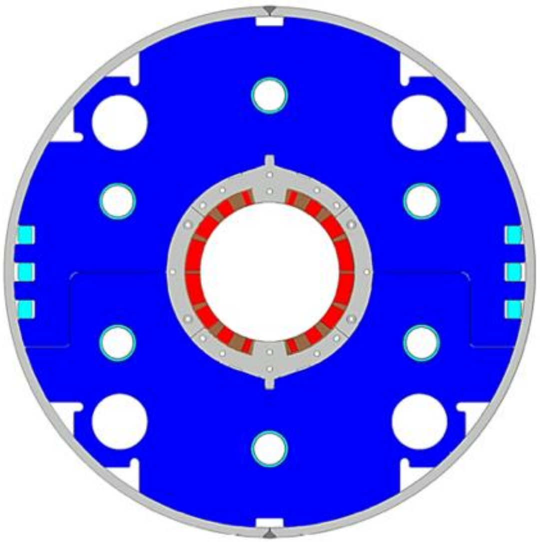
Status of D1 Construction and Test

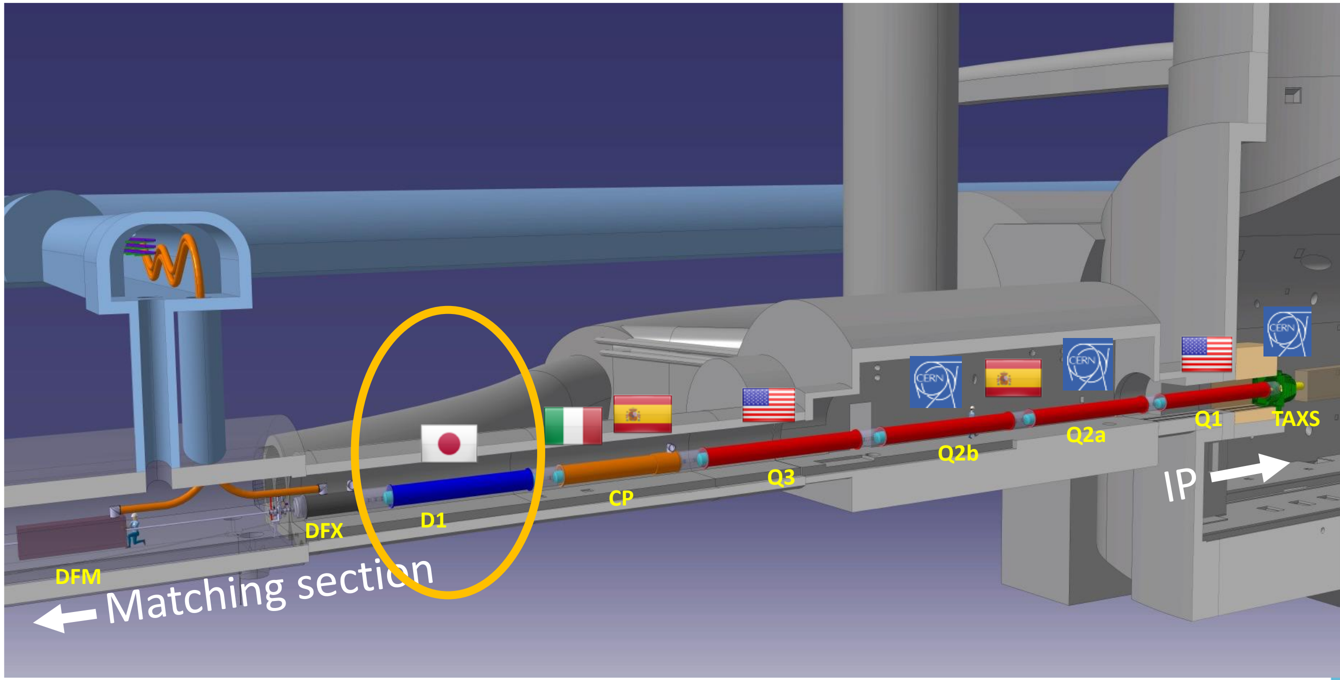
Tatsushi NAKAMOTO, KEK

On behalf of CERN-KEK Collaboration for D1 Construction for HL-LHC

13th HL-LHC Collaboration Meeting, Vancouver, Canada, Sept. 27, 2023

Japanese Contribution to HL-LHC: D1 magnets



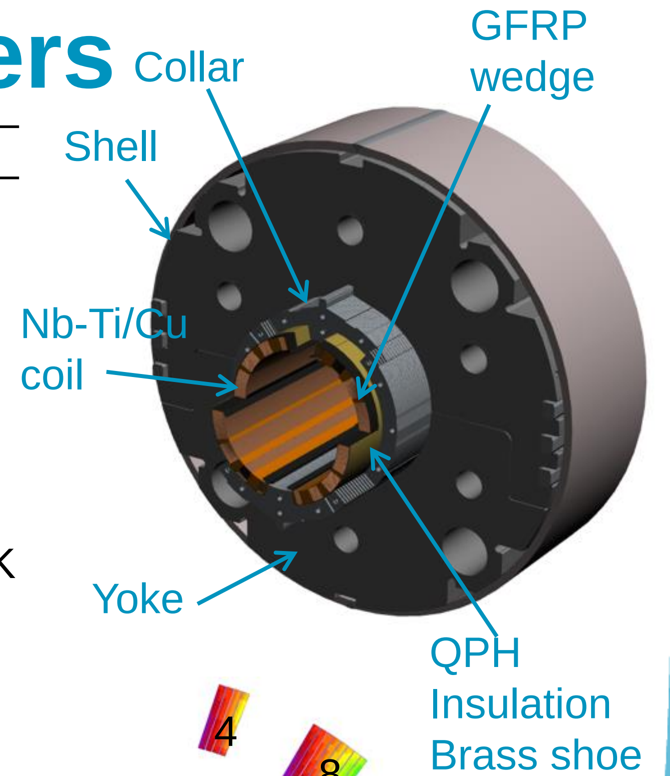


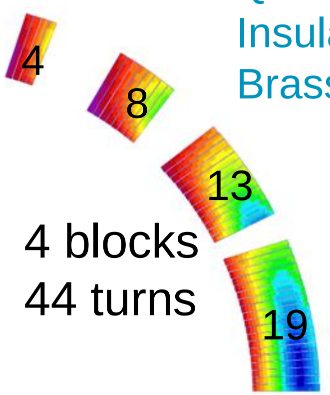
- Beam separation dipole (D1) by KEK
  - ➢ Design study of D1 for HL-LHC within the framework of the CERN-KEK collaboration since 2011.
  - ➢ 150 mm single aperture, 35 Tm (5.6 T x 6.3 m), Nb-Ti technology.
  - ➢ Development 2-m long model magnets (3 units) at KEK
- Deliverables for HL-LHC
  - ➢ *1 full-scale prototype cold mass (LMBXFP)*
  - ➢ *6 series cold masses (LMBXF1-6)*

7 units x 7-m long cold masses

Design parameters

	prototype, series production (7m)
Coil aperture	**150 mm**
Field integral	**35 T m**
Field (3D)	Nominal: 5.60 T, Ultimate: 6.04 T
Peak field (3D)	Nominal: 6.58 T, Ultimate: 7.14 T
Current	Nominal : 12.11 kA, Ultimate 13.23 kA
Operating temperature	1.9 K
Field quality	$<10^{-4}$ w.r.t B_1 (R_{ref}=50 mm)
Load line ratio (3D)	Nominal: 76.5%, Ultimate: 83.1% at 1.9 K
Differential inductance	Nominal: 4.0 mH/m
Conductor	Nb-Ti: LHC-MB outer cable
Stored energy	Nominal: 340 kJ/m
Magnetic length	6.26 m
Coil mech. length	6.58 m
Magnet mech. length	6.73 m 12 ton
Heat load	**135 W (Magnet total)** **2 mW/cm^3 (Coil peak)**
Radiation dose	**> 25 MGy**





Large-aperture single layer coil →
Mechanical support of a coil is challenging

Three 2 m model magnets were developed at KEK.

Powering Tests of Full-scale D1 Magnets

- MBXFP1: June – Sep. 2021
  - The magnet reached 106 % of I_{nom} but training up to the ultimate current (108 % of I_{nom}) was NOT demonstrated due to test facility limitation.
  - The coil cross section was NOT fully optimized since the cable thickness was deviated from the original one for the 2-m models.

- MBXF1: April – June 2023
  - Upgrade of test facility allowing the powering tests up to the ultimate.
  - The coil cross section for the series magnet was redesigned and the improved FQ is qualified by the MFM of MBXF1.

- MBXF5: Oct. – Dec. 2023
  - ~~The cold powering test has been suspended due to the trouble of the test facility.~~
  - The revolution indicator of the cold turbine has been repaired. Commissioning is being carried out until Oct. 6. Cooling of MBXF5 is anticipated at Oct. 9.

- MBXF2: early 2024

Upgrade of Test Facility

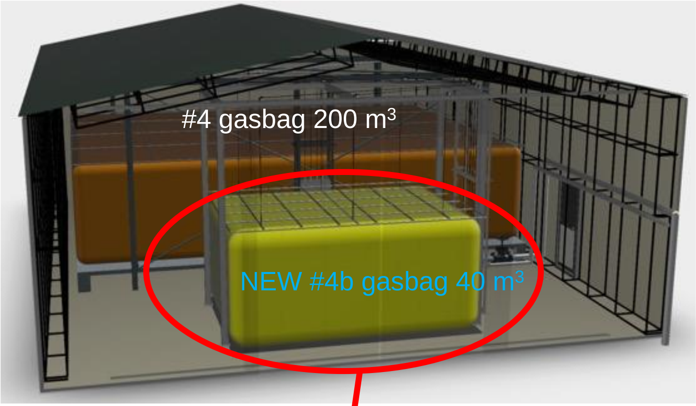
Remaining Issues in KEK Test Facility after MBXFP1 Powering Test

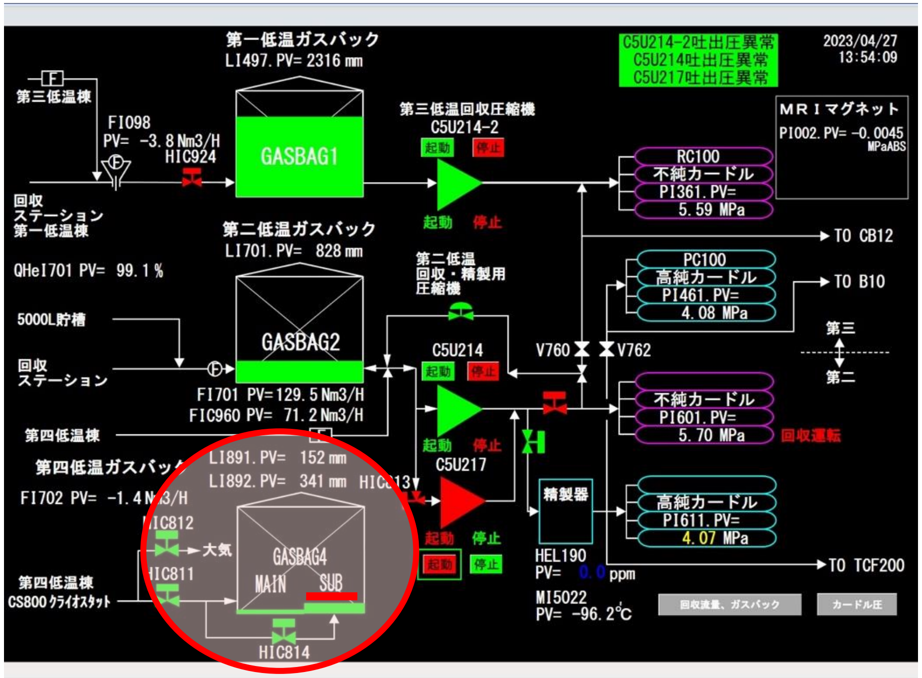
Training quench up to the ultimate current (13.2 kA) was NOT demonstrated in the powering test of MBXFP1 due to limitation of the test facility…

- Original energy extraction using dump resistors of 25 mΩ or 50 mΩ up to the cold powering test of MBXFP1.
  - 25 mΩ: Insufficient energy extraction resulted in incomplete helium gas recovery.
  - 50 mΩ: The maximum voltage exceeded the allowable limit of 600 V for the DCCB of the power converter. Training test above 106% of the nominal current could not be performed.
- Targets of new facility
  - Maximum voltage below 600 V at the ultimate current.
  - Magnet dissipation energy below the safety limit of 1.5 MJ.
  - Increase of helium gasbag capacity.
- To satisfy these targets, new energy extraction using **varistors** and **the additional helium gasbag** were implemented before the cold test of MBXF1.

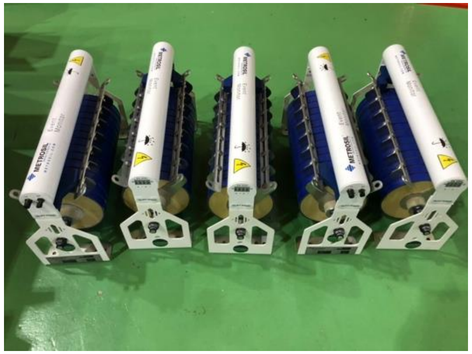
Additional Helium Gas Storage Bag

- New Helium gasbag (#40-sub, 40 m^3):
  - construction and system commissioning completed in March 2023.
- In operation for MBXF1 powering test.

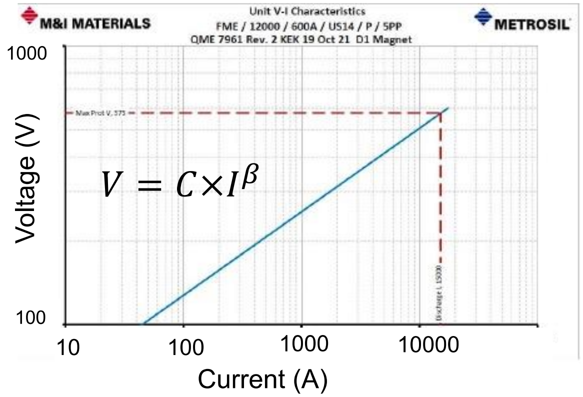


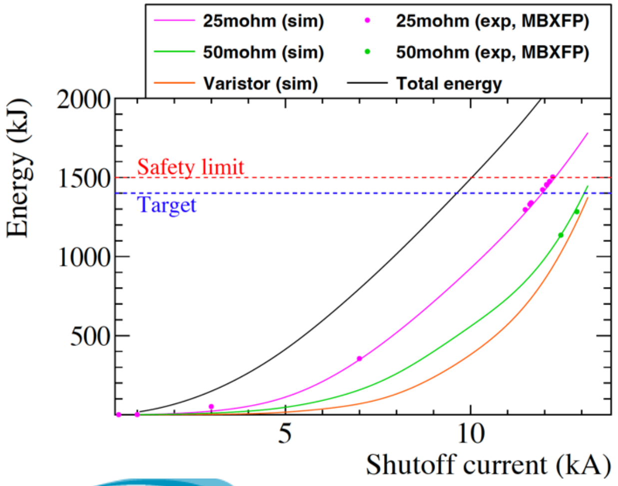


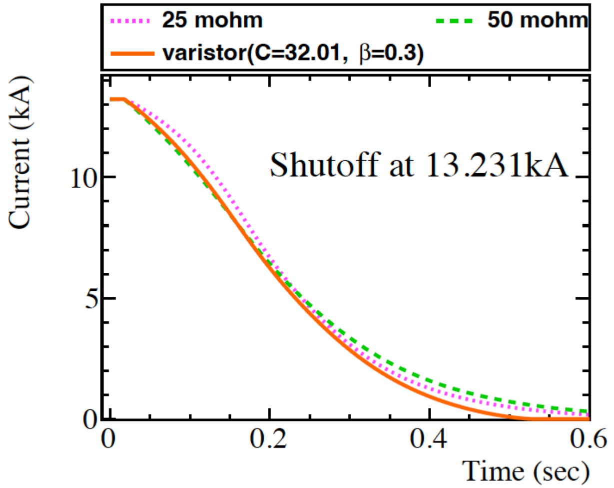
New EE with Metrosil Varistors

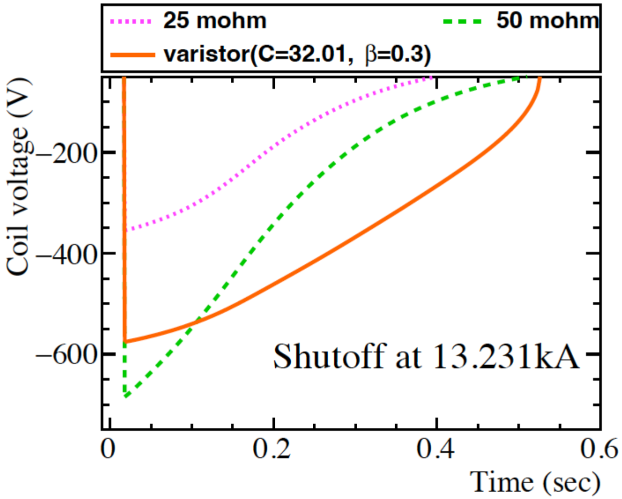


- SiC Varistors manufactured by Metrosil for overvoltage protection and effective energy extraction.
- Non-linear characteristics: $V = C \times I^{\beta}$, C=32.01, β=0.3
- Design
  - 5 units in parallel circuit
  - Energy extraction: 2.5 MJ
  - Up to 15 kA
- The system was installed so that it can coexist with the original dump resistor.

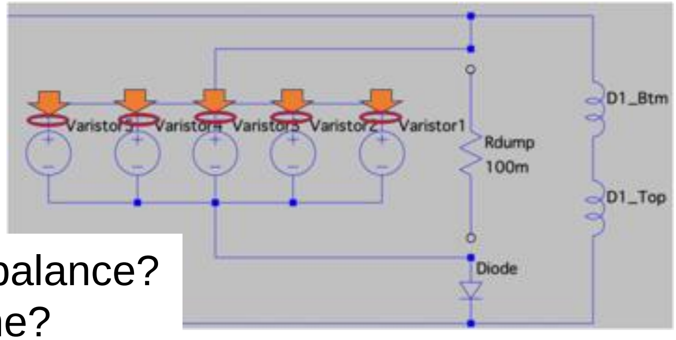






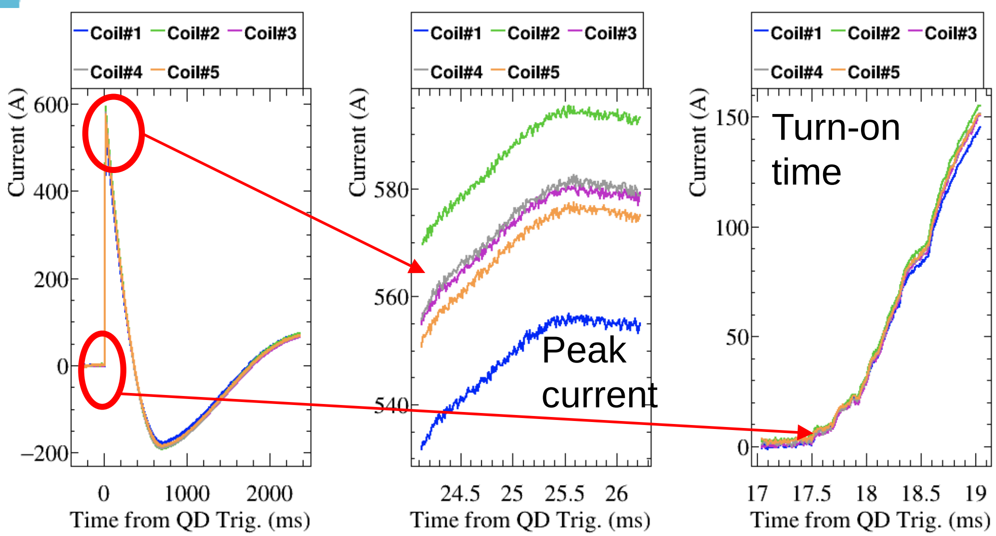


Validation of EE System with Varistors

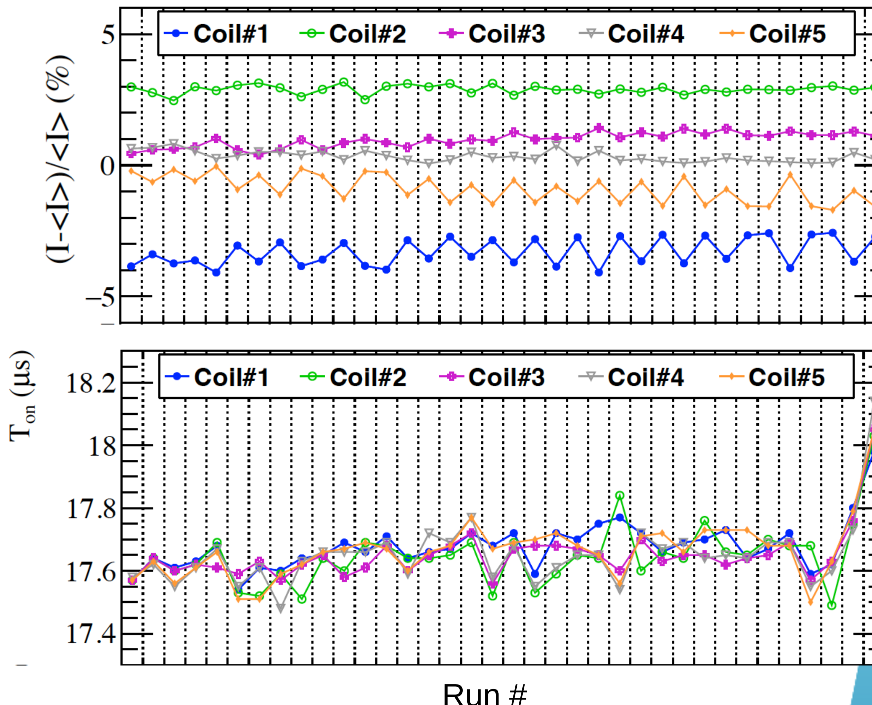


Current imbalance?
Turn-on time?

- Signals from Rogowski coils and temperature of SiC disks has been monitored every shutoff/quench event to check indication of imbalance.
- Before powering to higher current, we performed 3kA shutoff to check reproducibility.



A typical dumped current waveforms reconstructed by Rogowski coils and integrators.

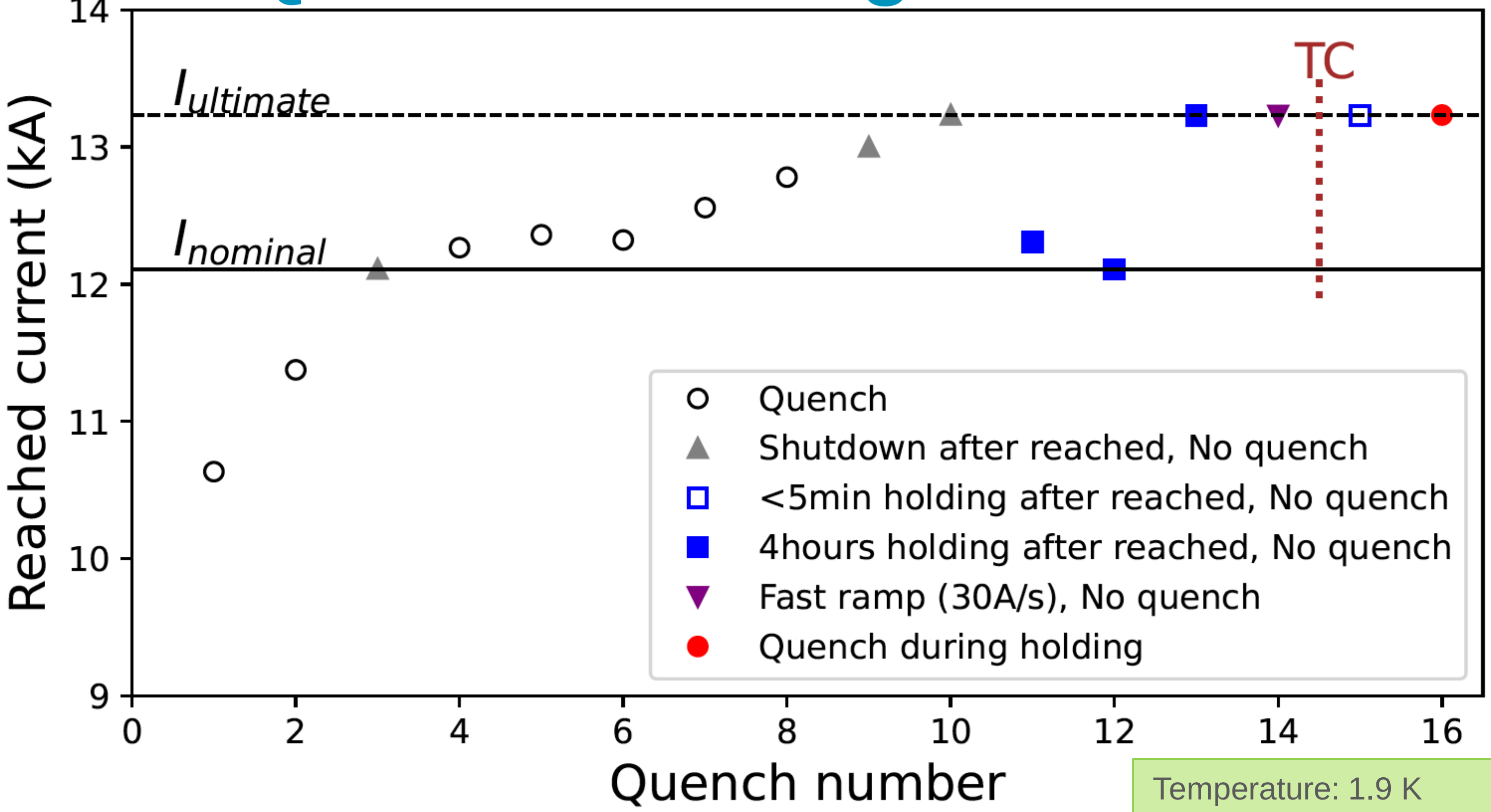


- **Current imbalance at peak was found to be reproducible within ± 4%**
- **Turn-on time among the varistor units : < 0.3 msec.**
- **Stable operation of Varistors was confirmed.**

Test Results of MBXF1
- Training Quench -

The detailed reports at WP3 meeting
https://indico.cern.ch/event/1290076/

Quench Training of MBXF1



Temperature: 1.9 K
Ramp rate: 12 A/s or 30 A/s
Quench detection: 0.1 V, 10 msec
Quench protection: QPH and varistor
Quench start location: quench antenna

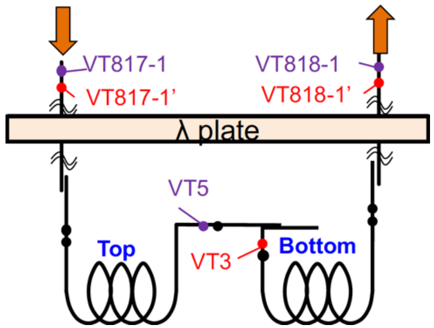
- Nominal current ($I_{nominal}$, 12.11 kA) : **2** quenches
- **Ultimate current ($I_{ultmate}$, 13.231 kA) : 7 quenches**
- Furthermore **NO** quench was required to reach $I_{ultmate}$ after the thermal cycle
- The last quench at $I_{ultmate}$ occurred during the long holding test (4 hours)

First achievement of the ultimate current rating for the full scale magnet with an excellent training memory

Quench Localization Analysis

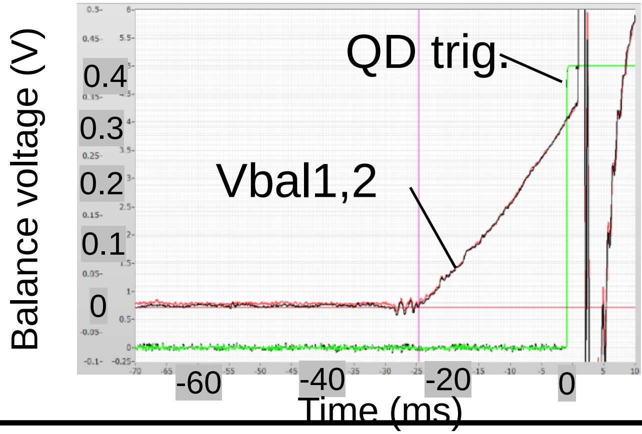
Voltage taps

Localize either the top or bottom coil



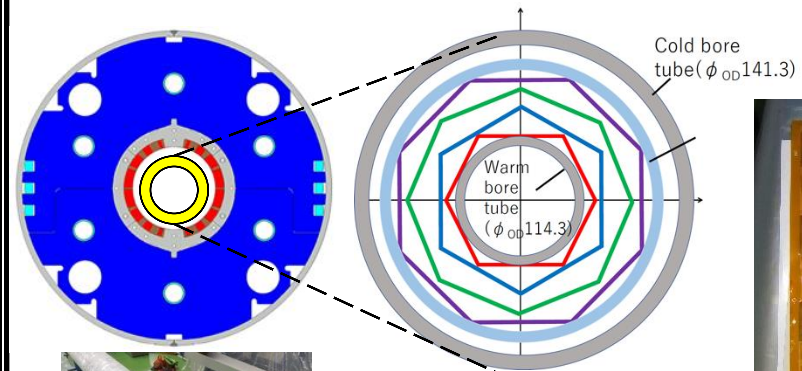
Vbal1 = (<VT817-1> – <VT5>) – (<VT5>-<VT818-1>)

Vbal2 = (<VT817-1'> – <VT5>) – (<VT5>-<VT818-1>)

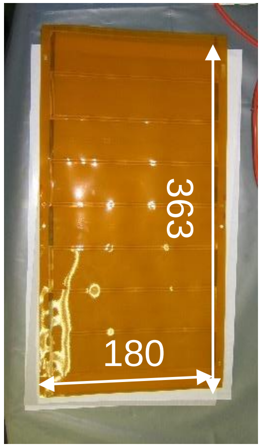


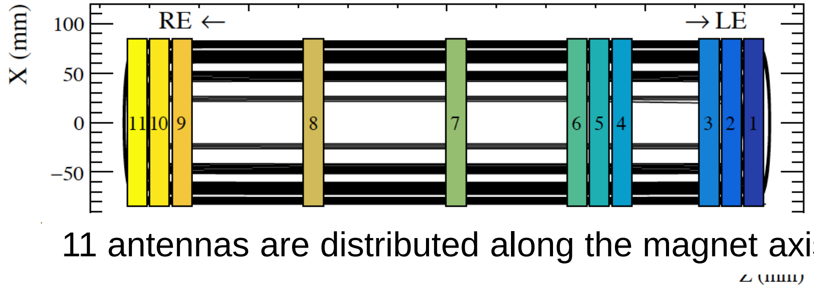
Quench Antenna

Localize both longitudinal and azimuthal position



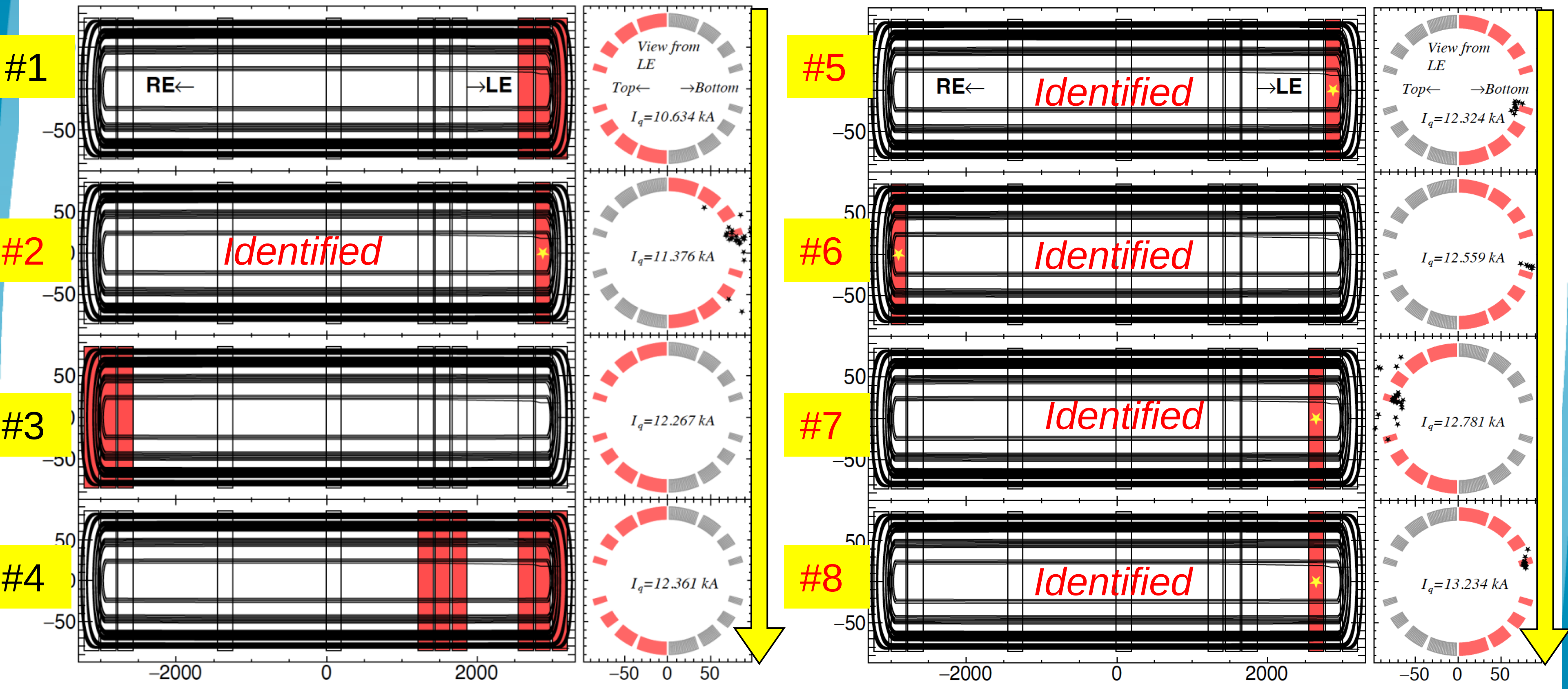
Skew octupole (8S)
Normal octupole (8N)
Skew sextupole (6N)
Normal sextupole (6S)





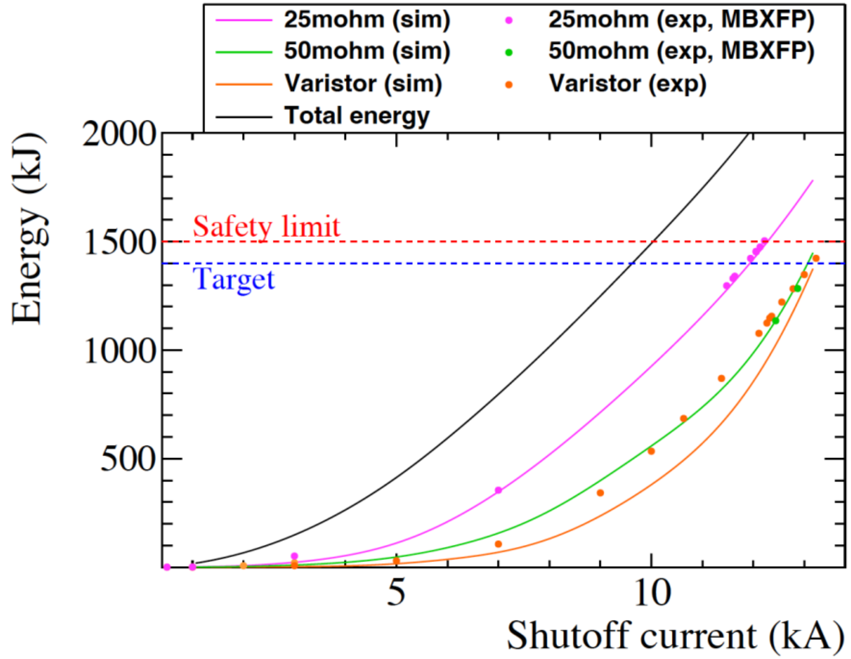
11 antennas are distributed along the magnet axis

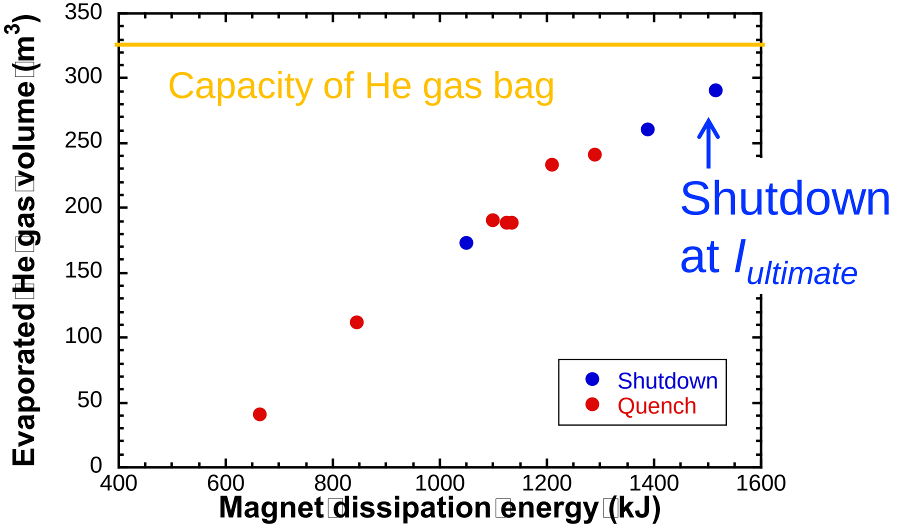
Quench Location



Quench location changed event by event, indicating the magnet has no specific weak point

Energy Curve / Helium Gas Recovery



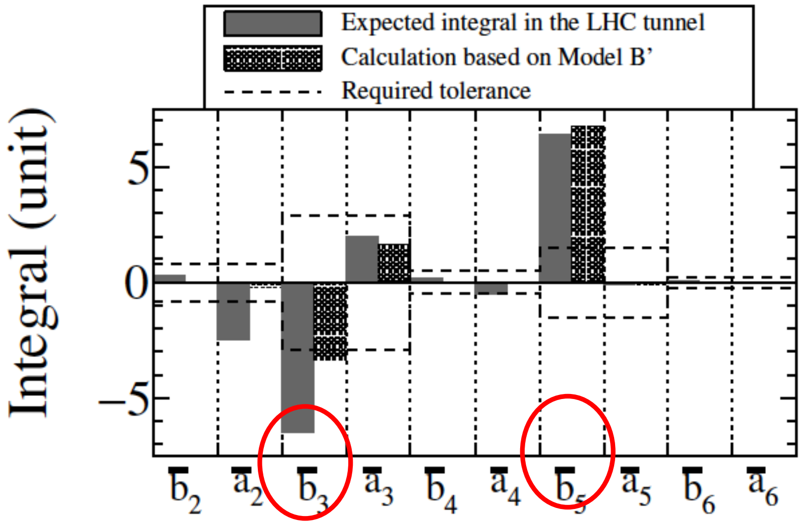


- Varistor: discrepancy observed between the simulation (design) and measured data but **an amount of energy dissipated in the magnet is always below ~1.4 MJ**
- **All evaporated helium gas was successfully recovered.**

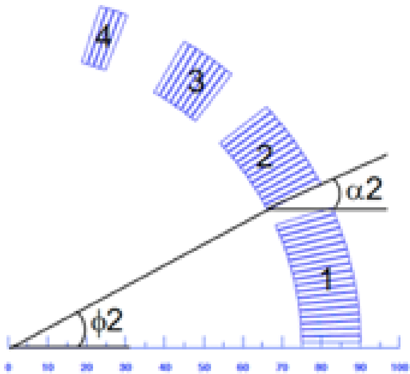
Test Results of MBXF1
- Field Quality -

Remarks on the MBXFP1 Test – Field Quality

K.Suzuki et al. IEEE TASC vol.32, no.6 Sept 2022, 9000407

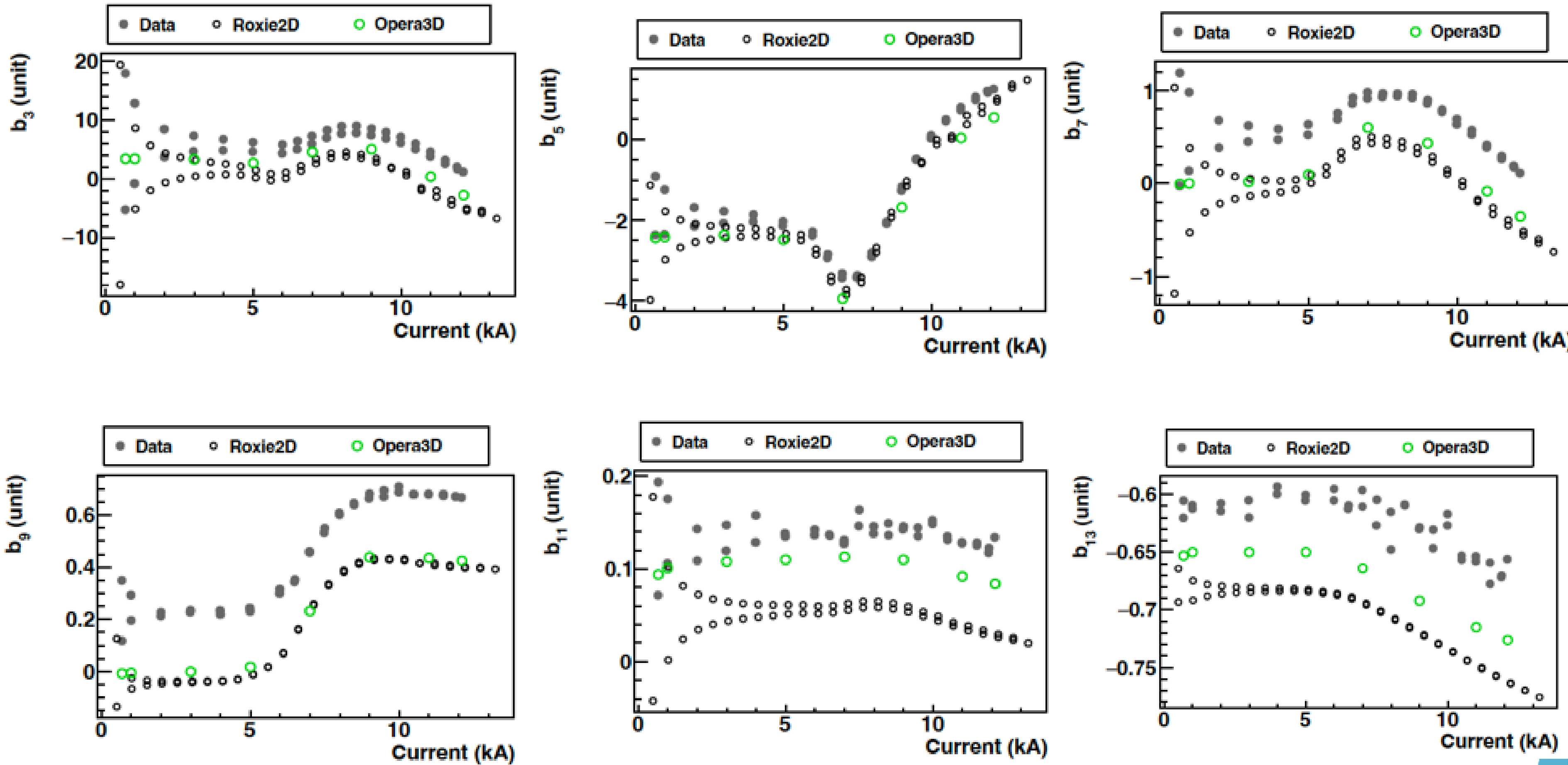


	Parameters for MBXFP	Parameters for Series
$\phi 1$	**1.1238**	**1.1680**
$\phi 2$	**28.0254**	**27.8471**
$\phi 3$	**50.6798**	**50.3830**
$\phi 4$	**71.1408**	**70.7156**
$\alpha 2$	**27.3545**	**27.5527**
$\alpha 3$	**52.2239**	**52.5639**
$\alpha 4$	**68.7646**	**70.3048**
Azimuthal insulation thickness (mm)	**0.1297**	**0.1297**



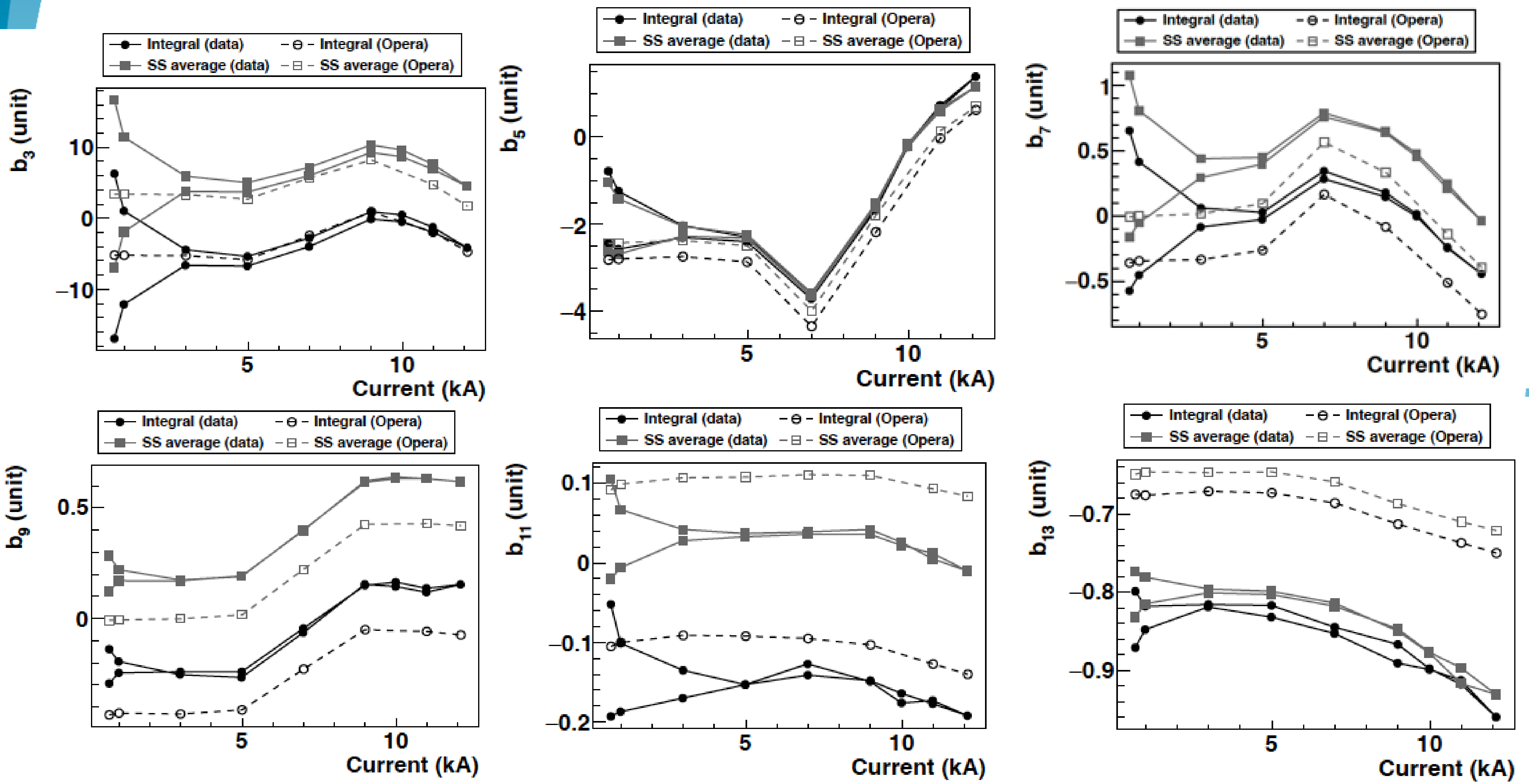
- MBXFP1:
  - Compromised model was adopted due to the time restriction etc.
  - Measured $\boldsymbol{b_3}$ and $\boldsymbol{b_5}$ are out of tolerances.
- The series magnet (MBXF1-)
  - **We completed design study and optimized parameters are adopted.**

DC loop at the Z center for allowed normal (n=3-13) - MBXF1 -



- Measured b_3 differs from the calculation by < 4 unit at $I_{nominal}$ (12.11 kA).
- For other allowed multipoles, measurement agrees with the calculation within 0.5 unit.

Integral DC loop for allowed normal (n=3-13)
- MBXF1 -



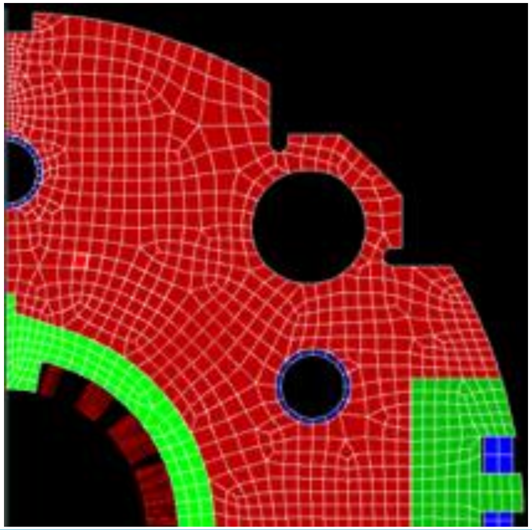
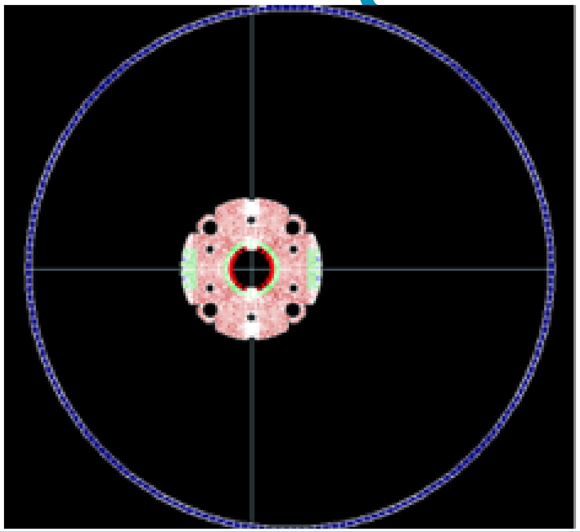
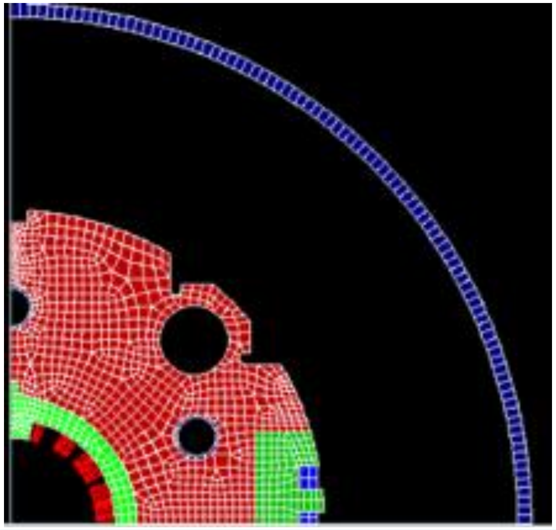
FQ table of MBXF1 for $I_{nominal}$ (12.11kA)

RE: -3353 mm - -2853 mm
SS: -2853 mm - 2648 mm
LE: 2648 mm - 4148 mm
Central: -250 mm - 250 mm

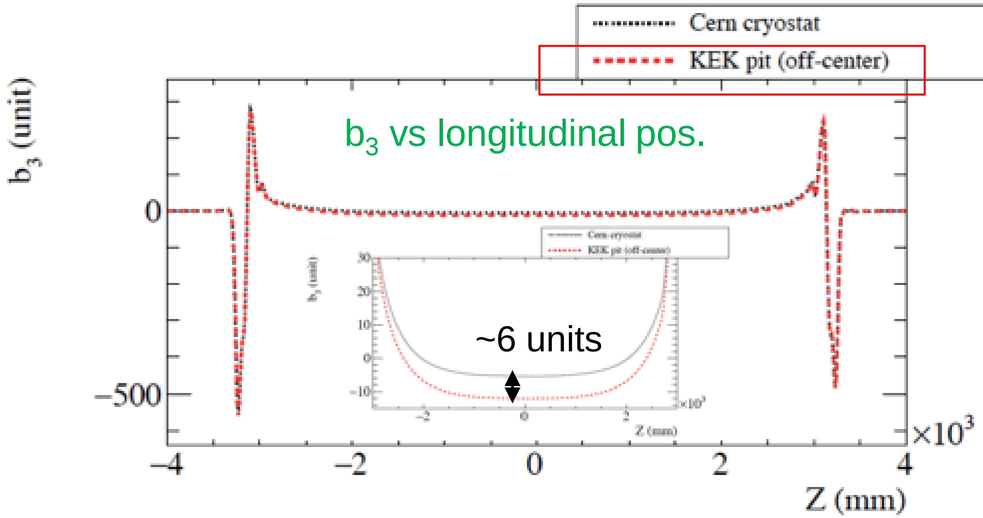
$$\frac{\int_{\mathrm{RE}} B_n(z)dz}{\int_{\mathrm{total}} B_1(z)dz} \times 10^4 \quad \frac{\int_{\mathrm{SS}} B_n(z)dz}{\int_{\mathrm{total}} B_1(z)dz} \times 10^4 \quad \frac{\int_{\mathrm{LE}} B_n(z)dz}{\int_{\mathrm{total}} B_1(z)dz} \times 10^4$$

n	Central		SS (average)		RE		SS		LE		Total	
	an	bn	an	bn	an	bn	an	bn	an	bn	an	bn
2	-3.92	0.05	-3.88	0.31	-0.41	0.09	-3.41	0.28	-0.02	-0.25	-3.84	0.11
3	-0.07	1.19	-0.30	4.48	0.13	-5.08	-0.26	3.94	2.04	-3.01	1.90	-4.15
4	-0.46	0.07	-0.59	0.38	-0.07	0.07	-0.52	0.33	-0.04	0.15	-0.63	0.55
5	0.01	1.25	0.06	1.16	0.02	-0.25	0.05	1.02	-0.13	0.62	-0.06	1.39
6	0.30	-0.06	0.15	0.09	-0.02	0.07	0.13	0.08	0.02	-0.02	0.13	0.14
7	0.05	0.12	0.10	-0.04	0.03	-0.36	0.09	-0.03	0.16	-0.05	0.28	-0.44
8	0.24	0.03	0.07	0.27	-0.03	0.09	0.06	0.24	-0.03	-0.05	0.00	0.27
9	0.03	0.67	0.06	0.62	0.03	-0.28	0.06	0.54	0.01	-0.11	0.09	0.15
10	0.14	0.02	0.06	0.05	-0.02	0.03	0.05	0.05	0.00	-0.05	0.04	0.03
11	0.00	0.13	0.06	-0.01	-0.01	-0.11	0.06	-0.01	0.04	-0.07	0.09	-0.19
12	0.01	-0.12	0.11	-0.41	0.00	0.02	0.10	-0.36	0.00	-0.06	0.11	-0.40
13	-0.02	-0.66	0.08	-0.93	0.00	-0.07	0.07	-0.82	0.02	-0.07	0.09	-0.96
14	-0.09	-0.25	0.15	-0.78	0.00	0.01	0.13	-0.69	0.01	-0.07	0.14	-0.76
15	-0.03	-1.15	0.06	-1.36	0.01	-0.03	0.05	-1.20	0.02	-0.08	0.08	-1.31
16	-0.08	-0.21	0.09	-0.53	0.01	0.01	0.08	-0.46	0.00	-0.05	0.08	-0.51
17	0.02	-0.77	-0.03	-0.63	-0.01	-0.01	-0.03	-0.56	0.00	-0.01	-0.03	-0.58
18	0.08	0.10	-0.04	0.29	0.00	0.01	-0.03	0.26	-0.02	0.01	-0.05	0.28
19	0.00	0.38	0.00	0.38	0.00	0.00	0.00	0.33	0.00	0.03	-0.01	0.37
20	-0.01	0.02	0.00	0.02	0.00	-0.01	0.00	0.02	0.00	-0.01	0.00	-0.01

Effect of Ferromagnetic Environment on FQ of D1

w/o Cryostat	KEK pit	CERN cryostat
Horizontal bench	Vertical test stand - Off-centered by 150mm	Used for design - Centered*



b_3 Summary

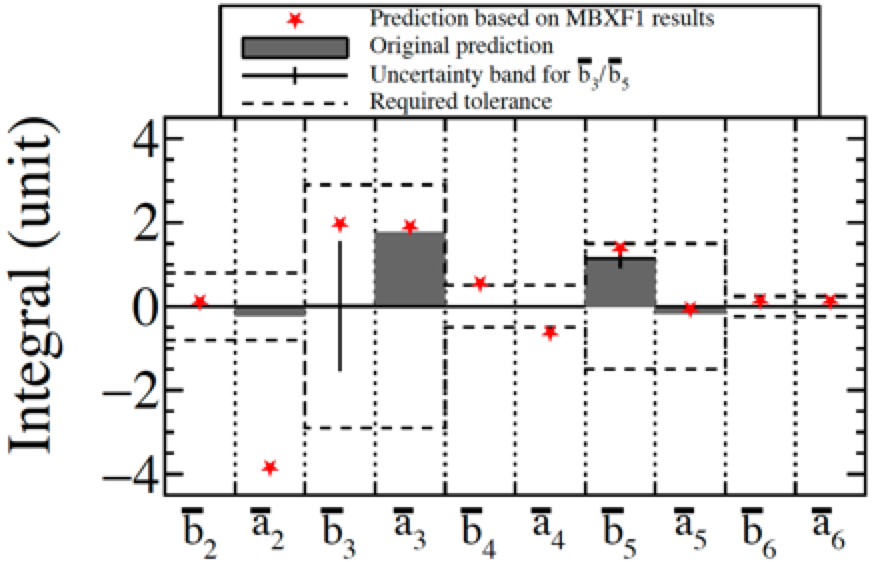
		Opera3D (for series)	MBXFP1	**MBXF1**	MBXF5
Horizontal by portable MM system			-4.87	**1.96**	1.00
Horizontal warm	Central		-4.12	**4.06**	
	SS average			**3.04**	
	Integral			**-7.55**	
Vertical, warm	Central				
	SS average		-4.37	**2.90**	
	Integral		-14.38	**-7.55**	
Vertical, 12.11kA	Central	-2.74	-8.51	**1.19**	
	SS average	1.70	-4.25	**4.48**	
	Integral	-4.72	-12.31	**-4.15**	

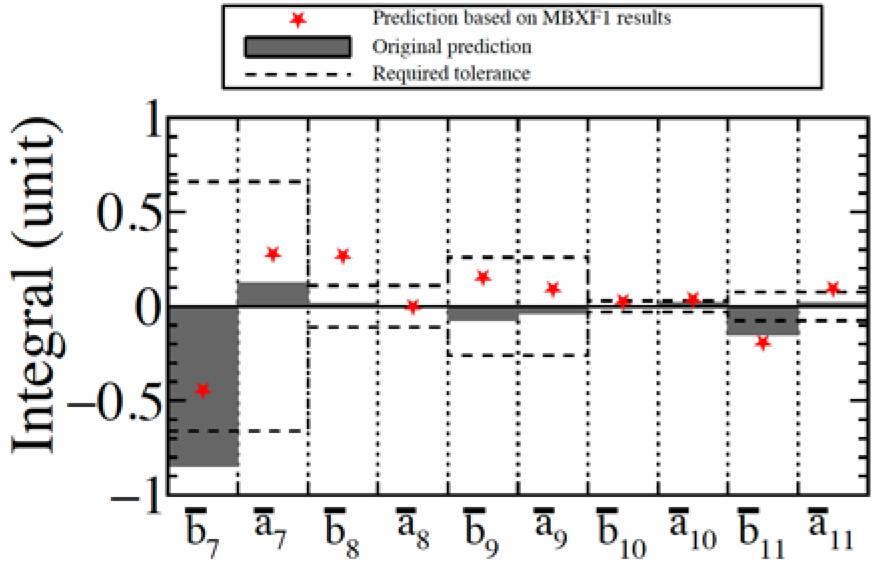
b_5 Summary

		Opera3D (for series)	MBXFP1	**MBXF1**	MBXF5
Horizontal by portable MM system			2.86	**-2.34**	-2.49
Horizontal warm	Central		2.90	**-2.31**	
	SS average			**-2.49**	
	Integral			**-2.63**	
Vertical, warm	Central				
	SS average		2.85	**-2.43**	
	Integral		2.31	**-2.51**	
Vertical, 12.11kA	Central	0.55	6.72	**1.25**	
	SS average	0.70	6.76	**1.16**	
	Integral	0.63	6.51	**1.39**	

Predicted FQ (Integral) in the LHC cryostat - MBXF1 -

Note: difference of ferromagnetic environment between KEK test stand and LHC cryostat.

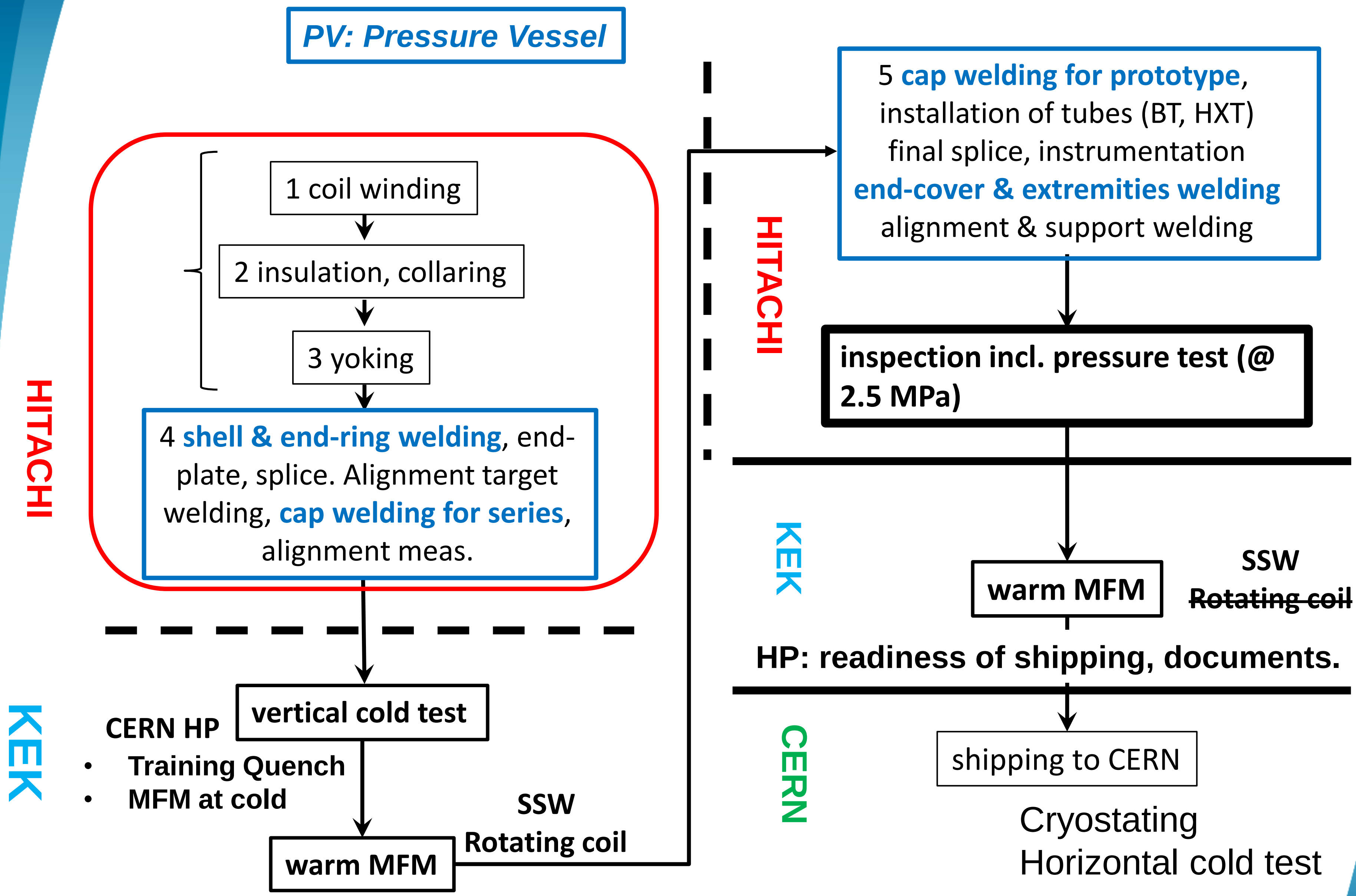




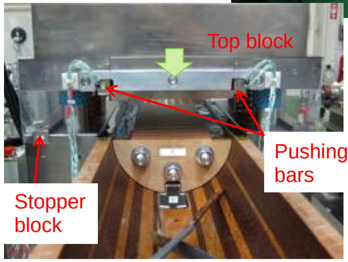
- From the obtained field quality in the KEK cryostat, we estimated the actual field quality predicted in the LHC cryostat.
  - Requirements will be fulfilled in most of the harmonics.
- MFM of the D1 prototype cold mass at SM18 will be crucial to confirm the effect of the LHC cryostat on FQ.

Summary of Construction of D1 Cold Mass

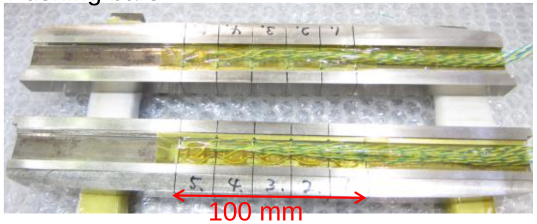
Flow of D1 Cold Mass Production

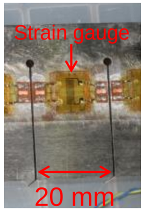


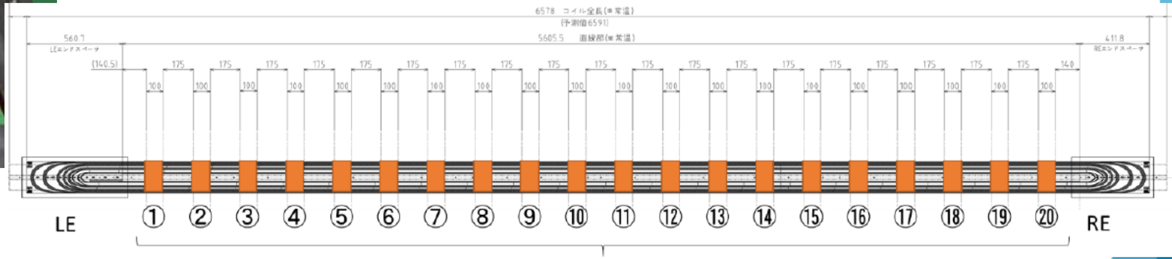
Manufacturing of D1 Magnet



Pushing bars







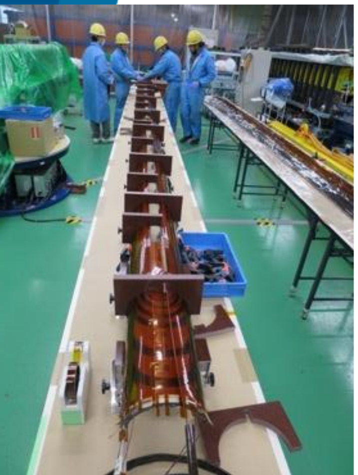
Control of the coil size is crucial for the D1
- to attain the sufficient preload for the training performance, and
- not to exceed the mechanical limit of insulation.

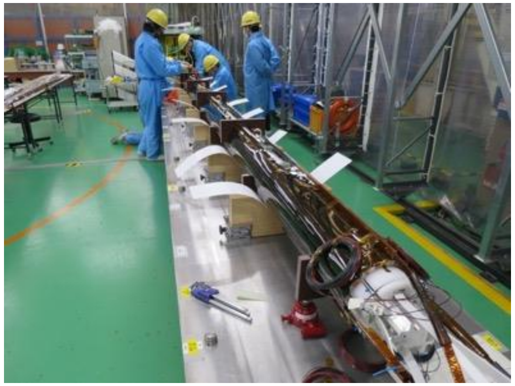
Summary of results of coil size measurement

Magnet	Coil	Average 20 pts (MPa)	Max value (MPa)	Min value (MPa)	Standard deviation (MPa)	Cable thickness (44 stack) wrt S2-4 cable (mm)*
MBXFP1 Tested	LPT-1	112	116	106	2.0	0.262
	LPB-1	110	113	108	1.4	0.256
MBXF5	LT-1	122	125	119	1.5	0.418
	LB-1	122	125	118	1.8	0.422
MBXF1 Tested	LT-2	117	120	114	1.3	0.397
	LB-2	125	128	112	1.6	0.403
MBXF2	LT-3	123	127	119	1.9	0.321
	LB-3	117	122	114	1.9	0.327

- Target range of the total average: 115±10 MPa.
  - Ave. prestresses are within the target range.
  - Excesses were observed at a few points.
- Thickness of the insulated SC cables from 19 spools was determined by the "10-stack measurement" before the coil winding.
- Dimension control of the wedge thickness: <30 μm
- A pair of superconducting cables with similar thickness were selected for each magnet so far. This resulted in the close values of average stress between two coils in MBXFP1 and MBXF5, while the difference in total average is relatively large in MBXF1 and MBXF2.

Manufacturing of D1 Magnet

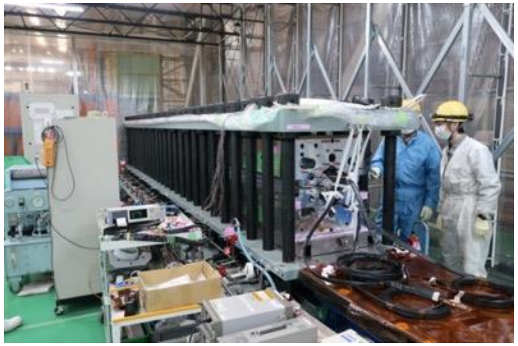

QPH, ground insulation wrapping

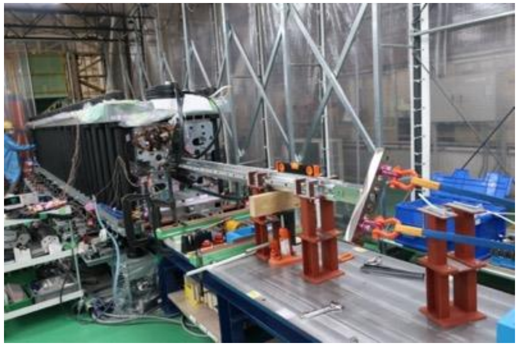

Top/bottom coil assembly


Brass shoe assembly


Collaring


Collared coil on bottom yoke


Yoking


Removal of collaring mandrel

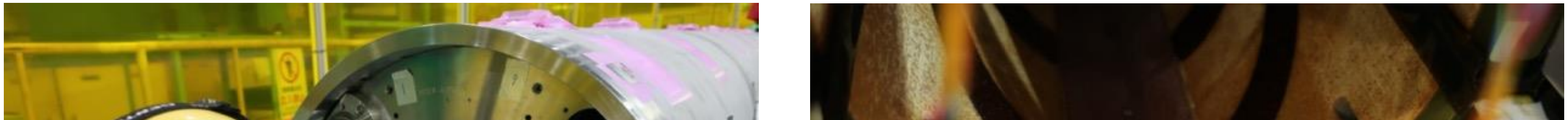

Shell welding


Welding of alignment markers

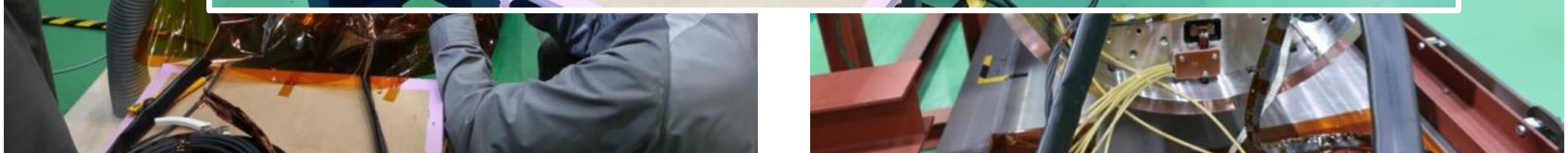

End ring welding

Manufacturing of D1 Magnet

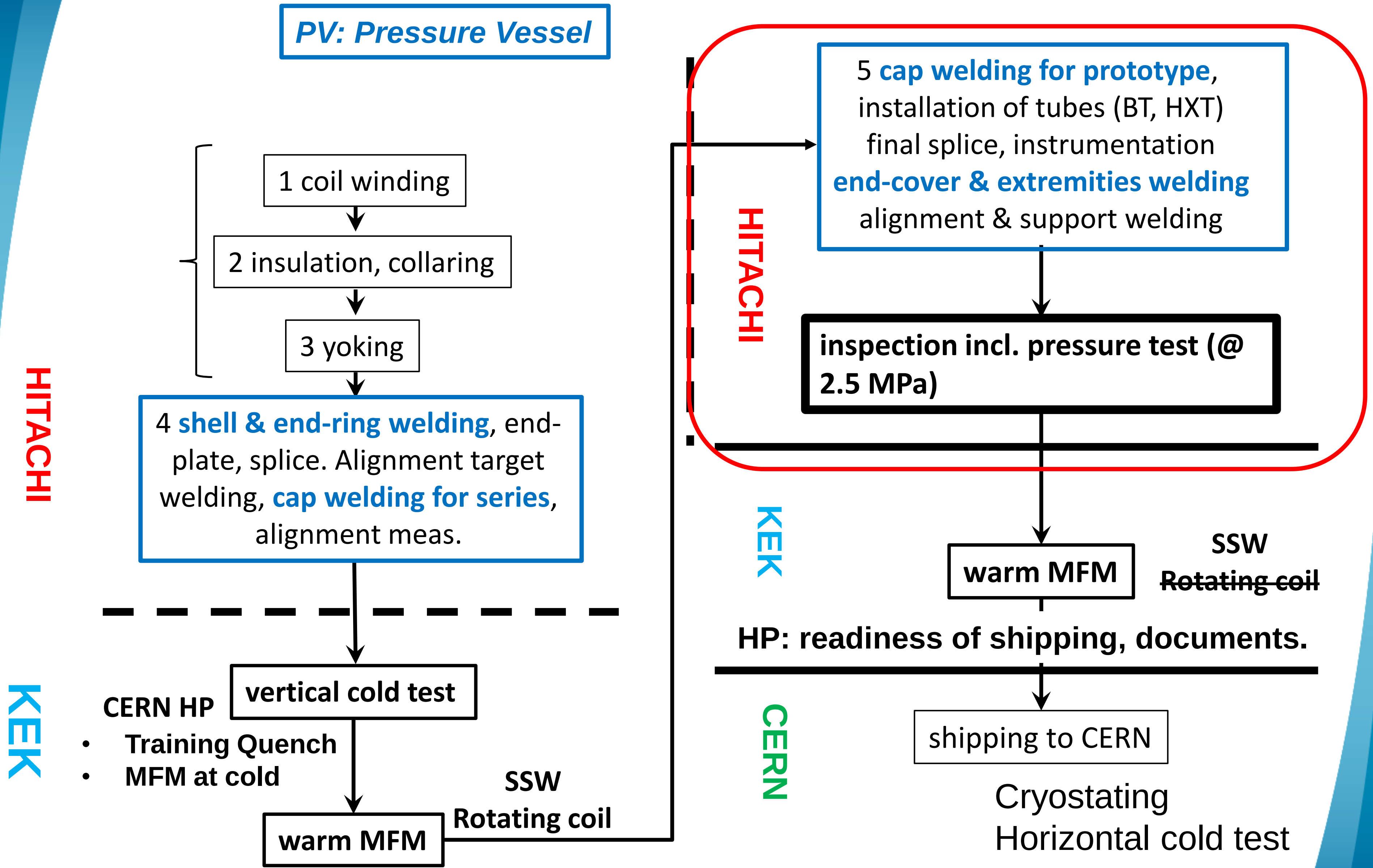
- Axial compression on SC coils



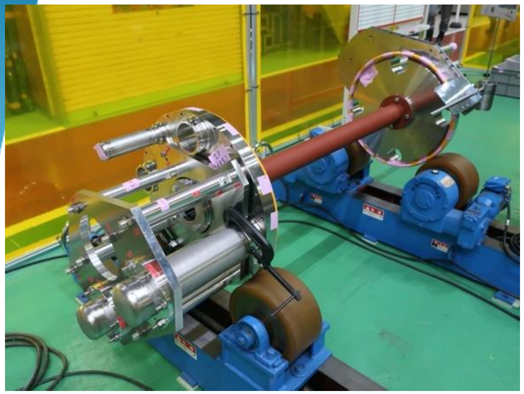
- Splice v



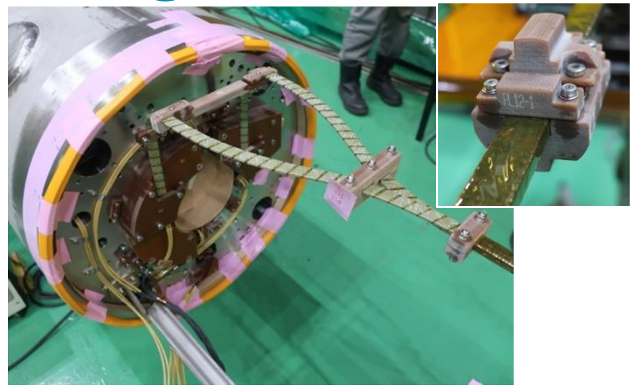
Flow of D1 Cold Mass Production



Manufacturing of D1 Cold Mass

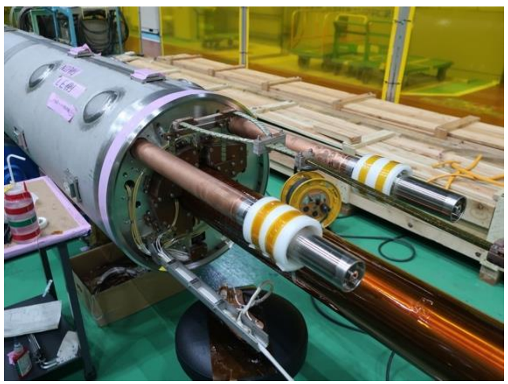


Extremities welding

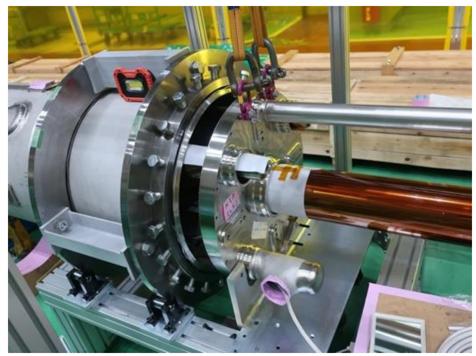


SC bus leads and “spider”

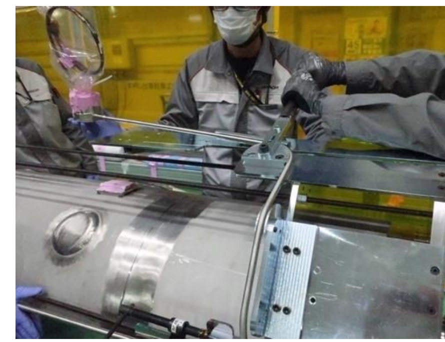
Insertion of CBT



Insertion of HXs



Welding of end-dome, end cover



IFS assembly

Welding of saddles

Completed D1 cold mass

Non-Conformities

Closed
In work

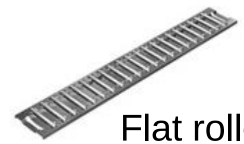
- Welding Qualification
  - EDMS 2469433: Invalid Qualification Result of Fatigue Pre-cracking Requirement for 4 K Fracture Toughness Test of PQR2 HAZ Specimen for the D1 Cold Mass Manufacturing, **Non-critical**
- MBXFP1
  - EDMS 2426526: Deformation of SC cable due to over-tension, **Non-critical**
  - EDMS 2437654: Small crack at GFRP ramp-box of LPT-1 Coil, **Non-critical**
  - EDMS 2443118: Insulation Damage after Curing of D1 Prototype Bottom Coil, **Non-critical**
  - EDMS 2464985: Partial Damage of Ground Insulation, **Non-critical**
  - EDMS 2581587: Weld Defect of the D1 Cold Mass Prototype (end-cover), **Non-critical**
  - EDMS 2595209: Crane Incident at KEK, **Non-critical**
  - EDMS 2731453: Partial peeling of surface insulation of cryo-heater wire for MBXFP1, **Non-critical**
  - EDMS 2753741: Partial peeling of surface insulation of QPH wire for MBXFP1, **Non-critical**
  - EDMS 2753742: Weld Defect of Joint G-2 of MBXFP1, **Non-critical**
  - EDMS 2753743: Weld Defects of Joints I-L2 and I-R2 of MBXFP1, **Non-critical**
  - EDMS 2753744: Weld Defect of Joint D of MBXFP1, **Non-critical**
  - EDMS 2753745: Out of Tolerance of the Length of the D1 Cold Mass Prototype, **Non-critical**
  - EDMS 2753746 Out of Tolerance of the Transversal Positions of the Extremity Pipes of the D1 Cold Mass Prototype, **Non-critical**
- MBXF5
  - EDMS 2753776: Insulation damage of inner surface of MBXF5 coils, **Critical**
  - EDMS 2913654: Weld Defect of the D1 Cold Mass (MBXF5): B-2 Joint, **Non-critical**
- MBXF1
  - EDMS 2955218: Cable deformation at coil end after cold test in MBXF1
- MBXF2
  - EDMS2863016: Insulation damage in the top coil for MBXF2, **Non-critical**
  - EDMS2912993: Insulation damage of the bottom coil for MBXF2, **Non-critical**

Coil (EDMS 2426526, 2437654, 2443118, 2464985)
Welding (EDMS 2581587)
Wiring (EDMS 2731453, 2753741)
Welding (EDMS 2753742–2753746)
Removal of collaring mandrel (EDMS 2753776)
Welding (EDMS 2913654)
Test/Coil (EDMS 2955218)
Coil (EDMS2863016, 2912993)

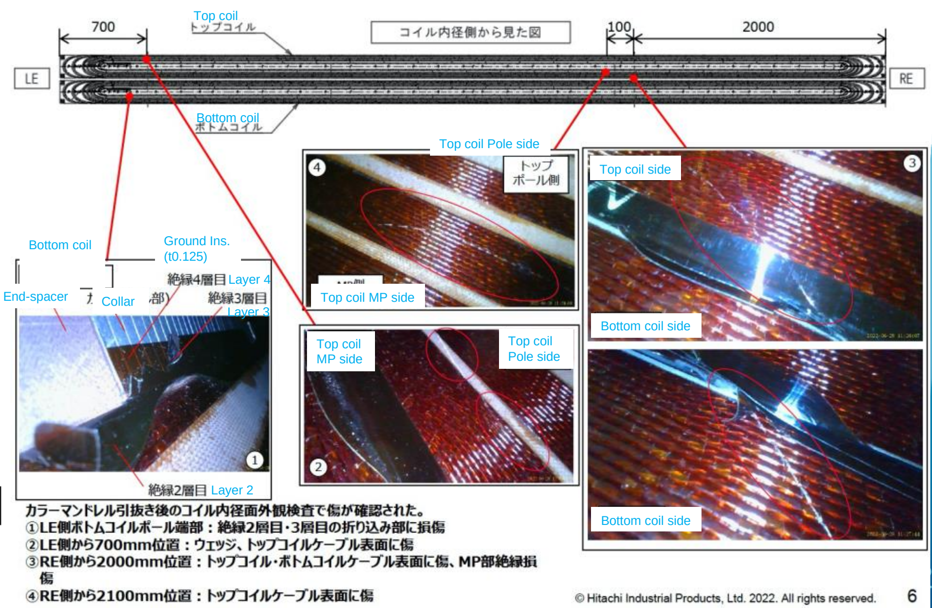
Recall Major NC in Manufacturing of MBXF5

EDMS 2753776

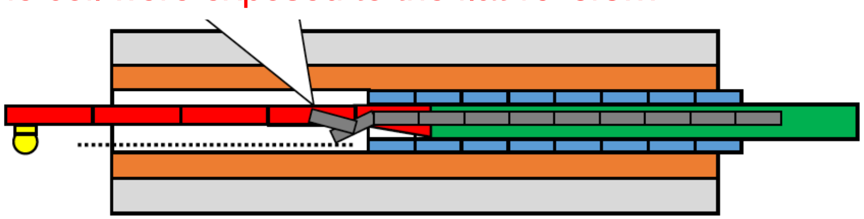
- LT-1 and LB-1 coils for MBXF5 were completed.
  - ➢ Estimated coil pre-stress: Good.
    - LB-1: L120.7 (L) & 122.9 (R), LT-1: 121.7 (L) & 122.2 (R) (unit: MPa).
    - EDMS 2724784
- All components for the magnet were already fabricated.
- Collaring and yoking processes were successfully done in June 2022.
- NC: potential coil insulation damage was found after removal of the collaring-mandrel. EDMS 2753776.
  - ➢ Investigation is underway.



Flat rollers

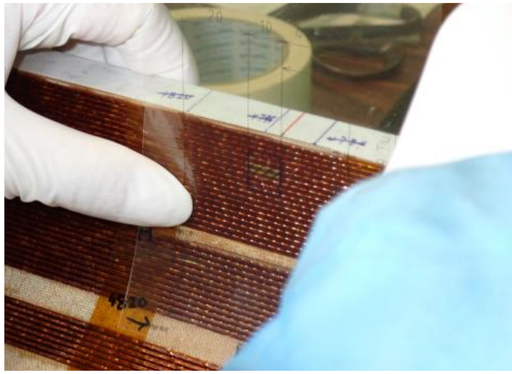


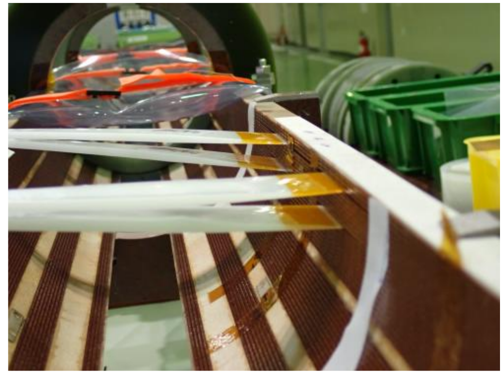
Spacers more than plan were removed from the RE side and the coil were exposed to the flat-rollers…



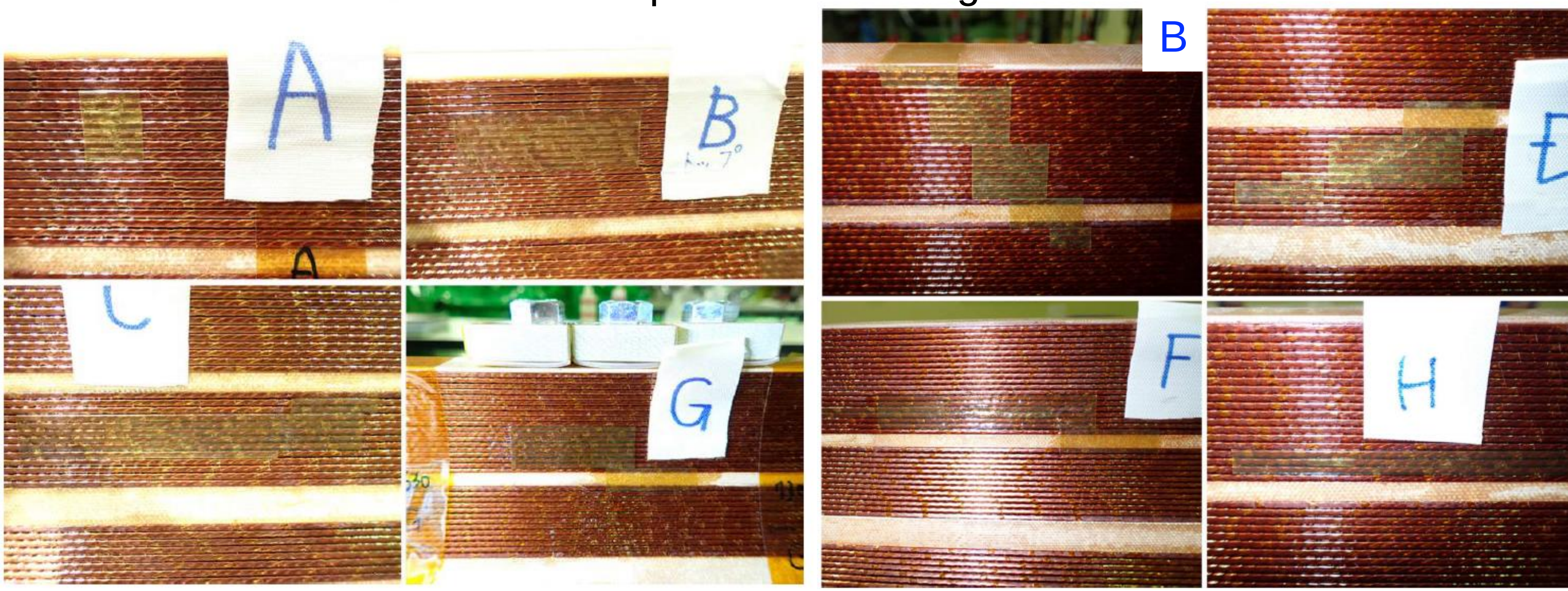
Repair of MBXF5 Coils

EDMS 2753776
Closed





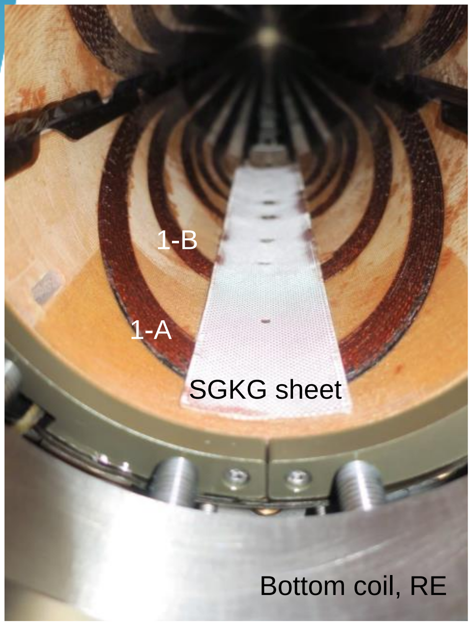
After repair of the damaged insulation



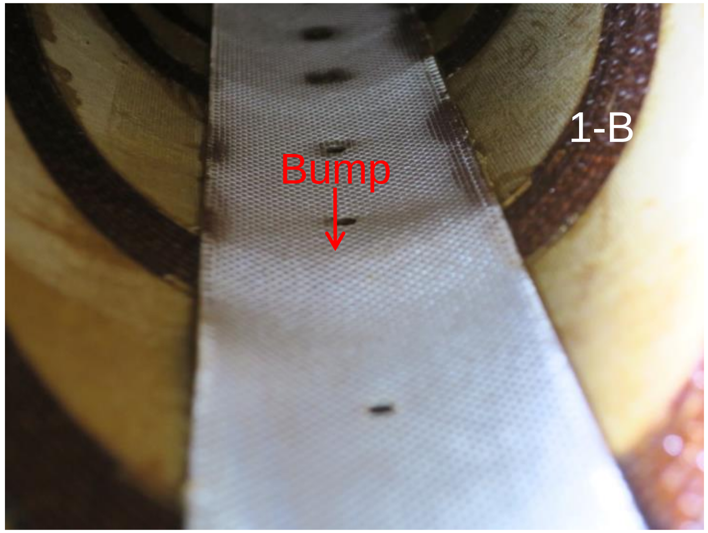
Electrical soundness of the repaired coils was validated by electrical test (coil resistance, inductance, impulse test at 1.3 kV).

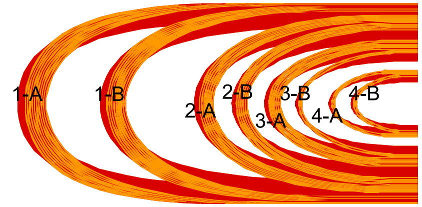
Cable deformation at coil end of MBXF1 after cold test

EDMS 2955218



Height: 1~1.5mm





ID of coil end block

Insertion of Go/No-go gage (OD: 146.2mm) was confirmed.

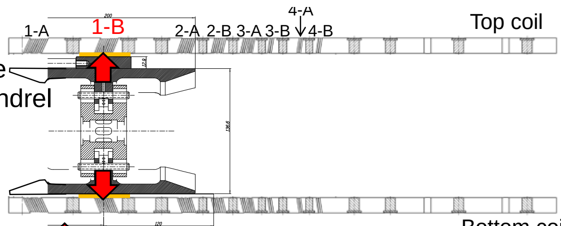
- After the cold test of MBXF1 at KEK, the inner bore of the magnet was visually inspected. As a result, cable deformation towards the coil bore was found at both coil ends, around the innermost turn of the coil block (CB)-1B.
- This cable deformation was probably caused by Lorentz force during excitation. The same issue occurred in all the 2 m-long model magnets, but no noticeable cable deformation was observed in the full-scale prototype (MBXFP1) thanks to the modification.
- There is a concern that a smaller inner coil diameter can cause trouble in the insertion work of a cold bore tube (CBT).

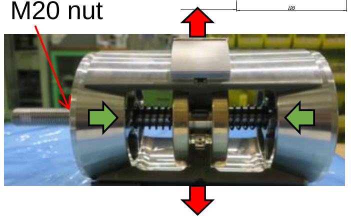
https://indico.cern.ch/event/848426/
https://indico.cern.ch/event/897298/

Repair Work

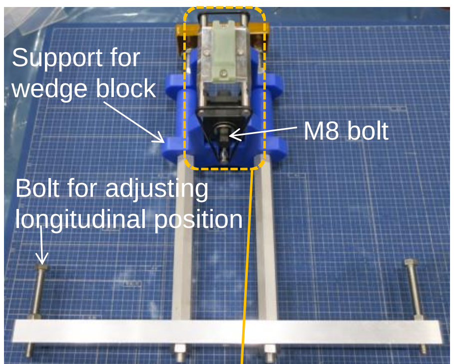
EDMS 2955218

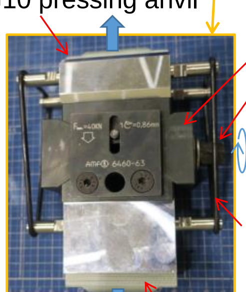
KEK is planning to place back the deformed cable mechanically.

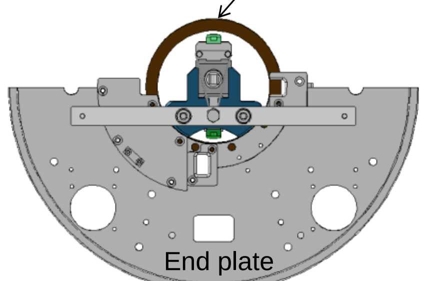




- A proof-of-principle test was conducted using a CBT welding mandrel and MBXFS2 with the cable deformation (~1 mm) per coil.
- The cable was successfully placed back and the vertical inner diameter was increased by 0.7 mm at an estimated vertical force of 22 kN.
- Electrical inspection showed no detectable change.







- New tooling developed for the repair work
  - Max. force: 40 kN
  - Stroke: 13 mm
  - Longitudinal positioning wrt end plate.
- Repair will start in this week.

Status of Construction

- MBXFP1: Delivered to CERN in April 2023. Horizontal cold test in October is planned.
- MBXF5: After a major NC with coil insulation damages, the magnet was successfully recovered and completed in June 2023. ~~The cold powering test has been suspended due to the trouble of the test facility.~~ **The powering test is anticipated in Oct. 2023.**
- MBXF1: The test result of the cold powering test looks good. The final cold mass assembly at Hitachi is underway. Delivery to CERN as the first series cold mass is anticipated in May 2024.
- MBXF2: Coil winding was already started in February 2023 and magnet assembly (yoking) is underway.
- MBXF3: Coil winding will be started in October 2023.
- MBXF4: Coil winding is planned in 2024.
- MBXF6: The deliverables in JFY2023 will be the whole parts needed for the coil winding and the magnet assembly, but NOT including the actual manufacturing work at Hitachi. The coil winding is foreseen in April/May 2024.

Summary

- Powering test of MBXF1
  - Quench performance
    - 2 quenches to $I_{nominal}$ and 7 quenches to $I_{ultimate}$
    - No quench was needed to reach $I_{ultimate}$ after the thermal cycle
    - No helium loss thanks to the system upgrades
  - Field quality
    - Comparison of the central field shows $\Delta b_{n\neq3}$ < 0.5 units and Δb_3~4 units.
    - The magnetic design in a series magnet was confirmed to be tuned well.
    - We expect almost all the harmonics will be within the requirements.
- Through the manufacturing experience of the D1 cold mass prototype (MBXFP1), the manufacturing and inspection process have been established.
  - Many lessons learnt…
- A good collaboration with Hitachi.
- Control of the coil parts (wedges, shims, end-spacers) is very crucial for the good training performance.
  - Reproducibility of coil fabrication has been confirmed.
- Non-conformities
  - Major NC of the insulation damages of MBXF5 was closed.
  - KEK and Hitachi have a mutual concern about the coil fabrication process causing the several NCs. Preventive actions have been considered and implemented.