Status of the Superconducting Final Focus Magnet at SuperKEKB

N. Ohuchi

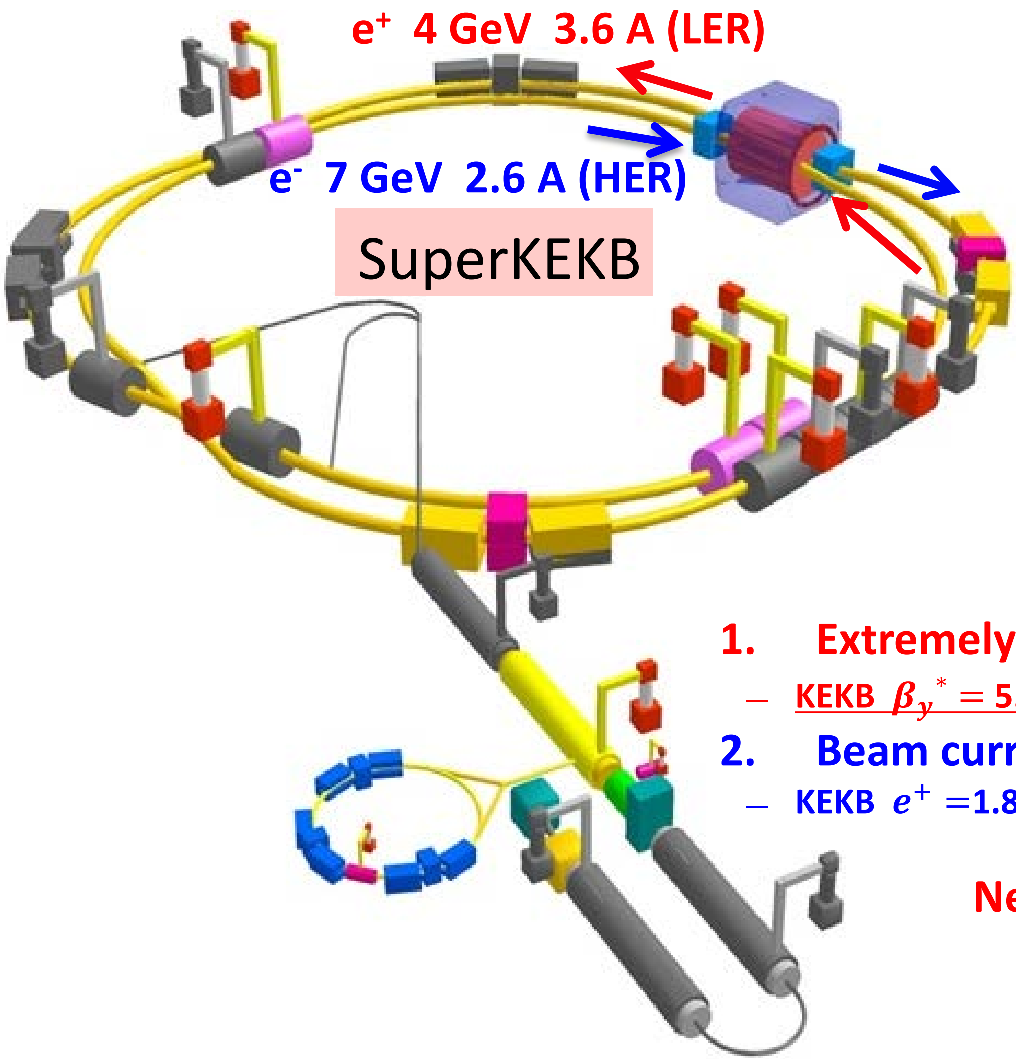
Y. Arimoto, H. Yamaoka, M. Kawai, Z. Zong, X. Wang, K. Aoki, R. Ueki, K. Tsuchiya

KEK, High Energy Accelerator Research Organization

Contents

1. SuperKEKB Interaction region (IR)
2. IR superconducting magnets
3. Operation of superconducting magnets in SuperKEKB Phase-2 and 3 commissioning
4. Summary

SuperKEKB



KEKB ⇨ SuperKEKB

$L = 2.1 \times 10^{34} cm^{-2}s^{-1}$ → $8 \times 10^{35} cm^{-2}s^{-1}$

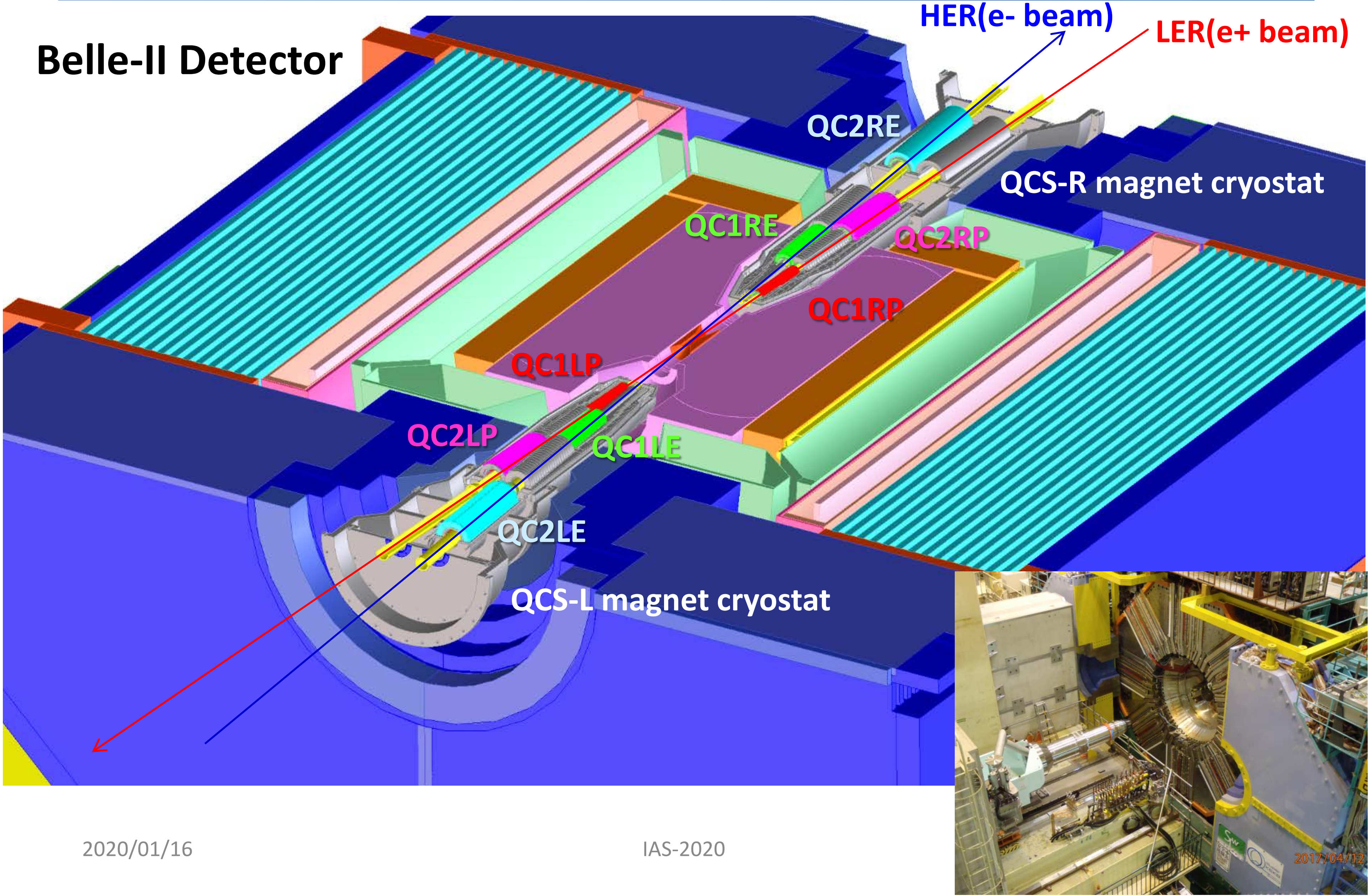
Feb. – Jun. 2016 : Phase-1 commissioning
Mar. – Jul. 2018: Phase-2 commissioning
Mar. 2019 –: Phase-3 commissioning

1. **Extremely small β_y^***
   - KEKB $\beta_y^* = 5.9$ mm→ SuperKEKB $\beta_y^* = 0.27$ (LER), 0.30 (HER)
2. **Beam current double**
   - KEKB $e^+ = 1.8$ A, $e^- = 1.3$ A → SuperKEKB $e^+ = 3.6$ A, $e^- = 2.6$ A

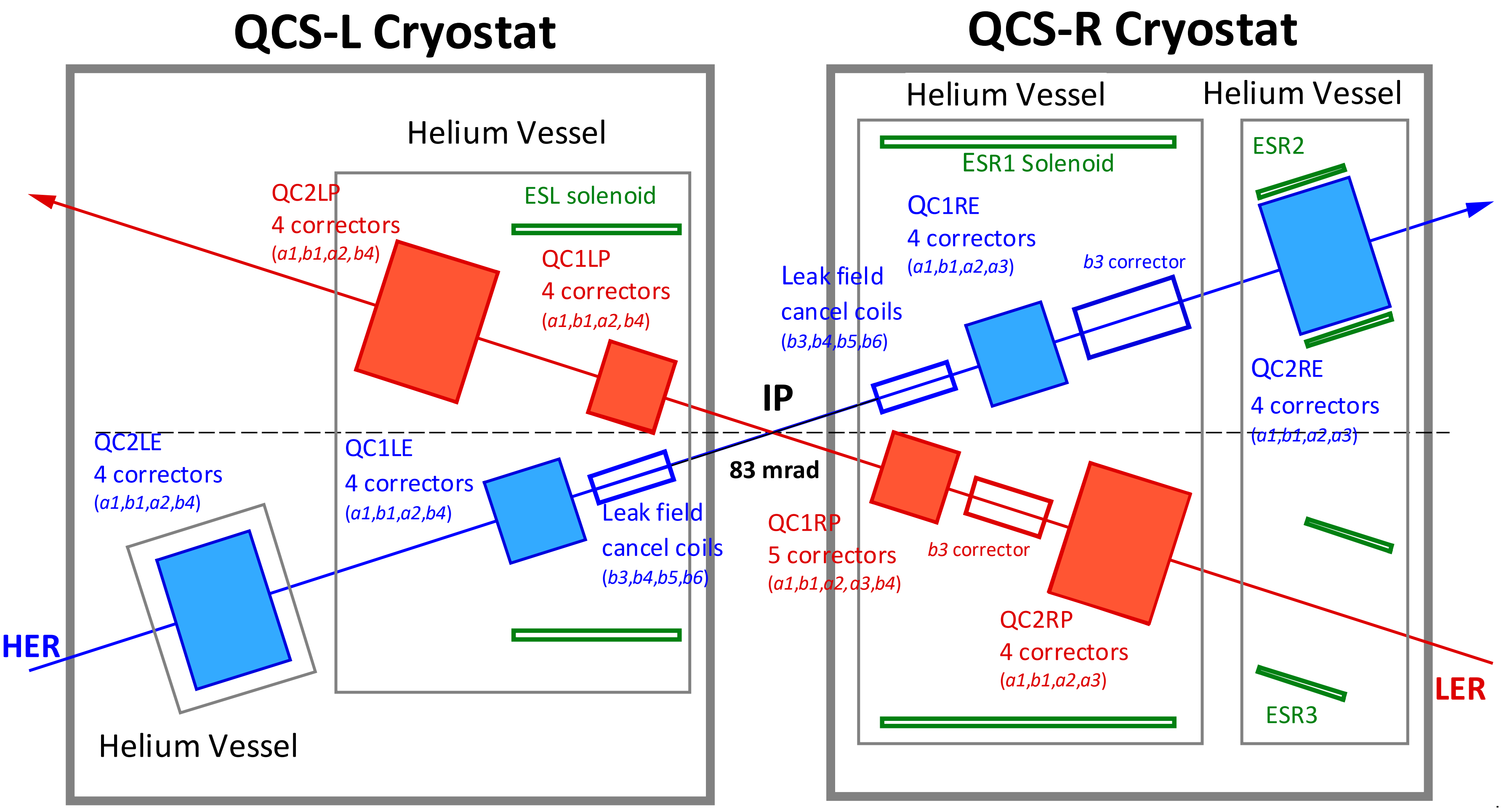
New Final Focus System

Beam size: e^- =48 nm, e^+=62 nm at IP

SuperKEKB IR Overview



Configuration of IR magnets



25 SC magnets in QCSL

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

30 SC magnets in QCSR

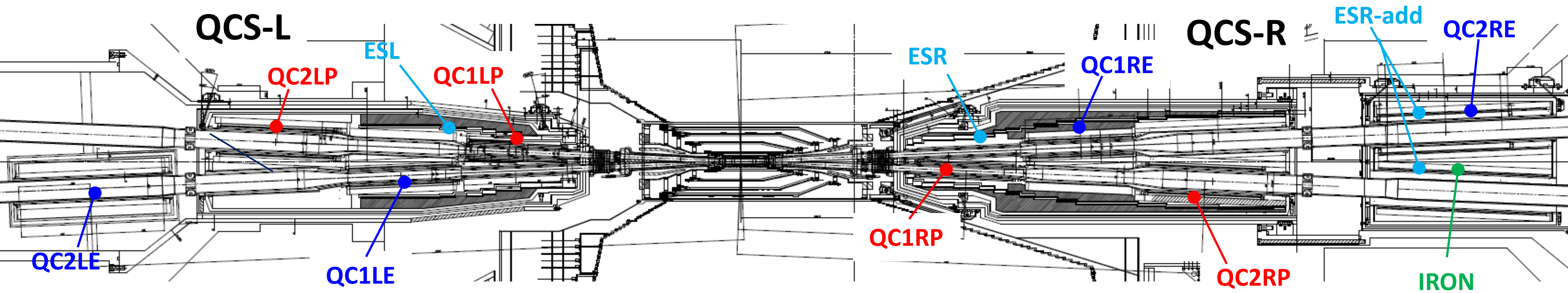
4 SC main quadrupole magnets: 1 collared magnet, 3 yoked magnets
19 SC correctors: a1, b1, a2, a3, b3, b4
4 SC leak field cancel magnets: b3, b4, b5, b6
3 compensation solenoid

IR SC magnets

- Main quadrupoles [QC1, QC2]: 8 magnets
  - Forming final beam focusing system with quadrupole doublets.
- Correctors [a_1, b_1, a_2, a_3, b_3, b_4]: 35 magnets
  - a_1, b_1, a_2: magnetic alignment of the magnetic center and the mid-plane phase angle of main quadruple.
  - a_3, b_3: correction of sextupoles induced by magnet construction errors.
  - b_4:increasing the dynamic transverse aperture (increasing the Touschek life time).
- Compensation solenoid[ESR, ESL]: 4 magnets
  - Canceling the integral solenoid field by the particle detector (Belle II).
  - By tuning the B_z profile, the beam vertical emittance is designed to be minimized.
  - The compensation solenoids are designed to be overlaid on the main quadrupoles and correctors.
  - ESR consists of three solenoid magnets of ESR1, ESR2 and ESR3.
- Leak field cancel coils [b_3, b_4 , b_5, b_6]: 8 magnets
  - Canceling the leak field on the electron beam line from QC1P (collared magnet).
- <u>Total number of the SC devices in two cryostats = 55</u>

IR SC magnets

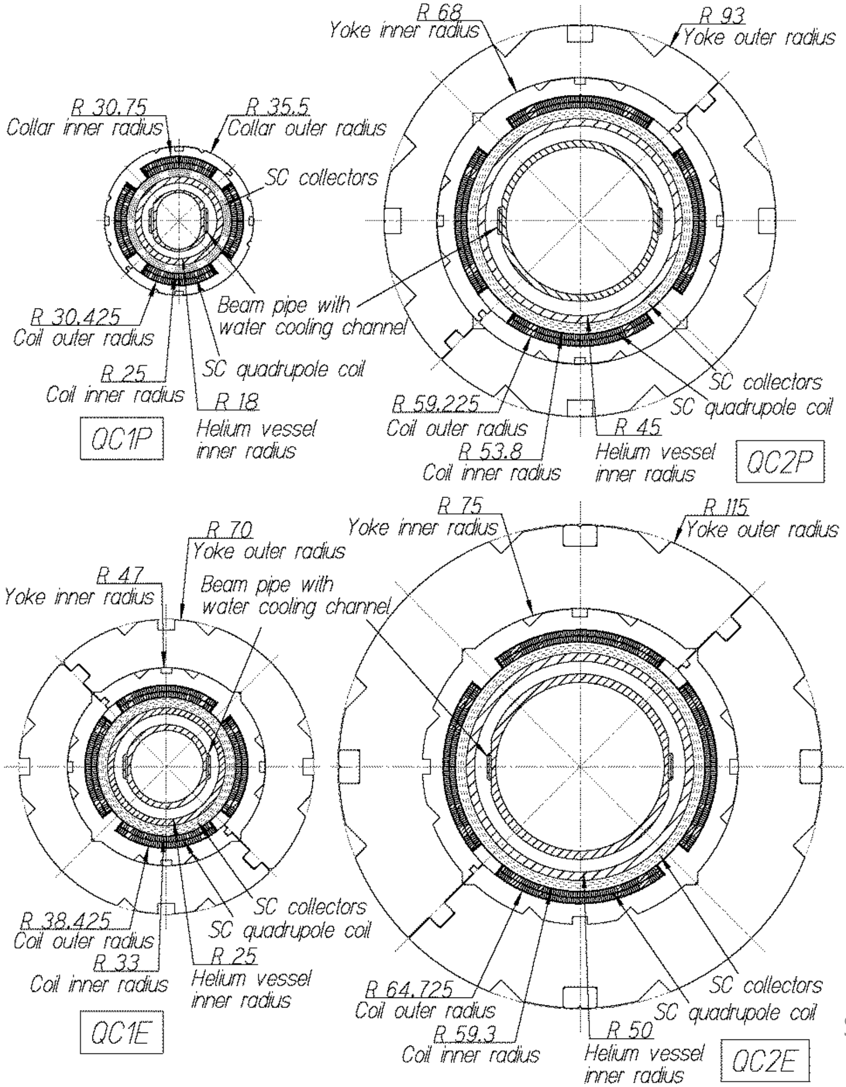
- Main quadrupoles [QC1, QC2]
  - QC1L(R)P, QC2L(R)P for the left (right) side cryostat to IP and for the positron beam line.
  - QC1L(R)E, QC2L(R)E for the left (right) side cryostat to IP and for the electron beam line.



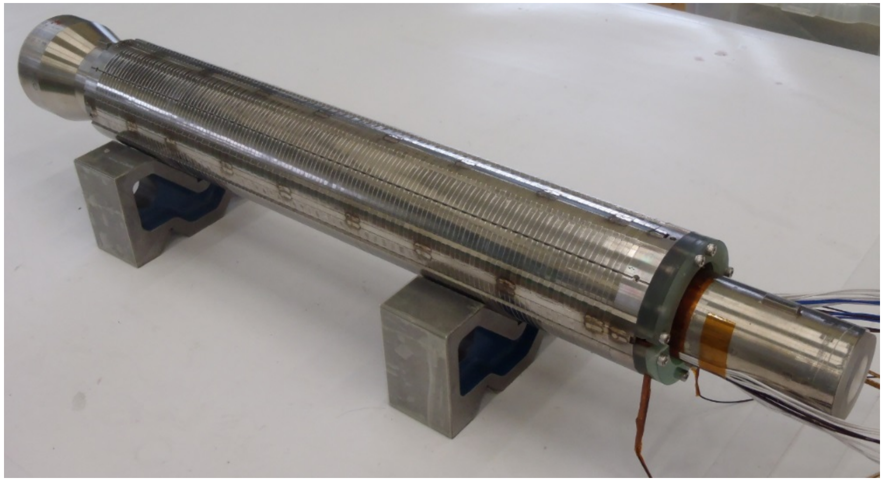
	Integral field gradient, (T/m)·m	Magnet type	Z pos. from IP, mm	θ, mrad	ΔX, mm	ΔY, mm
QC2RE	13.58 [32.41 T/m × 0.419m]	Iron Yoke	2925	0	-0.7	0
QC2RP	11.56 [26.28 × 0.410]	Permendur Yoke	1925	-2.114	0	-1.0
QC1RE	26.45 [70.89×0.373]	Permendur Yoke	1410	0	-0.7	0
QC1RP	22.98 [68.89×0.334]	**No Yoke**	935	7.204	0	-1.0
QC1LP	22.97 [68.94×0.334]	**No Yoke**	-935	-13.65	0	-1.5
QC1LE	26.94 [72.21×0.373]	Permendur Yoke	-1410	0	+0.7	0
QC2LP	11.50 [28.05 × 0.410]	Permendur Yoke	-1925	-3.725	0	-1.5
QC2LE	15.27 [28.44×0.537]	Iron Yoke	-2700	0	+0.7	0

IR SC magnets

- Cross section design of main quadrupoles [QC1, QC2]
  - The quadrupole magnets are designed with the two layer SC coils (double pane cake design).

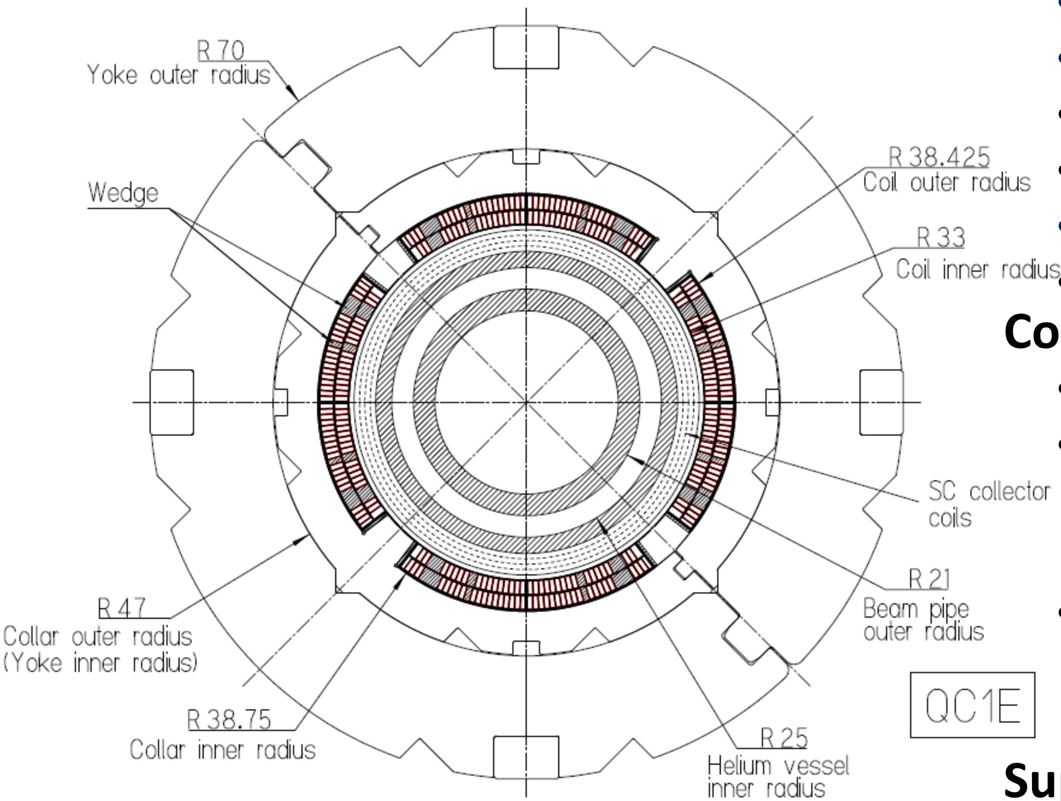


SC Coils for QC1LP



QC1LP Quadrupole Magnet

QC1E (Permendur yoke)



QC1E magnet cross section

QC1E magnet design (QC1RE, QC1LE)

- **Design field gradient = 91.57 T/m @ 2000 A**
- **Effective magnetic length = 0.3731 m**
- Magnet length = 0.4554 m
- B_p = 3.50 T
- **Load line ratio at 4.7 K = 73.4 %**
- Inductance = 2.19 mH

Coil design

- 2 layer coils (3 coil blocks for each layer)
- Error field in 2 D cross section
  - **b_6 = −0.06 units, b_{10} = −0.34 units, b_{14} = −0.01 units**
- Integral error field in 3D model
  - **b_4 = −0.02 units, b_6 = −0.04 units, b_8 = 0.05 units , b_{10} = −0.43 units**

Superconducting cable

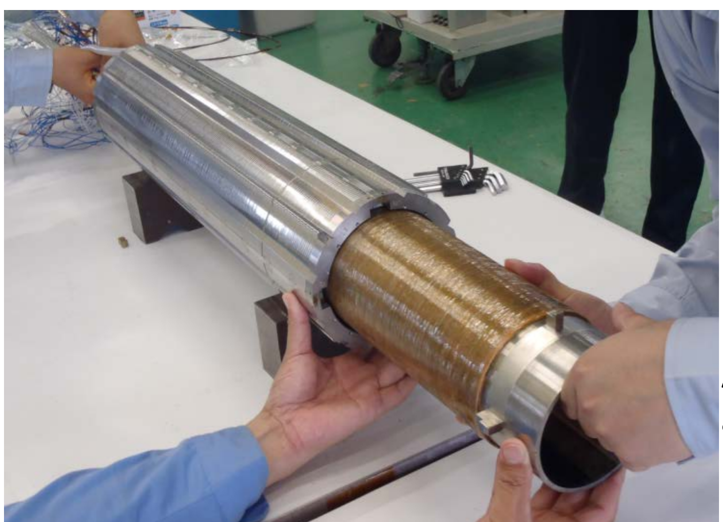
- **Cable size : 2.5 mm × 0.93 mm**
- **Keystone angle = 1.59 degree**

IR SC magnets

- Corrector magnets
  - The SC correctors were designed and directly wound on the support bobbin (helium inner vessel) by BNL under the US-Japan Science and Technology Cooperation Program in HEP.
    - Multi-layer coil [maximum layer=4 by limiting with the gap distance between the main quadrupole magnet and the helium inner vessel]
    - Some correctors were assembled on the outer surface of QC1LP and QC1RP (no magnetic yoke).

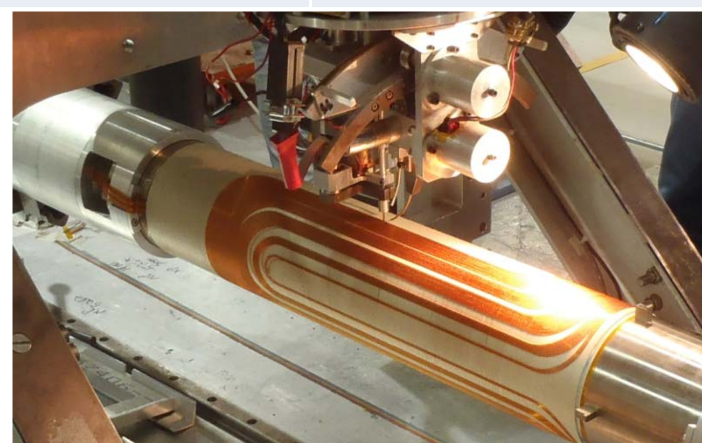
QCSL- Main Quadrupole	Corrector
QC1LP	a_1, b_1, a_2, b_4
QC2LP	a_1, b_1, a_2, b_4
QC1LE	a_1, b_1, a_2, b_4
QC2LE	a_1, b_1, a_2, b_4

QCSR-Main Quadrupole	Corrector
QC1RP	a_1, b_1, a_2, b_4, b_3
QC2RP	a_1, b_1, a_2, a_3
QC1RE	a_1, b_1, a_2, a_3
QC2RE	a_1, b_1, a_2, a_3
Between QC1RP and QC2RP	b_3
Between QC1RE and QC2RE	b_3



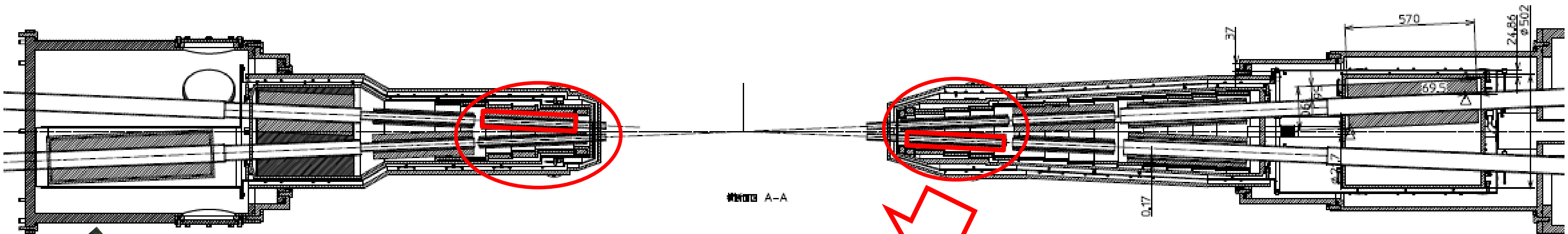
Assembly of QC2LE and correctors

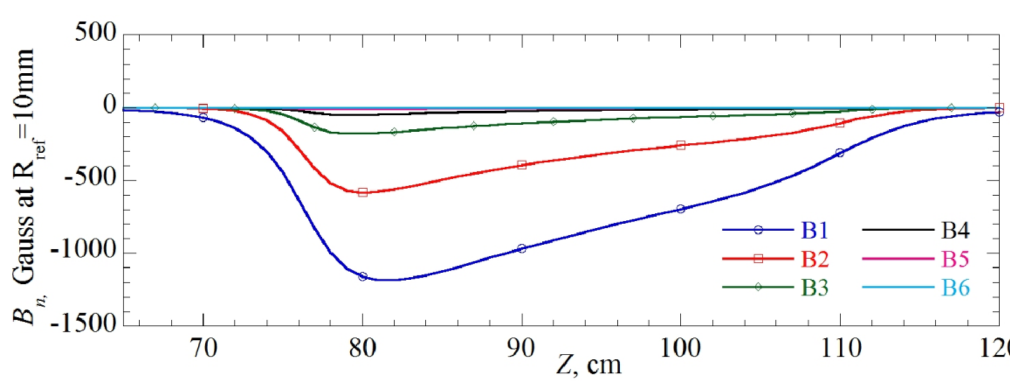
Direct winding process @BNL



IR SC magnets

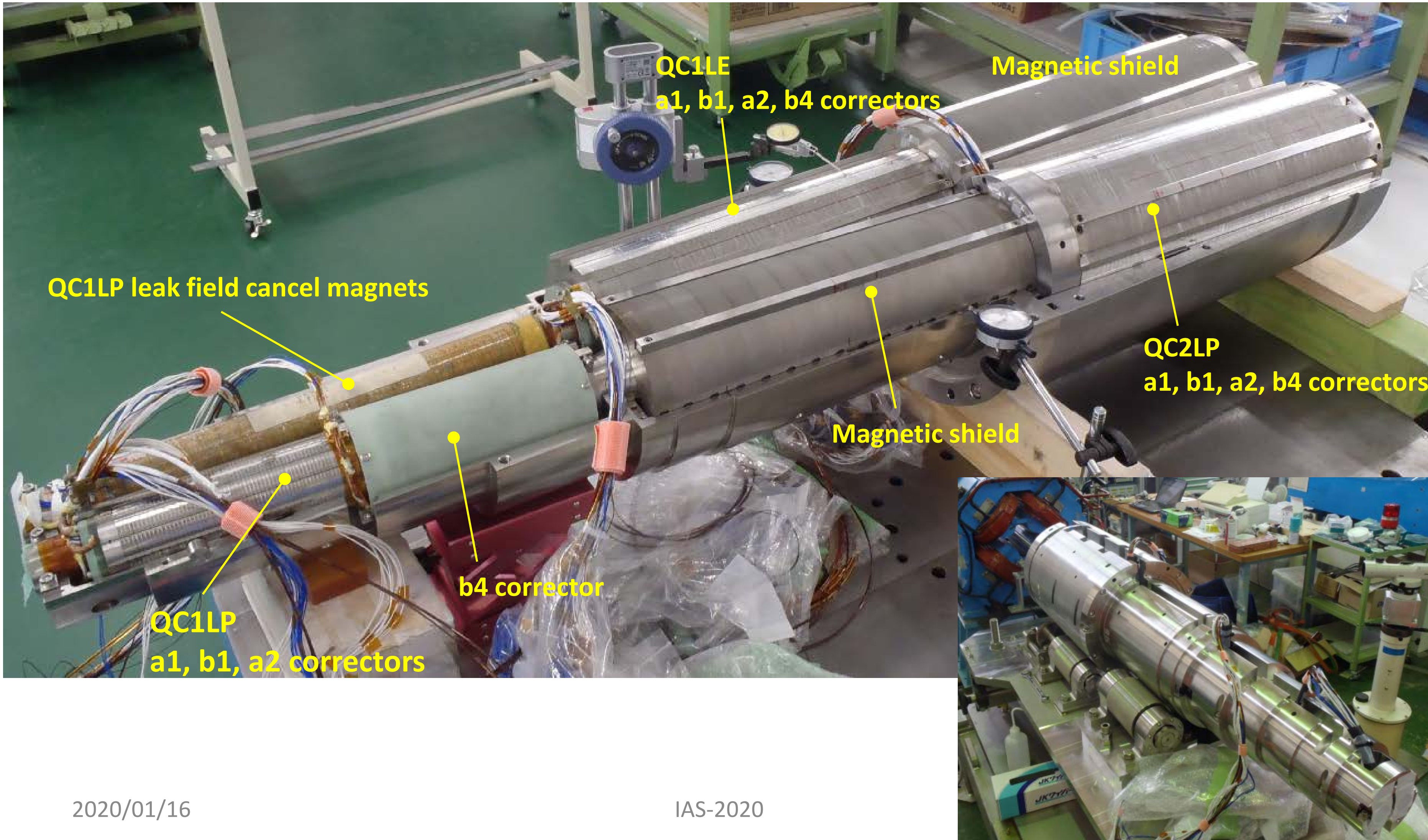
- QC1P leak field cancel magnets
  - QC1P for the e+ beam line is non-iron magnet and the e- beam line is very close to QC1P. The leak fields from QC1P go through the e- beam line.
  - ***B_3, B_4, B_5*** and ***B_6*** components of the leak fields are designed to be canceled with the SC cancel magnets.
  - B_1 and B_2 components are not canceled, and they are included in the optics calculation.





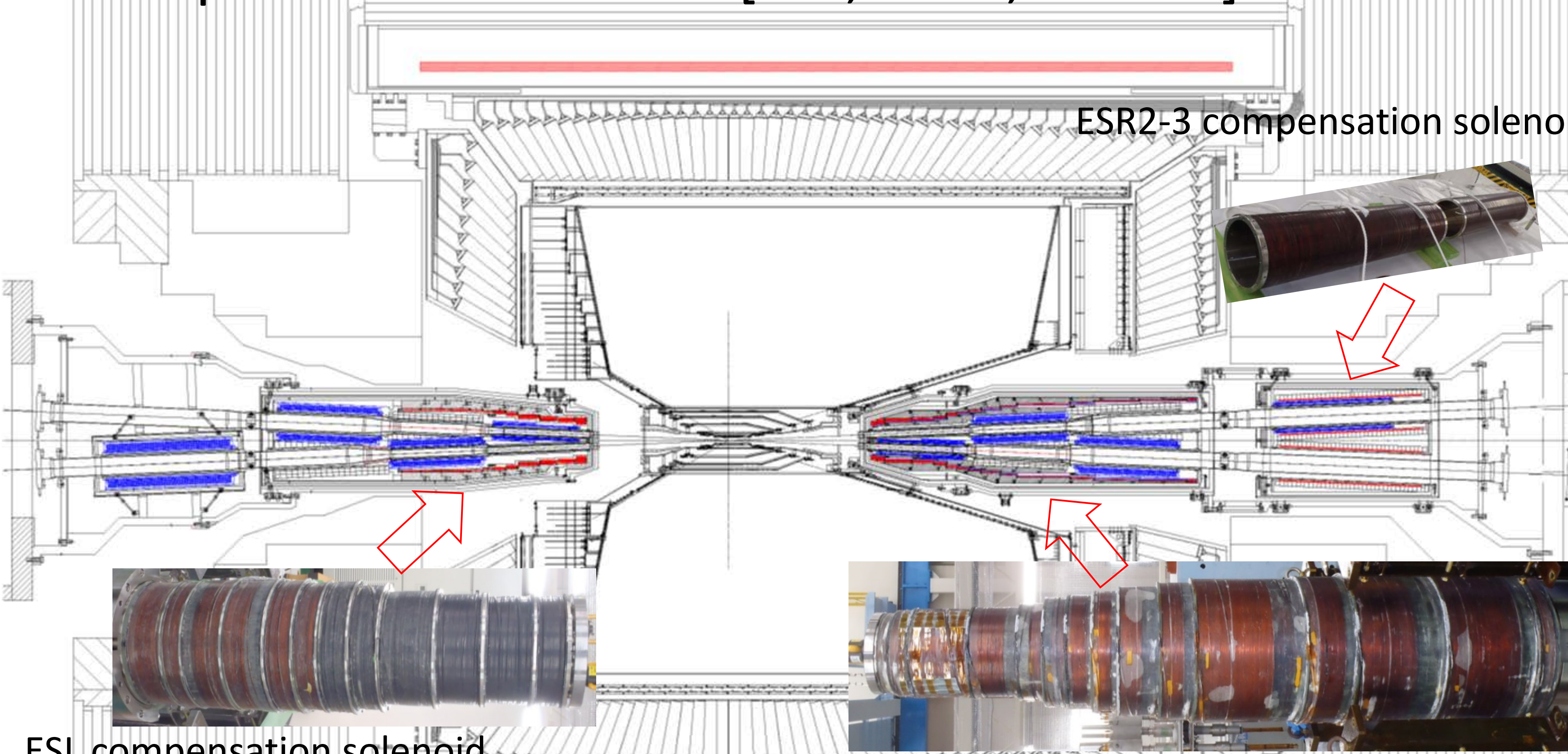
IR SC magnets

Assembly of the QC1LP, QC2LP, QC1LE, correctors and QC1LP leak field cancel magnets (Front cold mass of QCSL)



IR SC magnets

- Compensation solenoids [ESL, ESR1, ESR2-3]



ESR2-3 compensation solenoid

ESL compensation solenoid

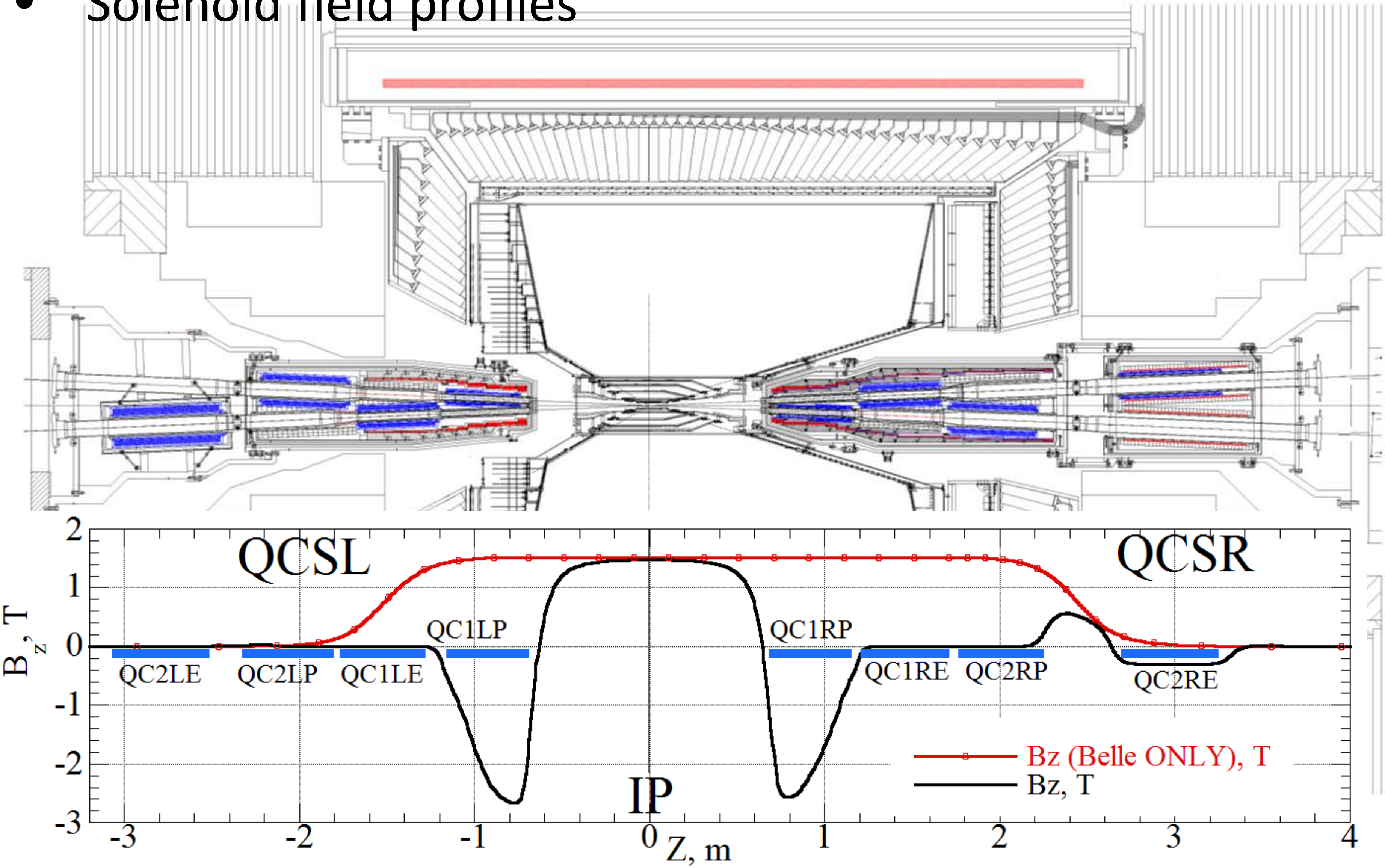
Magnet length= 914 mm
Maximum field at 404 A= 3.53 T
Stored Energy= 118 kJ

ESR1 compensation solenoid

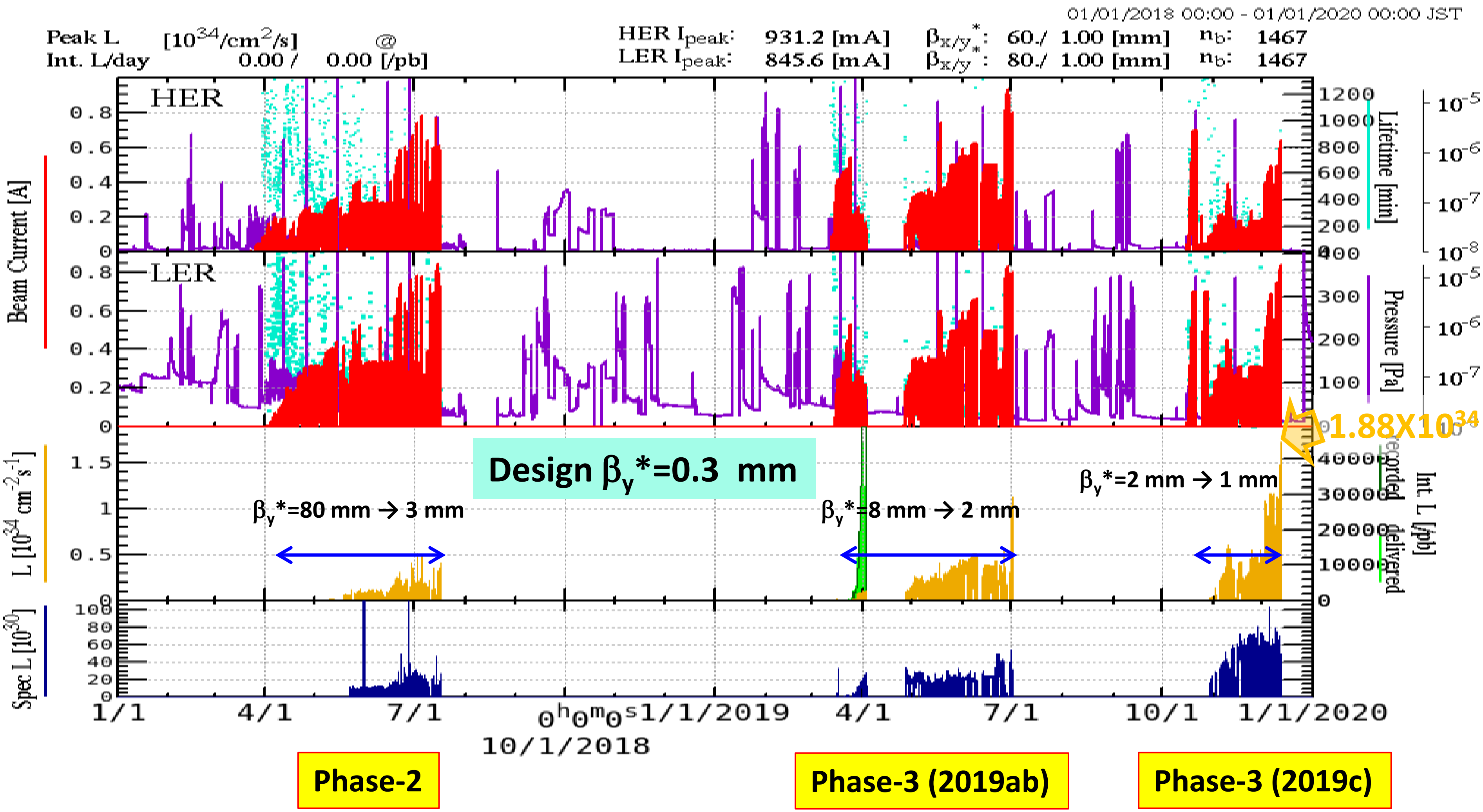
Magnet length= 1575 mm
Maximum field at 450 A=3.19 T
Stored Energy= 244 kJ
Cold diode quench protection system

IR magnets

- Solenoid field profiles



Operation of SuperKEKB



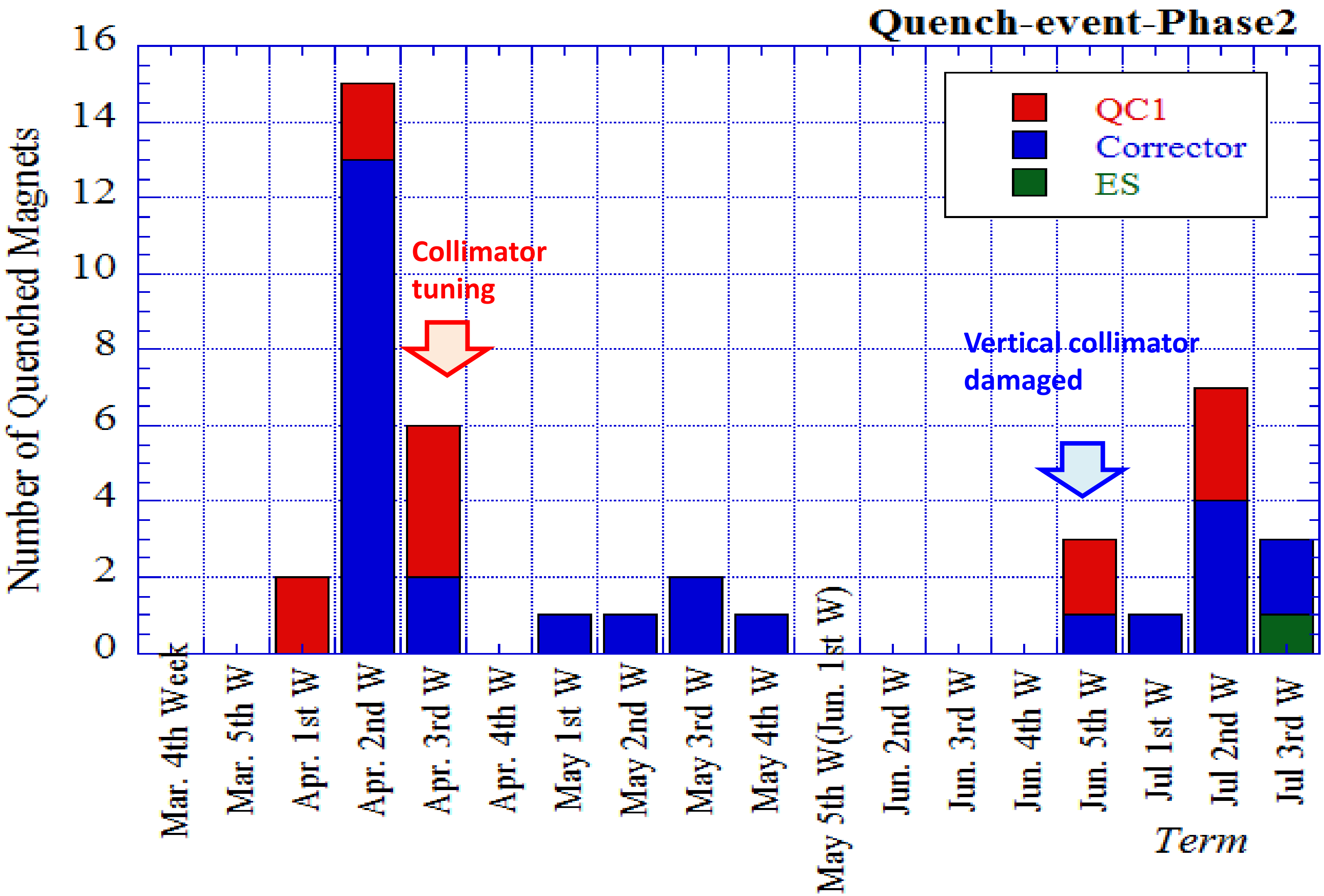
Operation of QCS in Phase-2, 3

Operation of QCS superconducting magnet system for Phase2 and 3

- **Cryogenic system**
  - Two cryogenic systems were cooled down to 4 K from February 9, 2018.
  - Cooling two magnet-cryostats to 4 K completed in February 11, 2018.
- **SuperKEKB Phase2 operation (Mar. 16, 2018 ~ Jul. 17, 2018)**
  - 55 superconducting magnets were stably excited with the target currents required by beam optics, and under the Belle-II solenoid field of 1.5 T.
  - **During this operation, 25 magnet quench events were induced by the beams.**
- **SuperKEKB Phase3-2019ab operation (Mar. 11, 2019~Jul. 1, 2019)**
  - 6 magnet quench events happened.
    - 3 magnet quench events by the power converter trouble
    - 3 magnet quench events by the beams.
- **SuperKEKB Phase3-2019c operation (Oct. 15, 2019~Dec. 12, 2019)**
  - In total, 3 magnet quench events happened. Two events were induced by the beam.

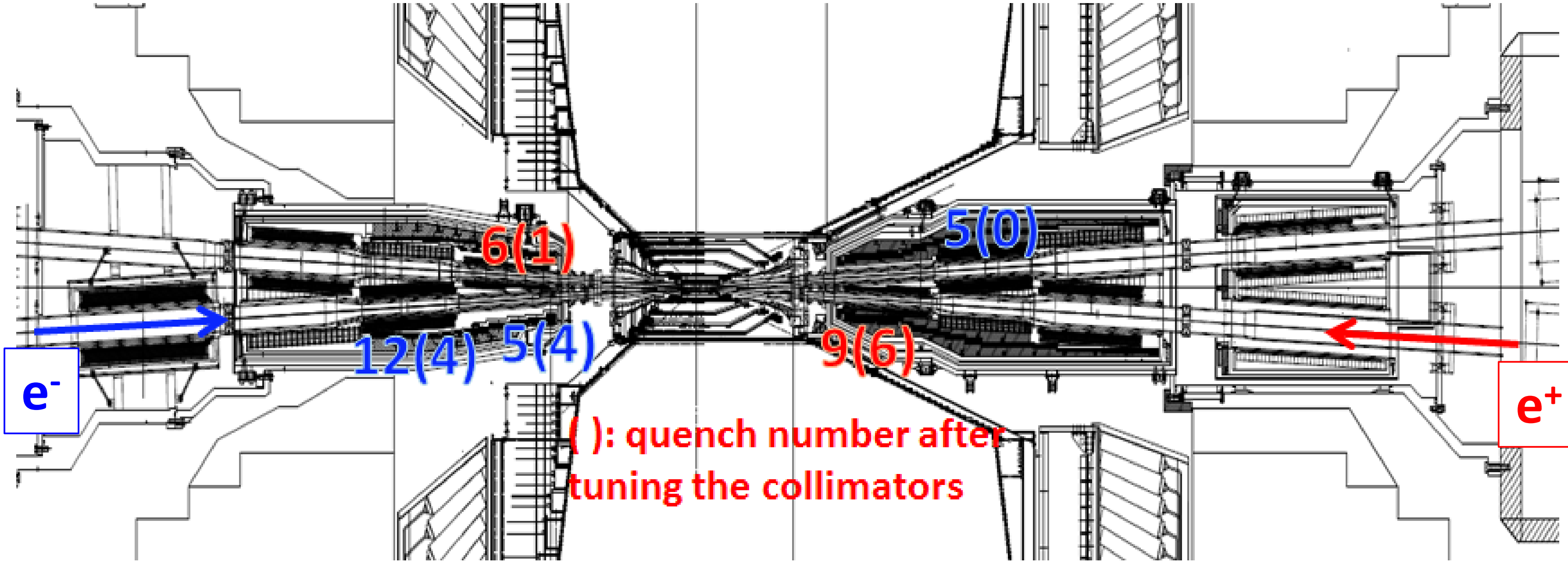
QCS operation and quench in Phase-2

Phase-2 (Mar. 16, 2018 ~ Jul. 17, 2018)



QCS operation and quench

Quenched magnets by beams (Phase-2)

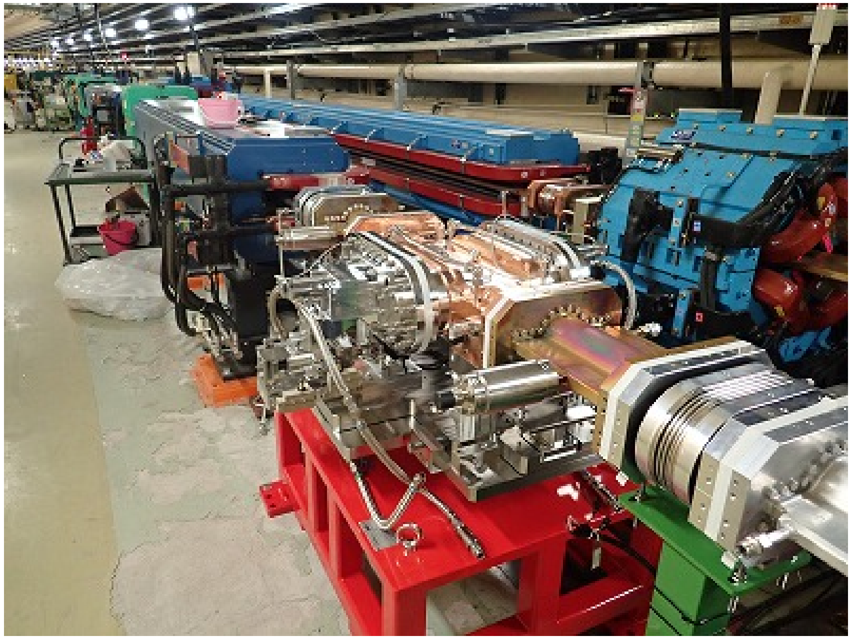


- The quenched magnets were concentrated in the QC1 magnets and the accompanying correctors.
- Some magnet quenches were induced with the power supply trouble.
- From Phase-3-2019ab, in order to correlate the magnet quench and the beam operation, the kicker trigger signal was added to the QCS logger data, and the logger system was upgraded with the sampling time of 1 μs.

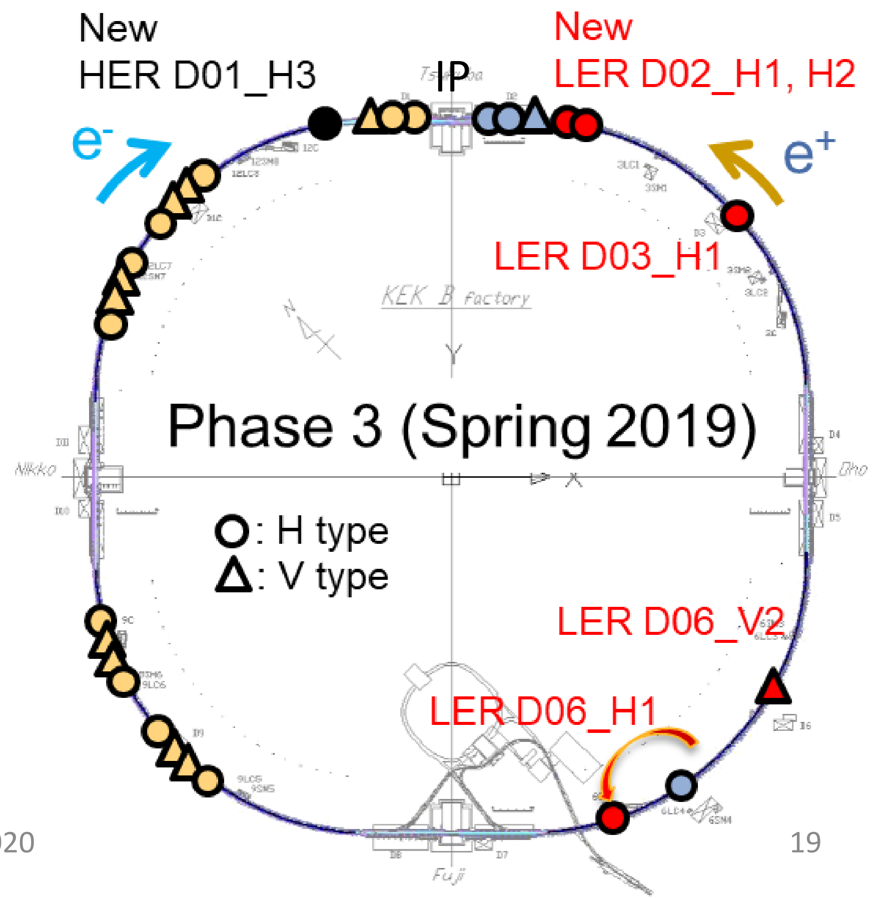
Experiences in Phase-2 Commissioning

- From the operation results in Phase-2, the collimator system was improved for Phase-3.
  - Following 5 collimators were newly installed into the tunnel.
    - **LER D02_H1, D02_H2, D03_H1, D06_V2**
    - **HER D01_H3**
  - LER D06_H4 was relocated to D06_H1.
  - LER D06_V1 vertical-type collimator was ready in Dec. 20, 2019.

Horizontal type collimator (D02_H1) installed in the LER.

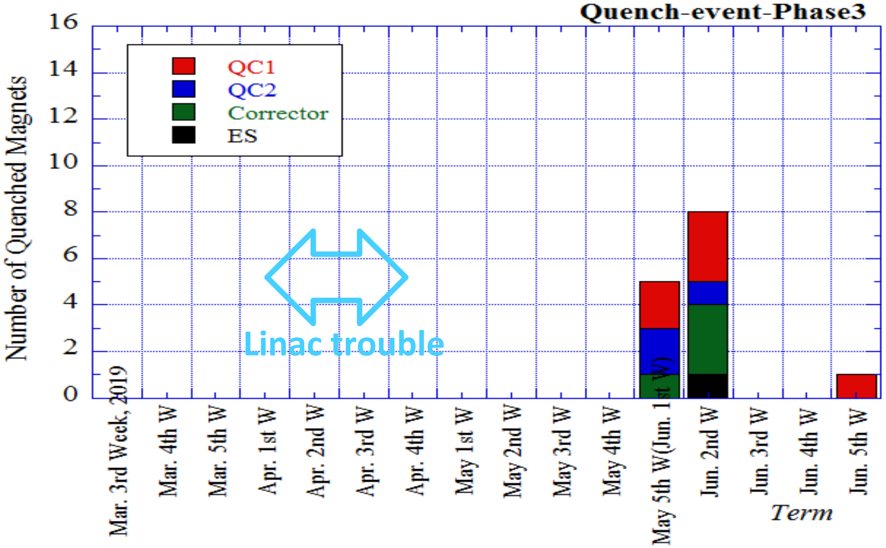


Collimator system in Phase-3(Mar.-Jun., 2019)

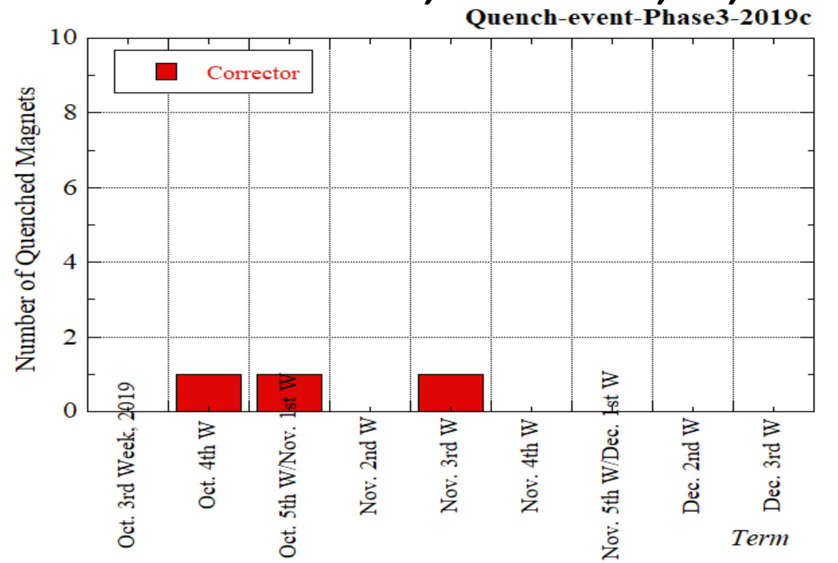


QCS operation and quench

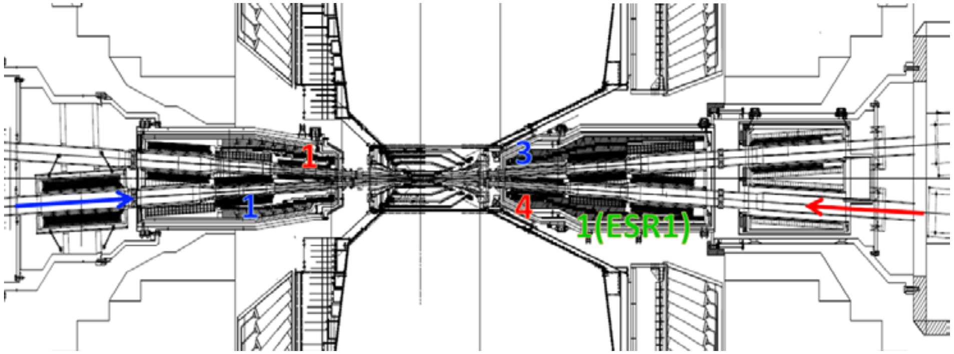
Phase-3-2019ab:Mar. 11, 2019~Jul., 1, 2019

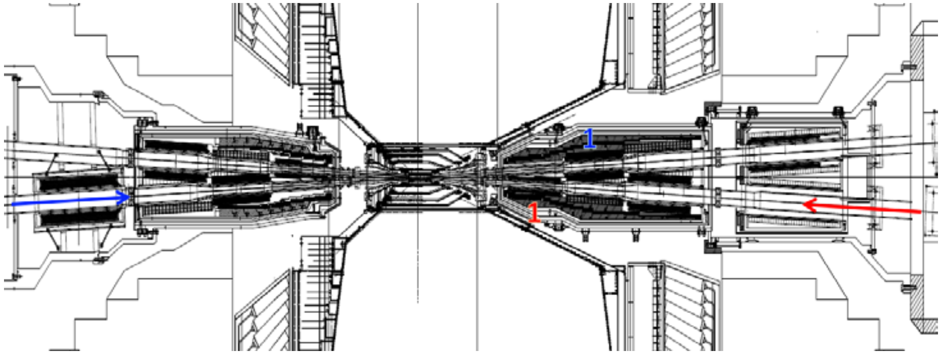


Phase-3-2019c:Oct. 15, 2019~Dec., 12, 2019

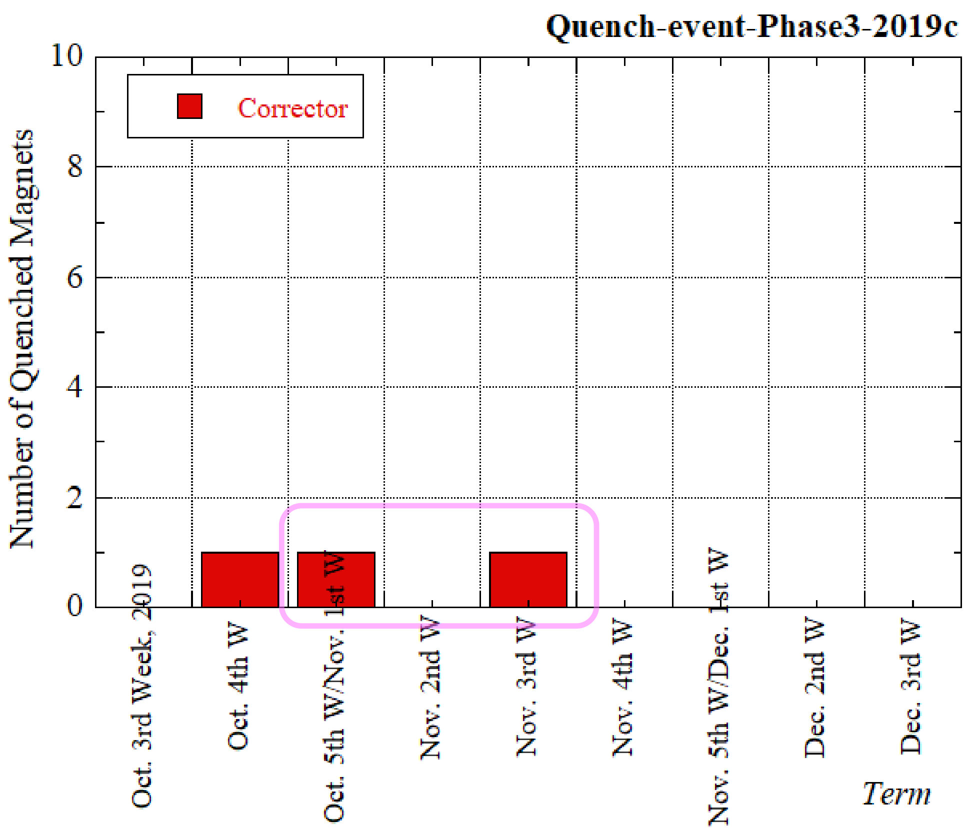


Quenched magnets by beams





QCS magnet quenches in Phase-3-2019c

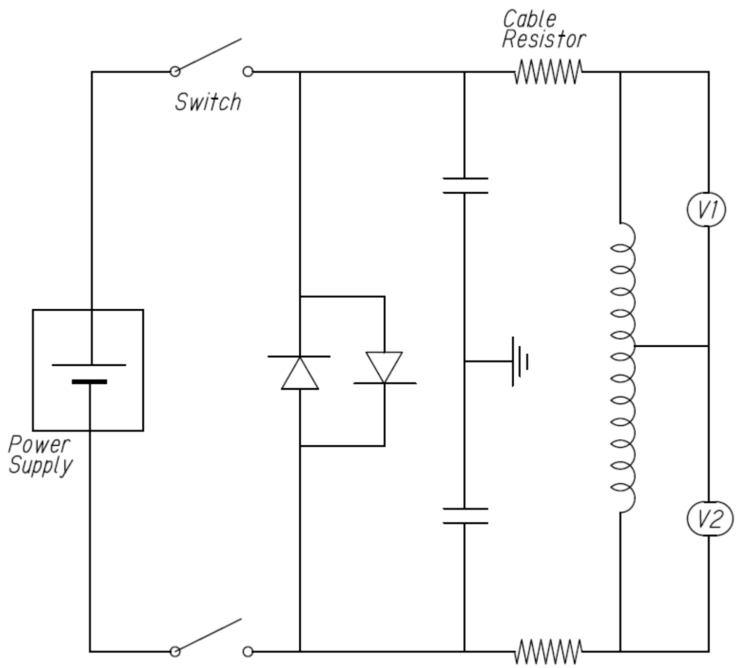


- Oct. 21, 2019: QC2RP b1 corrector magnet power converter trouble
- Oct. 30, 2019: QC1RE b1 corrector magnet quench induced by the HER beam during the optics correction
- Nov. 15, 2019: QC1RP b1 corrector magnet quench induced by the LER beam when the HER beam was aborted.

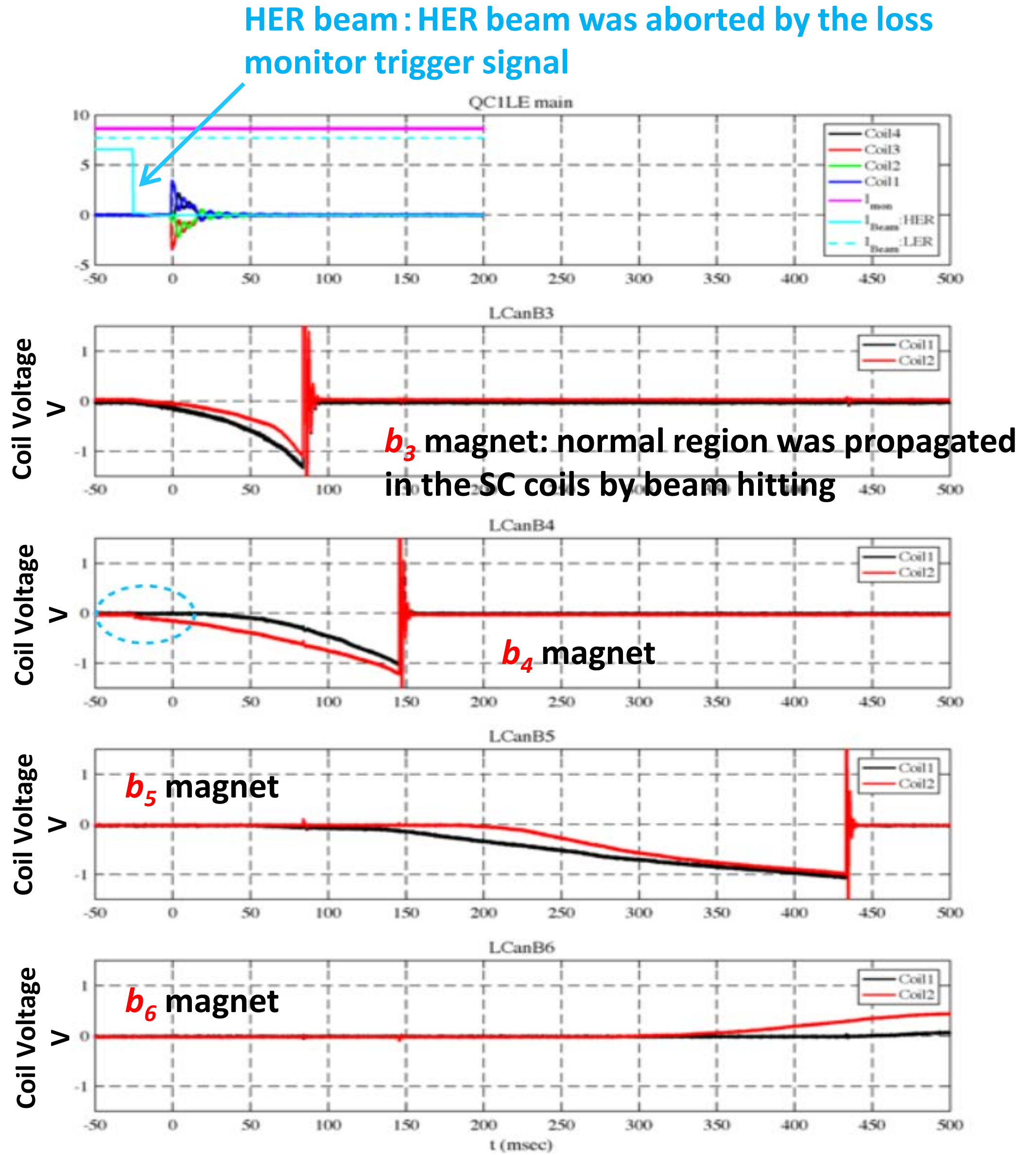
- HER and LER beams were well controlled to the QCS superconducting magnets by the collimator and the beam abort system.
- The quench of the superconducting magnets are reduced drastically.

QCS magnet quenches in Phase-2

Induced voltages in the QCS-L QC1LP leak field cancel magnets by quenches at July 16, 2018.

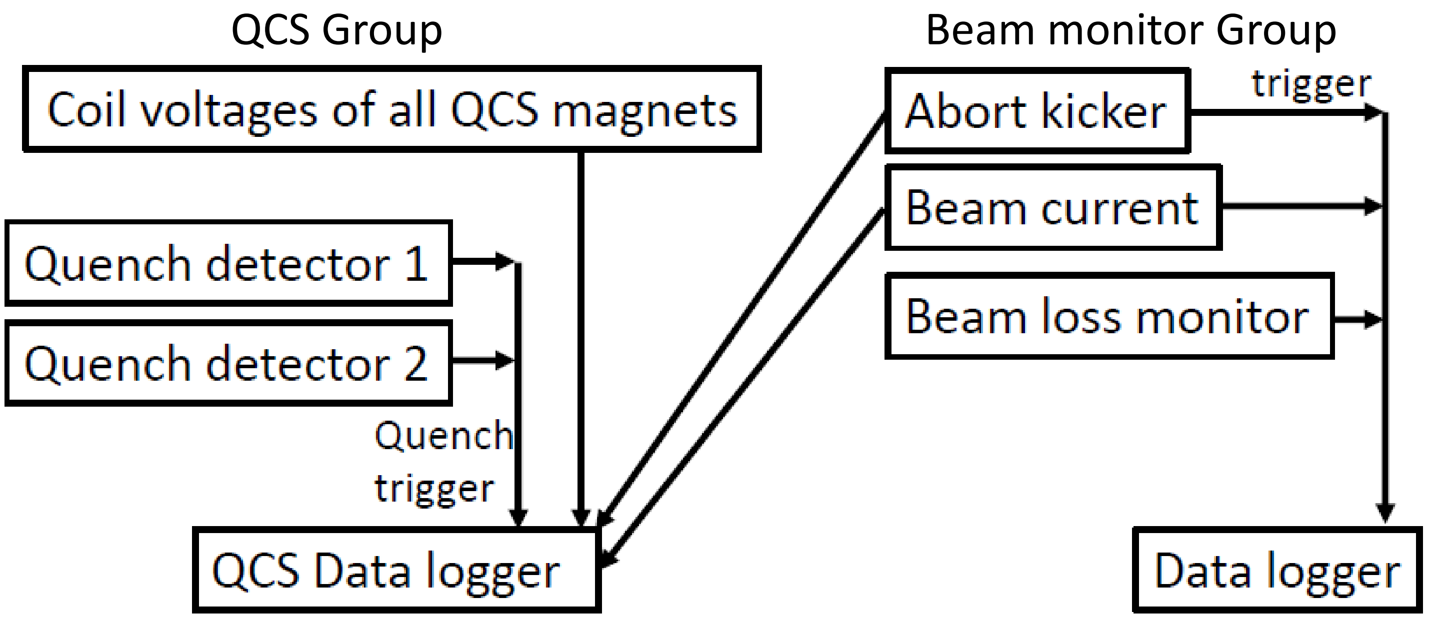


For corrector magnet



Countermeasures of the magnet quench for Phase-3

- **Improvement of the quench detector system and the quench monitoring system**
- Increasing the collimators in both beam lines
- New beam loss monitor sensor at the SuperKEKB interaction region
- Strengthen the beam abort system by the Belle-II background monitor system

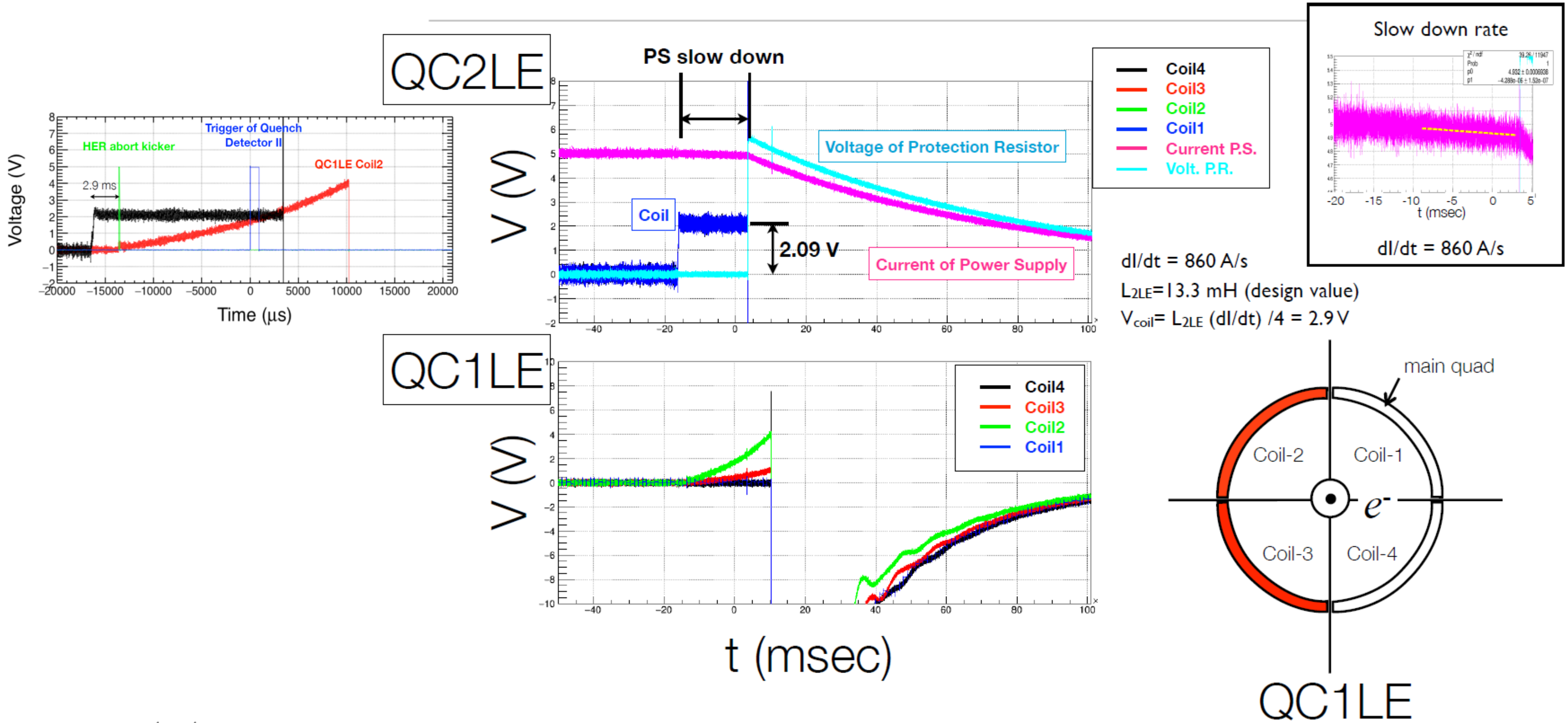


- Coil voltages of 55 QCS magnets are monitored by QCS data logger.
- We can compare the QCS magnet voltages with the beam loss signals of the monitor group by using the same trigger signals of the abort kickers and the beam currents

QCS magnet quenches in Phase-3

- 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)

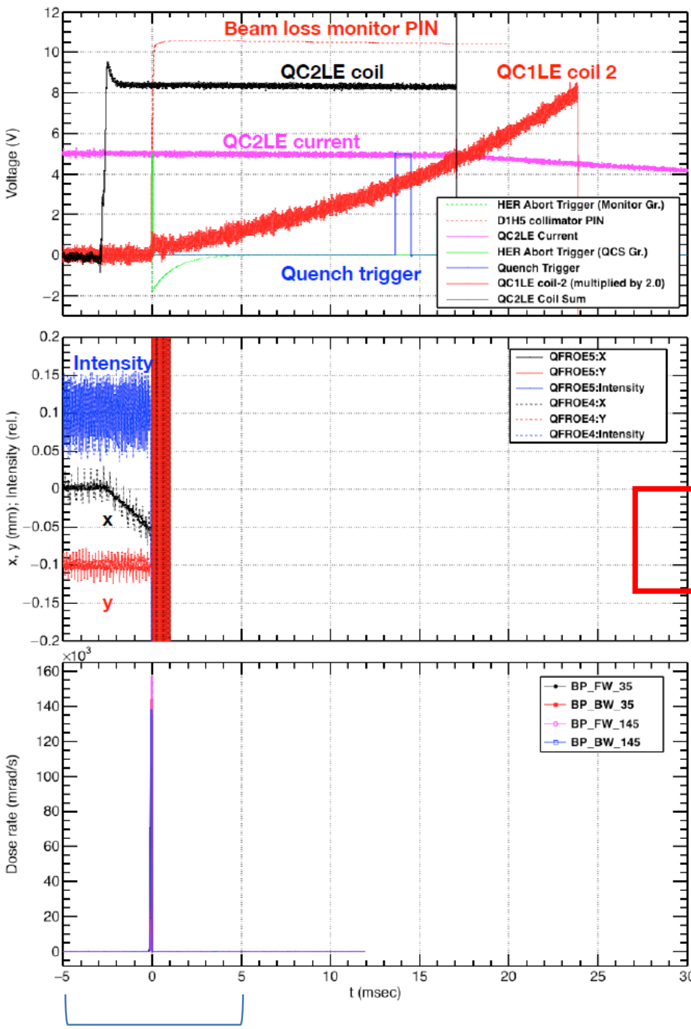
V_{coil}= L_{2LE} (dI/dt) /4 = 2.9 V

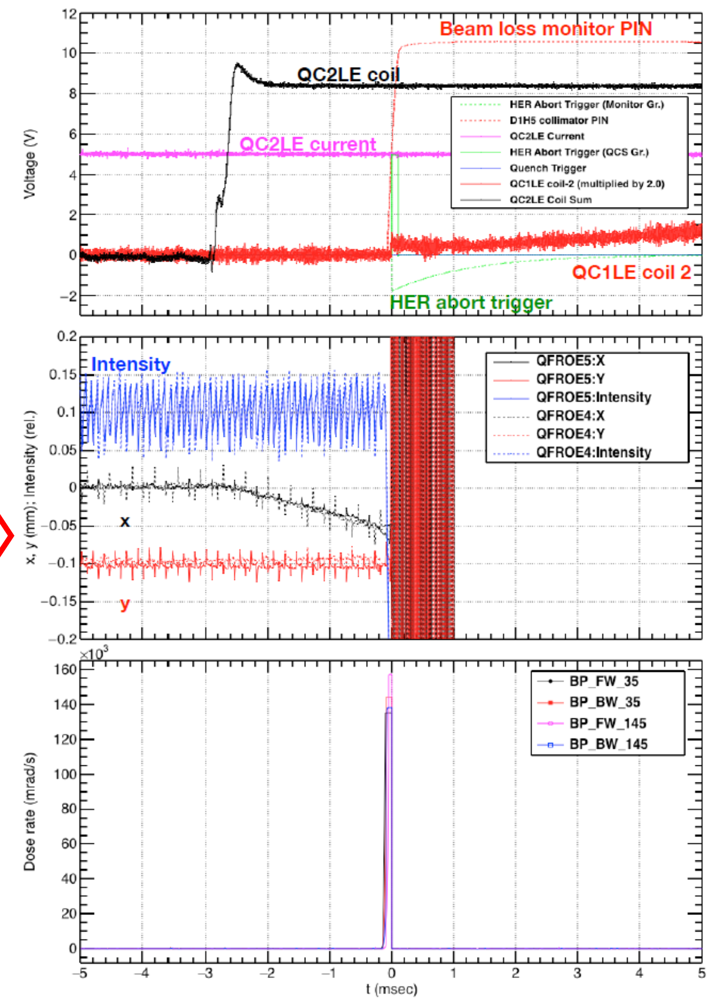
QCS magnet quenches in Phase-3

QCS
&
Beam loss monitor

BPM (Libera)

Diamond detector





Expanded in the right plots

Summary

- The quite sophisticated final focus system, QCS, for SuperKEKB showed a sufficient performance for the beam operation of the Phase-2 commissioning (Mar. 16, 2018 ~ Jul. 17, 2018).
- In Phase-2 beam operation, the QCS system had 25 quench events induced by beams.
  - Countermeasures against the magnet quench are prepared for the Phase-3 commissioning.
    - Improvement of the collimator system
    - Improvement of the beam abort triggers by the beam loss monitors and the Belle-II background signals.
    - Updating the data acquisition system for the magnet quench including the measurement items.
- In Phase-3 operation (2019ab and 2019c), the number of the magnet quenches was drastically reduced.

Thank you for your attention !