Test result of MBXF2 in CD1

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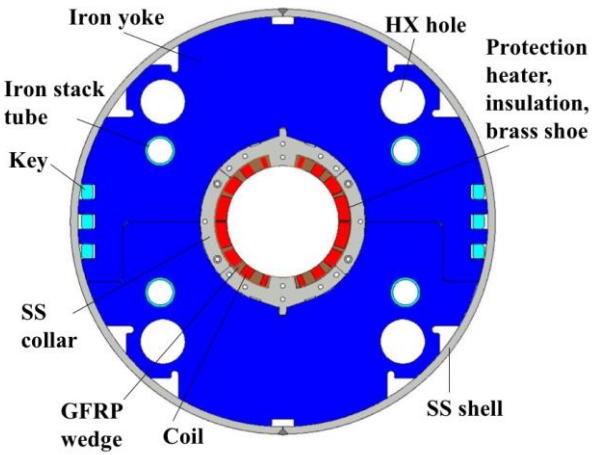
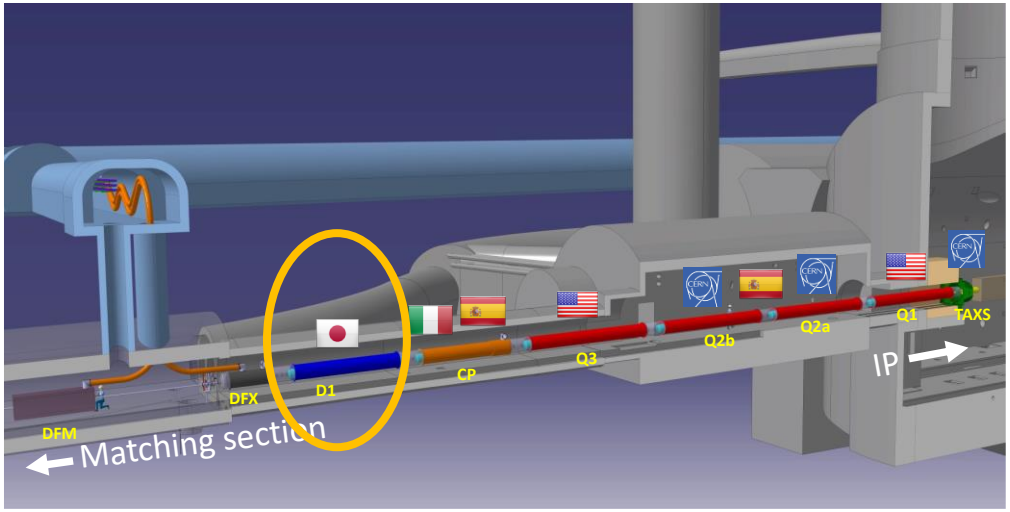
KEK

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

WP3 meeting, 5 June 2024

Japanese contribution to HL-LHC: D1 magnets



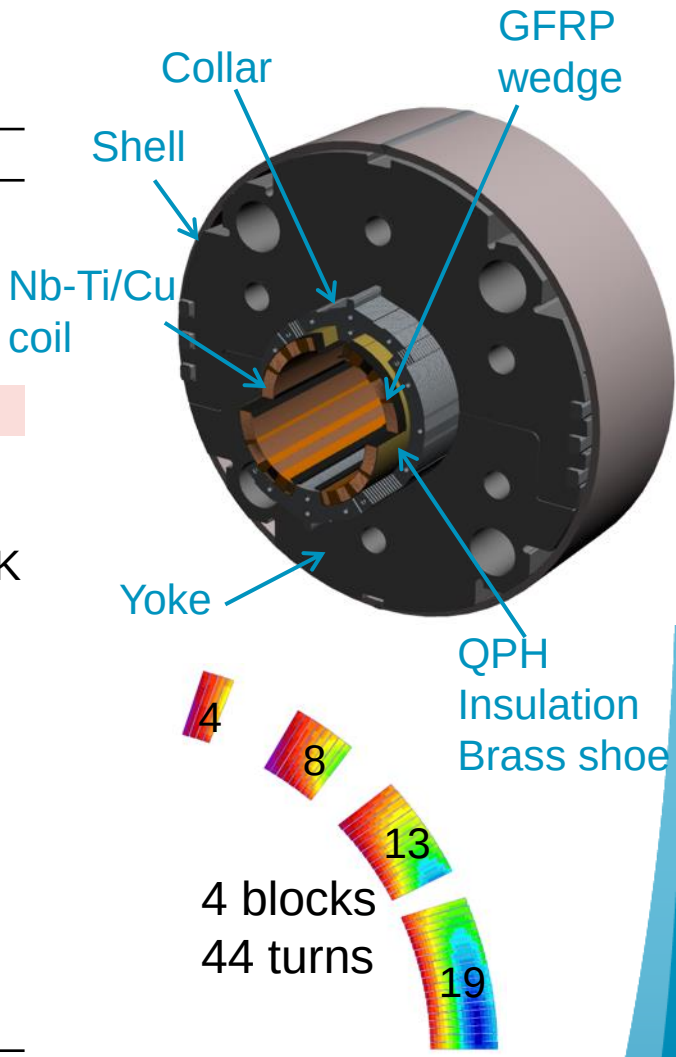


- Beam separation dipole (D1) by KEK
  - Design study of D1 for HL-LHC within the framework of the CERN-KEK collaboration since 2011.
  - 150 mm single aperture, 35 Tm (5.6 T x 6.3 m), Nb-Ti technology.
  - Development of 2-m long model magnets (3 units) at KEK
- Deliverables for HL-LHC
  - 1 full-scale 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/cm³ (Coil peak)**
Radiation dose	**> 25 MGy**

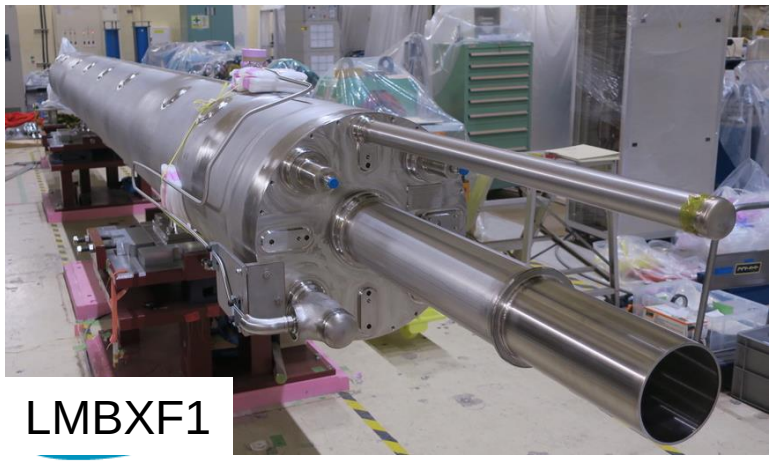


Large-aperture single layer coil

→ Mechanical support of a coil is challenging

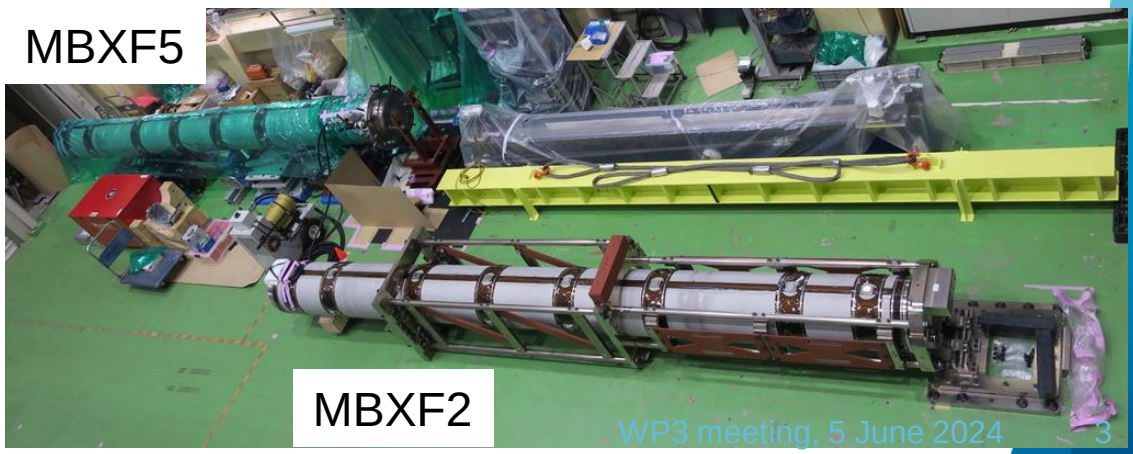
Current status of each series production magnet

- 1. MBXF1
  - Cold mass was completed and transported to KEK in March, 2024.
  - A shipping company to be determined by bidding in July. We expect the cold mass will be delivered to CERN in September.
- 2. MBXF5
  - Test result of CD1 was reported in WP3 meeting on Nov 8th, 2023.
  - CD2 was postponed due to the malfunction of the He refrigerator in KEK.
- 3. MBXF2
  - Test result of CD1 is reported in this slide.
- 4. MBXF3
  - The magnet assembly in Hitachi is almost completed. The magnet will be delivered to KEK in August.



LMBXF1

MBXF5



MBXF2

Test program of MBXF2 in CD1

- Period: May 7th – 31st

- Hi-pot test at NOC
- System check
- Training
  - Up to the ultimate current (13.231 kA)
- Magnetic field measurement
  - z-scan to evaluate field integral
  - DC-loop at the magnet center
- Other items
  - Current holding test for 4h at the ultimate
  - Fast ramp test at ±30 A/s
  - Measurement of 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**

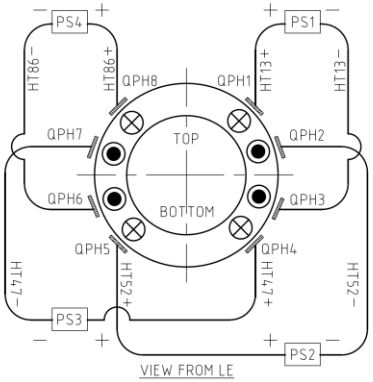
#2 Liquefier (Primary)

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

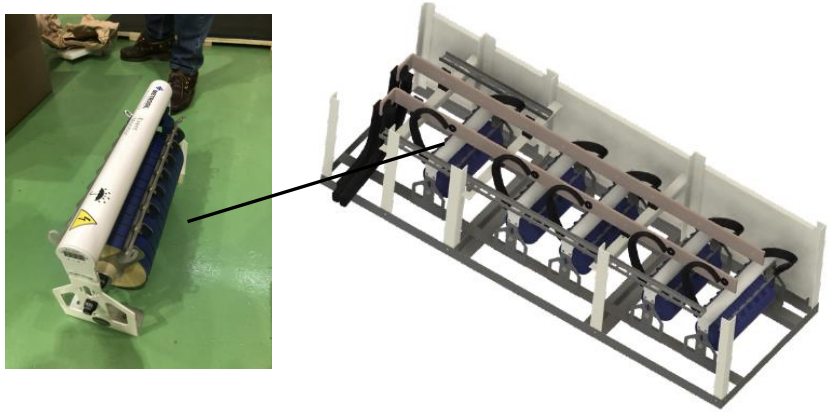
- During CD1 of MBXF5, we had trouble with the warm turbine of #4 refrigerator.
- Cooling test of dual operation of the #4 refrigerator and #2 liquefier was conducted before this magnet test. Sufficient total liquefaction ability of 490 L/h was confirmed.
- MBXF2 could be cooled down to 1.9 K with such a dual operation.

Quench protection

- Quench detection
  - Voltage threshold: 0.1 V, detection time: 10 msec
- Quench protection heaters
  - 2 strips x 4 circuits
- Varistor (Metrosil)
  - 3 kA x 5 units
  - Validated in cold test of MBXF1
  - Healthiness is monitored by the Rogowski coils



QPH



Varistor

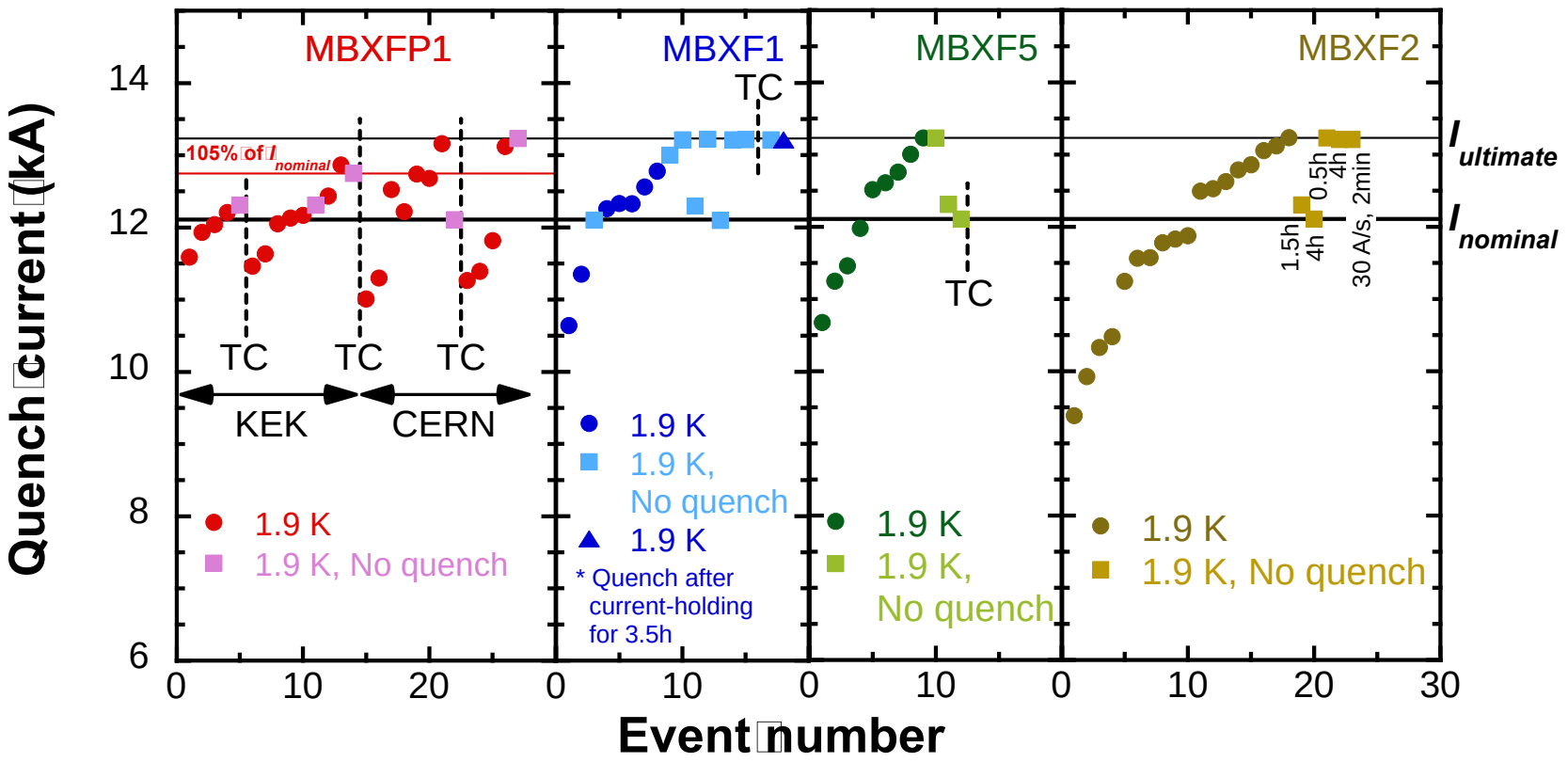
Hi-pot test, system check

- Hi-pot test at NOC
  - Criterion: Leak current < 10 μA
  - Coil – GND: 1.3 kV, 30sec
  - QPH – GND: 2.3 kV, 30sec
  - Between QPH strips: 2.3 kV, 30sec

    → Passed

- System check
  - The soundness of varistors was confirmed by signals from Rogowski coils in shutdown test and training quench at any current.

Training



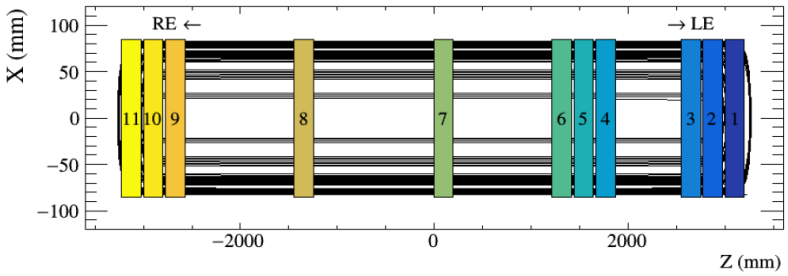
- Relatively long training in MBXF2
  - 10 quenches to the nominal current
  - 18 quenched to the ultimate current
  - Quench current never decreased during training.
- The current holding test at the ultimate current for 4h was successful.
- Fast ramp test with ±30 A/s was also done.
- Training memory will be checked in CD2.

Quench start location

Red: Successful localization

Run No.	Quench number	Quench current (A)	Top/ Bottom coil	Long. position	Quench antenna
013	1	9383	B	LE	1, 2, **3**
014	2	9925	B	LE	1, 2, 3
015	3	10327	T		1, 2, 3, 4, 5, 6
016	4	10480	B		1, 2, 3, 4, 5, 6, 7, 8
019	5	11243	T	LE	1, 2, 3
020	6	11563	B	LE	**2**
021	7	11572	T	LE	**2**, 3
022	8	11780	B	LE	1, **2**, 3, 4, 5
023	9	11832	T		1, 2, 3, 4, 5, 6, 7
024	10	11878	B		1, 2, 3, 4, 5, 6, 7
025	11	12493	T	LE	1, **2**, 3
026	12	12529	B	LE	1, **2**, 3
027	13	12628	B	RE	9, 10, **11**
028	14	12790	B	RE	9, 10, **11**
029	15	12860	T	LE	**1**, 2, 3
030	16	13054	B	LE	1, **2**, 3
031	17	13119	T	RE	**11**
032	18	13234	B	RE	**11**

- The coil at which quench initiated changed almost alternately.
- Training started with quenches at LE which is a common nature of D1 magnet.
- The last quench occurred a few seconds after the ultimate current was reached.
- A voltage spike appeared at the onset of a balance voltage at quenches at high current, suggesting wire motion.

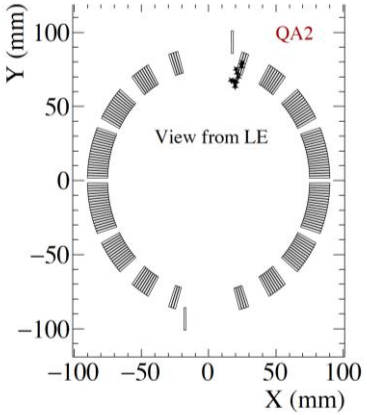


Quench antenna analysis

Successful case

Run No.021

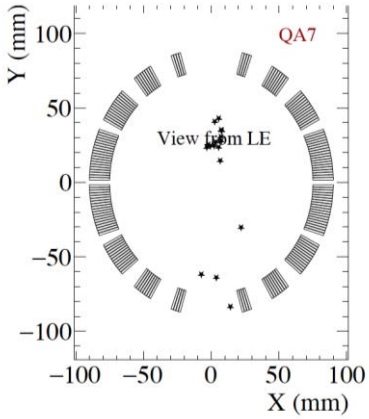
Quench occurred at QA2.



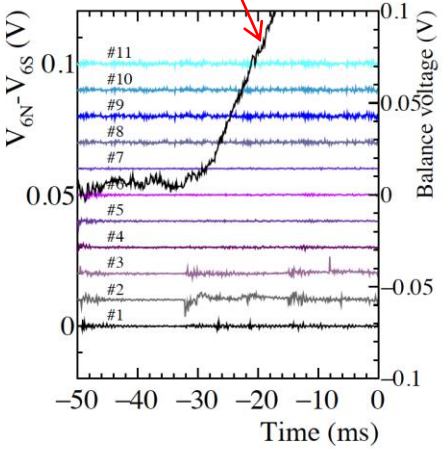
Failed case

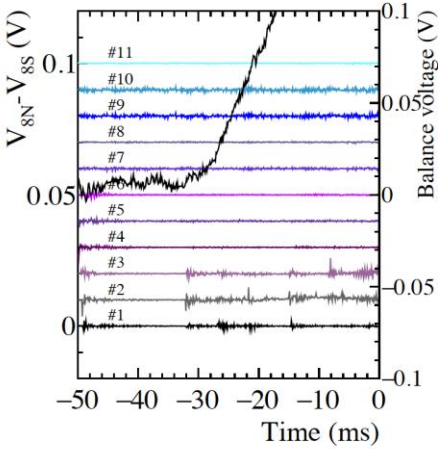
Run No.016

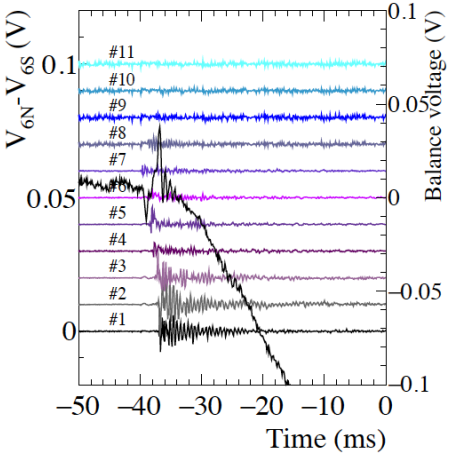
Many QAs detected signals even in SS.

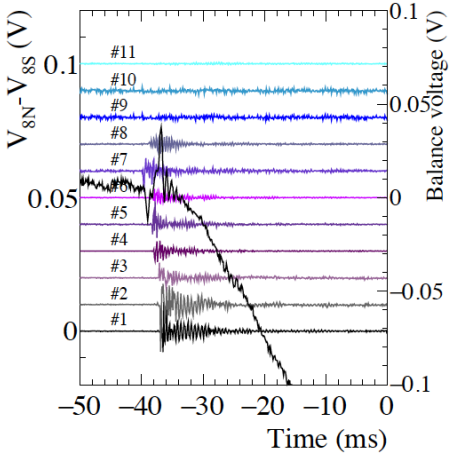


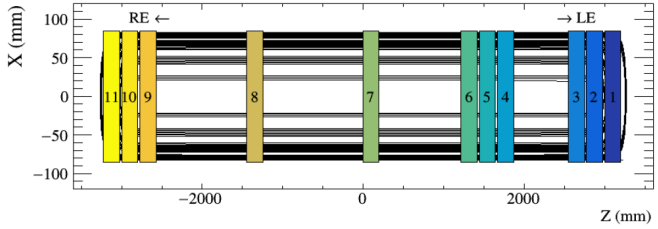
Balance voltage



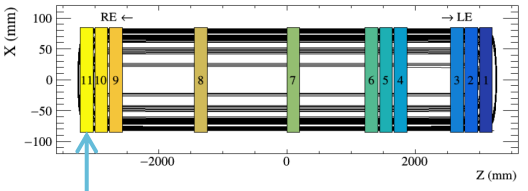


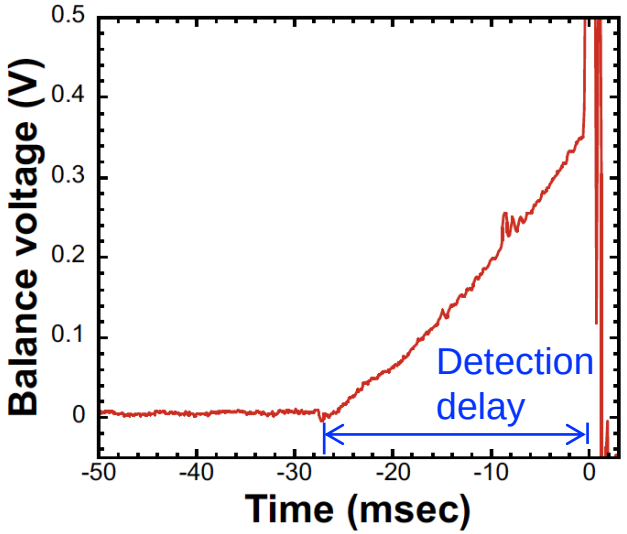


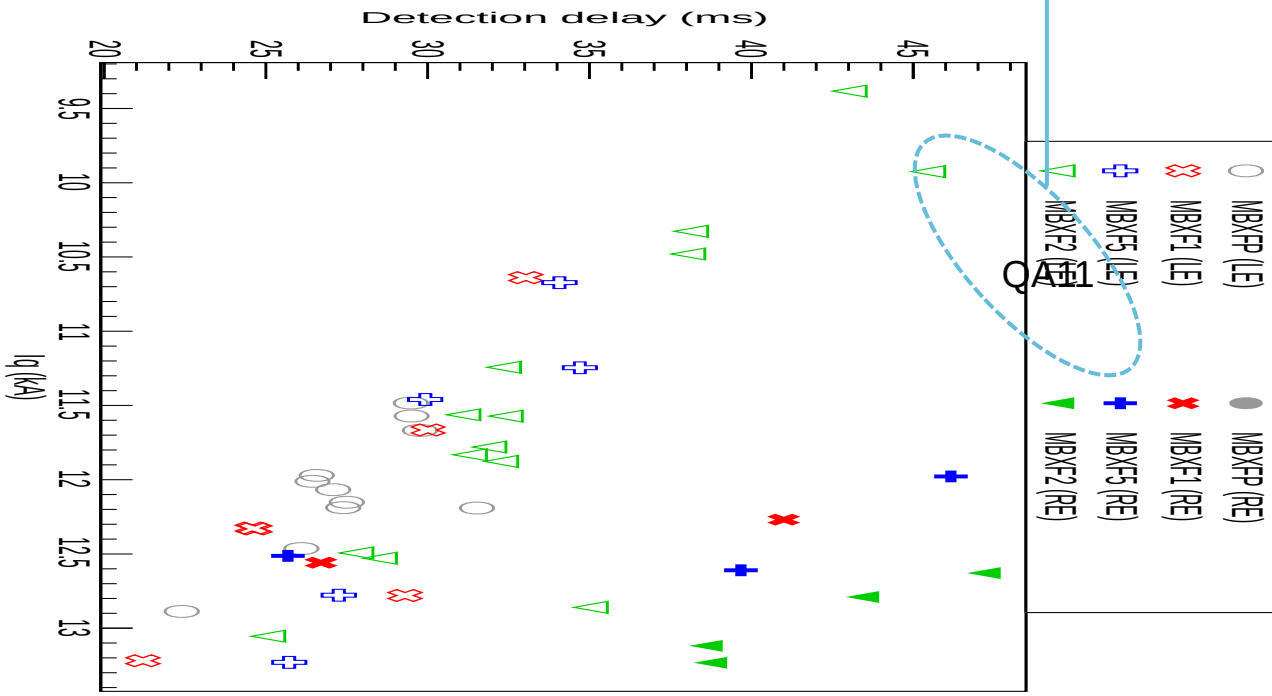




Iq vs Detection delay



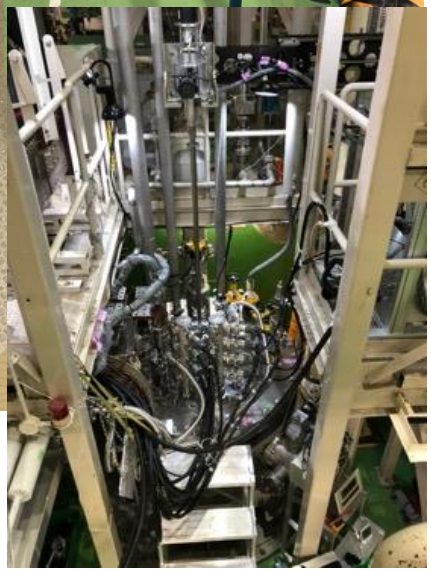




- In any magnets, training started from the LE side
- The first RE-side quench emerged in the latter part of training with a detection delay of ~40ms.
- Longer detection delay in quenches at RE would be due to quench start location in the low field region.

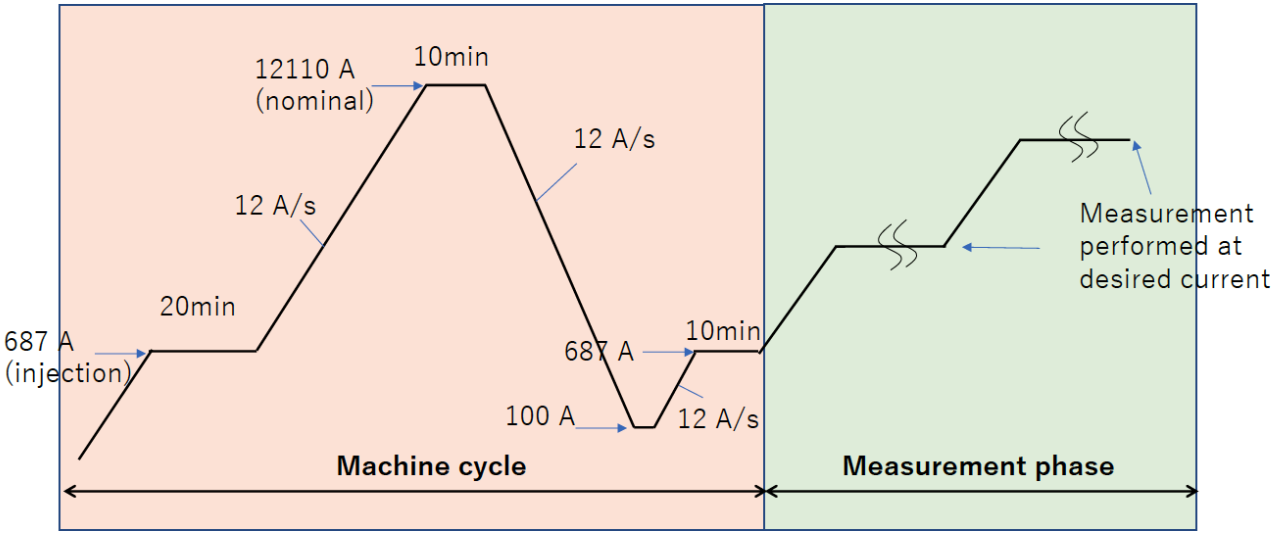
Vertical magnetic field measurement system

- Field quality of MBXF5 at room temperature / 1.9 K using the KEK's vertical measurement system
  - Rotating coil (PCB):
    - 3 sets of radial coils
    - Long coils (500 mm) for integral measurement
    - Short coils (50 mm) for fine search
  - Scanning capability
    - Stepping motor and Magnescale®
    - 10-m-shaft to cover the full-length of the magnet

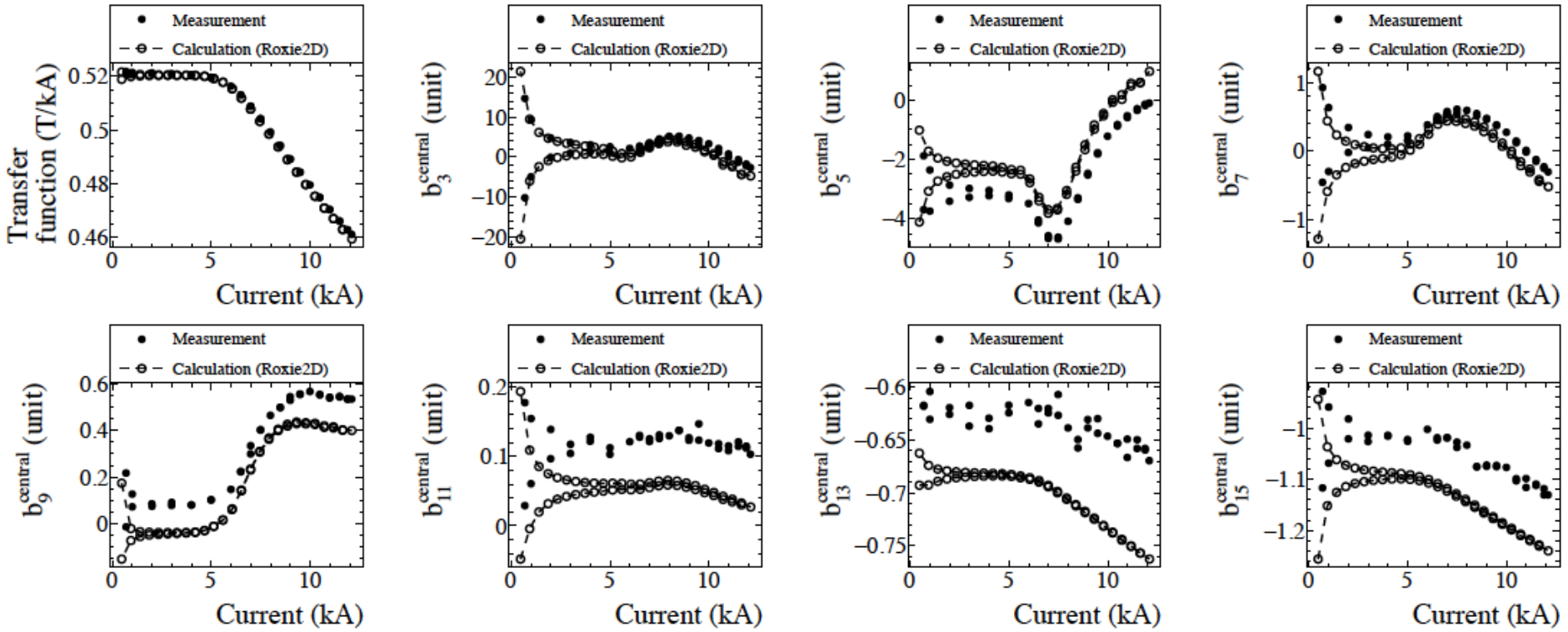


Measured Items

- Z-scan
  - Warm, before cooling
  - ***I*** =3 kA, before training
  - ***I*** = [687, 1k, 3k, 5k, 7k, 9k, 10k, 11k, 12.11k, 11k, 10k, 9k, 7k, 5k, 3k,1k, 687] A, after training and machine cycle (see below)
- DC loop at 1.9 K
  - Rotating coil position is fixed at the magnet center (z=0)

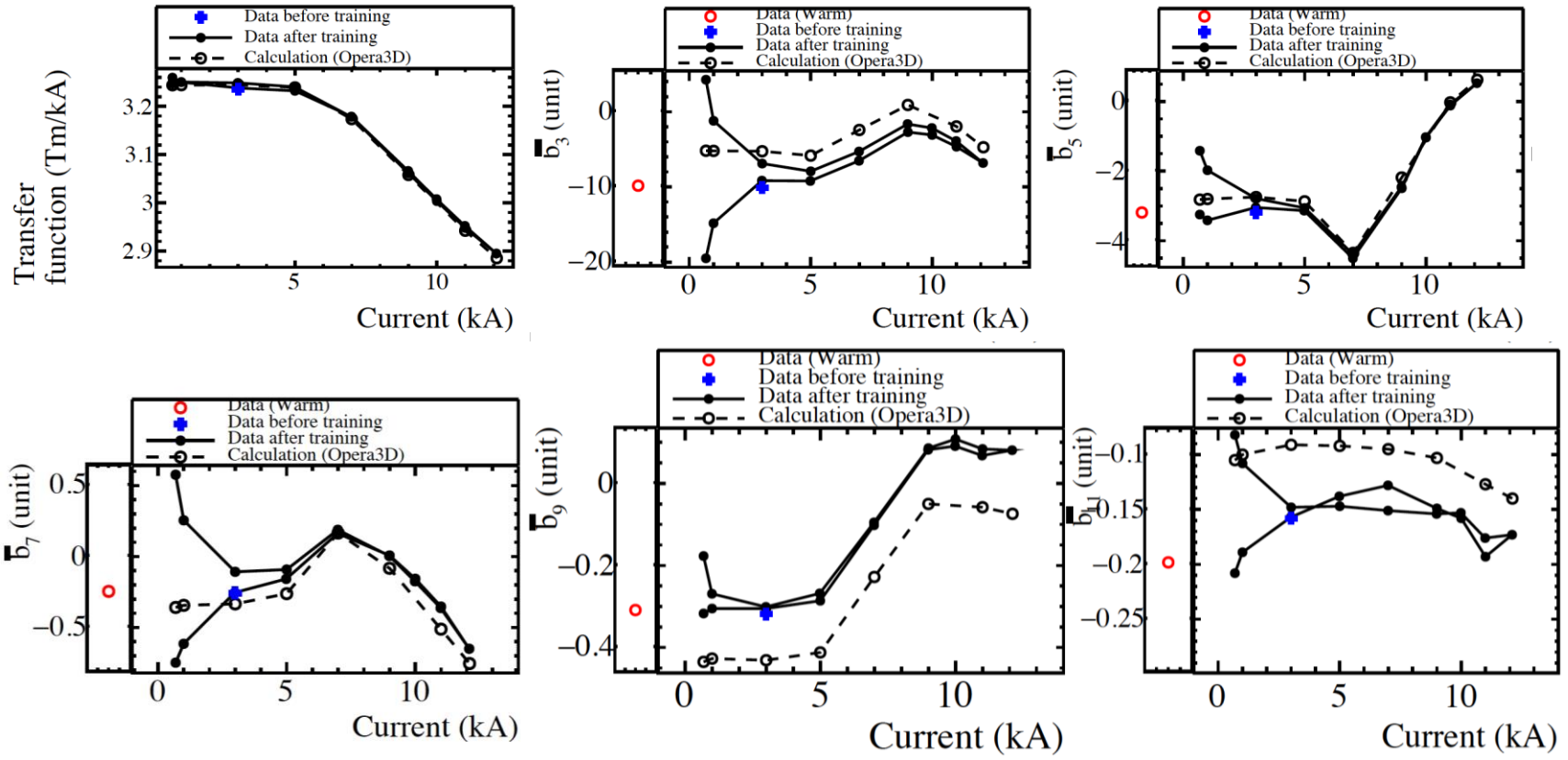


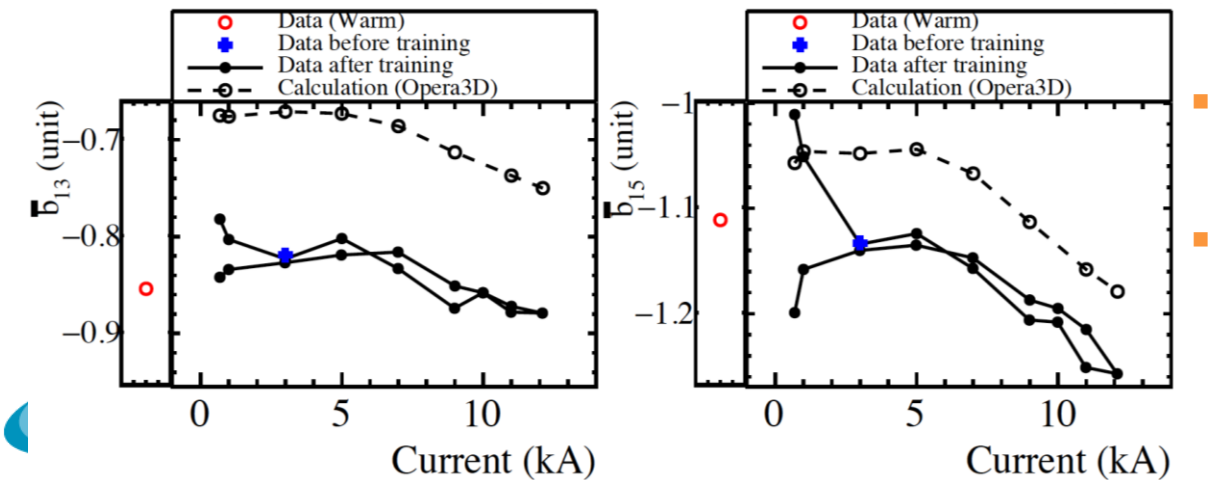
DC loop – comparison with calc.



- Central field quality was measured by the long coil (L=500) positioned at the longitudinal magnet center (z=0)
- Measured curves are reproducible by the calc. (Roxie2D)

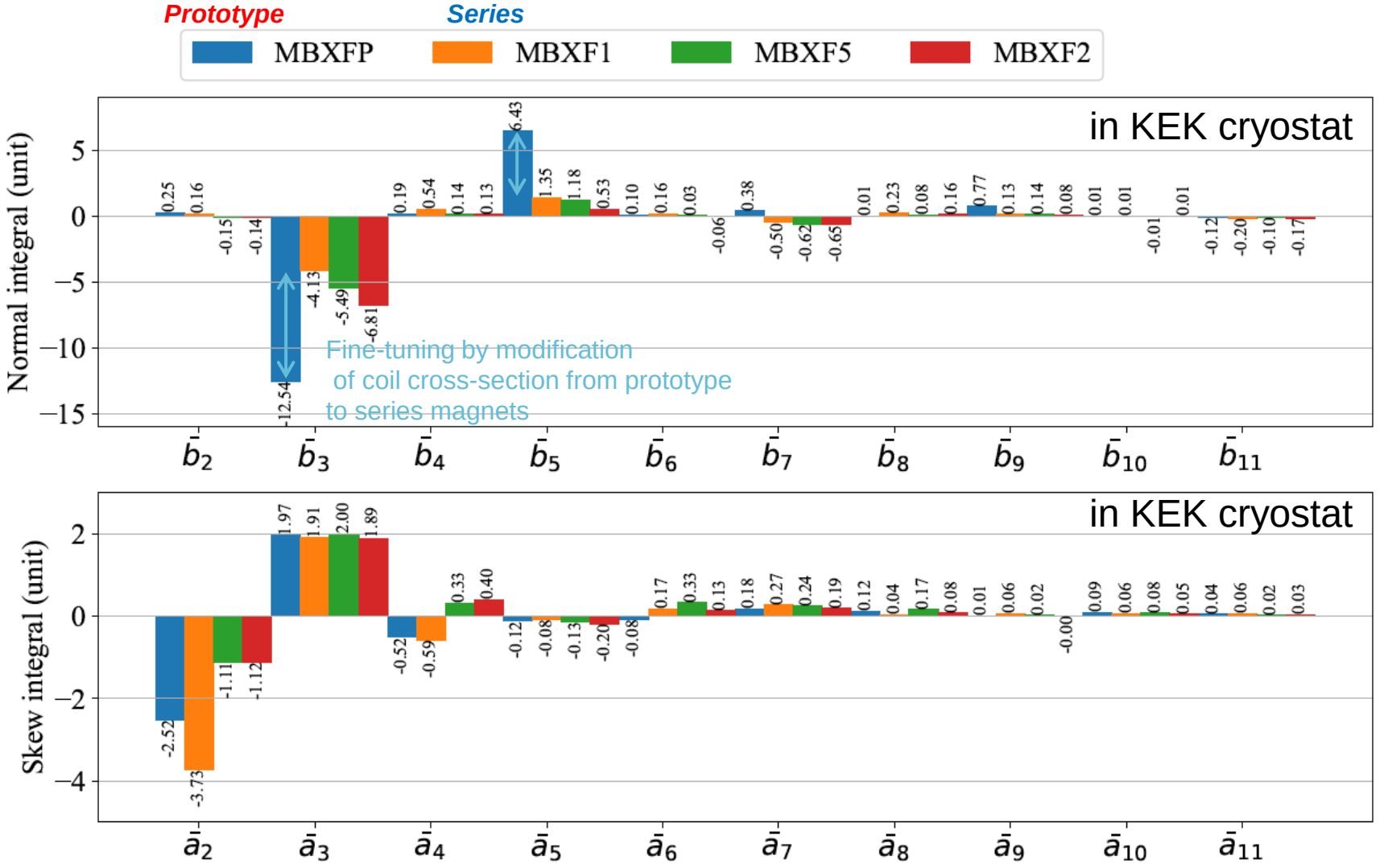
Integral Measurement – comparison with calc.





- Good agreement between warm and cold
- Measurements agrees well with simulation with Opera3D.

FQ Summary (integral) so far



∗) MBXFP's cross-section design is different from the series

Good reproducibility was confirmed among the series production magnets.

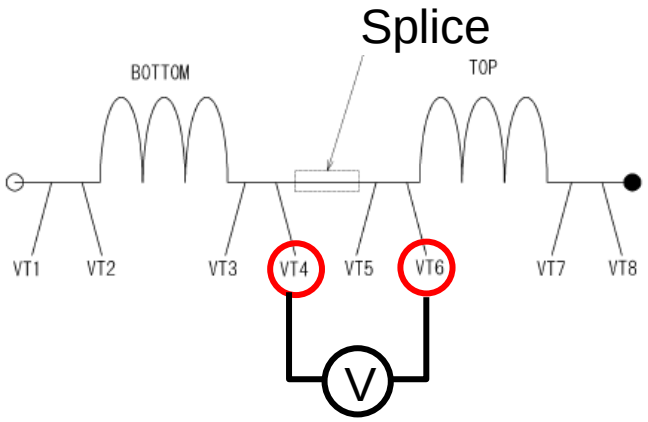
FQ Summary and Expectation

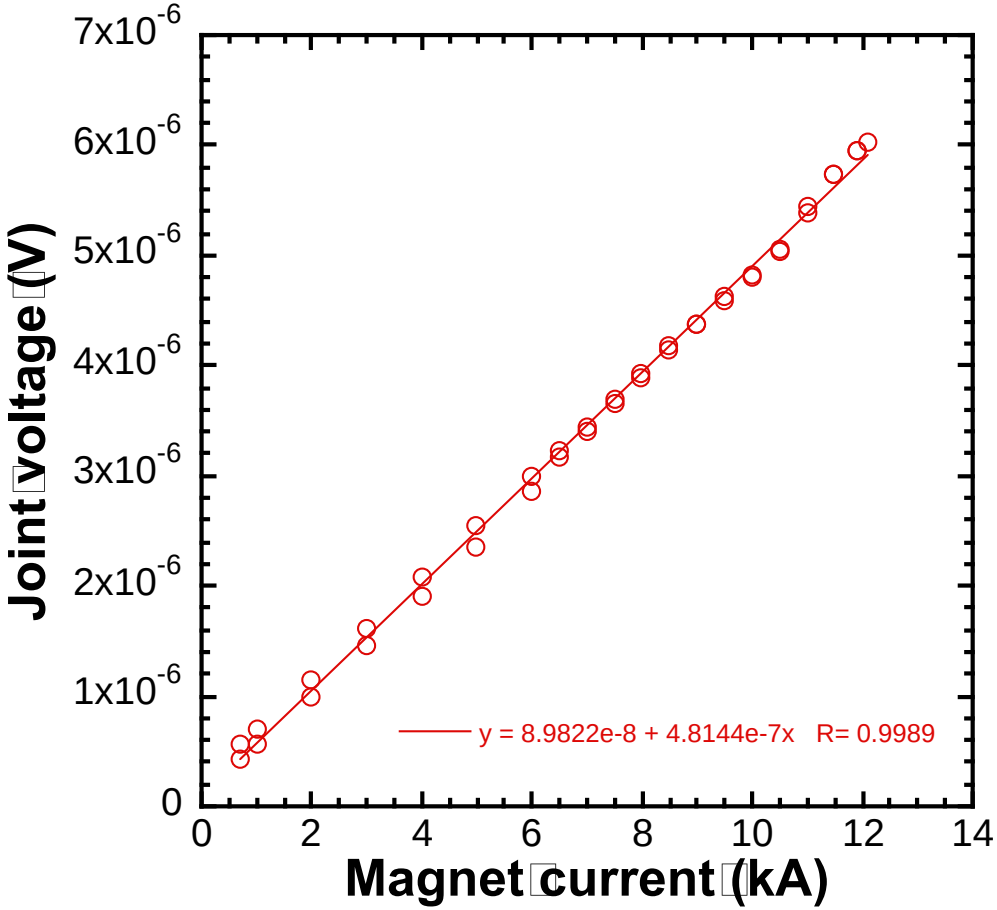
b3		Prediction based on Opera3D (for series)	MBXF1	MBXF5	MBXF2
Horizontal warm after yoking			1.96	1.00	-0.08
Horizontal warm	Central		4.06	TBD	TBD
	SS average		3.04		
	Integral		-7.55		
Vertical in KEK cryostat, warm	SS average		2.90	1.82	0.29
	Integral		-7.55	-8.61	-9.98
Vertical in KEK cryostat, 12.11kA	Central	-2.74	1.19	-0.62	-2.70
	Integral	-4.72	-4.15	-5.49	-6.81
CERN (prediction)	Central	3.74	7.67	5.86	3.78
	Integral	-1.55 / +1.40	1.97	0.63	-0.69

b5		Prediction based on Opera3D (for series)	MBXF1	MBXF5	MBXF2
Horizontal warm after yoking			-2.34	-2.84	-3.00
Horizontal warm	Central		-2.31	TBD	TBD
	SS average		-2.49		
	Integral		-2.63		
Vertical in KEK cryostat, warm	SS average		-2.43	-2.61	-3.27
	Integral		-2.51	-2.72	-3.22
Vertical in KEK cryostat, 12.11kA	Central	0.55	1.25	1.00	-0.10
	Integral	0.63	1.39	1.18	0.53
CERN (prediction)	Central	0.77	1.47	1.21	0.11
	Integral	0.89	1.66	1.45	0.80

Measured field quality of MBXF2 with CERN cryostat agreed with OPERA3D simulation.

Joint resistance





- Joint resistance across the splice: 0.481 nΩ < 1 nΩ → OK

Summary

- CD1 test was conducted for MBXF2. The results are summarized as follows.
  - Hi-pot test at NOC → passed
  - Training: 10 quenches to nominal, 18 quenches to ultimate
  - Successful current holding for 4h at ultimate
  - Fast ramp with ±30 A/s up to ultimate → OK
  - Joint resistance < 1nΩ
  - Good and reproducible field quality was confirmed in magnetic field measurement. Measured field quality of MBXF2 with CERN cryostat agreed with OPERA3D simulation.

- CD2 will start on June 9th.

Summary of training

Red: Successful localization

Run No.	Quench number	Quench current (A)	Top/ Bottom coil	Long. position	Quench antenna	Detection delay (ms)	Quench integral from quench (MA^2s)
013	1	9383	B	LE	1, 2, **3**	-43.0	21.6
014	2	9925	B	LE	1, 2, 3	-45.5	23.7
015	3	10327	T		1, 2, 3, 4, 5, 6	-38.1	24.2
016	4	10480	B		1, 2, 3, 4, 5, 6, 7, 8	-38.0	24.8
019	5	11243	T	LE	1, 2, 3	-32.4	26.1
020	6	11563	B	LE	**2**	-31.1	26.6
021	7	11572	T	LE	**2**, 3	-32.4	27.1
022	8	11780	B	LE	1, **2**, 3, 4, 5	-31.9	27.4
023	9	11832	T		1, 2, 3, 4, 5, 6, 7	-31.3	27.7
024	10	11878	B		1, 2, 3, 4, 5, 6, 7	-32.3	27.8
025	11	12493	T	LE	1, **2**, 3	-27.8	28.4
026	12	12529	B	LE	1, **2**, 3	-28.5	28.9
027	13	12628	B	RE	9, 10, **11**	-47.2	32.1
028	14	12790	B	RE	9, 10, **11**	-43.4	31.9
029	15	12860	T	LE	**1**, 2, 3	-35.0	30.7
030	16	13054	B	LE	1, **2**, 3	-25.1	29.0
031	17	13119	T	LE	**11**	-38.6	31.9
032	18	13234	B	RE	**11**	-38.7	31.9

FQ Summary Table - SS averaged & Integral for MBXF2

in KEK cryostat

Warm

n	SS (average)		Total	
	an	bn	an	bn
1		-0.028Tm	-9.031	-0.032Tm
2	-0.075	-0.389	-0.548	-0.306
3	-0.158	0.288	1.878	-9.98
4	0.657	-0.624	0.488	-0.371
5	-0.06	-3.265	-0.201	-3.222
6	0.155	-0.017	0.101	0.064
7	-0.025	0.1	0.142	-0.254
8	0.075	0.003	0.078	0.004
9	0.011	0.105	0.01	-0.311
10	0.091	-0.019	0.132	-0.034
11	0.039	-0.007	0.055	-0.199
12	0.144	-0.357	0.125	-0.331
13	0.107	-0.796	0.084	-0.855
14	0.136	-0.586	0.15	-0.571
15	0.025	-1.162	0.047	-1.112
16	0.055	-0.379	0.07	-0.37
17	-0.052	-0.583	-0.037	-0.579
18	-0.002	0.233	-0.032	0.249
19	-0.004	0.339	-0.018	0.288
20	0.006	0.024	0.028	0.061

1.9 K, 12.11 kA

n	Central		SS (average)		Total	
	an	bn	an	bn	an	bn
1		-5.58 T	2.033	-30.794Tm	-7.951	-35.017Tm
2	-0.504	0.372	-0.543	-0.279	-1.123	-0.137
3	-0.061	-2.699	-0.224	1.722	1.894	-6.813
4	0.623	0.037	0.564	-0.116	0.396	0.133
5	0.064	-0.103	-0.043	0.187	-0.195	0.526
6	0.217	0.009	0.177	-0.117	0.129	-0.06
7	0.058	-0.304	0.018	-0.299	0.186	-0.65
8	0.191	0.004	0.098	0.141	0.077	0.156
9	0.040	0.534	0.019	0.547	-0.003	0.081
10	0.101	-0.013	0.068	0.01	0.052	0.008
11	0.013	0.103	0	0.015	0.034	-0.173
12	0.002	-0.090	0.023	-0.367	0.024	-0.337
13	-0.013	-0.669	-0.023	-0.867	-0.006	-0.879
14	-0.062	-0.179	-0.004	-0.68	0.021	-0.658
15	-0.024	-1.131	-0.016	-1.3	-0.014	-1.257
16	-0.030	-0.143	0.01	-0.471	0.029	-0.453
17	-0.002	-0.766	0.01	-0.658	0.008	-0.628
18	0.037	0.062	0.012	0.264	0.009	0.247
19	0.003	0.350	-0.002	0.377	0.015	0.369
20	-0.010	0.021	-0.006	0.019	-0.007	0.011

Field quality specified in Acceptance criteria

EDMS No. 2045899

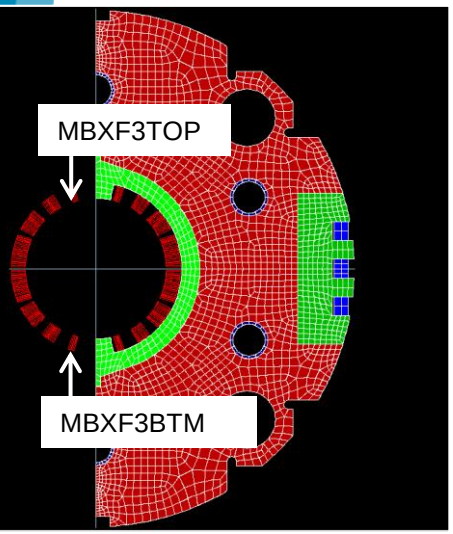
Table I. Target table for multipole errors at nominal field, R_{ref} = 50 mm, in 10^{-4} units of main field

	Systematic	uncertainty	random	lower limit	upper limit
b_2	0.000	0.200	0.200	-0.800	0.800
b_3	0.000	0.727	0.727	-2.900	2.900
b_4	0.000	0.126	0.126	-0.500	0.500
b_5	0.000	0.365	0.365	-1.500	1.500
b_6	0.000	0.060	0.060	-0.240	0.240
b_7	0.000	0.165	0.165	-0.660	0.660
b_8	0.000	0.027	0.027	-0.110	0.110
b_9	0.000	0.065	0.065	-0.260	0.260
b_{10}	0.000	0.008	0.008	-0.030	0.030
b_{11}	0.000	0.019	0.019	-0.076	0.076
a_2	0.000	0.200	0.200	-0.800	0.800
a_3	0.000	0.727	0.727	-2.900	2.900
a_4	0.000	0.126	0.126	-0.500	0.500
a_5	0.000	0.365	0.365	-1.500	1.500
a_6	0.000	0.060	0.060	-0.240	0.240
a_7	0.000	0.165	0.165	-0.660	0.660
a_8	0.000	0.027	0.027	-0.110	0.110
a_9	0.000	0.065	0.065	-0.260	0.260
a_{10}	0.000	0.008	0.008	-0.030	0.030
a_{11}	0.000	0.019	0.019	-0.076	0.076

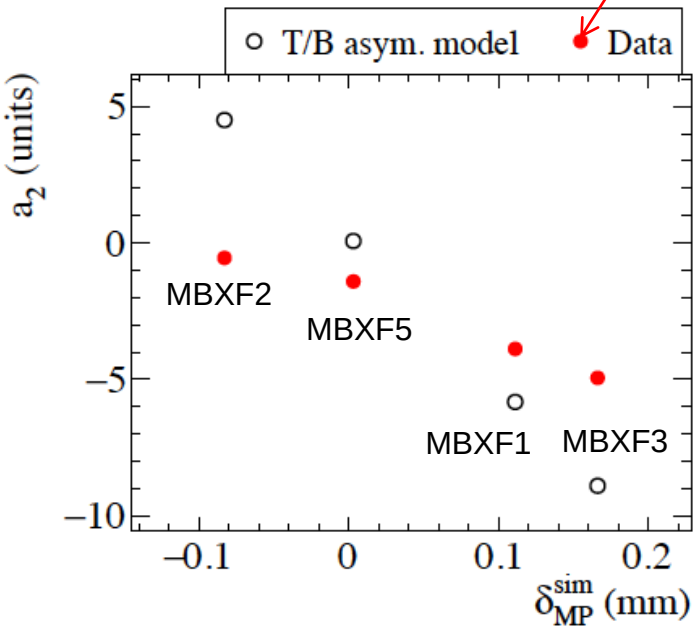
Results of coil size measurement

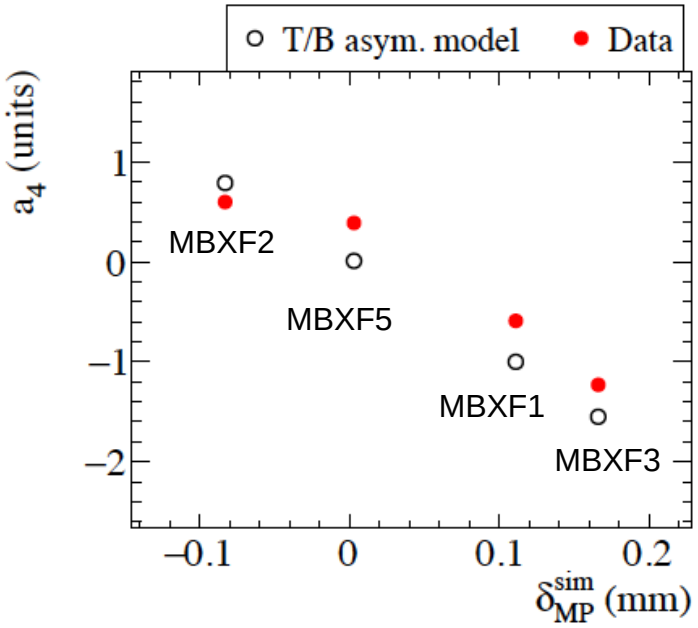
Magnet	Coil	Total average (MPa)	Max value (MPa)	Min value (MPa)	Standard deviation (MPa)
MBXFP1	LPT-1	112	116	106	2.0
	LPB-1	110	113	108	1.4
MBXF5	LT-1	122	125	119	1.5
	LB-1	122	125	118	1.8
MBXF1	LT-2	117	120	114	1.3
	LB-2	125	128	112	1.6
MBXF2	LT-3	123	127	119	1.9
	LB-3	117	122	114	1.9
MBXF3	LT-4	117	124	112	2.9
	LB-4	129	136	124	2.9

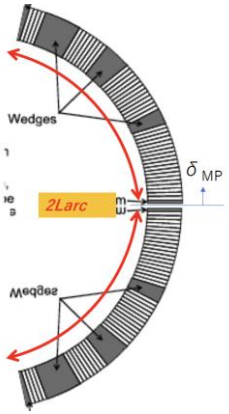
Estimation of a2 and a4 by an MP shift model



Measured data after yoking at Hitachi







δ_{MP}^{sim} was estimated from the measured coil-size asymmetry, assuming no friction between the cables and collar.
The measured skew quadrupole is largest in MBXF3, but still within 5 units