Operation of Superconducting Final-Focus Magnet System at SuperKEKB

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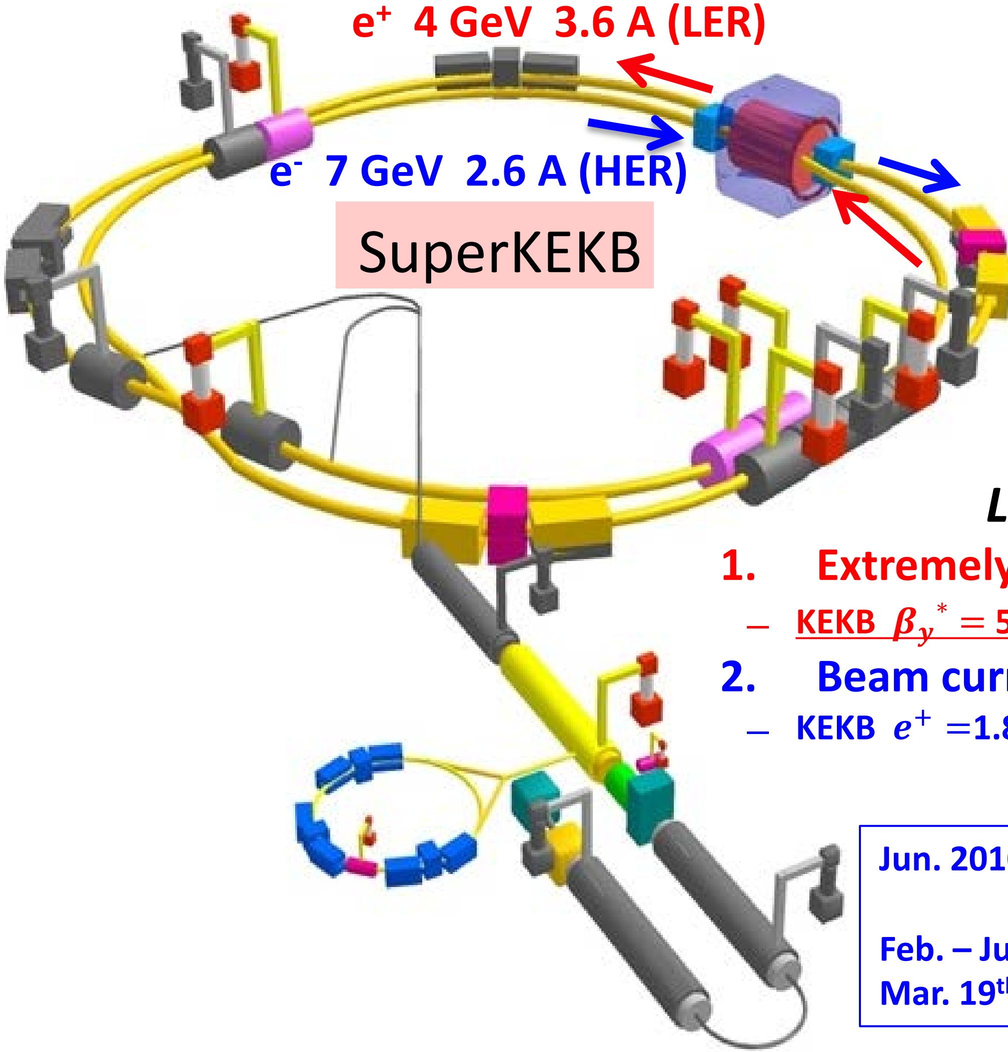
From KEKB to SuperKEKB



New Final Focus System

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

Apr. 2009 : Start of nano-beam scheme IR design
Jul. 2012 : kickoff of building the 1st quadrupole
Dec. 2015 : Completion of 1st magnet cryostat (QCS-L)
Mar. 2017 : Completion of the FF system
May-Aug. 2017: Commissioning of the FF system

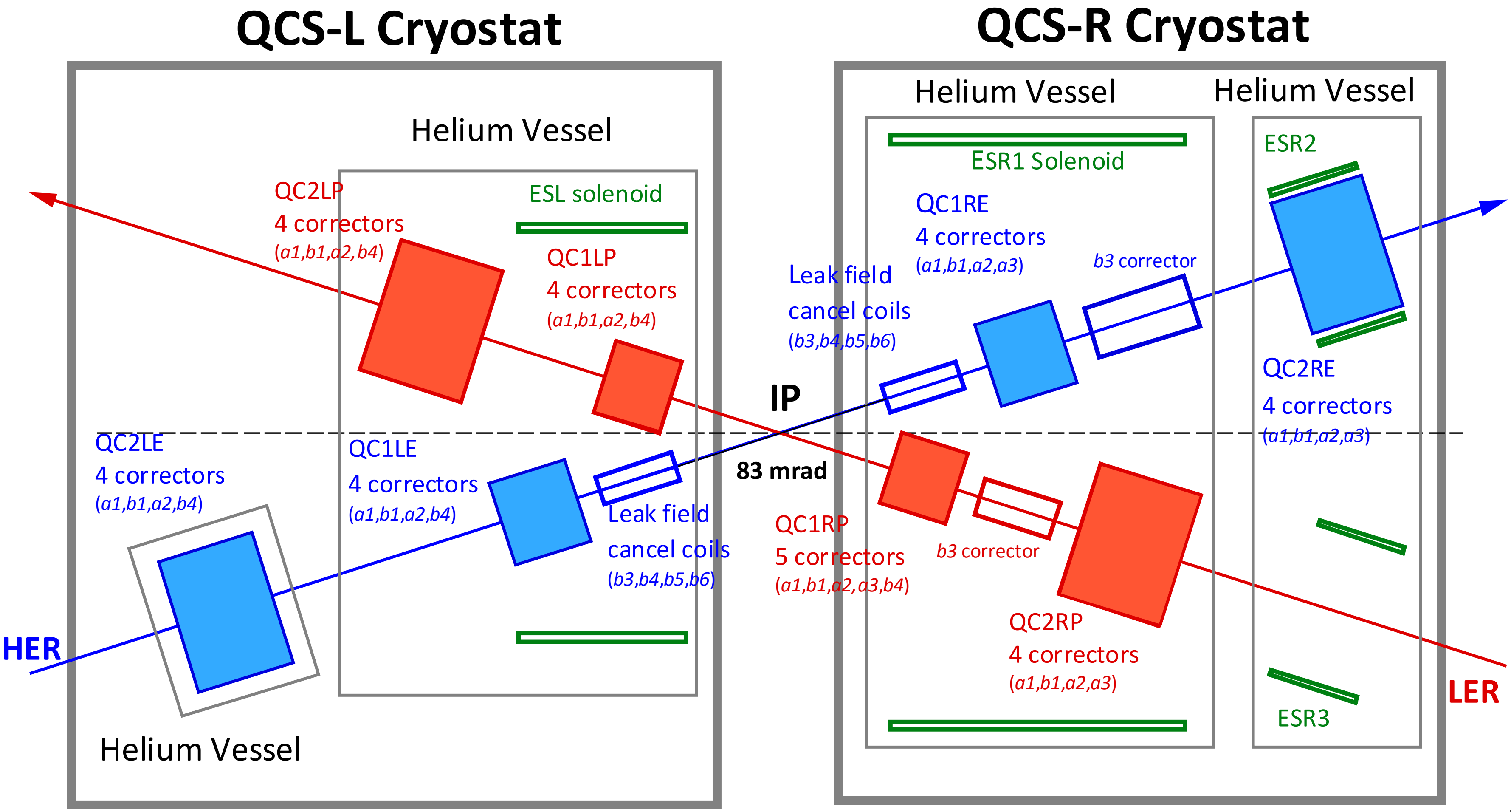
KEKB ⇨ SuperKEKB

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

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

Jun. 2010: Shut-down of KEKB operation
Kickoff of SuperKEKB construction
Feb. – Jun. 2016 : Phase-1 commissioning
Mar. 19th, 2018: Phase-2 commissioning has started

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

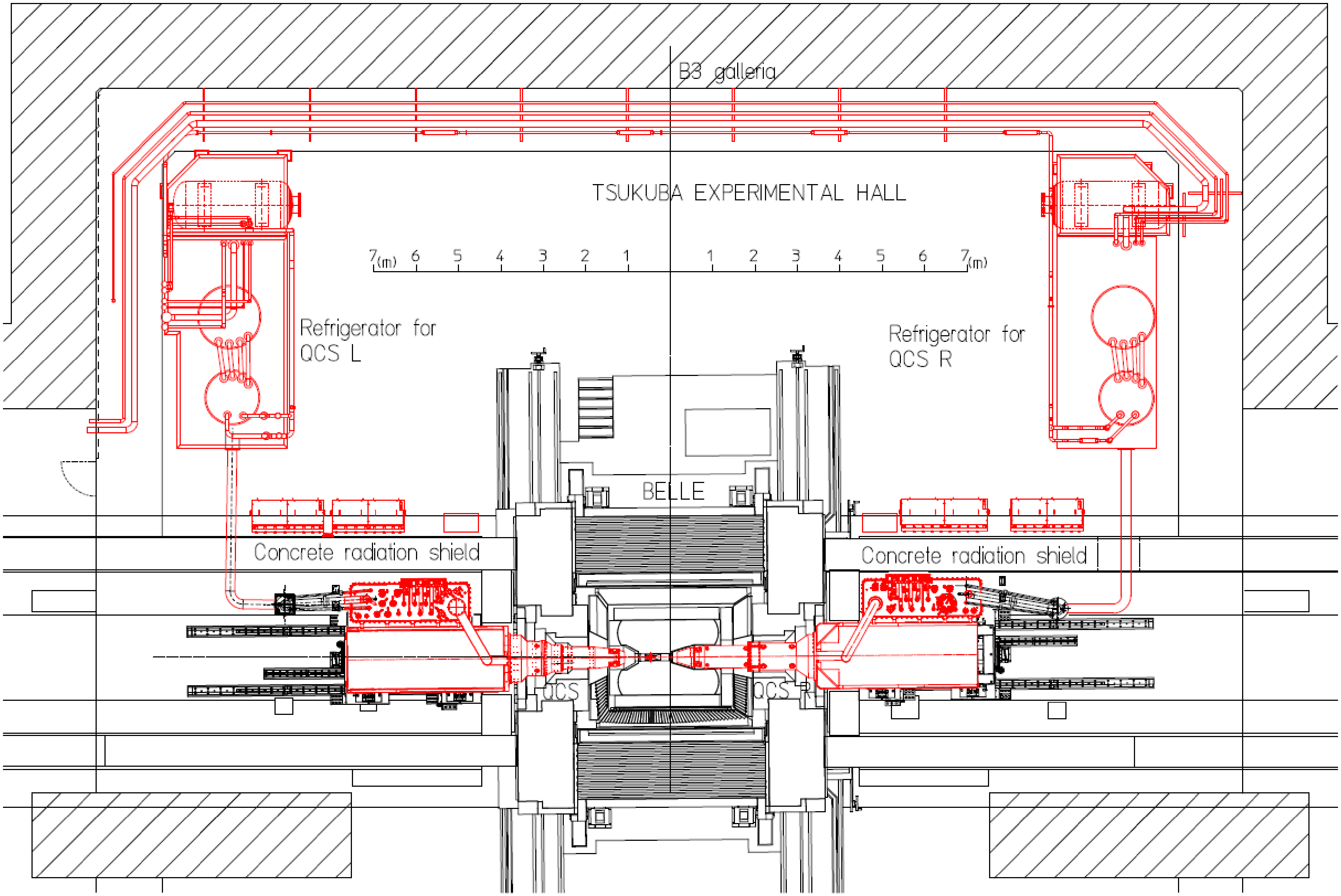
30 SC magnets in QCSR

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

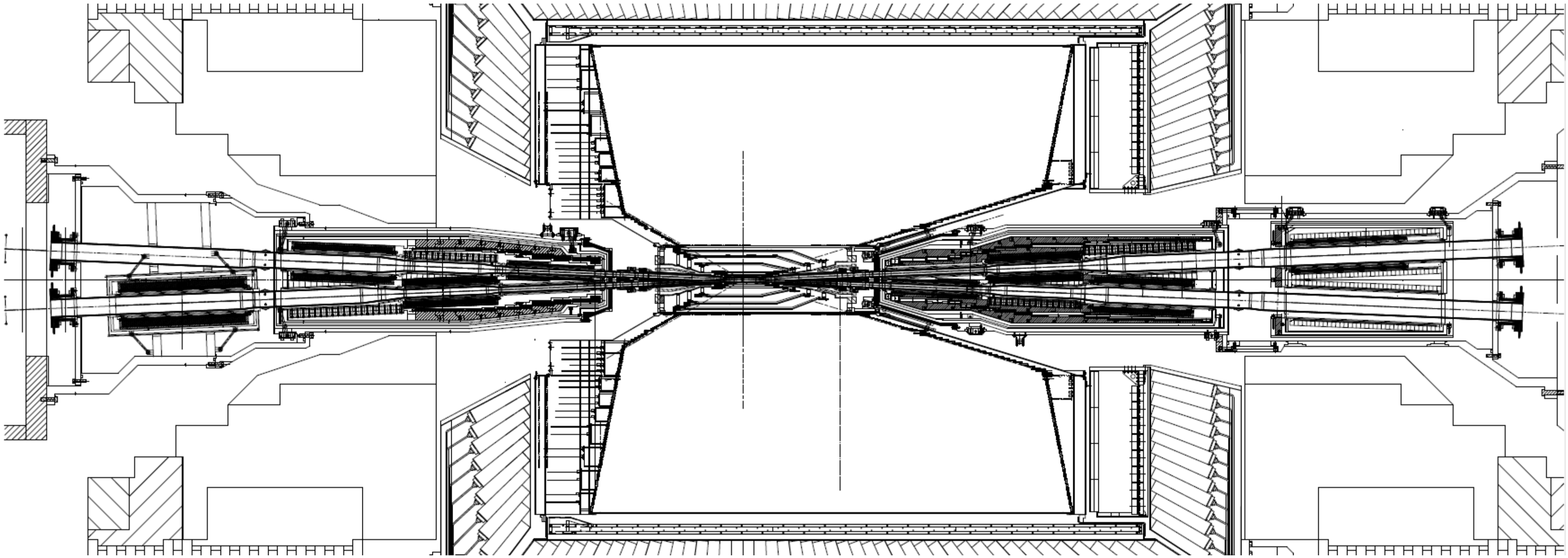
IR SC magnets

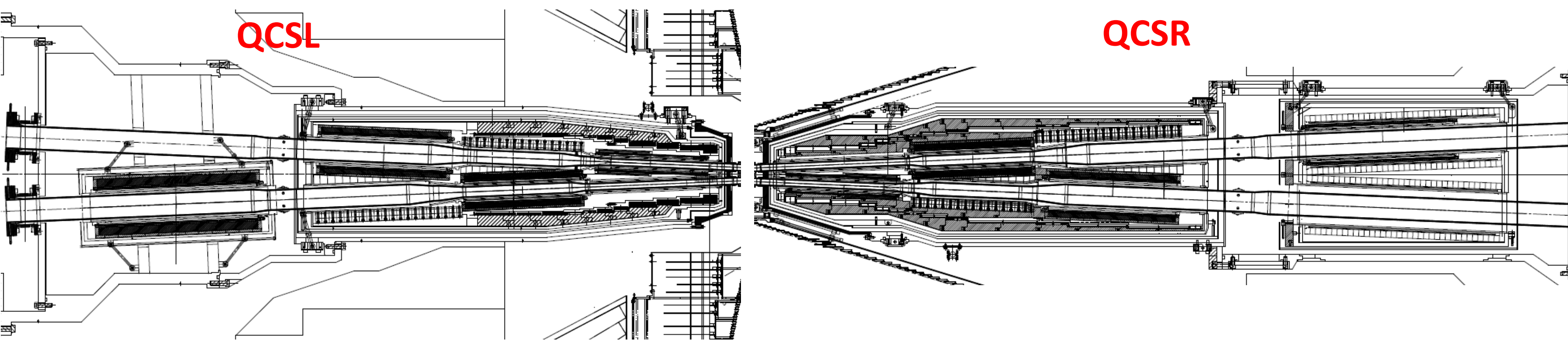
- Main quadrupoles [QC1, QC2]: 8 magnets
  - Forming final beam focusing system with quadrupole doublets.
- Correctors [a_1, b_1, a_2, a_3, b_3, b_4]: 35 magnets
  - a_1, b_1, a_2: magnetic alignment of the magnetic center and the mid-plane phase angle of main quadruple.
  - a_3, b_3: correction of sextupoles induced by magnet construction errors.
  - b_4:increasing the dynamic transverse aperture (increasing the beam 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>

Configuration of IR magnet system



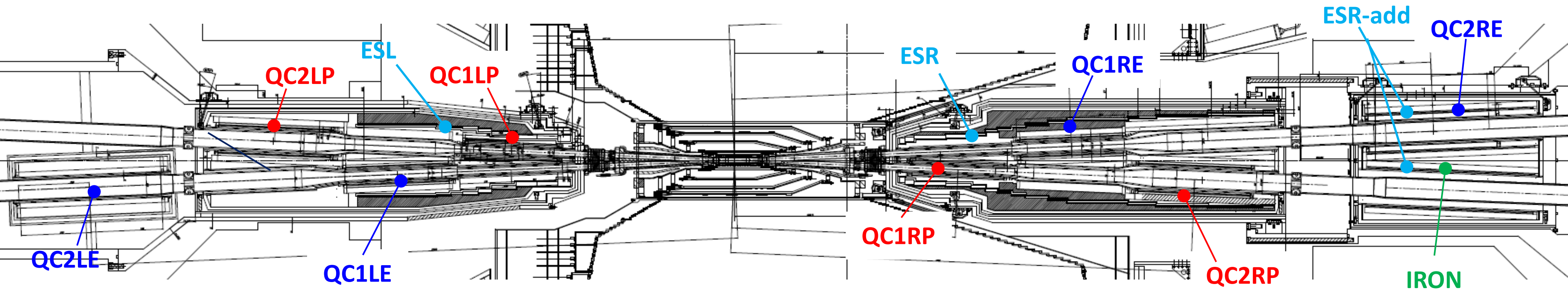
Configuration of IR magnet systems





IR SC magnets

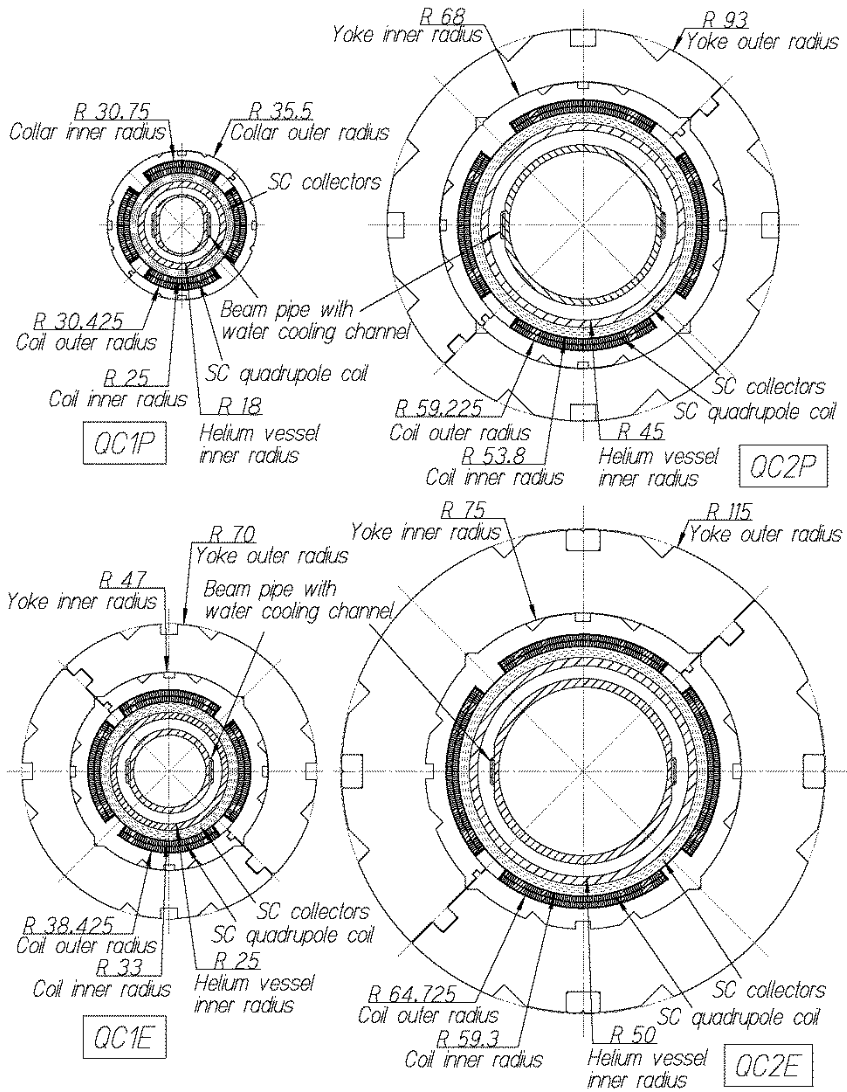
- Main quadrupoles [QC1, QC2]
  - QC1L(R)P, QC2L(R)P for the left (right) side cryostat to IP and for the positron beam line.
  - QC1L(R)E, QC2L(R)E for the left (right) side cryostat to IP and for the electron beam line.



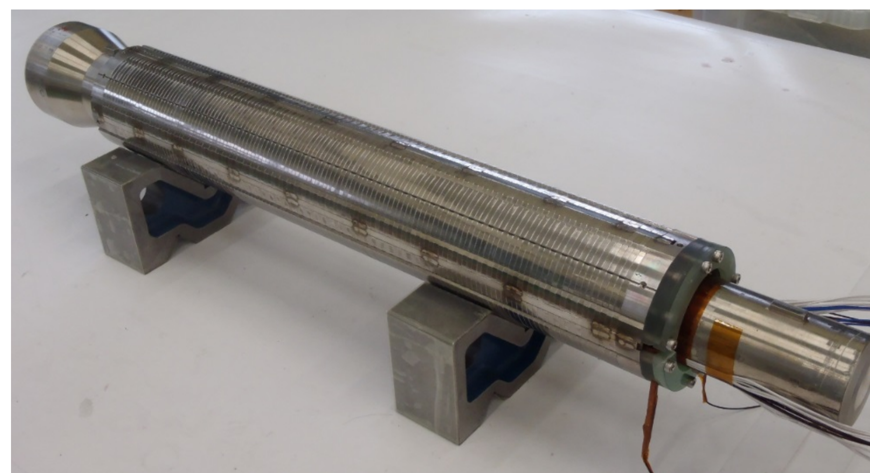
	Integral field gradient, (T/m)·m	Magnet type	Z pos. from IP, mm	θ, mrad	ΔX, mm	ΔY, mm
QC2RE	13.58 [32.41 T/m × 0.419m]	Iron Yoke	2925	0	-0.7	0
QC2RP	11.56 [26.28 × 0.410]	Permendur Yoke	1925	-2.114	0	-1.0
QC1RE	26.45 [70.89×0.373]	Permendur Yoke	1410	0	-0.7	0
QC1RP	22.98 [68.89×0.334]	**No Yoke**	935	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).

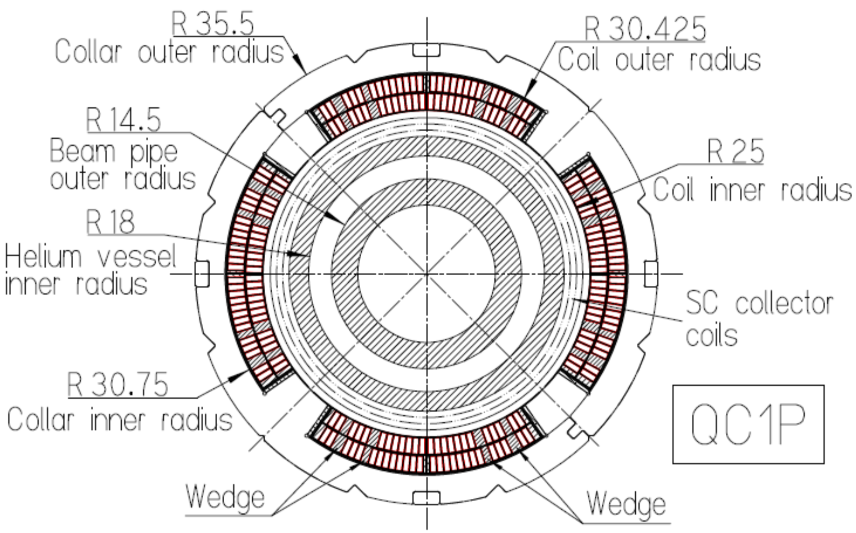


SC Coils for QC1LP



QC1LP Quadrupole Magnet

QC1P (No iron yoke)



QC1P magnet cross section

QC1P magnet design (QC1RP, QC1LP)

- **Design field gradient = 76.37 T/m @ 1800 A**
- **Effective magnetic length = 0.3336 m**
- Magnet length = 0.4093 m
- B_p = 4.56 T (with solenoid field of B_z=2.6 T, B_r=1.1 T)
- **Load line ratio at 4.7 K = 72.3 %**
- Inductance = 0.88 mH

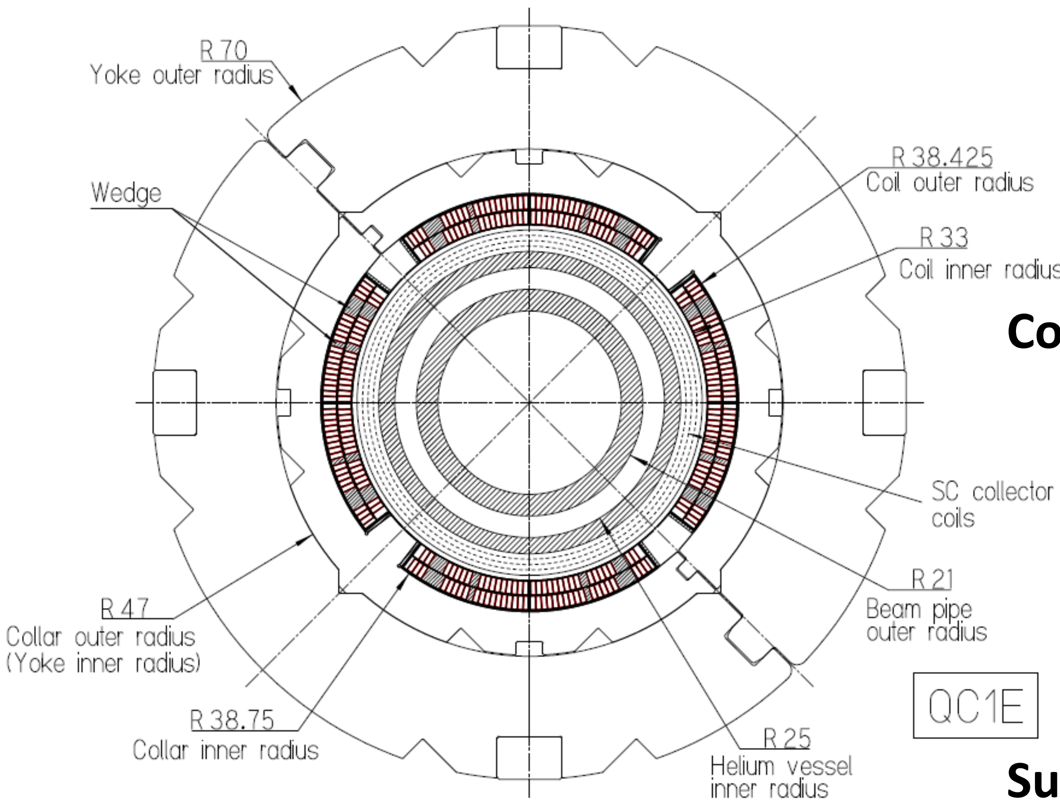
Coil design

- 2 layer coils (3 coil blocks for each layer)
- Error field in 2 D cross section @ R=10 mm
  - **b_6 = 0.10 units, b_{10} = −0.21 units, b_{14} = 0.02 units**
- Integral error field in 3D model
  - **b_4 = 0.24 units, b_6 = 0.54 units, b_8 = 0.01 units , b_{10} = −0.21 units**

Superconducting cable

- **Cable size : 2.5 mm × 0.93 mm**
- **Keystone angle = 2.09 degree**

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

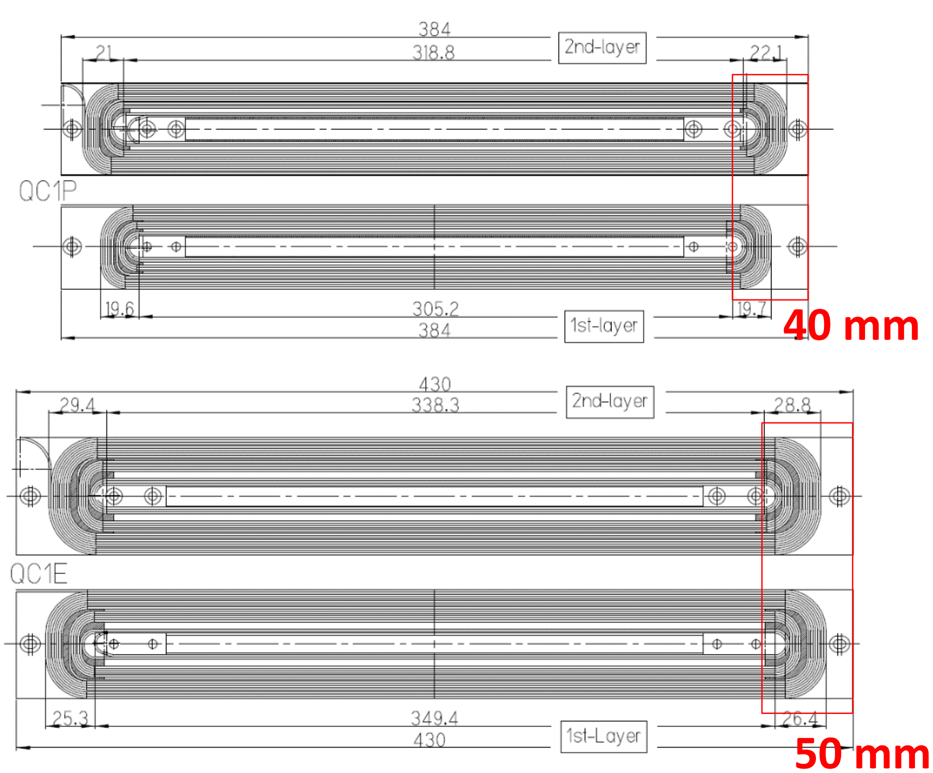
Coil design

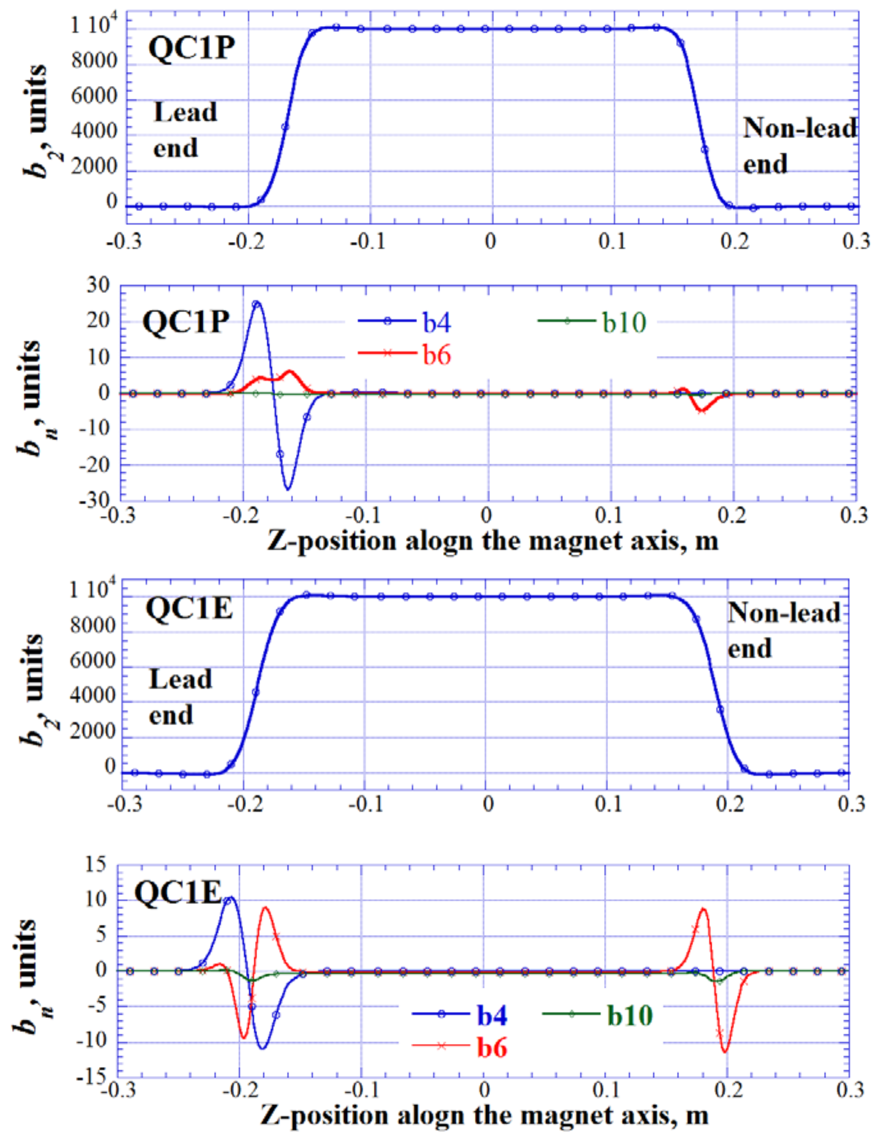
- 2 layer coils (3 coil blocks for each layer)
- Error field in 2 D cross section
  - b_6 = −0.06 units, b_{10} = −0.34 units, b_{14} = −0.01 units
- Integral error field in 3D model
  - b_4 = −0.02 units, b_6 = −0.04 units, b_8 = 0.05 units , b_{10} = −0.43 units

Superconducting cable

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

3D magnet design of QC1P/1E

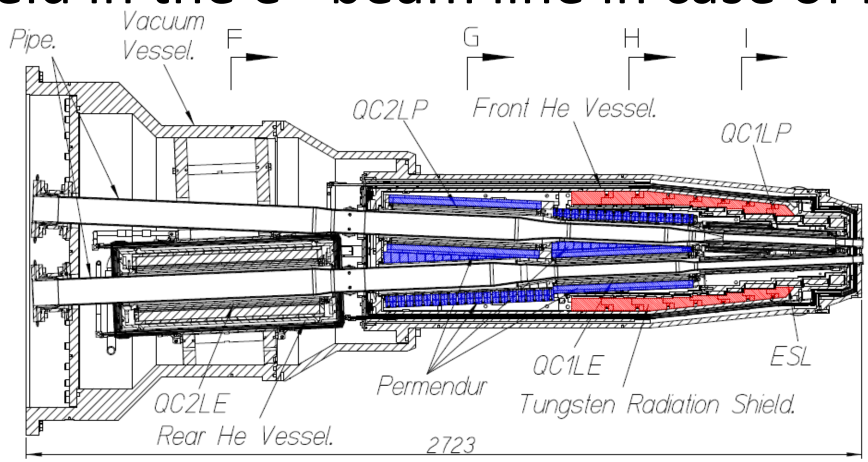


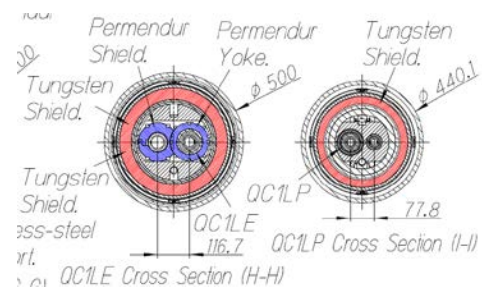


- The coil ends were designed to be as short as possible.
- In order to exclude the skew components in the lead end, the quadrant coils have mirror symmetry to the neighbor coils.

Magnet design: Permendur yoke

Leak field in the e+ beam line in case of Iron and Permendur Yokes





In the nominal operation of 4s:

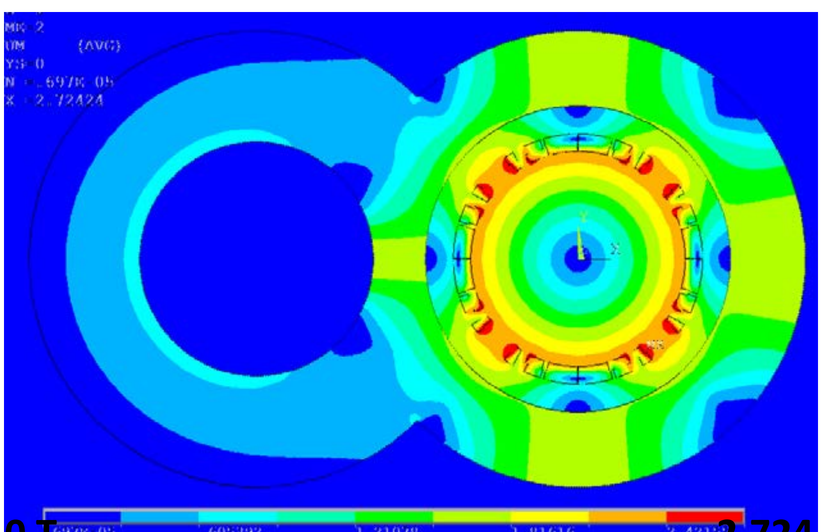
G = 72.21 T/m with 1577 A

Max. field in the magnet = 2.724 T

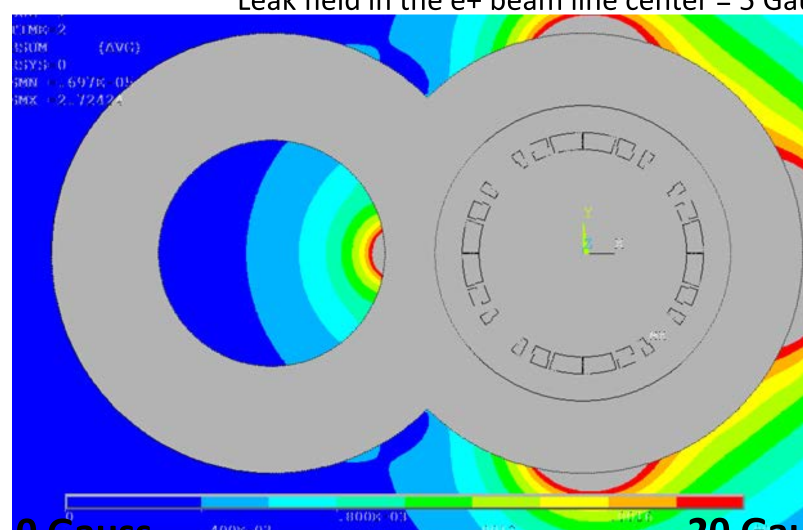
Leak field in the e+ beam line center = 5 Gauss

2D field calculation of QC1E (4s) : Yoke material= Iron

<u>With 0T bias field</u>



0 T 2.724 T



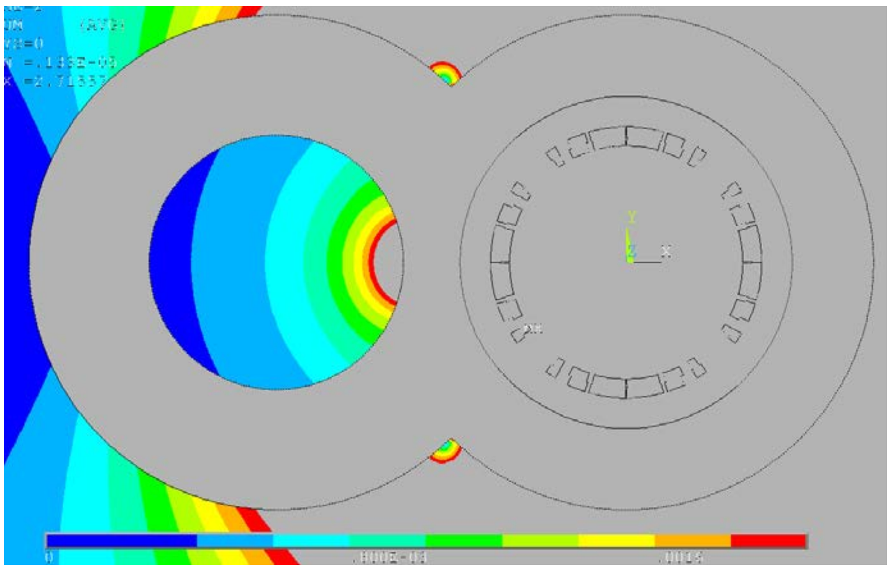
0 Gauss 20 Gauss

Magnet design: Permendur yoke

Leak field in the e+ beam line in case of Iron and Permendur Yokes

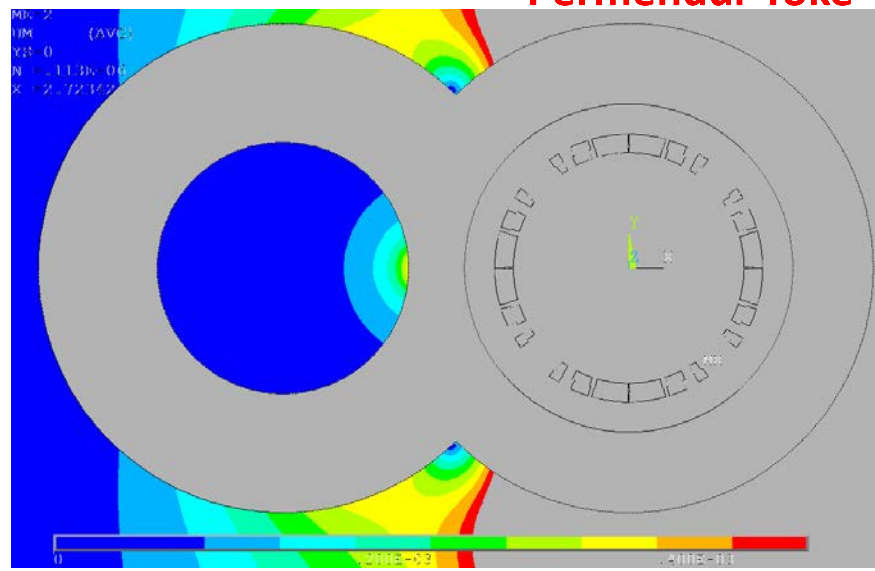
<u>With 0.5 T field in the Yoke (4s)</u>

Iron



0 Gauss **10 Gauss**

Permendur Yoke



0 Gauss **5 Gauss**

Leak field at e+ center = 6 Gauss

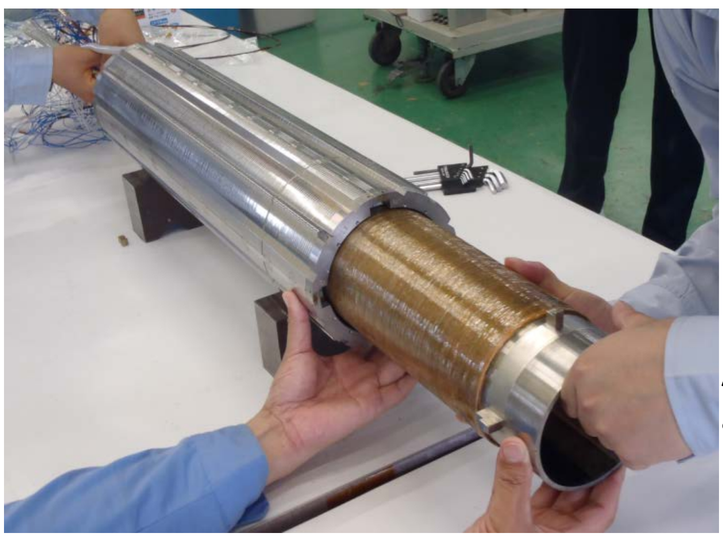
Leak field at e+ center <1 Gauss

SC 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).

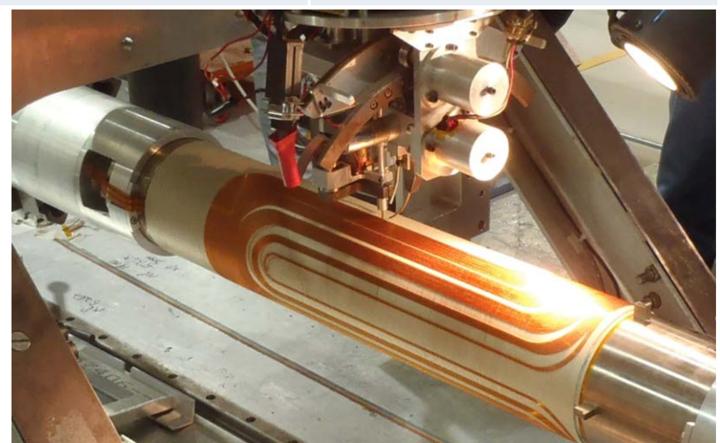
QCSL- Main Quadrupole	Corrector
QC1LP	a_1, b_1, a_2, b_4
QC2LP	a_1, b_1, a_2, b_4
QC1LE	a_1, b_1, a_2, b_4
QC2LE	a_1, b_1, a_2, b_4

QCSR-Main Quadrupole	Corrector
QC1RP	a_1, b_1, a_2, b_4, $\boldsymbol{a_3 \rightarrow b_3}$
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

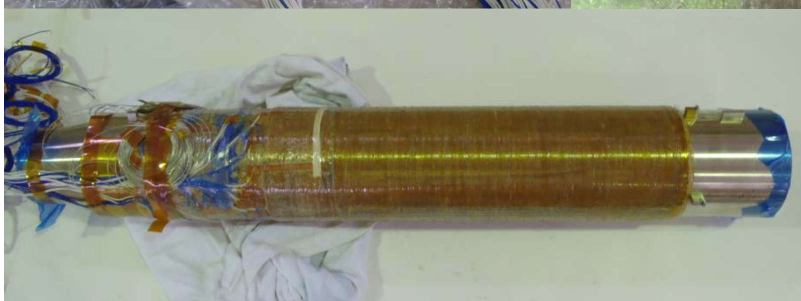
Direct winding process @BNL



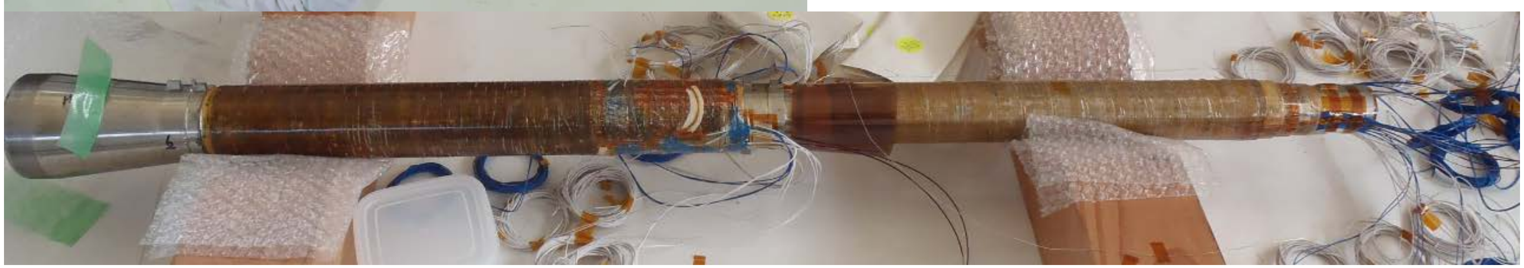
SC Corrector Magnets

Corrector magnets in the left side:

QC1LP correctors : a_1, b_1, a_2, b_4



QC2LP correctors : a_1, b_1, a_2, b_4



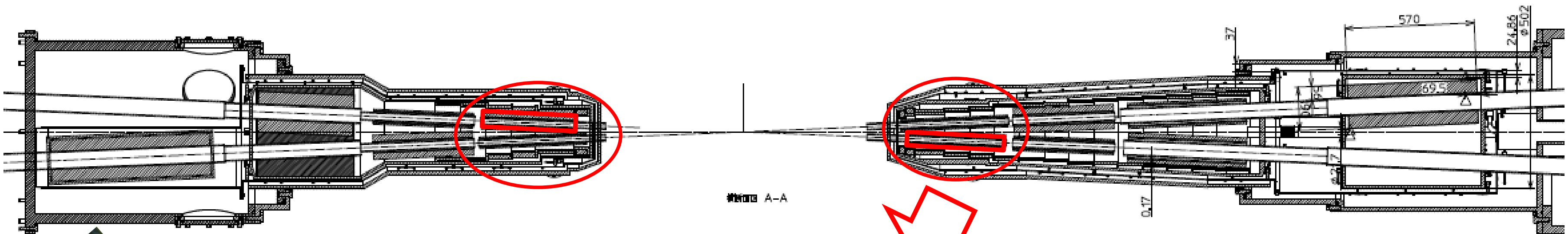
QC1LE correctors : a_1, b_1, a_2, b_4

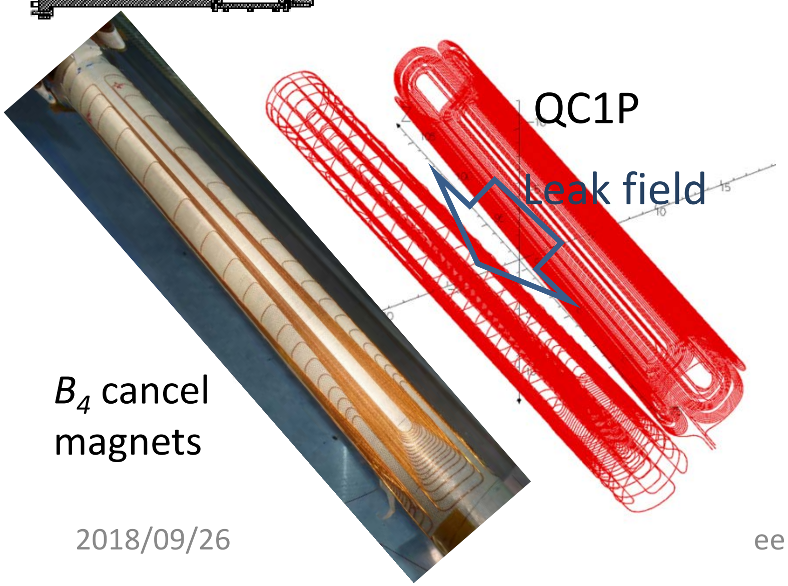
QC1LP leak field cancel coils : b_3, b_4, b_5, b_6

The correctors for the QC2LE magnet will be delivered from BNL in March.
The cold test of the correctors is scheduled in March.

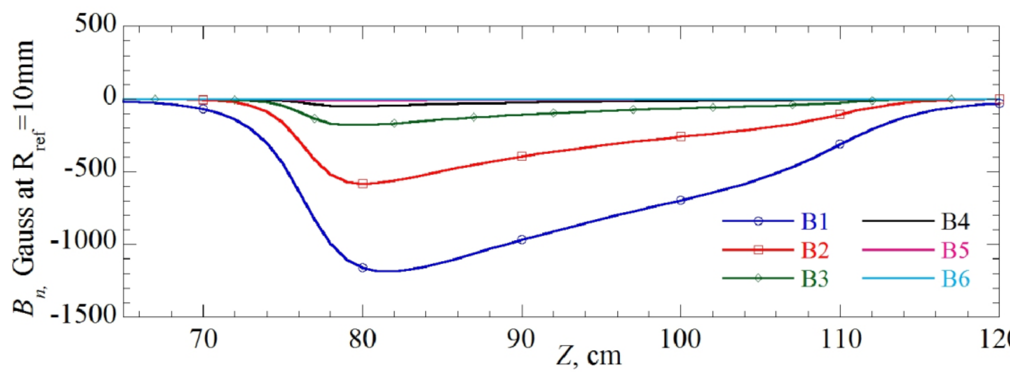
SC Corrector Magnets

- 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.



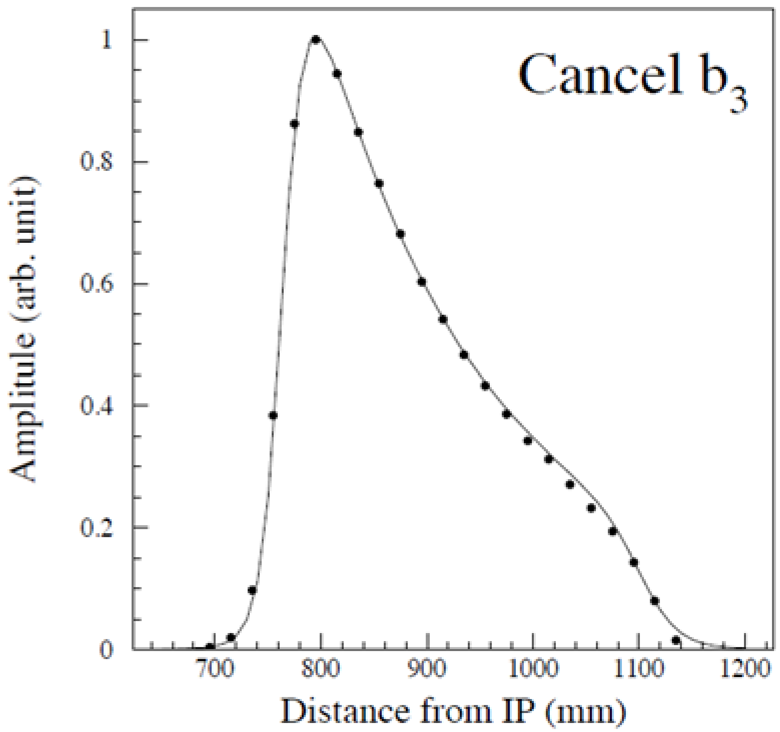


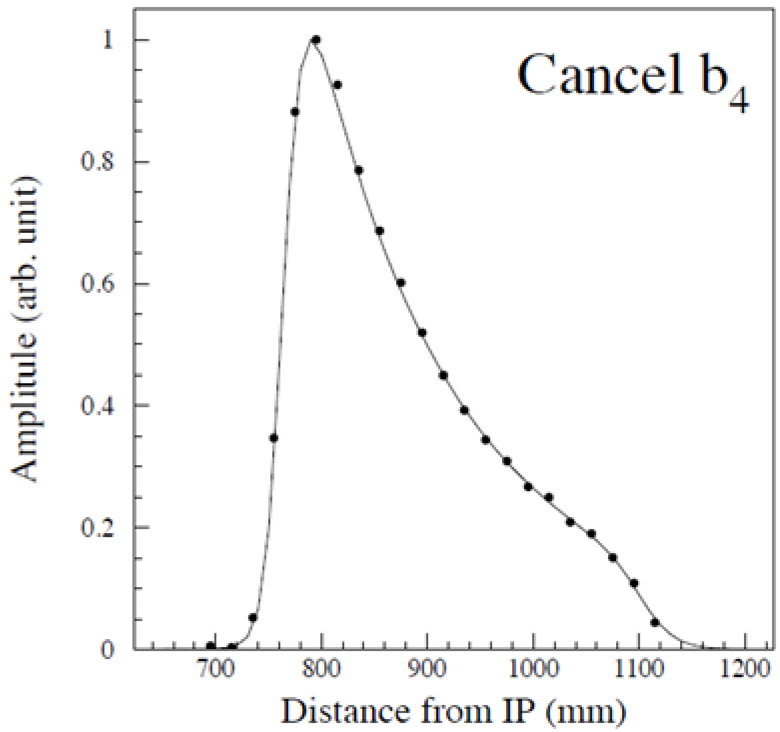
B_4 cancel magnets



SC Corrector Magnets

- Field measurements of the leak field cancel coils (b_3, b_4, b_5, b_6)
  - The field profiles of the cancel coils measured with the 20 mm long harmonic coil.

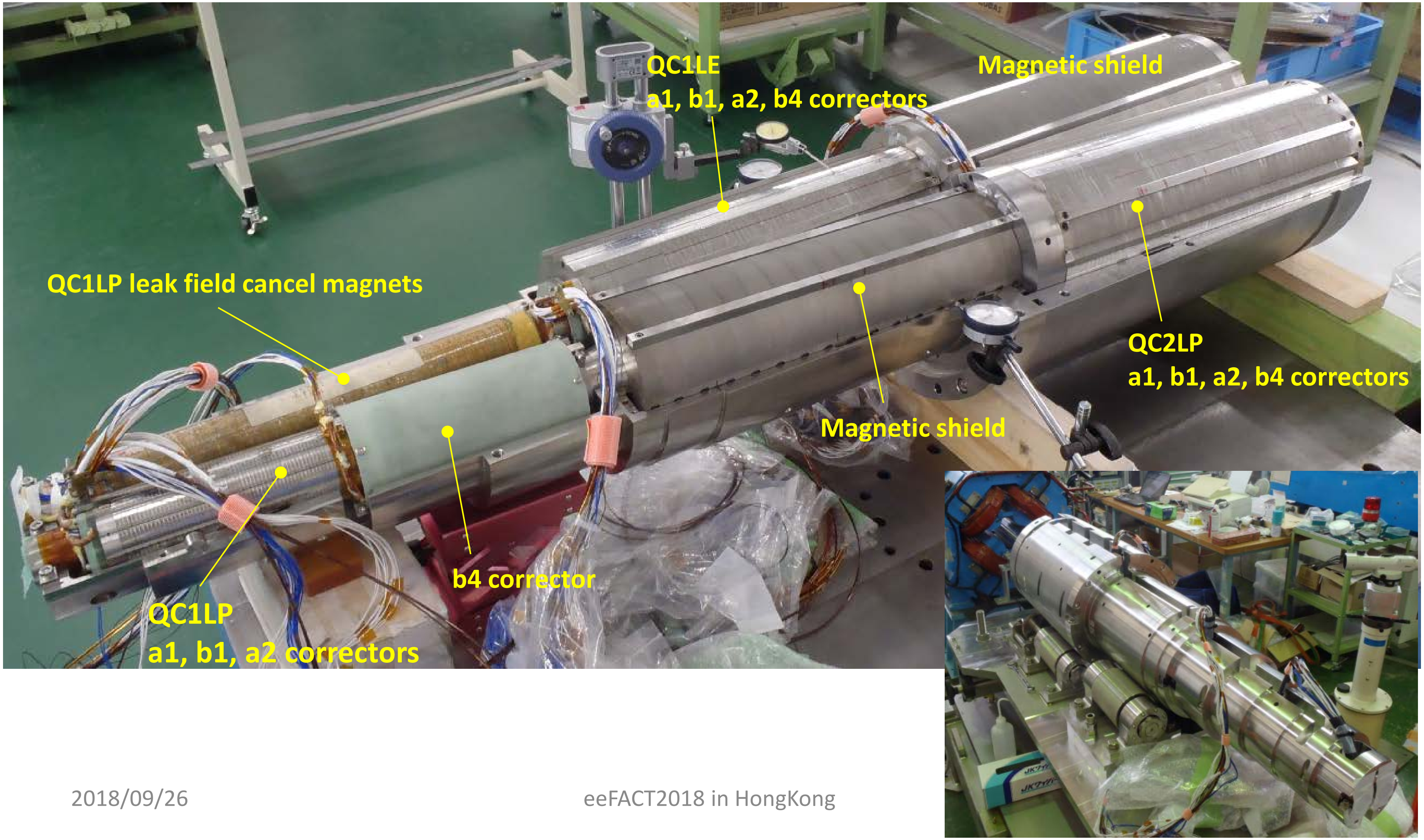




Line : Opera3D (Leak field from QC1LP)   Dot : Measurement

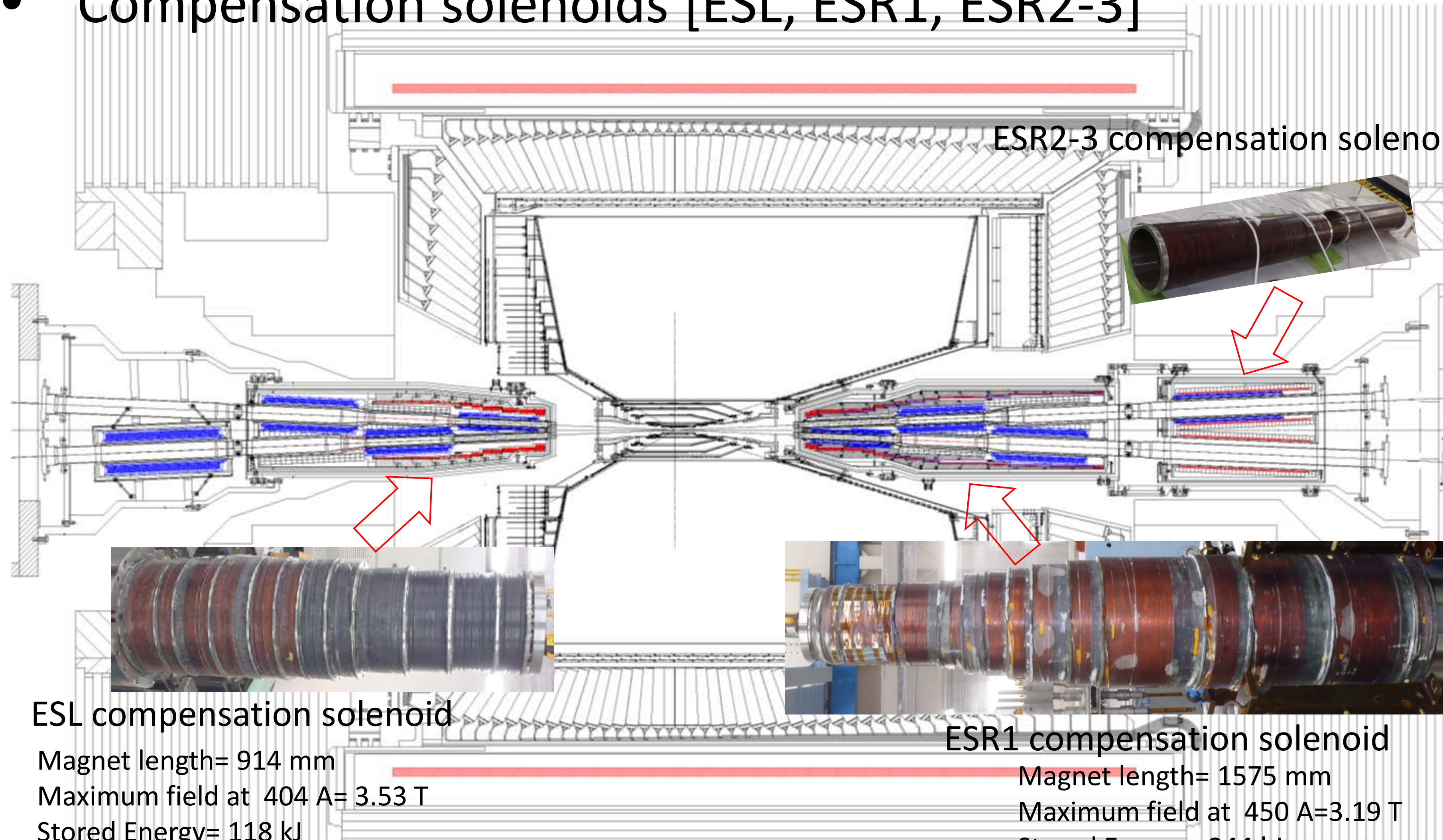
IR SC magnets

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

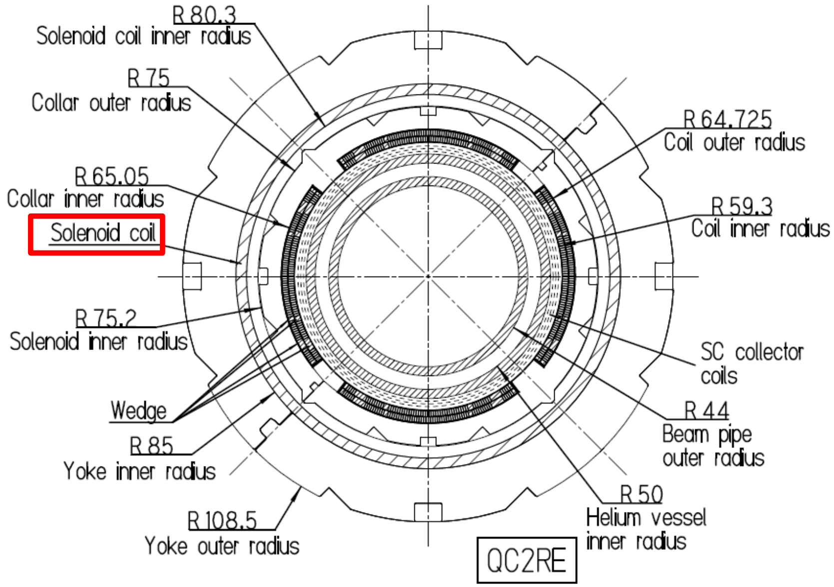
ESR1 compensation solenoid

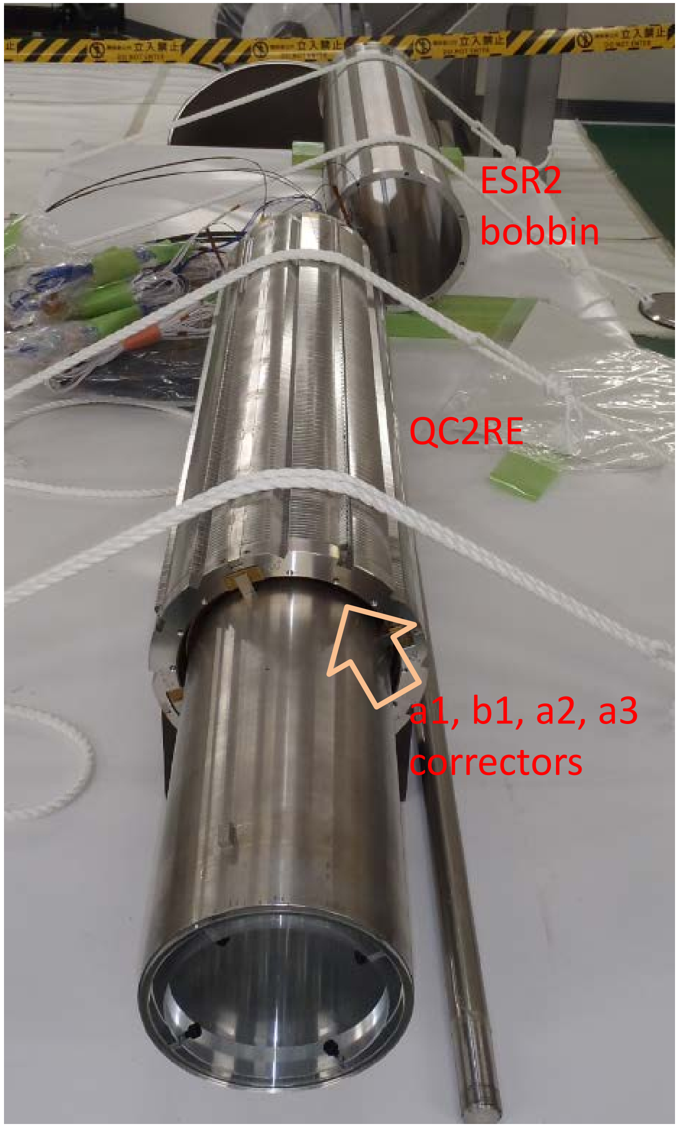
Magnet length= 1575 mm
Maximum field at 450 A=3.19 T
Stored Energy= 244 kJ
Cold diode quench protection system

IR SC magnets

- Compensation solenoids [ESR2, ESR3]

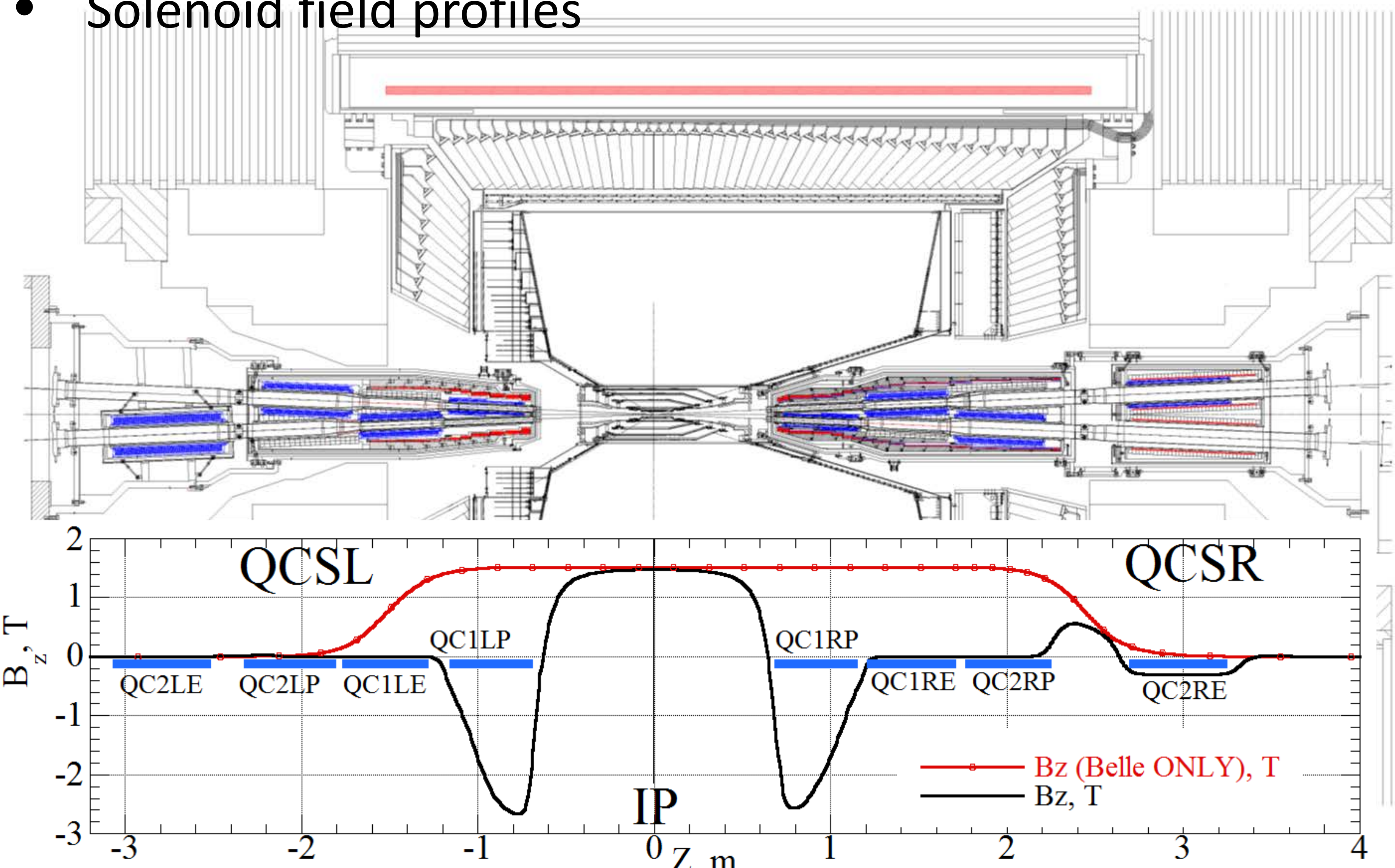
ESR3 for LER beam line



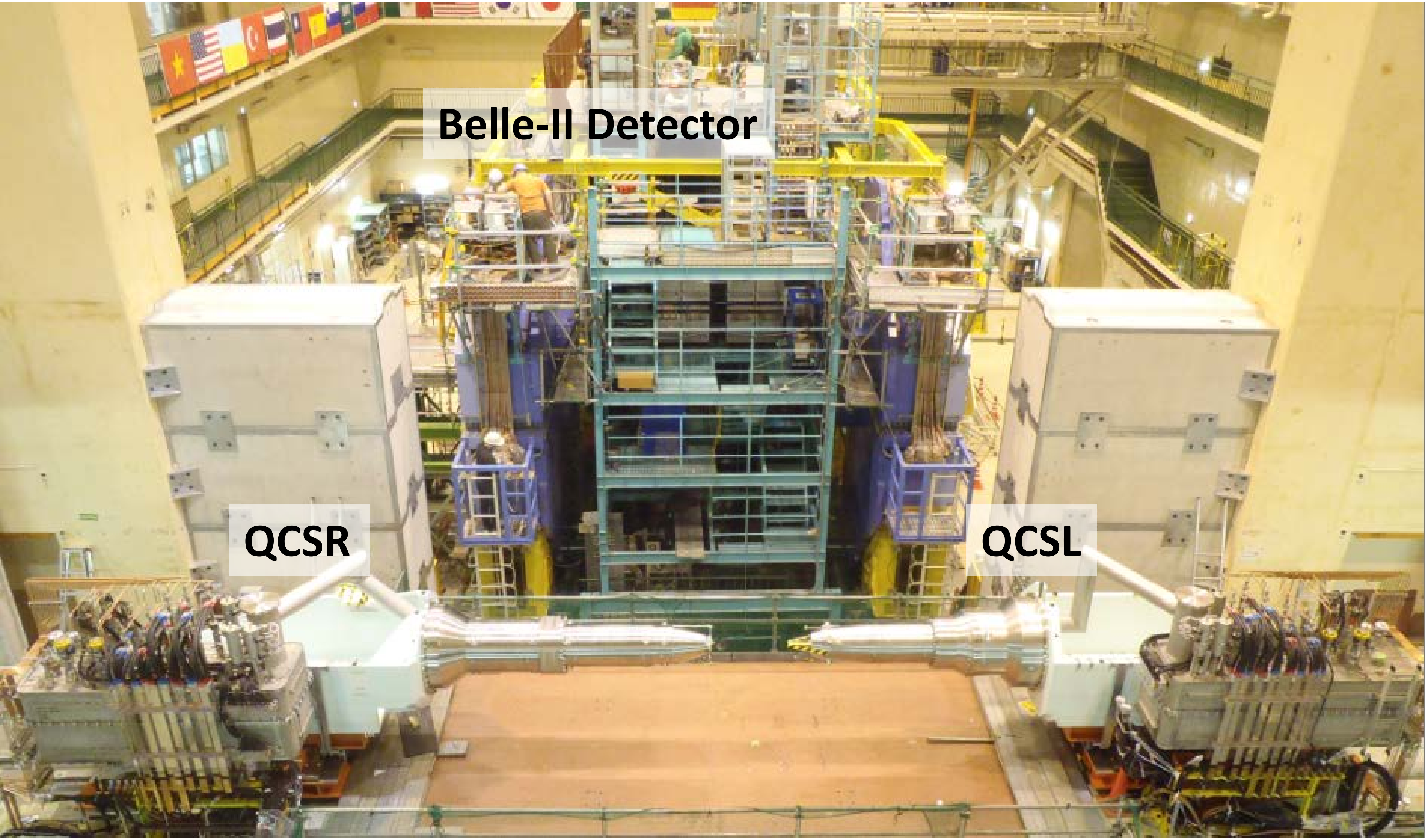


IR SC magnets

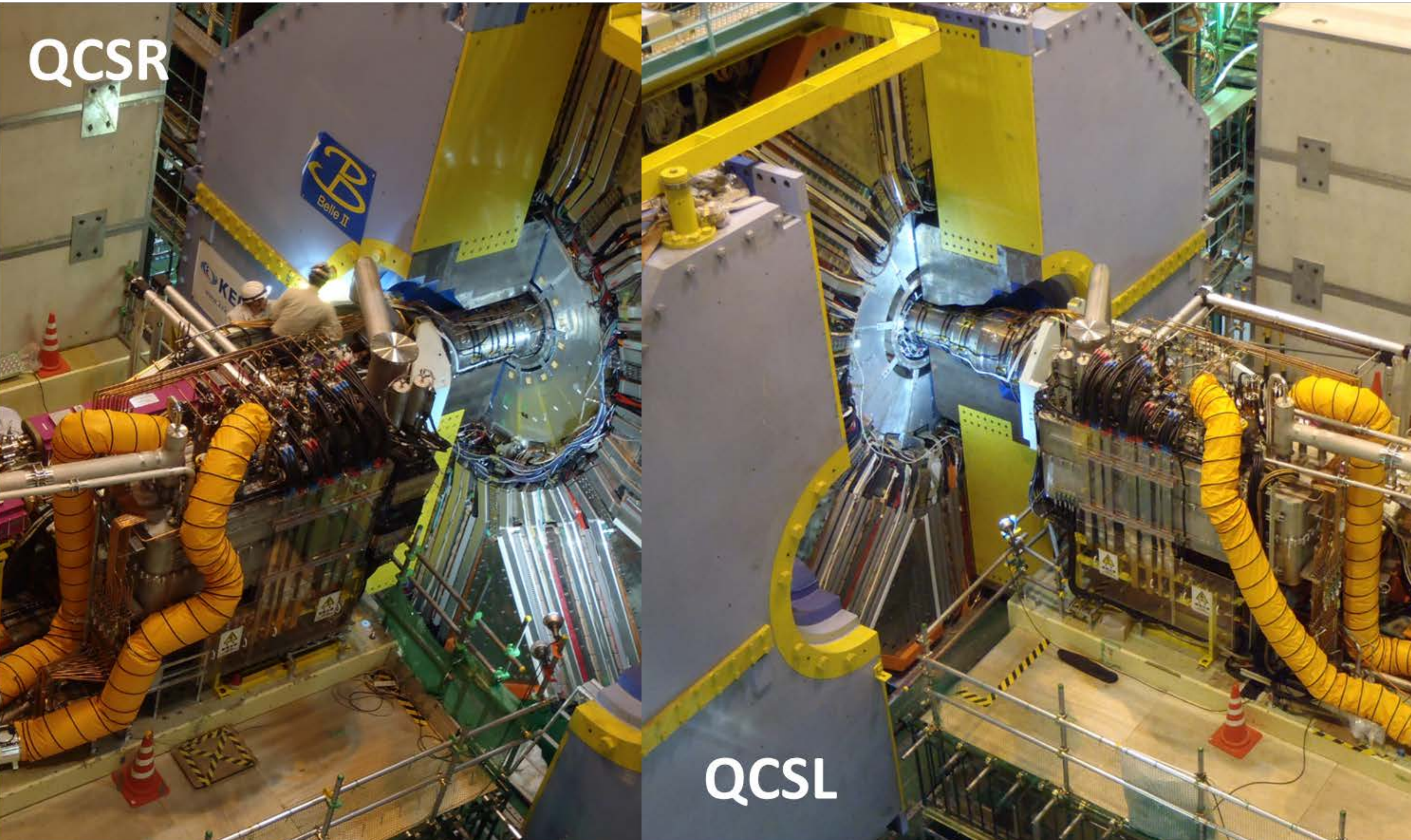
- Solenoid field profiles



Two cryostats in SuperKEKB IR



Installation of QCS cryostats into Belle-II

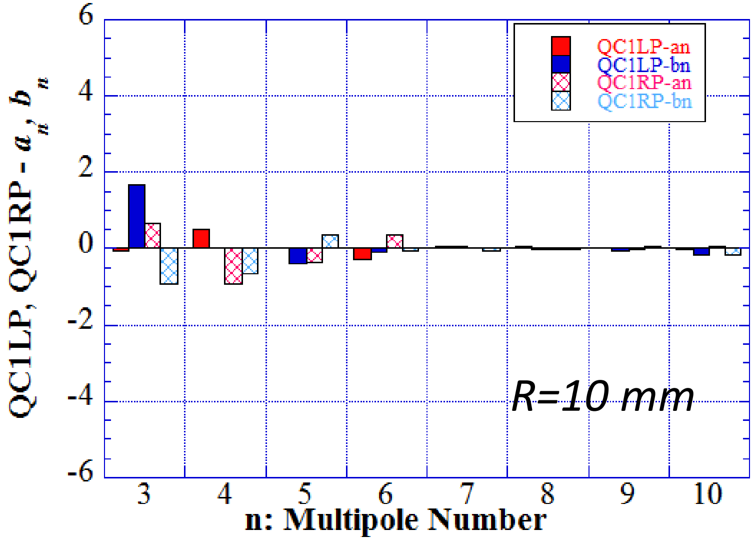


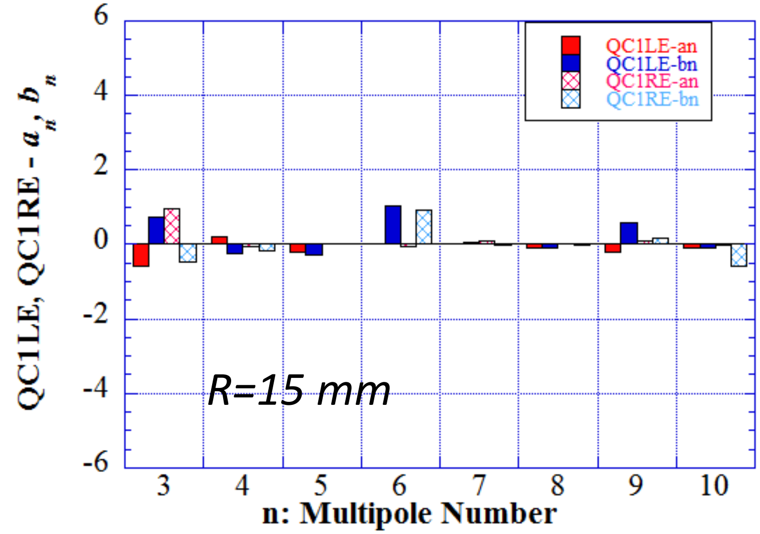
Magnetic field measurements

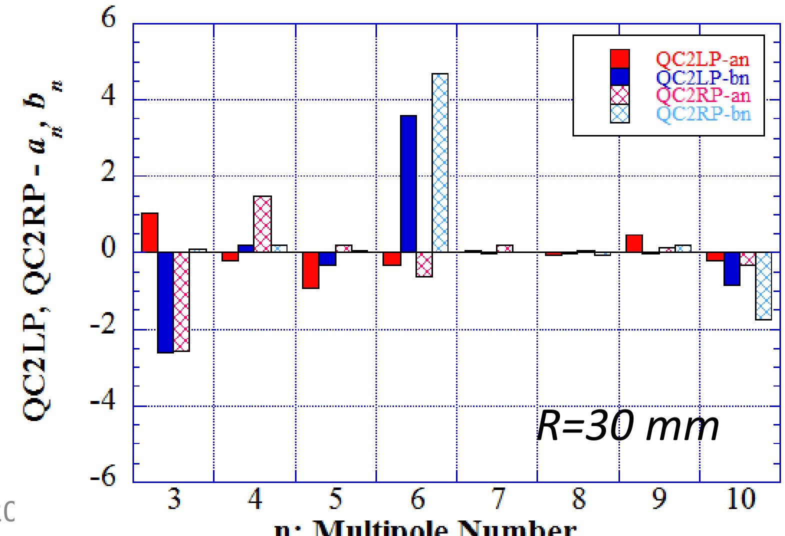
- **Single Stretched Wire measurement (SSW)**
  - Measurements of magnetic field centers and angles of the quadrupole field of QC1 and QC2
- **Harmonic coil measurement**
  - Integral magnetic field quality measurements of the SC magnets
  - Higher order multipole field profile measurements along the beam line.
- **3 axis-hall probe measurement**
  - Solenoid field profile measurements along the beam lines

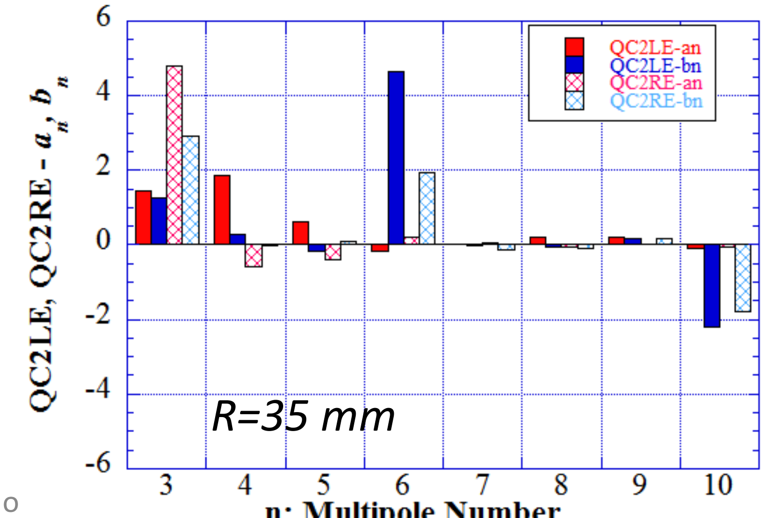
Integral field quality of the QC1/2 magnets
(measured under solenoid fields)

The strengths of the multipole field components are normalized with the B_2 field strength as 10,000. The magnetic field qualities of QC1 magnets were quite good.









Operational Experiences of QCS in Phase-2

Operation of QCS superconducting magnet system for Phase2

- **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.
- **Power supplies**
  - Tuning parameters of the power supplies from February 13 to February 16, 2018.
- **Water leak problem for Belle-II detector**
  - Opening the Belle-II end yoke in the QCS-L side at February 27, 2018.
  - Countermeasure for the water leaks
  - Closing the Belle-II end yoke at March 5, 2018
  - Assembly of the concrete radiation shields from March 9 to March 14, 2018.
- **SuperKEKB Phase2 beam operation (March 16, 2018 ~ July 17, 2018)**
  - **Many magnet quenches during beam operation**

QCS magnet quenches in Phase-2

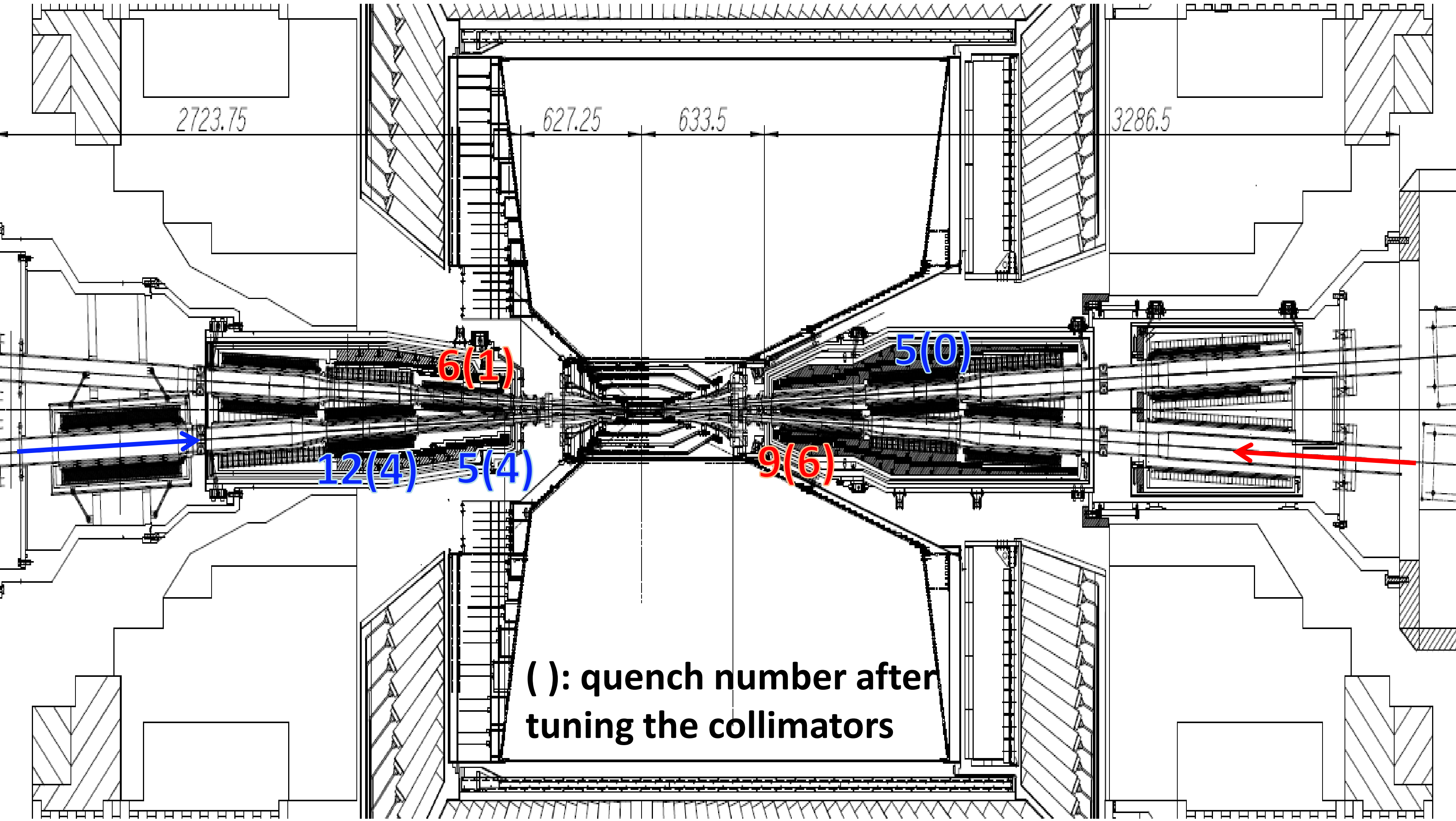
QCS magnet quench history in Phase2

#	Date	Time	Quenched Magnet	Beam Line	Beam condition	Magnet current (A)
1	2018/4/1	20:54:53	QC1LP	LER	LER **Beam injection**	QC1LP=1600.1
2	2018/4/2	19:31:21	QC1LP	LER	LER **Beam injection**	QC1LP=1600.1
3	2018/4/9	17:32:41	QC1LE-b1	HER	HER **Optics Tuning**	b1=-32.57
4	2018/4/9	20:07:48	QC1LE-b1	HER	HER **Beam injection**	b1=-32.57
5	2018/4/9	20:54:58	QC1LE-b1	HER	HER **Beam injection**	b1=-32.57
6	2018/4/9	21:42:14	QC1LE-b1	HER	HER **Beam injection**	b1=-32.57
7	2018/4/10	17:45:15	QC1LE-b1	HER	HER **Beam injection**	b1=-32.57
8	2018/4/10	21:58:15	QC1RE-b1	HER	HER=20mA	b1=33.20
9	2018/4/11	14:21:10	QC1RE-b1	HER	HER=28.9mA	b1=33.20
10	2018/4/11	15:27:15	QCSL cancel	HER	HER **Beam injection**	b3=-40.30, b4=-25.60, b5=-17.60
11	2018/4/11	15:30:57	QC1LE	HER		QC1LE=1583.0
12	2018/4/11	15:31:18	QC1LP	LER	LER=78.8mA	QC1LP=1600.1
13	2018/4/11	18:47:07	QC1RE-b1	HER	**Beam injection, HER=9.9mA**	b1=33.20
14	2018/4/11	20:24:48	QC1RE-b1	HER	HER=5.3mA	b1=33.20
15	2018/4/11	21:15:06	QC1RE-b1	HER	HER=8.3mA	b1=33.20
16	2018/4/20	14:38:53	QC1RP, QC1LP, QC1RP-b1	LER	LER=47.9mA	QC1RP=1603.8, QC1LP=1600.1, QC1RP-b1=-13.88
17	2018/4/21	0:23:44	QC1LP, QC1RP	LER	LER **RF Room Phase scan,** LER=18.5mA	QC1RP=1603.8, QC1LP=1600.1
18	2018/4/21	0:24:06	QC1RP-b1	LER		b1=-13.88
19	2018/5/6	11:28:14	QC1LE-b1	HER	HER **Optics Tuning**, HER=38.5mA	b1=-32.57
20	2018/5/13	2:45:43	QC1RP-b1	LER	LER **Beam injection**, LER=390.6mA	b1=-13.88
21	2018/5/17	2:09:30	QC1RP-b1	LER	LER **Beam injection**, LER=229.7mA	b1=-13.88
22	2018/5/17	4:06:19	QC1RP-b1	LER	LER **Beam injection**, LER=106.5mA	b1=-13.88
23	2018/5/24	17:17:00	QCSL cancel	HER	HER **Beam injection,** HER=20.9mA	b3=-40.30, b4=-25.60, b5=-17.60, b6=14.40
24	2018/6/25	11:20:34	QC1RP, QC1RP-b1, QC1LP	LER	HER **Beam injection**, **D2V1collimator damage**, LER=727.9mA/HER=613.0mA	QC1RP=1597.6, b1=-13.88, QC1LP=1598.4
25	2018/7/3	5:14:17	QC1RP-b1	LER	LER **Beam injection**, LER=285.9mA	b1=-13.88
26	2018/7/9	11:17:18	QC1LE, QC1LE-b1, QCSL cancel	HER	LER/HER **Beam injection,** LER=487.0mA, HER=766.1mA	QC1LE=1581.4, b1=-32.57, Cancel-b3=-40.34, Cancel-b4=-25.55
27	2018/7/15	22:32:14	QC1RP, QC1LE, QC1LE-b1, QCSL cancel	LER, HER	LER/HER **Beam injection,** LER=794.7mA, HER=487.6mA	QC1RP=1597.6, QC1LE=1579.62, QC1LE-b1=-32.58, Cancel-b3=-40.34, Cancel-b4=-25.55
28	2018/7/16	17:53:03	QC1LE-b1, QCSL cancel	HER	HER=670.0mA	QC1LE=1579.2, Cancel-b3=-40.34, Cancel-b4=-25.55

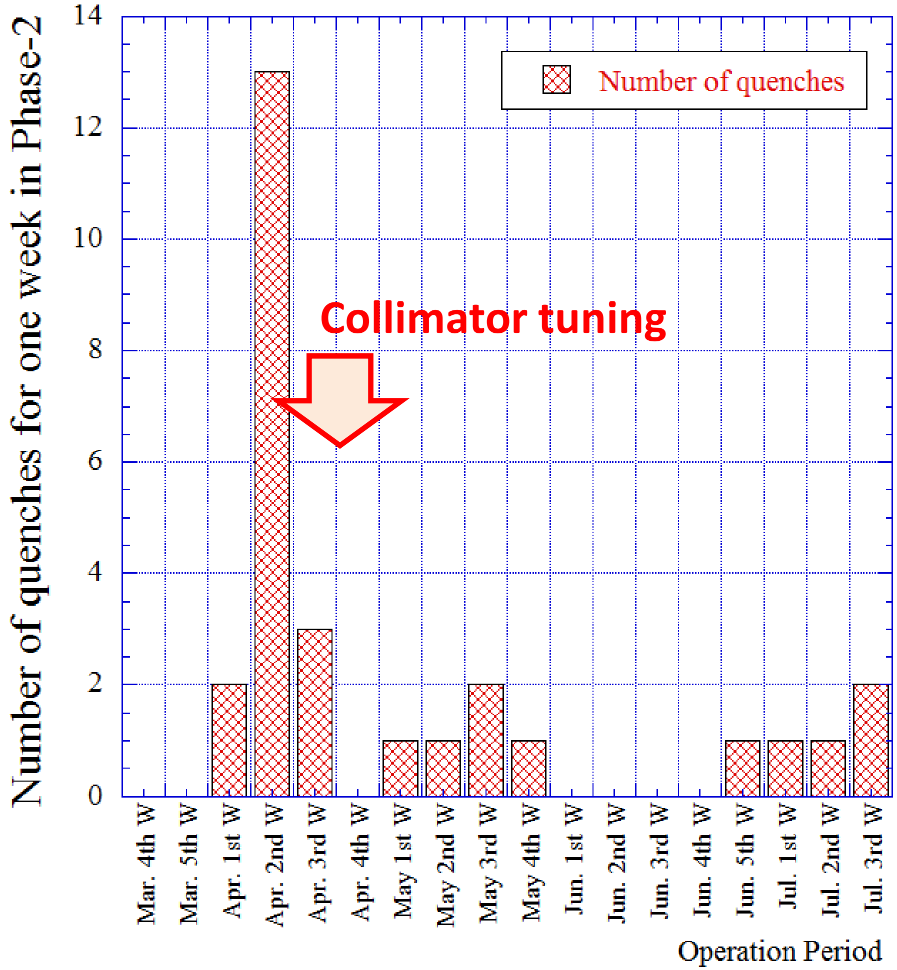
Tuning collimators

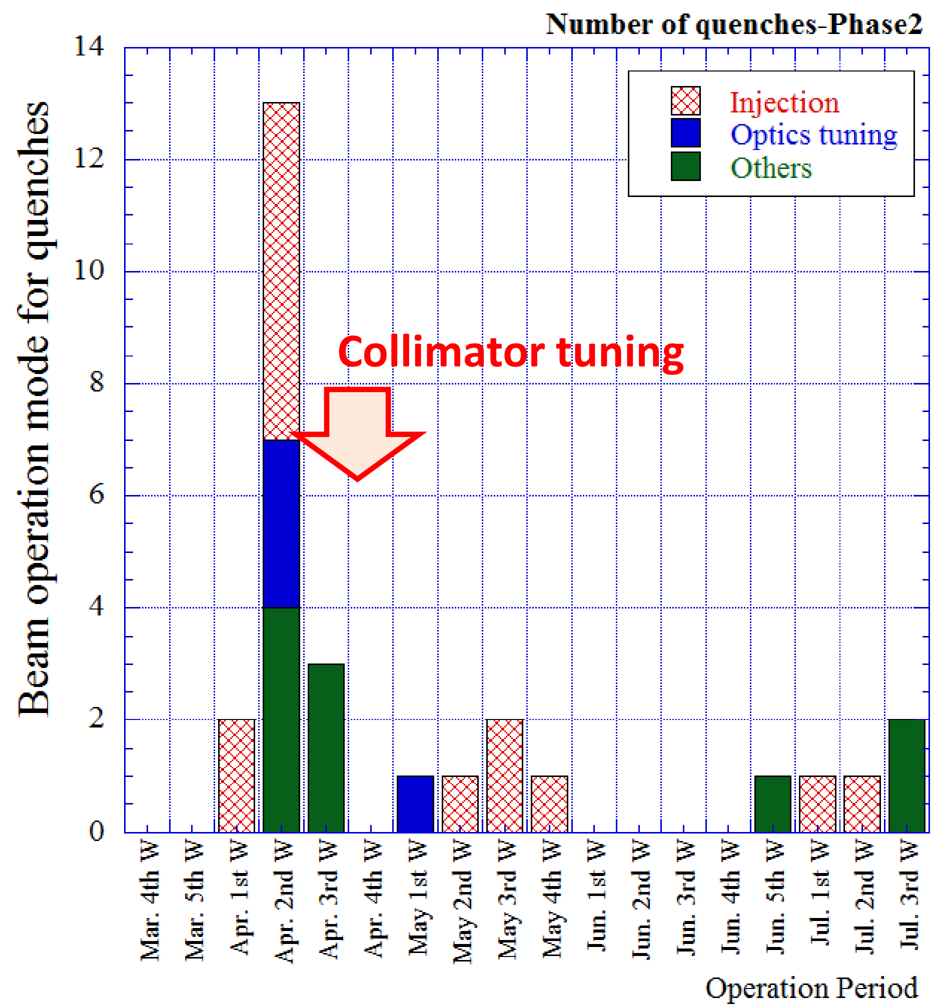
QCS magnet quenches in Phase-2

Quenched magnets by beams



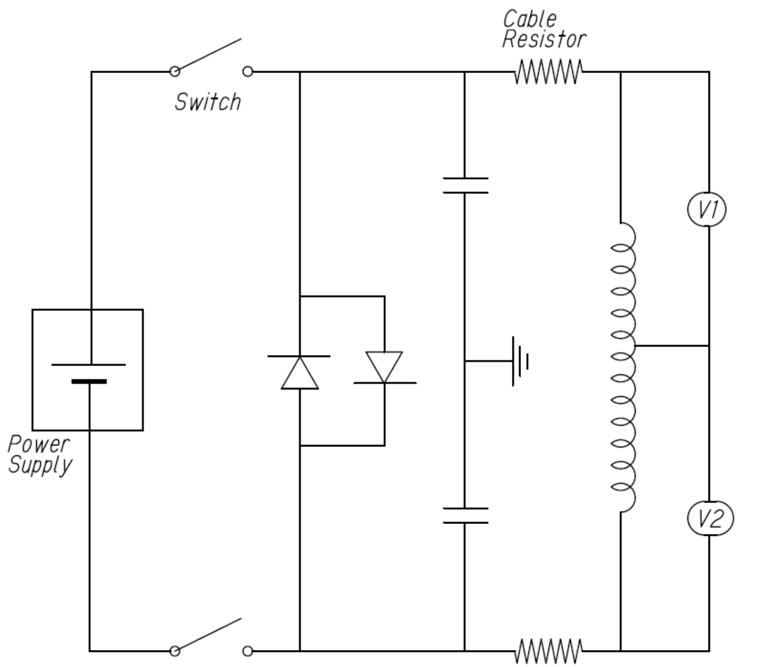
QCS magnet quenches in Phase-2





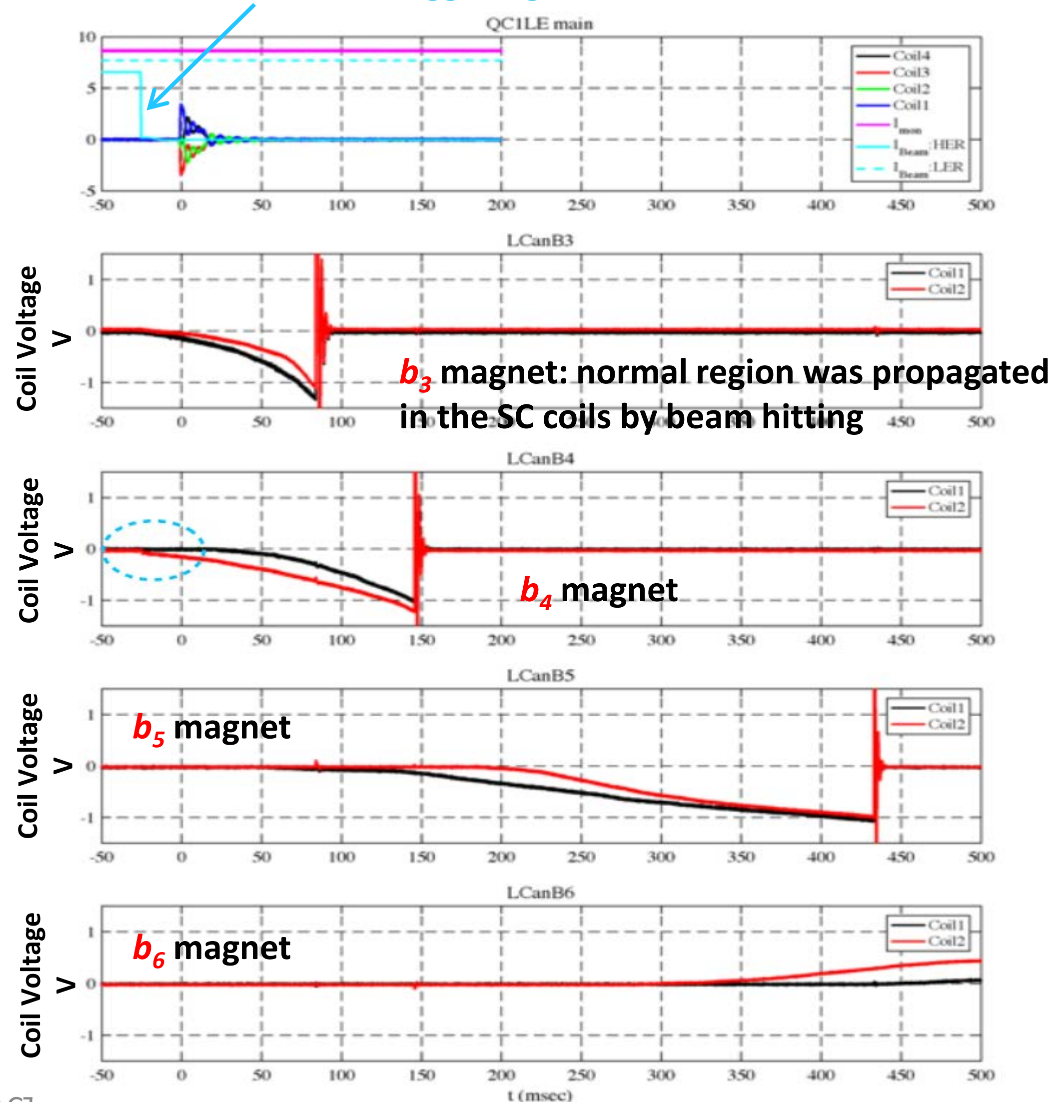
QCS magnet quenches in Phase-2

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



For corrector magnet

HER beam : HER beam was aborted by the loss monitor trigger signal

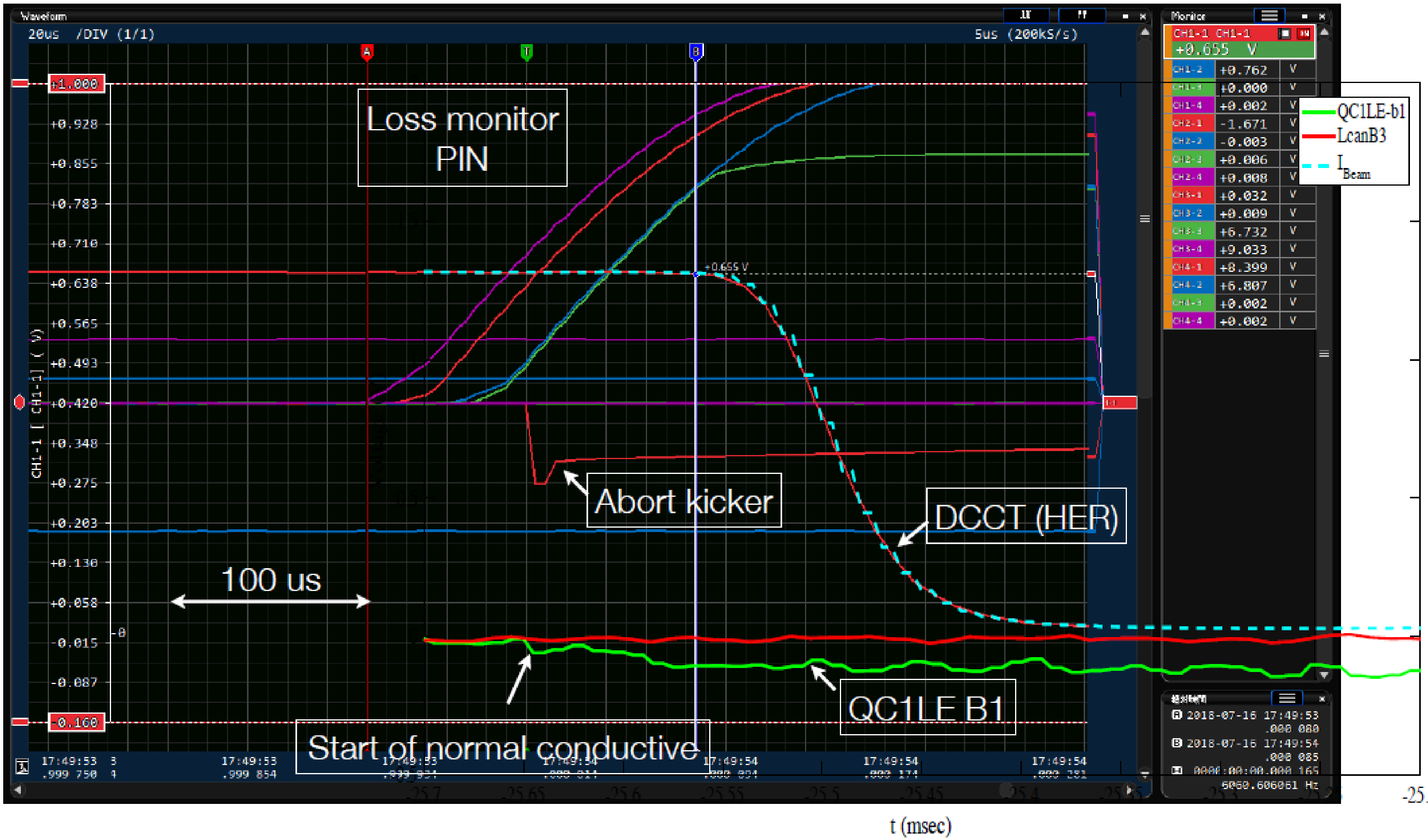


Summary

- The beam final focus system, QCS, for SuperKEKB was constructed and the Phase-2 beam commissioning with the system was successfully completed.
- The first collision of e- and e+ beams successfully was carried out at April 26th, 2018. The reached luminosity was 5.55×10^{33} $cm^{-1}s^{-1}$ at the beam currents of LER=800 mA and HER=780 mA, 1576 bunches/beam at July 5th, 2018.
- **Magnet quenches by beams were serious problem.**
  - Enhancement of beam diagnosis system and magnet quench detection system is planed for Phase-3 beam operation.
- Data of the magnetic field measurements on the beam lines are still being studied.
  - With the field measurement data, the precise and complete 3D field calculation model will be constructed for the Phase-3 operation.

Back-up

QCS magnet quenches in Phase-2



Jul/16/2017 QC1LE-b1 Quench