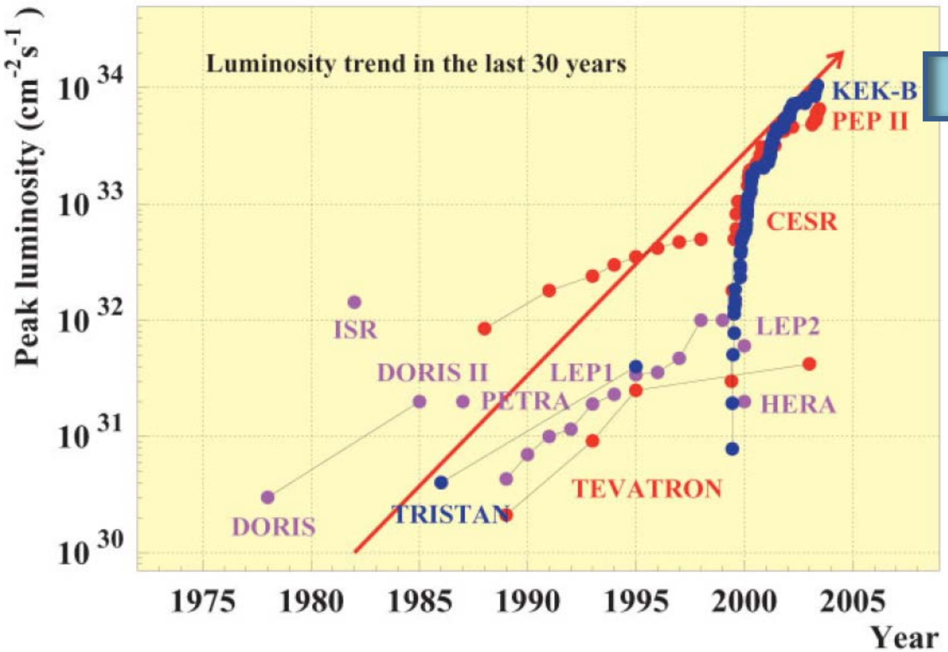
SuperKEKB Final Focus Superconducting Magnet System (QCS)

Norihito Ohuchi

KEK

Contents

SuperKEKB



SuperKEKB/Belle II

x 40 times higher luminosity

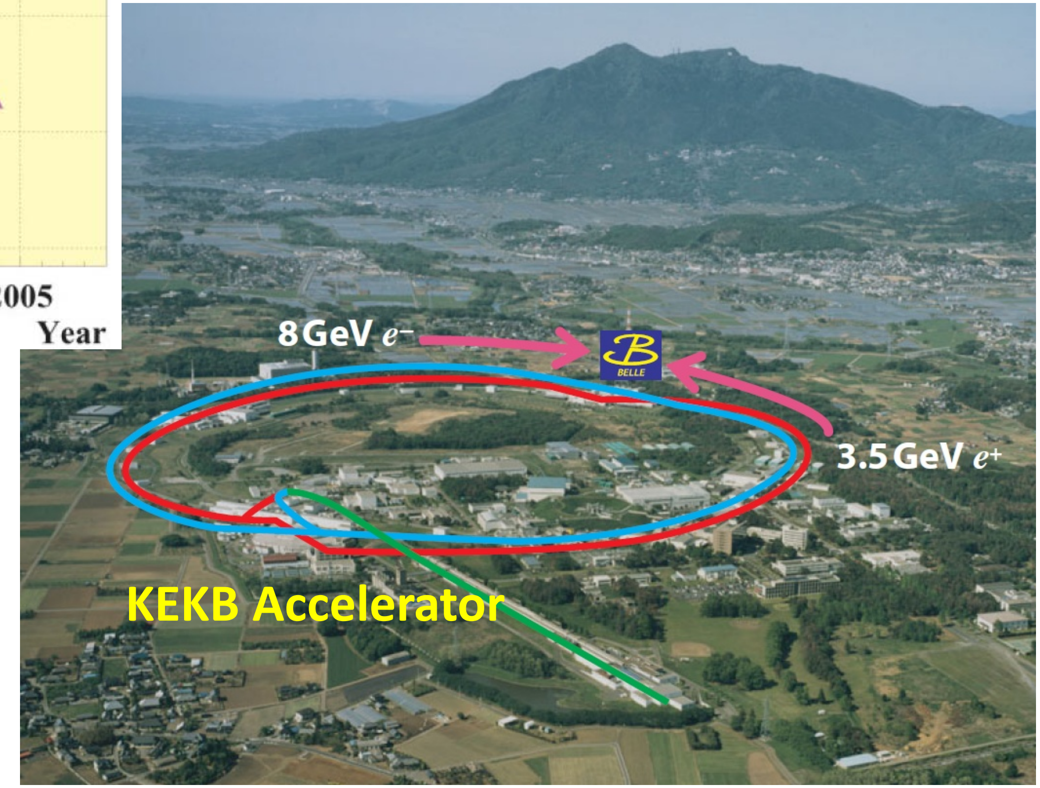
$L=8\times10^{35}$ cm^{-2}s^{-1}

KEKB/Belle (1999~2010)

- **2001:Disconery of "CP Violation (matter-antimatter asymmetries)"**
- **Verification through experiment of "Kobayashi and Maskawa's hypothesis for the origin of the CP violation"**

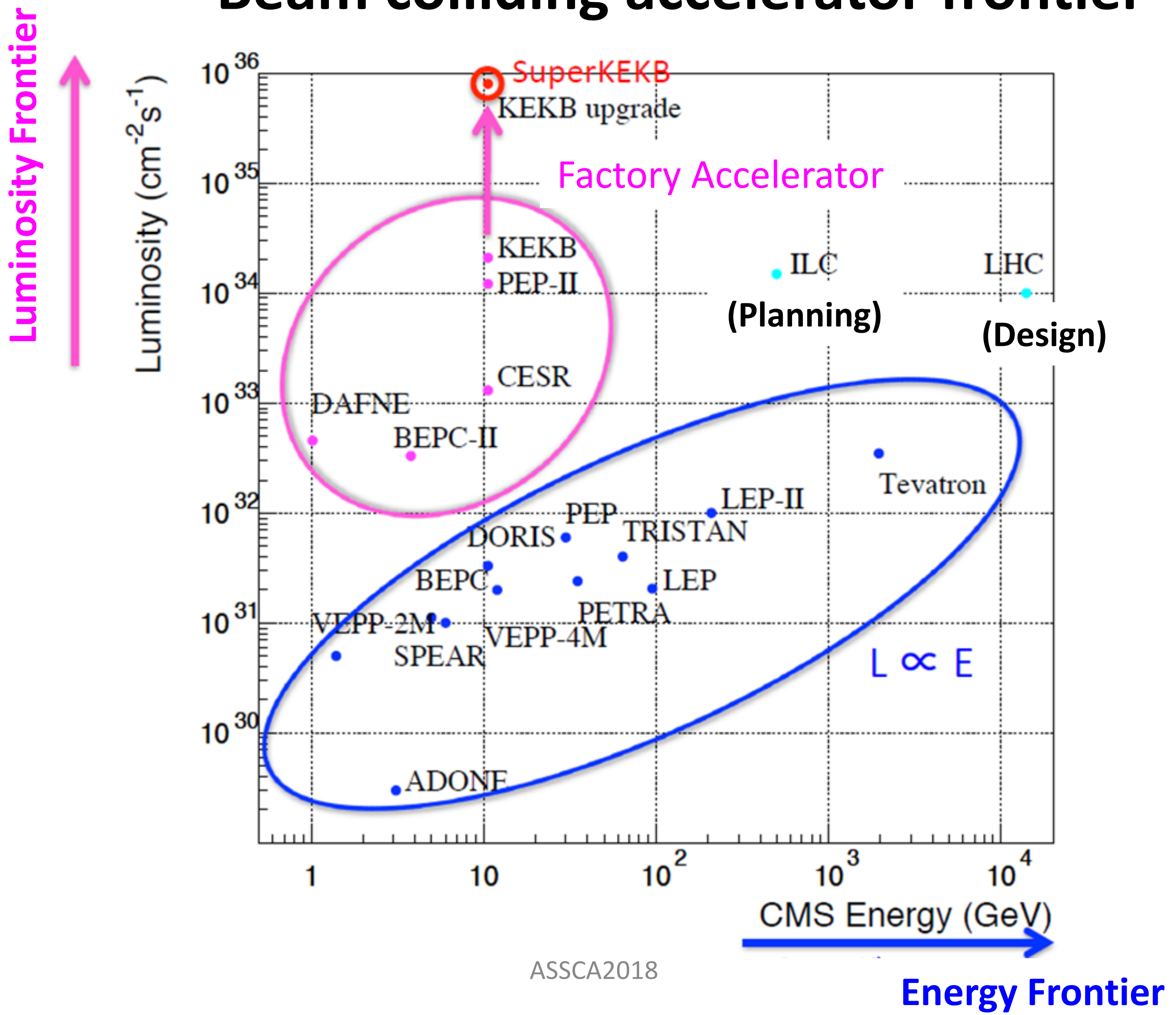
The Nobel Prize in Physics 2008
Yoichiro Nambu, Makoto Kobayashi, Toshihide Maskawa

- **Accumulation of experimental data indicating NP**
  - **Understanding the data by upgrading KEKB to 40 times higher accelerator performance**



SuperKEKB

Beam colliding accelerator frontier



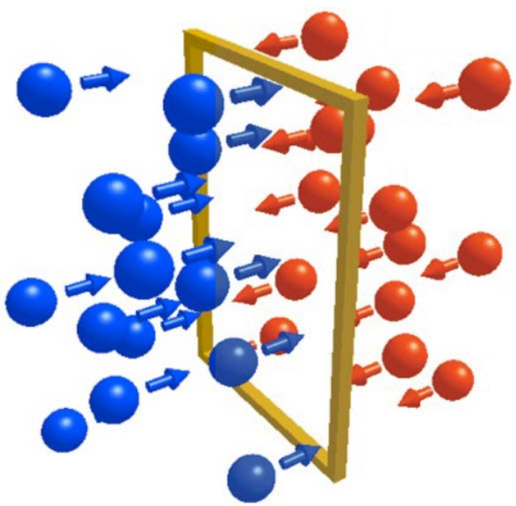
SuperKEKB

（Luminosity）＝Unit Time × Colliding Frequency of Particles in Unit Area

The performance of the colliding accelerator is measured by Luminosity.
（Reaction frequency in unit time）＝（Reaction Cross-section）×（Luminosity）

Fixed by Physical Law
(Function of colliding energy)

Increased by human effort



$$\mathcal{L} = \frac{N_1 N_2 f}{A}$$

High number of particles are intersected many times in a small area: **High luminosity**

SuperKEKB

Target of SuperKEKB: L = 8 × 10^{35} cm^{-2} s^{-1}

$$L = \frac{1}{4\pi k f}\left(\frac{I_+ I_-}{e^2}\right)\frac{1}{\sigma_x \sigma_y}$$

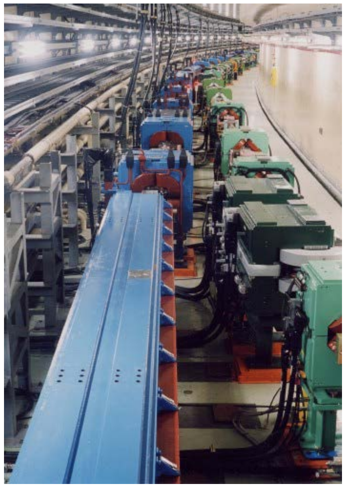
k: bunch number in a beam, f: circulating frequency of beam in the ring,
I_+: positron current value, I_-: electron current value,
σ_x: horizontal beam size at IP, σ_y: vertical beam size at IP

1. **Extremely small beam size ($^1/_{20}$) at colliding point: [L × 20]**
   - KEKB $\sigma_y = 1$ μm (attained value) → SuperKEKB $\sigma_y = 48$ nm(e^+), 62 nm(e^-)
2. **Beam current : [L × 2]**
   - KEKB $e^+ = 1.8$ A, $e^- = 1.3$ A → SuperKEKB $e^+ = 3.6$ A, $e^- = 2.6$ A

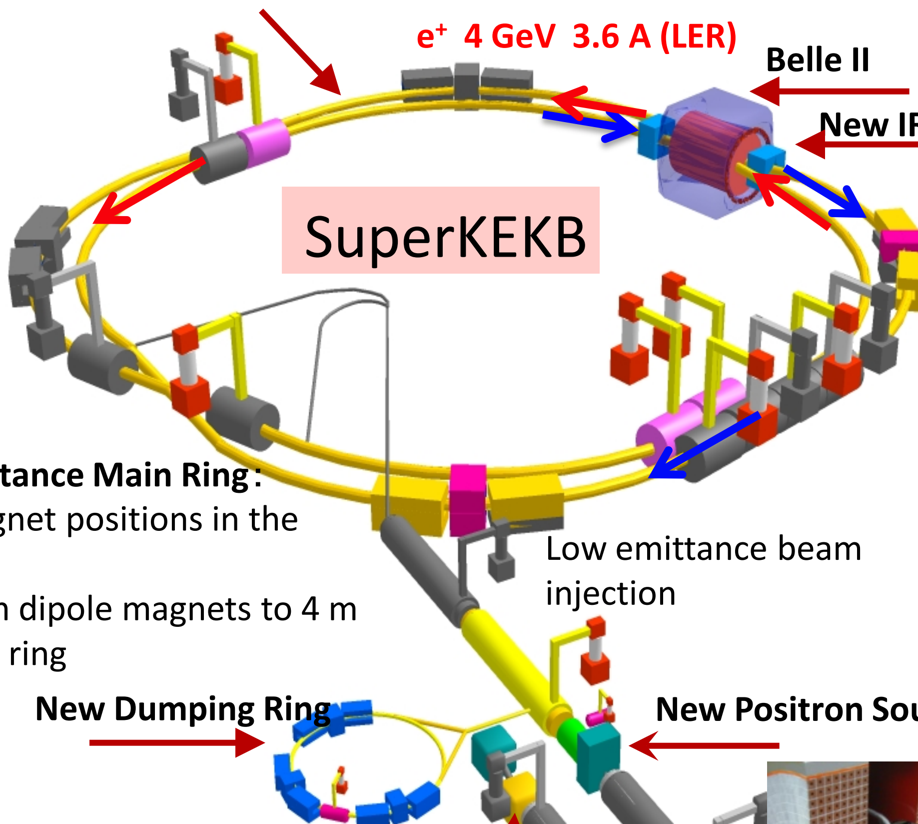
(× 40 times with1. and 2.)＋Belle II detector upgrade

⇨ **Experimental efficiency : 50 times higher**

SuperKEKB



New Beam Pipe and Vacuum Bellows



QCS System:

New Beam Final Focus System (increasing *L* by 20 times than KEKB)

Realization of Low Emittance Main Ring:

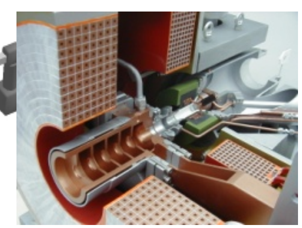
- Optimization of magnet positions in the main rings
- Changing the 0.76 m dipole magnets to 4 m magnets in positron ring

Low emittance beam injection

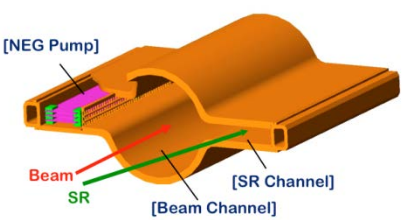
Enhancement of RF system

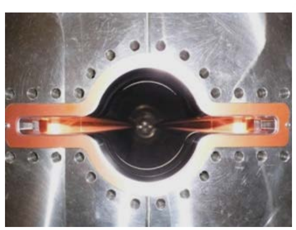
New Dumping Ring

New Positron Source



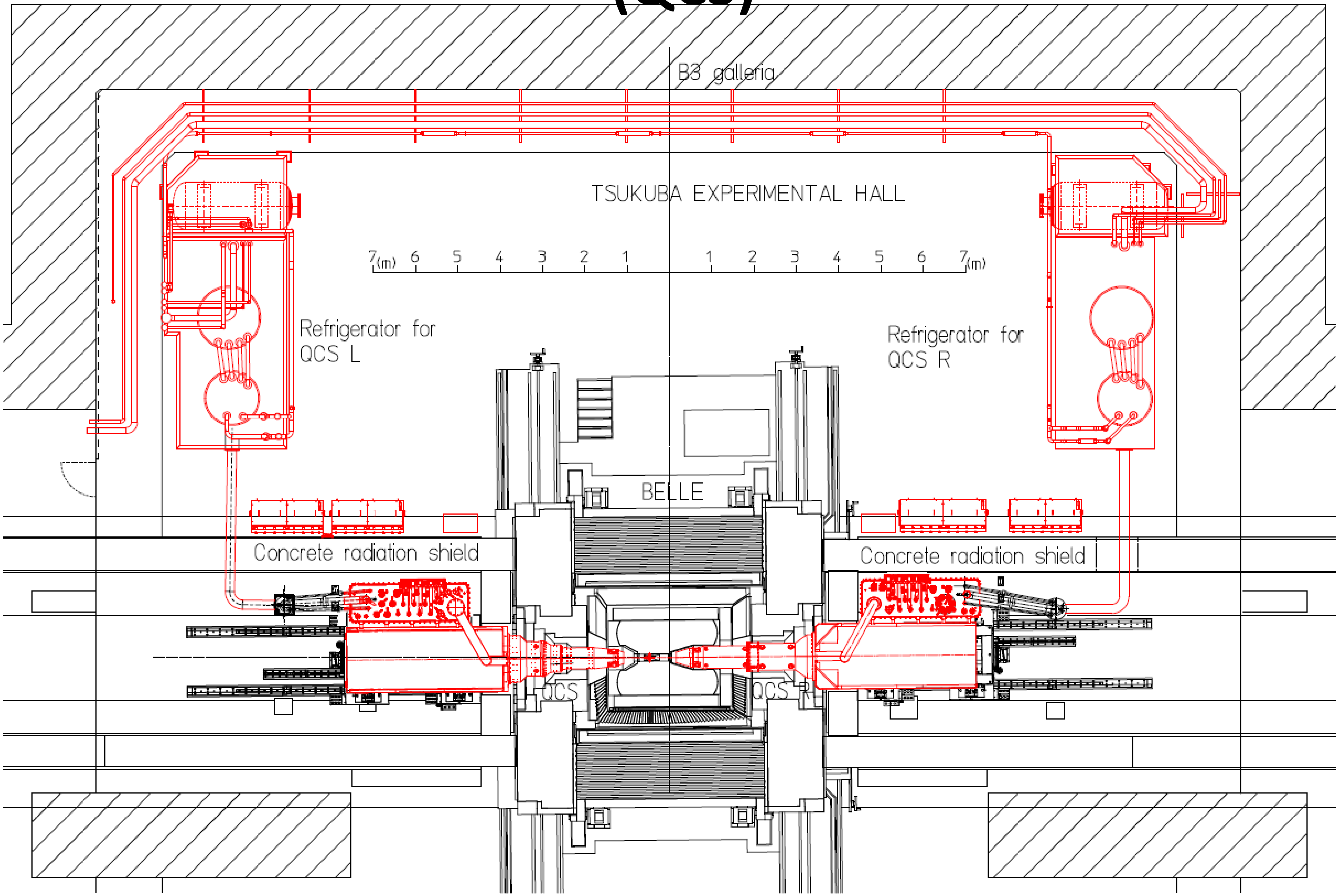
Beam pipe coated by TiN [with side room]



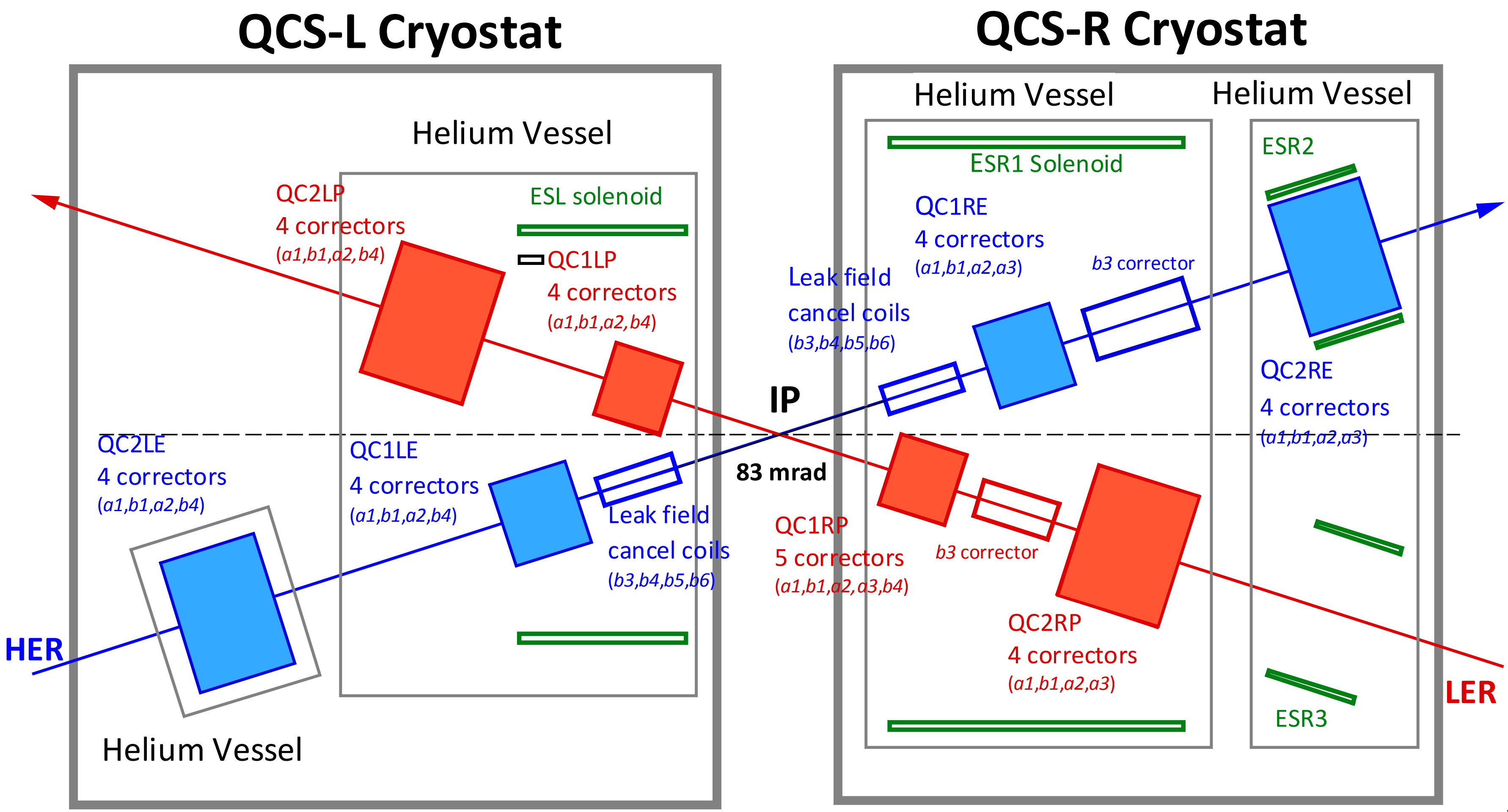


Low emittance electron source

Beam Final Focus SC Magnet System (QCS)



Final Focus SC Magnet System (QCS)



SC quadrupole magnet(4): 1= without YOKE, 3=with YOKE
SC corrector magnet(16): B1/A1, A2, B4
QC1LP leak field cancel SC magnet (4): B3, B4, B5, B6
SC compensation solenoid (1)

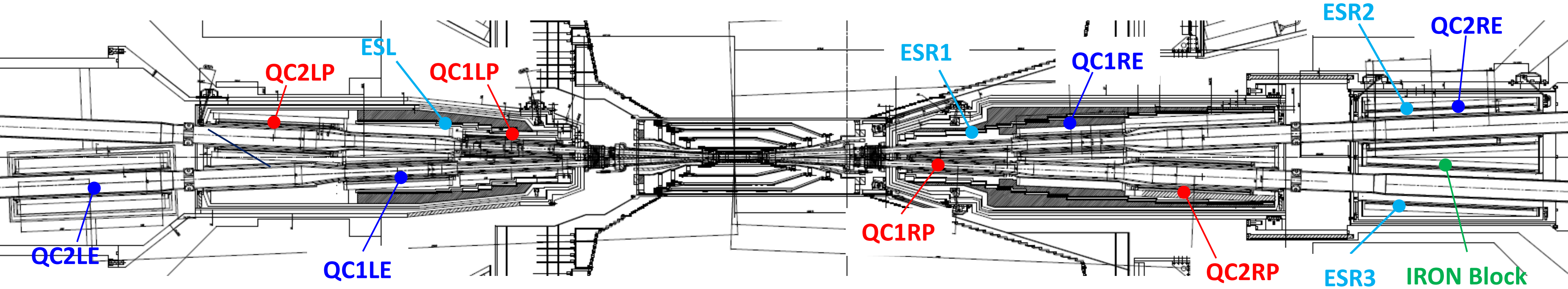
SC quadrupole magnet(4): 1= without YOKE, 3=with YOKE
SC corrector magnet(19): B1/A1, A2, B3/A3, B4
QC1RP leak field cancel SC magnet (4): B3, B4, B5, B6
SC compensation solenoid (3)

Final Focus SC Magnet System (QCS)

- **Superconducting Quadrupole Magnets [QC1, QC2] : 8 magnets**
  - With the quadrupole doublets, the incoming beams to IP are focused, and the outgoing beams from IP are defocused and returned to the Main Rings.
  - QC1 magnets closest to IP focus the incoming beam in vertical direction, and QC2 magnets focus the beams in horizontal direction. After through IP, QC1/2 defocus the beams in the same way.
- **Corrector Magnets [a_1, b_1, a_2, a_3, b_3, b_4] : 35 magnets**
  - a_1, b_1, a_2: correction of the quadrupole field centers and the field angles
    - Skew & normal dipole(a_1, b_1), skew quadrupole (a_2)
  - a_3, b_3: correction of the sextupole field components due the construction errors of quadrupole magnets
    - Skew & normal sextupole(a_3, b_3)
    - Sextupole fields have a strong effect on the beam life time
  - b_4:Improving the beam life time
- **Compensation Solenoids[ESR, ESL] : 4 magnets**
  - The solenoids cancel the Belle-II SC solenoid field of 1.5 T integrally.
    - The electron and positron beams go through in the solenoid field with a crossing angle of 83 mrad, and then the beams are rotated in the passing direction. The processes have a wrong effect in the performance of beam-colliding.
  - The combined solenoid field profile with the Belle-II solenoid and the compensation solenoids has influence on increment of beam emittance. The field profiles by the compensation solenoids are optimized.
- **QC1P Leak Field Cancel Magnets [b_3, b_4 , b_5, b_6] : 4 magnets × 2**
  - QC1P quadrupole magnets does not have the iron yoke because of generating the optimized compensation solenoid field.
  - The b_3, b_4 , b_5 and b_6 leak magnetic fields by QC1P are cancelled by the magnets.

IR SC magnets

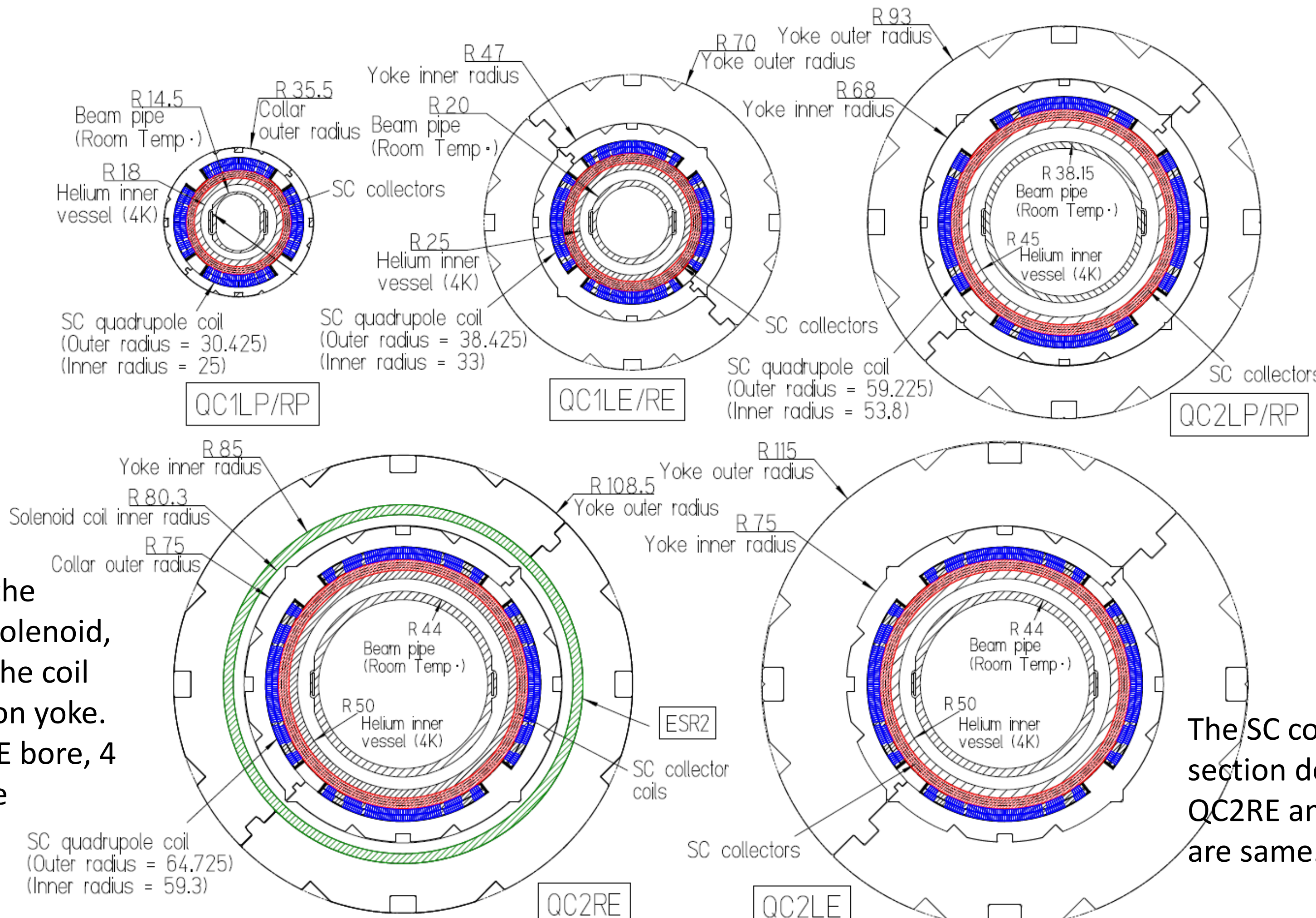
- Main quadrupoles [QC1, QC2]
  - QC1L(R)P, QC2L(R)P for the left (right) side cryostat to IP and for the positron beam line.
  - QC1L(R)E, QC2L(R)E for the left (right) side cryostat to IP and for the electron beam line.



	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 have the different cross section design because of the different beam size.



The QC2RE has the compensation solenoid, ESR2, between the coil collar and the iron yoke. Inside the QC2RE bore, 4 SC correctors are installed.

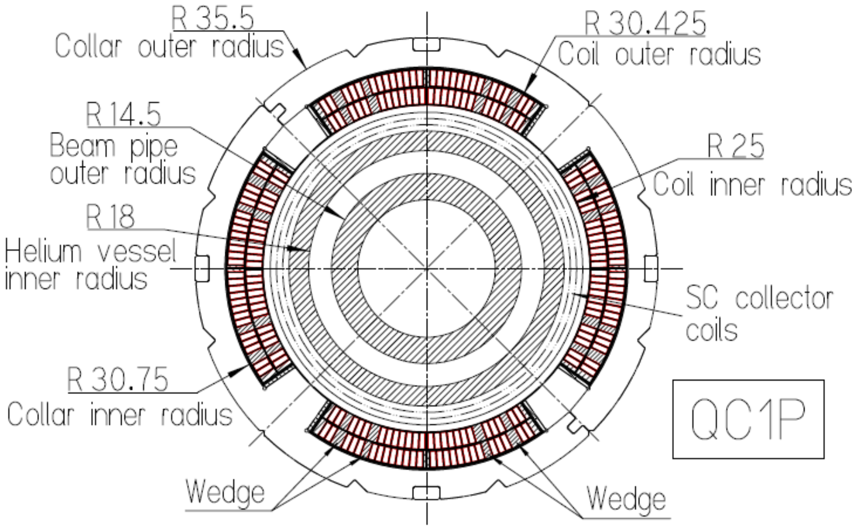
The SC coil cross section designs of QC2RE and QC2LE are same.

IR SC magnets

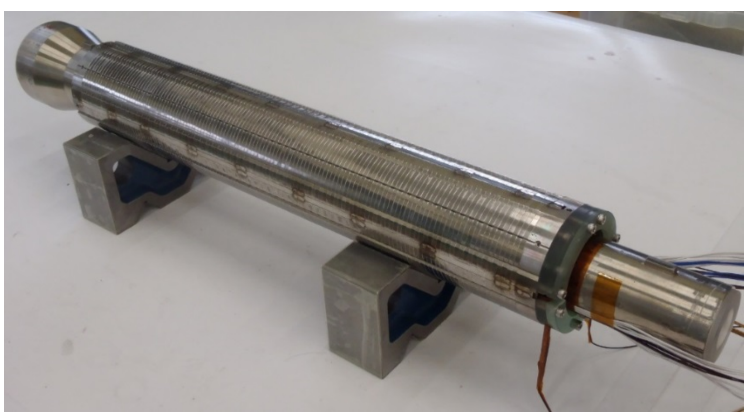
- Parameters of the quadrupole magnets and cables

	QC1P	QC1E	QC2P	QC2LE	QC2RE
G_D, T/m	**76.37**	**91.57**	**31.97**	**36.39**	
I_D, kA	1.8	2.0	1.0	1.25	
B_P, T	4.56	3.50	2.43	2.63	
Load Ratio @4.7 K, %	72.3	73.4	44	39	
SC coil inner radius, mm	**25.0**	**33.0**	**53.8**	**59.3**	
Yoke outer radius, mm	NA	70.0	93.0	115.0	108.5
Yoke material	**NA**	**Permendur**	**Permendur**	**Iron**	**Iron**
Magnet physical length, mm	409.3	455.4	495.5	618.9	560.9
Effective magnetic length, mm	**333.6**	**373.1**	**409.9**	**537.0**	**419.0**
SC cable (NbTi): Rutherford cable					
Strand diameter, mm	0.498	0.498	0.498	0498	
Strand number	10	10	10	10	
Cu/NbTi ratio	1.0	1.0	1.0	1.0	
I_c @ 5 T and 4.22 K, A	3170	3070	3090	3130	
Cable width, mm	**2.50**	**2.50**	**2.50**	**2.51**	
Cable mid-thickness, mm	0.931	0.931	0.931	0.930	
Keystone angle, degree	**2.1**	**1.6**	**1.0**	**0.94**	

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

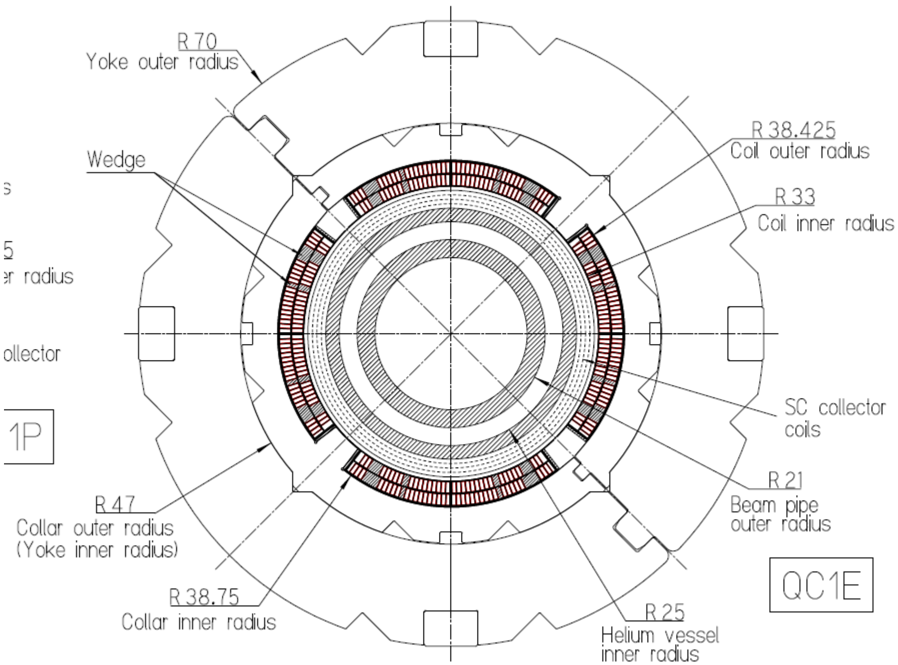
Coil design

- 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**

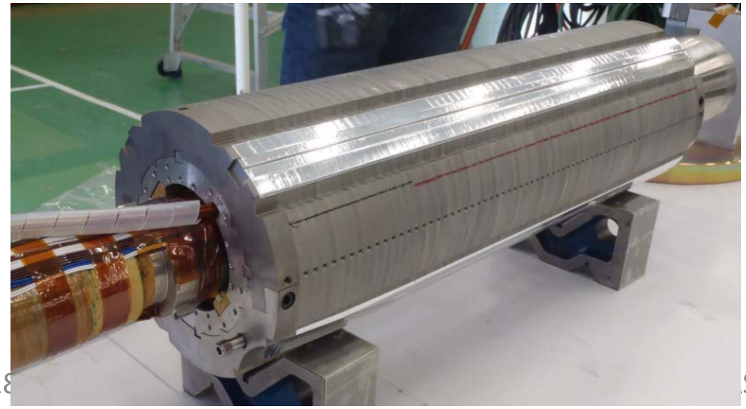
Superconducting cable

- **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

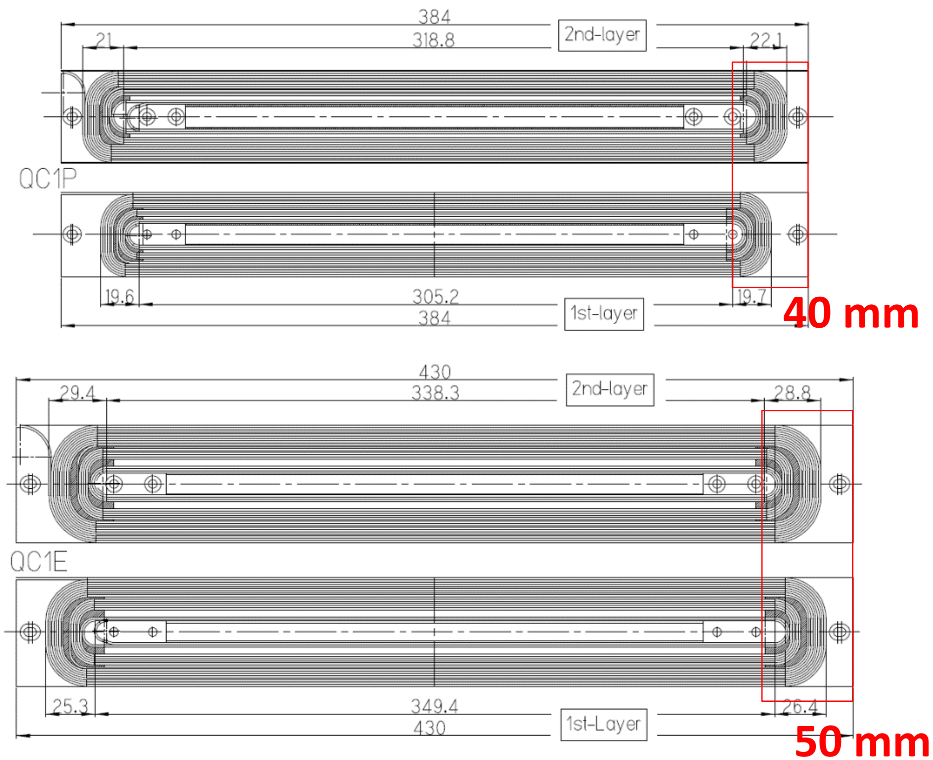
Coil design

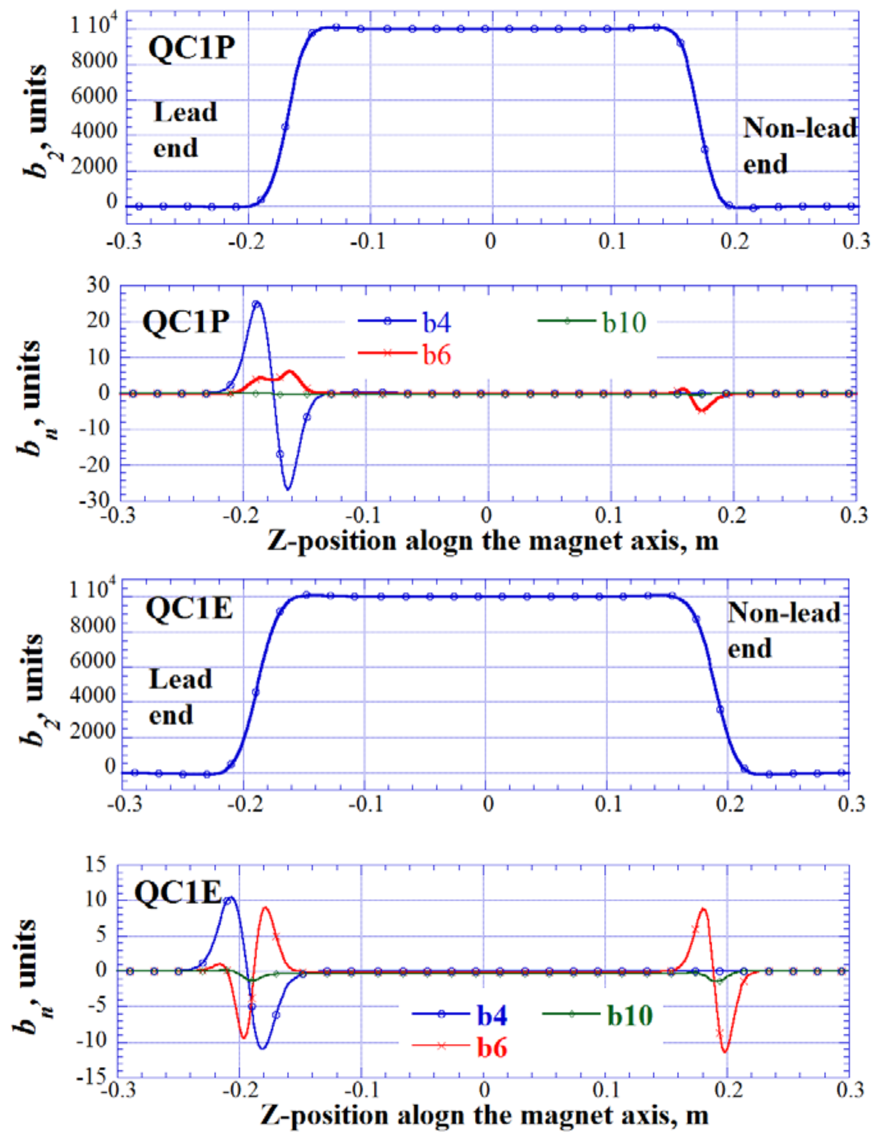
- 2 layer coils (3 coil blocks for each layer)
- Error field in 2 D cross section
  - **b_6 = −0.06 units, b_{10} = −0.34 units, b_{14} = −0.01 units**
- Integral error field in 3D model
  - **b_4 = −0.02 units, b_6 = −0.04 units, b_8 = 0.05 units , b_{10} = −0.43 units**

Superconducting cable

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

3D magnet design of QC1P/1E

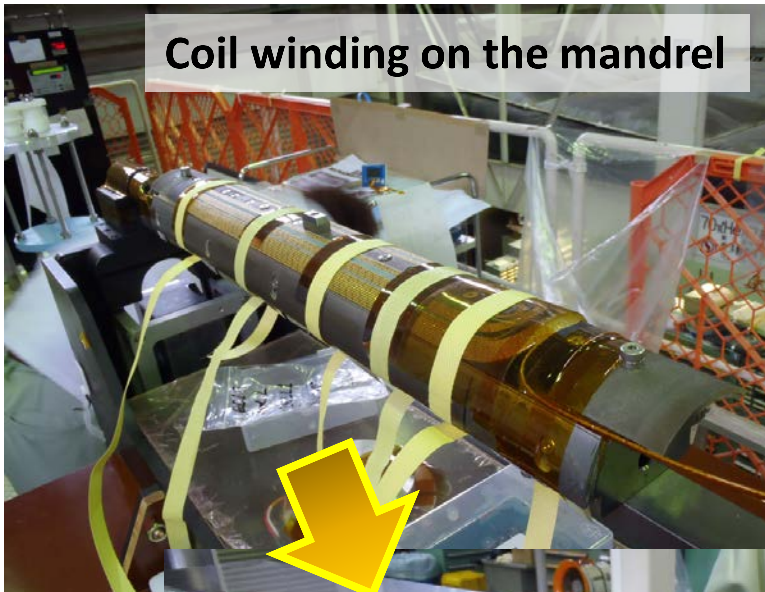




- The coil ends were designed to be as short as possible.
- In order to exclude the skew components in the lead end, the quadrant coils have mirror symmetry to the neighbor coils.

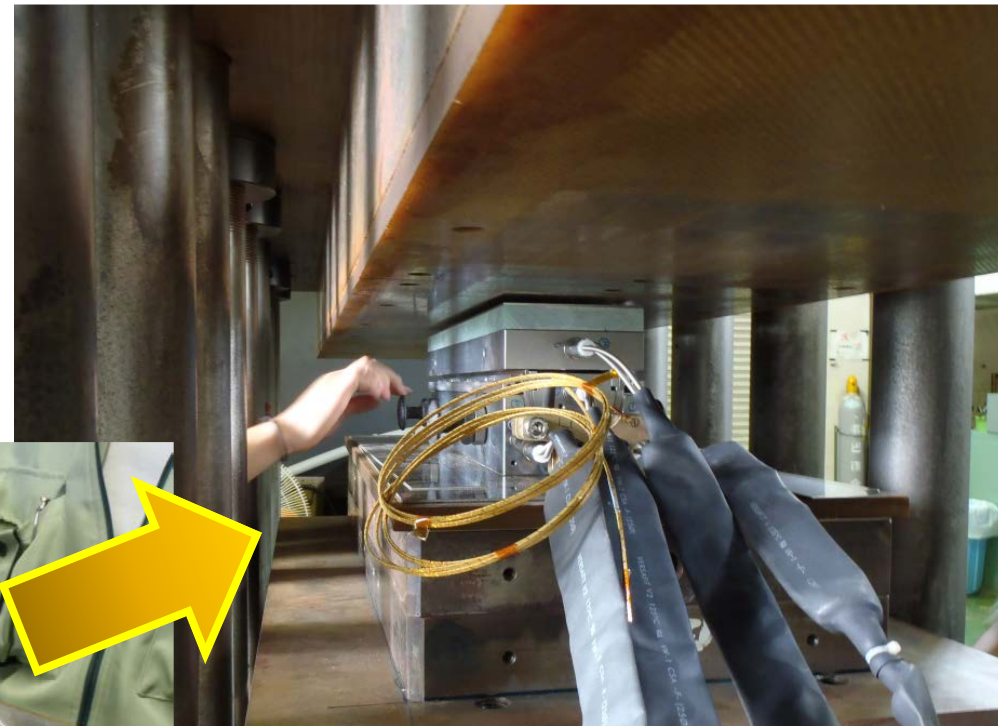
QC1E Magnet Construction

- Production of the QC1E prototype magnet



Coil winding on the mandrel

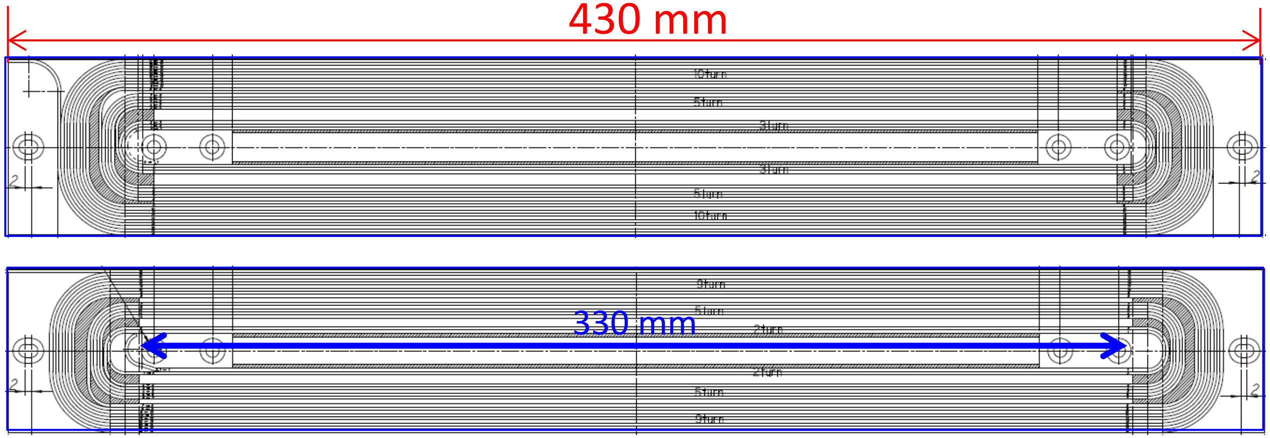
The coil was baked at 130 °C and pressed.



The wound coil was set in the forming block.

QC1E Magnet Construction

- Production of the QC1E prototype magnet



2[nd] layer coil

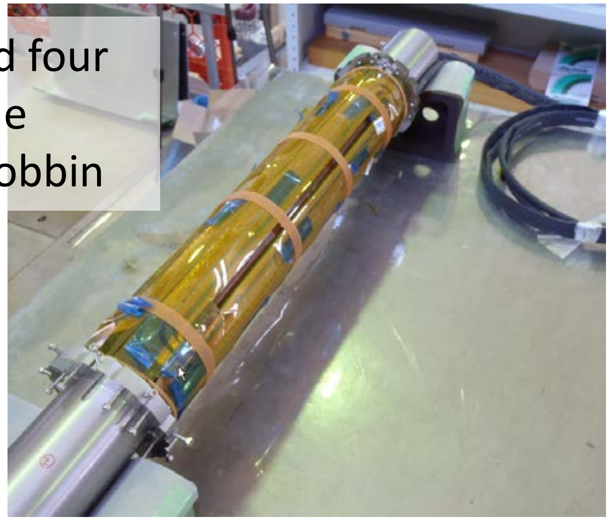
1[st] layer coil

The coil length is 46 mm longer than QC1P. The length of the coil straight section is 330 mm.

QC1E four double layer coils

QC1E Magnet Construction

- Production of the QC1E prototype magnet



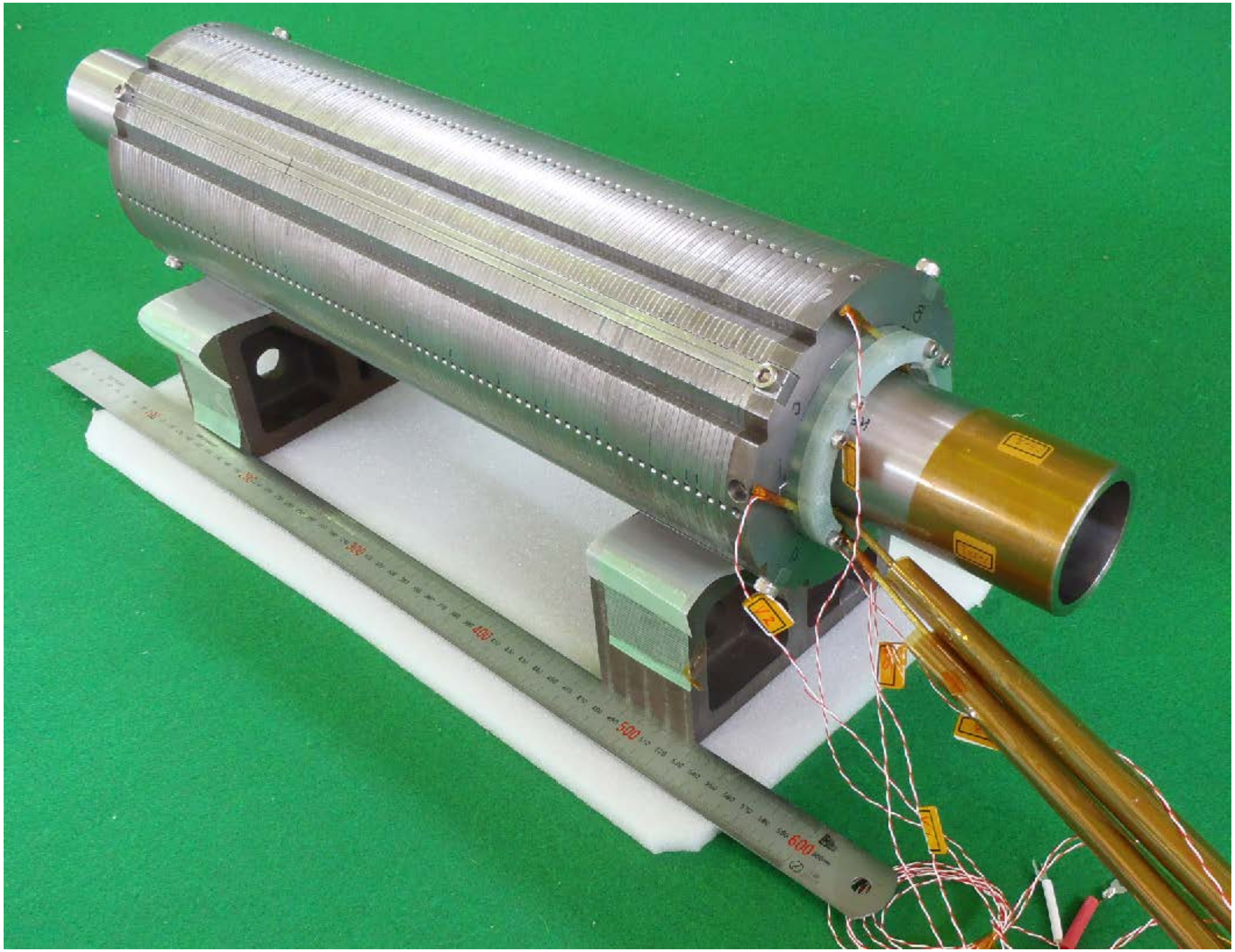
Assembled four coils on the support bobbin

SS316LN collars

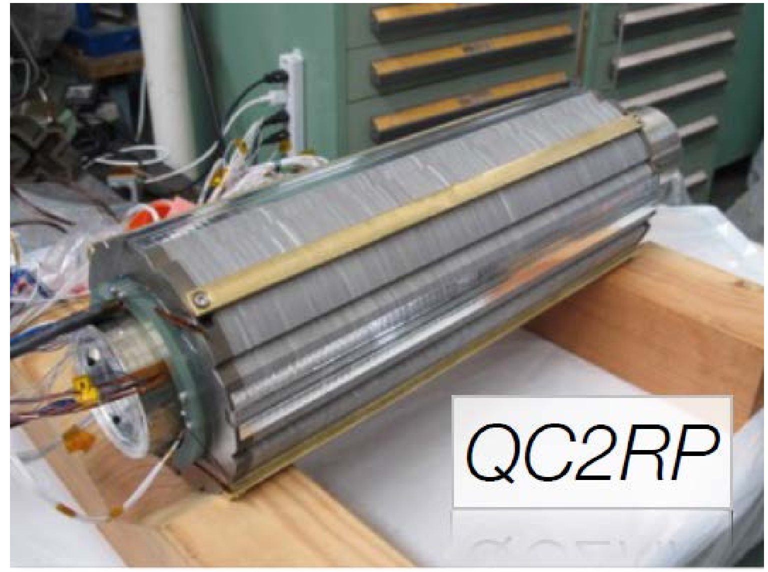
Collaring press
(Yoking process is same as the collaring process)

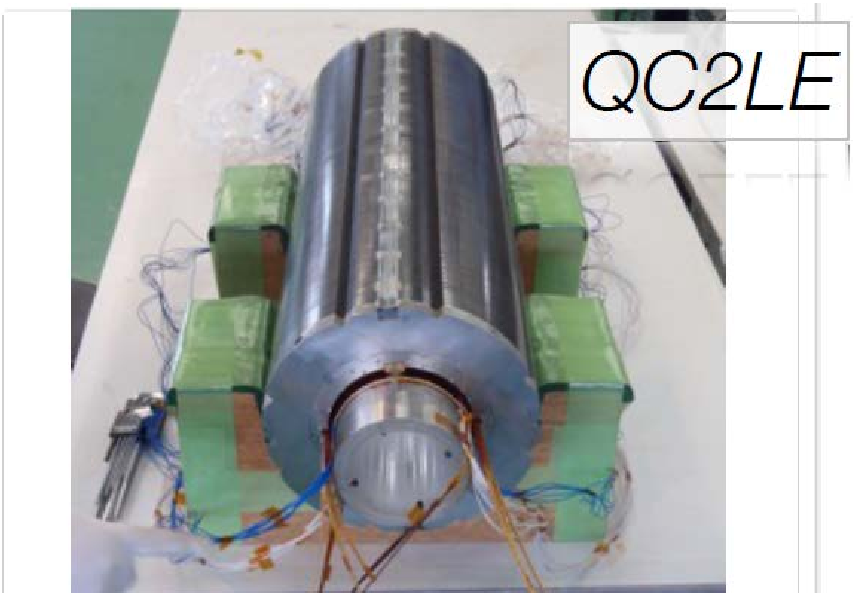
QC1E Magnet Construction

- Production of the QC1E prototype magnet



QC2P/2E Magnets





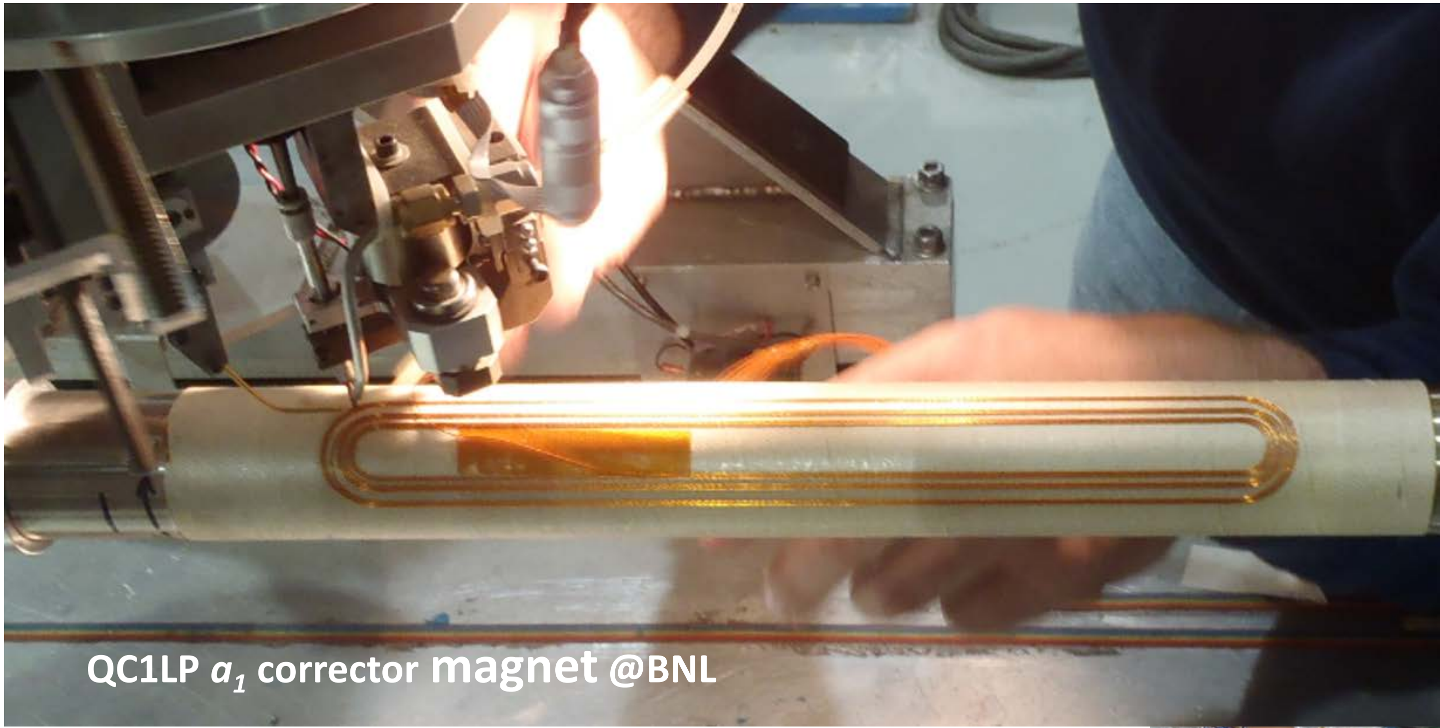
SC Corrector Magnets

- Correctors
  - From space constraint, the SC correctors were designed inside of the quadrupole bores .
  - The SC correctors were designed and directly wound on the support bobbin (helium inner vessel) by BNL.
    - 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 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, 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

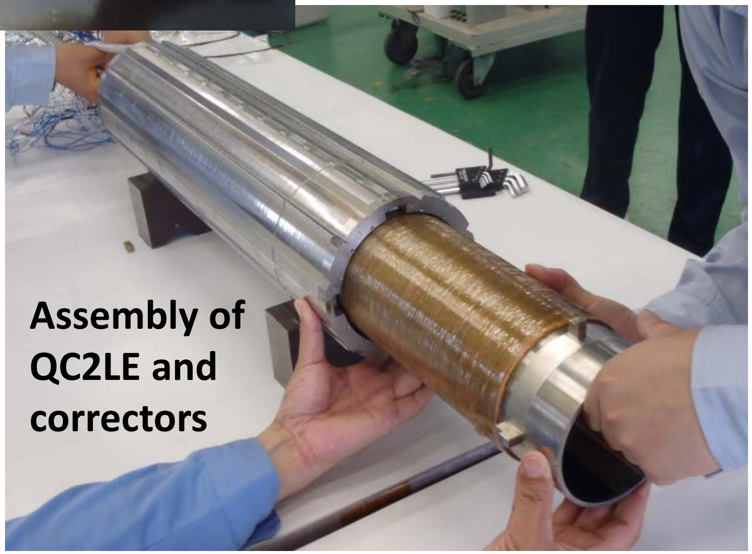
SC Corrector Magnets



QC1LP a_1 corrector magnet @BNL

Direct Winding Method

Parameters of SC wire	
Cable diameter, mm	0.351
Cu/NbTi ratio	1.0
NbTi filament diameter, μm	5.4
Number of NbTi filaments in a strand	2113
I_c at 4.2 K and 4 T/5T, A	156/132



Assembly of QC2LE and correctors

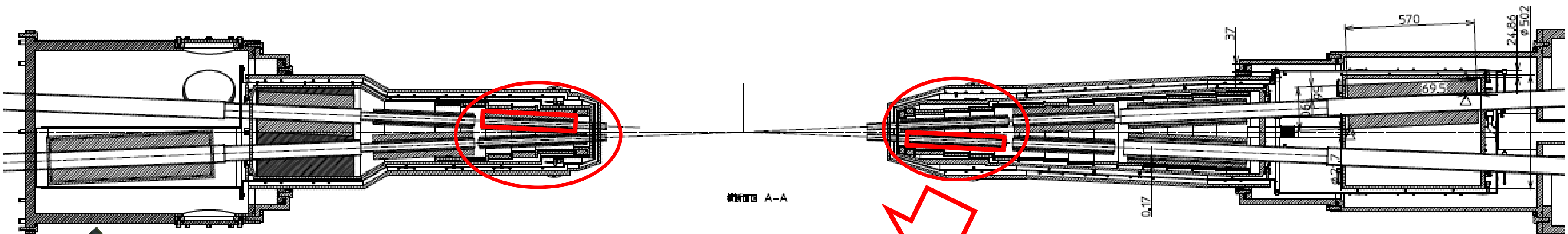
SC Corrector Magnets

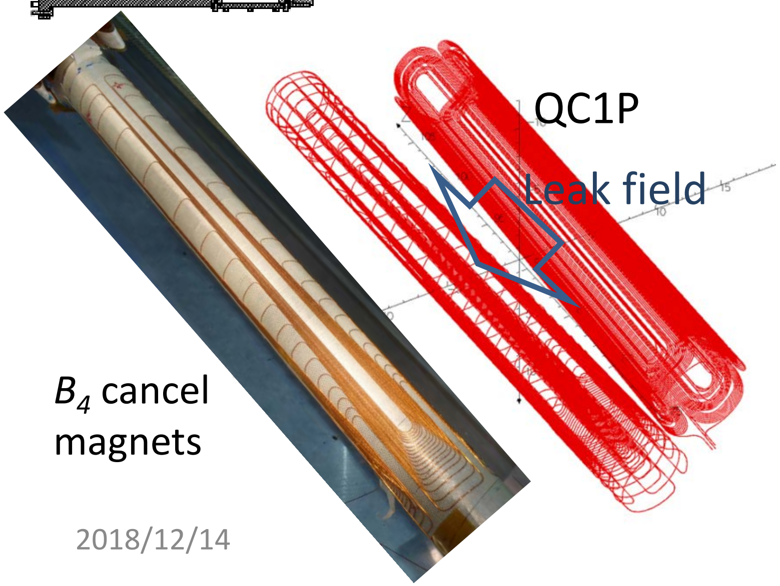
- SC corrector magnets field strength (specification)

Quadrupole Magnet	a_1, Tm	b_1, Tm	a_2, T	a_3, T/m	b_3, T/m	b_4, T/m^2
QC2RE	0.015	0.015	0.37	1.1	NA	NA
QC2RP	0.03	0.03	0.31	0.9	NA	NA
QC1-2RE	NA	NA	NA	NA	18.2	NA
QC1-2RP	NA	NA	NA	NA	11.5	NA
QC1RE	0.027	0.046	0.75	4.6	NA	NA
QC1RP	0.016	0.016	0.64	NA	5.1	60
QC1LP	0.016	0.016	0.64	NA	NA	60
QC1LE	0.027	0.046	0.75	NA	NA	60
QC2LP	0.03	0.03	0.31	NA	NA	60
QC2LE	0.015	0.015	0.37	NA	NA	60

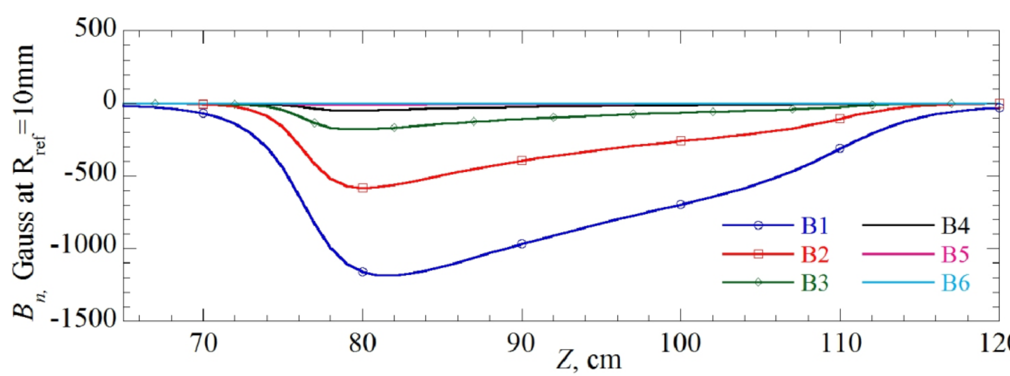
SC Corrector Magnets

- 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

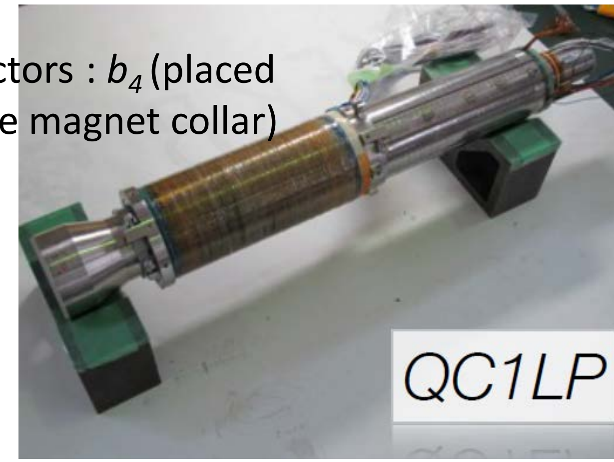


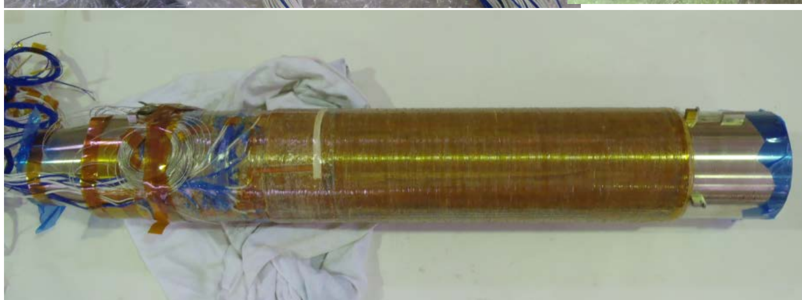
SC Corrector Magnets

Corrector magnets in the left side:

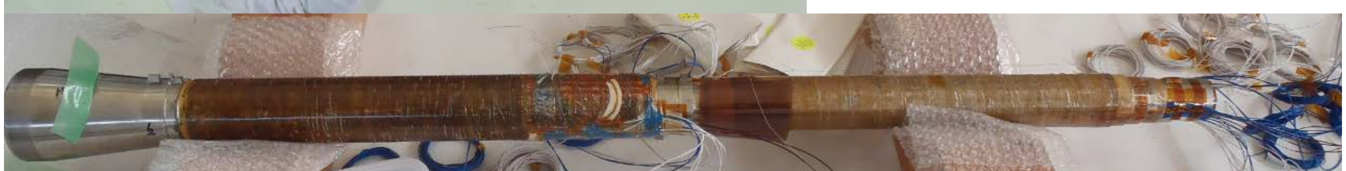
QC1LP correctors : a_1, b_1, a_2 (placed inside of the quadrupole magnet bore)

QC1LP correctors : b_4 (placed outside of the magnet collar)



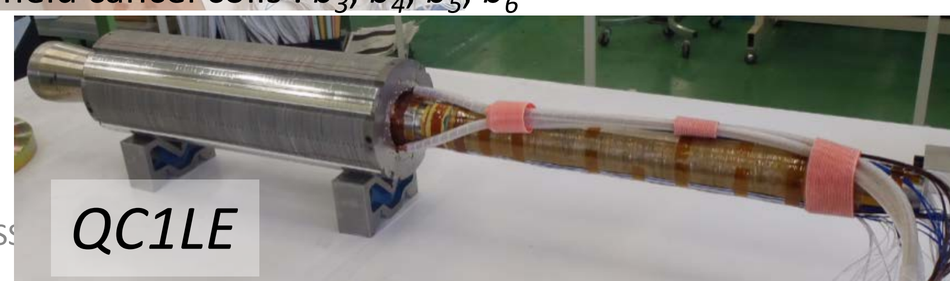


QC2LP correctors : a_1, b_1, a_2, b_4



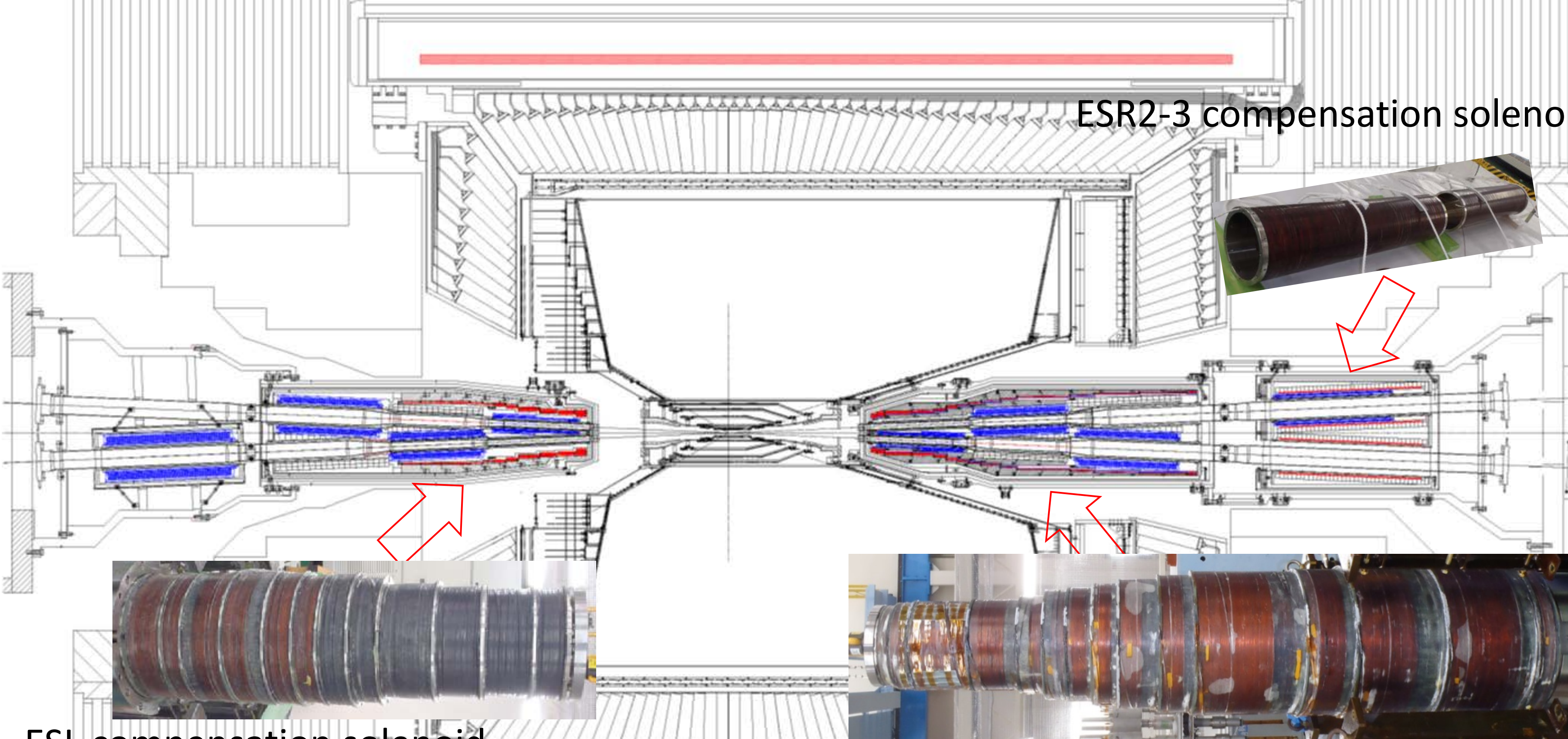
QC1LE correctors : a_1, b_1, a_2, b_4

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



IR SC magnets

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



ESR2-3 compensation solenoid

ESL compensation solenoid

Magnet length= 914 mm
Maximum field at 390 A= 3.41 T
Stored Energy= 190 kJ

ESR1 compensation solenoid

Magnet length= 1575 mm
Maximum field at 450 A=3.19 T
Stored Energy= 810 kJ
Cold diode quench protection system

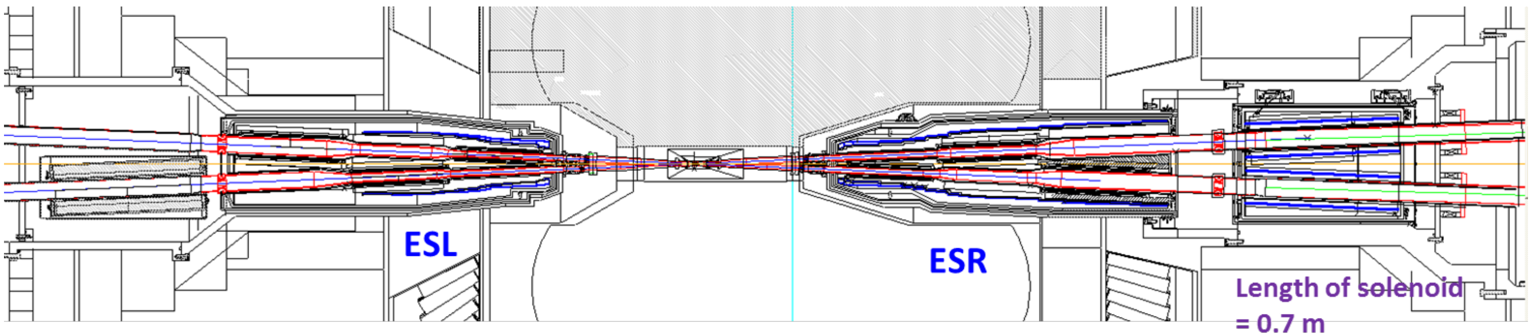
IR SC magnets

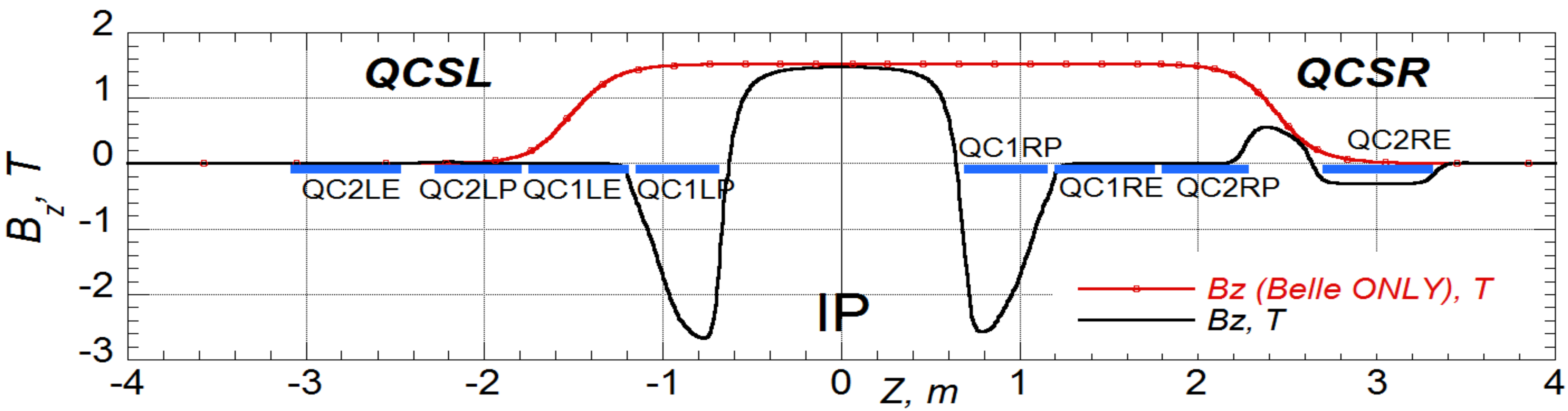
- Parameters of the compensation solenoids and cables

	ESL	ESR1	ESR2/3
Integral solenoid field, Tm	2.31	3.69	0.17
I_D, A	390	450	151
B_P, T	3.41	3.19	0.48
Number of element solenoids	12	15	1
Total turn number	4610.1	6237.1	1356
Inductance, H	2.5	8.0	0.14
Load Ratio @4.7 K, %	52	51	11
Magnet physical length, mm	905	1575	720
SC cable	NbTi		
Cable size, mm	0.932 × 1.384		
Cu/NbTi ratio	1.7		
I_c @ 4 T and 4.22 K, A	1814		

IR SC magnets

- Required solenoid field profile



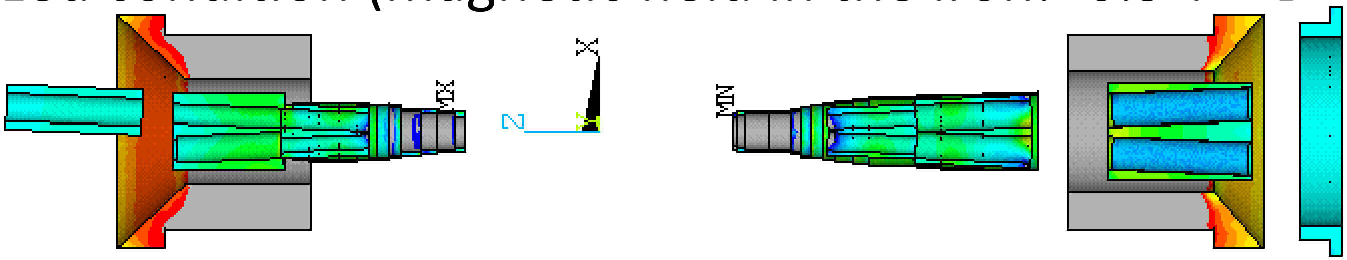


- In the left cryostat, one solenoid (12 small solenoids) is overlaid on QC1LP and QC1LE.
- In the right cryostat, the 1st solenoid (15 small solenoids) is overlaid on QC1RP, QC1RE and QC2RP.
  - The 2nd and 3rd solenoids on the each beam line in the QC2RE vessel.

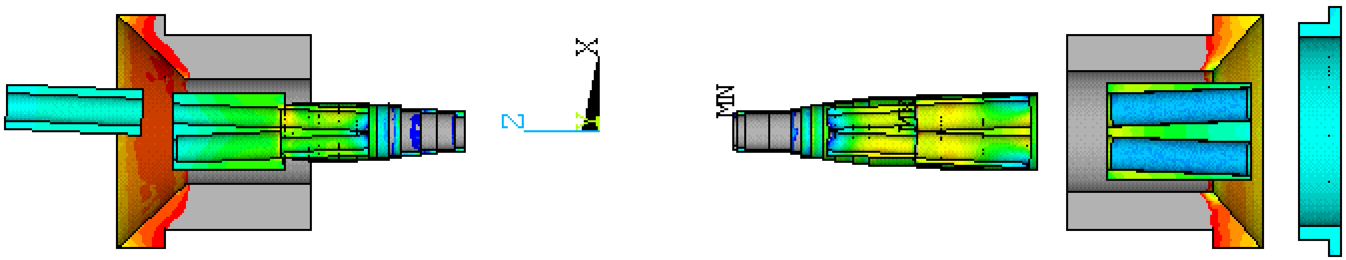
IR SC magnets

Field profile in the iron components (3D ANSYS)

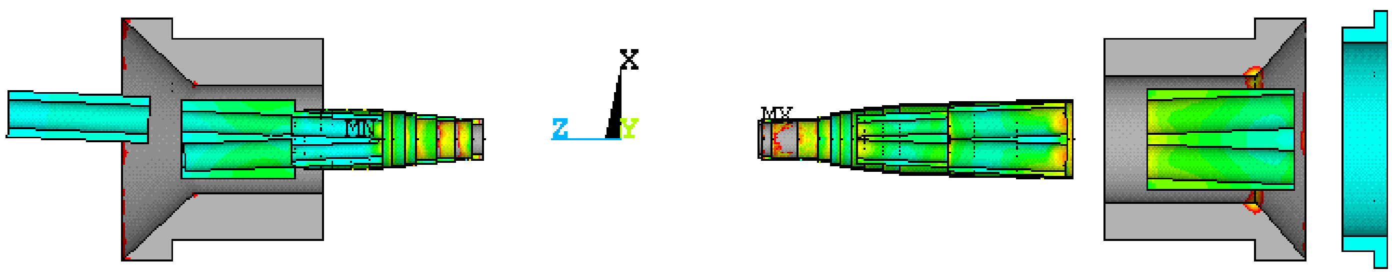
Optimized condition (magnetic field in the iron: -0.5 T < B < 0.5 T)

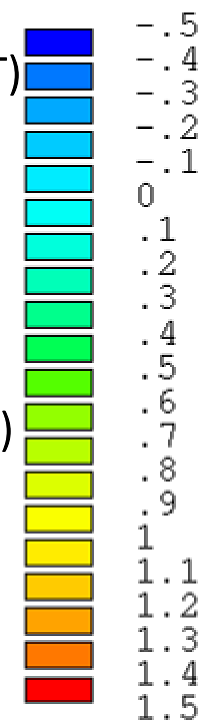


Increasing Belle solenoid current by 1 % (magnetic field in the iron: -0.5 T < B < 1 T)



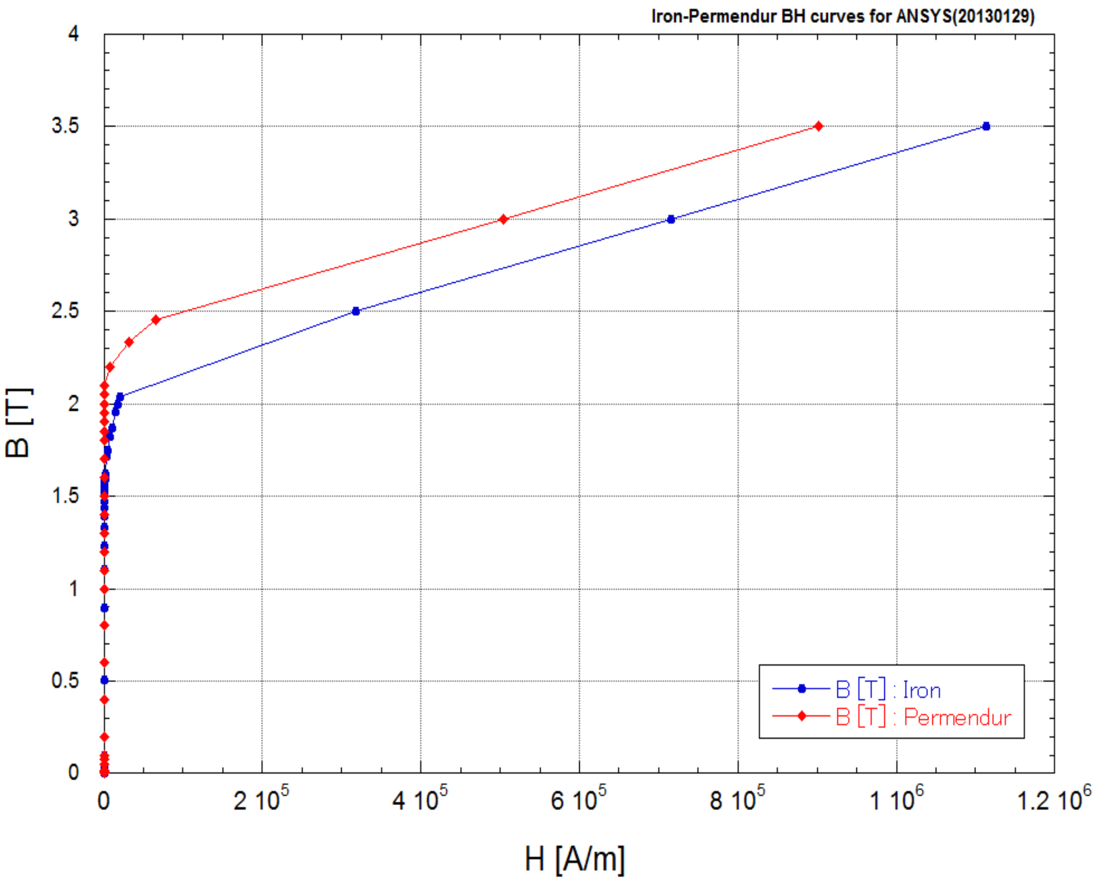
Increasing acc. solenoid current by 1 % (magnetic field in the iron: -0.1 T < B < 1 T)





IR SC magnets

B-H curves of Iron and Permendur



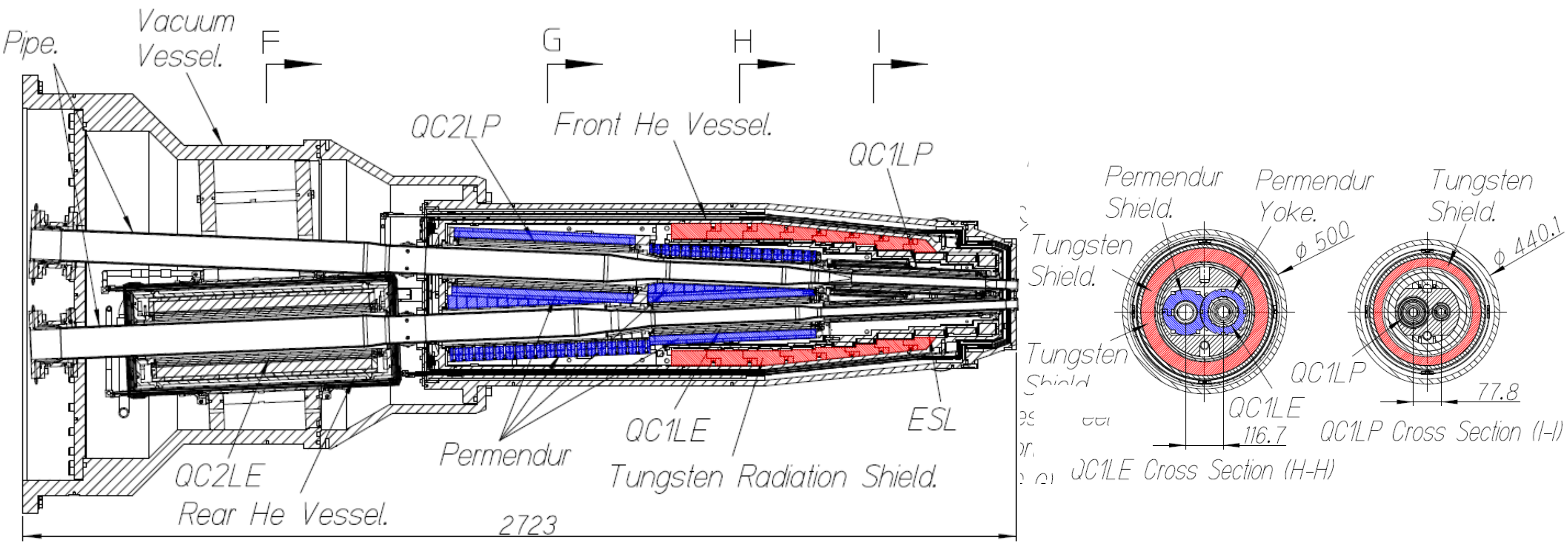
Permendur:

Fe=49.2%, Co=49 %, V=1.8%

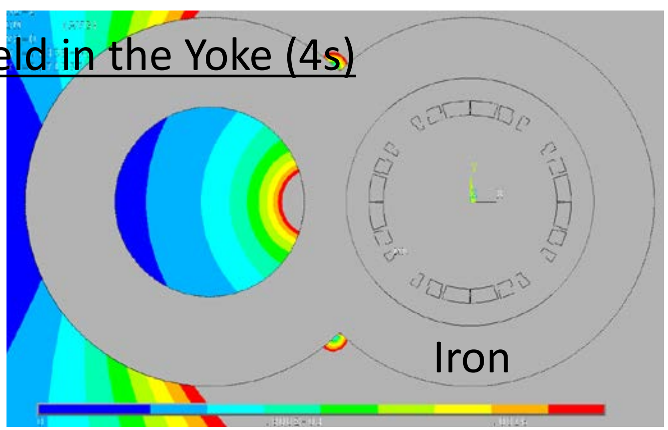
ρ= 8.3 g/cm^3

Bs > 2.35 T

IR SC magnets

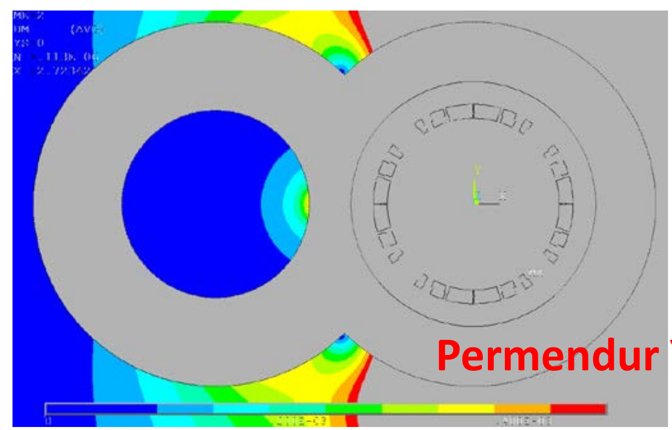


With 0.5 T field in the Yoke (4s)



0 Gauss 10 Gauss

Leak field at e+ center = 6 Gauss

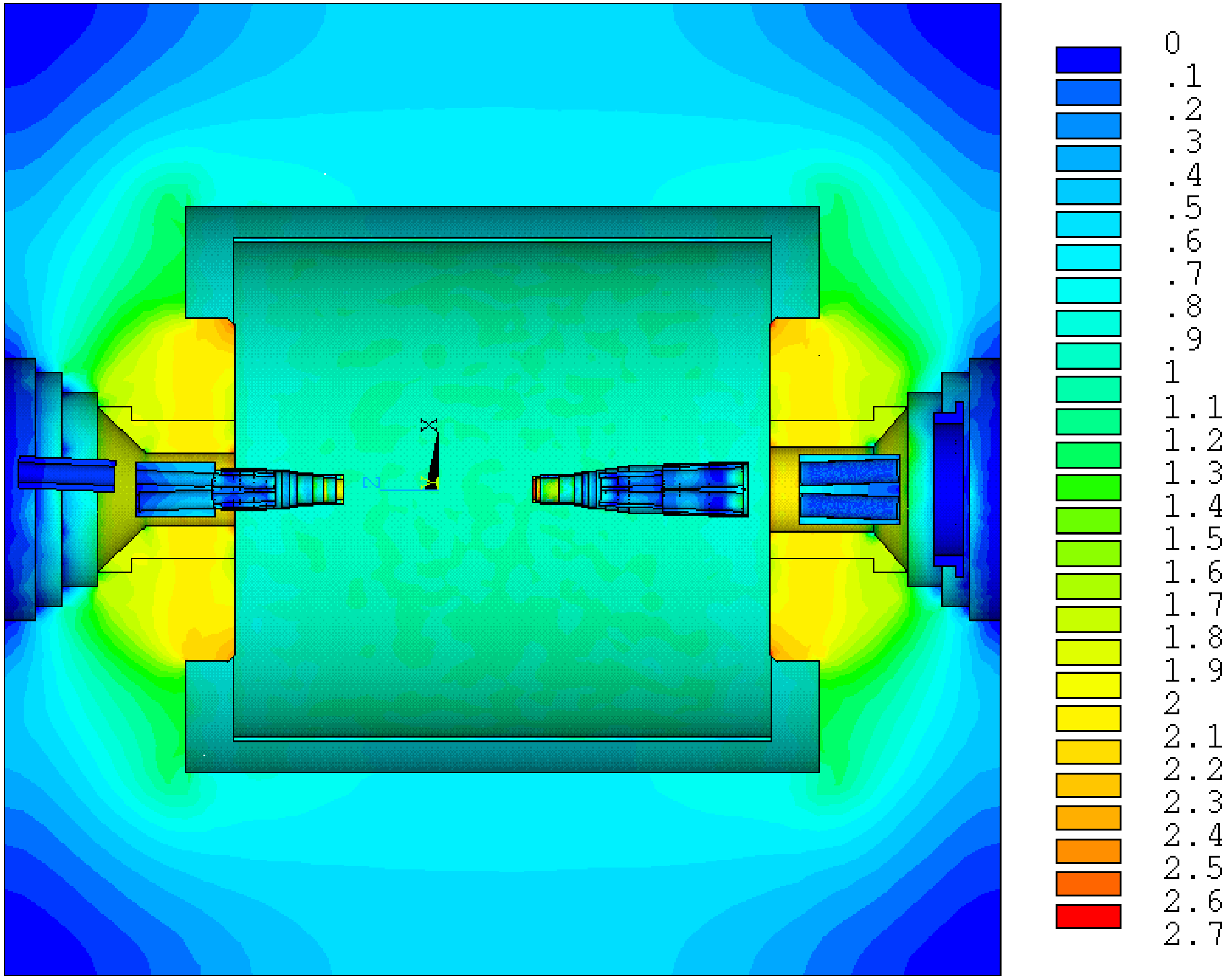


0 Gauss 5 Gauss

Leak field at e+ center <1 Gauss

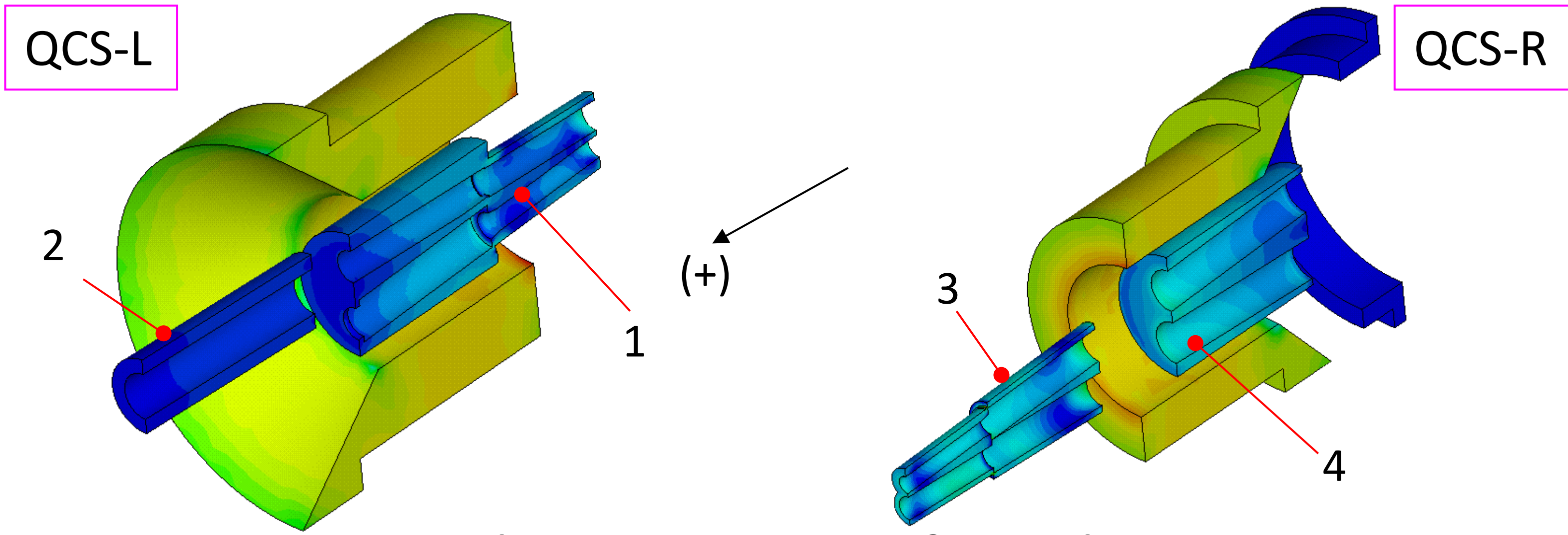
IR SC magnets

- Magnet cryostat mechanical design
  - Magnetic field profile in Belle-II



IR SC magnets

- Electro-magnetic forces on the iron components and solenoids



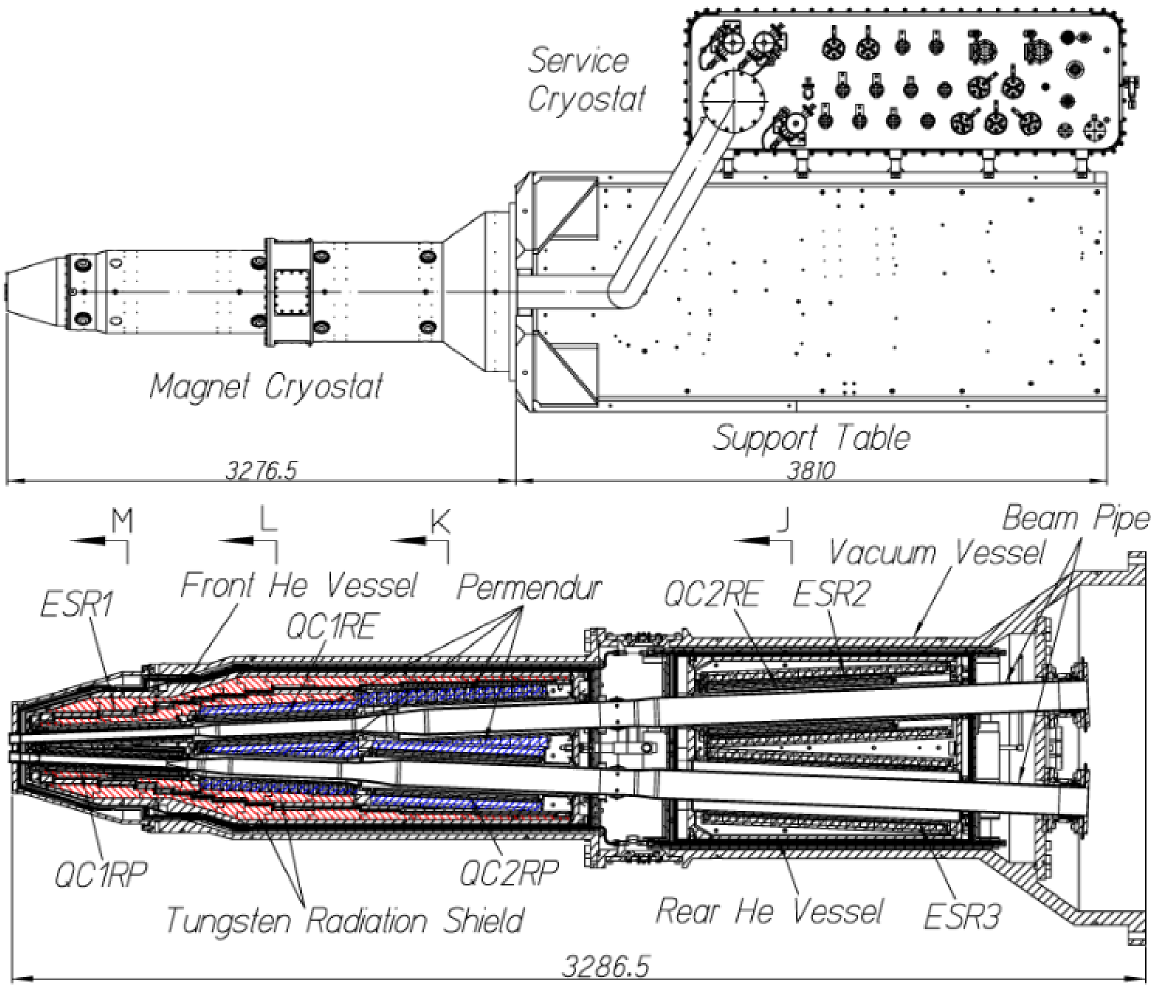
Electro-magnetic force, kN

	QCSL			QCSR		
	1	Solenoid	2	3	Solenoid	4
Acc. Solenoid ON	-0.81	**48.3**	-0.05	-1.89	**-39.7**	8.4
Acc. Solenoid OFF	-60.9	0	-0.15	6.01	0	15.3

The largest EMF for the one He vessel

Assembly of Magnet Cryostat

- Design of the magnet cryostat (QCS-R)



Cryostat design parameters

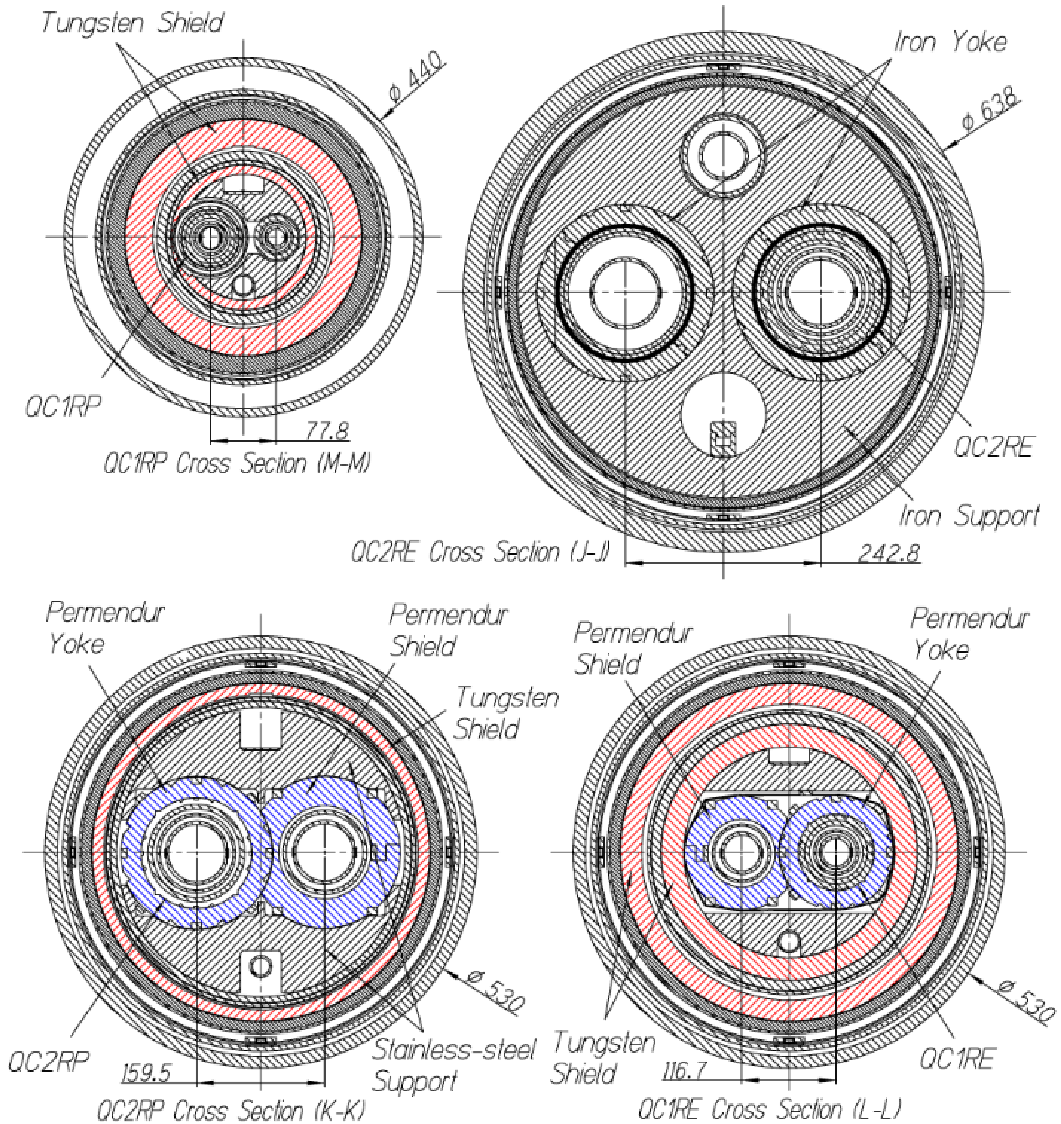
	QCS-L	QCS-R
Magnet Cryostat		
Vac. vessel length (mm)	2724	3287
Vac. vessel max. diameter (mm)	ϕ1100	ϕ638
Vac. vessel mass (kg)	1570	1472
4 K Cold Mass		
Front magnets and others (kg)	949	805
Tungsten radiation shield (kg)	231	1271
Rear magnets and others (kg)	342	1063
80 K thermal radiation shield (kg)	45	36
Service Cryostat		
Vac. vessel length (mm)	2757	2757
Vac. vessel height (mm)	917	917
Vac. vessel wide (mm)	900	863
Vac. vessel mass (kg)	2523	2501
80 K thermal rad. shield, kg	79	77
He gas-cooled current leads		
Conventional leads	10 pairs+1	10 pairs
Compact 8 terminal leads	5 units	7 units
Control valves	2	2
Support Table		
Length, mm	3810	3810
Mass, kg	6279	6061
Total Cryo. System Length (mm)	6533	7087
Total Cryo. System Mass (kg)	12550	15000

Assembly of Magnet Cryostat

- Design of the magnet cryostat (QCS-R)

QC1RP

QC2RE

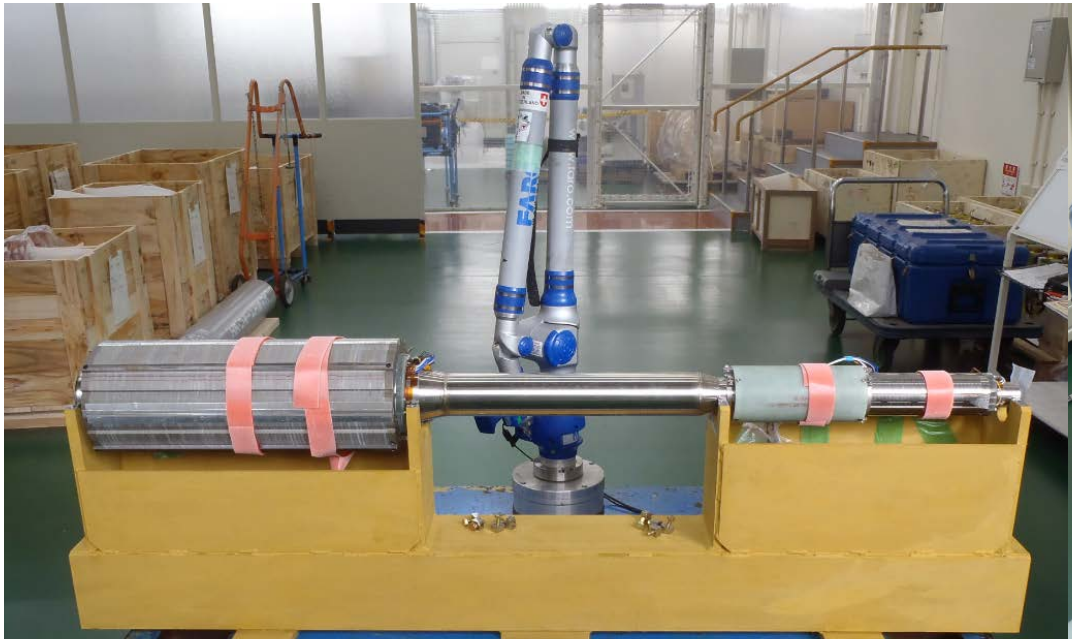


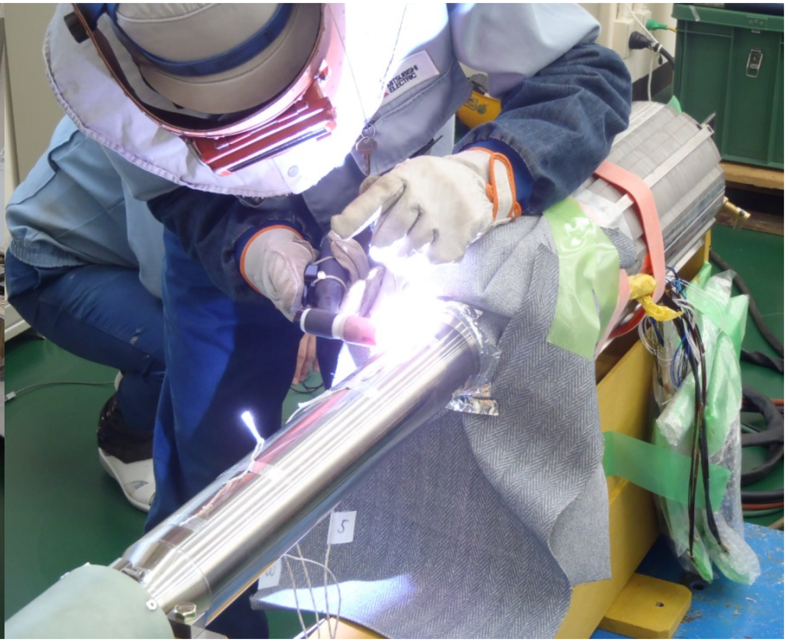
QC2RP

QC1RE

Assembly of Magnet Cryostat

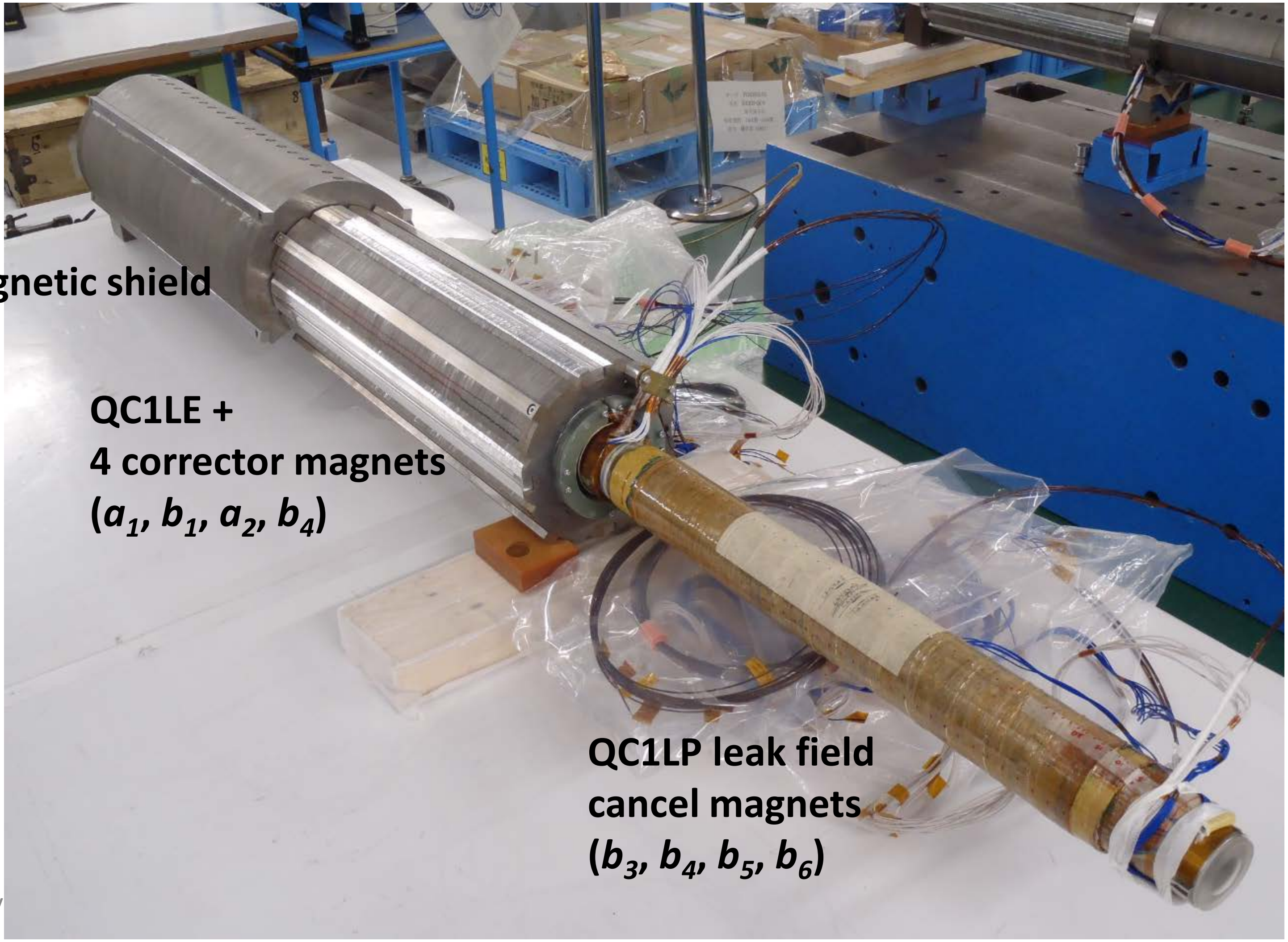
- Alignment of the magnets and components with the special jig
  - The magnets and the pipes are aligned with the special jig.
    - The shape of the jig was measured with the FARO 3D surveying instrument.
    - The magnets were assembled on the jig, and the position of the magnets were measured before and after welding the support bobbins and pipe.
    - The alignment errors were within 20 μm.





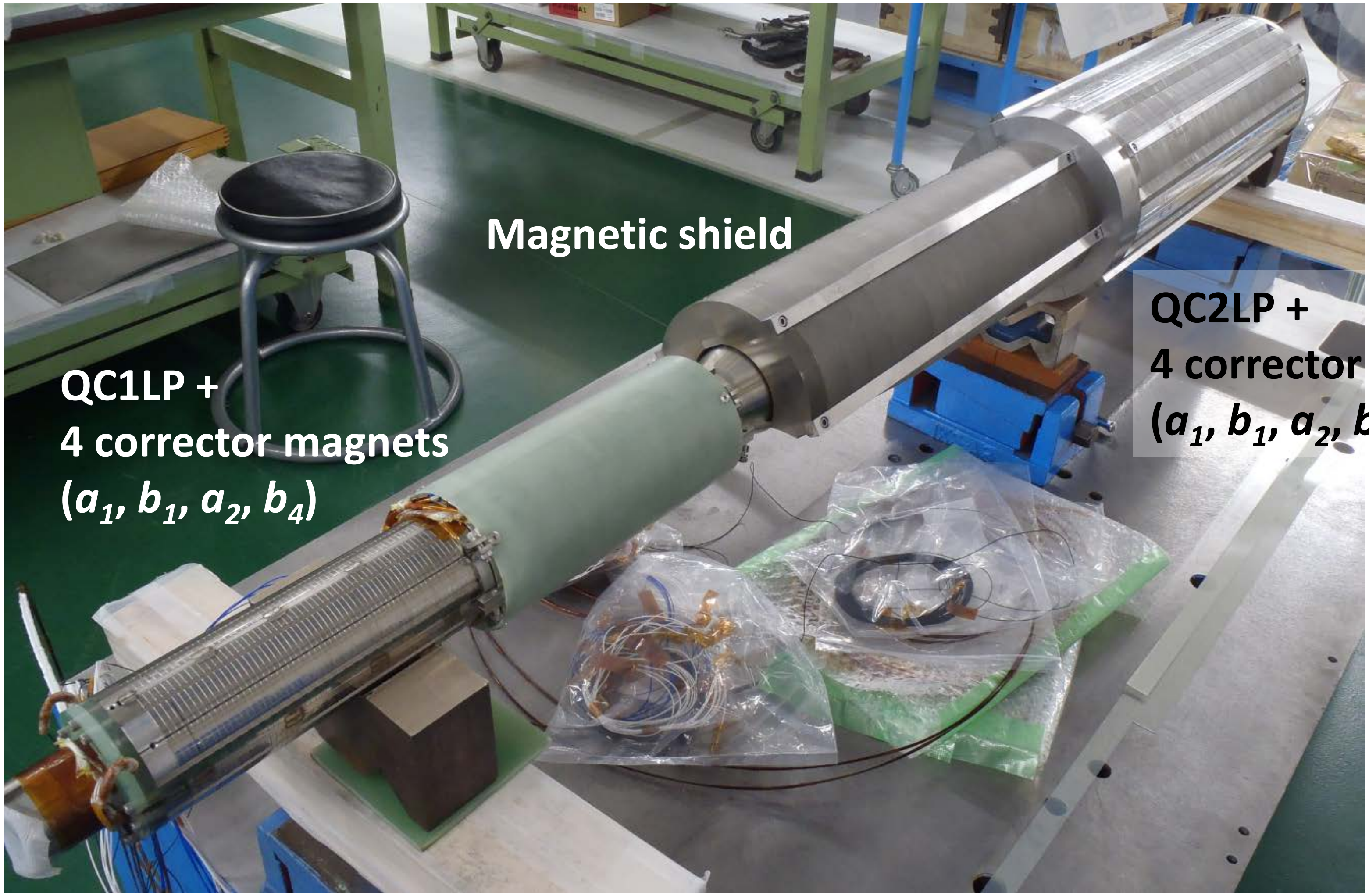
Assembly of Magnet Cryostat

- Combined QC1LE, QC1LP leak field cancel magnets and magnetic shield



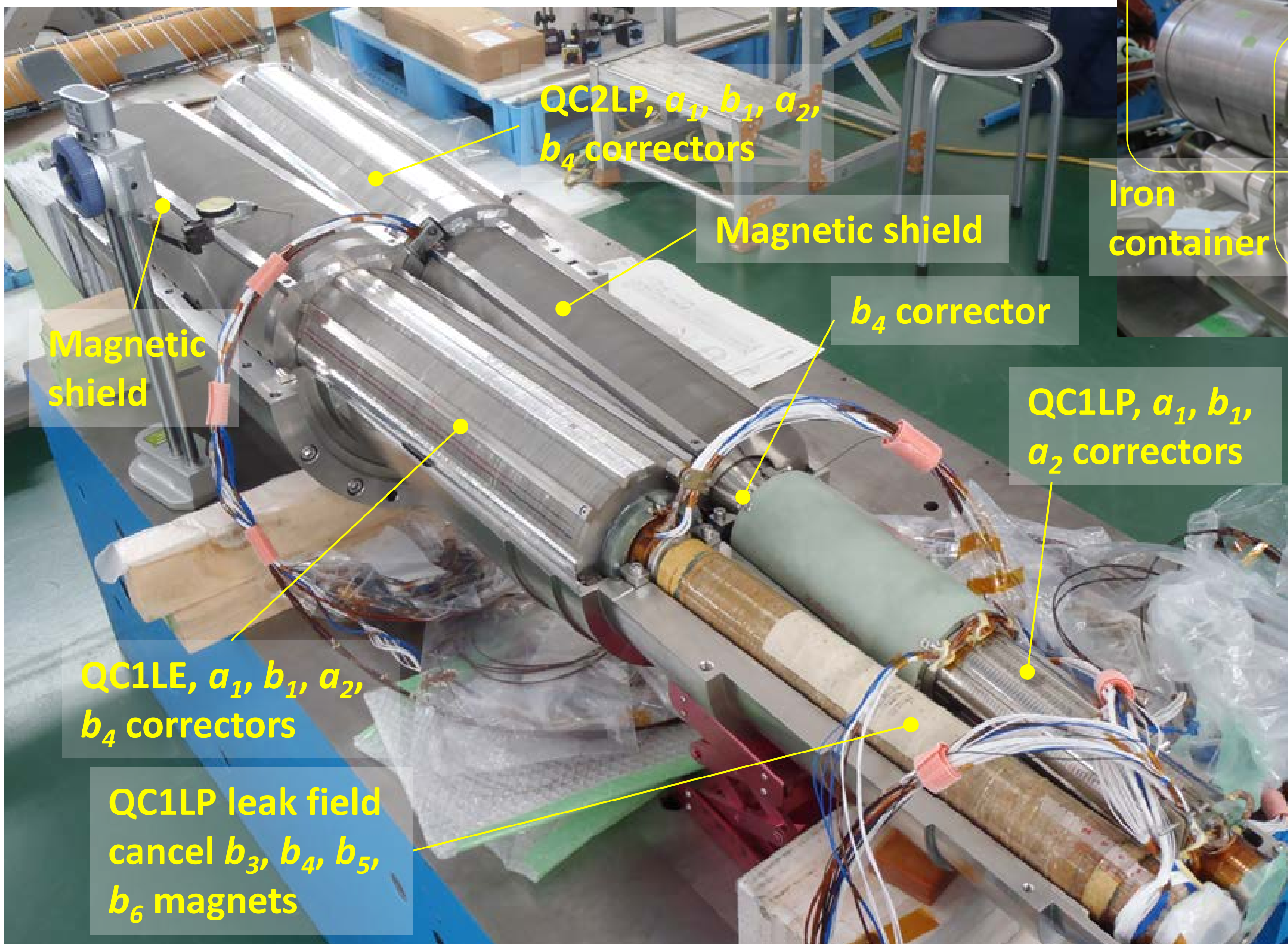
Assembly of Magnet Cryostat

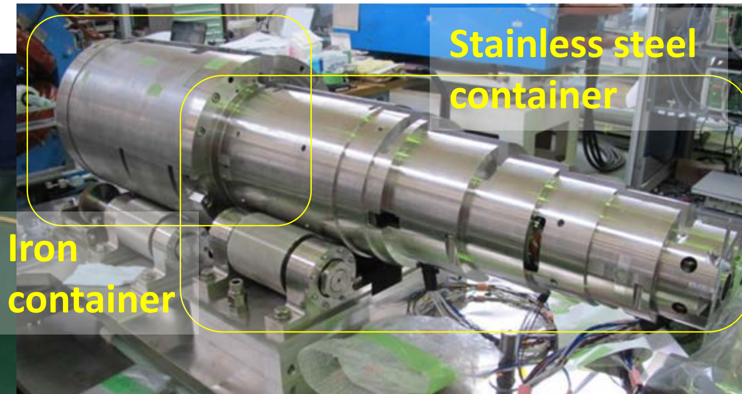
- Combined QC1LP, magnetic shield and QC2LP



Assembly of Magnet Cryostat

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





The assembled magnets were set inside the stainless steel and the iron support containers to keep the precise position between the magnets.

Assembly of Magnet Cryostat

Important component for beam operation: **radiation shield**

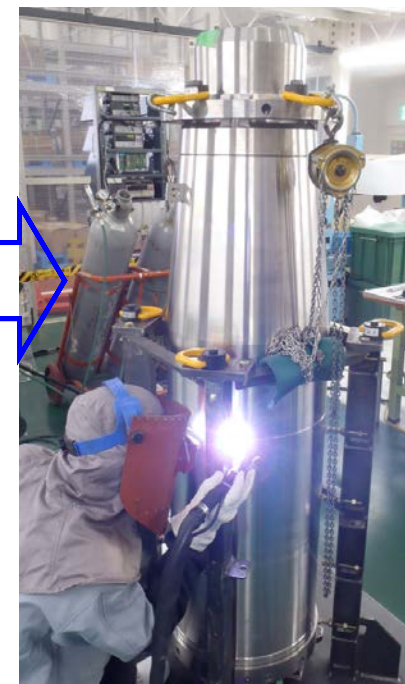
- **W alloy radiation shields are cooled with the superconducting magnets at 4K**

QCSL cold mass of the superconducting magnets and components

Assembling the ESL on to the cold mass.

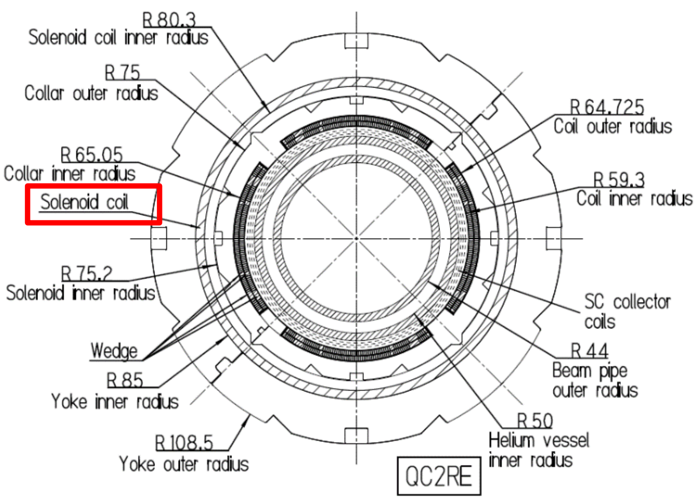
Setting the W alloy radiation shield on to the ESL

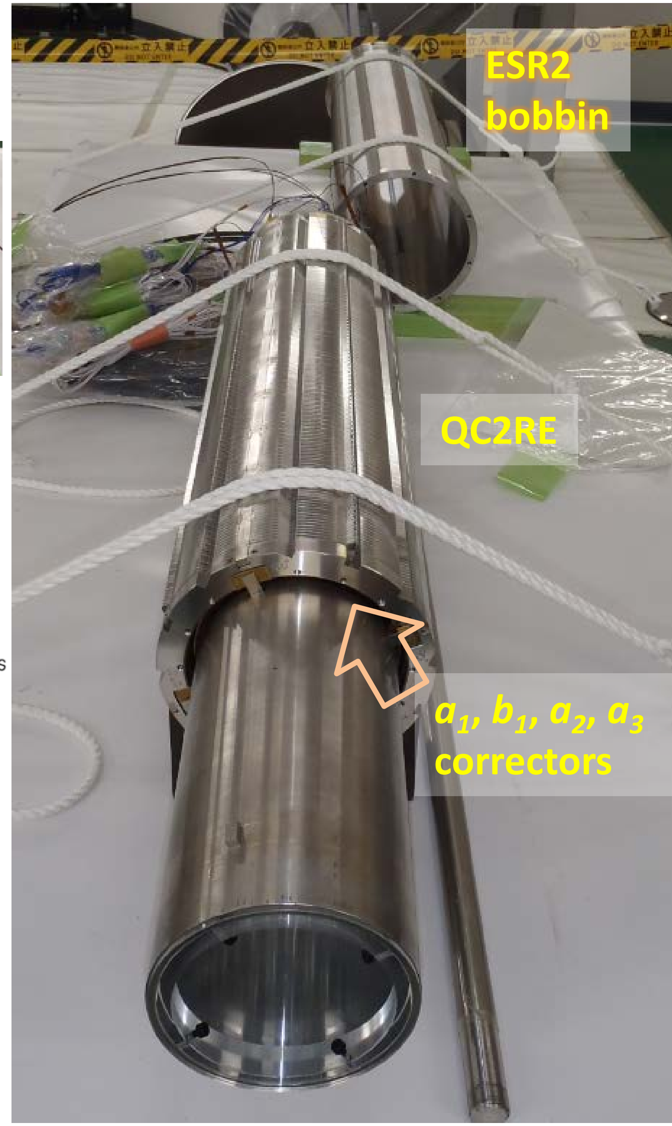
The completed cold mass was contained in the helium can and welded.



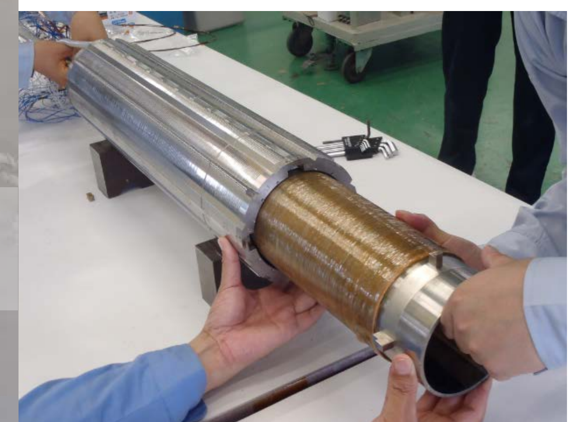
Assembly of ESR2, QC2RE and corrector magnets

ESR2





The completed unit of the corrector magnets was inserted and set inside of the QC2RE magnet bore.

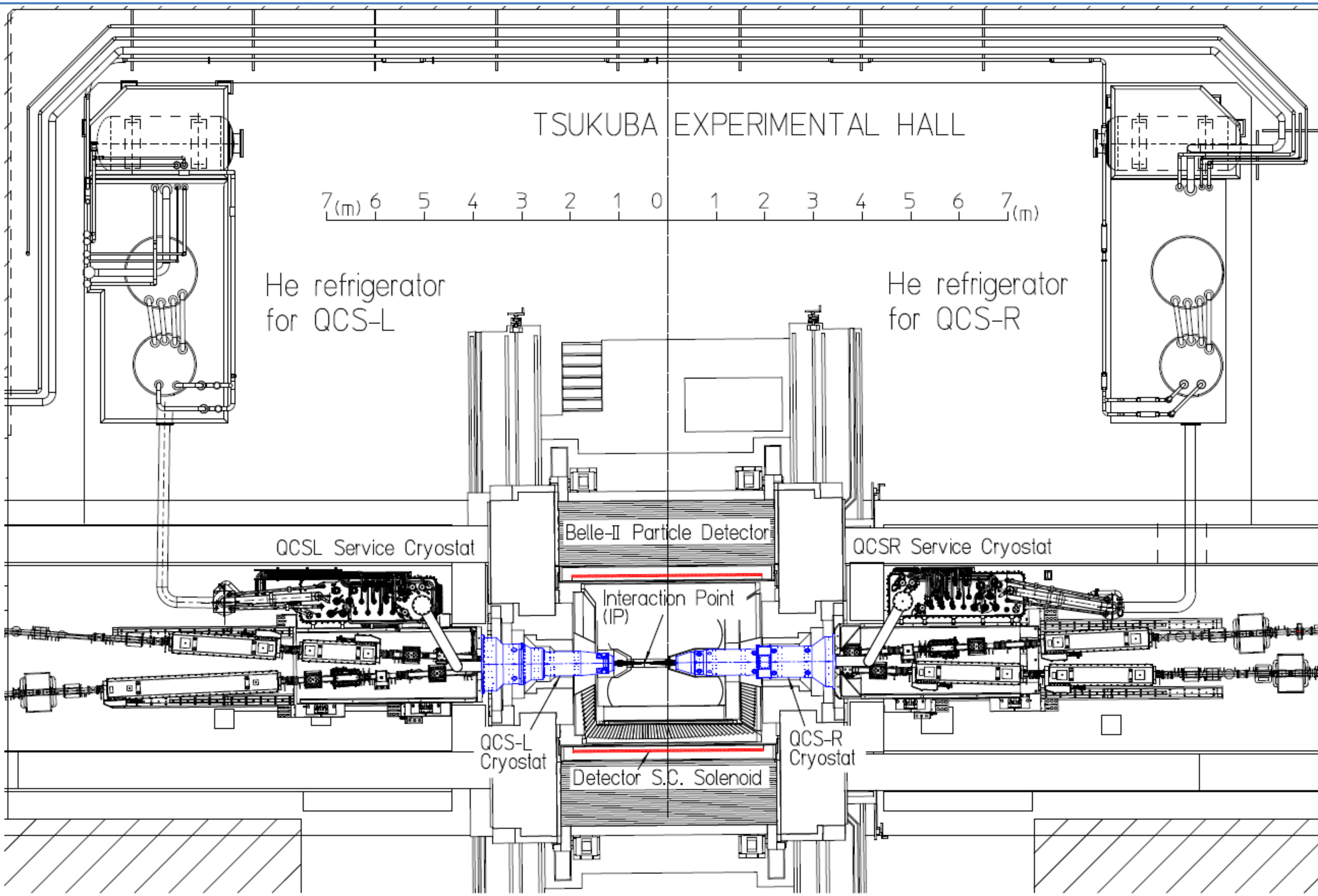


Assembly of Magnet Cryostat

QCS-R magnet cryostat

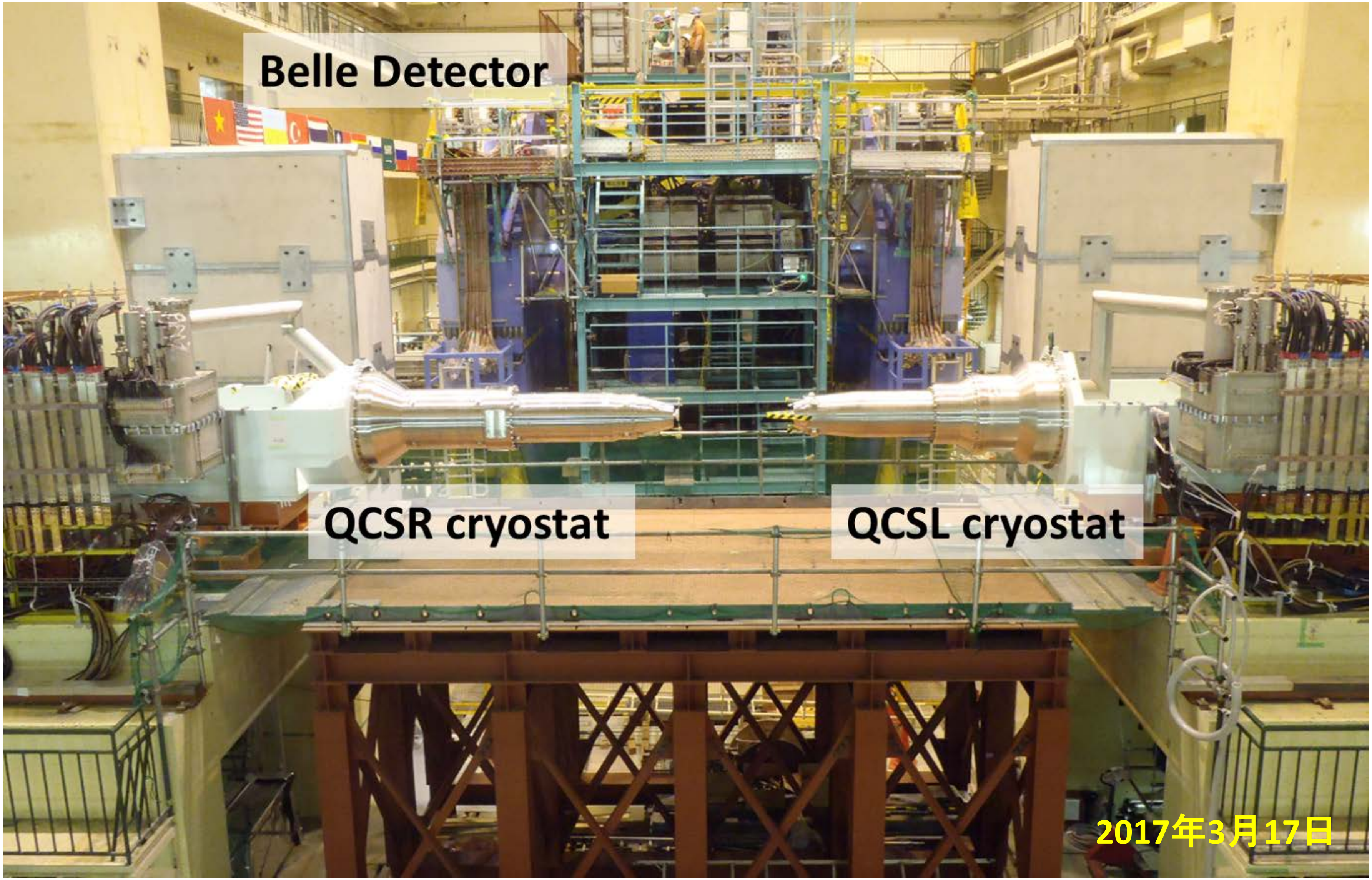
QCS-L magnet cryostat

QCS System

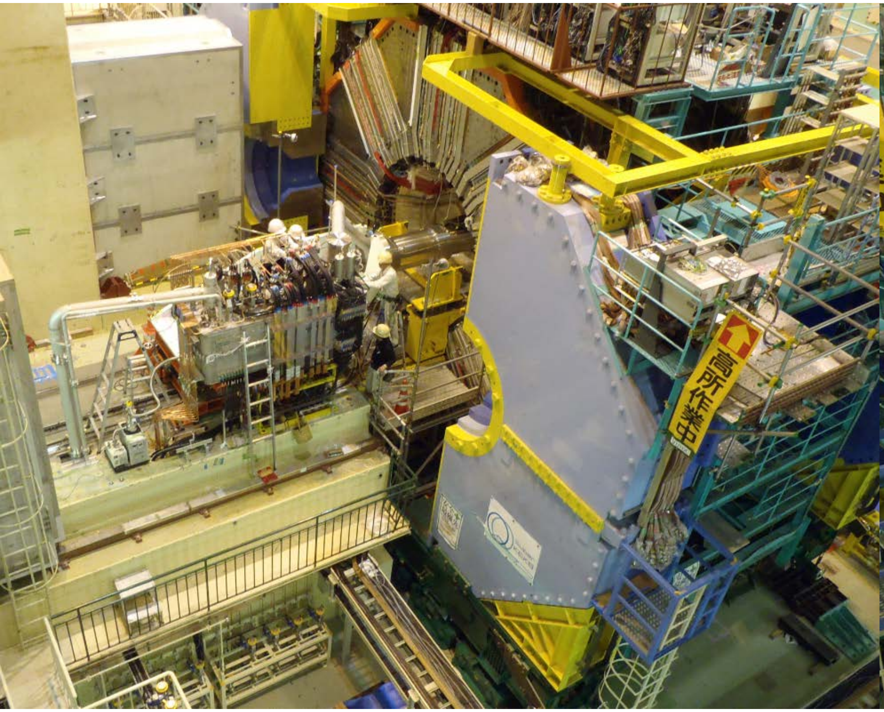


TSUKUBA EXPERIMENTAL HALL
7(m) 6 5 4 3 2 1 0 1 2 3 4 5 6 7(m)
He refrigerator for QCS-L
He refrigerator for QCS-R
Belle-II Particle Detector
QCSL Service Cryostat
QCSR Service Cryostat
Interaction Point (IP)
QCS-L Cryostat
QCS-R Cryostat
Detector S.C. Solenoid

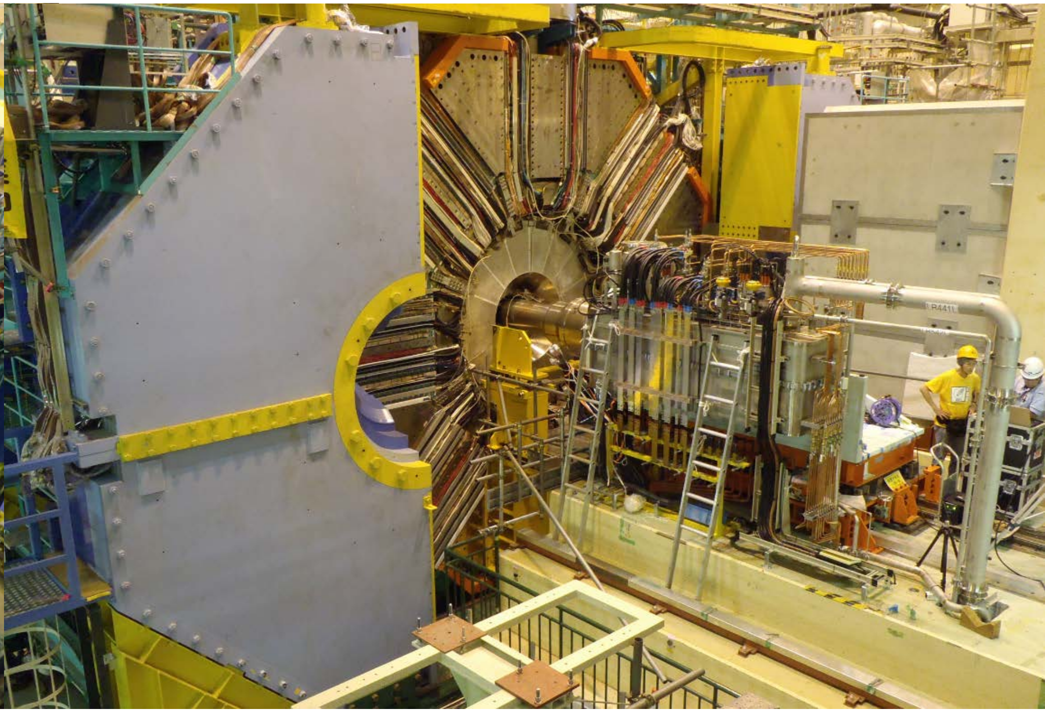
Installation of QCS cryostats on the beam lines



Moving QCS cryostats to the design positions on the beam lines inside of the Belle-II detector



QCS-R cryostat



QCS-L cryostat

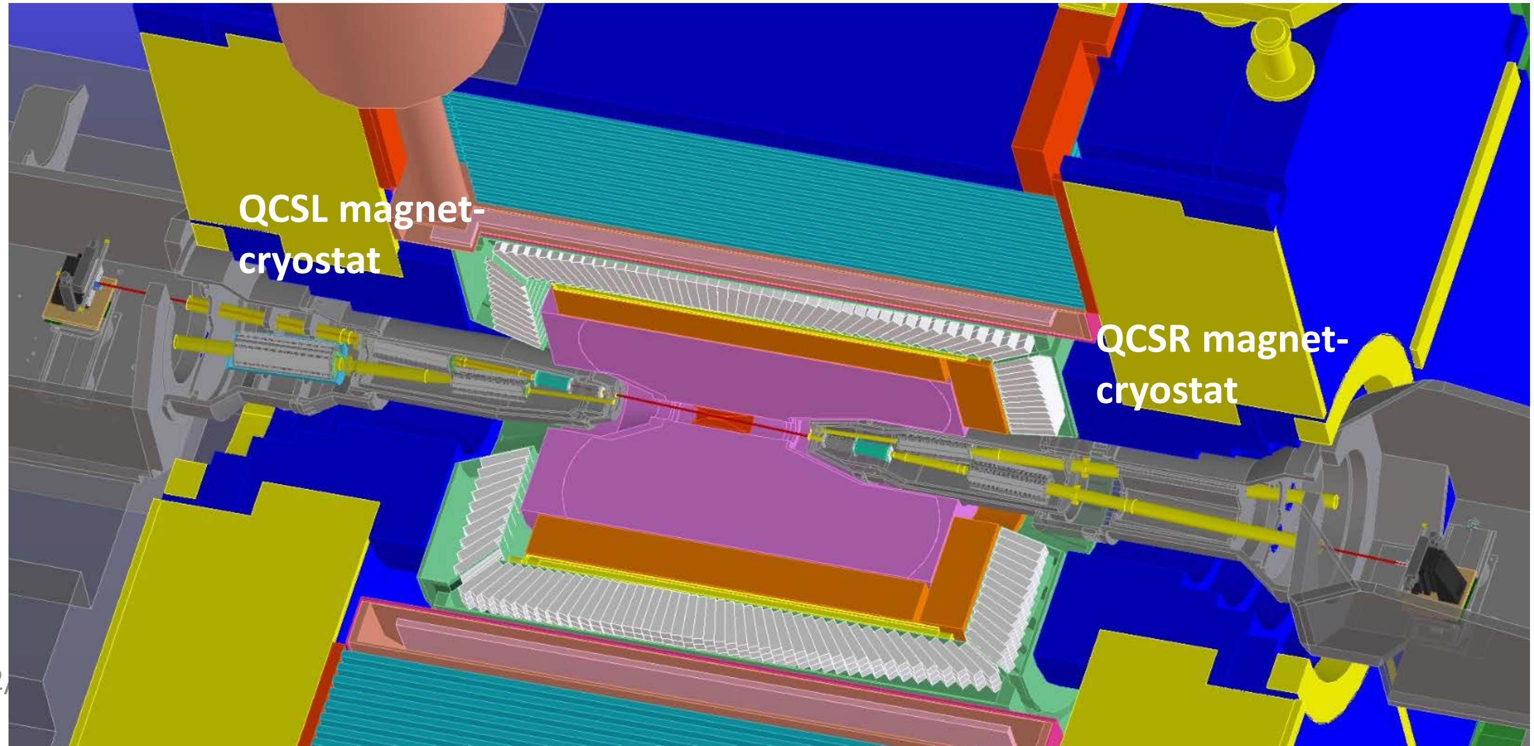
Magnetic field measurements

Magnetic fields of all superconducting magnets were measured on the beam lines with the following special devices.

- **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.

Magnetic field measurements

- **Measurements of quadrupole centers and field angles by SSW**
  - A BeCu single wire of ϕ0.1 mm, which was aligned to the design beam line, was stretched through QCSR and QCSL cryostat bores.
  - **By moving the wire in the magnetic field and analysis of the induced voltage in the wire**, the quadrupole field center and the field angle are measured .
    - 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.



Magnetic field measurements

- 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)

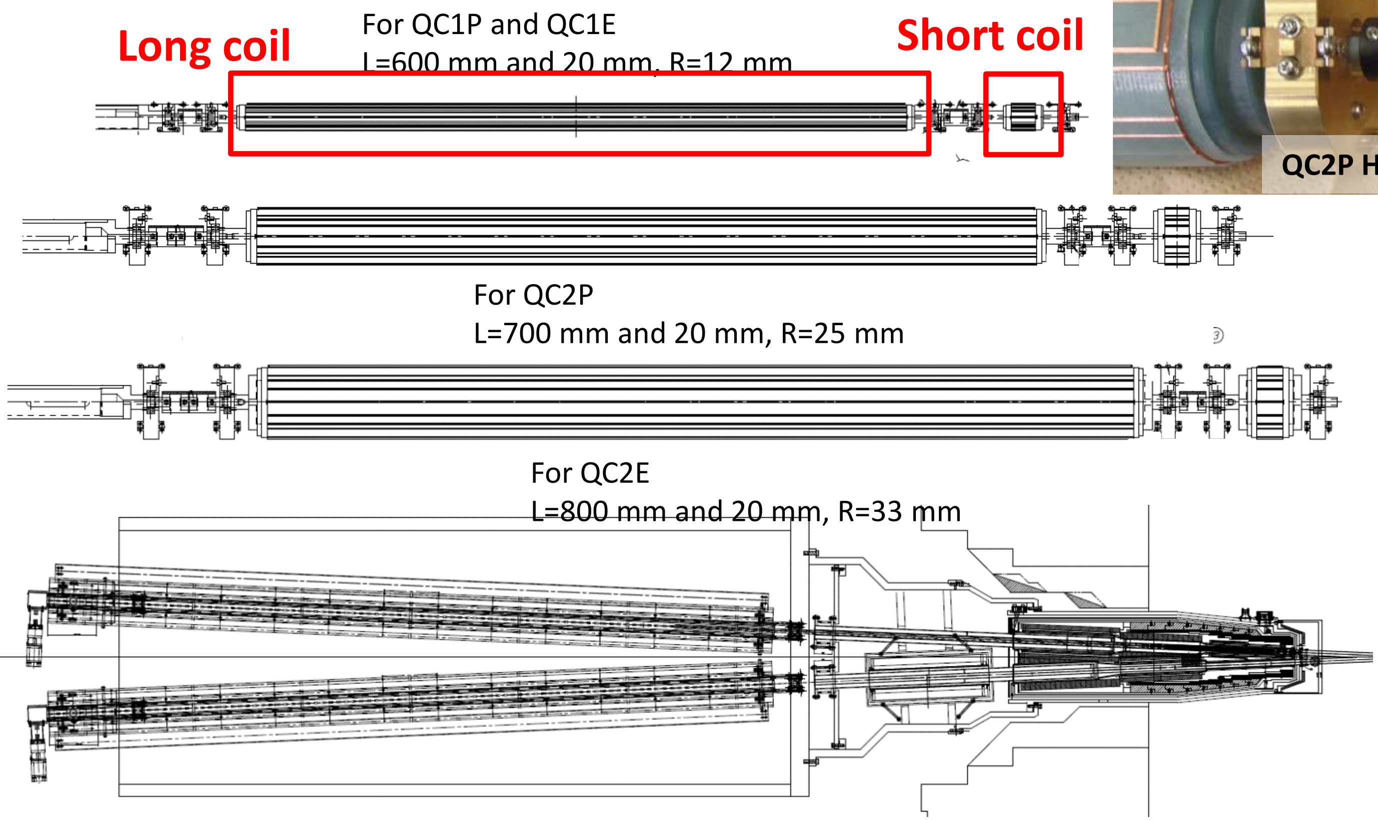
	QC1LE	QC2LE	QC1RE	QC2RE
Δx, mm	-0.212	0.129	0.245	0.079
Δy, mm	-0.286	-0.535	-0.373	-0.581
$\Delta\theta$, mrad	-1.60 (0.0)	-1.54 (0.0)	-0.14 (0.0)	-0.73 (0.0)

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

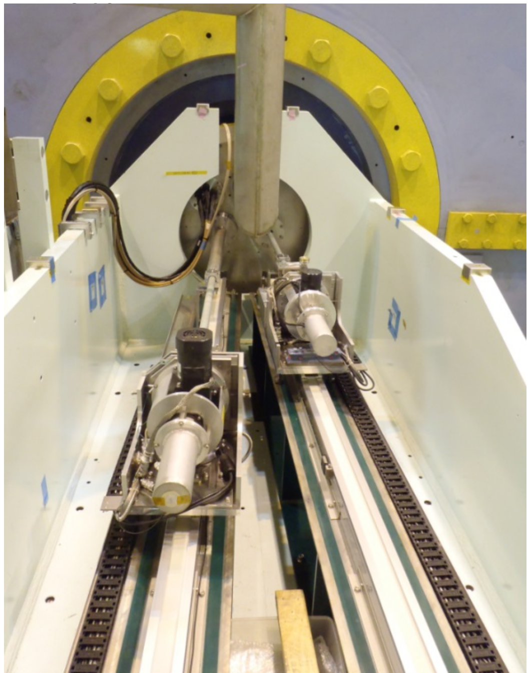
- Electro-magnetic forces acting on the cryostats:
  - QCSL = 52.6 kN, QCSR=35.7 kN (calculation)

Magnetic field measurements

- **Field quality measurements of the quadrupole magnets by Harmonic Coils**
  - One unit of measurement system has two harmonic coils.
    - **Long coil**: integral field measurement, **Short coil**: field mapping measurement (field profile)
    - Harmonic coils: tangential coil, three dipole coils, three quadrupole coils
  - The harmonic coils are moved by the mover, the movement is measured by the digital scaler.




QC2P Harmonic Coil

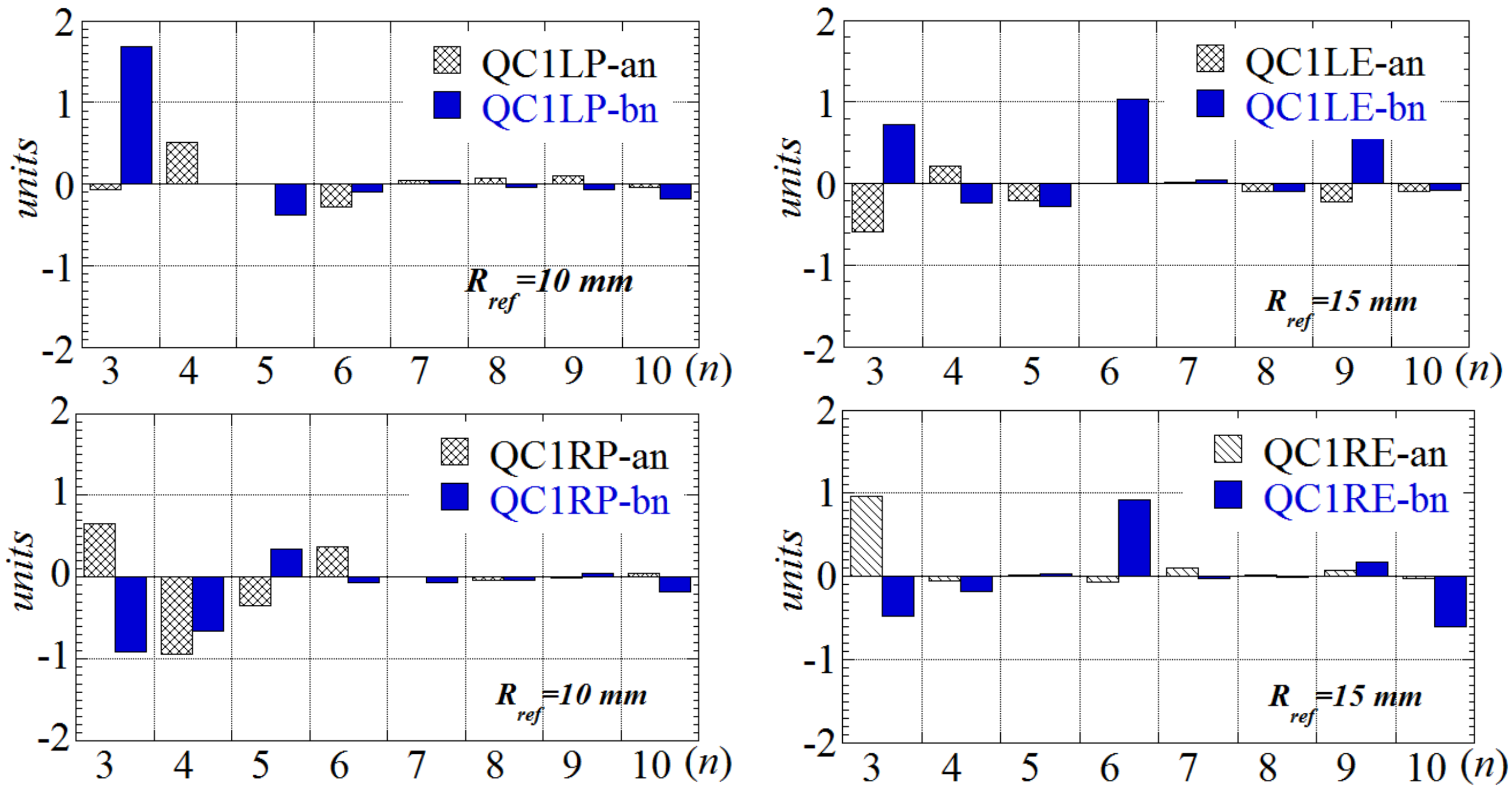


Magnetic field measurements

- **Field quality of the quadrupole magnet (QC1) by Harmonic Coils**
  - The multi-pole magnetic field components in the quadrupole magnet are shown by the following equation:.

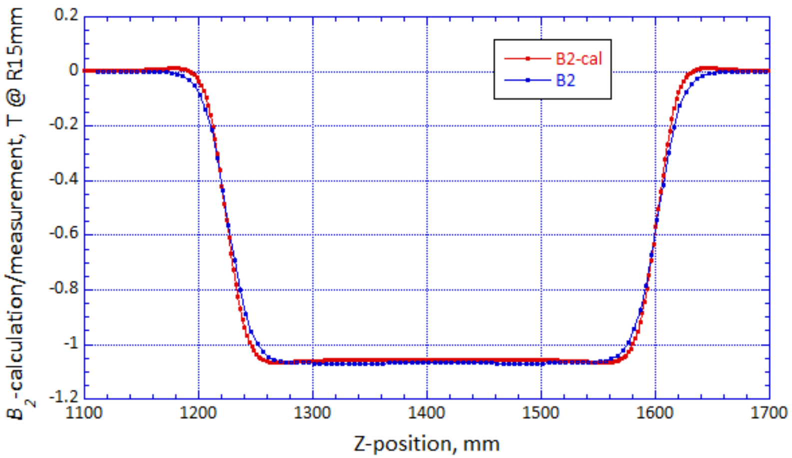
$$B_y + iB_x = 10^{-4} B_2 \sum_{n=1}^{\infty} (b_n + ia_n) \left(\frac{x+iy}{R_{ref}} \right)^{n-1}$$

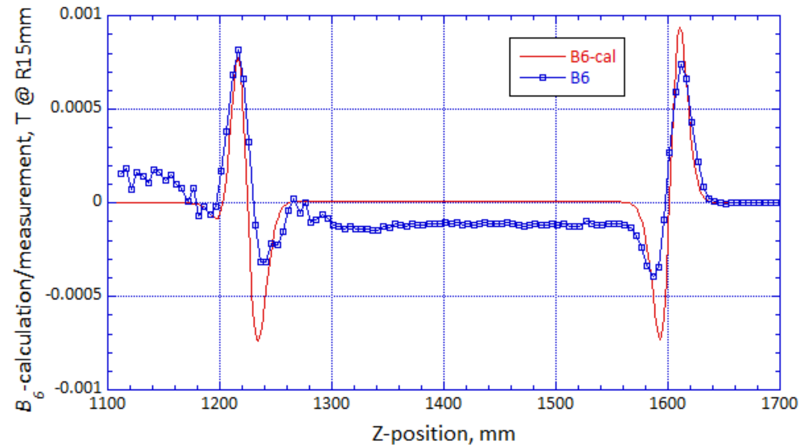
Higher order multipole fields (n>2) are normalized by B_2 (n=2) as 10000. B_2 is the quadrupole field.

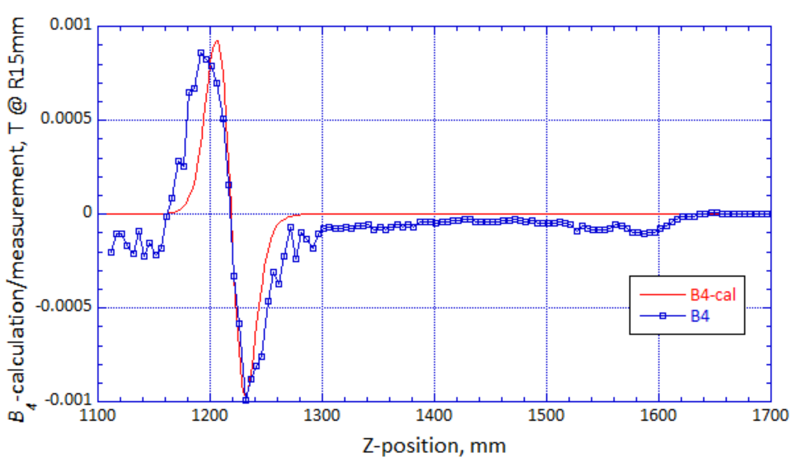


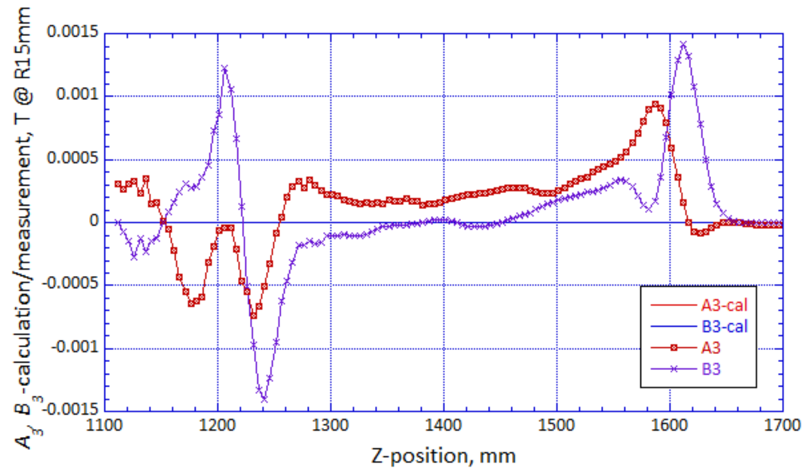
Magnetic field measurements

- **Field profile of the quadrupole magnet (QC1LE) along the HER beam line**
  - The measured magnetic field values in the plots are the field strength at each position and R=15 mm.
  - The field profiles are now being included into the beam calculation, and the effect on the beam operation is being studied.





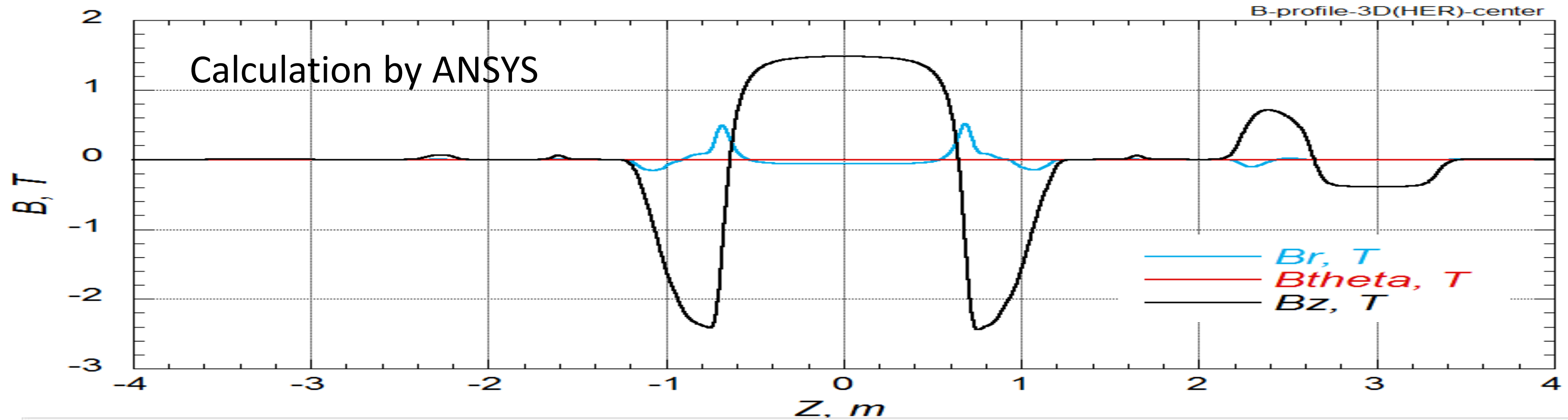


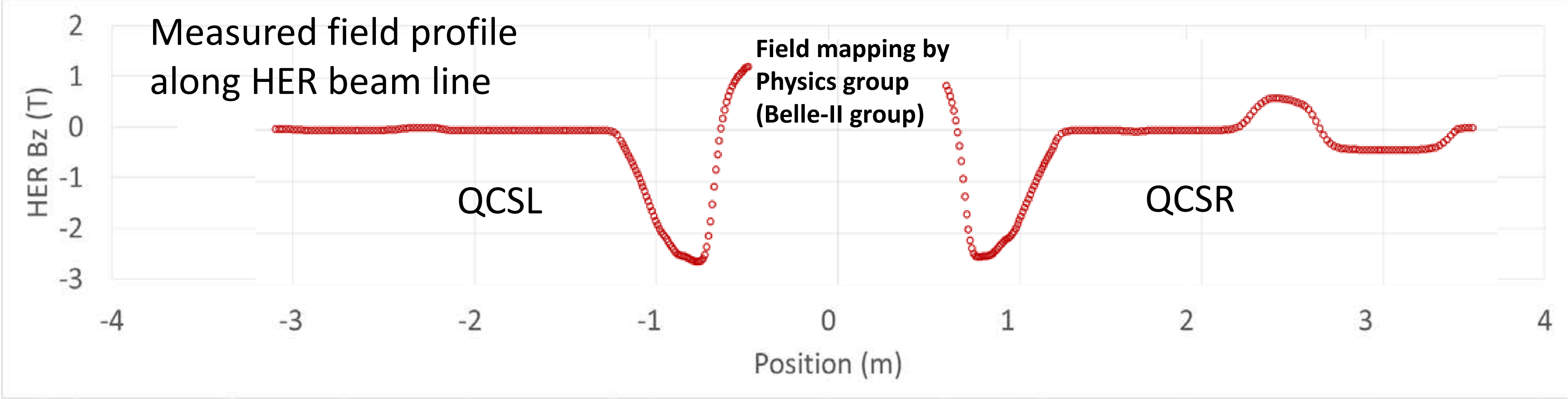


Magnetic field measurements

Mapping the magnetic field along the beam lines

- The measurement system consisted of the commercial Hall probe and the scanning mover.

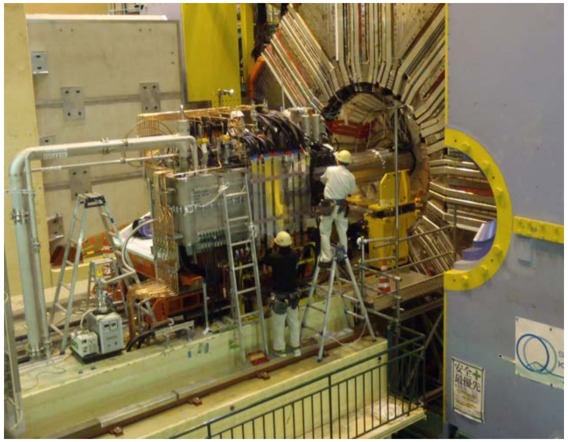




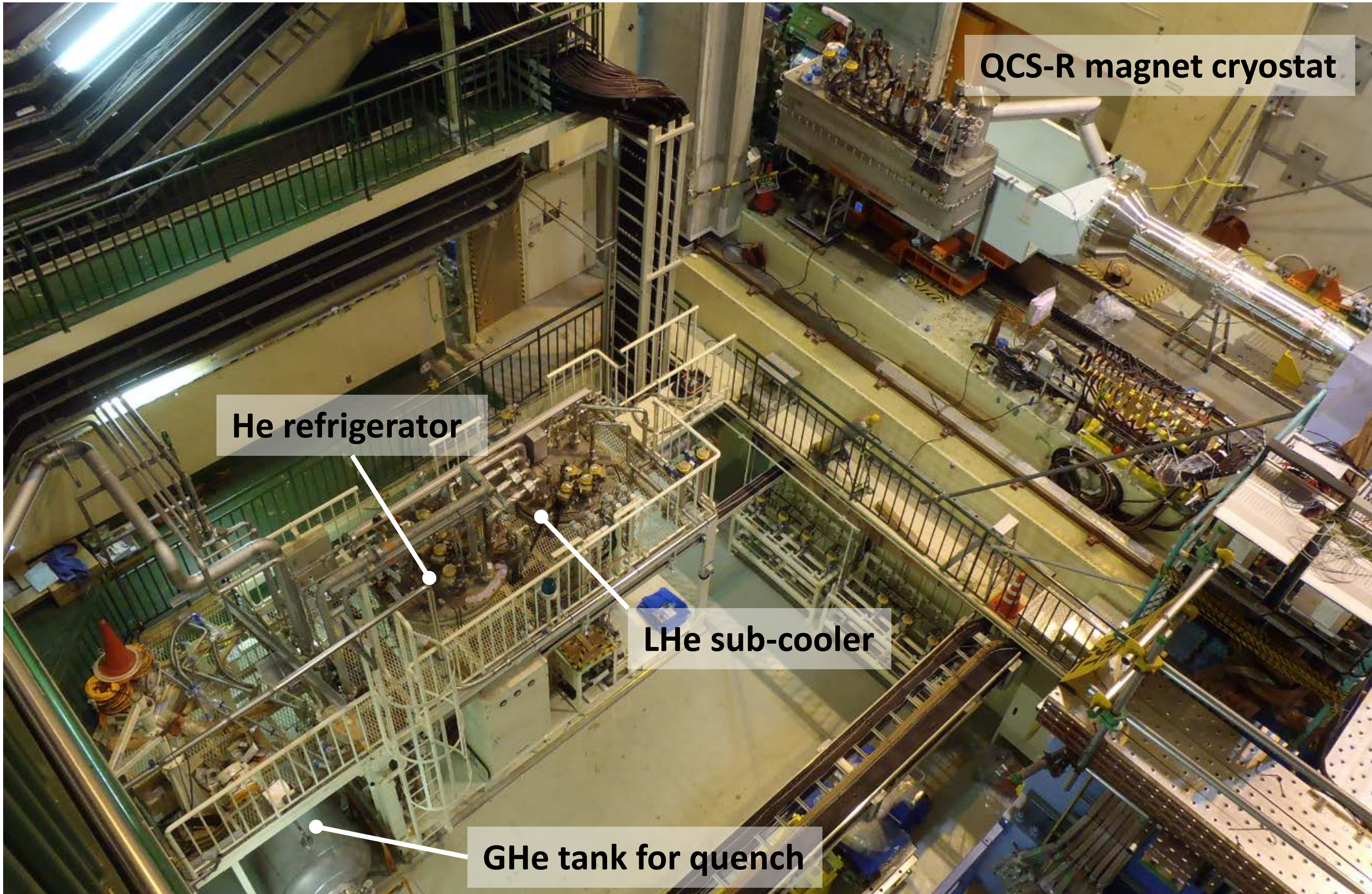
Cryogenic System

Cryogenic system:

- Helium refrigerator (250 W @ 4.4 K with LN_2)
- Sub-cooler (GHe 20g/s, 0.16 MPa, 4.75 K→Subcooled LHe 20g/s, 0.16 MPa, 4.35 K)
- Helium compressor (1250 Nm^3/h)
- LN_2 storage tank (9800 L)
- Cryostat (magnet cryostat + service cryostat)
- Cryogenic transfer tubes
- Process controller

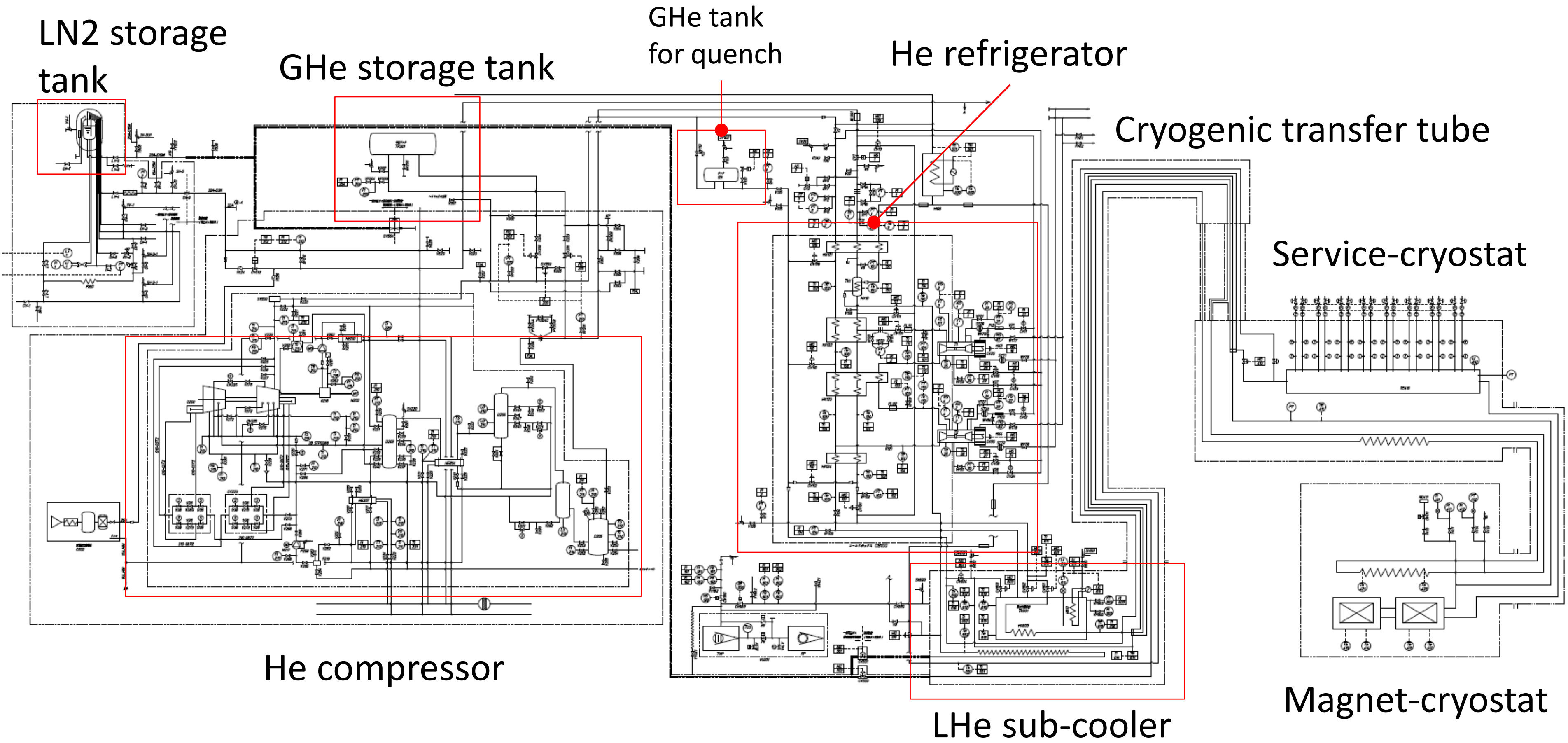


Cryogenic System



Cryogenic System

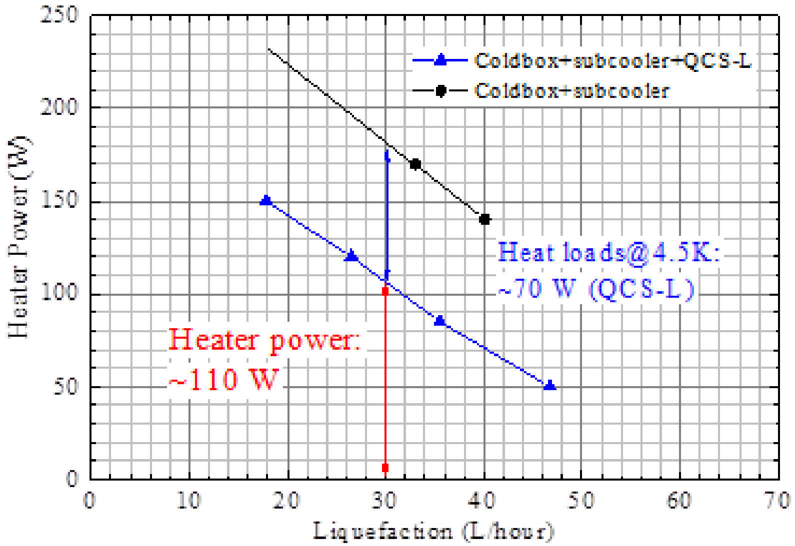
Flow diagram of QCS cryogenic system



Cryogenic System

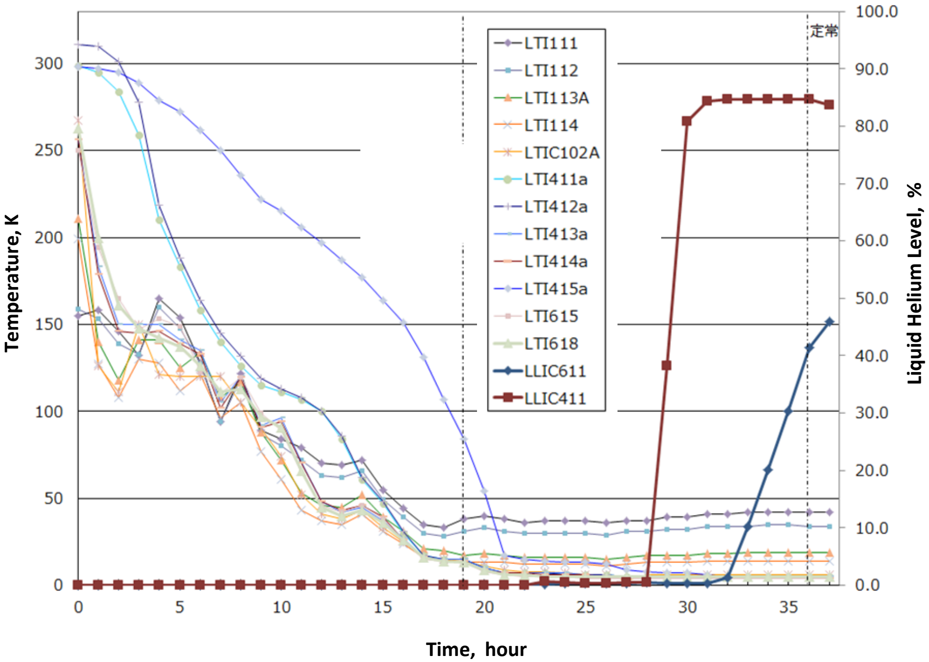
Design Heat load of QCS cryostats

	QCS-L	QCS-R
Magnet Cryostats		
Support rod, W	9.7	5.8
Thermal radiation, W	6.6	10.1
Sub-total, W	16.3	15.9
Service Cryostat		
Thermal radiation, W	1.9	2.1
Current lead pipe, W	11.5	12.5
Trans. tube, valves, W	6.0	6.0
Instrument wire, W	3.8	3.4
He gas for C. L., g/s	1.00	1.03
Sub-total	23.2 W + 1.00 g/s	24.0 W + 1.03 g/s
Total	40.5 W + 1.00 g/s	40.7 W + 1.03 g/s

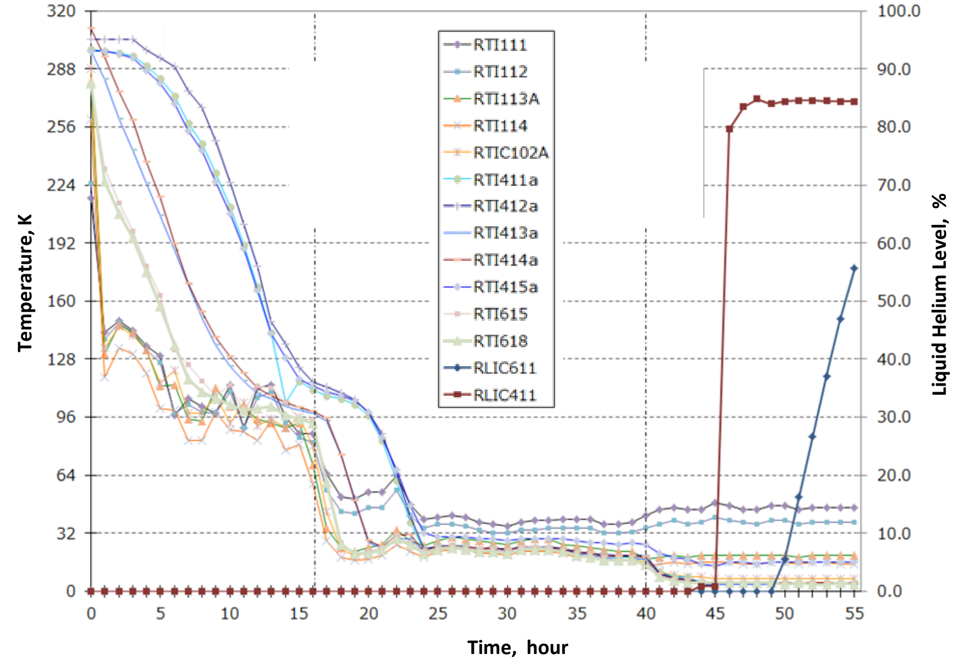


Cryogenic System

Cool-down of QCS cryostats



38 hours for cooling QCS-L



57 hours for cooling QCS-R

TI111=Inlet of 1st turbine,
TI112=Outlet of 1st turbine,
TI113=Inlet of 2nd turbine,
TI114=Outlet of 2nd turbine,
TI102=Outlet of refrigerator high pressure line,

TI411a=Front He vessel,
TI412a=Front He vessel,
TI413a=Rear He vessel,
TI414a=Rear He vessel,
TI415a=Inside of the current lead box,

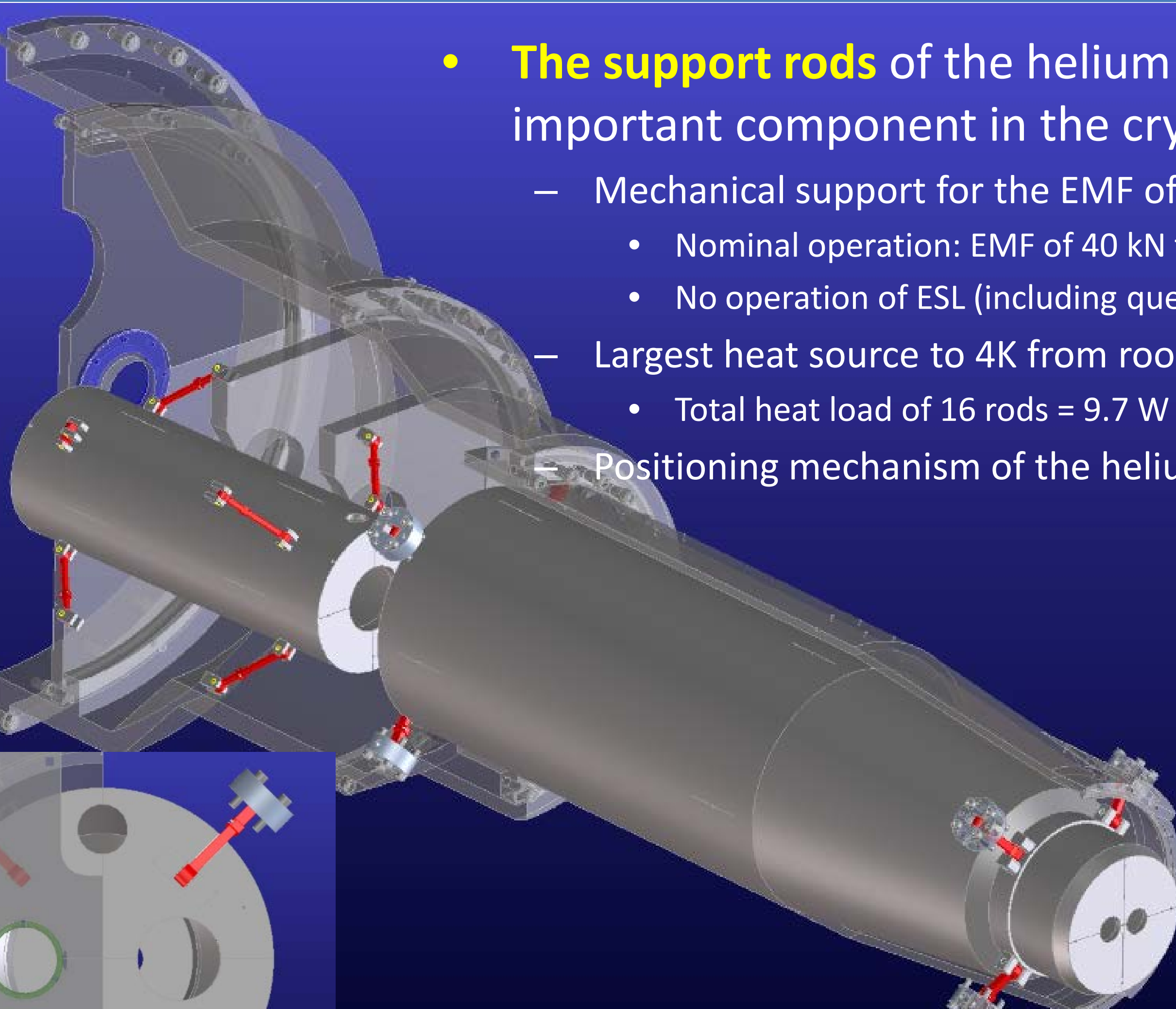
TI615=Inside of He vessel in the sub-cooler,
TI618=Outer surface of He vessel in the sub-cooler,
LI611=LHe level in the sub-cooler ,
LI411=LHe level in the current lead box.

Summary

1. Beam final focusing in SuperKEKB is performed by quadrupole doublets, which consist of 8 superconducting quadrupole magnets (QCS).
2. The QCS system has 43 superconducting corrector magnets and 4 superconducting compensation solenoids for tuning beam condtions.
3. All magnets worked well in the SuperKEKB Phase-2 operation.
   - Electron and positron beams successfully collided at April 26, 2018 and the beams were squeezed to β_y^*=3 mm (at final 0.3 mm).
4. The cryogenic system was being very steadily operated from January 30, 2018 to July 26, 2018.
5. The next operation of the system is scheduled in March 2019.

Back-up

QCS Cryostat



- **The support rods** of the helium vessel are the most important component in the cryostat.
  - Mechanical support for the EMF of Belle solenoid field
    - Nominal operation: EMF of 40 kN to the outside of IP
    - No operation of ESL (including quench): EMF of 70 kN into IP
  - Largest heat source to 4K from room temperature
    - Total heat load of 16 rods = 9.7 W
  - Positioning mechanism of the helium vessel (magnets)