SuperKEKB IR Over View and SC Magnets

(The 16th KEKB Accelerator Review Committee)

Norihito Ohuchi

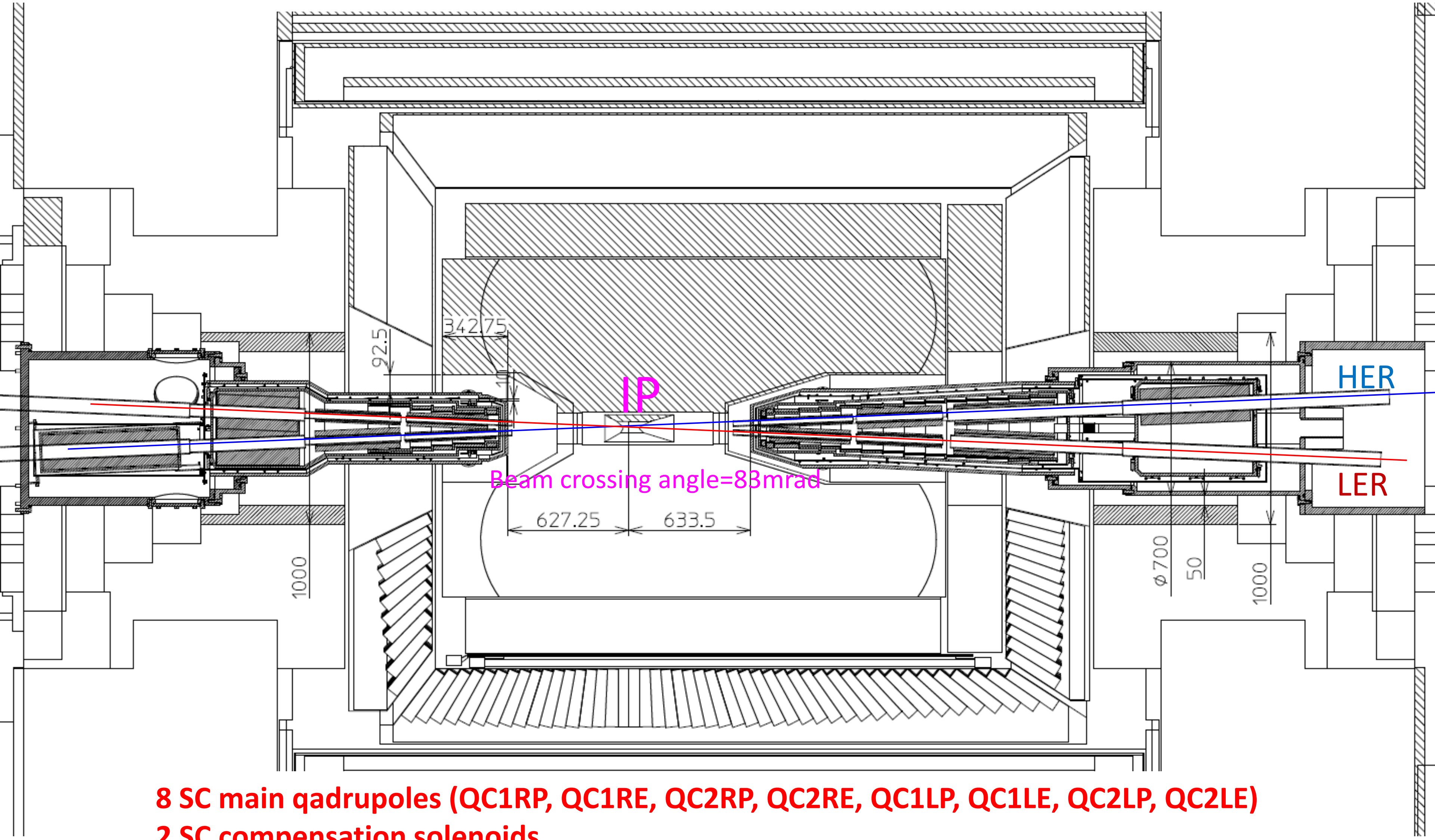
Outline

1. IR overview
2. IR SC magnets
   - SC quadrupoles, correctors
   - Leak field cancel coils
   - Compensation solenoids
3. Cryostat and support mechanism
4. Construction schedule

1. IR overview
(Status of IR design)

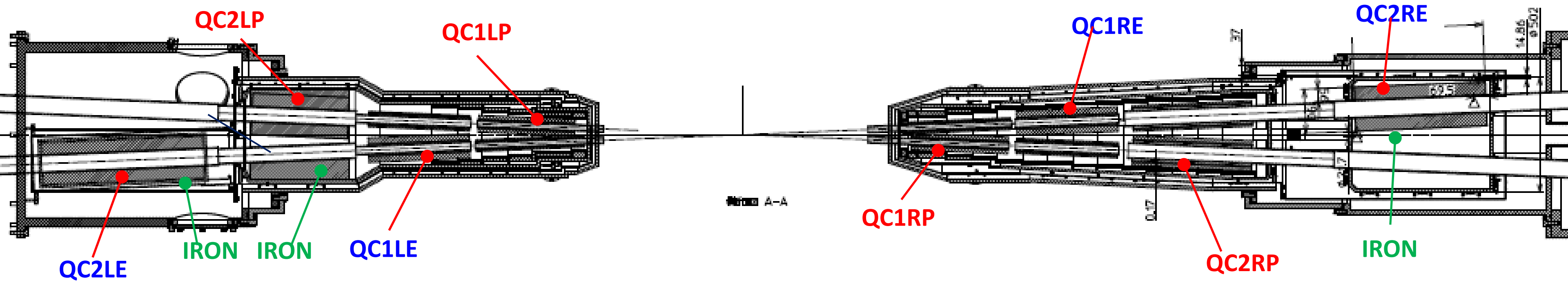
- Beam optics
  - Touschek Lifetime: LER=410 sec, HER=511 sec
    - LER/HER lifetimes are expected to be 577 sec/724 sec by improving the cancellation of leak field by QC1E/P.
  - Beam sizes of both beam lines are re-defined for designing the hardware.
    - Beam pipe and some SC coils have been re-designed.
    - Beam background noise is being studied with the new pipe design.
- IR magnet design
  - All magnets and correctors are designed to be superconducting.
  - Iteration of design work of SC magnets is in progress by the requirement of the beam optics.
- Cryostat and support design
  - The QCS cryostats and supports in the 1st version have been designed.
  - The vibration analysis was performed for these designed cryostats and supports.

IR SC magnets, cryostat and Belle



8 SC main qadrupoles (QC1RP, QC1RE, QC2RP, QC2RE, QC1LP, QC1LE, QC2LP, QC2LE)
2 SC compensation solenoids
52 SC correction coils

IR magnets



	Integral field gradient (T/m)･m	Position from IP mm	Magnet type	Corrector	Leak field cancel coil
QC2RE	12.91	2925	S.C. + Iron Yoke	a_1, b_1, a_2, b_4	
QC2RP	10.92 [31.21T/m×0.350m]	1956	S.C.	a_1, b_1, a_2, b_4	b_3, b_4, b_5, b_6
QC1RE	26.22 [79.03×0.360]	1410	S.C.	a_1, b_1, a_2, b_4	b_3, b_4, b_5, b_6
QC1RP	22.43 [66.52×0.3372]	932	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]	-932	S.C.	a_1, b_1, a_2, b_4	b_3, b_4, b_5, b_6
QC1LE	26.03 [82.75×0.360]	-1410	S.C.	a_1, b_1, a_2, b_4	b_3, b_4, b_5, b_6
QC2LP	10.96	-1930	S.C. + Iron Yoke	a_1, b_1, a_2, b_4	
QC2LE	14.13	-2700	S.C. + Iron Yoke	a_1, b_1, a_2, b_4	

LER Optics

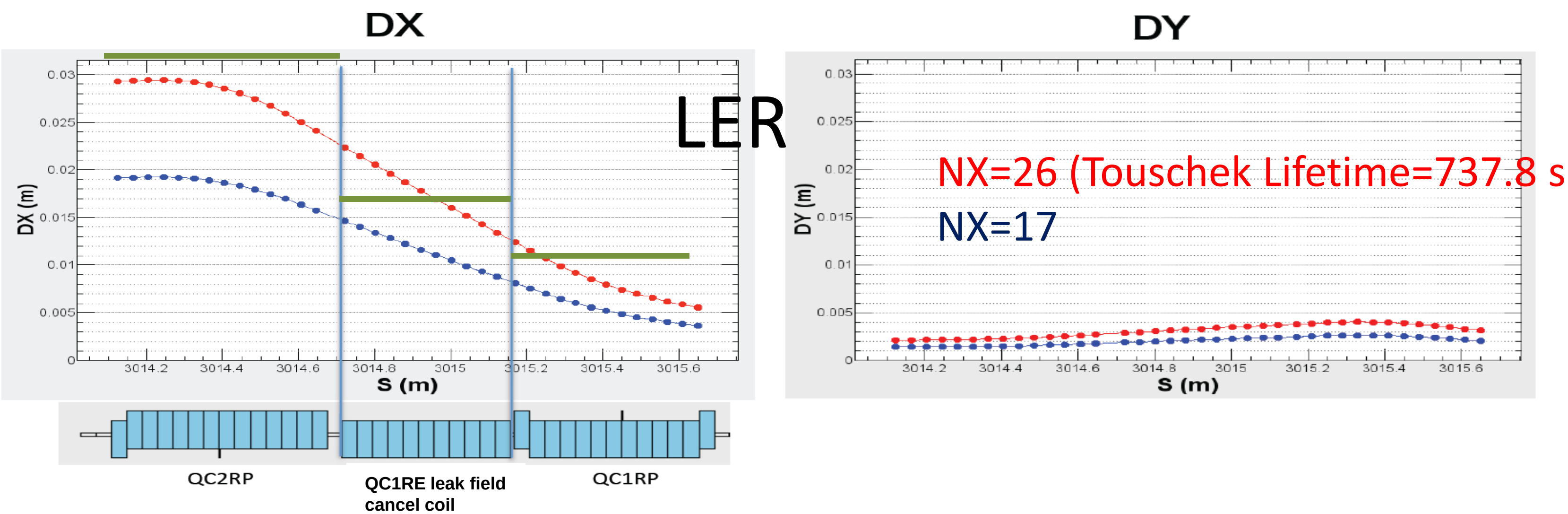
Changes since the previous version:

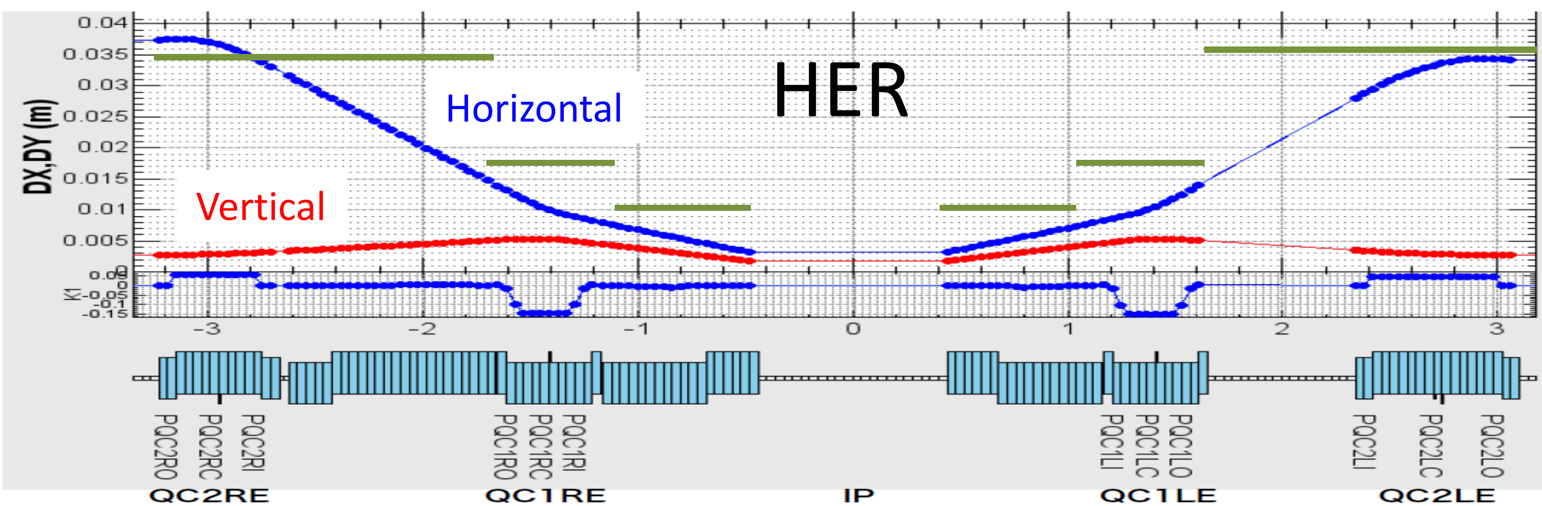
- IP Solenoid/Quads Model V9 (A. Morita, M. Tawada, ...)
  - Larger aperture (a = 35 mm) at QC2, etc.
- Touschek lifetime to ≈ 410 sec.
- Dependence of Tousheck on multipoles & aperture:

QC*EP* (leak from HER)			QC2{RL}P		Aperture @ QC1 Exit (mm)	Touschek Lifetime (sec)
K5	K8	SK2	K5	K8		
*	*	*	*	*	10	416
0	*	*	0	*	10	↑
*	0	*	*	0	10	↑
0	0	*	*	*	10	518
0	0	*	0	0	10	520
0	0	0	*	*	10	540
0	0	*	*	*	13	577
					No Aperture limit	737.8

- /ldata/SuperKEKB/Lattice/lerfqlc_1407.{sad,disp,dispg}

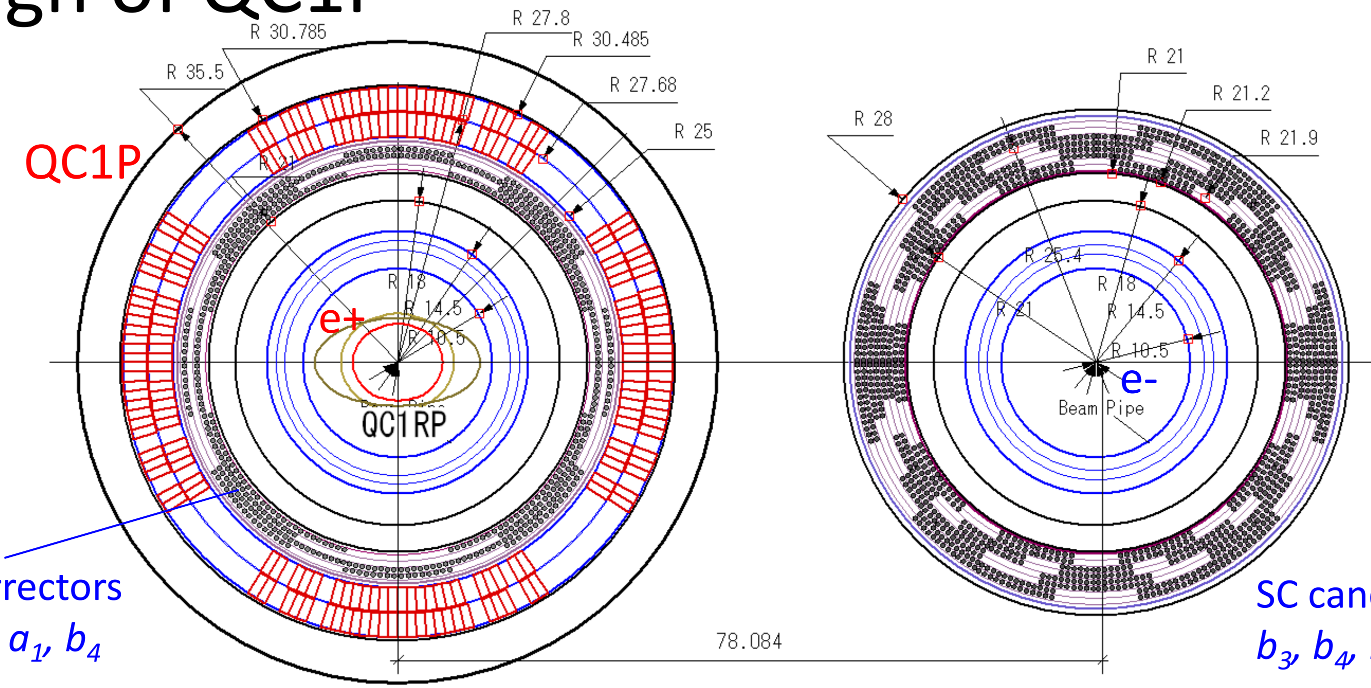
Requirement on beam pipe from beam size





2. IR SC magnets

Design of QC1P



SC correctors
a_2, b_1, a_1, b_4

SC cancel correctors
b_3, b_4, b_5, b_6

QC1P magnet design (QC1RP, QC1LP)

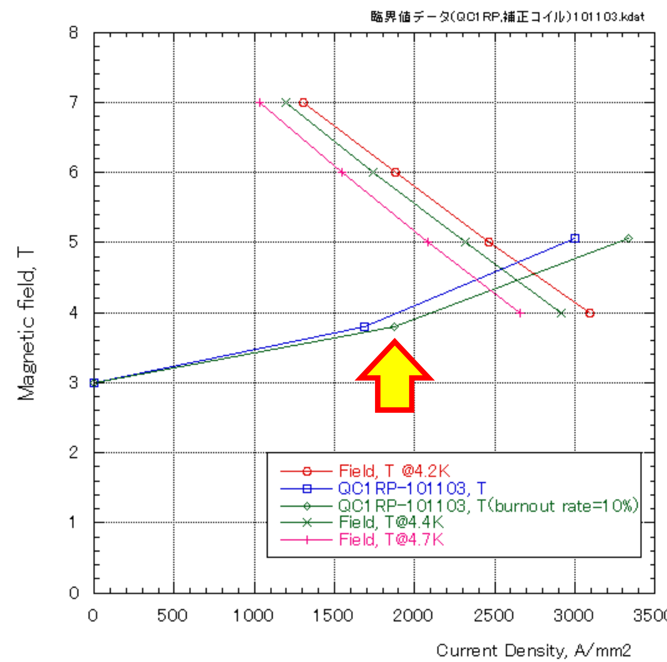
- Same cross section and longitudinal design for QC1RP and QC1LP
- 2 layer coils [double pancake]
- Designed SC cable
  - Cable size : 2.5 mm in height, and 0.93 mm in width
  - SC strand cable : ϕ 0.5 mm, 10 wires in the cable
- SC correctors inside of the magnet bore
  - a_2, b_1, a_1, b_4 from the inside, single layer coil
- 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

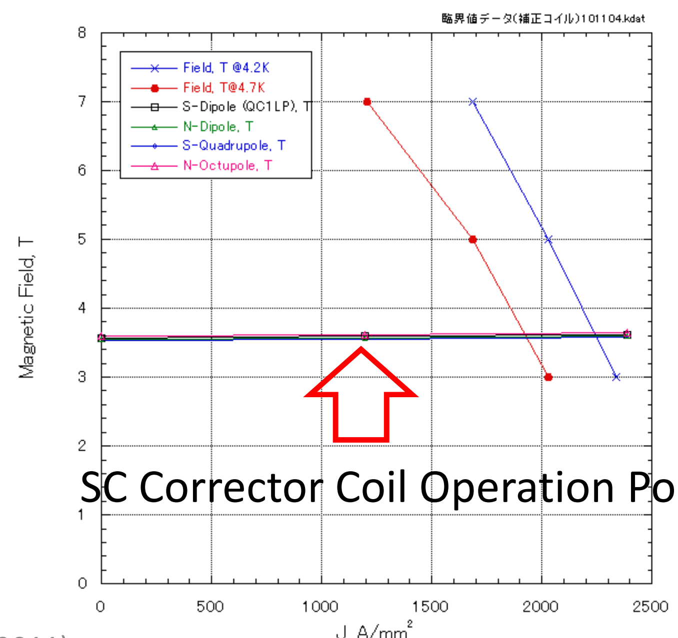
QC1RP, QC1LP Magnet Parameters

	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	3.0	3.2
Max. field in the coil without solenoid field, T	2.28	2.28
Max. field in the coil with solenoid field, T	3.79	3.93
Operating point with respect to B_c at 4.7 K	76%	79%
Magnet physical length, mm	416	
Error field at r=1 cm (2D calculation)	$b_6 = 2.55 \times 10^{-5}$ $b_{10} = -2.04 \times 10^{-6}$ $b_{14} = 6.07 \times 10^{-7}$	
Error field at r=1 cm (3D calculation)	$b_6 = 1.96 \times 10^{-6}$ $b_{10} = 3.93 \times 10^{-6}$	

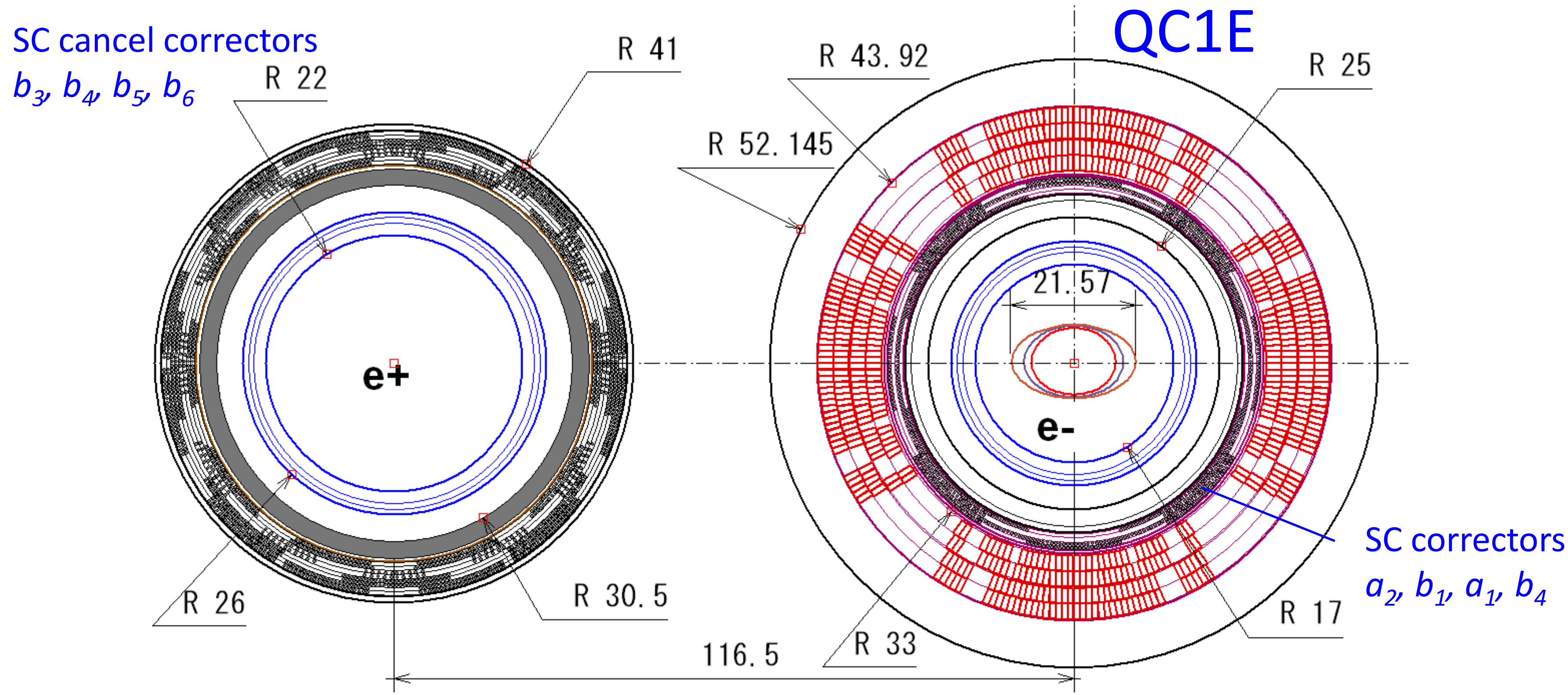


QC1RP, QC1LP SC corrector coils

	b_4	a_2	b_1	a_1
Coil inner radius, mm	23.4	21.3	22.0	22.7
Coil outer radius, mm	24.1	22.0	22.7	23.4
Turns on one pole	8	16	31	31
Design current, A	50	50	50	50
Magnetic field at R=1cm	3398 T/m^3	2.284 T/m	0.045 T	0.043 T
Bias magnetic field by QC1R/LP and Solenoids, T	3.59	3.53	3.55	3.57
Operating point with respect to J_c at 4.7 K	< 65 %	< 65 %	< 65 %	< 65 %
Capacity for magnetic alignment for QC1RP at R= 1 cm	NA	± 17.17 mrad	± 0.676 mm	± 0.646 mm
Capacity for magnetic alignment for QC1LP at R= 1 cm	NA	± 16.81 mrad	± 0.662 mm	± 0.633 mm



Design of QC1E



SC cancel coils against the leak field from QC1E

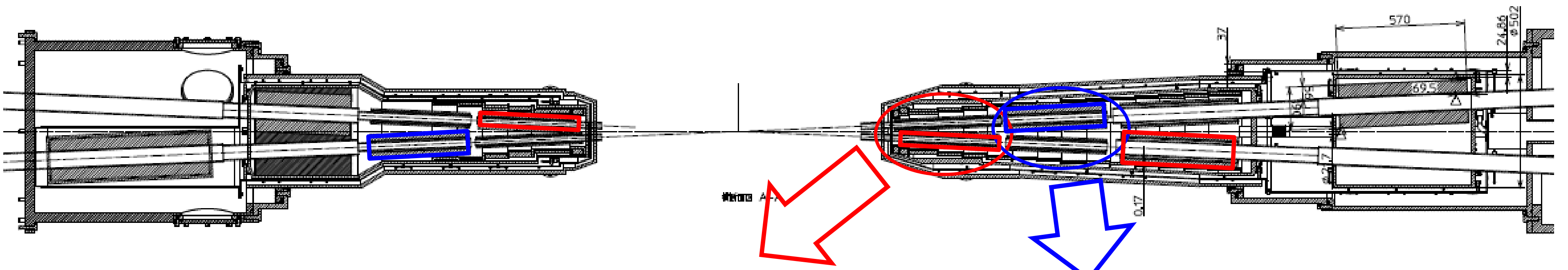
- b_5, b_6, b_4, b_3 from the inside
- Cryostat inner bore radius=30.5 mm
- Beam pipe(warm tube)
  - inner radius=22.0 mm, outer radius=26.0 mm

QC1E magnet design (QC1RE, QC1LE)

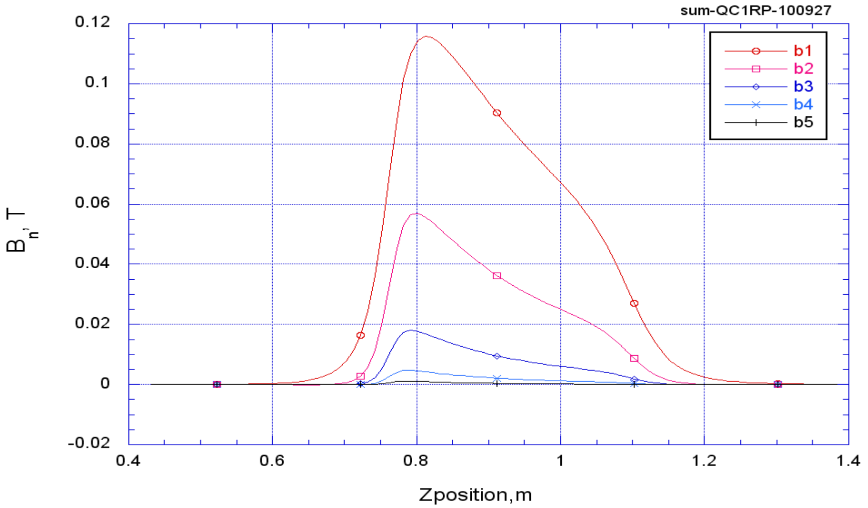
- Same cross section and longitudinal design for QC1RE and QC1LE
- 4 layer coils [double pancake]
- Cryostat inner bore radius=25.0 mm
- Beam pipe (warm tube)
  - inner radius=17.0 mm, outer radius=21.0 mm
- G_R = 79.03 T/m at I_{op}=1242.1 A, I_{op}/I_c= 72.7 %
- G_L = 82.75 T/m at I_{op}=1300.6 A, I_{op}/I_c= 75.8 %

Cancel coils for the leak field of QC1P/E and QC2RP

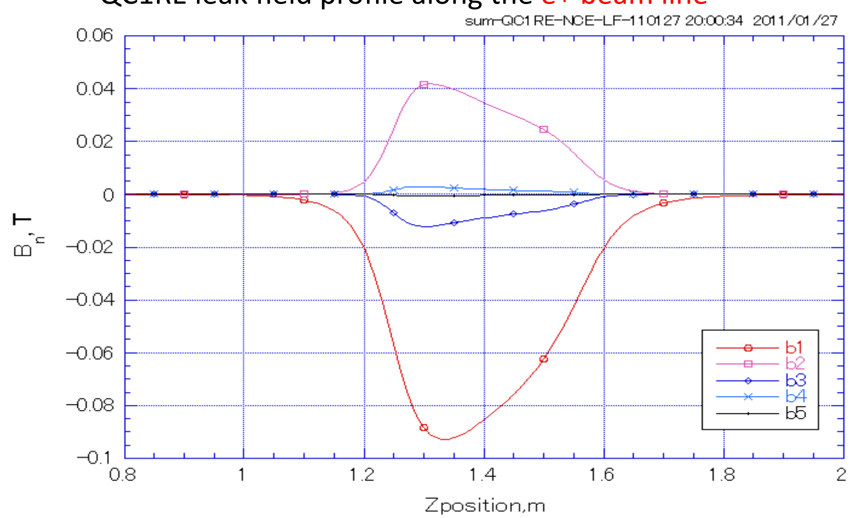
- The leak field profiles along the opposite lines are calculated.
- The leak magnetic fields of the main quadrupoles on the opposite beams are designed to be canceled with the SC correctors of ***b_3, b_4, b_5*** and ***b_6***.
- B_1 and B_2 components in the leak field are not canceled, and they are included in the optics calculation.
  - B_2 component is used for focusing and defocusing e-/e+ beams.



QC1RP leak field profile along the e- beam line

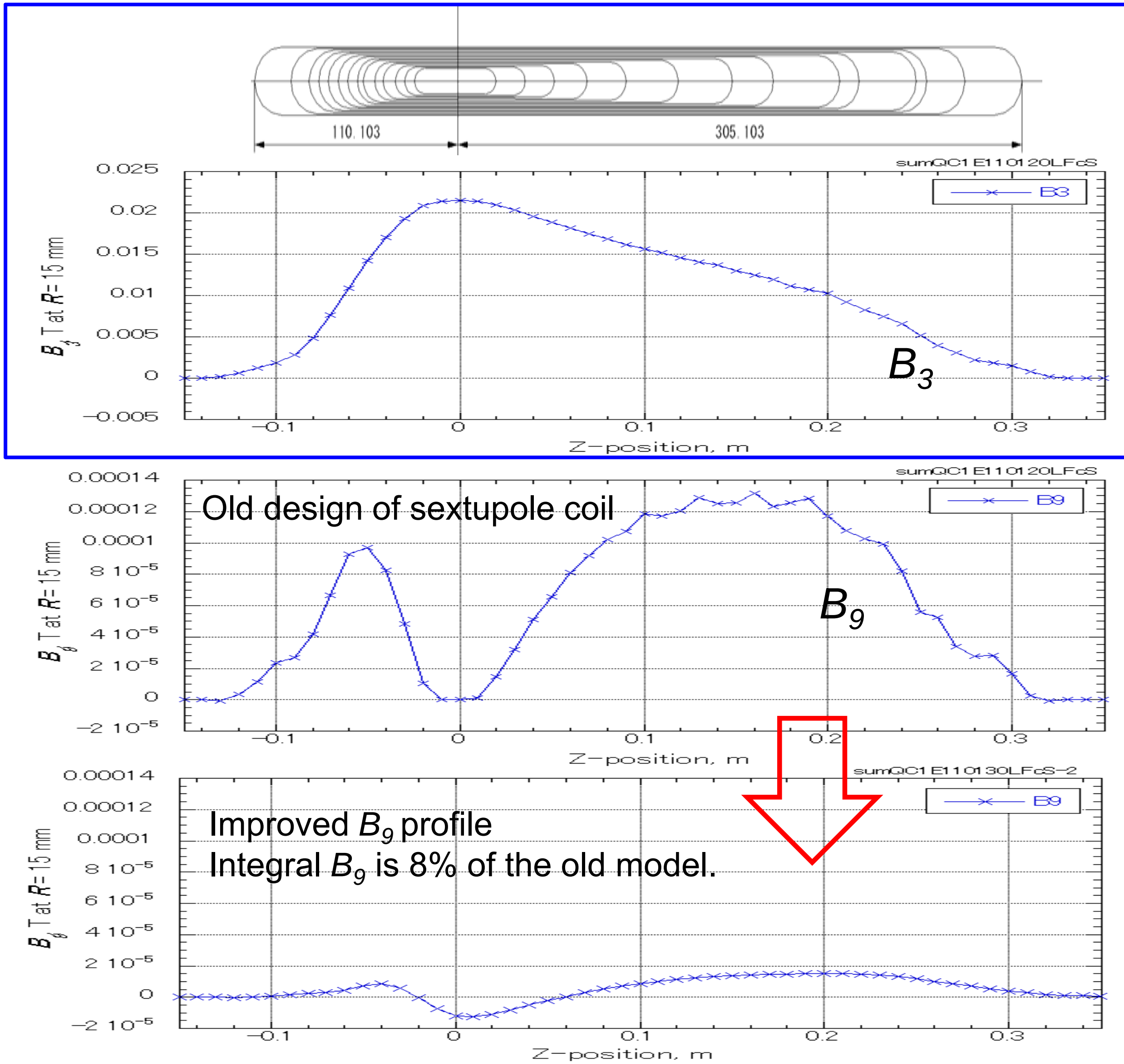


QC1RE leak field profile along the e+ beam line



Design of SC cancel coils

QC1RE leak field cancel sextupole coil



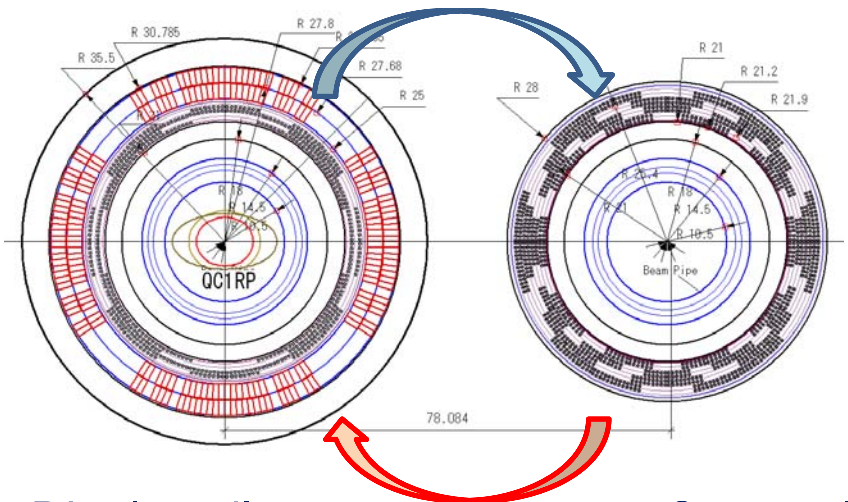
Coil parameters

- Double pancake coil
- Turn/pole = 44
- Inner radius = 38.4 mm
- Outer radius = 39.8 mm
- Coil current = 53.0 A
- SC wire= ϕ 0.4mm
  - J_c > 85 A @5T, 4.2 K

Improvement

1. Change of location in the coil package
   - R_{in} = 21.2 mm→ R_{in} = 38.4 mm
2. Modification of 2D cross section design of the sextupole coil
   - $B_9 < 0$

Leak field by SC cancel coils

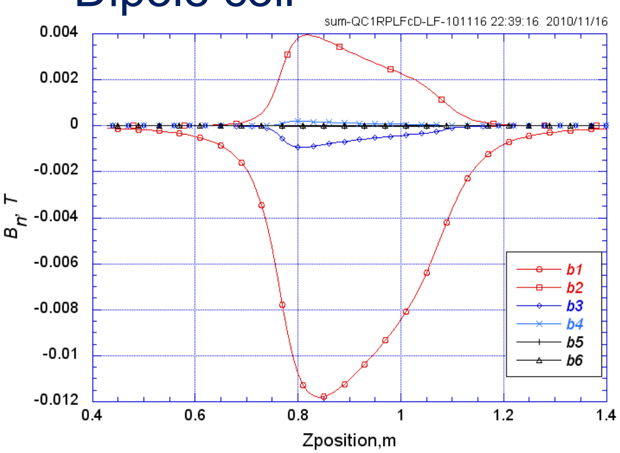


In the 15th KEKB Accelerator Committee, the followings were pointed:

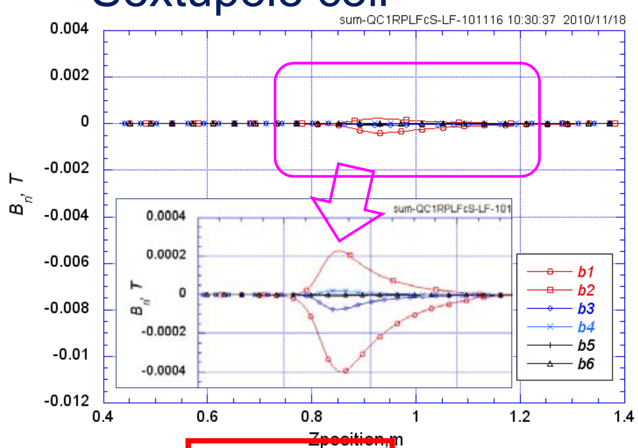
- The cancel coils produce the leak fields in the quadrupole bore.
- These leak fields should be studied carefully.

In the first design of the coil package, the b_1, b_3 and b_4 coils were designed for cancelling.

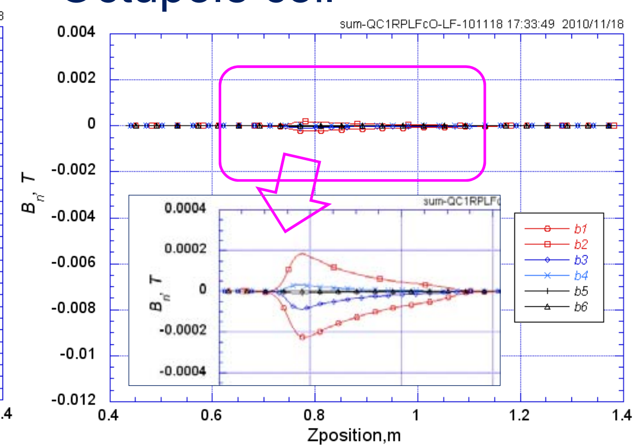
Dipole coil



Sextupole coil



Octupole coil

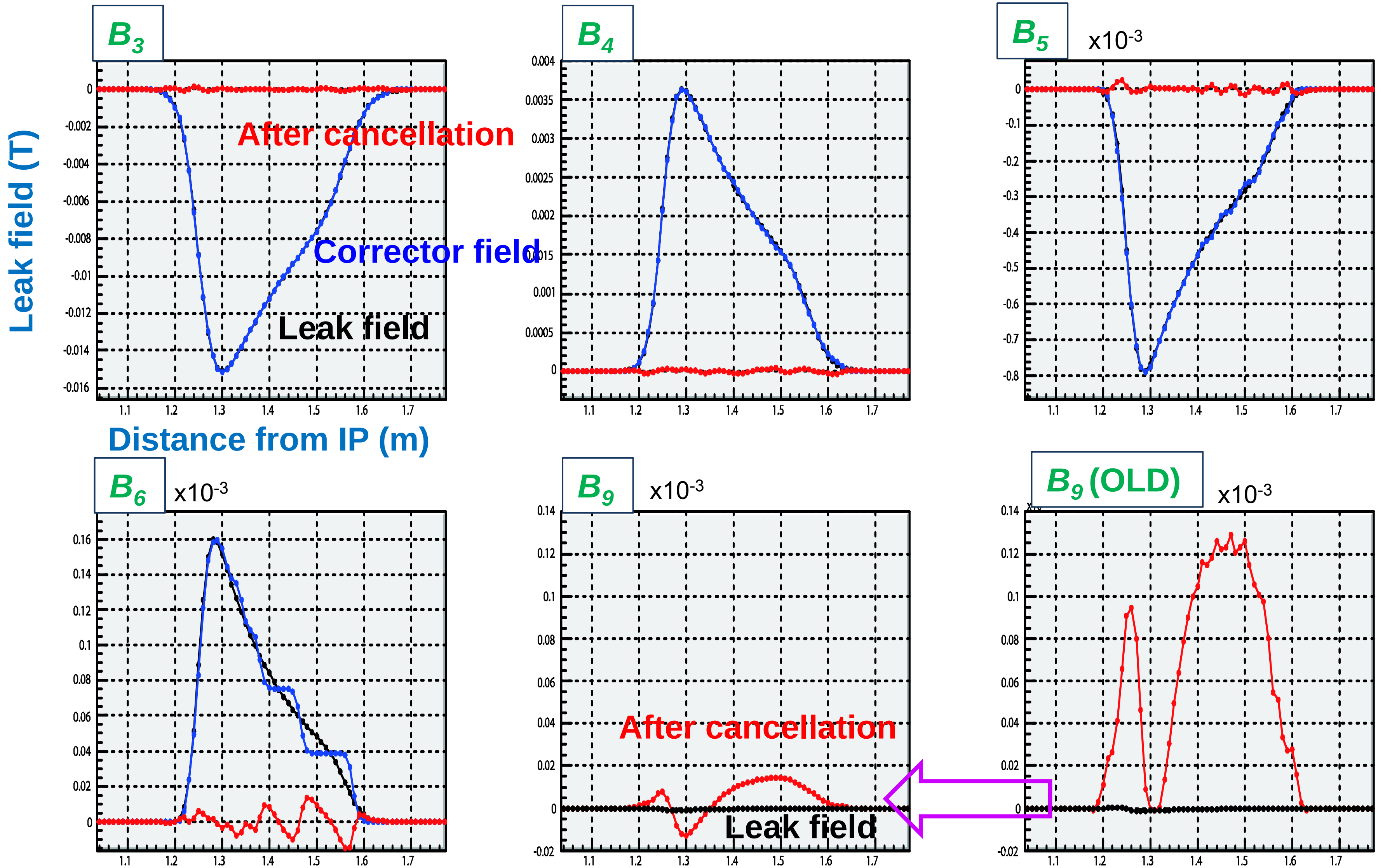


b_3, b_4, b_5 and b_6 coils are selected for cancelling the quadrupole leak field.

QC1RE leak field profile and cancellation along LER beam line

No cancellation of dipole and quadrupole fields

Calculation by M. Iwasaki



Parameters of cancel coils for QC1RE leak field (2D cross section)

	b_5	b_6	b_4	b_3
Coil inner radius, mm	34.2	35.6	37.0	38.4
Coil outer radius, mm	35.6	37.0	38.4	39.8
Turns /pole	21	10	28	8
Design current, A	12.17	12.17	30.42	52.35
Magnetic field @R=1.5 cm, Gauss	8.24	1.66	37.8	157.0
Bias magnetic field by Solenoids, T	0.5	0.5	0.5	0.5
Operating point with respect to J_c at 4.7 K	< 50 %	< 50 %	< 50 %	< 50 %

Cancelling QC1P and QC2RP leak fields for HER beam

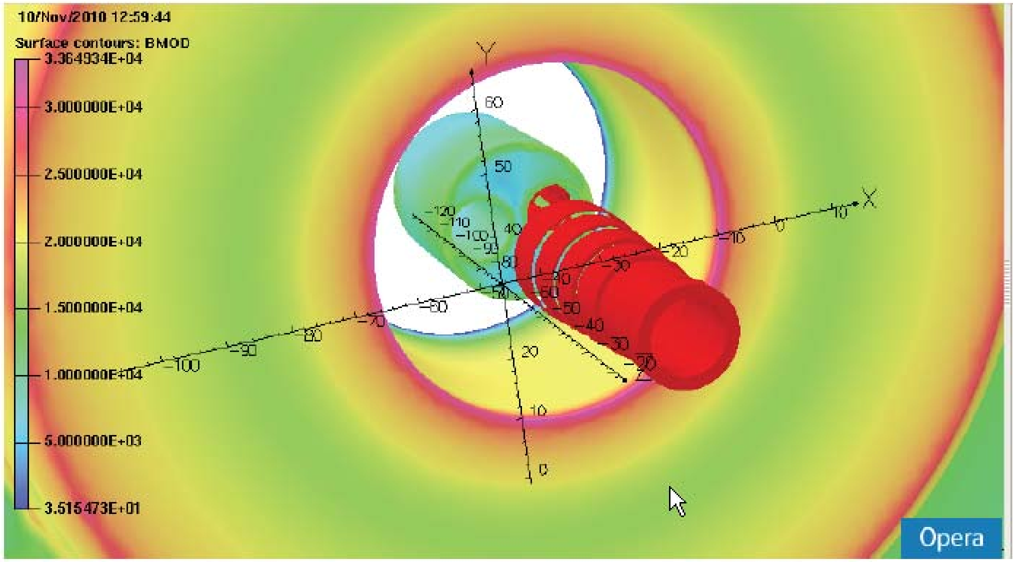
- Coil design works are now in progress.
- For QC1P:
  - Sextupole coil design was completed.
  - Integral octupole field is canceled, but local field is not canceled. → The coil should be re-designed for cancelling the local field.
  - Decapole and dodecapole coils are not designed at present. → These coils will be designed.
- For QC2RP:
  - Integral sextupole and octupole fields are canceled, but local field is not canceled. → These coils should be re-designed for cancelling the local field.
  - Decapole and dodecapole coils are not designed at present. → These coils will be designed.

QC2

- QC2RP
  - Design concept of magnet as same as QC1RP. SC quadrupole without iron yoke.
  - Magnetic designs of the quadrupole and the correctors were completed.
  - Cancelling coils of QC2RP leak field: $\boldsymbol{b_3}$, $\boldsymbol{b_4}$, $\boldsymbol{b_5}$ and $\boldsymbol{b_6}$.
  - In the optics calculation, the field profile and the leak field are included.
- QC2RE, QC2LP, QC2LE
  - SC quadrupole with iron yoke.
  - Leak fields on the opposite beam line are negligible.
    - No cancelling coils.
  - Correctors of a_1, b_1, a_2 and b_4 are assembled in the qudrupole bore.
  - Calculation of quadrupoles are in progress.
    - 3D calculation of quadrupoles with iron yoke
    - Mutual Influence between Belle and compensation solenoid fields and the iron yoke.

Magnetic field calculation of QC2LP

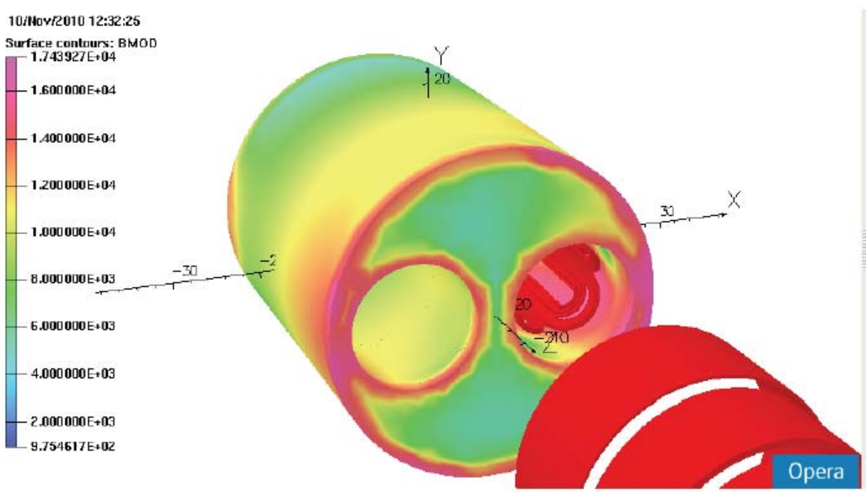
Calculation by M. Tawada

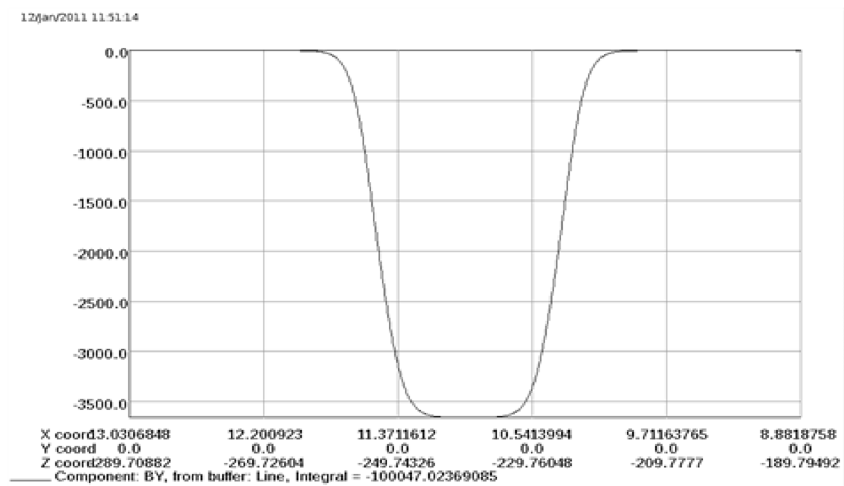


QC2LP

I=1170A

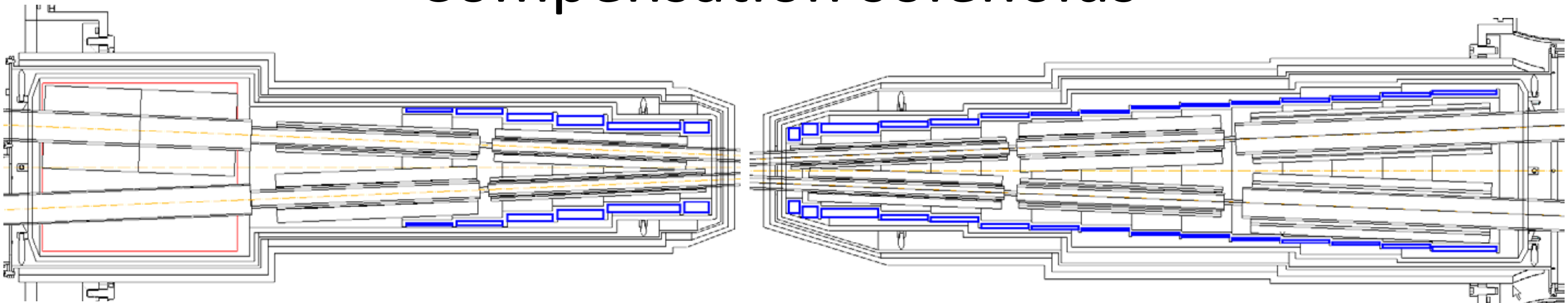
1. No iron yoke
   G=26.3 T/m
2. With iron yoke
   G=36.0 T/m
   Leak field along e- beam line<1 Gauss

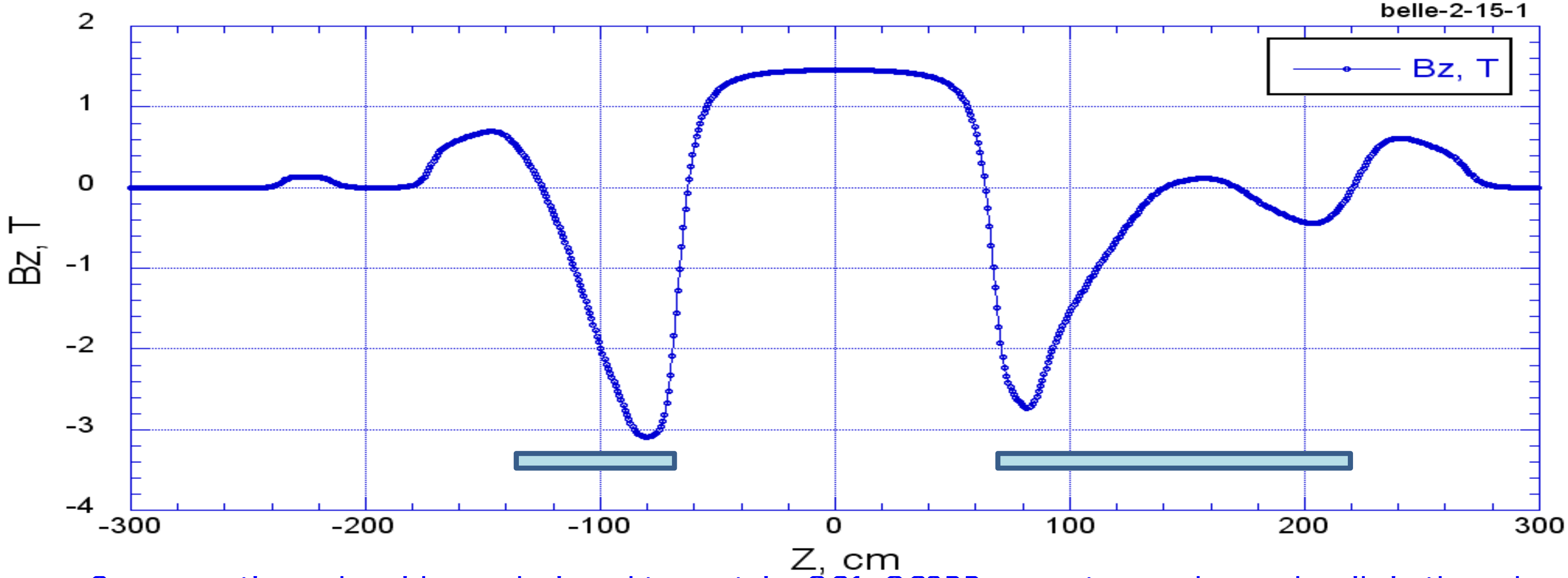




B'=3600 Gauss /1 cm=36 T/m

Compensation solenoids



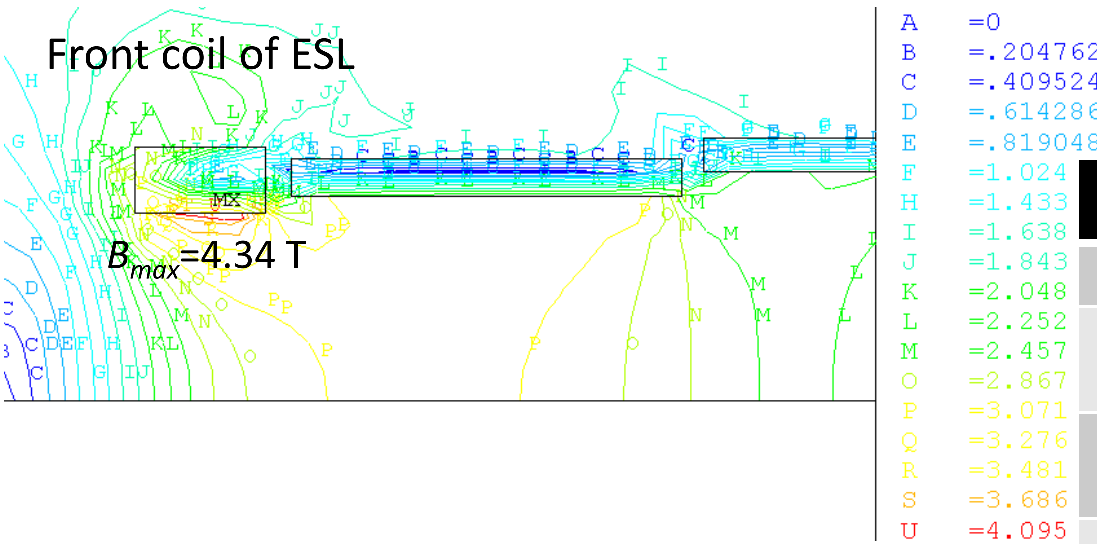


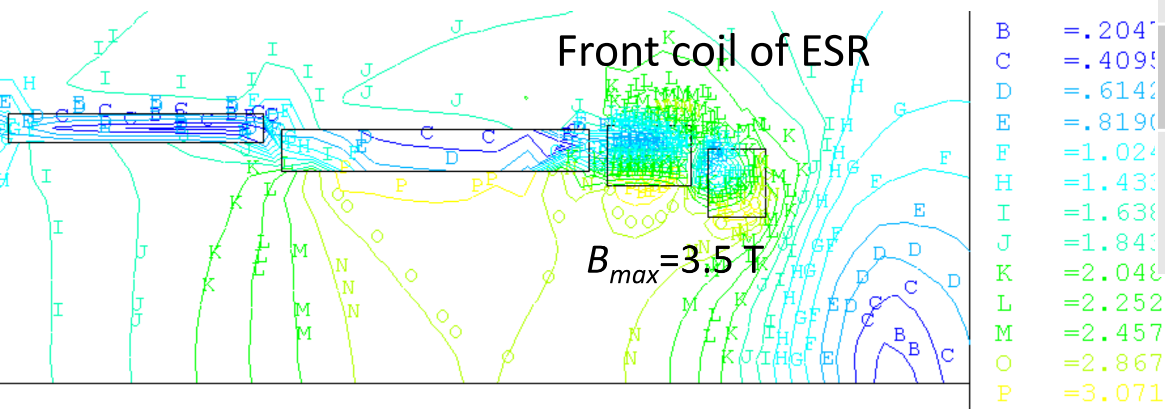
V.9

Calculation by M. Tawada

- Compensation solenoids are designed to contain QC1, QC2RP, correctors and cancel coils in the solenoid bores.
- Solenoids are divided into small coils to produce the field profiles to make the Vertical Emittance within the optics requirement.
  - HER = 4.0 pm, LER = 2.0 pm
- Electro-magnetic forces（Fz）
  - ESR = 39.6 kN、QC2RE = -12.9 kN → Total＝26.7 kN
  - ESL =-21.3 kN、QC2LP = 13.6 kN → Total ＝－7.7 kN

Solenoid field profile and magnet parameters

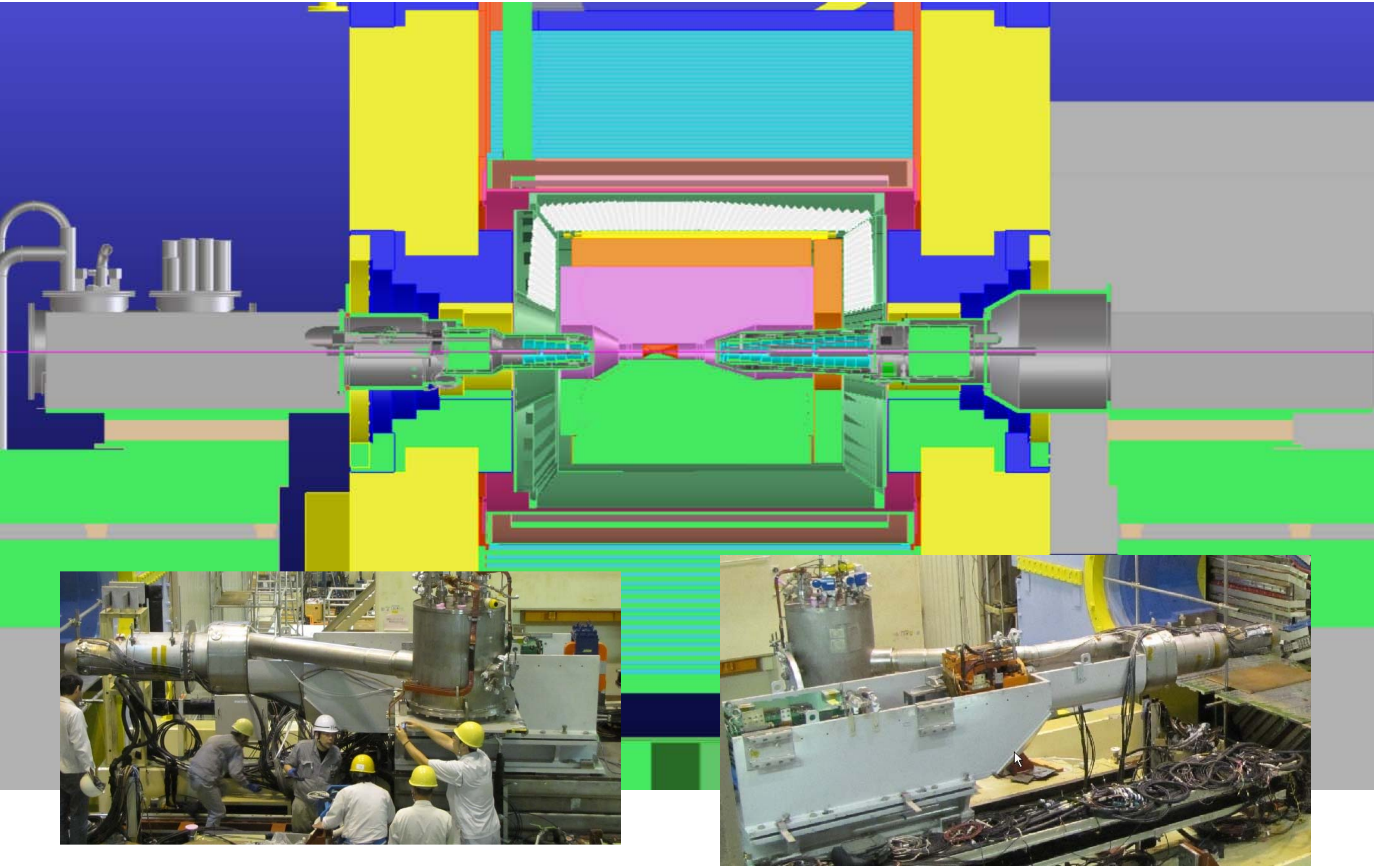




	ESR	ESL
Current	411.7 A	382.2 A
SC cable	1.63mm (W)× 0.67mm(H) Cu ratio＝1.0	
Current density (SC area)	754.0 A/mm^2	700.0 A/mm^2
Current density (in the cable)	377.0 A/mm^2	350.0 A/mm^2
Maximum field in the coil	3.50 T	4.34 T
Operating point with respect to J_c at 4.7 K	68 %	75 %

3. Cryostat and support mechanism

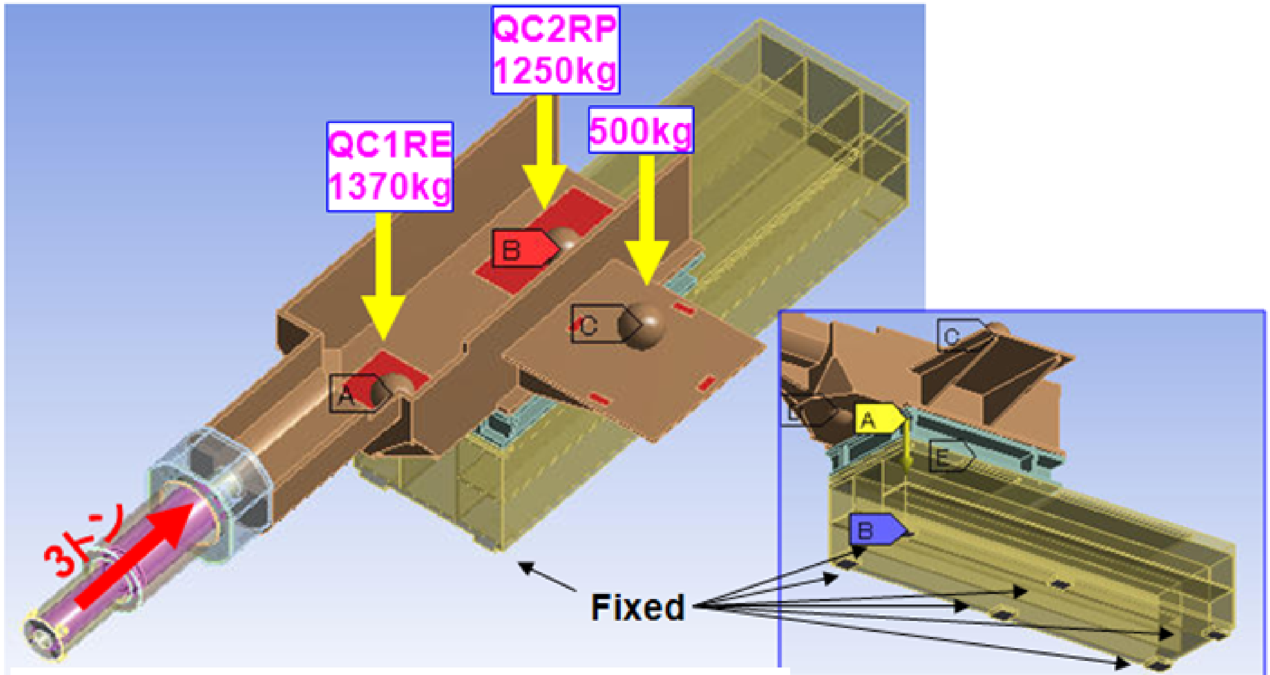
- The problem that need to be overcome：vibration of cryostat and support
- The front positions of SuperKEKB QCS cryostats are almost same as the KEKB cryostats
  - **Front positions** from IP and **lengths** of cryostats
    - KEKB：QCSR＝ 765mm [1850mm], QCSL＝ 580mm [1720mm]
    - Super KEKB：QCSR＝ 633.5mm [2884mm], QCSL＝ 627mm [2534mm]
  - EMF
    - KEKB：QCSR＝ 2.8 kN 、QCSL＝22 kN
    - Super KEKB：QCSR＝ 26.7 kN、QCSL＝7.7 kN
- Understanding the mechanical characteristics of KEKB-QCS cryostat and support mechanism
  - Vibration measurement of the KEKB QCS cryostats and supports
  - Mechanical analysis by ANSYS
    - Comparison of calculation and measurement of KEKB QCS cryostats and supports
    - Vibration study of SuperKEKB QCS cryostats and supports



Mechanical analysis of KEKB cryostat and support

QCS-R(FEM model)

Calculation
by H. Yamaoka



1. Loads
- Self-weight
- QC1RE: 1370kg
- QC2RP: 1250kg
- Box: 500kg

2. Materials
Cryostat: SUS
Coil: Cu
Supp.-rod: Ti-alloy
QCS table: SS400

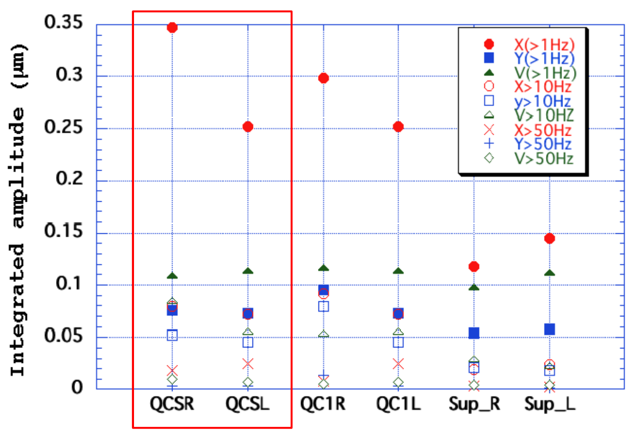
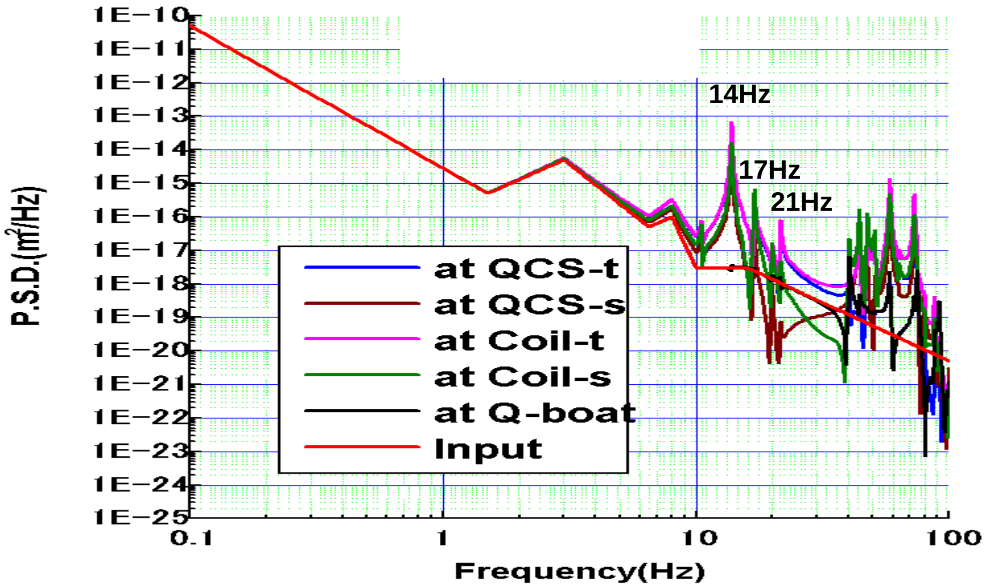


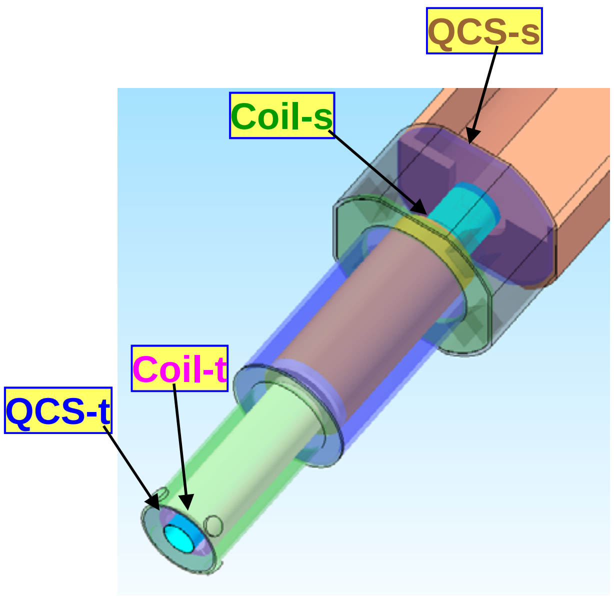
Fig. 6 The integrated amplitude of the IR magnet for different frequency ranges.

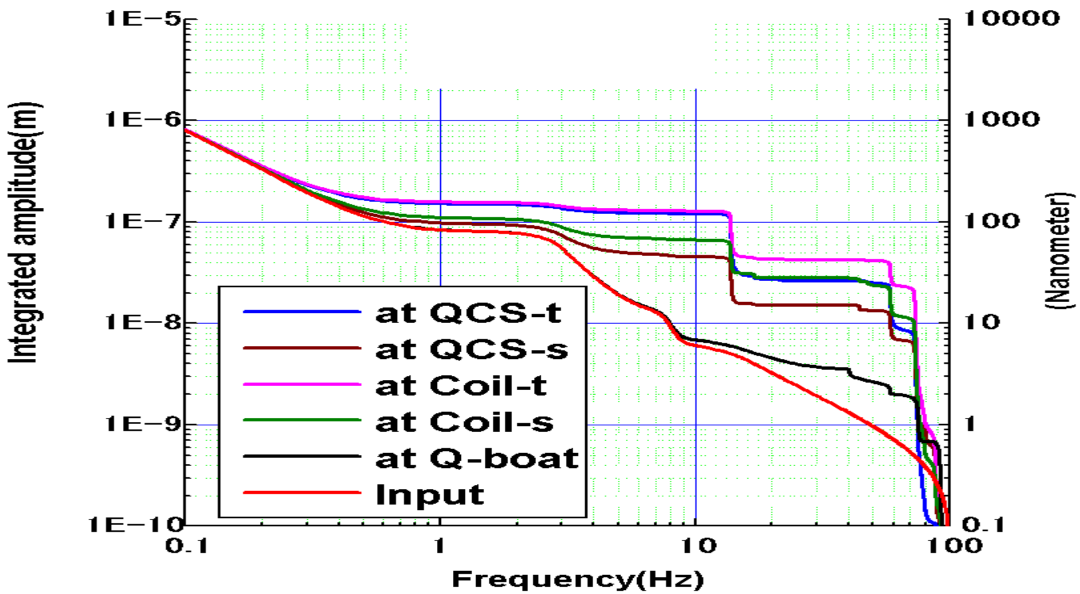
Measured integrated amplitude of vibration
QCS-R: 0.11 μm (>1Hz), 0.085 μm (>10Hz)
QCS-L : 0.11 μm (>1Hz), 0.055 μm (>10Hz)

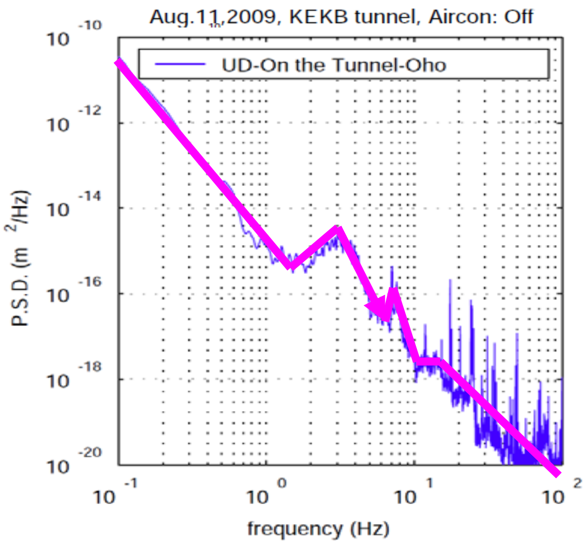
Measurement
by M. Masuzawa

Vibration analysis of KEKB QCS cryostat



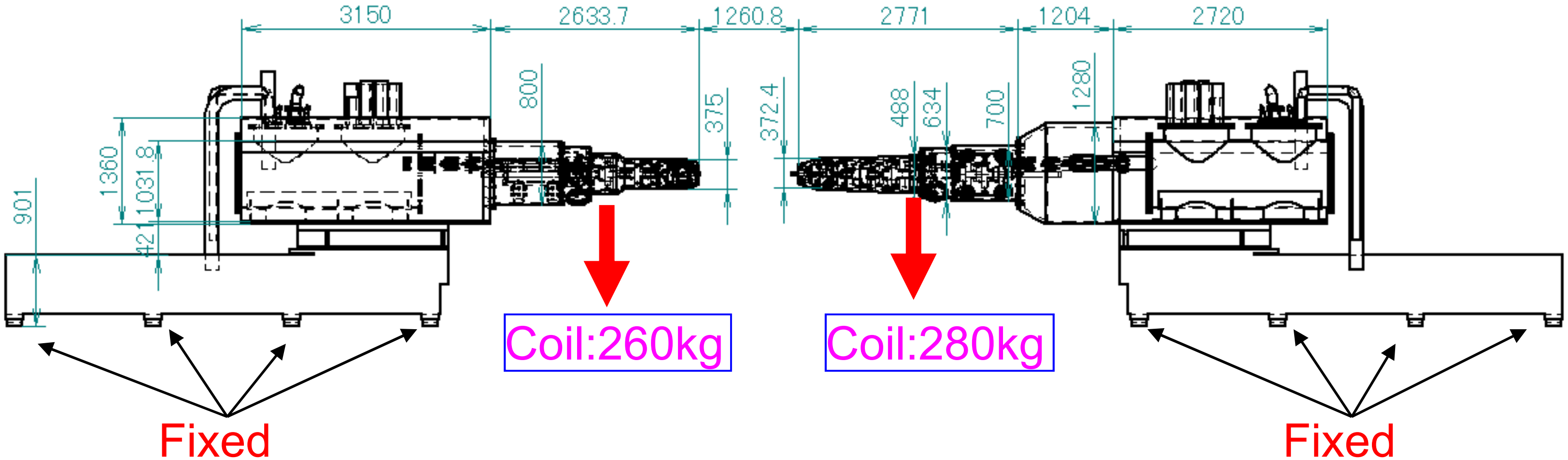


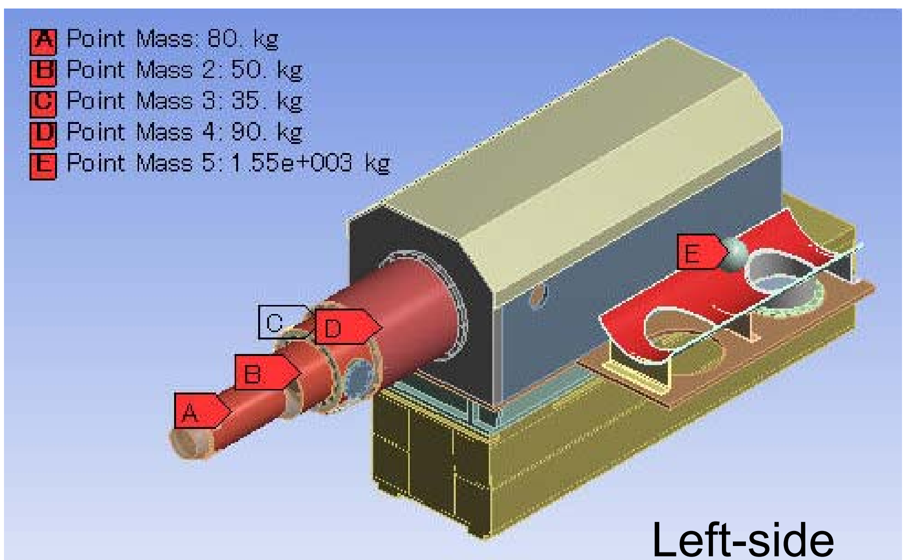


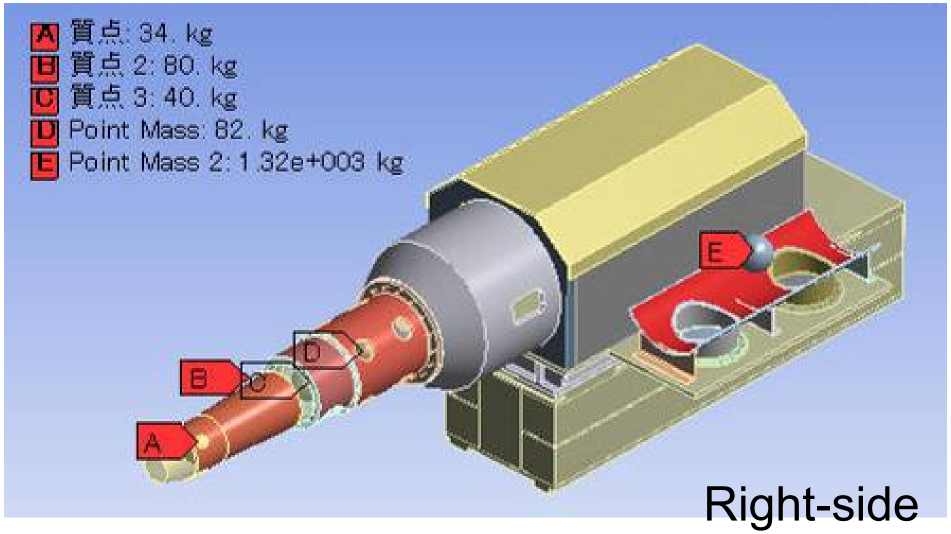


Calculation model of SuperKEKB cryostats

FEM model

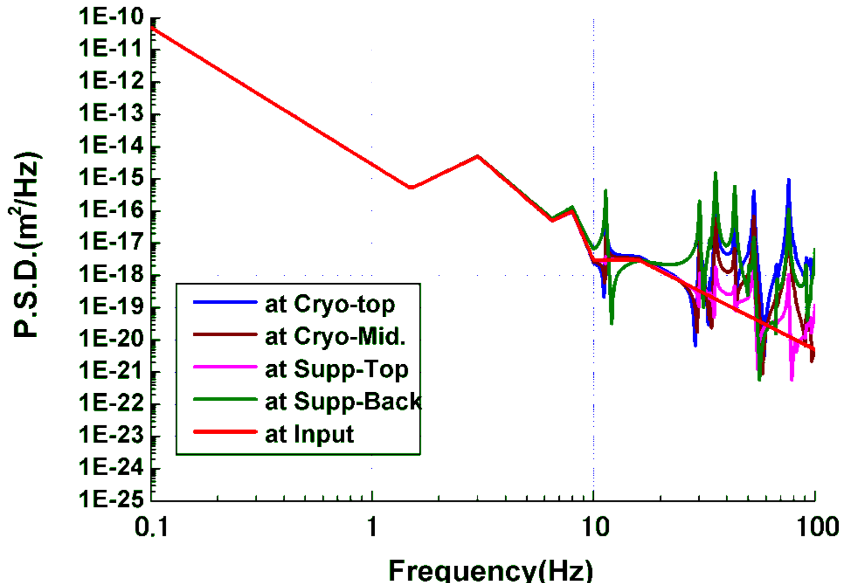




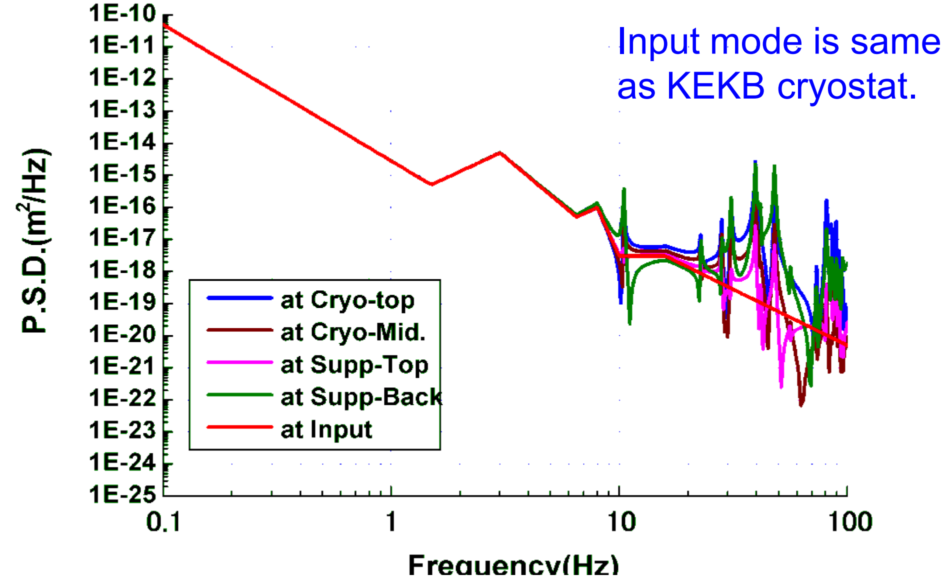


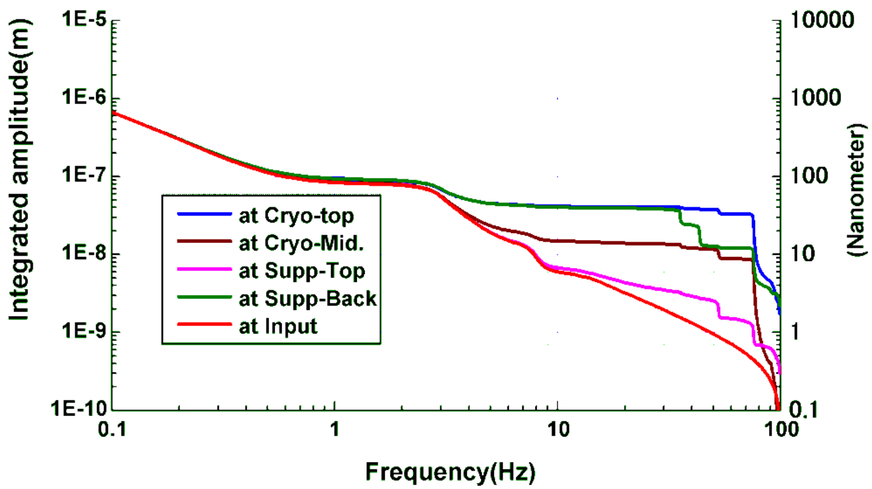
Vibration analysis of SuperKEKB cryostats

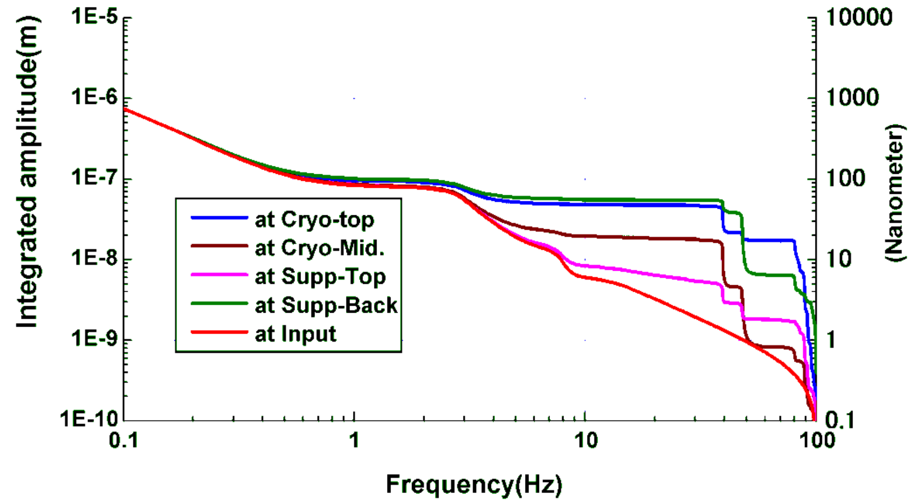
QCS-L



QCS-R

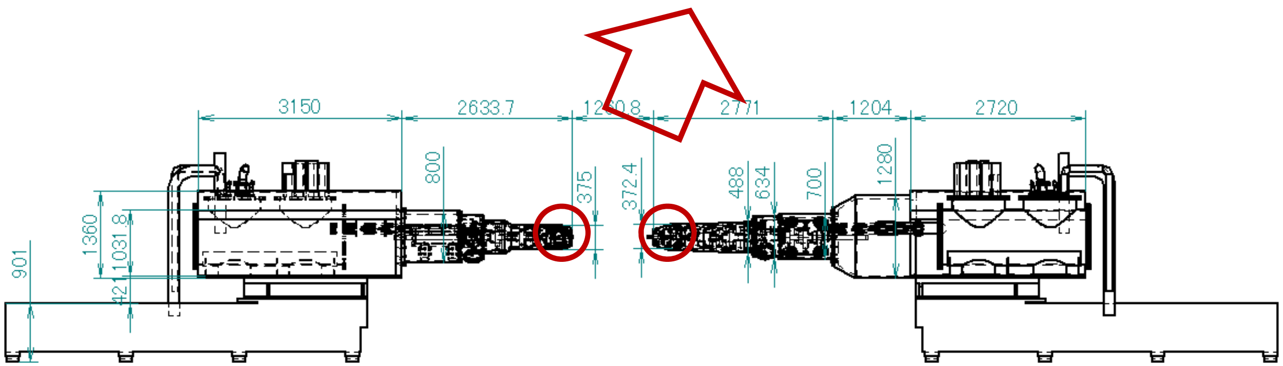


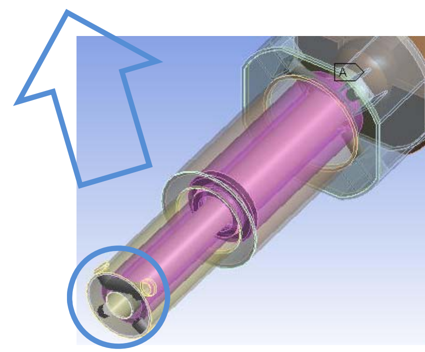




Summary of vibration analysis

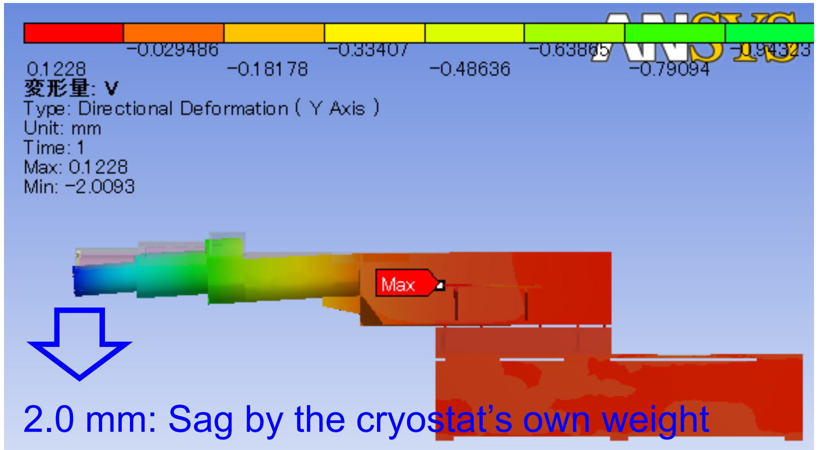
	SuperKEKB QCS				KEKB QCS	
	Left		Right		Right	
	> 1Hz	> 10Hz	> 1Hz	> 10Hz	> 1Hz	> 10Hz
Hori. transverse	87	80	107	100	119	112
Hori. axial	37	9	37	8	40	11
Vertical	87	28	90	33	151	120

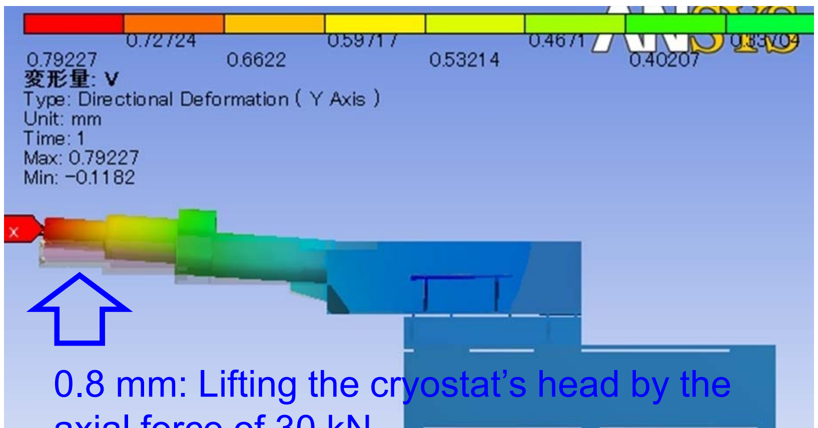




Static mechanical analysis

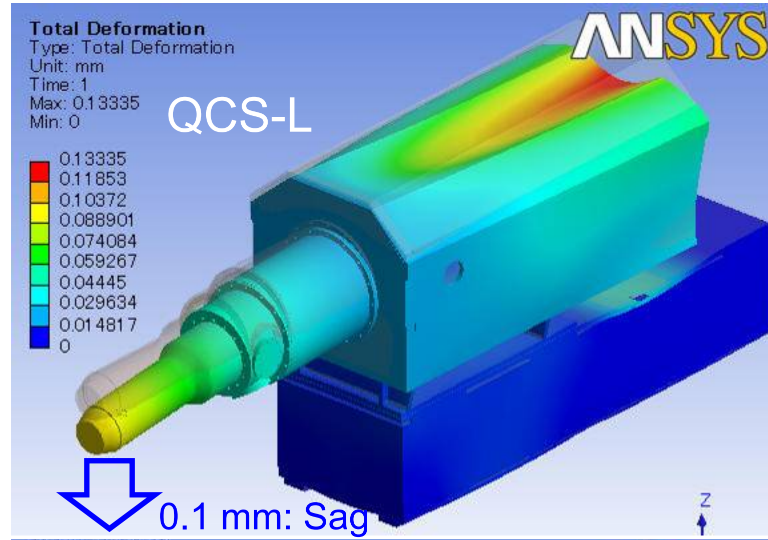
KEKB QCS-R cryostat

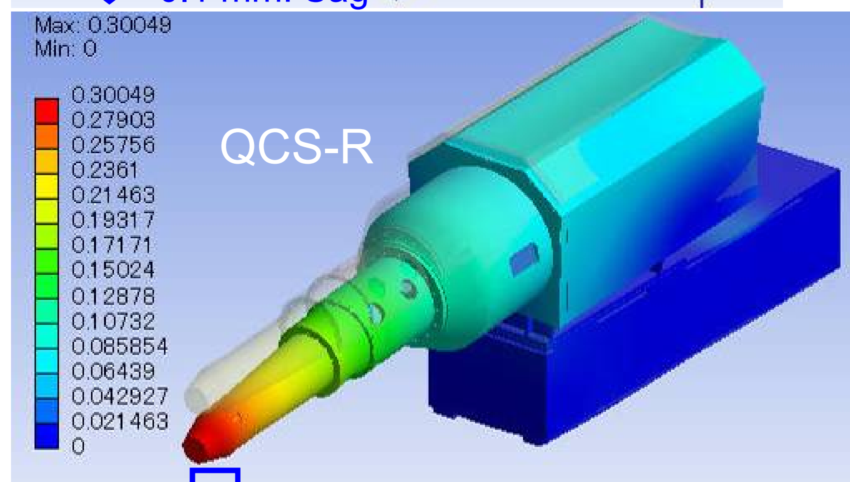




0.8 mm: Lifting the cryostat's head by the axial force of 30 kN.
This axial force corresponds to the EMF acting on the compensation solenoid.

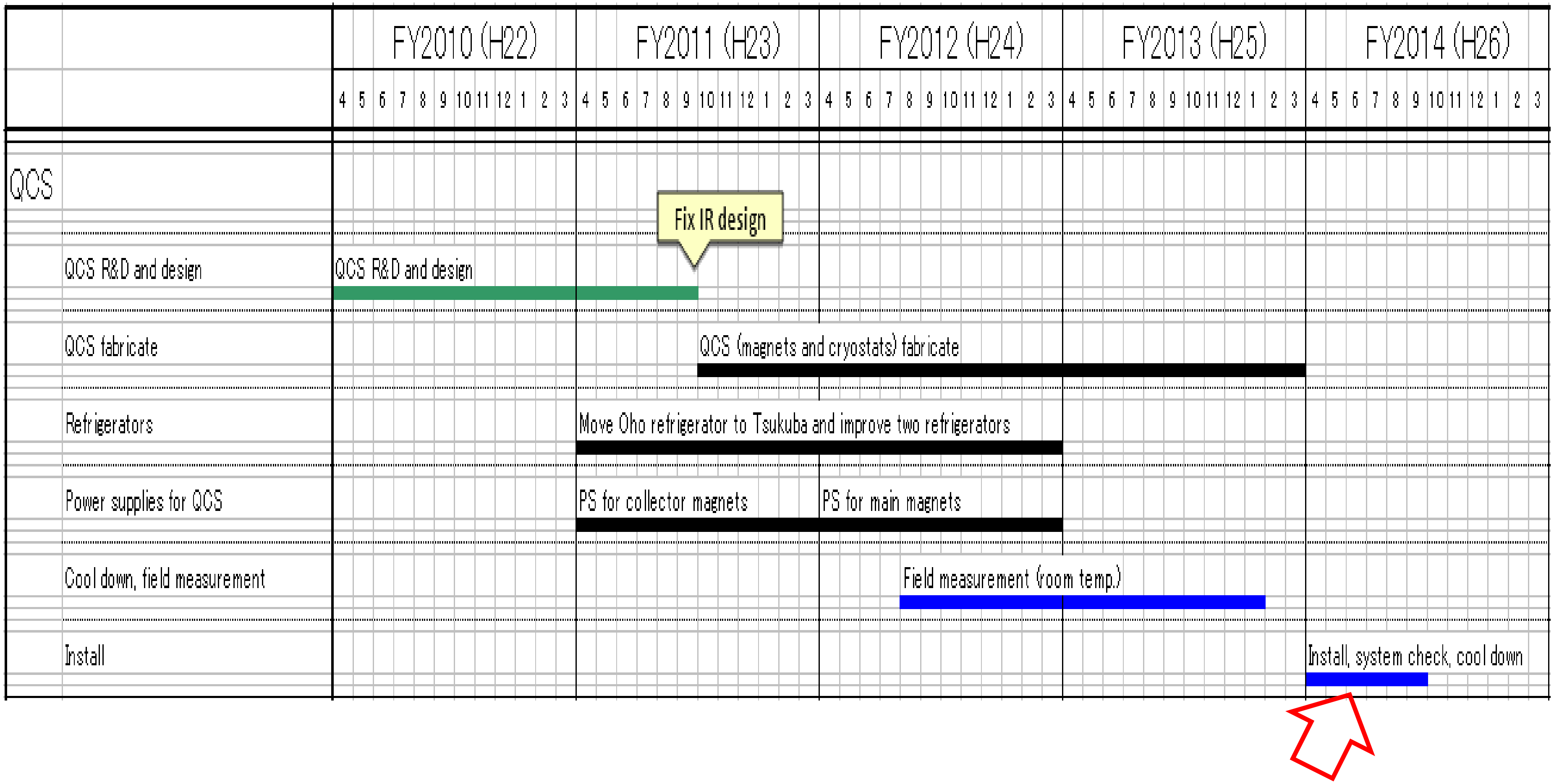
SuperKEKB QCS-L/R cryostats





0.3 mm: Sag

IR magnet construction schedule



Field measurements on beam lines

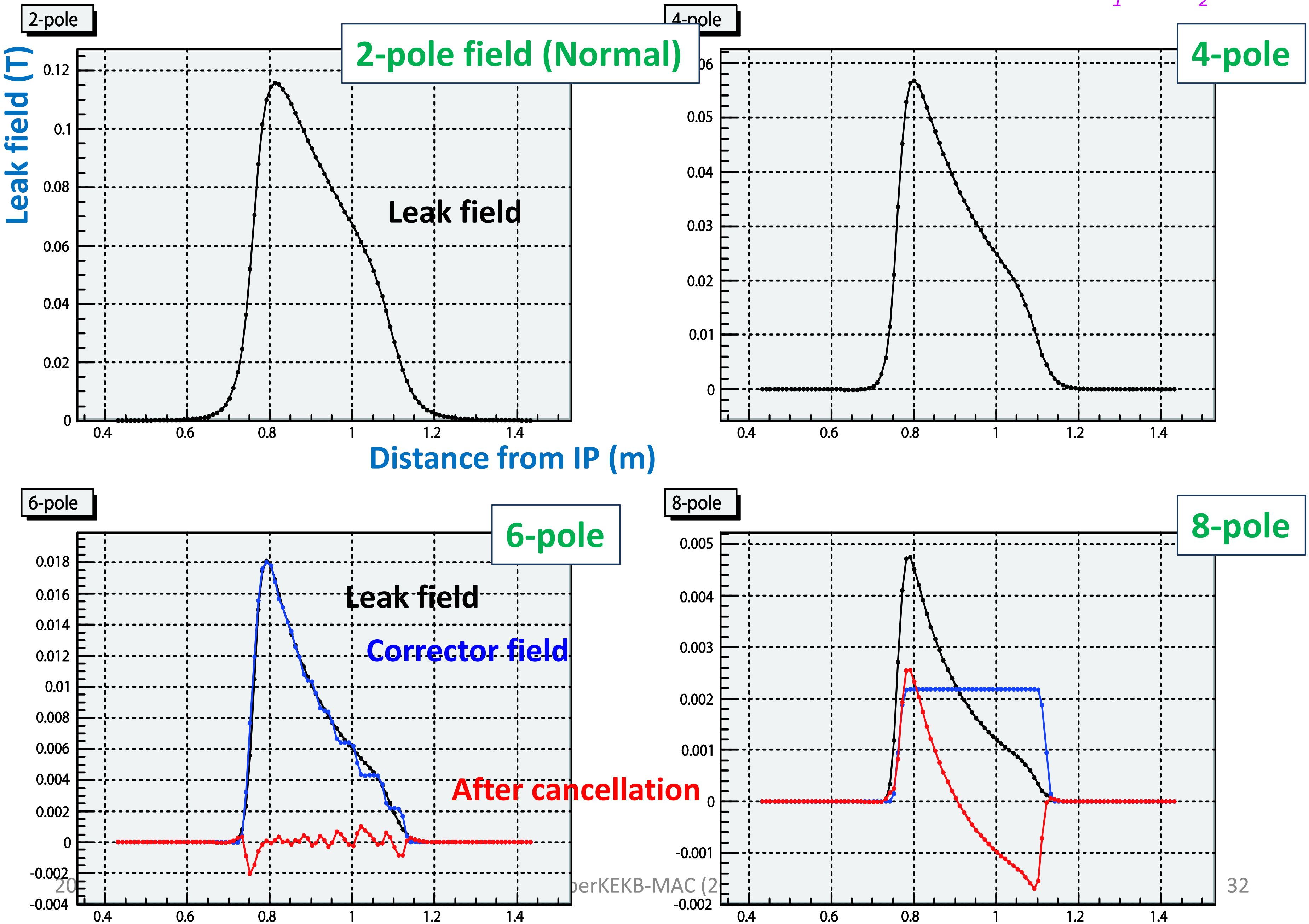
Summary

- Beam optics (Touschek Lifetime)
  - The leak field by QC1P/E and the field performance of B_3 cancelling coil are improved.
    - LER/HER lifetimes are expected to be 577 / 724 sec, respectively.
    - Optics calculation will be performed soon.
- SC magnet design
  - The magnetic designs of QC1E/P and QC2RP [no iron yoke] are almost completed.
    - Need to complete the designs of cancelling coils for the leak fields and correctors.
  - The magnetic designs of QC2LP and QC2R/LE [with iron yoke] are ongoingly pushed through.
    - Influence of the iron yokes on the field profile along the beam line.
- Cryostat and support mechanism design
  - Mechanical analysis of KEKB and SuperKEKB cryostats and supports have been performed.
    - Vibration of the cryostats is able to be reduced within an acceptable value.
    - The calculation model will be brushed up by comparing the measured data of the KEKB cryostat.
  - Vibration study will be performed by using the KEKB QCS cryostat.
    - High vibration damping material for the support component. [MnCuNiFe Alloy]

Back-up

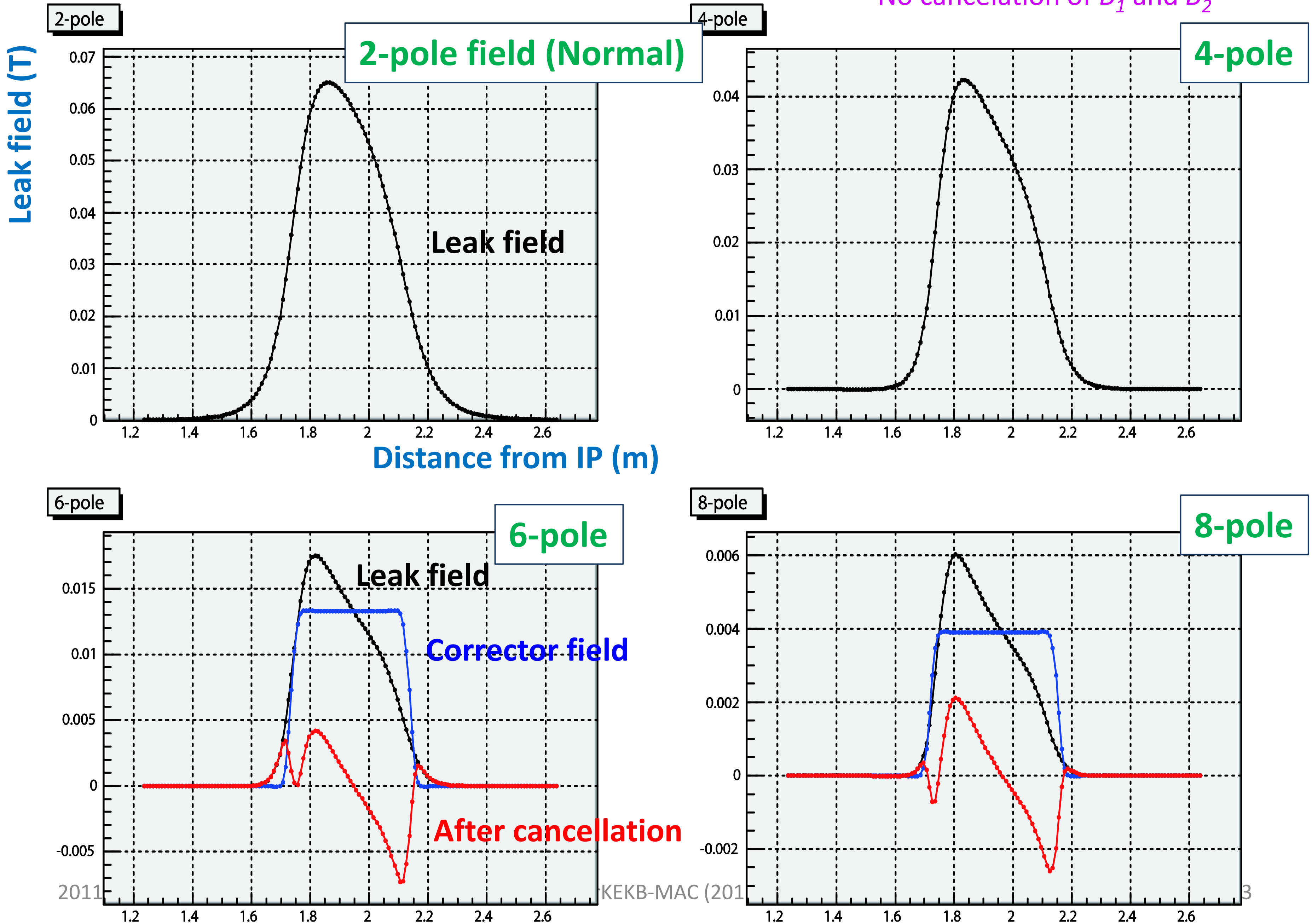
Leak field from QC1RP

No cancelation of B_1 and B_2



Leak field from QC2RP

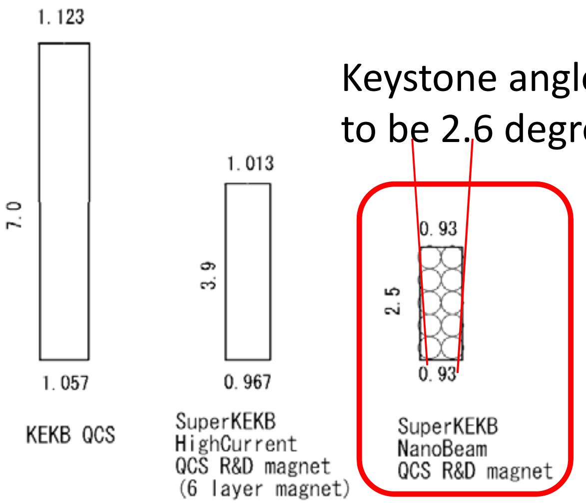
No cancelation of B_1 and B_2

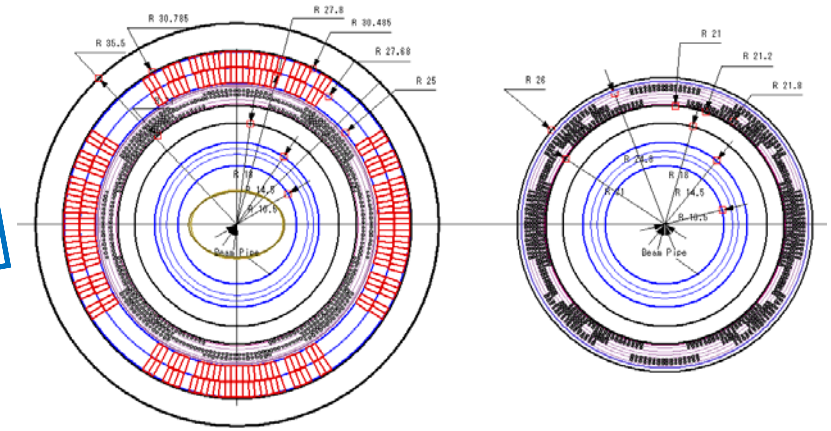


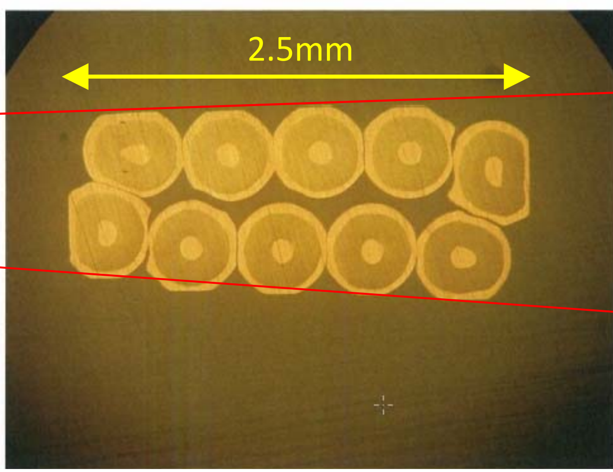
QC1RP R&D

Development of small cross section SC Rutherford cable

Keystone angle needs to be 2.6 degree







Cross section of cable C (2.6 deg.)

Cable Performance (I_c @5T, 4.2K)

before cabling : 320A

after cabling (A=1.5 deg.) : 297A

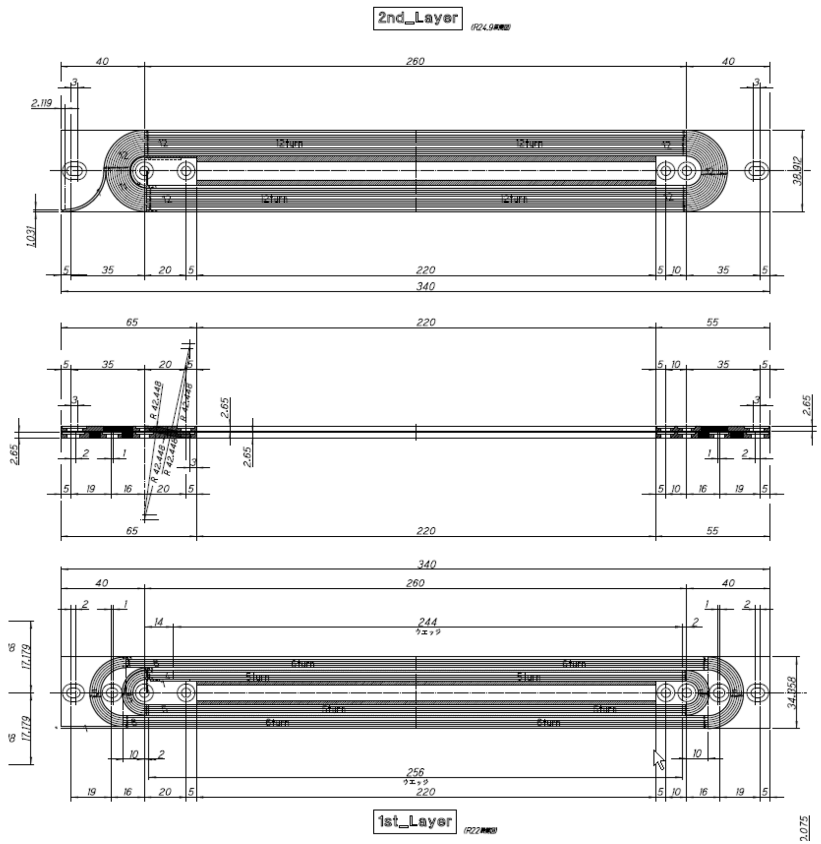
after cabling (B=2.0 deg.) : 307A

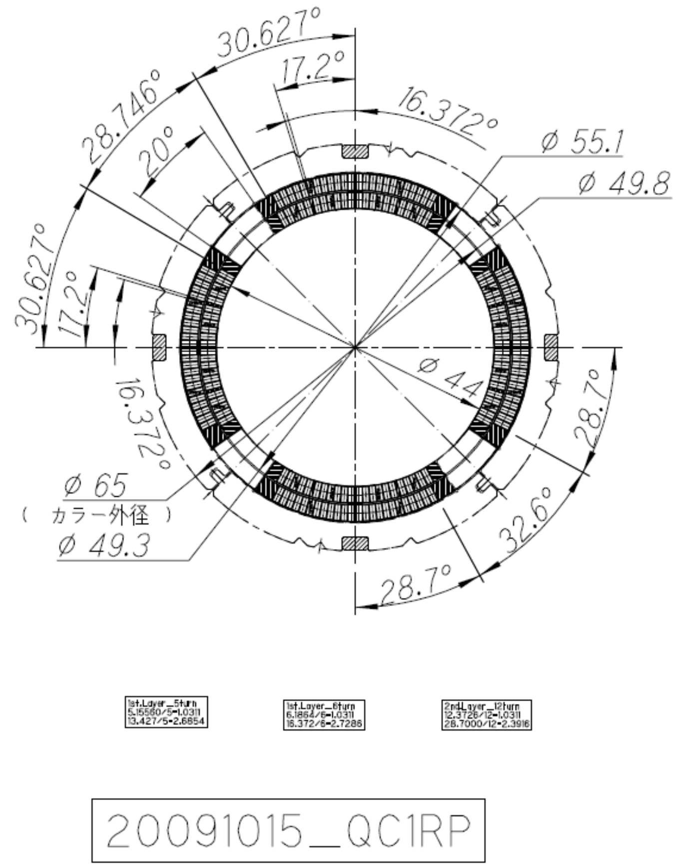
after cabling (C=2.6 deg.) : 305A

Average =303A (94.7%)

SC cable for QC1,2 : possible for production

QC1RP R&D magnet





- QC1RP R&D magnet components： completed.
- Production of small cross section SC cable：completed.
- Coil winding machine and cable tensioning device: being tuned for winding coil
- Production of SC coils will start from April.
- Cold test is scheduled at June.
  - The R&D magnet will contain the corrector coils in the magnet bore.