Superconducting Magnet System for SuperKEKB Interaction Region

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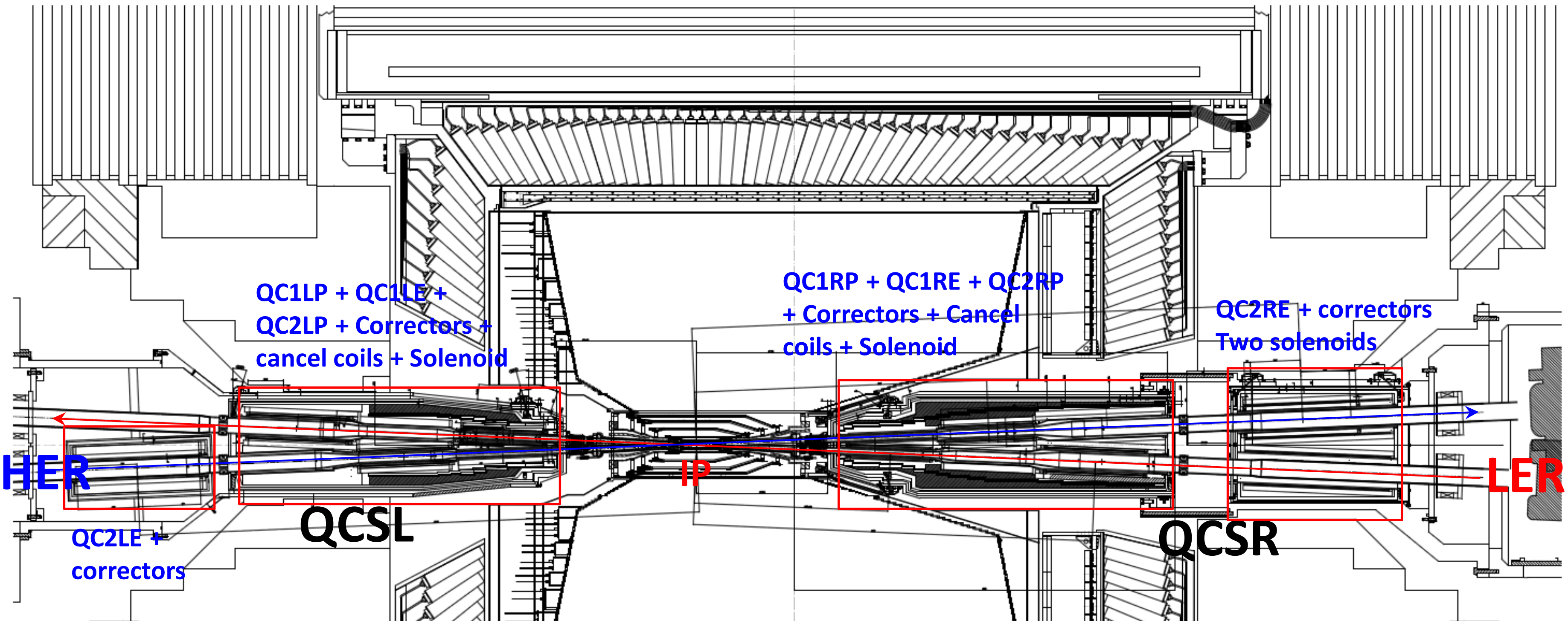
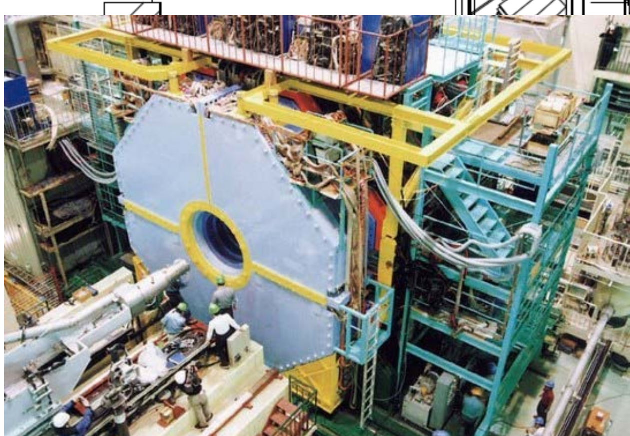
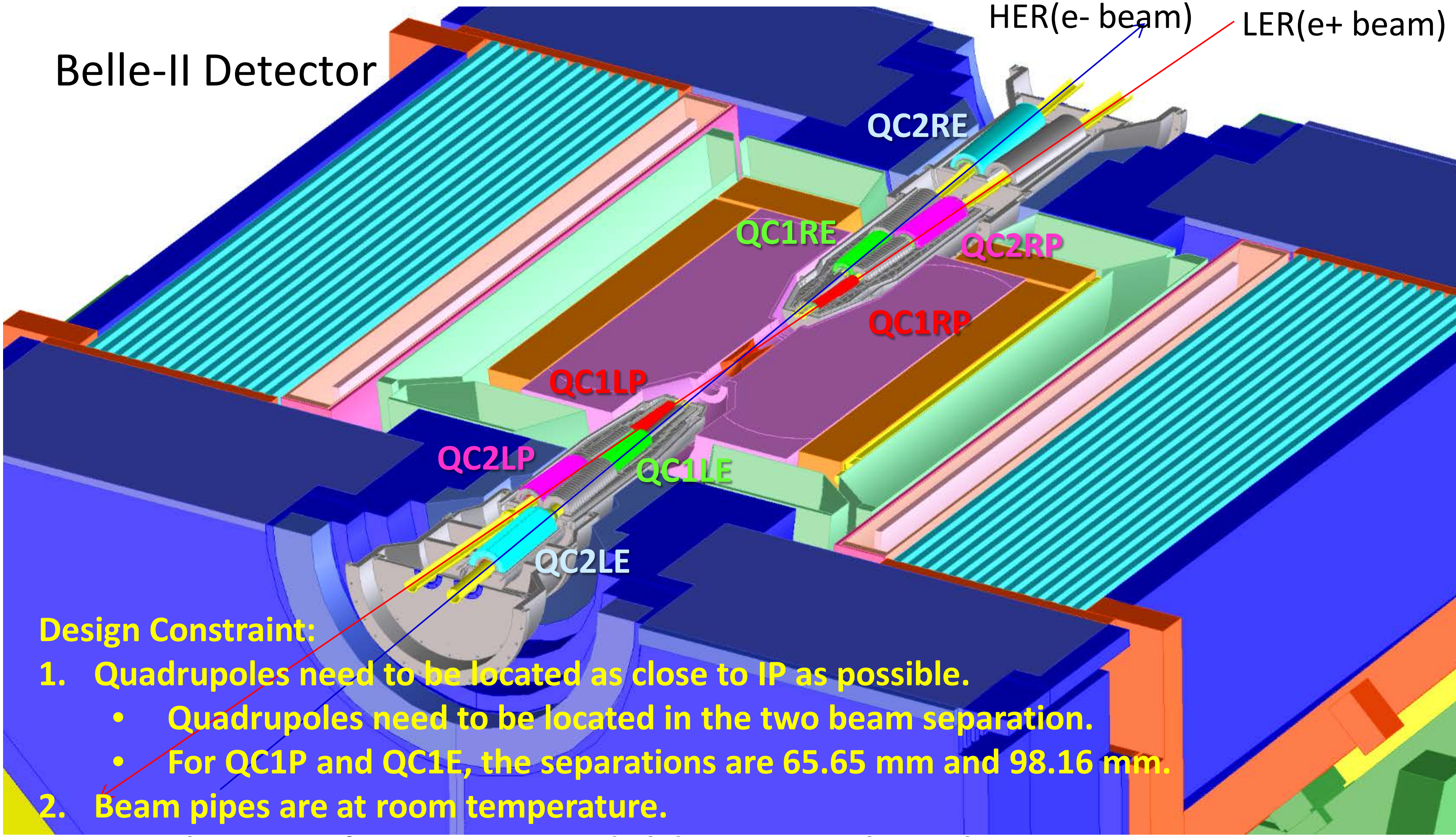
IR Magnets Overview





Belle-II particle detector

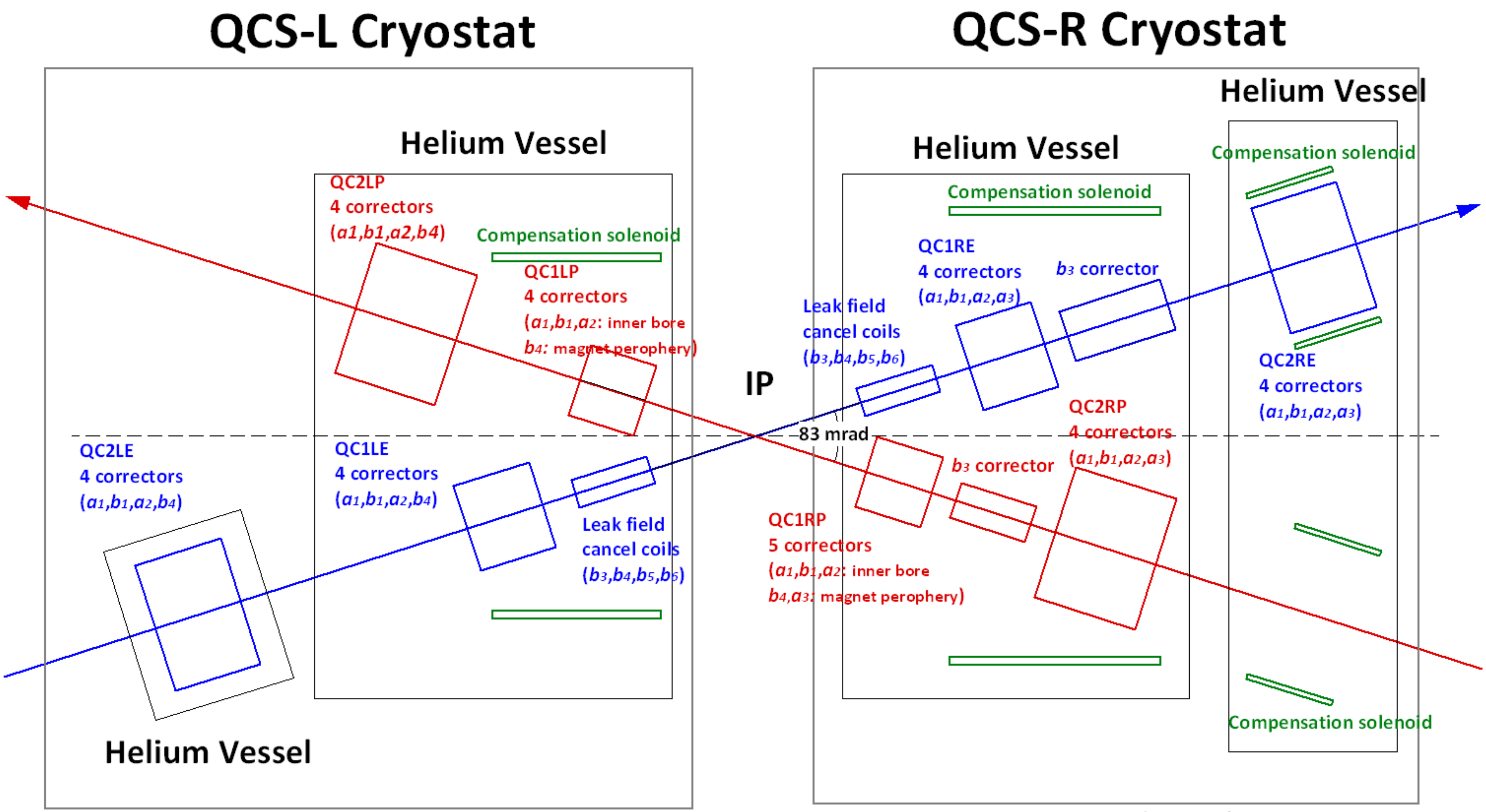
SuperKEKB IR Overview



Design Constraint:

1. **Quadrupoles need to be located as close to IP as possible.**
    - **Quadrupoles need to be located in the two beam separation.**
    - **For QC1P and QC1E, the separations are 65.65 mm and 98.16 mm.**
2. **Beam pipes are at room temperature.**
    - **The spaces for magnets in radial direction are limited.**
3. **Solenoid magnetic fields are superimposed on QC1P and QC1E.**

S.C. Magnet System



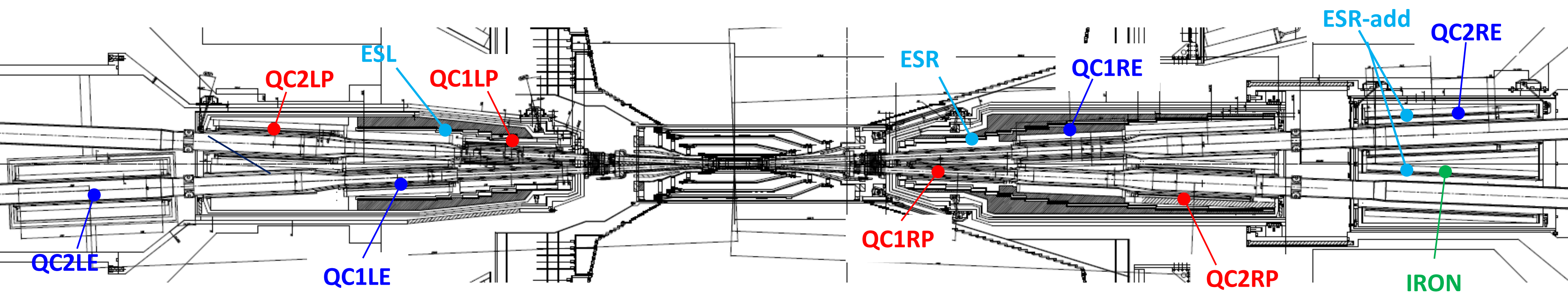
Target luminosity = 8 $\times 10^{35}$ cm^{-2} s^{-1}
Beam size at IP: e- = 62 nm, e+= 46nm

S.C. quadrupole: 8
S.C. solenoid: 4
S.C. corrector: 43

S.C. Magnets

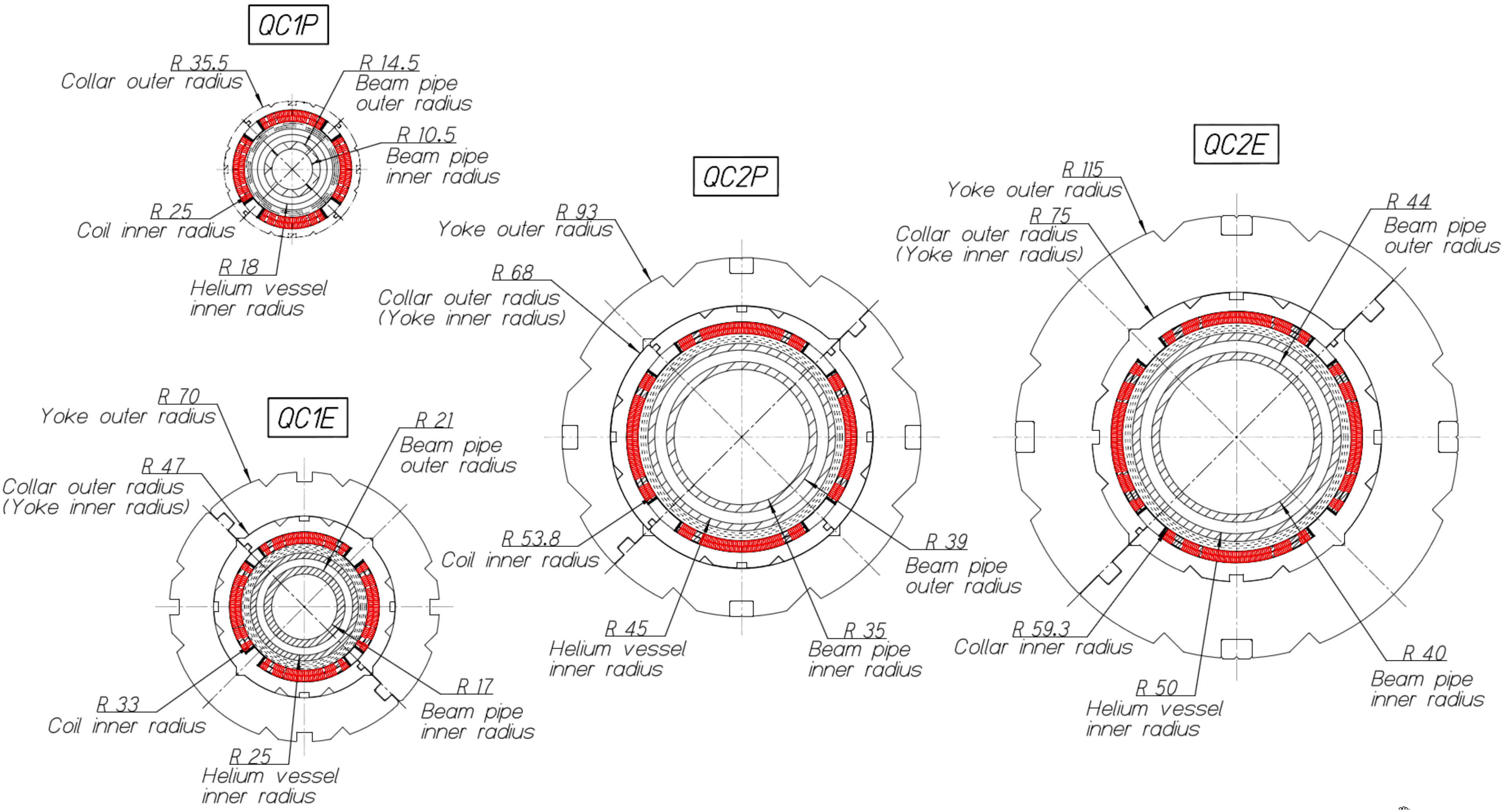
- **Main quadrupoles [QC1, QC2]**
  - Consisting final beam focusing system with quadrupole doublets.
- **Correctors [a_1, b_1, a_2, a_3, b_3, b_4]**
  - a_1, b_1, a_2: Magnetic alignment of magnetic center and mid-plane of main quadruple.
  - a_3, b_3: Correction of sextupoles induced by magnet construction errors.
    - Increasing the dynamic transverse aperture (increasing the Touschek life time).
  - 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 quadrupoles and correctors.
- **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).

S.C. magnets in SuperKEKB IR

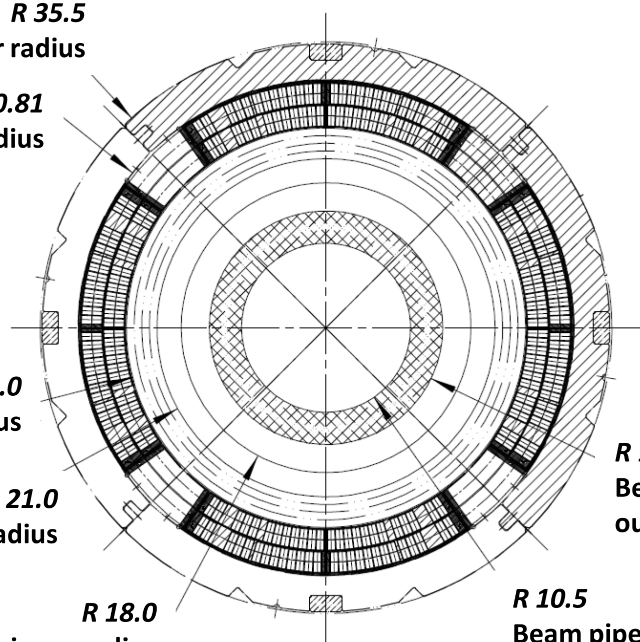


	Integral field gradient, (T/m)･m Solenoid field, T	Magnet type	Z pos. from IP, mm	θ, mrad	ΔX, mm	ΔY, mm
QC2RE	13.58 [32.41 T/m × 0.419m]	Iron Yoke	2925	0	-0.7	0
QC2RP	11.56 [26.28 × 0.410]	Permendur Yoke	1925	-2.114	0	-1.0
QC1RE	26.45 [70.89×0.373]	Permendur Yoke	1410	0	-0.7	0
QC1RP	22.98 [68.89×0.334]	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

Cross section of four quadrupoles



QC1P (No iron yoke)



QC1P magnet cross section

QC1P magnet design (QC1RP, QC1LP)

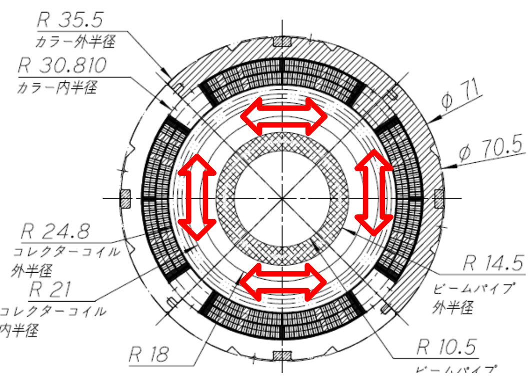
- Same design for QC1RP and QC1LP
- 2 layer coils [double pancake]
- **SC correctors [designed by BNL]**
  - **a_2, b_1 and a_1 inside of the magnet bore**
  - **b_4 , a_3 outside of the magnet collar**
- Cryostat inner bore radius=18.0 mm
- Beam pipe (warm tube)
  - inner radius=10.5 mm, outer radius=14.5 mm

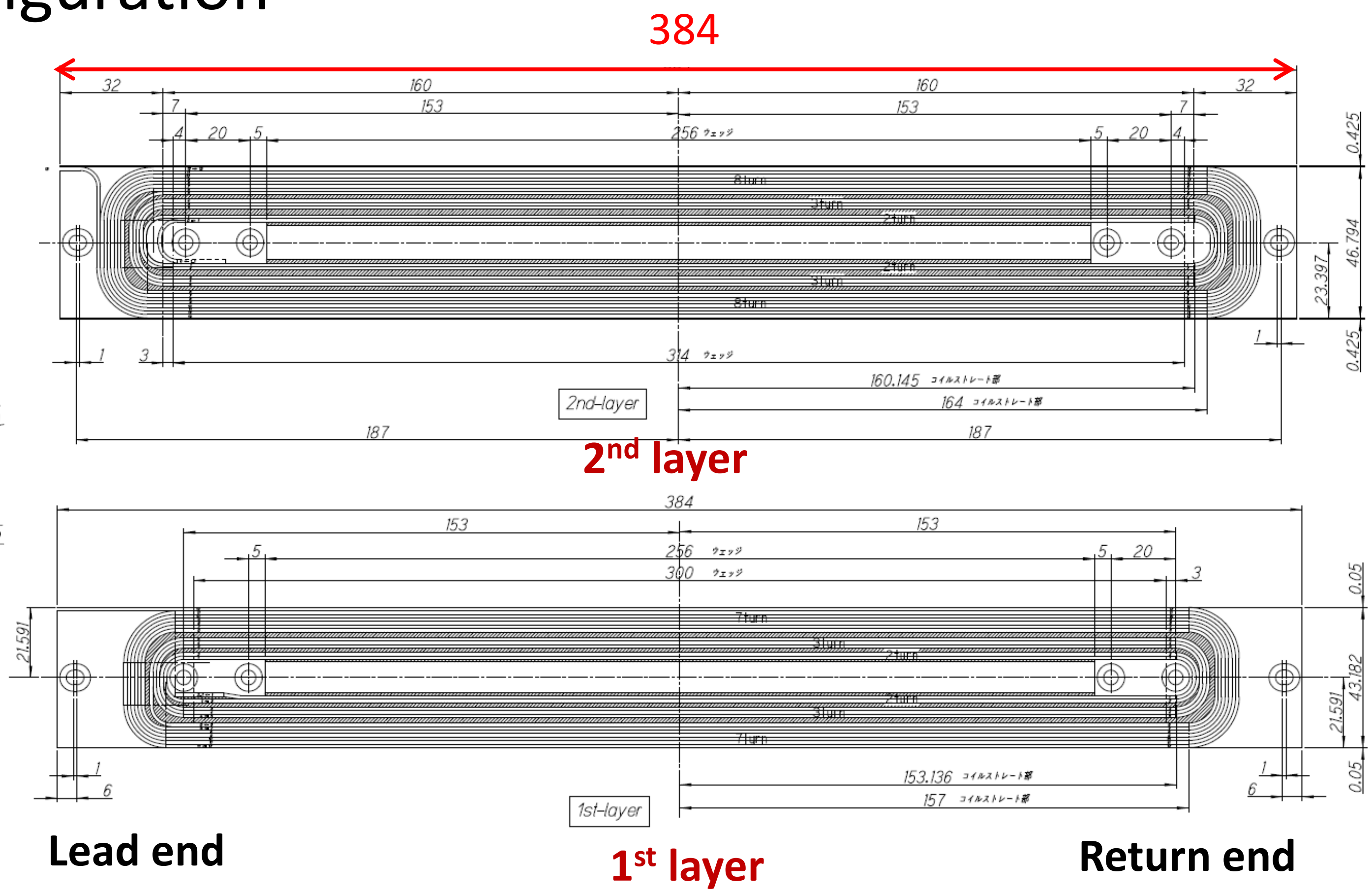
Superconducting cable

- Cable size : 2.5 mm × 0.93 mm
- **Keystone angle = 2.09 degree**
- Number of strands = 10
- Strand diameter = 0.5 mm
- Cu/SC ratio = 1.0
- Critical current (measured) = 3160 A @5 T & 4.2 K

3D magnet design of QC1R/LP

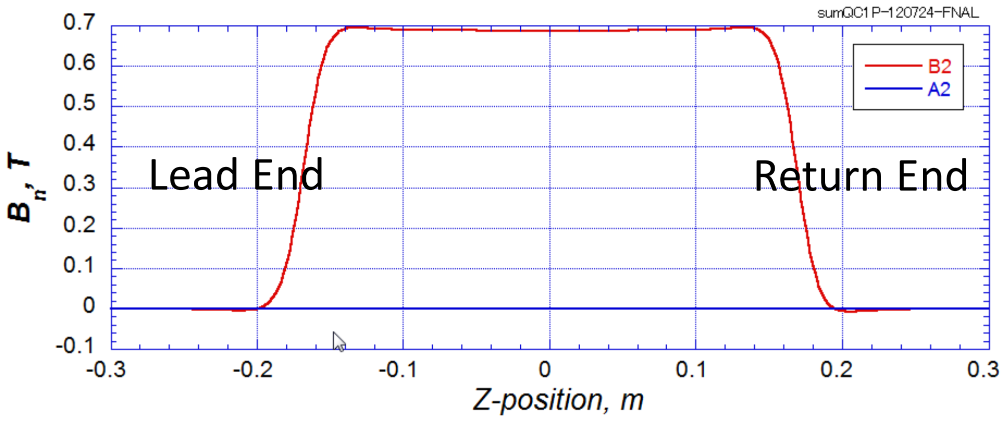
QC1P coil configuration

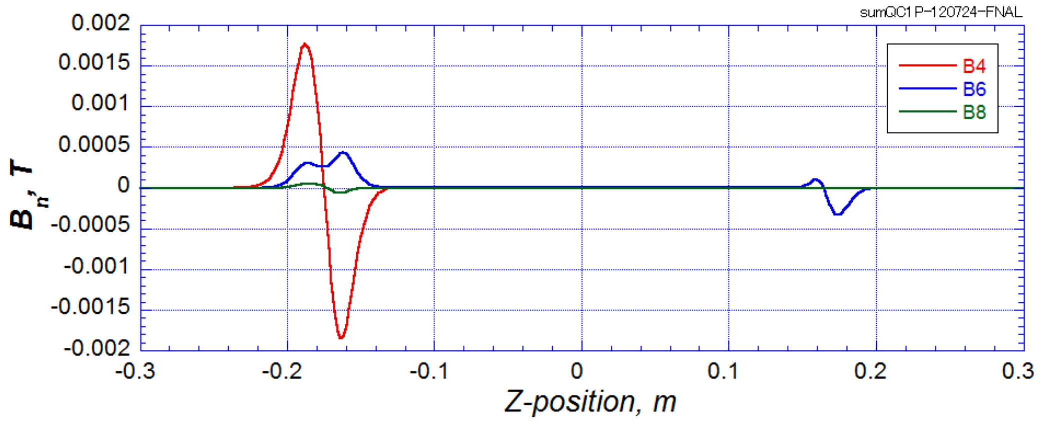




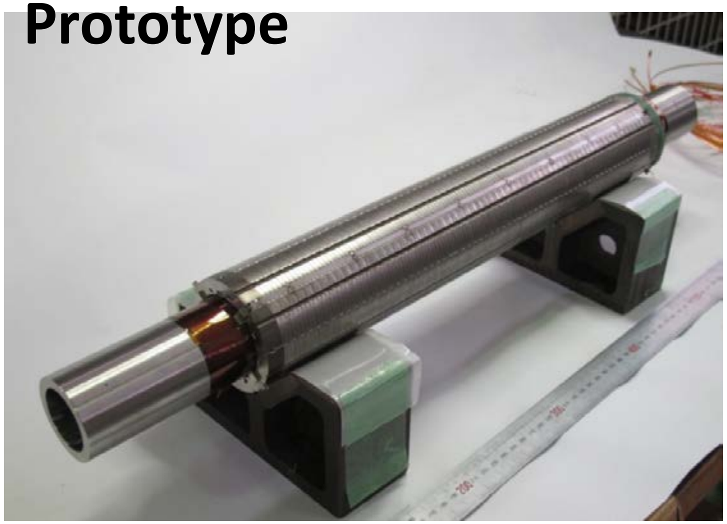
Mirror symmetry for reducing the skew quadrupole field in the lead end.

Field profile of QC1R/LP





Prototype



Multipole field at R=10 mm

Integral $b_4 = 2.38 \times 10^{-5}$

Int. $b_6 = 5.42 \times 10^{-5}$

Int. $b_8 = 1.10 \times 10^{-6}$

Peaks of $B_4 = \pm 18$ Gauss at 1625 A

Peaks of $B_6 = +4.4/-3.3$ Gauss at 1625 A

Lead end locates at IP side in the cryostat.

QC1P prototype and QC1LP real magnet

Proto-type QC1P

Measured *Int. G* = 23.22 T/m at *I*=1625A
Design *Int. G* = 23.00 T

Integral field components, units
@ R_{ref}=10 mm

n	a_n	b_n
2	0.0	10000
3	**2.96**	**3.84**
4	2.29	0.26
5	0.40	0.26
6	0.04	-0.71
7	0.09	0.16
8	0.04	0.01
9	-0.11	0.07
10	0.03	0.01

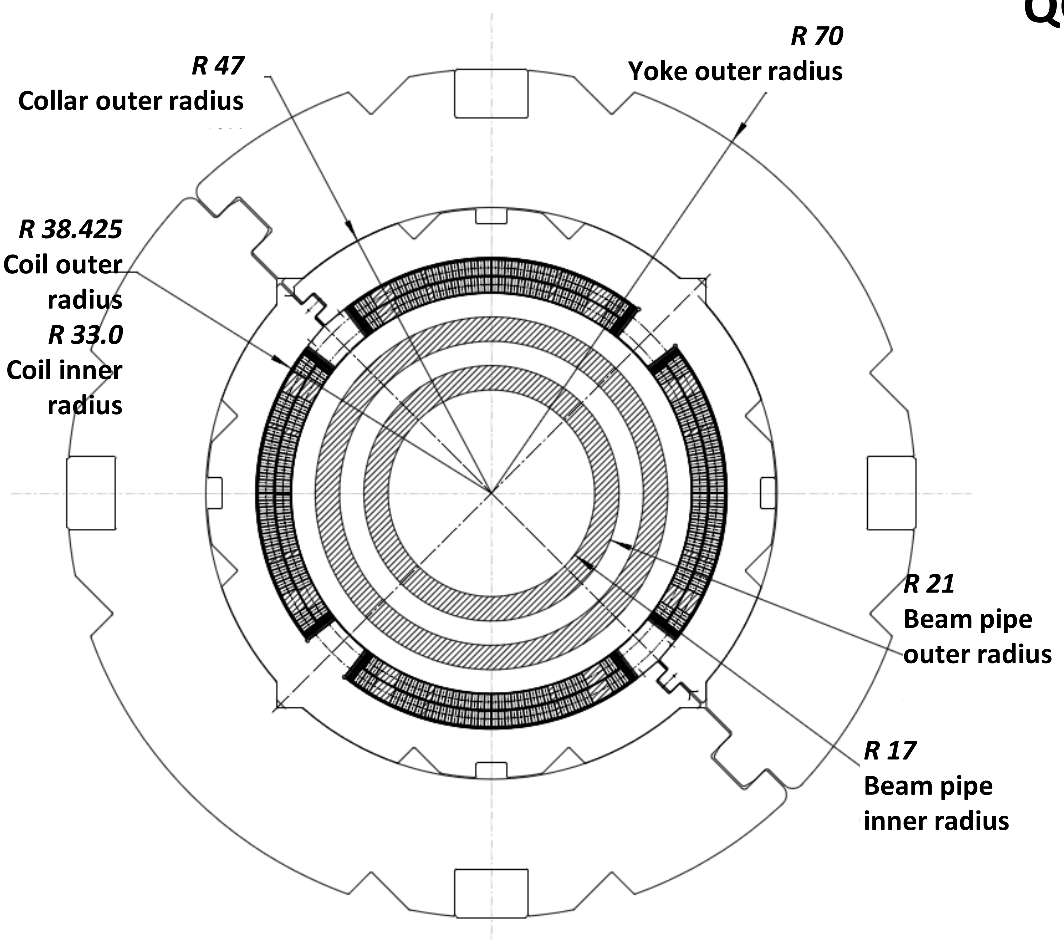
QC1LP

Measured *G* = 23.01 T/m at *I*=1625A
Design *Int. G* = 23.00 T

Integral field components, units
@ R_{ref}=10 mm

n	a_n	b_n
2	0.0	10000
3	**-0.52**	**1.16**
4	-0.98	0.19
5	0.27	-0.11
6	0.29	-0.11
7	-0.12	0.03
8	-0.02	-0.04
9	-0.06	0.02
10	0.11	-0.23

QC1E magnet design: Permendur yoke



QC1E magnet cross section

QC1E magnet design (QC1RE, QC1LE)

- Yoked magnet: **Permendur yoke**
- 2 layer coils [double pancake]
- $I_{op@4S}$ =1577 A for QC1LE
  - G =72.2 T/m, L_{eff} = 0.373 m
- <u>**SC correctors**</u>
  - a_2, b_1, a_1 inside of the magnet bore
  - b_4 [QC1LE], a_3 [QC1RE] inside of the magnet bore
- Cryostat inner bore radius=25.0 mm
- Beam pipe (warm tube)

QC1E prototype and QC1LE real magnet

Proto-type QC1E

Measured *Int. G* = 26.95 T at *I*=1577.1 A
Design *Int. G* = 26.94 T

Integral field components, units
@ R_{ref}=15 mm

n	a_n	b_n
2	0.	10000
3	**1.78**	**8.59**
4	0.44	-0.68
5	0.23	-1.83
6	-0.39	-1.85
7	-0.09	0.10
8	0.69	-0.02
9	0.51	-0.09
10	-0.10	-0.62

Proto-type QC1LE

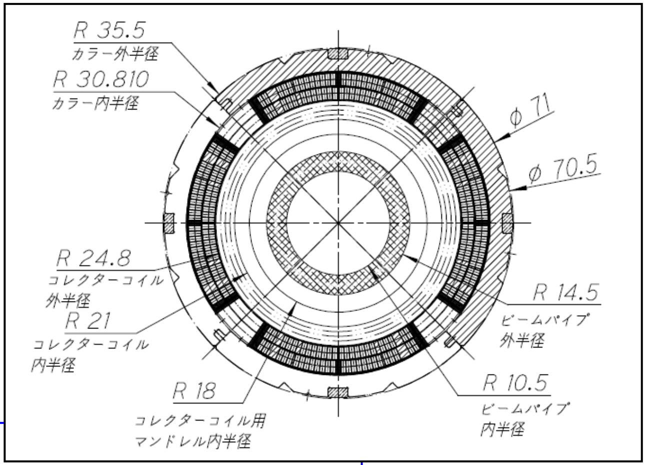
Measured *Int. G* = 26.84 T at *I*=1577.1 A
Design *Int. G* = 26.94 T

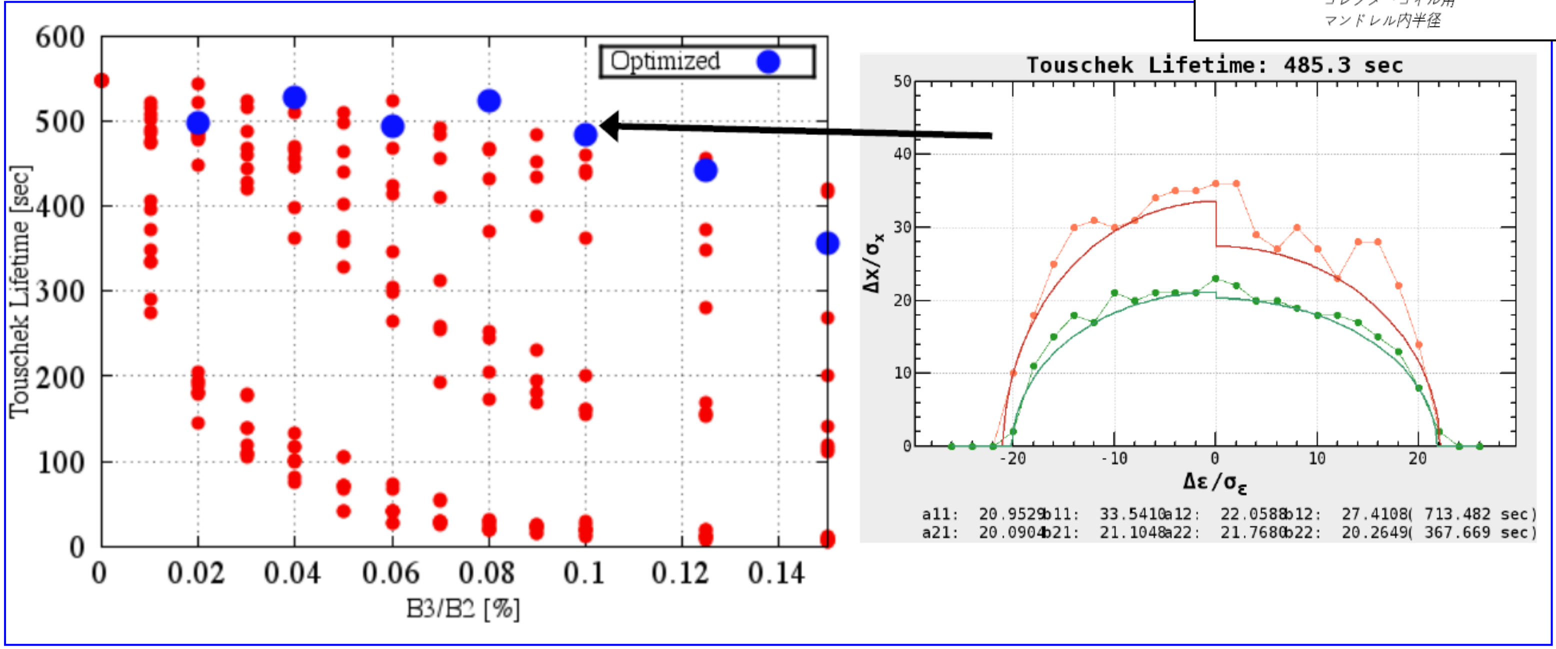
Integral field components, units
@ R_{ref}=15 mm

n	a_n	b_n
2	0.	10000
3	**-0.24**	**-0.62**
4	-0.14	-0.20
5	-0.25	0.11
6	-0.00	0.98
7	0.02	-0.01
8	0.06	-0.06
9	-0.05	0.06
10	0.30	-0.35

Effect of a_3 on beam life time

- Beam lifetime (Touschek lifetime) reduction by error fields of quadrupole magnets
  - **The sextupole field component** of 2×10^{-4} with respect to quadrupole field (B_3/B_2) is induced by the deformation of 8 μm in the coil shape.
  - The field component degrades the beam life time from 550 s to 150 s.
  - The reduced life time is recovered to 500 s with the sextupole corrector magnets.



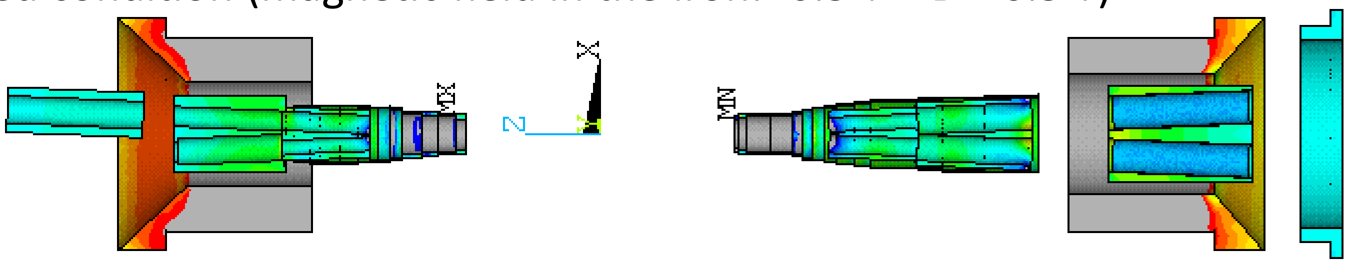


Magnet design: Permendur yoke

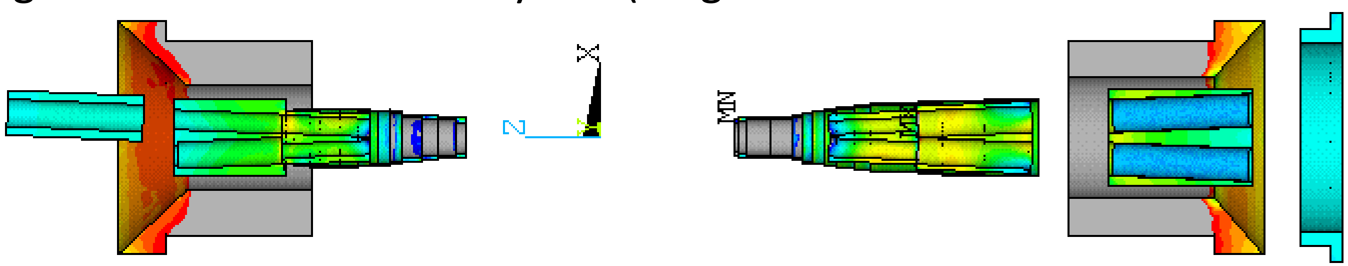
- The final focus system is designed to be operated under the Belle II solenoid field at 1.5 T.
- This field is cancelled with the accelerator compensation solenoids along the beam line. This cancellation is not perfect.

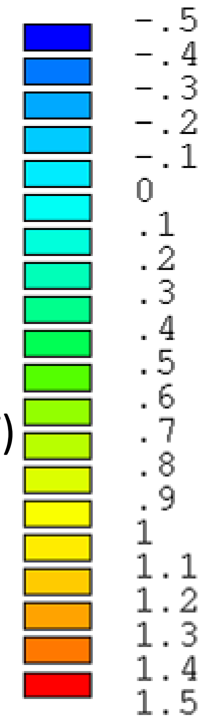
Field profile in the iron components (3D ANSYS)

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

- **Choice of Permendur for QC1E and QC2P Yoke.**
  1. Space between LER and HER beam lines along the QC1E is insufficient not to have leak field of QC1E in the LER beam area.
  2. Compensation of Belle solenoid field by the accelerator solenoid is not perfect in the local position.
     - The remanent solenoid field easily goes into the Yokes and the magnetic field in the yokes is enhanced.
  3. 12 GeV accelerator operation is the severer magnetic condition for the magnets than the 4S (nominal) operation.

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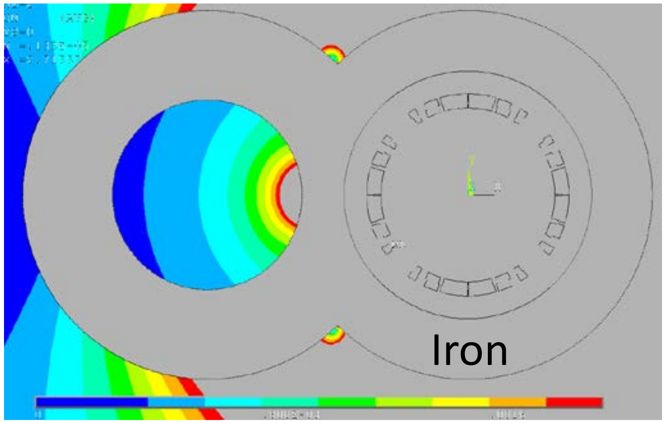
Permendur Yoke and Magnetic Shield

Magnet design: Permendur yoke

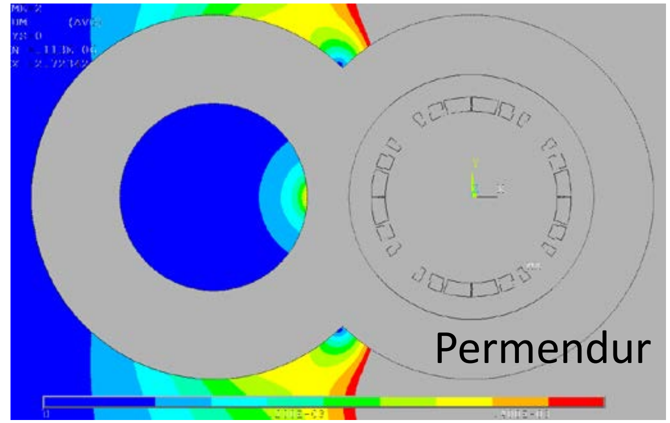
Comparison between Iron and Permendur

With 0.5 T field in the Yoke (4s)



0 Gauss **20 Gauss**

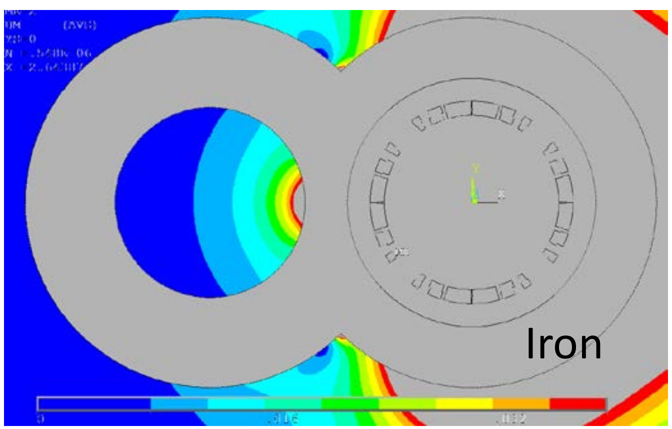
Leak field at e+ center = 6 Gauss



0 Gauss **5 Gauss**

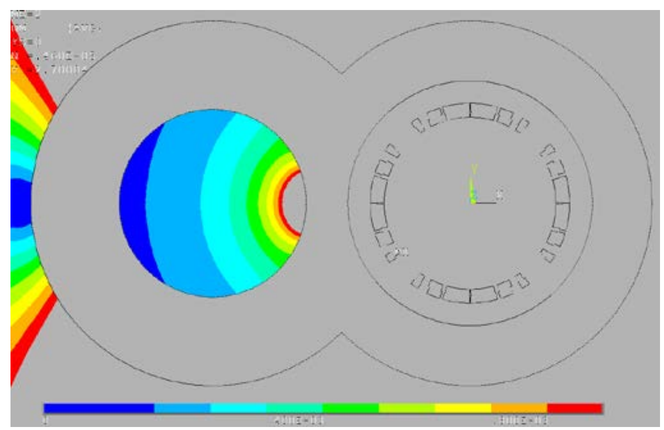
Leak field at e+ center <1 Gauss

With 1 T field in the Yoke (4s)



0 Gauss **400 Gauss**

Leak field at the e+ center = 100 Gauss

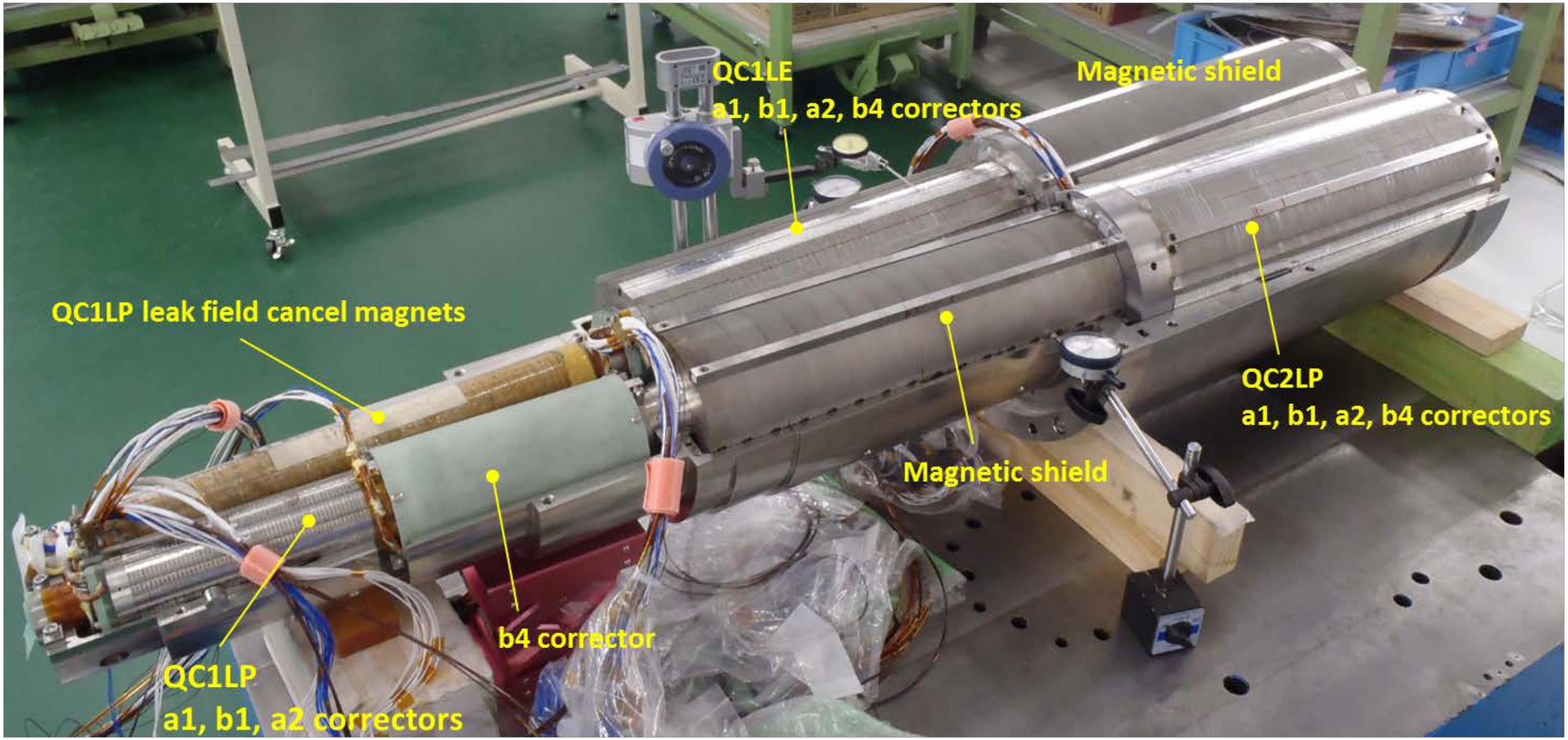


0 Gauss **10 Gauss**

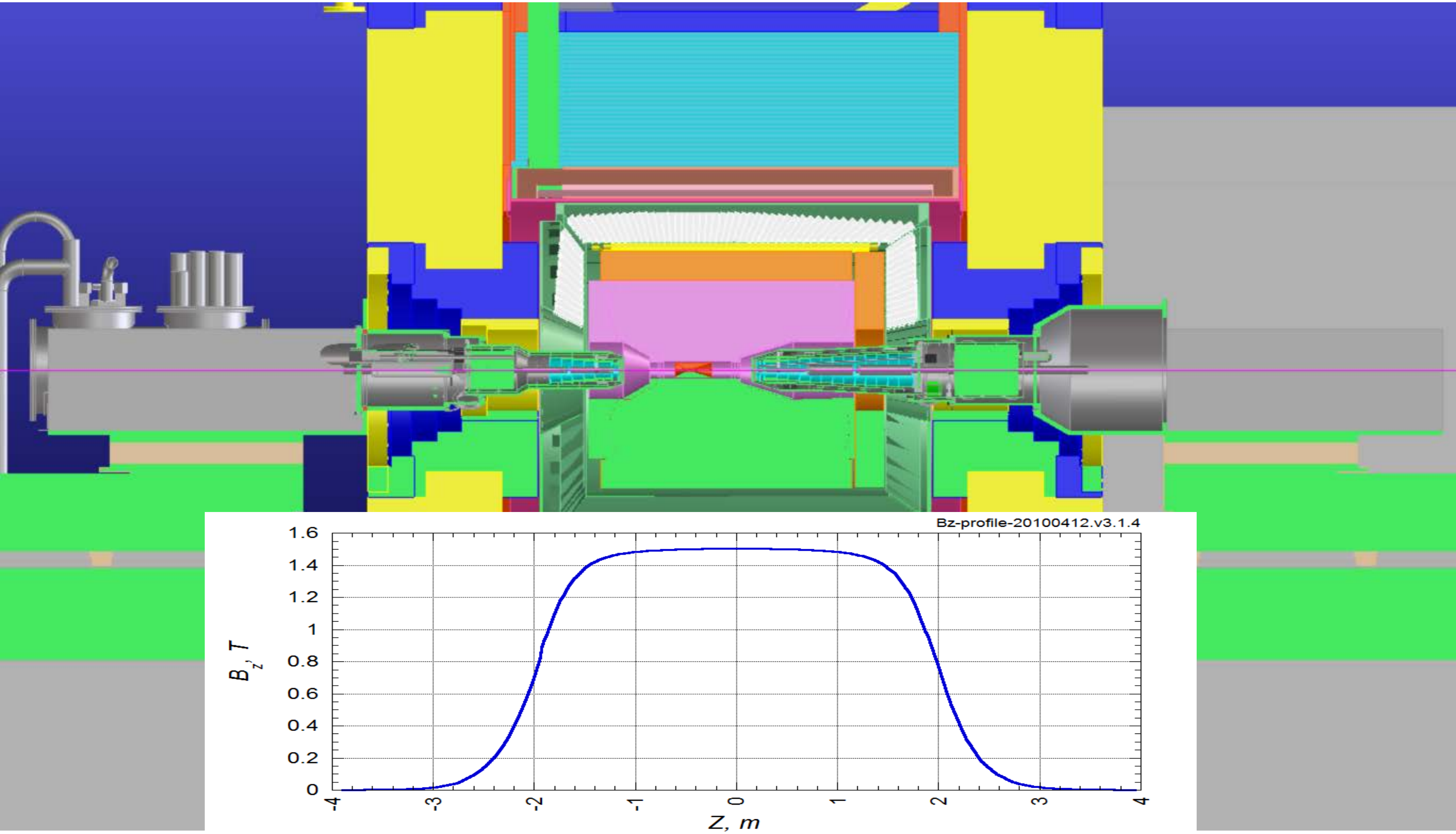
Leak field at e+ center = 6 Gauss

Magnet Construction

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

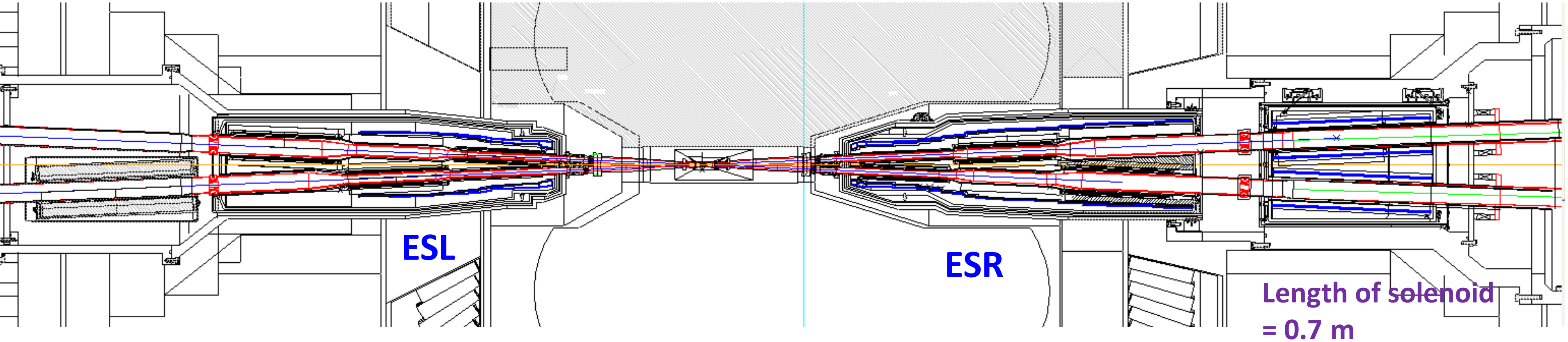


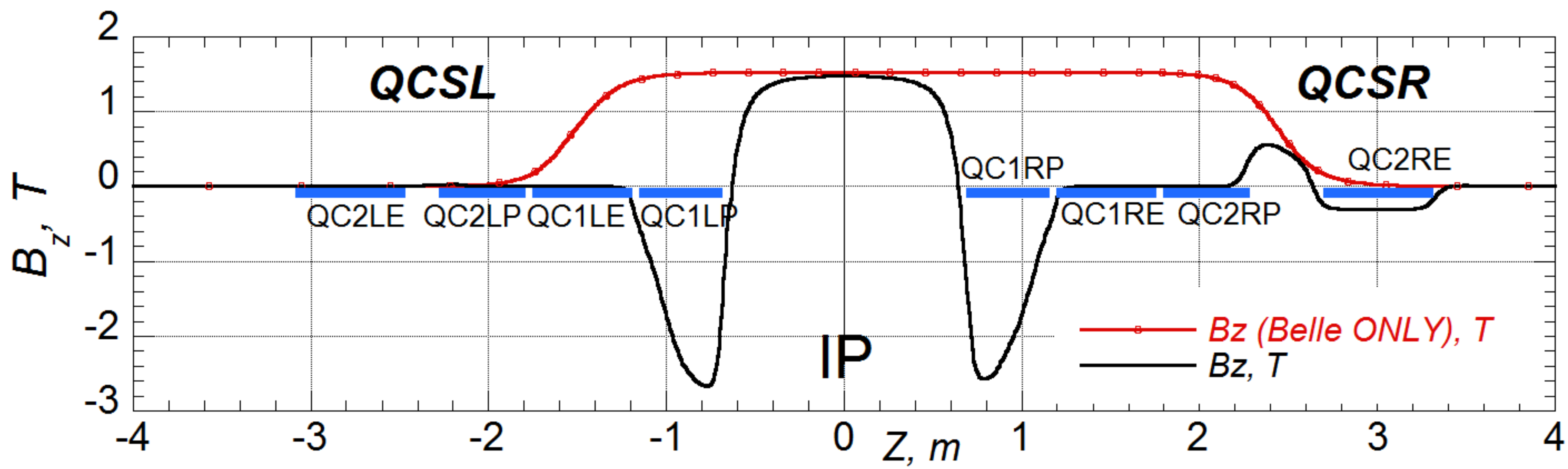
Compensation Solenoids



Belle II solenoid field profile along beam line

Compensation Solenoids

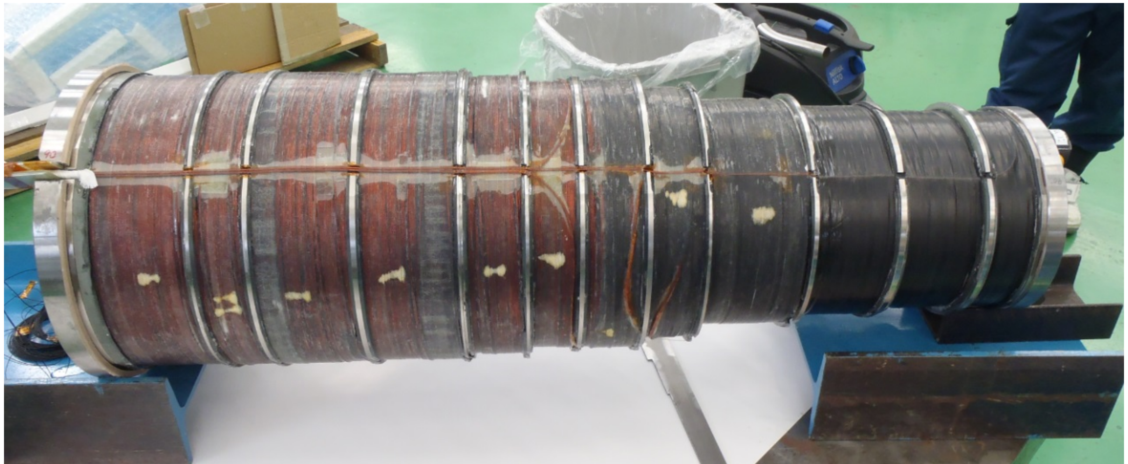




- In the left cryostat, one solenoid (12 small solenoids) is overlaid on QC1LP and QC1LE.
- In the right cryostat, the 1st solenoid (15 small solenoids) is overlaid on QC1RP, QC1RE and QC2RP.
  - The 2nd and 3rd solenoids on the each beam line in the QC2RE vessel.

Solenoid Construction

- Compensation solenoids [ESL, ESR1]



ESL consists of 12 coils:
Magnet length= 914 mm
Maximum field at 403 A= 3.53 T
Stored Energy= 118 kJ

ESR1 consists of 15 coils:
Magnet length= 1575 mm
Maximum field at 450 A=3.19 T
Stored Energy= 244 kJ

SC correctors

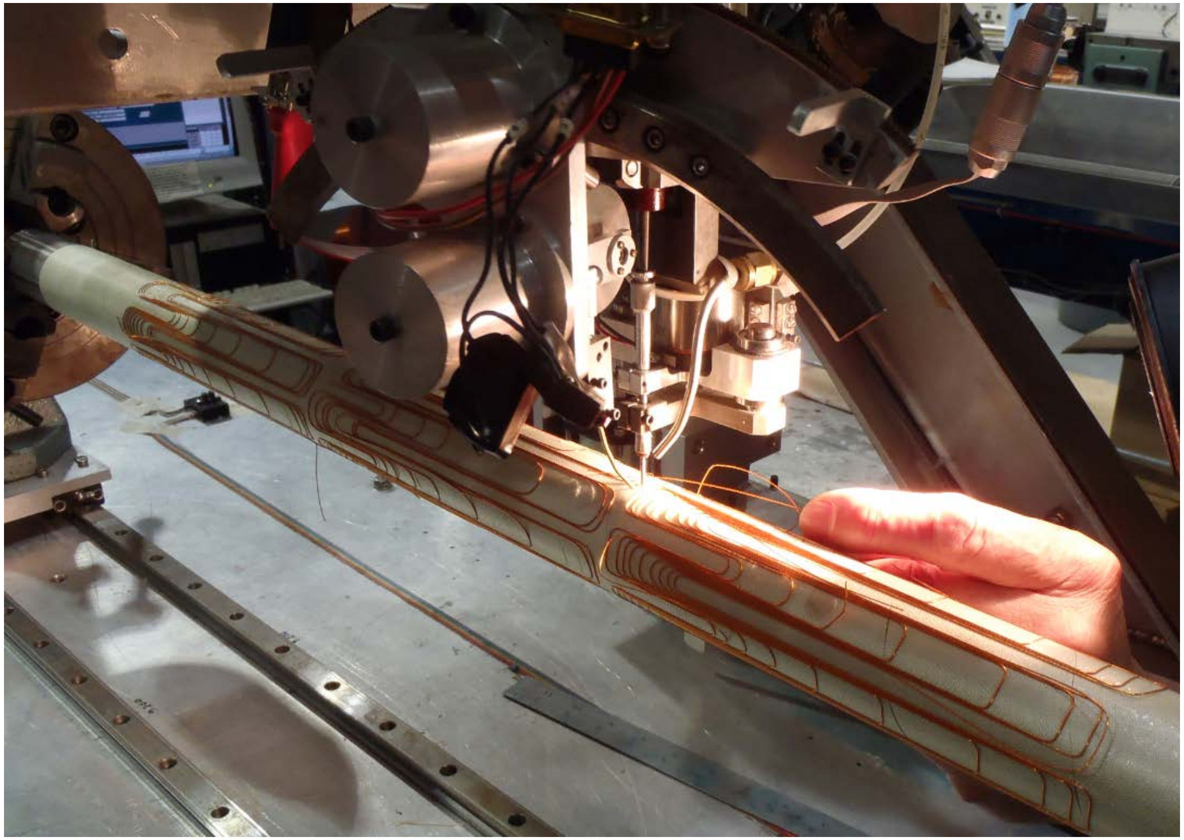
Magnet	R_0 mm	I_{max} A	A_1 T·m	B_1 T·m	A_2 T	A_3 T/m	B_3 T/m	B_4 T/m^2	B_5 T/m^3	B_6 T/m^4
QC1LP	10	70	0.016	0.016	0.64			60		
QC2LP	30	70	0.03	0.03	0.31			60		
QC1LE	15	70	0.027	0.046	0.75			60		
QC2LE	35	70	0.015	0.015	0.37			60		

Magnet	R_0 mm	I_{max} A	A_1 T·m	B_1 T·m	A_2 T	A_3 T/m	B_3 T/m	B_4 T/m^2	B_5 T/m^3	B_6 T/m^4
QC1RP	10	60	0.016	0.016	0.64	5.1		60		
QC2RP	30	60	0.03	0.03	0.31	0.9				
QC1RE	15	60	0.027	0.046	0.75	4.8				
QC2RE	35	60	0.015	0.015	0.37	1.0				
B.T. QC1RP and QC2RP	15	60					7.5			
B.T. QC1RE and QC2RE	30	60					4.8			

The number of correctors is 35, and they are wound in multi-layer for each main quadrupole.

SC correctors

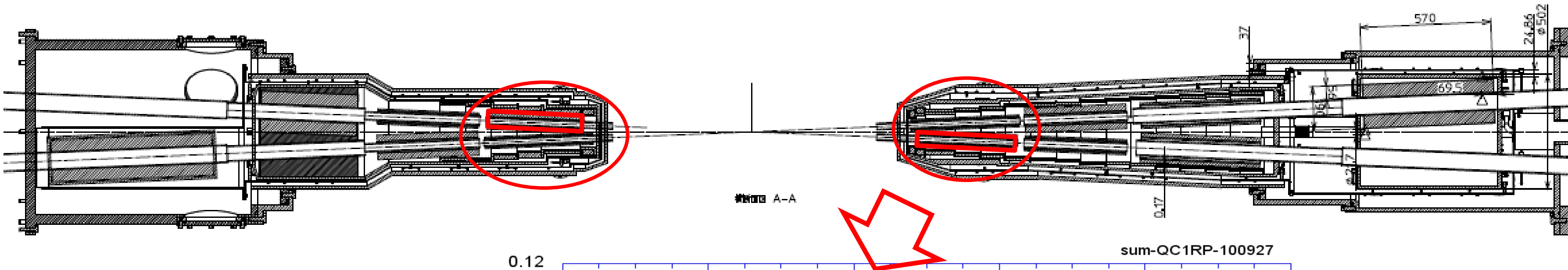
- SC correctors were constructed by BNL under the US-Japan research collaboration program.
- The spaces for the correctors are very tight, and then the coils are wound by the direct winding method and in multi-layers.



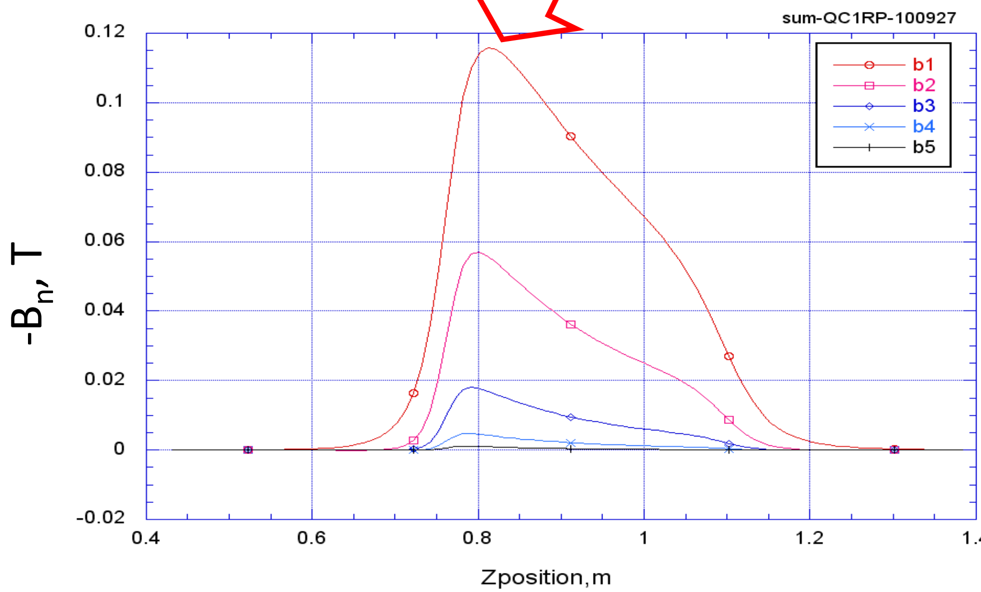
BNL direct winding machine

SC leak field cancel coils

- QC1P for the e+ beam line is non-iron magnet and the e- beam line is very close to QC1P. The leak fields along the e- beam line by QC1P are calculated.
- ***B_3, B_4, B_5*** and ***B_6*** components of the leak fields are designed to be canceled with the SC cancel coils.
- B_1 and B_2 components are not canceled, and they are included in the optics calculation.
  - B_2 component is used for focusing and defocusing the e- beam.

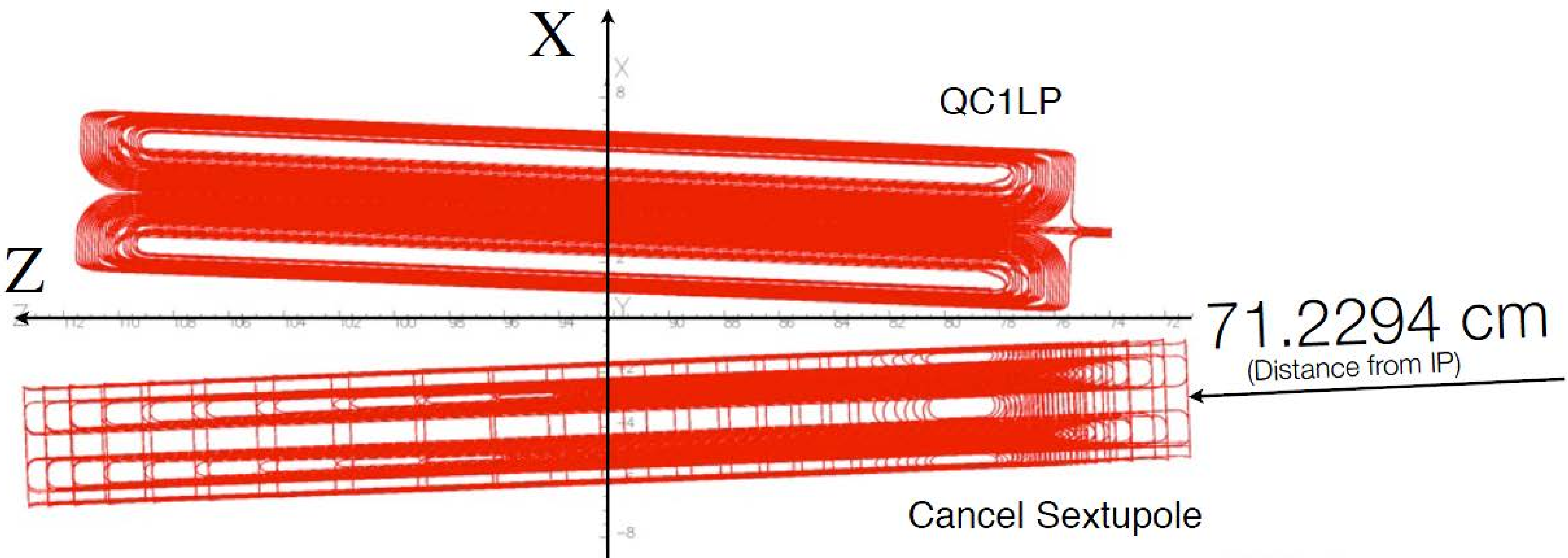


QC1RP leak field profile along the e- beam line



SC leak field cancel coils

- The leak field cancel coils are now designed and constructed by BNL under the US-Japan research collaboration program.
- The field model is constructed with the collaboration between BNL and KEK.



Cancel coil designed by B. Parker [BNL]
Sextupole cancel coil : 2 layer serpentine coils

Summary

- KEK is now constructing the SuperKEKB accelerator.
  - The target luminosity = 8×10^{35} cm^{-2} s^{-1}
    - The e- and e+ beams are designed to collide with a finite crossing angle of 83 mrad and beam sizes of about 50 nm at IP.
- IR SC magnet system is the most important and complicate hardware in SuperKEKB.
  - The final focusing system was designed with 8 quadrupoles, 4 compensation solenoids and 43 corrector coils.
- Further required studies:
  - Alignment of the quadrupoles on the beam lines.
    - Elector-magnetic forces on the compensation solenoids and the magnetic components from the Belle solenoid field of 1.5 T.
    - The EMF on the compensation solenoid (Max) = 8×10^4 N
  - Vibration effect of the quadrupole fields on the beam operation.