SuperKEKB IR Design

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IR Design Work Overview

- Works already done
  - **Choice of basic machine parameters**
  - **Geometrical boundary conditions**
    - Relationship between SuperKEKB and SuperBelle
  - **Estimation of required ring acceptance**
- Design works in progress
  - **Optics design**
    - Layout of magnets, dynamic aperture
  - **Magnet design**
    - Basic design, field quality, leakage field, e.m. force, SOR, interference with other components etc.
  - **Damping Ring**
  - **IP chamber, detector beam background**
- Works to be done in near future
  - **Engineering study**
    - Vacuum design, 3D design of magnets, estimation of HOM, etc.
  - **Beam monitor system**

Design parameters of KEKB and SuperKEKB

	KEKB (design)		SuperKEKB	
	LER	HER	LER	HER
I [A]	2.6	1.1	9.4	4.1
$\square_y^*$[mm]	10	10	3	3
$\square_y$	0.05	0.05	0.1~0.26	0.1~0.26
L [/cm^2/sec]	1×10^{34}		$2\sim6 \times 10^{35}$	
$\square_l$ [mm]	5	5	3	3

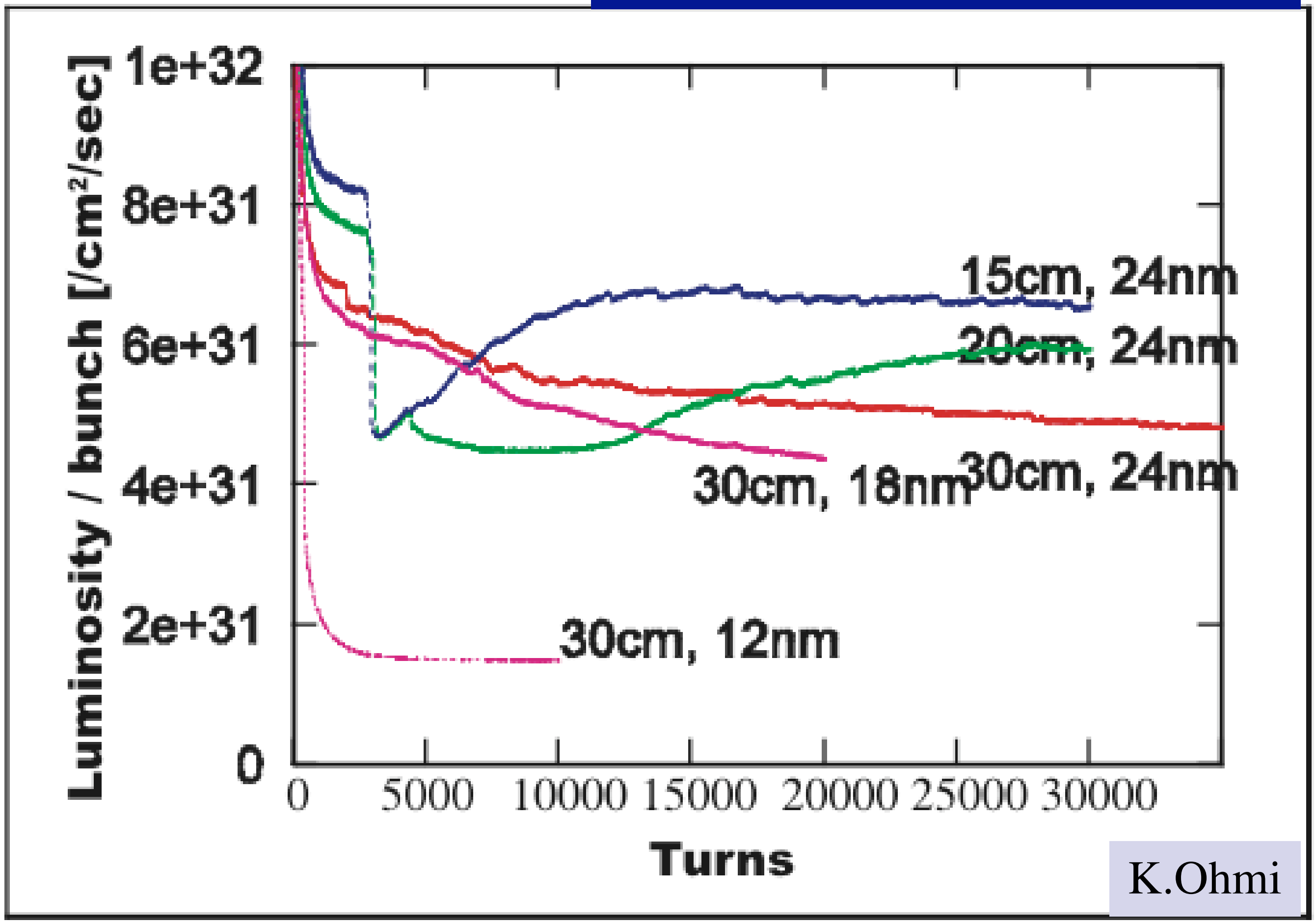
IR basic parameters

	KEKB (design)		SuperKEKB	
	LER	HER	LER	HER
□ [mrad]	11		15	
□$_y^*$ [mm]	10	10	3	3
□$_x^*$ [cm]	33	33	20	20
□$_x$ [nm]	18	18	24	24

Choice of β_x and ε_x

- β_x=30, 20, 15 cm
- ε_x=24, 18, 12 nm

Strong-Strong Simulations



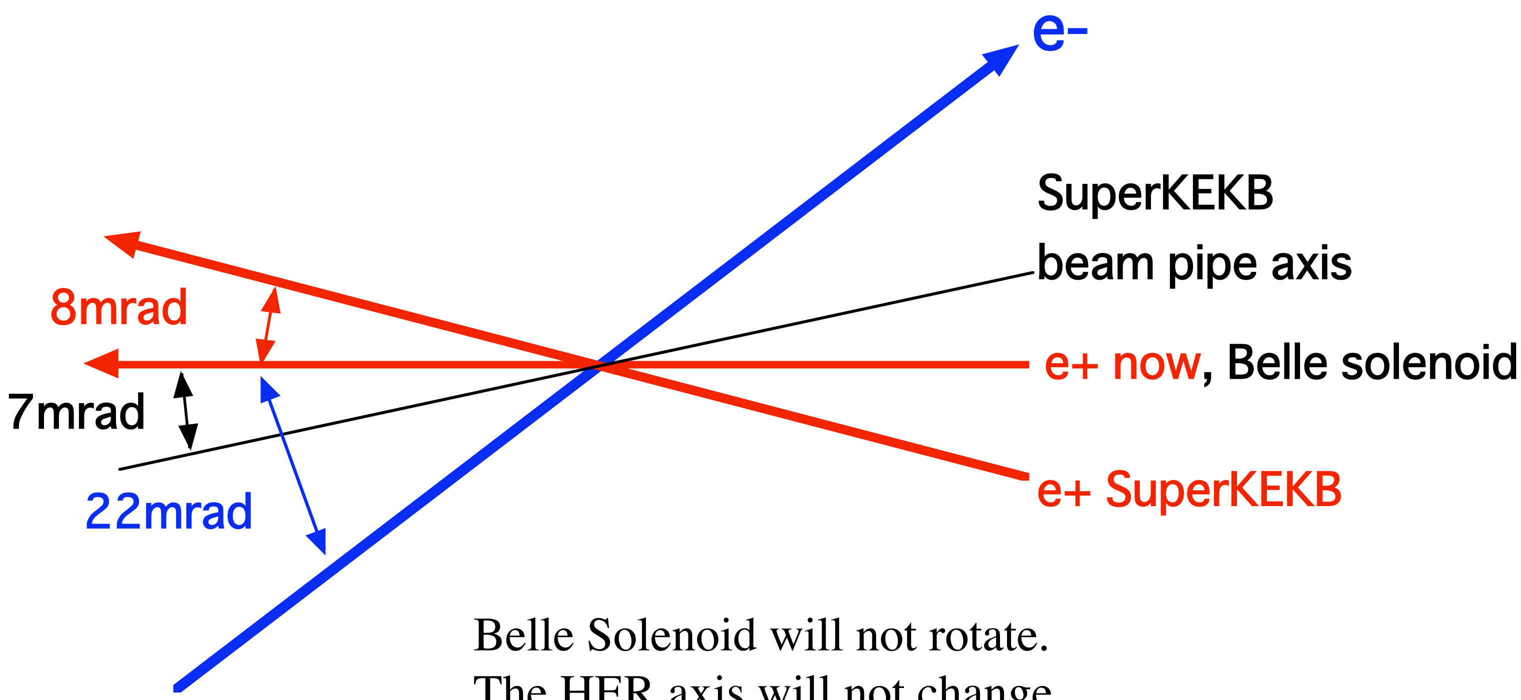
K.Ohmi

High β_x, low ϵ_x model

ϵ_x (nm)	24	24	24	18	12
ϵ_y (nm)	0.18	0.18	0.18	0.18	0.18
σ_z (mm)	3	3	3	3	3
β_x (cm)	30	20	15	30	30
β_y (mm)	3	3	3	3	3
ξ_x	0.14	0.14	0.14	0.19	0.28
ξ_y	0.16	0.20	0.23	0.19	0.23
L_b (10^{31})	7.7	9.5	11	8.9	11
L (10^{35})	3.9	4.7	5.5	4.5	5.5
L_b (10^{31})	4.8	6.0	6.6	4.4	1.5
L (10^{35})	2.4	3	3.3	2.2	0.75

Simulation results

Relationship between SuperBelle and SuperKEKB



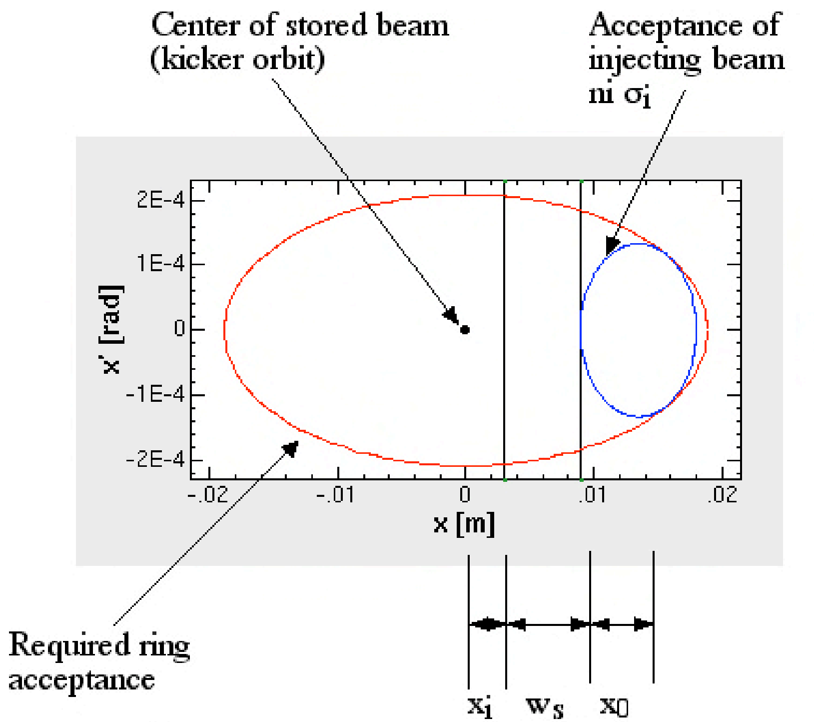
Belle Solenoid will not rotate.
The HER axis will not change.
The LER axis will rotate by 8mrad.
The beam pipe (and SVD) have a finite angle of 7mrad with respect to Belle Solenoid.
QCS magnets will be set parallel to Belle Solenoid.

Estimation of required ring acceptance

- Spread of injected beams determines ring acceptance.
  - **Injection error (Horizontal injection is used at KEKB.)**
  - **Linac beam emittance**
  - **Optics parameters at injection point (□□function）**
  - **Optics matching (optimization)**

Related parameters

- We assume □=0 at the injection point.
- Acceptance is determined by the following parameters.
  - **Ring emittance: □$_{xr}$**
  - **nr**
  - **w$_s$**
  - **ns**
  - **ni**
  - **Ring □: □$_{xr}$**
  - **Linac beam emittance : □$_{xi}$**
  - **Injection line □: □$_{xi}$**
- In the following, □$_{xi}$ is determined so as to minimize required acceptance.
- If a part of injection error is shared by the stored beam, required acceptance can be reduces. However, we do not consider this possibility.



$X_{inj} = x_i + w_s + x_0$ (injection error)

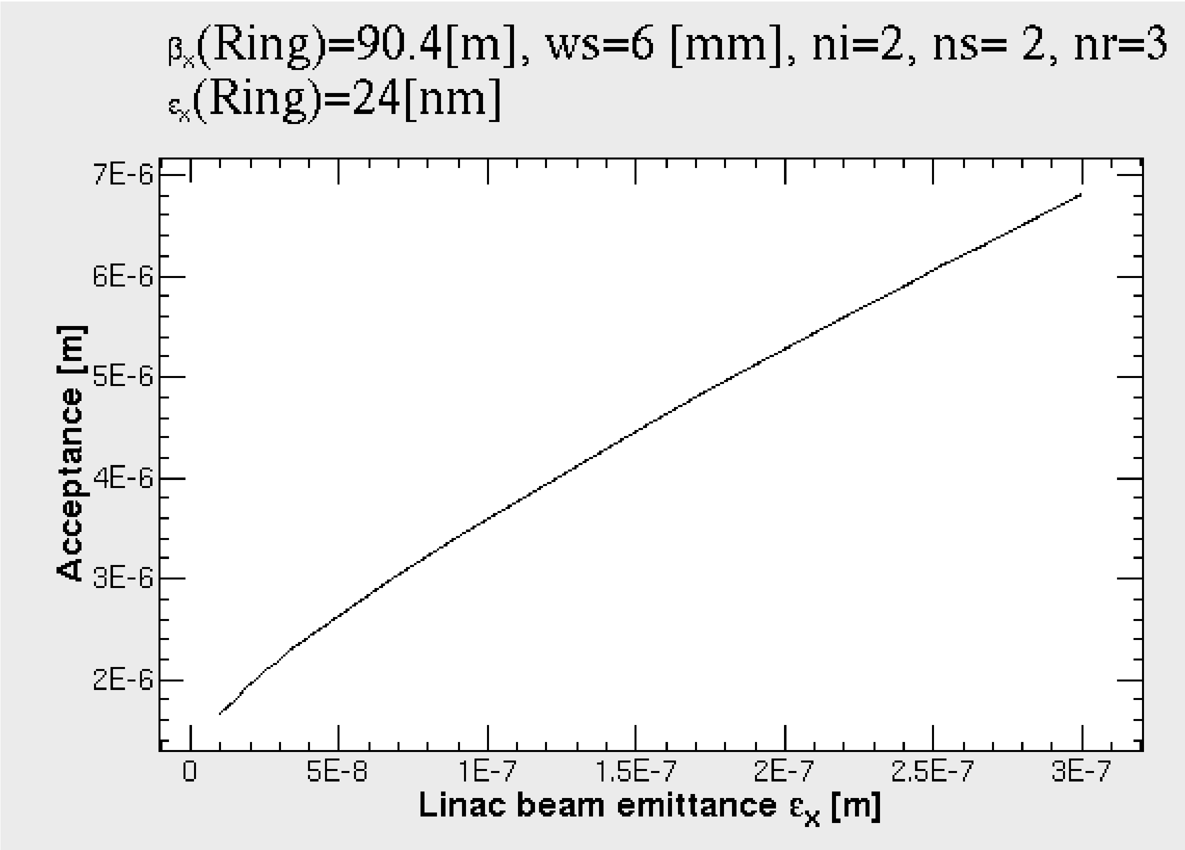
x_i: Distance between the center of stored beam and Septum wall -> nr σ_r

w_s: Septum thickness

x_0: Distance between the center of injecting beam and Septum wall ->ns σ_i

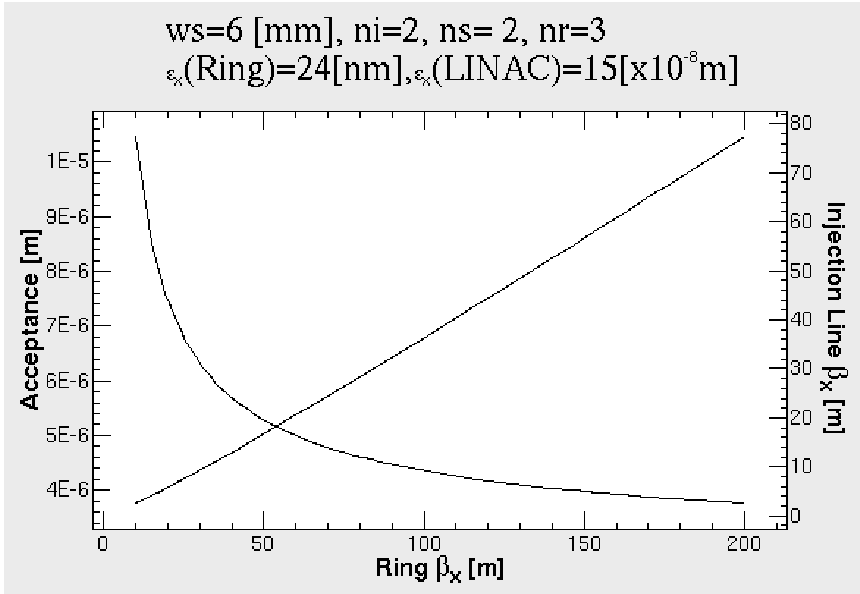
Linac beam emittance

- When we estimate required acceptance, the most important parameter is the emittance of the injected beam.

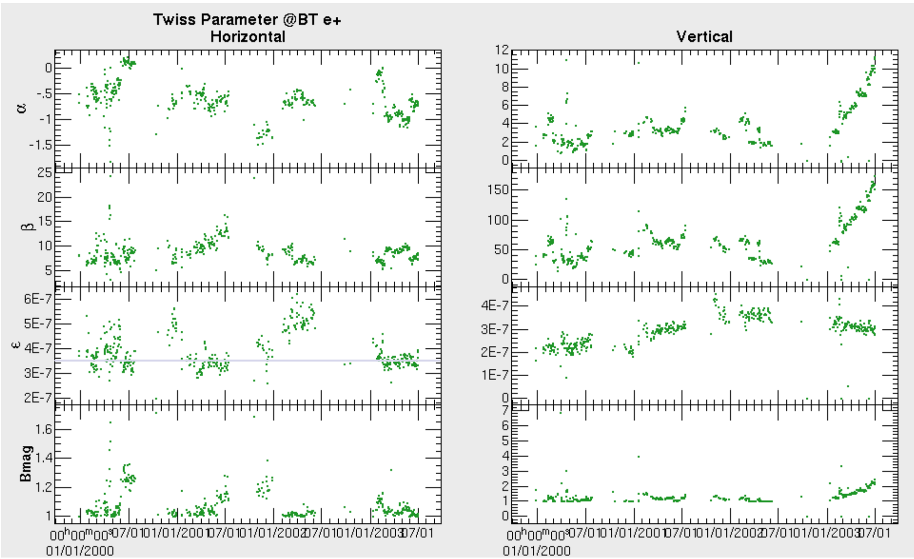


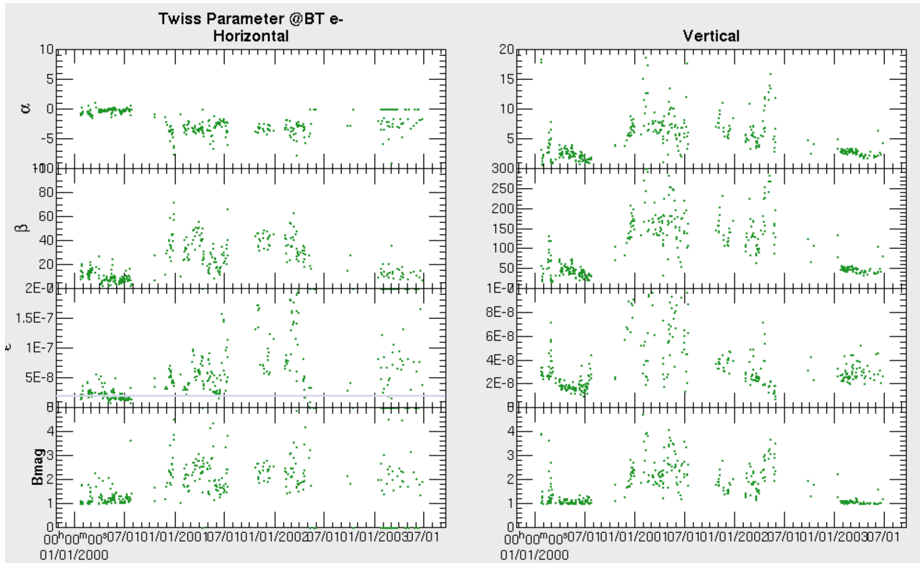
Ring β function

- Ring β_x: 90.4m -> 200m
  - **Acc: 4.5μm -> 3.8μm**



Linac beam emittance Experiences at KEKB





$\varepsilon_x = 3.5 \times 10^{-7}$ m @ 3.5GeV (e+)

$\varepsilon_x = 2 \times 10^{-8}$ m @ 8GeV (e−)

IR aperture requirements

- Do we need a damping ring for positron?
  - **Present assumption: YES**
- Electron beam determines required ring acceptance.
  - **Horizontal**
    - Required ring acceptance
      - A_x =1.9x10^{-6}m (HER)
      - A_x =2.6x10^{-6}m (LER)
    - Coherent oscillation due to injection error
      - A_x=1.5x10^{-6}m (HER)
      - A_x=1.8x10^{-6}m (LER)
  - **Vertical**
    - Required ring acceptance
      - A_x =0.8x10^{-7}m (HER)
      - A_x =1.8x10^{-7}m (LER)

IR aperture requirements

- Strategy
  - We will take the “adiabatic construction” scenario into consideration.
  - The Linac energy switch will be realized some time later after the IR reconstruction is completed.
  - This means that the both rings will have to accept the electron beam.

Strategy for lower beta

- Strategy
  A common and standard technique for squeezing the beta function further is to move the final focus quads closer to the IP.
- Basic idea
  The QCS magnets will be located closer to the IP by making the compensation solenoids overlap with them.

Interaction Region Design for SuperKEKB

(1) The crossing angle is 30 mrad (15mrad $\times$ 2). (cf. KEKB:11mrad $\times$ 2)

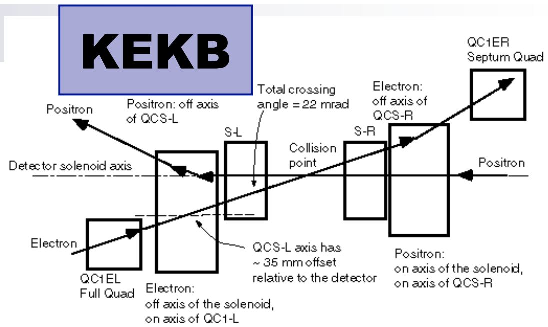
(2) $\beta_x^* = 15\sim30$ cm, $\beta_y^* = 3$ mm

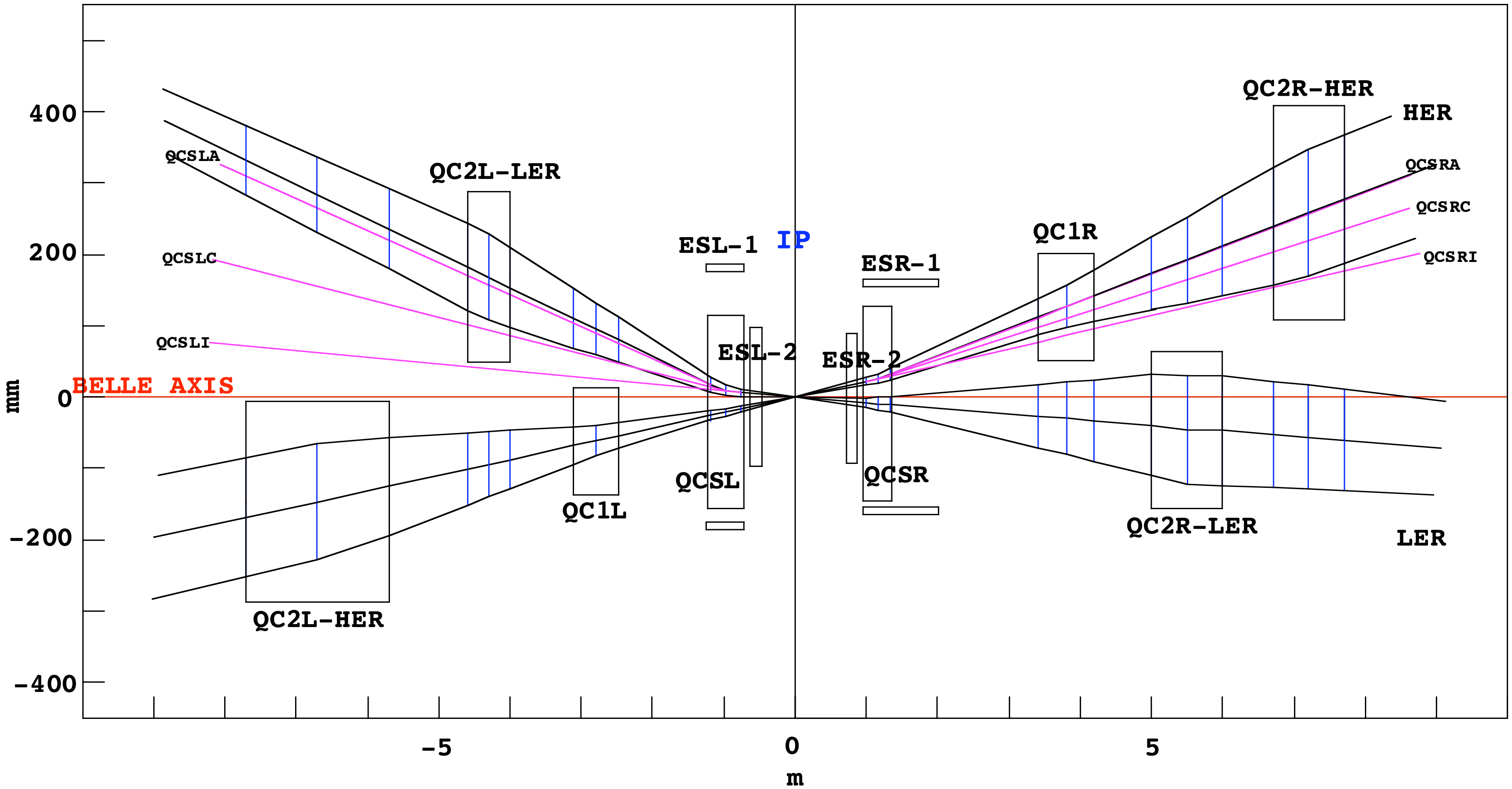
(3) Final focusing quadrupoles (QCS) are located as close to the IP as possible.
QCS magnets are overlaid with the compensation solenoids (ES).

Pos. from the IP	KEKB	Super-KEKB
QCS-R	1920 mm	1163.3 mm
QCS-L	1600 mm	969.4 mm

(4) Spatial constraints of the QCS cryostats for the Belle are the same as KEKB.

IR Magnets Configuration





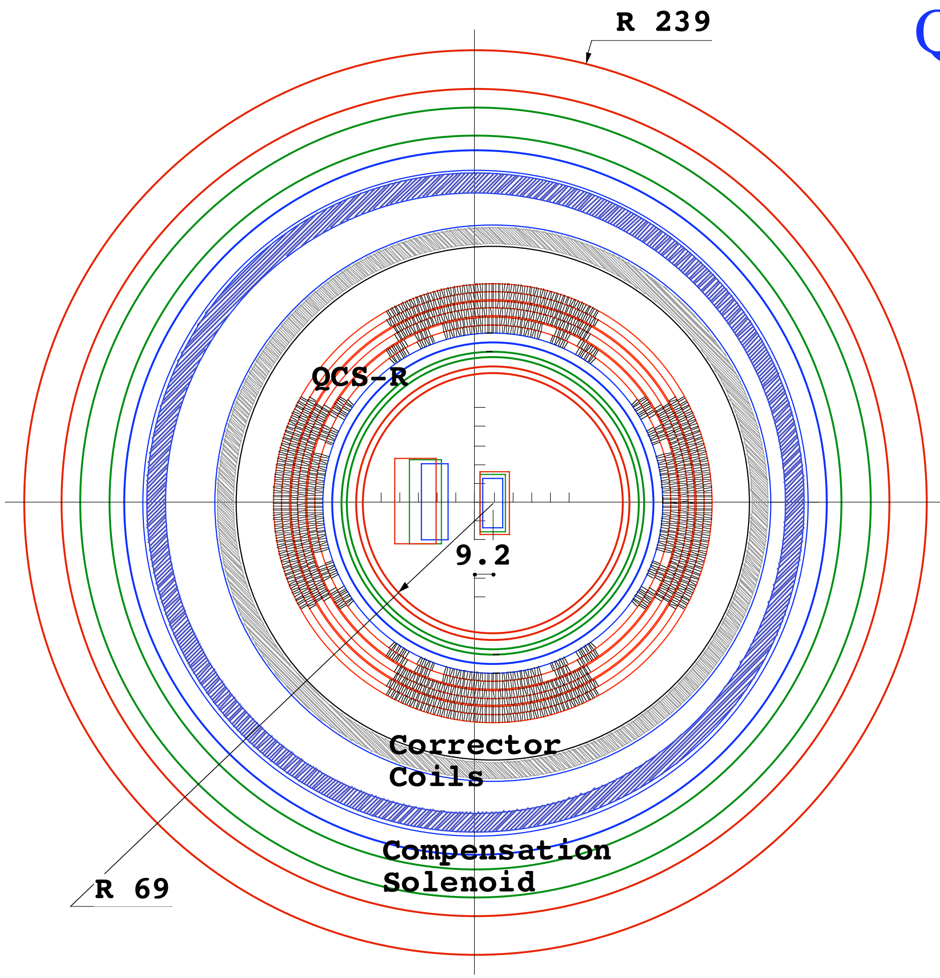
IR quadrupole magnets *G* and *L*

IR-Quad.	G, T/m	L_{eff}, m	Bore radius, mm	
QC2L-HER	3.37	2.0	100.0	Normal
QC2L-LER	5.87	0.6	60.0	Normal
QC1L-HER	15.54	0.64	36.0	Normal, Super, Permanent
QCSL	34.24	0.418	90.0	Super
3 corrector coils				Super
QCSR	36.01	0.333	90.0	Super
3 corrector coils				Super
QC1R-HER	11.28	0.64	49.0	Normal, Super, Permanent
QC2R-LER	2.77	1.0	70.0	Normal
QC2R-HER	7.03	0.6	110.0	Normal

Compensation solenoid

	B_z, T	L, m	Bore radius, mm	
ESR-1	3.0	0.15	82.0	Super
ESR-2	3.0	1.05	164.0	Super
ESL-1	5.0	0.175	77.0	Super
ESL-2	2.66	0.52	185.0	Super

QCS and Compensation Solenoid



QCS in the right side

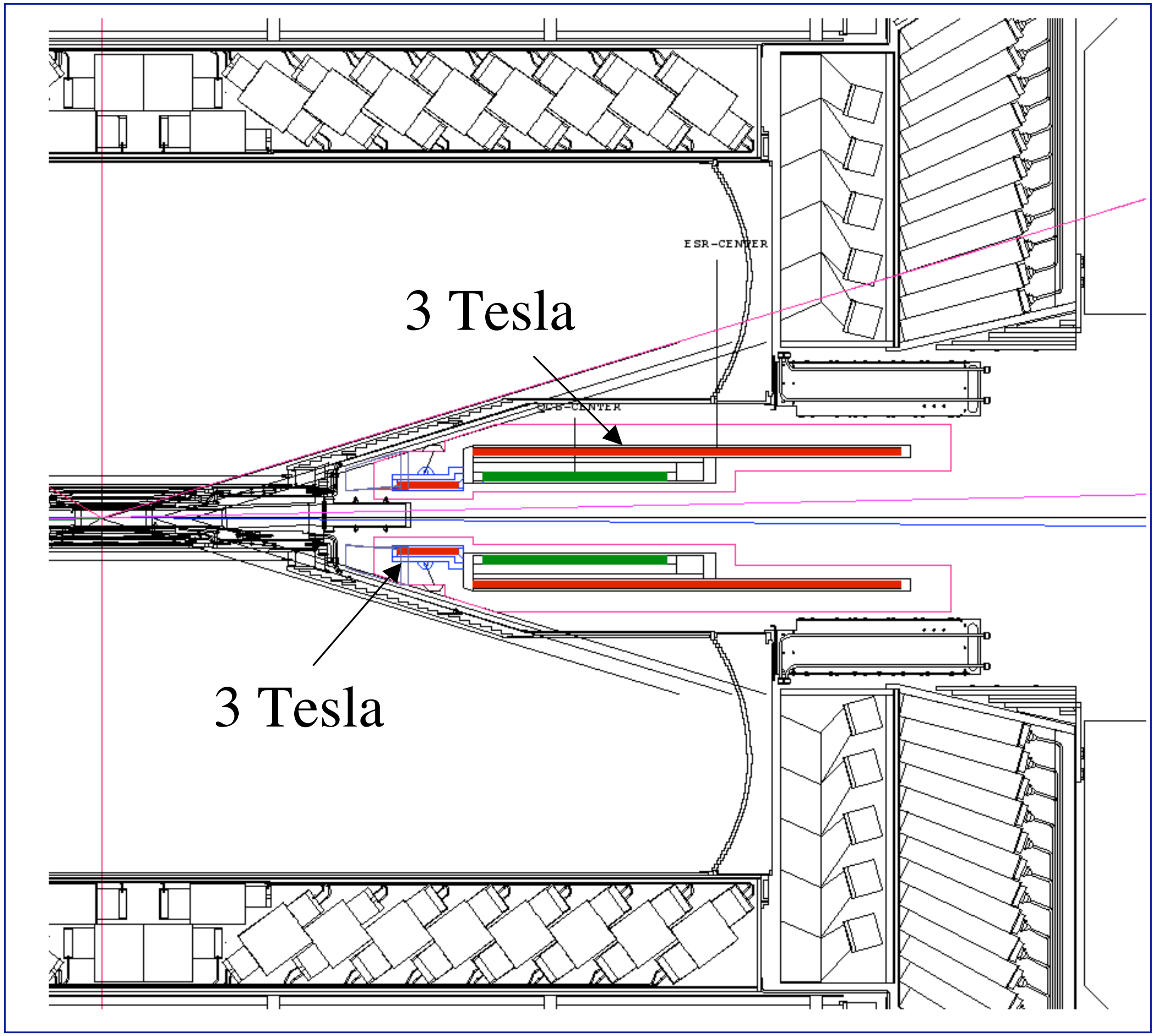
QCS

1. The QCSR center is shifted by 9.2 mm from the Belle axis. For the QCSL, this shift is 21.2mm.
2. 6 layer coils (3-double pane cake coils)
3. Cable size : 1.09mm(W), 4.08mm (H)
4. Field Gradient = 41 T/m @1291A
5. $I_{op}/I_c = 73$ %
6. Field quality (@ r=55mm)
   b_2=10000, b_6=0.16, b_{10}=0.61, b_{14}=0.43

Compensation Solenoid

1. Max. field in the coil with Belle field
   3.27 T for ESL-1 @ I_{op} = 615A
   $I_{op}/I_c = 50$ %
2. Max. field without Belle field
   4.77 T
   $I_{op}/I_c = 67$ %

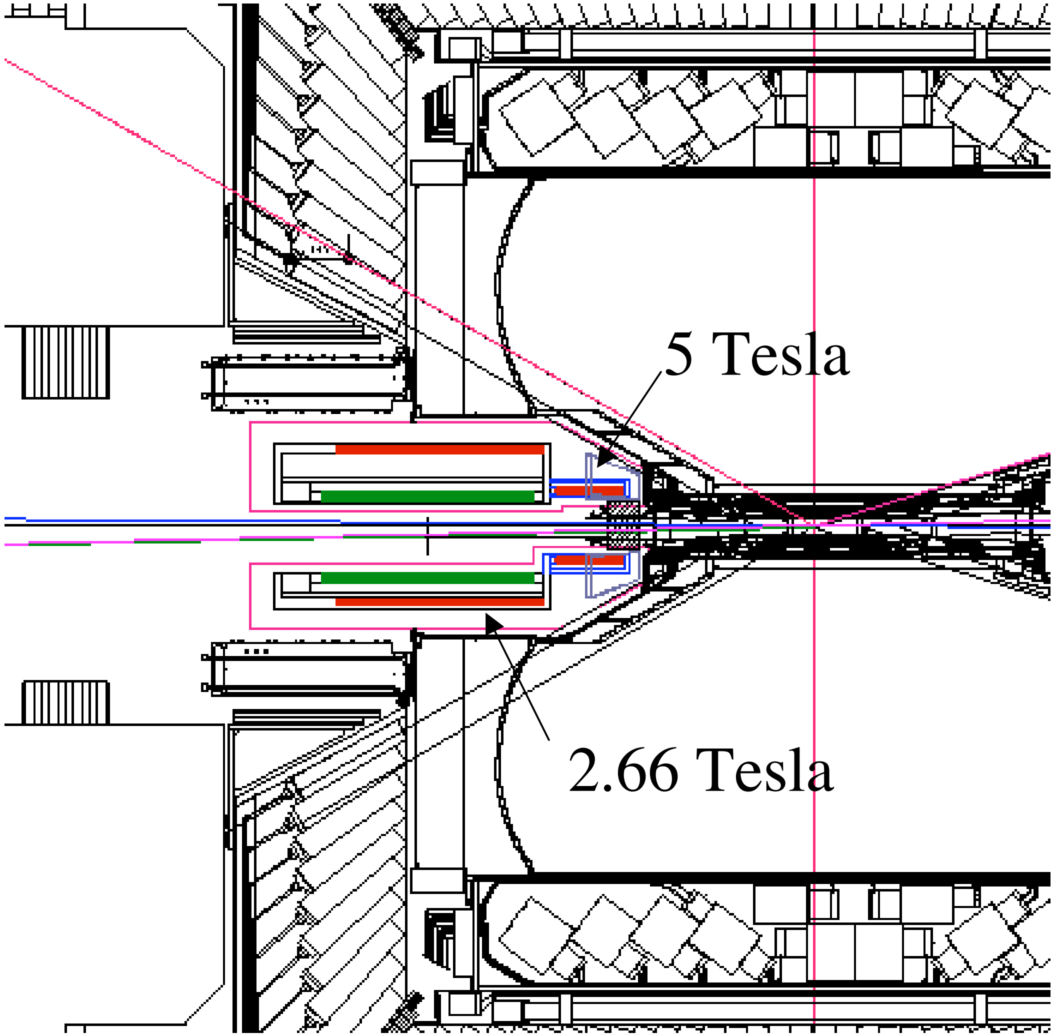
QCS magnets and cryostat for the right side



Electro-magnetic force
4.2×10^{4}N —> 2.2×10^{4}N
(0.7×10^{4}N for KEKB)

Heat load from support system
3.4 W(KEKB) —> 3.5 W

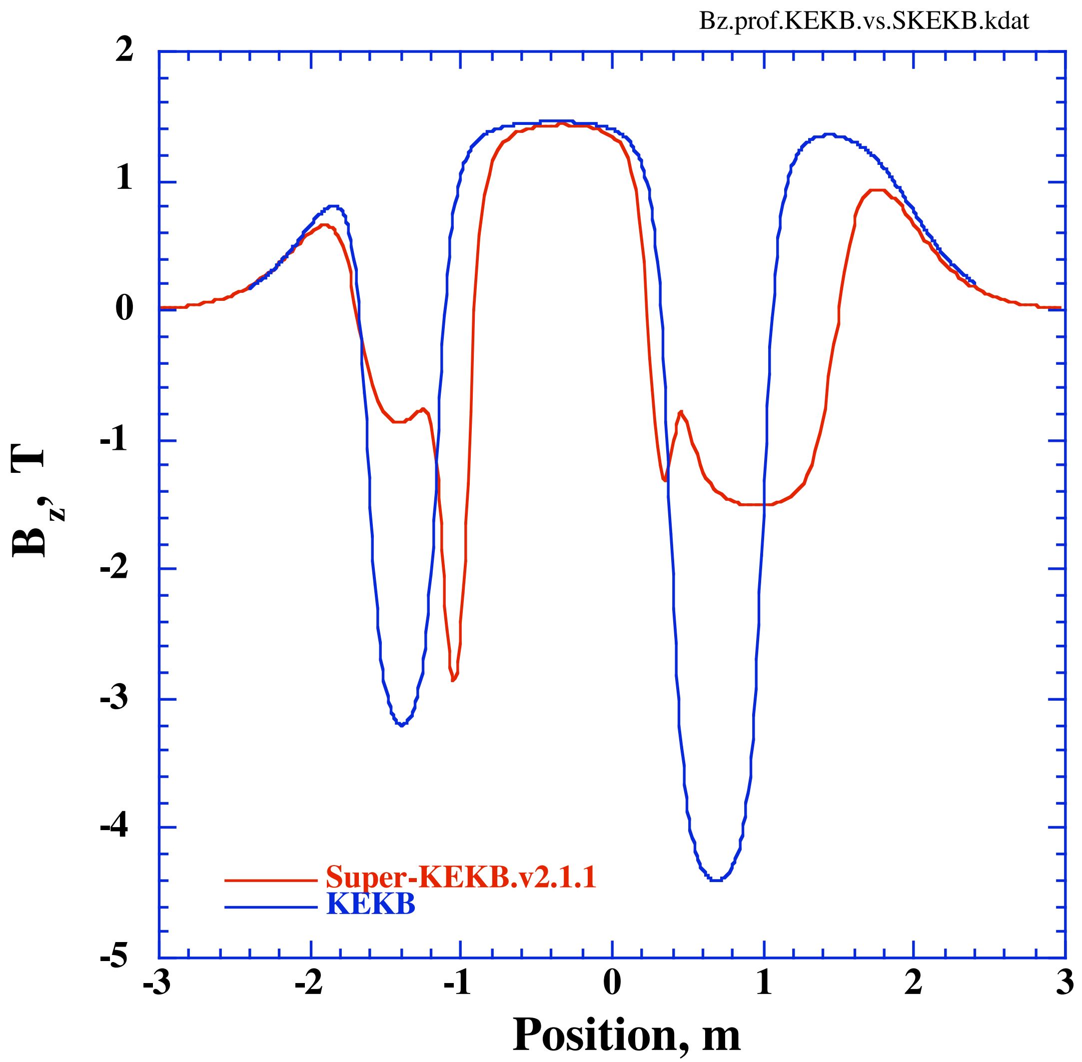
QCS magnets and cryostat for the left side



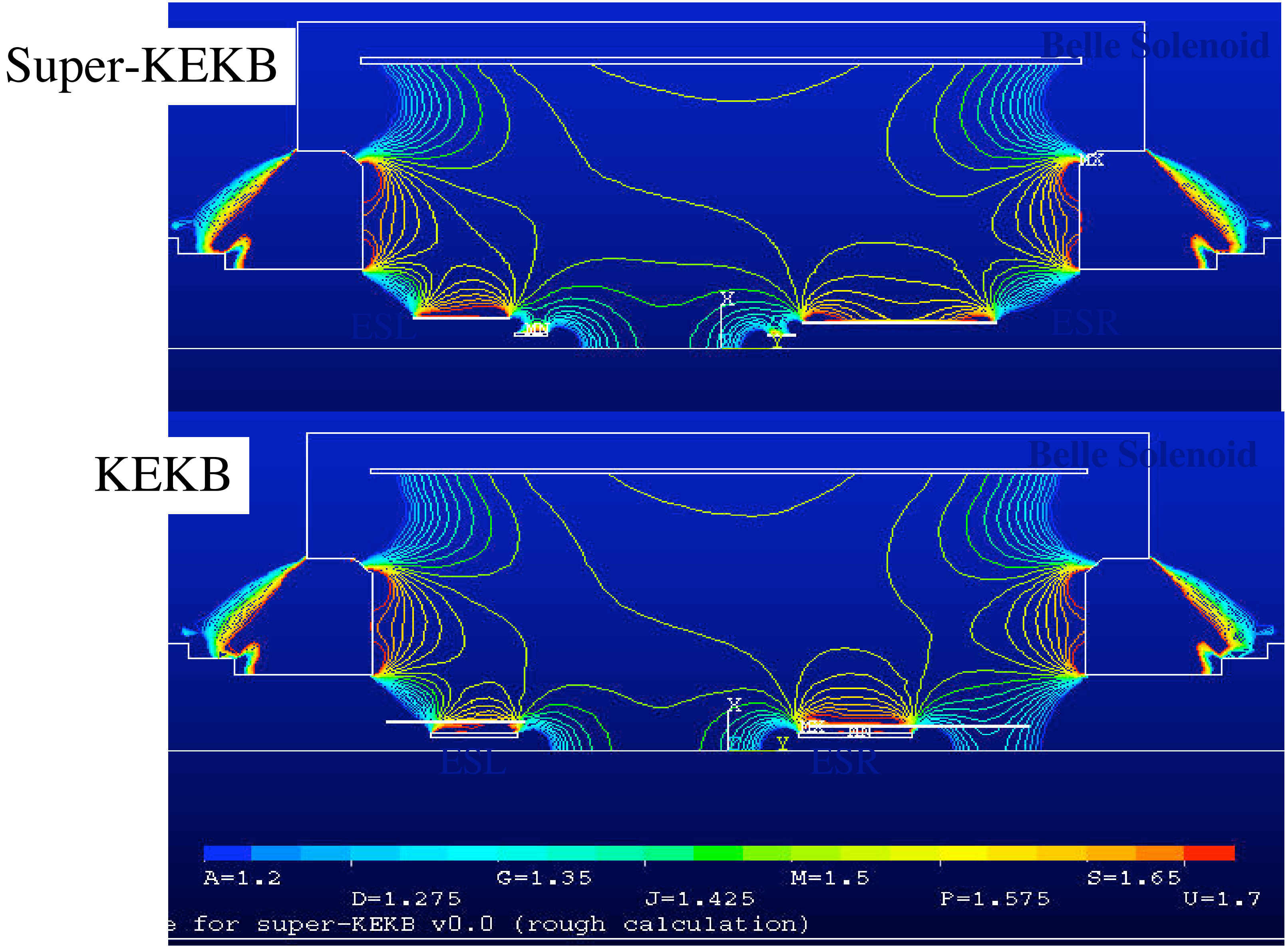
Electro-magnetic force
13.5×10^4N —> 4.8×10^4N
(2.4×10^4N for KEKB)

Heat load from support system
3.2W(KEKB) —> 4.5W

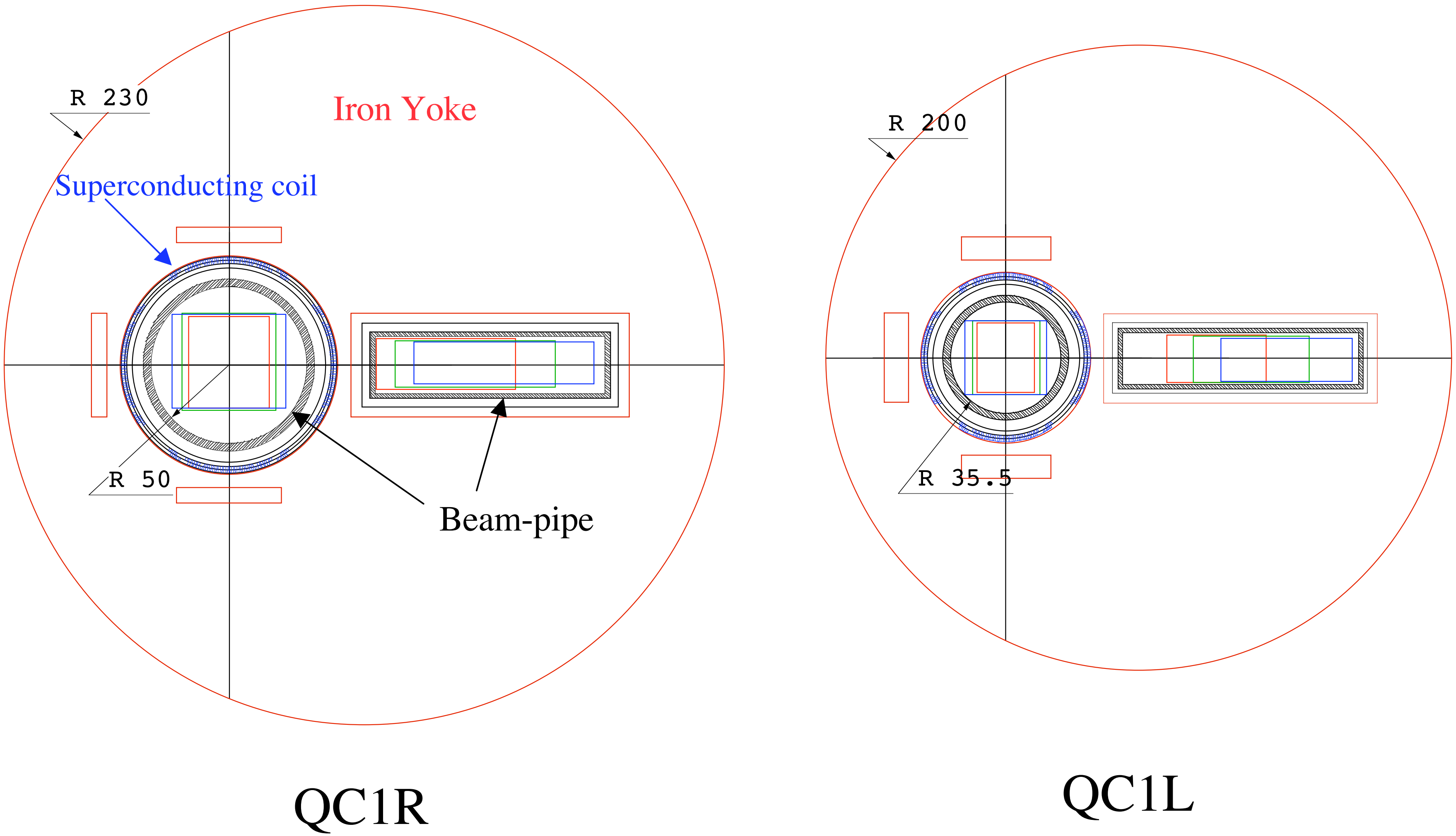
B_z profile along the Belle axis



Belle field profile

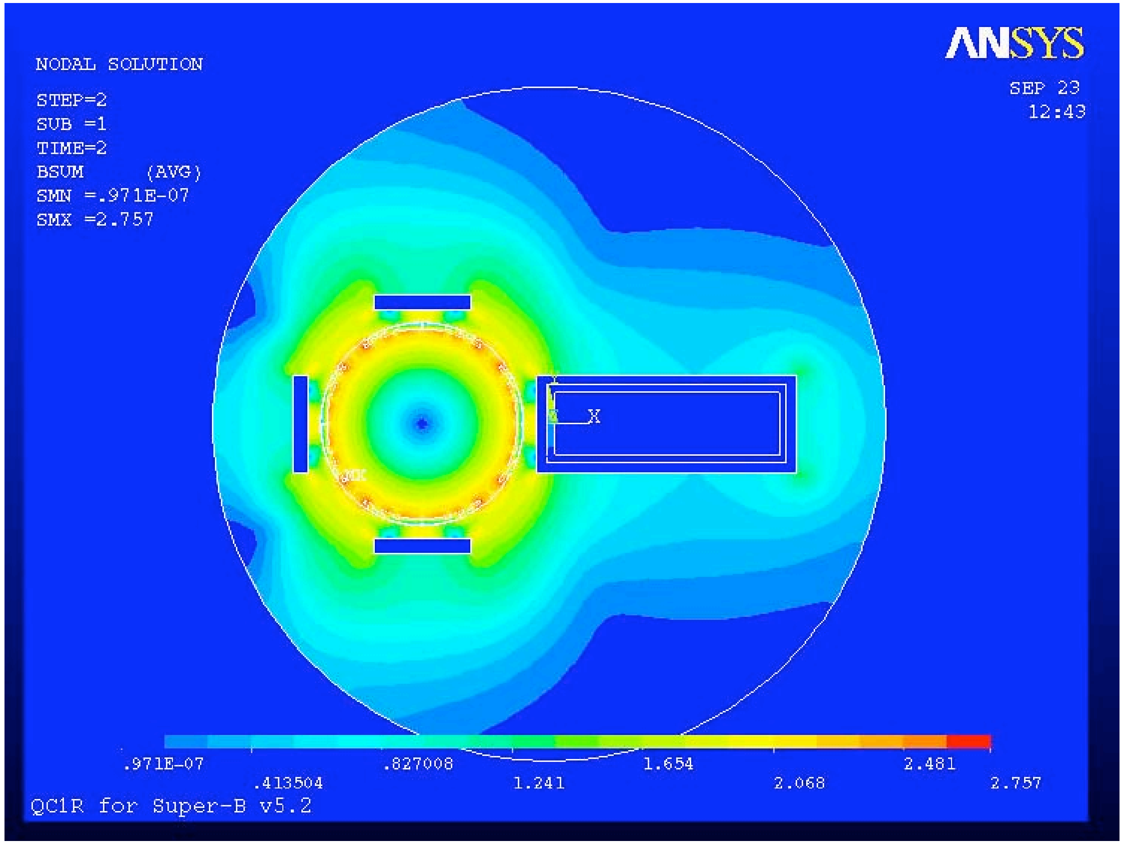


QC1 (superconducting magnet)



QC1R field calculation

Field profile in the magnet



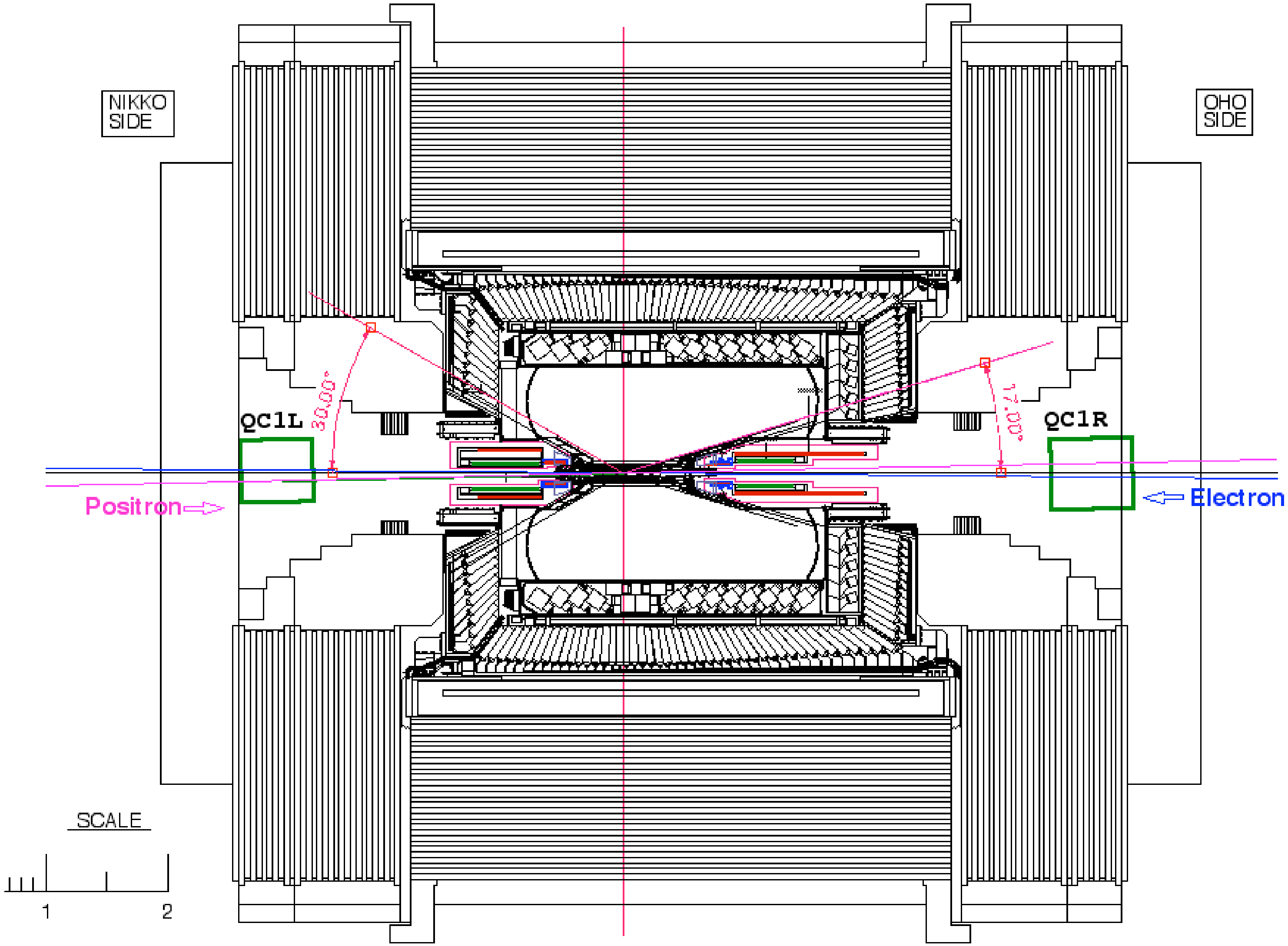
Conductor current=1319A
Max. field in the magnet=2.757 T
Field gradient=35.9 T/m
Effective Magnetic Length=0.2m
Leak field on LER beam<2 Gauss
Error field:

n	a_n	b_n
1	-0.047	-0.834
2	-0.042	10000.0
3	-0.050	-0.260
4	-0.036	0.040
5	-0.004	-0.113
6	0.076	0.081
7	0.000	-0.074
8	0.005	0.003
9	-0.000	-0.050
10	0.153	-1.581
14	0.014	-5.171
18	-0.093	-3.591

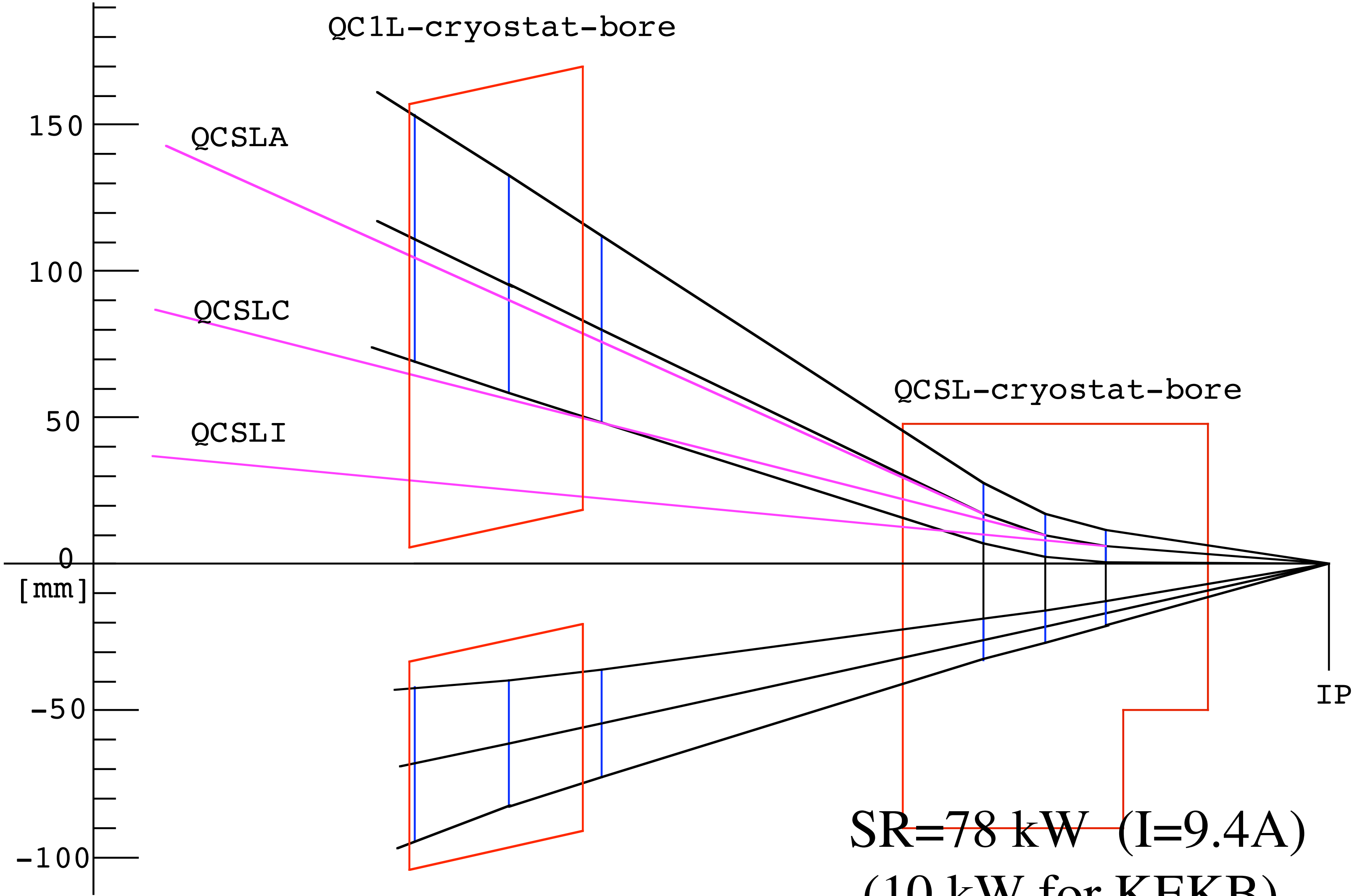
Critical energy of SOR from QCS’

	QCSR	QCSL
Distance from IP to magnet center [mm]	1163.3	969.4
□x [mm]	34.5	29.1
G [T/m]	37.2	35.4
E_b [GeV]	8.0	3.5
u_c [keV]	54.7	8.40

QC1 cryostat and Belle yoke

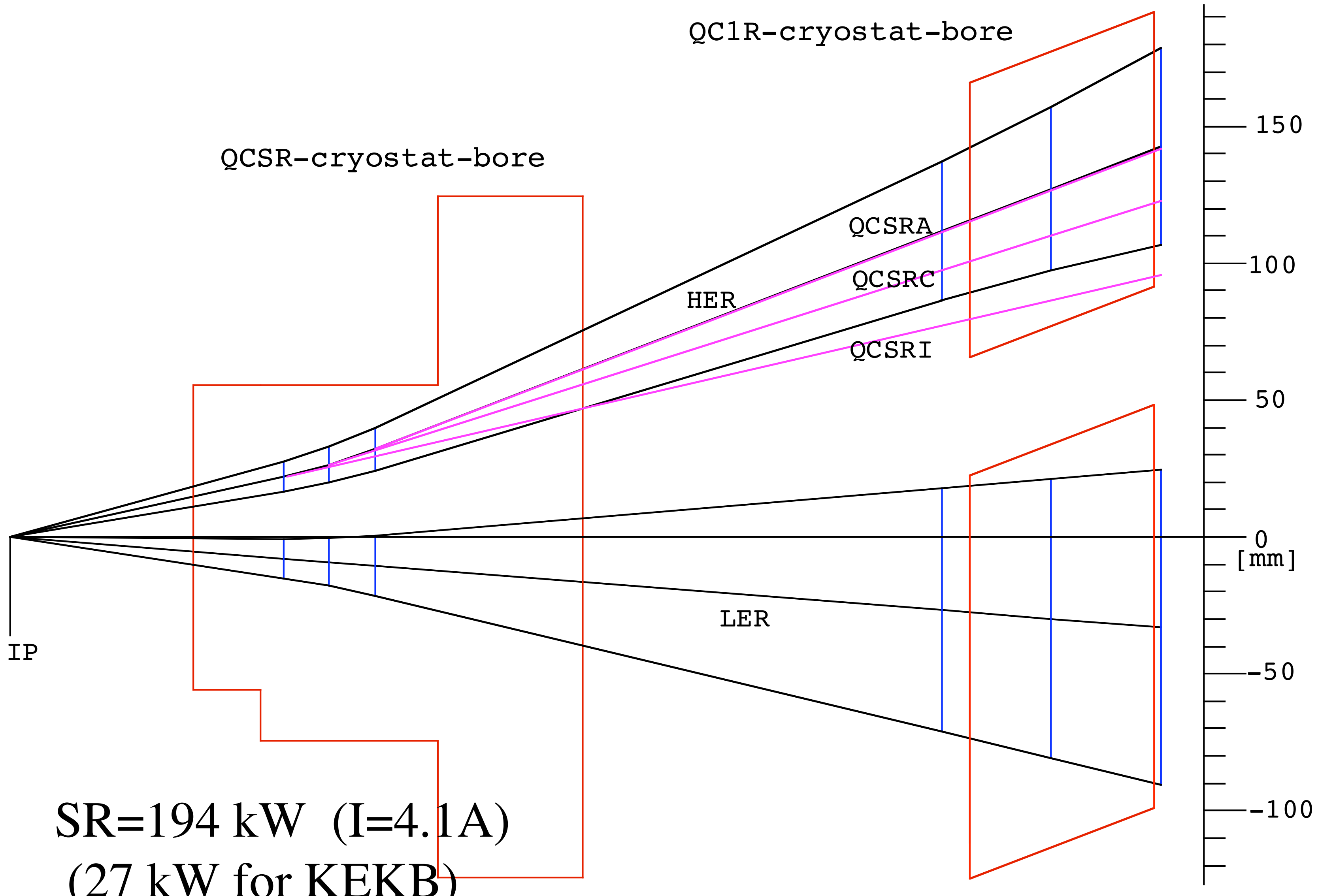


SR from QCSL in the QCSL & QC1L bores



SR=78 kW (I=9.4A)
(10 kW for KEKB)

SR from QCSR in the QCSR & QC1R bores



SR=194 kW (I=4.1A)
(27 kW for KEKB)

Synchrotron light from QCS

- Issue
  - **Synchrotron lights from QCSL and QCSR may hit QC1 magnets.**
- Necessary estimation
  - **Path of the synchrotron lights from particles on the nominal orbits (-> Ohuchi)**
  - **Effects of COD**
  - **Effects of beam size**
    - Consider 3 σ beam size

Effects of COD

- Sources of COD
  - **Drifts of orbits**
    - Heating of IR magnets
    - Other sources
  - **Artificial bumps**
    - Machine study
    - Other tunings
      - **Heating of IR components**
  - **iBump tuning**
    - Mainly offset at IP
- Method of COD estimation
  - **IP horizontal angle -> check of KBLog**
  - **IP horizontal offset -> check of KBLog**

COD estimation

- Angle at IP
  - ± 0.5mrad(KBLog) -> ± 0.41mrad (KEKB) (β_x^* = 59cm) (with a correction based on SAD calculations on effects of QCS magnets)
  - ± 0.82 mrad (SuperKEKB) (β_x^* = 15cm) (normalized by a square root of a gamma factor at IP)
- Offset at IP
  - ± 1mm(KEKB) -> ± 0.73mm (KEKB)
  - ± 0.37mm (SuperKEKB)

Effects of beam size

- Methods of estimation
  - **Consider 3 □$_x$**
  - **Effects of phase space**
    - A particle distribution in the phase space at the source point transformed with a transfer matrix of a drift space gives a distribution of synchrotron light.
  - **Effects of dynamic-□ and dynamic-emittance**

Summary (without dynamic effects)

Source point	QCSRE(IP side) HER	QCSRE(Arc side) HER	QCSLE(IP side) LER	QCSLE(Arc side) LER
□$_x$[nm]	24			
Distance from a source point [m]	3.20	2.87	2.12	1.79
□x[mm] COD	4.0	5.6	2.9	6.0
□x[mm] 3 □$_x$	4.5	6.0	3.3	6.0
□x[mm] Total	8.5	11.6	6.2	12.0

Dynamic □ and emittance

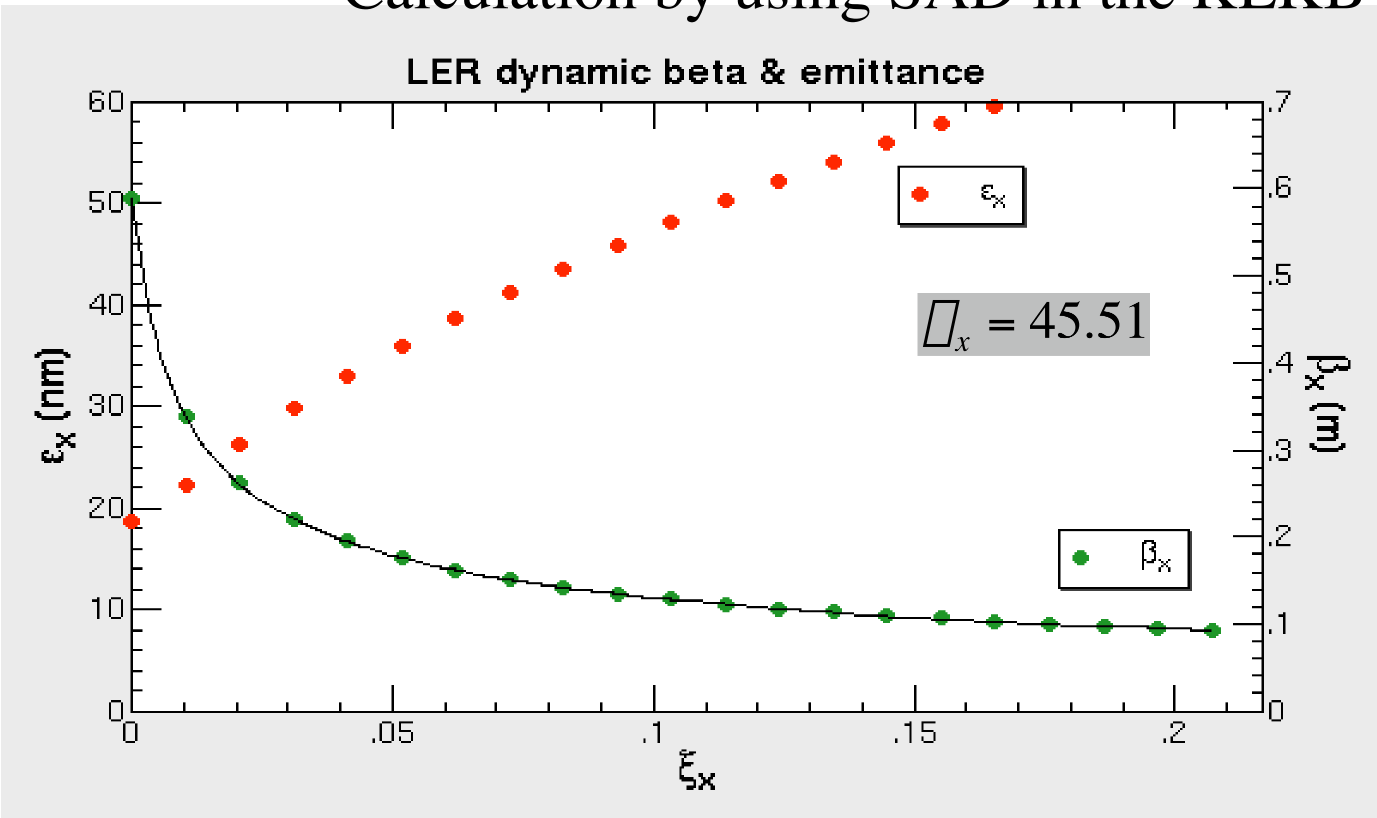
- Large effects in the horizontal direction
  - **H tune is very close to the half-integer.**
  - **Beta function at IP shrinks.**
  - **Emittance becomes large.**
- KEKB case
  - **Calculation by using SAD.**
- SuperKEKB case
  - **The above calculation for KEKB is applicable.**
    - Both of $\square_x^*/\square_{x0}^*$ and $\square_x/\square_{x0}$ are functions of the horizontal tune and $\square_{x0}$.
    - With $\square_{x0}$=0.1, $\square_x^*$ is around 1/5 of a nominal value and $\square_x$ is twice as large as a nominal value.

Dynamic and emittance [cont'd]

- Effects on SOR from QCS magnets.
  - **Calculation is on the way.**
  - **The angular divergence get very large with the dynamic effects at QCS magnets.**
  - **The beam size at QCS magnets also get large.**
  - **The horizontal size of synchrotron light at QC1 magnets gets (more than) three times larger than that without the dynamic effects.**

Dynamic and emittance [cont'd]

Calculation by using SAD in the KEKB case

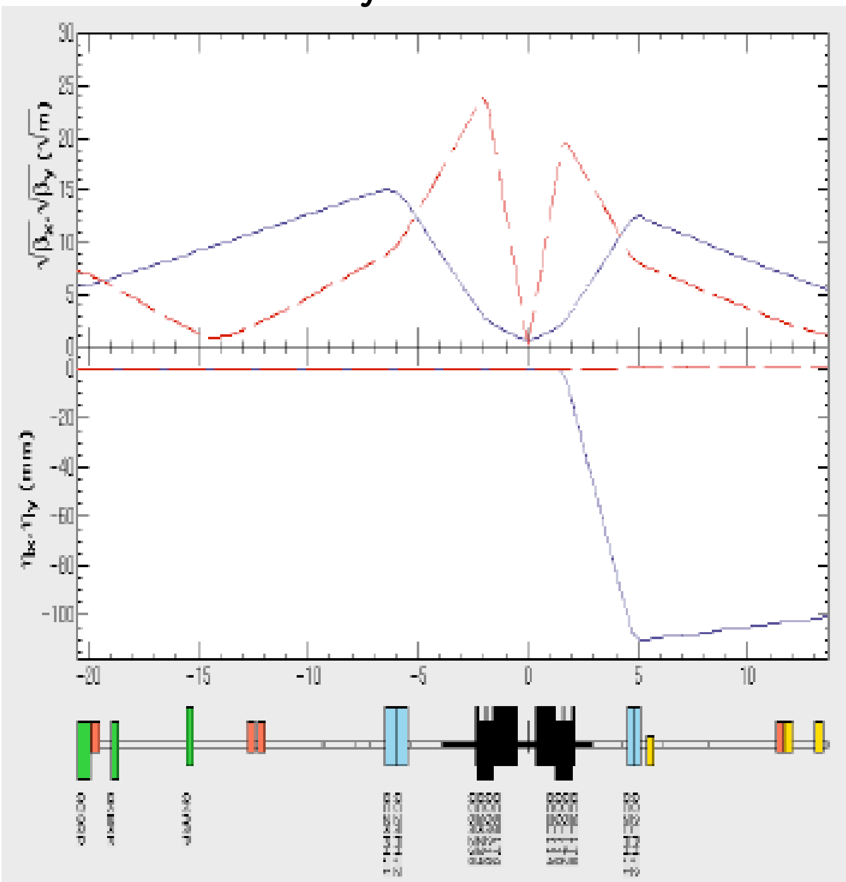


Machine Parameters of the KEKB (May 13 2003)

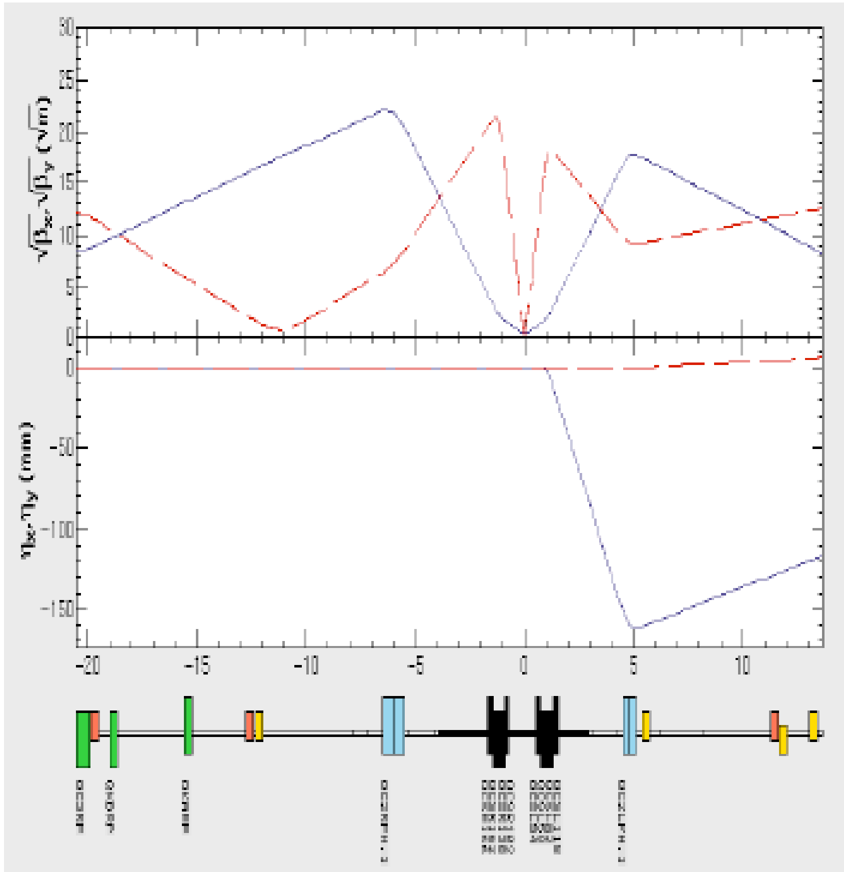
	LER	HER	
Horizontal Emittance	18	24	nm
Beam current	1377	1050	mA
Number of bunches	1284		
Bunch current	1.07	0.818	mA
Bunch spacing	2.4		m
Bunch trains	1		
Total RF volatage Vc	8.0	13.0	MV
Synchrotron tune ν_s	-0.0249	-0.0207	
Betatron tune ν_x / ν_y	45.507/43.546	44.512/41.580	
beta's at IP β_x^* / β_y^*	59/0.58	58/0.7	cm
Estimated vertical beam size at IP σ_y^*	2.2	2.2	μm
beam-beam parameters ξ_x / ξ_y	0.096/0.069	0.065/0.052	
Beam lifetime	127@1377	256@ 1050	min.@mA
Luminosity (Belle CsI)	10.567		10^{33}/cm^2/sec
Luminosity records per day / 7days/ month	579/3876/12760		/pb

LER IR Lattice

KEKB (β_x/ β_y=59/0.62 cm)

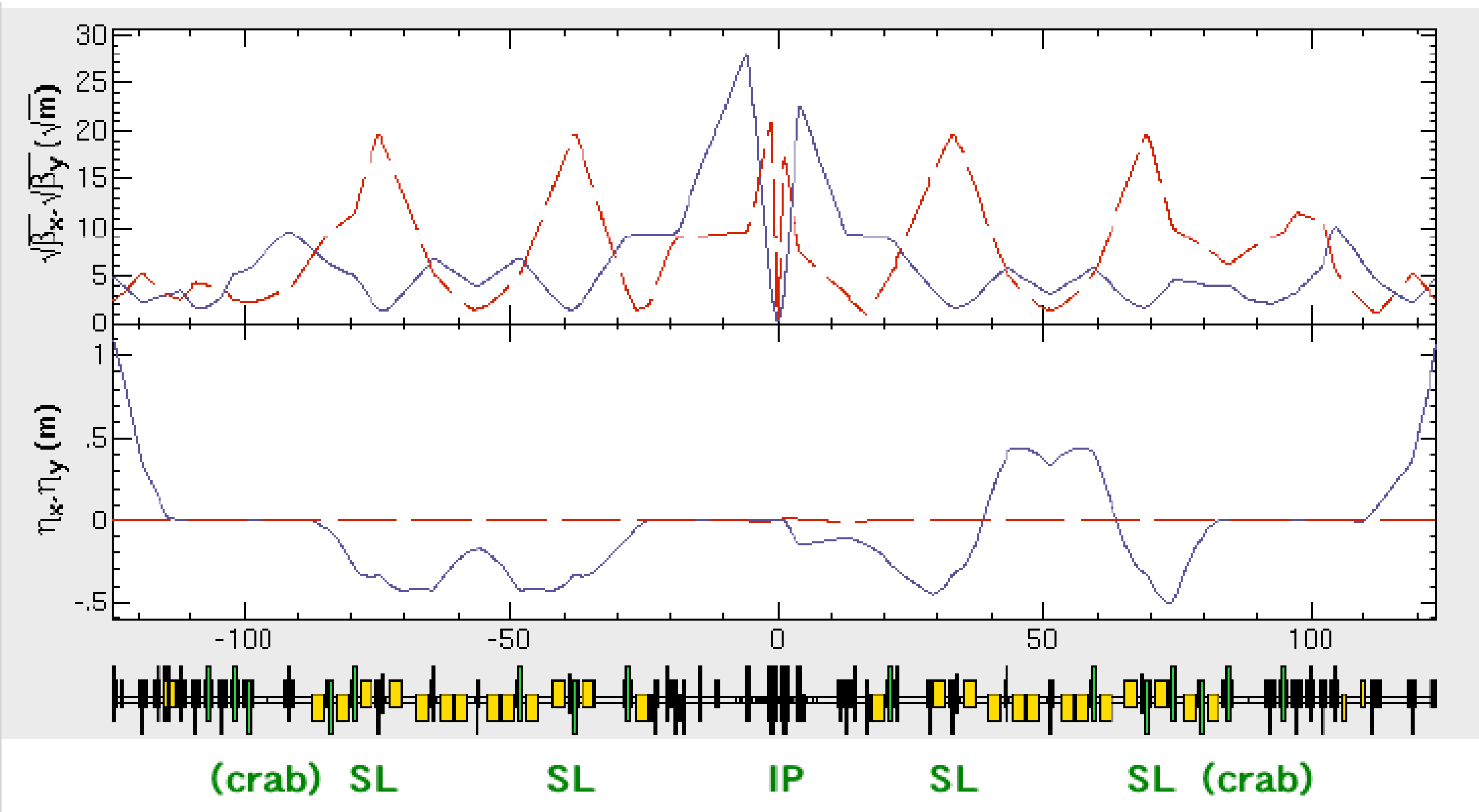


SuperKEKB (β_x/ β_y=30/0.3 cm)

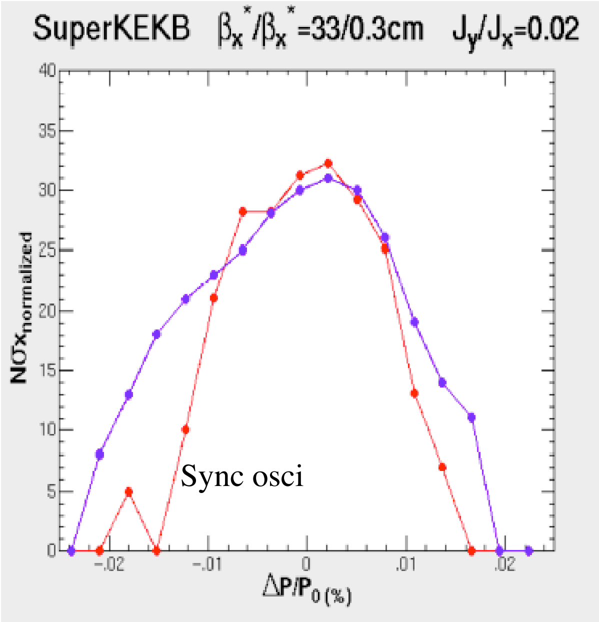


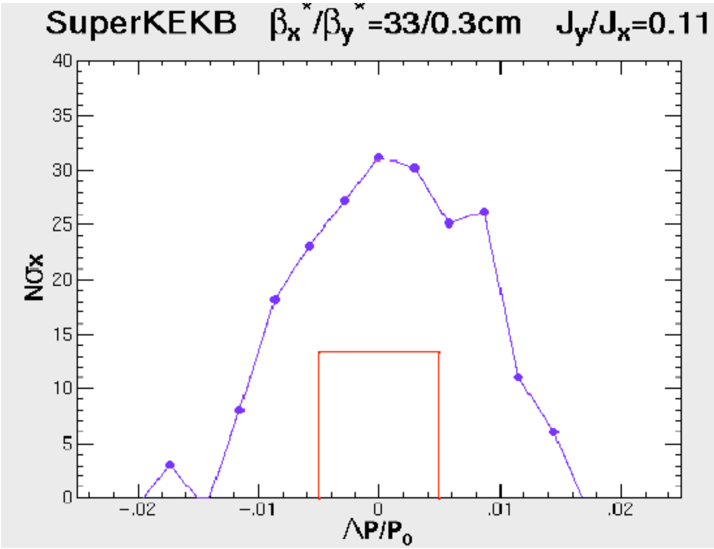
LER IR with local chromaticity correction

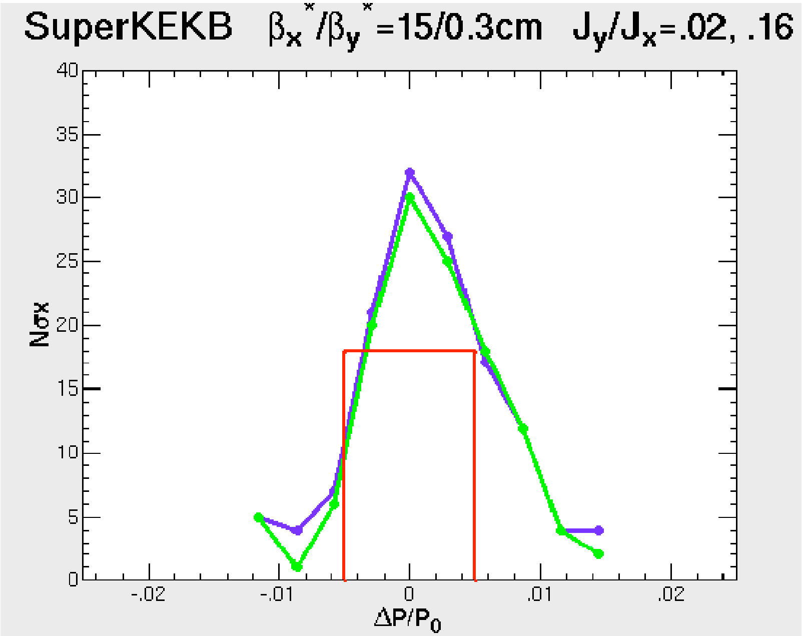
(β_x / β_y = 15/0.3 cm)

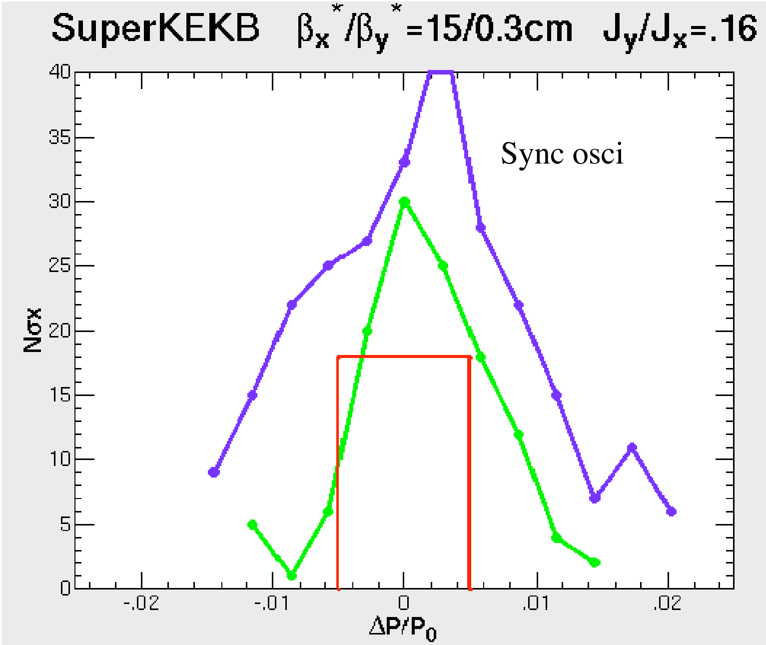


Dynamic Aperture Simulations (LER)









Status of IR Lattice Design

- **LER**
  - Chromaticity correction is difficult for particles with finite transverse and longitudinal amplitudes with $\square_x$=.510.
  - The dynamic aperture has shrunk when $\square_x$* =30->15 cm.
  - If we want to realize $\square_x$* of 15cm, we need to be improved even without multiples of IR quads, by reoptimizating both linear optics and sextupole strengths.
  - We changed design value of $\square_x$*=15cm -> 20cm very recently.
  - Optics at crab cavities have not yet been optimized.
- **HER**
  - Estimations and optimization of dynamic aperture will start, after we find a resonable solution for the LER lattice.