Test result of MBXF1

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KEK

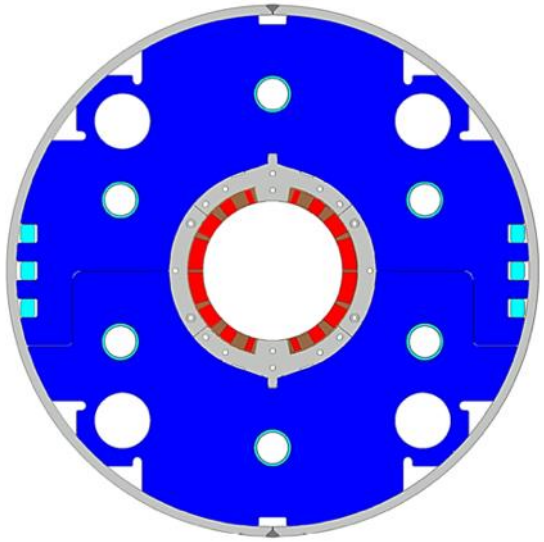
On behalf of CERN-KEK Collaboration for D1 Development for HL-LHC

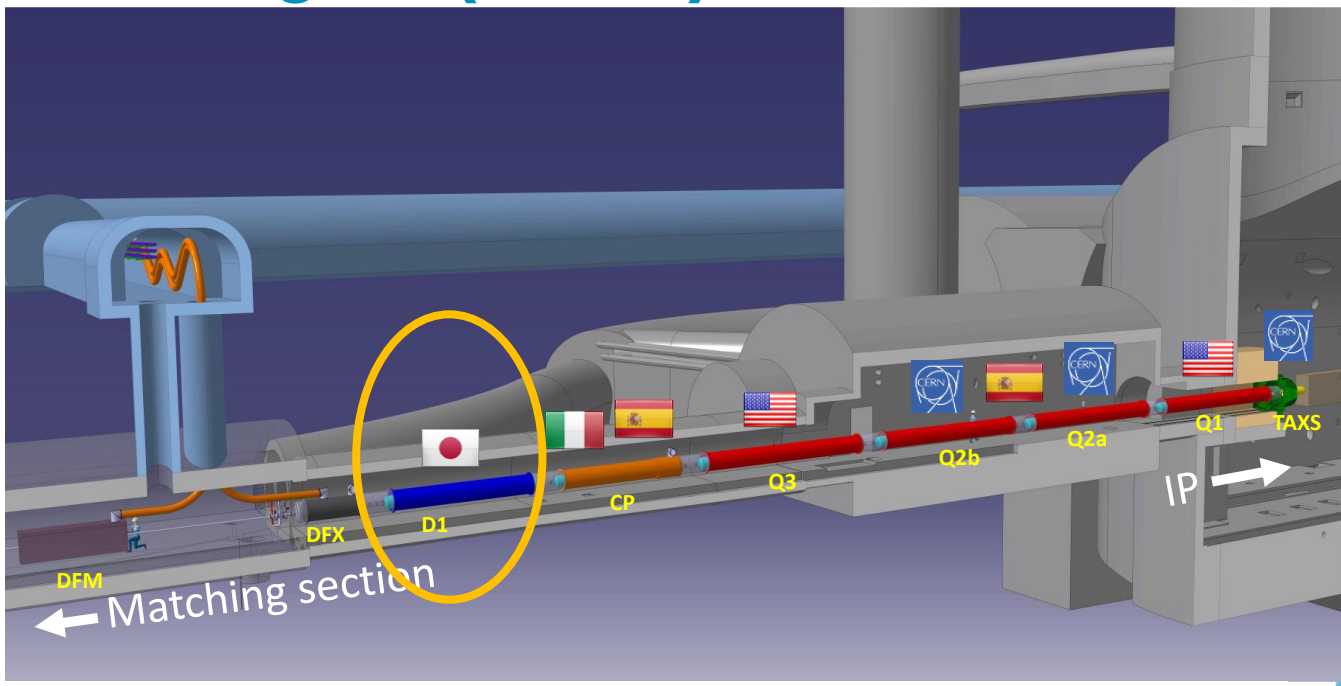
Outline

- Test result of the 1st cycle for MBXF1
  - 1.9 K Hi-pot test
  - Validation of newly implemented varistor
  - Training performance
  - Energy extraction with varistor
  - He gas recovery with an additional storage bag
  - Other test items (Joint resistance, RRR measurement)

The results of MFM will be presented in another talk by Kento SUZUKI.

D1 magnet (MBXF)





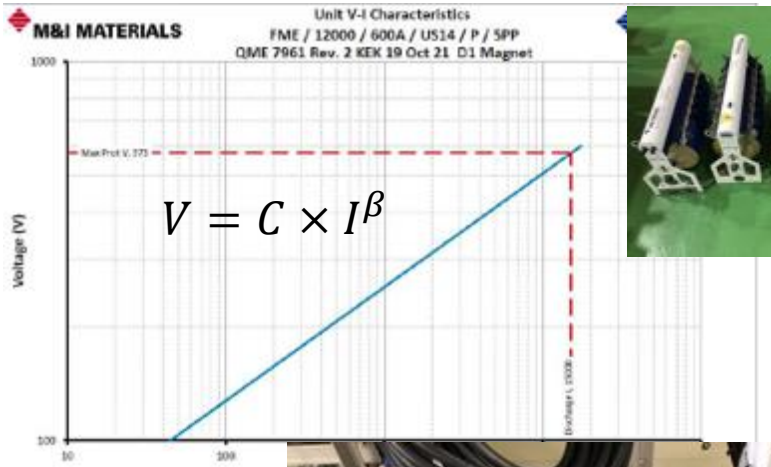
- Beam separation dipole (D1) by KEK
  - Design study of D1 for HL-LHC within the framework of the CERN-KEK collaboration since 2011.
  - 150 mm single aperture, 35 Tm (5.6 T x 6.3 m), Nb-Ti technology.
  - Development 2-m long model magnets (3 units) at KEK
- Deliverables for HL-LHC
  - *1 full-scale prototype cold mass (LMBXFP)*
  - *6 series cold masses (LMBXF1-6)*
- Current status of D1 prototype and series production magnet
  - MBXFP1 : In preparation for the horizontal test at CERN
  - **MBXF1: The 1st test cycle was completed. The 2nd test cycle is being conducted.** ← This slide
  - MBXF5: Magnet assembly has been almost completed in Hitachi.
  - MBXF2: Coil winding and curing was completed.

Remaining issues in the KEK test facility

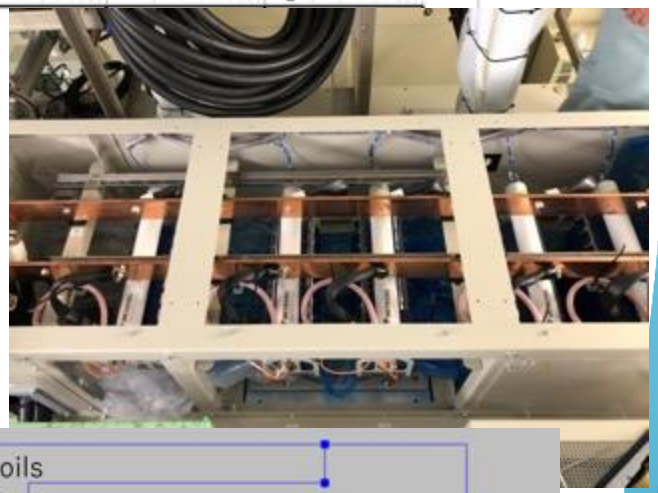
- Sufficient energy extraction with the allowable maximum voltage and complete He gas recovery is needed.
- Dump resistors of 25 mΩ or 50 mΩ were used for the cold test of MBXFP1.
  - 25 mΩ: Insufficient energy extraction resulted in incomplete He gas recovery.
  - 50 mΩ: The maximum voltage exceeded the allowable limit of 600 V for the DCCB of the power converter. Training above 106% of the nominal current could not be performed.
- Target: Maximum voltage < 600 V at the ultimate current
  Magnet dissipation energy < Safety limit = 1.6 MJ
  (Max. experienced energy in the cold test of MBXFP1)
- To satisfy these targets, varistor and additional He gas bag were implemented before the cold test of MBXF1.

Installation of the new EE system: Varistor

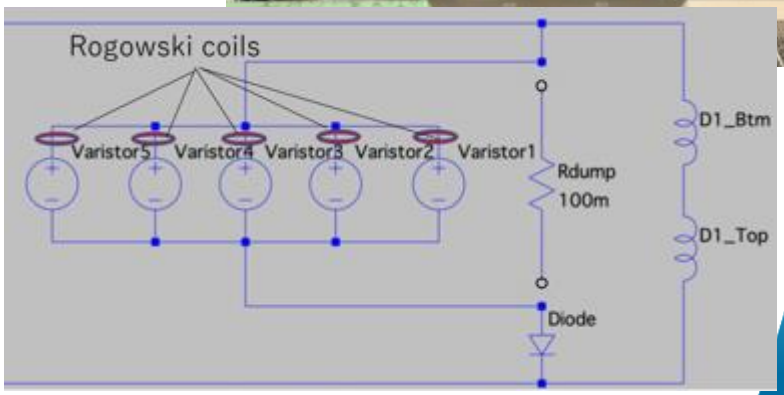
- Non-linear resistor: varistor (Metrosil®)
  - Composed of SiC disks
  - C=32.01
  - β =0.3



- Technical meetings with CERN experts had been held twice so far, and some concerns attributed to “parallel connection scheme” were raised
  - Imbalance of the circuit current
  - Imbalance of the turn-on time



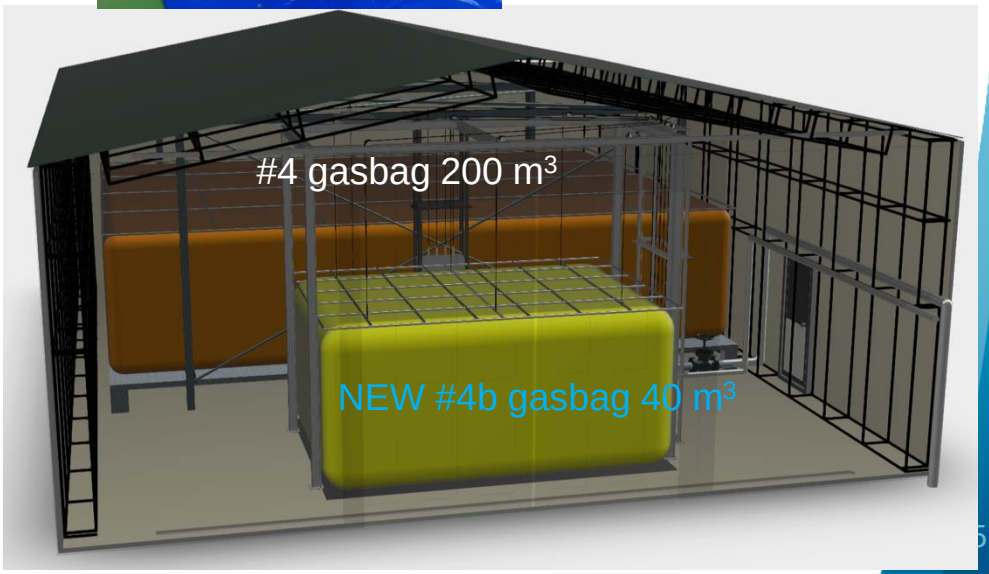
- KEK had proposed a “gradual powering plan” to check the EE system and setup for monitoring current imbalance using Rogowski coils (PEM Ltd.)



Additional Helium Gas Storage Bag

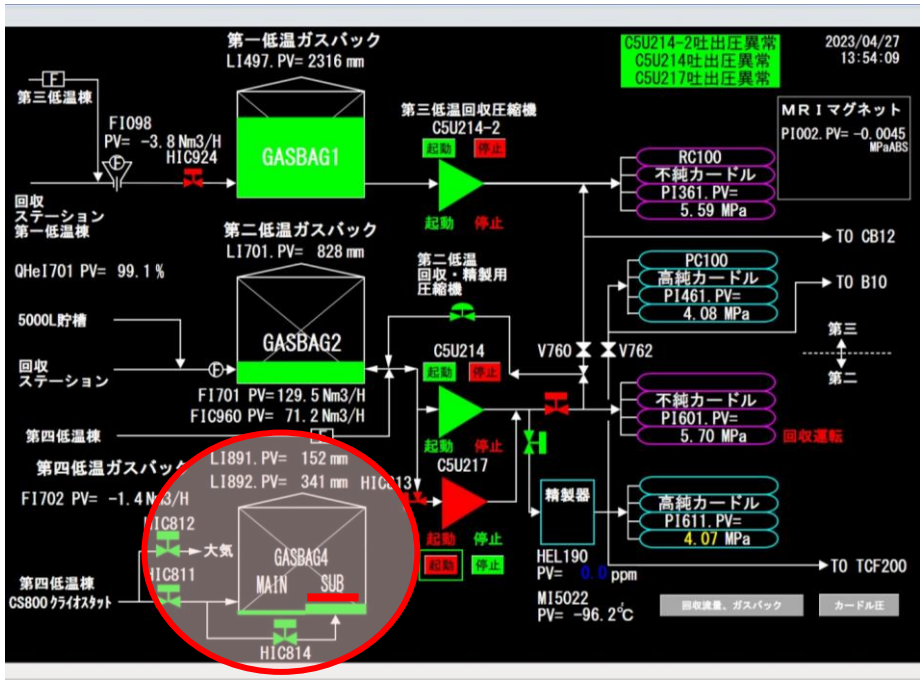
- Limitation of helium gas recovery at quenches of MBXFP1.
- Present capacity: 280 m^3 (#2: 80 m^3, #4: 200m^3)
- Helium gas at 13.23 kA w/ Varistors: 294 m^3 (prediction)
- Plan: new Helium gasbag (#4b, 40 m^3)
  - Total capacity: 320 m^3 > 294 m^3
  - #4b Gasbag to be installed next to #4 Gasbag in the same tent warehouse
  - The gasbag is already available. The drawings are being prepared in a rush.

In the event of MBXFP1 quench



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.



Test schedule

- Insertion of MBXF1 into the vertical cryostat: April 7
- 1st test cycle
  - Cool-down: April 12 – 17
  - 1.9 K Hi-pot test: April 17
  - System check: April 18 – 26
  - MFM at 3 kA: April 19
  - Training: April 27 – May 2
  - MFM: May 10 – 17
  - Current holding at the ultimate current: May 18
  - Warm-up: May 18 – 26
- 2nd test cycle
  - Cool-down: May 28 – 31
  - 1.9 K Hi-pot test: June 1
  - System check: June 2
  - MFM at 3 kA: June 2
  - Training: June 5
  - MFM: June 6 –

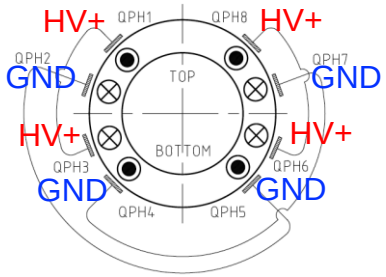
Test items

- 1.9 K Hi-pot test
  - Coils to ground: max 1.3 kV
  - Heater to coils: max 2.3 kV
  - R14: The magnet shall fulfil the electrical test requirements during assembly and at 1.9 K.
- System check with Metrosil varistors
- MFM at 3 kA
- Training up to the ultimate current
  - R1: Ramp to the ultimate current with ramp of 12 A/s and flattop for 4 hours.
  - R21: Ramp to and from the ultimate current at ±30 A/s
- MFM up to the nominal current
  - Perform Z-scan field measurement at [687, 1k, 3k, 5k, 7k, 9k, 10k, 11k, 12k, 11k, 10k, 9k, 7k, 5k, 3k, 1k, 687] A.
  - Perform DC-loop at the magnetic center.
  - Splice joint resistance and inductance measurements along with the field measurement.
  - R8: The integral multipoles of the magnet at 1.9 K and at nominal current shall target the range “upper limit, lower limit” as defined in Table 1.
  - R19: Each internal splice shall have an electrical resistance lower than 1 nΩ at 1.9 K.
- 1.9 K Hi-pot test (only at the end of the 2nd cycle)
- Warm-up
  - RRR measurement

1.9 K Hi-pot test

- Hi-pot test was performed after cool-down in the 1st and 2nd cycles.
- MBXF1 passed all the following tests.

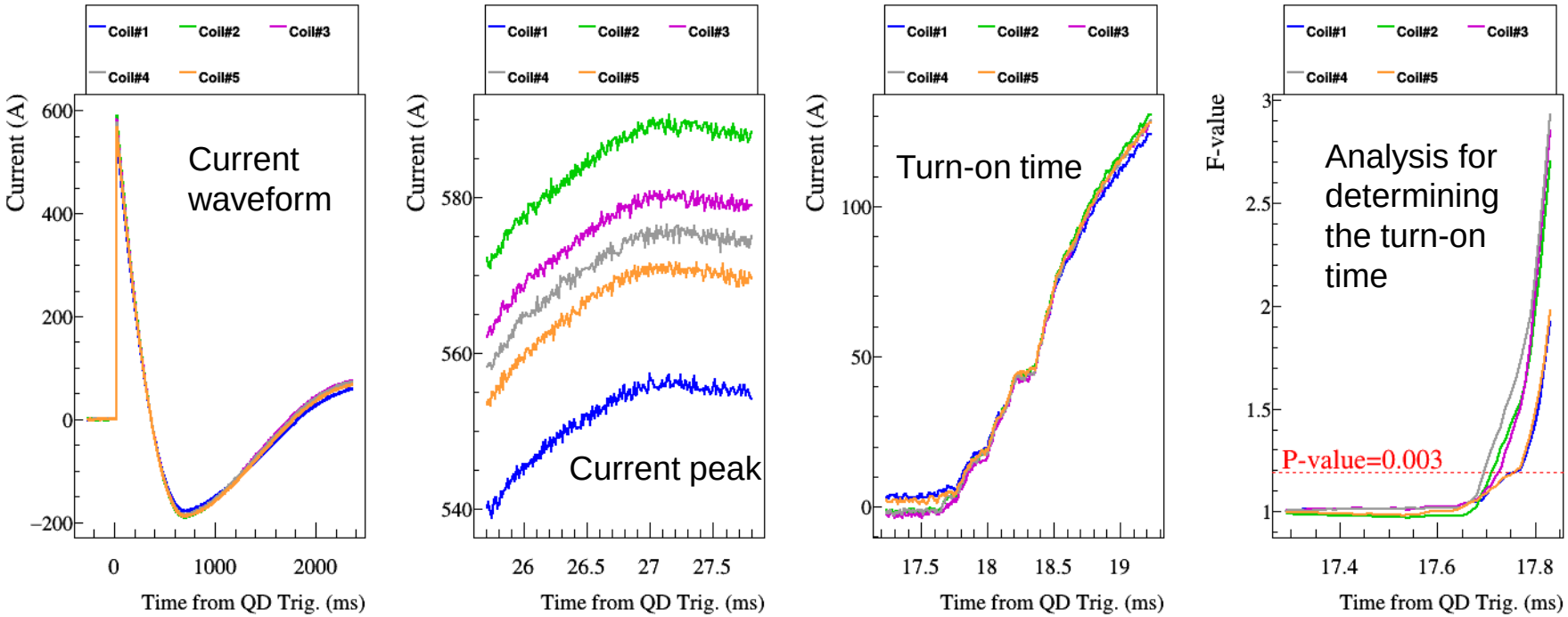
  Criteria: Leak current < 10 μA for 30sec
  - Coil-GND: 1.3 kV
  - Heater-GND: 2.3 kV
  - Between adjacent heater strips: 2.3 kV



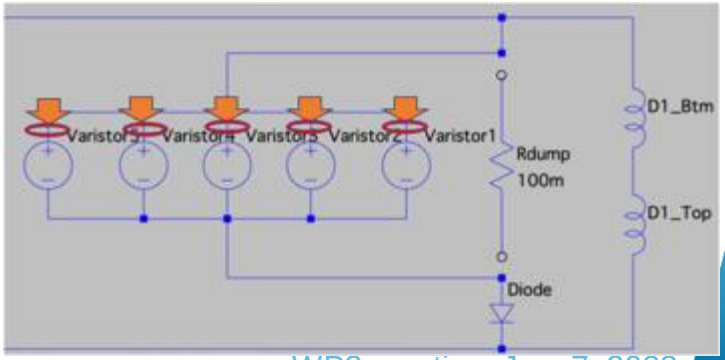
- Another 1.9 K Hi-pot test will be conducted before the 2nd warm-up.

Validation of varistor

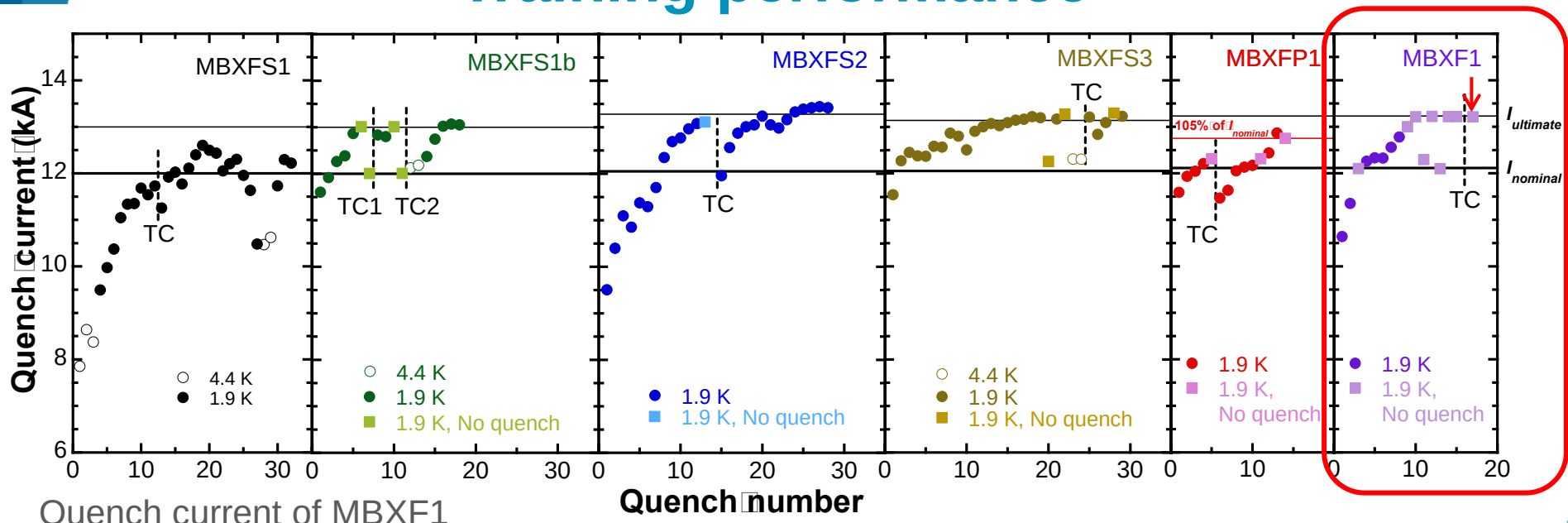
3kA shutdown



- Signals from Rogowski coils and temperature of SiC disks has been monitored every shutoff/quench event to ensure no sign of imbalance promotion
  - At every higher current we perform 3kA shutdown to check reproducibility
- In the 1st cycle:
  - Current imbalance < 7%
  - Turn-on time imbalance < 300 μs
- Detailed report can be found :
  - https://indico.cern.ch/event/1282199/



Training performance



Quench current of MBXF1

	Quench #	Run ID	Iq (A)	
1st TC	1	69	10639	
	2	71	11353	
	–	73	12099	← $I_{nominal}$
	3	75	12260	
	4	77	12331	
	5	79	12326	
	6	80	12559	
	7	82	12778	
	–	86	13214	← $I_{ultimate}$
2nd TC	–	508	13213	← $I_{ultimate}$

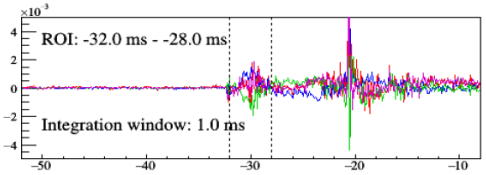
Temperature: 1.9 K
Ramp rate: 12 A/s or 30 A/s
Quench detection: 0.1 V, 10 msec
Quench protection: QPH and varistor
Quench start location: quench antenna

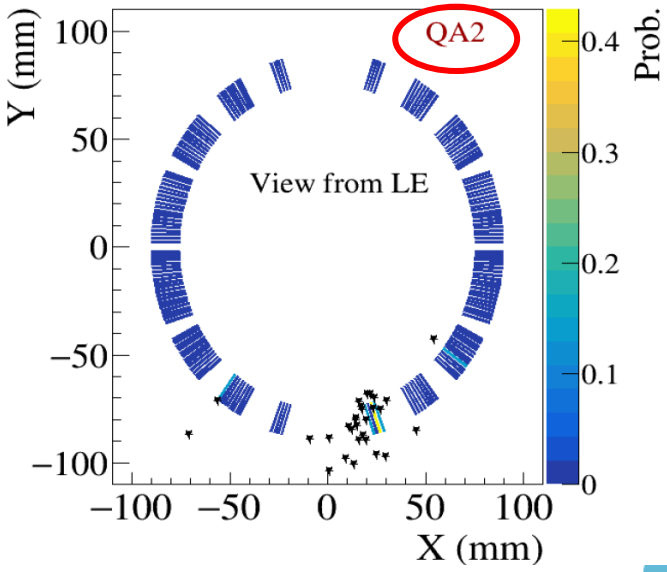
- The training quenches started at a lower current with respect to the prototype.
- After 2 quenches, the magnet current reached the nominal current.
- The ultimate current was attained after 7 quenches.
- After thermal cycle, the magnet reached the ultimate current without quench, showing perfect training memory.

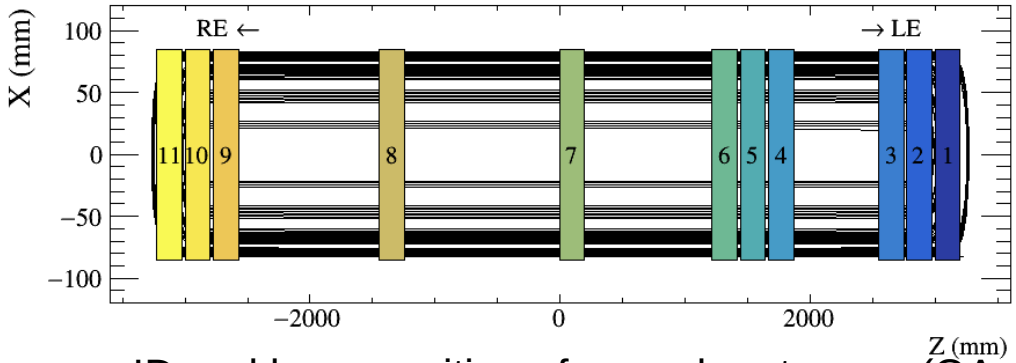
Quench start location

	Quench #	Run ID	Iq (A)	Quench origin	Longitudinal position by QA	Position
1st TC	1	69	10639	Top coil	1, 2, 3	LE
	2	71	11353	Bottom coil	2, 3	LE
	3	75	12260	Top coil	9, 10, 11	RE
	4	77	12331	Top coil	4, 5, 6	SS
	5	79	12326	Bottom coil	2	LE
	6	80	12559	Bottom coil	10	RE
	7	82	12778	Top coil	1, 2, 3	LE

Run 69: I_q=11353 A



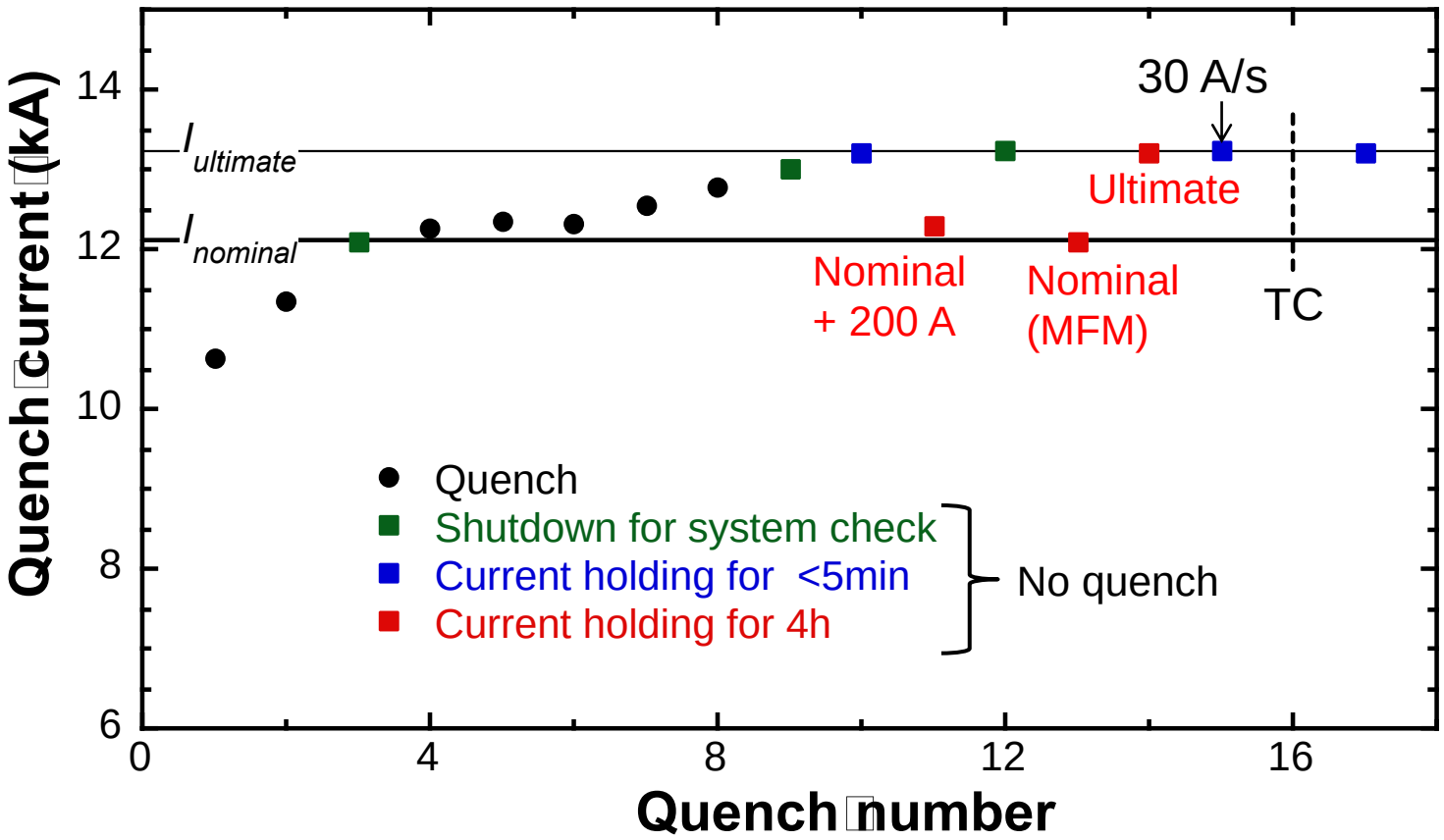




ID and long. position of quench antennas (QAs)

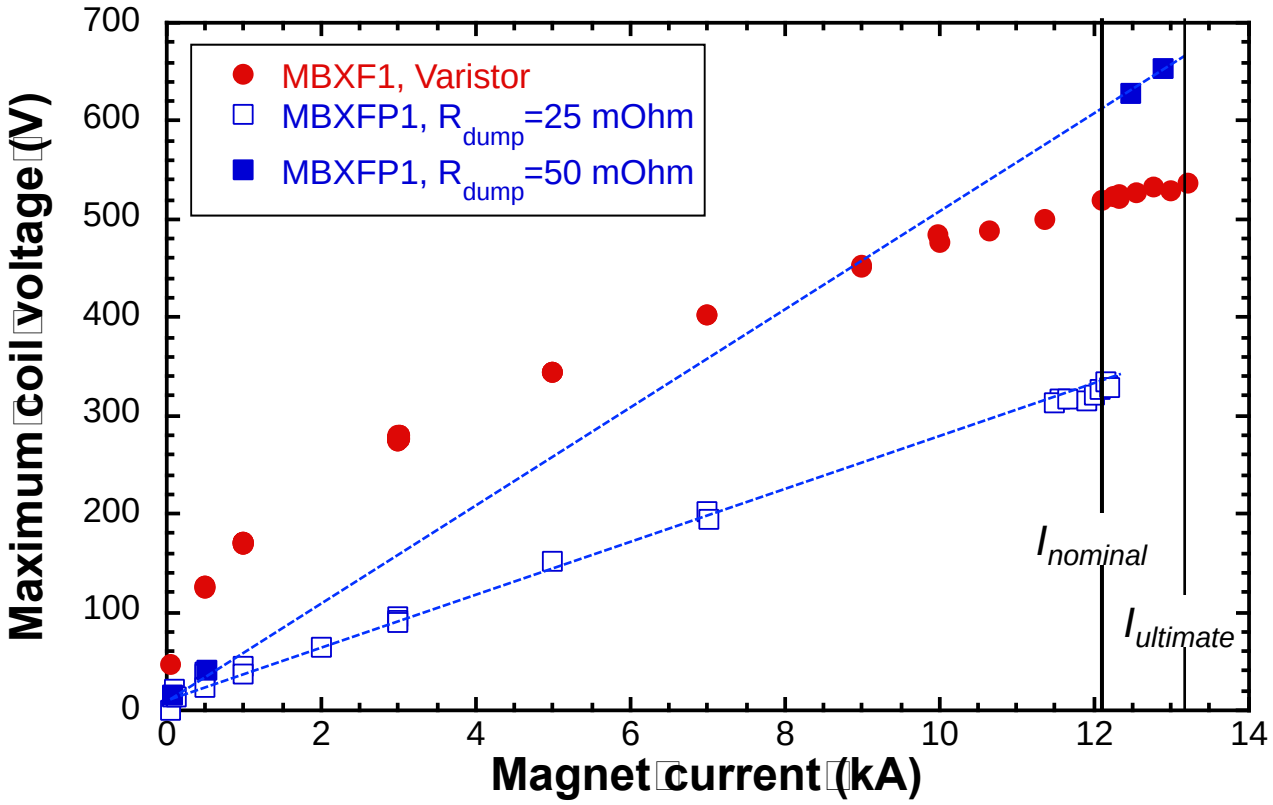
- The quench position was identified by using quench antennas.
- The first quench occurred at LE same as MBXFP1. Then the quench origin changed with progressing training. No specific weak point was found.
- Normal training behavior was confirmed.

Current holding



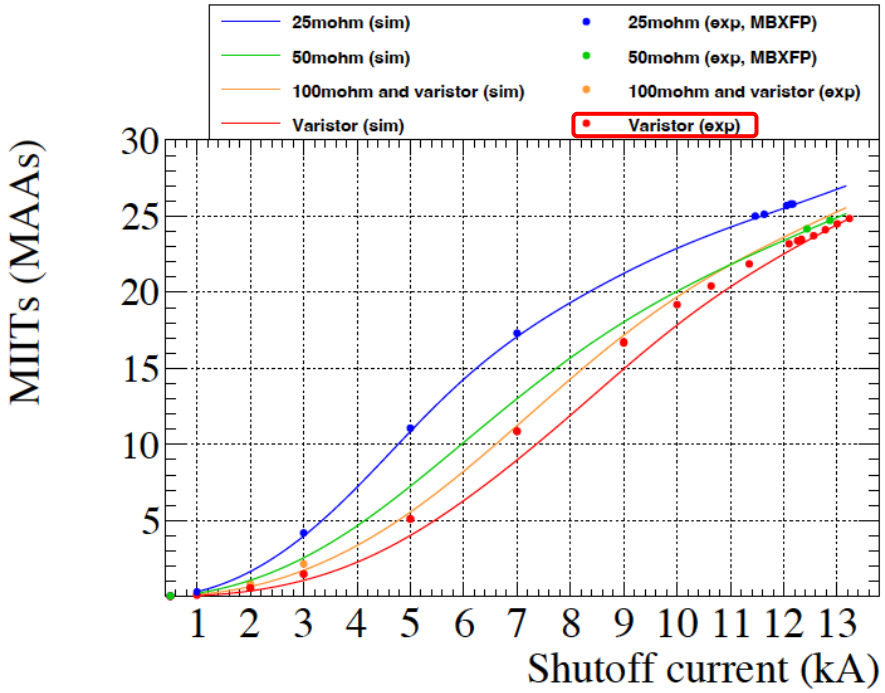
- The current holding for 4 hours was successfully done at the nominal, nominal +200 A, and the ultimate current. This is the first time of current holding at the ultimate current for more than a half hour including the 2 m-long model magnets.
- The ramping-up/down up to the ultimate current with a ramp rate of 30 A/s was also successful.

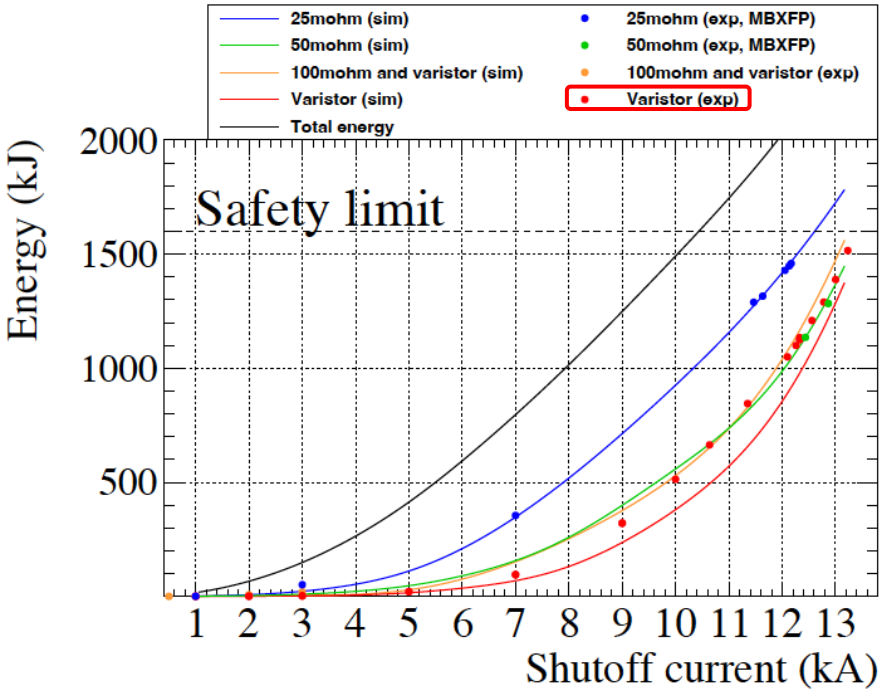
Measured maximum coil voltage



- The maximum coil voltage was evaluated by the current shutdown and quench.
- Dump resistors of 25 mΩ or 50 mΩ were utilized for MBXFP1.
  - R_{dump}=25 mΩ → Insufficient energy extraction
  - R_{dump}=50 mΩ → Maximum coil voltage exceeding 600 V below the ultimate current
- In MBXF1, the varistors are confirmed to be effective to suppress the maximum coil voltage thanks to their non-linear *V-I* characteristics.

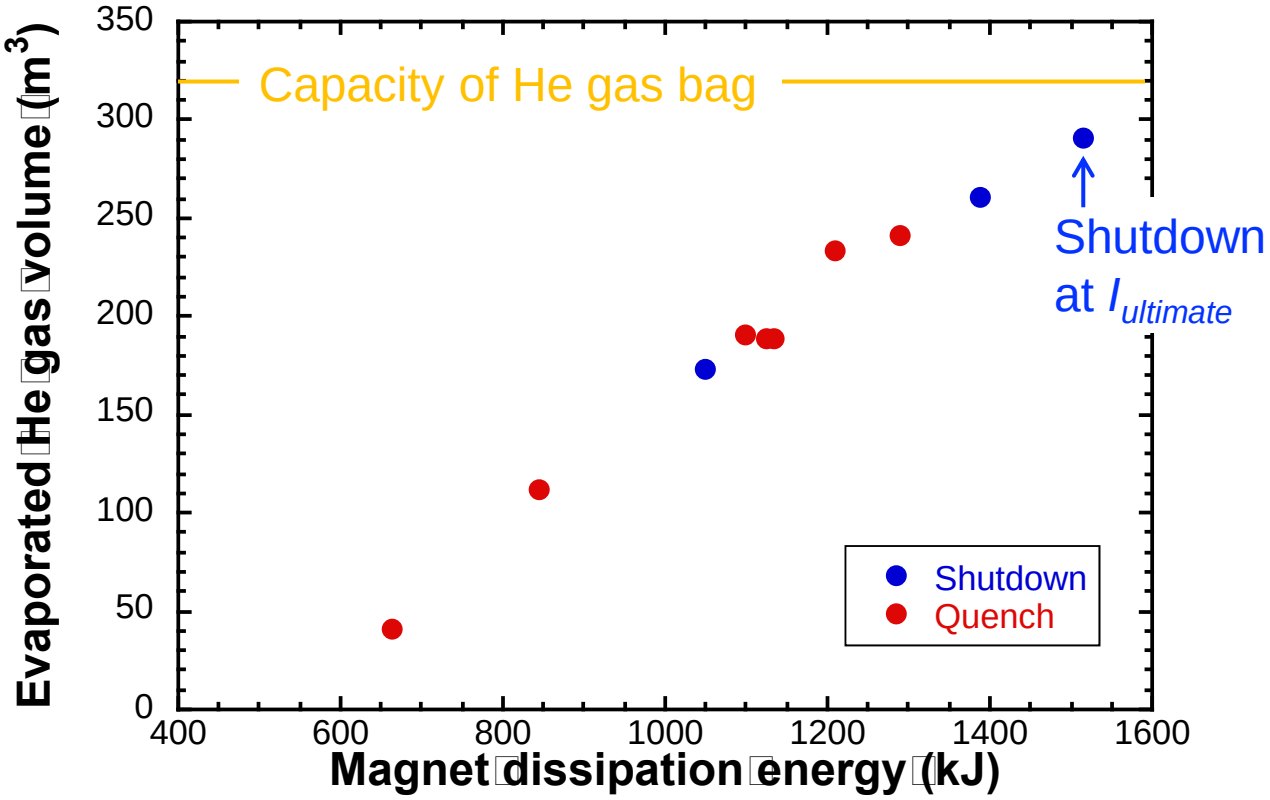
MITTs, magnet dissipation energy





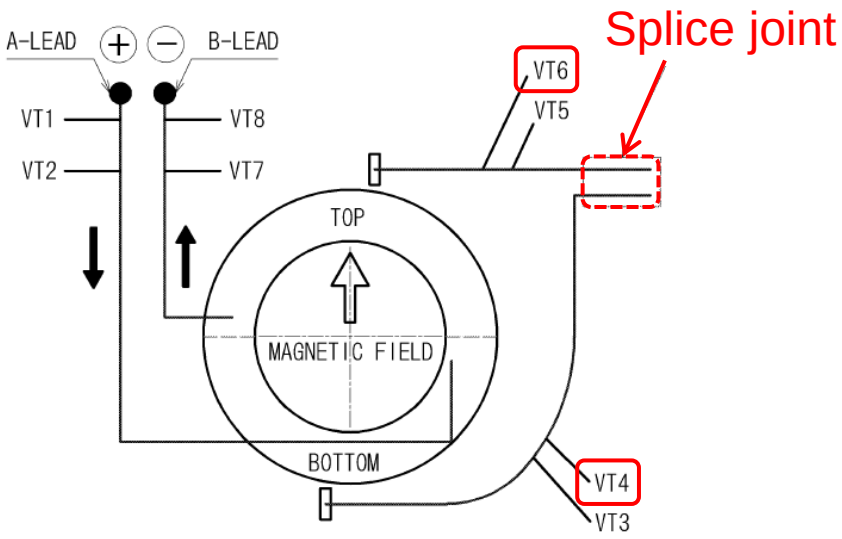
- Through the commissioning of the Varistor system, it was found that parameter β has a current dependence and is smaller at lower current.
  - It turns out to be the higher MIITs and lower energy extraction at the current below 10 kA wrt the design.
- Nevertheless, profit of using the Varistor is obvious: the dissipation energy during the training quenches are significantly reduced wrt R_{dump}=25 mΩ while the maximum voltage is below 600 V.

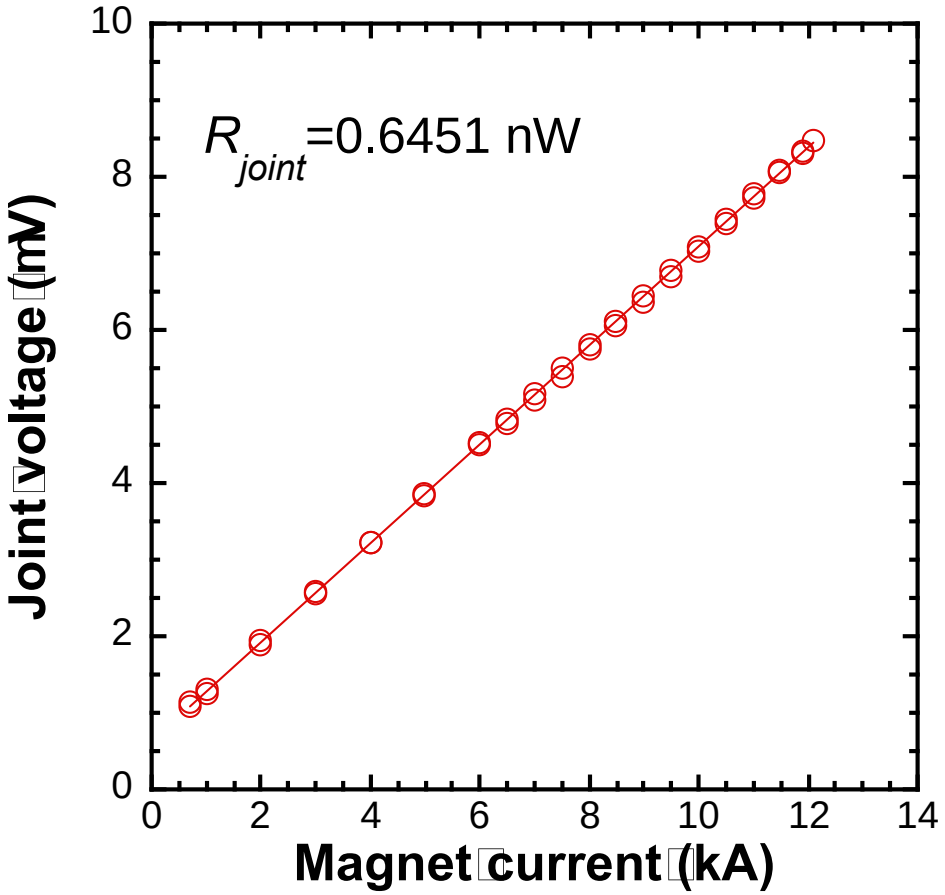
He gas recovery



- Measured evaporated He gas volume at the shutdown at the ultimate current = 290 m^3 (as prediction) < Capacity of the He gas bag = 320 m^3
- Evaporated He gas could be completely recovered up to the ultimate current. An increase in the capacity of He gas bag was successful.

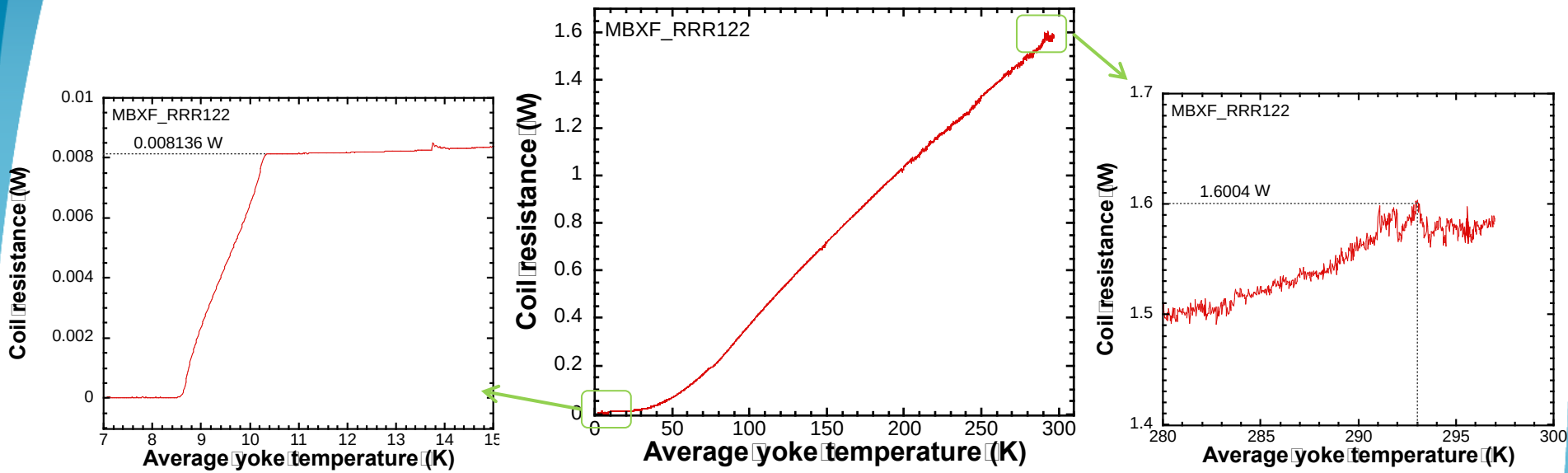
Joint resistance





- Joint resistance was evaluated to be 0.645 nΩ <1 nΩ.

RRR measurement



- RRR was evaluated during the warm-up after the 1st test cycle. RRR is defined as the following equation.

$$RRR = \frac{R(293K)}{R_{low}}$$, R_{low}: Normal resistance just before superconducting transition

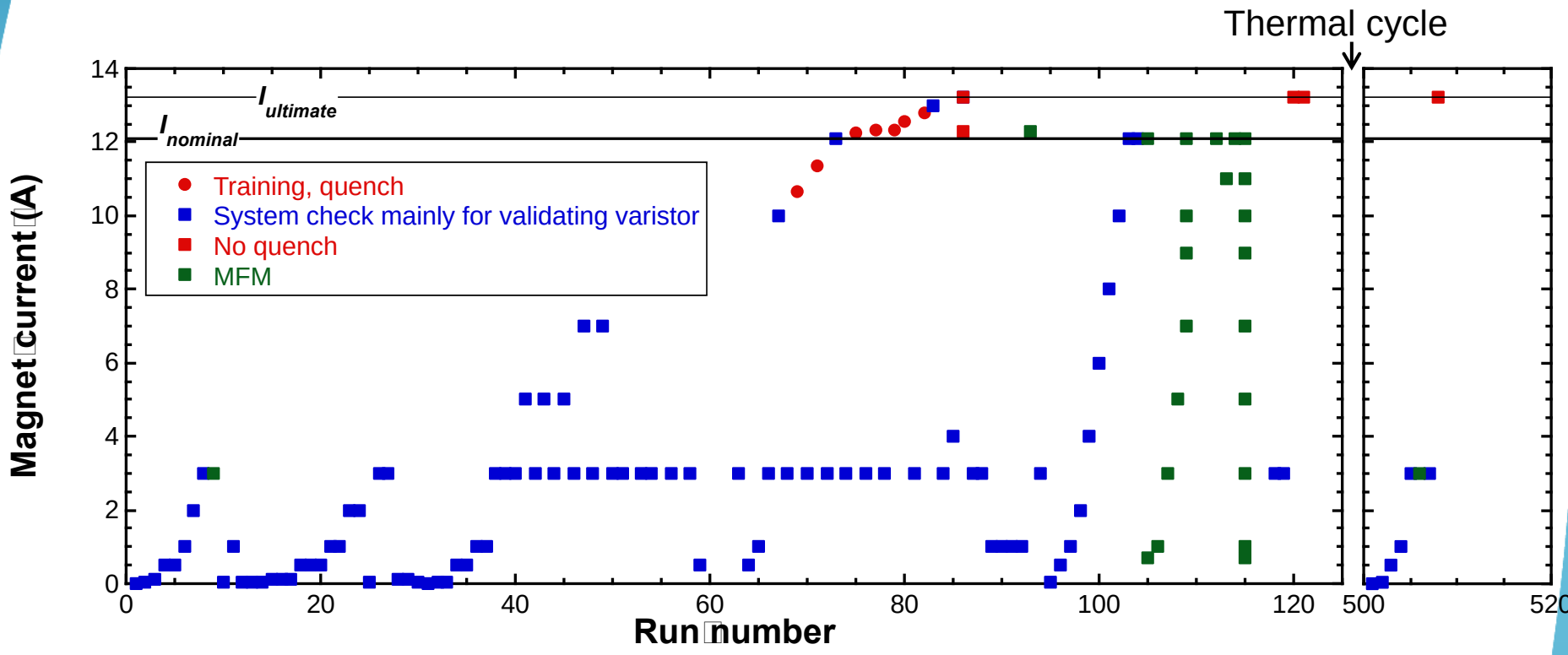
- RRR= 197 for MBXF1 (ex. RRR=217 for MBXFP1)

Summary

- Cold test of the first series production magnet (MBXF1) is being performed at KEK. The results are summarized as follows.
  - 1.9 K Hi-pot test → Passed
  - Successful validation of newly implemented varistor
  - Good training performance: 2 quenches to the nominal, 7 quenches to the ultimate
  - Reaching the ultimate without quench after thermal cycle, perfect training memory
  - Current holding at the ultimate for 4 hours → OK
  - Ramp to the ultimate with 30 A/s → OK
  - Complete recovery of evaporated He gas in the shutdown at the ultimate
  - Joint resistance < 1nΩ → OK

- MFM in the 2nd test cycle is ongoing. The 2nd test cycle will be completed in the week of June 12.

Current history



- Many shutdowns were repeated mainly for the validation test of the varistor.