Power Tests of the First Nested Orbit Corrector Prototype for HL-LHC

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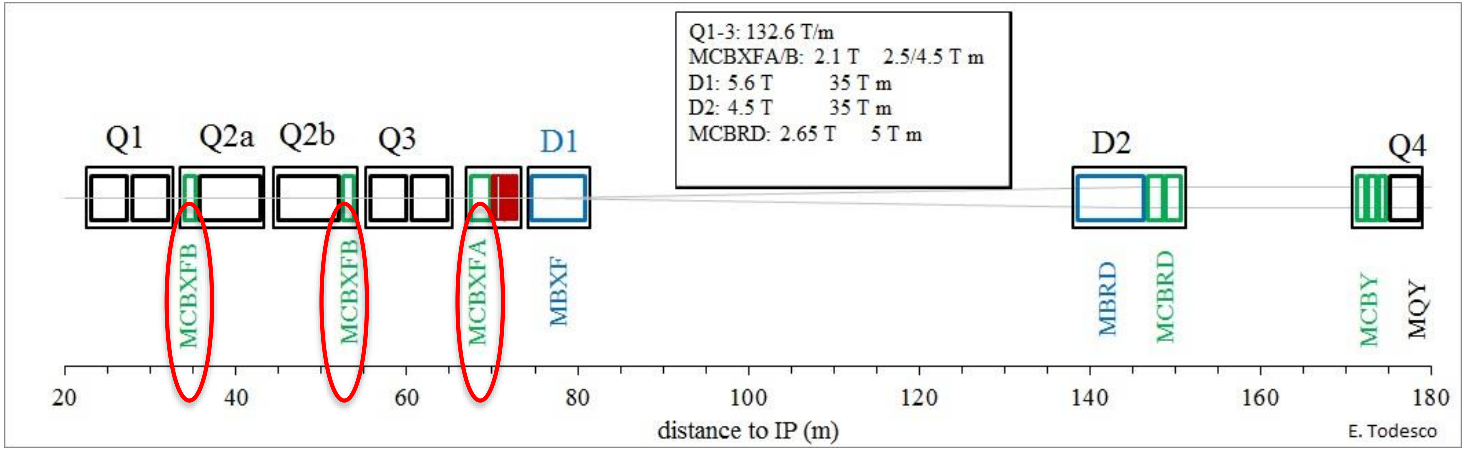
Index

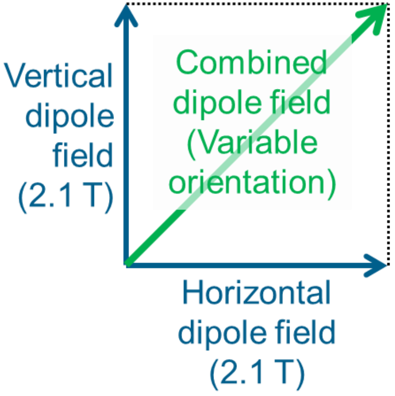
Orbit correctors for HL-LHC

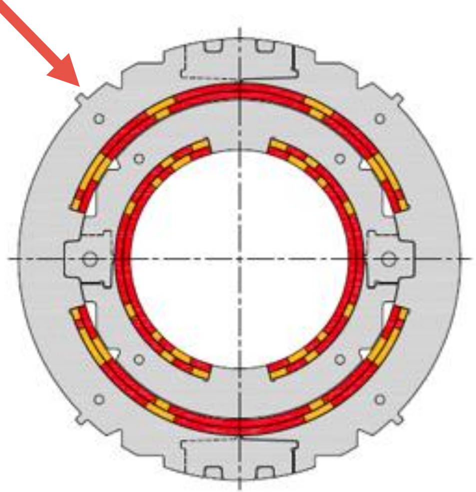


- Three MCBXF orbit correctors will be installed at each side of the interaction point in the LHC upgrade.
- Same cross section: type A is 2.5 m long while type B is 1.5 m long.

Magnet and cable specifications

MCBXFB Technical specifications	
Magnet configuration	Combined dipole (Operation in X-Y square)
Integrated field	2.5 Tm
Minimum free aperture	150 mm
Nominal current	< 2500 A
Radiation resistance	35 MGy
Physical length	< 1.505 m
Working temperature	1.9 K
Iron geometry	MQXF 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

Same nominal torque than 140 Porsche Taycan Turbo S

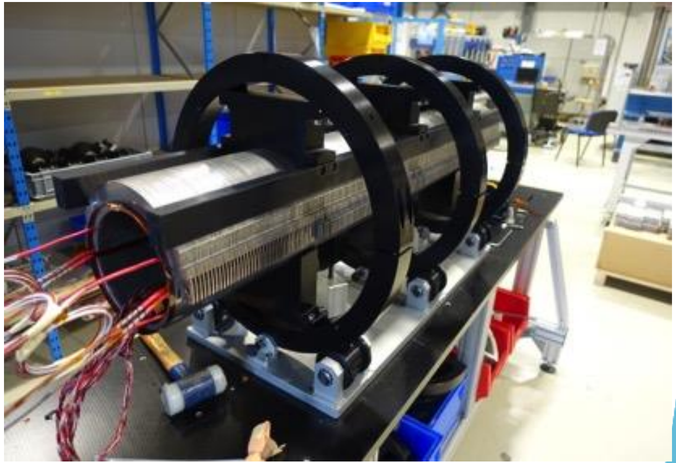
MCBXFB magnetic design

Parameter	Inner dipole	Outer dipole	Units
Nominal individual field	2.14	2.26	T
Nominal combined field	3.12	3.12	T
Aperture diameter	156.2	230	mm
Nominal current	1625	1474	A
Ultimate current	1755	1592	A
Differential self- inductance	58.5	124.8	mH
Magnetic energy	76.8	143.2	kJ
|b3|	<15	<15	units
Higher multipoles	<5	<5	units
Number of turns	140	191	
Cable length	360	487	m

- **Innovative coil fabrication techniques** 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
- In order to validate the coil fabrication techniques, it was decided to test the magnet **without the outer dipole coils** which were still under fabrication.

Inner dipole assembly (I)

- The **assembly techniques** of the final magnet were also validated.
- The first collaring attempt failed because excessive **friction** between the collaring shoes. It was solved by spraying Molykote D-631.
- Several **shimming** steps to reach the right preload, checked with collar strain gauges and Fujifilm Prescale paper. Coils were below nominal dimensions.
- 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.

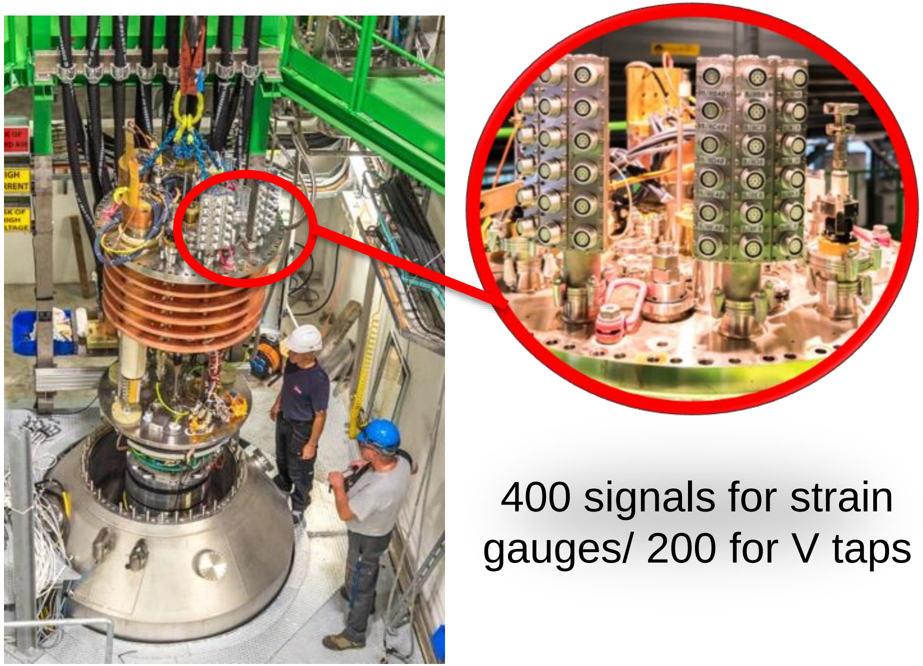


Inner dipole assembly (II)

- The outer dipole was replaced by 316 L stainless steel **spacers**.
- **Axial preload** was 6 kN per pusher (four per coil).
- **Endplates** hold the coil axial preload and compress the iron laminations.

Inner dipole power test

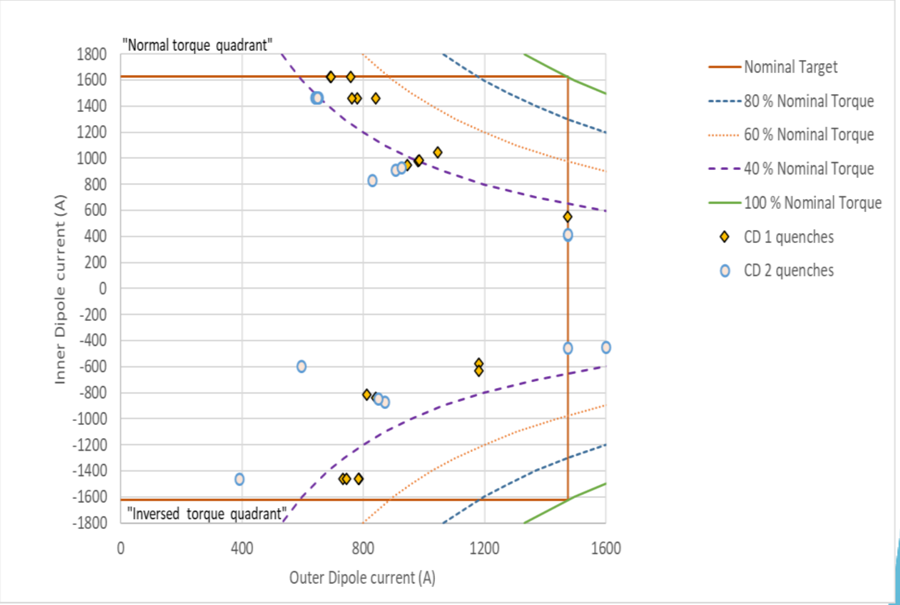
- Inner dipole reached **ultimate** current without any quench.
- Coils lost azimuthal preload. The assumed **thermal contraction coefficient** was too low (3.5 per mil) . By comparison with MQXF coils, it was recomputed as 4.7 per mil: additional shims of 150 microns.
- **Field quality**: b3 of 22.2 units instead of 9.2 units because of shimming. Higher order multipoles below 5 units.



400 signals for strain gauges/ 200 for V taps

Second power test

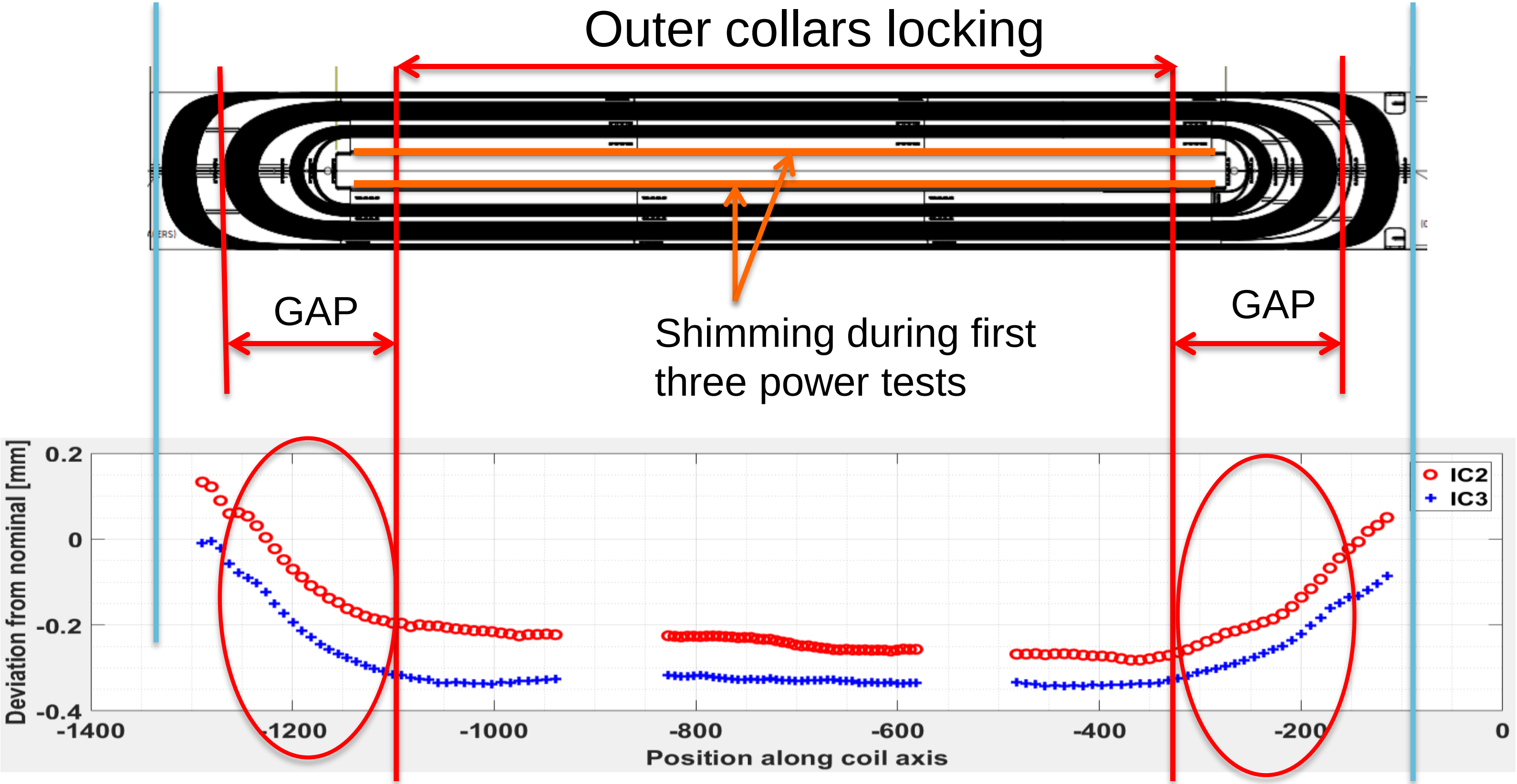
- The **inner dipole** was powered till ultimate current without quench. Azimuthal preload lower than expected.
- The **outer dipole** experienced a slower training:
  - First quench at 1006 A
  - 7 quenches till reaching nominal current.
  - 4 quenches more till reaching ultimate current.
- **Combined powering** with limited torque performance. Quenches at midplane cable block, inner dipole coils.
- After **thermal cycle**, with reduced axial preload for diagnosis, the performance was worse.
- **Decision**: to increase the friction at the coil ends and inner dipole azimuthal preload.



Third power test

- Both dipole coils were properly preloaded.
- **No significant improvement**:
  - Inner dipole reached ultimate current without quench.
  - Outer dipole reached ultimate current with 3 quenches above nominal one.
  - Combined operation performed with 8% more torque.
- During the **thermal cycle**, the axial preload was increased without effect.
- **What to do now?** Do we refurbish the magnet?

Magnet performance limited by torque (I)



Outer collars locking

GAP

GAP

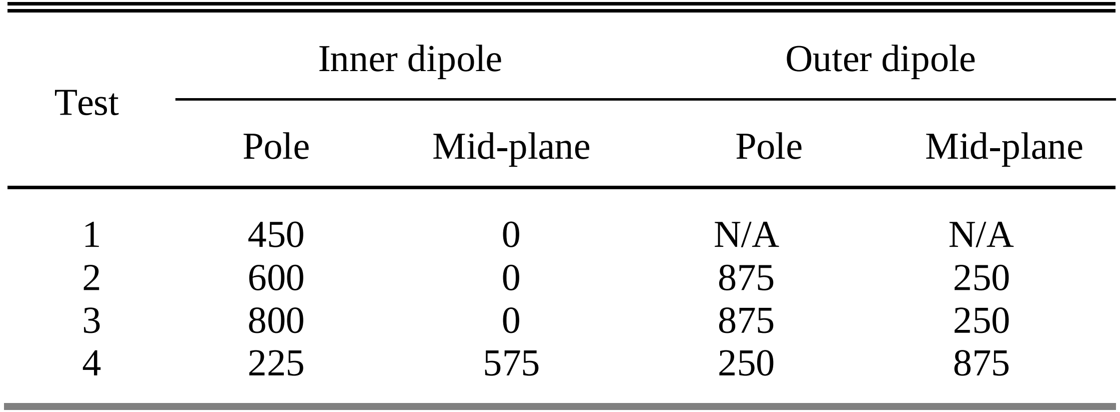
Shimming during first three power tests

Magnet performance limited by torque (II)

- 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 coefficient of **friction** at coil ends or **axial preload**.
  - Magnet performance slightly improved with higher **azimuthal preload** at inner dipole coils.

Magnet performance limited by torque (III)

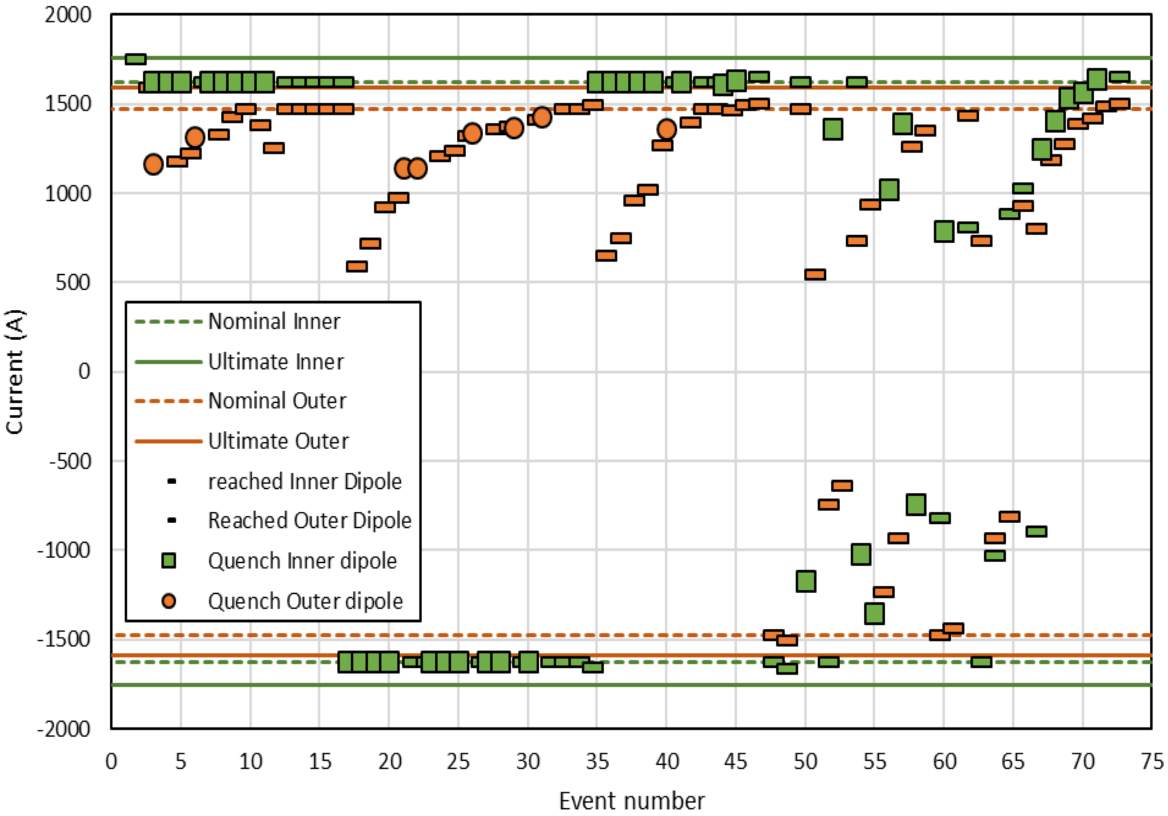
- It was decided to assemble the magnet with a new shimming configuration:



Test	Inner dipole		Outer dipole	
	Pole	Mid-plane	Pole	Mid-plane
1	450	0	N/A	N/A
2	600	0	875	250
3	800	0	875	250
4	225	575	250	875

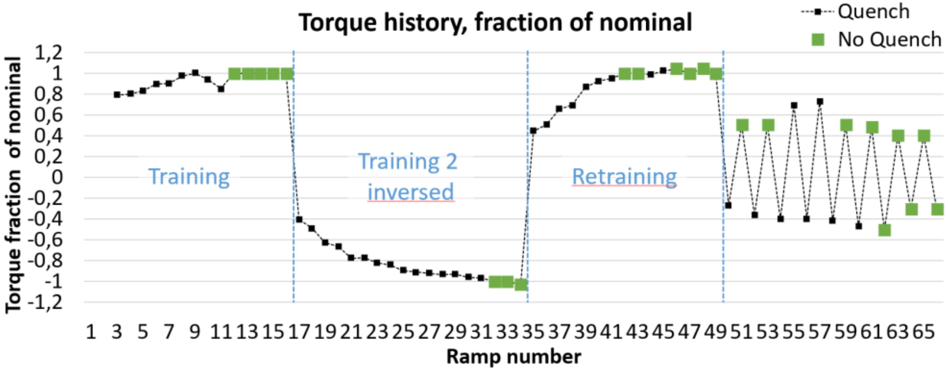
Fourth power test (I)

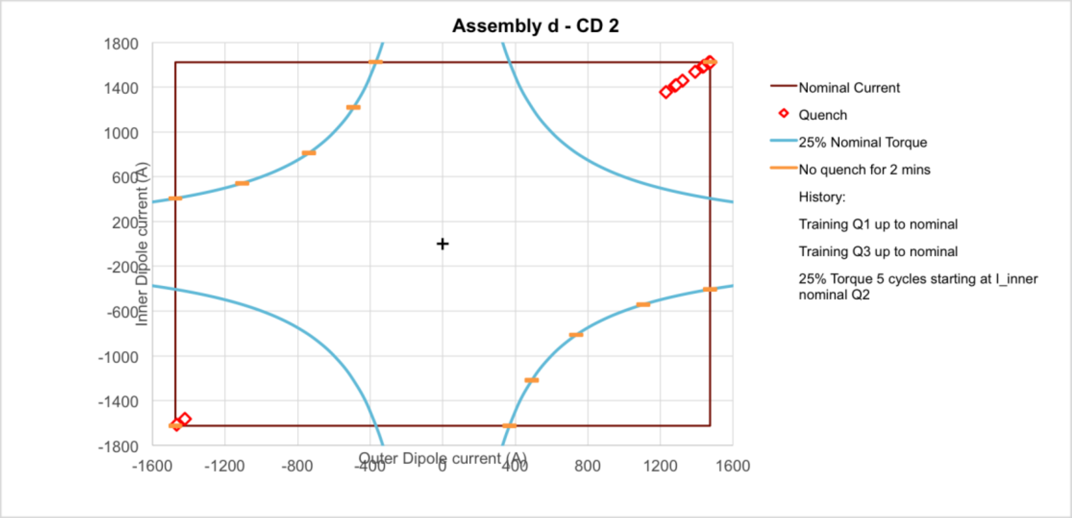
- **It reached nominal torque after training in both directions!**
- **No memory**: it needs training each time that the torque is reversed.



Fourth power test (II)

- The magnet can operate in a “safe” zone without quench, and in the full zone with training.
- **Field quality** is under control.
- No memory: same behaviour after the **thermal cycle.**





Conclusion

- The first power test (w/o outer dipole) allowed to **validate** the innovative coil fabrication techniques.
- Three power tests were necessary to **reach nominal torque** at combined operation.
- Few training quenches are needed to reach again nominal operation current when the torque is reversed.
- The first prototype reaches performance on 80% of required operational range.
- Additional shimming will be added at the coil ends in the ongoing **second prototype**.

HiLumi
HL-LHC PROJECT

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Thank you for your attention!

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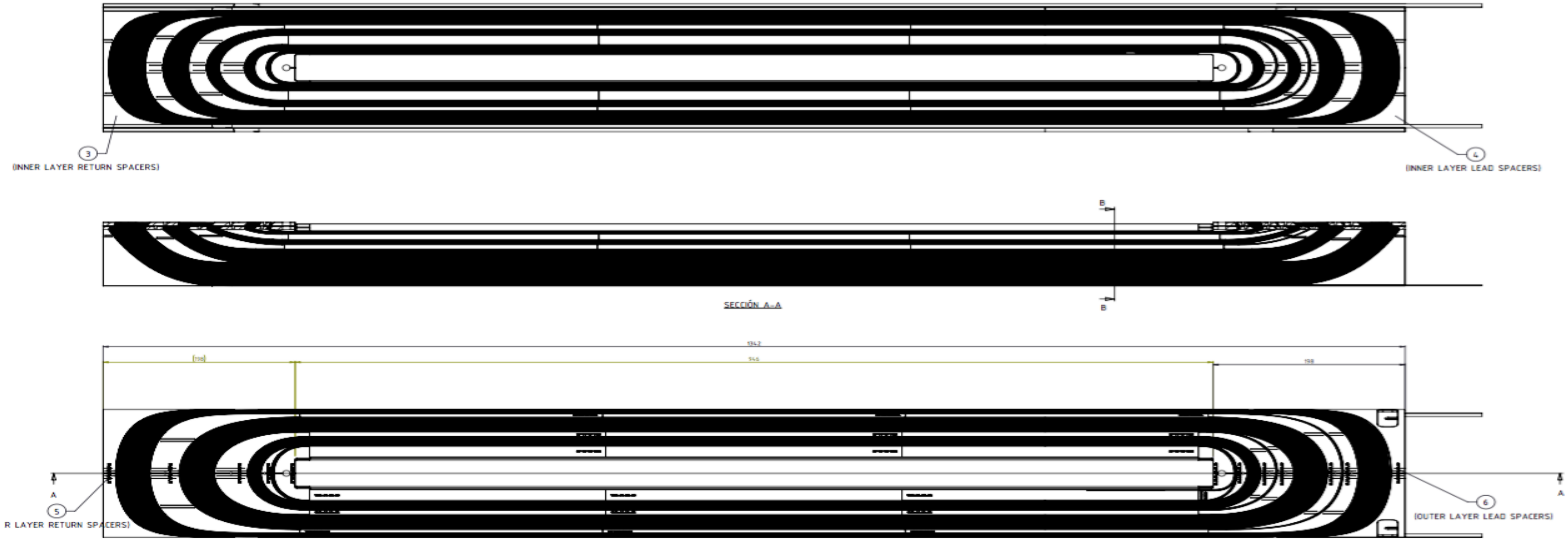
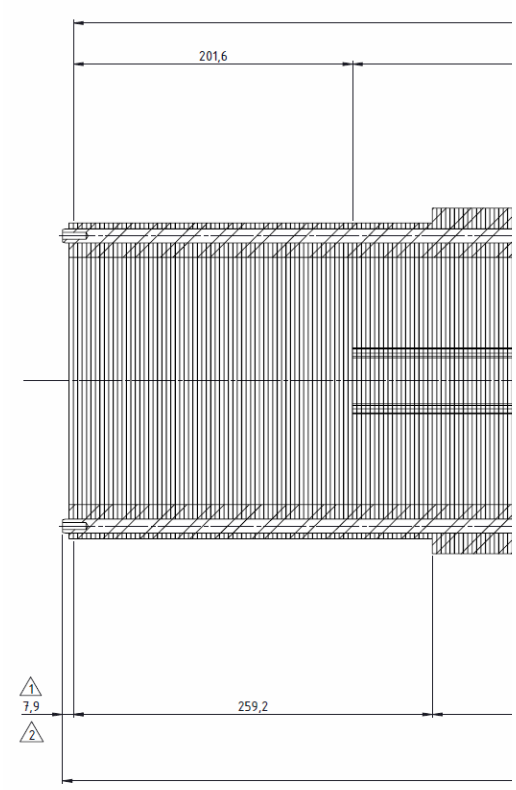
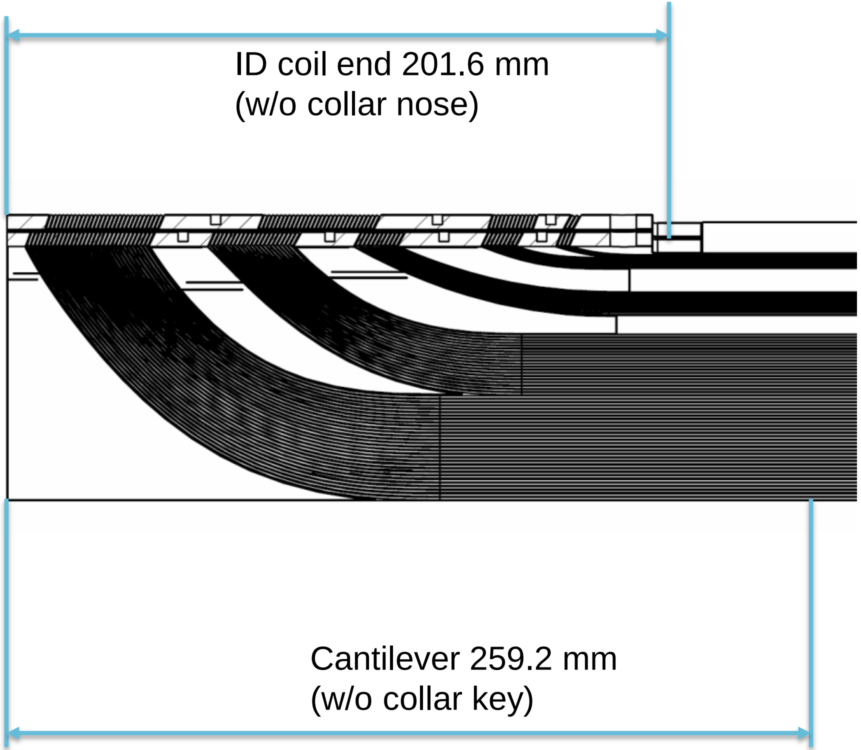
Backup slides

Inner dipole coil



Inner dipole coil





ID coil end 201.6 mm
(w/o collar nose)

Cantilever 259.2 mm
(w/o collar key)