Final Focus Magnet Design SuperKEKB

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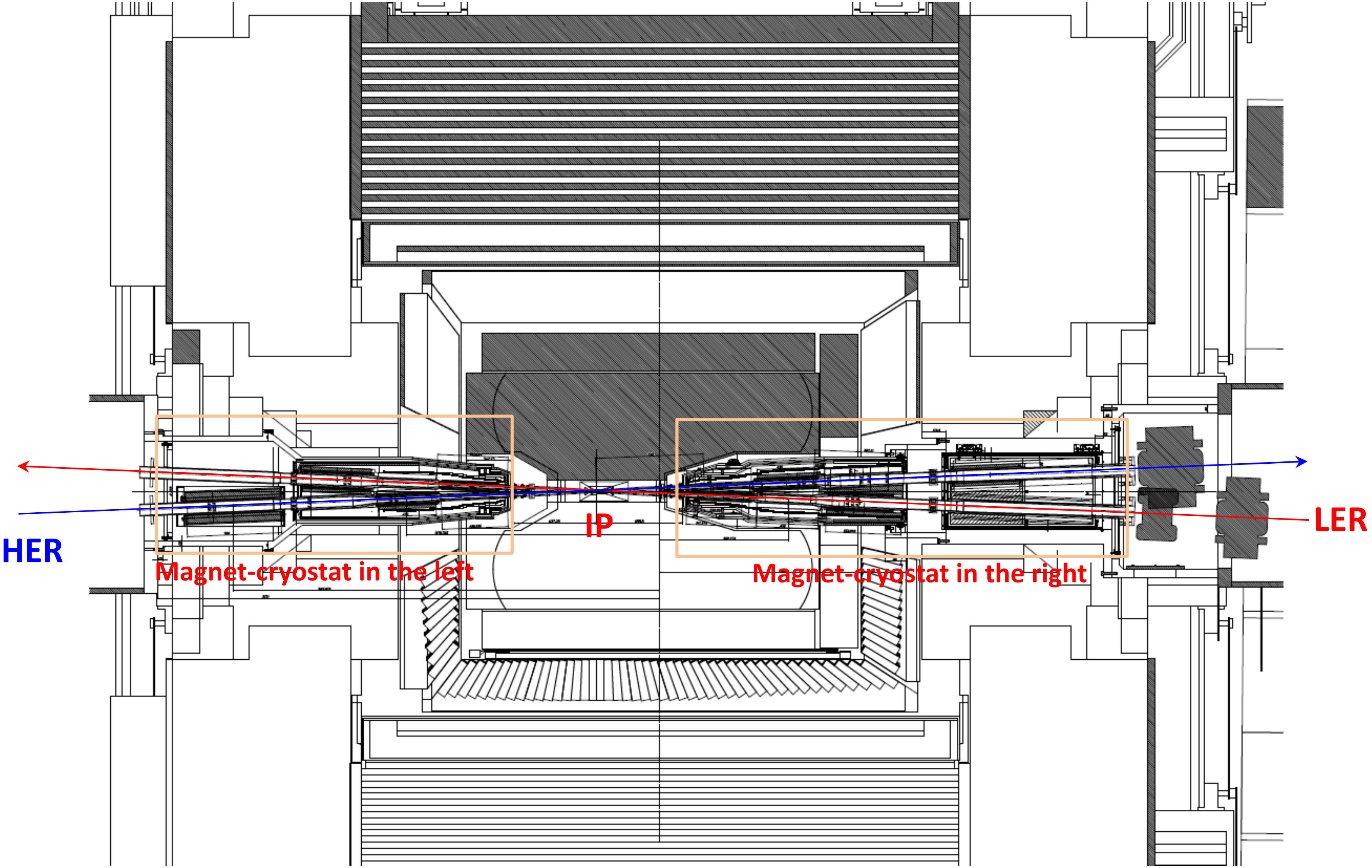
(on behalf of KEK SC magnet group, IR group and BNL SC magnet group)

Contents

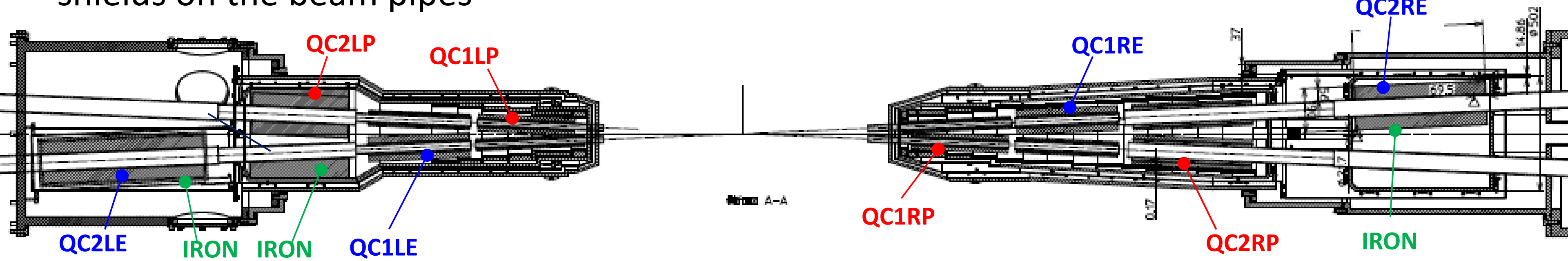
1. IR Overview
2. Design of S.C. magnets
3. R&D magnet status
4. Construction schedule

IR Overview


HER
LER
IP
Magnet-cryostat in the left
Magnet-cryostat in the right

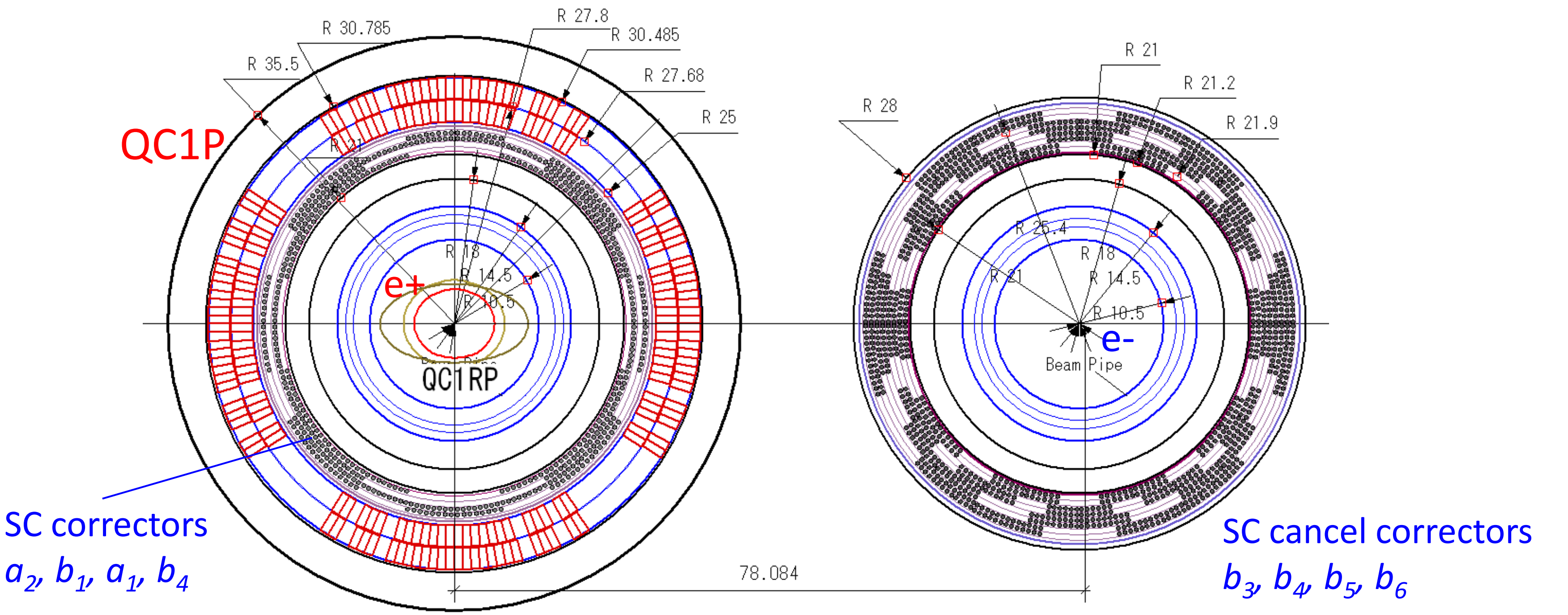
S.C. Magnets in SuperKEKB IR

Design changes in the magnets: introducing iron yokes to the quadrupoles and magnetic shields on the beam pipes



	Integral field gradient, (T/m)･m Solenoid field, T	Position from IP, mm	Magnet type	Corrector	Leak field cancel coil
QC2RE	12.91 [34.9 T/m × 0.370m]	2925	**S.C. + Iron Yoke**	a_1, b_1, a_2, b_4	
QC2RP	10.92 [27.17 × 0.4135]	1925	**S.C. + Iron Yoke**	a_1, b_1, a_2, b_4	
QC1RE	24.99 [66.22×0.3774]	1410	**S.C. + Iron Yoke**	a_1, b_1, a_2, b_4	
QC1RP	22.43 [66.52×0.3372]	935	**S.C.**	a_1, b_1, a_2, b_4	b_3, b_4, b_5, b_6
QC1LP	22.91 [67.94×0.3372]	-935	**S.C.**	a_1, b_1, a_2, b_4	b_3, b_4, b_5, b_6
QC1LE	26.67 [70.68×0.3774]	-1410	**S.C. + Iron Yoke**	a_1, b_1, a_2, b_4	
QC2LP	10.96 [27.15 × 0.4135]	-1925	**S.C. + Iron Yoke**	a_1, b_1, a_2, b_4	
QC2LE	14.13 [20.2×0.700]	-2700	**S.C. + Iron Yoke**	a_1, b_1, a_2, b_4	
ESR	4.3 T (max. field)		S.C. Solenoid		
ESR-add	0.3 T	Each beam	S.C. Solenoid **+ Iron Yoke**		
ESL	4.7 T (max. field)		S.C. Solenoid		

QC1P (No iron yoke)



QC1P magnet design (QC1RP, QC1LP)

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

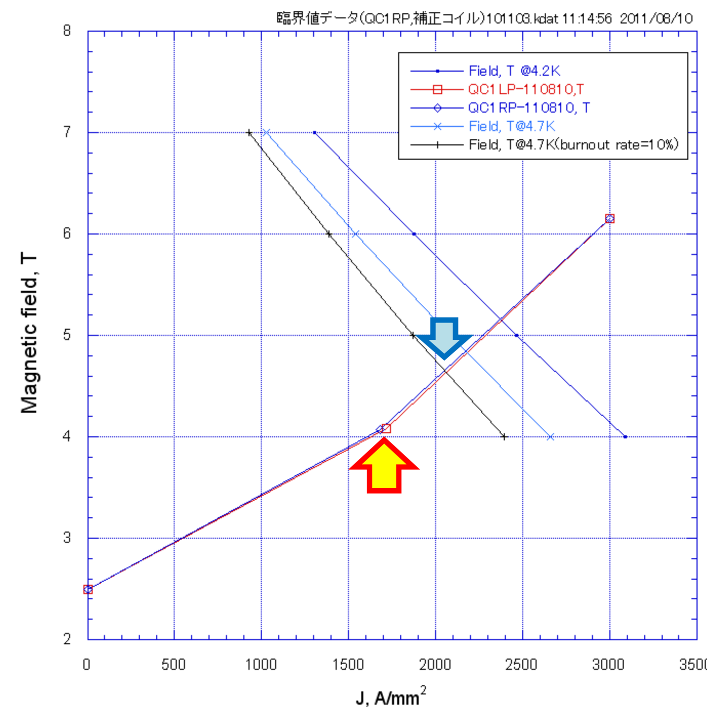
SC cancel coils against the leak field from QC1P

- b_5, b_6, b_4 , b_3 from the inside
- Cryostat inner bore radius=18.0 mm
- Beam pipe(warm tube)
  - inner radius=10.5 mm, outer radius=14.5 mm

QC1R/LP Magnet Parameters

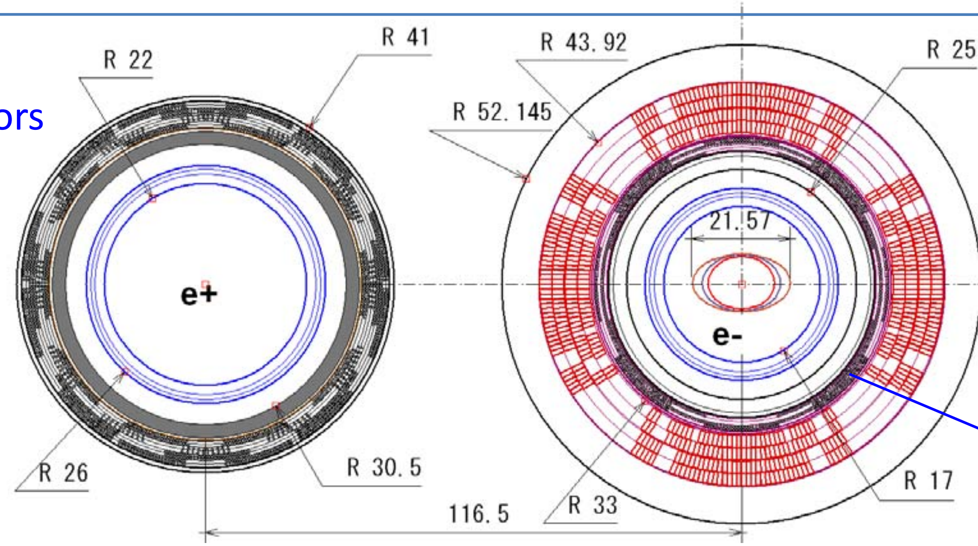
	QC1RP	QC1LP
Coil inner radius, mm	25.00	
Coil outer radius, mm	30.485	
Turns in one pole	12 (1st layer), 13 (2nd layer)	
Spec. of integral field, T	22.43	22.91
Field gradient, T/m	66.52	67.94
Effective magnetic length, m	0.3372	
Magnet current, A	**1575.58**	**1609.30**
Current density of the cable (SC area), A/mm^2	1685.0	1721.0
Current density of the cable (overall), A/mm^2	802.4	819.6
Magnetic field by Belle and comp. sol., T	2.5	2.5
Max. field in the coil without solenoid field, T	2.29	2.34
Max. field in the coil with solenoid field, T	**4.07**	**4.08**
Operating point with respect to B_c at 4.7 K	**81.8%**	**83.5%**
Magnet physical length, mm	416	
Error field at r=1 cm (2D calculation)	$b_6 = 1.60 \times 10^{-5}$ $b_{10} = -2.28 \times 10^{-6}$ $b_{14} = 6.20 \times 10^{-7}$	
Error field at r=1 cm (3D calculation)	$b_6 = -1.13 \times 10^{-5}$ $b_{10} = -4.71 \times 10^{-6}$	

QC1P operation point



QC1E with Iron Yoke

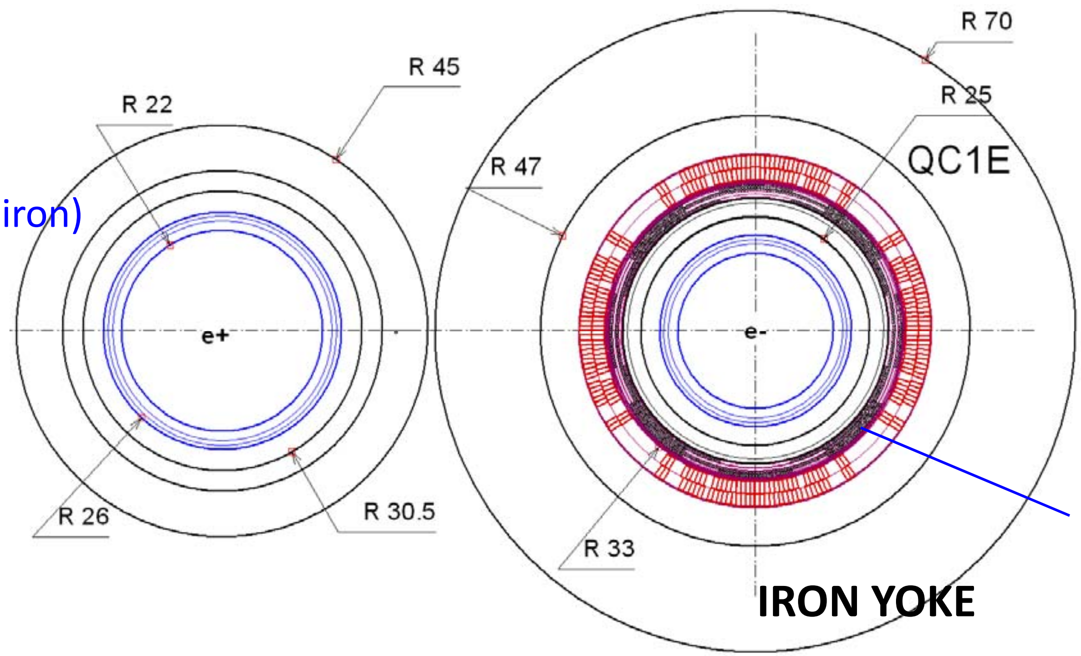
SC cancel correctors
b_3, b_4, b_5, b_6



QC1E without iron yoke (OLD DESIGN)

SC correctors
a_2, b_1, a_1, b_4

Magnetic shield (iron)

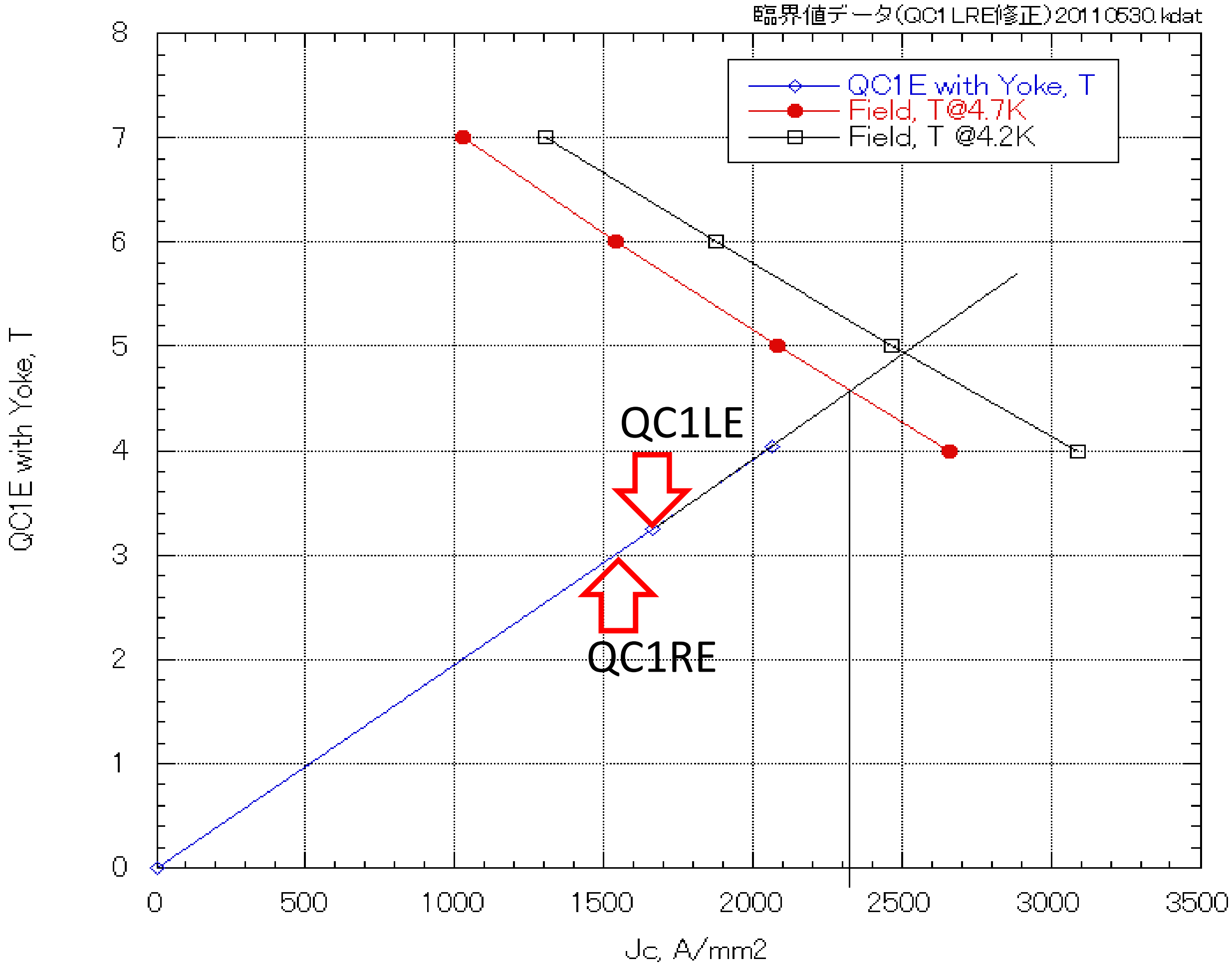


QC1E with iron yoke **(NEW DESIGN)**

SC correctors
a_2, b_1, a_1, b_4

QC1E Operation Point

QC1E load line



QC1RE

G=66.22 T/m

I_{op}=1460.3 A

J_{op}=1561.8 A/mm^2

$J_{op}/J_{c@4.7K}$=67.3 %

QC1LE

G=70.68 T/m

I_{op}=1558.5 A

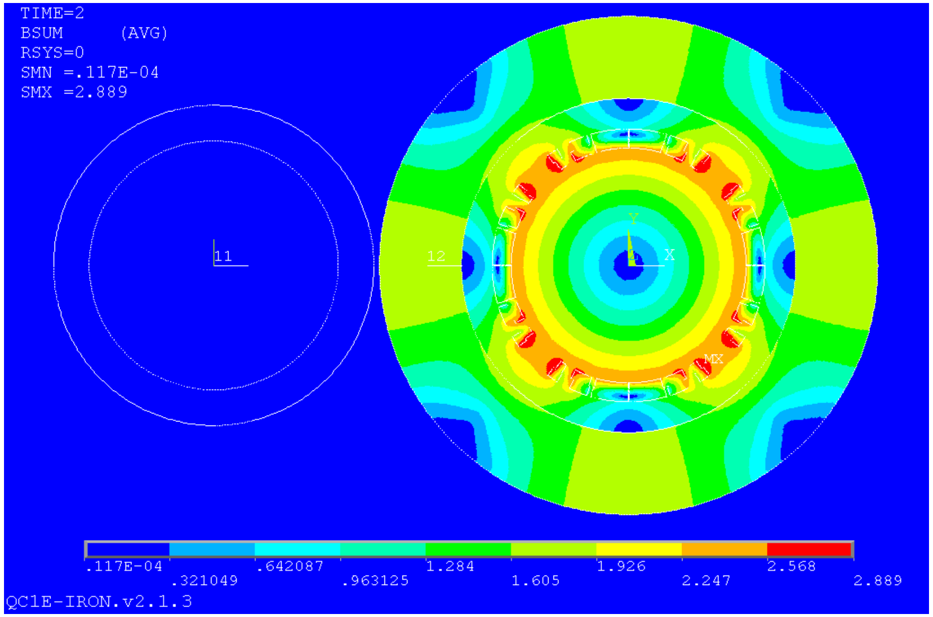
J_{op}=1666.9 A/mm^2

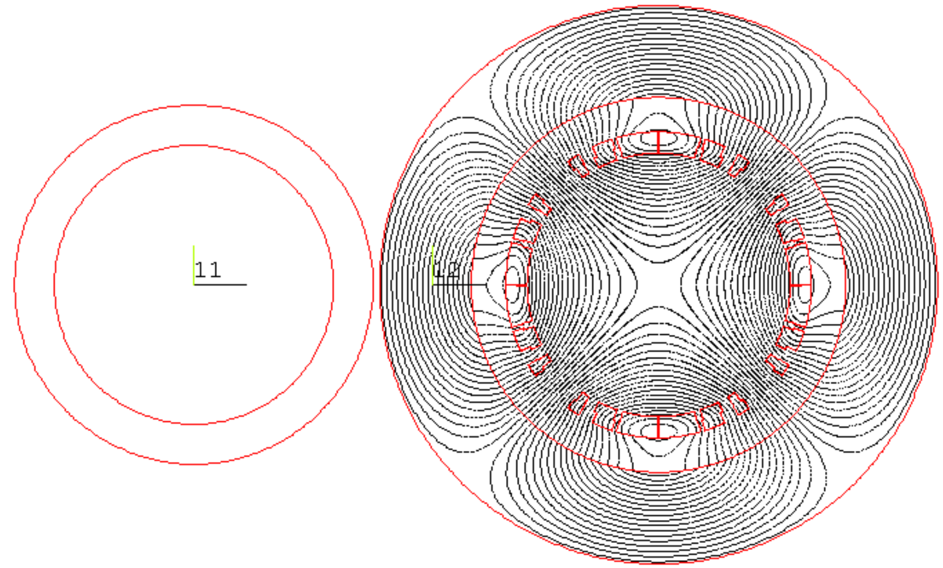
$J_{op}/J_{c@4.7K}$=71.8 %

(L_{eff}= 0.3774 m)

In case that the operating point of 85 % w.r.t. the critical point is acceptable, the quadrupole field can be increased by 18 %.

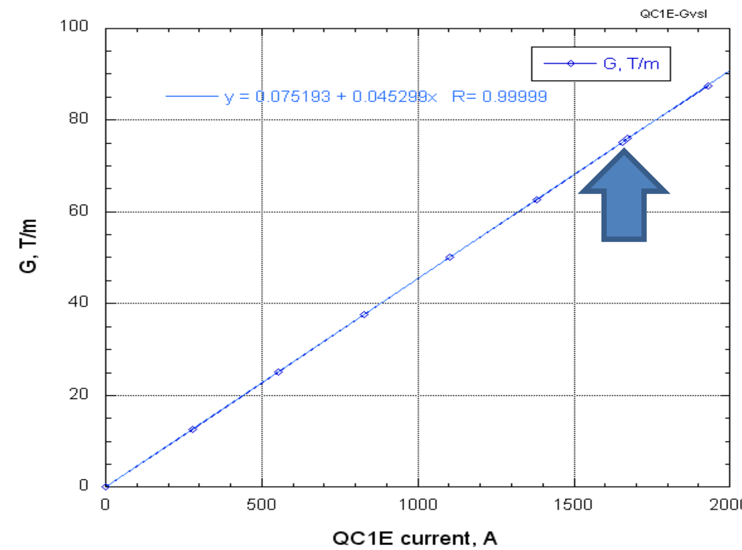
:1E magnetic field calculation in 2D





QC1E magnet design (QC1RE, QC1LE)

- 2 layer coils [double pancake]
- Cryostat inner bore radius=25.0 mm
- Beam pipe (warm tube)
  - Inner radius=17.0 mm, outer radius=21.0 mm
- Magnet current= 1655 A
  - Current density = 599.6 A/mm^2 (in the coils), 1770 A/mm^2 (in NbTi)
- G_R = 75.94T/m
- Maximum field in the magnet=2.89 T
- Ratio of field enhancement by iron is 1.338.

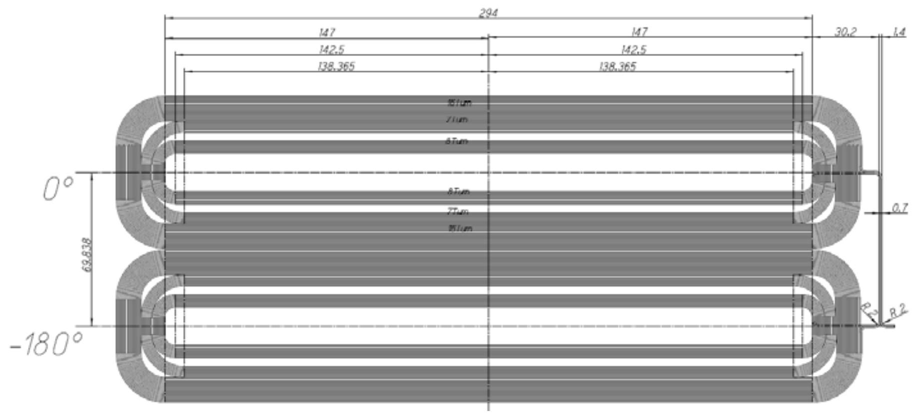


QC1, 2 Magnet Parameters

	Iron Yoke	Magnet current (A)	Field gradient (T/m)	Effective length (m)	Operating point (%)
QC1RP	No	1575.6	66.52	0.3372	82
QC1LP	No	1609.3	67.94	0.3372	84
QC2RP	Yes	817.9	27.17	0.4135	41
QC2LP	Yes	817.3	27.15	0.4135	41
QC1RE	Yes	1460.3	66.22	0.3774	67
QC1LE	Yes	1558.5	70.68	0.3774	72
QC2RE	Yes	1044.9	30.59	0.4221	55
QC2LE	Yes	724.1	22.07	0.6407	32

S.C. Correctors

- QC1 and QC2 quadrupoles have SC correctors of a_2, b_1, a_1 and b_4.
- All correctors and the leak field cancel coils will be manufactured by BNL under the international research collaboration.



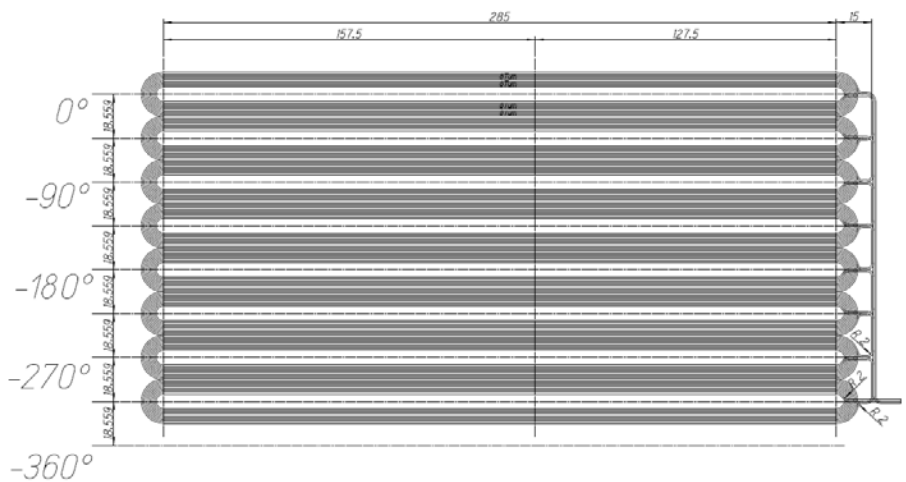
SC wire is wound in coil with the direct winding method.

QC1P b_1コイル

31 turns/pole

B_1=0.045 T at 50A

I_{op}/I_c= 68 % at 5.0 K



QC1P b_4コイル

8 turns/pole

B_4=3398 T/m^3 at 50A

I_{op}/I_c= 68 % at 5.0 K

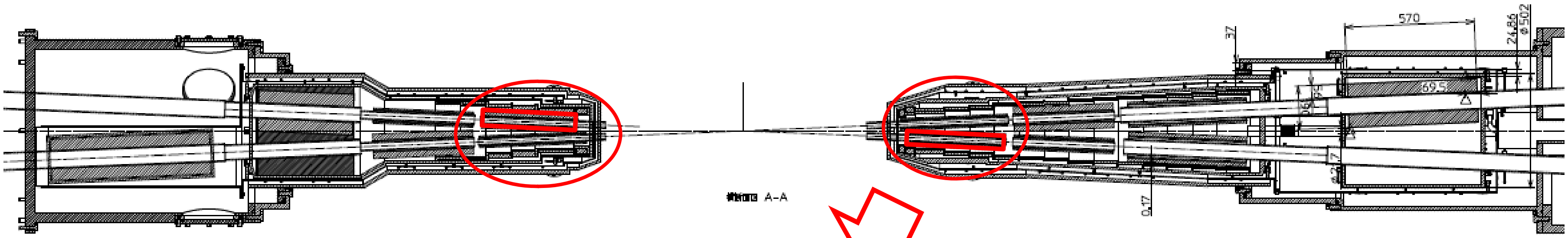
SC corrector design status

	G (T/m)	Corrector Current (A)	A1 (T)	B1 (T)	A2 (T/m)	B4 (T/m^3)	dy (mm)	dx (mm)	dθ (mrad)
QC1RP	66.52	50	0.045	0.046	2.28	3398	0.657	0.632	14.0
QC1LP	67.94	50	0.045	0.046	2.28	3398	0.644	0.618	13.7
QC2RP	27.17	50	0.0792	0.0785	1.253	442.4	2.91	2.89	23.1
QC2LP	27.15	50	0.0792	0.0785	1.253	442.4	2.92	2.89	23.1
QC1RE	66.22	50	0.067	0.130	1.770	1853.6	1.01	1.955 (0.69:Optics 1.265:alignment)	13.4
QC1LE	70.68	50	0.067	0.130	1.770	1853.6	0.95	1.839 (0.69:Optics 1.159:alignment)	12.5
QC2RE	34.90	50	0.0795	0.0783	1.137	327.6	2.28	2.24	16.3
QC2LE	20.20	50	0.0795	0.0783	1.137	327.6	3.94	3.88	28.1

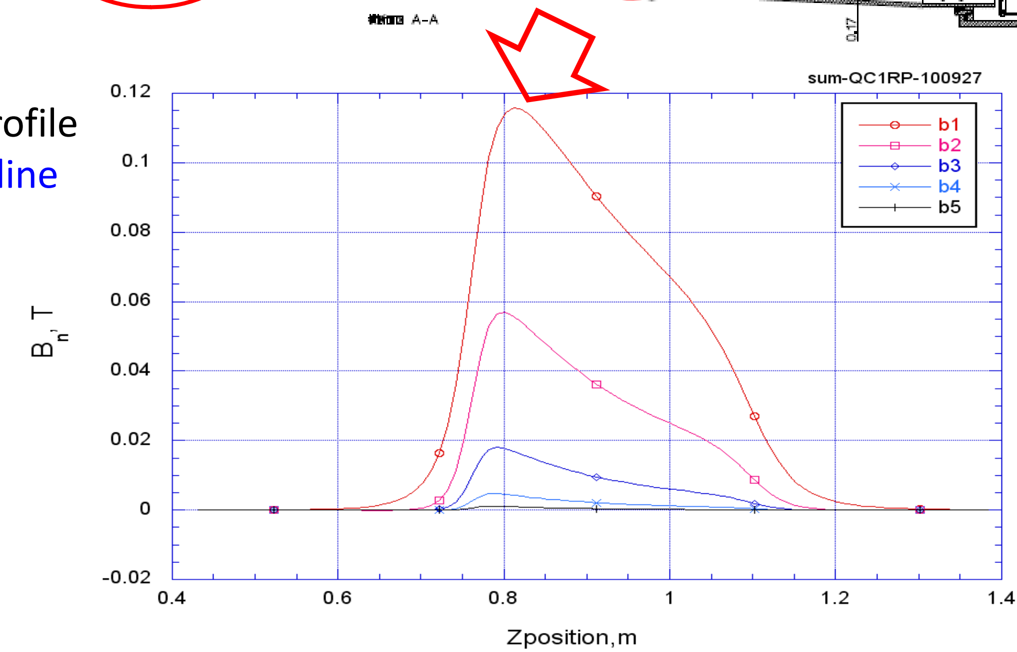
2D calculations of SC correctors have been completed.
3D design of the corrector coils for QC1P has been completed, and the other coils are evaluated under the condition that the coils have the same effective magnetic length as the main quadrupole.

Cancel Coils for QC1P Leak Field

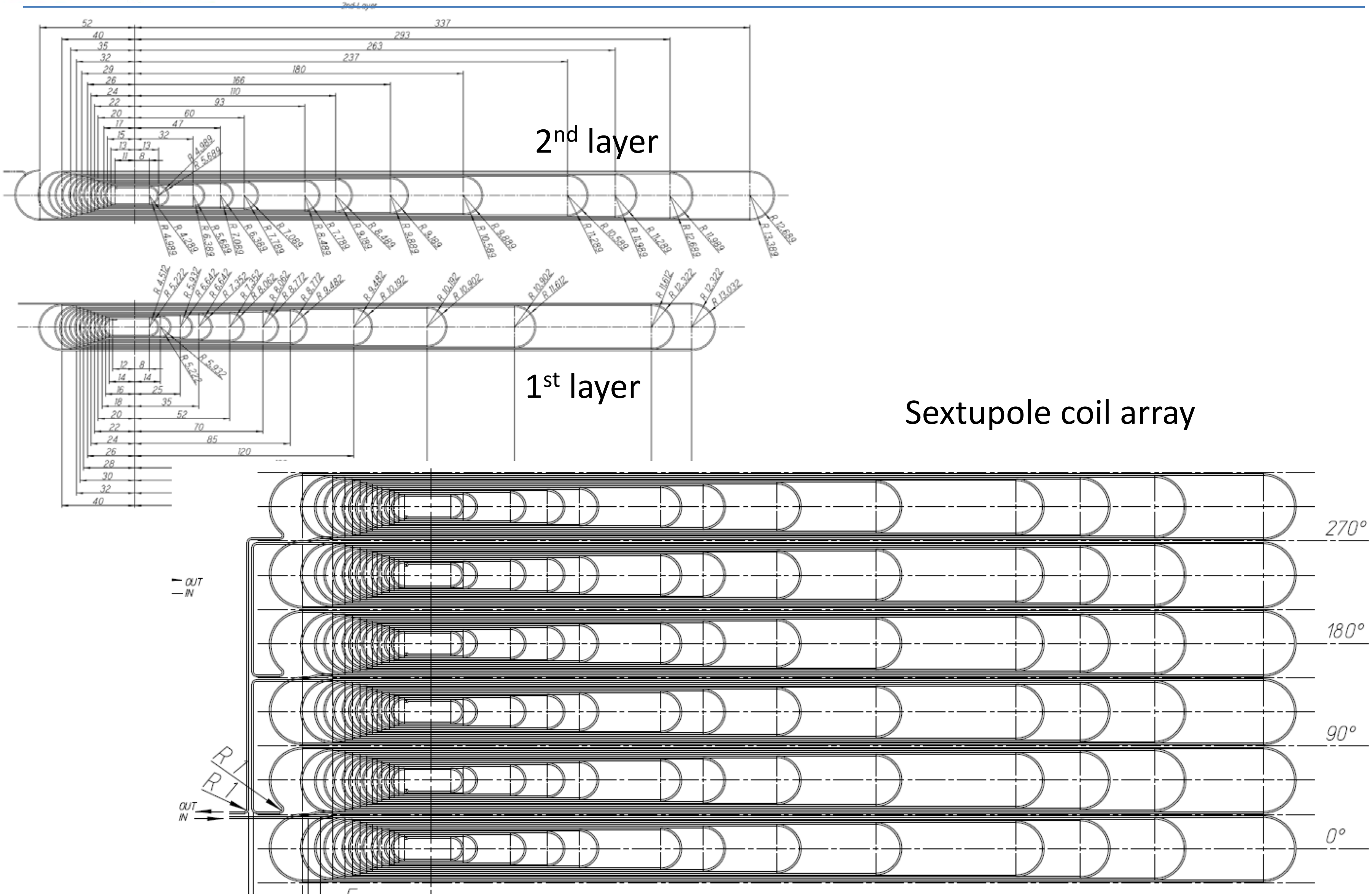
- QC1P for the e+ beam line is non-iron magnet and the e- beam line is very close to QC1P. The leak fields along the e- beam line by QC1P are calculated.
- ***B_3, B_4, B_5*** and ***B_6*** components of the leak fields are designed to be canceled with the SC cancel coils.
- B_1 and B_2 components are 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

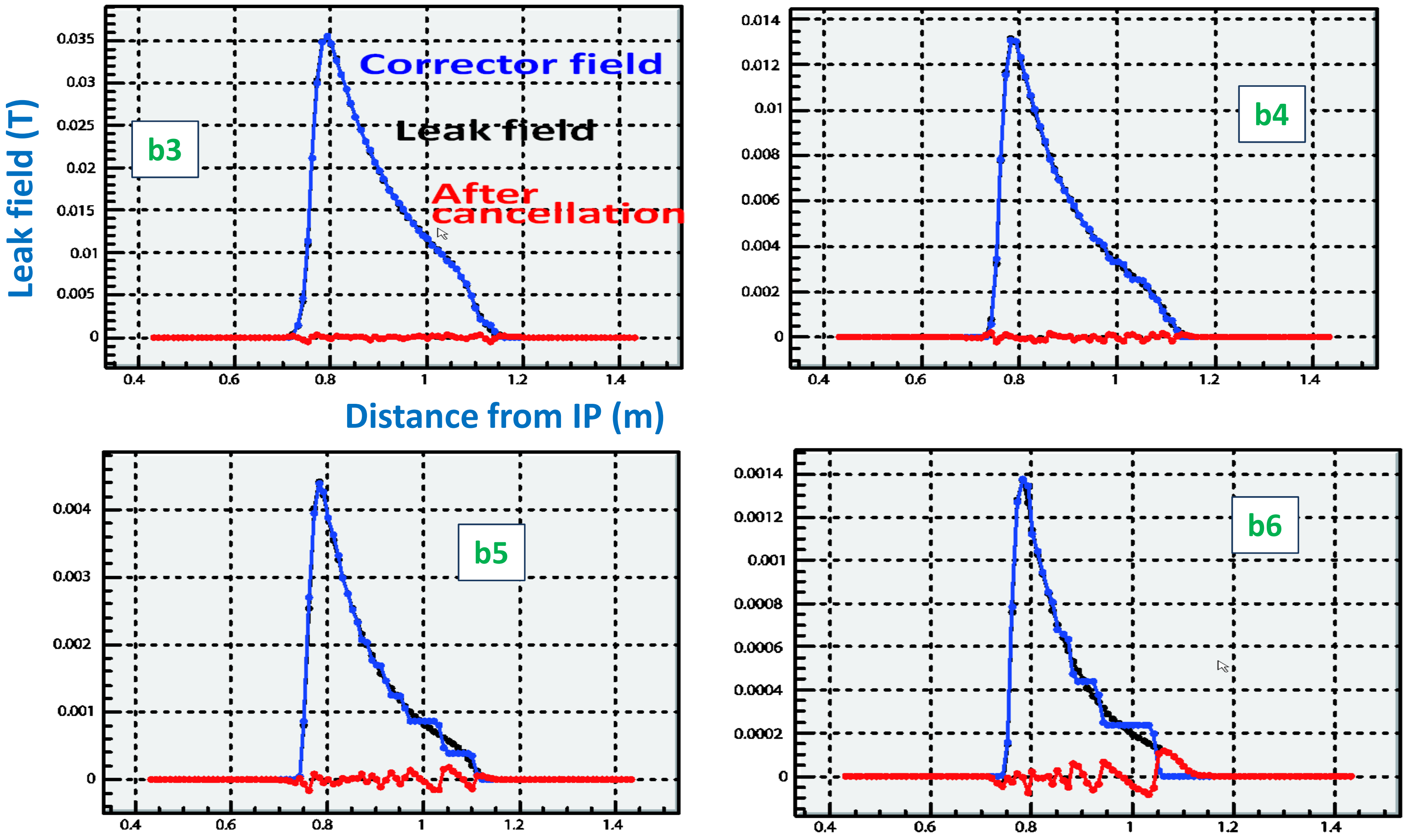


b_3 Cancel Coil Configuration

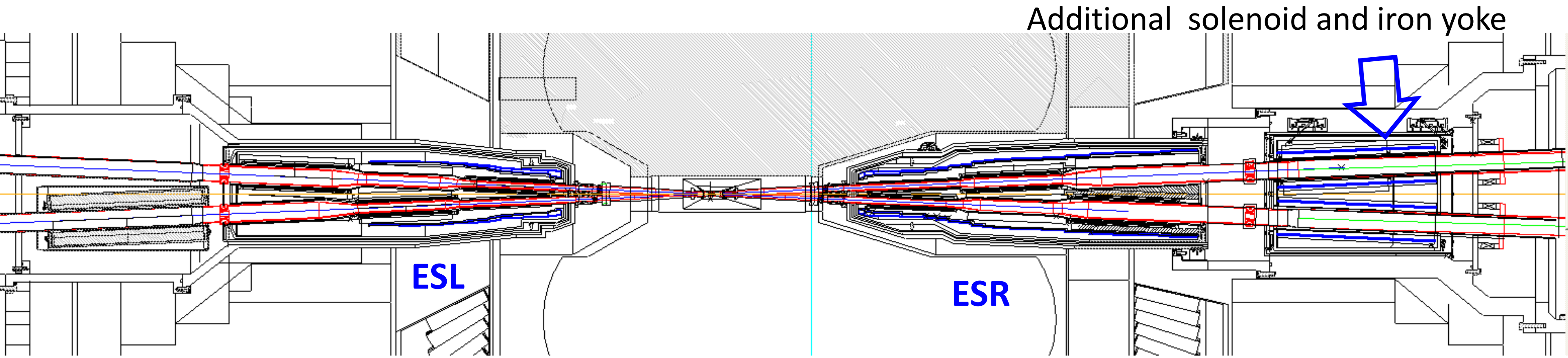


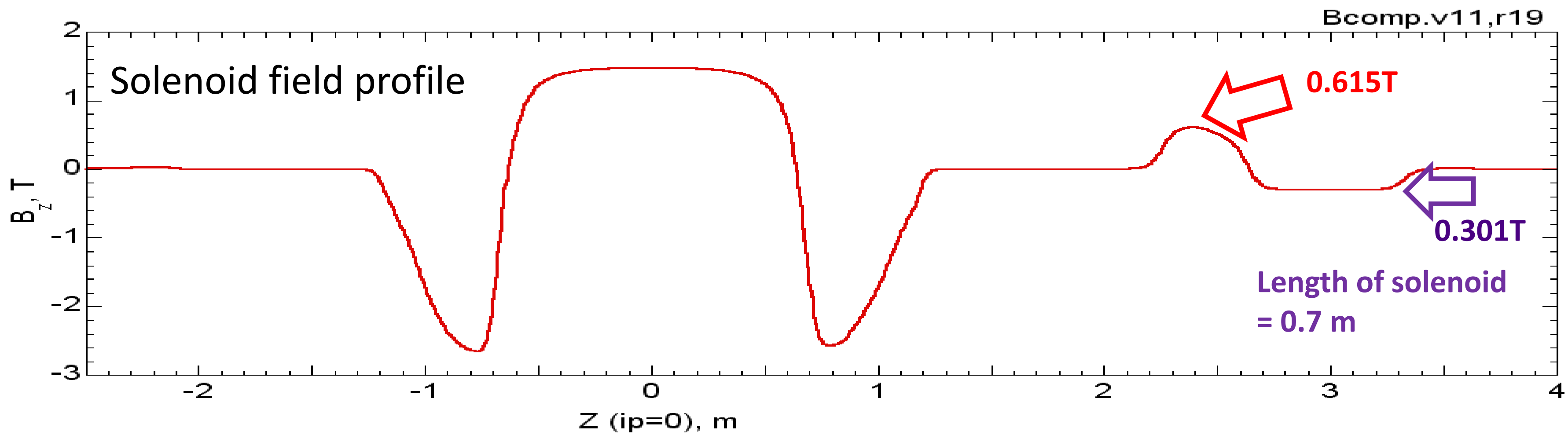
Canceling QC1P Leak Field

Cancelling the leak fields by SC multipole coils



Compensation Solenoids

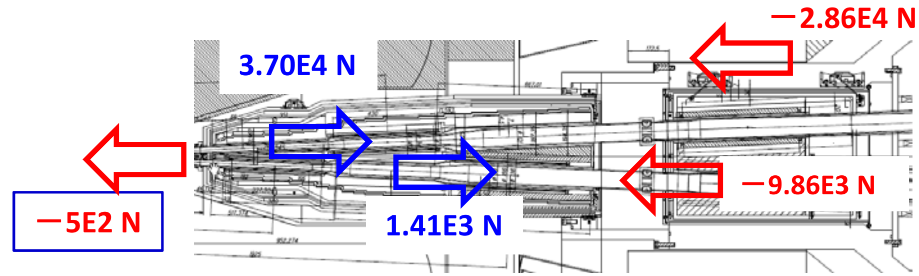


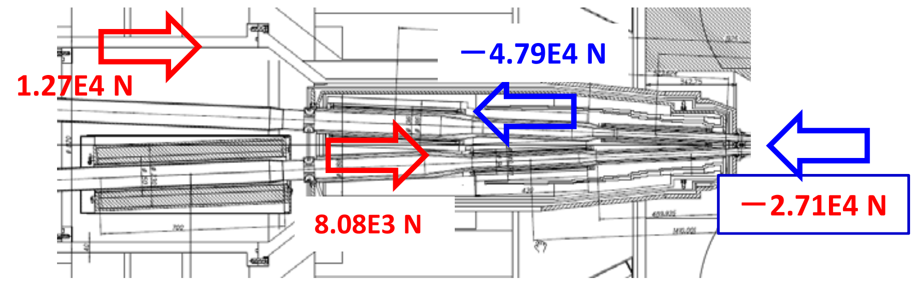


- In order to force the integrated solenoid field to zero from IP, the additional SC solenoids are designed inside of the QC2RE iron yoke on both beam lines.
- 3D magnetic field calculation is on going.

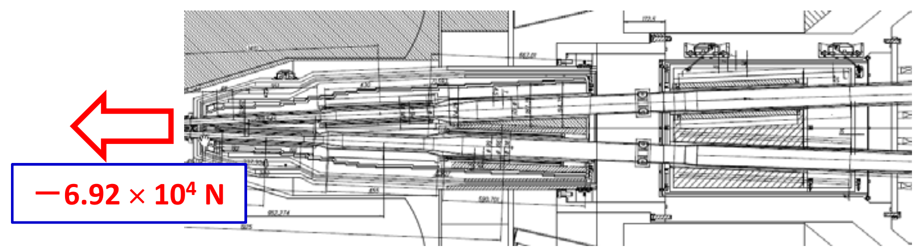
EMF on Solenoids and Iron

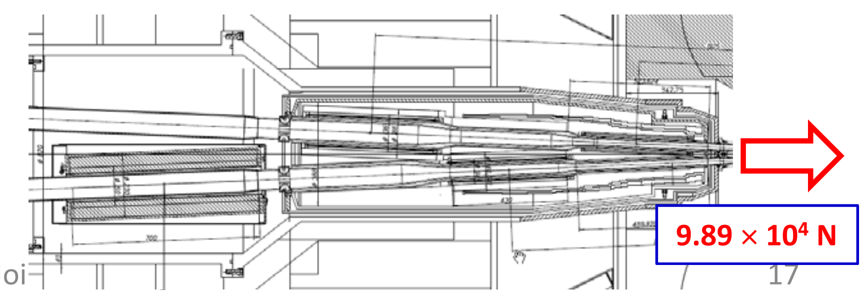
- ESL and ESR: **ON**
  - Right side
    - Superconducting solenoid : 3.70×10^4 N
    - Iron in the front helium vessel : 1.41×10^3 N
    - Iron in the rear helium vessel : -9.86×10^3 N
    - Vacuum vessel (room temp.) : -2.86×10^4 N
  - Left side
    - Superconducting solenoid : -4.79×10^4 N
    - Iron in the front helium vessel : 8.08×10^3 N
    - Vacuum vessel (room temp.) : 1.27×10^4 N





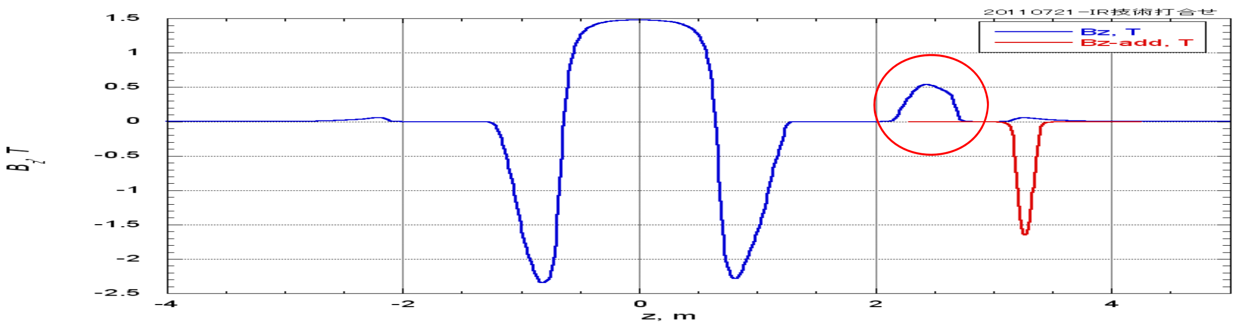
- ESL and ESR: **OFF**
  - Right side
    - Iron in the front helium vessel : -9.60×10^3 N
    - Iron in the rear helium vessel : -1.67×10^4 N
    - Vacuum vessel (room temp.) : -4.29×10^4 N
  - Left side
    - Iron in the front helium vessel : 8.47×10^4 N
    - Vacuum vessel (room temp.) : 1.42×10^4 N

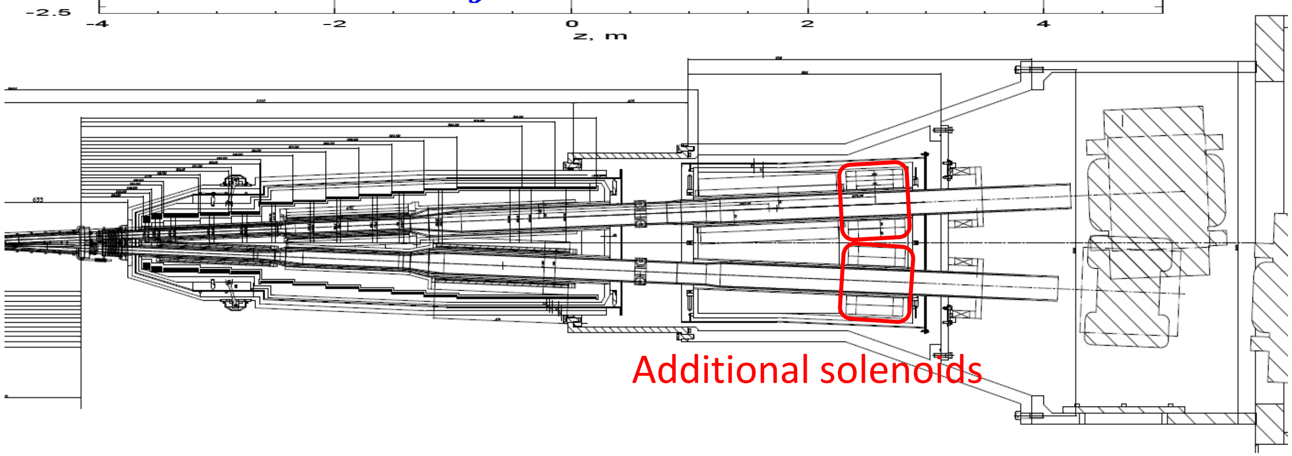




Effect of Solenoids on Beam Life

- Initial magnet configuration
  - In order to cancel the residual solenoid field between QC2RP and QC2RE, we placed 1.5 T additional solenoids behind QC2RE on each beam line.
- Optics calculation
  - This configuration reduced the LER beam life time from 570 s to 400 s. By reducing the peak field of the solenoid from 1.5 T to 0.2 T, the life time recovered to over 540 s. The optics calculation showed that the solenoid field bump between QC2RP and QC2RE had a small impact on the life time.
- Improving the solenoid design
  - By the above analysis and further calculation, we designed the additional solenoid of 0.7 m and 0.3 T inside of the QC2RE yoke.





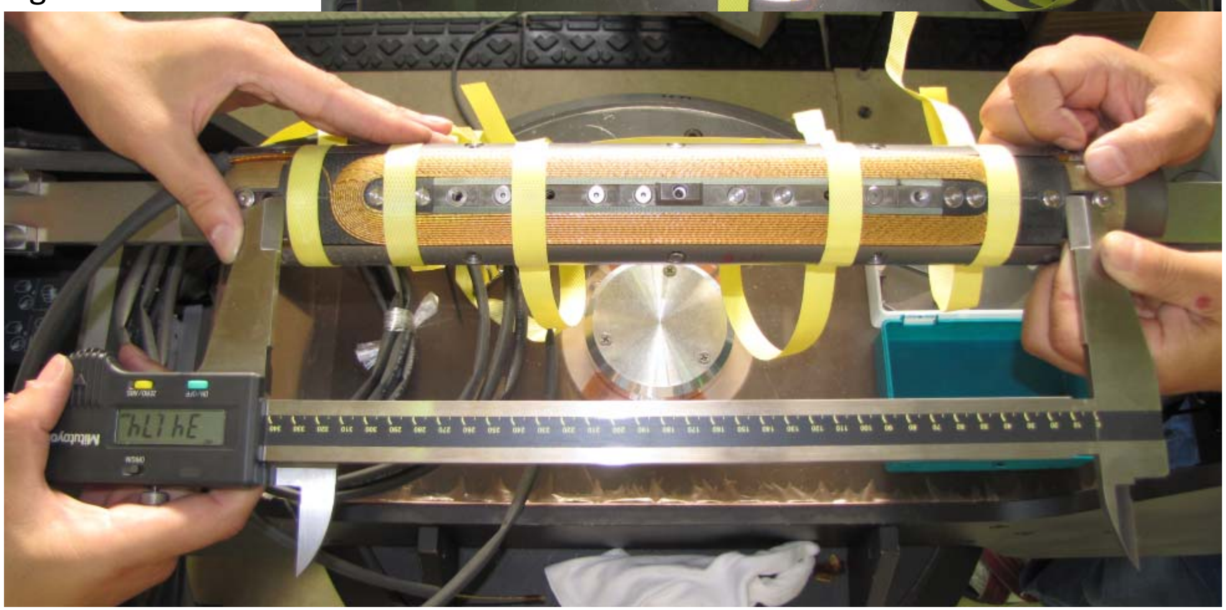
R&D magnet status

Construction of QC1P R&D magnet

Construction of QC1RP R&D magnet started at the end of August.

Winding machine

1st pole-inner layer coil

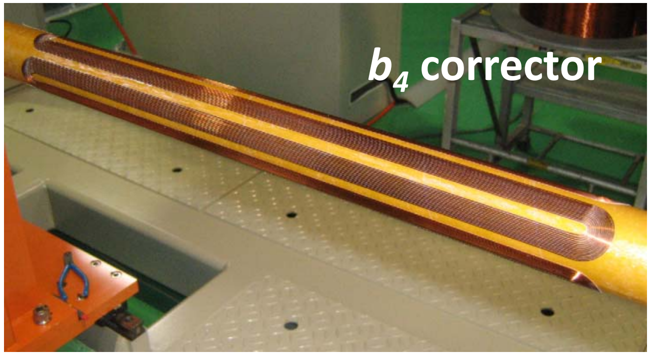


1st pole-outer layer coil

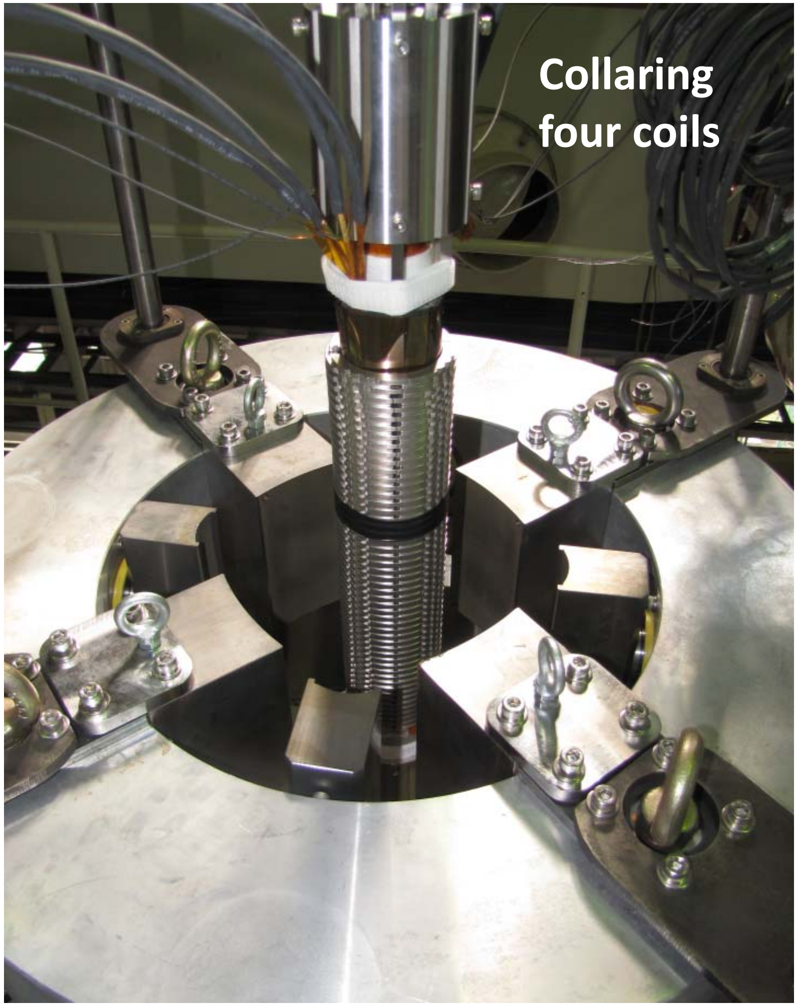
R&D magnet status (cont.)

Construction of QC1P R&D magnet (cont.)

Four coils completed at 3rd October.



4 correctors were constructed in 2010. The corrector package has a function of magnet bobbin for the QC1P R&D magnet.

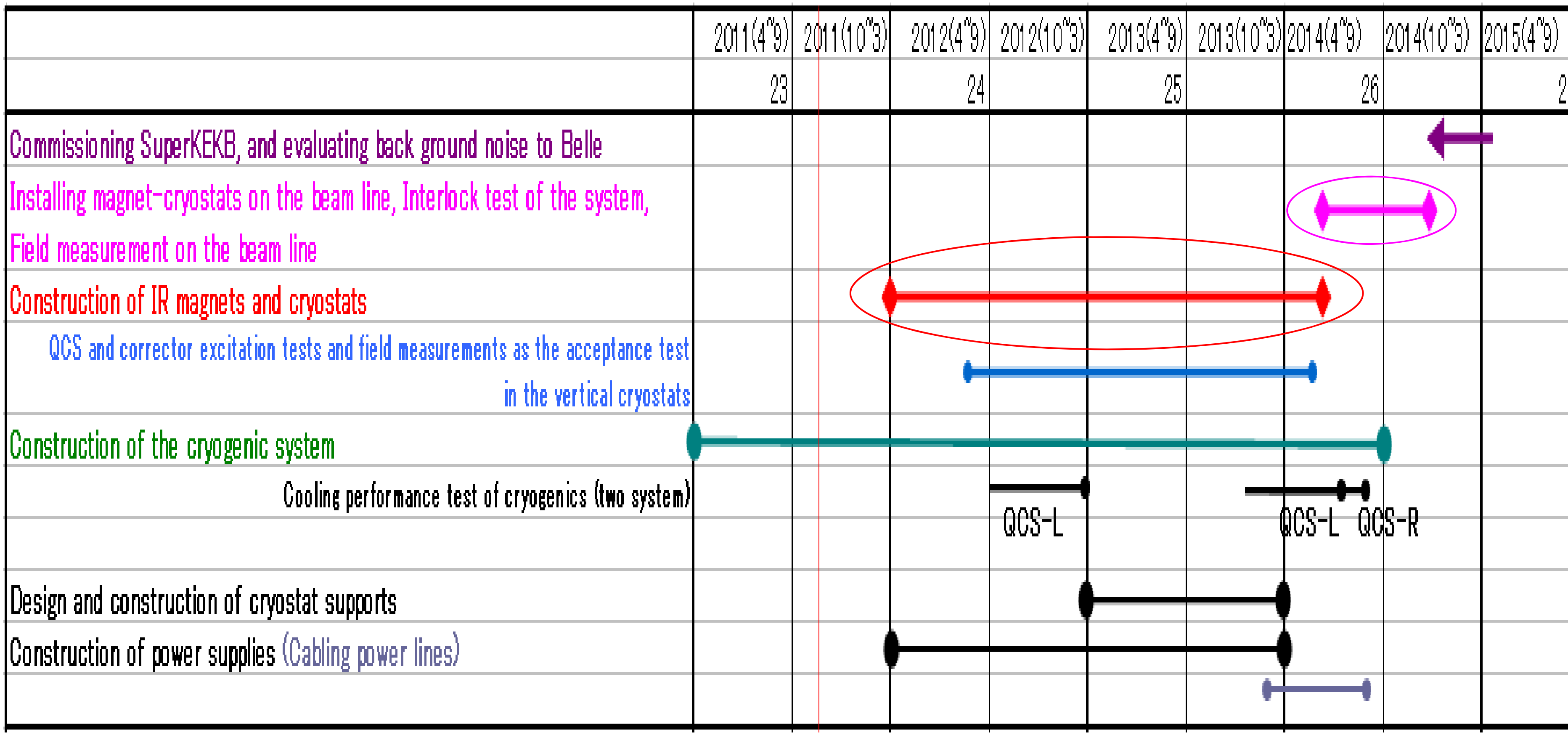


QC1P R&D magnet

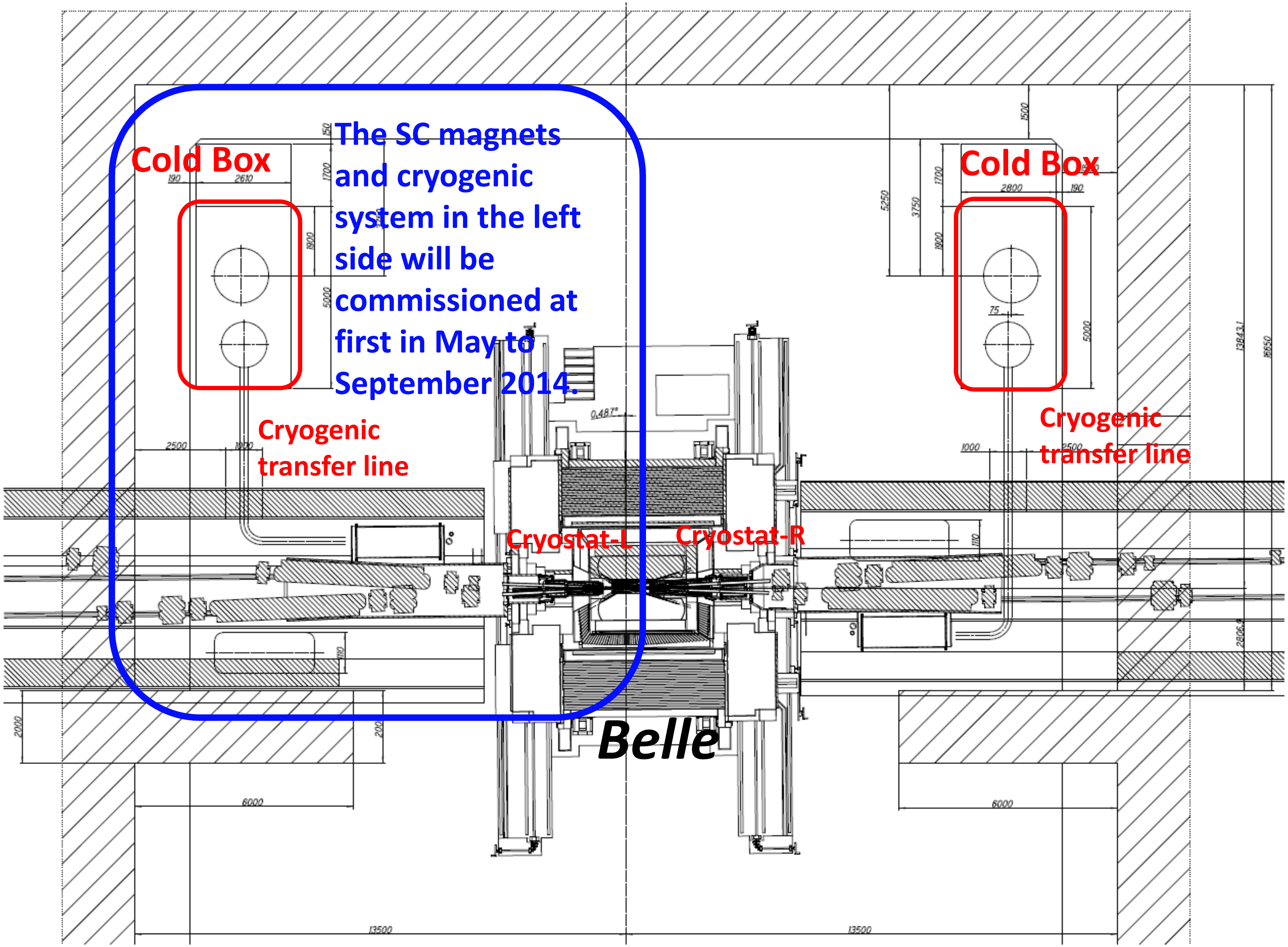
Magnet R&D schedule

- The QC1P R&D magnet has been tested at 4 K with the vertical cryostat in January.
  - Excitation results:
    - QC1P R&D magnet: no quench up to the nominal current (1510A and G=75.58 T/m).
    - Correctors (b_1, a_1, a_2, b_4), cancel coils (b_1, b_2, b_3): no quench to the nominal current of 50 A.
  - Field measurements:
    - There was some troubles in the harmonic coil.
    - Now the coil is repaired, and the cold test is scheduled from the 21th February.
- The proto-type of QC1E will be constructed in March and April 2012 and tested in May 2012.
- The proto-type of QC1P will be constructed in August 2012 with the company personnel after bidding the IR magnet-cryostat construction.

Construction schedule of IR magnets



IR magnet-cryogenic system commissioning



Summary

- Magnet and IR design
  - Basic magnet designs of SC-QCs and SC-correctors have been completed.
  - Calculation of 3D Solenoid field is on going.
    - Now improving the calculation precision.
- SC correctors and leak field cancel coils
  - All SC correctors and leak field cancel coils will be manufactured by BNL under the international research collaboration.
  - The construction schedule by BNL completely matches with SuperKEKB IR construction.
- R&D magnets
  - Construction of the QC1P R&D magnet was completed and cold tested.
  - The magnetic field measurements of the magnet will be carried out in this month.
  - The constructions of QC1P and QC1E prototypes are scheduled in this year.
- Completion of the IR superconducting magnet construction is scheduled at Nov. 2014.