QCS IR magnets

N. Ohuchi

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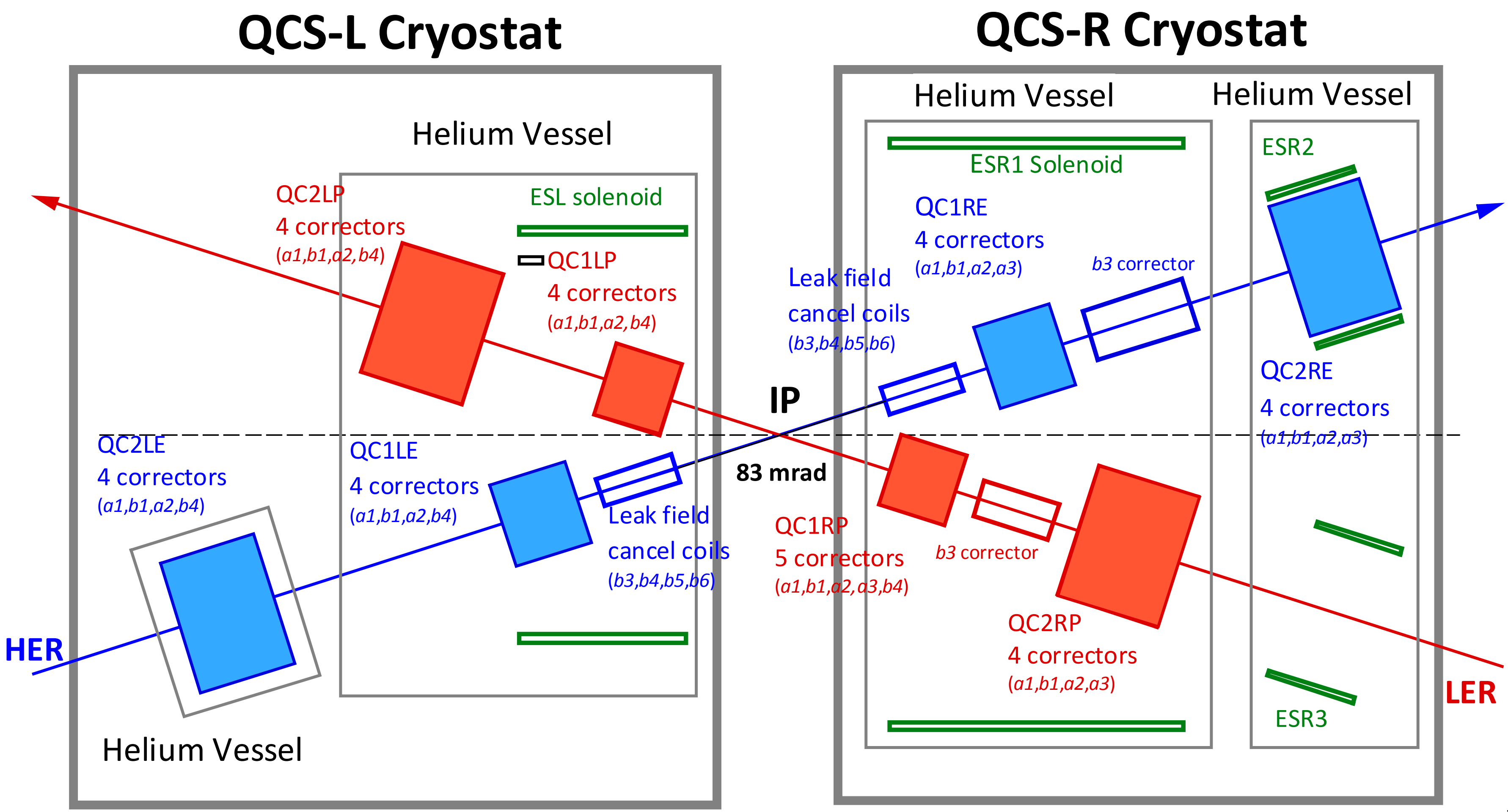
QCS SC magnet system



4 SC main quadrupole magnets: 1 collared magnet, 3 yoked magnets
16 SC correctors: a1, b1, a2, b4
4 SC leak field cancel magnets: b3, b4, b5, b6
1 compensation solenoid

4 SC main quadrupole magnets: 1 collared magnet, 3 yoked magnets
19 SC correctors: a1, b1, a2, a3, b3, b4
4 SC leak field cancel magnets: b3, b4, b5, b6
3 compensation solenoid

QCS operation and quench

Operation of QCS system for Phase2 (March 16, 2018 ~ July 17, 2018)

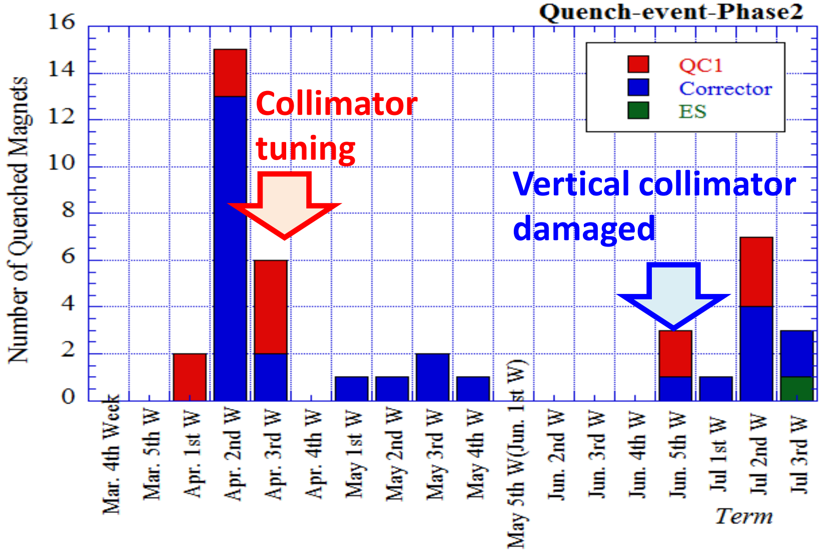
- **Operation of the QCSL and QCSR cryogenic systems**
  - QCSL:
    - Cool-down: 15:06 Feb. 9, 2018 – 4:18 Feb. 11, 2018: **37 h 10 min**
    - Warm-up: 16:08 Jul. 20, 2018 – 14:40 Jul. 26, 2018: 142 h 32 min
  - QCSR:
    - Cool-down: 10:06 Feb. 2, 2018 – 17:48 Feb. 4, 2018: **55 h 42 min**
    - Warm-up: 15:50 Jul. 19, 2018 – 16:14 Jul. 25, 2018: 144 h 24 min
- **<u>During the operation, 26 magnet quench events</u>**
  - 25 events: beam induced quench
  - 1 event: ESL power supply failure

Operation of QCS system for Phase3 (March 11, 2019 ~ July 1, 2019)

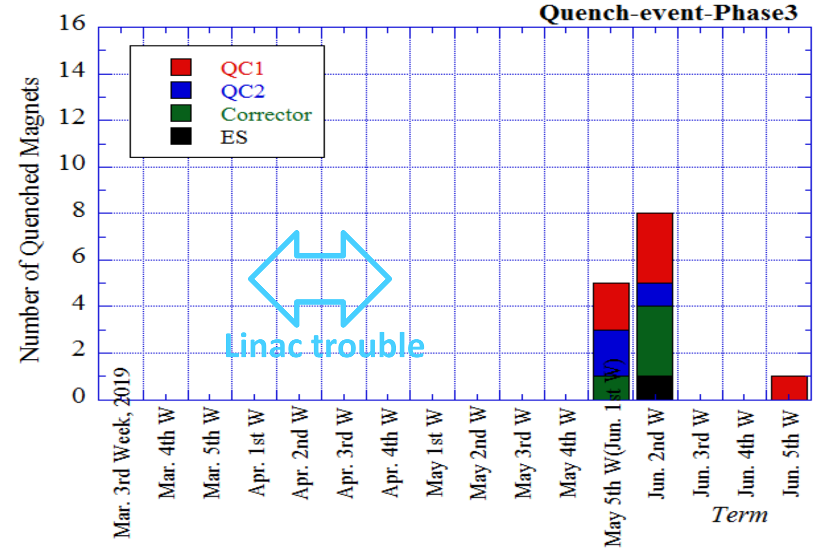
- **Operation of the cryogenic systems**
  - QCSL:
    - Cool-down: 9:43 Feb. 20, 2019 – 11:53 Feb. 22, 2018: **50 h 10 min**
  - QCSR:
    - Cool-down: 9:21 Feb. 25, 2018 – 00:44 Mar. 1, 2019: **87 h 23 min**
- **<u>During the operation, 6 magnet quench events</u>**
  - 3 events: beam induced quench
  - 3 events: QC2LE power supply failure (IMP abnormal work)

QCS operation and quench

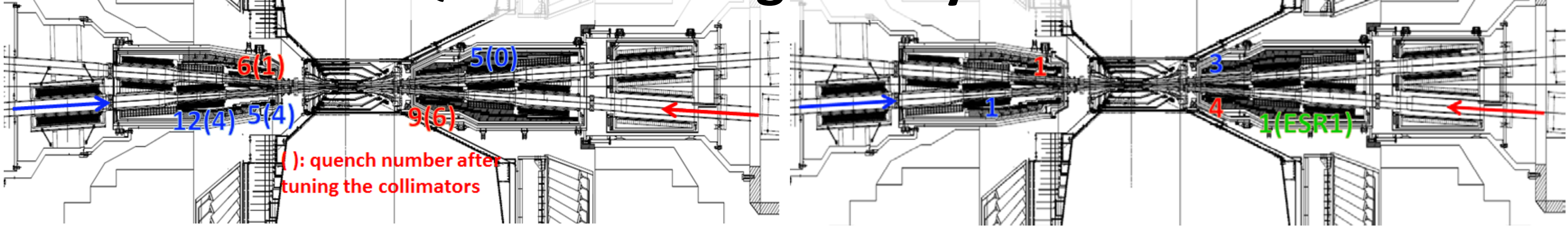
Phase-2



Phase-3



Quenched magnets by beams

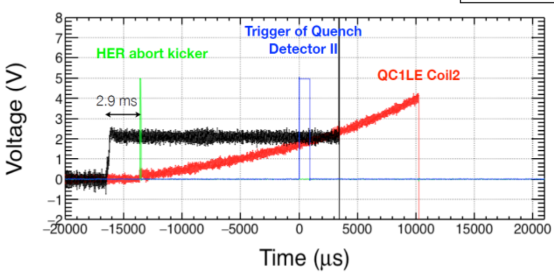


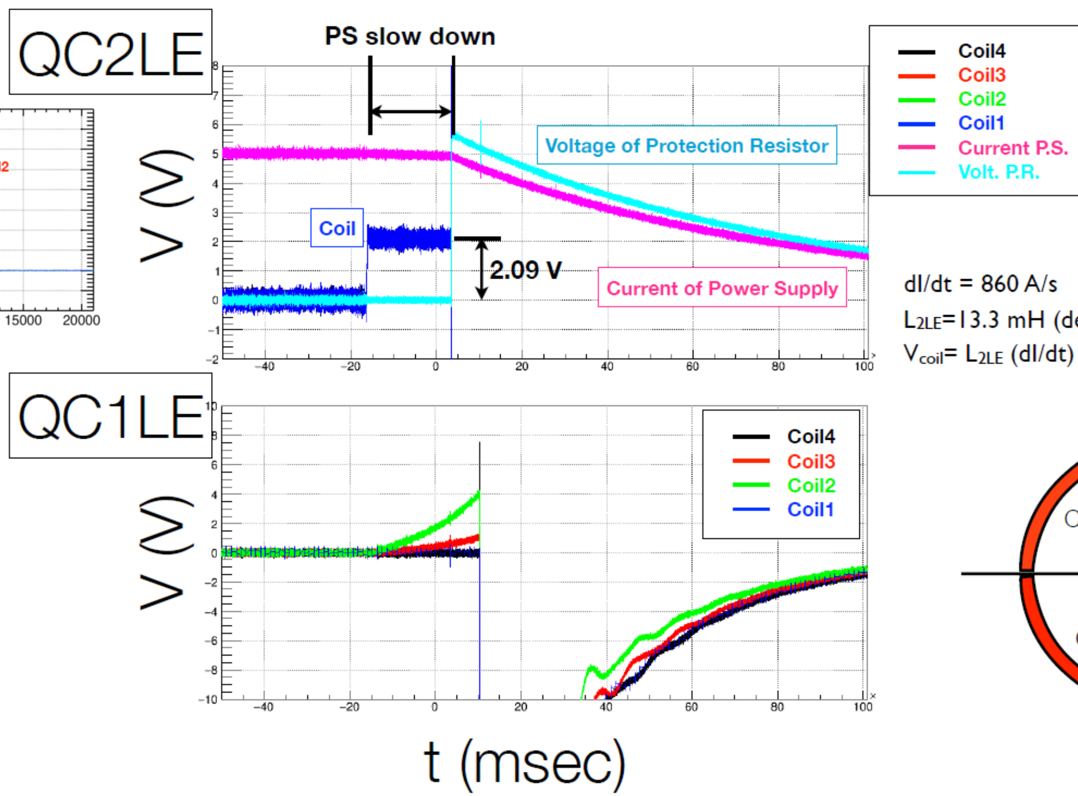
- The quenched magnets were concentrated in the QC1 magnets and the accompanying correctors.
- Some magnet quenches were induced with the power supply trouble.
- From Phase-3, in order to correlate the magnet quench and the beam operation, the kicker trigger signal was added to the QCS logger data, and the logger system was upgraded with the sampling time of 1 μs.

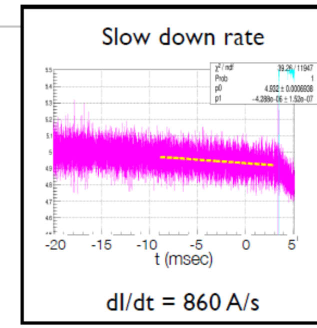
QCS operation and quench

- Magnet quench data (May 28th, 2019)
  - The origin of the trouble was QC2LE power supply failure (IPM trouble).
  - SVD had a serious damage.

Coil-voltage profiles of QC1LE and QC2LE



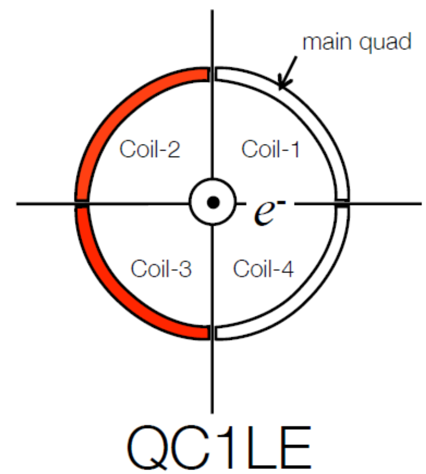




dI/dt = 860 A/s

L_{2LE}=13.3 mH (design value)

V_{coil}= L_{2LE} (dI/dt) /4 = 2.9 V



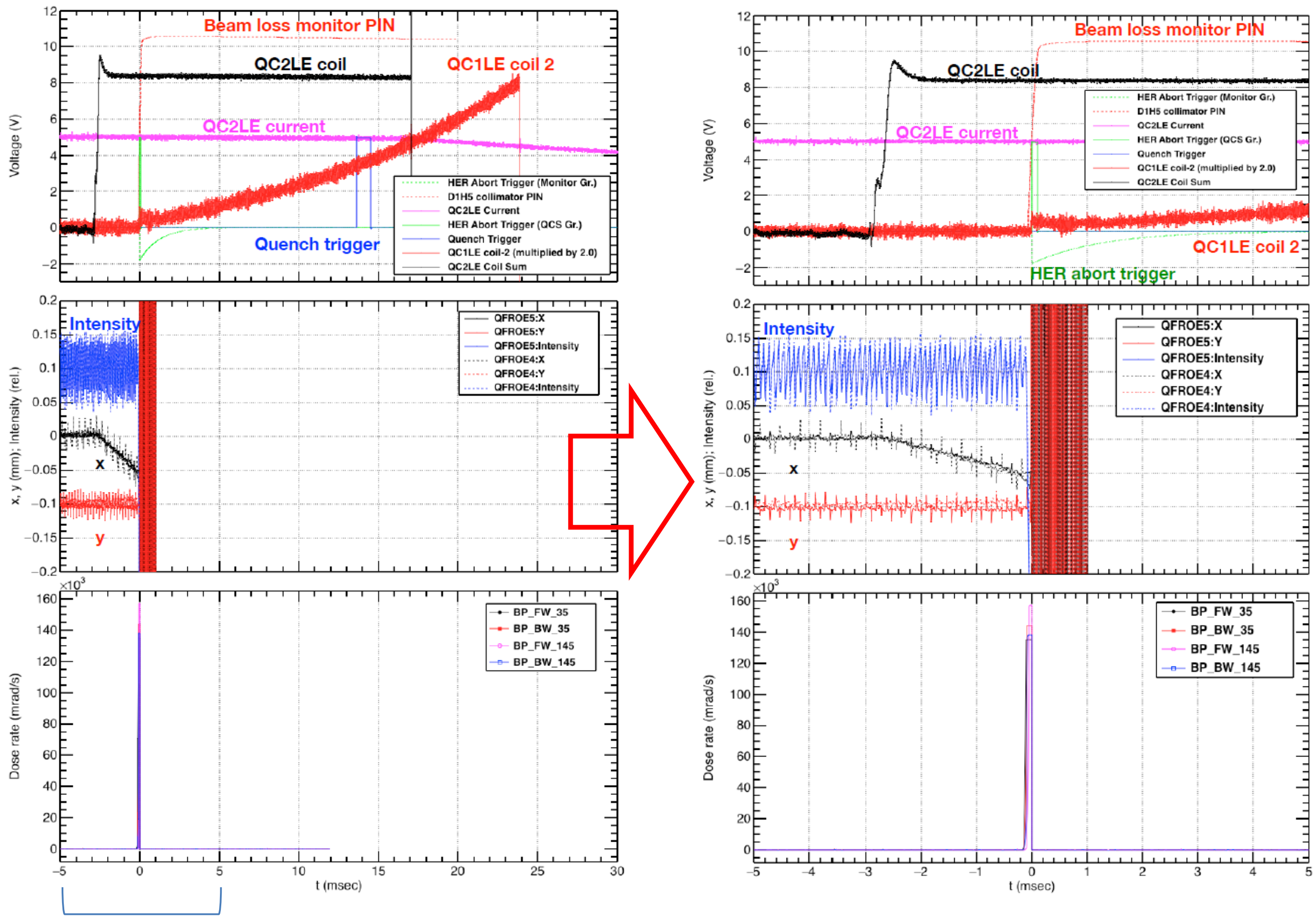
From the report by Y. Arimoto

QCS operation and quench

QCS
&
Beam loss monitor

BPM (Libera)

Diamond detector

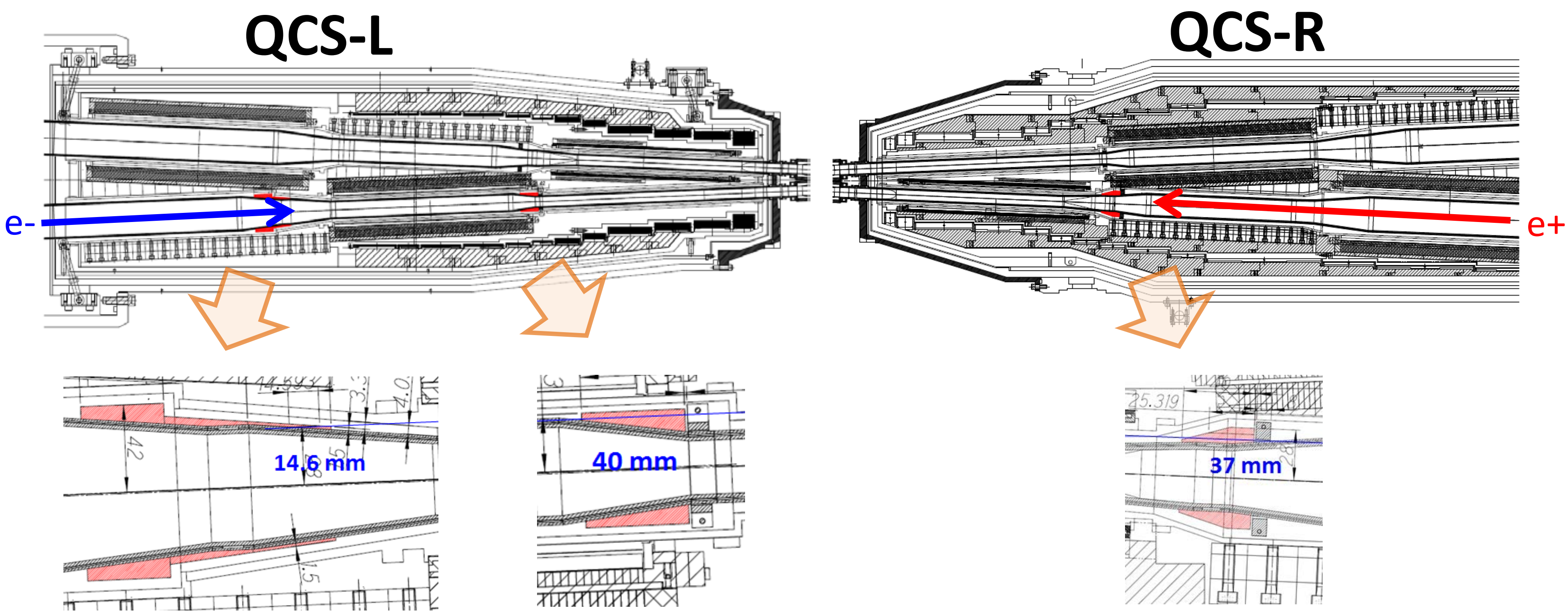


Expanded in the right plots

From the report by Y. Arimoto

QCS operation and quench

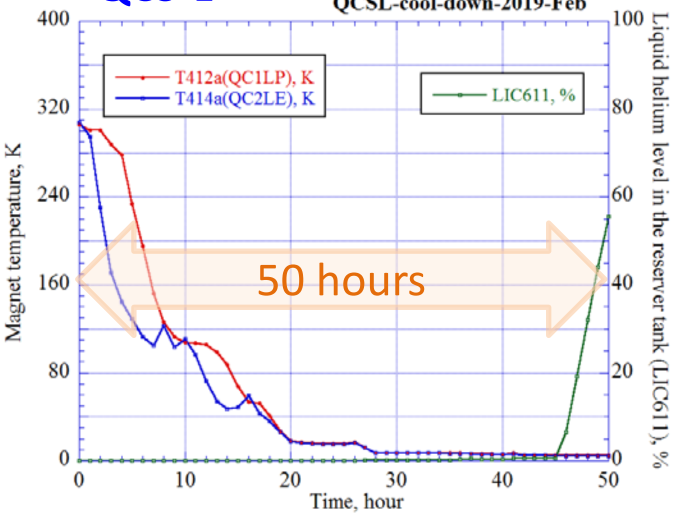
- The countermeasure to the quenches of the QC1 magnets has been proposed to assemble the W alloy shield on the incoming beam pipes by the QCS group.
  - The QCS group is waiting for the beam simulation results contained these shields concerning for the effectivity of the magnet quench protection.



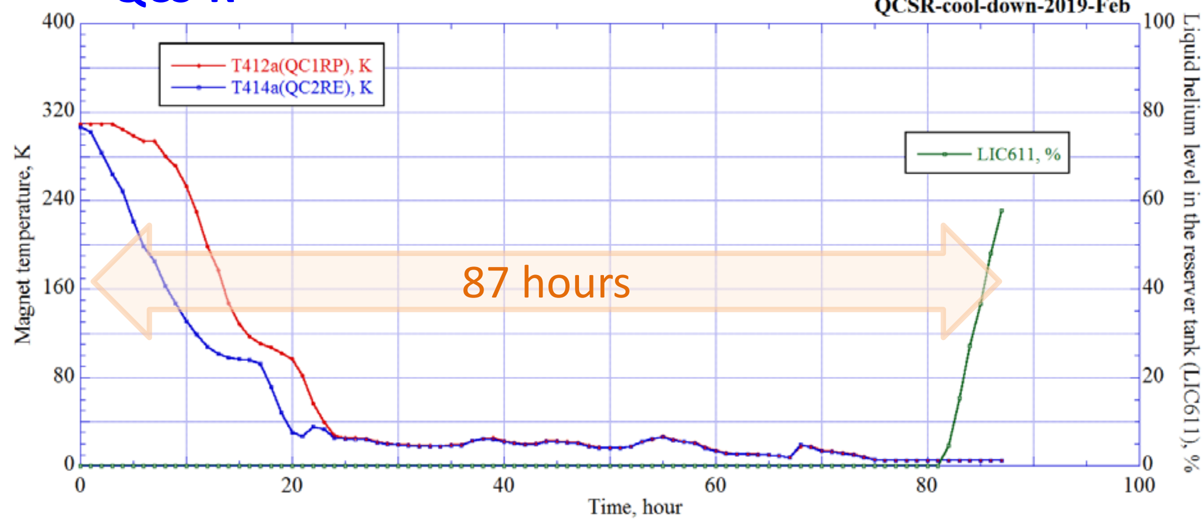
QCS operation and quench

Cool-down of the QCSL and QCS-R system

QCS-L



QCS-R



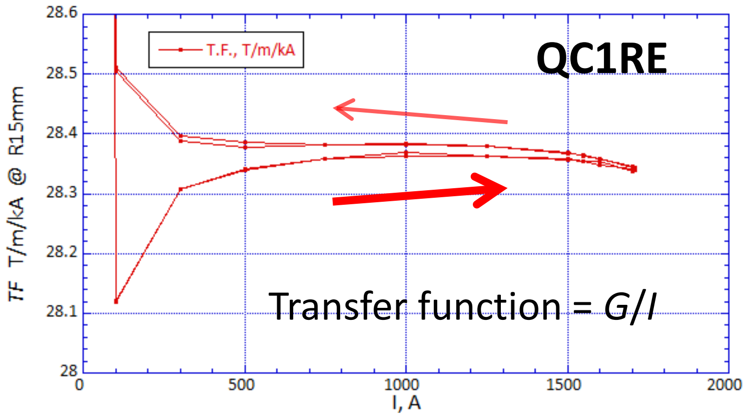
The required time for precooling the magnets to 4 K and immersing the magnets in LHe is longer than the expected time.

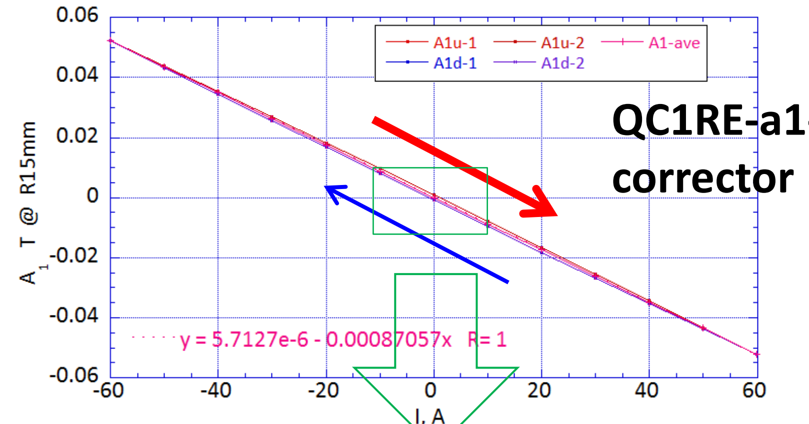
- Especially, from 20 K to the operation of the magnets:
  - QCSL= 30 hours, QCSR=67 hours
- The condition results in the slow recovery from the magnet quench (June 9, 2019).
  - The cause would be an unexpected heat load in the system, etc.
    1. Current leads
    2. Vacuum condition of the thermal insulation spaces
    3. Unoptimized operational procedure of the cryogenic system for the new QCS

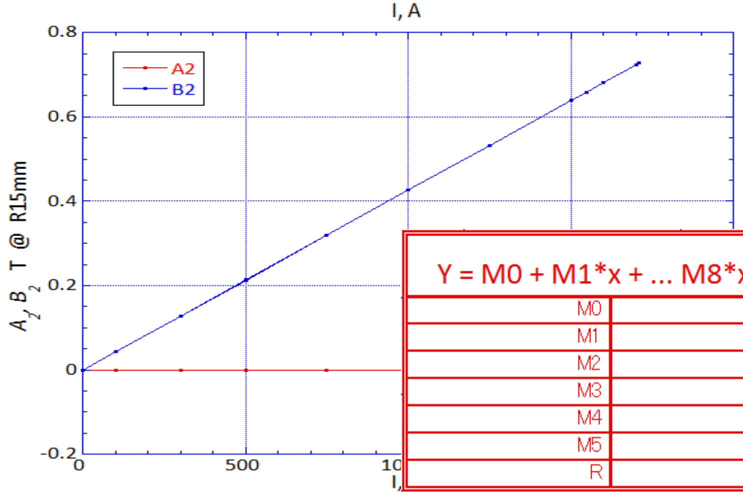
Magnetic field of QCS

All superconducting magnets have the hysteresis effect in the magnetic field.

- The exciting functions of the main quadrupole magnets are defined by the 5th polynomial fitting with the data during up-ramping.
- <u>The functions of the correctors are defined by the linear fitting with the averaged data between the up- and down-ramping.</u> ⇒ **Optics Error**

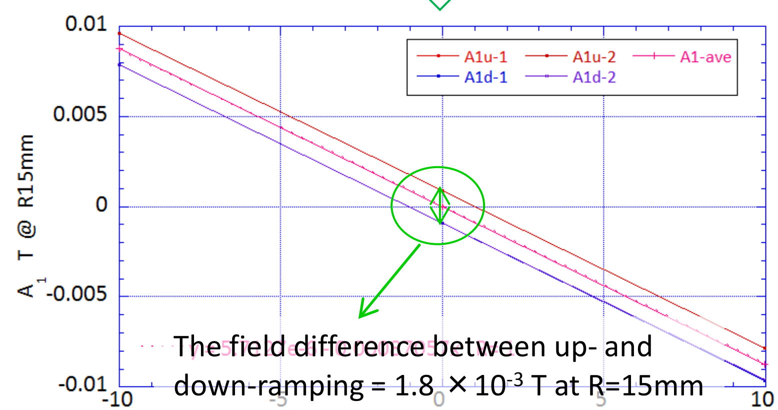






$Y = M0 + M1{*}x + \dots M8{*}x^8 + M9{*}x^9$

M0	−0.00055268
M1	0.00042727
M2	−3.7245e−9
M3	3.9943e−12
M4	−1.7664e−15
M5	1.9351e−19
R	1



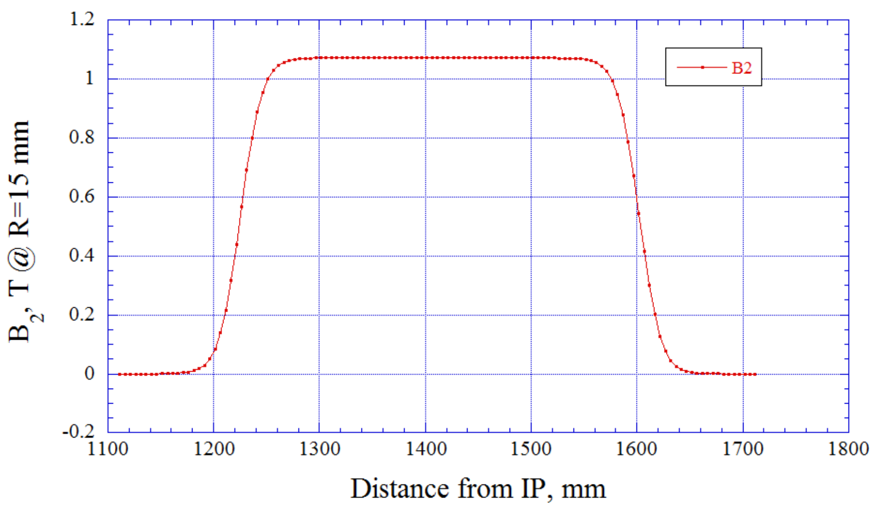
The field difference between up- and down-ramping = 1.8×10^{-3} T at R=15mm (3.5 % of the field strength at 60 A)

Magnetic field of QCS

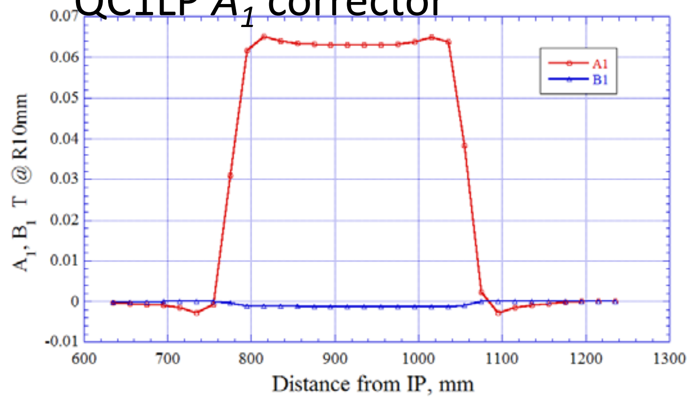
Magnetic field profiles along the beam lines:

1. The field profiles of all quadrupole magnets were reported with the distance function from IP.
2. The field profiles of the correctors are ready to be reported to the optics group.

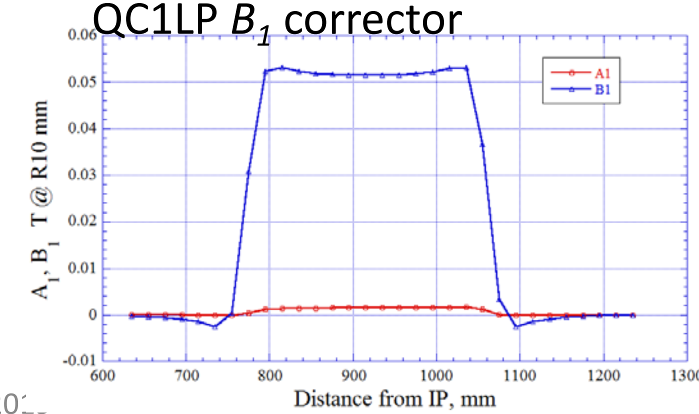
QC1LE B_2 field profile at R=15 mm



QC1LP A_1 corrector



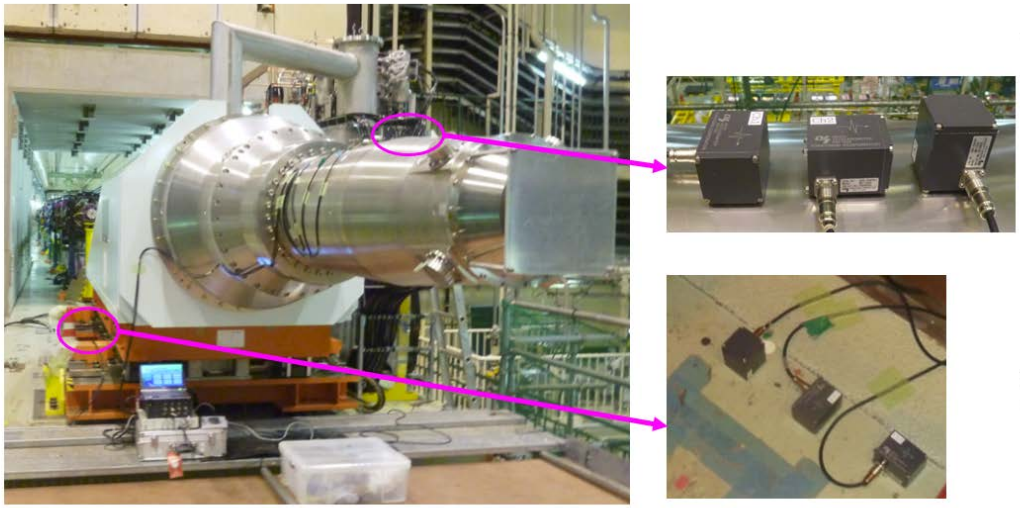
QC1LP B_1 corrector



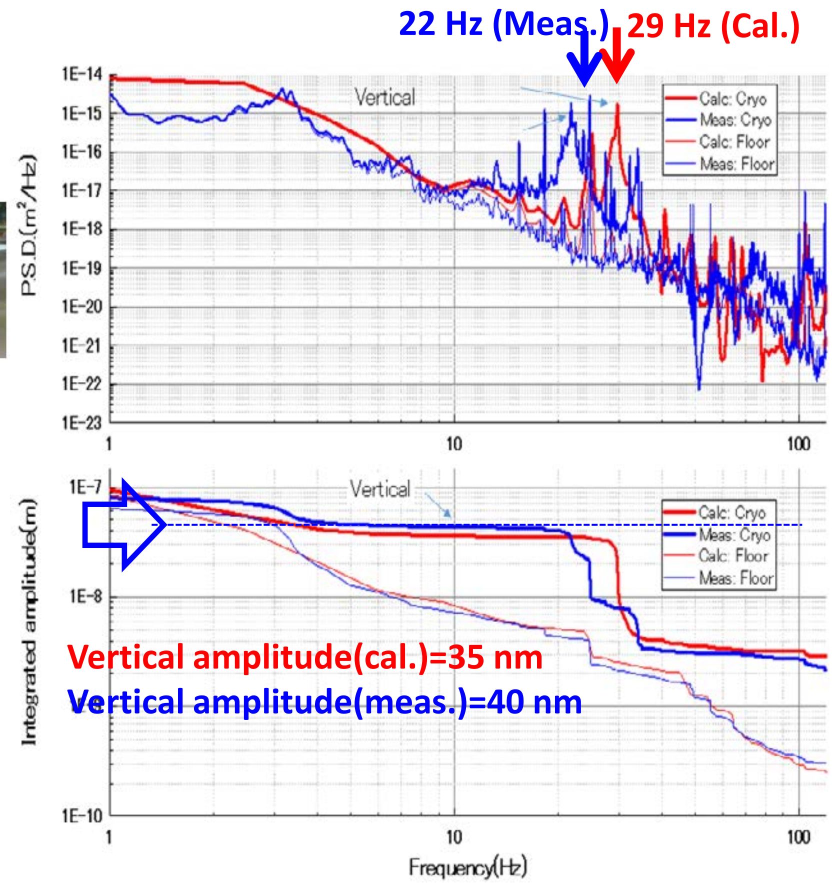
R&D devices and improvement issues

Field vibration measurement probe

Vibration measurement of the QCSL



- We use six acceleration sensors.
- Each sensor measures one direction, 3 sensors to measure (X,Y,Z).
- 2 sets of sensors, one set usually on the floor and the other on the magnet, for example.



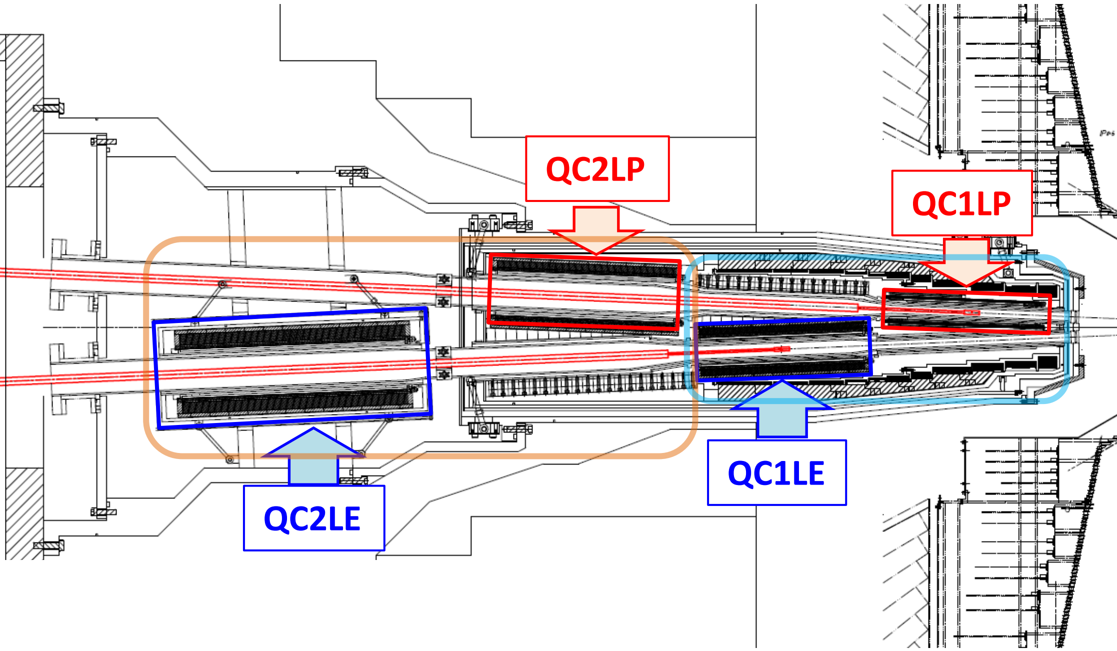
Vibration characteristics of the cryostat vacuum vessel were measured by the accelerator sensors.

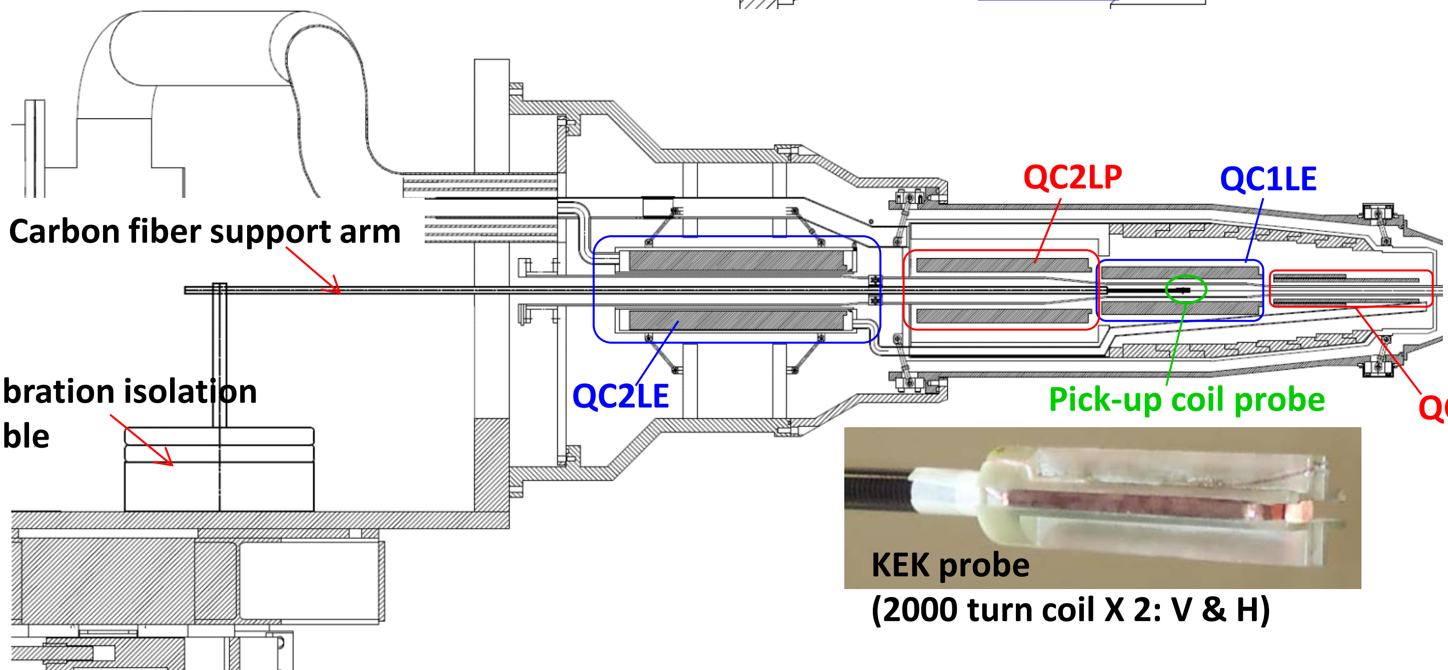
- The measured integrated amplitude at 20 Hz was 40 nm (≅ the design beam size at IP).
- By the measurement, vibration of each quadrupole magnet can not be measured.
- The amplitude of 40 nm has a sufficient degrading effect on Luminosity.

Field vibration measurement sensor

The measurement system of the field vibration is being developed with BNL under the US-Japan research collaboration.
The vibrations of quadrupoles in LER and HER are measured in the same instance.

- **Required key technology:**
  Vibration-free of the probe



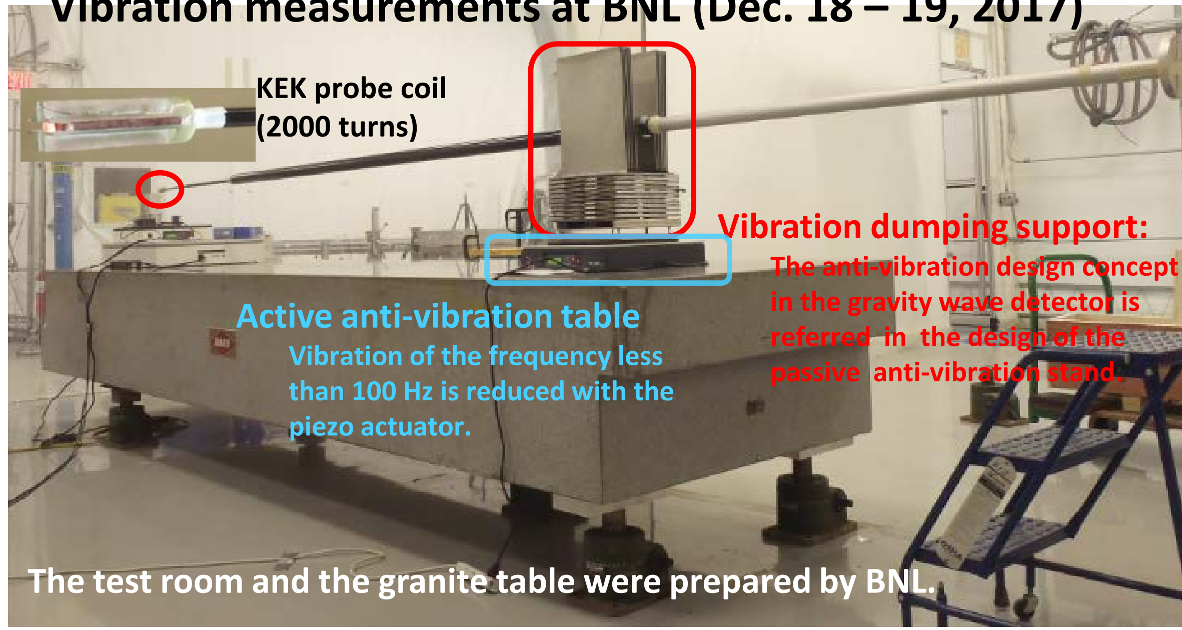


(2000 turn coil X 2: V & H)

Field vibration measurement sensor

Vibration measurements at BNL (Dec. 18 – 19, 2017)

The integrated amplitude of vibration at 10 Hz was reduced to 3 nm in horizontal plane with the single active anti-vibration table.



G10 and CFRP anti-vibration-support

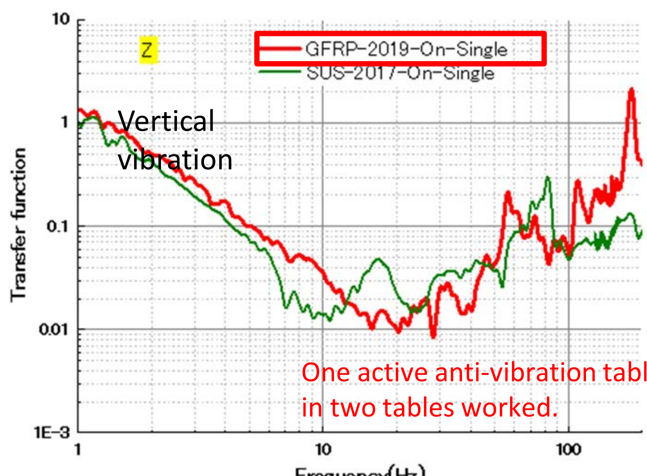
CFRP vertical plate

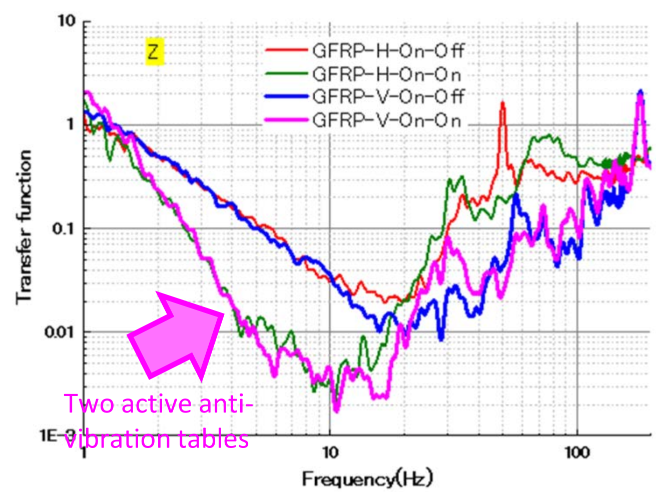
G10 horizontal plate

Double tables

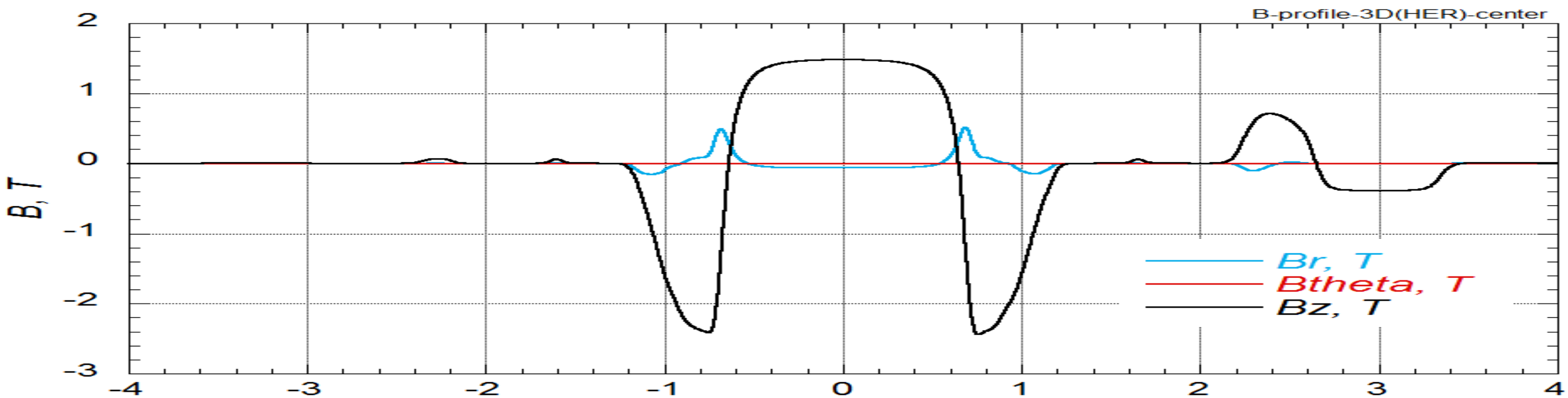
Completed in June, 2019

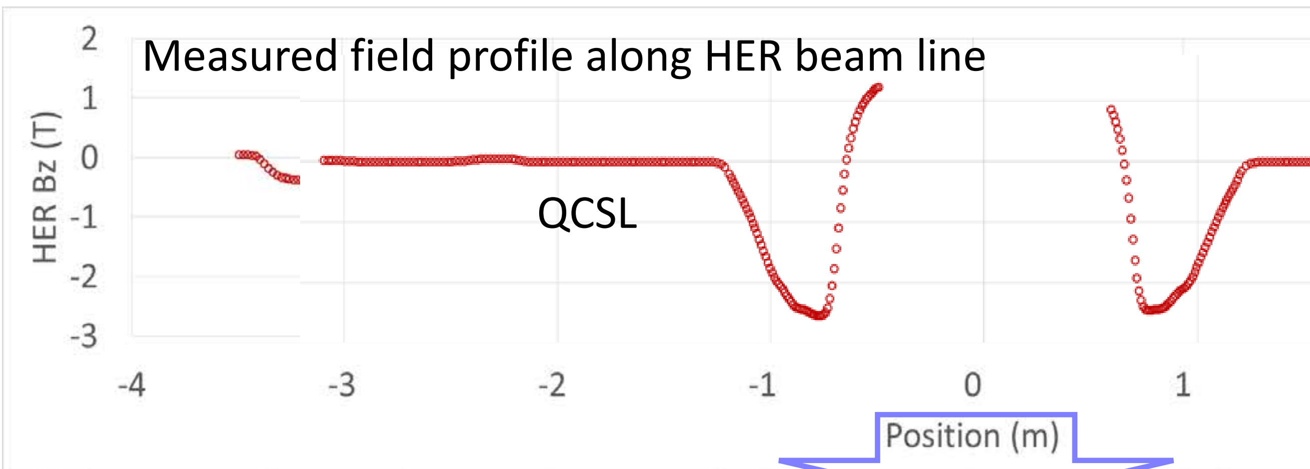
Tra. func. = Vibration on the stage/Vibration of the floor





Hall probe calibration measurement

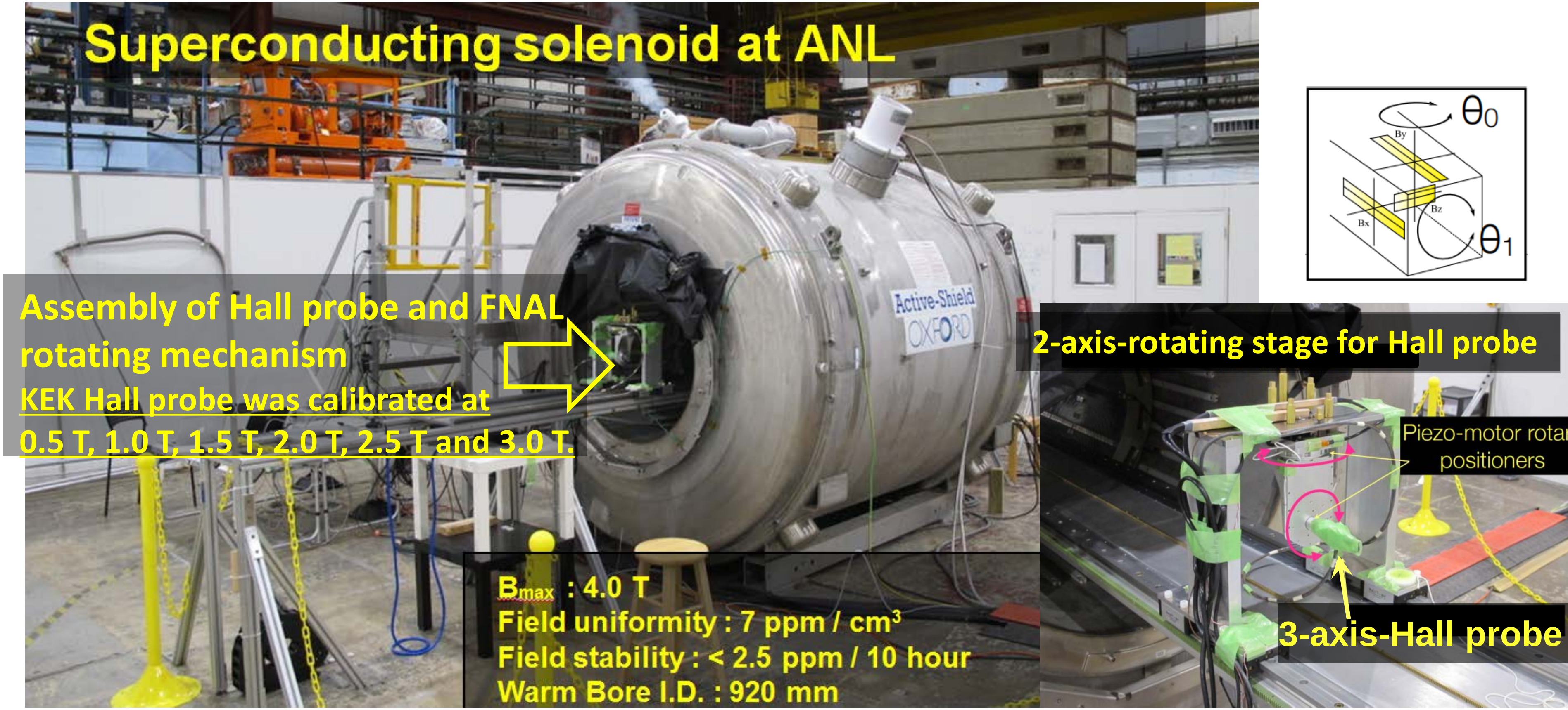




- Field error for beam operation ＜10 Gauss
- Field error for Belle-II detector ＜15 Gauss
- Specification error of 3-axial Hall prove：0.25 % B < 2 T、0.5 % B > 2 T

Requirement of Hall probe calibration

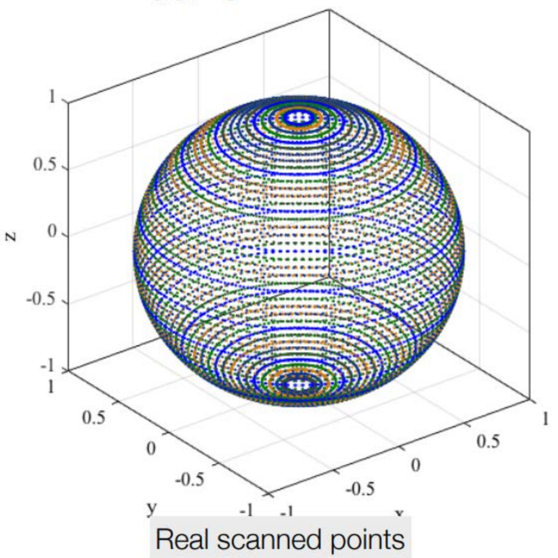
Hall probe calibration measurement

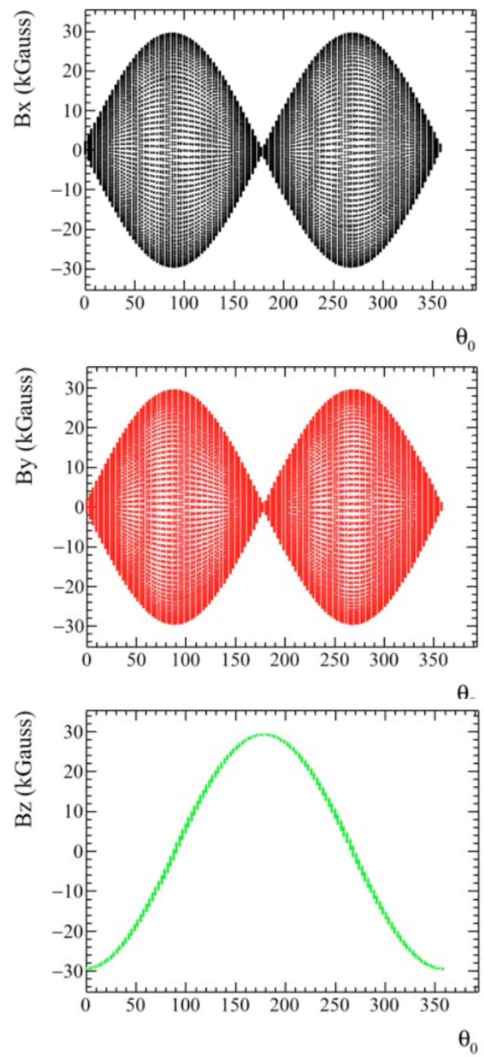


- Research collaboration with FNAL and ANL for the Hall probe calibration measurements
  - FNAL: Hall probe rotation mechanism in the solenoid field and the measurement software
  - ANL: 4 T MRI solenoid and the magnetic field mapping system
  - The first measurements were performed at Dec. 4 - 13, 2018.

Hall probe calibration measurement

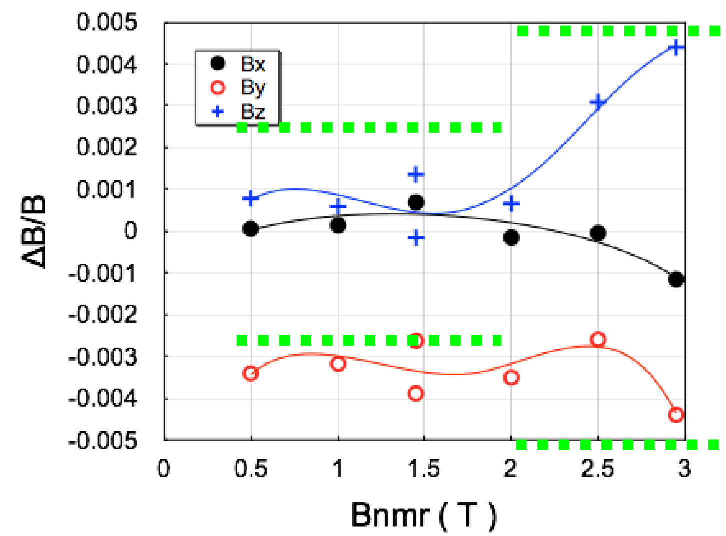
Span: 360°
dθ: 3°
} for θ_0 and θ_1





Calibration measurement results

$$\frac{\Delta B}{B} = \frac{B_{\text{Hall max}} - B_{\text{Hall min}}}{2B_{\text{NMR}}}$$



- The 3-axis Hall probe was calibrated with data of **14600 points** for one absolute magnetic field by the MRI solenoid.
- Measurement time = ~8 hours

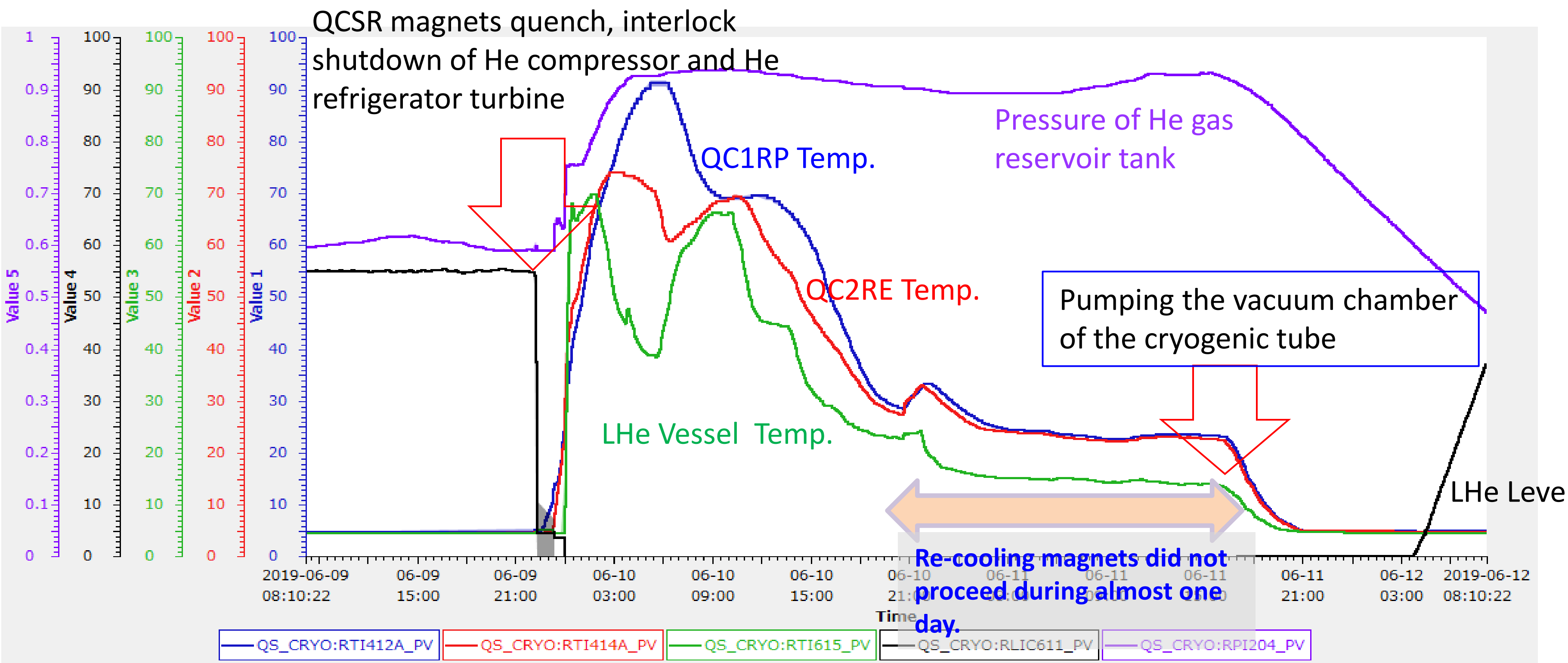
Hall probe calibration measurement

- Field calibration points of the Hall probe in Dec. 4~Dec. 12, 2018
  - With the 24 magnetic field strengths, the KEK Hall probe was planted to be calibrated.
  - The calibrated magnetic fields by the ANL MRI solenoid were 6 points, which are shown in the red points in the table.
- In Sept. or Oct. 2019, we plan to perform the measurement at 12 field points.
  - The field points are shown by the blue points in the table.
  - We would like to complete the measurements in 10 days.
- After the measurements in FNAL/ANL in Sept. or Oct. 2019.
  - The calibration measurements less than 1.5 T with the 1.5 T MRI solenoid in the KEK cryogenic science center.
  - The FNAL mover and driver will be used in the measurement with the kind cooperation of FNAL.

No.	Magnetic field, T	@FNAL/ANL 2018	@FNAL/ANL 2019	@KEK-Cryogenic center
1	0			○
2	0.1			○
3	0.2			○
4	0.3		●	○
5	0.4			○
6	0.5	●	●	○
7	0.6			○
8	0.7		●	○
9	0.8			○
10	0.9			○
11	1.0	●	●	○
12	1.2			○
13	1.1			○
14	1.3		●	○
15	1.4			○
16	1.5	●	●	○
17	1.75		●	
18	2.0	●	●	
19	2.25		●	
20	2.5	●	●	
21	2.75		●	
22	3.0	●	●	

Improvement of the cryogenic cooling margin

After the QCSR quench and He compressor stop at 22:11 June 9th 2019, it took about 60 hours to excite the QCSR magnets again.



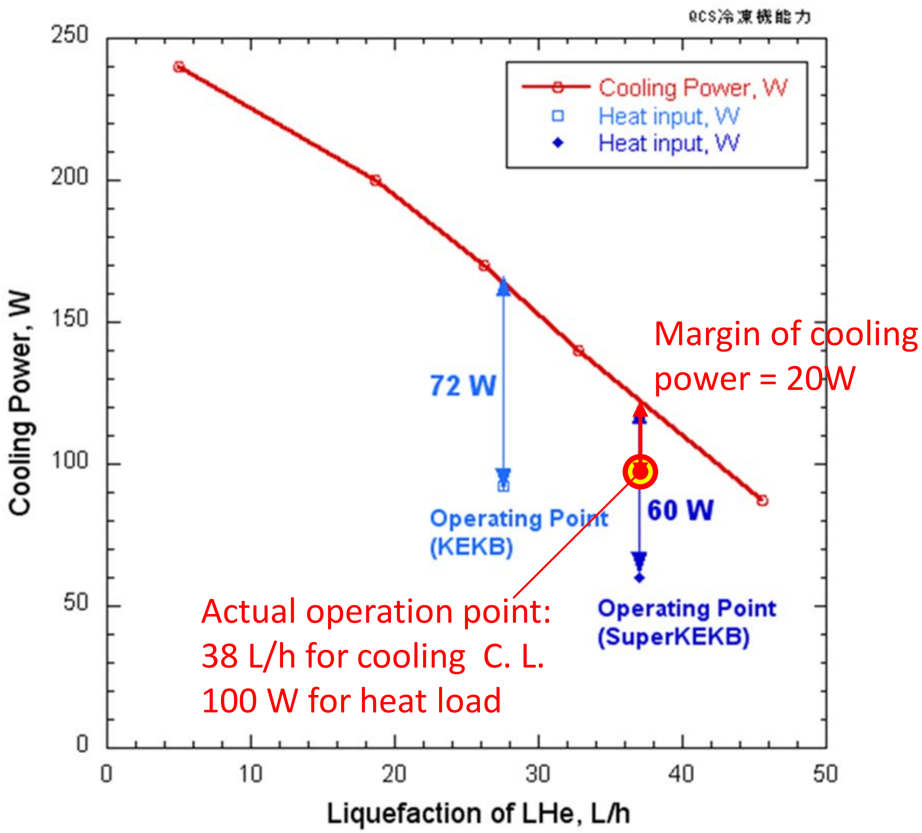
The cause of the delay of the re-cooling magnets to 4 K:

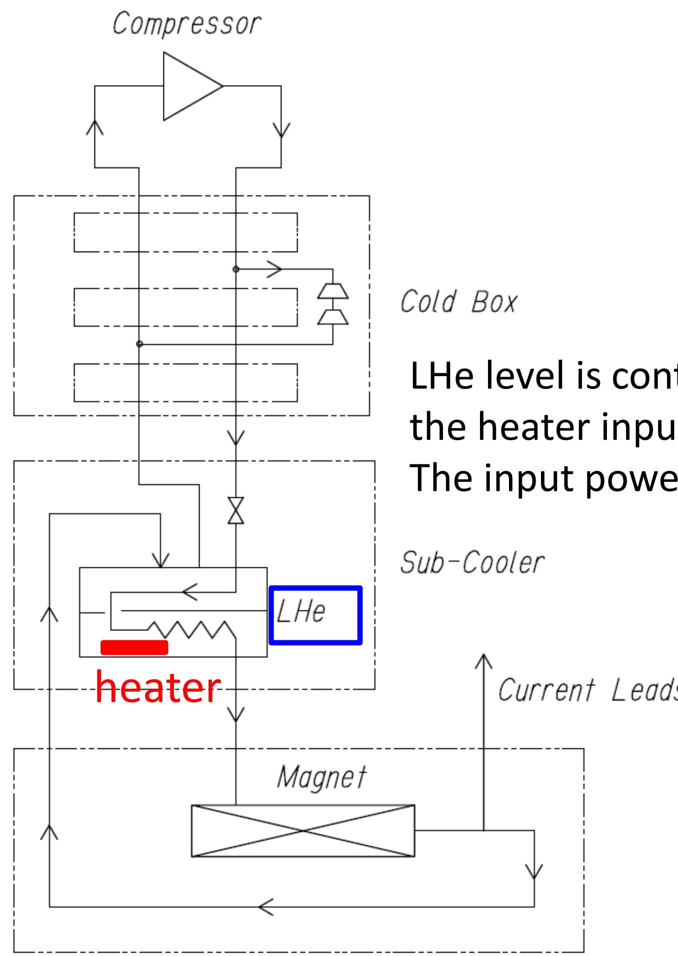
1. Relatively small margin of the cooling power of the He refrigerator w.r.t. the heat load,
2. Vacuum degradation in the thermal insulation spaces of the cryostat and the cryogenic transfer tube due to outgassing by stopping the liquid helium flow.

Improvement of the cryogenic cooling margin

The QCSL and QCSR cryogenic systems have the cooling margin of 20 W, individually, to the total cooling power of 240 W @ 4.5 K.

Cooling power of the QCS cryogenic system





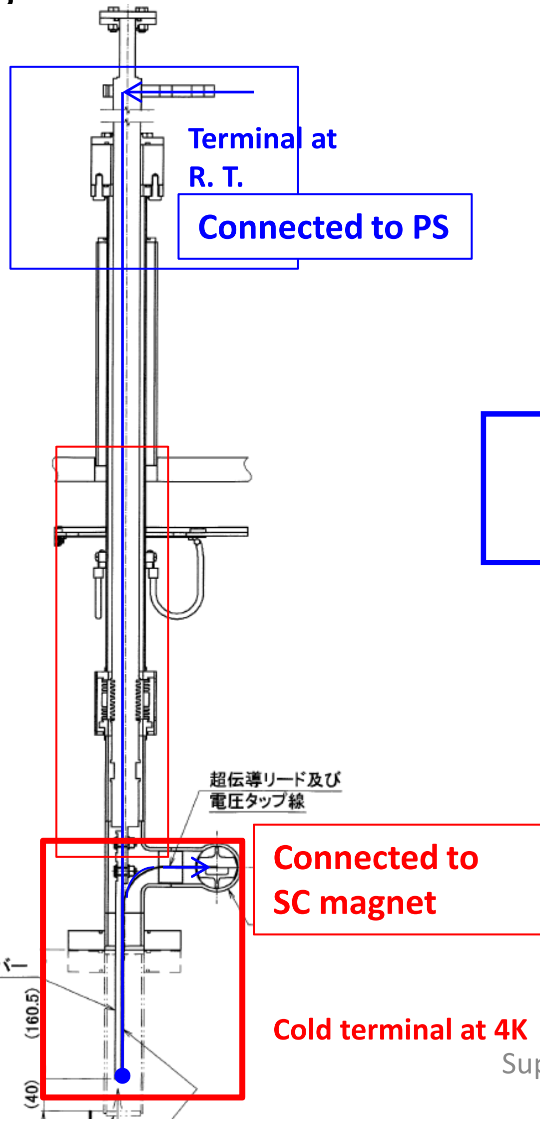
LHe level is controlled by the heater input.
The input power is 20 W.

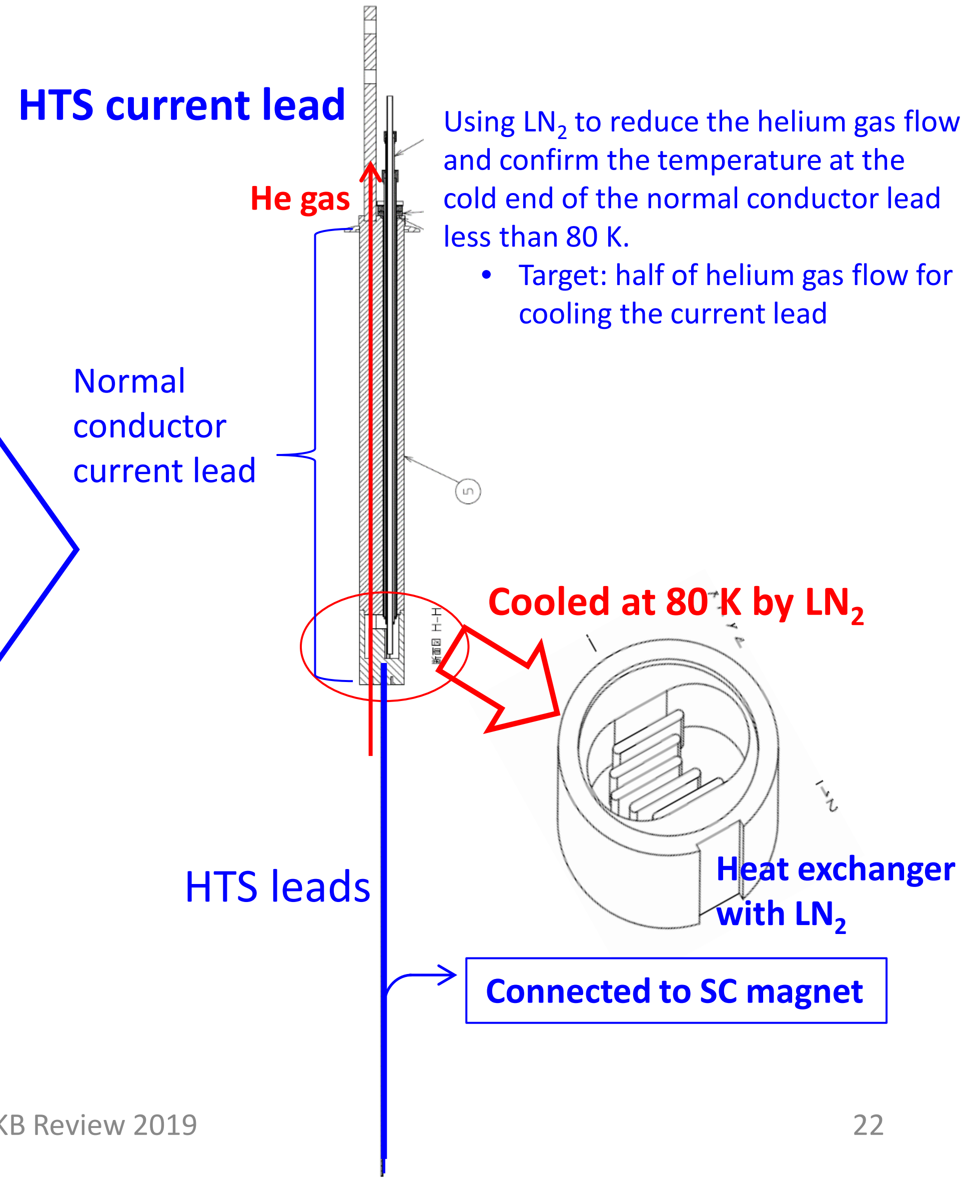
Improvement of the cryogenic cooling margin

The countermeasure to this thermal conditions is the reduction of amount of LHe for cooling the current leads.

Present 2000 A current lead (cooled with the evaporated helium gas)

Heat exchanger (Electrical conductor)





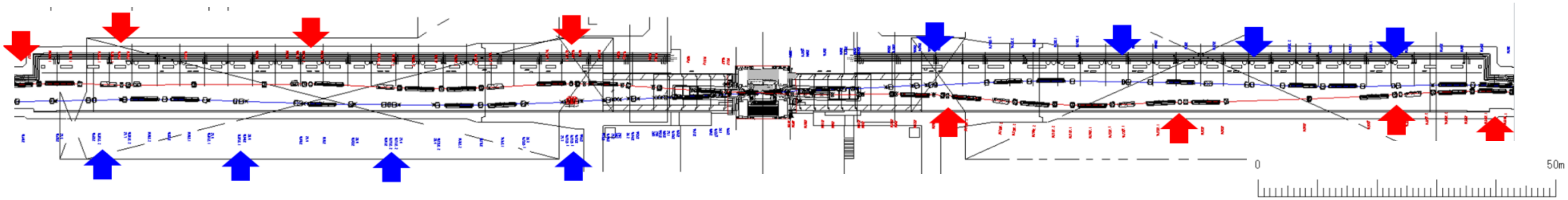
Using LN_2 to reduce the helium gas flow and confirm the temperature at the cold end of the normal conductor lead less than 80 K.

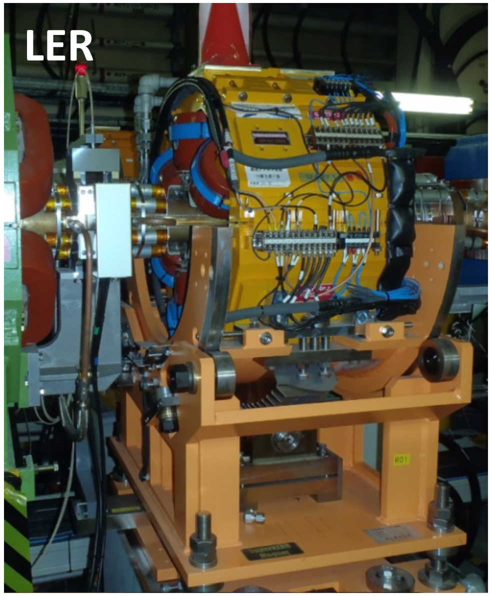
- Target: half of helium gas flow for cooling the current lead

Development of SC sextupole magnet

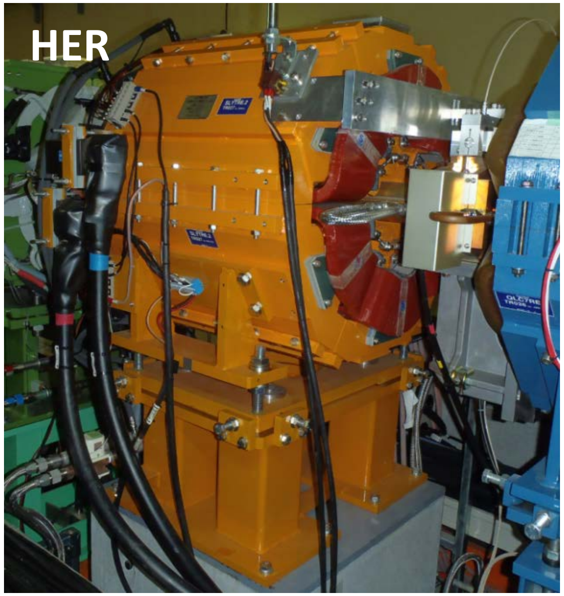
Sophisticate normal sextupole magnet system in the Tsukuba beam straight section

- The system consists of three types of the sextupole magnets.
- The required maximum GL=234 T/m





The sextupole magnet has a function of rotation.
G_D = 340 T/m^2, L_{eff} = 300 mm



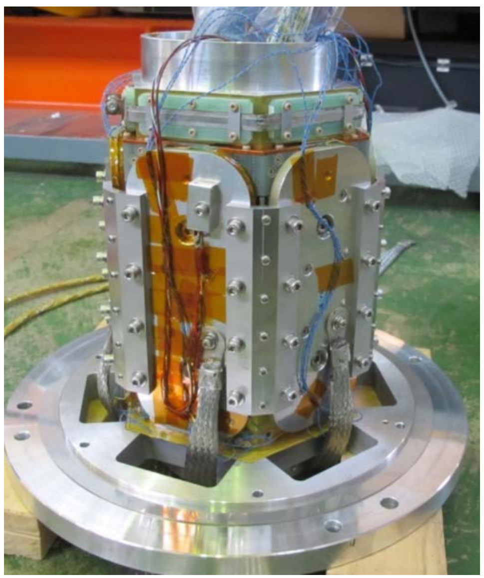
G_D = 480 T/m^2, L_{eff} = 600 mm

G_D = 480 T/m^2, L_{eff} = 500 mm

Development of SC sextupole magnet

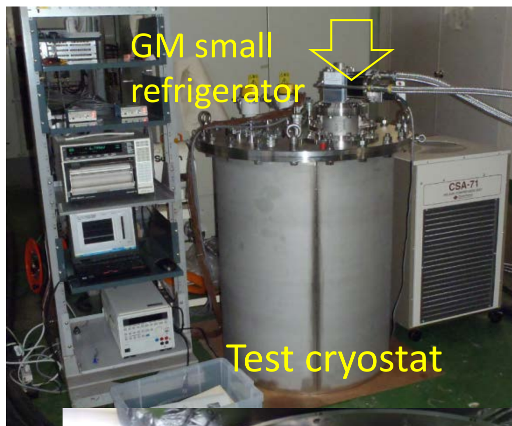
The superconducting sextupole magnet is being studied for the system.

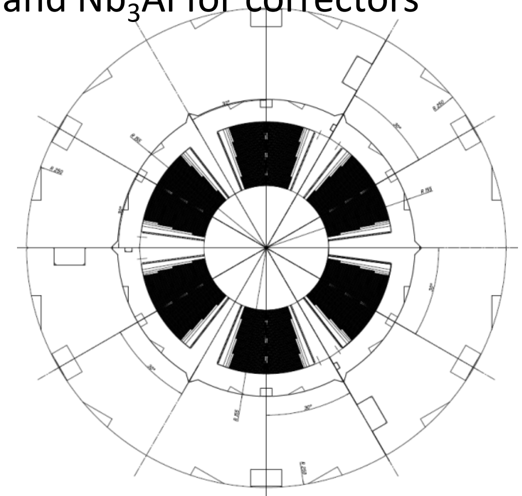
- G_D = 800 T/m^2
- Corrector magnets: a_3, b_2, a_2
- Small refrigerator cooling
  - The sextupole magnets are placed along the distance of 250 m including IP.
- Superconductor: HTS (REBCO) or Nb_3Sn for the sextupole, and Nb_3Al for correctors

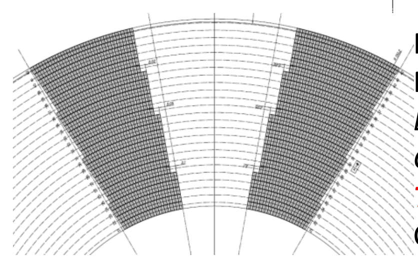


HTS (REBCO) sextupole magnet:

- The magnet was tested in KEK.
- Double pancake race track coils
- G=213.08 T/m^2 @ 4.2 K and 250 A







Nb_3Sn sextupole magnet
Max. B in coil= 6.02 T
D_{in} = 135 mm
G=890 T/m^2 @ 500 A
T_c= 12 K
Current density=730 A/mm^2

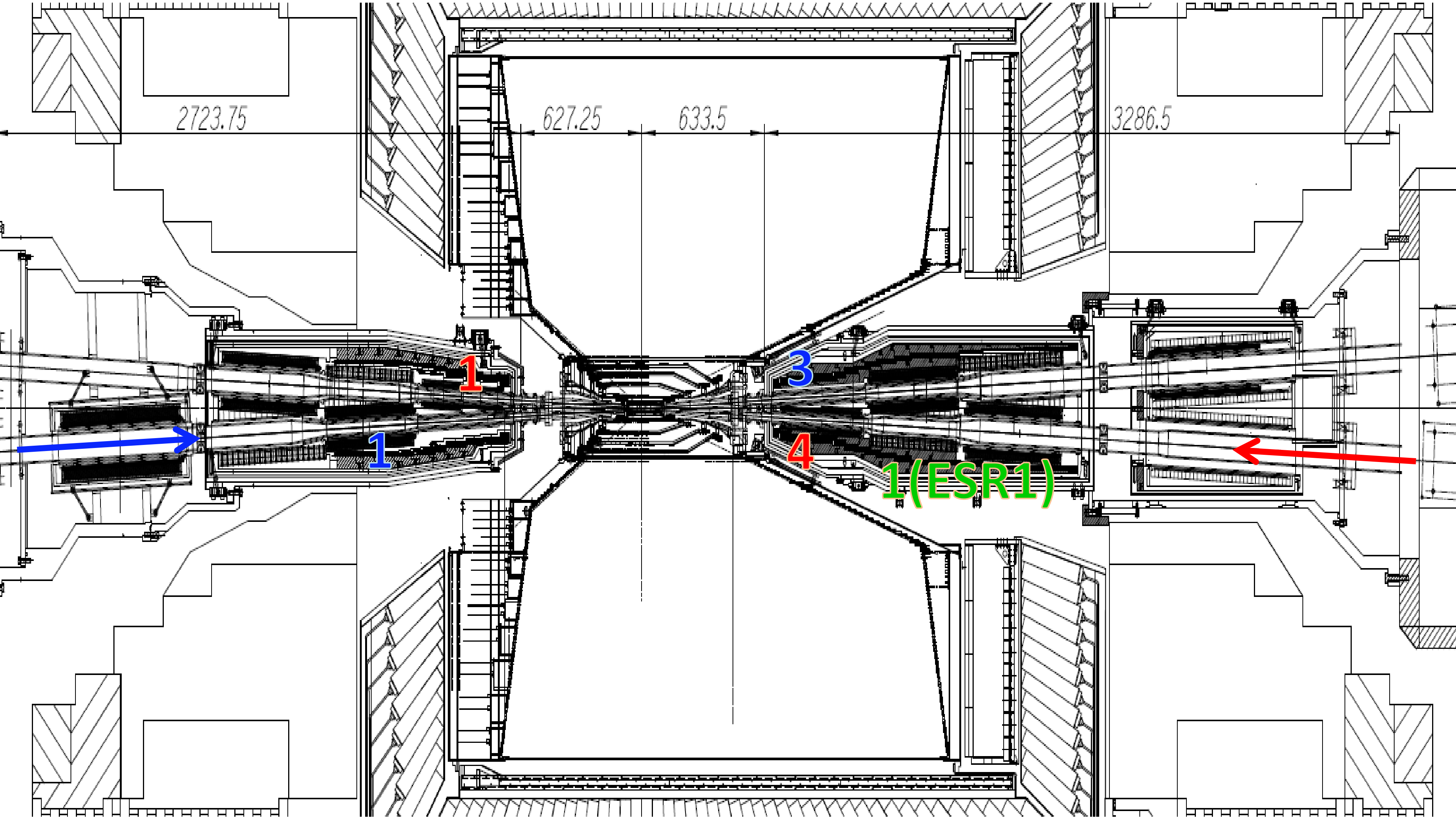
The Nb_3Sn and Nb_3Al cables are the candidates for the QCS upgrade.

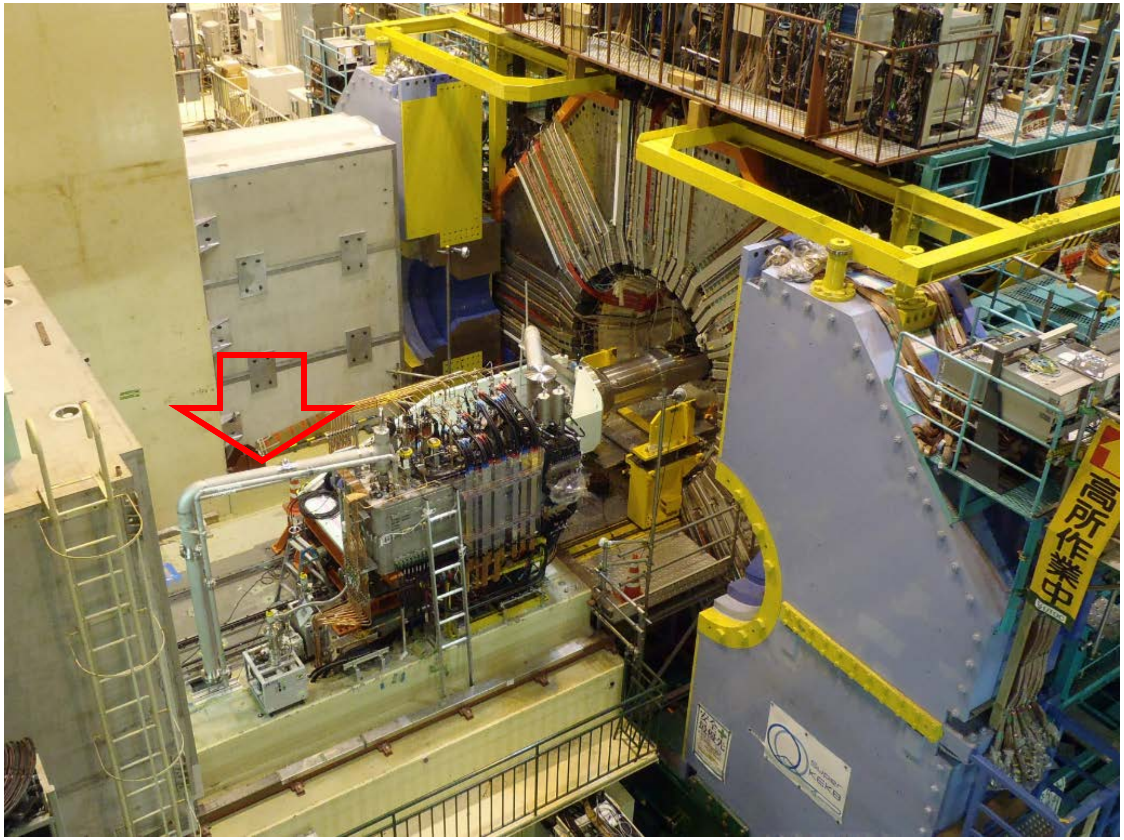
Summary

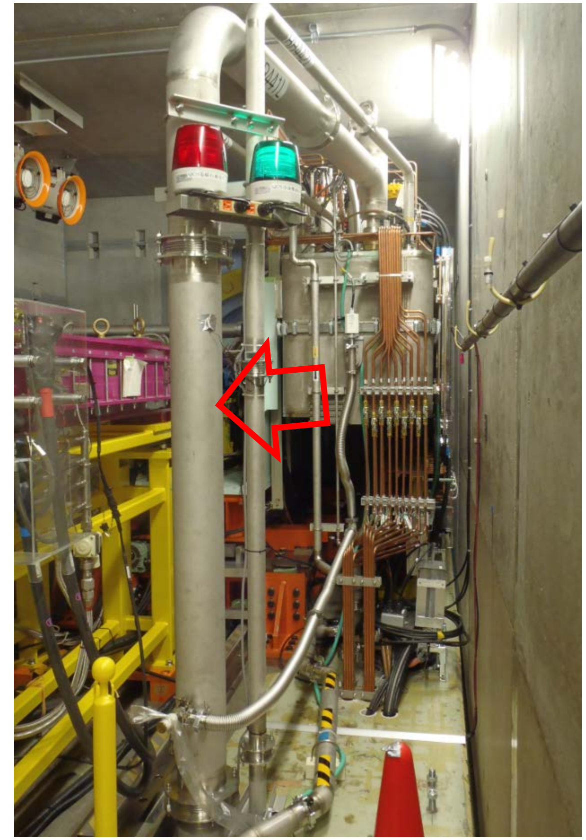
- QCS operation in Phase-2 and Phase-3
  1. 32 events of QCS quench happened in 31 weeks.
  2. The collimator and beam abort system were strengthened, and the number of the quench event was reduced.
  3. The monitor and the data logger systems of the magnet quench are improved, and they are well working for the quench diagnosis.
  4. For the quick recovery from the magnet quench and shortening the cool-down time from room temperature, the cryogenic system should be studied in terms of the origin of the heat load.
- R&D devices and improvement issues
  1. Magnetic field vibration measurement probe
     - Anti-vibration mechanism is almost completed, and the performance will be confirmed in September in BNL.
  2. Hall probe calibration measurement for the solenoid field profiles
     - The calibration measurement will be completed in 2019, and the up-date of the solenoid field will be available in the beam operation in 2020.
  3. HTS current lead
     - The development of the new HTS leads has started right now. The leads will reduce the heat load of the cryogenic system.
  4. SC sextupole magnet in IR beam straight section
     - HTS, Nb_3Sn, Nb_3Al materials are being studied for the sextupole magnet.
     - The magnet is designed to be cooled with the small refrigerator.

Back up

Quenched magnets by beams in Phase-3







QCSR main cryogenic transfer tube: 24.3 deg. C
Bypass cryogenic transfer tube: 25.1 deg. C

QCSL main cryogenic transfer tube: 25.0 deg. C
Bypass cryogenic transfer tube: 25.4 deg. C

Pumping the residual gas in the vacuum chamber of the tube.
At opening the cock of the chamber:
3.5×10^{-3} Pa $\rightarrow$ 5.9×10^{-3} Pa.