Final focus system at SuperKEKB

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- Overview of final focus system
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  - Corrector / Cancel magnets
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  - Magnetic field quality
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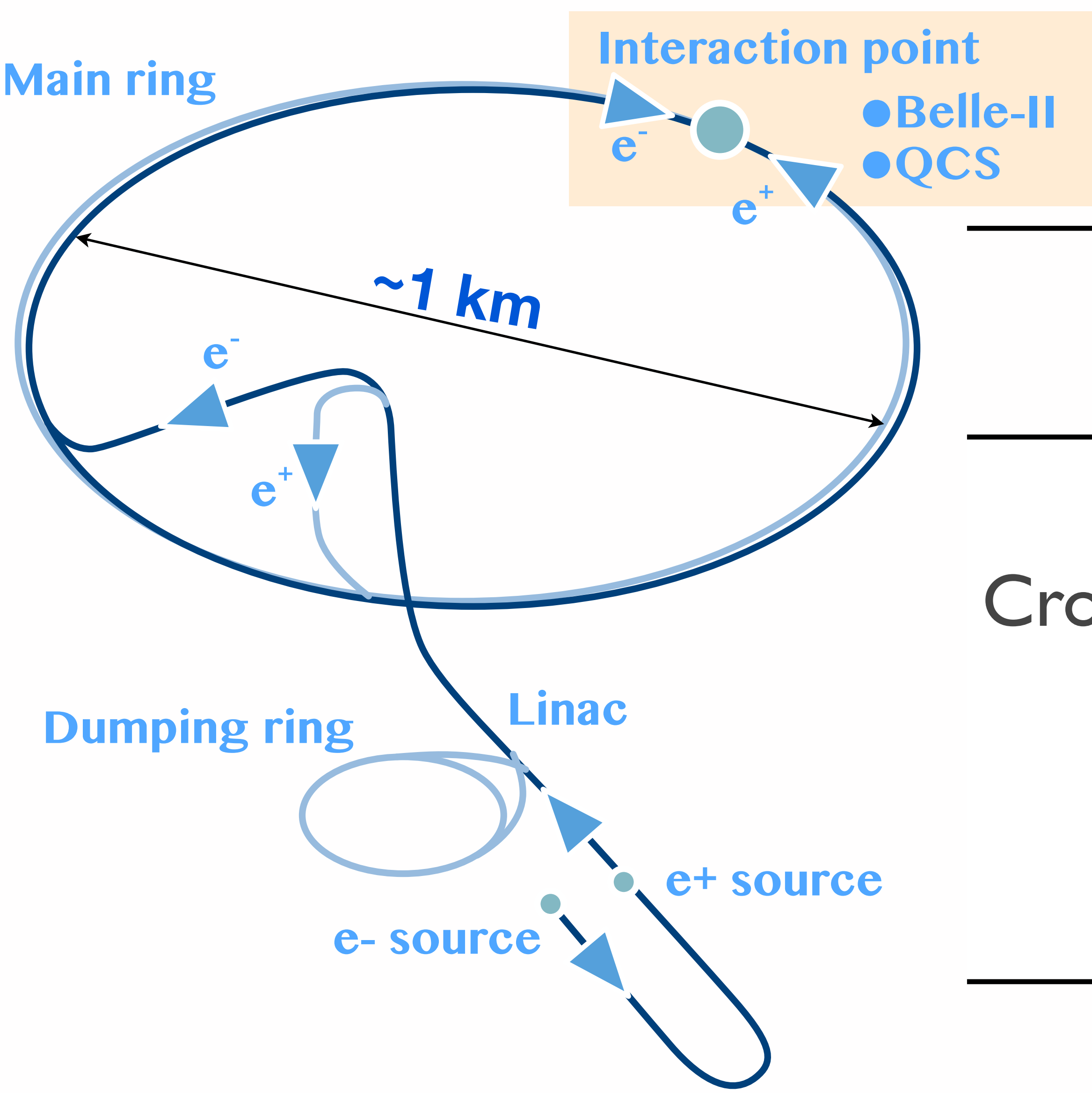
- Summary

Introduction (SuperKEKB)

- SuperKEKB is a high energy e+/e- collider upgraded accelerator from KEKB.
- SuperKEKB is aiming at high luminosity
  - Target luminosity : **8x10^{35}** cm^{-2} s^{-1}(40 times larger than KEKB)



	LER e^+	HER e^-
Energy [GeV]	4	7
Crossing angle [mrad]	83 mrad	
σ_y [nm]	48	62
σ_x [nm]	10,000	11,000
Current [A]	3.6	2.6

Y. Ohnishi, Prog. Theor. Exp. Phys. 2013, 03A011

SuperKEKB schedule

Feb. - Jun. 2016: Phase 1

No final focus

No Belle II detector

Feb.- Jul. 2018: Phase 2

With final focus

With Belle II detector (no VXD)

2019-: Phase 3

With Full Belle II detector

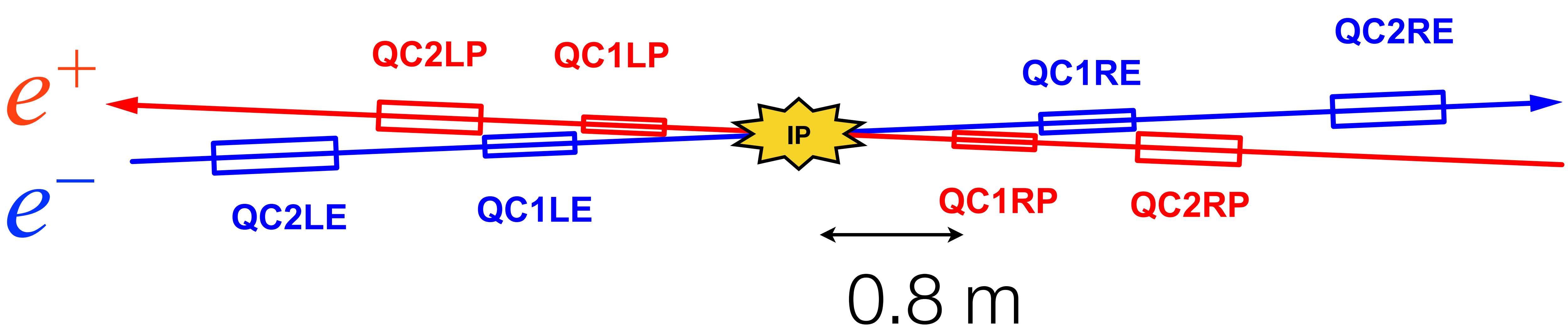
Final-focus-superconducting-quadrupole magnet system, **QCS**

QCS construction history

- Test of prototype of QC1 was performed on 2012.
- The construction of real magnets began at Jun. 2013.
- The construction of QCS have been completed and installed into beamline on Feb. 2017.
- Alignment of cryostats was finished on Mar. 2017
- Belle II rolled-in on Apr. 2017
- Magnetic measurement at the beamline : Jun.-Aug. 2017
- Installation of beam pipes and connection with QCS and Belle II was completed on Jan. 2018
- Beam operation started on Mar. 2018
- Electrons and Positrons Collide for the first time on 26 Apr 2018

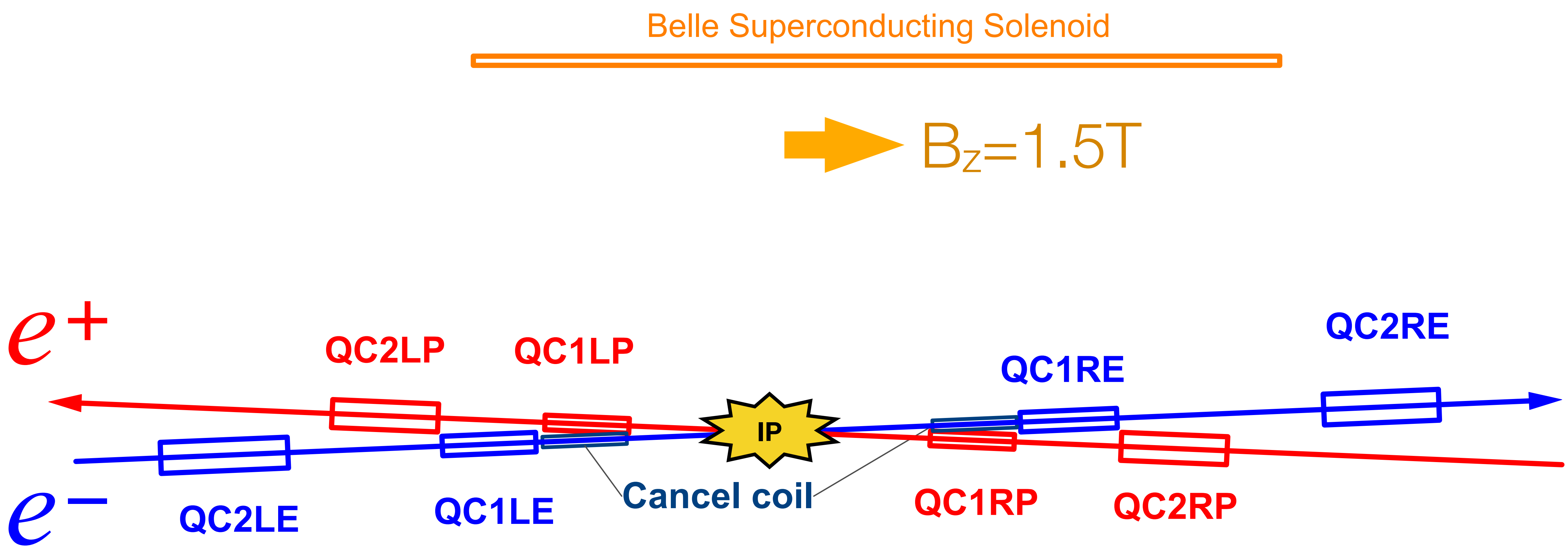
Final focus system (QCS) of SuperKEKB

- QCS consists of
  - 4 quadrupole magnets (= 2 pairs of doublets) for each beam line
  - 43 corrector/cancel coils



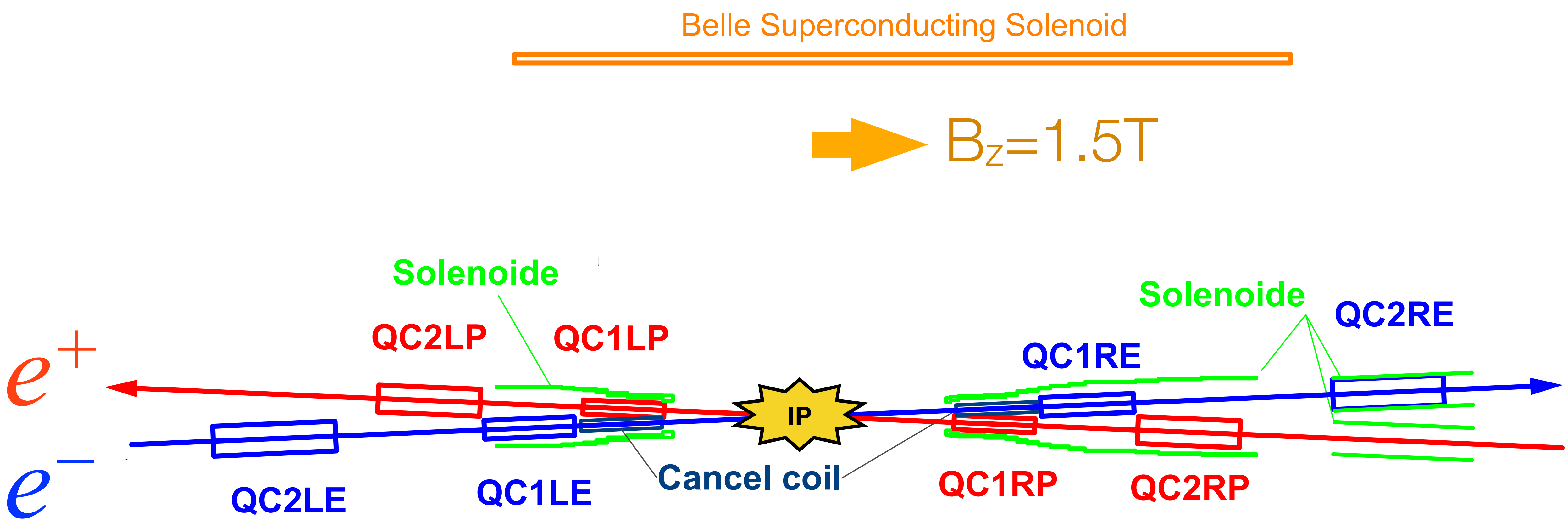
Final focus system of SuperKEKB

- QCS consists of
  - 4 quadrupole magnets (= 2 pairs of doublets) for each beam line
  - 43 corrector/cancel coils
- The final focus system is located in the large detector solenoid

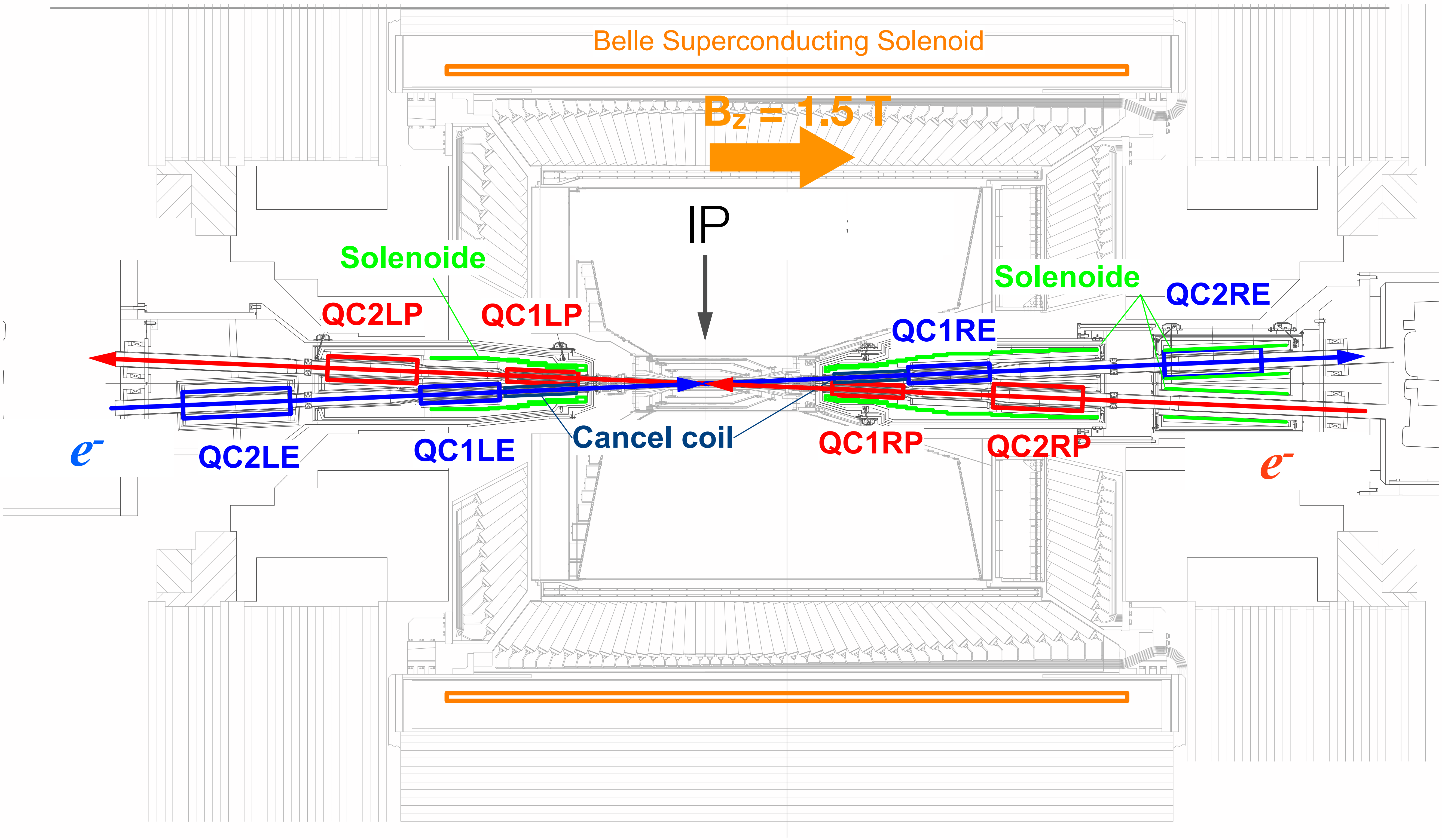


Final focus system of SuperKEKB

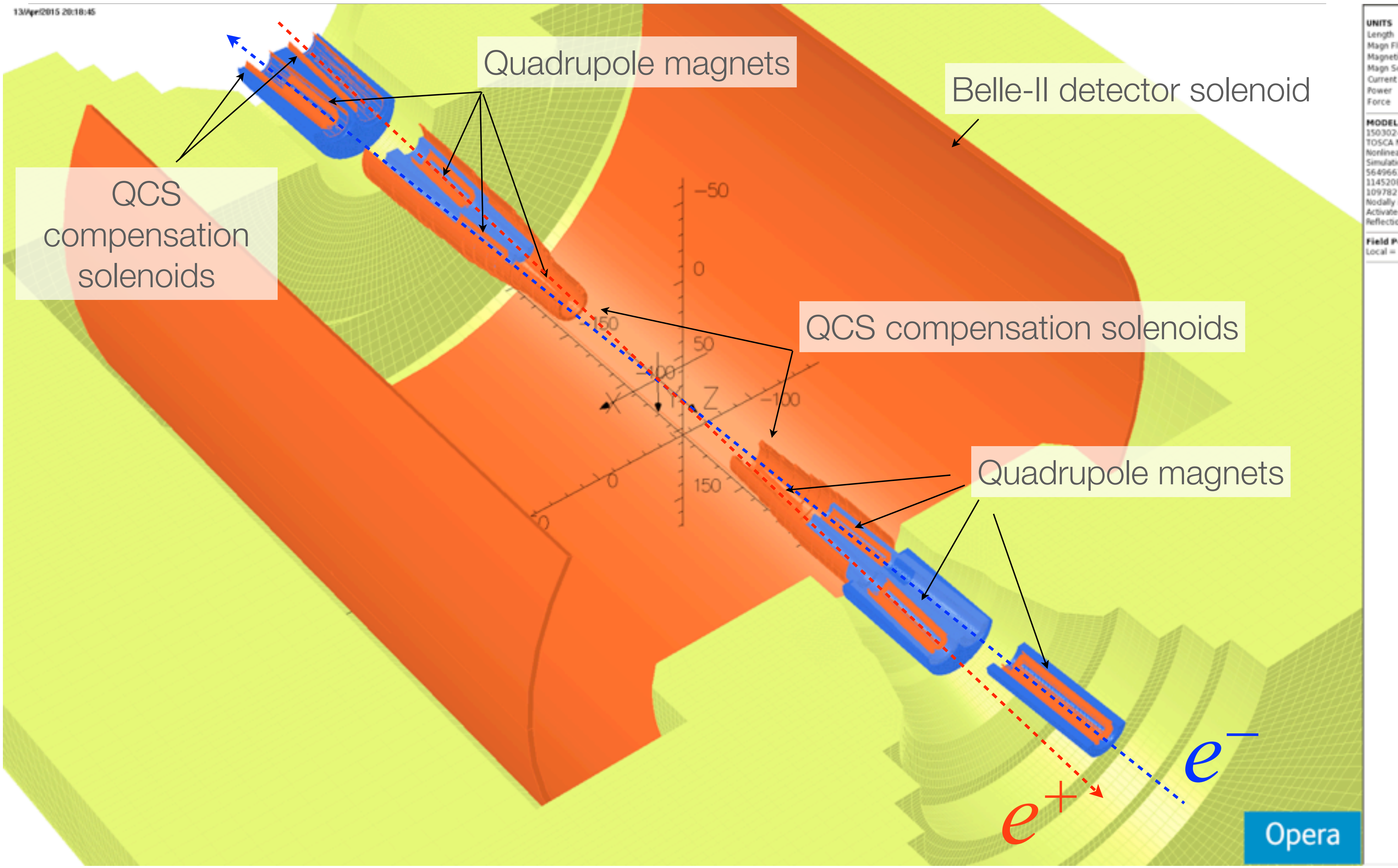
- QCS consists of
  - 4 quadrupole magnets (= 2 pairs of doublets) for each beam line
  - 43 corrector/cancel coils
  - 4 compensation solenoids (to compensate Belle II solenoid field)
- The final focus system is located in the large detector (Belle II) solenoid



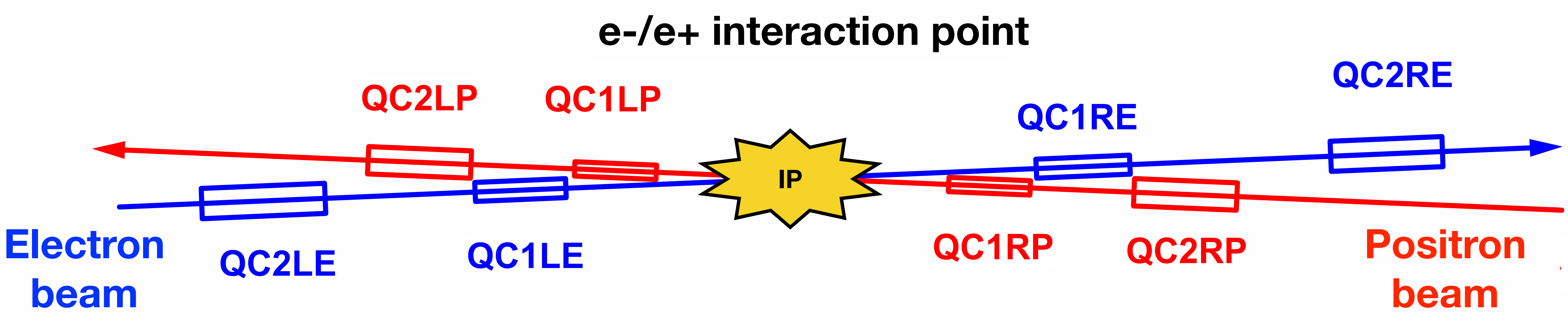
Belle II and QCS



Magnets layout at interaction region w/ solenoids

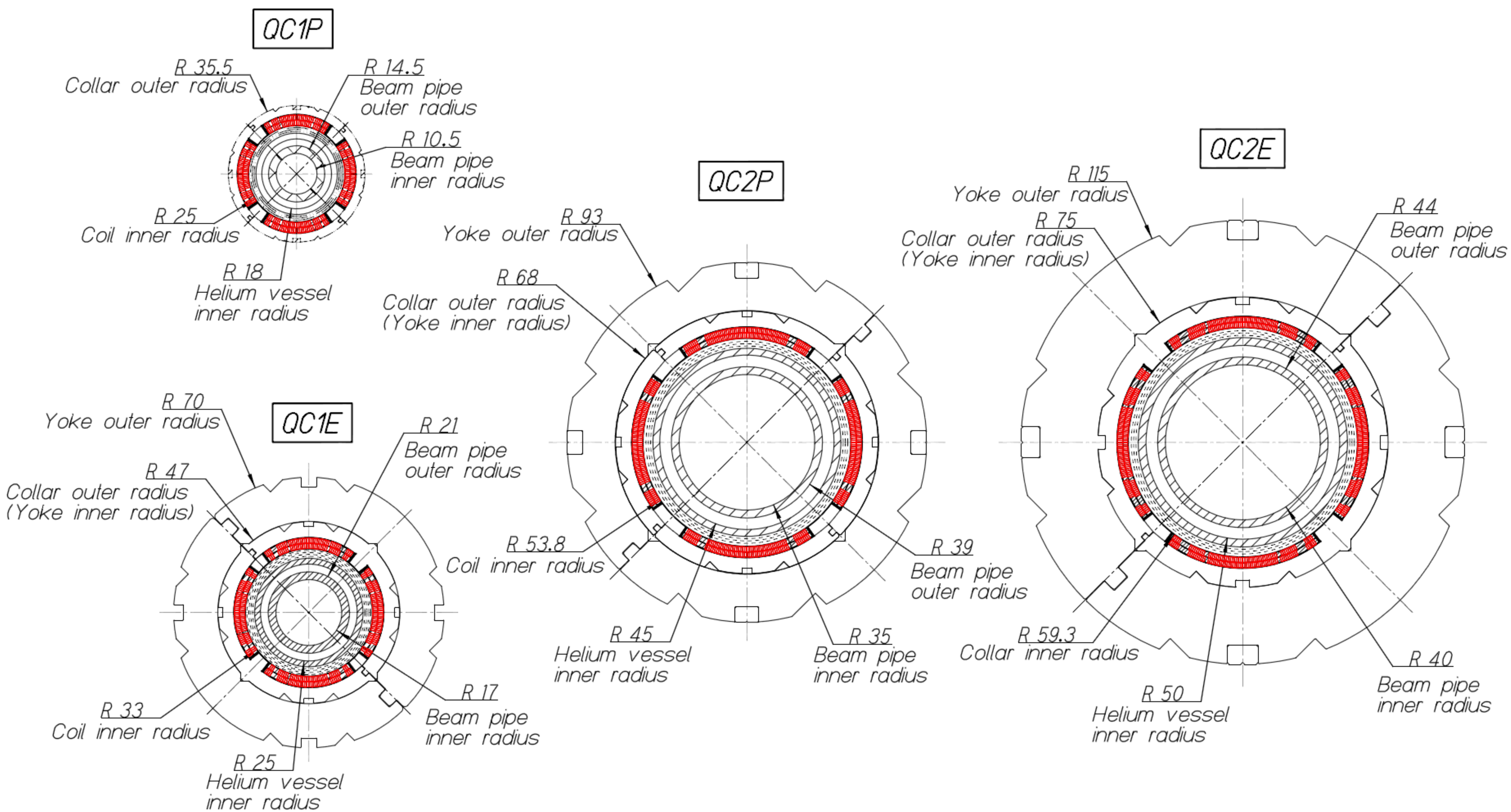


Main parameters of QCS quadrupoles

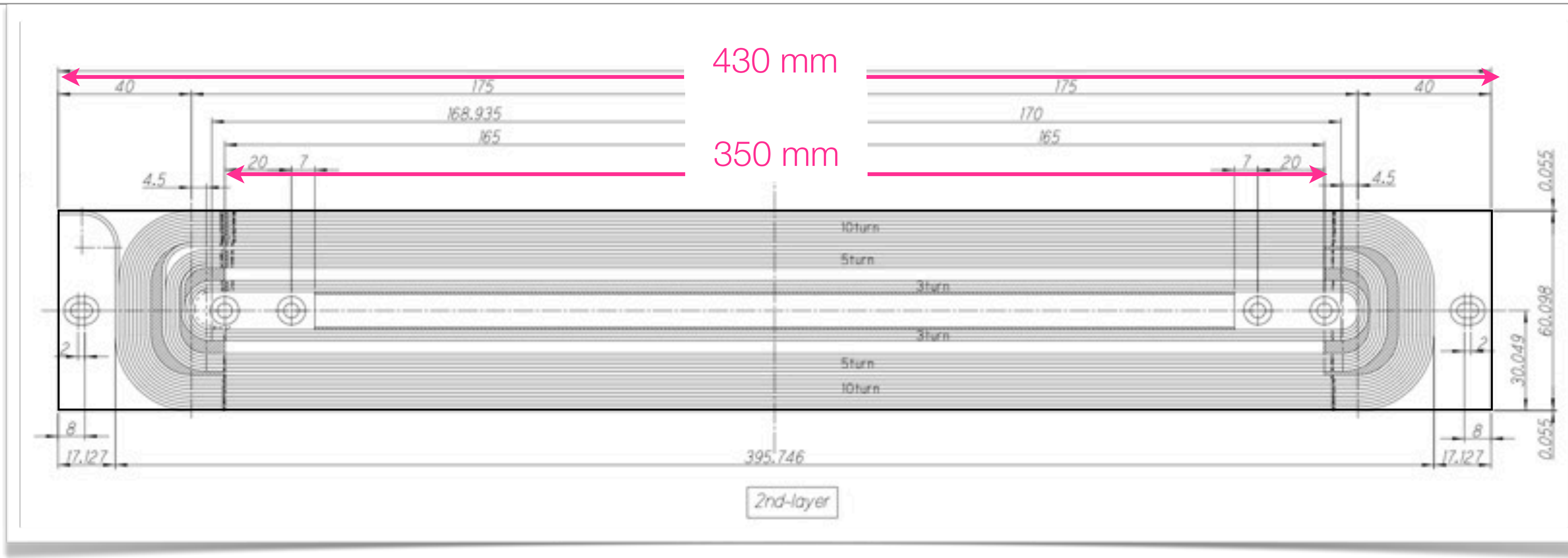


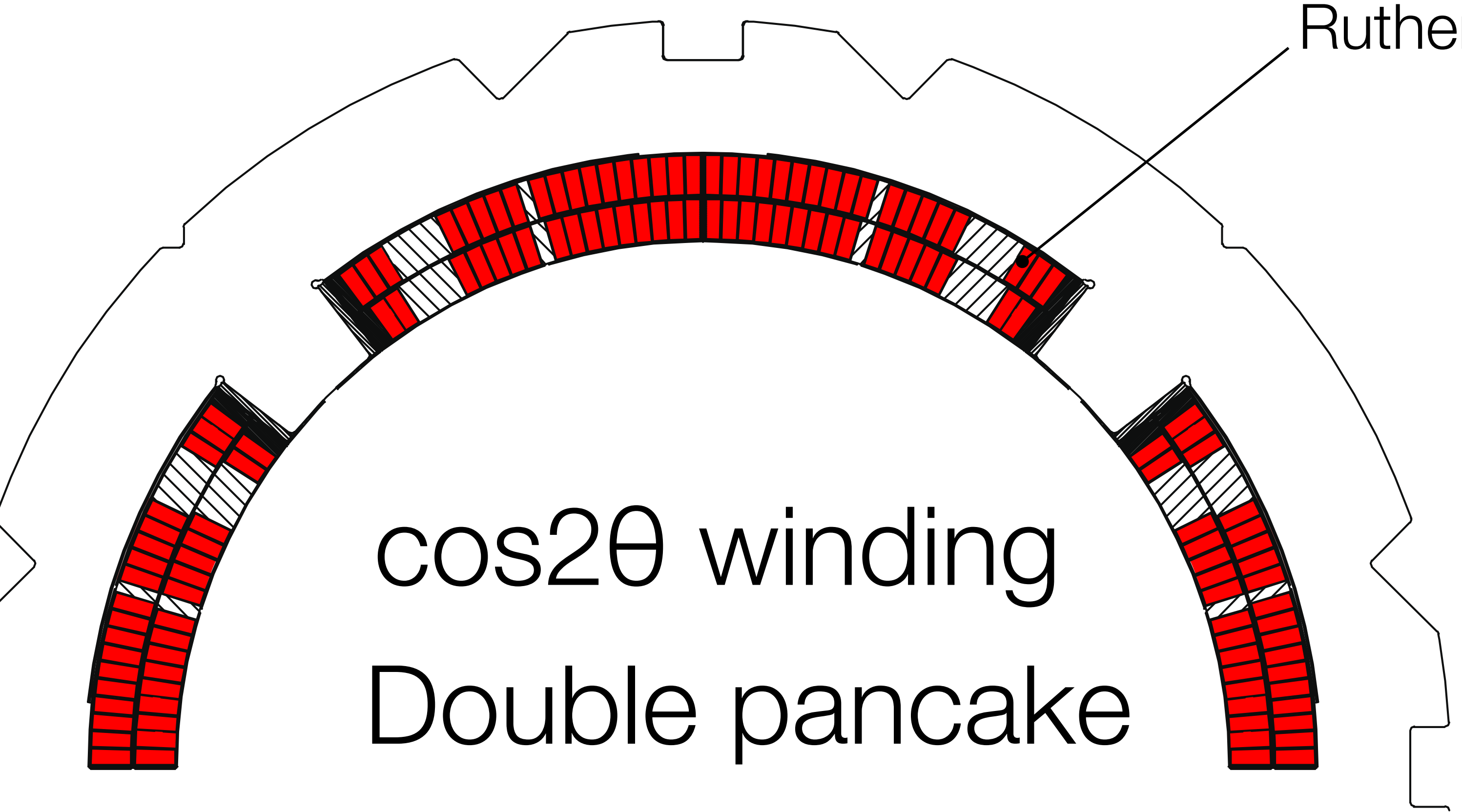
Magnet Name	G [T/m]	I [A]	Inner Radius [mm]	Effective Length [mm]
QC1LP/ QC1RP	68.94 / 68.89	1625 / 1624	25	334
QC2LP/ QC2RP	28.05 / 26.28	877.4 / 822.1	54	410
QC1LE/ QC1RE	72.21 / 70.89	1577 / 1486	33	373
QC2LE/ QC2RE	28.44 / 32.41	977.0 / 1068	59	537/419

Cross section of four quadrupole magnets

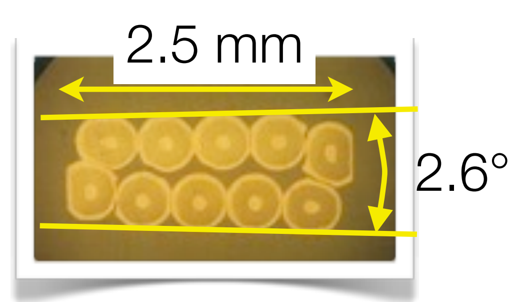


Quadrupole magnet (QC1E)

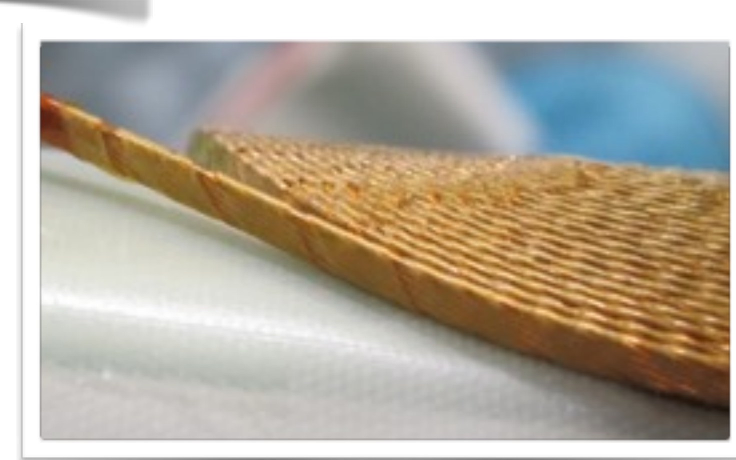




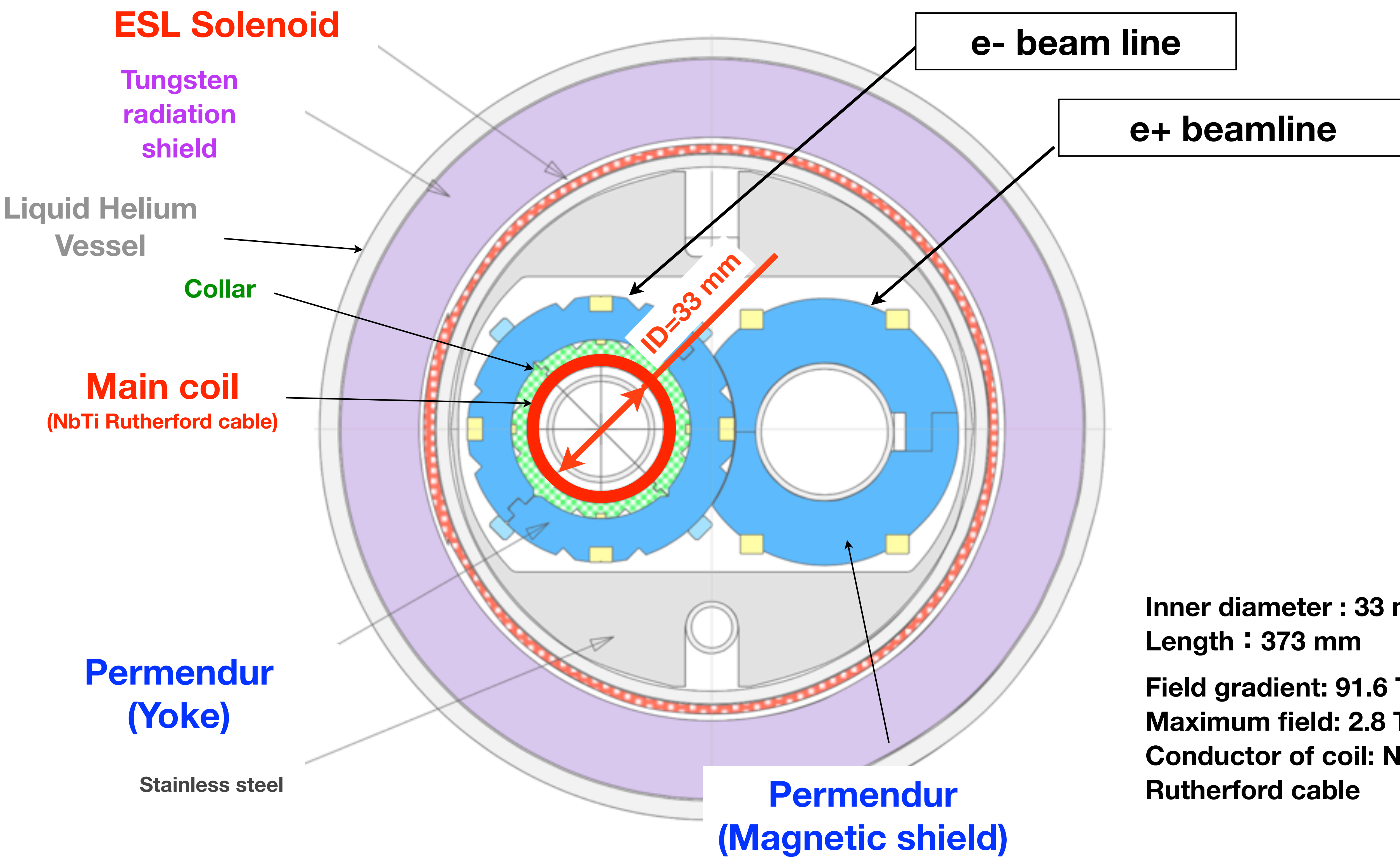
Rutherford cable



NbTi
RRR >150
Cu ratio 1.1
I_C : 305 A @5T, 4.2K



Cross section of QC1LE with Lq. Helium Vessel

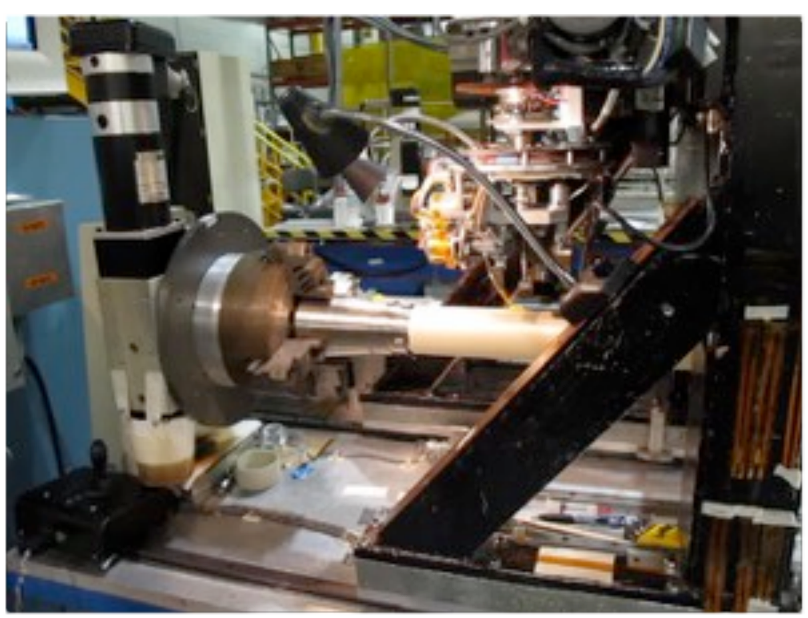
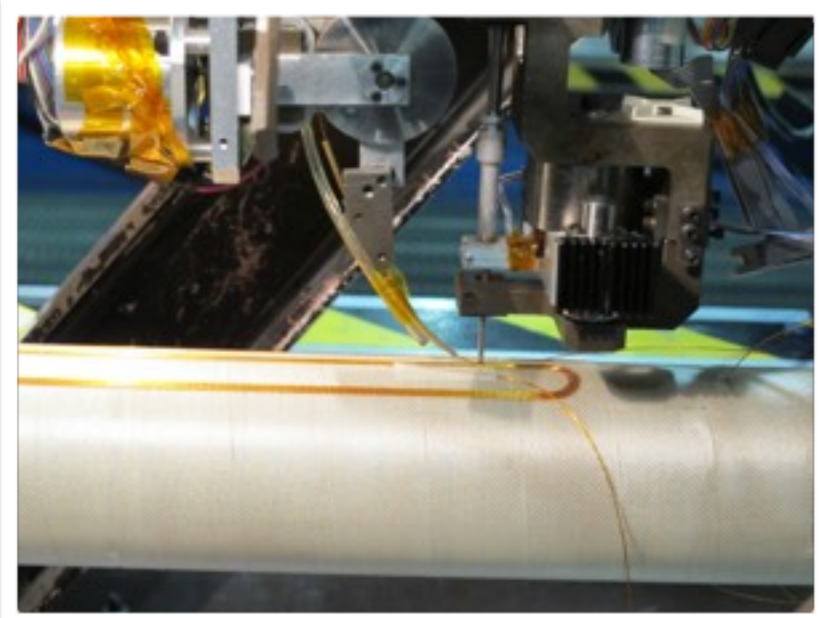


Inner diameter : 33 mm
Length：373 mm

Field gradient: 91.6 T/m
Maximum field: 2.8 T
Conductor of coil: NbTi Rutherford cable

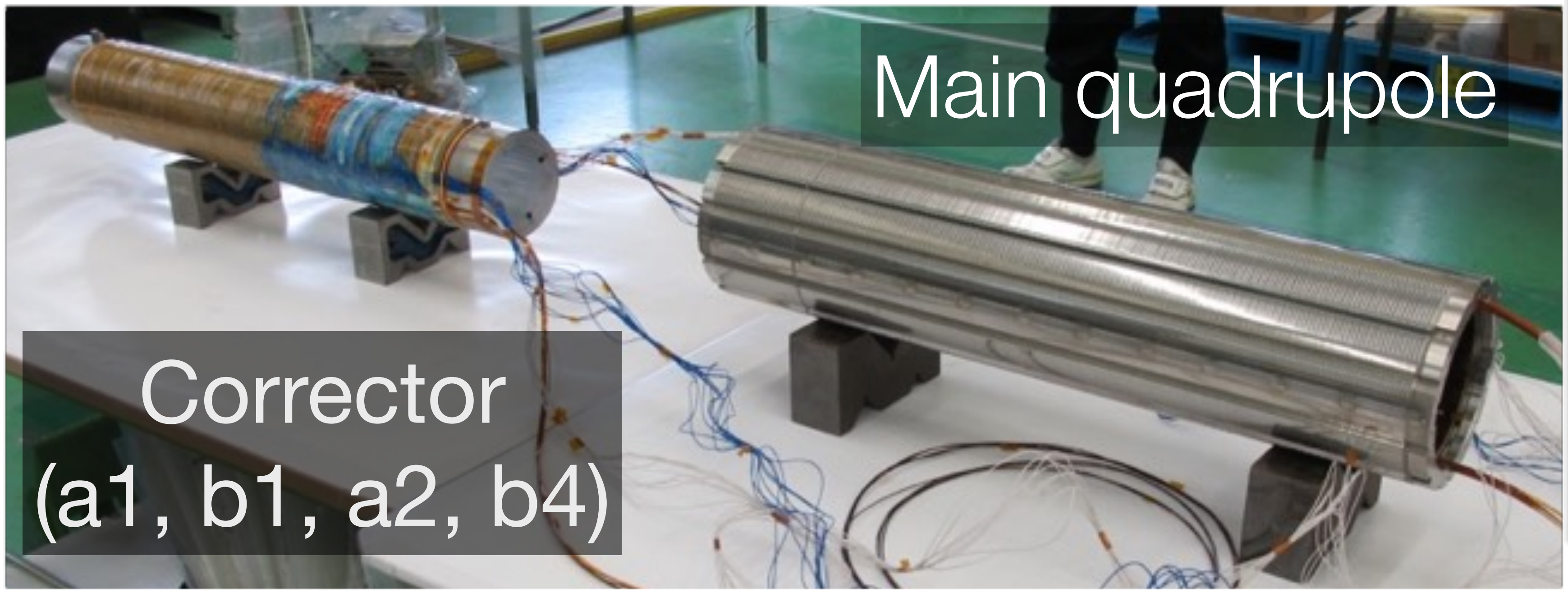
Corrector magnets

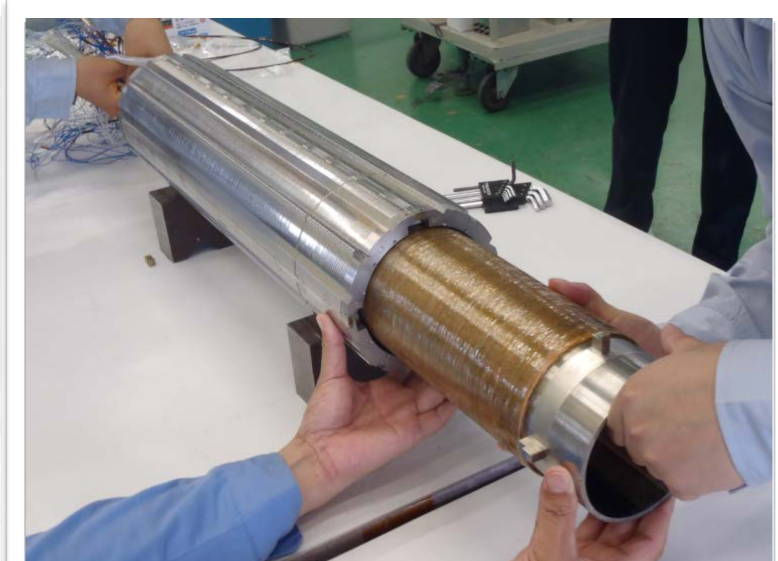
- One quadrupole magnet have 4 types of multipole correctors. (except for QC1RP; this has 5 correctors.)
- Types of multipoles of correctors: b1, a1, a2, a3, b3, b4
- NbTi wire, ϕ0.35 mm
- Direct winding method
- Produced by BNL under the US-Japan research collaboration

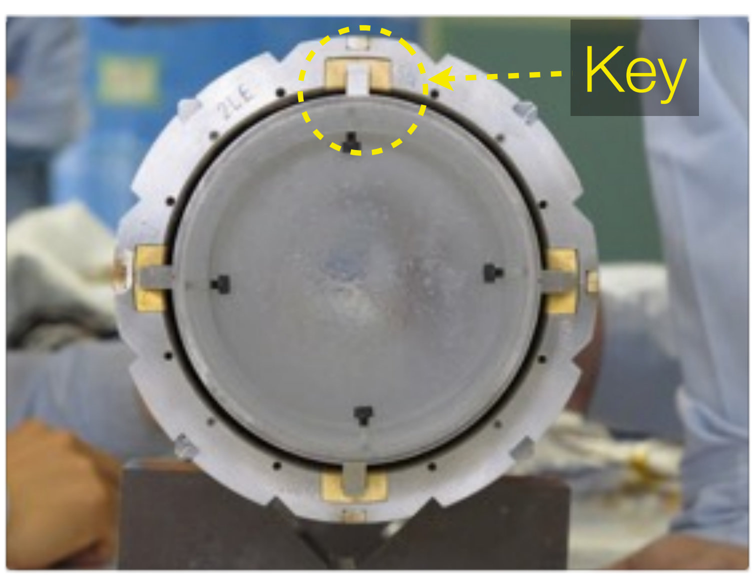



Winding process at BNL

Assembling of Corrector magnets



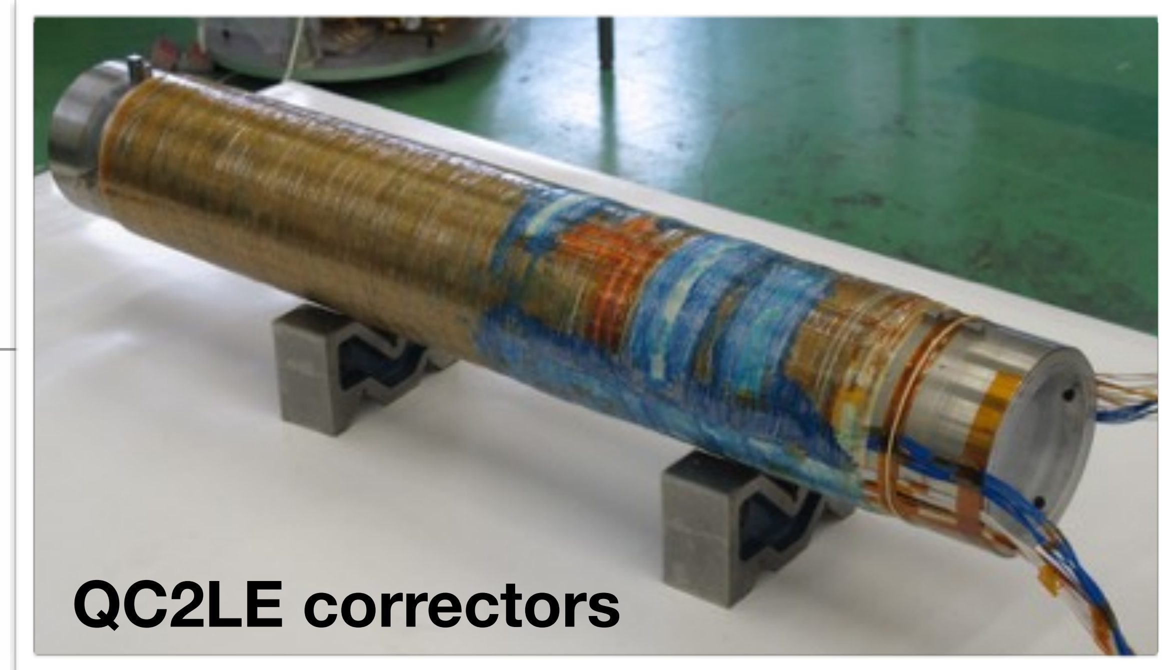


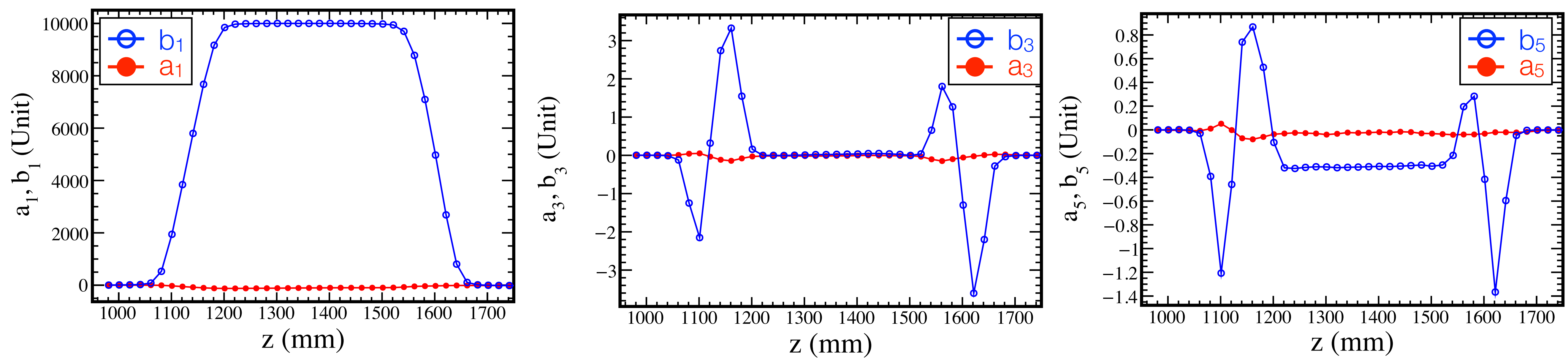


- Corrector and main quadrupole was independently wound. There is small gap between correctors and main quad. to avoid unwanted stress to the correctors.
- 4 types of correctors are wound at one bobbin
- Corrector are inserted inner side of main quadrupole magnet
- Roll angle between corrector and main quad is fixed with keys equipped on the corrector bobbin

B-field profile of corrector

B1 corrector of QC2LE





I=60 A Measured with harmonic coils

r=33 mm, L=20 mm

The profiles satisfy beam optics requirement

B. Parker, et. al, “THE SUPERKEKB INTERACTION REGION CORRECTOR MAGNETS”, Procs of IPAC2016, Busan, Korea, TUPMB041

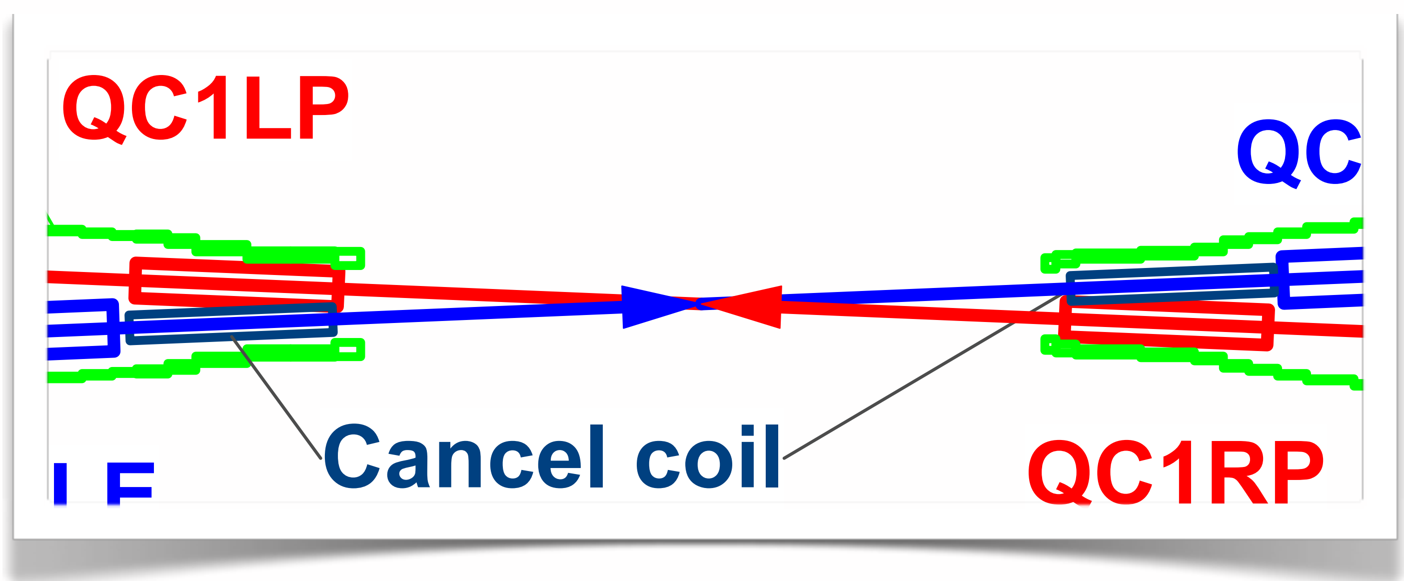
Cancel magnets

Cancel magnets **cancel a leak field** from the main quadrupole magnet on the positron beam line to the electron beam line.

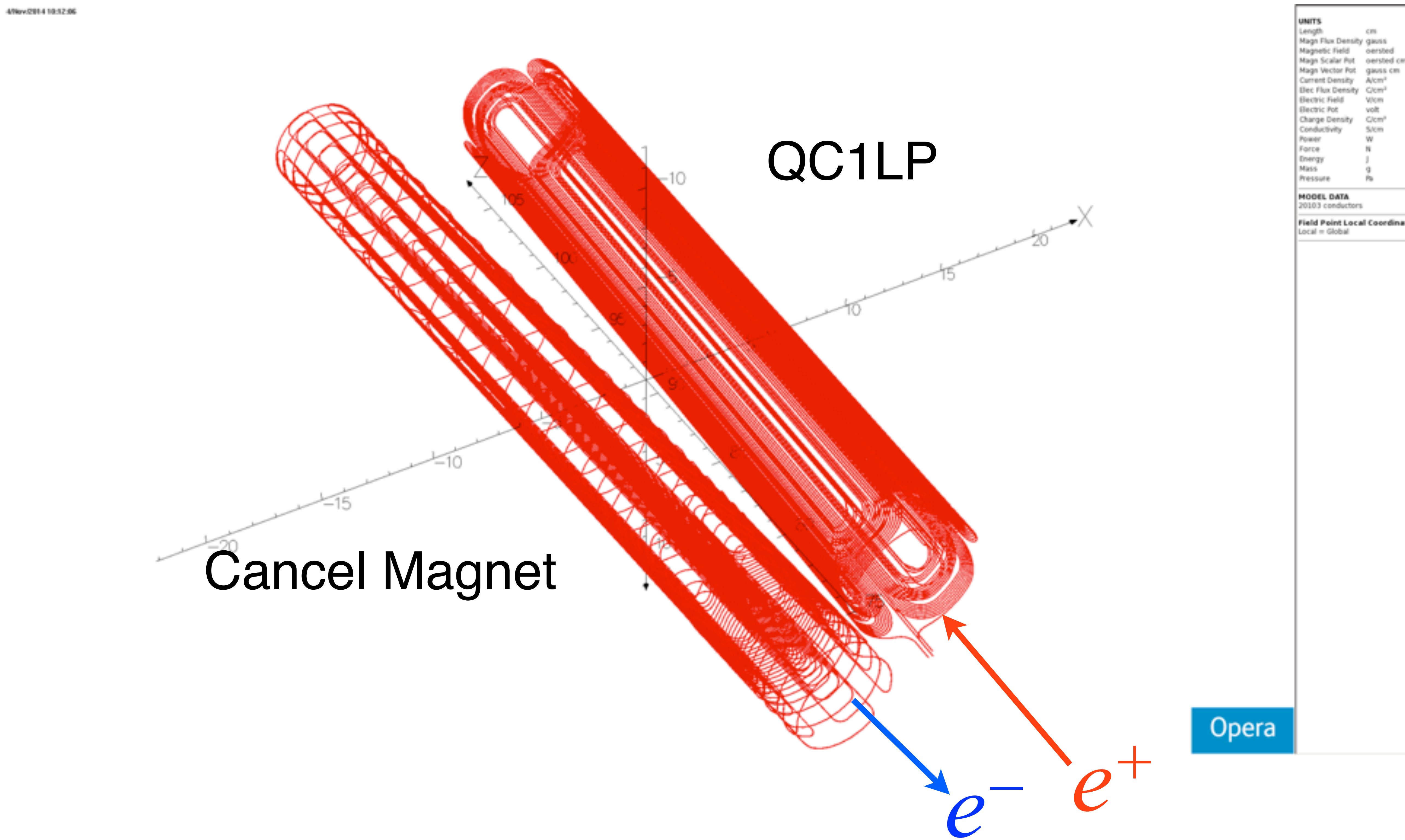
Cancel magnets consist of

- b3 magnet
- b4 magnet
- b5 magnet
- b6 magnet

on each (L/R) side.

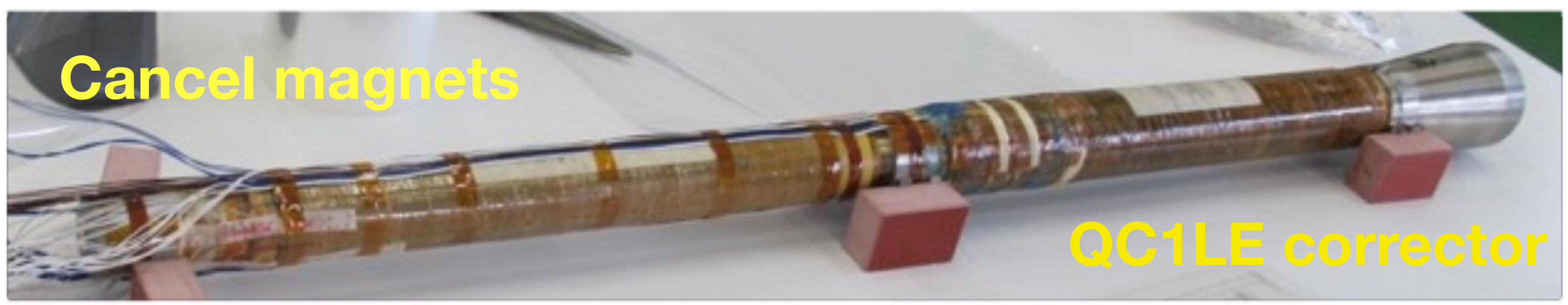


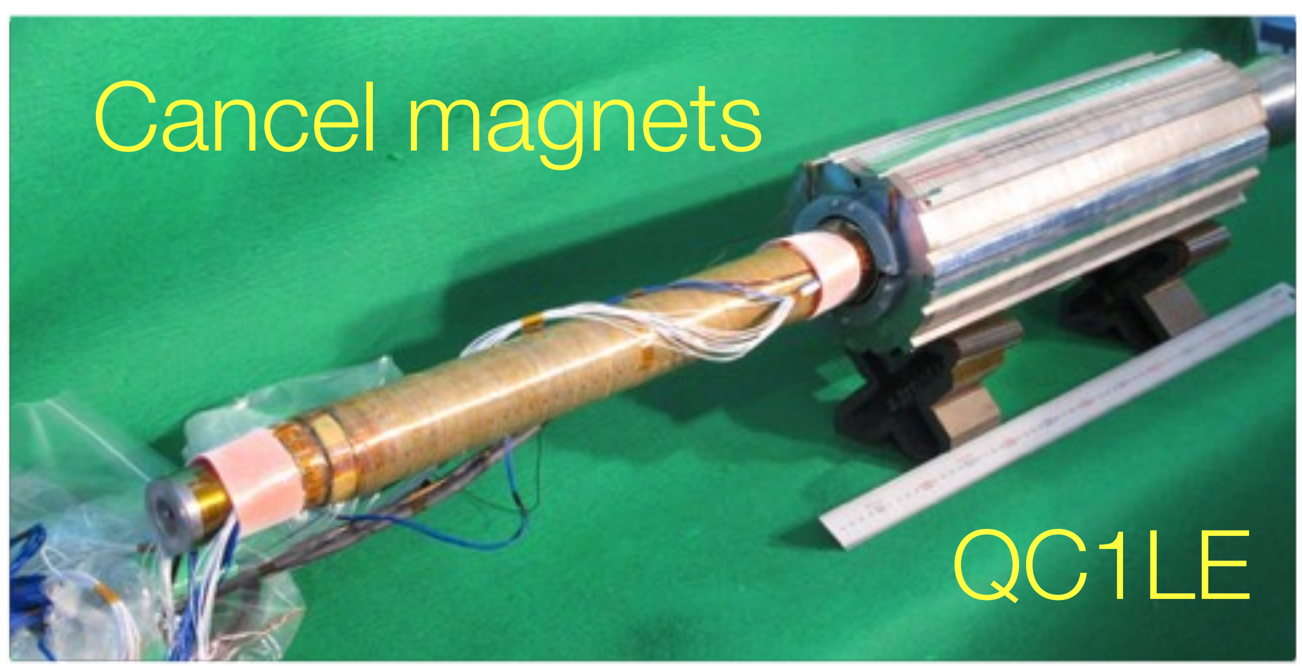
Layout of cancel magnets



Picture of cancel magnets

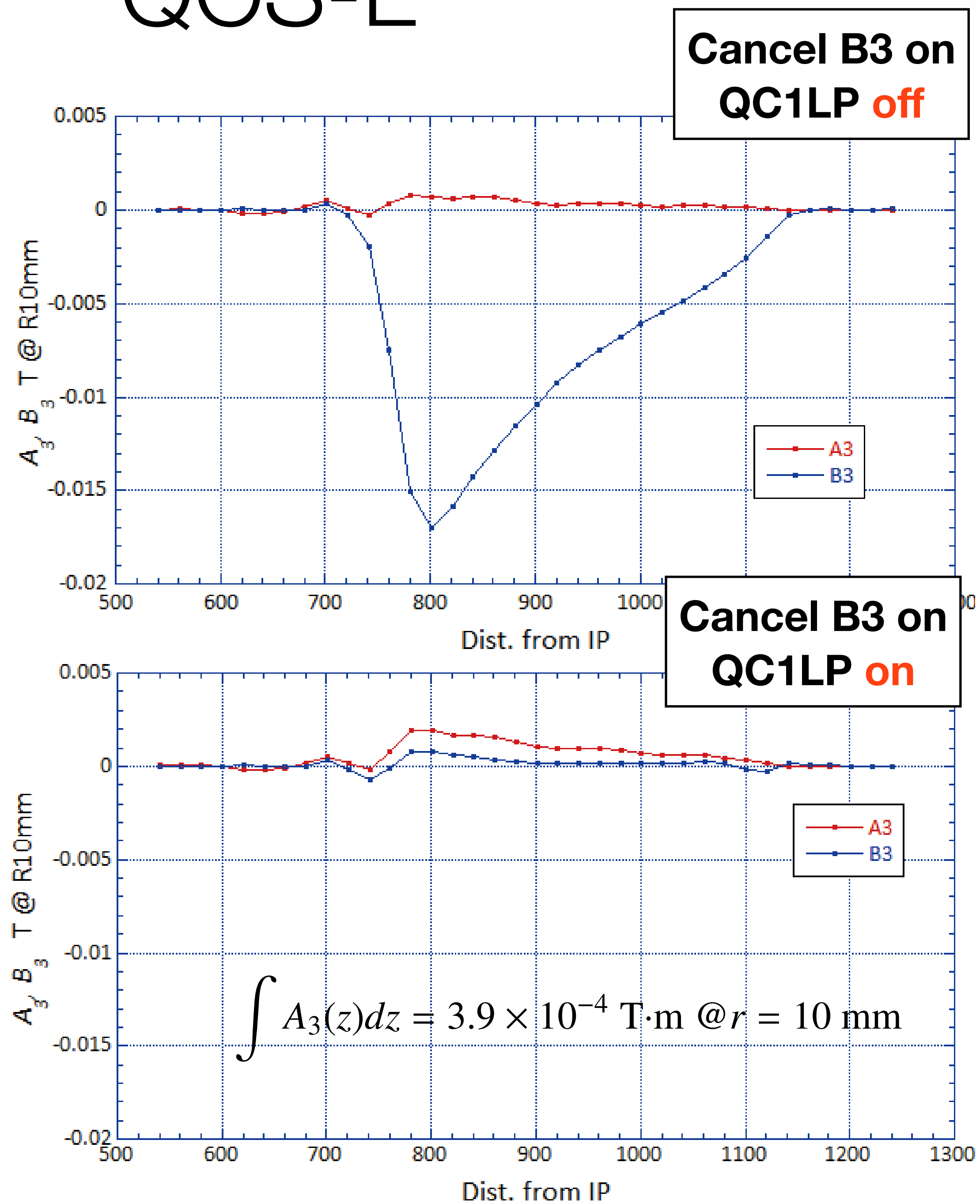
The cancel magnets and QC1LE correctors are wound to a same bobbin but these axial positions are different.



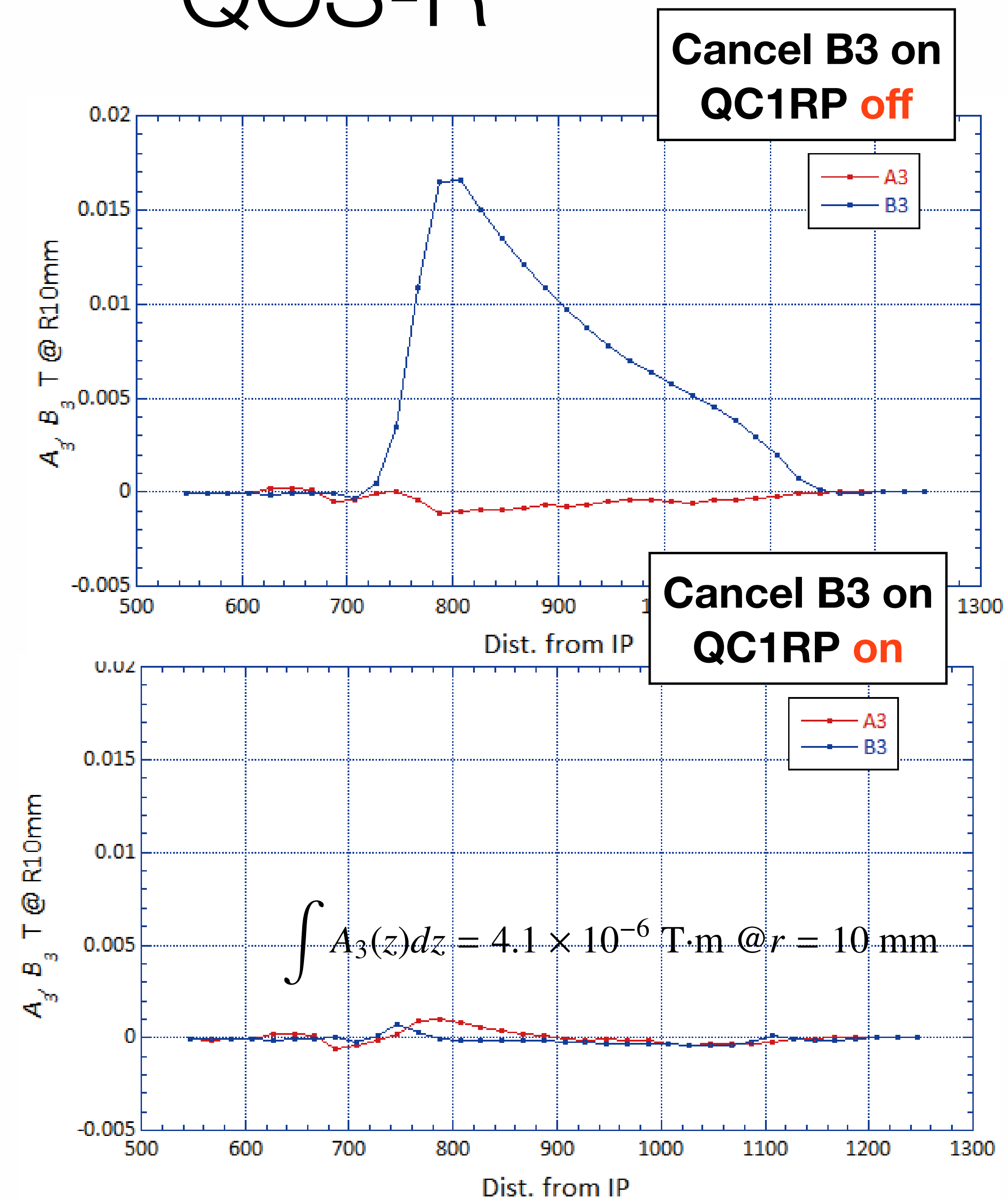


Sextupole components of Leak field on electron beam line

QCS-L



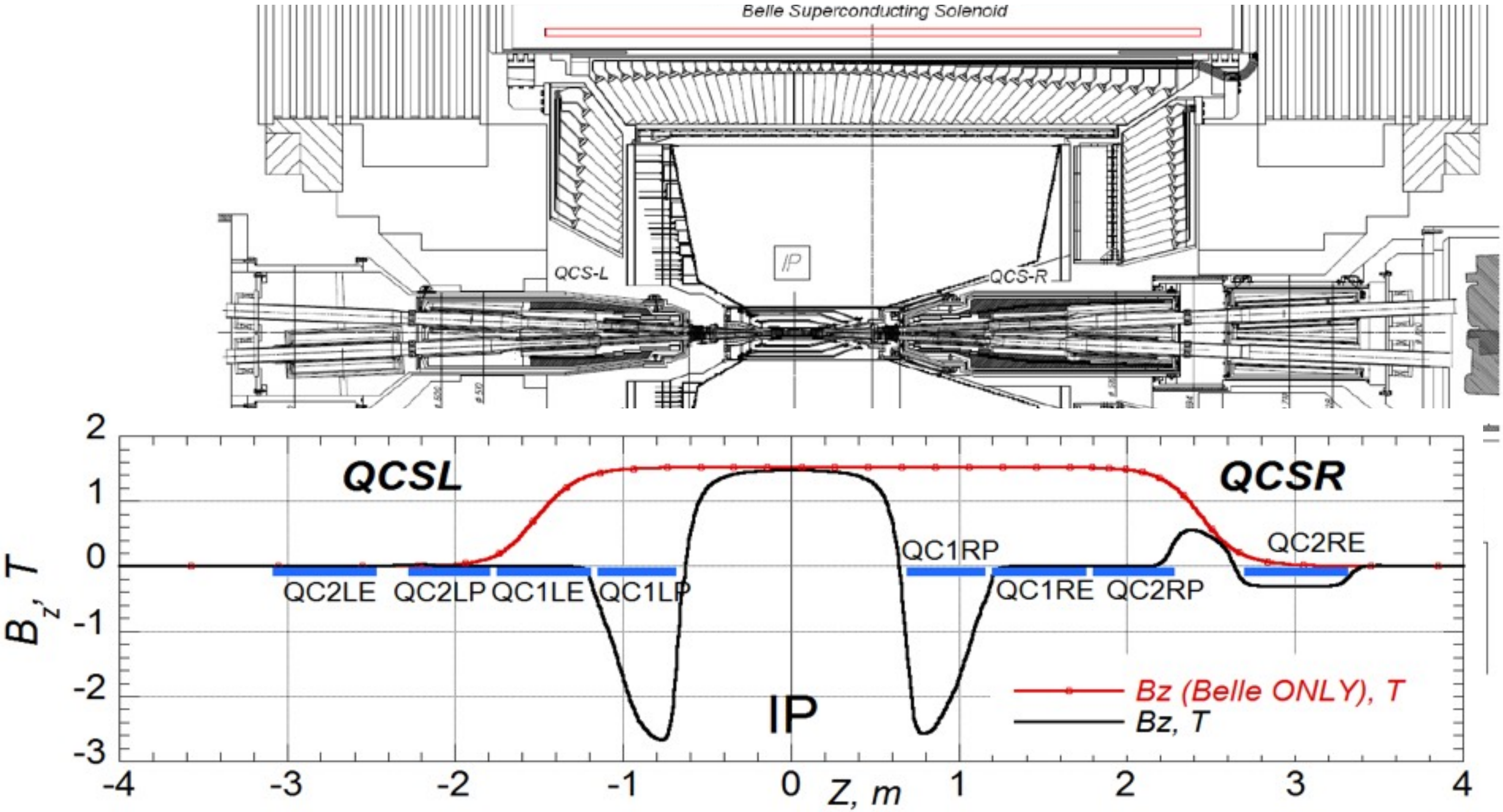
QCS-R



The energized current is optimized so that integral of B3 become to zero.
Sextupole component are reduced by the cancel magnet.

Compensation solenoids

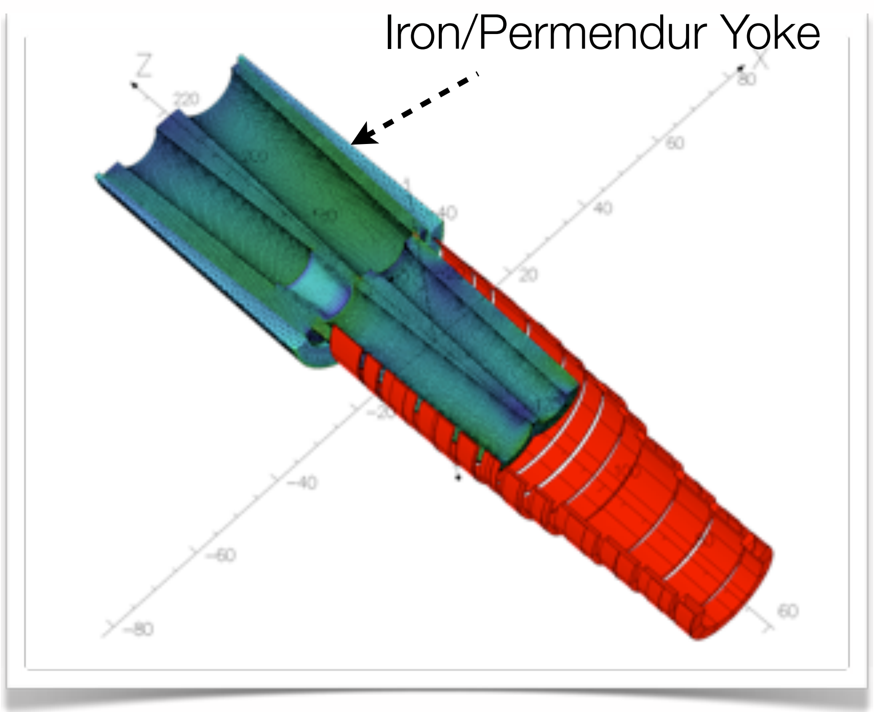
- The compensation solenoids generate inverse field wrt BelleII solenoid field (Bz=1.5T).
- Integral fields along beamlines become zero.



X. Wang

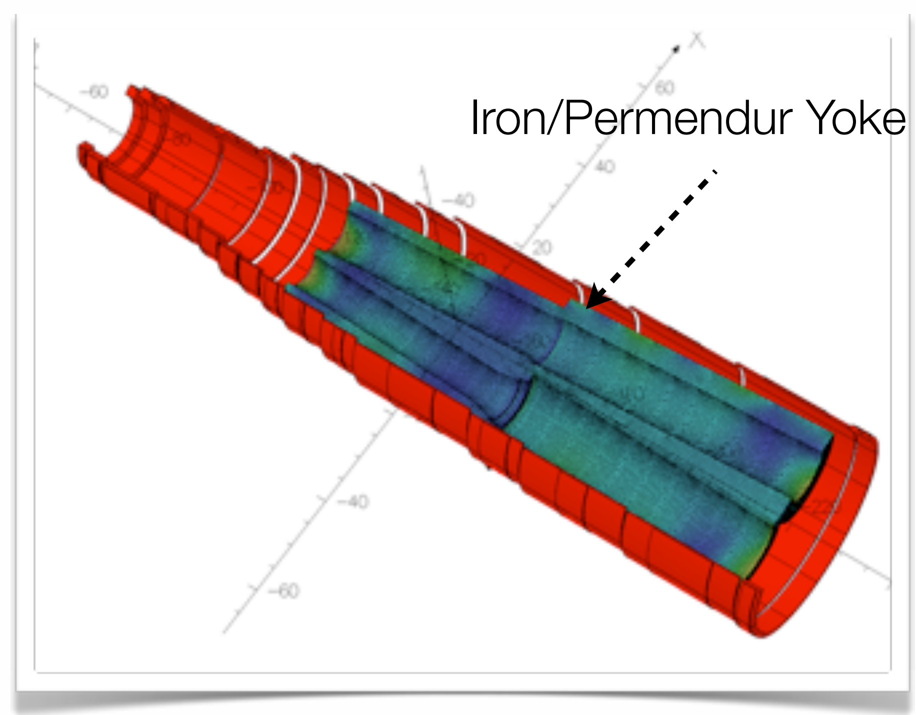
Compensation solenoids

ESL



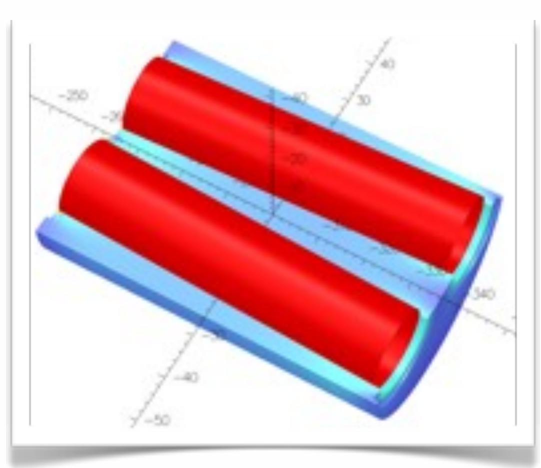
ESL consists of 12 coil blocks.

ESR1



ESR1 consists of 15 coil blocks.

ESR23



ESR23 consists of one solenoid on each beamline

Parameters of Compensation Solenoids

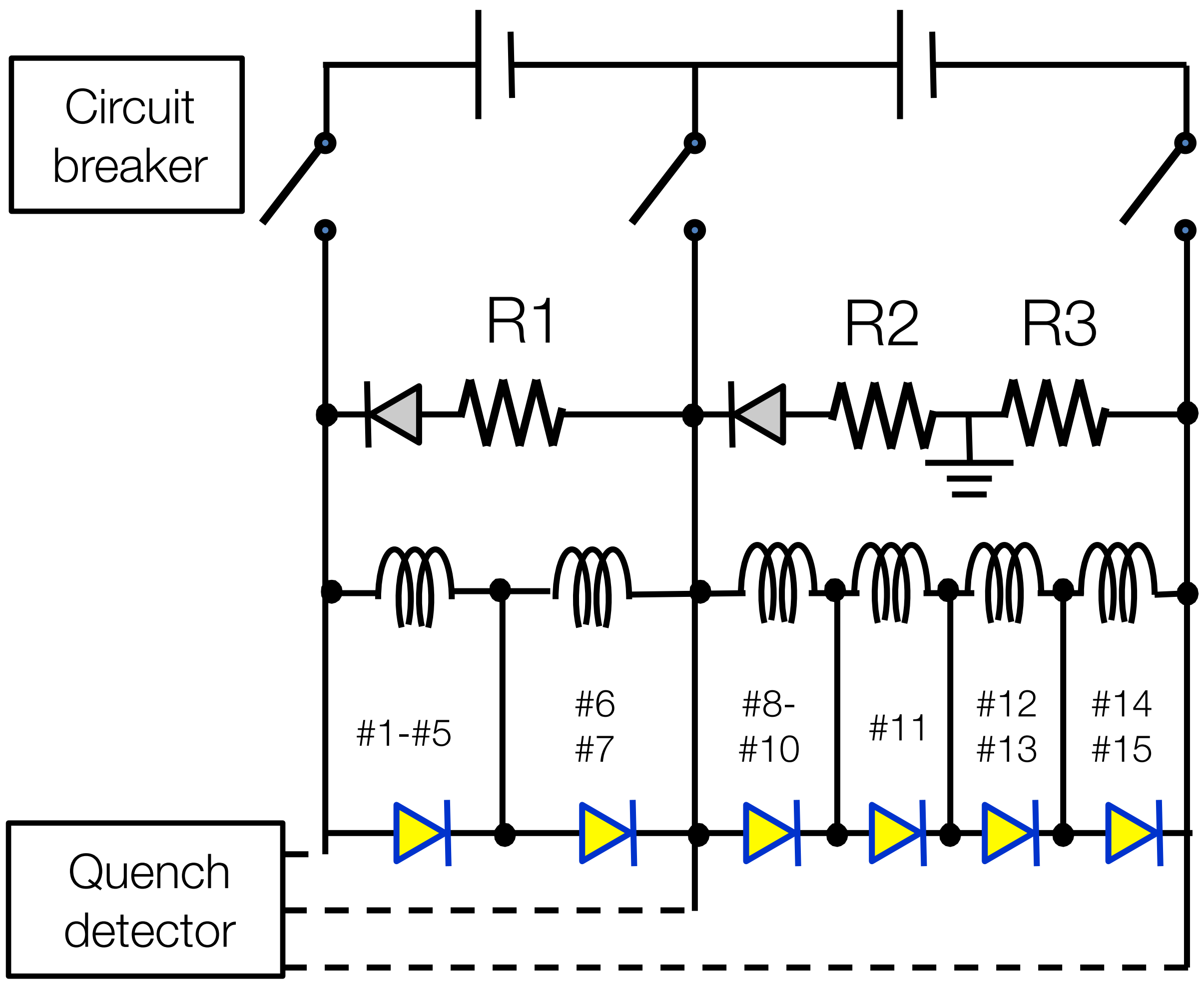
	ESL	ESR1	ESR2, 3
Number of coil blocks	12	15	1
Nominal operating current	404 A	450 A	151 A
Stored energy	118 kJ	244 kJ	1.6 kJ
Inductance	2.53 H	8.81 H	0.14 H
Maximum field in the coil	3.53 T	3.2 T	0.48 T
Load line ratio	0.53	0.51	0.11

ESL

ESR1

X. Wang

Quench protection of ESR1



Diode protection

For tuning field profile, the solenoid have two power sources.

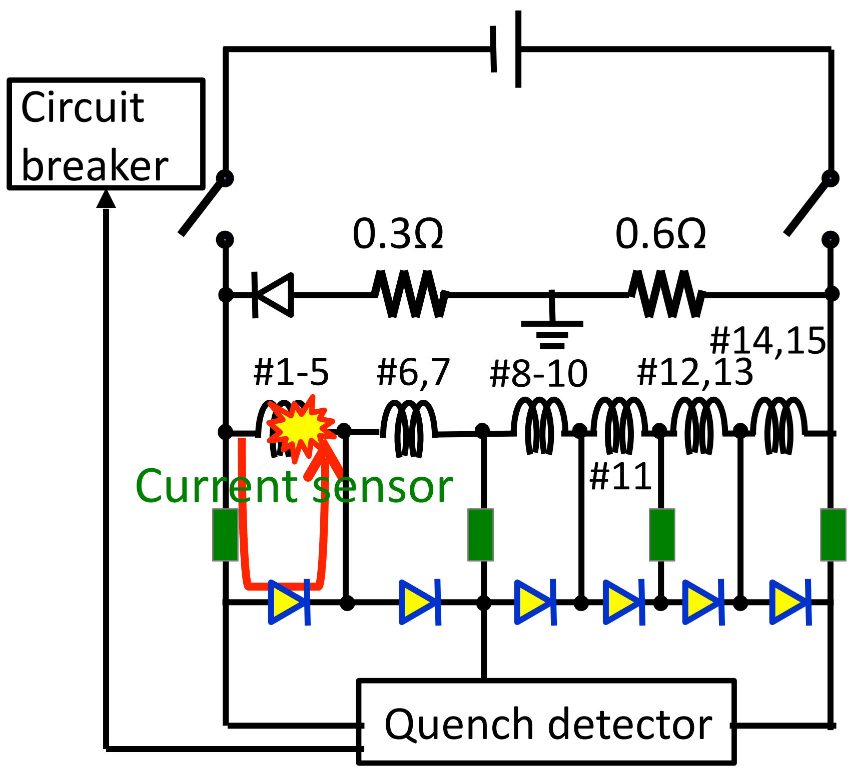
- Withstand voltage：< 200 V
- Temperature at quench：< 200 K

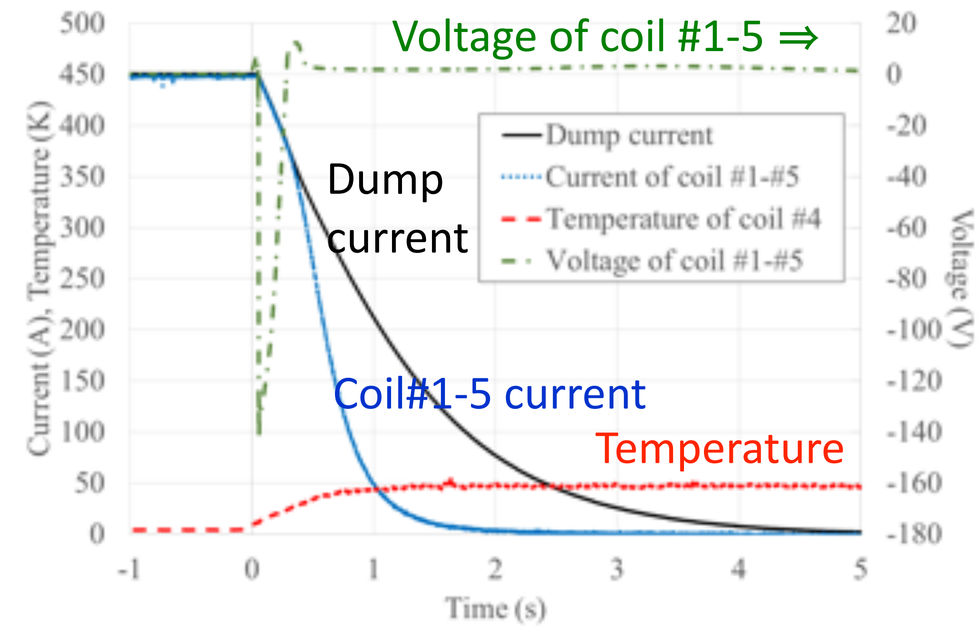
Grounded between R2 and R3.

$R_{total}(\Omega)$	R1(Ω)	R2(Ω)	R3(Ω)
0.828	0.34	0.074	0.414

X. Wang

Result from quench test





Coil ID	#4	#7	#8	#11	#12	#14
Measurement	50	50	50	50	60	50
Calculation	84	75	73	54	75	54

Maximum temperature (K)

- ✓ Maximum temperatures are less than 100 K
- ✓ This system is working well.

X. Wang

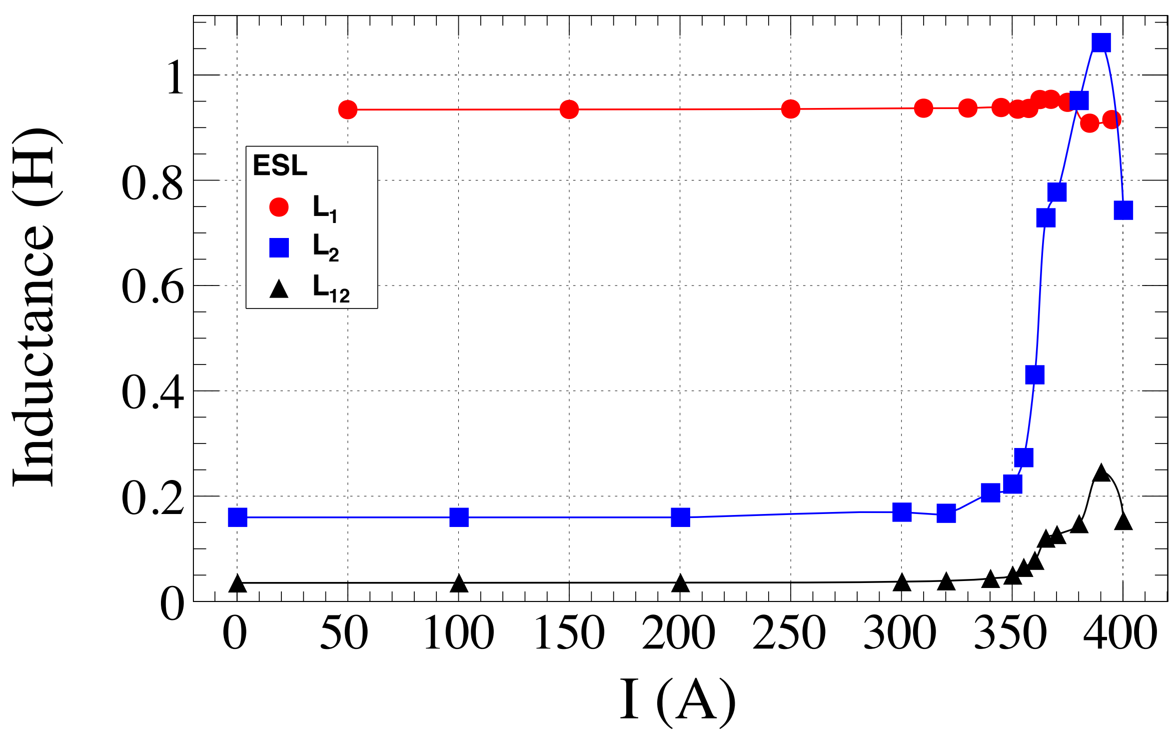
Variation of inductance of ESL/ESR1

If current of ESR/L is reduced, the B-field of Belle II is flown into the QCS yokes, the permeability is saturated.

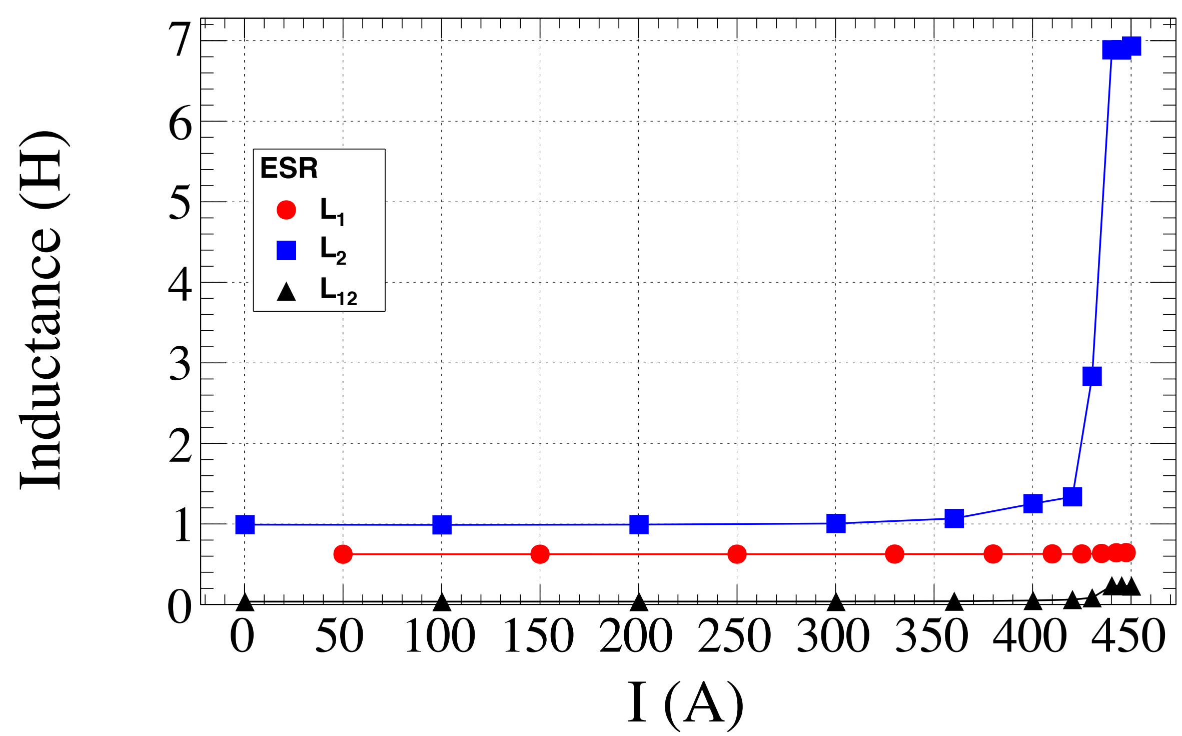
As the results, the inductance of ESL/R exhibit large variation.

This behavior makes difficult to design power supplies of ESL/ESR1 so that the power supplies do not oscillate during energizing the solenoids.

ESL (Belle II on)

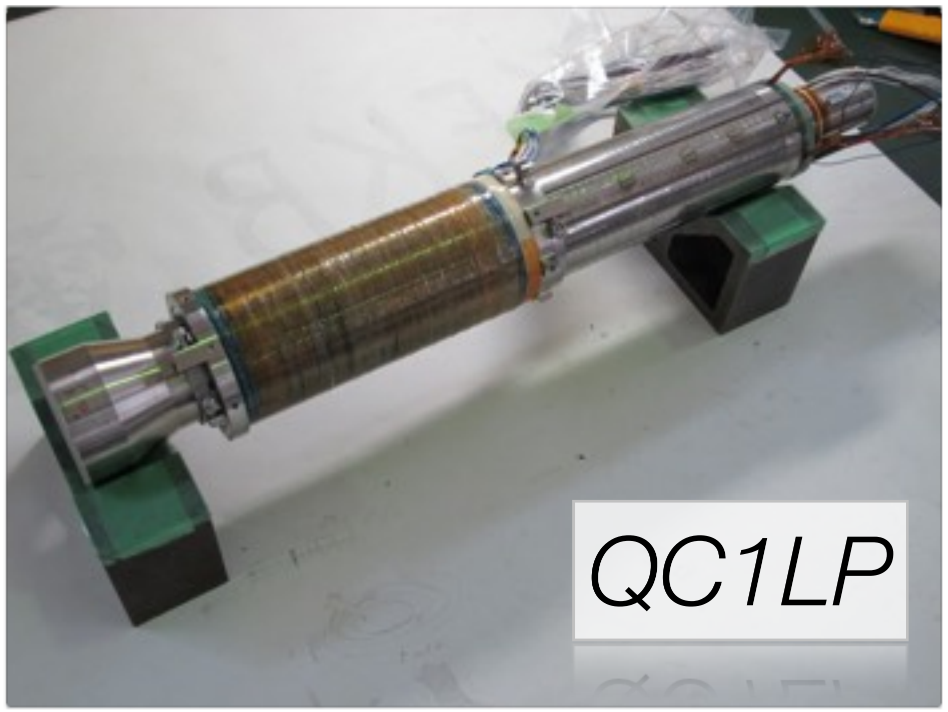


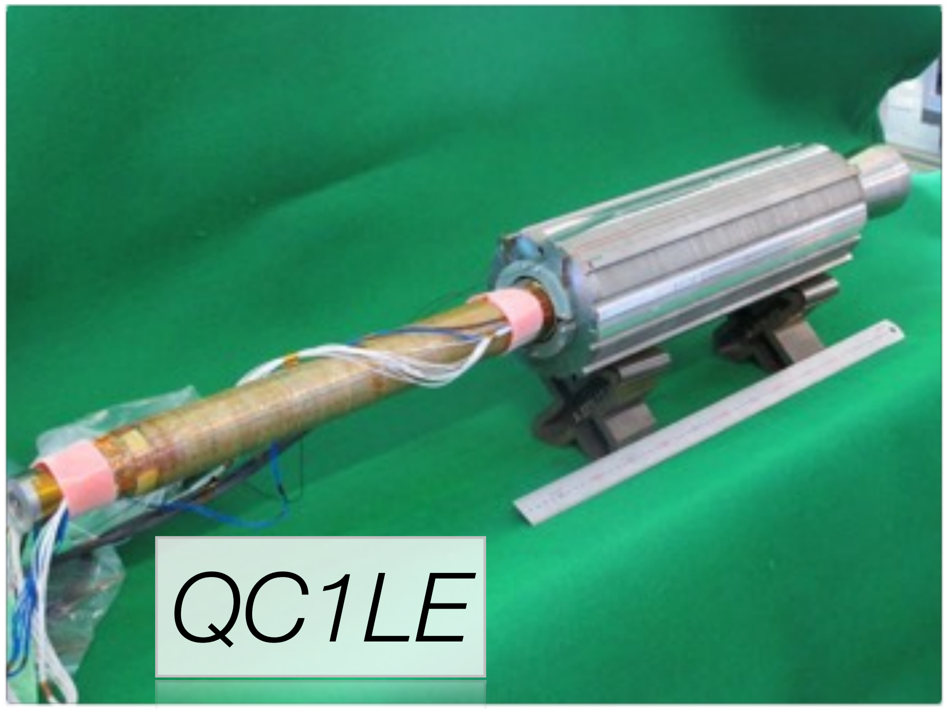
ESR1 (Belle II on)

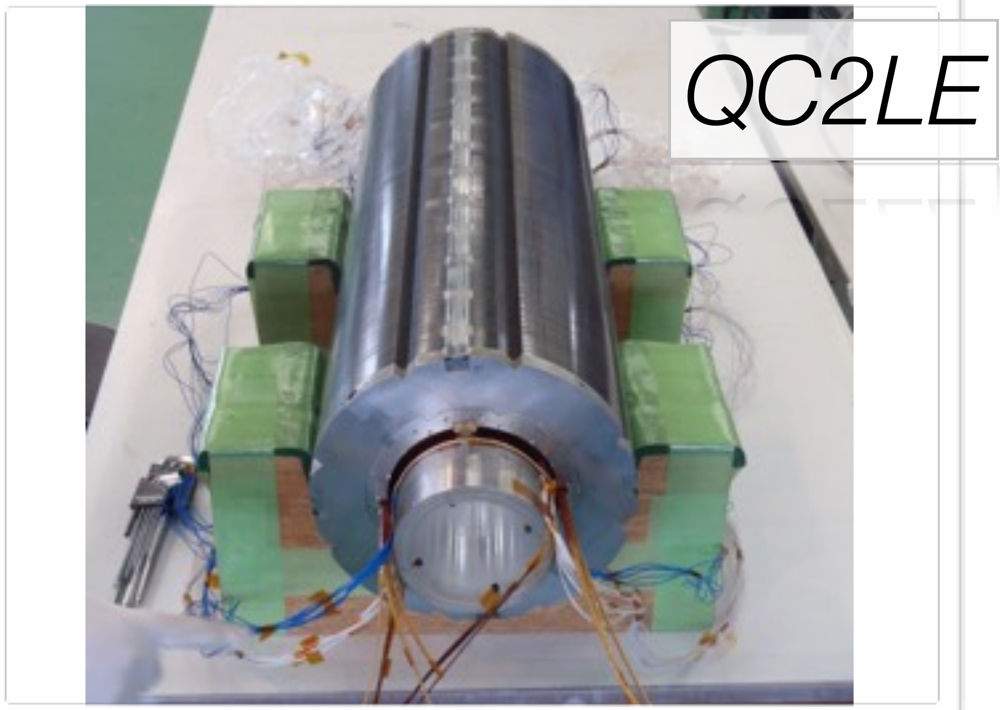


Assembling pictures of QCS

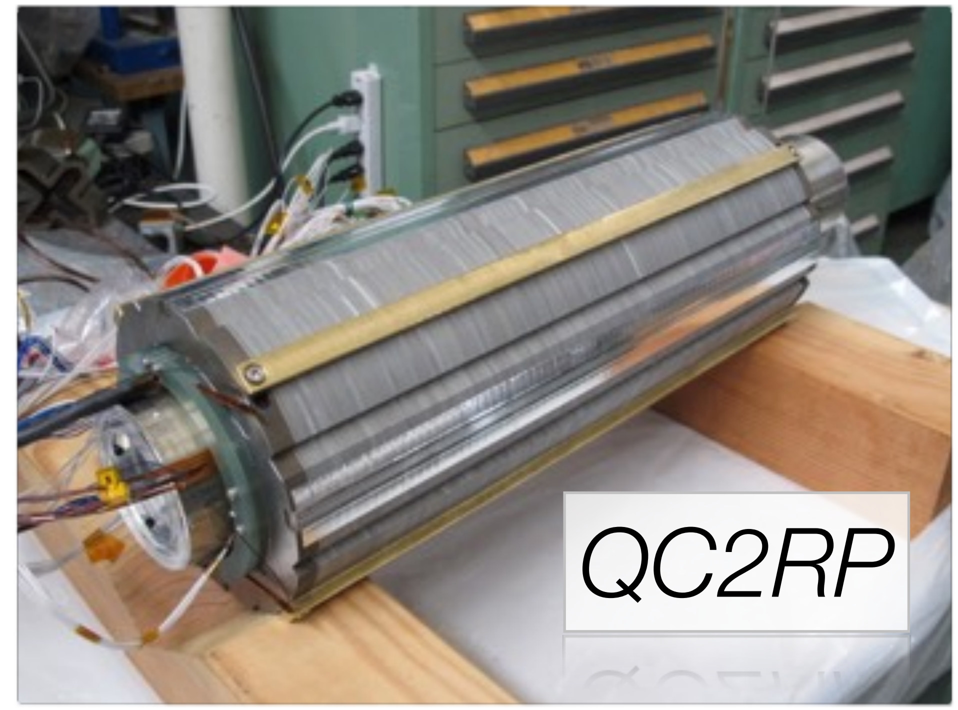
Quadrupole magnets (on left side of IP)

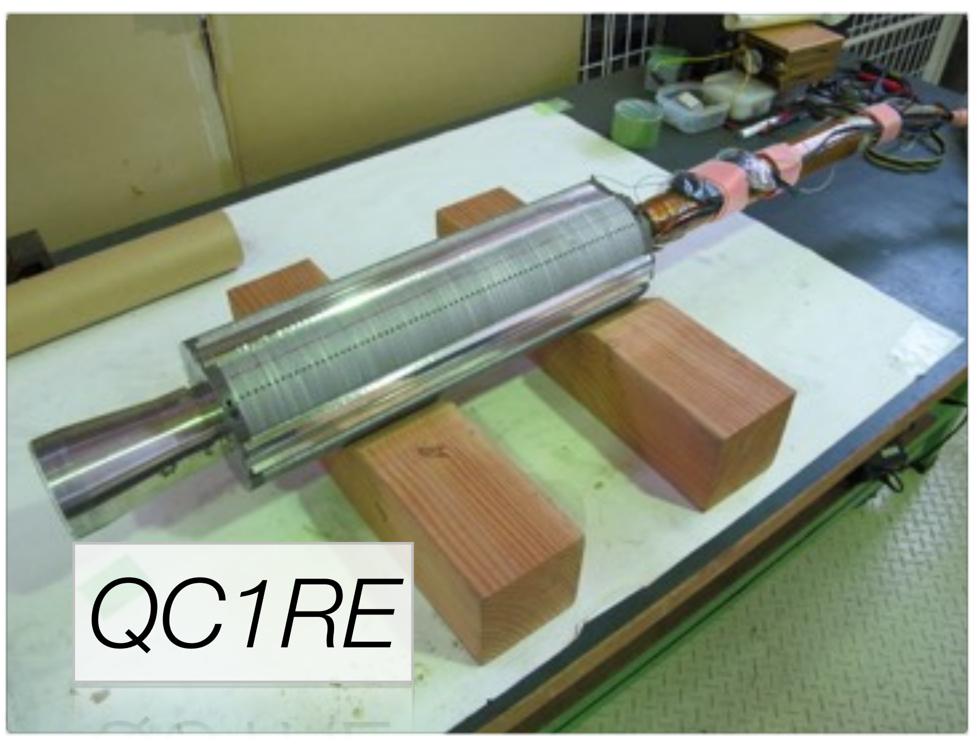




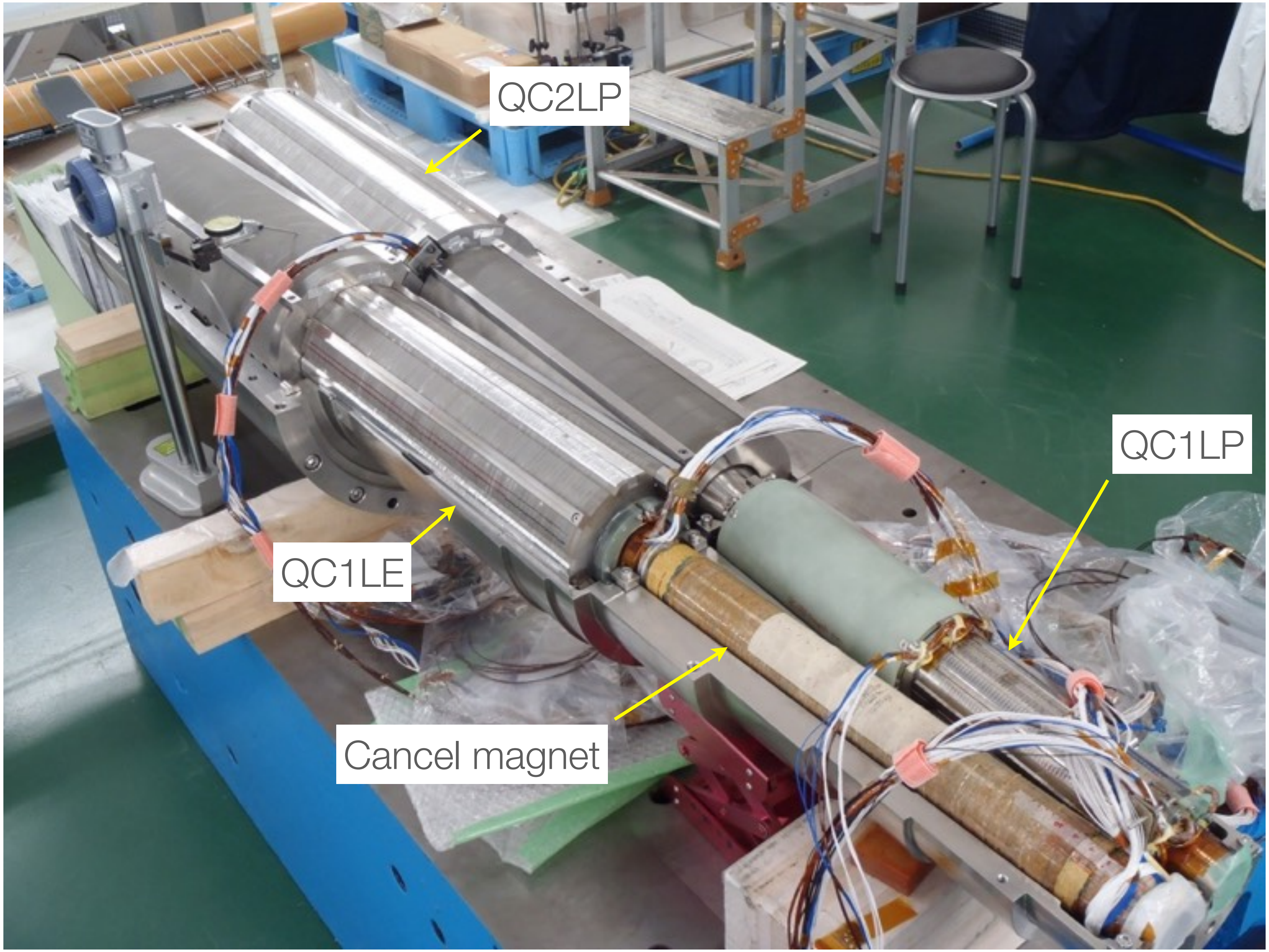


Quadrupole magnets (on right side of IP)

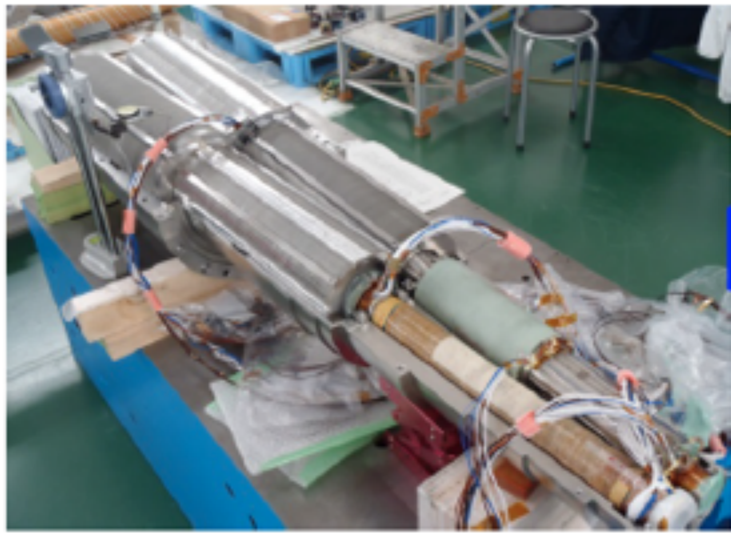


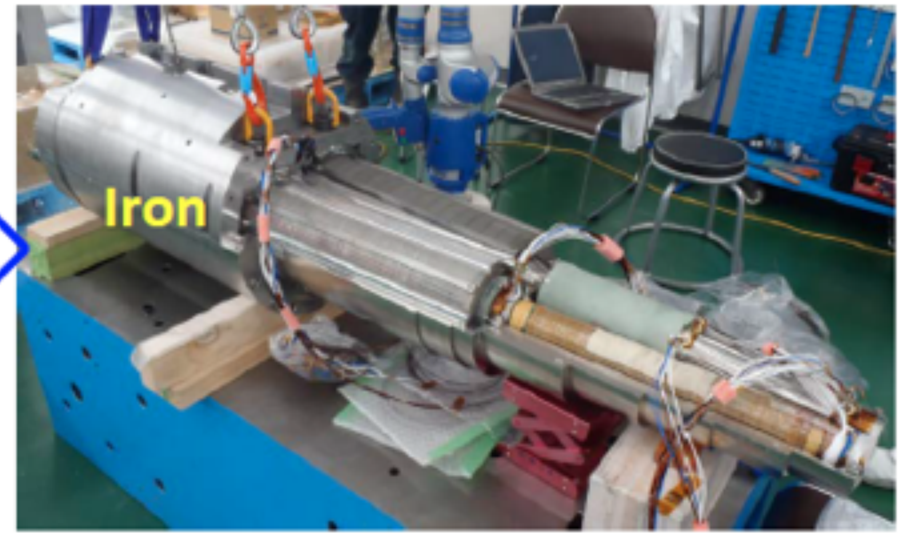


Assembled three quadrupole magnets



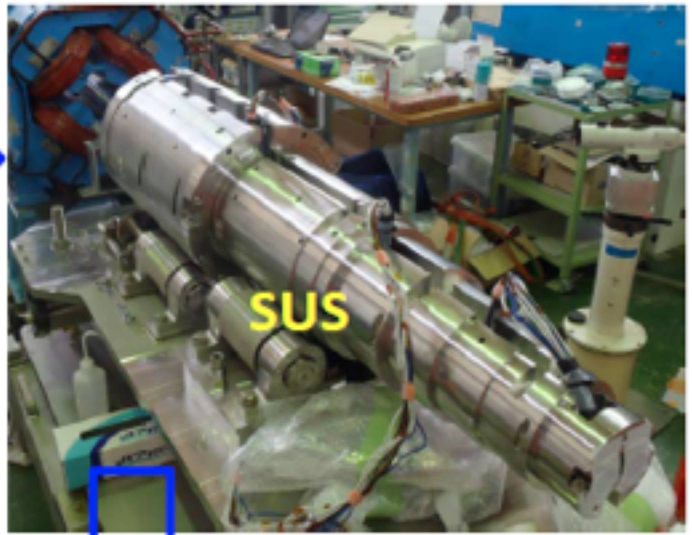
Assembly of the front cold mass of QCSL

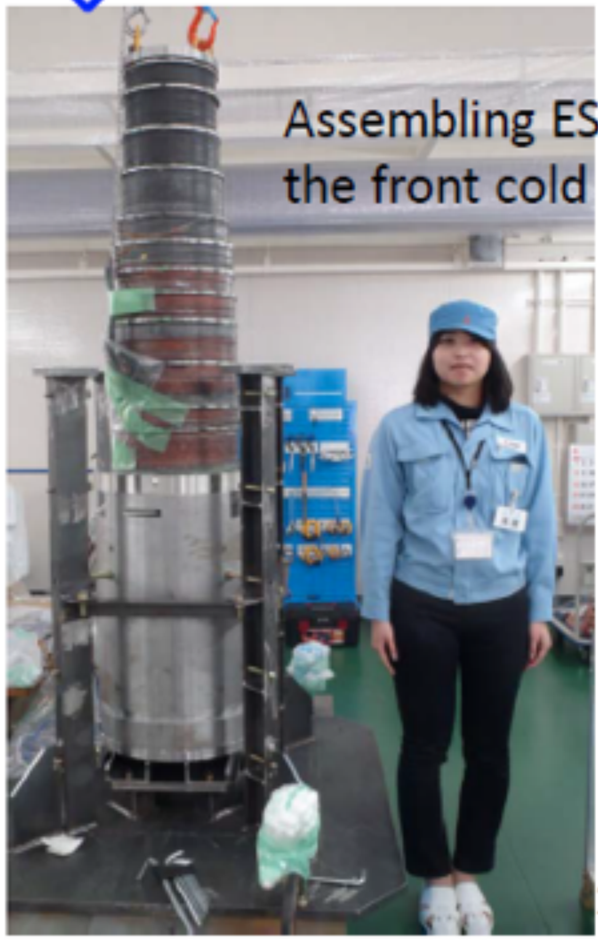




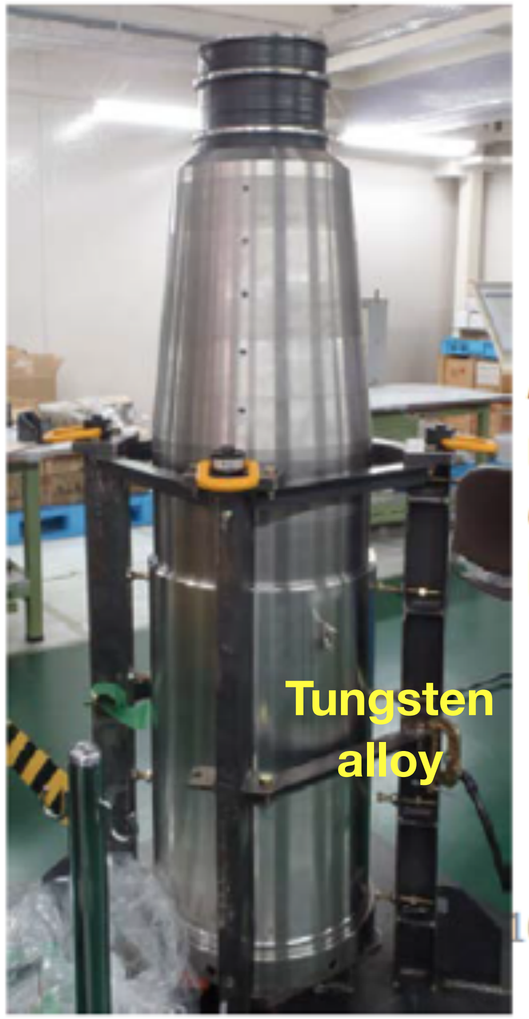
Fixing the magnets with the support components

Measurement of quadrupole alignment in the cold mass with the stationary harmonic coil at room temperature





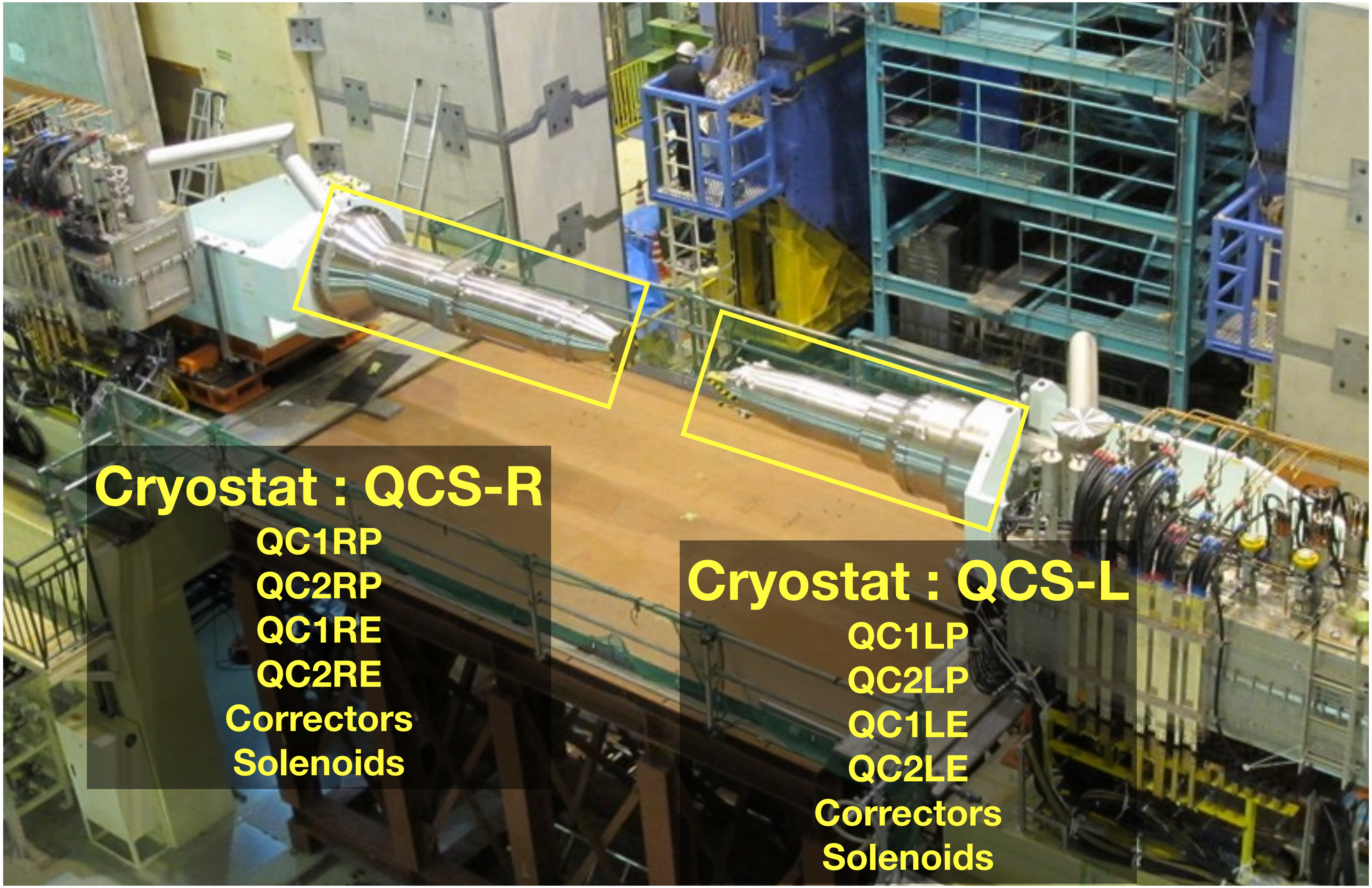
Assembling ESL on the front cold mass



Assembling the radiation shield of W alloy on ESL

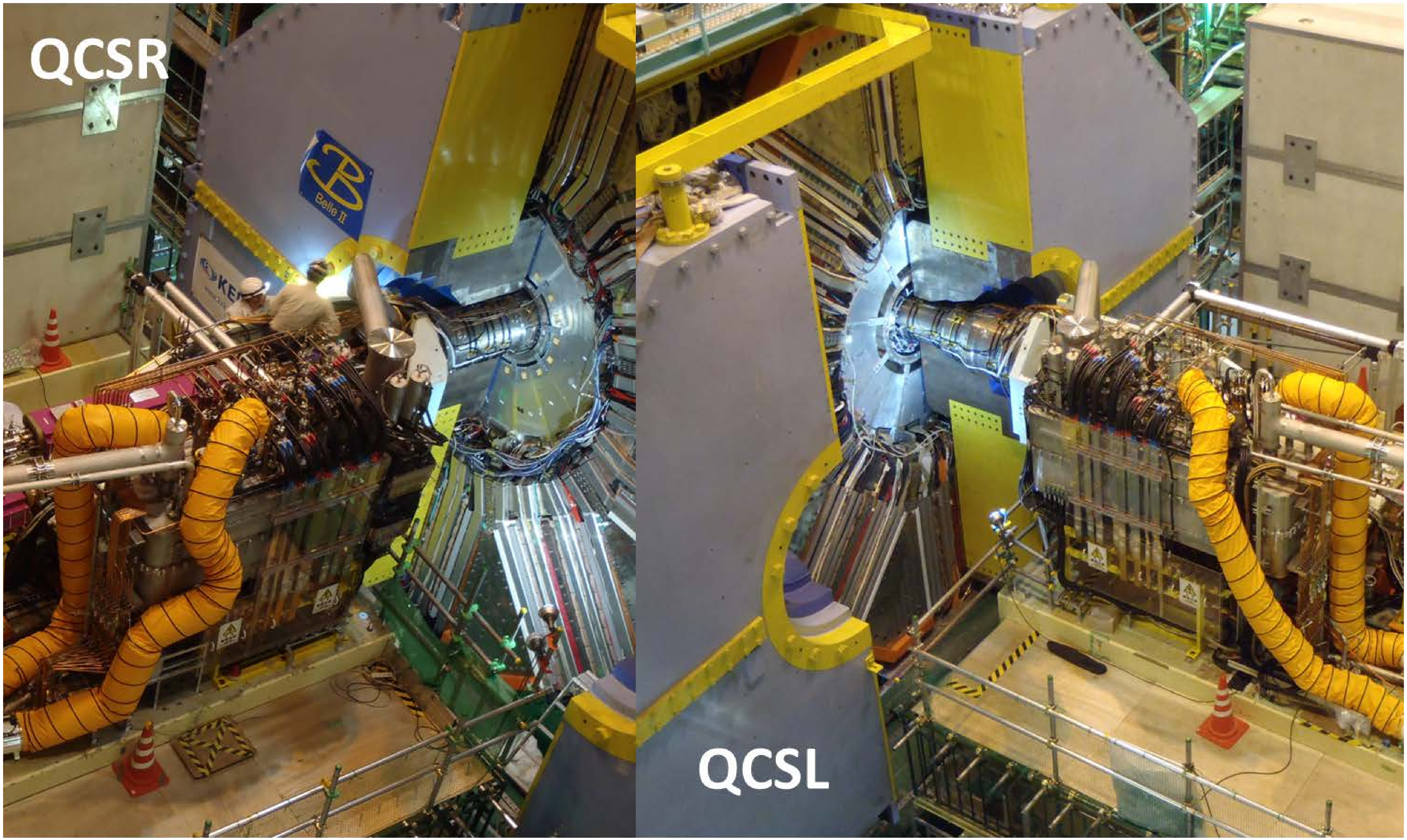
Covering the cold mass with the helium vessel and welding the vessels

QCS at IR



Cryostat : QCS-R
QC1RP
QC2RP
QC1RE
QC2RE
Correctors
Solenoids
Cryostat : QCS-L
QC1LP
QC2LP
QC1LE
QC2LE
Correctors
Solenoids

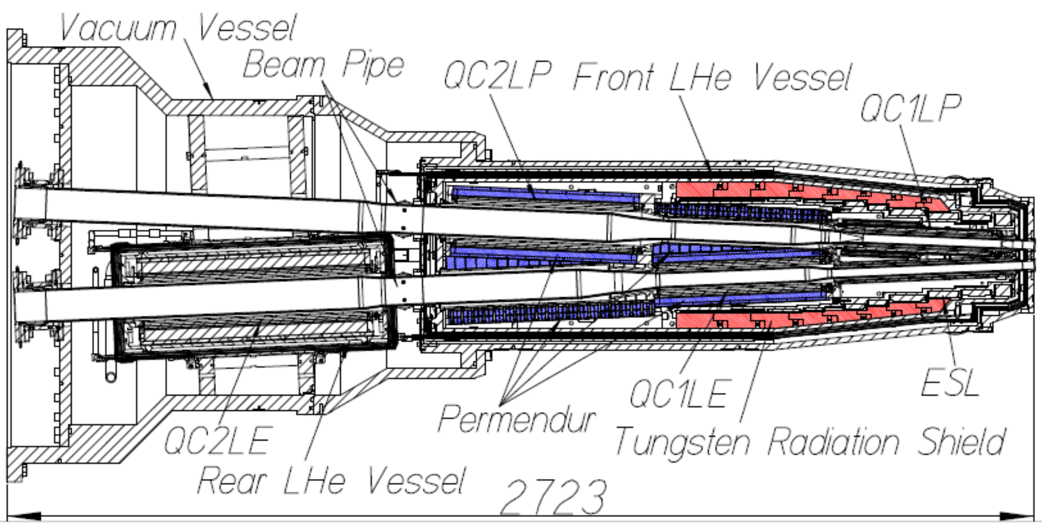
QCS and Belle II detector before closing concrete shield



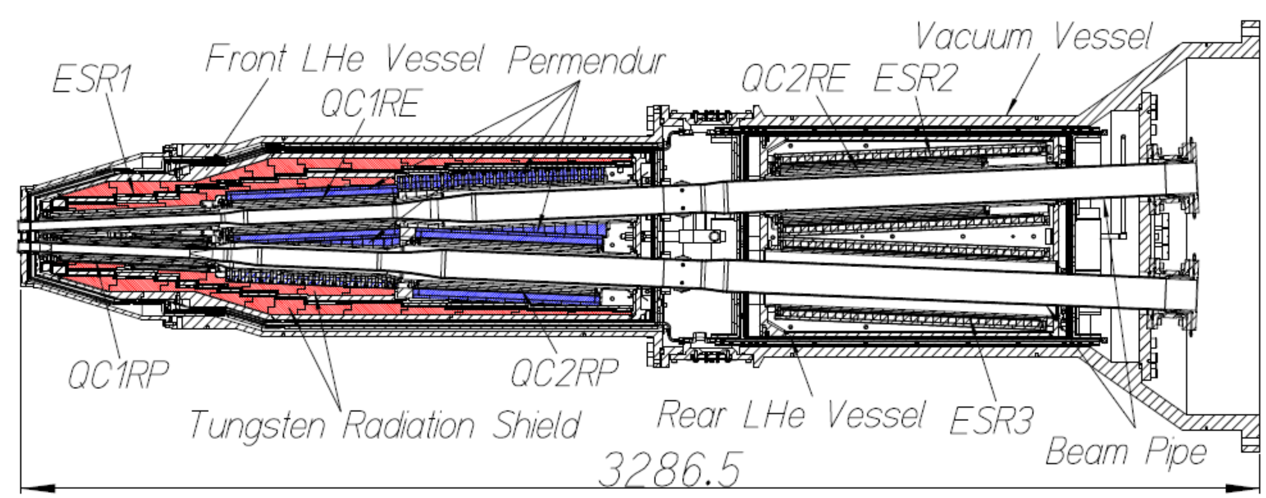
Cryostat and cooling system

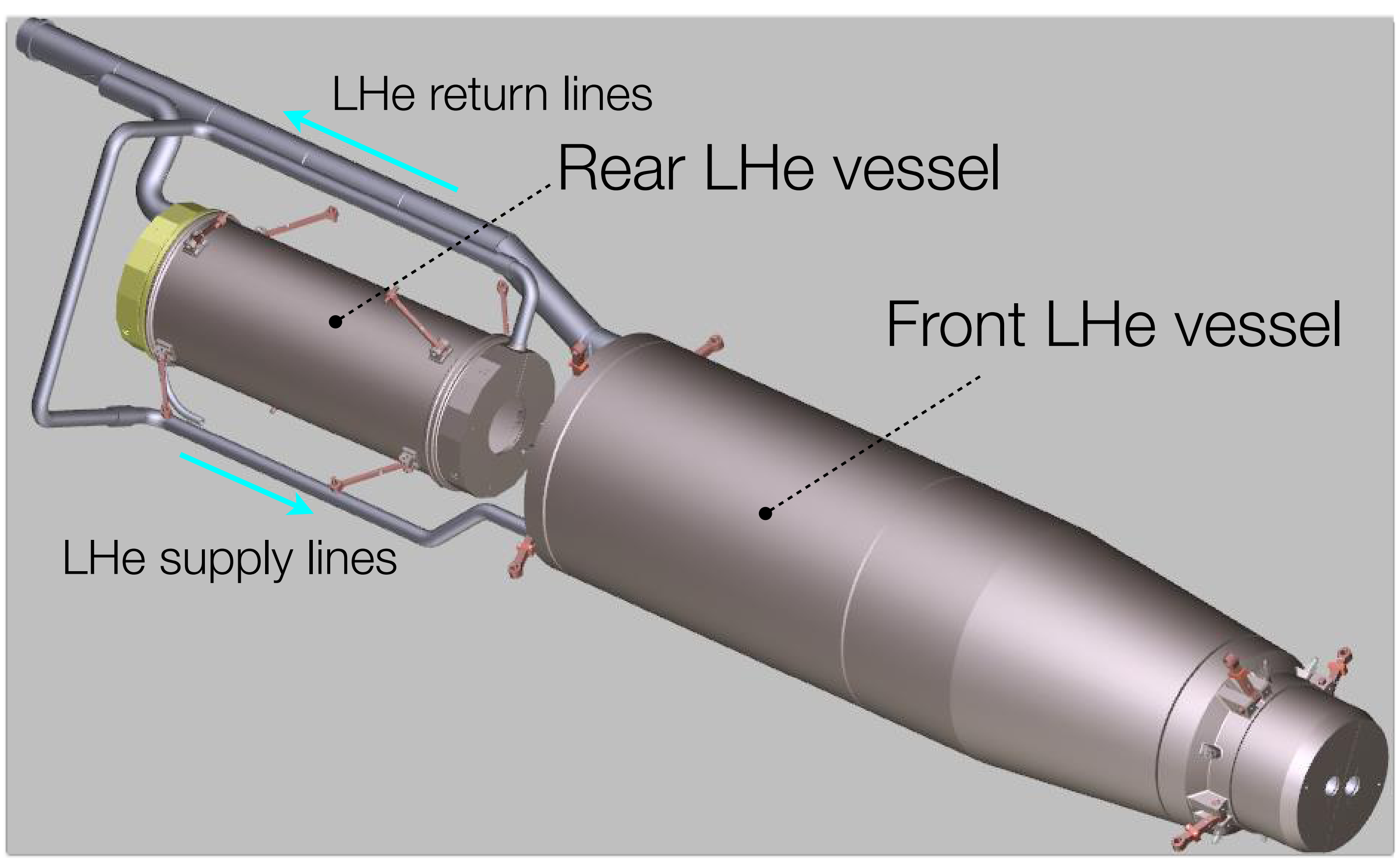
Cryostats

QCS-L cryostat



QCS-R cryostat





- Components: beam pipes with room temperatures, Permendur/iron yoke, tungsten shields, and SUS supports
- long and slim cooling channels or pipes (more than 6 m for a round-trip)
- Helium vessels are fixed to vacuum chamber with Ti-6Al-4V rods.

Magnet cryostat	QCSL	QCSR
Total cold mass (kg)	1522	3139
Front LHe vessel	1180	2076
Rear LHe vessel	342	1063

Z. Zong

Service cryostats

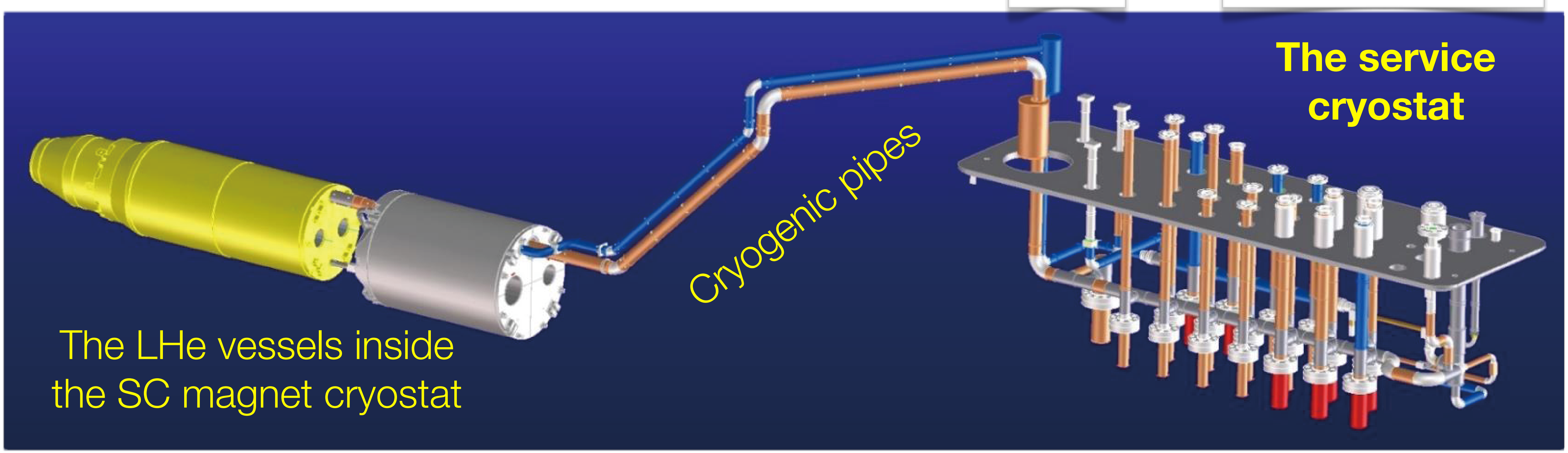
- To host the current leads of SC magnets (L/R: 16/17)

  Current leads for each side consumes about 30 L_{LHe} /hour.

- To install cryogenic valves, instrument wires, and to access cryogenic transfer lines from the sub-cooler.

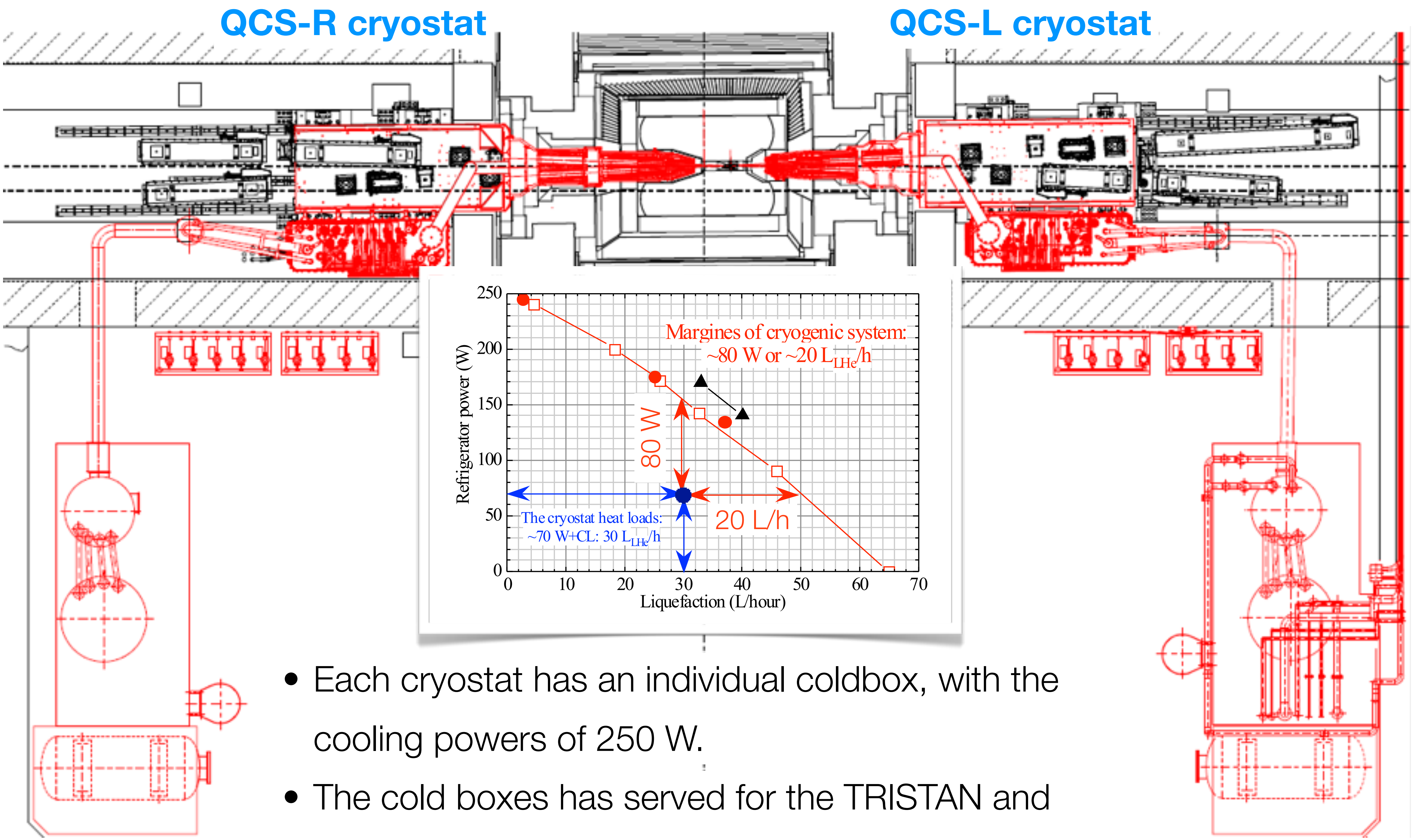
Current leads for corrector magnets

Current leads for main quadrupole magnets



Z. Zong

Cryogenic systems

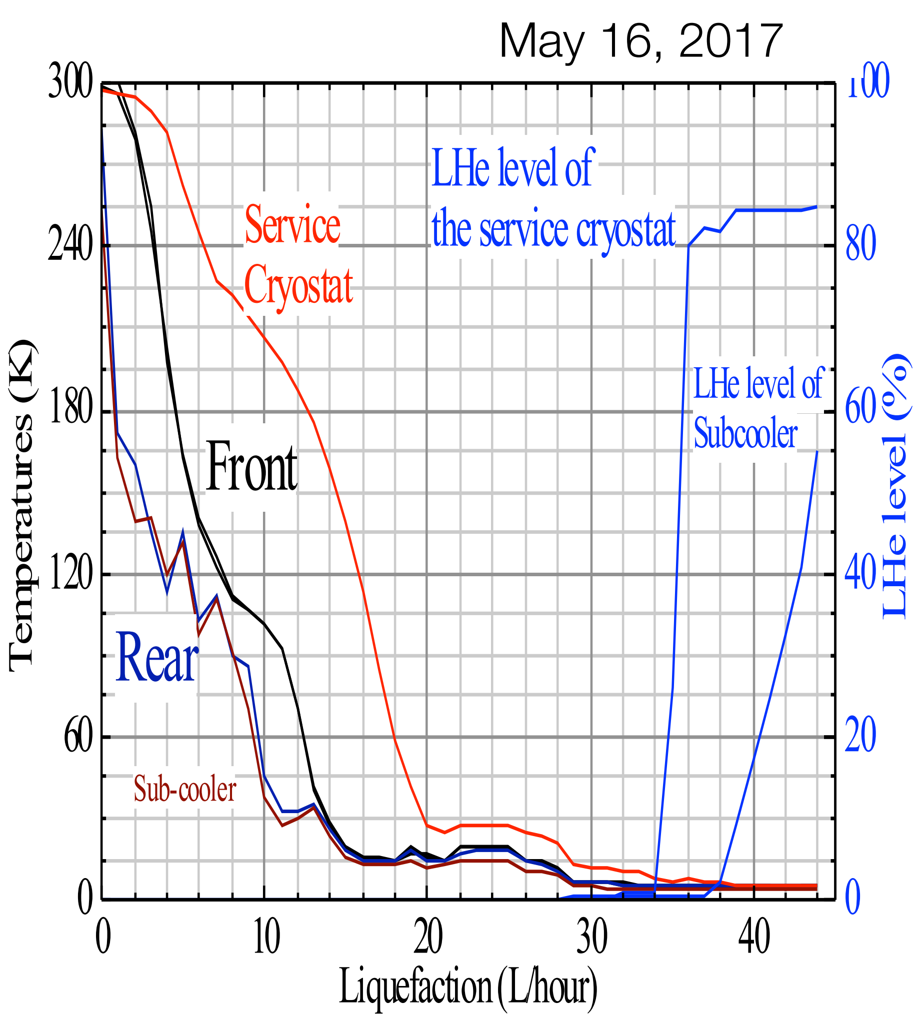


- Each cryostat has an individual coldbox, with the cooling powers of 250 W.
- The cold boxes has served for the TRISTAN and KEKB project for about 30 years.

Cool down of the QCS-L/R system

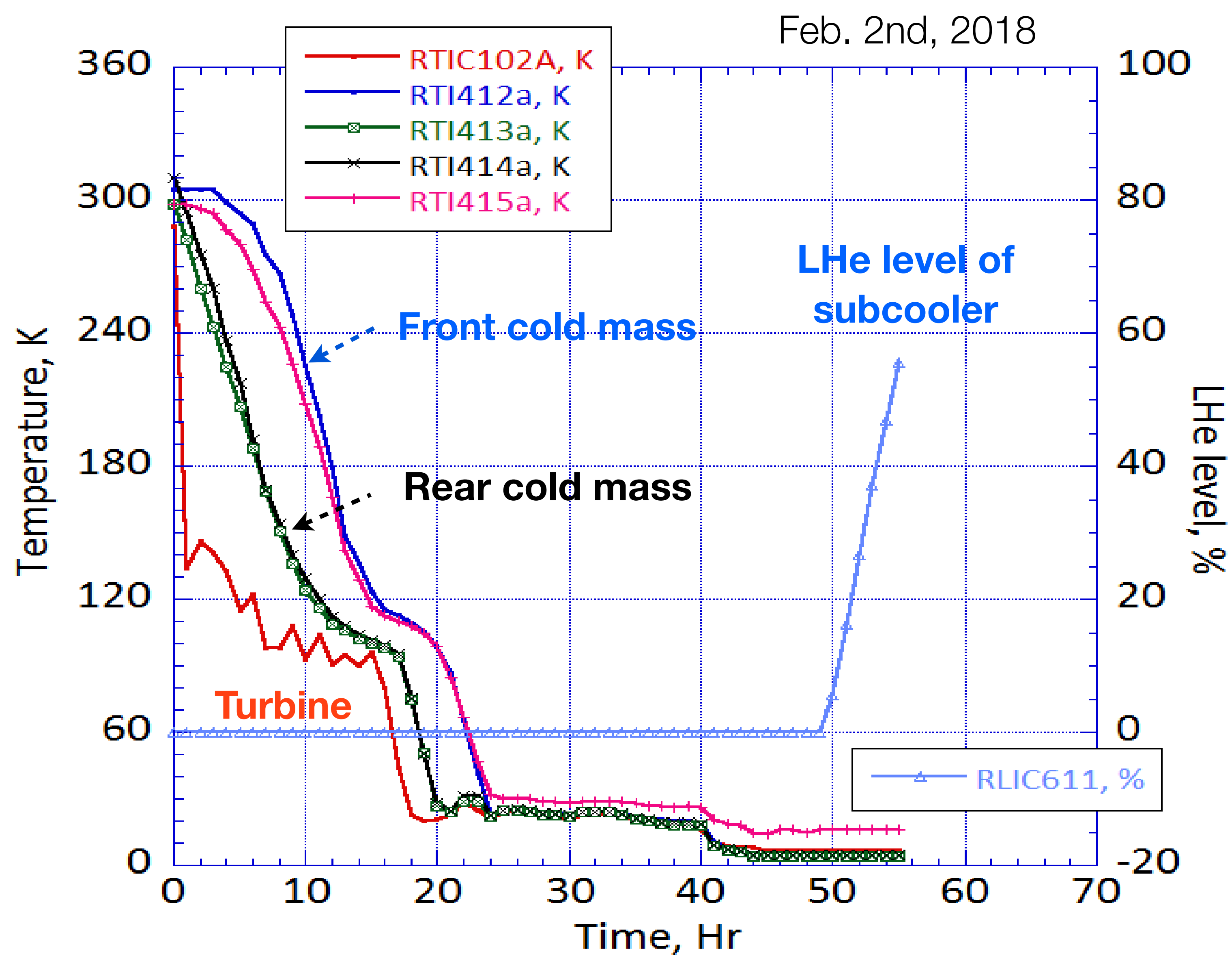
QCS-L

Cool down time: 44 hours



QCS-R

Cool down time: 55 hours



Magnetic measurements

Magnetic measurements

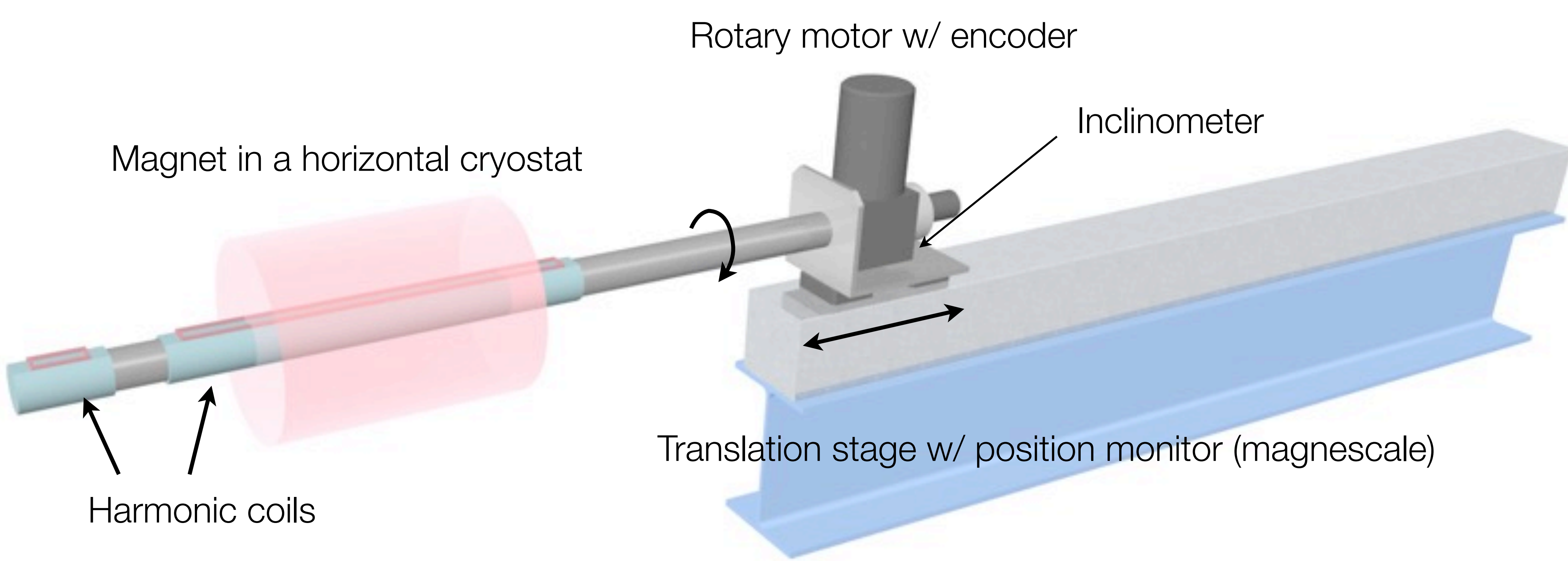
We performed magnetic measurements at the beamlines

- Field quality of quadrupole magnets and corrector/cancel magnets
  - Harmonic coils
- Profile of solenoid fields
  - Hall probe
- Magnet center
  - Single stretched wire

Harmonic coil system

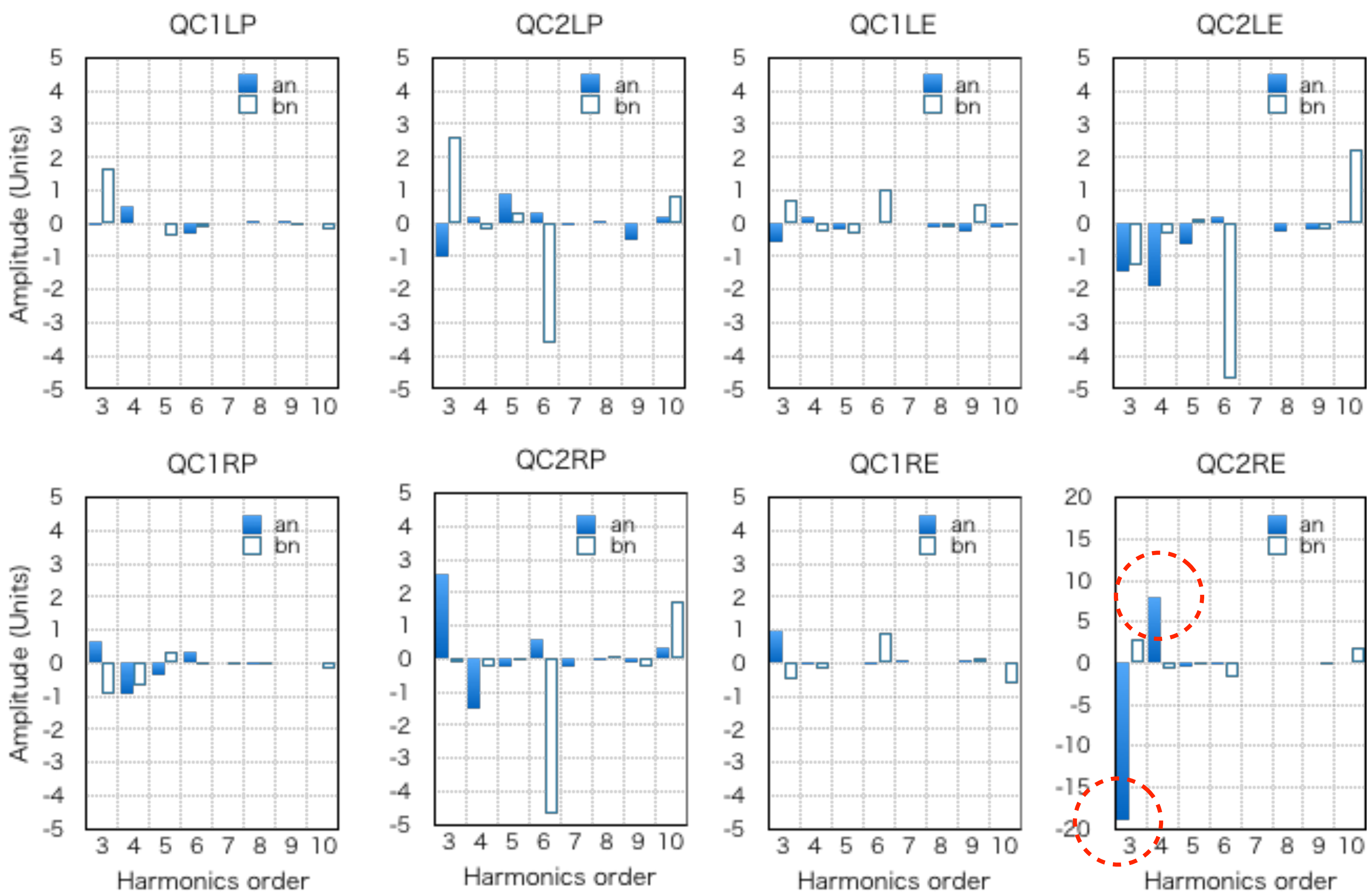
- Coils
  - Long coil (L = 600 ~ 800 mm)
  - Short coil (L = 20 mm)
- Winding radius
  - R=12 mm (for QC1P/E)
  - R=25 mm (for QC2P)
  - R=33 mm (for QC2E)

- Types of winding
  - Tangential winding
  - Dipole winding for bucking
  - Quadrupole winding for bucking



Higher order harmonics of quadrupole magnets

$$B_y + iB_x = B_2 \sum_{n=1}^{\infty} (b_n - ia_n) \left(\frac{x + iy}{r_0} \right)^{n-1}$$



“units” definition

$b_n = B_n/B_2 \times 10^4$

$a_n = A_n/B_2 \times 10^4$

Tolerances

Corrector magnet can correct

n=3 : < 10 units

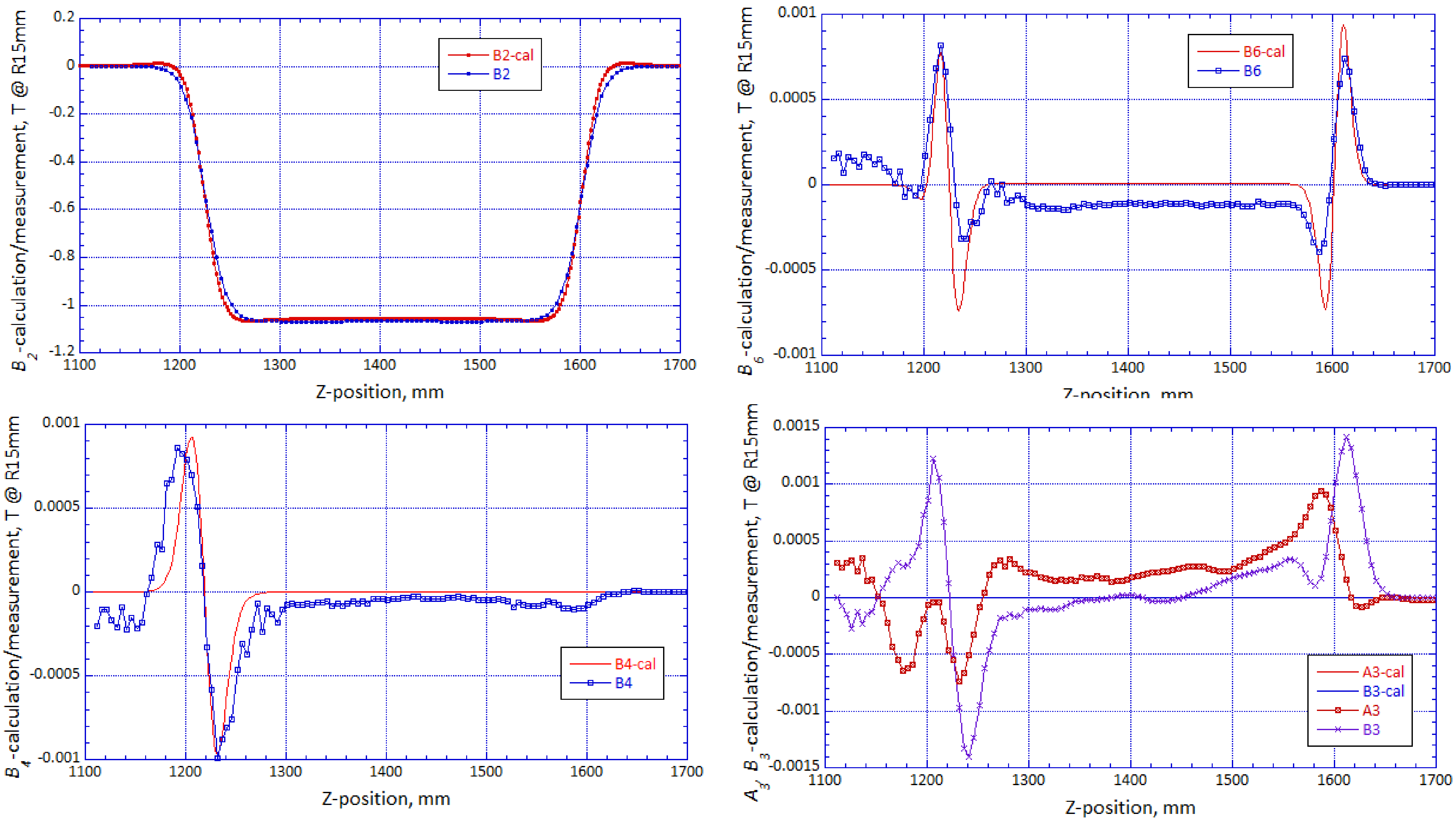
n=4 (normal) < 5 units

The other components: < 1 units

- The multipole for QC1L/RP and QC1L/RE are less than 1 units.
- QC2L/RP and QC2LE have a few units for several components.
- QC2RE shows large amplitude for sexupole and octupole

Measured profile of QC1LE

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

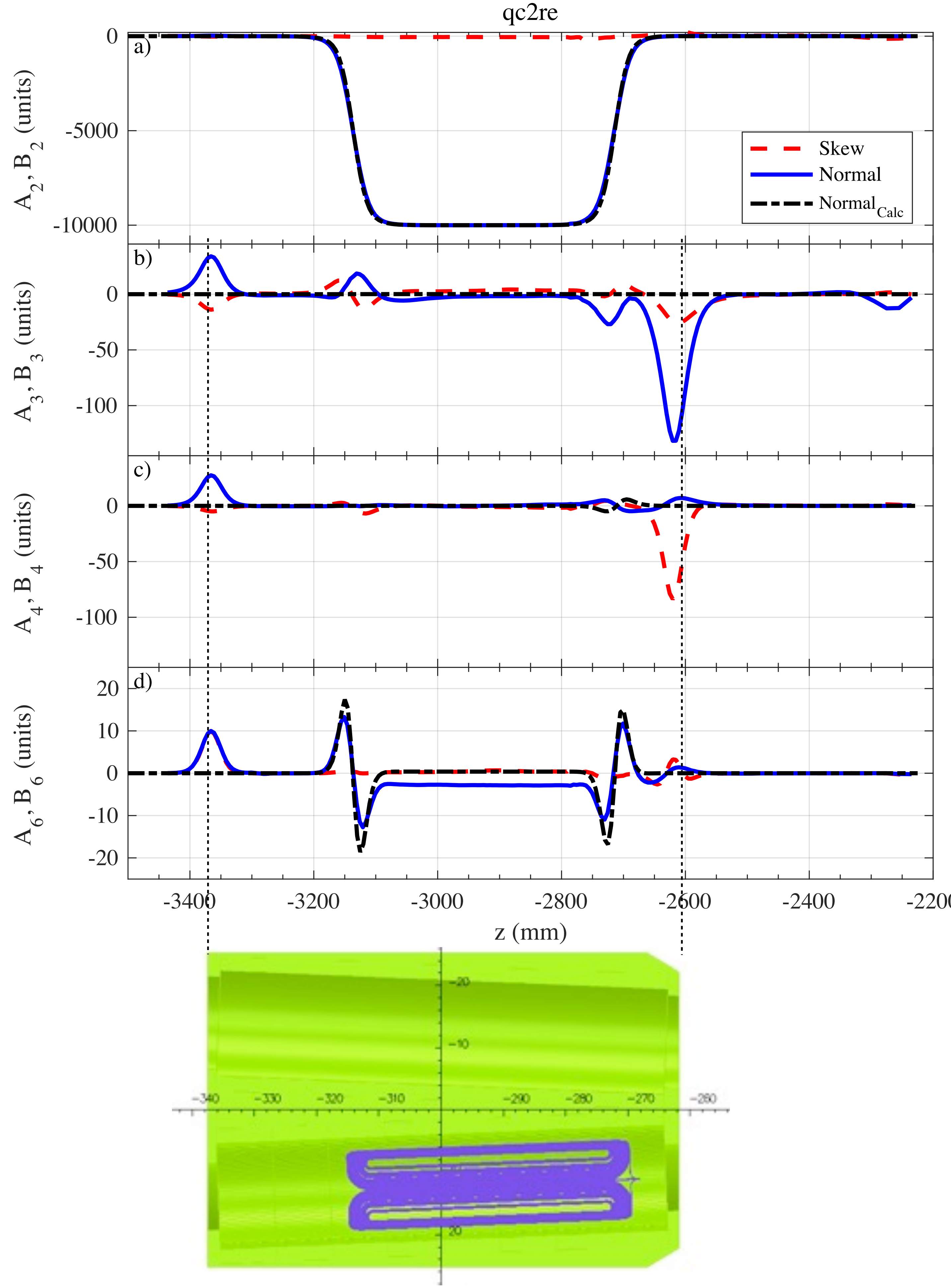


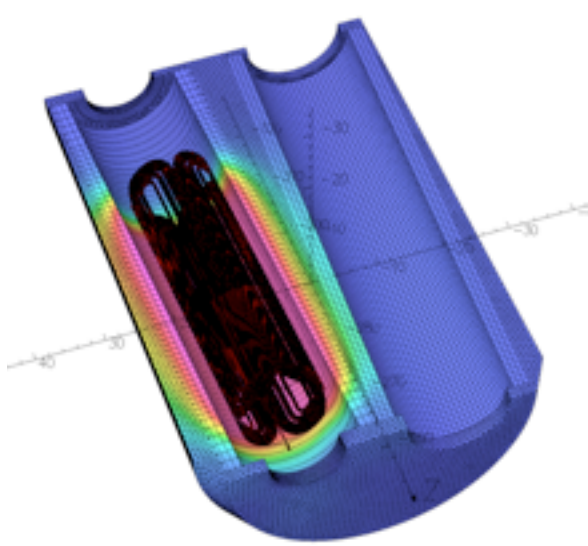
N. Ohuchi

Unexpected profile on QC2RE

Belle II solenoid and compensation solenoid are energized for this measurement.

- Large error field at yoke ends
- No large error is found in calculation without solenoid field
- It is caused by solenoid field which flows into yoke ends.
- This field error on QC2RE are acceptable.

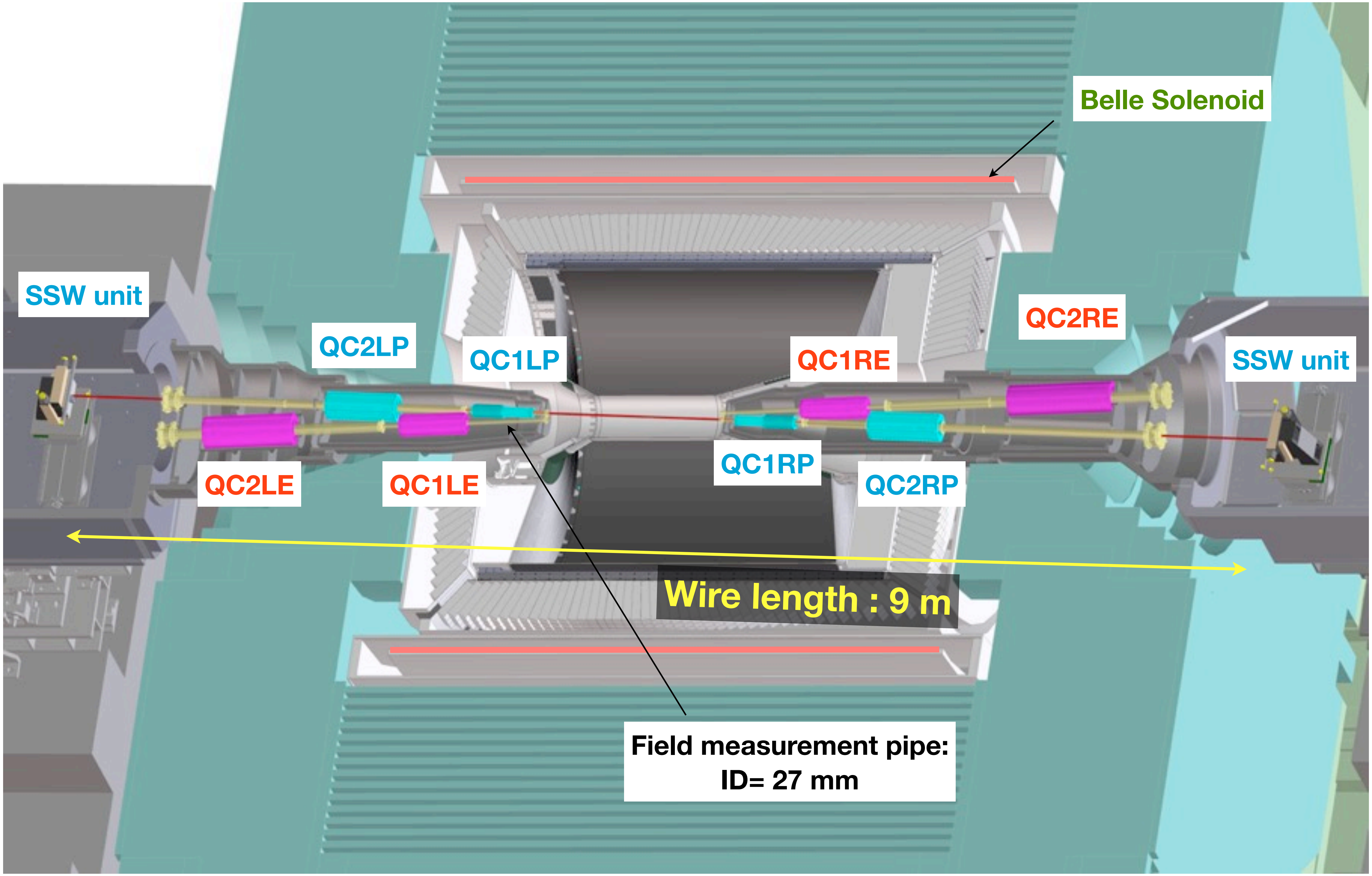




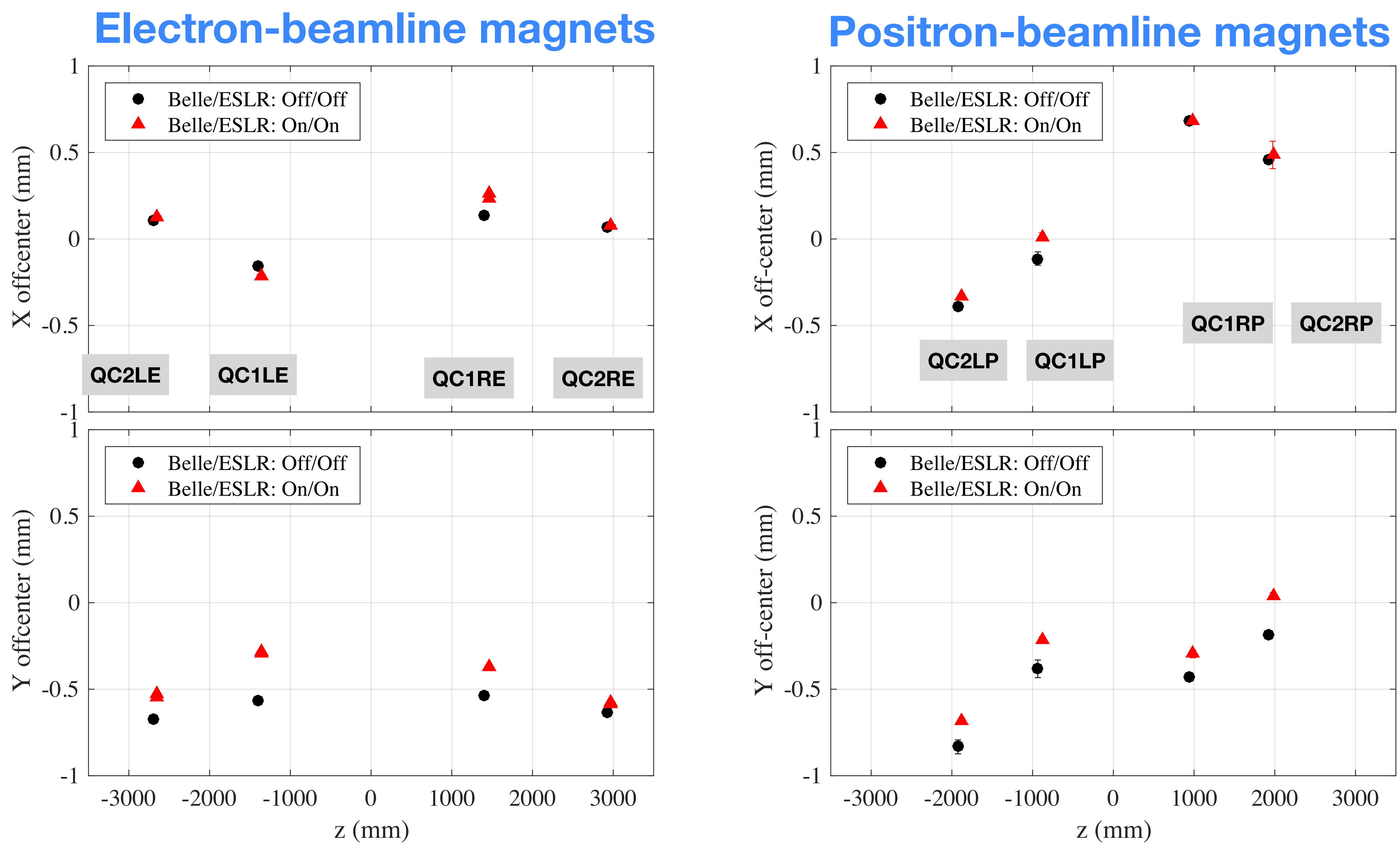
Single stretched wire

- Purpose
  - Measurement of magnet centers of quadrupole magnets
- Motivation
  - The quadrupole magnets are inside cryostats.
  - These quadrupole magnets are installed in helium vessels and they are lifted by support rods fixed to vacuum chamber.
  - The helium vessels move by magnetic force of solenoids.
  - We cannot see the quadrupole magnet with optical alignment tool.
  - We should measure quadrupole center in magnetically.
  - Single stretched wire method can measure magnet center.
- Collaboration
  - The device is newly constructed by Fermi National Accelerator Laboratory.
  - The measurement was performed by collaboration of KEK and FNAL.

Setup for single stretched wire



Magnet center for each magnet wrt beamline



Magnet positions are varied with solenoid field turned on/off.

dx ~ 0.1 mm, dy~0.3 mm

The maximum offset from beam line are 0.7 mm for QC1RP in x-direction.

The maximum offset from beam line are -0.6 mm for QC2LP in y-direction.

These offset can be corrected with dipole correctors.

Summary

- SuperKEKB starts operating with final focus system (QCS) on Mar. 2018
- QCS construction begin at June 2013 and completed on Feb. 2017
- QCS is complex superconducting magnet system, and consists of
  - 8 quadrupole magnets
  - 43 correctors/cancel magnets
  - 4 compensation solenoids
- Cool down was successful, the time from room temperature to 4K is
  - QCS-L : 44 hours,
  - QCS-R : 55 hours
- Field quality of main quadrupole satisfy requirements from optics simulation.
- Alignment of quadrupole center was confirmed with SSW method.
- The QCS system is in operation and stable
  - Some quenches was happened by beam injection tuning, quench detection is working well.