Final-Focus Superconducting Magnets for SuperKEKB

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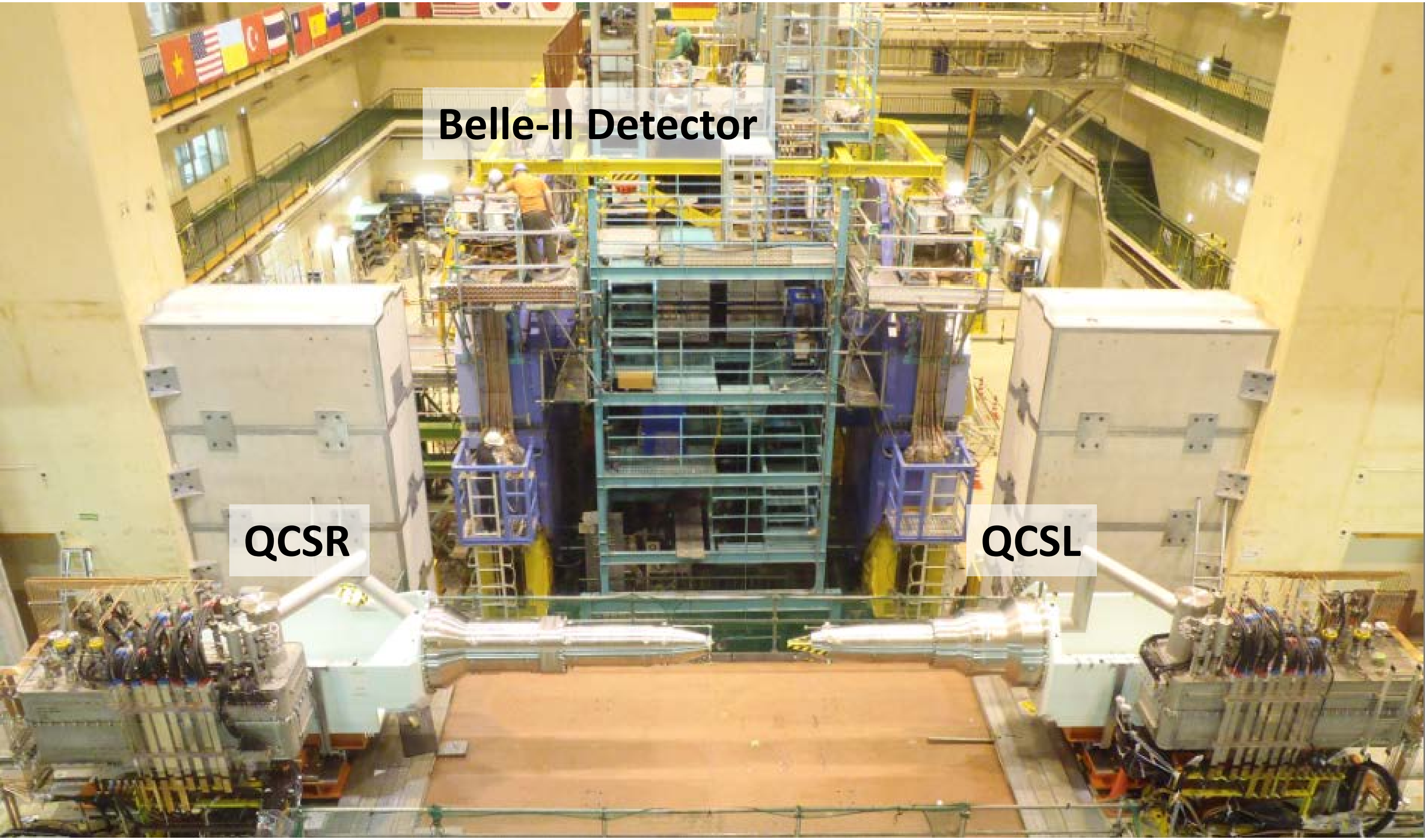
2. IR superconducting magnets
   - ✓ Quadrupole magnets
   - ✓ Corrector magnets
   - ✓ QC1P leak field cancel magnets
   - ✓ Compensation solenoids
3. Summary

Two cryostats in SuperKEKB IR



Configuration of IR magnet system

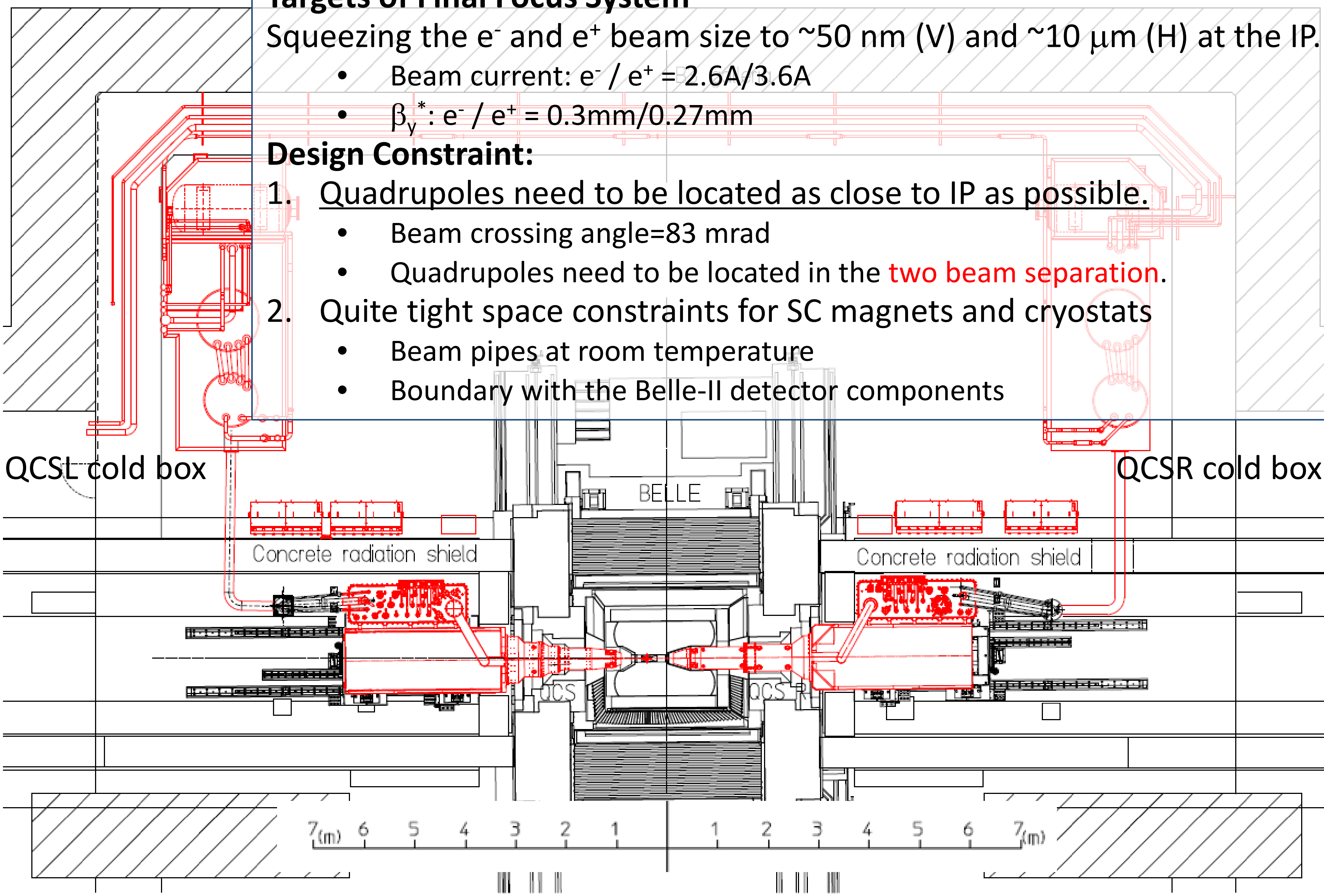
Targets of Final Focus System

Squeezing the e^- and e^+ beam size to ~50 nm (V) and ~10 μm (H) at the IP.

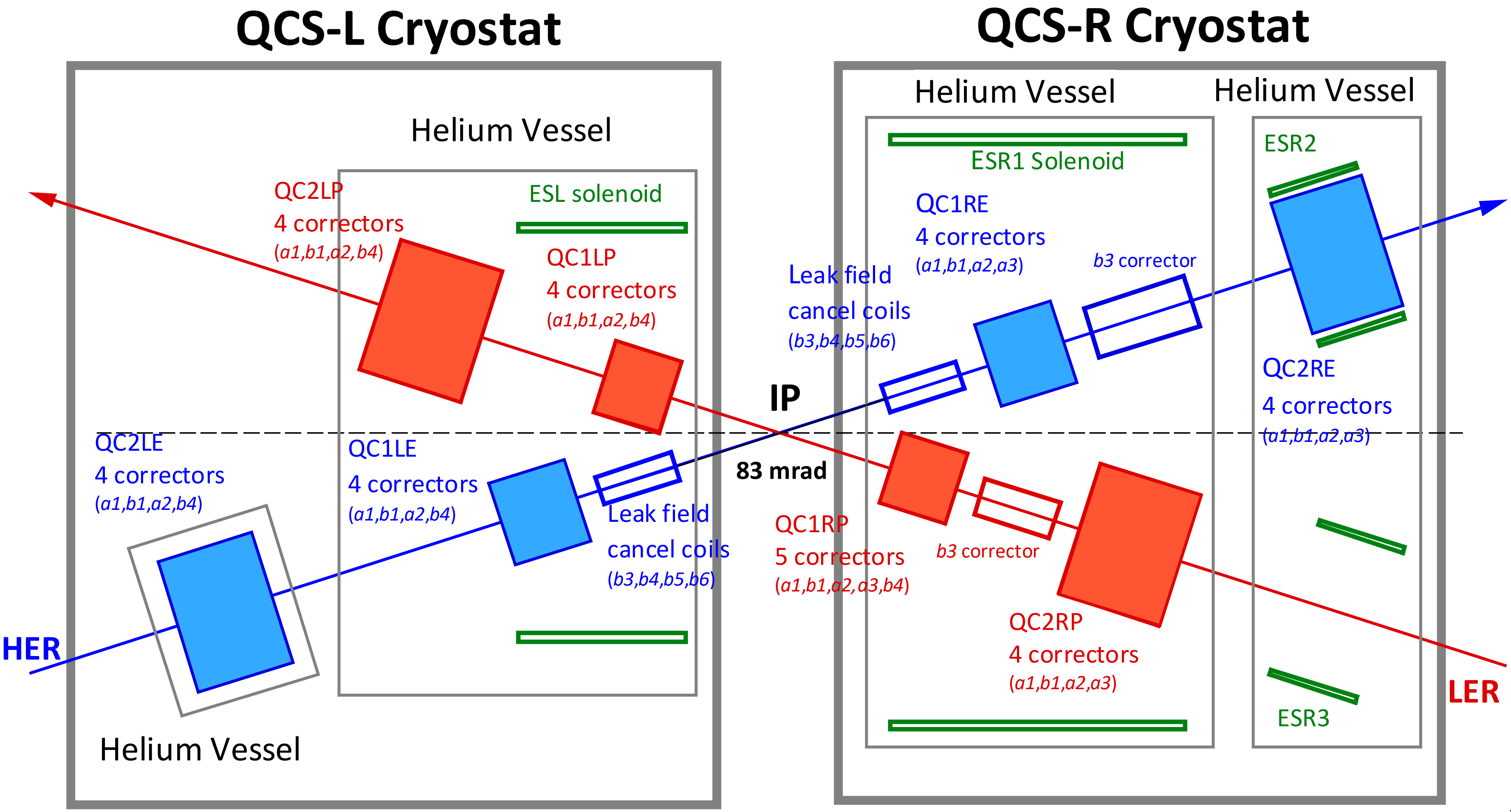
- Beam current: e^- / e^+ = 2.6A/3.6A
- β_y^*: e^- / e^+ = 0.3mm/0.27mm

Design Constraint:

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



Configuration of IR magnets



25 SC magnets in QCSL

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

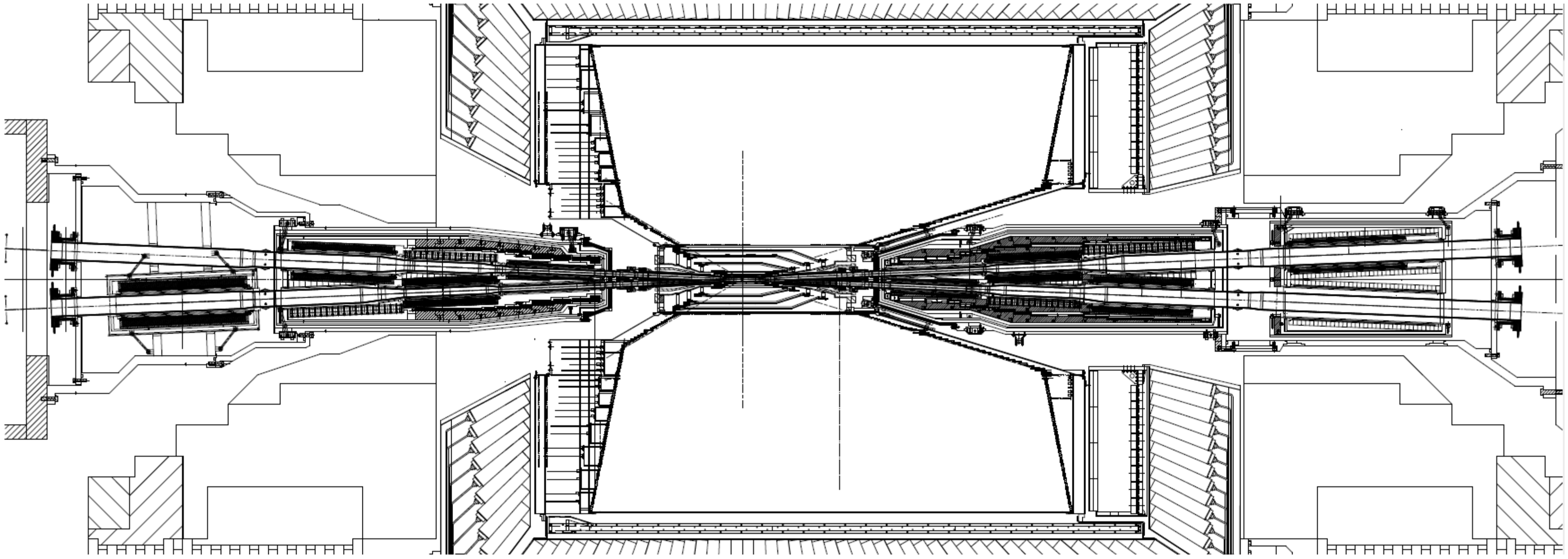
30 SC magnets in QCSR

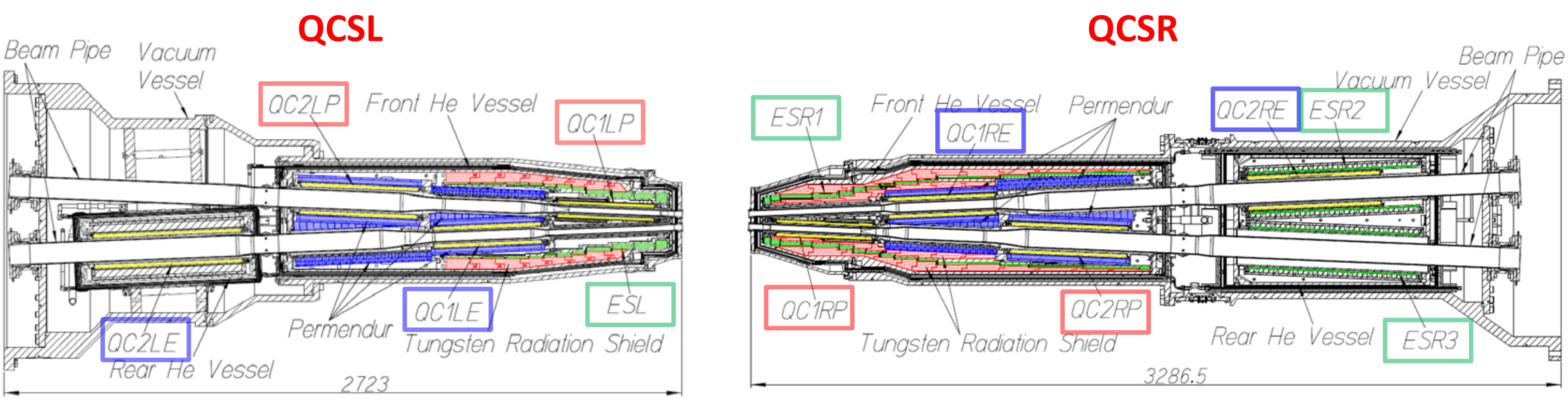
4 SC main quadrupole magnets: 1 collared magnet, 3 yoked magnets
19 SC correctors: a1, b1, a2, a3, b3, b4
4 SC leak field cancel magnets: b3, b4, b5, b6
3 compensation solenoid

IR SC magnets

- Main quadrupoles [QC1, QC2]: 8 magnets
  - Forming final beam focusing system with quadrupole doublets.
- Correctors [a_1, b_1, a_2, a_3, b_3, b_4]: 35 magnets
  - a_1, b_1, a_2: magnetic alignment of the magnetic center and the mid-plane phase angle of main quadruple.
    - Corrections of center shift> 0.5 mm, roll of the mid-plane angle>10 mrad
  - a_3, b_3: correction of sextupoles induced by magnet construction errors.
  - b_4:increasing the dynamic transverse aperture.
- Compensation solenoid[ESR, ESL]: 4 magnets
  - Canceling the integral solenoid field by the particle detector (Belle II).
  - By tuning the B_z profile, the beam vertical emittance is designed to be minimized.
  - The compensation solenoids are designed to be overlaid on the main quadrupoles and correctors.
  - ESR consists of three solenoid magnets of ESR1, ESR2 and ESR3.
- Leak field cancel coils [b_3, b_4 , b_5, b_6]: 8 magnets
  - Canceling the leak field on the electron beam line from QC1P (collared magnet).
- <u>Total number of the SC devices in two cryostats = 55</u>

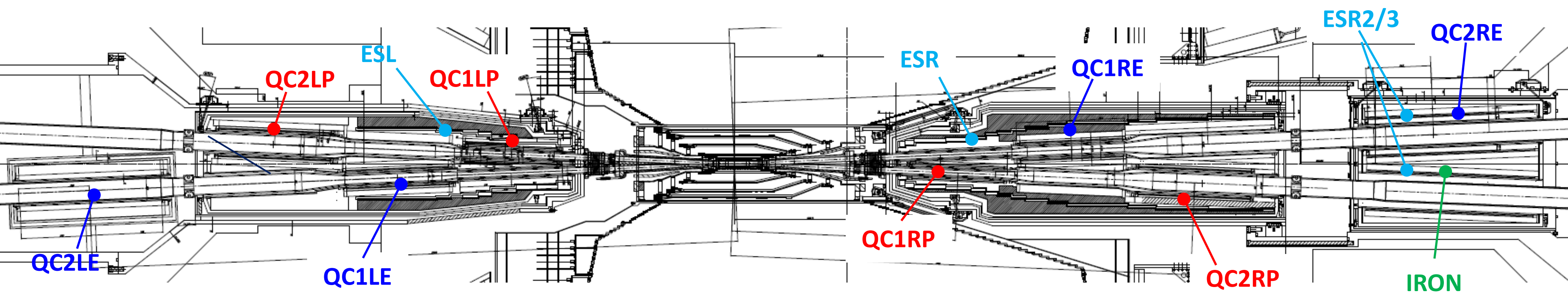
Configuration of IR magnet systems





IR SC magnets

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

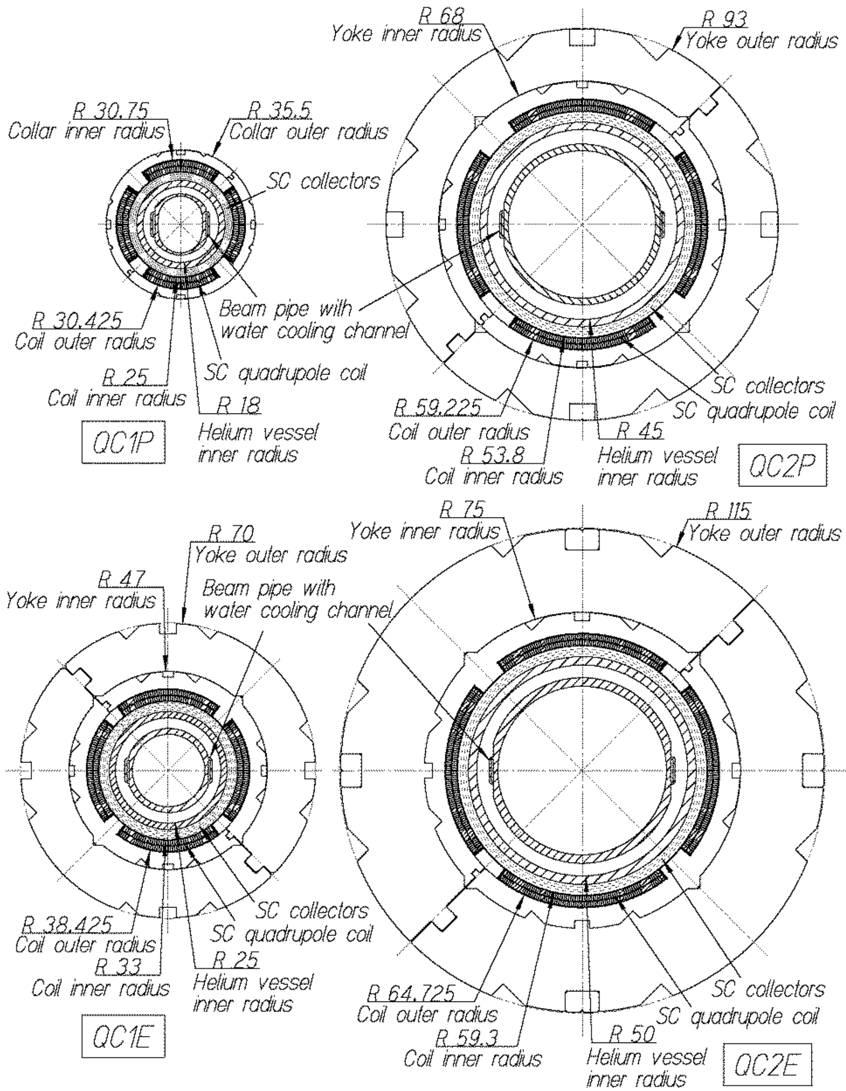


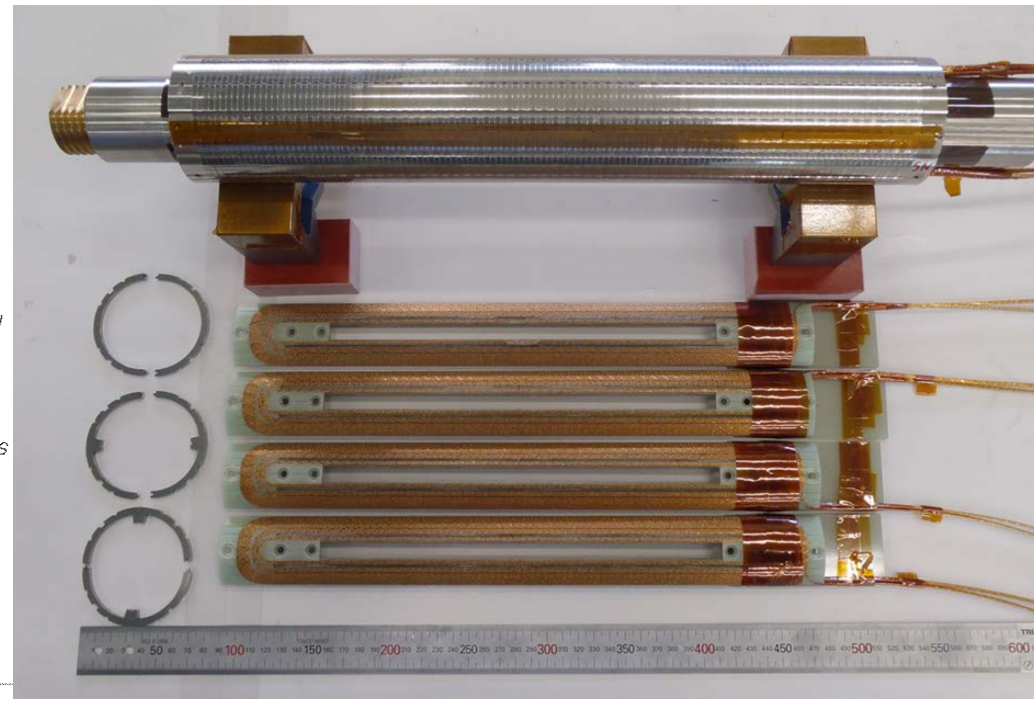
	Integral field gradient, (T/m)·m	Magnet type	Z pos. from IP, mm	θ, mrad	ΔX, mm	ΔY, mm
QC2RE	13.58 [32.41 T/m × 0.419m]	Iron Yoke	2925	0	-0.7	0
QC2RP	11.56 [26.28 × 0.410]	Permendur Yoke	1925	-2.114	0	-1.0
QC1RE	26.45 [70.89×0.373]	Permendur Yoke	1410	0	-0.7	0
QC1RP	22.98 [68.89×0.334]	**No Yoke**	935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

IP

IR SC magnets

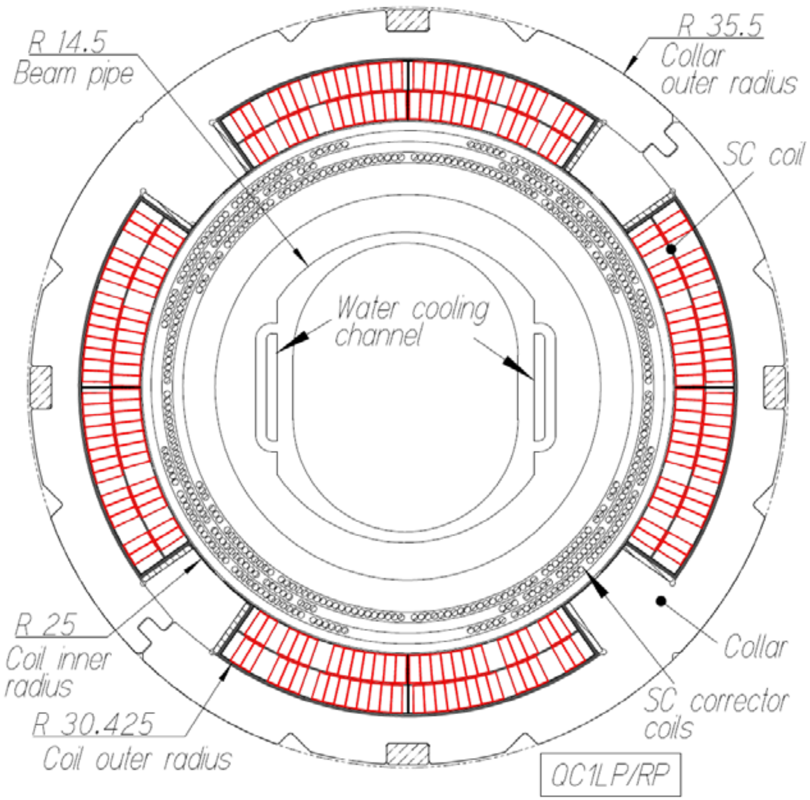
- Cross section design of main quadrupoles [QC1, QC2]
  - The quadrupole magnets are designed with the two layer SC coils (double pane cake design).





QC1LP Magnet, four superconducting coils for QC1RP

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

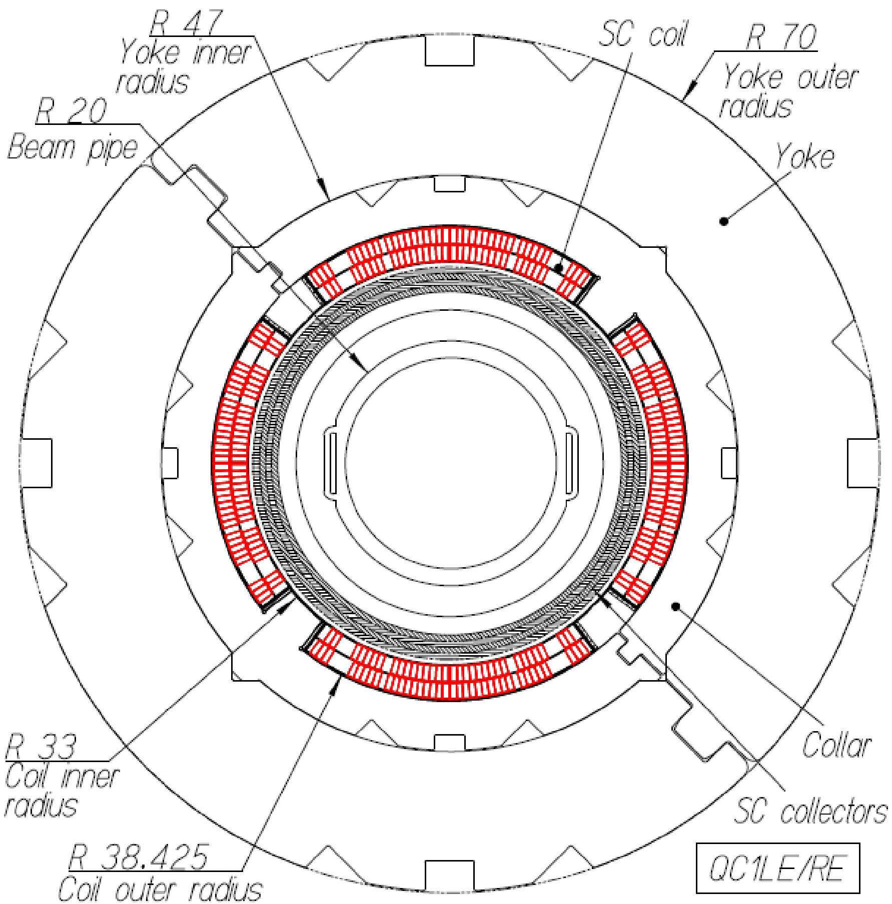
Coil design

- 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

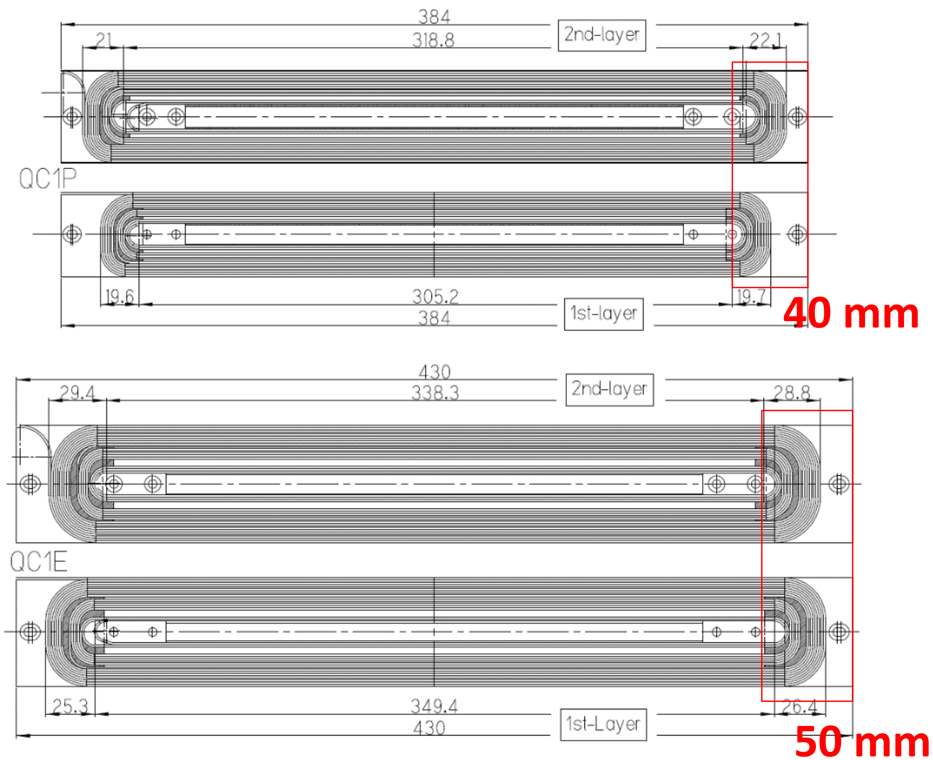
Coil design

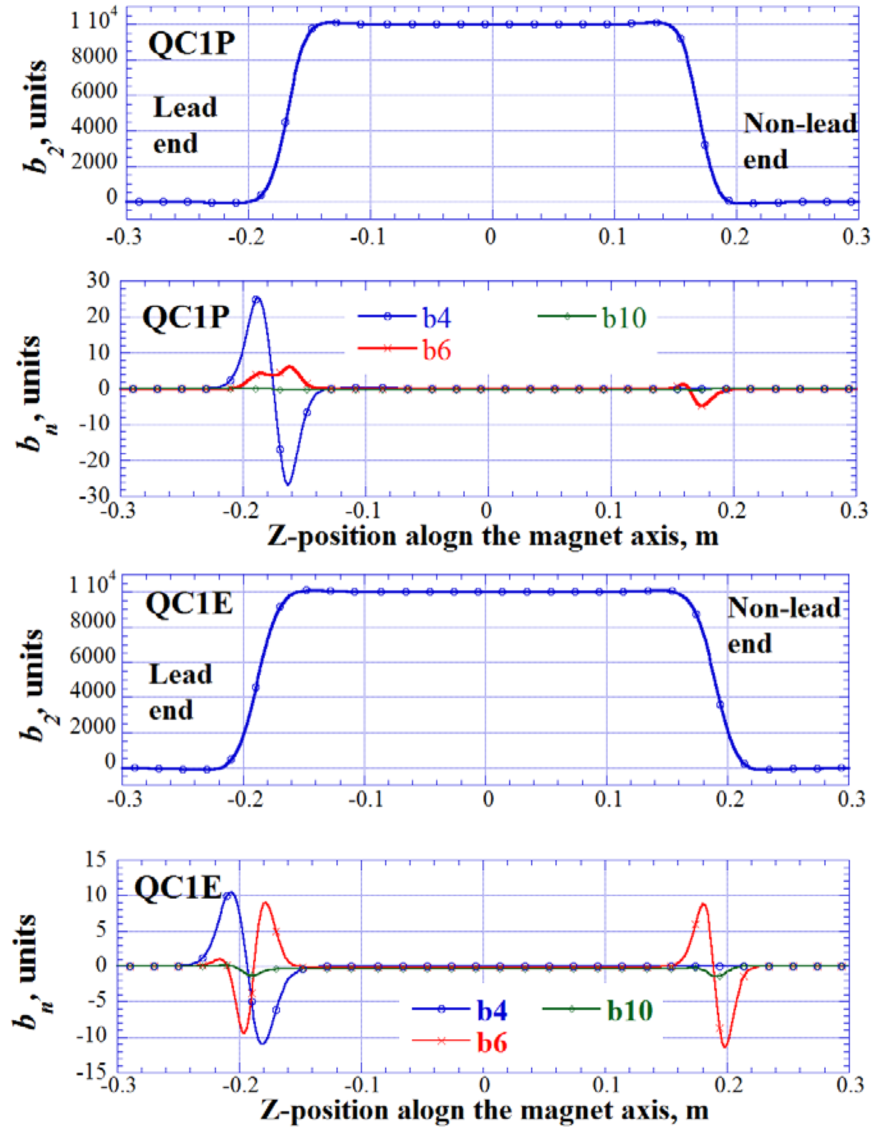
- 2 layer coils (3 coil blocks for each layer)
- Error field in 2 D cross section
  - **b_6 = -0.06 units, b_{10} = -0.34 units, b_{14} = -0.01 units**
- Integral error field in 3D model
  - **b_4 = -0.02 units, b_6 = -0.04 units, b_8 = 0.05 units , b_{10} = -0.43 units**

Superconducting cable

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

3D magnet design of QC1P/1E





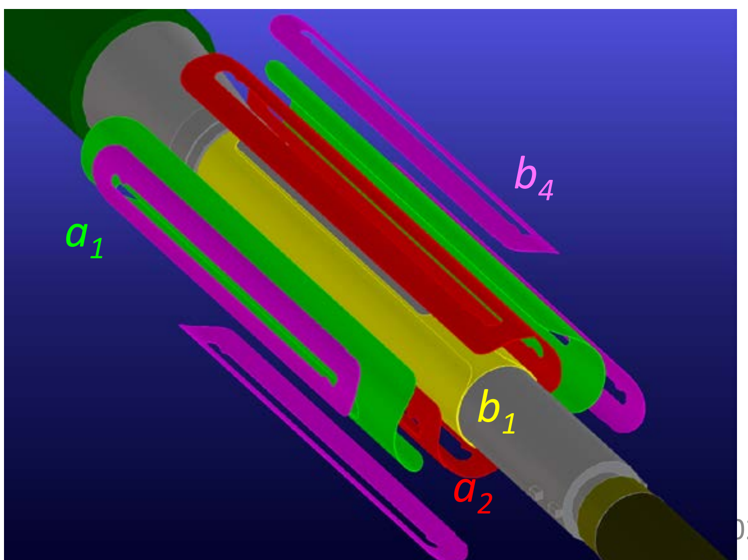
- The coil ends were designed to be as short as possible.
- In order to exclude the skew components in the lead end, the quadrant coils have mirror symmetry to the neighbor coils.

SC Corrector Magnets

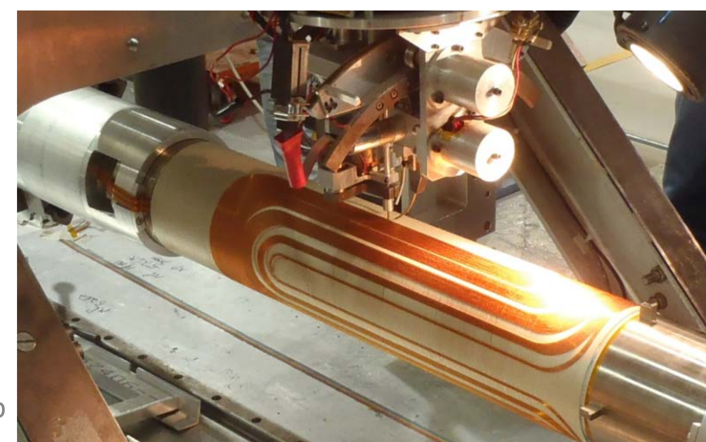
- **The SC correctors were designed and directly wound on the support bobbin (helium inner vessel) by BNL under the US-Japan Science and Technology Cooperation Program in HEP.**
  - Multi-layer coil [maximum layer=4 by limiting with the gap distance (5 mm) between the main quadrupole magnet and the helium inner vessel]
  - Some correctors were assembled on the outer surface of QC1LP and QC1RP (no magnetic yoke).

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

QCSR-Main Quadrupole	Corrector
QC1RP	a_1, b_1, a_2, b_4, a_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



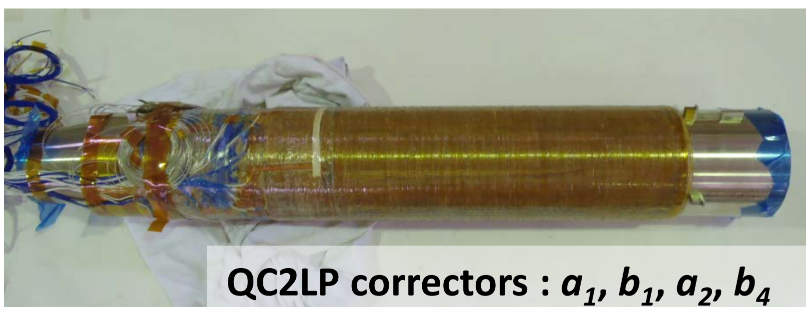
Direct winding method @BNL



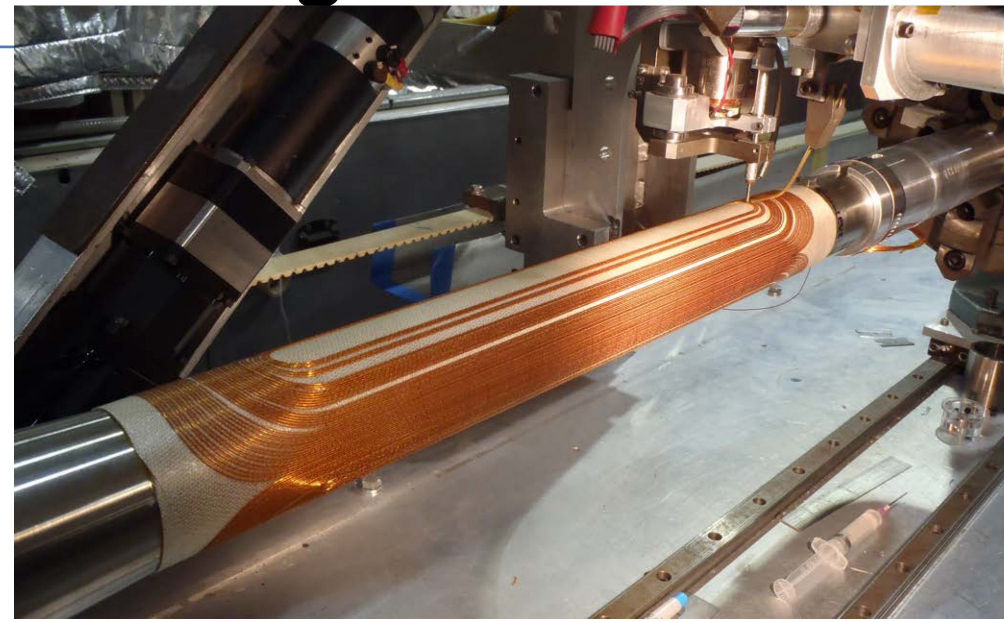
SC Corrector Magnets

Corrector magnets

QC1LP correctors : a_1, b_1, a_2, b_4



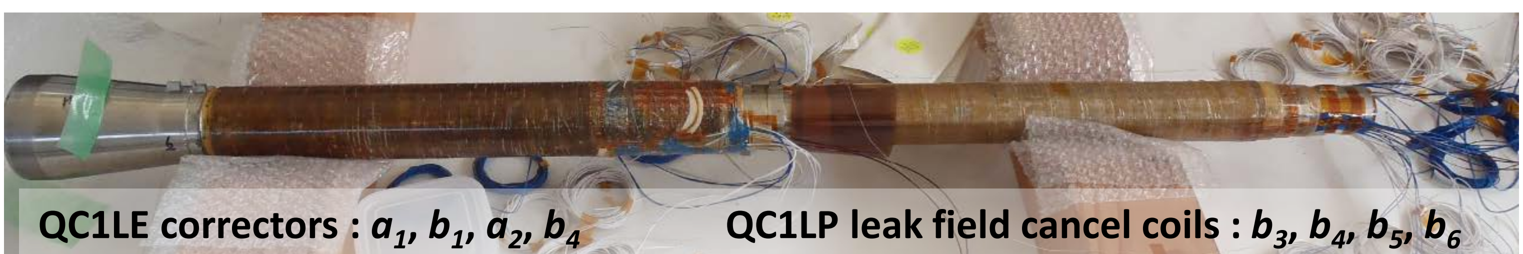
QC2LP correctors : a_1, b_1, a_2, b_4



The NbTi wire was directly attached on the outer surface of the cryostat inner pipe.

NbTi wire specification:

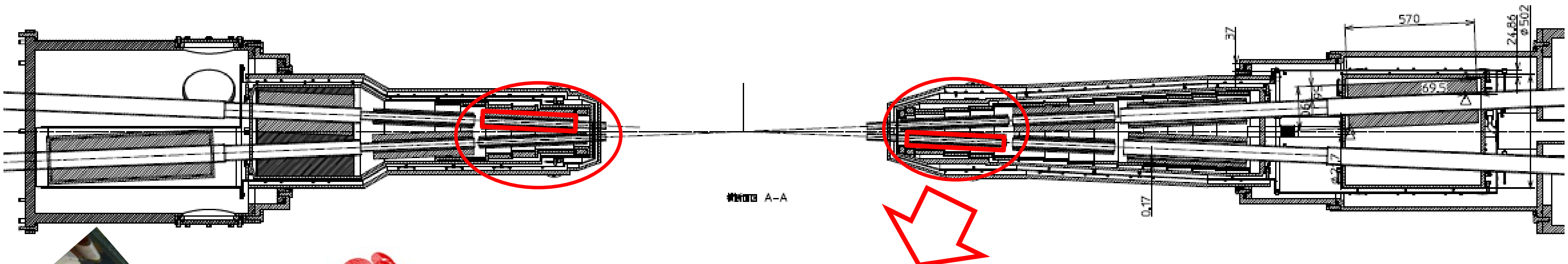
- Diameter=ϕ0.35 mm
- Filament diameter and number= ϕ5.4 μm, 2113
- I_c @ 4 T, 4.2 K=154 A

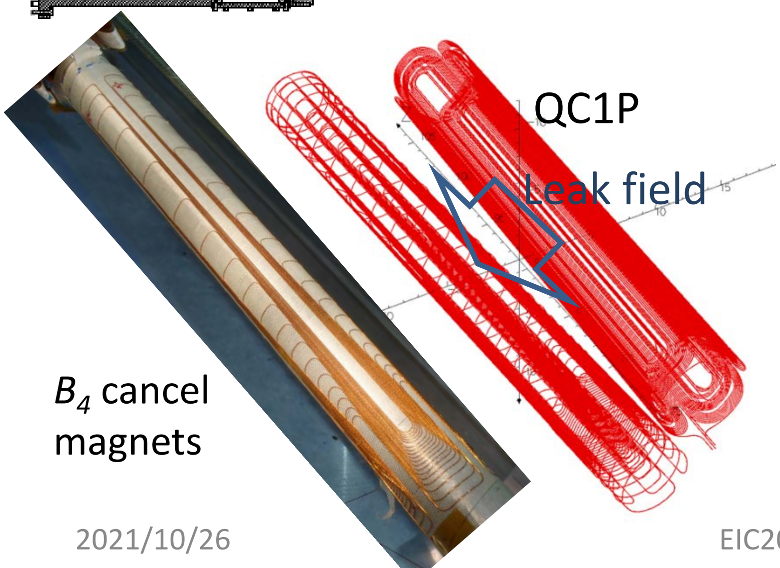


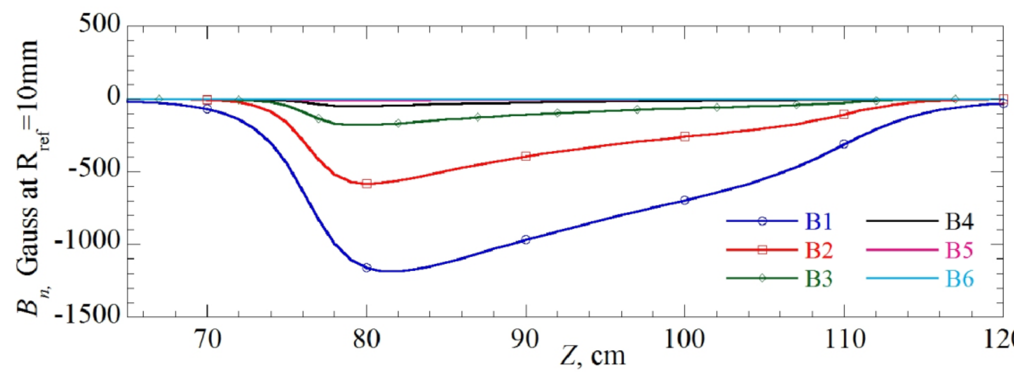
QC1LE correctors : a_1, b_1, a_2, b_4 **QC1LP leak field cancel coils : b_3, b_4, b_5, b_6**

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.

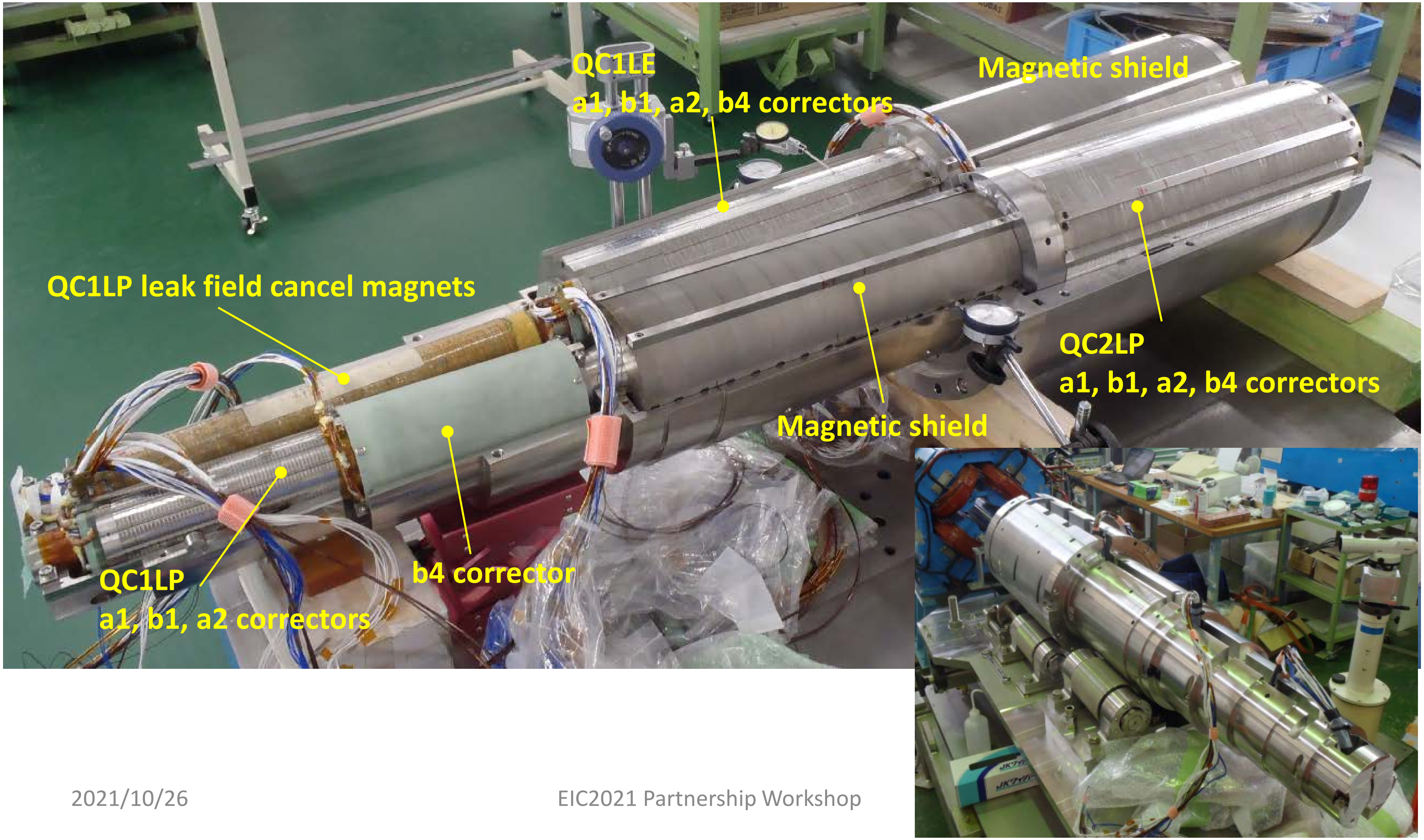






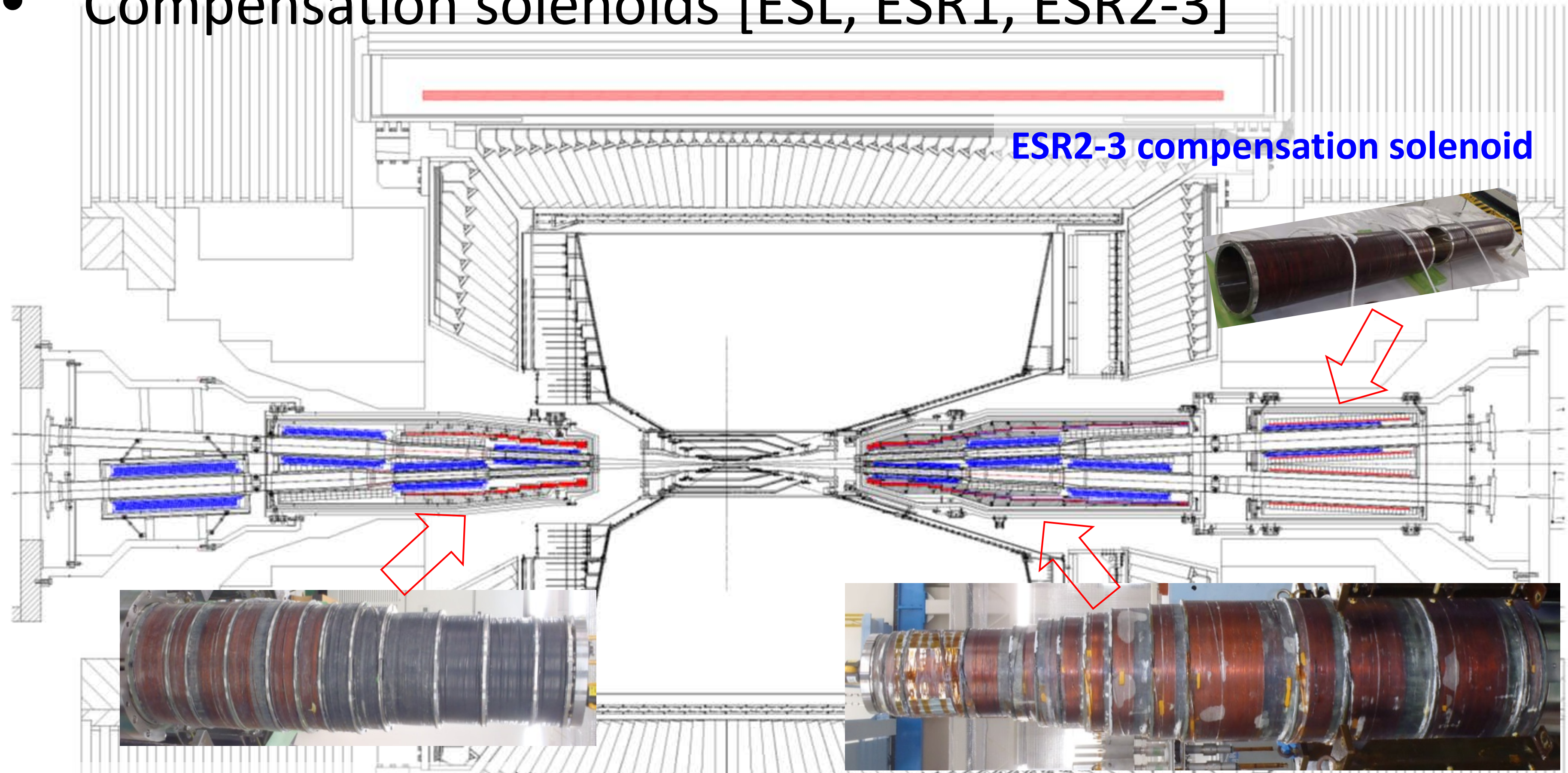
IR SC magnets

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



IR SC magnets

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



ESL compensation solenoid

Magnet length= 914 mm
Maximum field at 404 A= 3.53 T
Stored Energy= 187 kJ

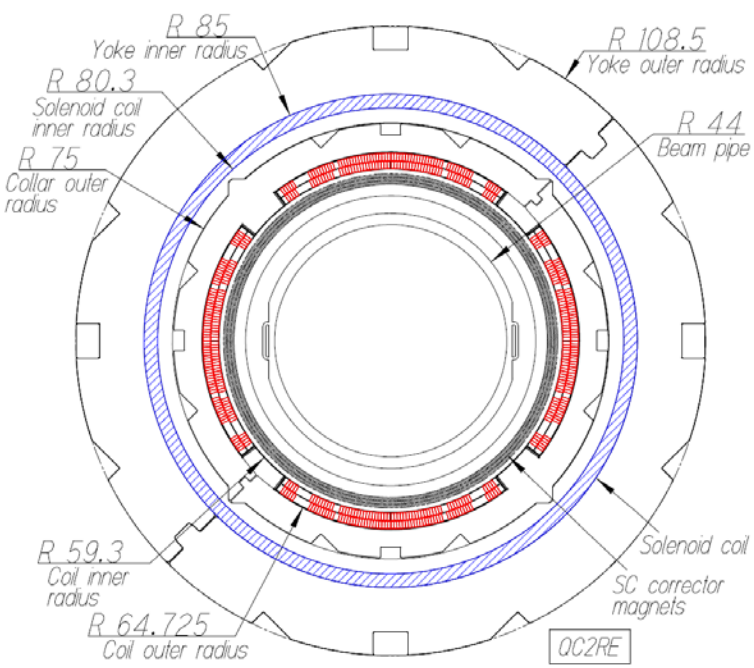
ESR1 compensation solenoid

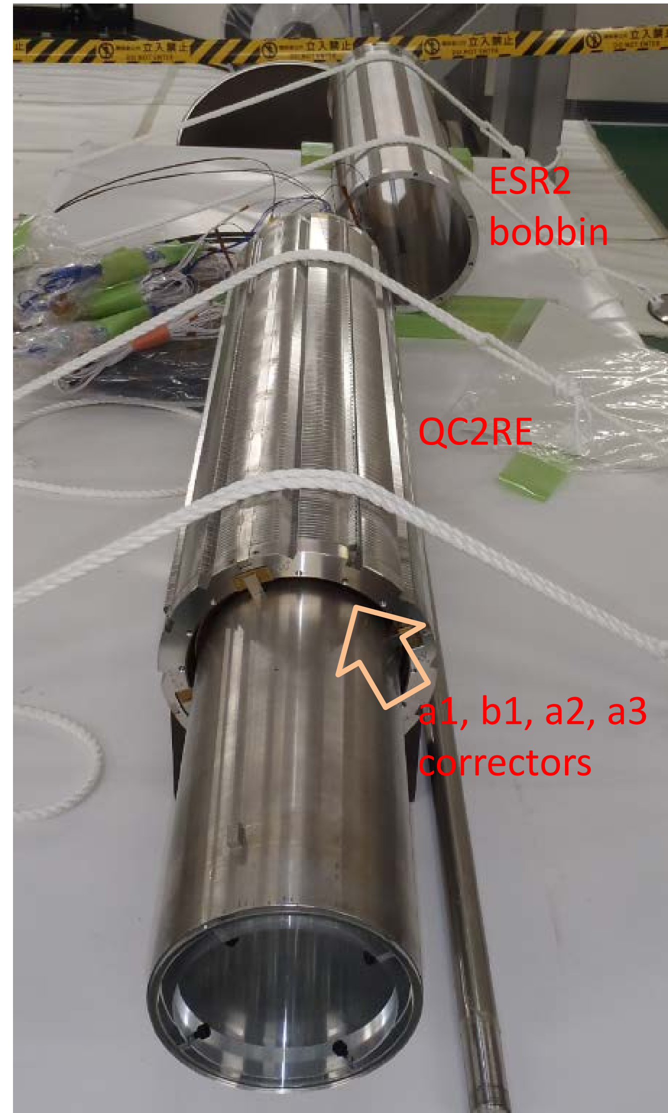
Magnet length= 1575 mm
Maximum field at 450 A=3.19 T
Stored Energy= 814 kJ
Cold diode quench protection system

IR SC magnets

- Compensation solenoids [ESR2, ESR3]

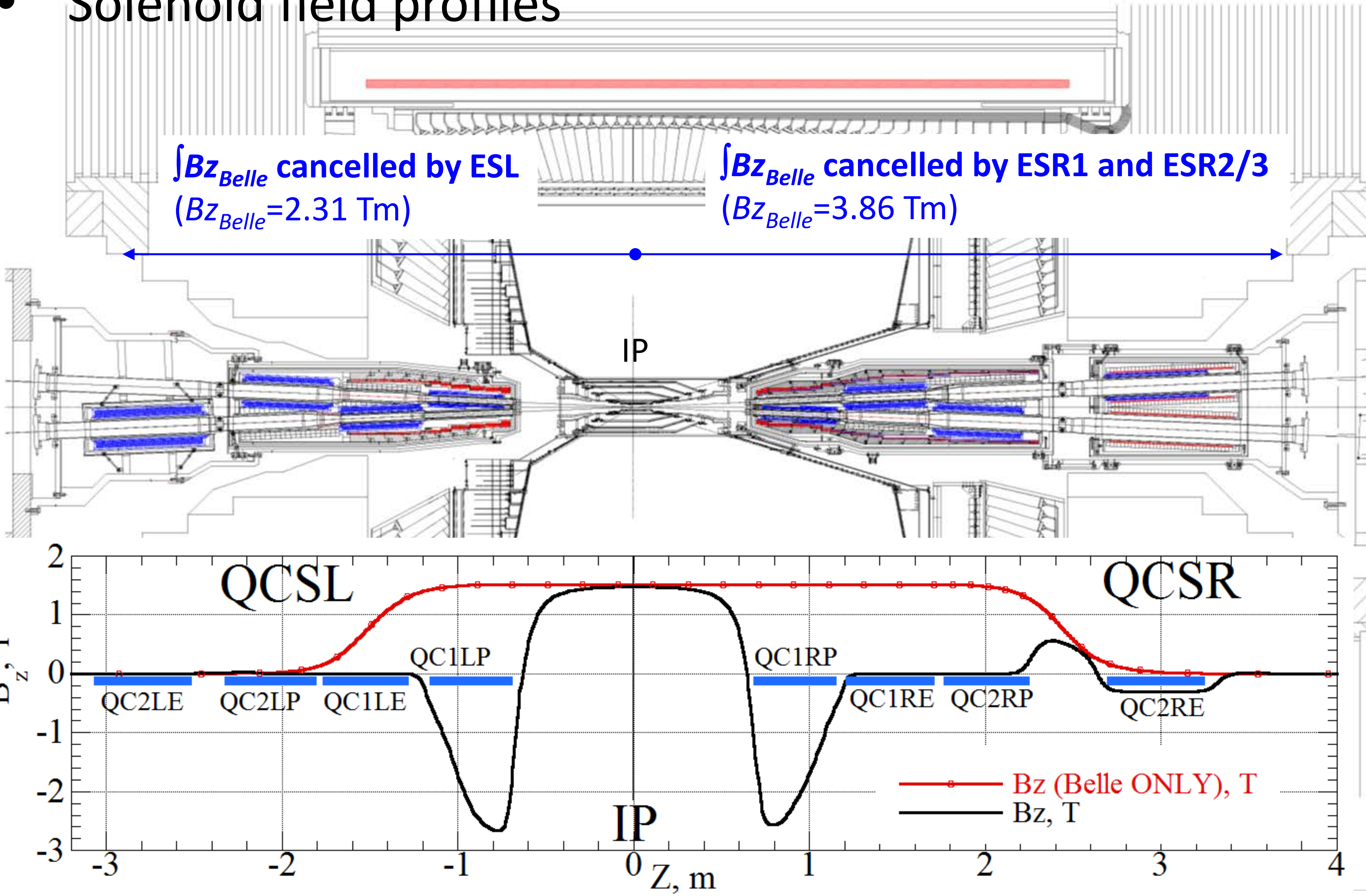
ESR3 for LER beam line



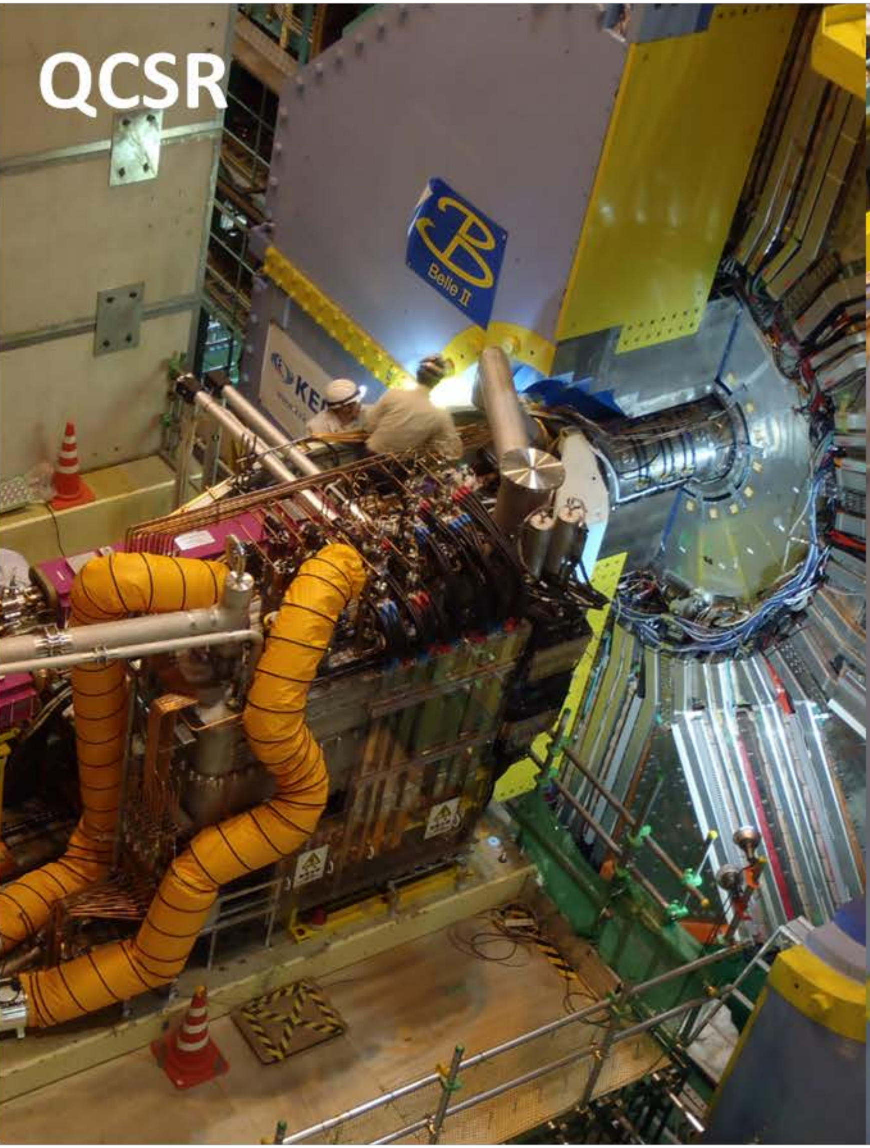


IR SC magnets

- Solenoid field profiles



QCS cryostats into Belle-II



Summary

- The superconducting final focus system for SuperKEKB has been designed and built. The magnet system is made up of 55 superconducting magnets.
  - 8 main quadrupoles (quadrupole doublets per beam)
  - 35 corrector magnets
  - 8 QC1P leak field cancel magnets
  - 4 compensation solenoid
- The system has operated very stably for three years so far.
- I would like to thank the research collaborators in BNL, FNAL and KEK for completing this very complicate system.

Back-up

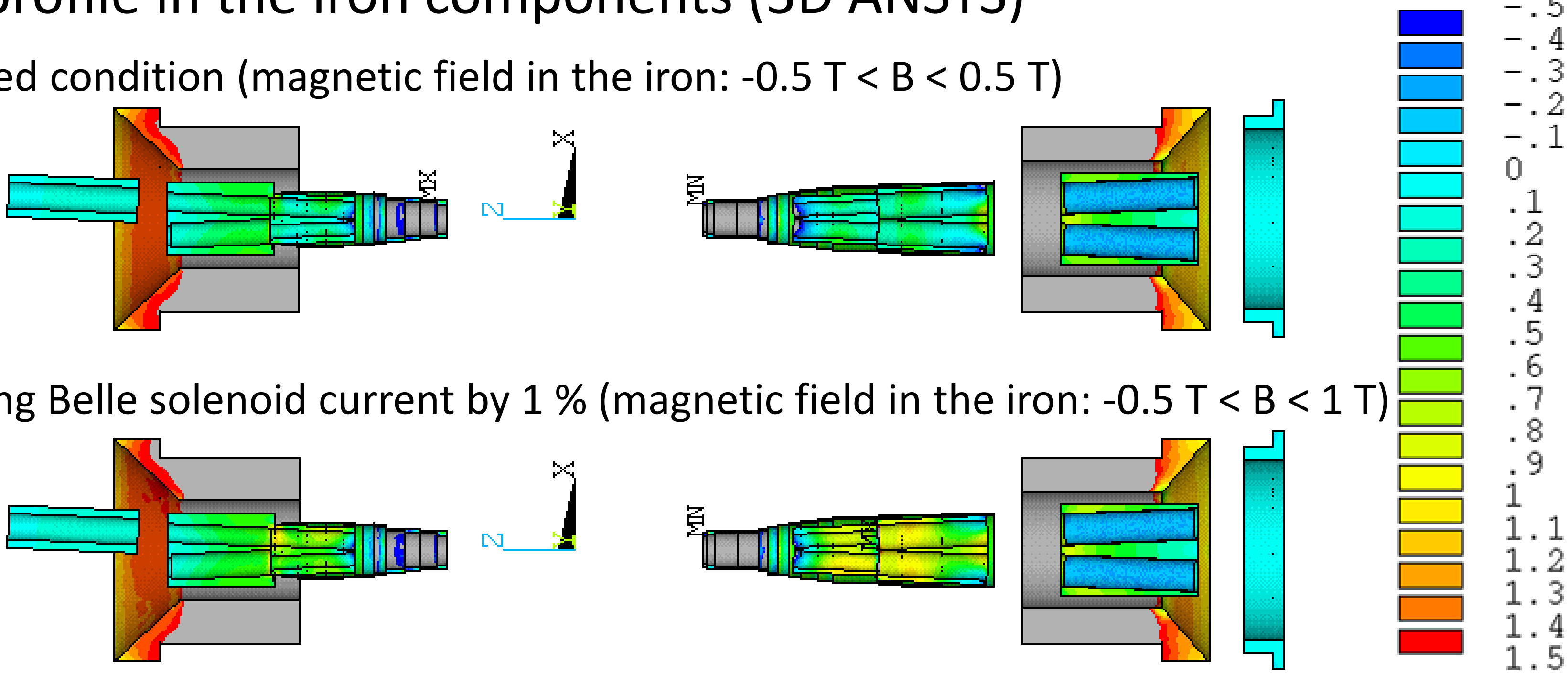
Magnet design: Permendur yoke

- The final focus system is designed to be operated under the Belle II solenoid field at 1.5 T.
- This field is cancelled with the compensation solenoids along the beam line. This cancellation is not perfect.

Field profile in the iron components (3D ANSYS)

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

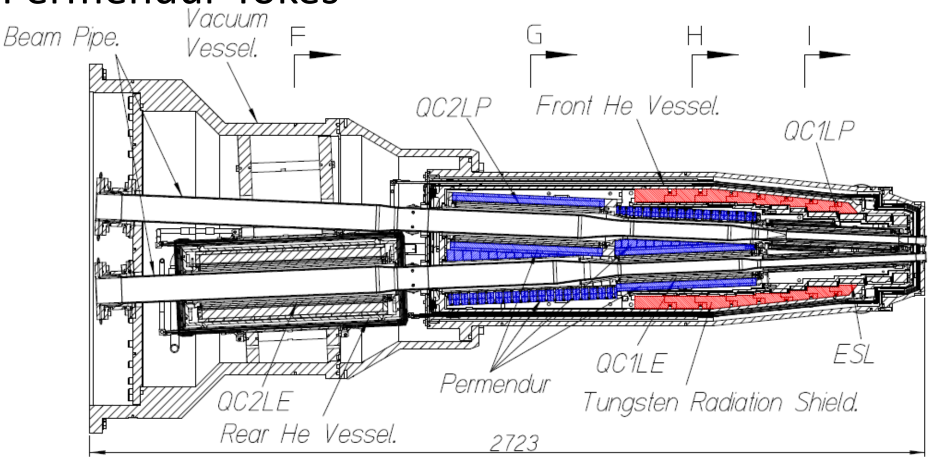
Increasing Belle solenoid current by 1 % (magnetic field in the iron: -0.5 T < B < 1 T)

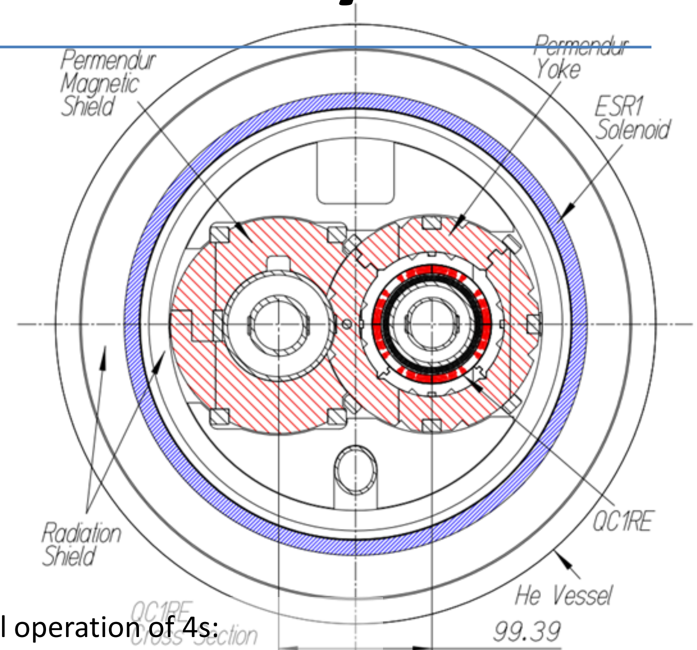


<u>At the good cancelling condition, the insides of iron components have magnetic field at 0.5T .</u>

Magnet design: Permendur yoke

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





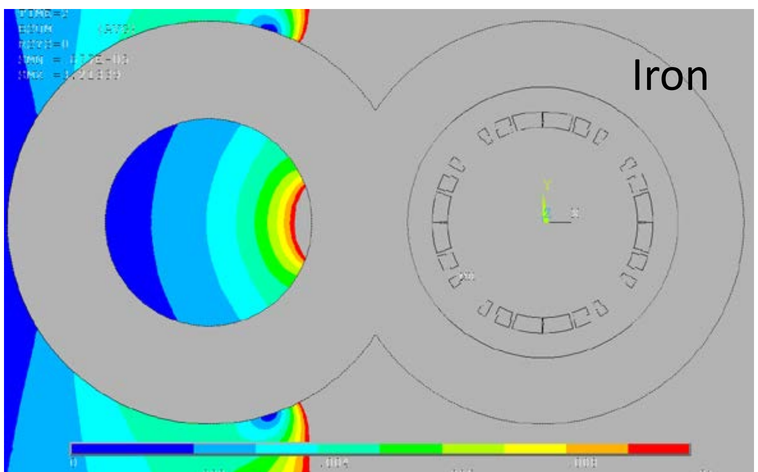
2D field calculation of QC1E (4s) : Yoke material= Iron

<u>With 1T field in the Yoke</u>

In the nominal operation of 4s:

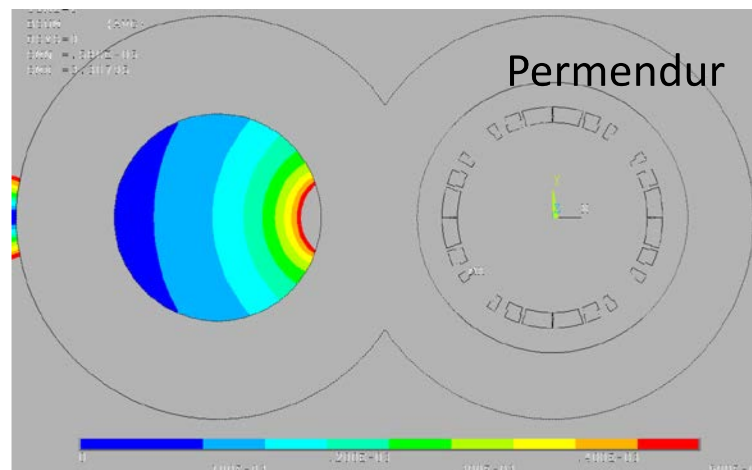
G = 72.21 T/m with 1577 A

Max. field in the magnet = 2.724 T



0 Gauss **400 Gauss**

Leak field at the e+ center = 100 Gauss



0 Gauss **5 Gauss**

Leak field at e+ center = 1.5 Gauss