QCS IR magnets

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On behalf of the SuperKEKB IR group

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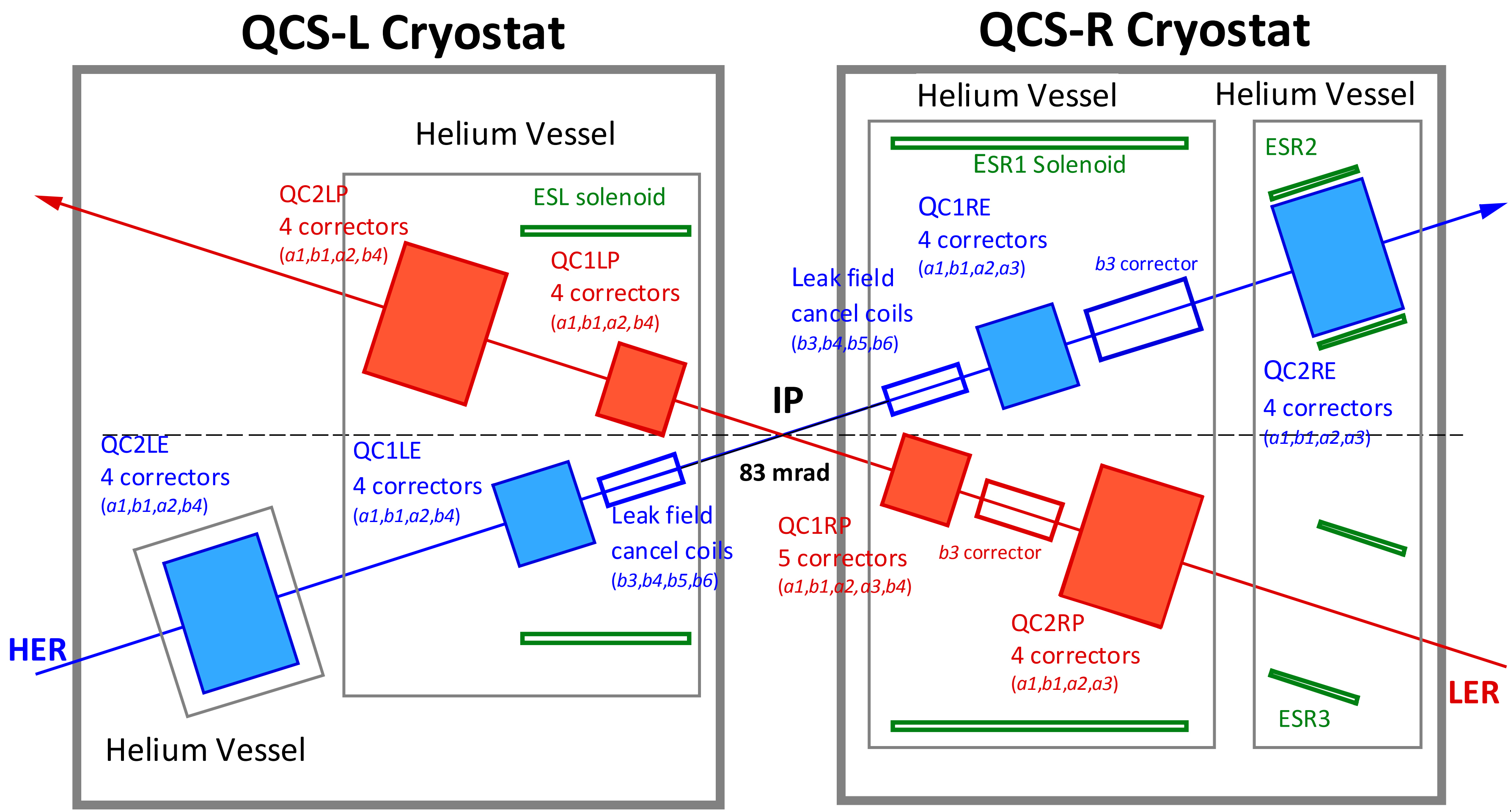
Overview of IR magnets



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

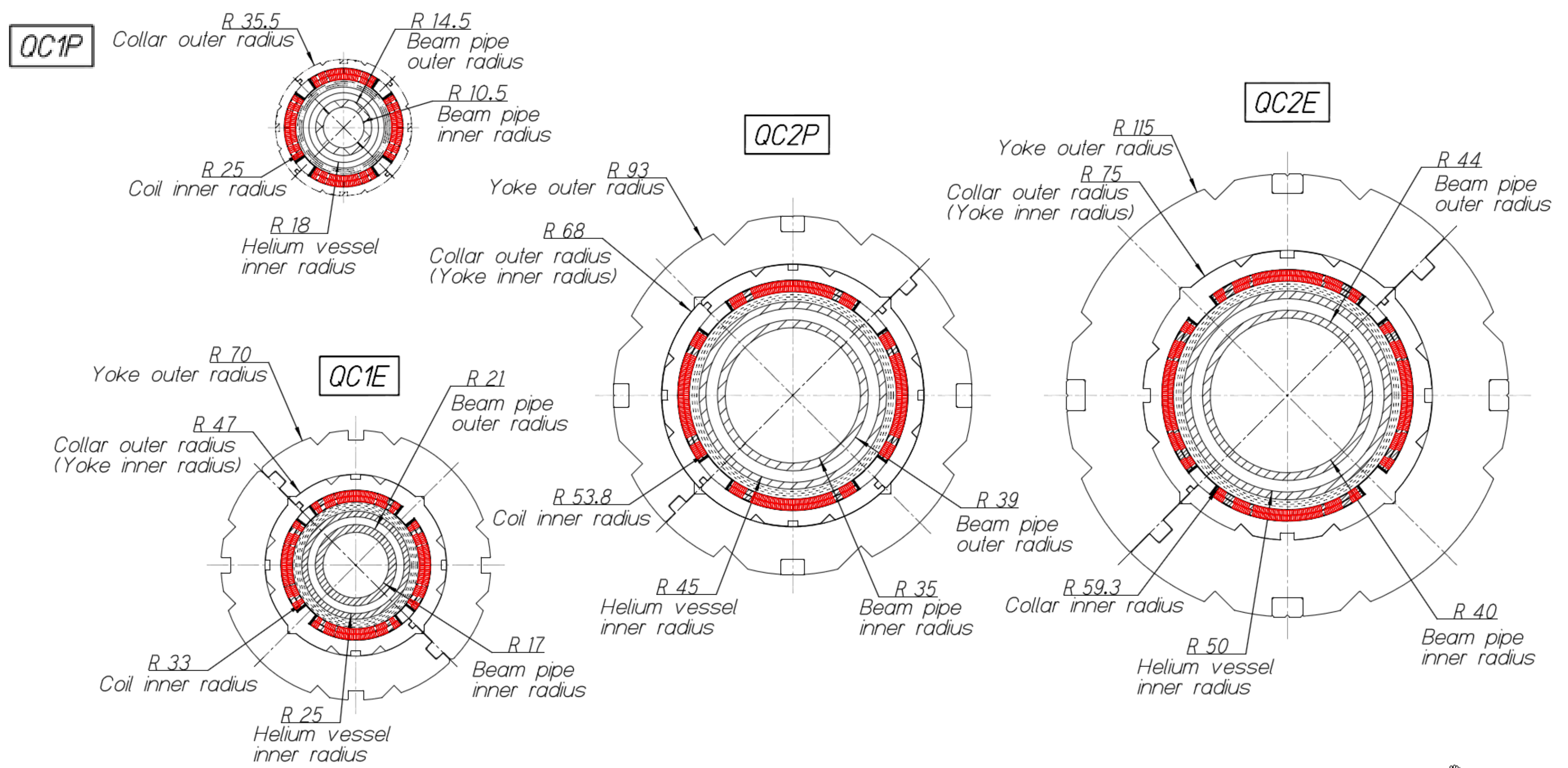
4 SC main quadrupole magnets: 1 collared magnet, 3 yoked magnets
19 SC correctors: a1, b1, a2, a3, b3, b4
4 SC leak field cancel magnets: b3, b4, b5, b6
3 compensation solenoid

IR magnets

- Main quadrupoles [QC1, QC2]
  - Forming final beam focusing system with quadrupole doublets.
- Correctors [a_1, b_1, a_2, a_3, b_3, b_4]
  - 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]
  - Canceling the integral solenoid field by the particle detector (Belle II).
  - By tuning the B_z profile, the beam vertical emittance can 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]
  - Canceling the leak field on the electron beam line from QC1P (collared magnet).
- Total number of the SC devices in two cryostats = 55

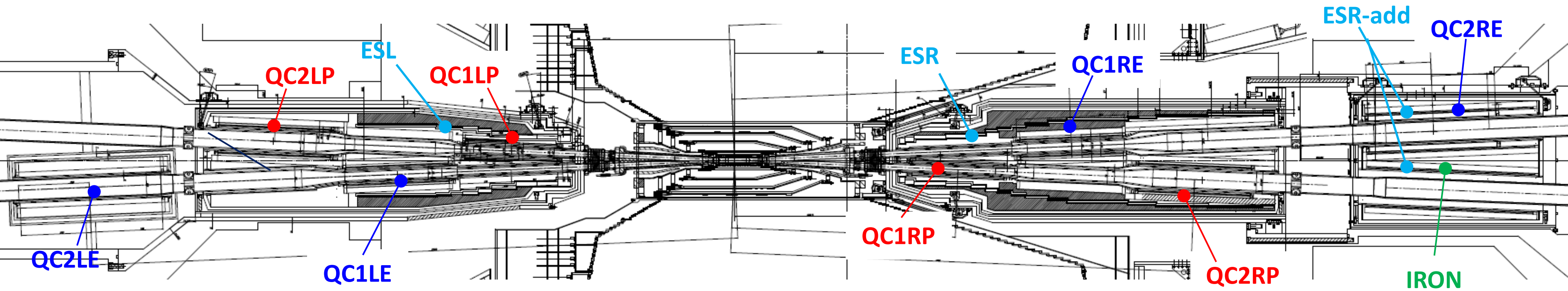
IR magnets

- Cross section design of main quadrupoles [QC1, QC2]
  - The quadrupole magnets are designed with the two layer coils (double pane cake design).
  - In the early design, the smaller young modulus of the SC cable than the real cable were applied.
    - As the result, 10 units sextupole field by the assembly error of the magnet was induced.
    - All magnet cross sections were redesigned, and a_3 and b_3 correctors have been installed in the right cryostat.



IR 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.



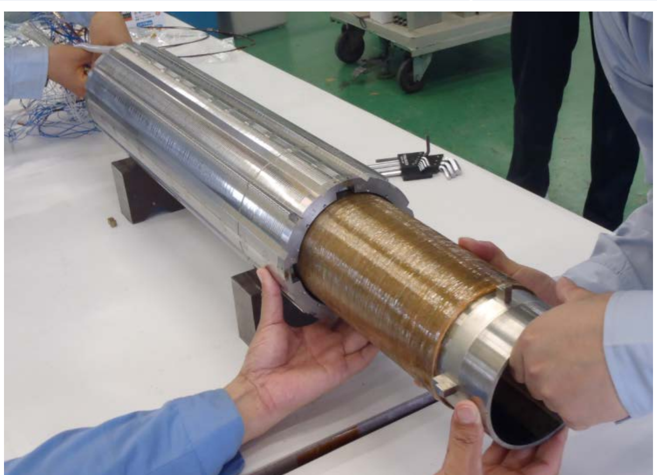
	Integral field gradient, (T/m)・m	Magnet type	Z pos. from IP, mm	θ, mrad	ΔX, mm	ΔY, mm
QC2RE	13.58 [32.41 T/m × 0.419m]	Iron Yoke	2925	0	-0.7	0
QC2RP	11.56 [26.28 × 0.410]	Permendur Yoke	1925	-2.114	0	-1.0
QC1RE	26.45 [70.89×0.373]	Permendur Yoke	1410	0	-0.7	0
QC1RP	22.98 [68.89×0.334]	No Yoke	935	7.204	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 magnets

- Correctors
  - The SC correctors were designed and directly wound on the support bobbin (helium inner vessel) by BNL under the US-Japan research collaboration
    - Direct winding method
    - 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 the main quadrupole magnets.
  - Each corrector magnet is excited by the individual bipolar power supply.

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, $\mathbf{a_3 \rightarrow b_3}$
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

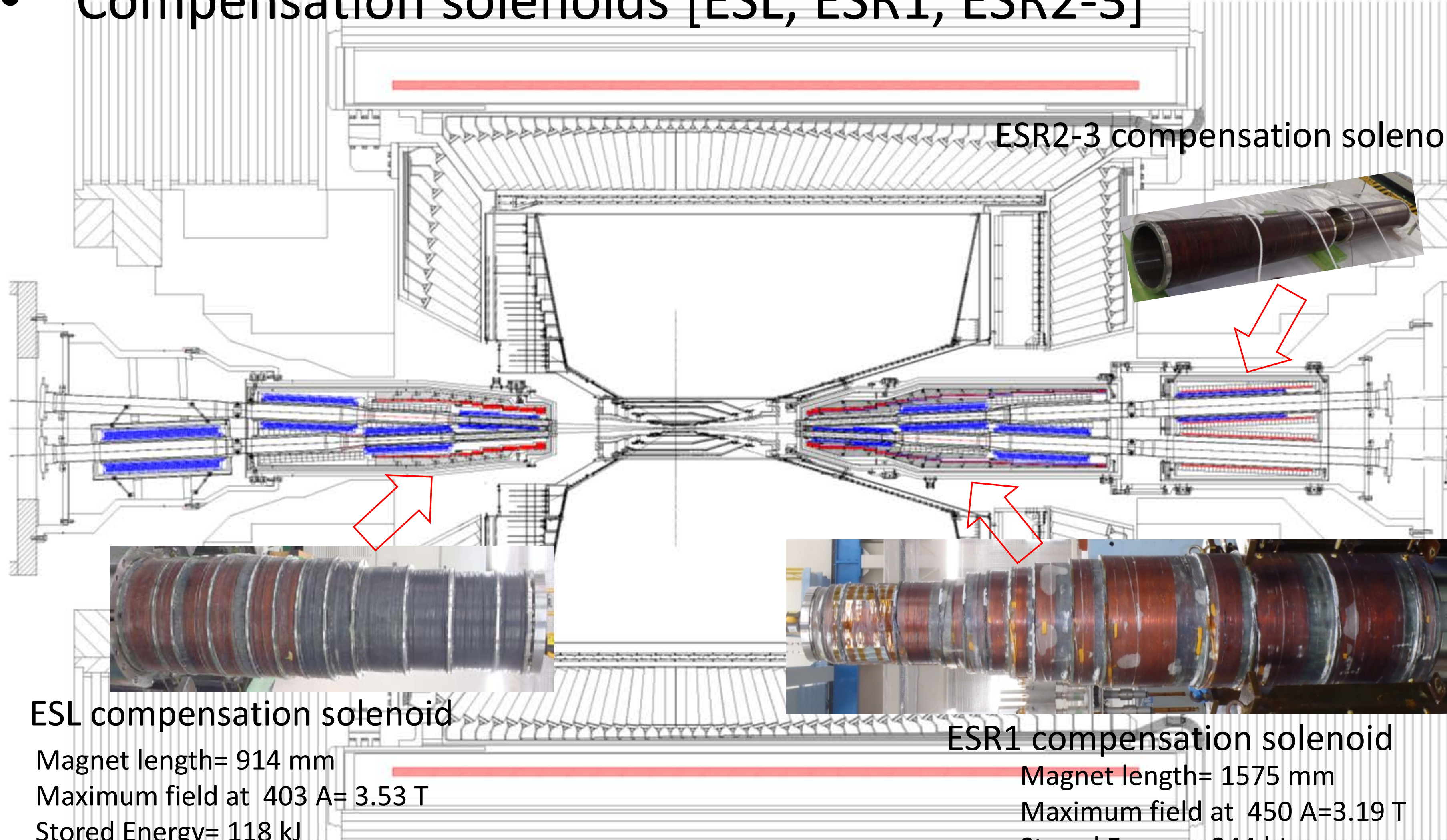


Assembly of QC2LE and correctors

a_1 corrector winding for QC1LP @BNL

IR magnets

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



ESR2-3 compensation solenoid

ESL compensation solenoid

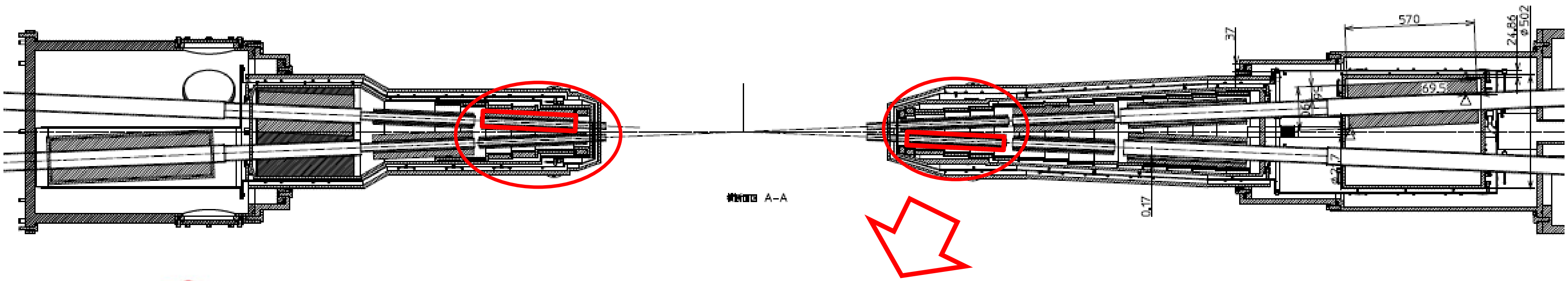
Magnet length= 914 mm
Maximum field at 403 A= 3.53 T
Stored Energy= 118 kJ

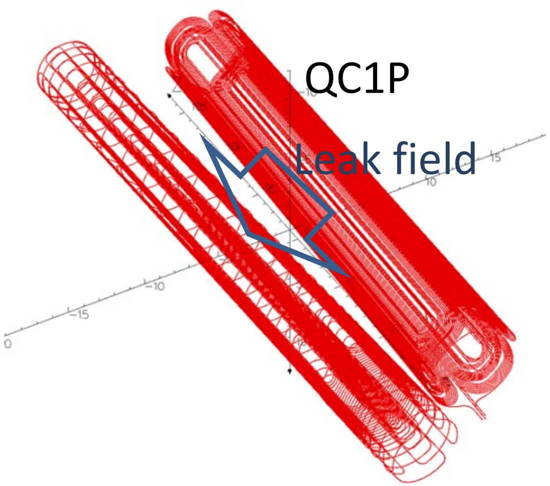
ESR1 compensation solenoid

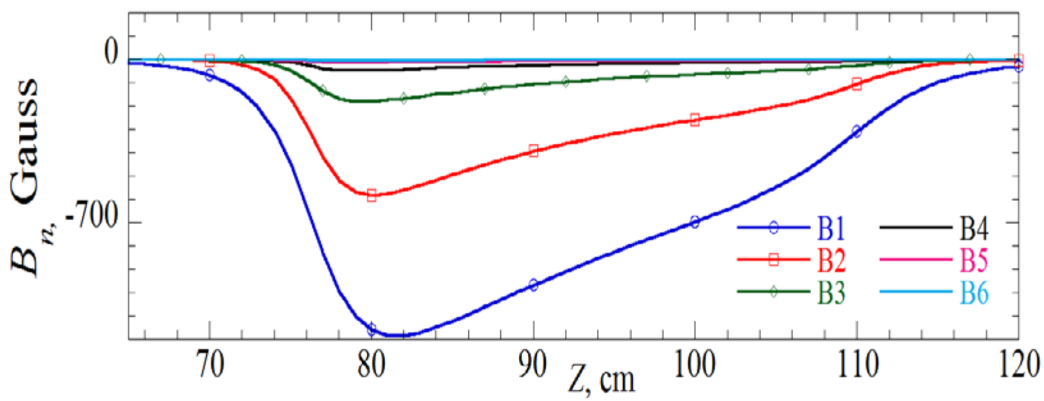
Magnet length= 1575 mm
Maximum field at 450 A=3.19 T
Stored Energy= 244 kJ
Cold diode quench protection system

IR magnets

- # 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.
  - By rolling QC1P in design and lower level of the QC1P axis than HER beam line, skew field components are induced. The cancel magnets are rotated to cancel the skew components in design.
  - *B_1* and *B_2* components are not canceled, and they are included in the optics calculation.



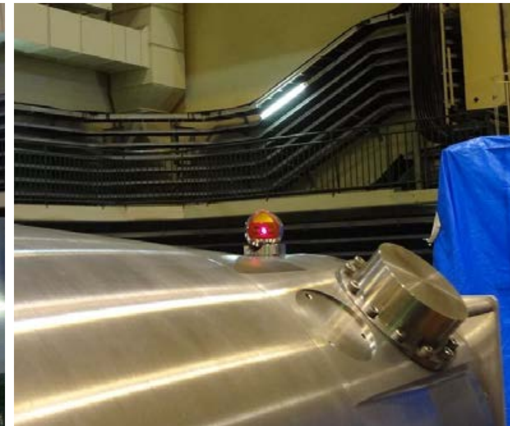


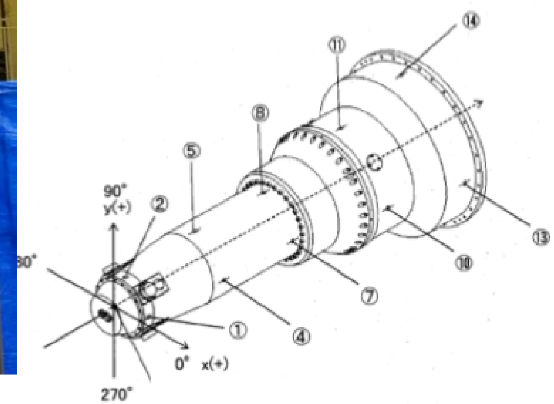


Construction status of IR magnets

- Construction and tests of QCS system on the SuperKEKB beam lines
  - August 1st, **2016**: Setting the QCSL cryostat on the beam lines in the SuperKEKB IR
  - September 1st, **2016** ~ October 20th, **2016**: Construction of the cryogenic system for QCSL
  - November 7th, **2016** ~ December 22nd, **2016**: Cool down test of the QCSL cryogenic system and the excitation tests of the SC magnets
  - November 1st, **2016**: During the final construction stage of ESR1, electrical insulation faults was found. The positions and the cause of the trouble were specified at Nov. 5th, 2016.
  - January 16th, **2017**: In the final electrical tests of the QCSR magnet-cryostat, the electrical insulation fault was detected at the cold diode for the quench protection of ESR1. The fault was repaired at January 17th, 2017.
  - January 31st, **2017**: The final electrical tests of the QCSR magnet-cryostat were passed in Mitsubishi.
  - February 13th, **2017**: Setting the QCSR cryostat on the beam lines in the SuperKEKB IR
  - March, **2017**: Construction of the cryogenic system for QCSR
  - **April 11th, 2017: Moving the Belle-II detector at the beam interaction point**
  - May ~ August, **2017**: Commissioning the QCSL/QCSR systems, excitation tests and magnetic field measurements of all magnets
  - September ~ December, **2017**: Final preparation of the system for the beam operation
    - Exchange of the cryostat inner pipe of the cryostat with the real beam pipes
    - Modification of the current lead ends for a safety operation of the SC magnets
    - Repairing the cold valve of the cold box for the QCSR system to recover the cooling power

Installation and alignment of QCSL/R cryostats

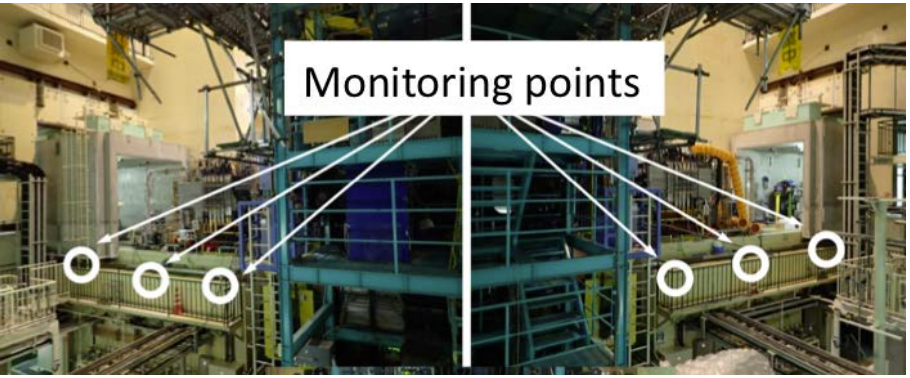


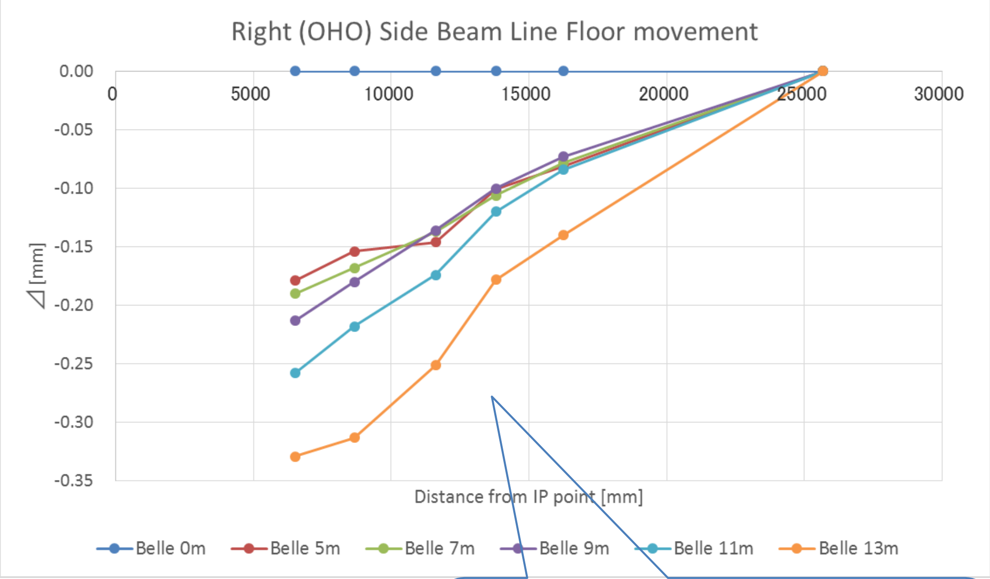


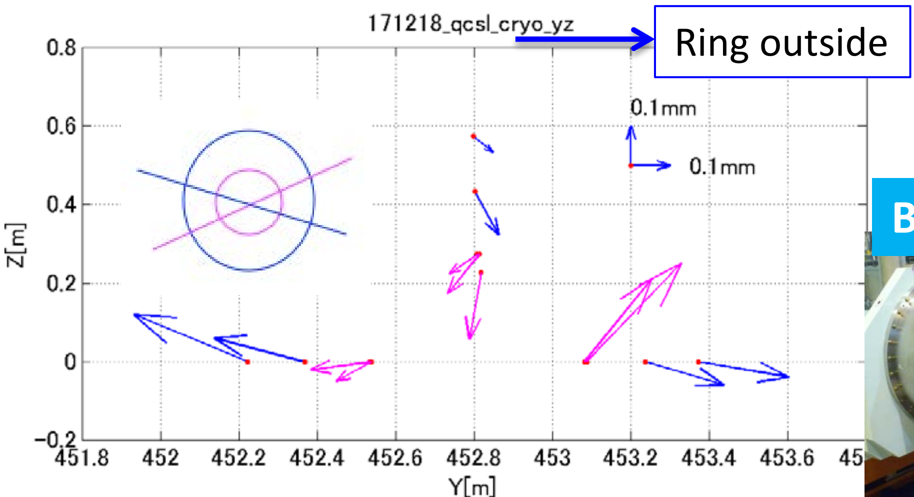
- Using the references on the cryostats, we aligned the cryostats to the HER/LER beam lines, which are defined by the normal conducting magnets and monuments on the tunnel walls/floor.
- The cryostats were in their final positions, but without BELLE II detector.
- The RMS of the best fits to the target coordinates are 0.2-0.3 mm.
  - Target position coordinates for QCSL are given by the QCS group. They are obtained from the SSW measurements carried out on the measurement bench.
  - The design coordinates from the cryostat drawing are used for aligning the QCSR cryostat, as they did not have time for SSW measurement on the measurement bench before installation.

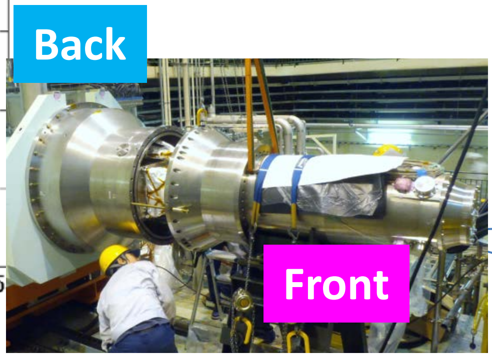
Misalignment concerns

- Beam line floor deformation (mainly sinking) after BELLE II roll-in is seen.
- QCSL cryostat was disassembled for the QCS beam pipe installation after the SSW measurements at the beam line. A very quick survey with limited view (not many data points) suggests that the front and back parts of the cryostat are twisted by a couple of hundred mrad. No SSW after reassembling. Not confirmed.







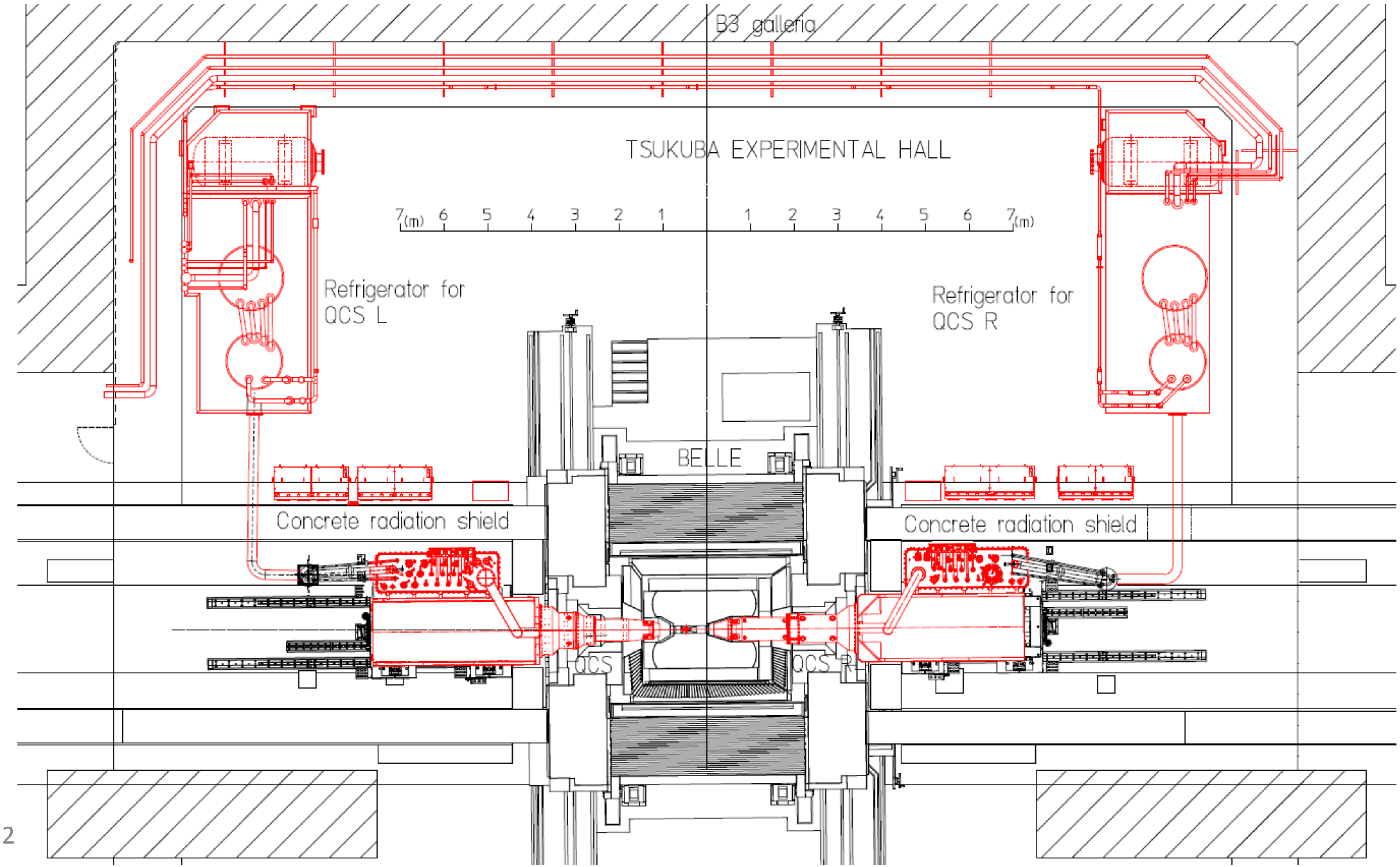


Beam line floor sinks towards the IP. QCS "nose" probably hangs more as it is cantilevered.

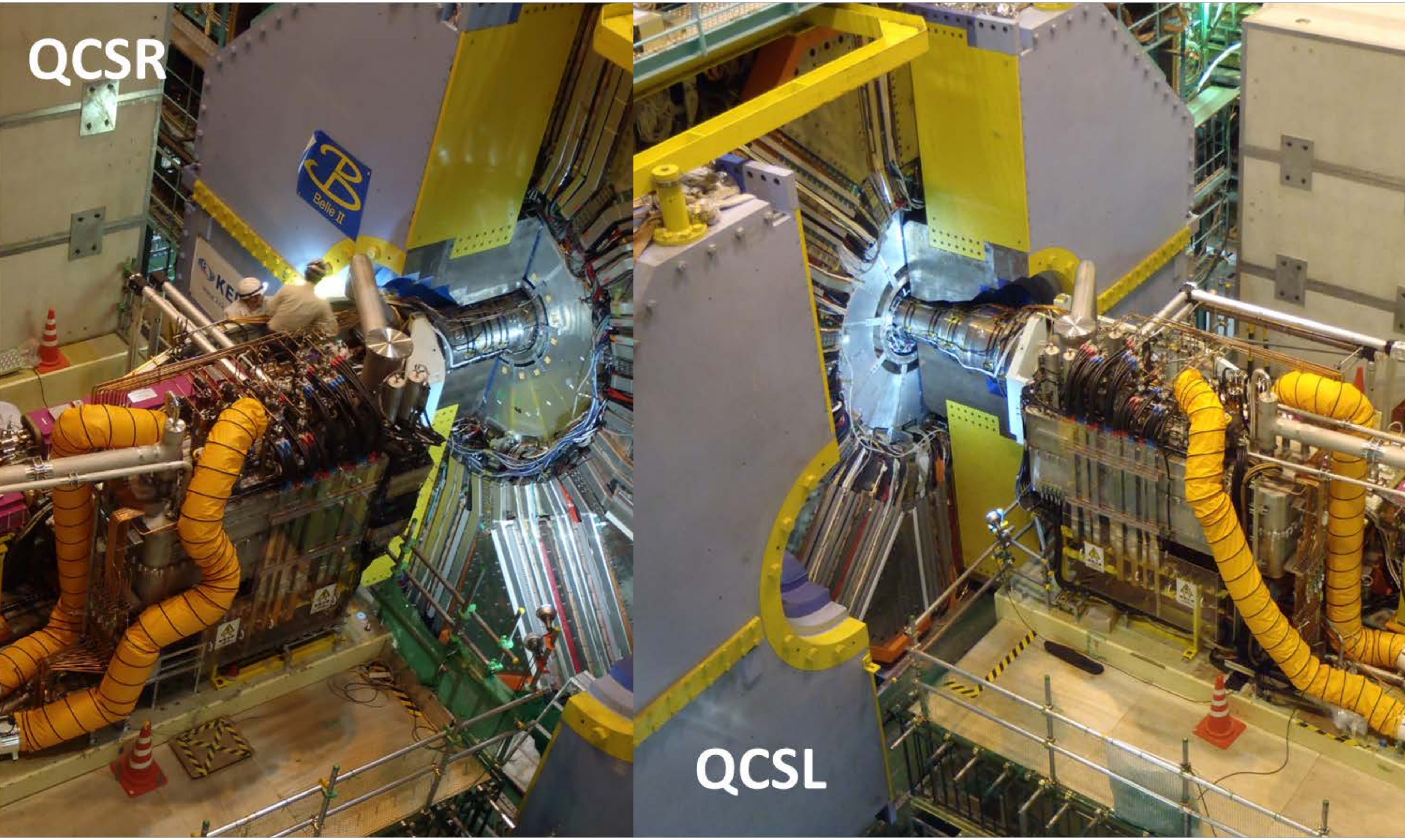
Front and back parts may be twisted when reassembled.

QCS System in Tsukuba Exper. Hall

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



Completed QCS systems



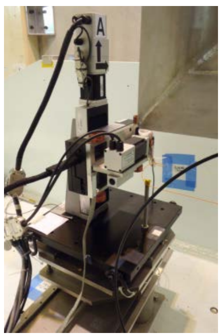
Magnetic field measurements

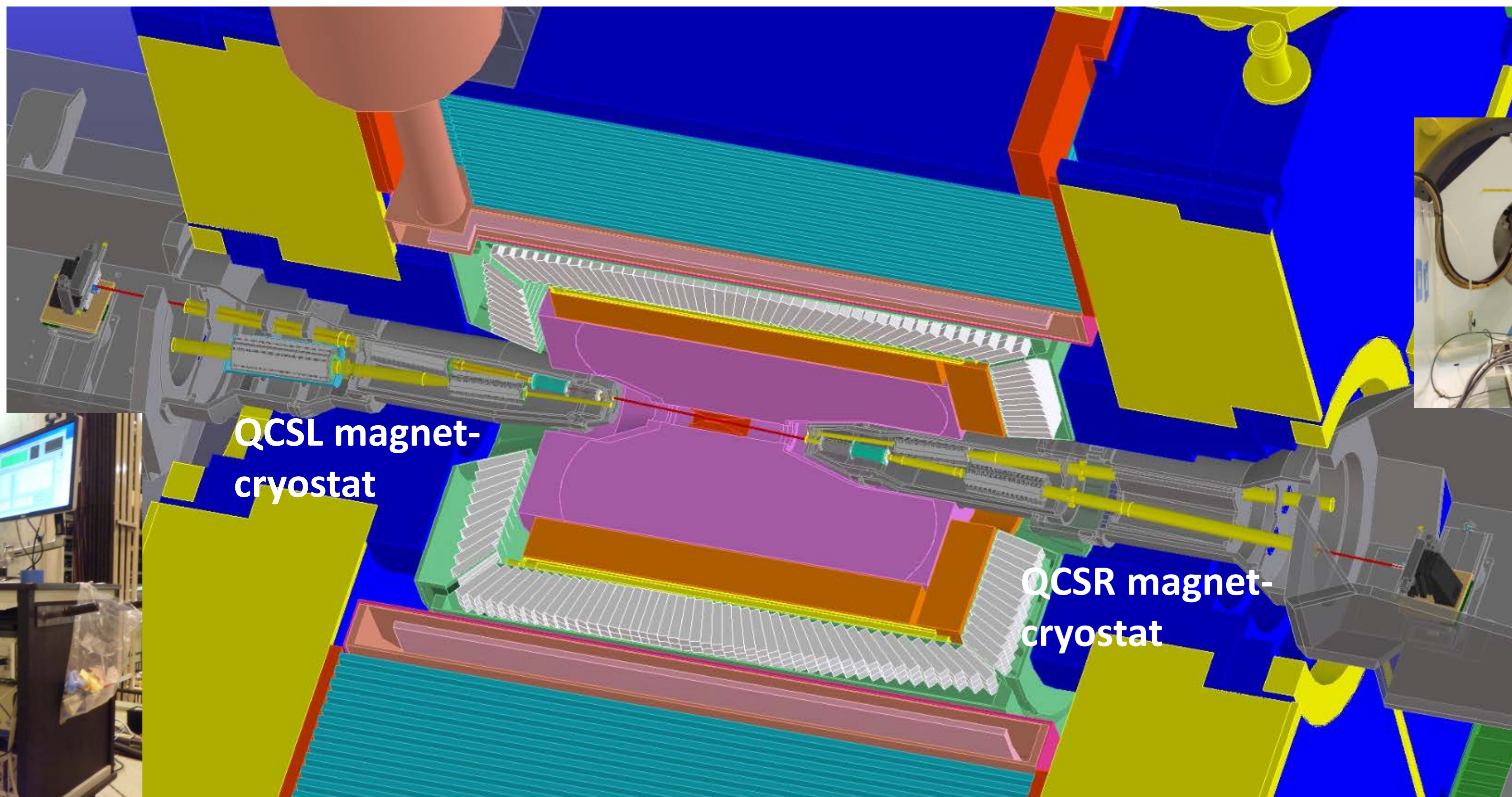
- **Single Stretched Wire measurement (SSW)**
  - Measurements of magnetic field centers and angles of the quadrupole field of QC1 and QC2
- **Harmonic coil measurement**
  - Magnetic field quality measurements of the SC magnets
  - Higher order multipole field profile measurements
  - Magnetic field 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.

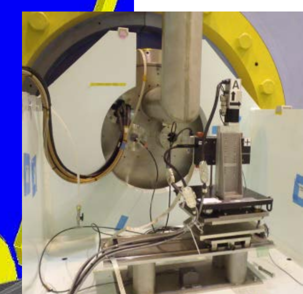
SSW measurement

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.



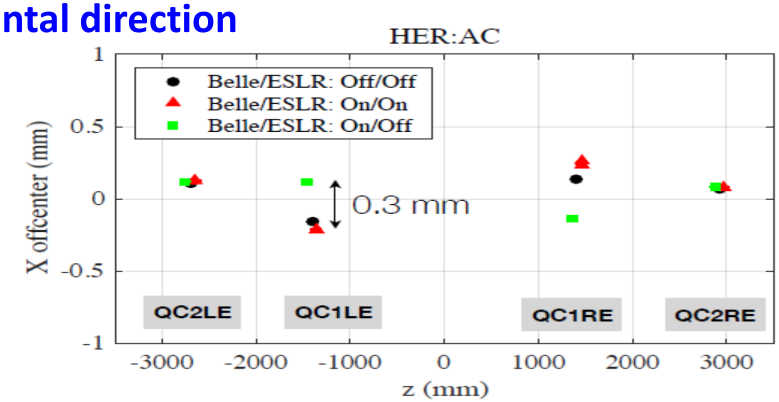


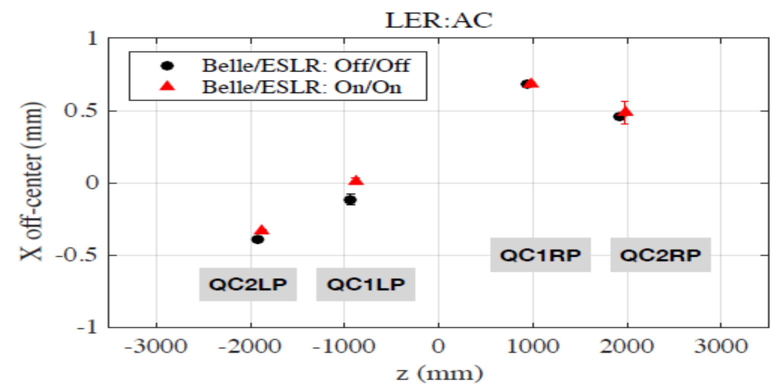


SSW measurement

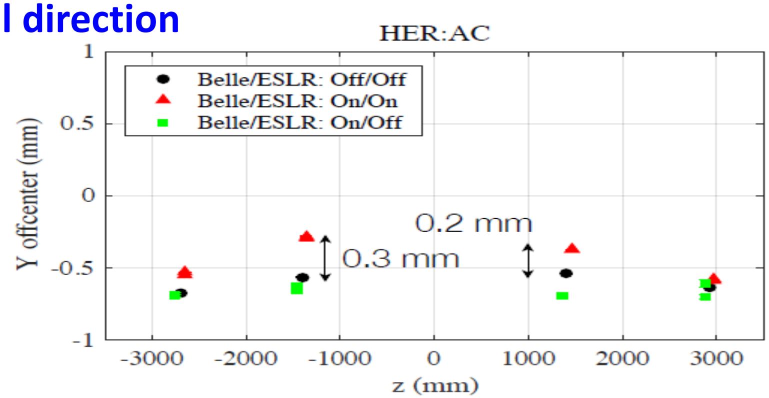
- The quadrupole field centers and angles of 8 SC quadrupole magnets in the QCSL/R magnet-cryostats from June 19, 2017 to June 30, 2017.
  - The FNAL research collaborator, Mr. Joseph DiMarco, was invited to complete the measurements .
  - The measurements were successfully completed, and the measured 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.

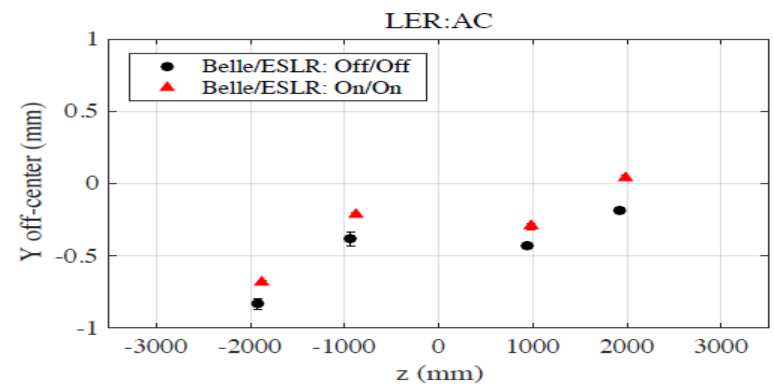
Horizontal direction





Vertical direction





SSW measurement

- 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	0.014	-0.335	0.684	0.486
Δy, mm	-0.211	-0.692	-0.296	0.042
$\Delta\theta$, mrad	-15.32 (-13.65)	-7.77 (-3.725)	9.22 (7.204)	-3.84 (-2.114)

	QC1LE	QC2LE	QC1RE	QC2RE
Δx, mm	-0.212	0.129	0.245	0.079
Δy, mm	-0.286	-0.535	-0.373	-0.581
$\Delta\theta$, mrad	-1.60 (0.0)	-1.54 (0.0)	-0.14 (0.0)	-0.73 (0.0)

The magnetic field measurements were performed under the conditions of operating the Belle solenoid and ESL/ESR solenoids.

- Electro-magnetic forces acting on the cryostats:
  - QCSL = 52.6 kN, QCSR=35.7 kN (calculation)

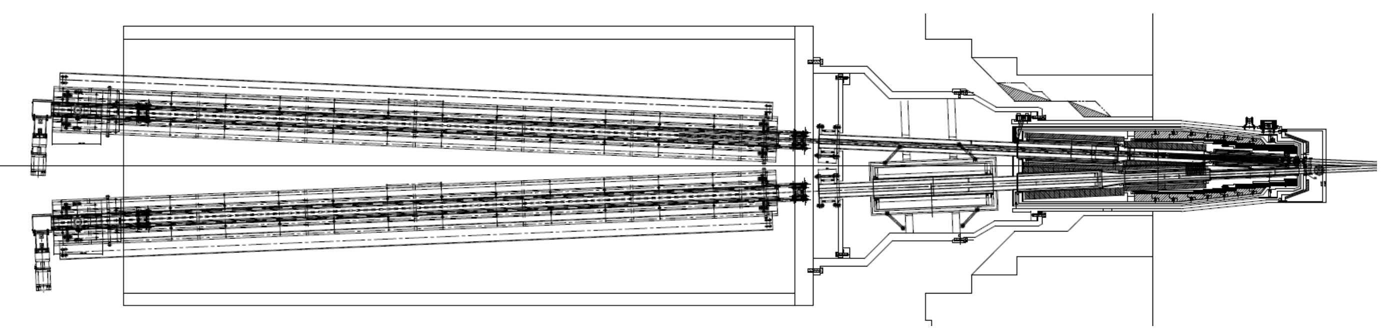
Harmonic coil measurements

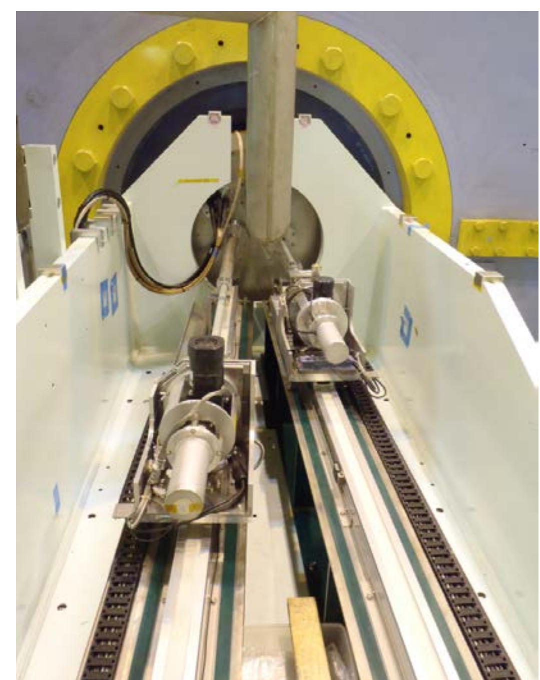
- Measurements of harmonic coils in **SuperKEKB IR** (in July, 2017)
  - One unit of measurement system has two harmonic coils.
  - The harmonic coils are moved by the mover, the movement is measured by the digital scaler.
  - **Two sets of the mover system were prepared for shortening the measurement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

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 and QC2 magnets

(measured under solenoid fields)

The strengths of the multipole field components are normalized with the B_2 field strength.

	QC1LP at R=10mm, I=1.71 kA		QC1RP at R=10mm, I=1.71kA		QC2LP at R=30mm, I=0.91kA		QC2RP at R=30mm, I=0.91kA	
n	a_n	b_n	a_n	b_n	a_n	b_n	a_n	b_n
1	790.2	232.9	1265.4	-140.25	399.7	13.8	-70.01	40.84
2	0.	**10000.**	0.	**10000.**	0.	**-10000.**	0.	**-10000.**
3	**-0.07**	**1.69**	**0.65**	**-0.91**	**-1.03**	**2.61**	**2.58**	**-0.09**
4	0.52	0.01	-0.94	-0.66	0.20	-0.20	-1.48	-0.22
5	0.01	-0.38	-0.35	0.35	0.92	0.32	-0.21	-0.07
6	-0.28	-0.10	0.37	-0.06	0.31	-3.58	0.62	-4.69
7	0.04	0.05	0.01	-0.06	-0.04	0.04	-0.21	0.00
8	0.07	-0.03	-0.04	-0.04	0.07	0.03	-0.07	0.07
9	0.10	-0.06	-0.01	0.05	-0.48	0.03	-0.12	-0.20
10	-0.03	-0.18	0.04	-0.18	0.21	0.86	0.34	1.77

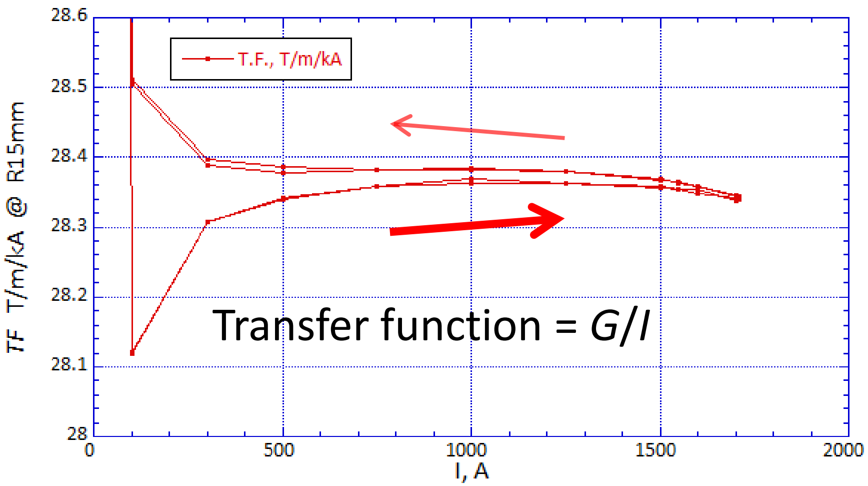
Integral field quality of the QC1 and QC2 magnets
(measured under solenoid fields)

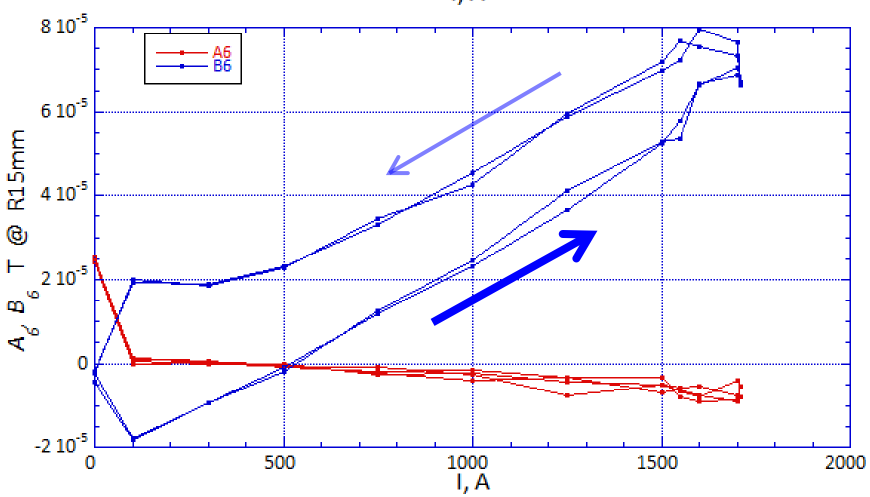
	QC1LE at R=15mm, I=1.71kA		QC1RE at R=15mm, I=1.71kA		QC2LE at R=35mm, I=1.11kA		QC2RE at R=35mm, I=1.11kA	
n	a_n	b_n	a_n	b_n	a_n	b_n	a_n	b_n
1	191.7	-313.2	131.2	-145.4	-12.8	170.64	15.4 (38.9)	114.0 (106.5)
2	0.	**10000.**	0.	**10000.**	0.	**-10000.**	0.	**-10000.**
3	**-0.59**	**0.72**	**0.97**	**-0.47**	**-1.44**	**-1.25**	**-18.9 (-4.79)**	**2.84 (-2.90)**
4	0.21	-0.24	-0.05	-0.18	-1.88	-0.29	8.09 (0.60)	-0.66 (0.04)
5	-0.20	-0.28	0.02	0.03	-0.63	0.16	-0.42 (0.40)	-0.21 (-0.10)
6	0.01	1.04	-0.07	0.92	0.18	-4.66	-0.22 (-0.19)	-1.60 (-1.95)
7	0.02	0.05	0.10	-0.02	-0.01	0.02	-0.11 (-0.05)	0.20 (0.14)
8	-0.09	-0.10	0.02	-0.01	-0.22	0.06	-0.06 (0.05)	0.16 (0.11)
9	-0.22	0.57	0.08	0.17	-0.20	-0.17	0.02 (-0.03)	-0.25 (-0.17)
10	-0.09	-0.08	-0.02	-0.60	0.08	2.22	0.06 (0.05)	1.80 (1.80)

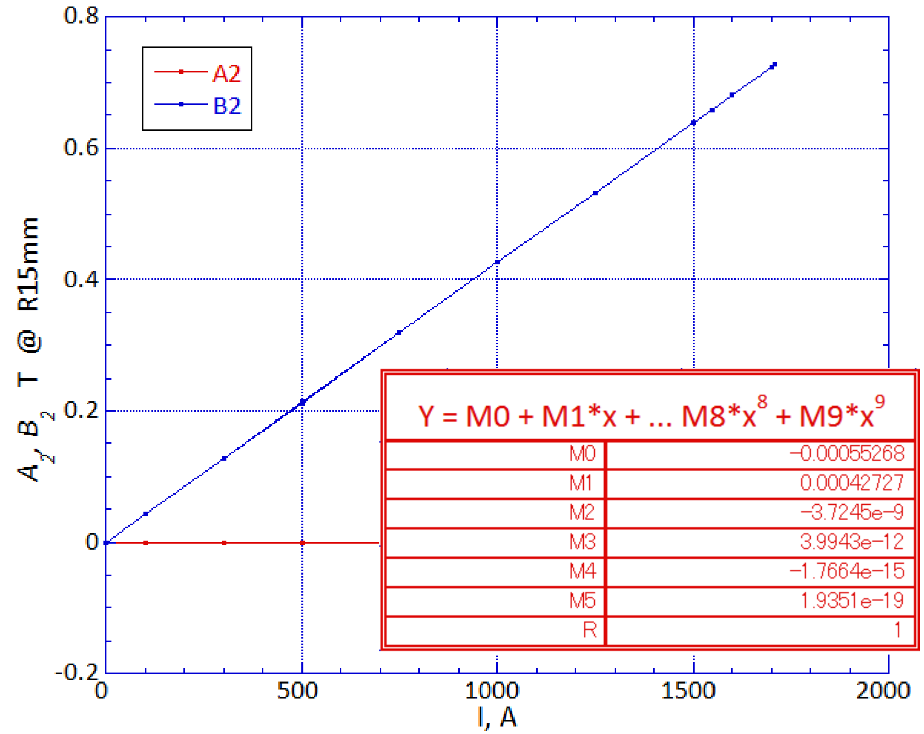
Without excitation of solenoids

Operation currents of the QC1/2 magnets

Current dependence of the magnetic field of QC1RE



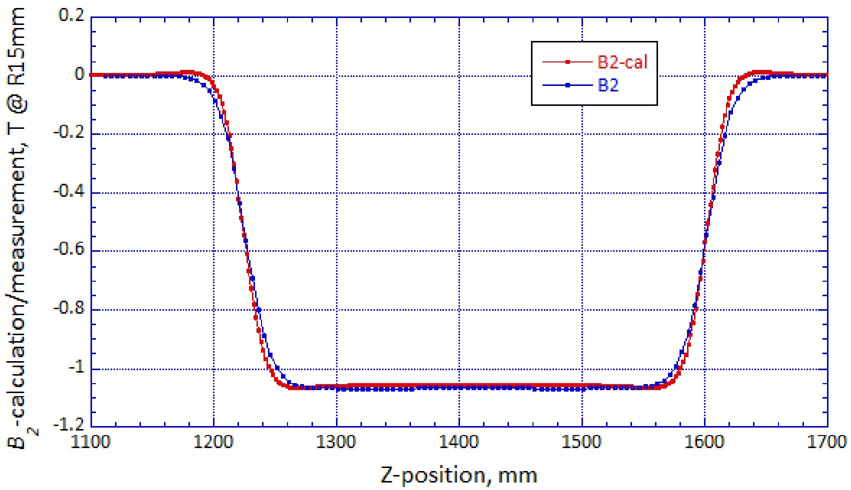


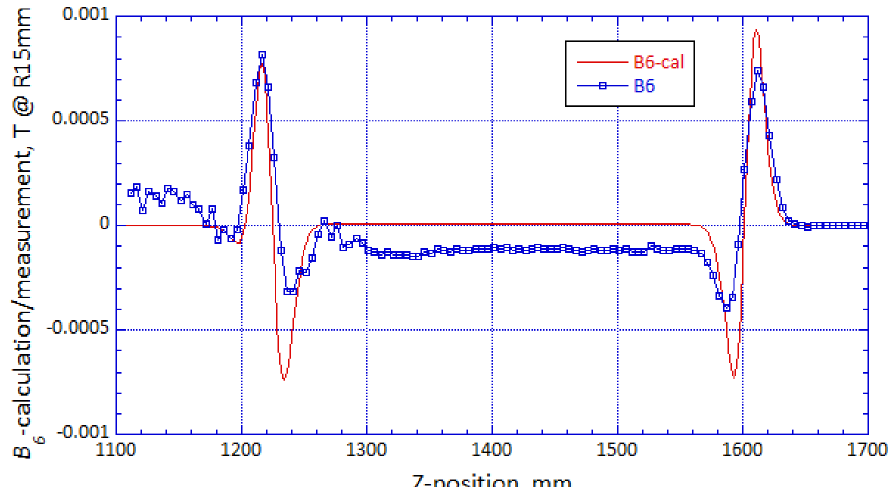


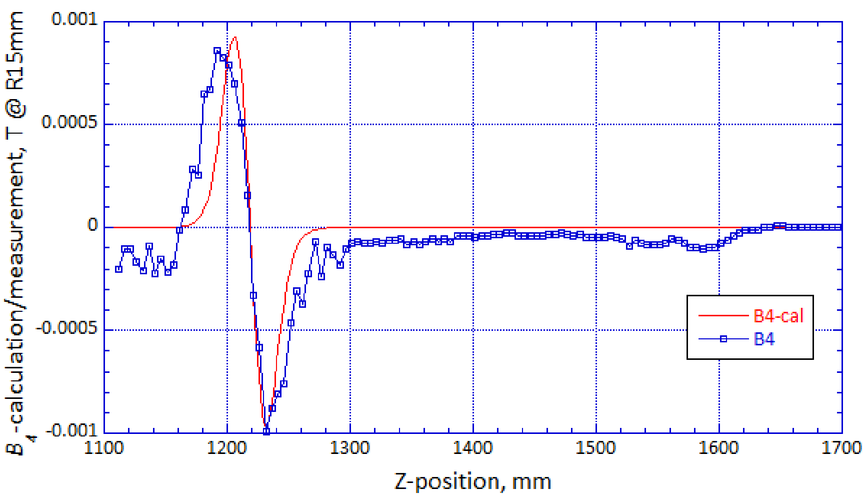
The magnet excitation parameters are defined by the 5th polynomial fitting with the data during up-ramping.

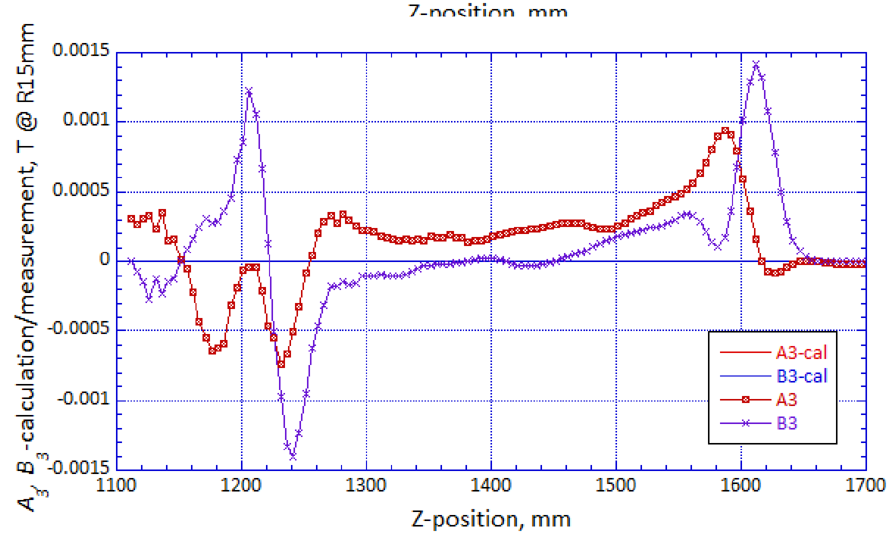
Magnetic field profile of the QC1/2 magnets

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



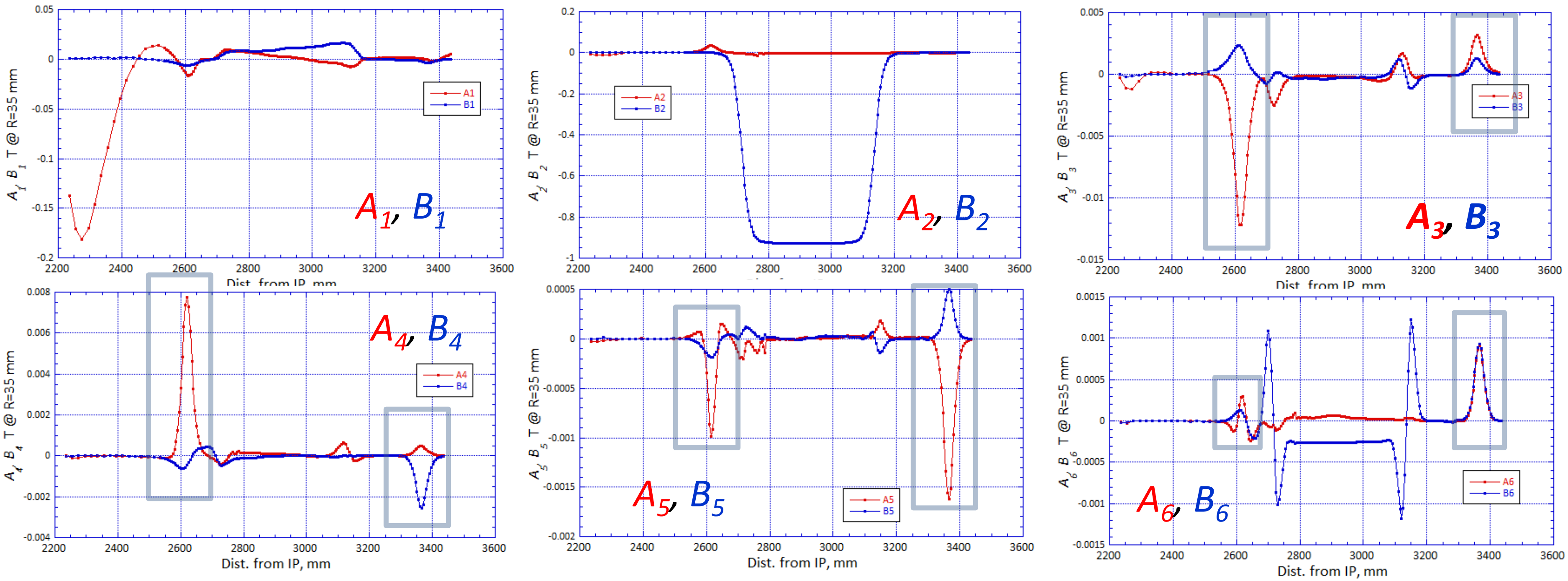


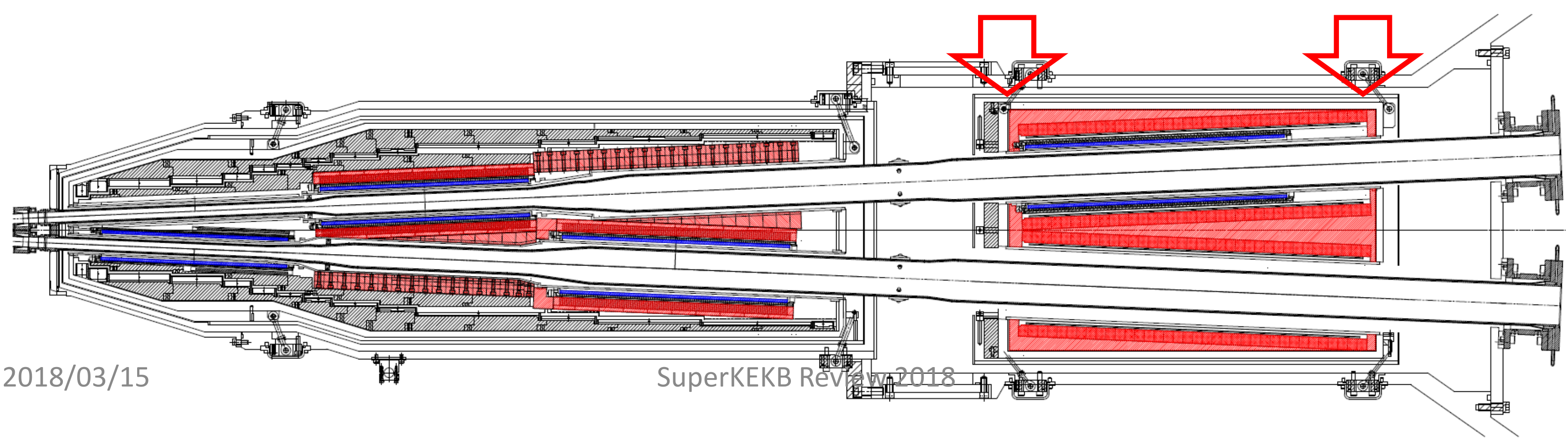




Magnetic field profile of the QC1/2 magnets

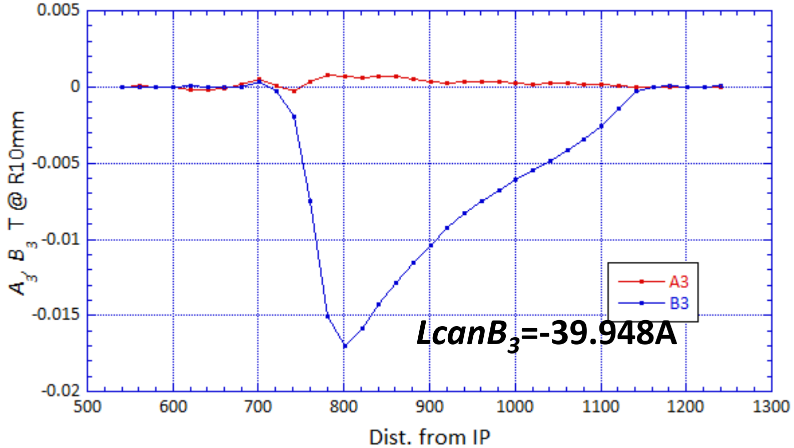
Measured results:QC2RE magnetic field profile along the HER beam line

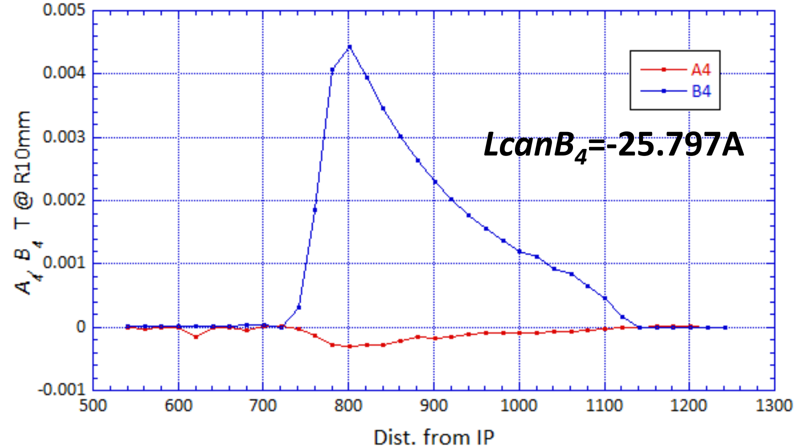


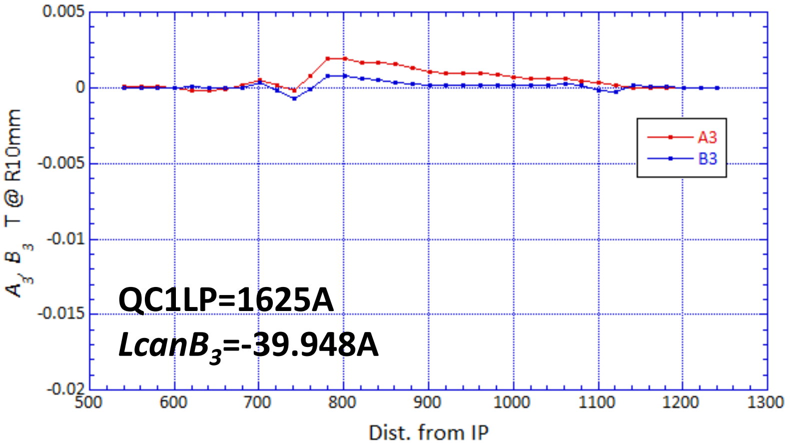


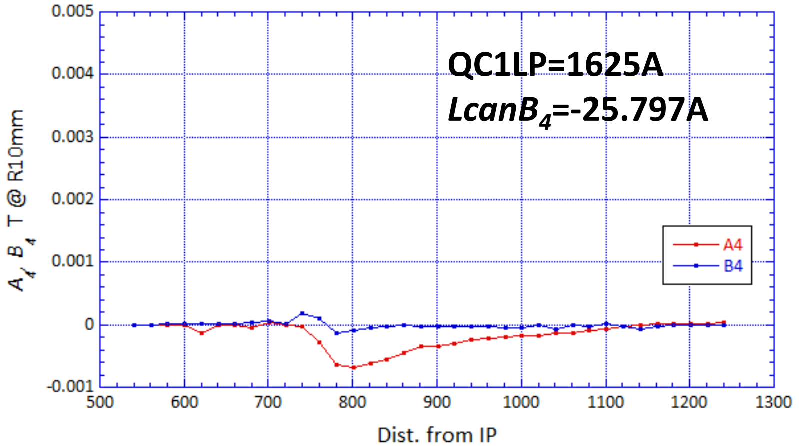
Magnetic field profiles of the cancel magnets

QCSL: From the measurement results of the harmonic coil and SSW (-1.6 mrad) for QC1LE, the scan data by the short harmonic coil were corrected.









QC1LP I_{op} = 1601.6 A, $\Sigma B_3=0$:

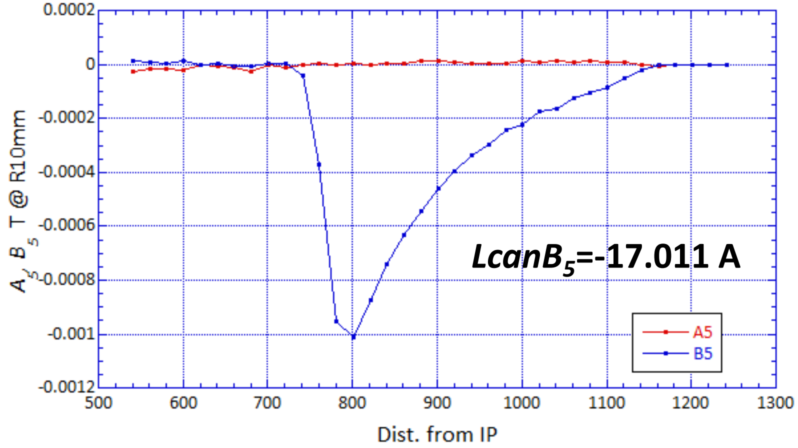
- B_3: operating current = **-40.3787 A**
- $\Sigma A_3 = 3.86\times10^{-4}$ Tm @ R=10mm

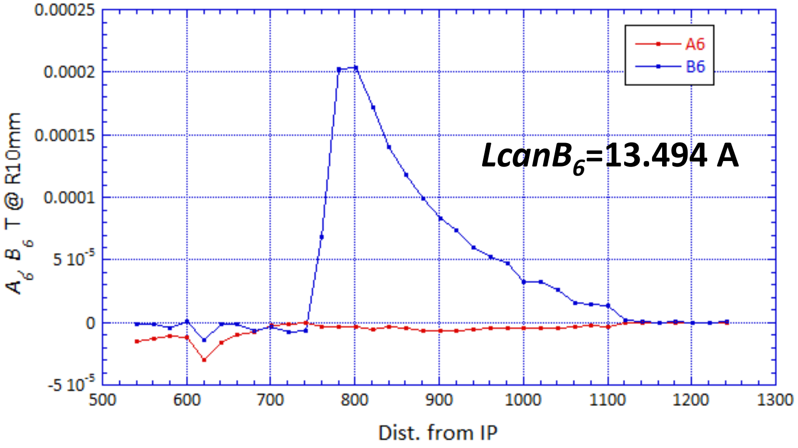
QC1LP I_{op} = 1601.6 A, $\Sigma B_4=0$:

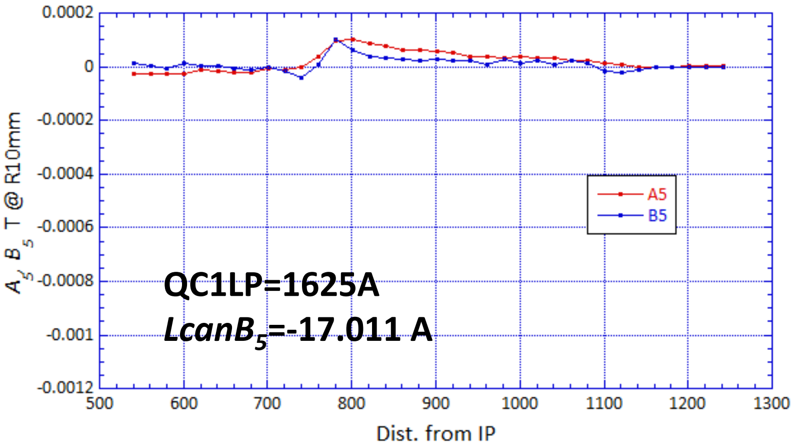
- B_4: operating current = **-25.5742 A**
- $\Sigma A_4 = 1.14\times10^{-4}$ Tm @ R=10mm

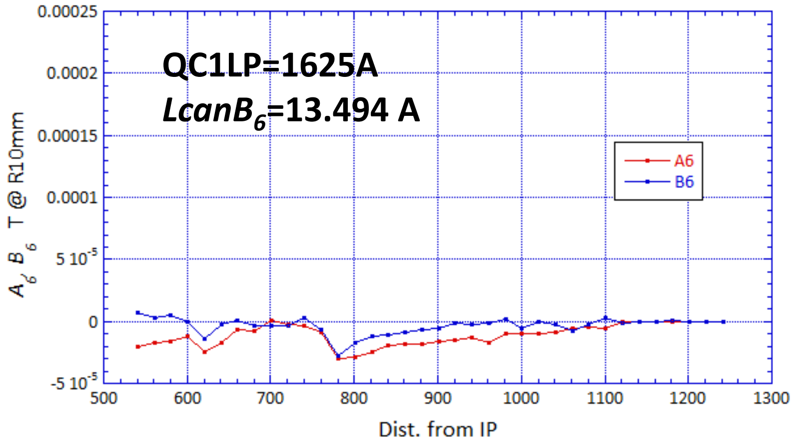
Magnetic field profiles of the cancel magnets

QCSL









QC1LP I_{op} = 1601.6 A, $\Sigma B_5 = 0$:

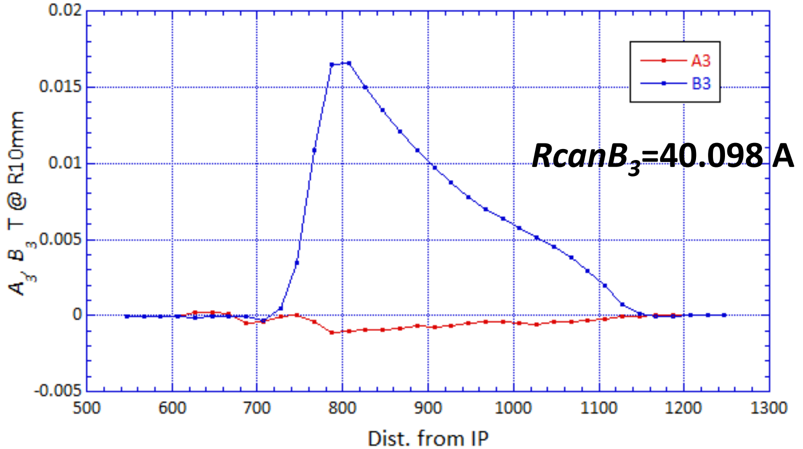
- B_5 : operating current = **-17.602 A**
- $\Sigma A_5 = 1.456 \times 10^{-5}$ Tm @ R=10mm

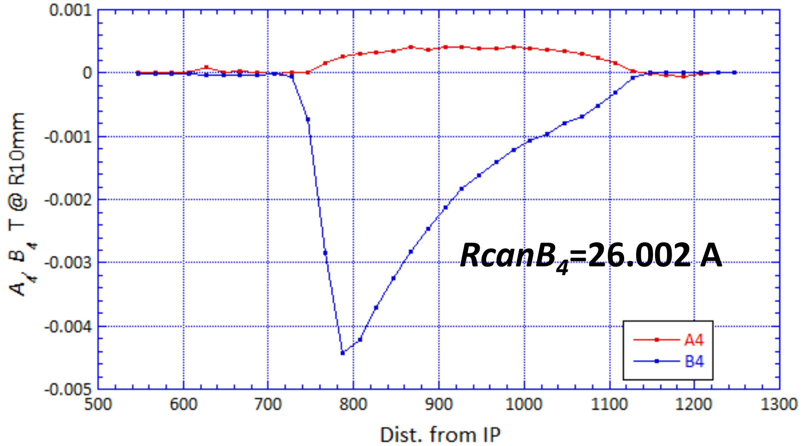
QC1LP I_{op} = 1601.6 A, $\Sigma B_6 = 0$:

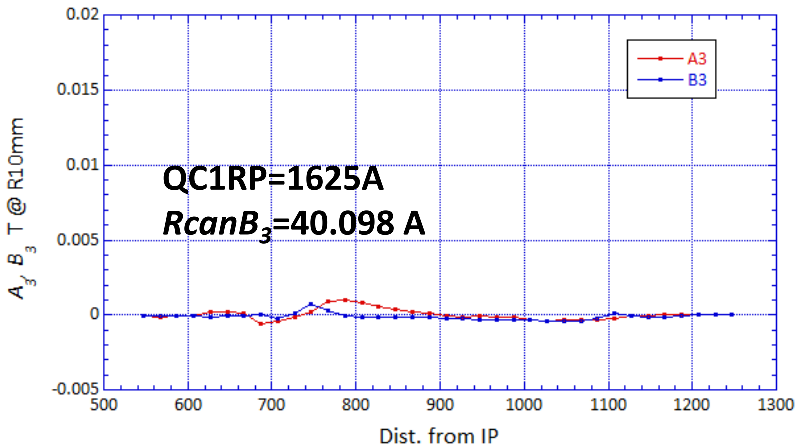
- B_6 : operating current = **14.442 A**
- $\Sigma A_6 = -8.018 \times 10^{-6}$ Tm @ R=10mm

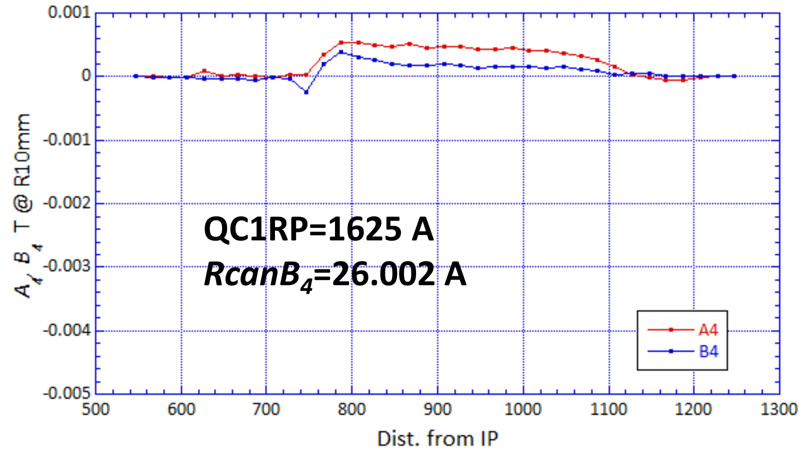
Magnetic field profiles of the cancel magnets

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：

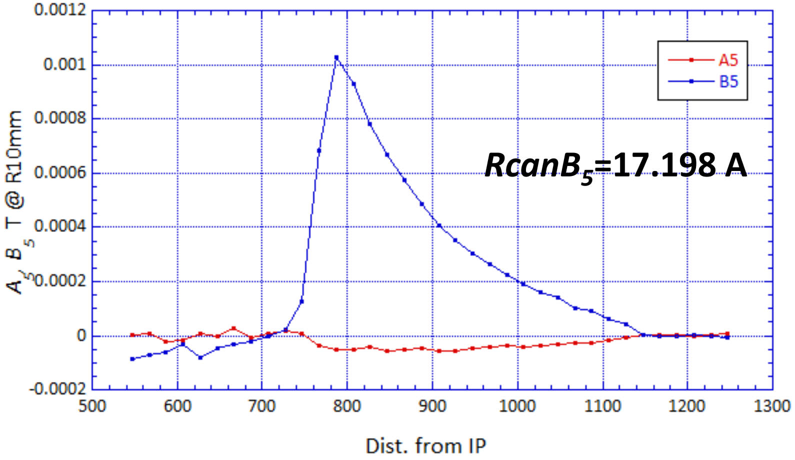
- B_3 : operating current＝**40.4403 A**
- ΣA_3＝4.098×10^{-6} Tm @ R=10mm

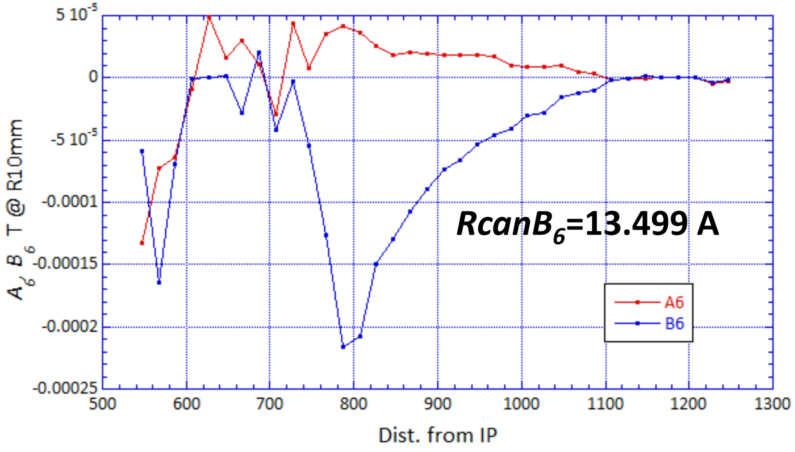
QC1RP I_{op}＝1602.2 A、ΣB_4=0：

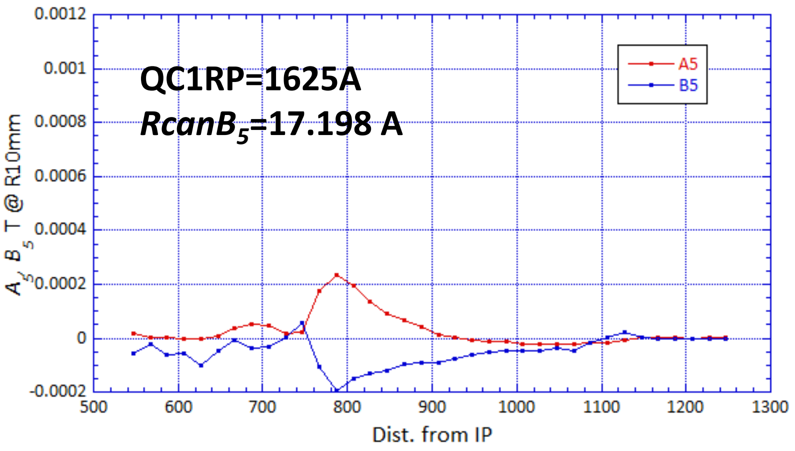
- B_4 : operating current＝**27.6702 A**
- ΣA_4＝1.62×10^{-4} Tm @ R=10mm

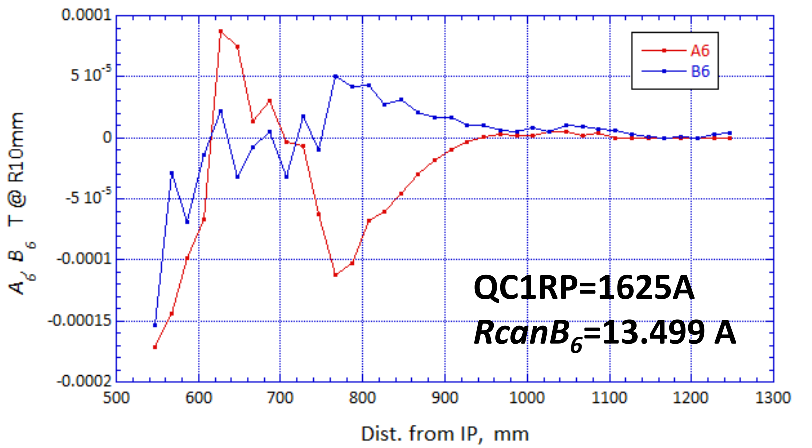
Magnetic field profiles of the cancel magnets

QCSR









QC1RP I_{op}=1602.2 A, $\Sigma B_5=0$:

- B_5 : operating current =**21.0970 A**
- $\Sigma A_5=1.6076\times10^{-5}$ Tm @ R=10mm

QC1RP I_{op}=1602.2 A, $\Sigma B_6=0$:

- B_6 : operating current =**13.5785 A**
- $\Sigma A_6=-1.5246\times10^{-5}$ Tm @ R=10mm

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	–

Magnetic field measurements of the correctors

	Corrector	Optics requirement	measurements at 60 A (on beam lines)	Allowable alignment at ±60 A
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	–

Hall probe field measurements along the beam lines

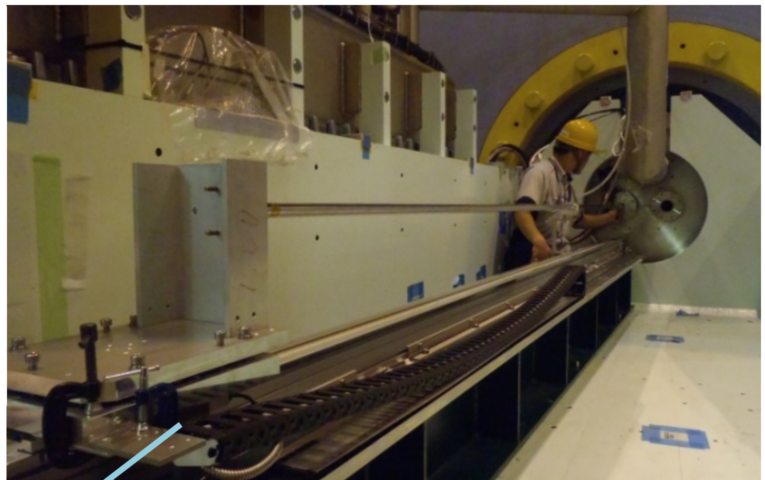
Required precision of the magnetic field in the SuperKEKB IR

- **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)

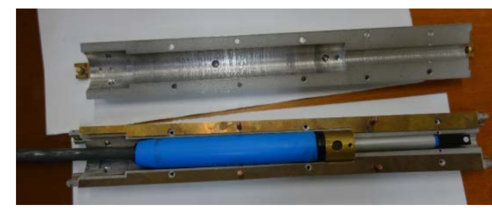
Measured magnetic field data are used for improving the 3D magnetic field calculation model which produces the precise field map in the SuperKEKB IR.

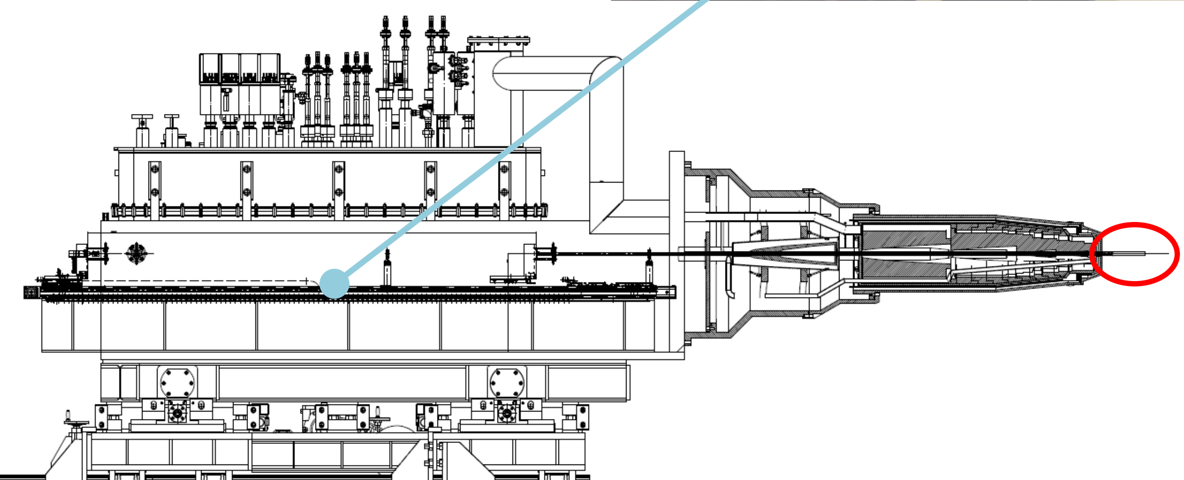
Mapping the magnetic field along the beam lines

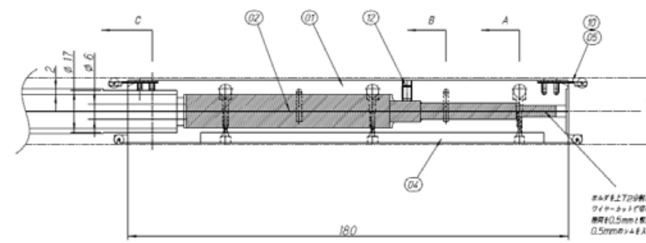
- The measurement system consisted of the commercial Hall probe and the scanning mover.
- The hall probe position was defined with the Belle end yokes.



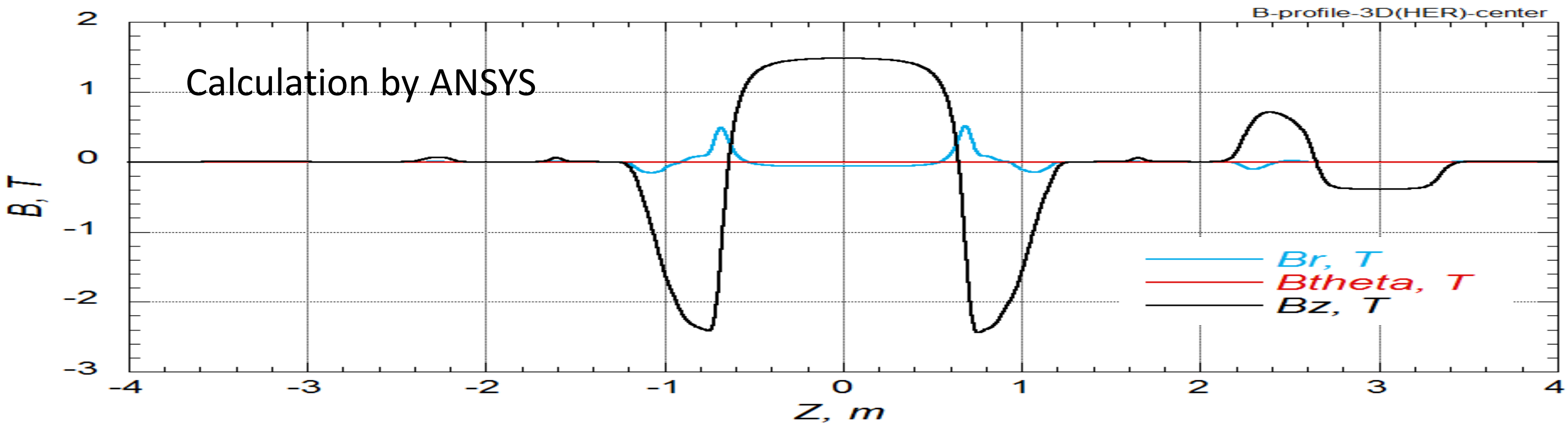
3 Axis-Hall-probe

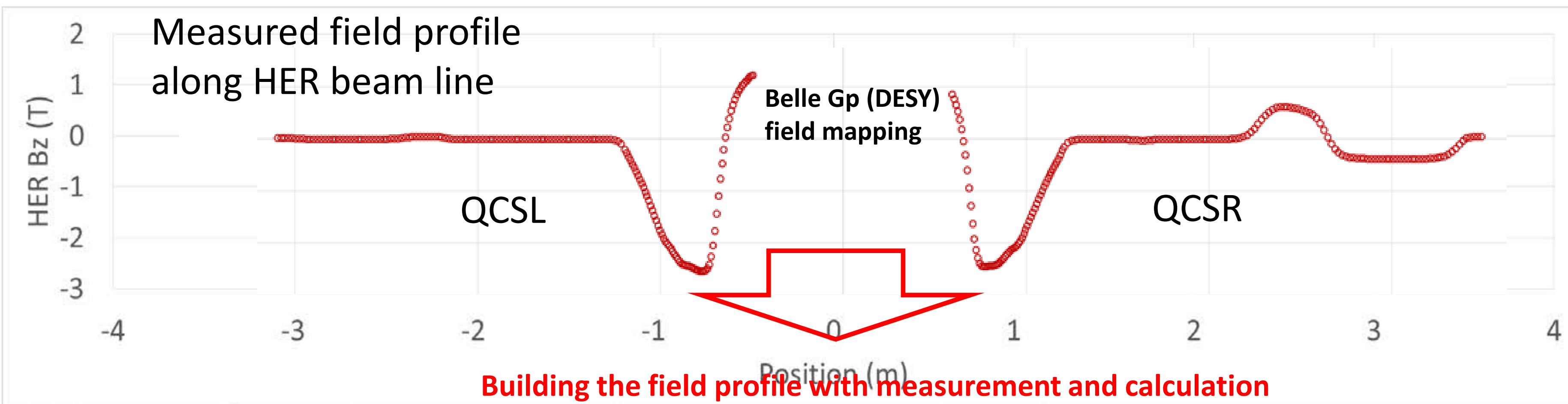






Hall probe field measurements along the beam lines



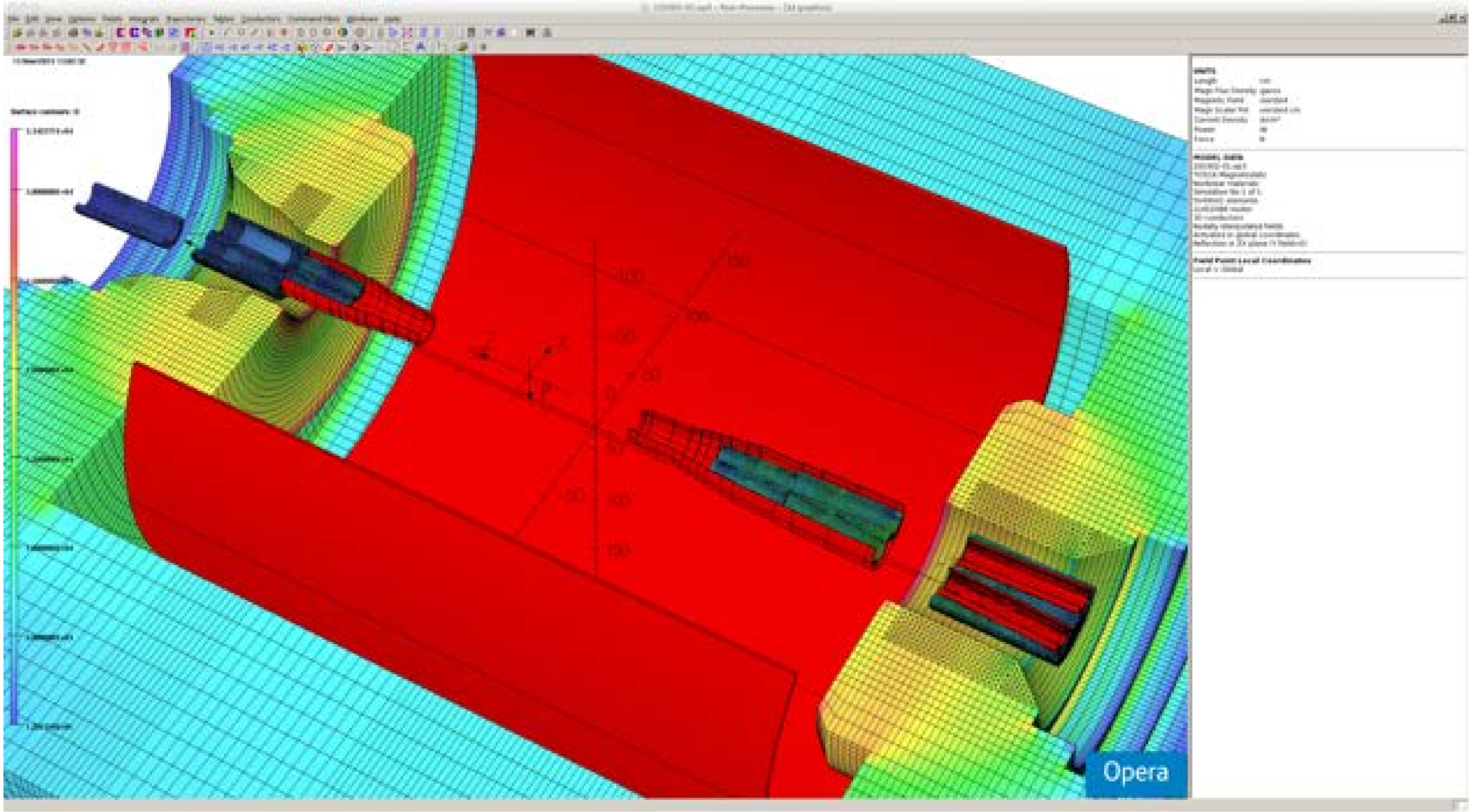


From the field measurements, the transport current of ESL was changed from 404 A to 390 A. The currents of ESR1 and ESR2-3 are 450 A and 151 A.

Hall probe field measurements along the beam lines

SuperKEKB IR magnetic field calculation model by OPERA-3D

- All SC magnets and magnetic components are included.



Some results from the cold tests

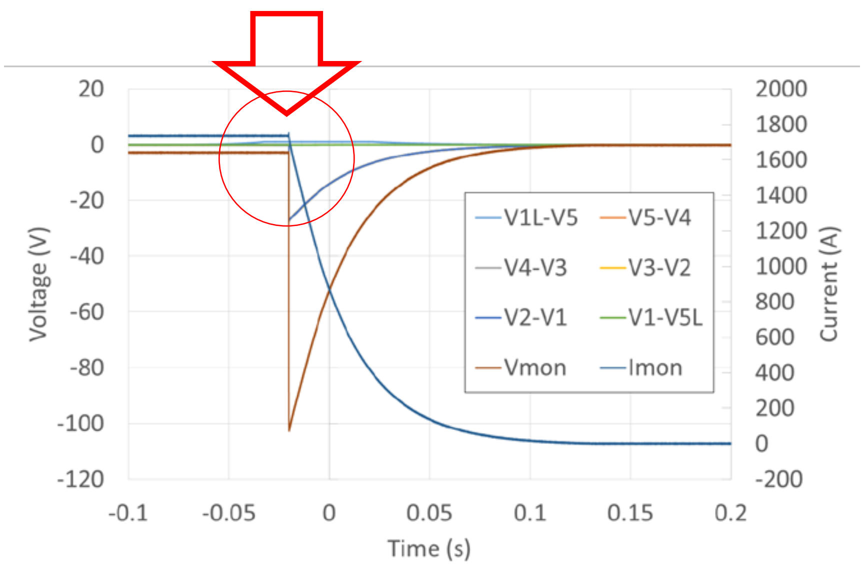
1. Quenches of the quadrupole magnets from the superconducting cables at the bottom of the current leads
2. Movement of the LHe vessels which have the SC magnets by the electro-magnetic forces from the Belle solenoid field at 1.5 T
3. Cold valve trouble of the He refrigerator for QCSR

Some results from the cold tests

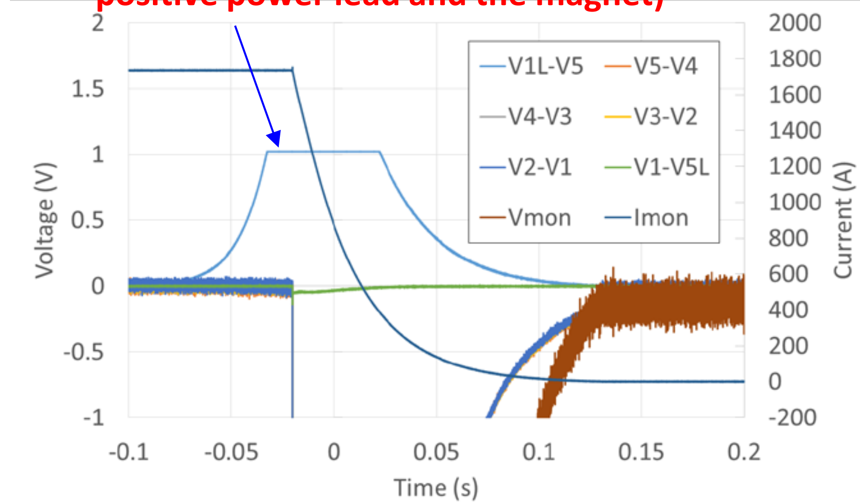
1. Quenches of the magnets from the superconducting cables at the bottom of the current leads
   - Dec. 6th, 2016: QC1LE quench at 1752 A during up-ramping to 2000 A
   - Dec. 9th, 2016: QC2LP quench at 1240 A during up-ramping to 1250 A
   - Jun. 13th, 2017: QC1LE quench at 1090 A during up-ramping to 1577 A

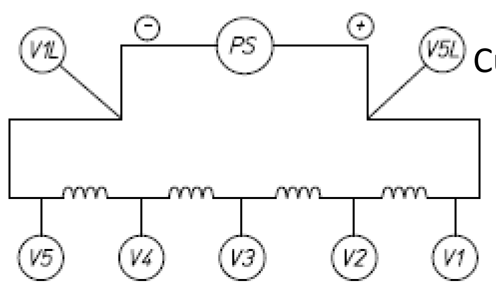
All quenches happened at the SC cable between the magnet and current lead

Quench onset



$V1_L$-V5 (Voltage between the bottom of positive power lead and the magnet)



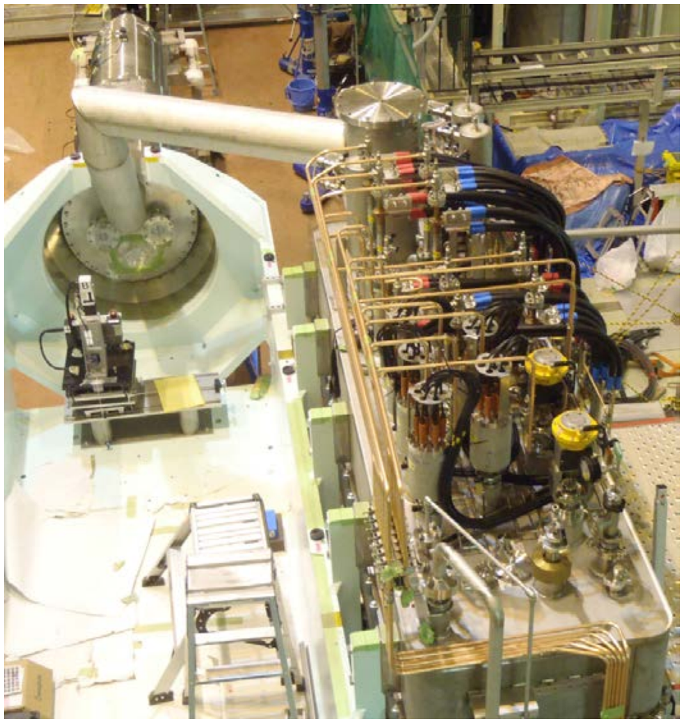


Current lead voltage taps

Quadrupole magnet and voltage taps

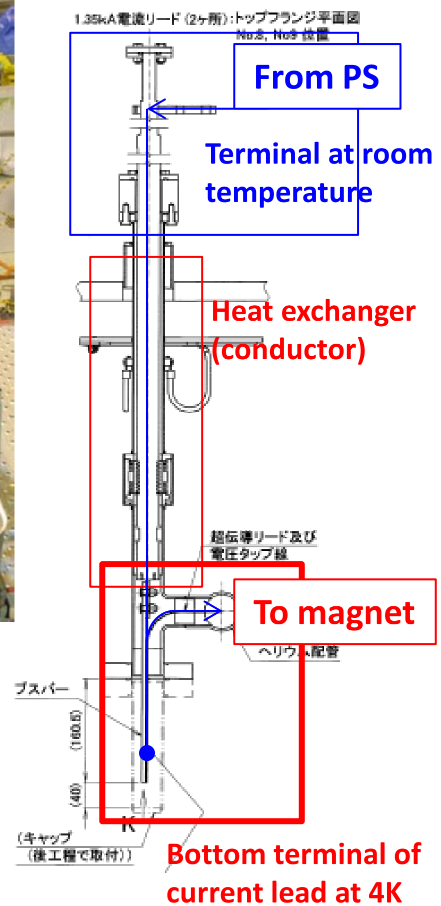
Some results from the cold tests

Estimation of temperature at the end of current leads



Top surface of the QCSR service cryostat (30 pairs + 1 current leads)

Configuration of current lead



Lead conditions at quench:

SC cables from magnet were connected to the bottom terminals of the current leads with solder

- Superconducting cable(*NbTi*)
  - Strand wire: O.D.=0.5mm (Cu ratio=1)
  - Strand number in cable=10
  - Performance of strand
    - 5T @ 4.22 K 307A
    - 6T @ 4.22 K 247A
- *NbTi*: J_c=5500 A/mm^2 at 0 T & 4 K
  - $T_{cs}=T_b + [\,T_c\,(B) - T_b\,][1-(I_{op}/I_c)]$
  - $T_c\,(0)$ = 9.2 K, T_b = 4.2 K
  - **T_{cs}= 7.52 K**
  - ➢ I_c=5500 A/mm^2, I_{op}=1848 A/mm^2 (corresponds to 1800 A of operating current)

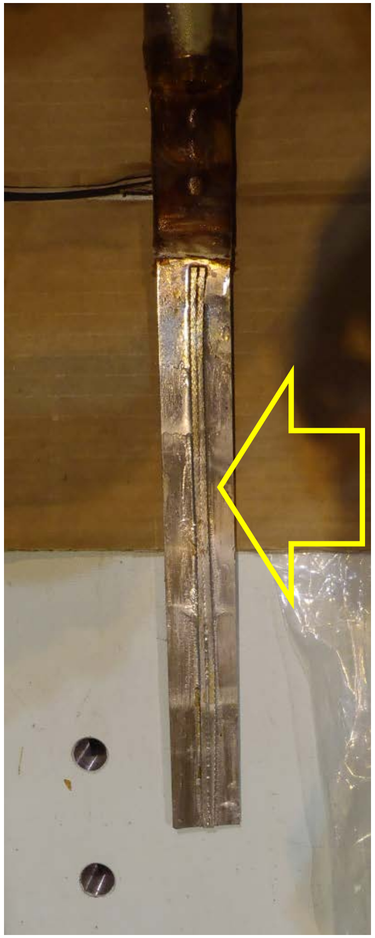
Improvement:

Two SC cables are added to the bottom terminal by soldering

- **T_{cs}= 8.64 K** by reducing the current density of the SC cables by one third

Some results from the cold tests

20 current leads of the main quadrupole magnets, ESL and ESR1 were improved by adding the additional SC cables to the bottom terminals from October to November, 2017.



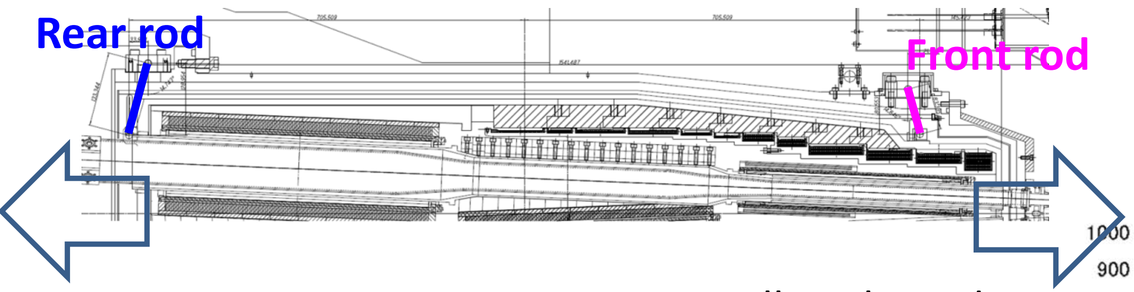
Soldered two cables to the terminal

Some results from the cold tests

2. Movement of the LHe vessels which have the SC magnets by the electro-magnetic forces from the Belle solenoid field at 1.5 T

QCSL helium vessel

The vessel is supported by the eight Ti alloy rods from the vacuum vessel.



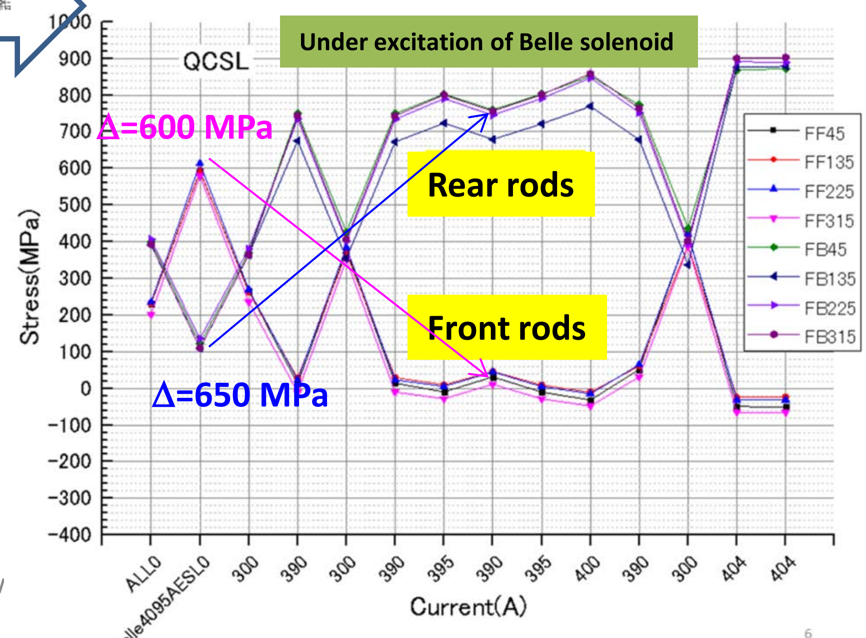
Belle solenoid + ESL excitation
EMF=52.6 kN

Belle solenoid excitation
EMF=57.3 kN

Rough estimation of the vessel movement

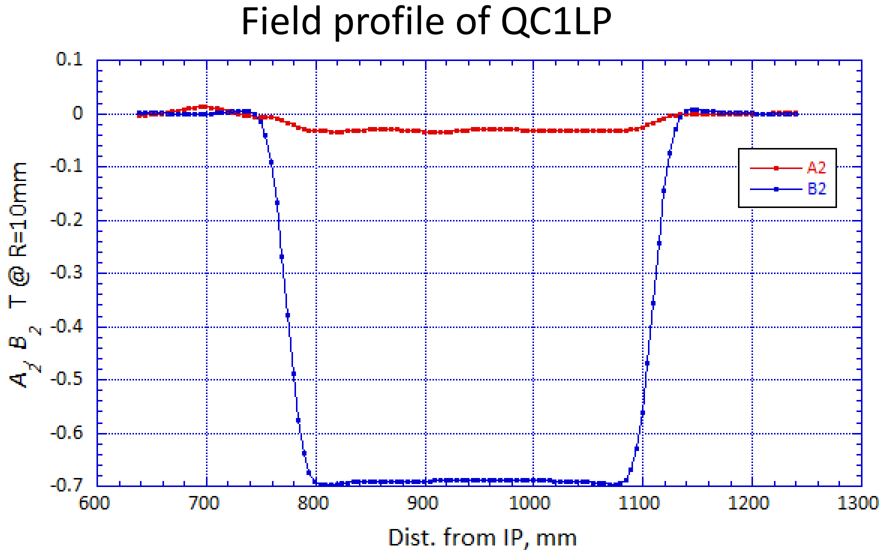
- Front rod for 600 MPa: movement =1.8 mm
- Rear rod for 600 MPa: movement=2.7 mm

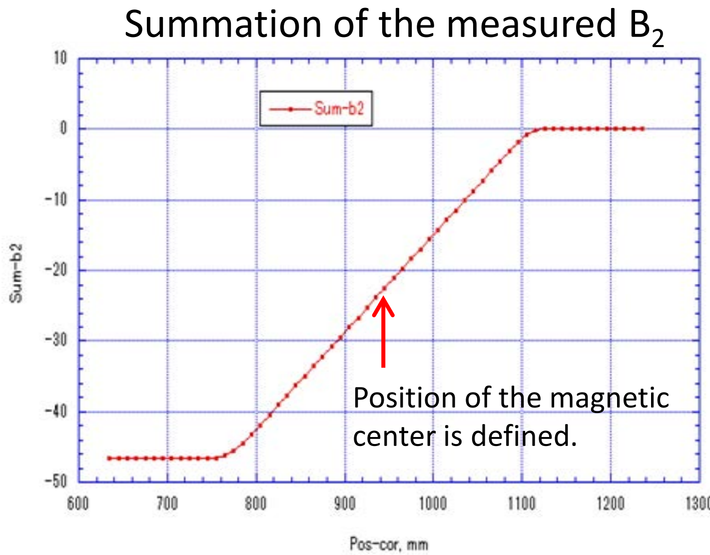
Measured stress in the QCSL support rods



Some results from the cold tests

- The magnetic center was measured by the quadrupole field profile





Distance of the quadrupole center from IP, mm

	QC1LP	QC1LE	QC2LE	QC1RP	QC1RE
With excitation of solenoids	939.50	1416.10	2695.10	938.46	1413.28
Without excitation of solenoids	937.02	1414.36	2695.18	937.52	1412.41
Δ (with-without)	2.48	1.74	0.08*	0.94	0.87

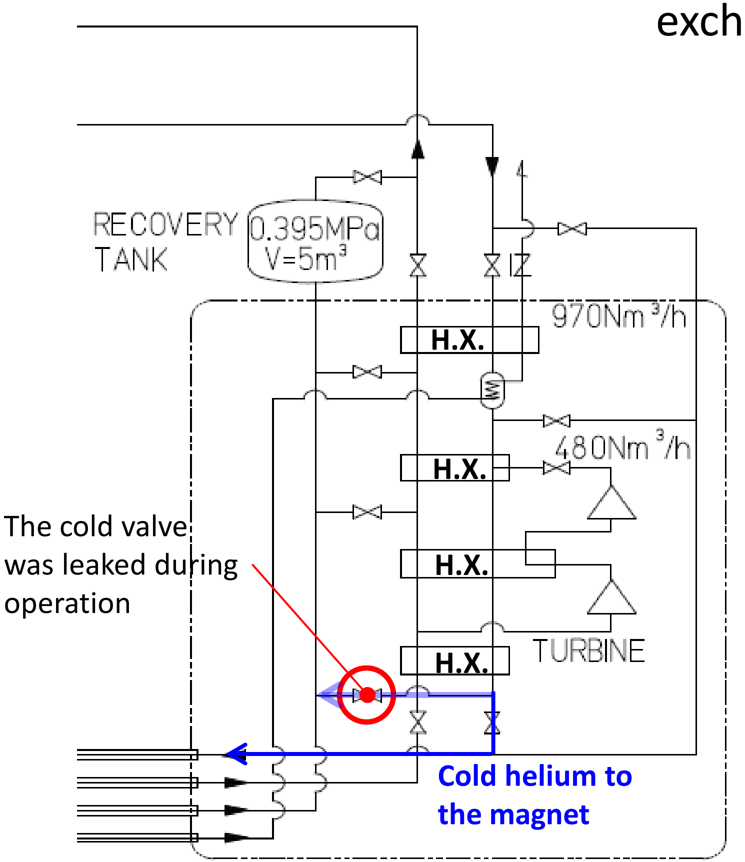
* EMF on QC2LE is small.

Some results from the cold tests

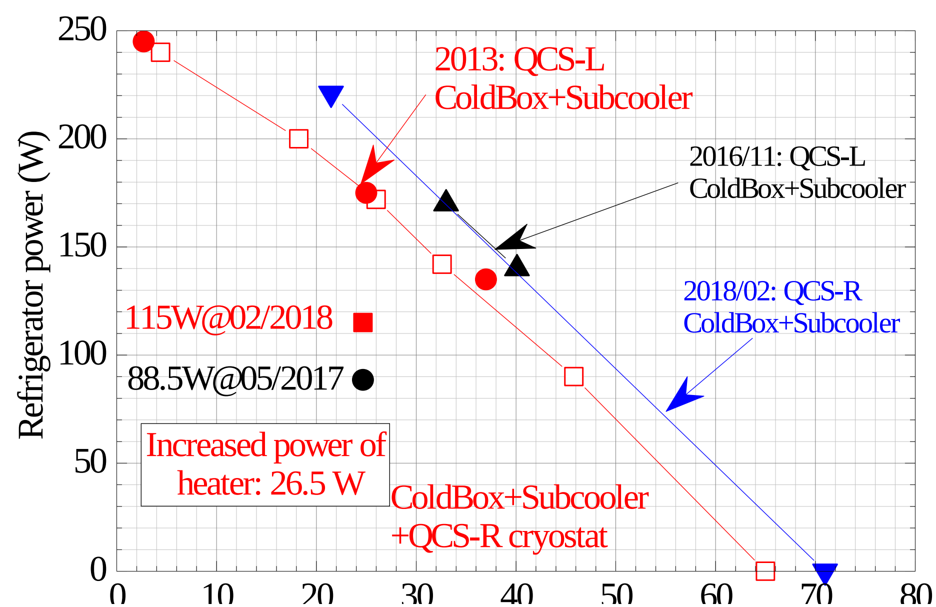
3. Cryogenic valve trouble of the He refrigerator for QCSR

The cryogenic valve, which connected to the final stage heat exchanger, did not close the helium gas line.

- By leaking the cold helium gas, the refrigerator lost the cooling power of 26.5 W at 4.4 K.
- The cryogenic valve was repaired in January 26th, 2018, the refrigerator recovers the cooling power as same as the QCSL refrigerator.



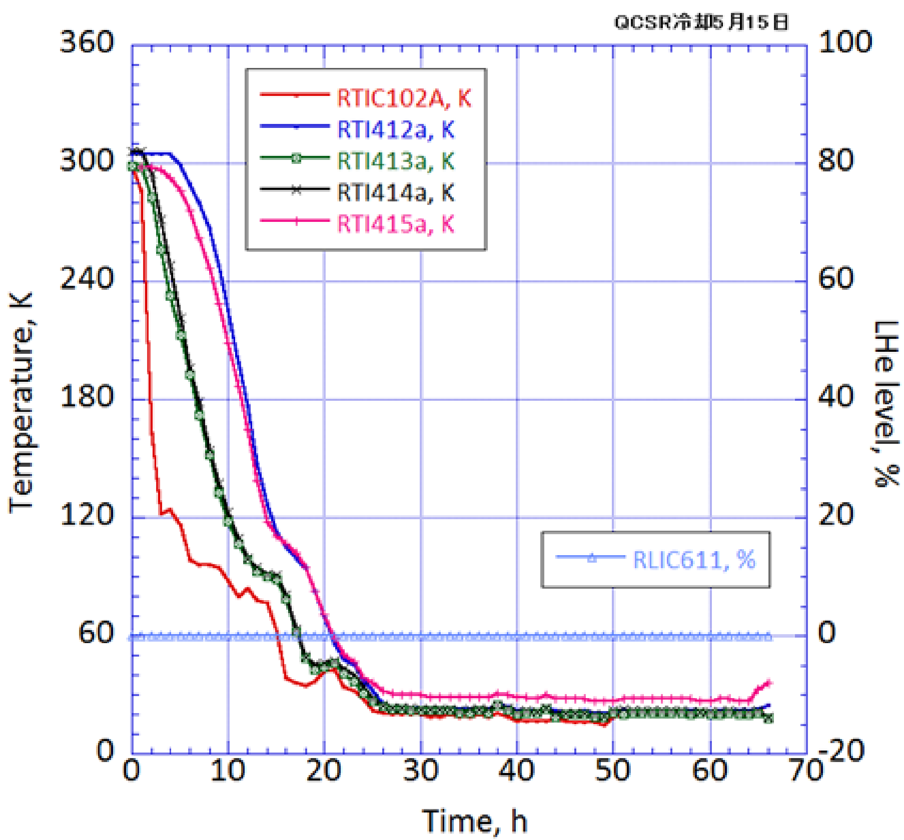
QCSR He refrigerator
250 W @ 4.4 K



Some results from the cold tests

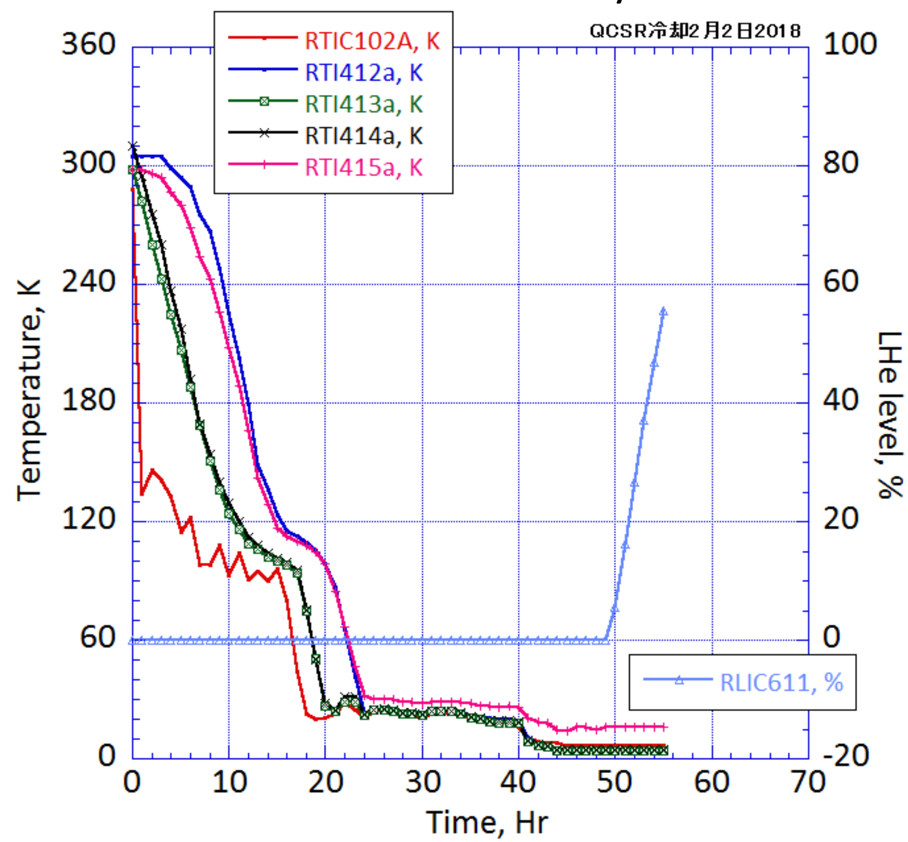
Cool-down of QCSR from room temperature to 4 K

May 2017



The cool-down of QCSR was not completed in 70 hours in May 2017.

February 2018



The cool-down of QCSR was completed in 55 hours in February 2018.

Summary

- The final focus system, QCS, has been completed and it is now ready to have beams.
- Data of the magnetic field measurements on the beam lines are still being studied.
  - Magnetic field profiles of the SC magnets will be included in the optics calculation.
  - Calibration of the Hall probe is now planed with research collaboration with FNAL to understand the solenoid field profiles along the beam lines.
  - With the field measurement data, the precise 3D field calculation model will be constructed for the Phase-3 operation.
- Concerning for the quadrupole magnet vibration, we started the development of the measurement system with BNL.

Back-up files

Major troubles of QCSR in company

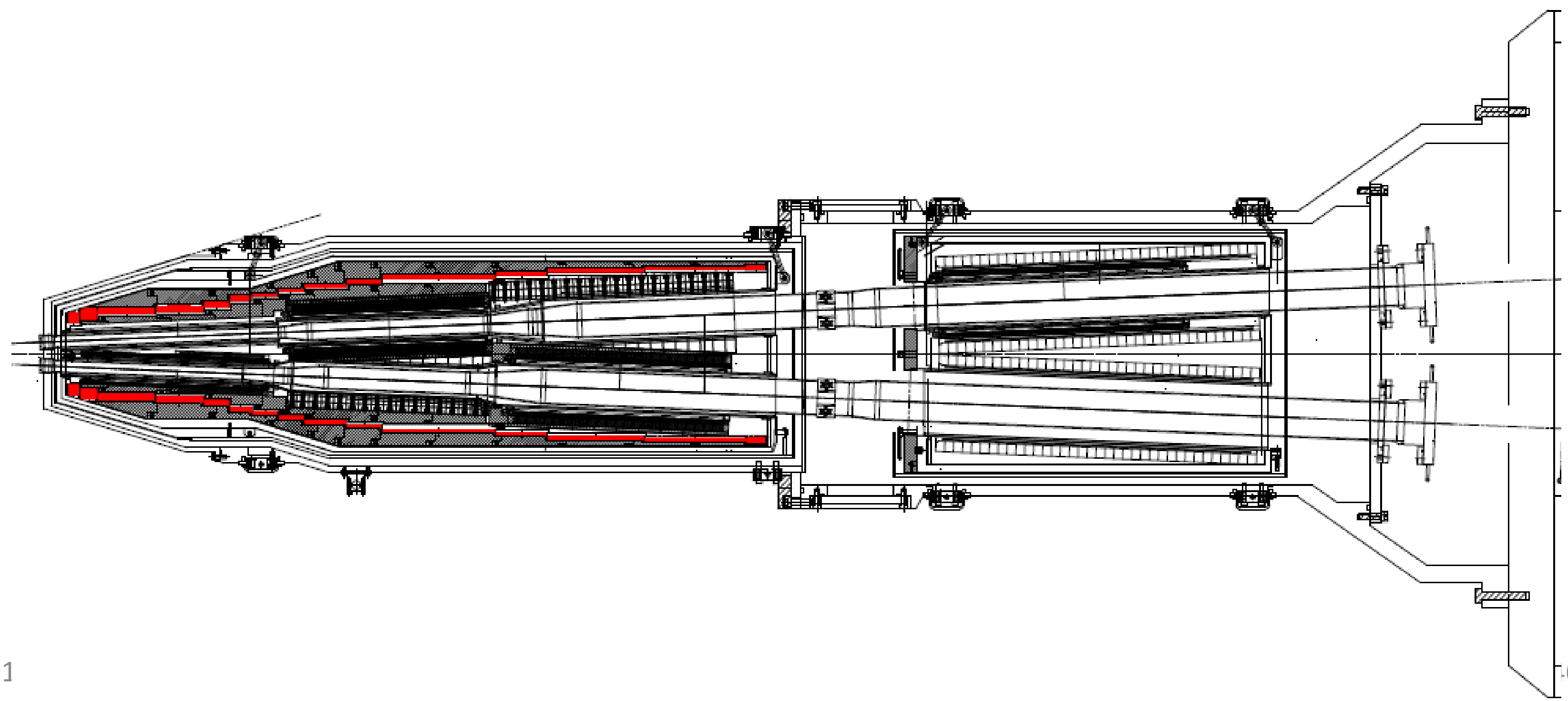
QCSR magnet cryostat

1. ESR1 electrical insulation fault at 1st Nov. 2016.

– The electrical insulation fault was detected at the withstanding voltage test after assembling the ESR1 to the helium vessel.

» For the ESR1 quench test with the KEK vertical test stand , film heaters were attached on the surface of ESR1.

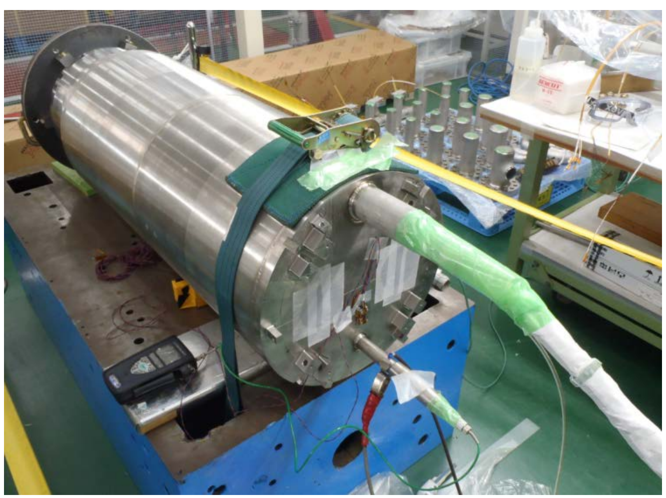
» After the quench tests, the heaters were removed from the solenoid surface. Some pin

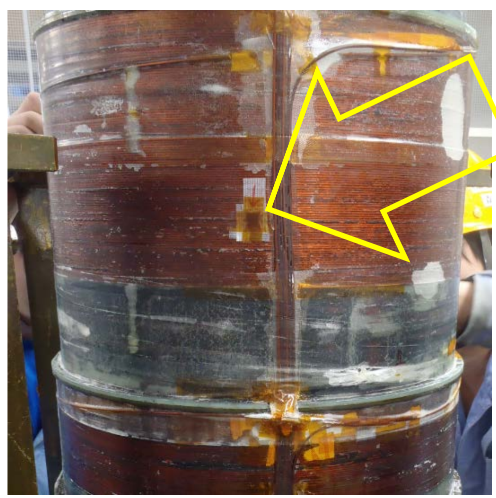


Major troubles of QCSR in company

Identifying the fault place in ESR1

- It took two weeks for detection:
  - The fault was detected after welding the pipe to the helium vessel. Inspection was centrally performed on the cables assembled in the pipe.
  - As the result, it turned out that the fault existed in the helium vessel, and then the helium vessel was cut along the welding line.
  - The ESR1 solenoid was pulled out from the vessel, and the electrical tests were performed on the surfaces of ESR1. One fault was detected.



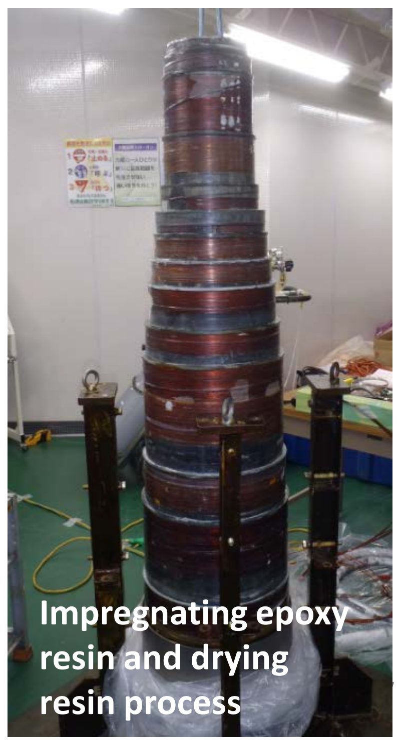


Major troubles of QCSR in company

Repair of the ESR1 electrical insulation damage

– Process for repair
  - Additional electrical insulation on the ESR1 solenoid surface by Kapton tape
  - Wrapping glass tape with impregnating epoxy resin on the Kapton tape
  - Assembling Tungsten radiation shields around ESR1
  - After setting the ESR1 with the shields in the helium vessel, the electrical tests were performed in the air. Test results were good.
  - After welding the vessel, the electrical tests in helium gas were performed. Test results were good. [22nd Nov. 2016]


Glass tapes on the surface of ESR1


Impregnating epoxy resin and drying resin process


Tungsten radiation shield


Setting helium vessel

Major troubles of QCSR in company

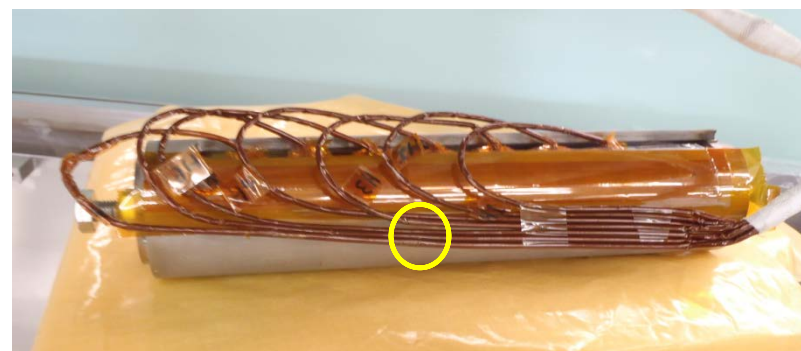
2. The second electrical insulation fault of ESR1

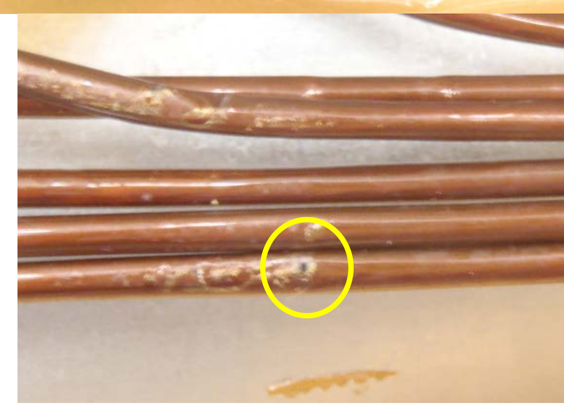
- 12^{th} Jan. 2017 : The final electrical tests of QCSR cryostat in Mitsubishi
  - Detecting the electrical insulation damage in the ESR1 electrical line
    - » Electrical discharge happened at AC1000 V against the test voltage of AC1800V.
  - Another 29 magnets showed good electrical performances.
- Fault place: the cable to the cold diode for the quench protection of ESR1 in the service cryostat

Major troubles of QCSR in company

Cold diode for the ESR1 quench protection

- Stored energy of ESR1= ~800 kJ
  - When we apply the same protection system to QCSR1 as the ESL system, the temperature of the 10 coil sections reach over 300 K. ERS1 consists of 15 coil sections.
  - For ESR1, 15 sections are divided into 6 groups. Each group is connected to the individual cold diode.
    - » Temperatures of all coil sections ＜150K
    - » The operation of the cold diode was confirmed in the cold test with the KEK vertical test stand.





Major troubles of QCSR in company

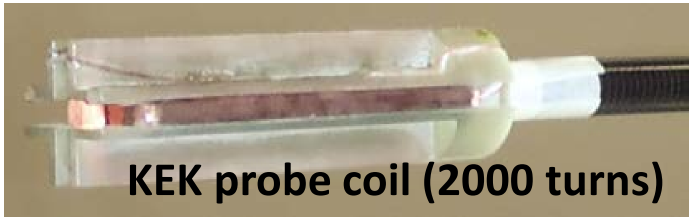
Electrical tests after repair of the cold diode cable

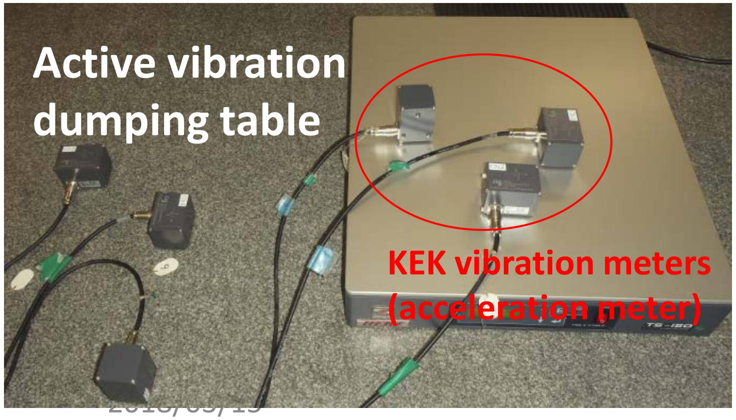
- 17^{th} Jan. 2017: After detecting the fault in the cable of the cold diode and repairing the electrical insulation of the cable, ESR1 passed the electrical tests in the air.
- 24^{th} Jan. 2017: The electrical tests for the magnets in the cryostat were performed in air and in helium gas.
  - » All magnets showed good electrical performances.
- 31^{st} Jan. 2017 : Success in the final electrical tests

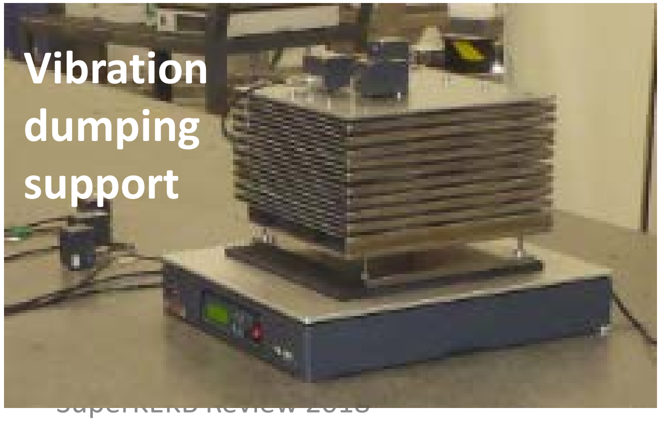
QCSR cryostat was delivered to KEK at 13^{th} Feb. 2017.

Vibration measurement system

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







Vibration measurement system