Final-Focus Superconducting Magnets for SuperKEKB

N. Ohuchi

KEK: Y. Arimoto, K. Aoki, M. Kawai, T. Kawamoto, H. Koiso, Y. Kondo, M. Masuzawa, A. Morita, S. Nakamura, Y. Ohnishi, T. Oki, Y. Ohsawa, H. Sugimoto, K. Tsuchiya, R. Ueki, X. Wang, H. Yamaoka, Z. Zong

BNL: P. Wanderer, B. Parker, M. Anerella, J. Escallier, A. Marone, A. Jain

FNAL: G. Velev, J. DiMarco, J. Nogiec, M. Tartaglia, T. Gardner

Mitsubishi Electric Corp.: T. Kim

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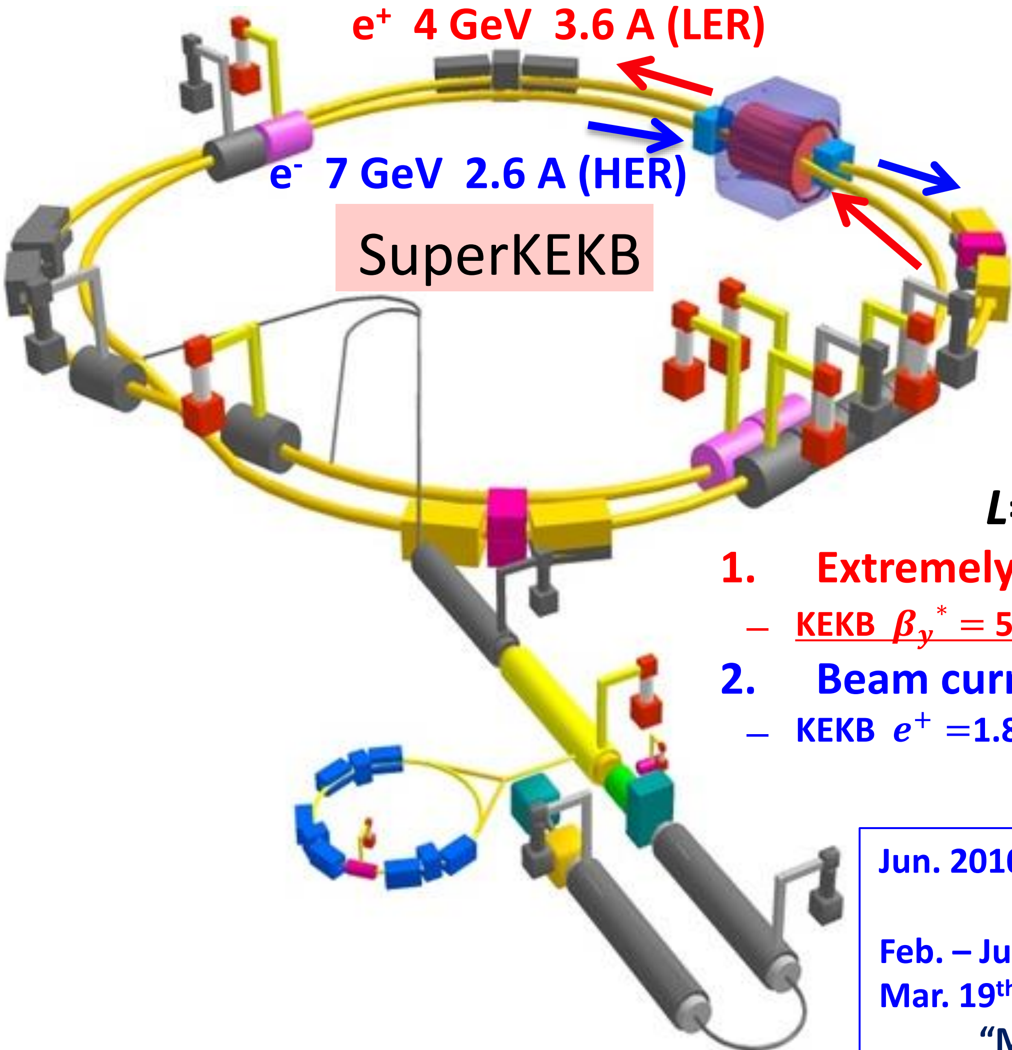
From KEKB to SuperKEKB



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

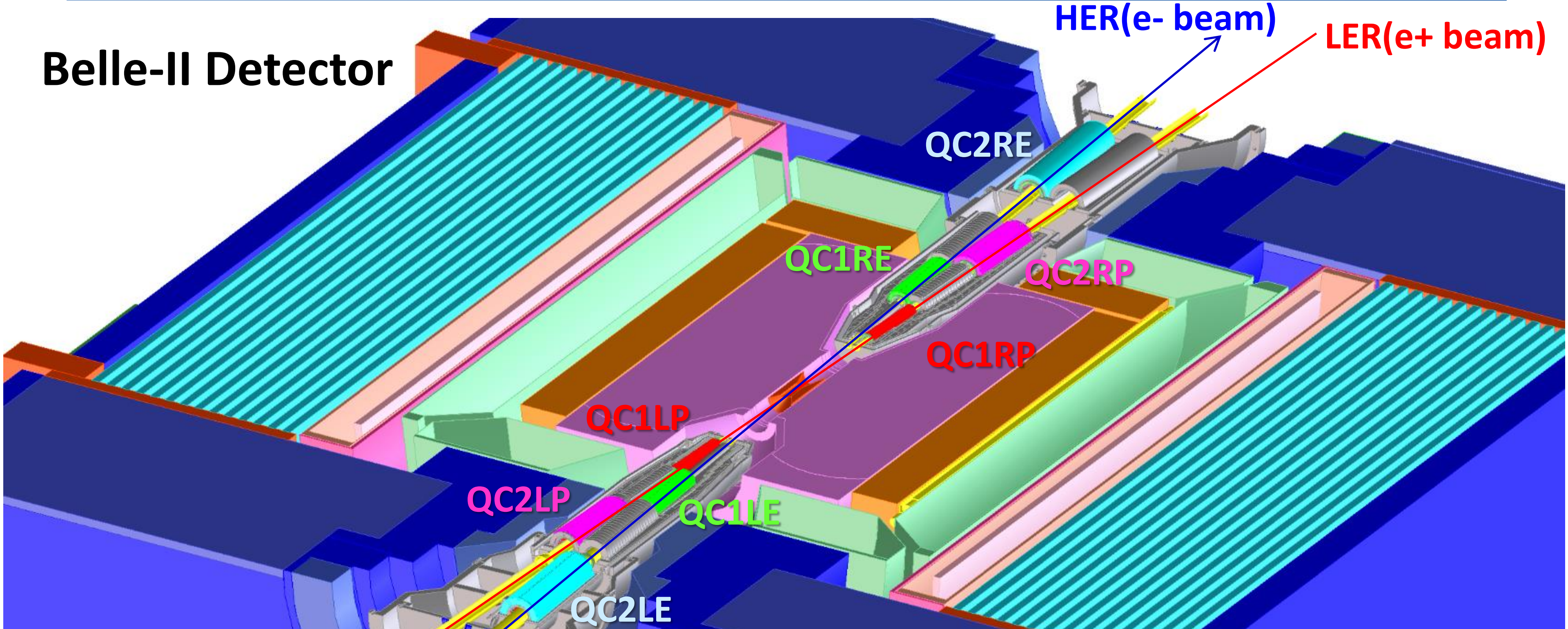
L=2.1×10^{34}cm^{-2}s^{-1} 8×10^{35}cm^{-2}s^{-1}

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
"MOXGB1: Report on SuperKEKB Phase 2 commissioning"
Yukiyoshi Ohnishi

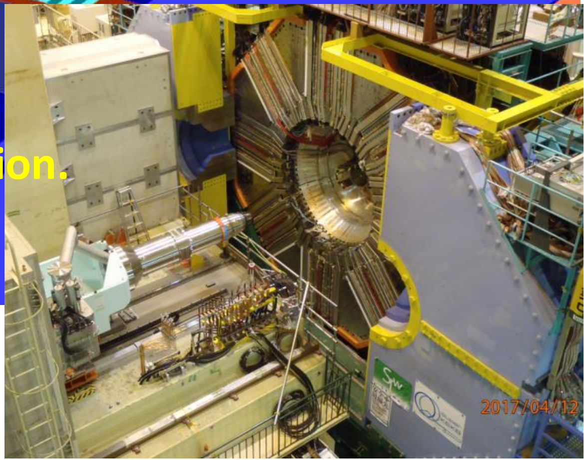
SuperKEKB IR Overview

Belle-II Detector

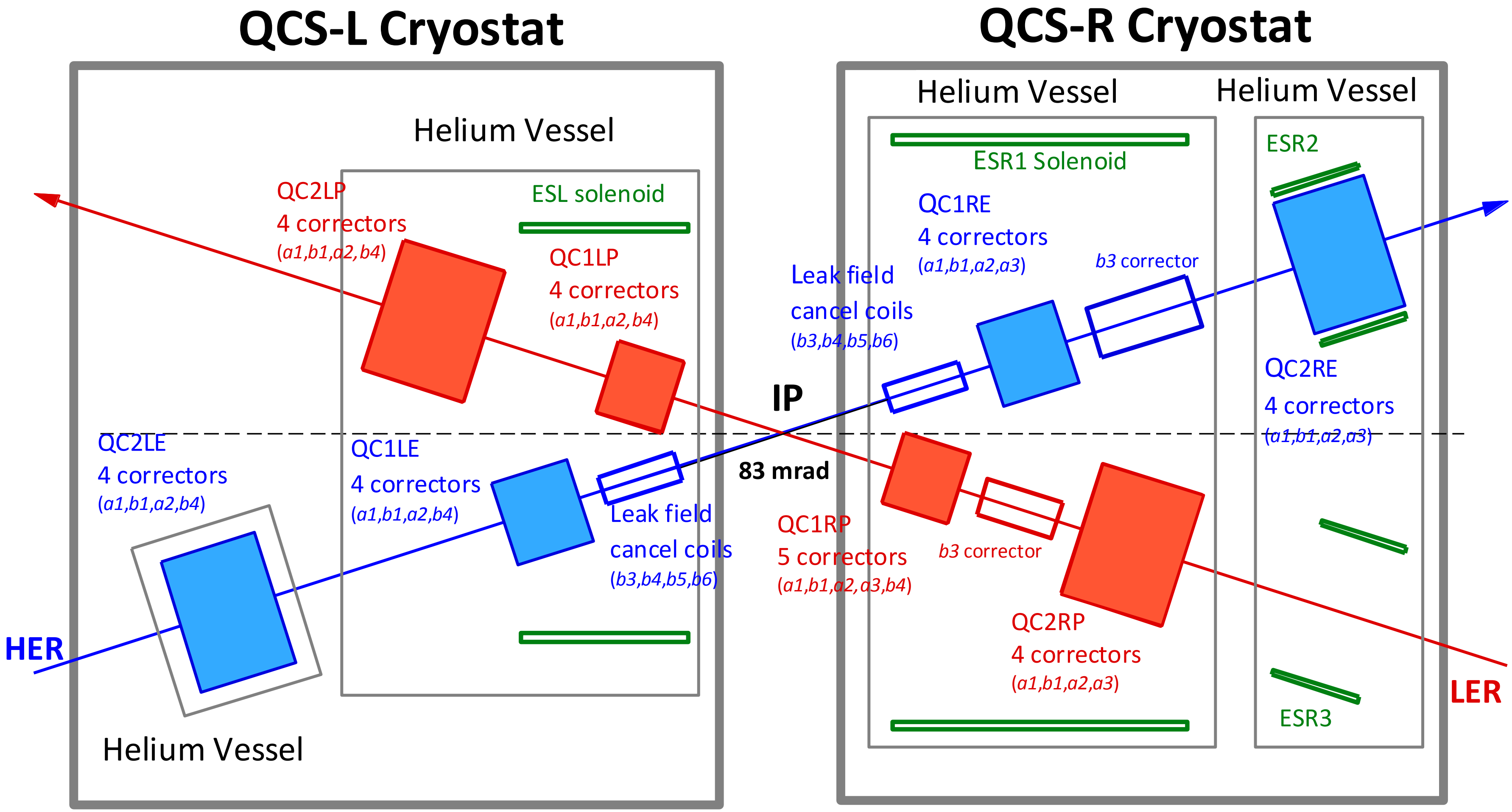


Design Constraint:

1. Quadrupoles need to be located as close to IP as possible.
    - Beam crossing angle=83 mrad
    - Quadrupoles need to be located in the two beam separation.
2. Quite tight space constraints for SC magnets and cryostats
    - Beam pipes at room temperature
    - Boundary with the Belle-II detector components
3. Belle-II solenoid field at 1.5 T superimposes on the FF system.



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

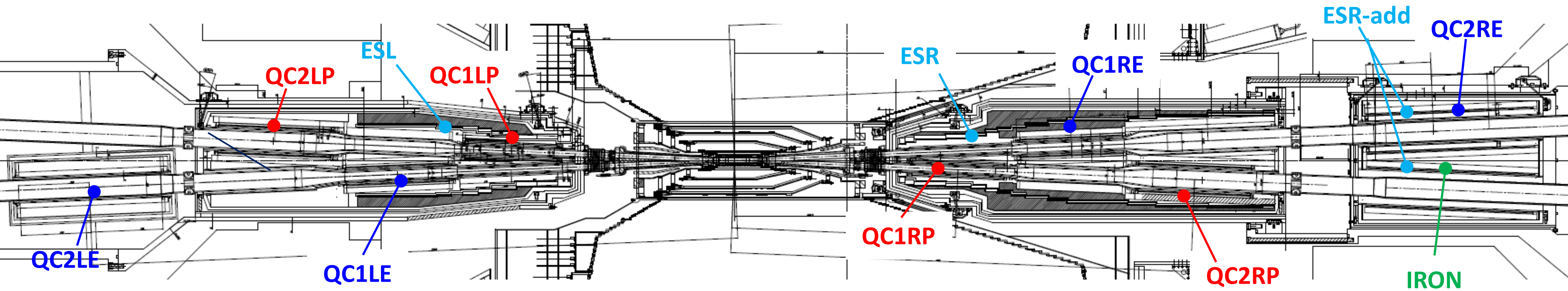
4 SC main quadrupole magnets: 1 collared magnet, 3 yoked magnets
19 SC correctors: a1, b1, a2, a3, b3, b4
4 SC leak field cancel magnets: b3, b4, b5, b6
3 compensation solenoid

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

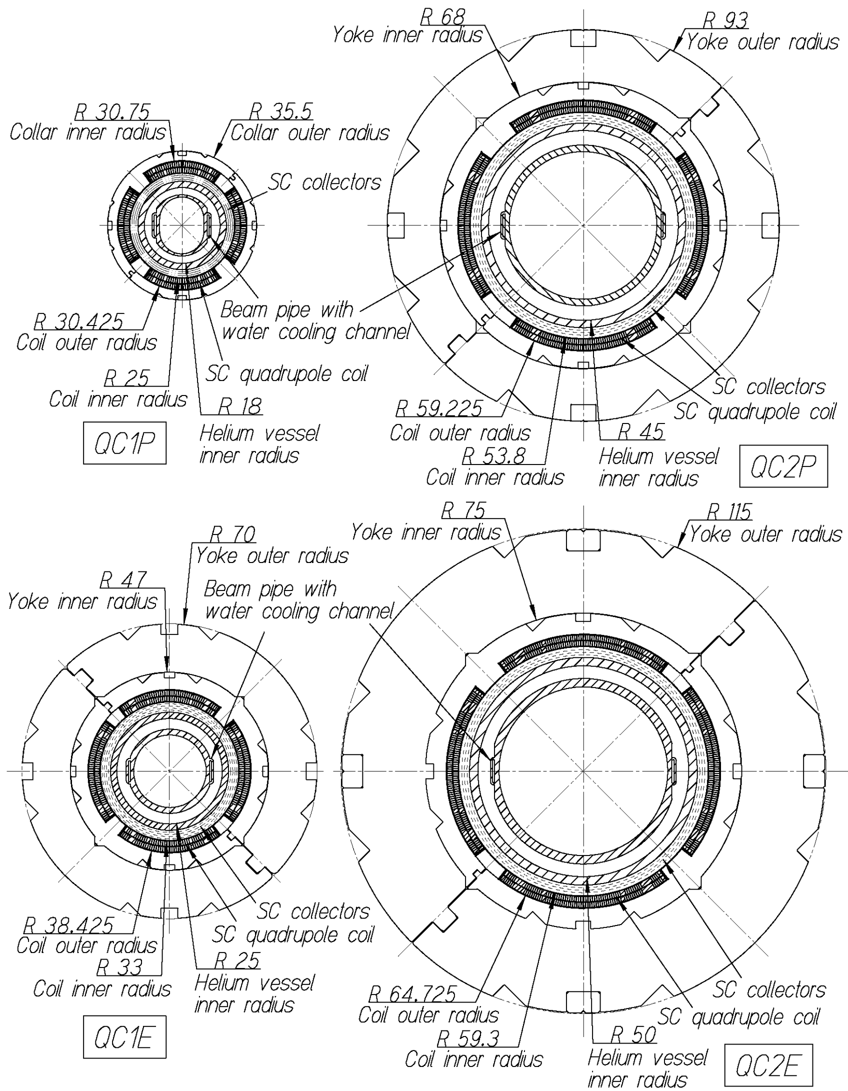
- Main quadrupoles [QC1, QC2]
  - QC1L(R)P, QC2L(R)P for the left (right) side cryostat to IP and for the positron beam line.
  - QC1L(R)E, QC2L(R)E for the left (right) side cryostat to IP and for the electron beam line.



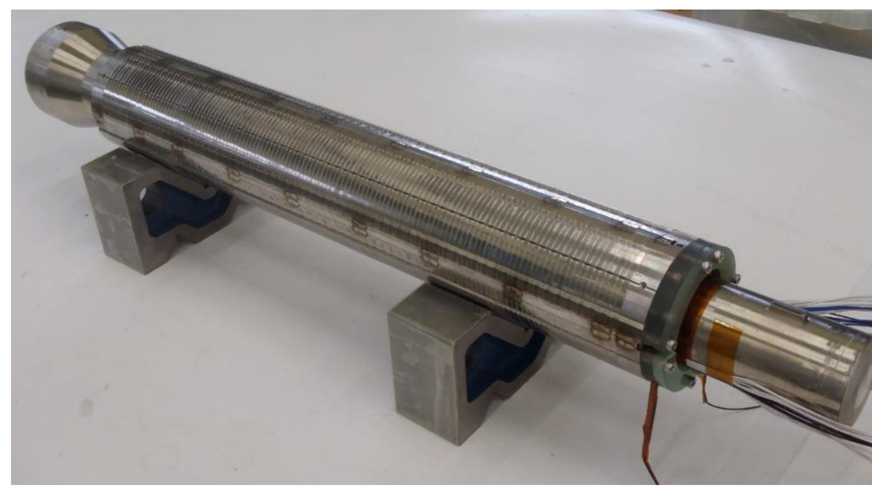
	Integral field gradient, (T/m)·m	Magnet type	Z pos. from IP, mm	θ, mrad	ΔX, mm	ΔY, mm
QC2RE	13.58 [32.41 T/m × 0.419m]	Iron Yoke	2925	0	-0.7	0
QC2RP	11.56 [26.28 × 0.410]	Permendur Yoke	1925	-2.114	0	-1.0
QC1RE	26.45 [70.89×0.373]	Permendur Yoke	1410	0	-0.7	0
QC1RP	22.98 [68.89×0.334]	**No Yoke**	935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



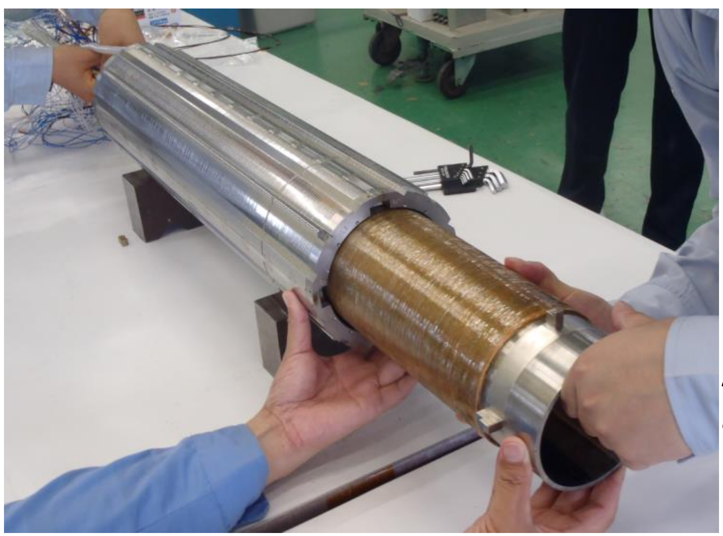
QC1LP Quadrupole Magnet

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).

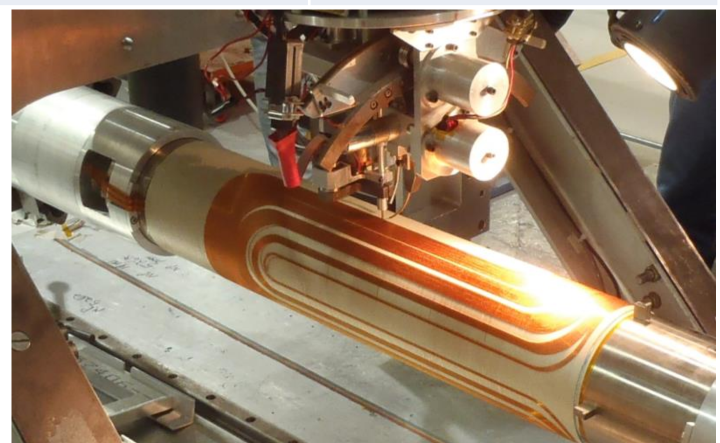
QCSL- Main Quadrupole	Corrector
QC1LP	a_1, b_1, a_2, b_4
QC2LP	a_1, b_1, a_2, b_4
QC1LE	a_1, b_1, a_2, b_4
QC2LE	a_1, b_1, a_2, b_4

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



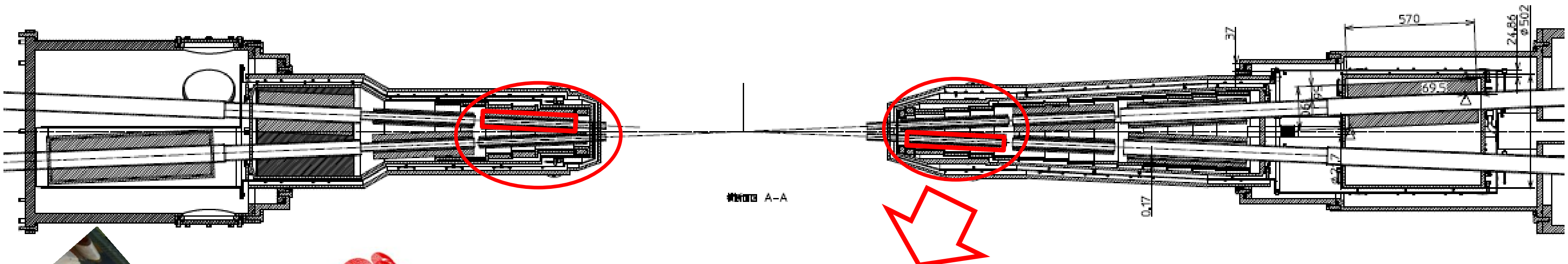
Assembly of QC2LE and correctors

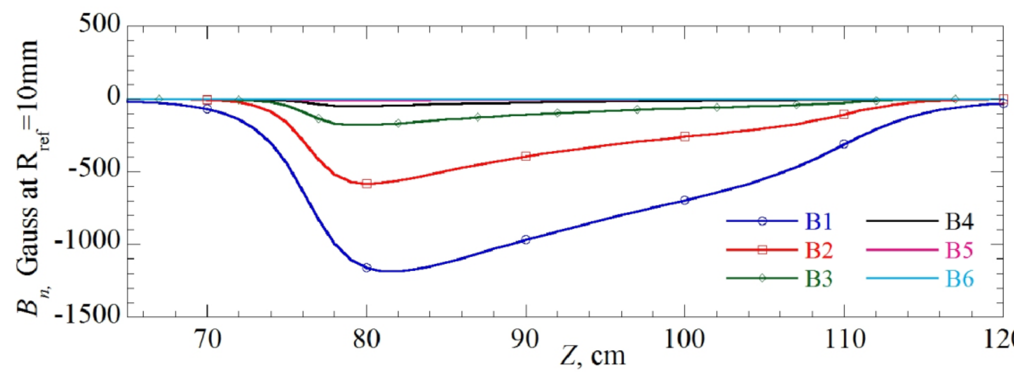
Direct winding process @BNL



IR SC magnets

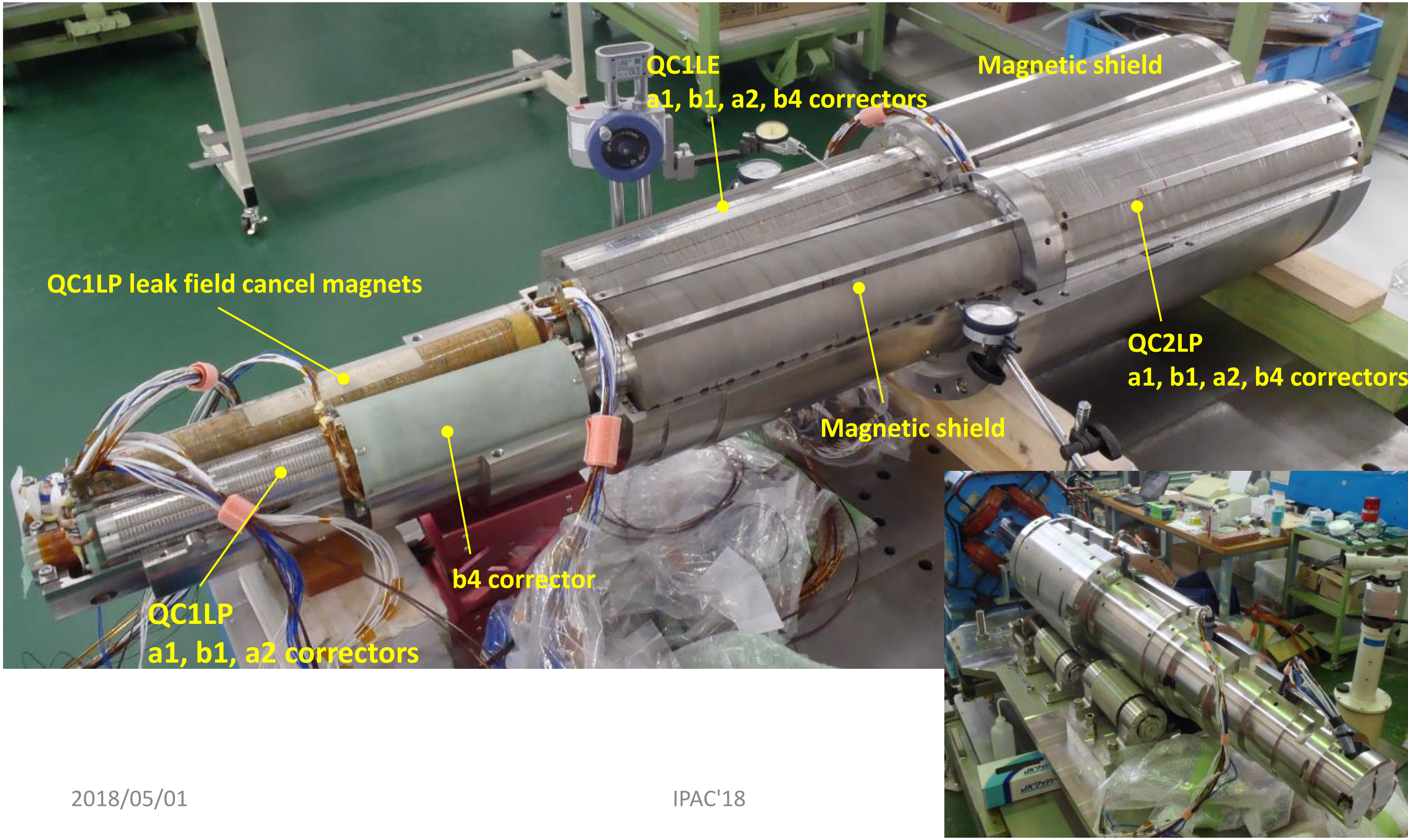
- QC1P leak field cancel magnets
  - QC1P for the e+ beam line is non-iron magnet and the e- beam line is very close to QC1P. The leak fields from QC1P go through the e- beam line.
  - ***B_3, B_4, B_5*** and ***B_6*** components of the leak fields are designed to be canceled with the SC cancel magnets.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





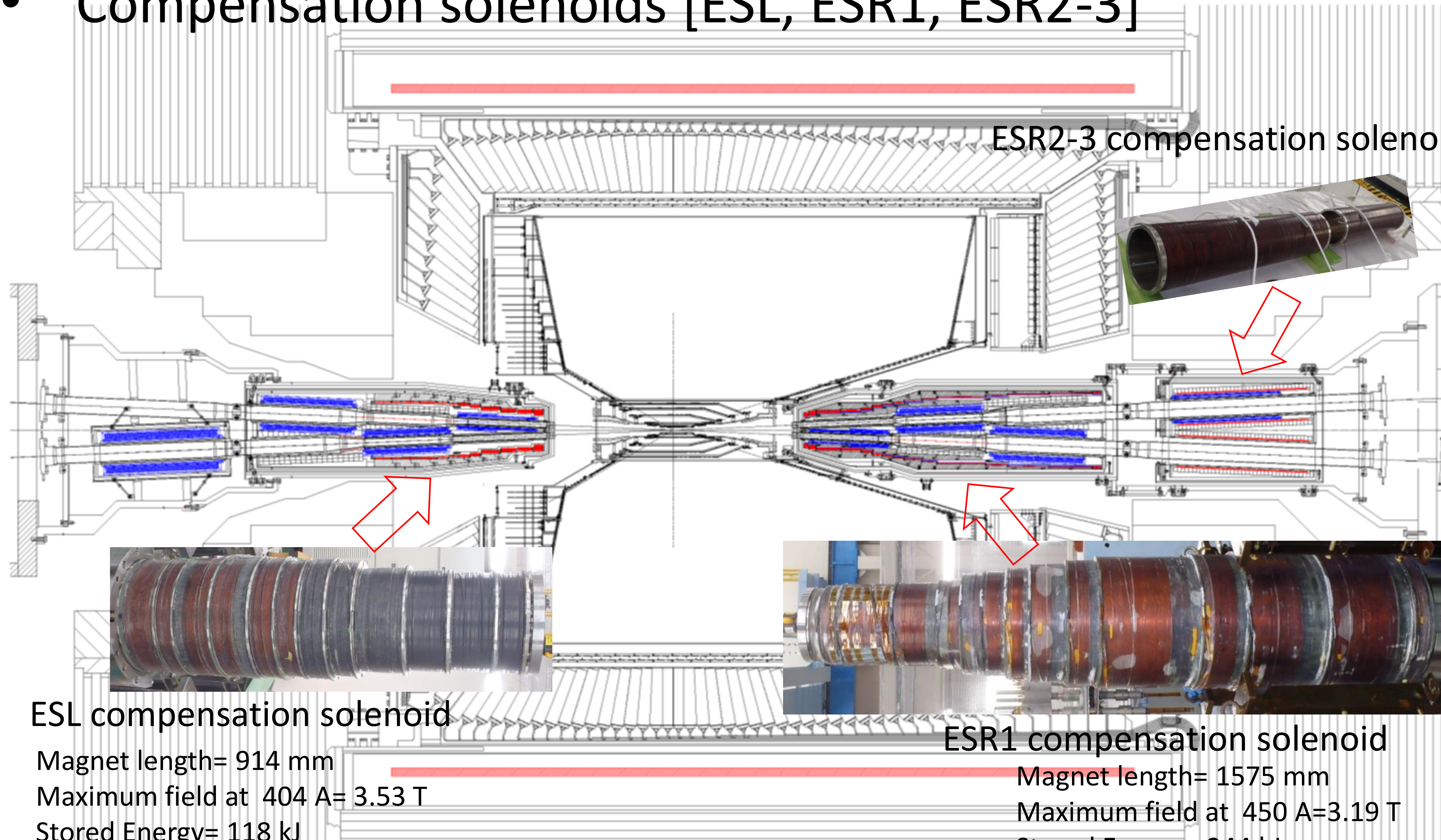
IR SC magnets

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

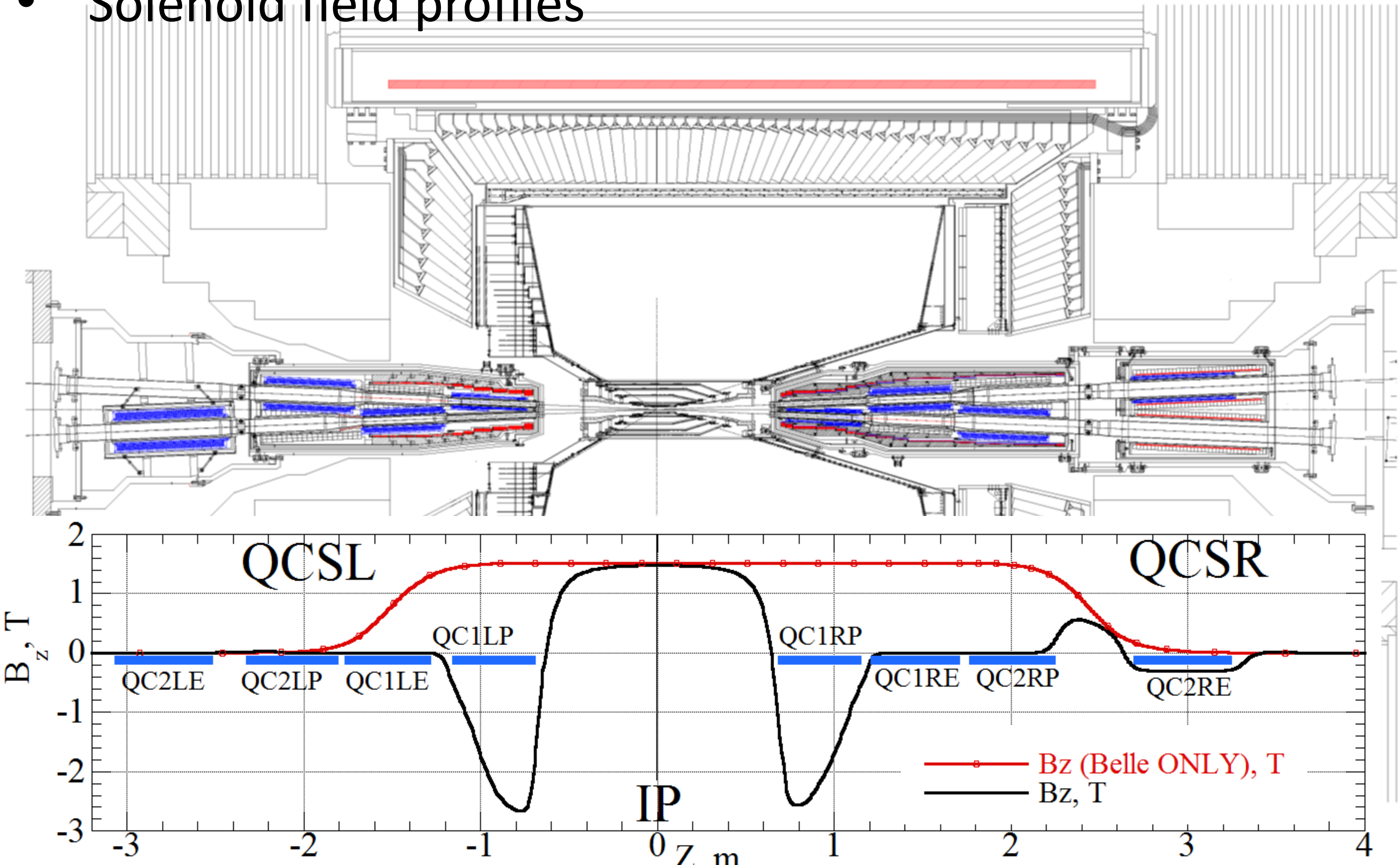
Magnet length= 914 mm
Maximum field at 404 A= 3.53 T
Stored Energy= 118 kJ

ESR1 compensation solenoid

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

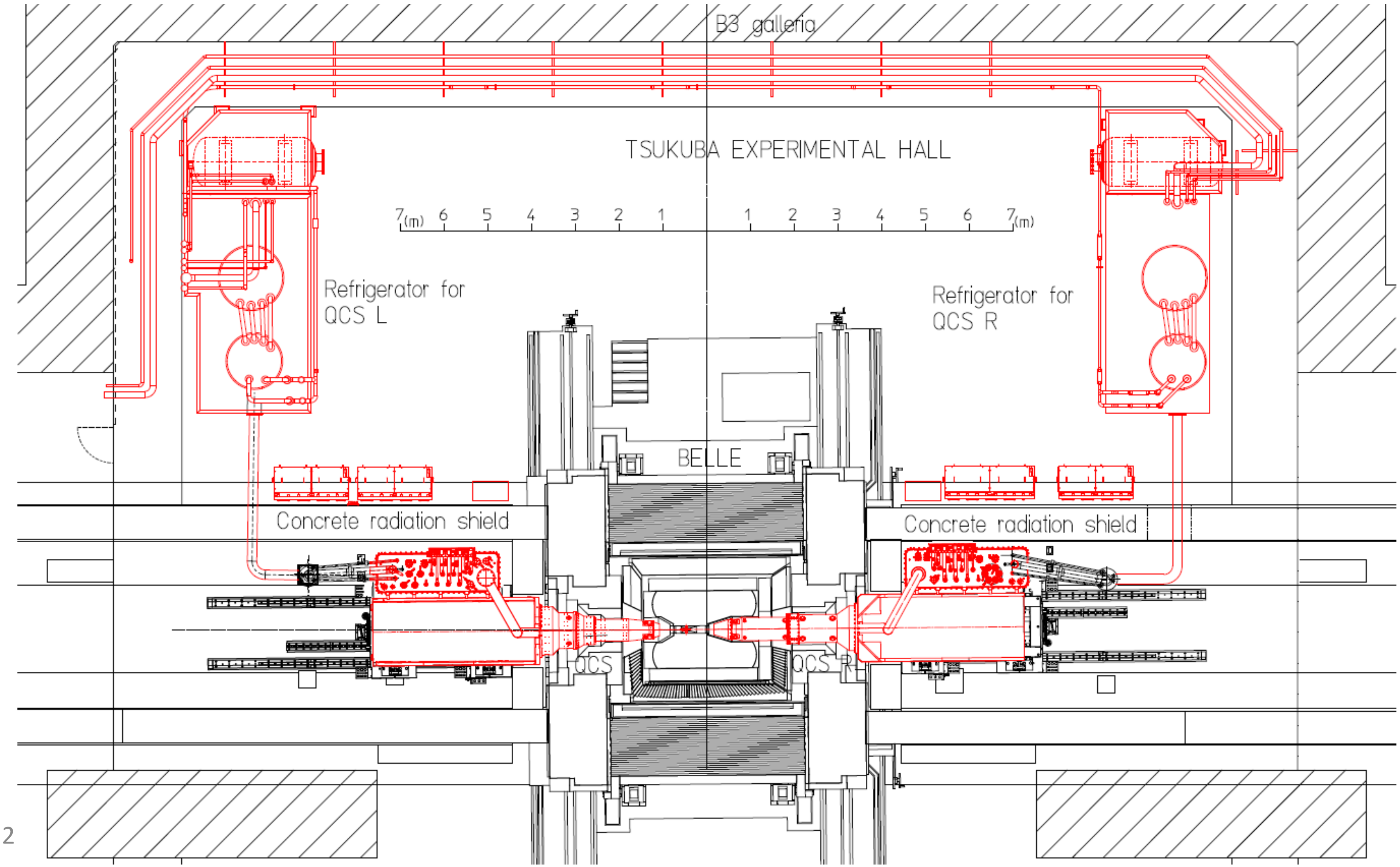
IR magnets

- Solenoid field profiles

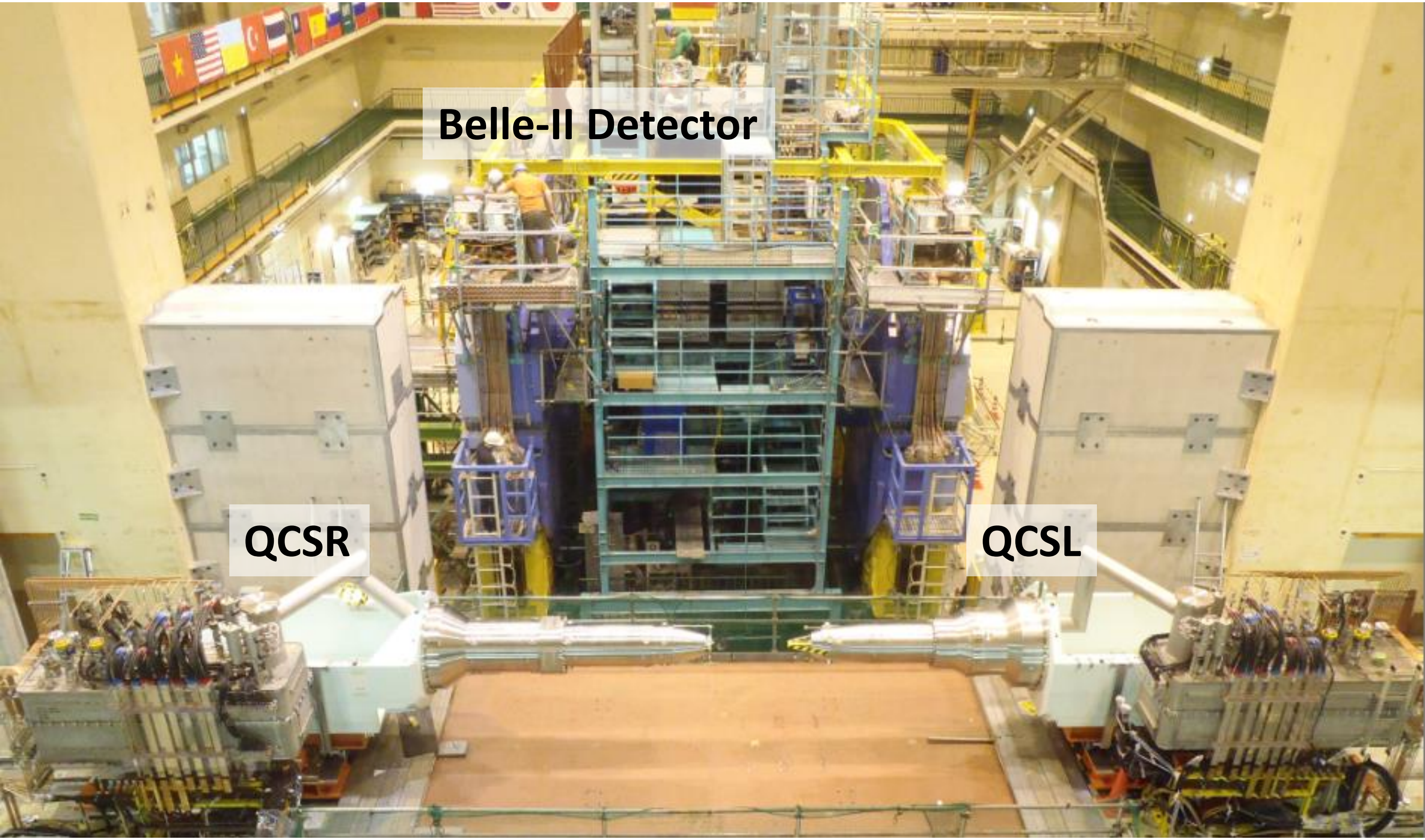


QCS System in Tsukuba Exper. Hall

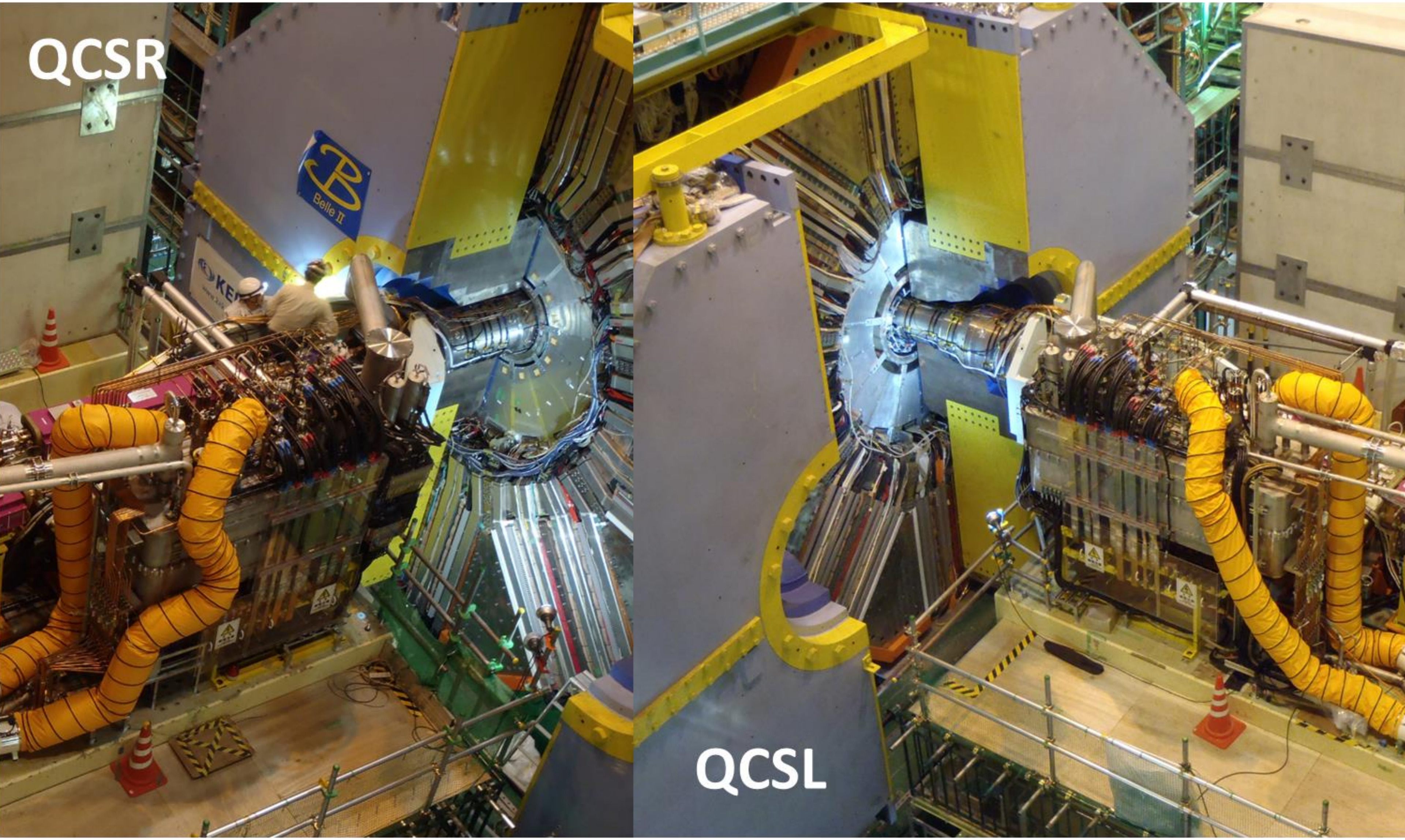
- Construction of final focus magnet system in SuperKEKB IR was completed in March, 2017.



Two cryostats in SuperKEKB IR



Installation of QCS cryostats into Belle-II



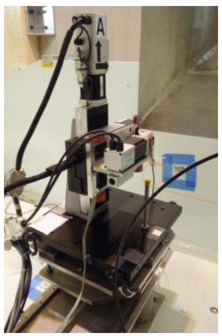
Magnetic field measurements

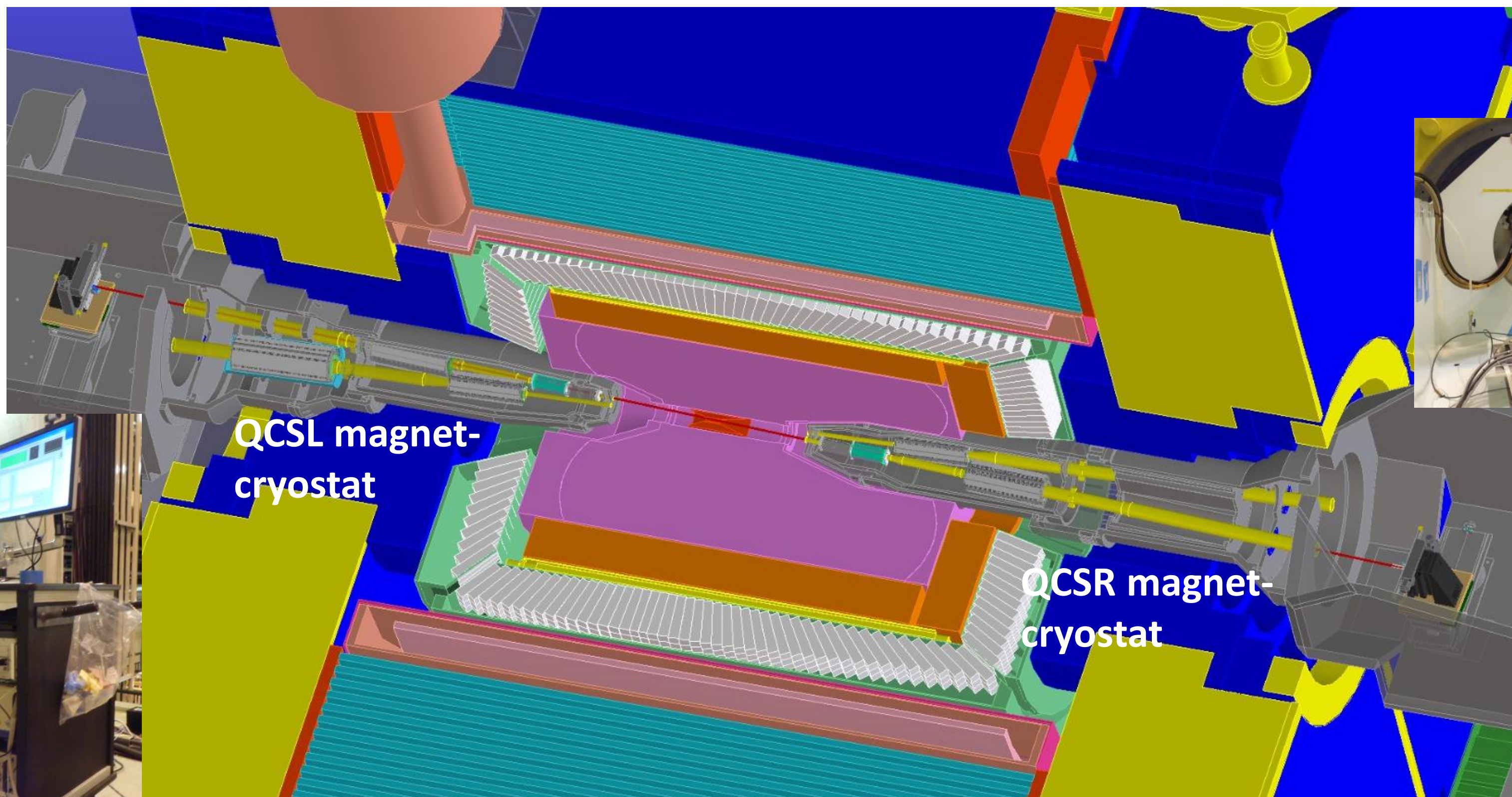
- **Single Stretched Wire measurement (SSW)**
  - Measurements of magnetic field centers and angles of the quadrupole field of QC1 and QC2
  - SSW system for SuperKEKB was developed by FNAL under the research collaboration of US-Japan Science and Technology Cooperation Program in High Energy Physics.
- **Harmonic coil measurement**
  - Integral magnetic field quality measurements of the SC magnets
  - Higher order multipole field profile measurements along the beam lines
  - Magnetic field strength measurements as the function of the transport magnet current
    - 6 harmonic coils were prepared for the integral field measurements and the field scan measurements (L=20 mm).
- **3 axis-hall probe measurement**
  - Solenoid field profile measurements along the beam lines
    - Tuning the field profiles along the beam lines to complete the cancelation of the integral Belle solenoid field.

SSW measurement

SSW measurement system in the IR

- Two magnet-cryostats of QCSL/R were aligned to the beam lines with the targets of the cryostats.
- A BeCu single wire of ϕ0.1 mm, which was aligned to the design beam line, was stretched through QCSR and QCSL cryostat bores.
- The measurements were performed with operating the Belle SC solenoid at 1.5 T, and ESL and ESR1 solenoids.
  - The measured data include the displacement by the electro-magnetic forces between solenoids and magnetic components in the cryostats.

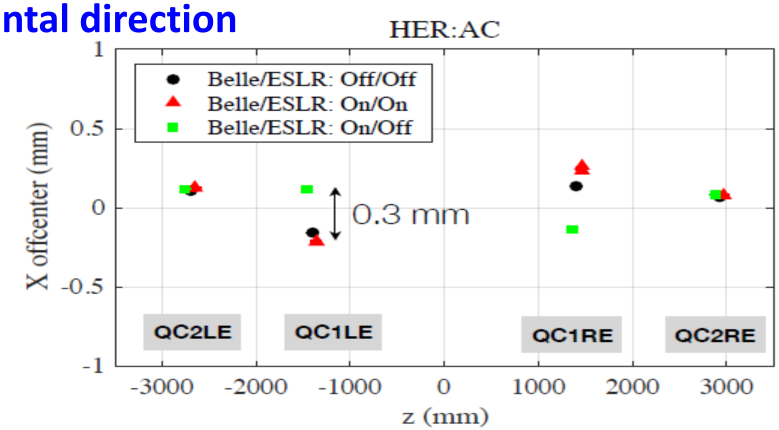


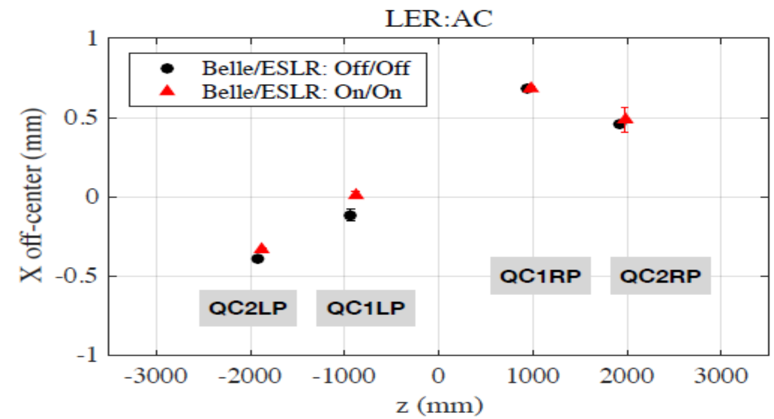


SSW measurement

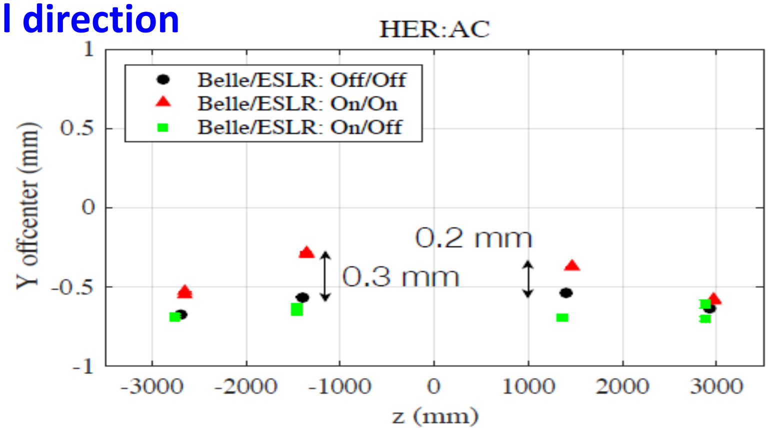
- The quadrupole field centers and angles of 8 SC quadrupole magnets in the QCSL/R magnet-cryostats from June 19, 2017 to June 30, 2017.
  - The measurements were successfully completed, and the measured results were shown in the graph below.
  - In order to exclude the solenoid field effect on the measurements, the transport currents to the magnets in the operation mode were AC 9 A.

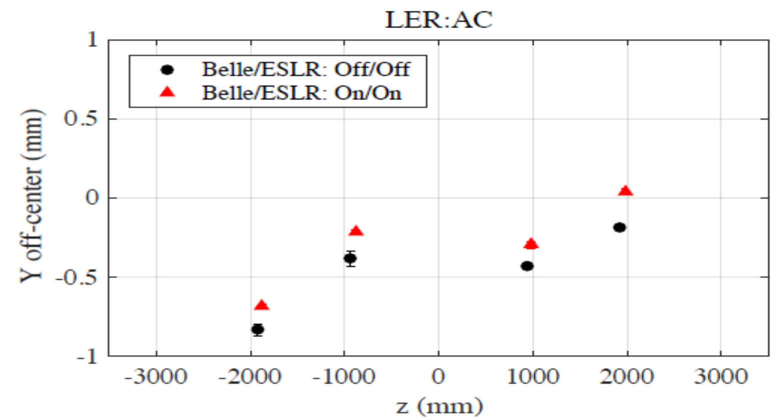
Horizontal direction





Vertical direction





SSW measurement summary

- Measured magnetic center shifts to the design values and field angles to the horizontal planes of the 8 main quadrupoles as follows:

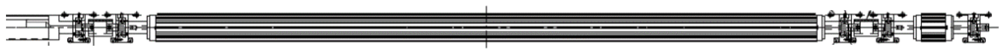
	QC1LP	QC2LP	QC1RP	QC2RP
Δx, mm	0.01	-0.34	0.68	0.49
Δy, mm	-0.21	-0.69	-0.30	0.04
$\Delta\theta$, mrad	-1.67	-4.05	2.02	-1.73

	QC1LE	QC2LE	QC1RE	QC2RE
Δx, mm	-0.21	0.13	0.25	0.08
Δy, mm	-0.29	-0.54	-0.37	-0.58
$\Delta\theta$, mrad	-1.60	-1.54	-0.14	-0.73

- Every alignment errors are able to be corrected by the corrector magnets.

Harmonic coil measurements

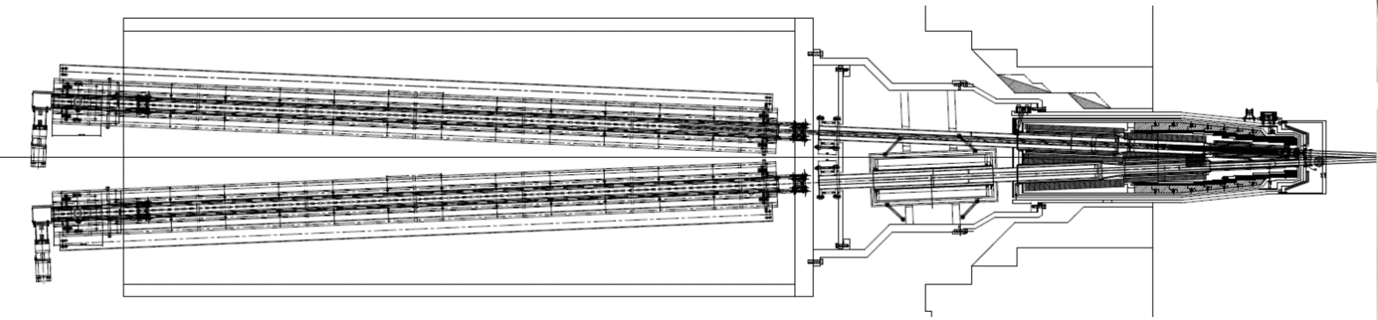
- Measurements of harmonic coils in **SuperKEKB IR** (in July, 2017)
  - One unit of measurement system has two harmonic coils.
  - The harmonic coils are moved by the mover, the movement is measured by the digital scaler.

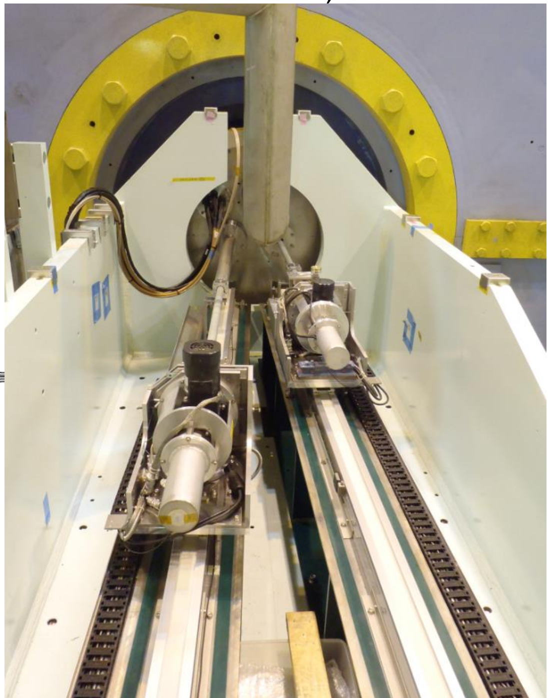


For QC1P and QC1E
L=600 mm and 20 mm, R=12 mm

For QC2P
L=700 mm and 20 mm, R=25 mm

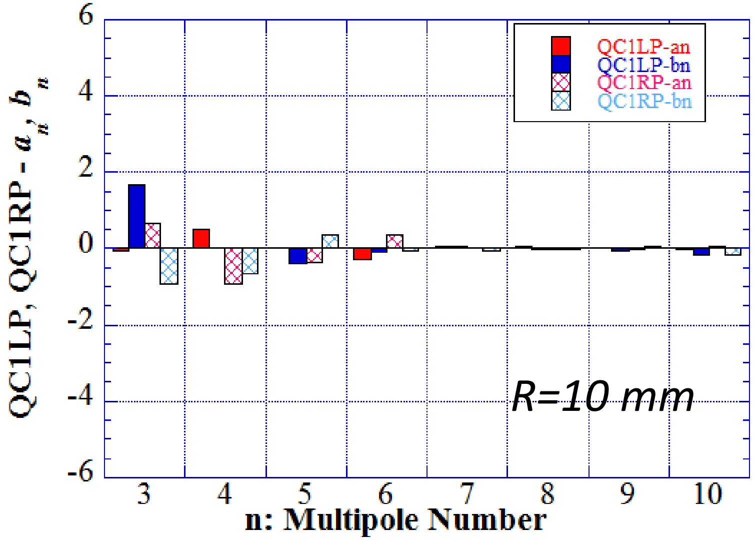
For QC2E
L=800 mm and 20 mm, R=33 mm

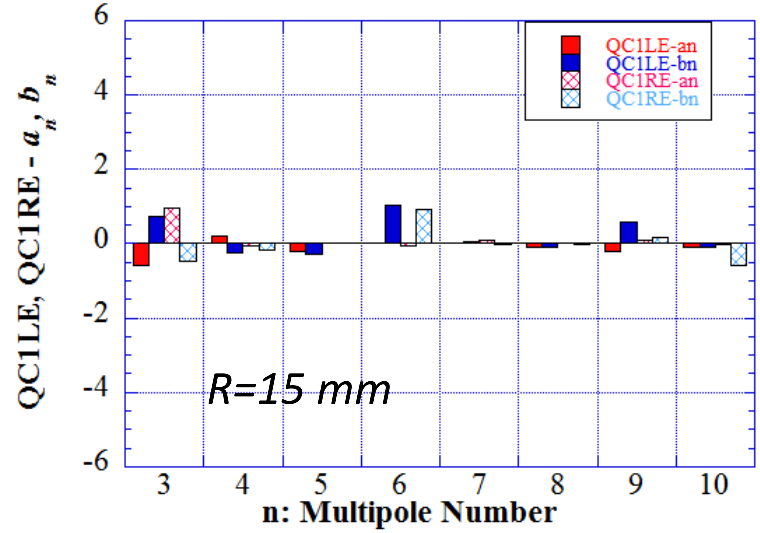


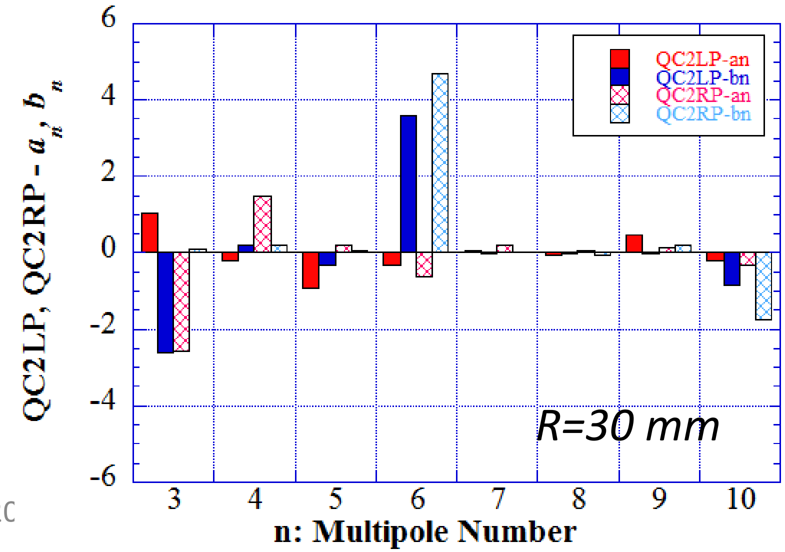


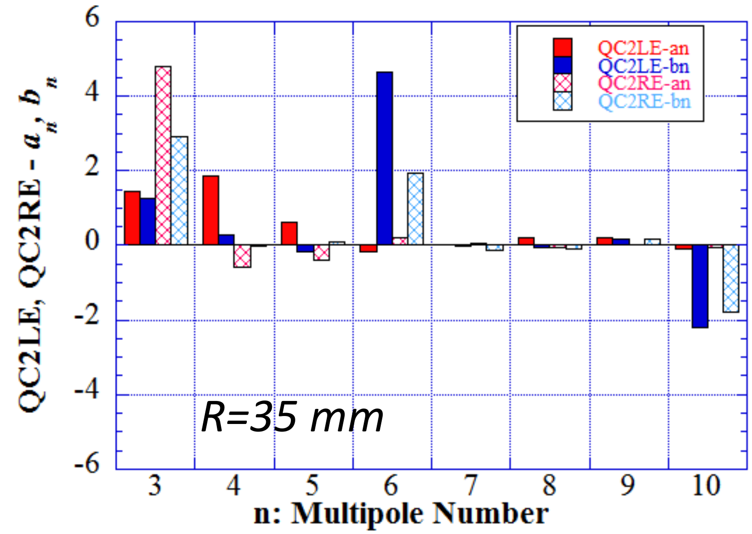
Integral field quality of the QC1/2 magnets
(measured under solenoid fields)

The strengths of the multipole field components are normalized with the B_2 field strength as 10,000.



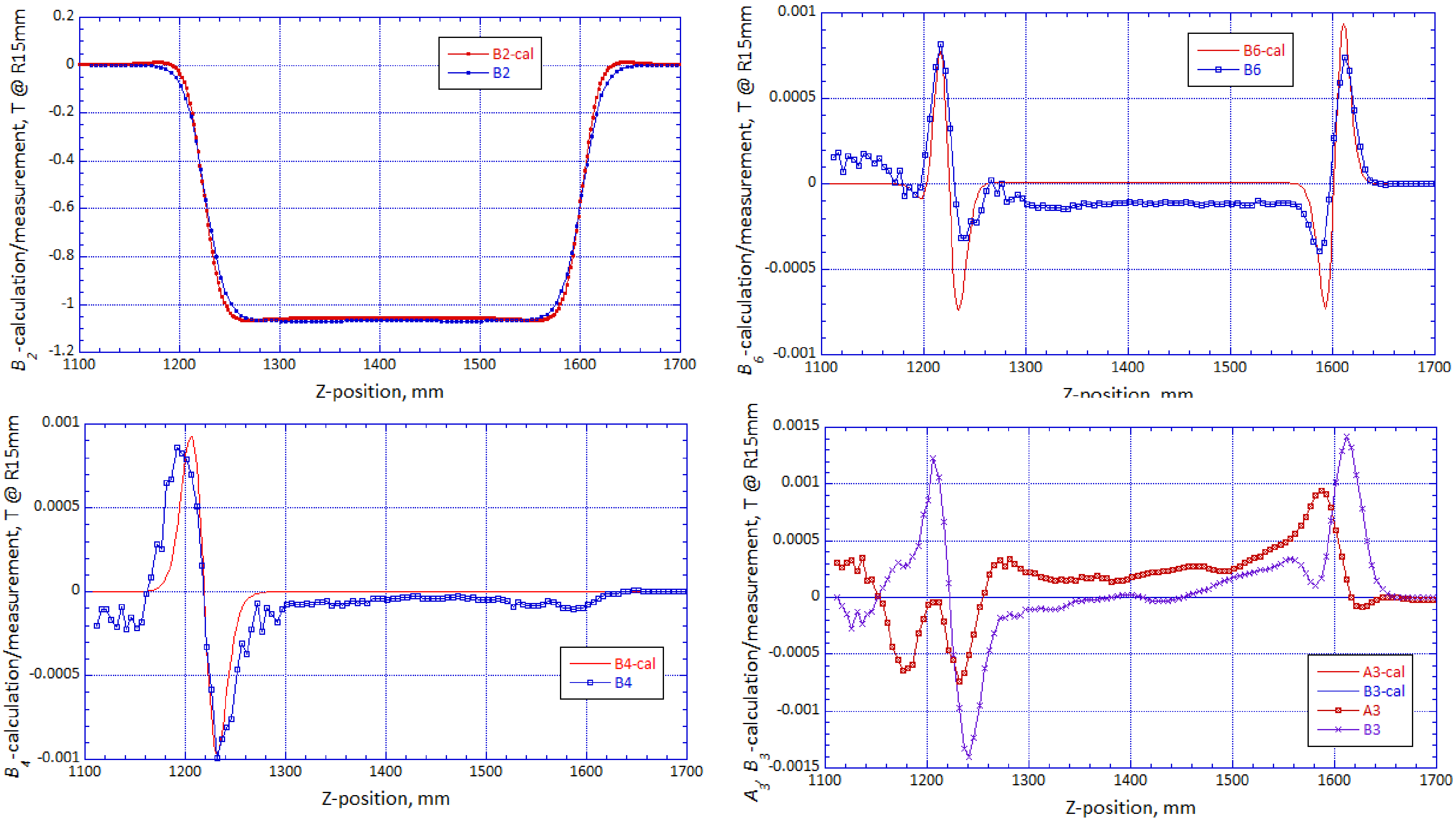






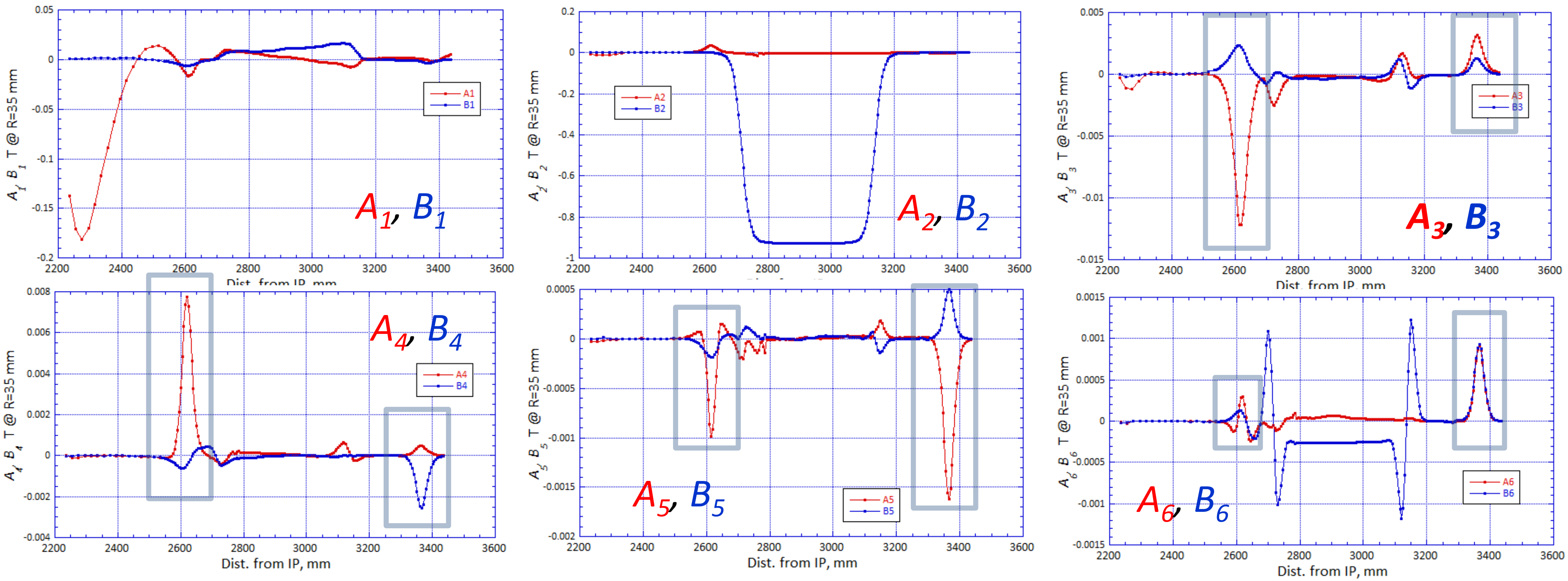
Magnetic field profile of the QC1/2 magnets

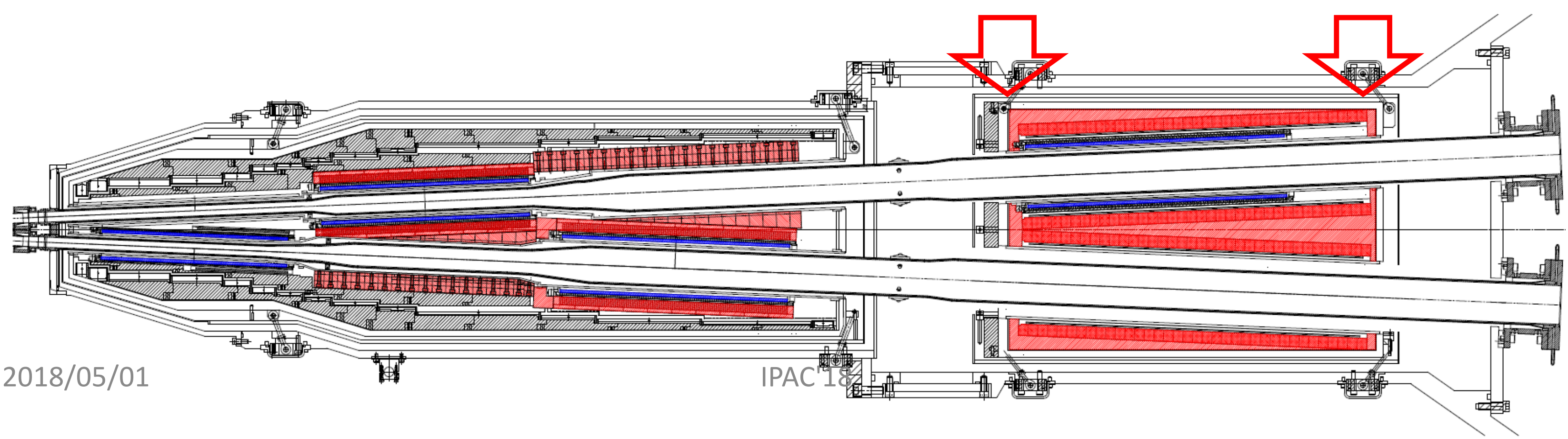
Measured results:QC1LE magnetic field profile along the HER beam line



Magnetic field profile of the QC1/2 magnets

Measured results:QC2RE magnetic field profile along the HER beam line





Magnetic field measurements of the correctors

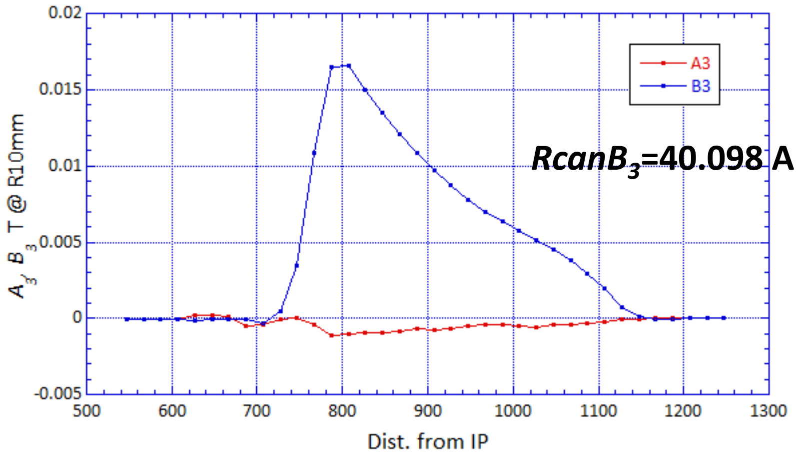
	Corrector	Specific requirement	Measurements at 60 A (on the beam line)	Allowable alignment at ±60 A
QC1LP	a1	0.016 Tm @ R=10mm	0.0177 Tm	± 0.73 mm
	b1	0.016 Tm	0.0146 Tm	± 0.63 mm
	a2	0.64 T	0.801 T	± 17.4 mrad
	b4	60 T/m^2	295 T/m^2	–
QC2LP	a1	0.03 Tm @ R=30mm	0.0350 Tm	± 1.18 mm
	b1	0.03 Tm	0.0409 Tm	± 2.33 mm
	a2	0.31 T	0.640 T	± 27.9 mrad
	b4	60 T/m^2	107.7 T/m^2	–
QC1LE	a1	0.027 Tm @ R=15mm	0.0323 Tm	± 0.92 mm
	b1	0.046 Tm	0.0551 Tm	± 0.93 mm
	a2	0.75 T	0.932 T	± 17.3 mrad
	b4	60 T/m^2	730 T/m^2	–
QC2LE	a1	0.015 Tm @ R=35mm	0.0400 Tm	± 2.52 mm
	b1	0.015 Tm	0.0442 Tm	± 2.89 mm
	a2	0.37 T	0.753 T	± 24.7 mrad
	b4	60 T/m^2	142.9 T/m^2	–

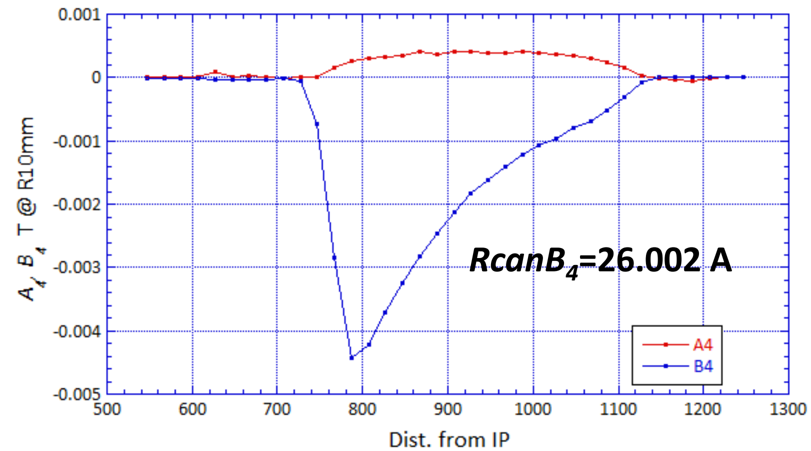
Magnetic field measurements of the correctors

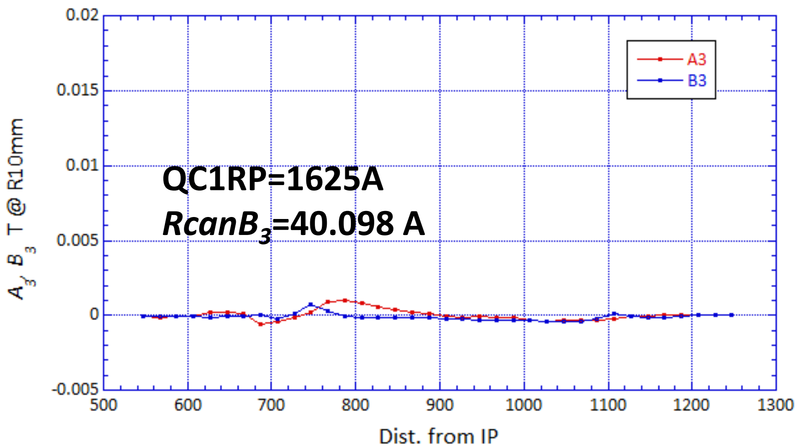
	Corrector	Optics requirement	Measurements at 60 A (on the beam line)	Allowable alignment at ±60 A
QC1RP	a1	0.016 Tm	0.0174 Tm	± 0.57mm
	b1	0.016 Tm	0.0159 Tm	± 0.53 mm
	a2	0.64 T	0.798 T	± 17.4 mrad
	a3-> b3	**5.1 T/m**	**9.57 T/m**	–
	b4	60 T/m^2	268 T/m^2	–
QC2RP	a1	0.03 Tm	0.0578 Tm	± 3.99 mm
	b1	0.03 Tm	0.0362 Tm	± 1.28 mm
	a2	0.31 T	0.630 T	± 27.3 mrad
	a3	0.905 T/m	1.087 T/m^2	–
QC1RE	a1	0.027 Tm	0.0313 Tm	± 0.96 mm
	b1	0.046 Tm	0.0550 Tm	± 0.92 mm
	a2	0.75 T	0.889 T	± 16.8 mrad
	a3	4.55 T/m	22.85 T/m	–
QC2RE	a1	0.015 Tm	0.0310 Tm	± 2.25 mm
	b1	0.015 Tm	0.0353 Tm	± 2.71 mm
	a2	0.37 T	0.602 T	± 23.1 mrad
	a3	1.05 T/m	6.51 T/m	–
QC1-2RE	b3	18.2 T/m	55.5 T/m	–
QC1-2RP	b3	11.48 T/m	28.3 T/m	–

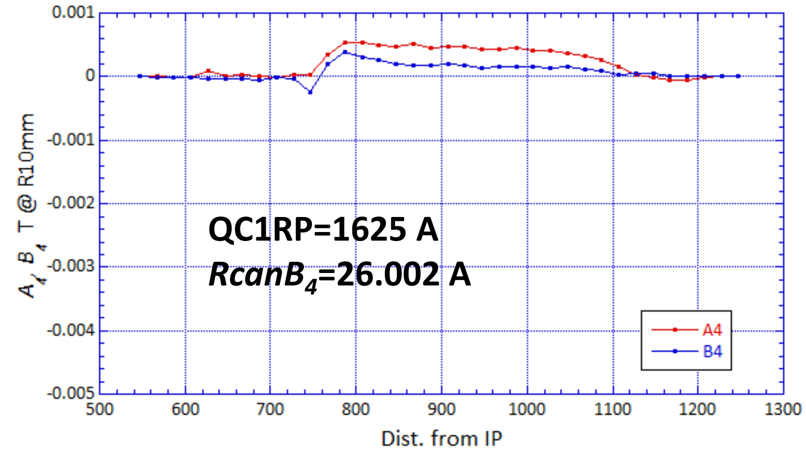
Magnetic field profiles of the cancel magnets

QCSR: From the measurement results of the harmonic coil and SSW (-0.14 mrad) for QC1RE, the scan data by the short harmonic coil were corrected.









QC1RP I_{op}＝1602.2 A、ΣB_3=0 :

- B_3 : operating current＝**40.4403 A**
- ΣA_3＝4.098×10^{-6} Tm @ R=10mm

QC1RP I_{op}＝1602.2 A、ΣB_4=0 :

- B_4 : operating current＝**27.6702 A**
- ΣA_4＝1.62×10^{-4} Tm @ R=10mm

Hall probe measurements along the beam lines

Required precision of the magnetic field in the SuperKEKB IR

- **Field error for accelerator beam operation < 10 Gauss**
  - **Magnetic field mapping of the beam lines by 3-axis Hall probe**
- **Field error for particle analysis < 15 Gauss**
  - Magnetic field measurements inside the Belle director with the field mapper of 3-axial Hall probes and the fixed 3-axial Hall probes (by DESY group under the Belle II collaboration)

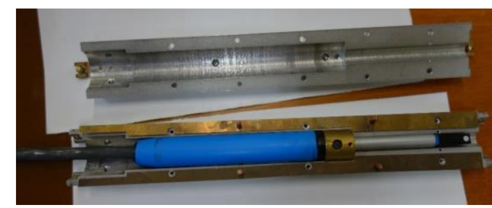
Measured magnetic field data are used for improving the 3D magnetic field calculation model which produces the precise field map in the SuperKEKB IR and in the Belle-II.

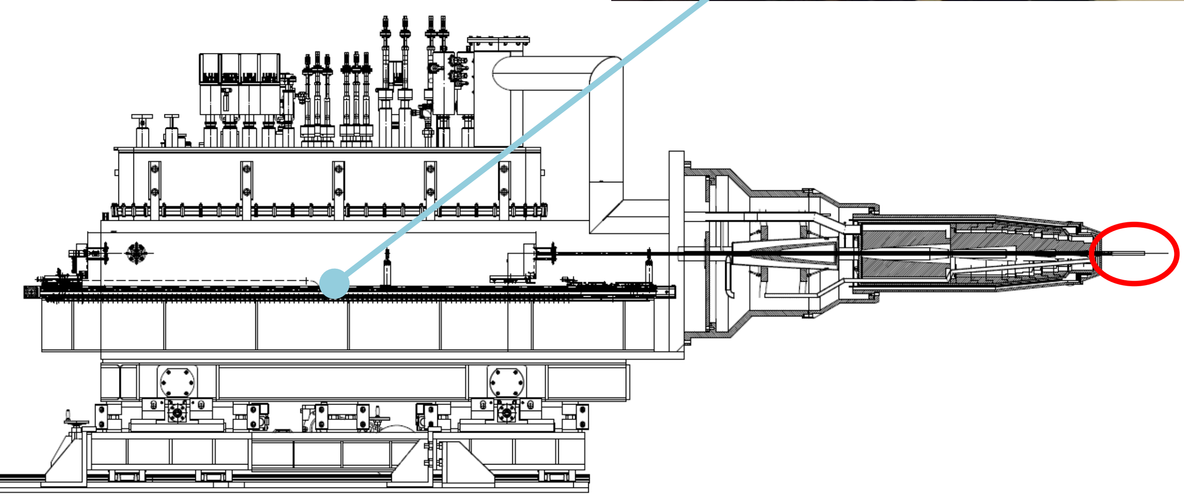
Hall probe measurements along the beam lines

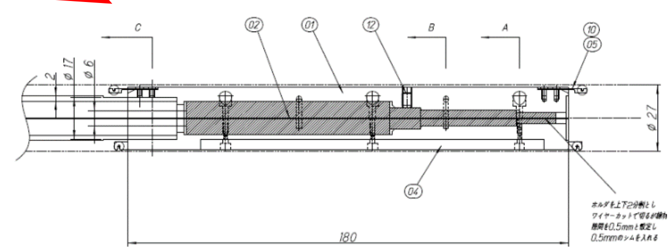
Mapping the magnetic field along the beam lines

- The measurement system consisted of the commercial Hall probe and the scanning mover.
- The hall probe position was defined with the Belle end yokes.

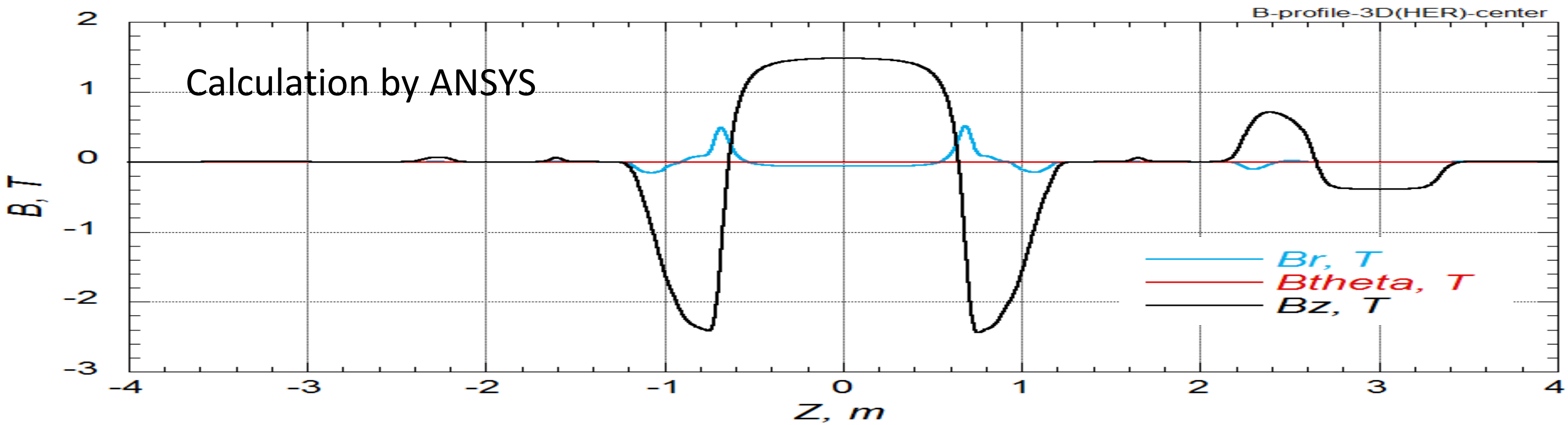
3 Axis-Hall-probe

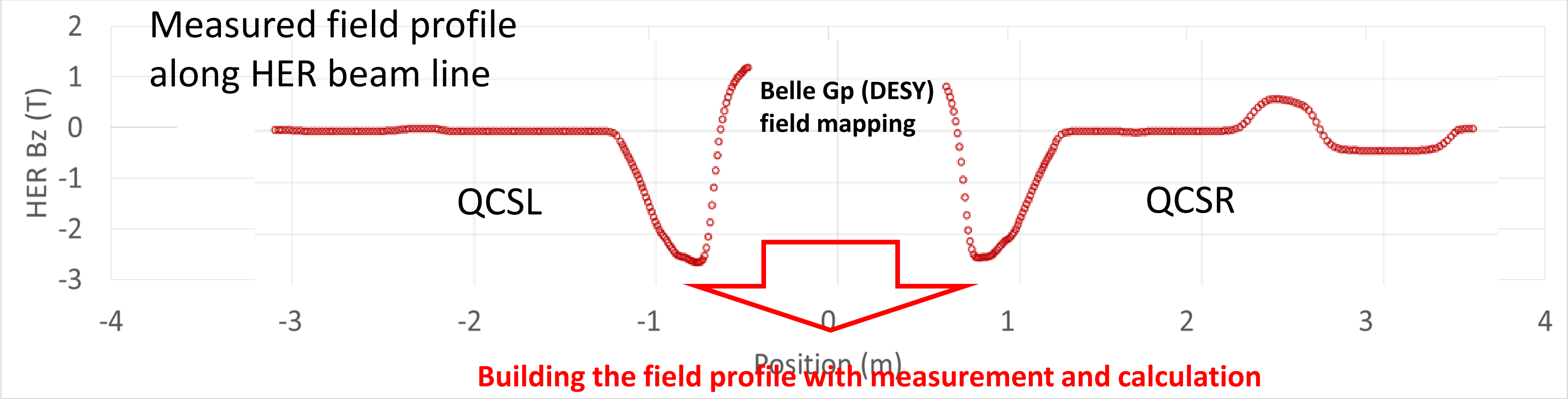






Hall probe measurements along the beam lines



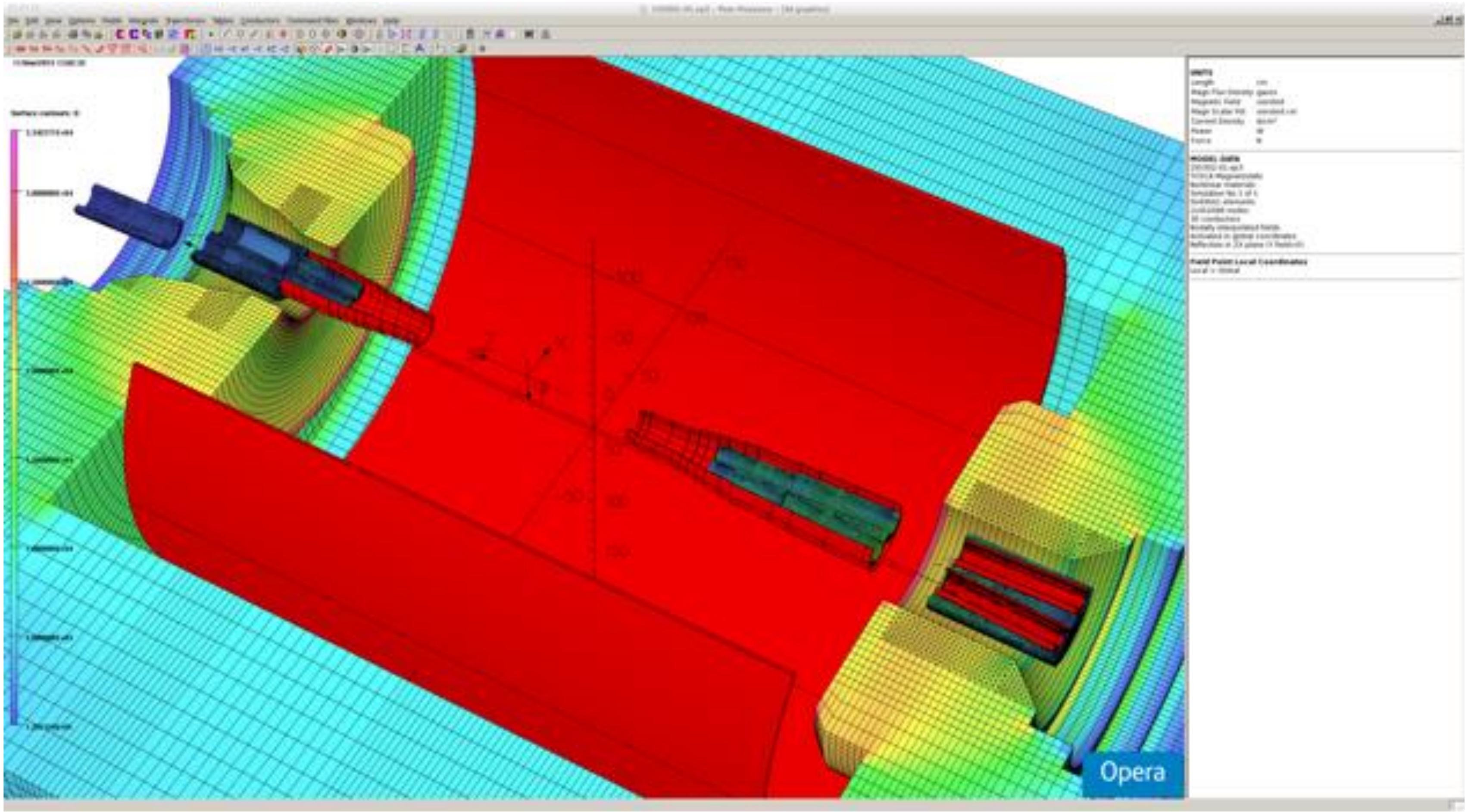


From the field measurements, the transport current of ESL was changed from 404 A to 390 A. The currents of ESR1 and ESR2-3 are 450 A and 151 A.

3D-magnetic field calculation model

SuperKEKB IR magnetic field calculation model by OPERA-3D

- All SC magnets and magnetic components are included.



Summary

- The quite sophisticated final focus system, QCS, for SuperKEKB has been completed and it is now having beams as SuperKEKB Phase-2 commissioning.
- The two beams successfully completed the first collision at April 26th, 2018.
  - **"MOXGB1: Report on SuperKEKB Phase 2 commissioning"   Yukiyoshi Ohnishi**
- 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.

Thank you for your attention !