Status of D1

Tatsushi NAKAMOTO, KEK

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

14th HL-LHC Collaboration Meeting, Genoa, Italy, Oct. 7, 2024

Acknowledgement

- KEK (in particular)

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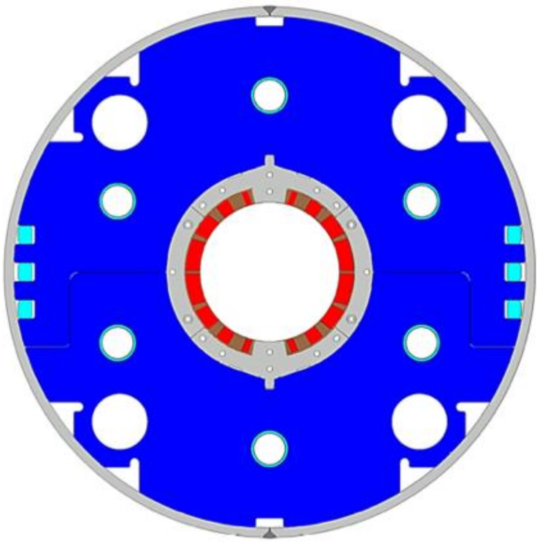
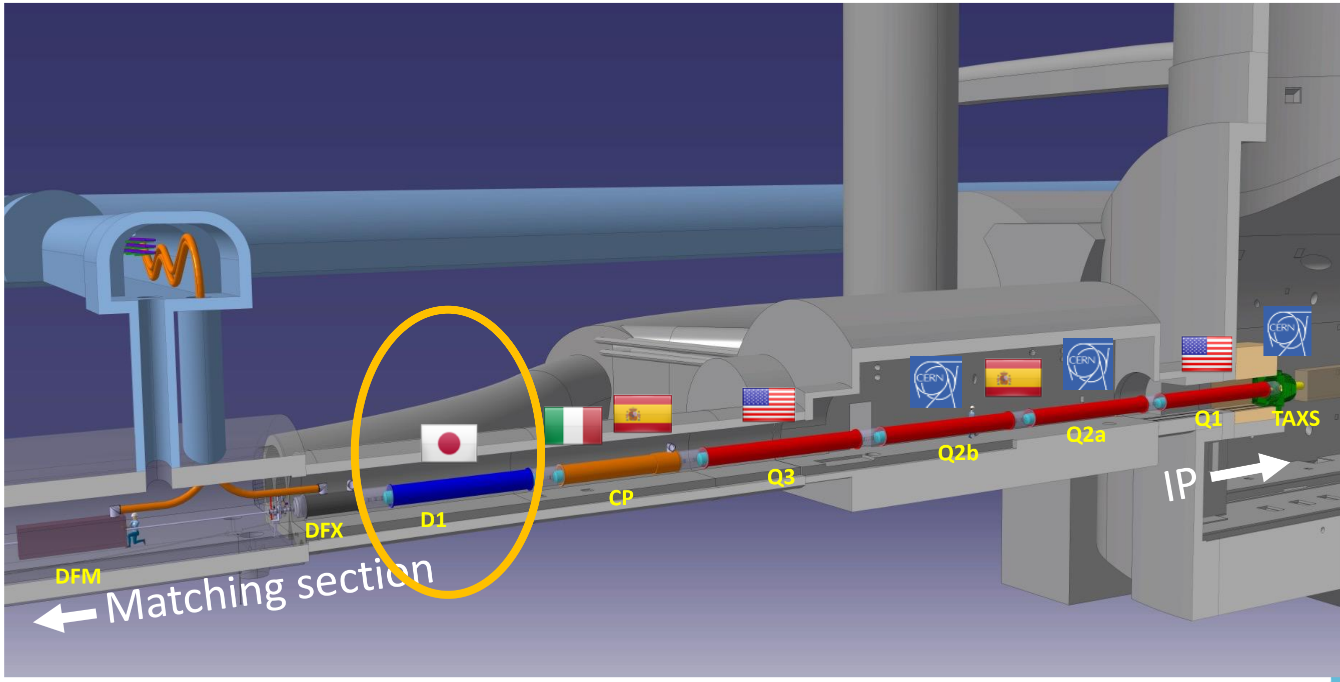
- Fusac Technologies

T. Ichihara.

Japanese Contribution to HL-LHC: D1 magnets



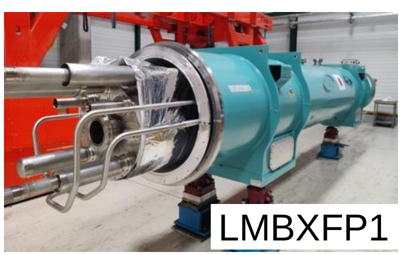


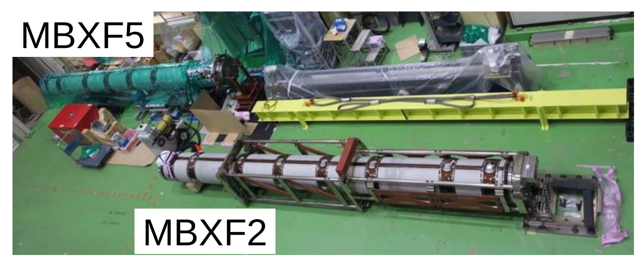
- Beam separation dipole (D1) by KEK
  - ➢ Design study of D1 for HL-LHC within the framework of the CERN-KEK collaboration since 2011.
  - ➢ 150 mm single aperture, 35 Tm (5.6 T x 6.3 m), Nb-Ti technology.
  - ➢ Development 2-m long model magnets (3 units) at KEK
- Deliverables for HL-LHC
  - ➢ *1 full-scale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

7 units x 7-m long cold masses

Current status of MBXF / LMBXF

	Prototype	Series production (in order of production sequence)					
	MBXFP1	MBXF1	MBXF5	MBXF2	MBXF3	MBXF6	MBXF4
Magnet assembly							
Cold test at KEK							
Cold mass assembly							
Delivery of completed cold-mass to KEK							
Transport to CERN							
Horizontal test at CERN							

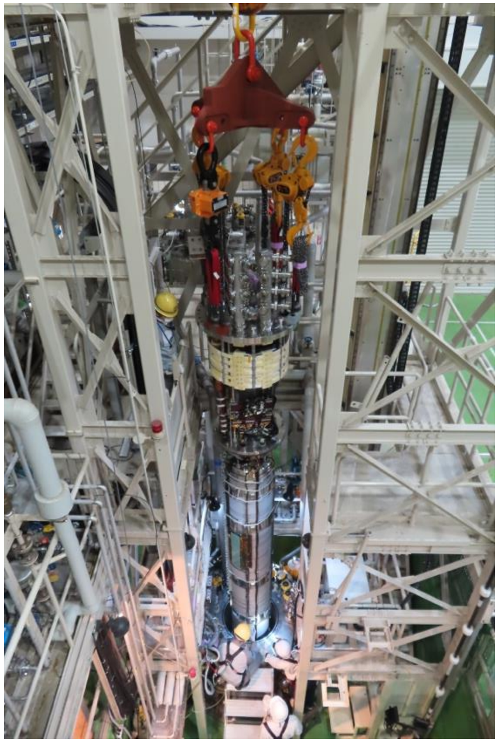




Powering test of series production magnets at KEK

Items of cold powering test at KEK

- Check of electrical integrity by a Hi-pot test at cold
- Training
  - Up to the ultimate current
  - Identification of quench start location by quench antennas
  - Training memory
  - Current-holding test at the ultimate current for 4h
- Magnetic field measurement
  - Field quality at the magnet center
  - Integrated field quality
- Joint resistance
- RRR measurement



Dual operation of refrigerators

20 m long LHe transfer line connecting #2 and #4 systems.

#4 Refrigerator/Liquefier for Test Stand

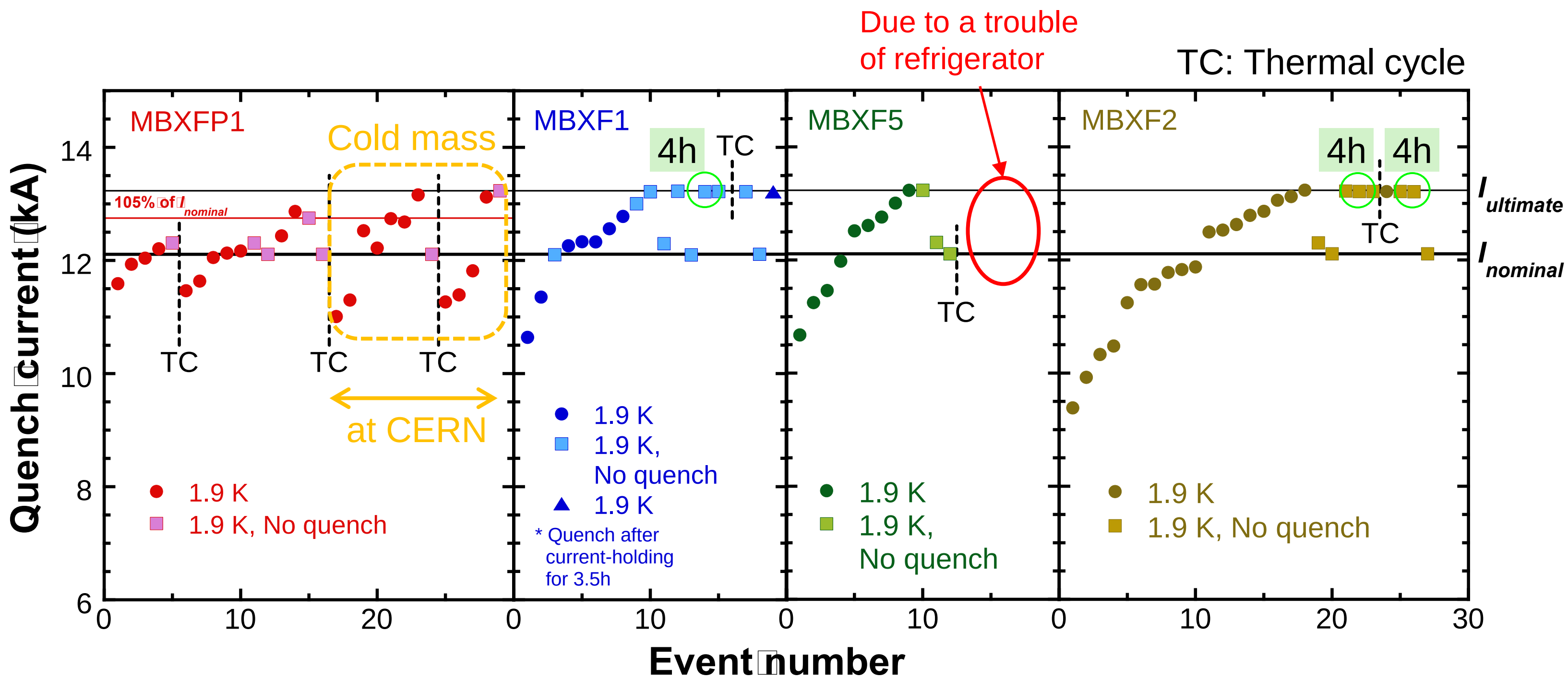
- **180 L/h, 2400 L dewar**
- **Manufactured by Teisan/Air Liquide in 1987**
- **New cold box in 2007**

#2 Liquefier (Primary)

- **400 L/h, 5000 L dewar**
- **LINDE LR280 in 2014**
- **Mandatory to supply LHe to users at KEK.**

- During CD1 of MBXF5, we had a trouble with the warm turbine of #4 refrigerator.
  - ✓ **CD2 of MBXF5 after TC was postponed.**
- Cooling test of dual operation of the #4 refrigerator and #2 liquefier was conducted in April 2024. Sufficient total liquefaction ability of 490 L/h was confirmed.
- Cooling down of MBXF2 was performed with such a dual operation.

Training Quenches



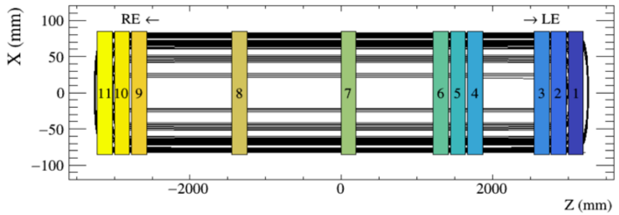
Number of quenches

	1st cycle		2nd cycle	
	Nominal	Ultimate	Nominal	Ultimate
MBXFP1	3	–	3	–
MBXF1	2	7	0	0
MBXF5	4	9	TBC	TBC
MBXF2	10	18	0	1

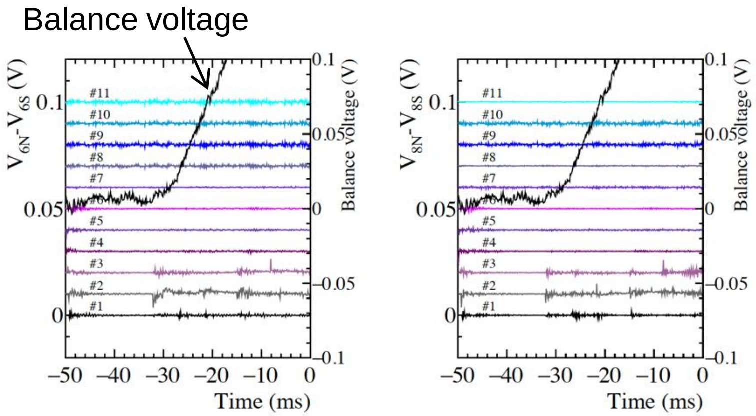
- All series magnets reached the ultimate current.
- The 2nd cycle for MBXF5 was postponed due to malfunction of the test facility of KEK.
- Good training memory in MBXF1 and MBXF2.
- Successful current-holding for 4h at the ultimate.
  → Stable operation of the magnets

Acceptable training performance

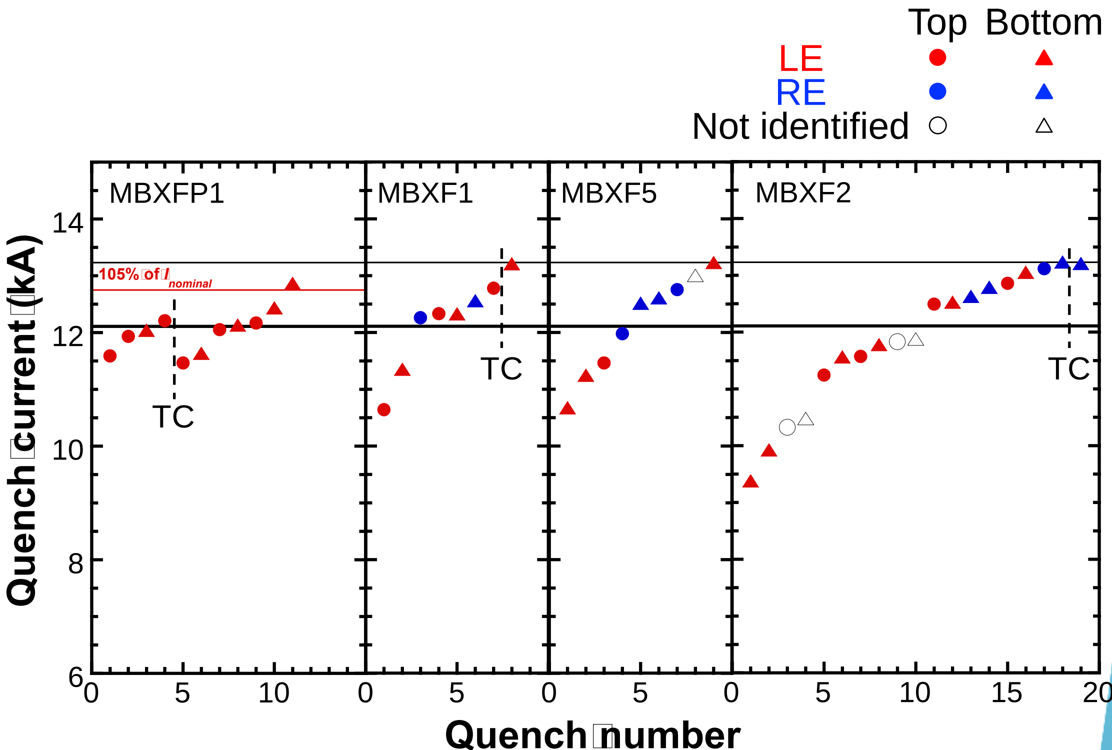
Quench start locations



Arrangement of quench antennas

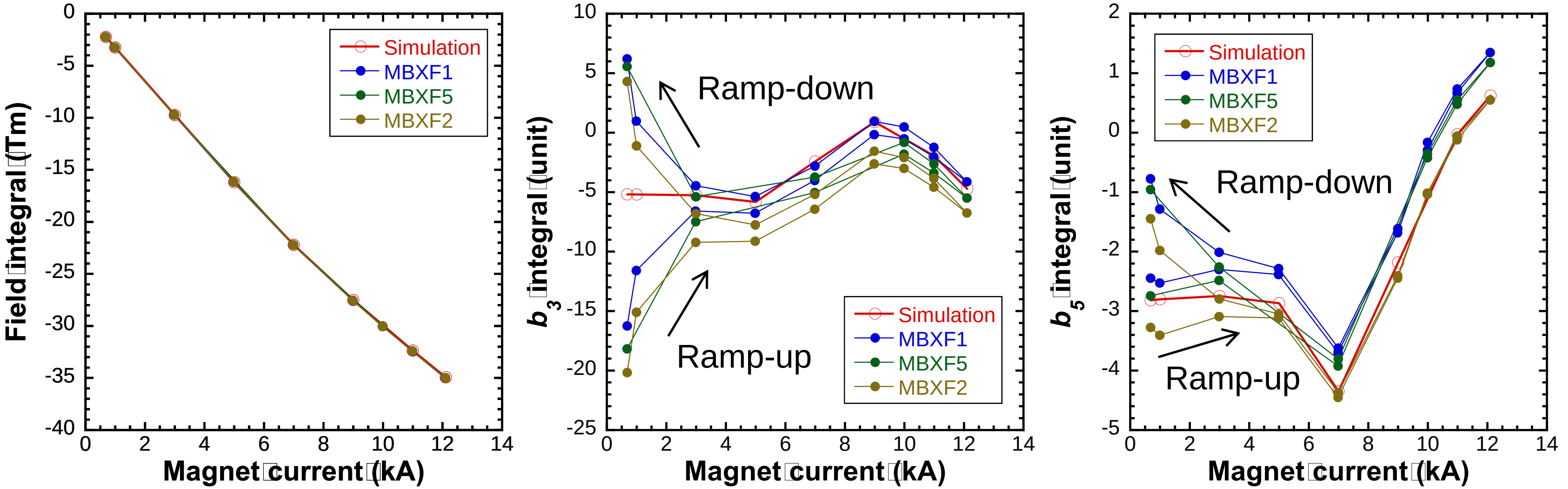


Signals detected by quench antennas



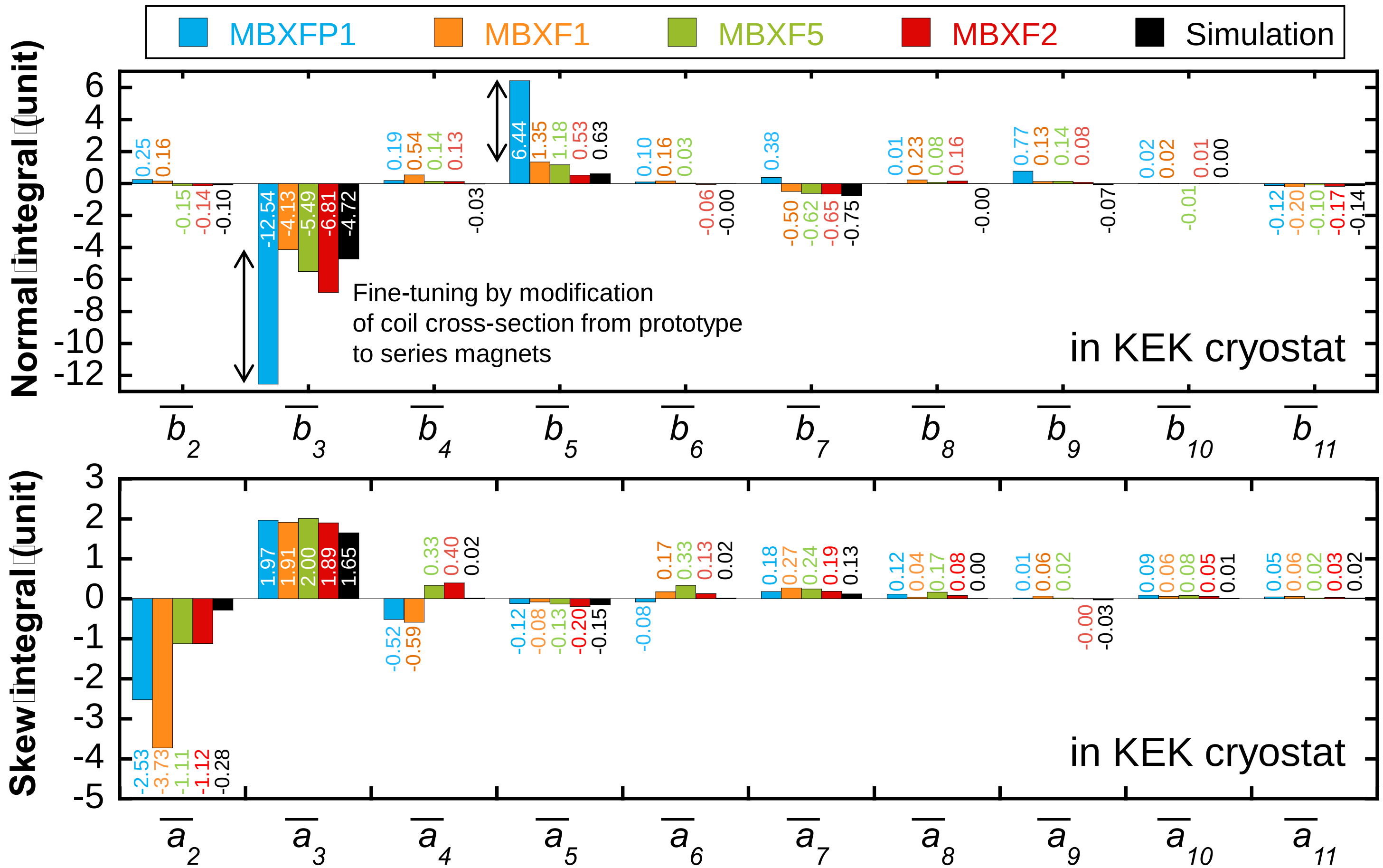
- Quench start locations were changed during the training. → No weak point.
- All quenches at a low current took place at LE, which is a common nature of MBXF.

Current dependence of integrated multipoles



- The field quality of series production magnets is predictable by OPERA 3D simulations.

Integrated multipoles at the nominal current (I=12.11 kA)

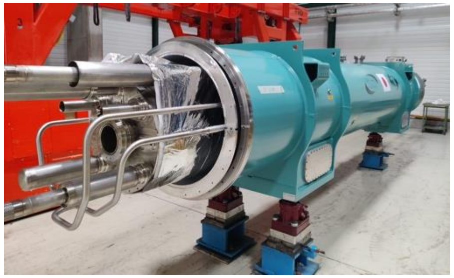


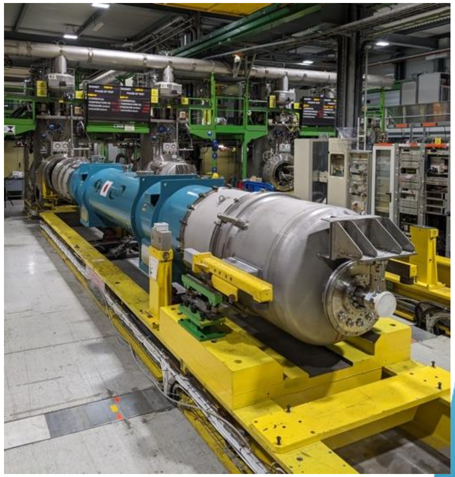
- Good reproducibility in integrated field quality among the series production magnets.

Powering test of prototype at SM18

Horizontal powering test of LMBXFP1 at CERN

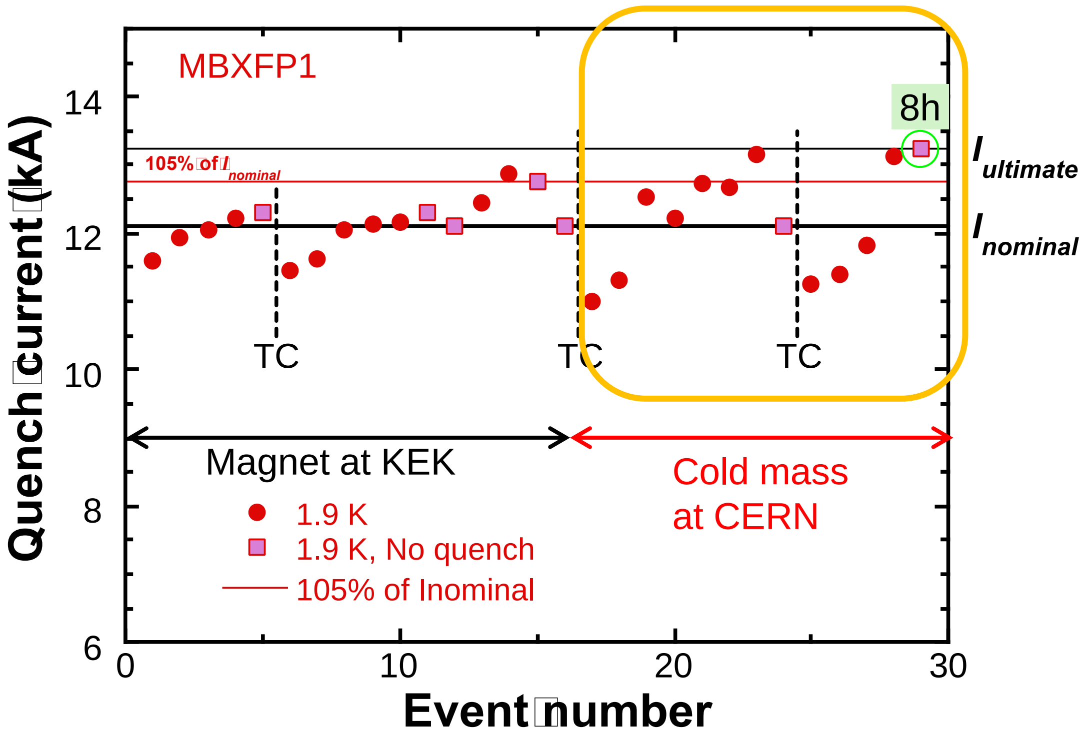
- MBXFP1 cold mass (LMBXFP1) was assembled into a cryostat at CERN.
- The first powering test for MBXF cold mass with a horizontal cryostat.
- The items to be checked in the horizontal test.
  - Training memory for the cold mass including newly designed bus leads.
  - Field quality including the influence of the magnetic LHC cryostat.
  - Long-time operation: current-holding test at the ultimate for 8 hours.
  - Endurance test: 500 powering cycles between 1 kA and 12.11 kA.

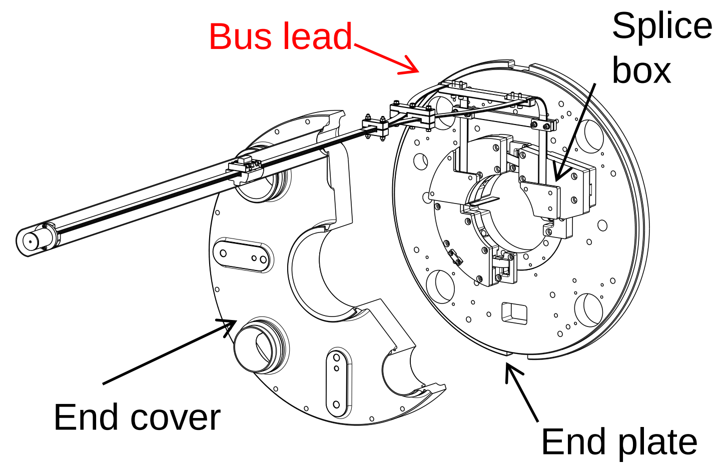




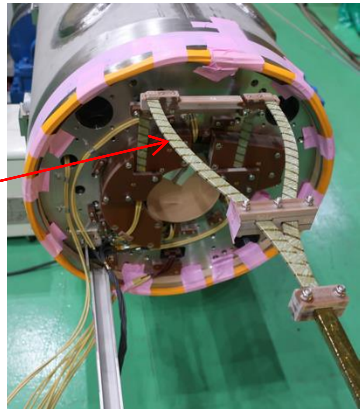
G. Willering, Gaëlle Ninet, Franco Mangiarotti, Piotr Rogacki, Lucio Fiscarelli
https://indico.cern.ch/event/1379959/
EDMS 3015584

Training Quenches of LMBXFP1





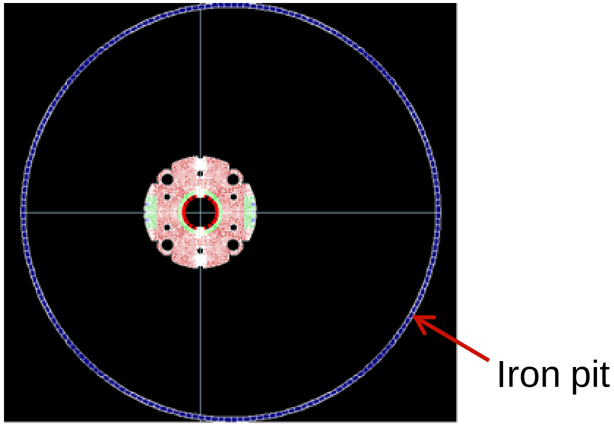
Bus lead



- The quench current reached the ultimate current in the second cycle.
- Current-holding at the ultimate current for 8h was also successful.
- 500 powering cycles between 1 kA and 12.11 kA could be stably completed.
  → The bus leads newly designed by KEK was validated.
- Training memory should be checked in the series production magnets.

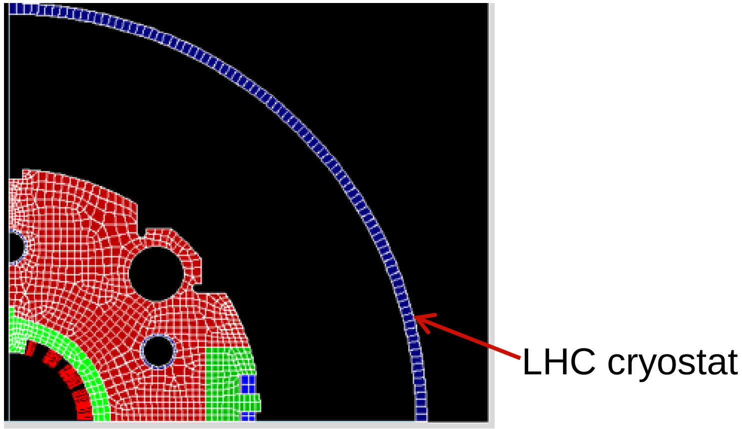
Magnetic design considering an effect of LHC cryostat

Test at KEK



- Vertical SS cryostat at KEK
- Iron pit surrounding the cryostat
- The magnet is off-centered by 150 mm

Test at CERN



- LHC cryostat made of magnetic iron
- The off-center of the magnet with respect to the cryostat is neglected.

- The effect of the LHC cryostat made of magnetic iron was considered in the magnetic design.
- The magnet cross-section was optimized so that the field quality was controlled within the target after the cold mass was assembled into the LHC cryostat.
- Offset estimated from OPERA 3D simulation: Δb_3=+6.1 units, Δb_5=+0.3 units
- The validity of this design strategy was checked in LMBXFP1 for the first time.

Field quality at the nominal current of LMBXFP1

Measurement by KEK KEK cryostat (MBXFP1)			Measurement by CERN LHC cryostat (LMBXFP1)		
Field integral (B_1)		34.935 Tm	Field integral (B_1)		35.188 Tm
n	b_n integral (unit)	a_n integral (unit)	n	b_n integral (unit)	a_n integral (unit)
2	0.25	-2.52	2	0.27	0.88
3	-12.54	1.96	3	-5.44	1.95
4	0.19	-0.52	4	0.05	0.12
5	6.43	-0.12	5	6.68	-0.19
6	0.10	-0.08	6	0.05	0.00
7	0.38	0.18	7	0.35	0.20
8	0.01	0.11	8	0.04	0.15
9	0.77	0.01	9	0.76	0.00
10	0.02	0.09	10	0.04	0.10
11	-0.12	0.05	11	-0.13	0.07
12	-0.02	0.02	12	0.03	0.03
13	-0.76	0.00	13	-0.73	0.05
14	-0.08	-0.06	14	0.00	0.00
15	-1.22	-0.01	15	-1.18	0.03

Note that the cross-section of LMBXFP1 was not fully optimized.
Fine-tuning has been applied to the series production magnets.

Shift of b_n by the LHC cryostat

Integrated b_3

Simulation: +6.1uits
Measurement: +7.1units

Integrated b_5

Simulation: +0.27uits
Measurement: +0.25units

The field quality of LMBXF cold mass with the LHC cryostat can be well predicted from the field quality of the magnet measured at KEK.

The proposed magnetic design is valid.

Prediction of integrals of b_3 and b_5 for series production cold mass with LHC cryostat

At the nominal current

b_3 integral (unit)	Measurement by KEK with KEK cryostat	Prediction for cold mass with LHC cryostat	Acceptance criteria
MBXF1	-4.13	**1.97**	b_3 integral <±2.9 units
MBXF5	-5.49	**+0.61**	
MBXF2	-6.81	**-0.71**	

Δb_3=+6.1 units

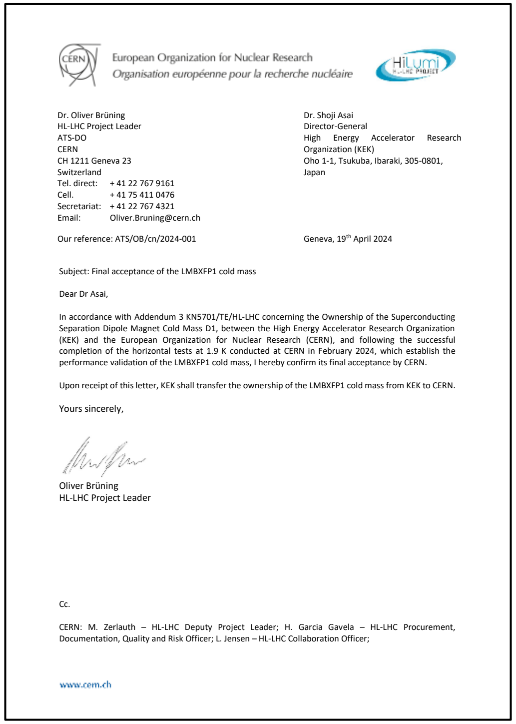
b_5 integral (unit)	Measurement by KEK with KEK cryostat	Prediction for cold mass with LHC cryostat	Acceptance criteria
MBXF1	1.35	**1.62**	b_3 integral <±1.5 units
MBXF5	1.18	**1.45**	
MBXF2	0.53	**0.80**	

Δb_5=+0.27 units

- **The field quality can be expected within the acceptance criteria for the series production cold masses with the LHC cryostat.**

Status of Series Production and Tests

- LMBXFP1
  - Horizontal powering test at CERN was completed.
  - The cold mass was accepted by CERN.
  - Installation to IT String will be started within 2024.
- LMBXF1
  - The cold mass was completed and delivered to KEK at March 2024.
  - The issue of the tendering of shipping was resolved. The cold mass is expected to be delivered to CERN in early December.
- MBXF5
  - The trouble of a the refrigerator forced to stop the cold test (CD2) after T.C.
  - Plan of CD2 in early 2025, after the cold test of MBXF3.
- MBXF2
  - Final assembly of the cold mass is underway at Hitachi.
  - Completion will be in April 2025.
- MBXF3
  - The magnet was nearly completed in August, but the delivery to KEK has been delayed due to the NC (cut of voltage tap wires).
  - Delivery to KEK will be on Oct. 28 and cooling will be started in 2 weeks.
- MBXF6
  - Two coils (LT-5, LB-5) were already wound but the collaring will be only possible in December due to an issue of resources in Hitachi.
- MBXF4
  - Coil winding is planned in December 2024.



European Organization for Nuclear Research
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Japan

Our reference: ATS/OB/cn/2024-001

Geneva, 19th April 2024

Subject: Final acceptance of the LMBXFP1 cold mass

Dear Dr Asai,

In accordance with Addendum 3 KN5701/TE/HL-LHC concerning the Ownership of the Superconducting Separation Dipole Magnet Cold Mass D1, between the High Energy Accelerator Research Organization (KEK) and the European Organization for Nuclear Research (CERN), and following the successful completion of the horizontal tests at 1.9 K conducted at CERN in February 2024, which establish the performance validation of the LMBXFP1 cold mass, I hereby confirm its final acceptance by CERN.

Upon receipt of this letter, KEK shall transfer the ownership of the LMBXFP1 cold mass from KEK to CERN.

Yours sincerely,

Oliver Brüning
HL-LHC Project Leader

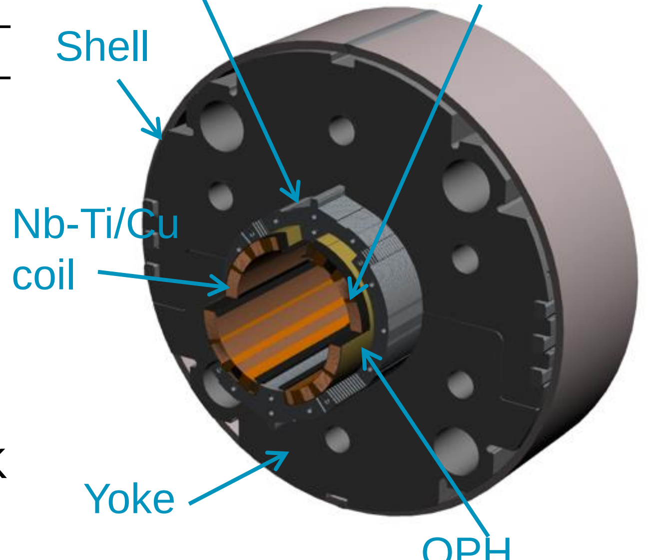
Cc.

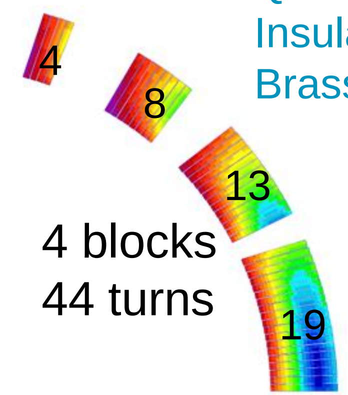
CERN: M. Zerlauth – HL-LHC Deputy Project Leader; H. Garcia Gavela – HL-LHC Procurement, Documentation, Quality and Risk Officer; L. Jensen – HL-LHC Collaboration Officer;

www.cern.ch

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.