Status of MBRD series production (KE4417)

S. Farinon INFN - Genova

On behalf of CERN-INFN WP3 Collaboration for D2 Construction for HL-LHC

Genova, October 7th, 2024

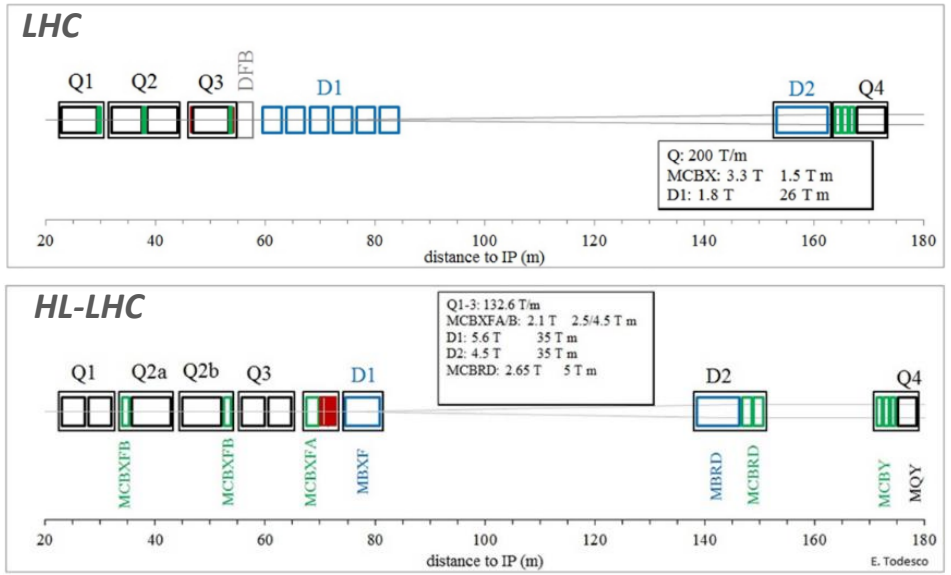
https://indico.cern.ch/event/1421594/contributions/5978352/

SUMMARY

- Introduction
- Status of series coil production
- Status of MBRD1
- Status of MBRD2
- Status of MBRD3
- Status of MBRD4—6
- Field quality
- Schedule

D2 LAYOUT AND FUNCTION

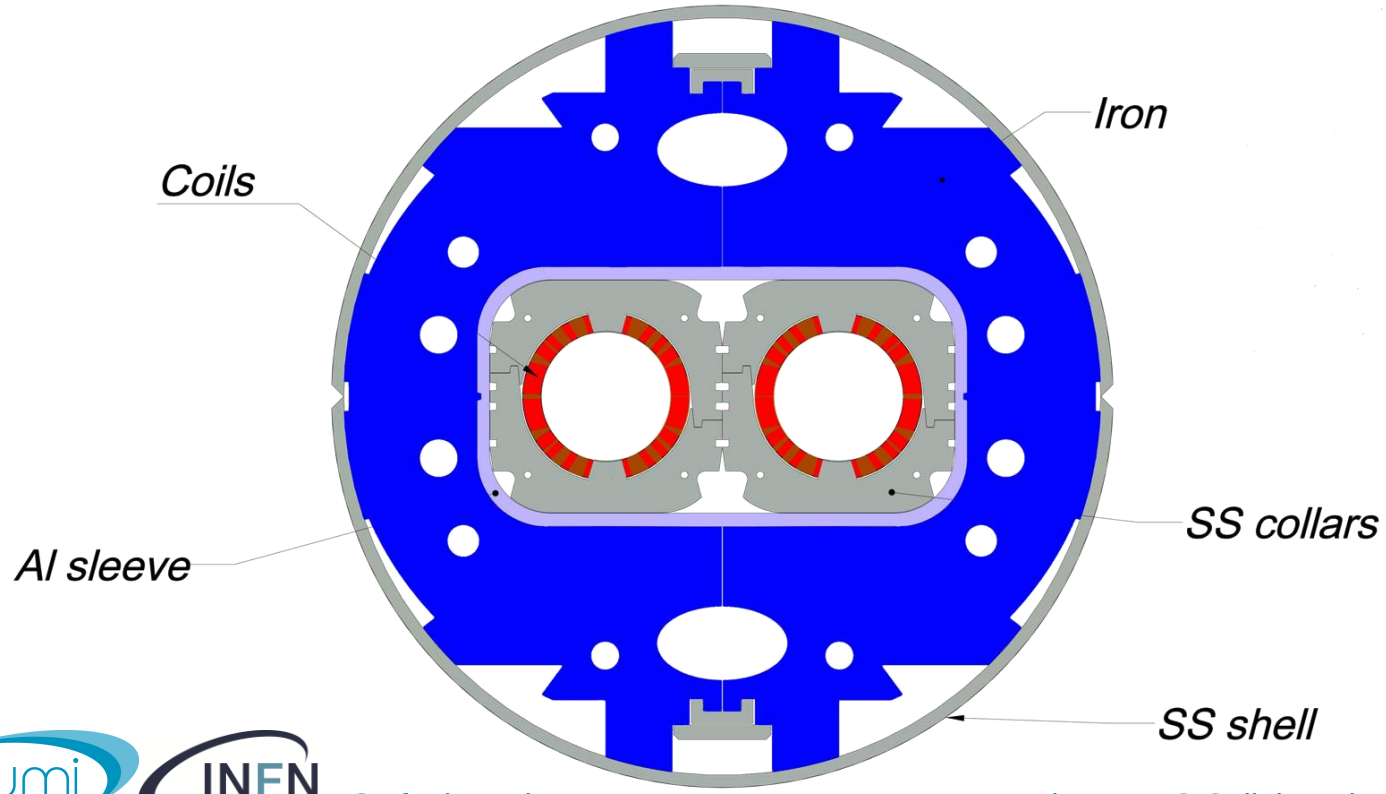
- The D2 dipole (MBRD, Main Bending Recombination Dipole) is housed within the D2 cold mass along with the orbit correctors around IP1 and IP5.
- **Key characteristics include**:
  - Identical field direction in both apertures, connected in series
  - Integrated field of 35 T·m at 7 TeV
  - Integrated field of 37.6 T·m at 7.5 TeV (ultimate field)
  - Two apertures, each 105 mm in diameter, with a total length of 8010 mm.



# magnets	# apertures	# coils
4 series	8	16
2 spares	4	8
Total = 6	Total = 12	Total = 24

MBRD MAGNET CHARACTERISTICS

- Bore field: 4.5 T (4.8 T ultimate field)
- Magnetic length: 7.8 m (8.01 m physical length)
- Challenges:
  - Field quality optimization based on asymmetric coils
  - Novel mechanical structure for the two apertures based on aluminum shells



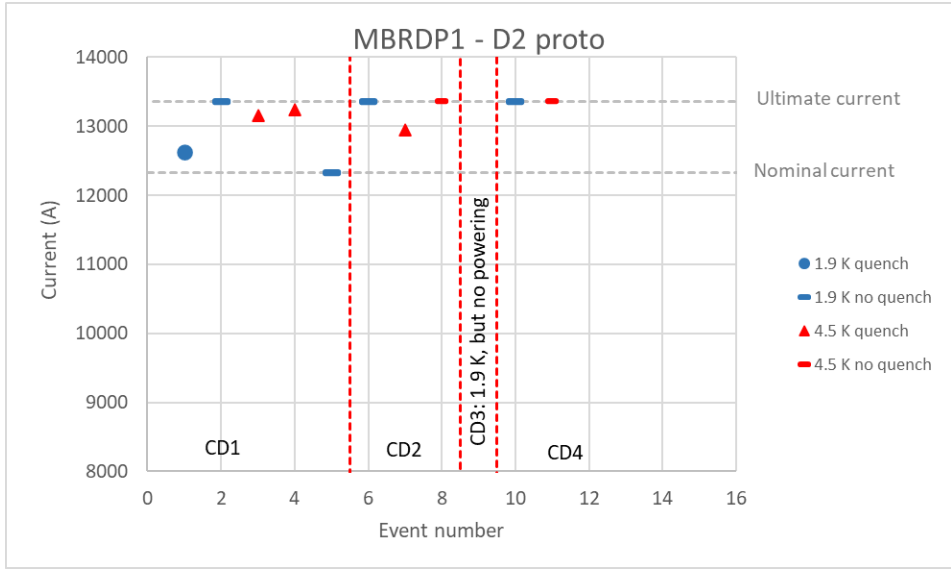
Main characteristics of the D2 dipole	
Bore magnetic field	4.5 T
Magnetic length	7.78 m
Peak field	5.26 T
Operating current	12.330 kA
Stored energy	2.26 MJ
Overall current density	478 A/mm^2
Magnet physical length	8.01 m
Aperture	105 mm
Beam separation at cold	188 mm
Operating temperature	1.9 K
Loadline fraction	67.5%
Multipole variation due to iron saturation	<10 units

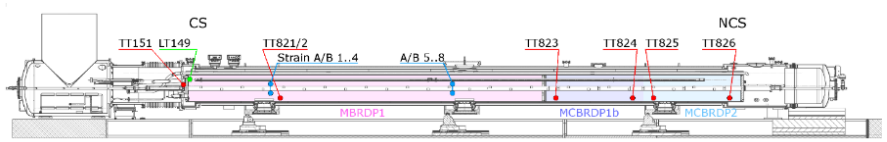
CERN/INFN COLLABORATION AGREEMENTS

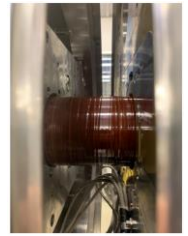
- Framework agreement KN3083
  - Addendum No.1 KE3084/TR/HL-LHC
    - Collaboration on the design and prototyping of MBRD superconducting magnets before series production, as part of the High Luminosity upgrade for the LHC at CERN.
    - *Main deliverables:* a **short model (MBRDS1)** and a **prototype (MBRDP1)** of the MBRD magnet. The manufacturing of both these components were contracted to ASG Superconductors.
  - Addendum No.11 KE4417/TR/HL-LHC
    - Collaboration on the construction of the series MBRD magnets within the framework of the High Luminosity upgrade for the LHC at CERN.
    - *Main deliverables:* **six magnets of the series (MBRD1 to MBRD6)**. The manufacturing of these magnets was awarded to ASG Superconductors on March 9th, 2021.

D2 PROTOTYPE

- D2 prototype cold mass was tested at CERN in Oct. 2022 to May 2023, in 4 cool-downs:
  - in the **first thermal cycle**:
    @ 1.9 K: it reached nominal current without quenching
    @ 1.9 K: it reached ultimate in 1 quench
    @ 4.5 K: it quenched @ 96% of SS limit
    no other natural quench occurred in the first test campaign
    ramp rate studies were performed up to 200 A/s
  - in the **second thermal cycle**
    @ 1.9 K: it reached ultimate without quenching
    @ 4.5 K: it reached ultimate in 1 quench
  - In the **fourth thermal cycle** it reached ultimate without quenching at both 1.9 and 4.5 K







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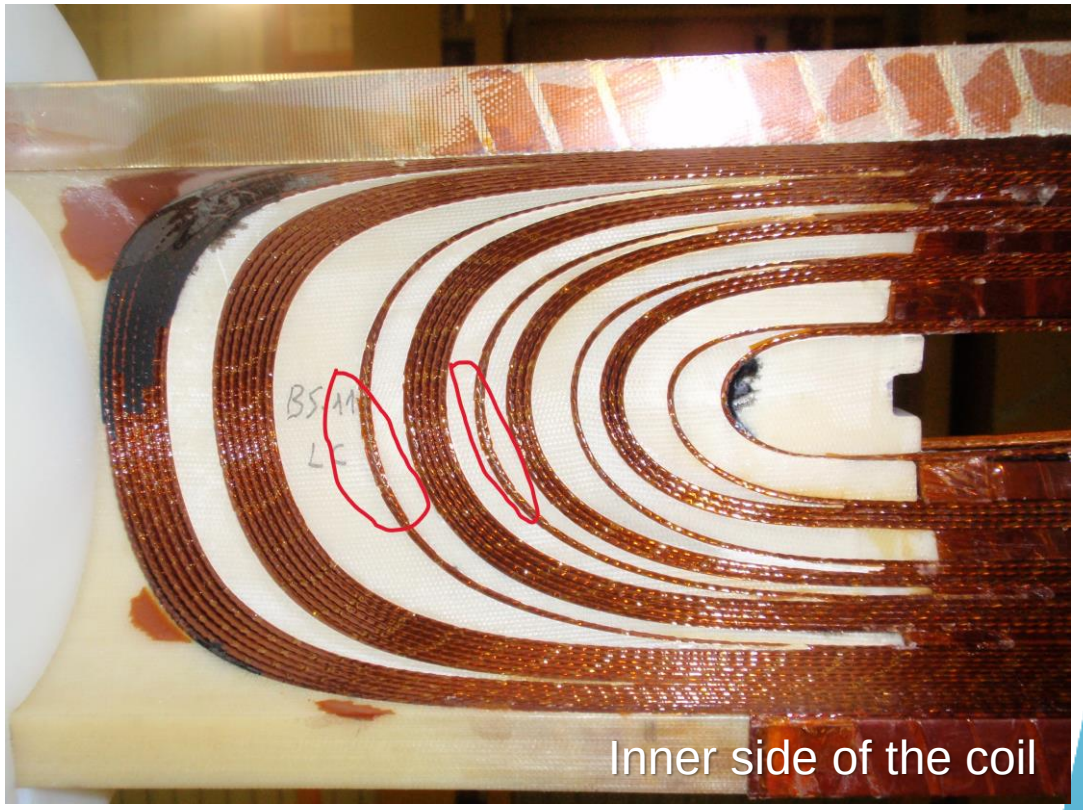
STATUS OF COIL PRODUCTION

- The winding and curing of all 24 coils have been completed.
- Two issues have been identified:
  1. Insulation damage at the coil ends
     - During the curing process, the coil is pressed against the mandrel at 90 MPa, which can cause damage to the turn insulation in certain areas.
     - ASG has developed a process to restore the insulation in both collared and single coils (approved by CERN/INFN).
     - This repair has already been implemented on MBRD2 at CERN and on MBRD1 at ASG;
       The remaining coils will undergo the same repair procedure before collaring.
       (https://edms.cern.ch/ui/file/3088308/1.0/28837_1_MBRD_TURN_INSULATION_RESTORING.pdf)
  2. Excess coil size


Inner side of the coil

SINGLE COIL STATUS

- Type A Coils
  - AS-03: No issues to report.
  - **AS-08: Requires two repairs: one on the CS and one on the NCS, located on the first turn adjacent to the filler.**
  - AS-09: No issues to report.
  - **AS-10: One point on the NCS needs further investigation to determine if it is dirt or insulation damage (the coil needs to be rotated). Everything is OK on the CS.**
  - **AS-11: Requires a repair on the first turn adjacent to the first filler on the CS. Everything is OK on the NCS.**
  - **AS-12: Requires a repair on the first turn adjacent to the first filler on the CS. Everything is OK on the NCS.**

- Type B Coils
  - BS-03: No issues to report.
  - **BS-05: Requires a repair on the first turn adjacent to the first filler on the NCS. No issues to report on the CS.**
  - **BS-09: Requires a repair on the second turn adjacent to the first filler on the NCS. No issues to report on the CS.**
  - BS-10: No issues to report.
  - **BS-11: Requires a repair on the CS and two repairs on the NCS**.
  - BS-12: No issues to report.

STATUS OF COIL PRODUCTION

- The winding and curing of all 24 coils have been completed.
- Two issues have been identified:
  1. Insulation damage in the coil ends
  2. Excess coil dimension in 4 coils
     - The issue arises from the lack of sufficient margin with the available shimming sheets to accommodate the larger coils while maintaining the nominal field quality.
     - We collaborated with WP2 to adjust the coil pairing strategy, distributing the dimensional variations across the last two magnets.

Coil dimensions are measured at 70 MPa

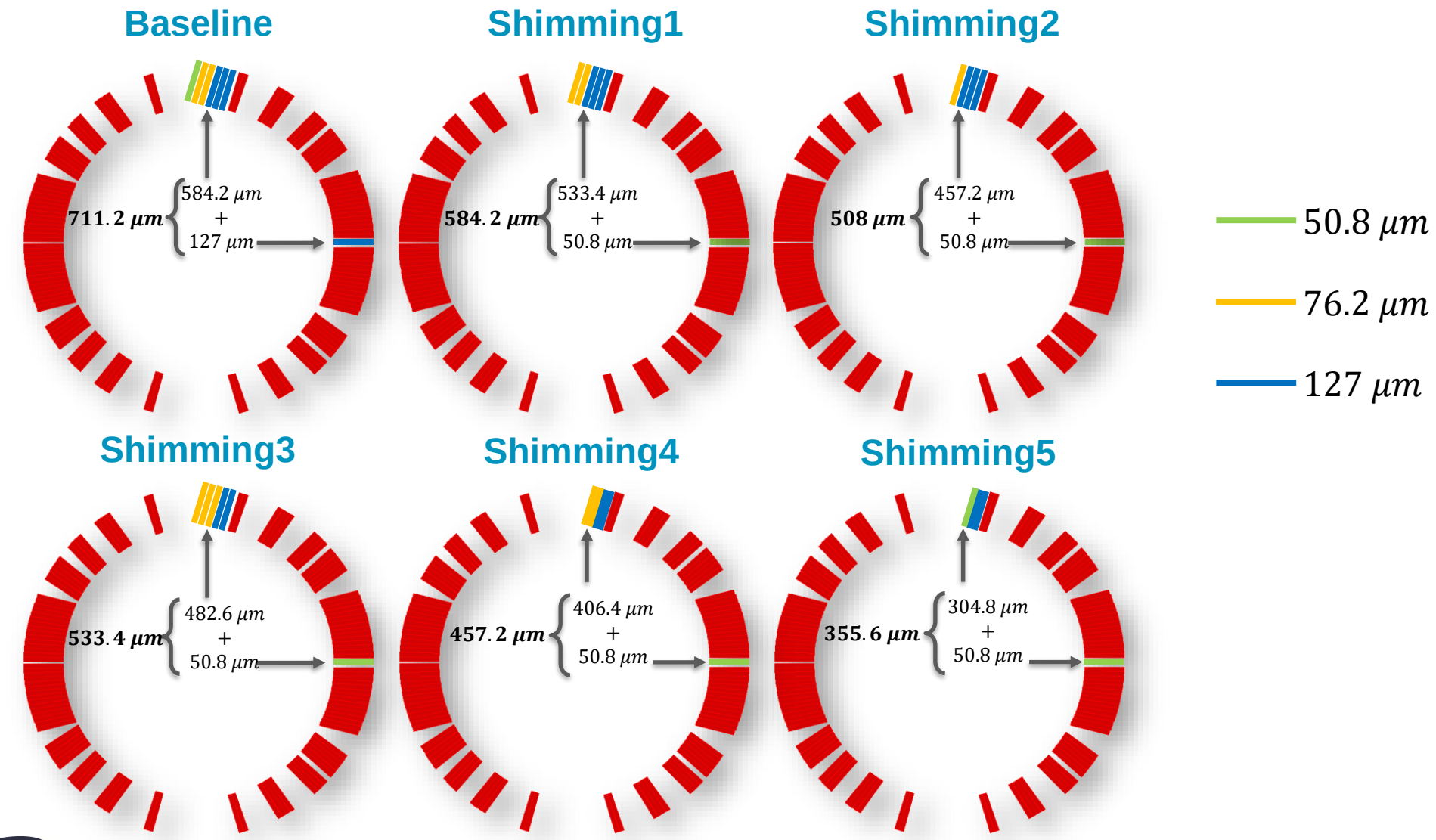
Coil type	*I meas*	*II meas*	*Aperture*	*Shimming scheme*	*Magnet #*
AS01	0.41	\	I aperture	Shimming 1	I magnet
BS01	0.48	\			
AS02	0.53	\	II aperture	Shimming 2	
BS02	0.46	\			
AS04	0.53	\	III aperture	Shimming 2	II magnet
BS04	0.48	\			
AS06	0.49	\	IV aperture	Shimming 2	
BS06	0.50	\			
AS05	0.52	\	V aperture	Shimming 2	III magnet
BS07	0.47	\			
AS07	0.46	\	VI aperture	Shimming 3	
BS08	0.48	\			

collared apertures

single coils

AS03	0.63
BS03	0.65
BS05	0.57
AS08	0.43
AS09	0.45
BS09	0.67
AS10	0.43
BS10	0.46
AS11	0.54
BS11	0.43
AS12	0.43
BS12	0.46

SHIMMING SCHEMES



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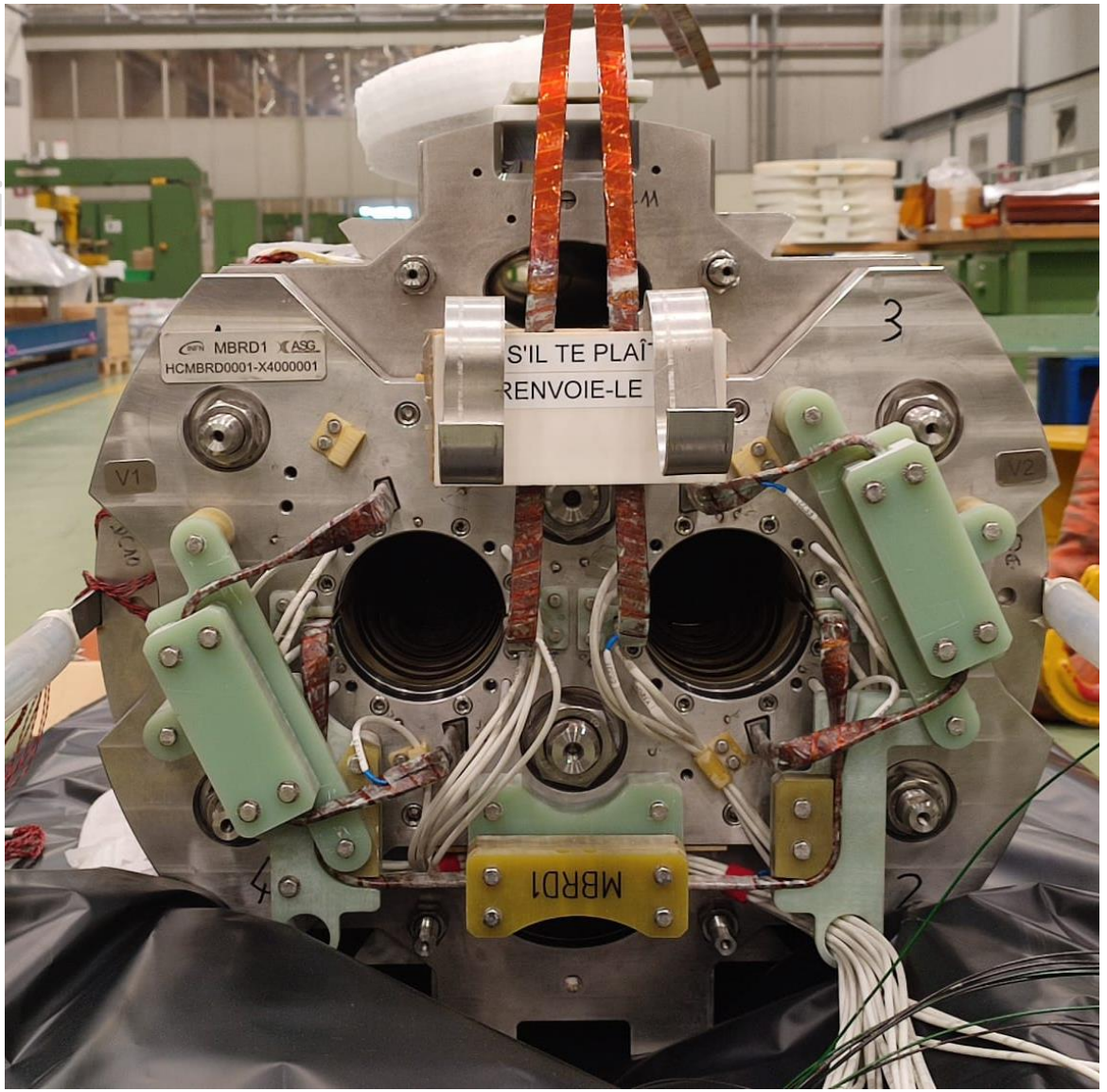


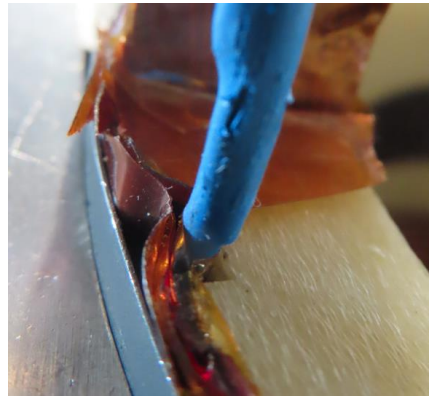
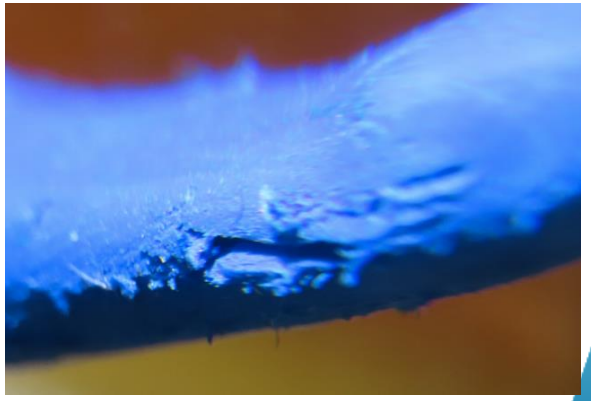
MBRD1 STATUS

- MBRD1 arrived at CERN in October 2023 (with partial loading of the longitudinal tie rods).
- In December 2023, with INFN staff, the tie rods were successfully loaded to their nominal load.
- Subsequent electrical tests at high voltage (3.1 kV) revealed a short circuit to ground in QH Y112.
  - Since no electrical tests were planned upon receipt, it's impossible to determine whether the short occurred during transportation or during the loading of the tie rods.
  - The revised acceptance procedure now includes high-voltage electrical tests upon receipt.
- CERN technicians attempted to locate the source of the fault using endoscopy but, in the end, it was decided to disassemble the end plate.

MBRD1 STATUS

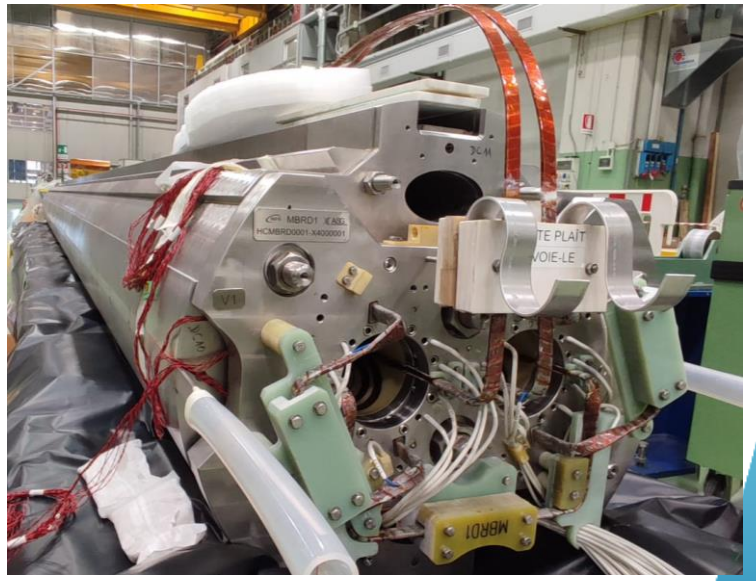
- After end plate removal, an anomaly is found at QH Y112 wasn’t traced by ASG.
- A local electrical test at 3.1 kV was performed between YT112 and an aluminum sheet enclosing the wire. The investigation precisely identified the defect's location at the repaired section with the polyimide tape.



MBRD1 STATUS

- Corrective actions:
  - MBRD1 has been temporarily reassembled for transportation back to ASG, a decision made by ASG.
    - However, this transportation process experienced some delays due to customs documentation, and has been delivered to ASG on July 2024.
  - MBRD1 has been repaired with the highest priority.
    - The repair process has involved several steps, including repairing of QH Y112, bending of the SS protection sheets, reassembling of the end plate, repairing of the stabilizer brazing, splicing, and attaching VTs according to CERN's procedural guidance.
    - According to the current schedule, its delivery to CERN is expected in the second half of October 2024, possibly next week.



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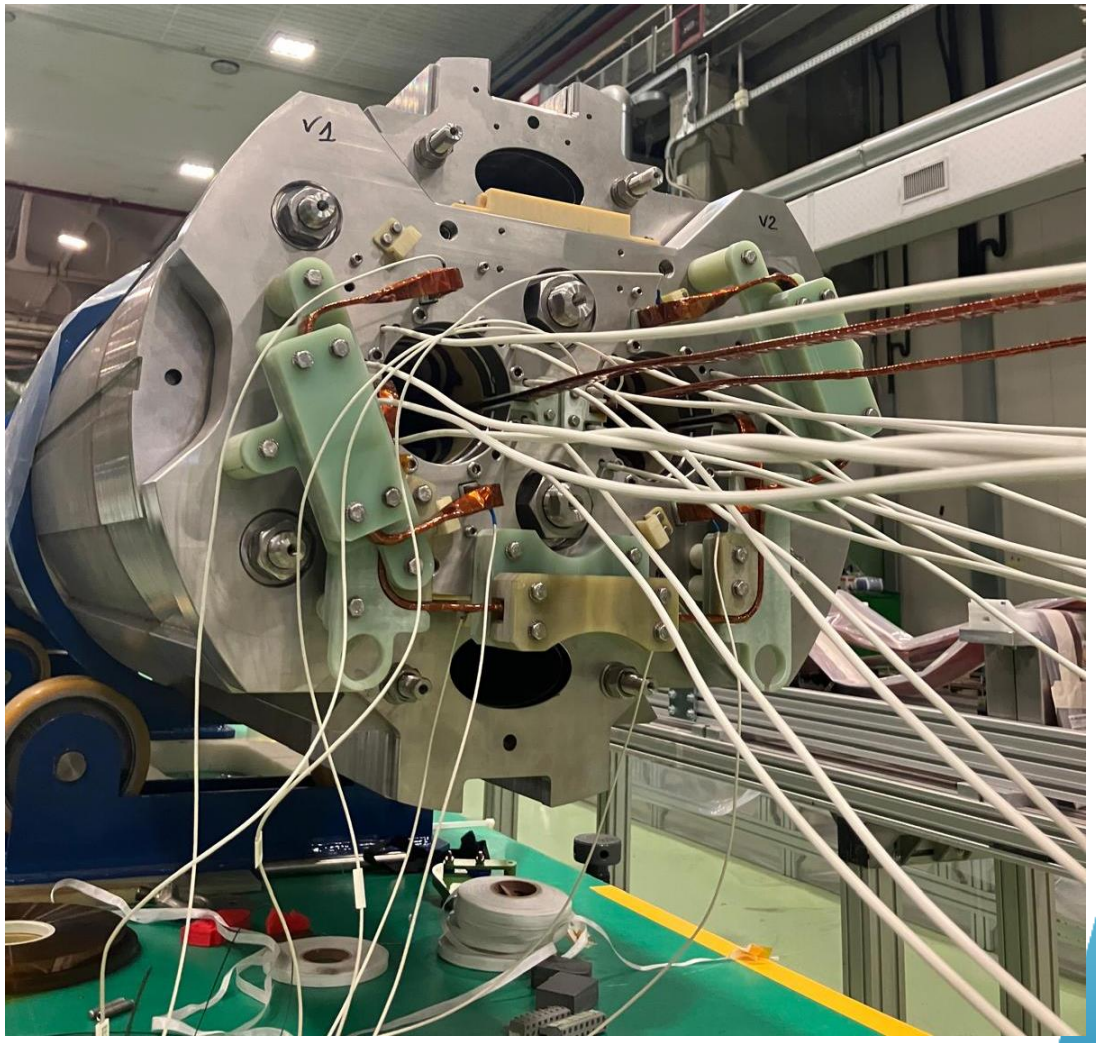
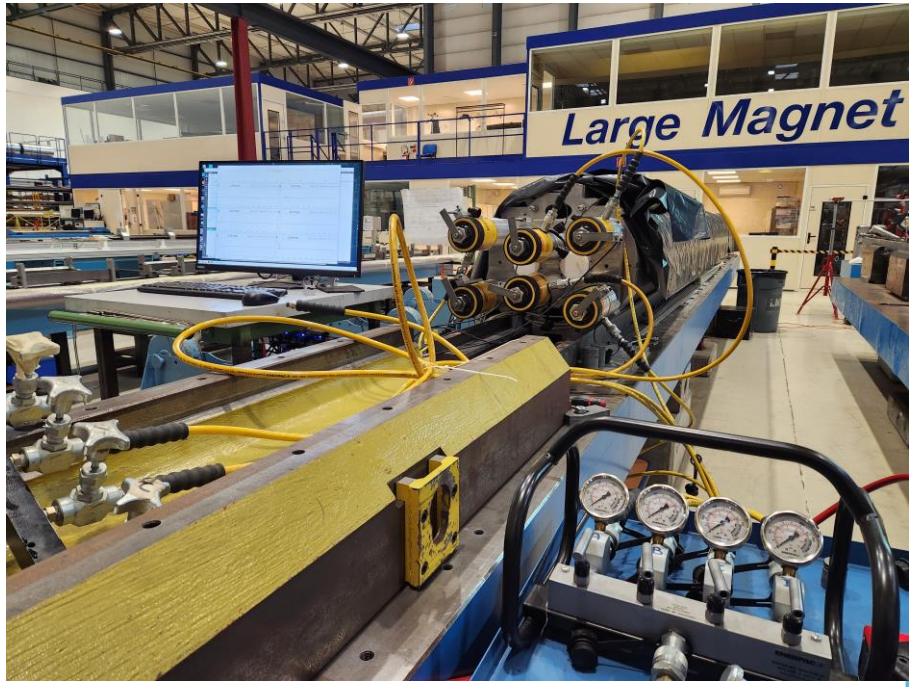


MBRD2 STATUS

- MBRD2 arrived at CERN in April 2024.
- Following the findings on MBRD1, in ASG the tie rods were loaded up to nominal load.
  - Upon reception at CERN, about 50% of this load was lost (most likely due to vibrations during transportation) and had to be restored with the new developed hydraulic tightening system.
- MBRD2 successfully passed all reception tests and was accepted.
- It is the first MBRD magnet to be assembled in the D2 cold mass.
- The first D2 cold mass with MBRD2 is completed and it is now in the cryostating phase.



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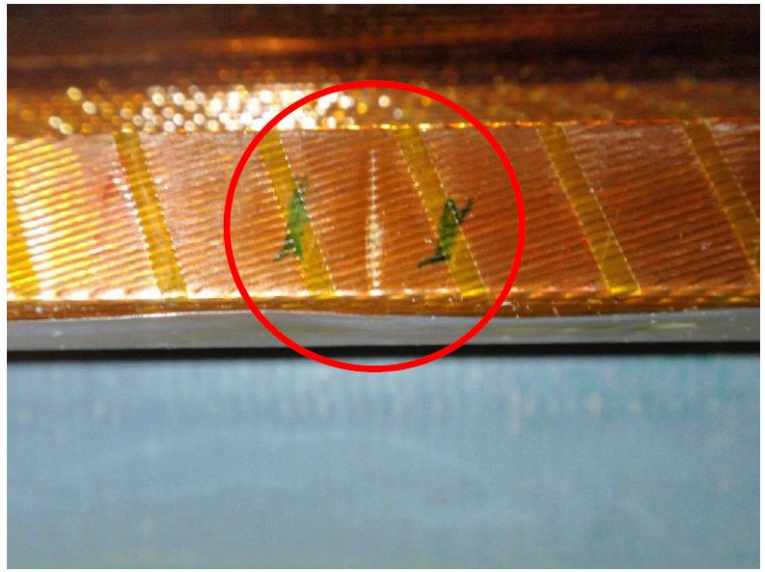
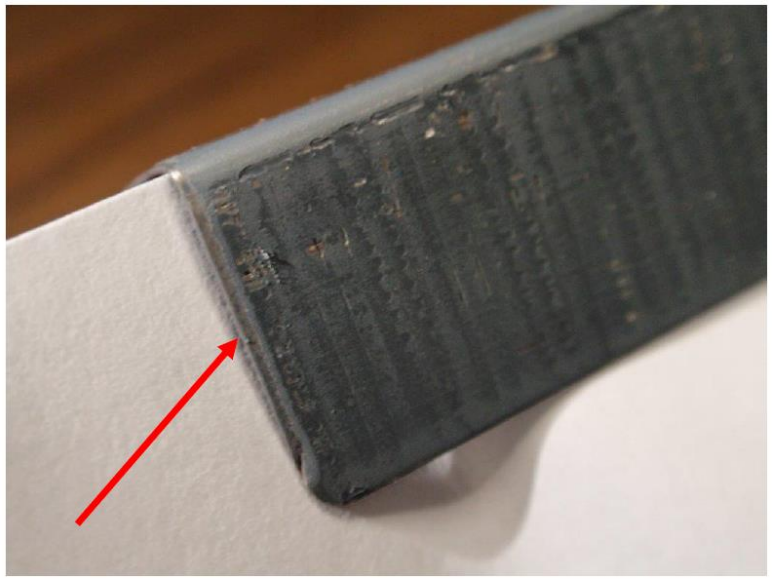
MBRD3 STATUS

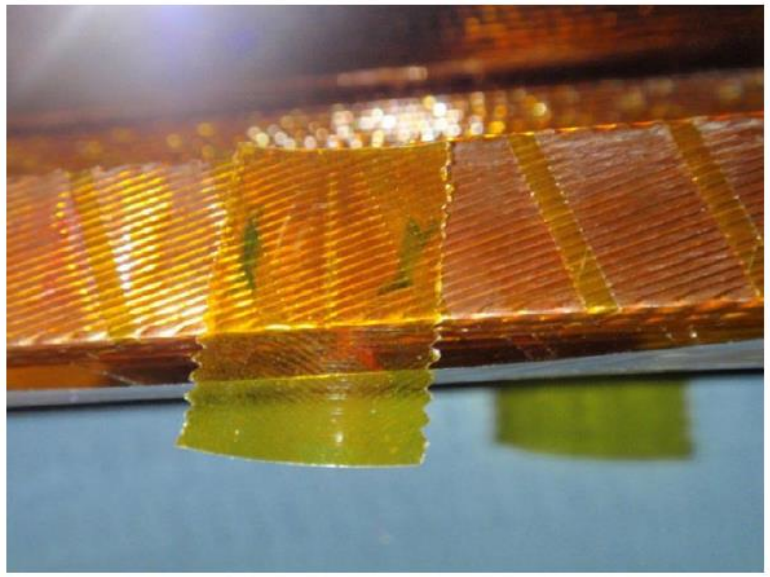
- MBRD3 will consist of apertures:
  - VS-05 which includes AS-05 and BS-07 coils, coupled with shimming scheme 2.
    - This aperture has been collared without any issues.
  - VS-06 which includes AS-07 and BS-08 coils, coupled with shimming scheme 3.
    - This aperture encountered several issues:
      - Event 1 (10.04.2024): a short QH vs coil AS-07.
      - Event 2 (17.04.2024): a short coil BS-08 vs ground.
      - Event 3 (28.05.2024): a short QH vs coil BS-08.
        - After this event, specific activities focused on cleaning the coil and its surrounding environment in the workshop were carried out.
      - Event 4 (01.07.2024): a short QH vs coil BS-08.
        - Following this event, a design change has been agreed upon and will be implemented in future magnets as well.
    - VS-06 has been successfully collared on September 19th 2024.
      - The collaring pressure was lower than expected (320 vs 375 bars), but it remained within acceptable limits.
      - This may suggest localized and limited plastic deformation in some components.
        - The single aperture field quality measurements of VS-06 are consistent with those of the other apertures.

SHORT COIL BS-08 VS GROUND

- The cause of this issue was the unforeseen overlapping of two adjacent coil protection sheets side by side.
- This overlapping resulted in an increase in thickness, which under pressure led to damage to all the ground insulation layers (no damage to the conductor strands).
- Accepted repair proposal includes the replacement of damaged GI and QH and the local application of a single layer of polyimide adhesive tape (20 mm in width and 0.05 mm in thickness).



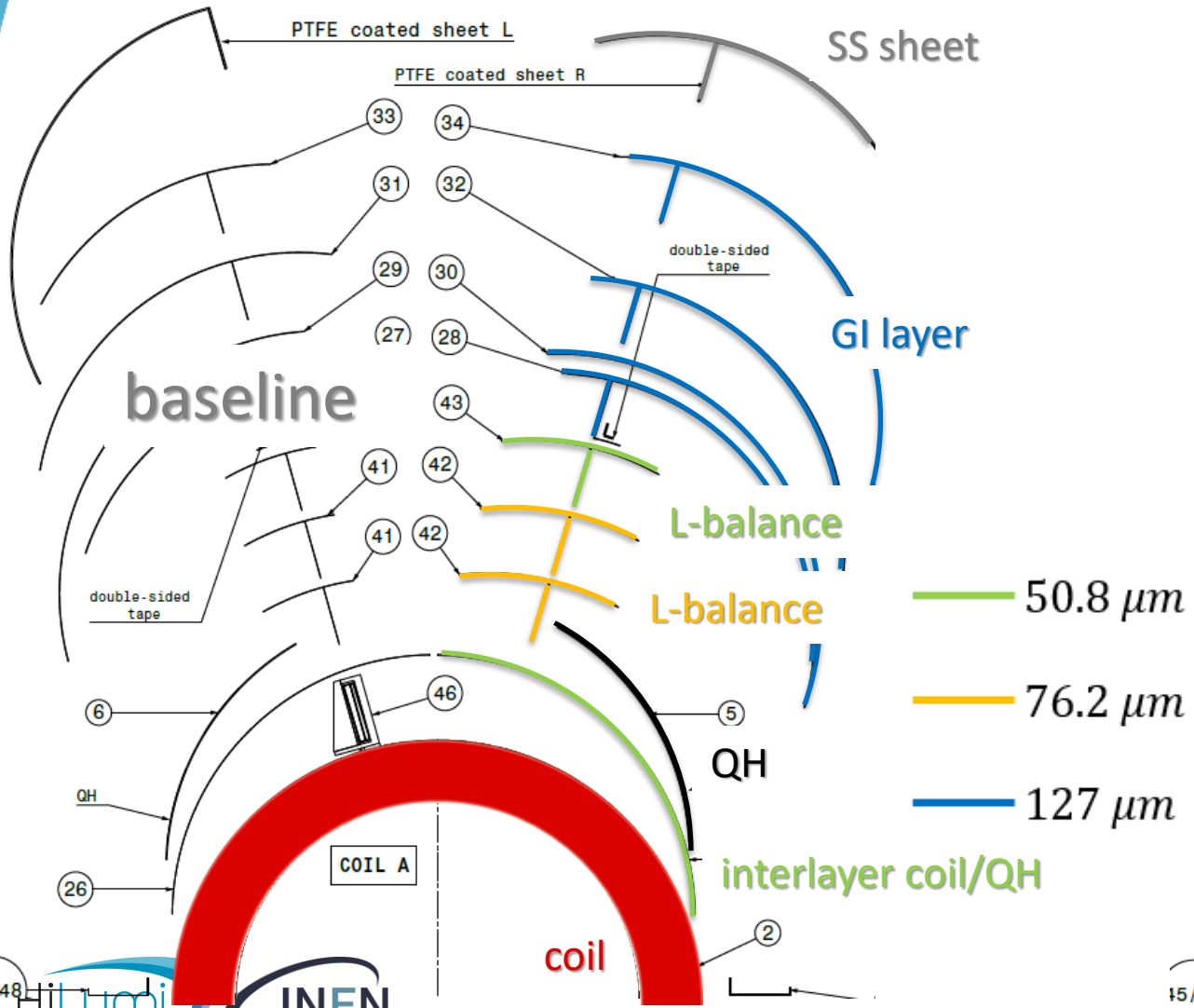


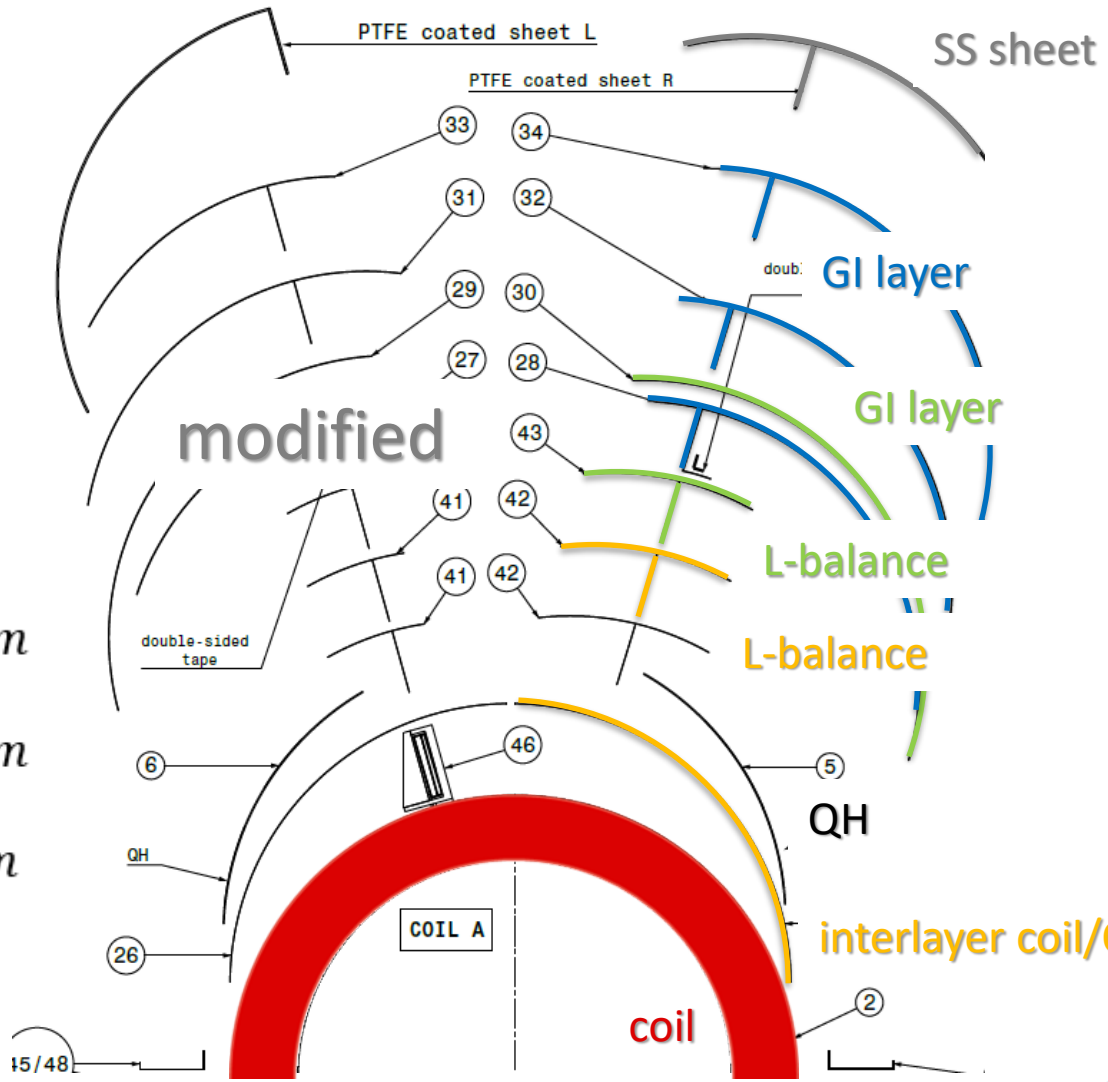


DESIGN CHANGES TO MITIGATE THE ISSUE OF QH SHORTS

- Interlayer coil/QH increase from 51 to 76 μm
- 1 GI layer 127 μm thick replaced with 76 μm

} radial thickness reduced by 25 μm





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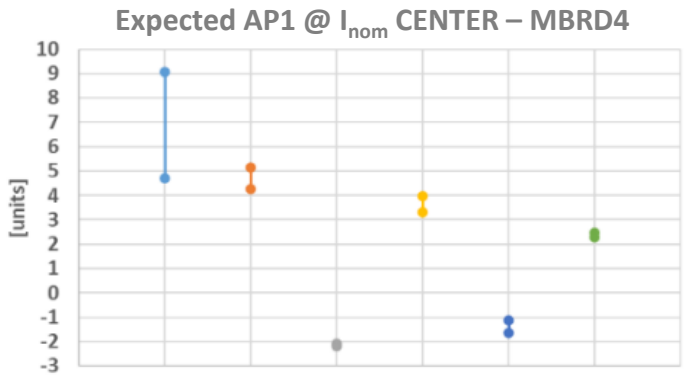
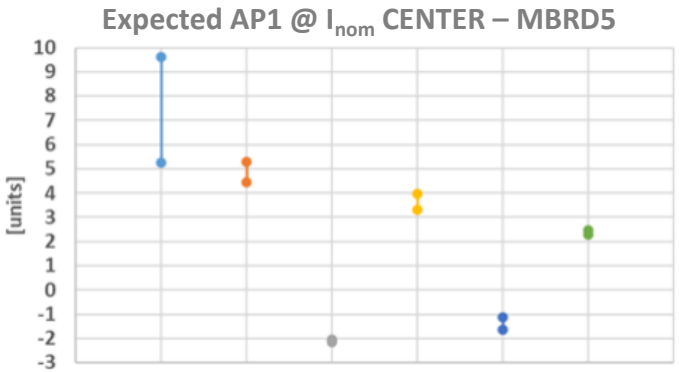
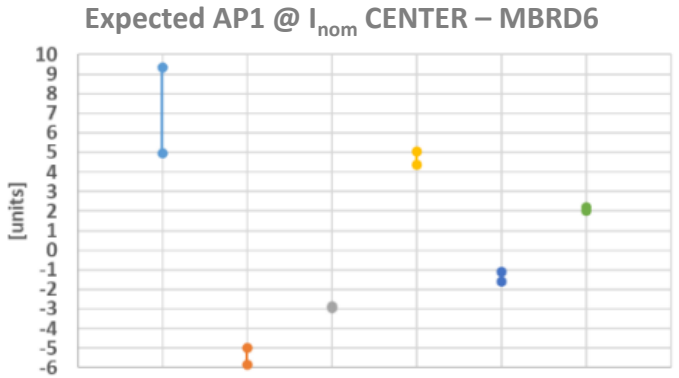
STATUS OF MBRD4–6

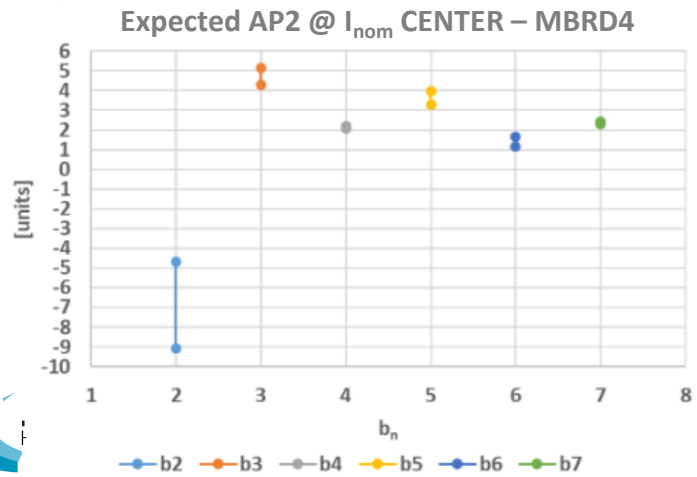
- The pairing of coils into apertures and apertures into magnets has been fully defined with support from WP2.
- The baseline plan from ASG involves producing the magnets in series, ensuring a consistent completion rate.
- If necessary, acceleration of the process can be considered.

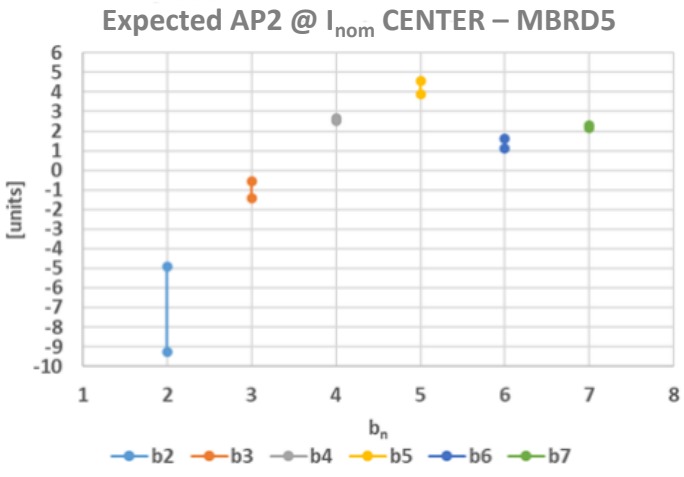
Coil type	Min [mm]	Max [mm]	Avg [mm]	# Aperture	Shimming scheme	# Magnet
AS09	0.39	0.55	0.45	AP07	Shimming1	MBRD4
BS11	0.37	0.52	0.43			
AS08	0.34	0.52	0.43	AP08	Shimming1	
BS10	0.36	0.58	0.46			
AS10	0.37	0.52	0.43	AP09	Shimming1	MBRD5
BS12	0.42	0.57	0.46			
AS11	0.47	0.62	0.54	AP10	Shimming4	
BS05	0.42	0.68	0.57			
AS03	0.56	0.7	0.63	AP11	Shimming5	MBRD6
BS09	0.56	0.81	0.67			
AS12	0.34	0.52	0.43	AP12	Shimming4	
BS03	0.52	0.82	0.65			

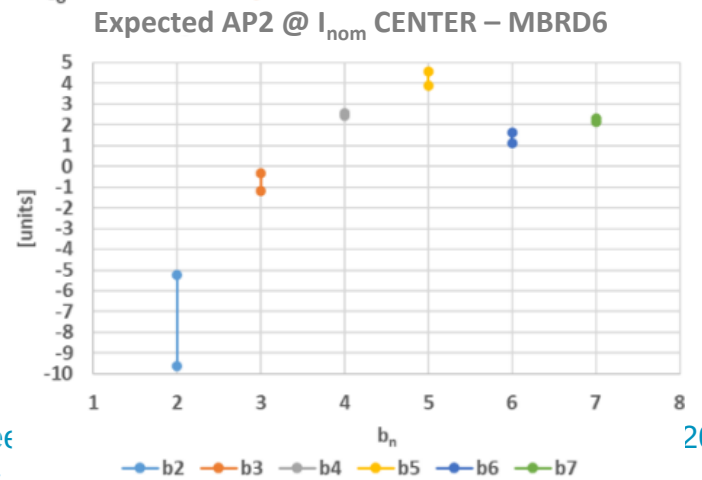












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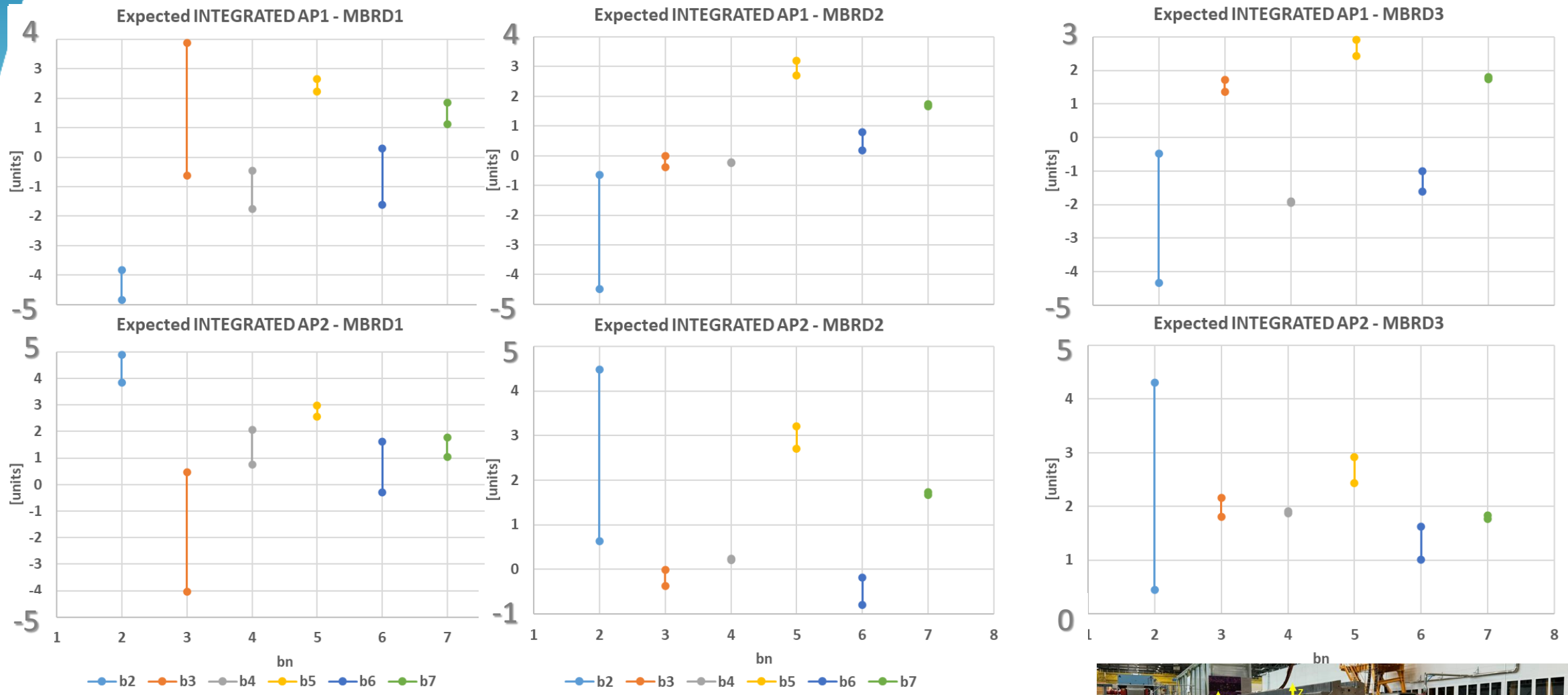
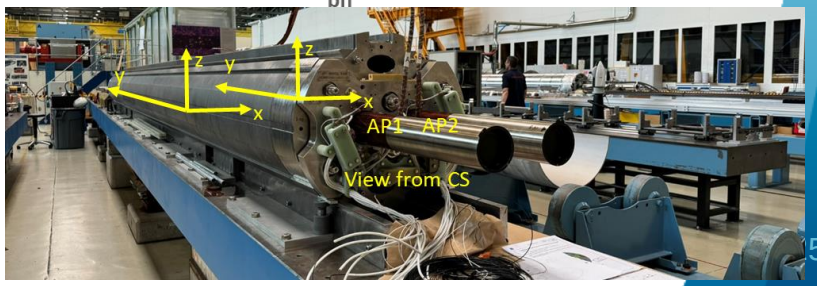
EXPECTED INTEGRATED HARMONICS @ NOMINAL CURRENT



- The error bars in the expected harmonics at I_{nom} depend on how the expectations are calculated. They can be based on either:
  - Cold measurements of the prototype
  - Warm measurements of the series magnets



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Schedule

- Magnet delivery schedule (ASG plan):
  - MBRD1 October 2024
  - ~~MBRD2 April 2024~~ delivered
  - MBRD3 December 2024
  - MBRD4 April 2025
  - MBRD5 September 2025
  - MBRD6 January 2026

CONCLUSIONS

- Series Coil Production:
  - All 24 coils have been successfully wound and cured, though some issues were identified, including insulation damage and excess coil size. These have been addressed through repairs and adjustments.
- MBRD Magnet Status:
  - MBRD1: Electrical issues were resolved, with the magnet expected for delivery in Oct. 2024.
  - MBRD2: Successfully passed tests and will be the first magnet integrated into the cold mass.
  - MBRD3: Faced several short circuits but VS06 was successfully collared and assembled by Sept. 2024.
- Future Magnet Production:
  - MBRD4 to MBRD6 are planned for completion between April 25 and January 26.
- Design Improvements:
  - Various corrective measures, such as adjustments to SS protection sheets and design changes to mitigate short circuits in quench heaters, were implemented to prevent recurring issues.

- The overall conclusion is that production is progressing well, with significant lessons learned from first magnet assembly. The delivery schedule remains on track for the final integration phase.

HiLumi
HL-LHC PROJECT

THANKS FOR THE ATTENTION

Acknowledgments

INFN: A.Bersani, B.Caiffi, F.Levi, A.Pampaloni

CERN: A.Foussat, E.Todesco

HiLumi HL-LHC PROJECT

INFN Istituto Nazionale di Fisica Nucleare

COIL PAIRING IN MAGNETS

- MBRD1 and MBRD2 completed
- MBRD3: both apertures collared

Coil type	Min [mm]	Max [mm]	Avg [mm]	# Aperture	Shimming scheme	# Magnet
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BS01	0.39	0.6	0.48			
AS02	0.47	0.64	0.53	AP02	Shimming2	
BS02	0.31	0.55	0.46			
AS04	0.37	0.61	0.53	AP03	Shimming2	MBRD2
BS04	0.42	0.6	0.48			
AS06	0.41	0.59	0.49	AP04	Shimming2	
BS06	0.36	0.66	0.5			
AS05	0.42	0.61	0.52	AP05	Shimming2	MBRD3
BS07	0.42	0.54	0.47			
AS07	0.37	0.55	0.46	AP06	Shimming3	
BS08	0.41	0.59	0.48			

- MBRD4 to MBRD6 pairing planning
- Largest coils (>0.6 mm) in MBRD6

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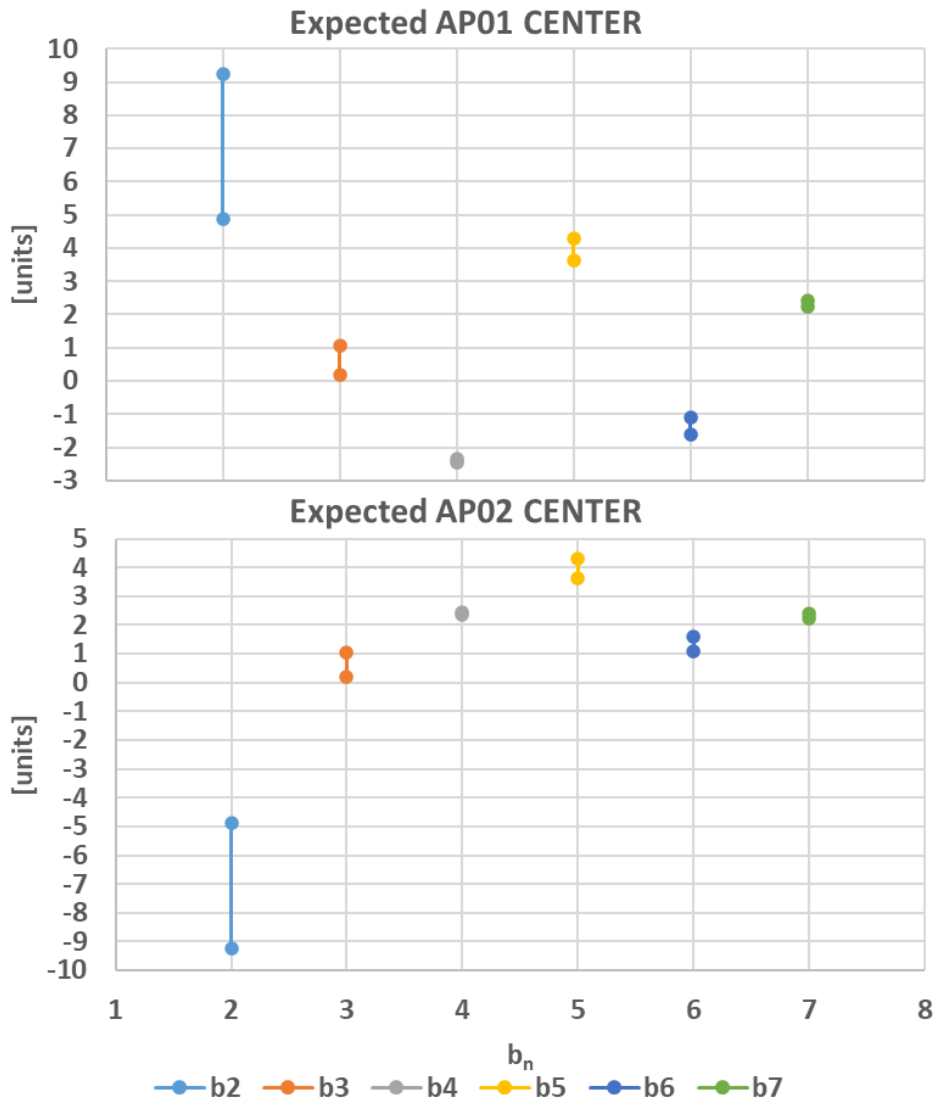
AS08	0.34	0.52	0.43	AP08	Shimming1	
BS10	0.36	0.58	0.46			
AS10	0.37	0.52	0.43	AP09	Shimming1	MBRD5
BS12	0.42	0.57	0.46			
AS11	0.47	0.62	0.54	AP10	Shimming4	
BS05	0.42	0.68	0.57			
AS03	0.56	0.7	0.63	AP11	Shimming5	MBRD6
BS09	0.56	0.81	0.67			
AS12	0.34	0.52	0.43	AP12	Shimming4	
BS03	0.52	0.82	0.65			

Expected Field Quality of MBRD2 @ Nominal Operation

	CENTER					
	AP03			AP04		
	SIMU	EXPE PROTO	EXPE SERIE	SIMU	EXPE PROTO	EXPE SERIE
b2	5.70	4.87	9.24	-5.70	-4.87	-9.24
b3	-15.18	0.19	1.05	-15.18	0.19	1.05
b4	-1.57	-2.34	-2.45	1.57	2.34	2.45
b5	-1.06	3.62	4.29	-1.06	3.62	4.29
b6	-0.52	-1.59	-1.09	0.52	1.59	1.09
b7	2.44	2.40	2.23	2.44	2.40	2.23
b8	1.00	2.85	0.79	-1.00	-2.85	-0.79
b9	1.51	1.06	1.14	1.51	1.06	1.14
b10	0.10	-2.18	0.74	-0.10	2.18	-0.74
a2	0.00	3.48	1.56	0.00	-3.47	-1.56
a3	-0.01	2.62	-2.62	0.01	2.63	-2.61
a4	0.00	0.16	0.55	0.00	-0.16	-0.55
a5	0.00	1.67	-0.32	0.00	1.67	-0.32
a6	0.00	0.08	0.00	0.00	-0.08	0.00
a7	0.00	0.94	0.86	0.00	0.94	0.86
a8	0.00	-1.50	-0.20	0.00	1.51	0.20
a9	0.00	1.57	-0.62	0.00	1.57	-0.62
a10	0.00	2.78	0.13	0.00	-2.78	-0.13



$$\Delta_1 = Meas_{PROTO}^{@\ I_{nom}} - Simu_{PROTO}^{@\ I_{nom}}$$

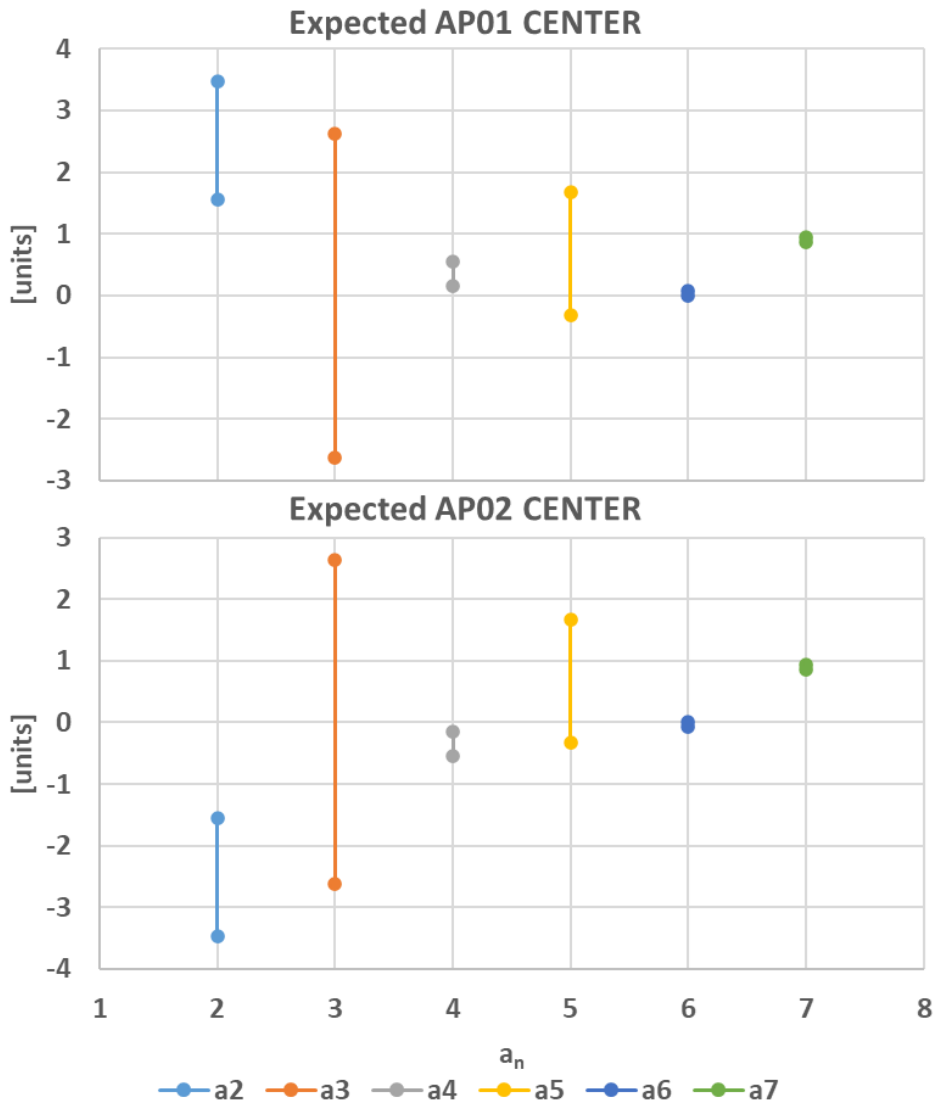
$$EXPE\ PROTO = Simu_{SERIE}^{@\ I_{nom}} + \Delta_1$$

$$\Delta_2 = Meas_{SERIE}^{iron\ @\ RT} - Simu_{SERIE}^{iron\ @\ RT}$$

$$EXPE\ SERIE = Simu_{SERIE}^{@\ I_{nom}} + \Delta_2$$

Expected Field Quality of MBRD2 @ Nominal Operation

	CENTER					
	AP03			AP04		
	SIMU	EXPE PROTO	EXPE SERIE	SIMU	EXPE PROTO	EXPE SERIE
b2	5.70	4.87	9.24	-5.70	-4.87	-9.24
b3	-15.18	0.19	1.05	-15.18	0.19	1.05
b4	-1.57	-2.34	-2.45	1.57	2.34	2.45
b5	-1.06	3.62	4.29	-1.06	3.62	4.29
b6	-0.52	-1.59	-1.09	0.52	1.59	1.09
b7	2.44	2.40	2.23	2.44	2.40	2.23
b8	1.00	2.85	0.79	-1.00	-2.85	-0.79
b9	1.51	1.06	1.14	1.51	1.06	1.14
b10	0.10	-2.18	0.74	-0.10	2.18	-0.74
a2	0.00	3.48	1.56	0.00	-3.47	-1.56
a3	-0.01	2.62	-2.62	0.01	2.63	-2.61
a4	0.00	0.16	0.55	0.00	-0.16	-0.55
a5	0.00	1.67	-0.32	0.00	1.67	-0.32
a6	0.00	0.08	0.00	0.00	-0.08	0.00
a7	0.00	0.94	0.86	0.00	0.94	0.86
a8	0.00	-1.50	-0.20	0.00	1.51	0.20
a9	0.00	1.57	-0.62	0.00	1.57	-0.62
a10	0.00	2.78	0.13	0.00	-2.78	-0.13



$$\Delta_1 = Meas_{PROTO}^{@\ I_{nom}} - Simu_{PROTO}^{@\ I_{nom}}$$

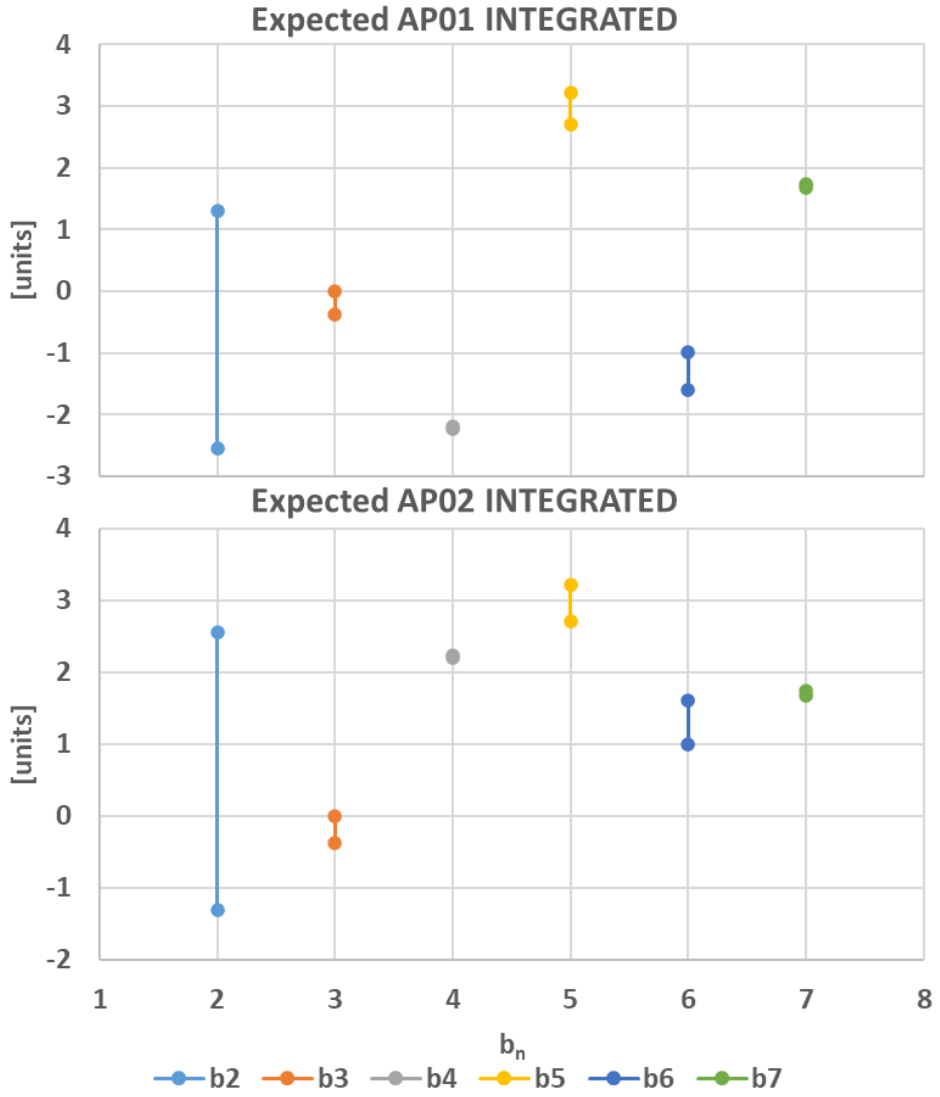
$$EXPE\ PROTO = Simu_{SERIE}^{@\ I_{nom}} + \Delta_1$$

$$\Delta_2 = Meas_{SERIE}^{iron\ @\ RT} - Simu_{SERIE}^{iron\ @\ RT}$$

$$EXPE\ SERIE = Simu_{SERIE}^{@\ I_{nom}} + \Delta_2$$

Expected Field Quality of MBRD2 @ Nominal Operation

	INTEGRATED					
	AP03			AP04		
	SIMU	EXPE PROTO	EXPE SERIE	SIMU	EXPE PROTO	EXPE SERIE
b2	-1.59	-2.55	1.30	1.59	2.55	-1.30
b3	-15.51	-0.01	-0.37	-15.51	-0.01	-0.37
b4	-1.22	-2.20	-2.23	1.22	2.20	2.23
b5	-2.05	2.71	3.21	-2.05	2.71	3.21
b6	-0.41	-1.61	-1.00	0.41	1.61	1.00
b7	1.99	1.73	1.67	1.99	1.73	1.67
b8	1.07	3.23	0.84	-1.07	-3.23	-0.84
b9	1.33	0.68	0.68	1.33	0.68	0.68
b10	0.20	-2.47	0.80	-0.20	2.47	-0.80
a2	0.16	2.46	1.49	-0.16	-2.46	-1.49
a3	-0.55	2.49	-3.23	-0.55	2.49	-3.23
a4	0.00	-0.11	0.43	0.00	0.11	-0.43
a5	-0.02	1.63	-0.35	-0.02	1.63	-0.35
a6	0.01	-0.04	-0.04	-0.01	0.04	0.04
a7	0.00	0.93	0.90	0.00	0.93	0.90
a8	0.00	-1.18	-0.17	0.00	1.18	0.17
a9	0.00	1.41	-0.72	0.00	1.41	-0.72
a10	0.00	0.83	0.07	0.00	-0.83	-0.07

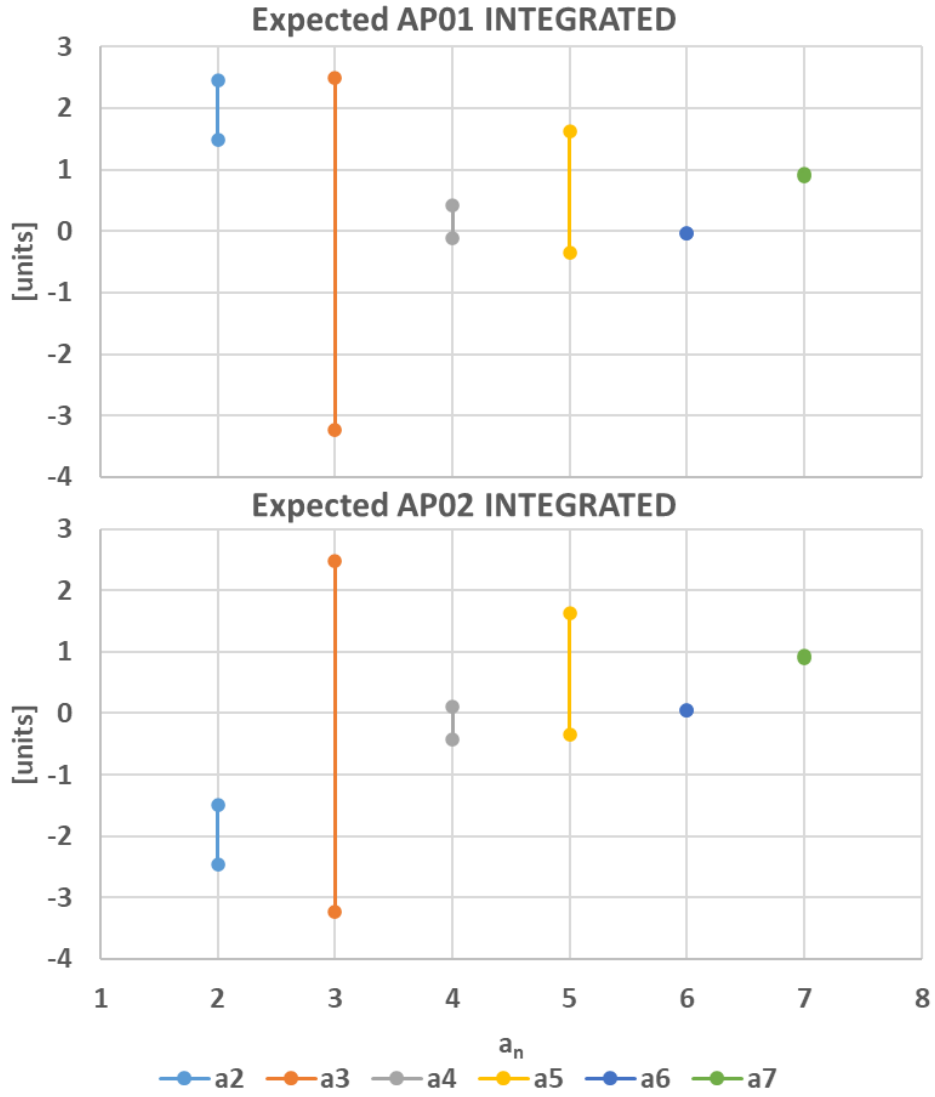


$$\Delta_1 = Meas_{PROTO}^{@\ I_{nom}} - Simu_{PROTO}^{@\ I_{nom}}$$
$$EXPE\ PROTO = Simu_{SERIE}^{@\ I_{nom}} + \Delta_1$$

$$\Delta_2 = Meas_{SERIE}^{iron\ @\ RT} - Simu_{SERIE}^{iron\ @\ RT}$$
$$EXPE\ SERIE = Simu_{SERIE}^{@\ I_{nom}} + \Delta_2$$

Expected Field Quality of MBRD2 @ Nominal Operation

	INTEGRATED					
	AP03			AP04		
	SIMU	EXPE PROTO	EXPE SERIE	SIMU	EXPE PROTO	EXPE SERIE
b2	-1.59	-2.55	1.30	1.59	2.55	-1.30
b3	-15.51	-0.01	-0.37	-15.51	-0.01	-0.37
b4	-1.22	-2.20	-2.23	1.22	2.20	2.23
b5	-2.05	2.71	3.21	-2.05	2.71	3.21
b6	-0.41	-1.61	-1.00	0.41	1.61	1.00
b7	1.99	1.73	1.67	1.99	1.73	1.67
b8	1.07	3.23	0.84	-1.07	-3.23	-0.84
b9	1.33	0.68	0.68	1.33	0.68	0.68
b10	0.20	-2.47	0.80	-0.20	2.47	-0.80
a2	0.16	2.46	1.49	-0.16	-2.46	-1.49
a3	-0.55	2.49	-3.23	-0.55	2.49	-3.23
a4	0.00	-0.11	0.43	0.00	0.11	-0.43
a5	-0.02	1.63	-0.35	-0.02	1.63	-0.35
a6	0.01	-0.04	-0.04	-0.01	0.04	0.04
a7	0.00	0.93	0.90	0.00	0.93	0.90
a8	0.00	-1.18	-0.17	0.00	1.18	0.17
a9	0.00	1.41	-0.72	0.00	1.41	-0.72
a10	0.00	0.83	0.07	0.00	-0.83	-0.07

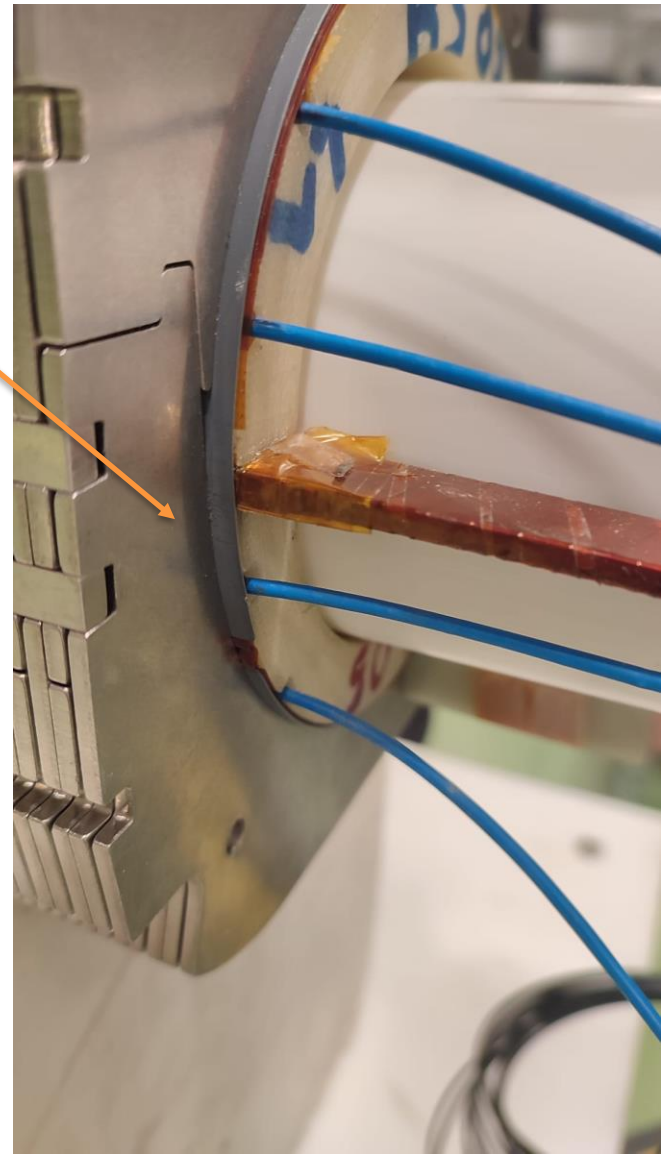


$$\Delta_1 = Meas_{PROTO}^{@\ I_{nom}} - Simu_{PROTO}^{@\ I_{nom}}$$
$$EXPE\ PROTO = Simu_{SERIE}^{@\ I_{nom}} + \Delta_1$$

$$\Delta_2 = Meas_{SERIE}^{iron\ @\ RT} - Simu_{SERIE}^{iron\ @\ RT}$$
$$EXPE\ SERIE = Simu_{SERIE}^{@\ I_{nom}} + \Delta_2$$

PROTRUDING SS PROTECTION SHEETS

- This issue, which has affected all collared apertures, was initially detected on MBRD1.
- The root cause consists in the fact that, according to the drawings, the SS protection sheets are as long as the coils.
- Due to the inherent difficulty of precisely controlling their position, this protrusion occurs in almost all apertures, leading to the encountered problems.



PROTRUDING SS PROTECTION SHEETS: accepted solution

- In assembled apertures & magnets:
  - The SS protection sheets have been bent towar the collars
- In apertures yet to be collared:
  - The length of the SS sheet positioned on the coil end will be reduced by 2.5±0.5 mm using a rotating rasp abrasion method.
  - It is expected that this action will completely solve the issue of protrusion.
  - However, there is a possibility that the SS sheet might end up slightly recessed under the last collar: this is not expected to cause any issues.