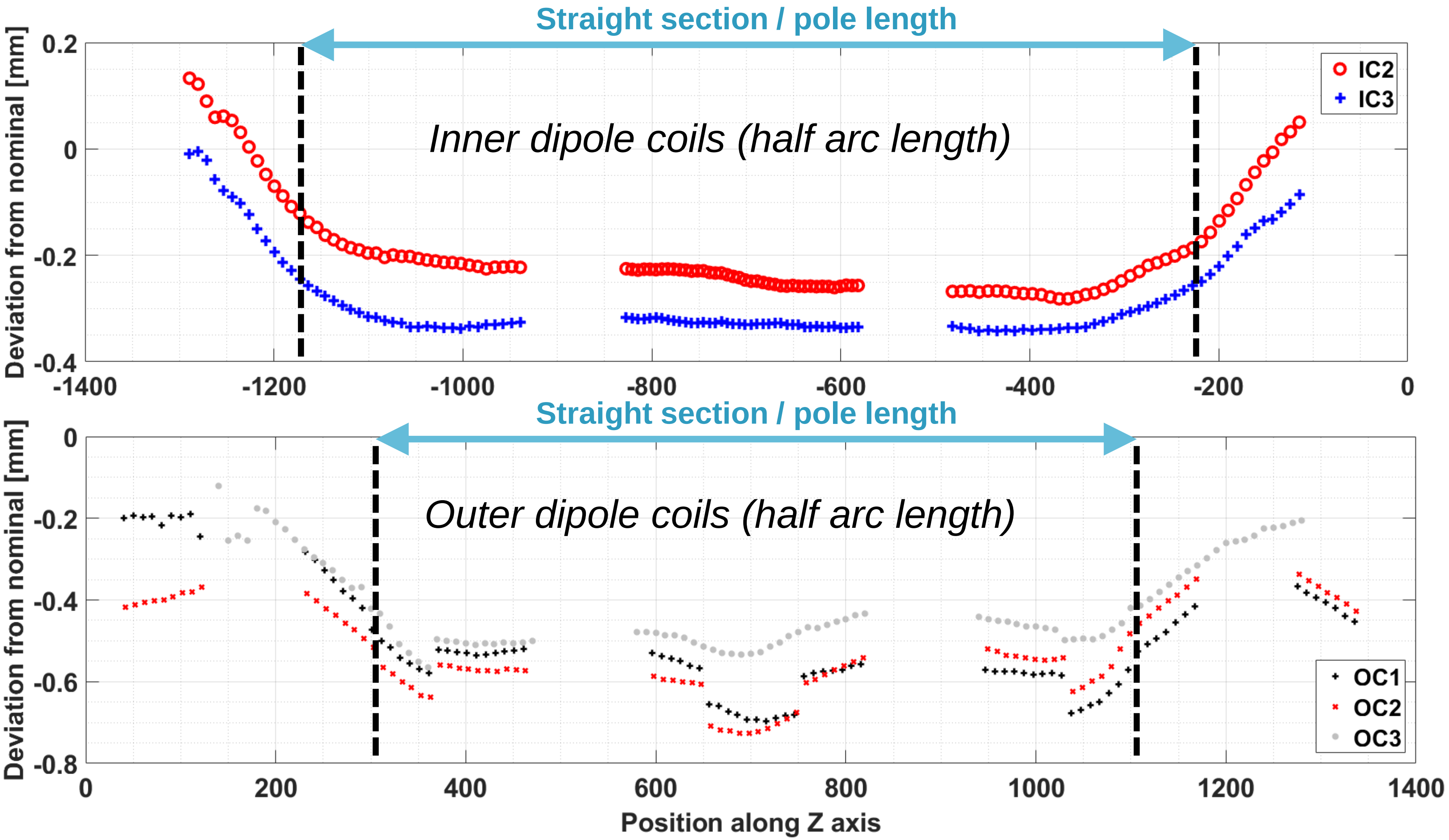
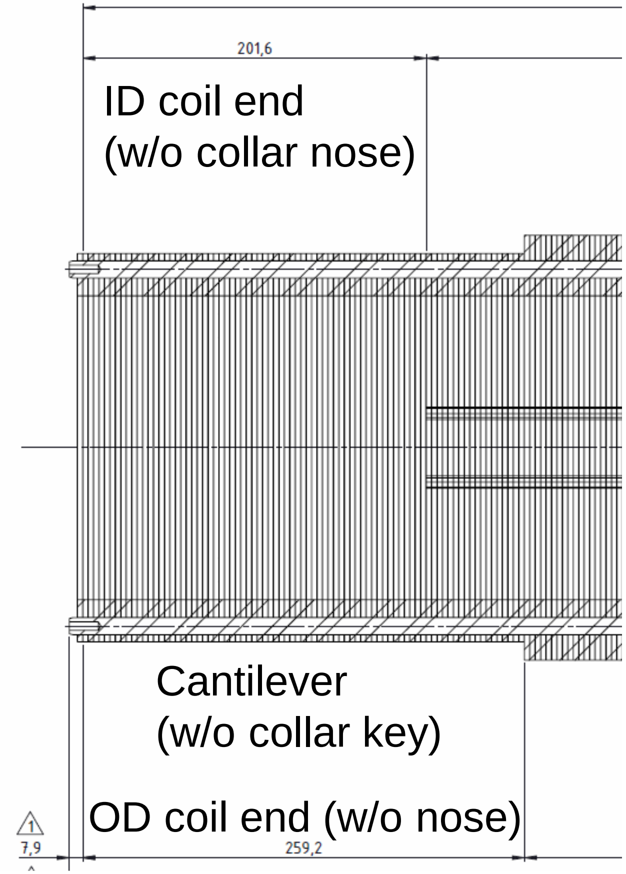
# Coils dimensional control

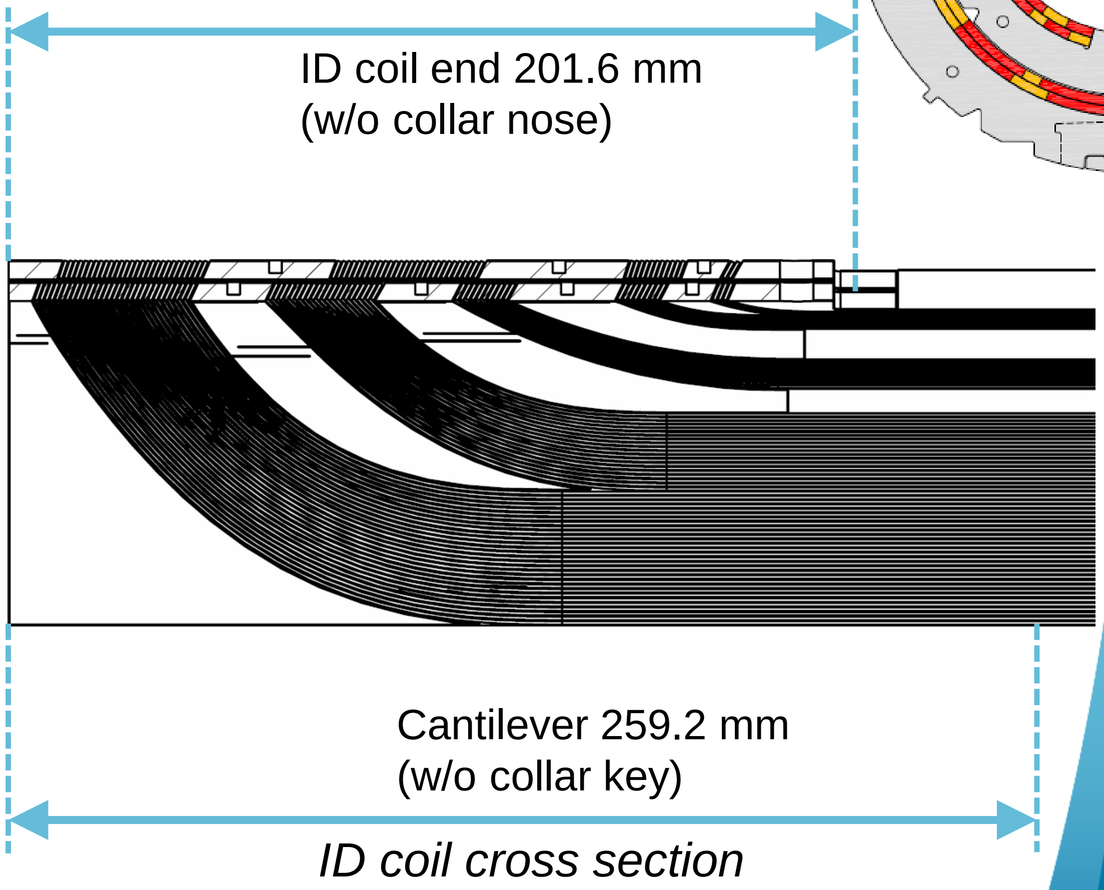
The coil ends are significantly long. Part of the coil end is below nominal dimension.

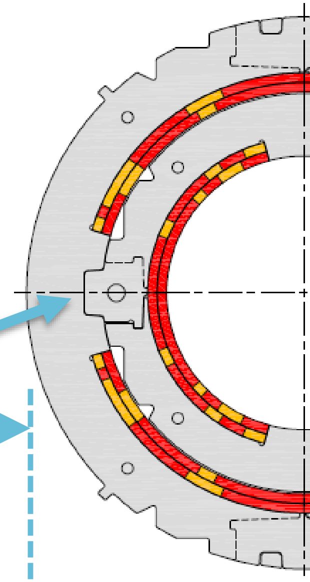


# Midplane gap between the coils

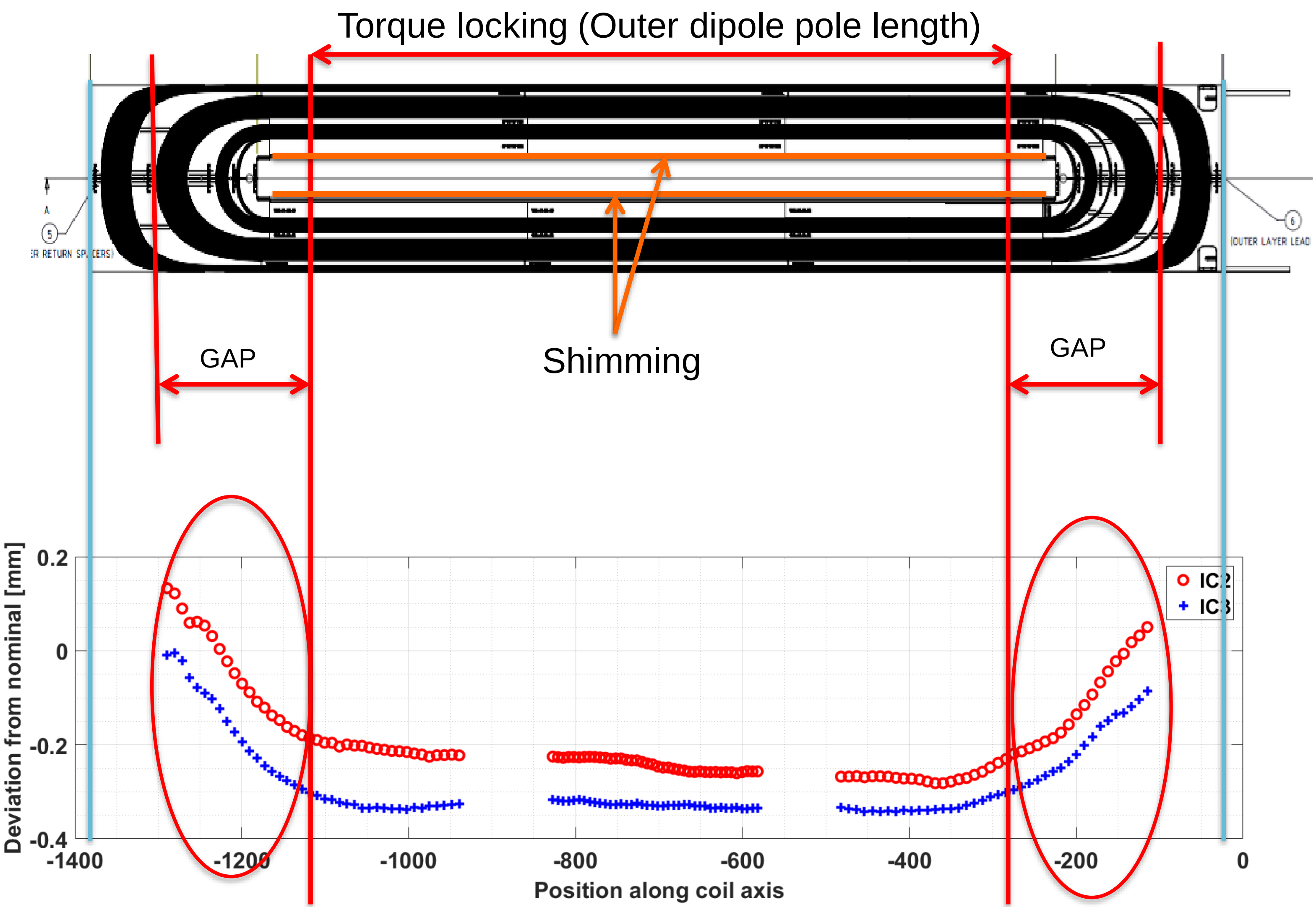
- There is a gap between both coils, at the mid-plane, because of the coil dimensions and the differential thermal contraction wrt the collars. Gap width is about 0.8 mm.
- Torque is not clamped at the coil ends (140 kNm/m of straigth section!!)



# Midplane gap between the coils



# Conclusions & actions for MCBXFP1d

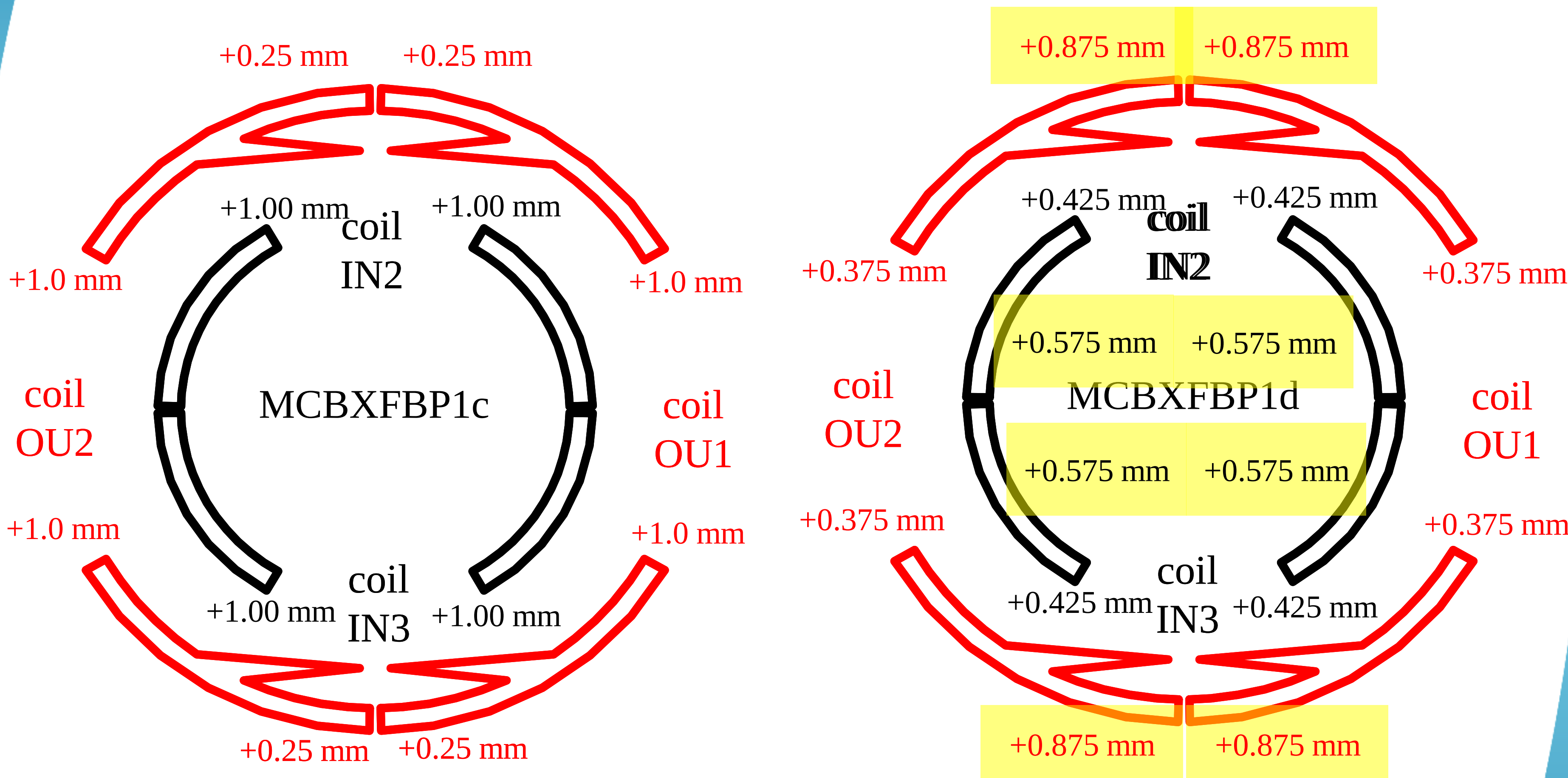
All the measurements can be explained by this gap at mid-plane:

- The gap closes during individual training, but keeps open in combined one.
- Quench starts always at coil ends: no difference between both ends.
- Quench starts at mid-plane block, inner layer: the lowest field, but the cables are the first to slide.
- Quench current is very repetitive:
  - Not training, mechanical limitation.
  - Sliding between the coil outer diameter and the ground insulation, very smooth surface.
- Magnet performance does not improve with higher friction coefficient at coil ends or axial preload.
- Magnet performance slightly improved with higher azimuthal preload at inner dipole coils.

↓

- It was decided to assemble MCBXFBP1d with a new shimming configuration, changing part of the shimming to the midplane to fill the gap properly.
- Longitudinal force on the bullet gauges increased by 50% wrt to initial configuration (9 kN / bullet instead of 6 kN)

# Shimming plan change for MCBXFBP1d



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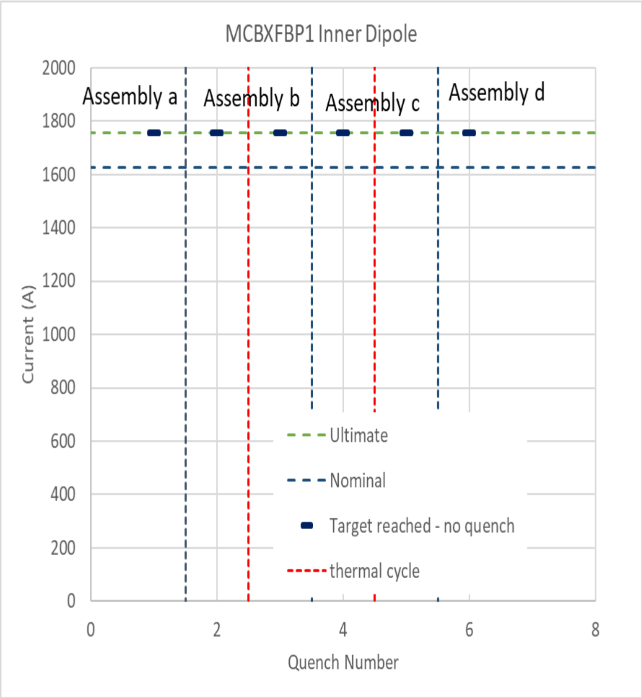
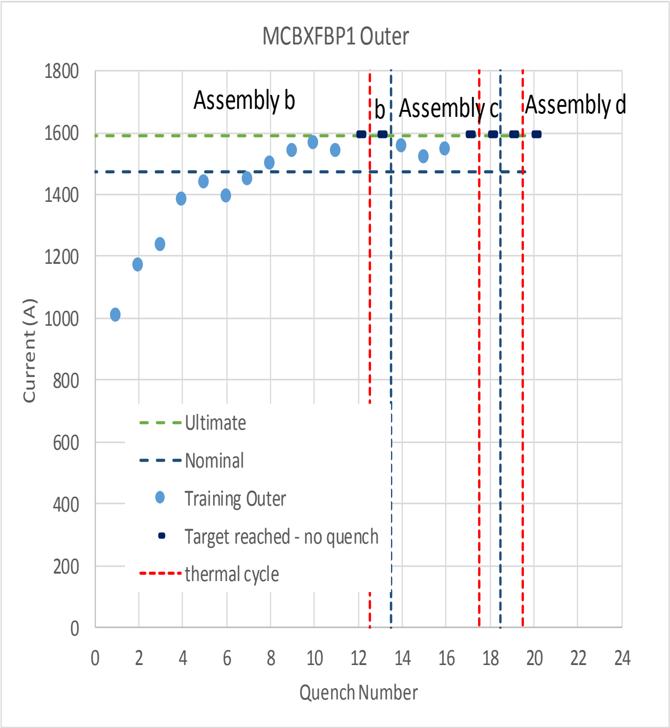
# Individual training



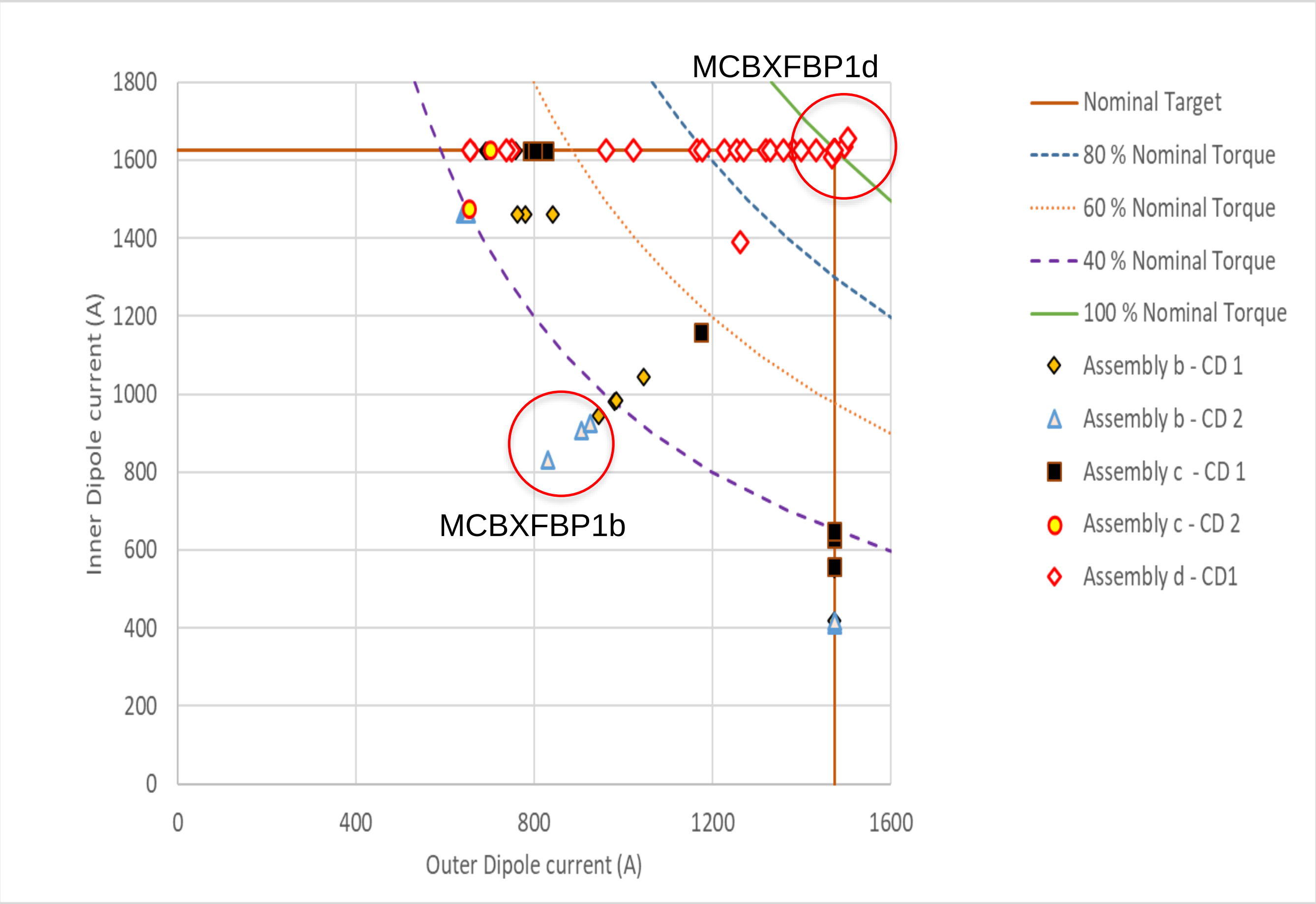

The inner dipole never quenched during individual powering.




- 11 Quenches in first cool down during initial training in assembly b
- 3 Quenches in first cool down of assembly c
- No quenches in assembly d

No detraining quenches following combined powering tests. Coil memory very good.

# Combined powering: Assembly b, c and d compared

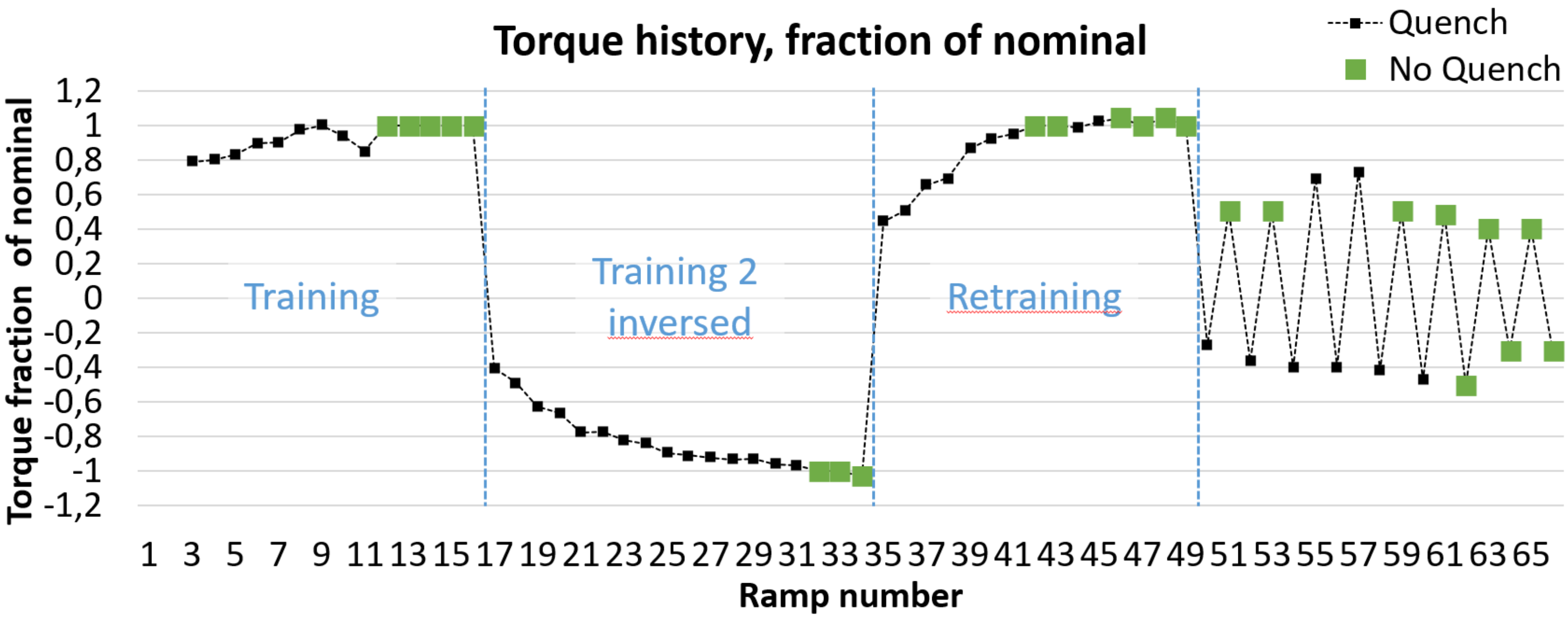



Assembly b and c had limited performance. Highest percentage of about 50 % of the nominal torque reached.

Assembly d trained to nominal current in both dipoles. Later a maximum of 104 % of nominal torque was reached (102 % $I_{nom}$)

**Main conclusion**
***First assembly reaching nominal!***

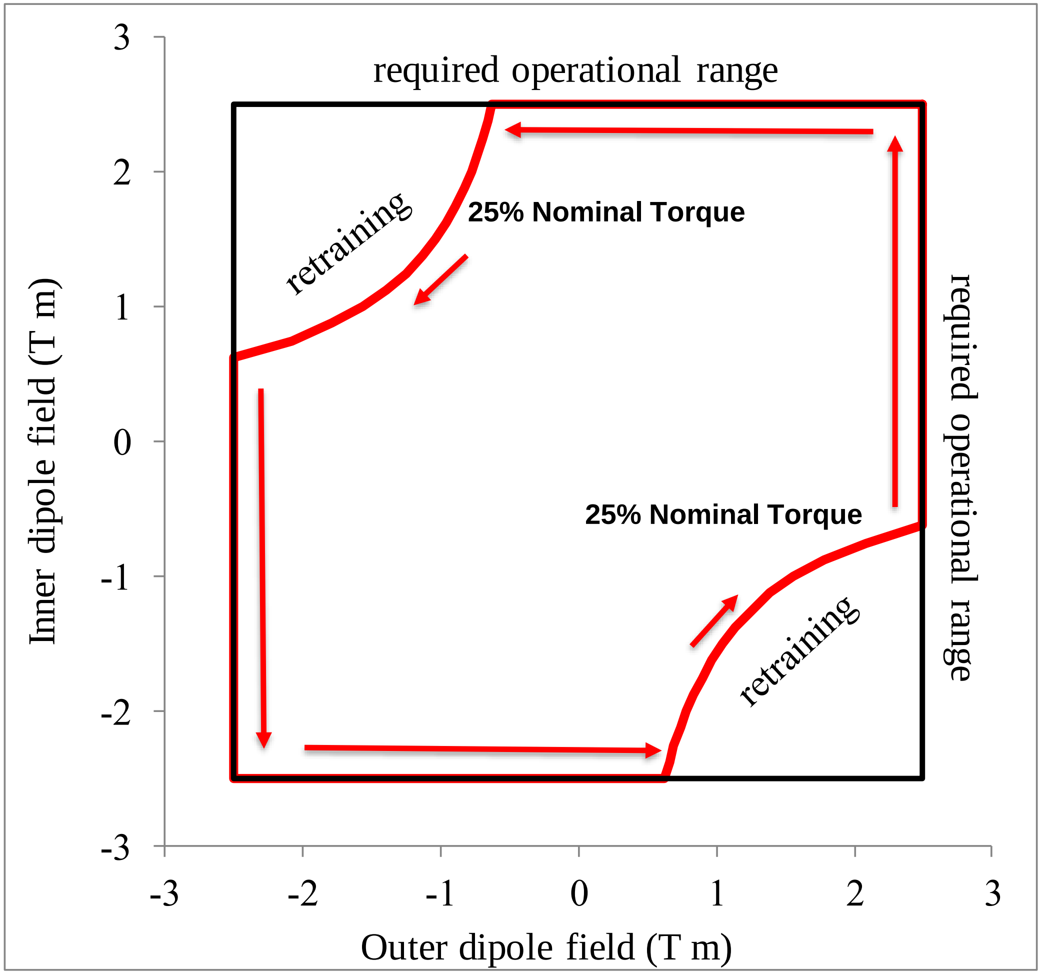
# Combined powering: changing torque direction




- It reached nominal torque after training in both torque directions.
- Magnet has no memory: it needs training each time that the torque is reversed.

# No quench cycle after thermal cycle

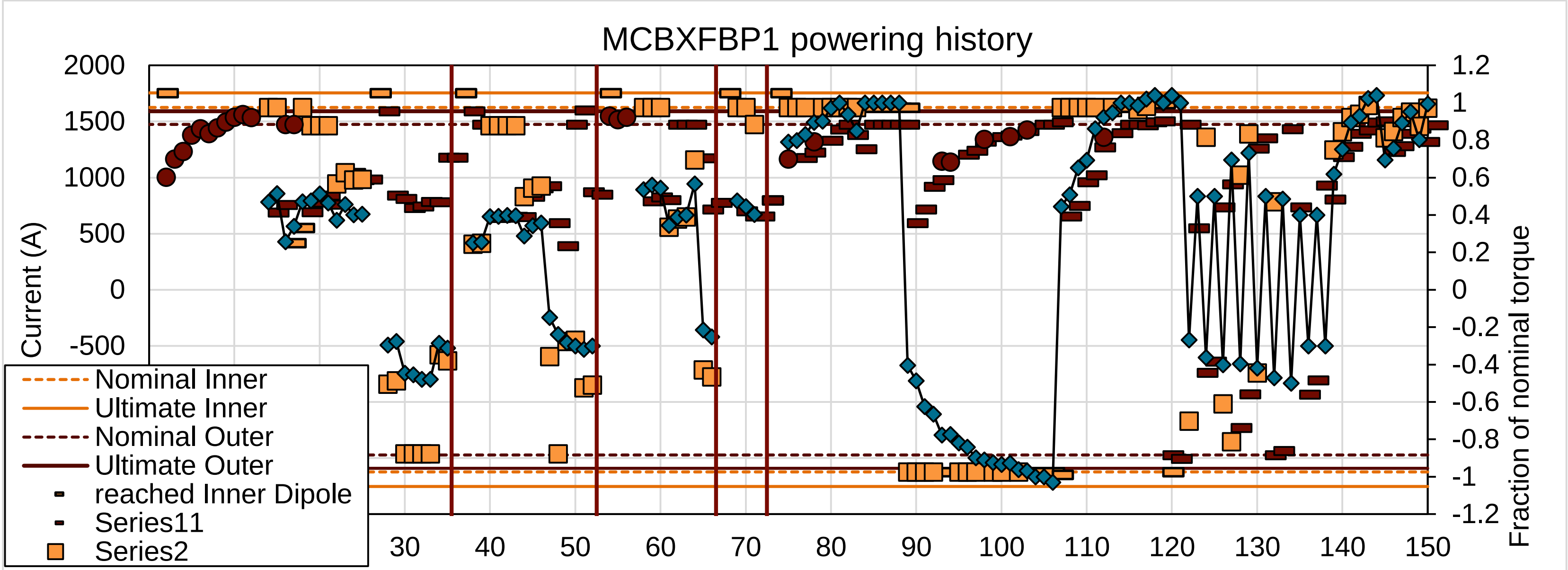
- No memory: same behaviour after the **thermal cycle.**
- The magnet can operate in the 80% of its operation range area without quench**. No quench all along red line.**
- The rest of the area is accessible with some training




Operational cycle preformed without quenches after training(in red) at last assembly (d)

# MCBXFBP1 needs a rest…

- This first prototype has been assembled and tested 4 times.
- It is decided not to risk the magnet with further testing.
- Performance improvements will be tested on the second prototype currently in production.



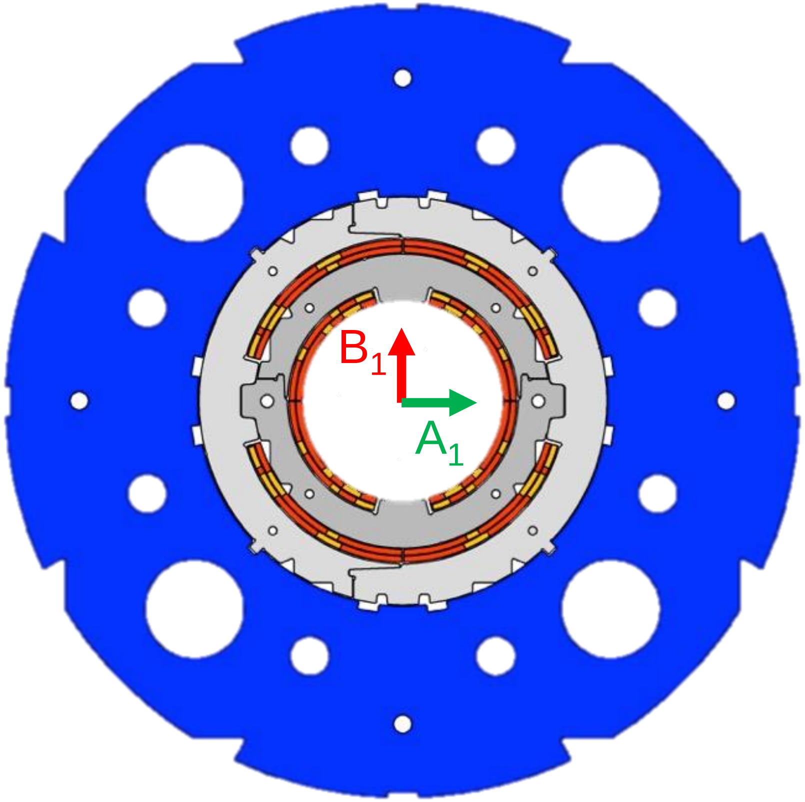

| Assembly | Number of Cycles | Number of Quench | Thermal cycles |
|---|---|---|---|
| MCBXFBP1a | 2 | 0 | 1 |
| MCBXFBP1b | 35 + 17 | 52 | 2 |
| MCBXFBP1c | 14 + 6 | 19 | 2 |
| MCBXFBP1d | 72 + 17 | 44 | 2 |
| Total | **163** | **115** | 7 |

*Courtesy of L. Fiscarelli*

# Field quality: Measurement setup

At 1.9 K, rotating-coil in the helium bath of vertical cryostat clusterD in SM18

- 5 segments (422 mm each, 2.114 m total)




Vertical field from the inner coils:

- Main field $B_1$

- First allowed $b_3$

Horizontal field from the outer coils:

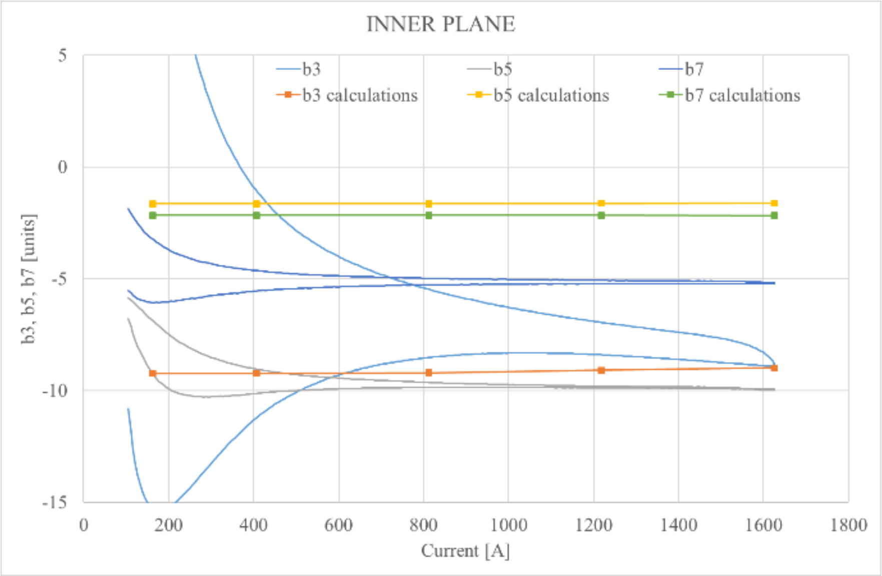
- Main field $A_1$

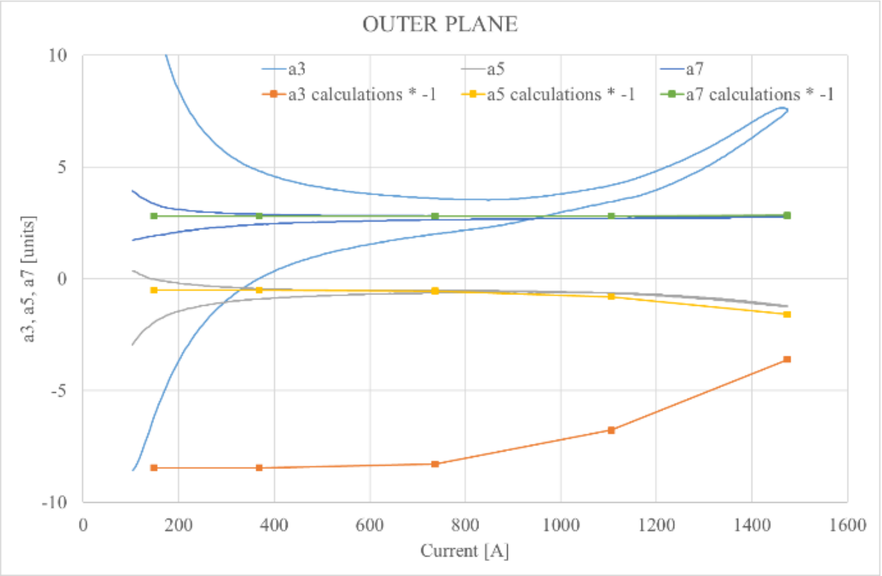
- First allowed $a_3$

**Reference radius 50 mm**

Courtesy of L. Fiscarelli

# Multipoles vs current individual powering




Difference calculations - measurements

- Inner coils plane

  Δb3 of 0 units

  Δb5 of +8 units

  Δb7 of +3 units

- Outer coils plane

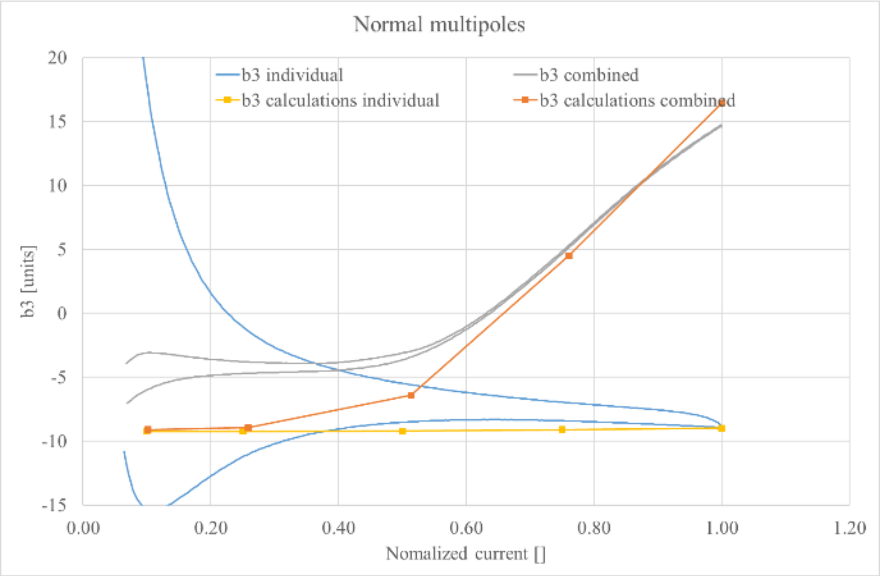
  Δa3 of -11 units

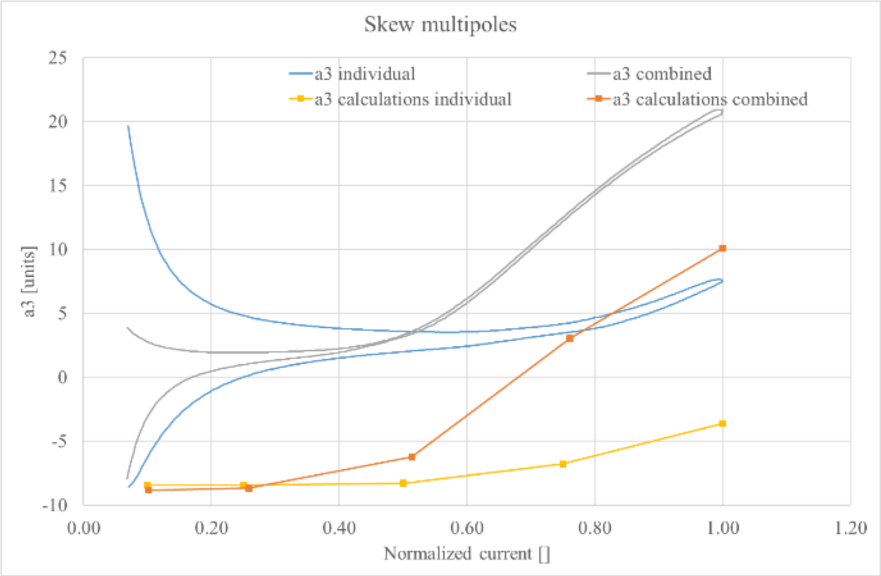
  Δa5 of 0 units

  Δa7 of 0 units

# Multipoles vs current combined powering

*Courtesy of L. Fiscarelli*




Effect of combined powering:

- Inner coils plane

  Δb3 of +22 units

- Outer coils plane

  Δ a3 of +13 units

- Change in perfect agreement with calculations.
- Multipoles sign variation depending of the operation quadrant currently under study

Courtesy of
L. Fiscarelli

# Field-quality table

| INNER at 1625 A OUTER at 0 A | | | INNER at 0 A OUTER at 1474 A | | | INNER at 1625 A OUTER at 1474 A | | |
|---|---|---|---|---|---|---|---|---|
| n | bn | an | n | bn | an | n | bn | an |
| 2 | 1.37 | 0.19 | 2 | -0.75 | 1.56 | 2 | 0.55 | 0.86 |
| 3 | -8.80 | 1.01 | 3 | -0.30 | 7.57 | 3 | 14.66 | 20.89 |
| 4 | -0.35 | 1.22 | 4 | 0.03 | 0.18 | 4 | -0.14 | 1.20 |
| 5 | -9.96 | 1.34 | 5 | 0.05 | -1.23 | 5 | -4.68 | -3.33 |
| 6 | -0.22 | 0.43 | 6 | -0.08 | -0.28 | 6 | -0.15 | 0.06 |
| 7 | -5.20 | 0.68 | 7 | -0.28 | 2.76 | 7 | -4.07 | 2.04 |
| 8 | -0.02 | 0.19 | 8 | 0.03 | 0.06 | 8 | -0.01 | 0.19 |
| 9 | -0.40 | 0.01 | 9 | 0.07 | -0.55 | 9 | -0.18 | -0.54 |
| 10 | 0.24 | -0.04 | 10 | 0.01 | 0.01 | 10 | 0.21 | -0.04 |
| 11 | 2.14 | -0.22 | 11 | 0.03 | -0.04 | 11 | 1.53 | 0.19 |
| 12 | -0.23 | 0.14 | 12 | 0.01 | 0.01 | 12 | -0.14 | 0.10 |
| 13 | -1.48 | 1.26 | 13 | -0.03 | 0.07 | 13 | -0.61 | -0.59 |
| 14 | 0.02 | -0.03 | 14 | -0.01 | 0.03 | 14 | -0.06 | 0.05 |
| 15 | 0.16 | -0.01 | 15 | 0.00 | -0.02 | 15 | 0.10 | 0.04 |

**Units of $10^{-4}$ at the reference radius of 50 mm**

**Field Quality acceptable for machine operation**

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# Quench protection

- Baseline:
  - FB (Short) = Self-protected.
  - FA (Long) = Dump resistor.
- Further analysis is necessary to determine if contribution of inter-strand losses justify the measures we have in quench compared with the results obtained from SQUID (CIEMAT in-house code) and Roxie.
- Current protection scheme:
  - FB inner dipole = Self-protected.
  - FB outer dipole = No decision made.
  - FA inner dipole = No decision made.
  - FA outer dipole = Dump resistor.

(FB outer dipole and FA inner dipole:) Studies and analysis are still ongoing

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# Second MCBXFB prototype (I)

- The production of the second short prototype is ongoing.
- Some small **modifications** have been made on the magnet design and tooling:
  - Cable insulation thickness is within specifications
  - Copper wedges for coils are produced by extrusion
  - Endspacer geometry has been modified to fit better the cable block geometry
  - Cable exit from the coils have been mechanically reinforced
  - Coil instrumentation has been removed
- **Tendering** for the collar production is closed, contract has been signed and their production is ongoing.

# Second MCBXFB prototype (II)

- First outer dipole coil has been finished (old wedges and end spacers).
- First inner dipole coil has been finished (extruded wedges but old end spacers).
- Second inner dipole coil is ongoing with extruded wedges and new end spacers. Next week it should start its transition from the binding mould to the impregnation one.
- Extruded copper wedges for outer dipole coil were delayed because of quality problems but they are already on their way.
- Quality assurance and documentation is being made following CERN procedures.

# Long magnet prototype

- The long magnet prototype will be made at CIEMAT and assembled at CERN (927 workshop).
- Same cross section, one meter longer. Same end spacers and wedges than in the short magnet.
- Most of the drawings have been already produced.
- The tooling concept is the same, but some design modifications are necessary.
- The fabrication of parts for the winding machine, the winding tooling, binding and impregnation moulds has been already started.
- Collars will be produced by fine blanking. Tendering has just started, including also the collars for series magnets.

# Second MCBXFB prototype schedule

| | Task | |
|---|---|---|
| Fabrication | Coils | Nov-19 |
| | Magnet components | Nov-19 |
| | Assembly at CERN | Dec-20 |
| Test | Magnet prototype in vertical cryostat | Jan-20 |

# Long magnet prototype schedule

| | | |
|---|---|---|
| Design | Magnet | Sep-19 |
| | Tooling | Oct-19 |
| Fabrication | Winding & binder tooling | Oct-19 |
| | Impregnation tooling | Nov-19 |
| | First ID coil | Jan-20 |
| | Rest of coils | Jul-20 |
| | Magnet components | Jul-20 |
| | Assembly at CERN | Aug-20 |
| Test | Magnet prototype in vertical cryostat | Sep-20 |

# Series production

- Technical specifications will be finished by November.
- Tendering will take four months.
- CIEMAT will make another call for tenders for the supply of the end-spacers, which are needed also for the long prototype.
- CERN will supply the insulated superconducting cable, steel for the collars and iron for the yokes.
- CIEMAT will supply the copper wedges, the end spacers and the collars (fine blanking).

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# Conclusions

- Three first power tests showed good individual performance and memory of the coils, but combined operation was limited to 50% of nominal torque.
- Finally, in the fourth power test, this limitation was overcome by adapting the coil-end shimming configuration in order to compensate the coils geometrical defaults in the midplane.
- Once trained to nominal torque in one quadrant the magnet can cover an 80% of the required operation range. Operation with the full torque in the opposite direction is possible via a limited training (<10 quenches).
- In order to improve this performance, a less conservative shimming plan for coil extremities will be applied on the second prototype. Further testing in MCBXFP1 could damage the magnet.
- Field quality is acceptable for machine operation.
- FB ID is self protected and FA OD will need dump resistor. Studies and analysis are still ongoing to decide the protection of FB OD and FA ID.
- Second short magnet is being produced at CIEMAT. First long one will be produced also at CIEMAT and assembled at CERN. The series tendering is under preparation.

# *Thank you for your attention*

Acknowlegdments to:

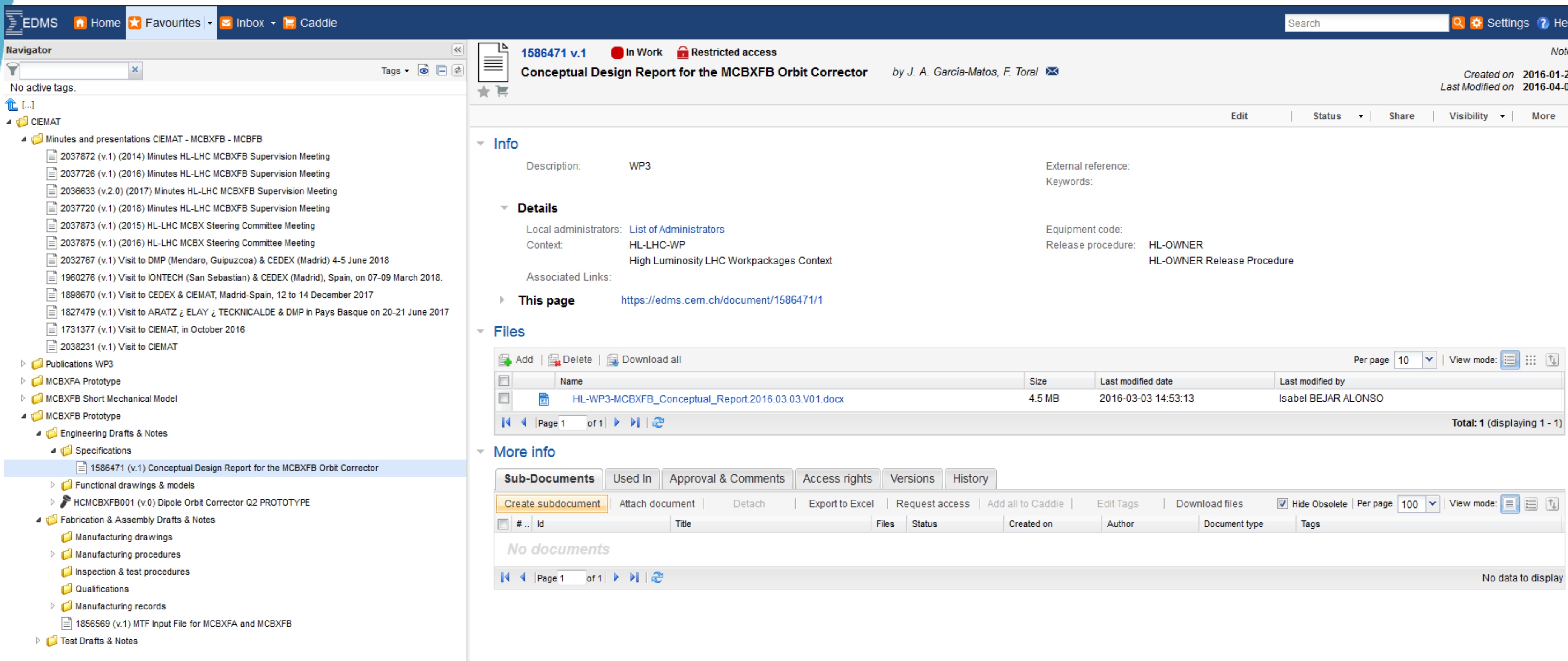
927 and SM18 teams at CERN.

Companies involved in the magnet and tooling fabrication:

APM, Apteca, Aratz, Bronymec, Egile, Focs, GAZC, Utillajes Jucar, Klero, Ramem and Teknicalde

## *Back-up slides*

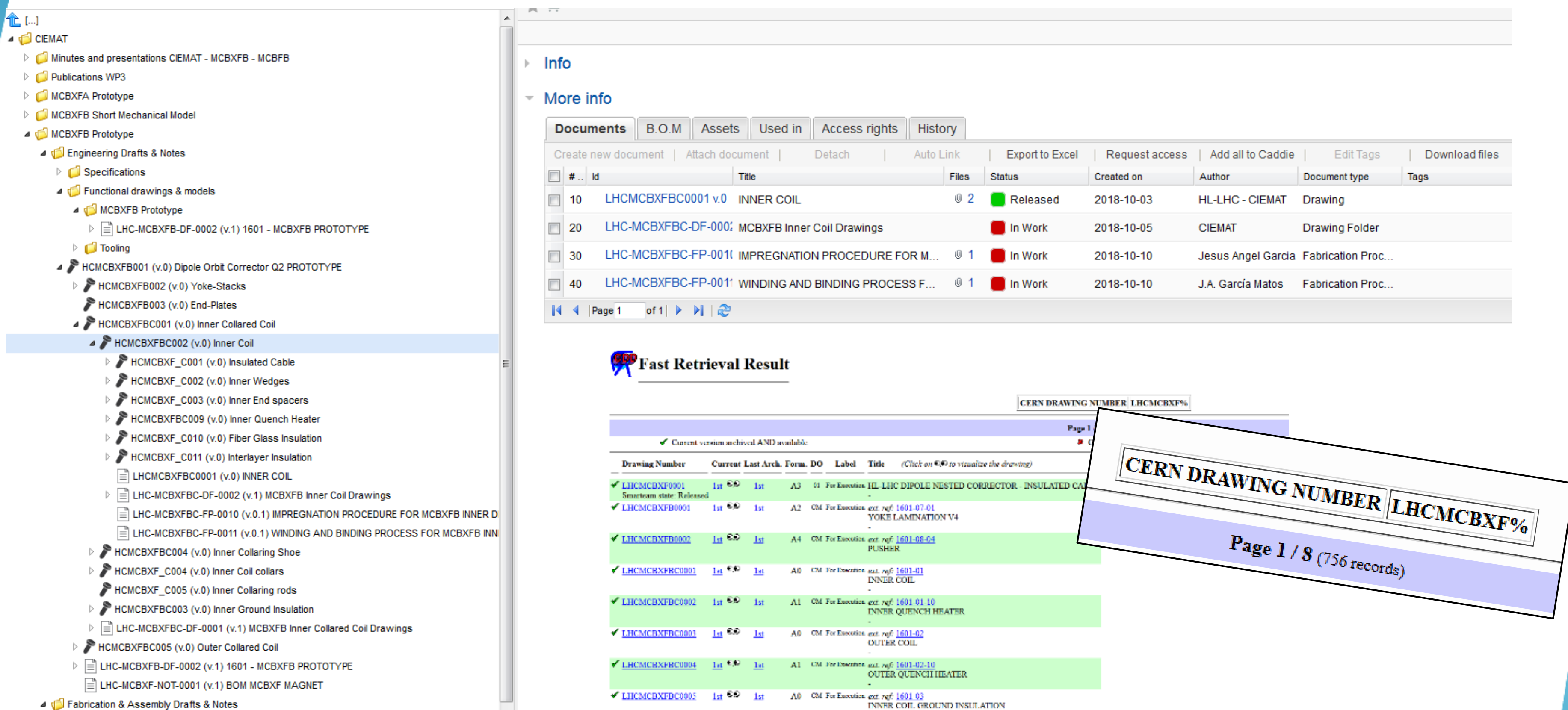
# Project EDMS structure for the documentation




All the project documentation will be accessible in EDMS (Minutes, specifications, drawings, manufacturing records, procedures…). A lot of documents have already been uploaded. More will come soon….

Special thanks to Hector, Beatriz, Ruth and Nicolas for their help

# Drawings




Around 50% of the 900 drawings generated for the project have been uploaded and controlled in EDMS/CDD.

They are linked to the equipment in the EDMS project structure.

The second batch of drawings is being prepared.

# Manufacturing documentation (MTF)

- CIEMAT
  - CIEMAT - CERN Mangement
  - CIEMAT - Acceptance criteria
  - CIEMAT - Parts exchanged
  - Minutes and presentations CIEMAT - MCBXFB - MCBFB
  - Publications WP3
  - MCBXFB Short Mechanical Model
  - MCBXFA Prototype
  - MCBXFB Prototype
    - Engineering Drafts & Notes
    - Fabrication & Assembly Drafts & Notes
      - Manufacturing drawings
      - Manufacturing procedures
      - Inspection & test procedures
      - Qualifications
      - Manufacturing records
        - Coils
          - HCMCBXFBC002-E9000001 - Inner Coil
          - HCMCBXFBC002-E9000002 - Inner Coil
          - HCMCBXFBC002-E9000003 - Inner Coil
          - HCMCBXFBC006-E9000001 - Outer Coil
          - HCMCBXFBC006-E9000002 - Outer Coil
          - HCMCBXFBC002-E9000004 - Inner Coil
          - HCMCBXFBC002-E9000005 - Inner Coil
          - HCMCBXFBC006-E9000003 - Outer Coil
          - HCMCBXFBC006-E9000004 - Outer Coil
        - Magnets
          - HCMCBXFB001-E9000011 - Dipole Orbit Corrector Q2
          - HCMCBXFB001-E9000012 - Dipole Orbit Corrector Q2
          - HCMCBXFB001-E9000013 - Dipole Orbit Corrector Q2
          - HCMCBXFB001-E9000014 - Dipole Orbit Corrector Q2
          - HCMCBXFB001-E9000021 - Dipole Orbit Corrector Q2
        - Tooling

***Equipment Identifier:*** **HCMCBXFB001-E9000011**
***Other Identifier:*** **MCBXFBP1a**
***Description:*** **Dipole Orbit Corrector Q2**

Main | Made of | Equipment data | Manufacturing | Operation | Documents | **History** | Map

**Actions :**

| Date | Type | Related value | Done by |
|---|---|---|---|
| 2017-10-31 | Creation | | MANEVES |
| 2017-11-07 | Child attached | HCMCBXFB002-E9000001 | JPEREZ |
| 2017-11-07 | Child attached | HCMCBXFB003-E9000001 | JPEREZ |
| 2017-11-07 | Child attached | HCMCBXFBC001-E9000001 | JPEREZ |
| 2017-11-07 | Child attached | HCMCBXFBC005-E9000001 | JPEREZ |
| 2017-11-14 | Status changed to | Manufacturing | MANEVES |
| 2019-02-27 | Renamed from | HCMCBXFB001-E9000001 | MANEVES |
| 2019-02-27 | Child detached | HCMCBXFB002-E9000001 | RDIAZVEZ |
| 2019-02-27 | Child detached | HCMCBXFB003-E9000001 | RDIAZVEZ |
| 2019-02-27 | Child attached | HCMCBXFB003-E9000001 | RDIAZVEZ |
| 2019-02-27 | Child detached | HCMCBXFB003-E9000001 | RDIAZVEZ |
| 2019-02-27 | Child detached | HCMCBXFBC001-E9000001 | RDIAZVEZ |
| 2019-02-27 | Child detached | HCMCBXFBC005-E9000001 | RDIAZVEZ |

***Equipment Identifier:*** **HCMCBXFB001-E9000014**
***Other Identifier:*** **MCBXFBP1d**
***Description:*** **Dipole Orbit Corrector Q2**

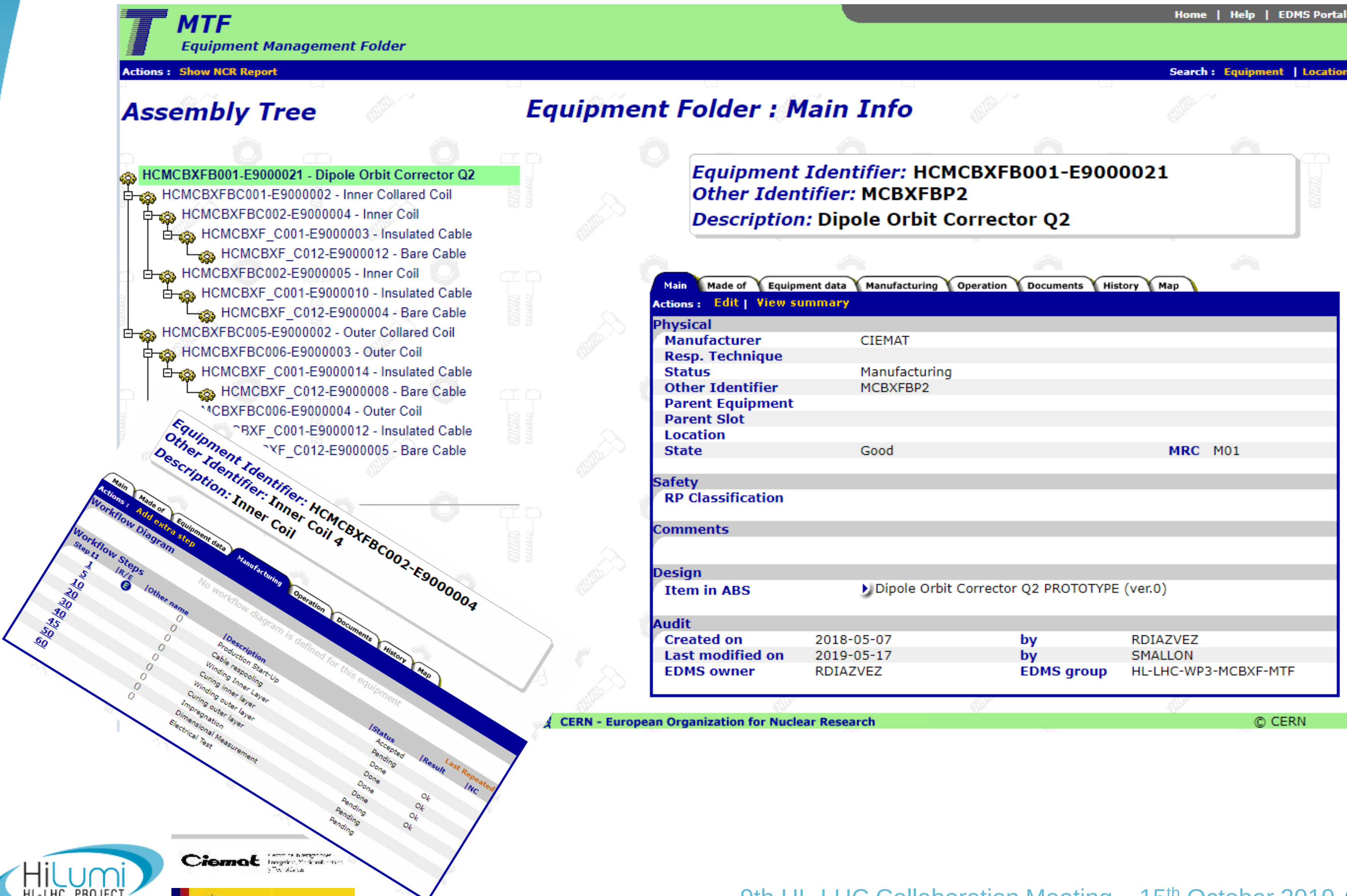
Main | Made of | Equipment data | Manufacturing | Operation | Documents | **History** | Map

**Actions :**

| Date | Type | Related value | Done by |
|---|---|---|---|
| 2019-07-16 | Creation | | RDIAZVEZ |
| 2019-08-01 | Child attached | HCMCBXFBC001-E9000001 | RDIAZVEZ |
| 2019-08-01 | Child attached | HCMCBXFBC005-E9000001 | RDIAZVEZ |
| 2019-08-01 | Child attached | HCMCBXFB002-E9000001 | RDIAZVEZ |
| 2019-08-01 | Child attached | HCMCBXFB003-E9000001 | RDIAZVEZ |
| 2019-08-06 | Attached to | 927/R-001 | RDIAZVEZ |

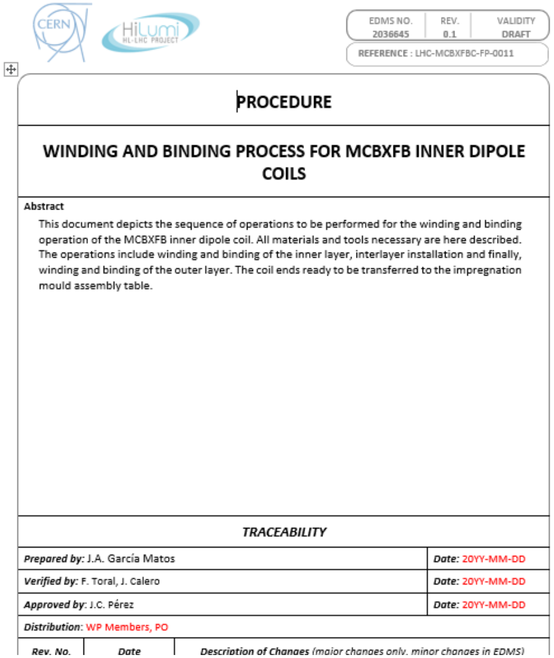
The first two magnets are being documented in MTF

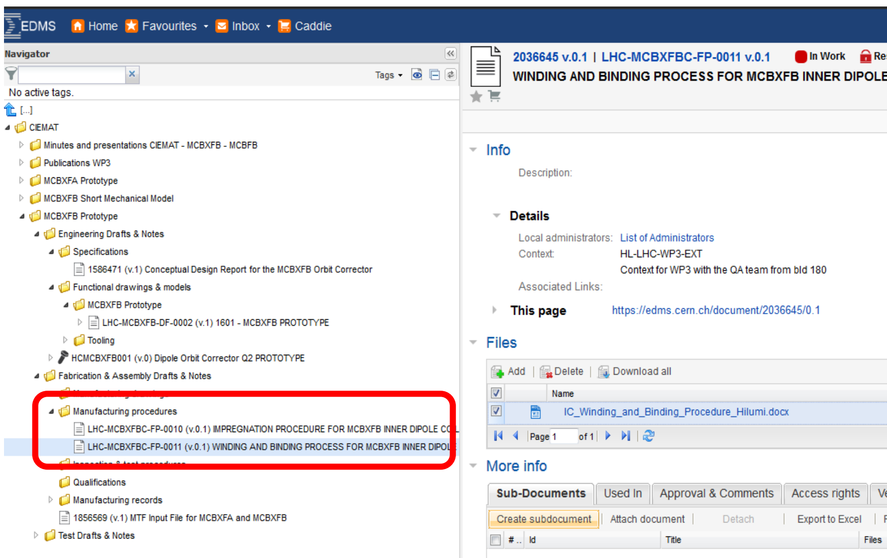
# View of the 2nd prototype structure in MTF



# Procedures

- The first draft procedures (winding and coil binding) are uploaded in EDMS and are being finalized.
- The coil impregnation procedure document is well advanced.
- The magnet assembly procedure will be produced in the next weeks, once validated during the prototype assembly at CERN.
- A draft of the MIP exists and will be reviewed in the coming weeks.

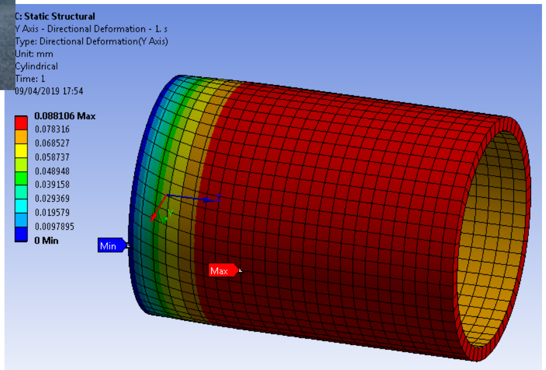


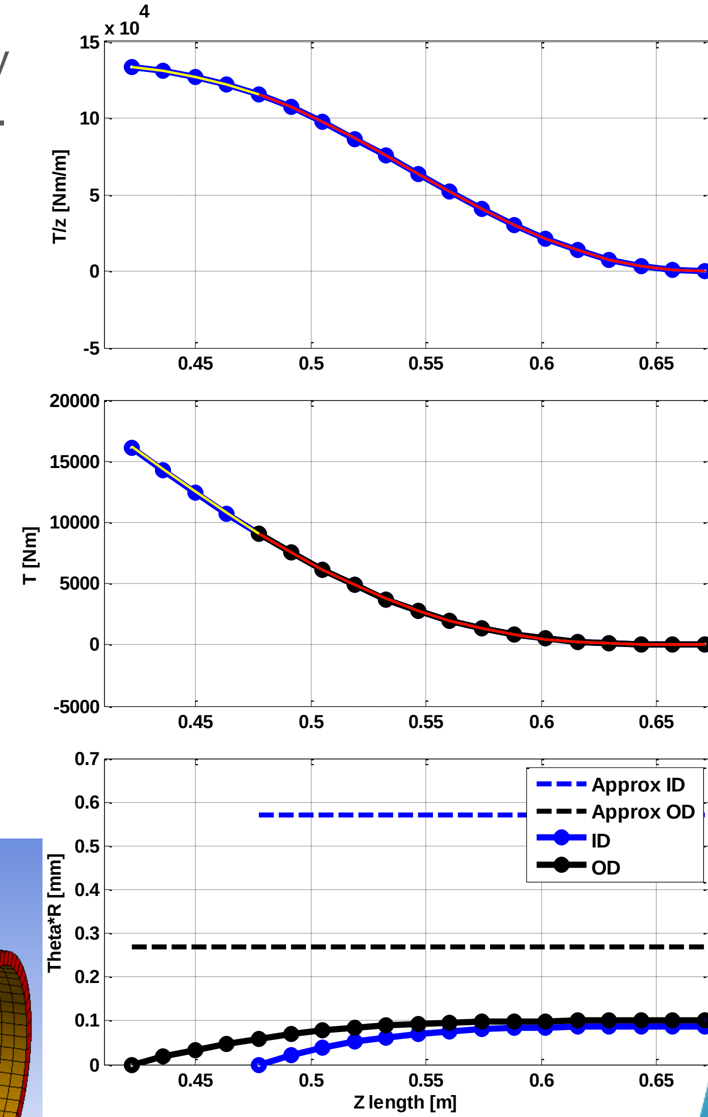




# Torque on combined powering configuration

- Nominal torque per unit length at straight section is very high: 140 kNm/m, about 80 MPa at the inner dipole coil. It is consistent with strain gauges measurements.
- The reaction force at the coil end is about 22 kN. At nominal current, the Lorentz axial force is about 76 kN. Therefore, we need a friction coefficient above 0.3 to avoid sliding.
- Coils are loose at the end of the straight part, between the last end spacer and the end of the collar nose cavity.

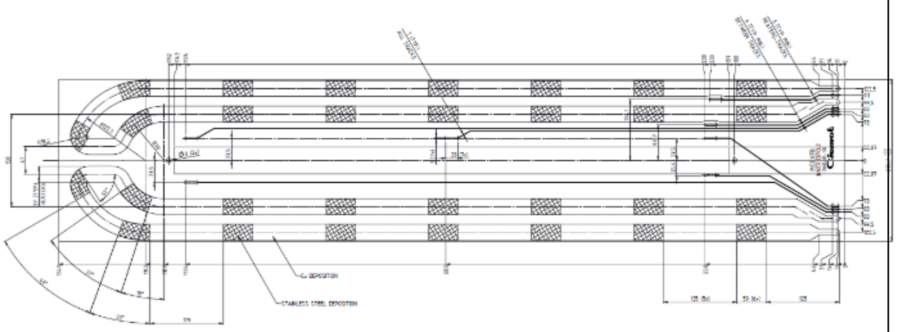
Porsche Taycan engine
1.05 kNm



# Protection (2016)

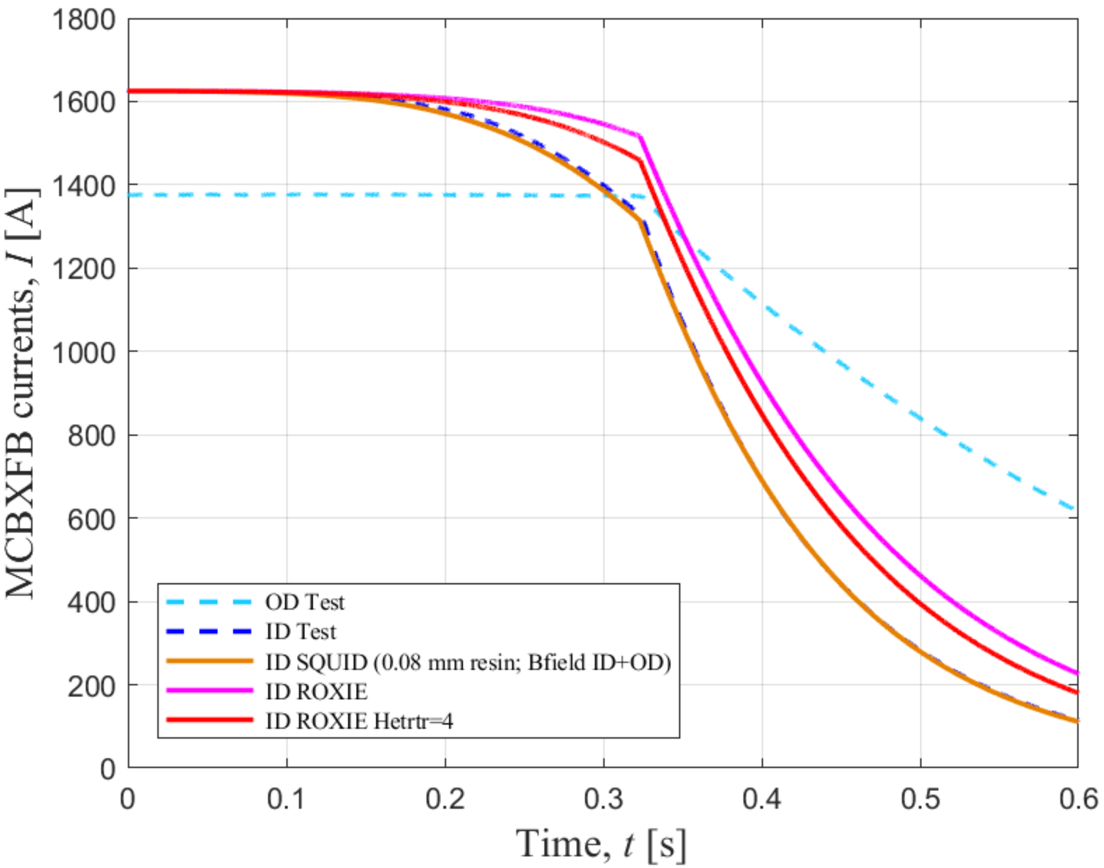
- Quench simulation with CIEMAT code **SQUID**, based on finite difference method.
- Baseline strategy is: short magnet is self-protected, long one is protected by dump resistor.
- Heaters are being implemented in the short prototype for **validation**. If successful, they will be likely implemented instead dump resistor.
- Heaters produced by **927** team.
- One **voltage tap** per cable block and at both sides of the layer jump.



| | Current | Dipole | Protection | Tmax (K) | Vmax (V) | Energy dissipated in magnet (kJ) |
|---|---|---|---|---|---|---|
| MCBXFA | Nominal | Inner | Heaters ON | 126 | 393 | 121 |
| | | | Heater OFF | 242 | 389 | 121 |
| | | | Dump resistor 0.3 ohm | 65 | 480 | 5 |
| | | Outer | Heaters ON | 133 | 643 | 215 |
| | | | Heater OFF | 284 | 618 | 215 |
| | | | Dump resistor 0.3 ohm | 106 | 441 | 26 |
| | 110% nominal | Inner | Heaters ON | 154 | 519 | 146 |
| | | | Heater OFF | 274 | 504 | 146 |
| | | | Dump resistor 0.3 ohm | 80 | 528 | 9 |
| | | Outer | Heaters ON | 160 | 847 | 260 |
| | | | Heater OFF | 322 | 798 | 260 |
| | | | Dump resistor 0.3 ohm | 141 | 485 | 46 |
| MCBXFB | Nominal | Inner | Heaters ON | 129 | 234 | 72 |
| | | | Heater OFF | 177 | 235 | 72 |
| | | | Dump resistor 0.3 ohm | 50 | 480 | 2 |
| | | Outer | Heaters ON | 137 | 383 | 129 |
| | | | Heater OFF | 211 | 376 | 129 |
| | | | Dump resistor 0.3 ohm | 65 | 441 | 7 |
| | 110% nominal | Inner | Heaters ON | 154 | 311 | 88 |
| | | | Heater OFF | 198 | 308 | 88 |
| | | | Dump resistor 0.3 ohm | 57 | 528 | 3 |
| | | Outer | Heaters ON | 163 | 504 | 156 |
| | | | Heater OFF | 243 | 489 | 156 |
| | | | Dump resistor 0.3 ohm | 79 | 485 | 11 |

# Q21: Quench in ID at 1625 A with dump resistor with 300 ms delay (August 2019)

- Quench in the pole turn of the Inner Dipole at nominal current with OD at 1376 A.
- t=0 at the initial quench. 13 ms for quench detection plus 10 ms for quench validation.
- 0.3 Ohm dump resistor with 300 ms delay from validated quench.
- Measured RRR=140.
- **SQUID predicts very good the discharge assuming an excess of resin.**
- **ROXIE is not able to reproduce the current decay even improving the transverse thermal conductivity.**

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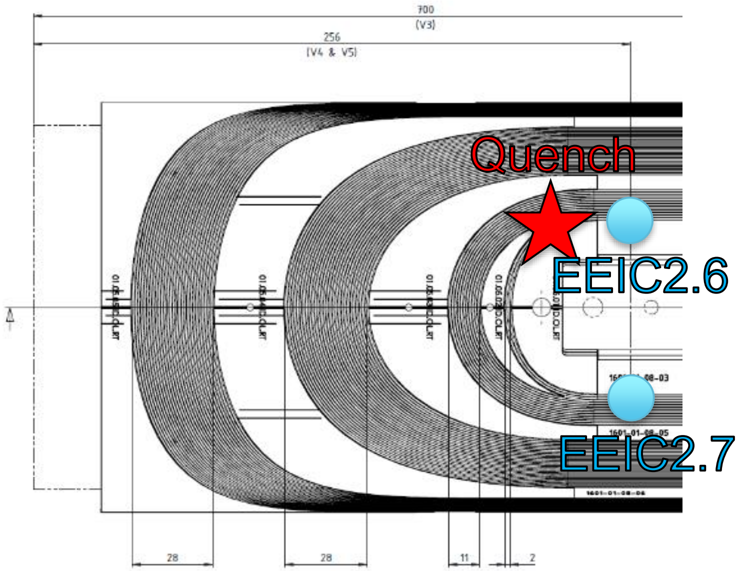
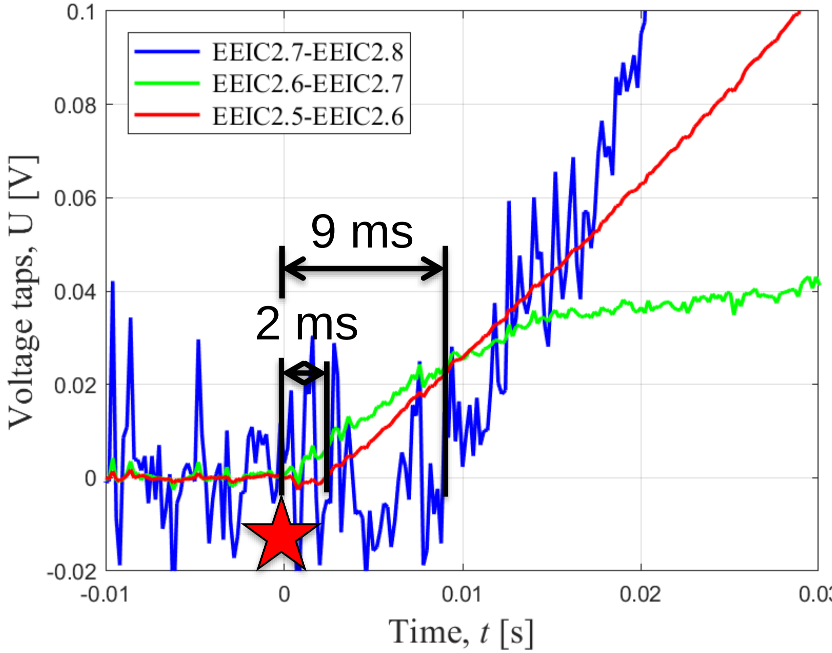
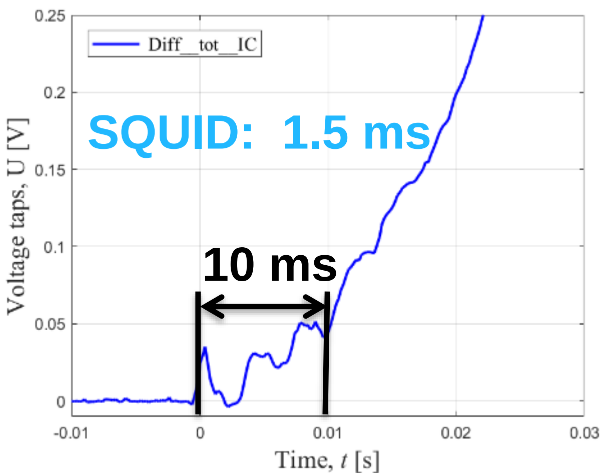
# Q21: Quench in ID at 1625 A. Quench propagation velocity

- **Longitudinal quench propagation velocity** calculated with the voltage taps information plus geometry (assuming velocity from quench to EEIC2.6 equals velocity to EEIC2.7): **12.6 m/s.** **SQUID: 7.4 m/s.**
  - Quench in the coil end pole turn.




- **Turn-to-turn propagation time**




**The SQUID underestimation of the initial longitudinal quench velocity compensates the overestimation of the transversal velocity.**

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# Q21: Quench in ID at 1625 A. Hot-spot temperature

- **Hot-spot temperature calculated from the current and voltage measurements,** from the initial quench until dump resistor triggering (afterwards the voltage signal is distorted). Assuming uniform temperature in the cable section EEIC2.6 to EEIC2.7.

  $U_{EEIC2.6} - U_{EEIC2.7}$ =0.69 V and $I_{ID}$ =1328 A before Dump resistor triggering at 323 ms from initial quench.
  $R_{Cu} = (U_{EEIC2.6} - U_{EEIC2.7})/I_{ID}$=0.52 mOhm.

  $\rho_{Cu} = R_{Cu} * S_{Cu}/l_{67}$ (being $S_{Cu}$ the Cu area in the cable and $l_{67}$ the length between EEIC2.6 and EEIC2.7).

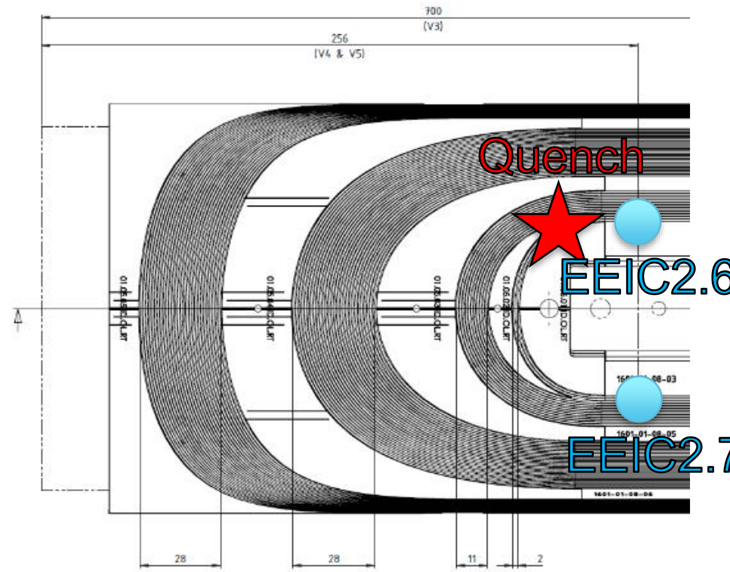
  $\rho_{Cu} = 7.98 * 10^{-9}$Ohm*m.

- CERN's formula:

  $\rho_{Cu}(B,T) = [c0/RRR + 1/(c1/T^5 + c2/T^3 + c3/T)] \cdot 10^{-8} + (0.37 + 0.0005 \cdot RRR) \cdot 10^{-10} \cdot B;$

  where RRR=140, and B~2.57 T is the combined field at $I_{ID}$ =1328 A. Using Excel, the temperature for the calculated $\rho_{Cu}$ is: **159 K.**

- **SQUID: 169 K** before dump resistor triggering (note that SQUID calculates 0.006 MIIts less than measurements, to compare with the same MIIts, **SQUID calculates 173 K**).



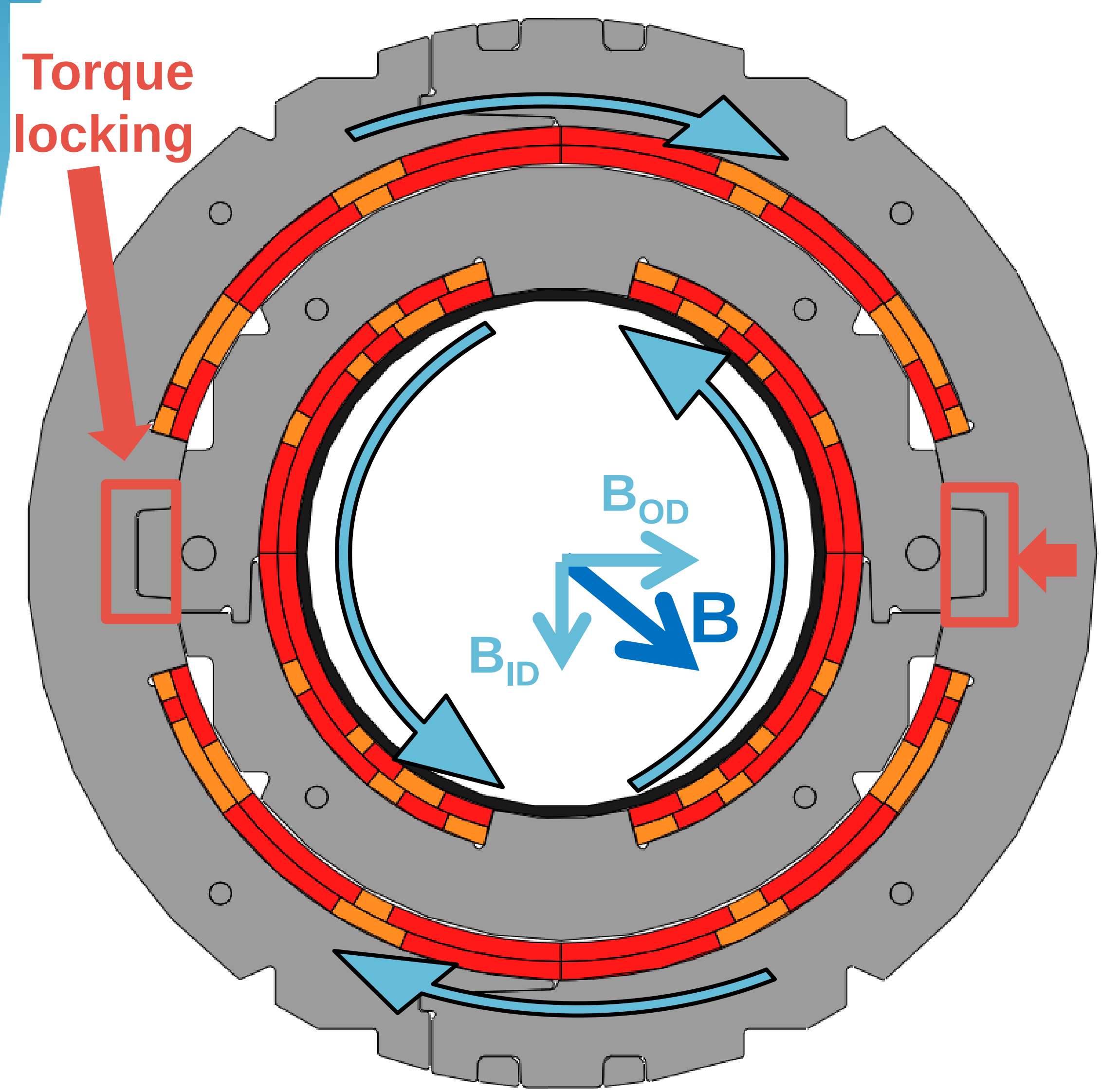

- **SQUID acceptably estimates the hot-spot temperature of the MCBXFB-ID, being conservative by ~8 %.**

# Predictions for the ID at ultimate current 1742 A

| Test parameters | Model | Maximum voltage (V) | MIIts ($MA^2s$) | Hot-spot temperature (K) |
|---|---|---|---|---|
| Dump resistor 0.3 Ohm; 350 ms delay | SQUID | 295 | 1.05 | 294 |
| | ROXIE | 408 | 1.17 | 312 |
| Dump resistor 0.3 Ohm; 400 ms delay | SQUID | 297 | 1.07 | 309 |
| | ROXIE | 346 | 1.21 | 338 |
| Without dump resistor | SQUID | 297 | 1.09 | 325 |
| | ROXIE | 174 | 1.28 | 377 |

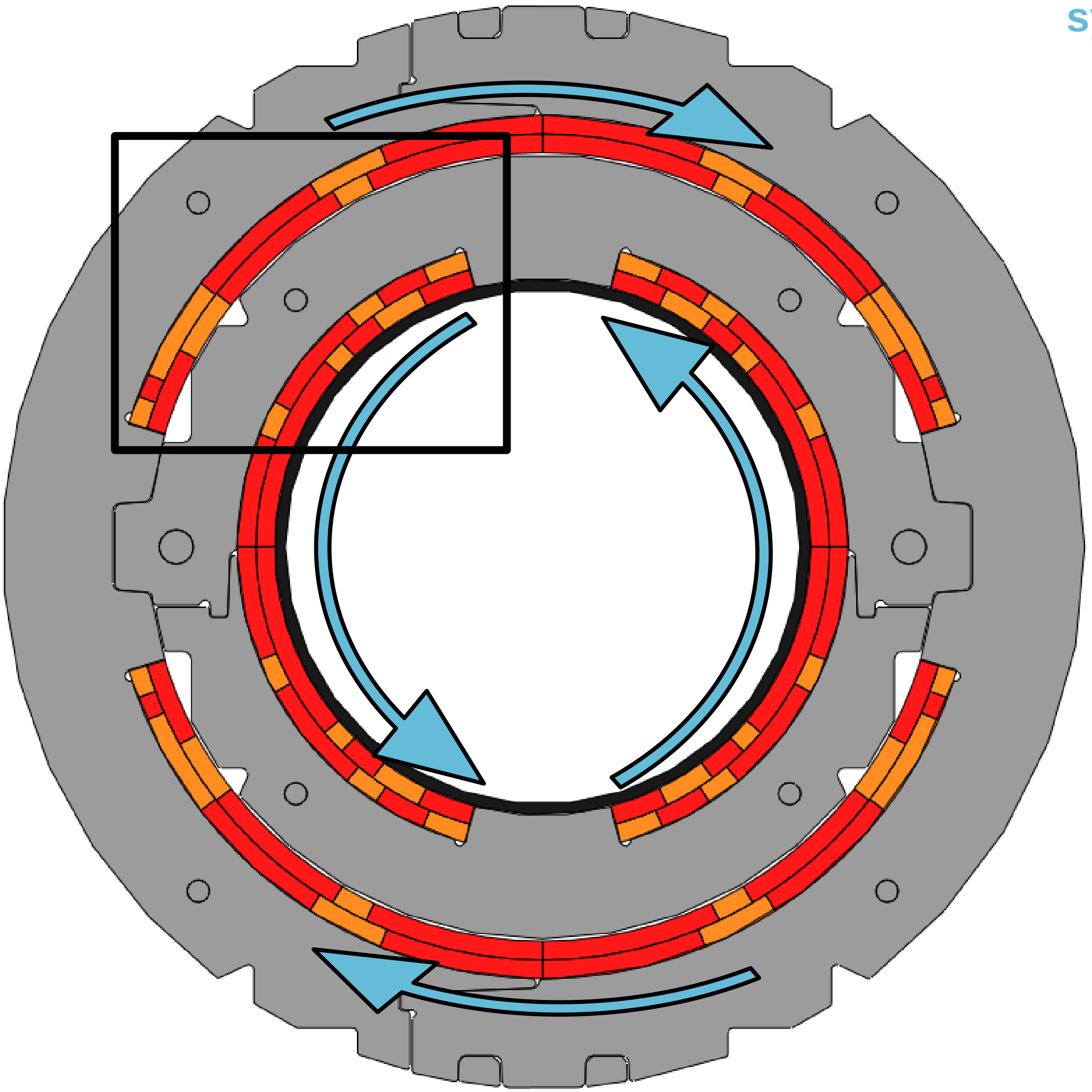
- Note that the calculated voltage is the voltage to ground in ROXIE simulations but it is only the resistive voltage in SQUID, so they cannot be directly compared. Moreover, ROXIE includes in the voltage calculation the voltage generated across the dump resistor, while SQUID takes into account only the magnet voltage.
- After matching the current decay, the hot spot temperature predictions are higher, because of the cable insulation properties. It is a pessimistic assumption.
- Results are also cross-checked with an adiabatic model. For real test data at nominal current, hot spot prediction is below 300 K without cable insulation, and below 200 K with cable insulation (G10).

# Mechanical Design Summary: Torque Locking




- When both dipoles are powered their perpendicular magnetic fields try to align the coils.
- This is avoided through key-shaped inner collars which mount into the outer ones.

# Mechanical Design Summary: Azimuthal Deformations



- **Azimuthal coil displacements are not symmetric respect the midplane.**

# Mechanical Design Summary: Azimuthal Deformations

- Azimuthal coil displacements are not symmetric respect the midplane.
- The pole turn on one side of the collar nose is compressed, as on the other side, it is prone to lose contact.