Effect of IR optics error on SuperKEKB

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KEK

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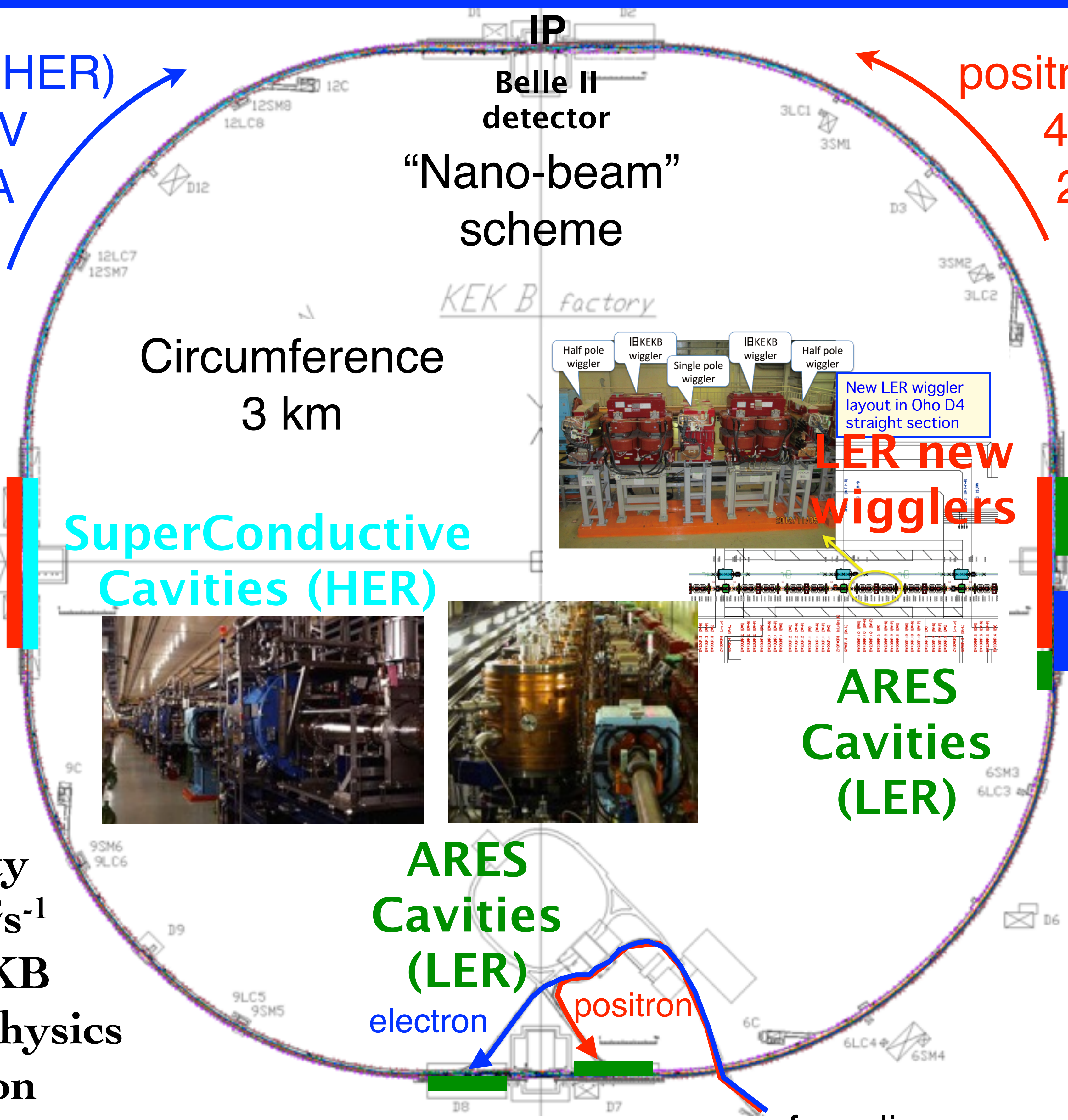
- Overview of SuperKEKB
- Optics design of the Interaction Region (IR)
- How the machine error affects the accelerator performance ?
- What is the requirement for the magnets ?
- Summary

Overview of SuperKEKB

electron (HER)
7 GeV
3.6 A

positron (LER)
4 GeV
2.6 A



LER new wigglers

ARES Cavities (HER)

HER wigglers

from linac

Luminosity
8x10^{35} cm^{-2}s^{-1}
x40 of KEKB
to study new physics
via B-meson

Luminosity formula:

$$L \propto \frac{N_+ N_-}{\sigma_z \phi_x \sqrt{\varepsilon_y \beta_y^*}}$$

~ 8 x 10^{35} $cm^{-2}s^{-1}$

Small β_y^*, small ε_y ⟶ High luminosity

$\tilde{\sigma}_x^* = \sigma_z \phi_x$ Long "bunch length" is OK.

(effective) (6 mm x 41.5 mrad)

Beam-Beam:

$$\xi_{y\pm} \propto \frac{N_\mp}{\sigma_z \phi_x} \sqrt{\frac{\beta_y^*}{\varepsilon_y}}$$

~ 0.09

To avoid too large ξ_y (dangerous), the **ratio of β_y^* to ε_y should be small.**

The hourglass condition is modified:

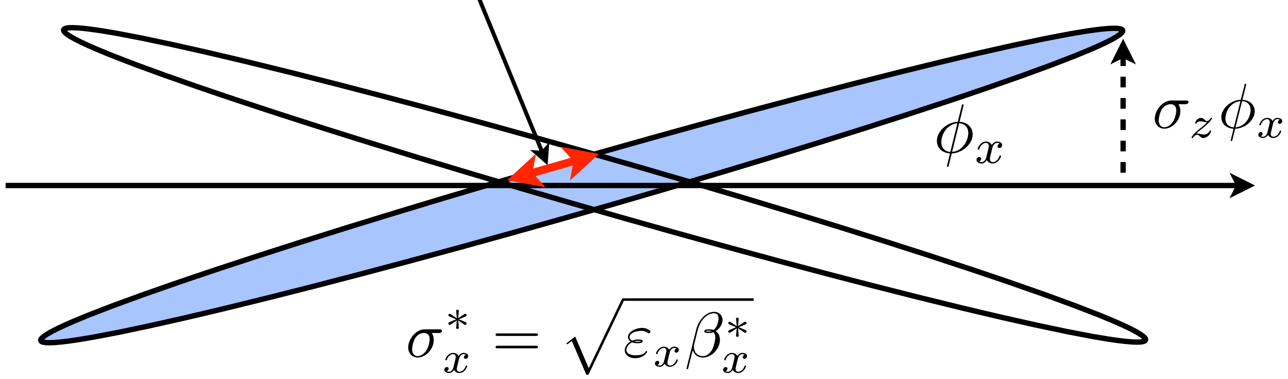
$$\beta_y^* > \tilde{\sigma}_z = \frac{\sigma_x^*}{\phi_x} \sim 250\ \mu m$$

(effective)

$$\xi_{x\pm} \propto \frac{N_\mp \beta_x^*}{(\sigma_z \phi_x)^2}$$

~ 0.003

Dynamic effects can be ignored.

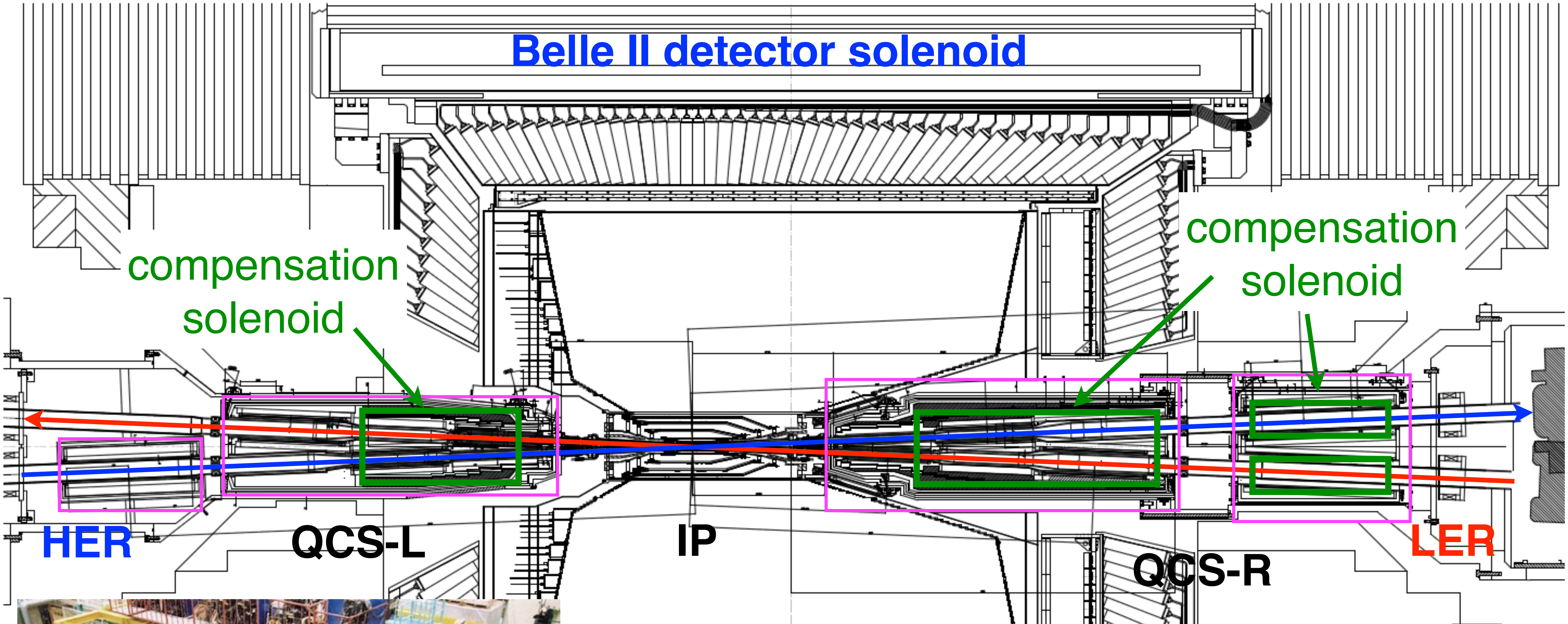


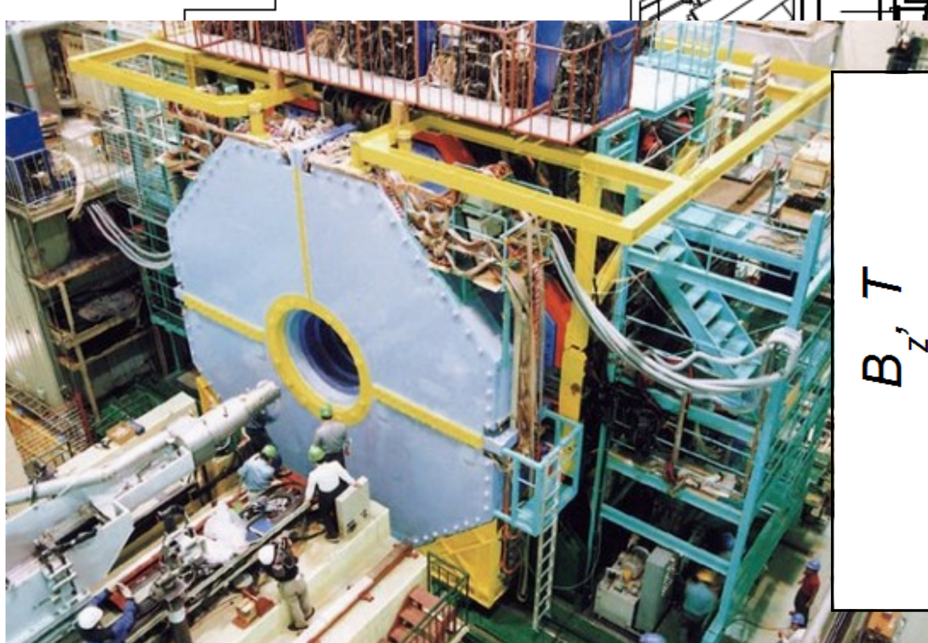
Large crossing angle and small beam size at IP in the Nano-beam scheme

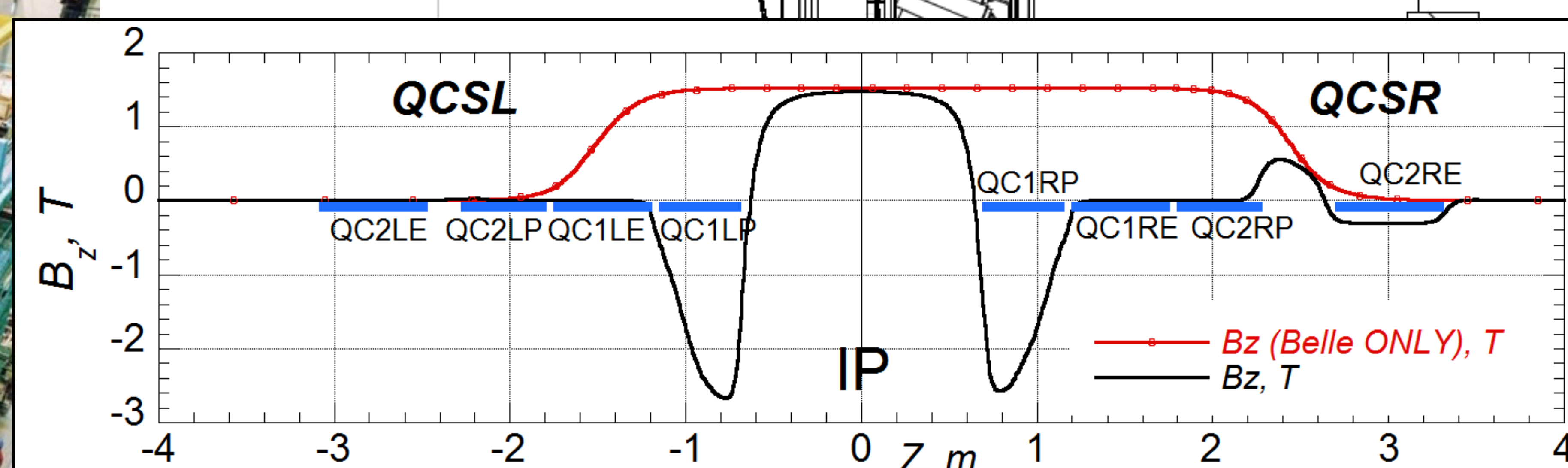
Very small vertical emittance is necessary.

	Symbol	LER	HER	Unit
Emittance	ε_x	3.2	4.6	nm
Beta at IP	β_x^*	32	25	cm
Beam size at IP	σ_x^*	10.1	10.7	µm
Emittance	ε_y	8.64	12.9	pm
Beta at IP	β_y^*	270	300	µm
Beam size at IP	σ_y^*	48	62	nm
Bunch length	σ_z	6	5	mm
Half crossing	ϕ_x	41.5		mrad

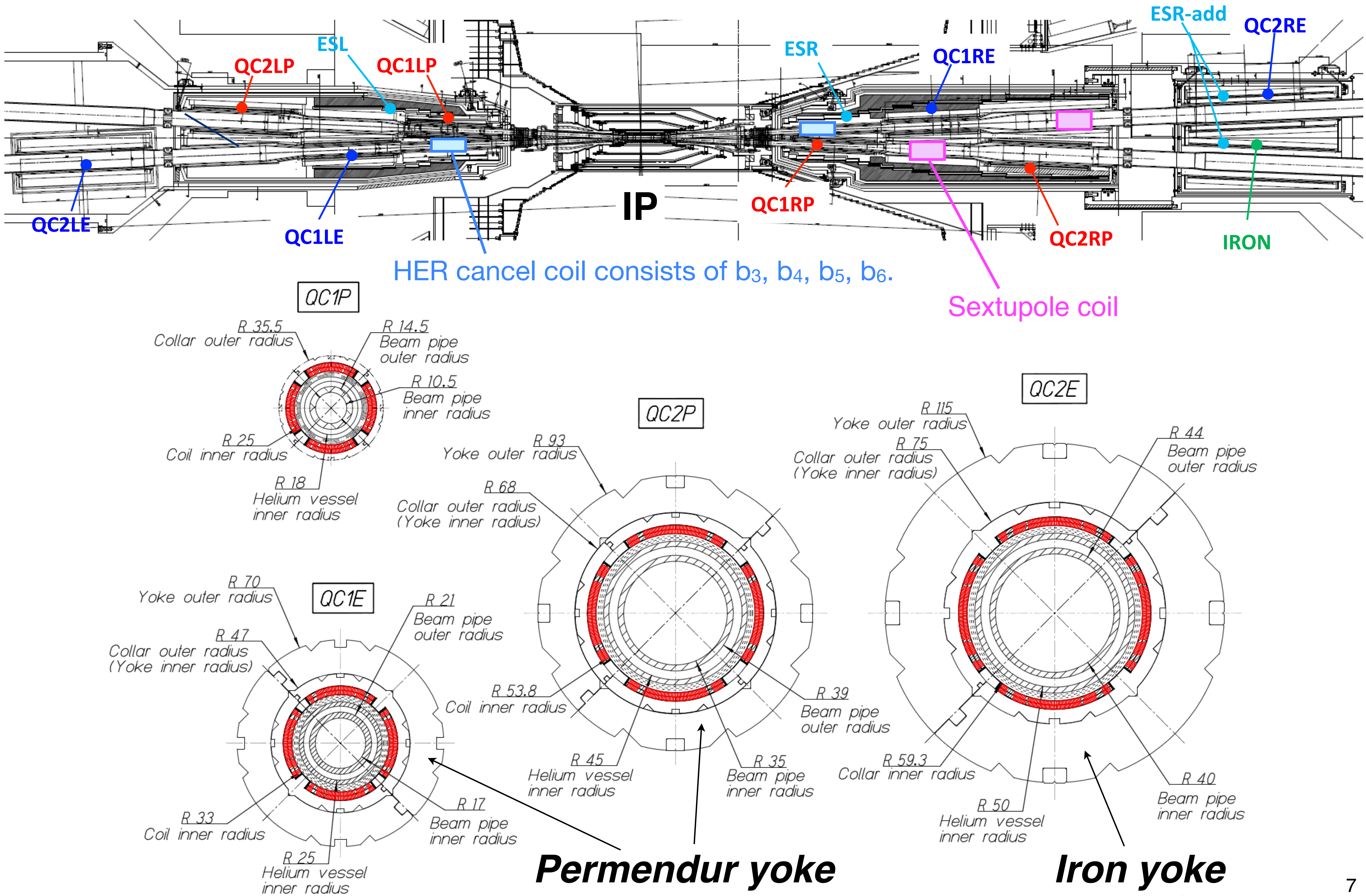
Interaction region







Final focus quadrupoles

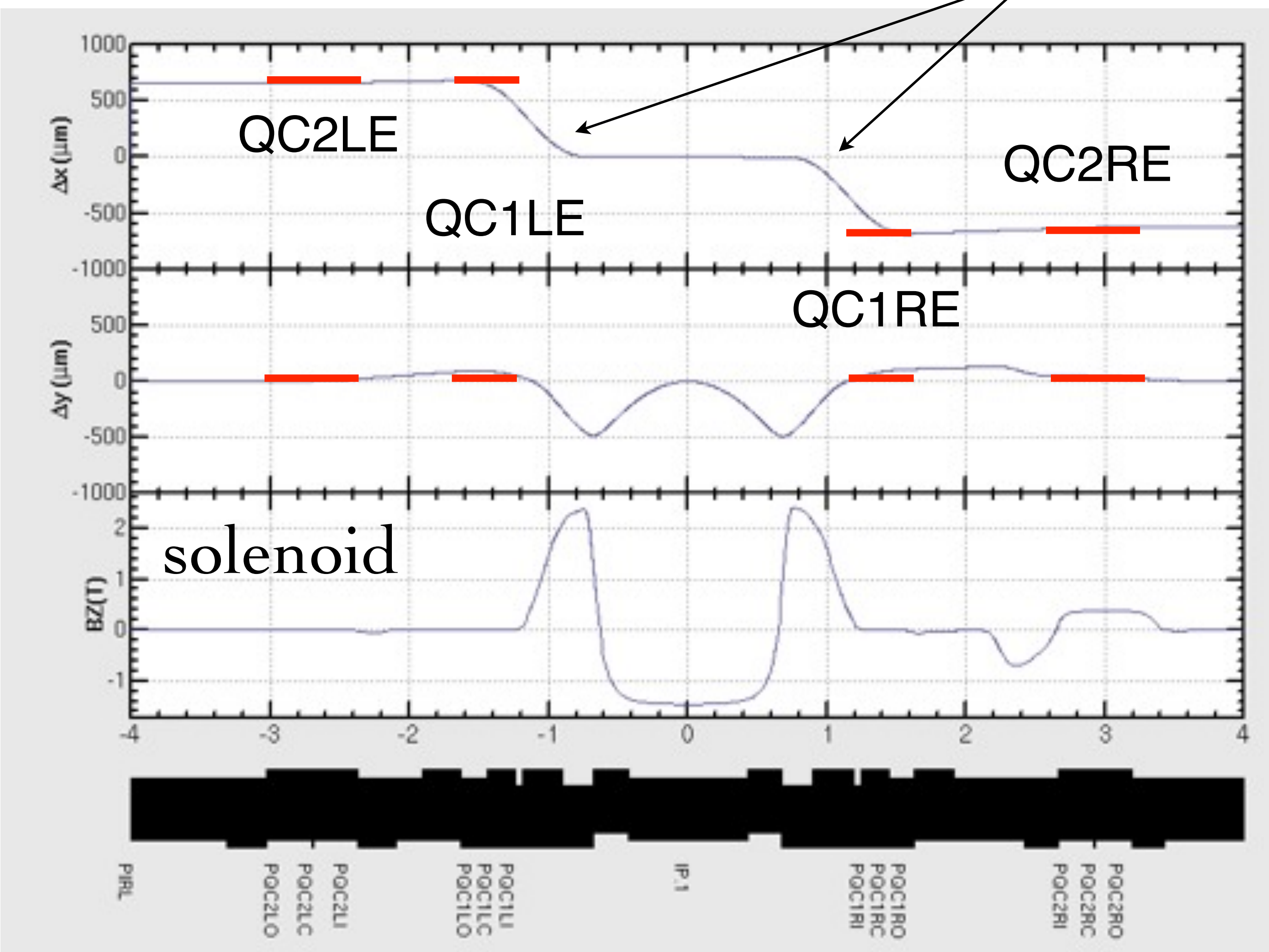


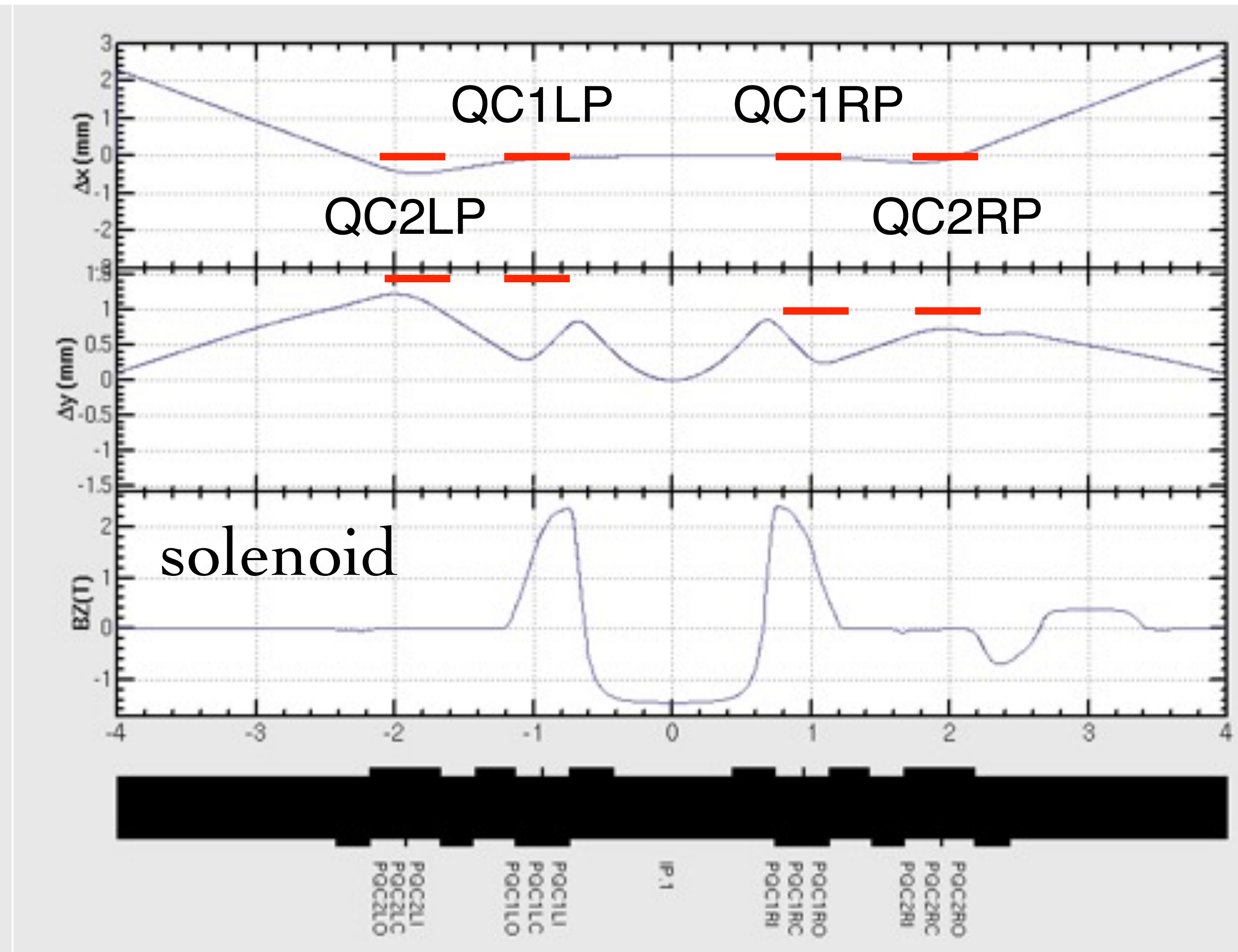
Orbit in the vicinity of IP

HER **electron** →

leakage field from QC1P(LER)

LER ← **positron**





offset/rot.	QC2LE	QC1LE	QC1RE	QC2RE
Δx (mm)	+0.7	+0.7	-0.7	-0.7
Δθ (mrad)	0	0	0	0

offset/rot.	QC2LP	QC1LP	QC1RP	QC2RP
Δy (mm)	+1.5	+1.5	+1.0	+1.0
Δθ (mrad)	-3.725	-13.65	+7.204	-2.114

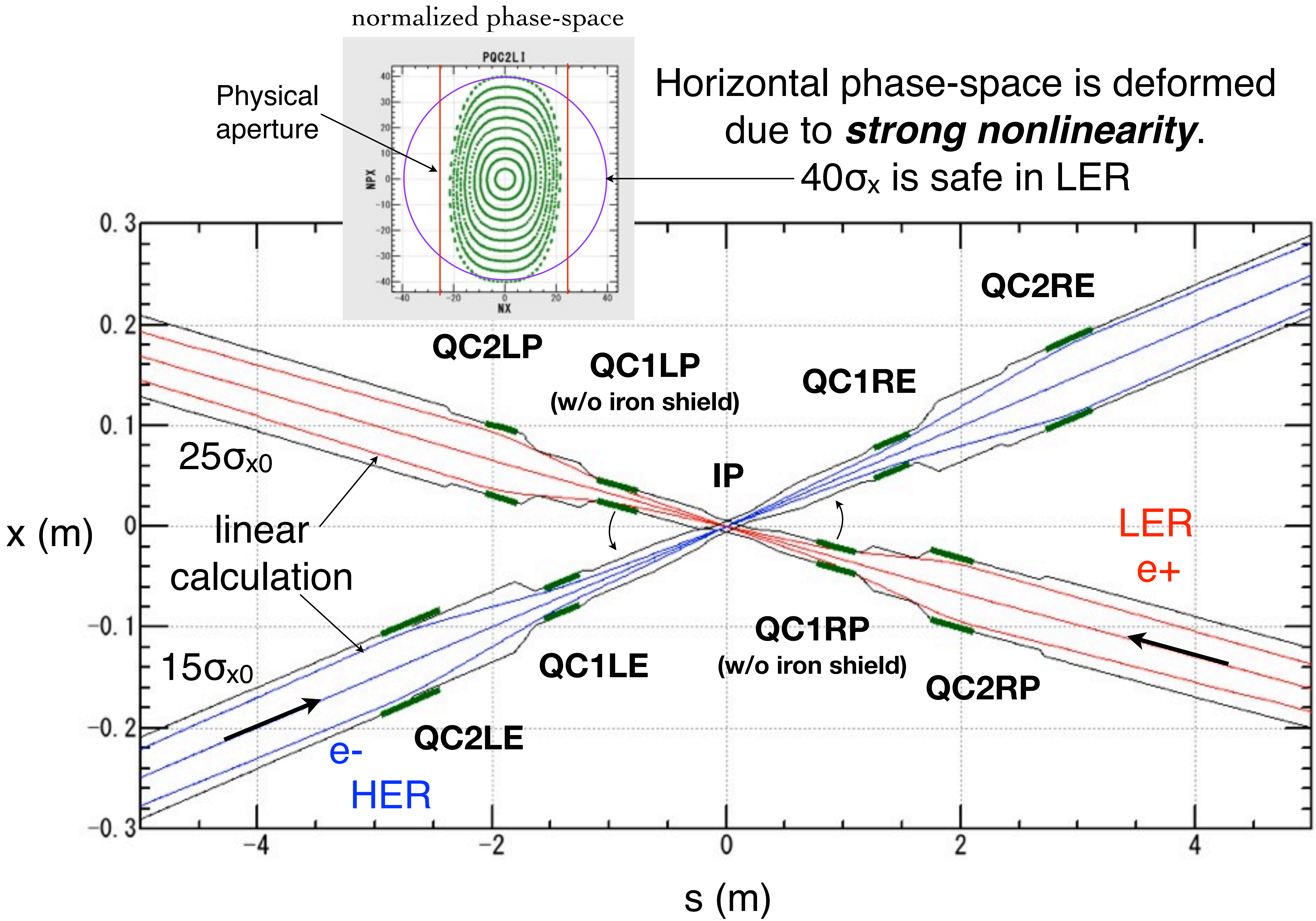
QC1/QC2 offset is adopted to control the orbit appropriately.

Slide model of 1 cm thickness is used for the optics calculation for IR.

Each slice has Maxwellian fringe and up to b_{22} and a_{22}.

Beam envelope for design parameters

Horizontal phase-space is deformed due to ***strong nonlinearity***.



IR design features

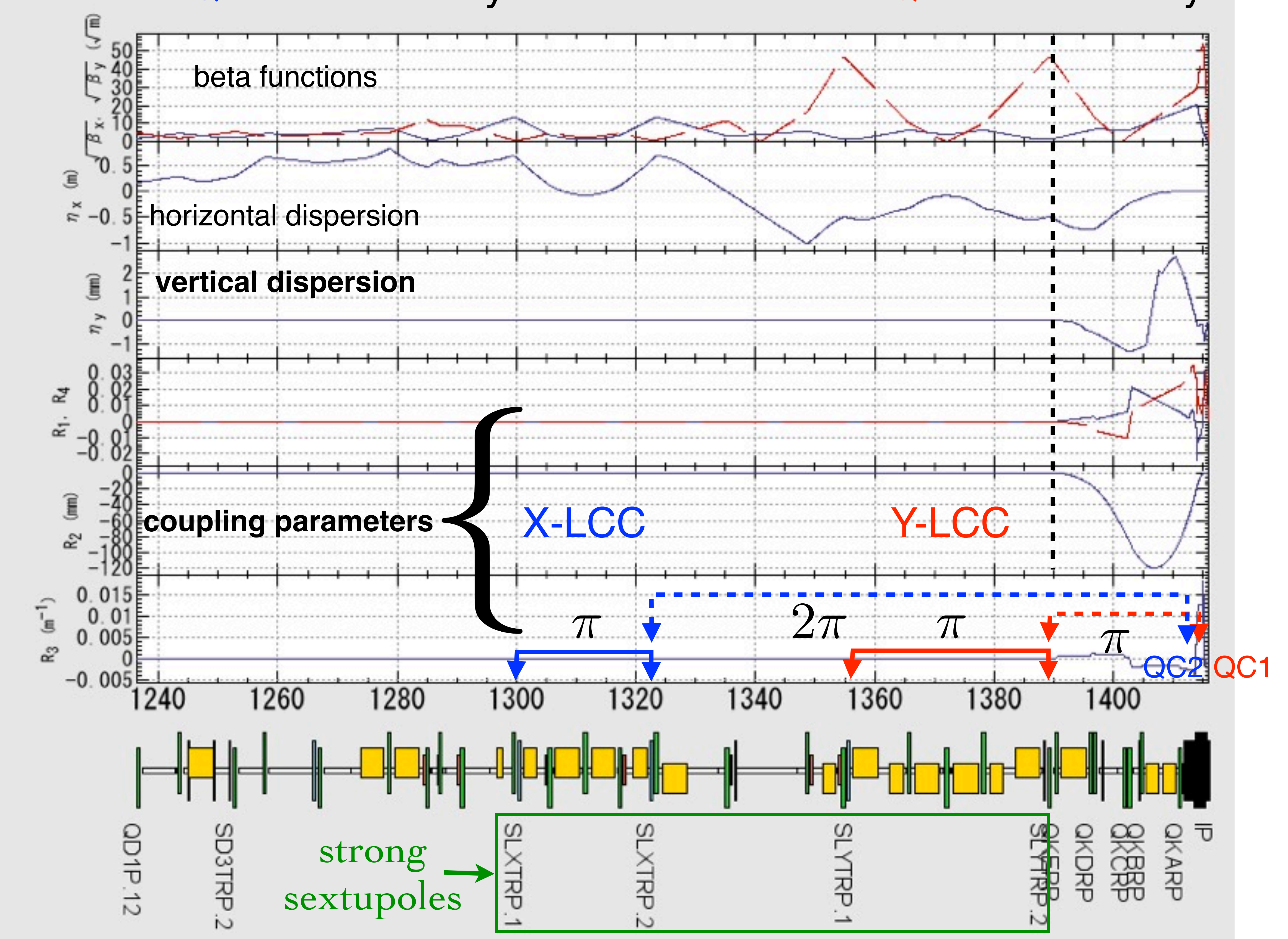
- Natural chromaticity:

	SuperKEKB		KEKB (1999~2010)	
	LER	HER	LER	HER
ξ_{x0}	**-105**	**-171**	-72	-70
ξ_{y0}	**-776**	**-1081**	-123	-124

- Approximately *80 %* of the natural chromaticity in the vertical direction is induced in the Final Focus. A "*local chromaticity correction*" is adopted to correct it.

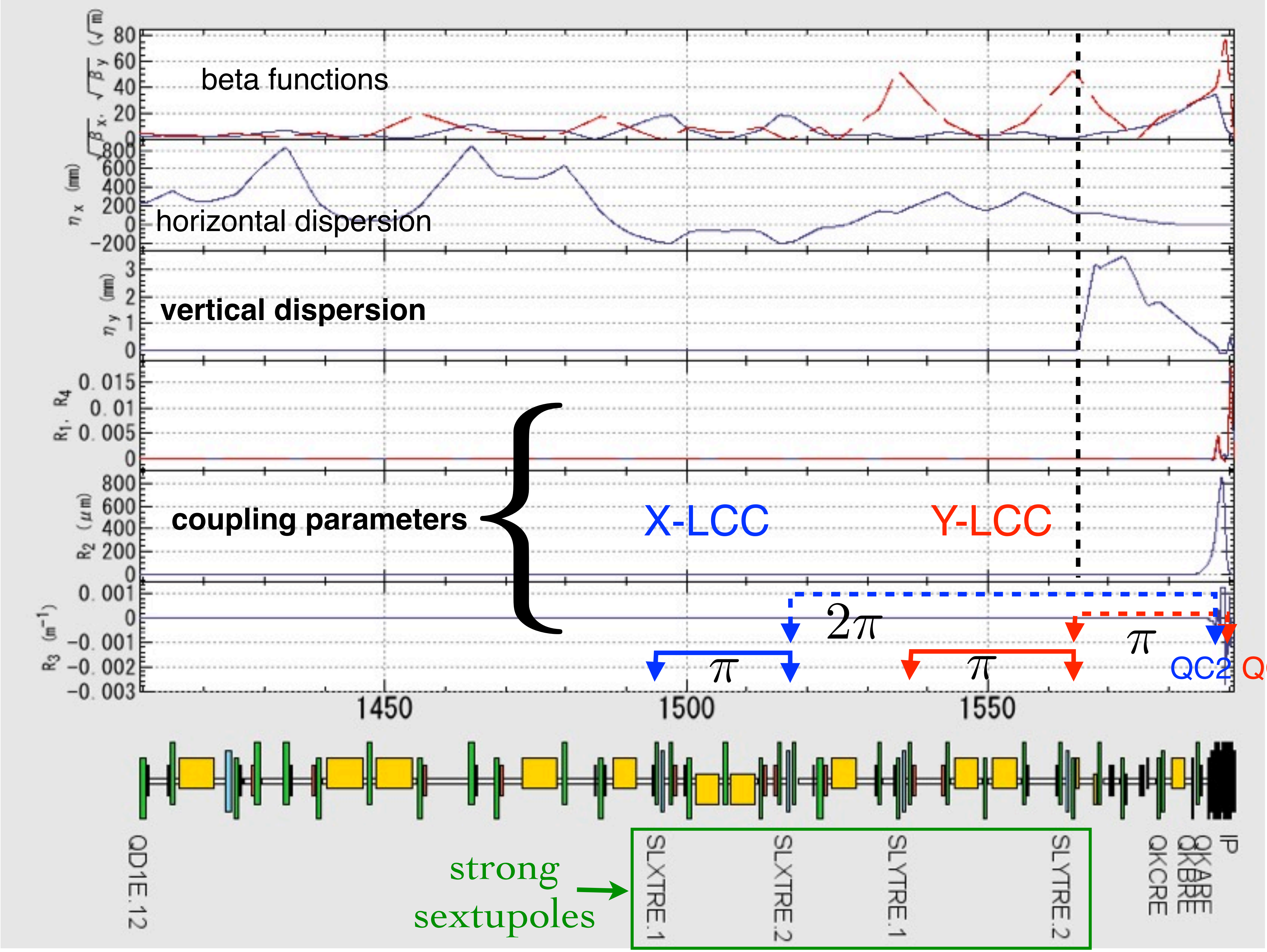
- The angle between Belle II Solenoid(1.5 T) and beam-axis is 41.5 mrad. Anti-solenoids are overlaid with QC1 and QC2 to compensate the Belle II solenoid field. The vertical emittance (about 1.5 pm) is generated due to the solenoid fringe field. Skew coils and/or rotation of QC1 and QC2 are used to correct the X-Y coupling and vertical dispersion between IP and the local chromaticity correction.

X-LCC corrects QC2 chromaticity and Y-LCC corrects QC1 chromaticity locally.

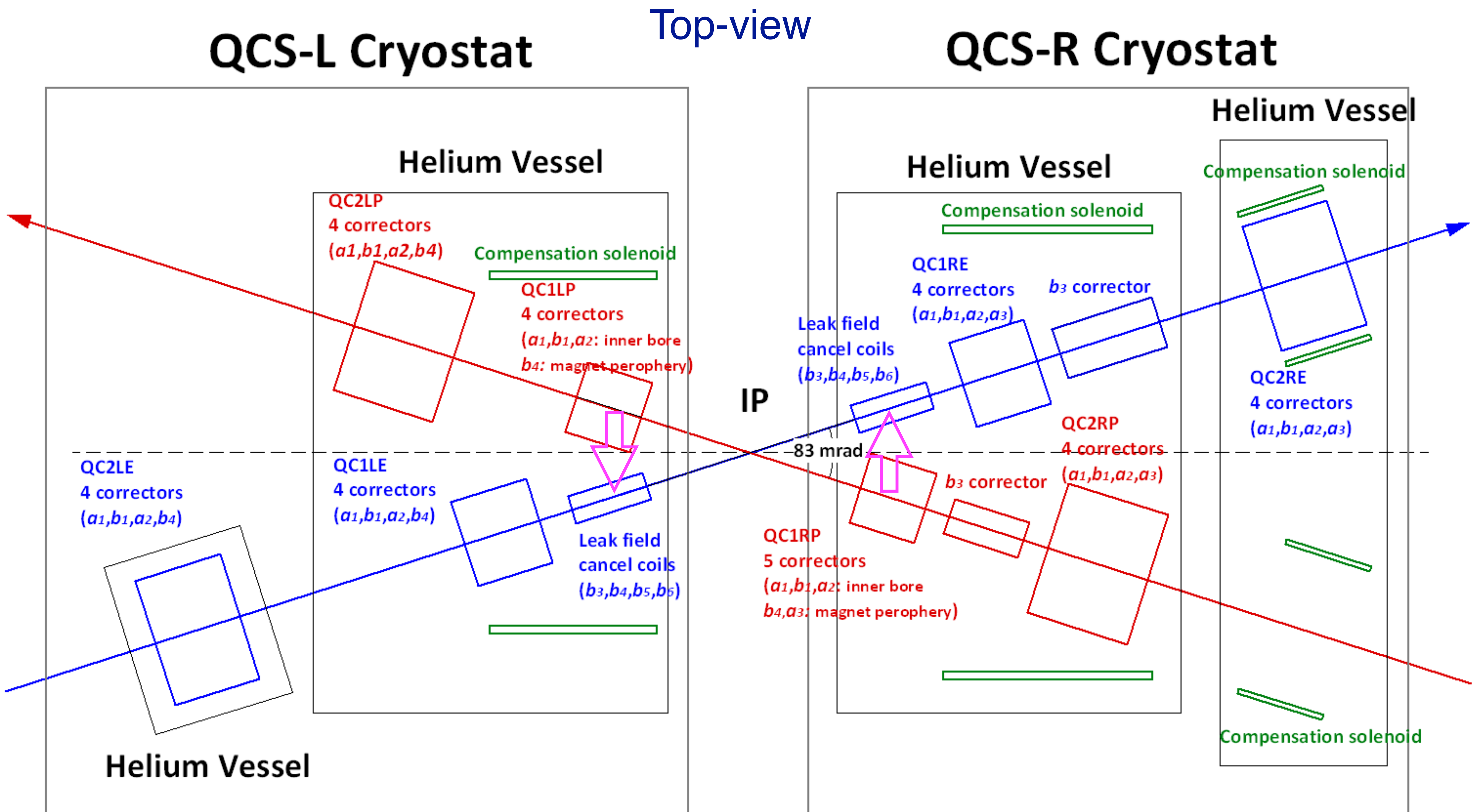


IR optics in HER

X-LCC corrects QC2 chromaticity and Y-LCC corrects QC1 chromaticity locally.



IR superconducting magnet



quadrupole	8	QC1{LR}P, QC2{LR}P, QC1{LR}E, QC2{LR}E
compensation solenoid	4	ESL, ESR1, ESR2, ESR3
corrector	*35*	cancel coil for leak field, dipole, skew quad, octupole, etc

Why so many corrector coils ?

necessary for design

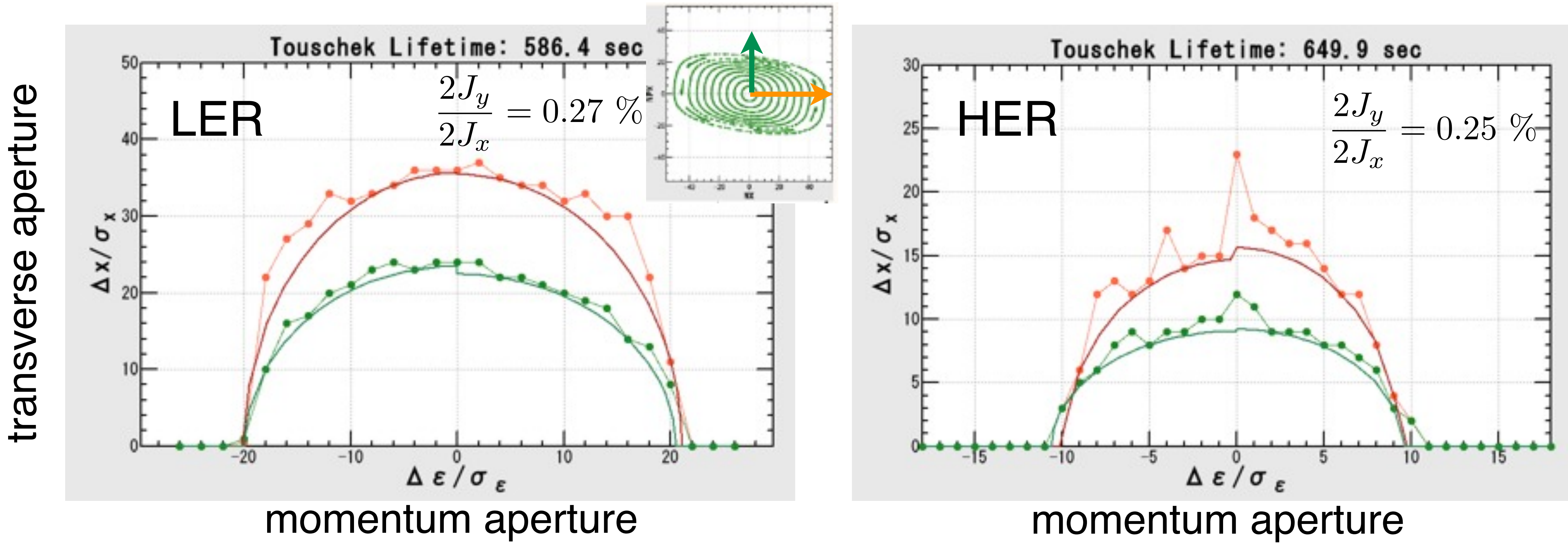
- Dipole and skew dipole coils adjust a beam orbit and correct dispersions in IR.
- Skew quadrupole coils correct X-Y couplings.
- HER cancel coils correct sextupole, octupole, decapole, and dodecapole leakage field from QC1P(no iron yoke) in LER.
- Octupole coils at QC1 and QC2 enlarge a transverse aperture.

cure for unexpected machine error

- *Sextupole and skew sextupole coils* correct error field due to a misalignment of quadrupole coils. This error field affects the dynamic aperture significantly.

All corrector coils are designed and made by BNL.

- Touschek lifetime depends on dynamic aperture.



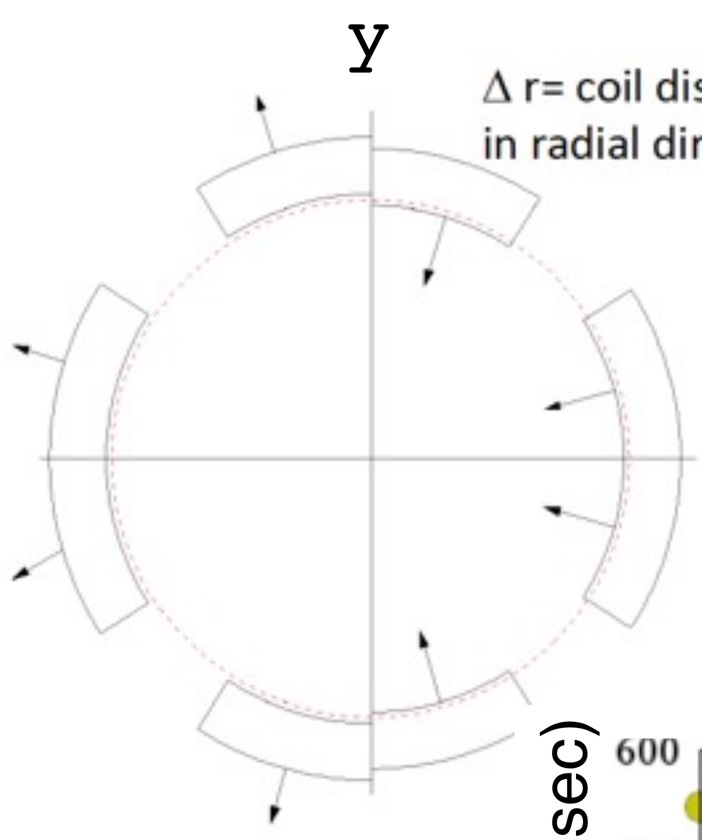
- Loss rate in the design current is **375 GHz** for LER and **272 GHz** for HER. (Touschek lifetime ~ 600 sec)

$$\frac{dN}{dt} = -\frac{N}{\tau}$$

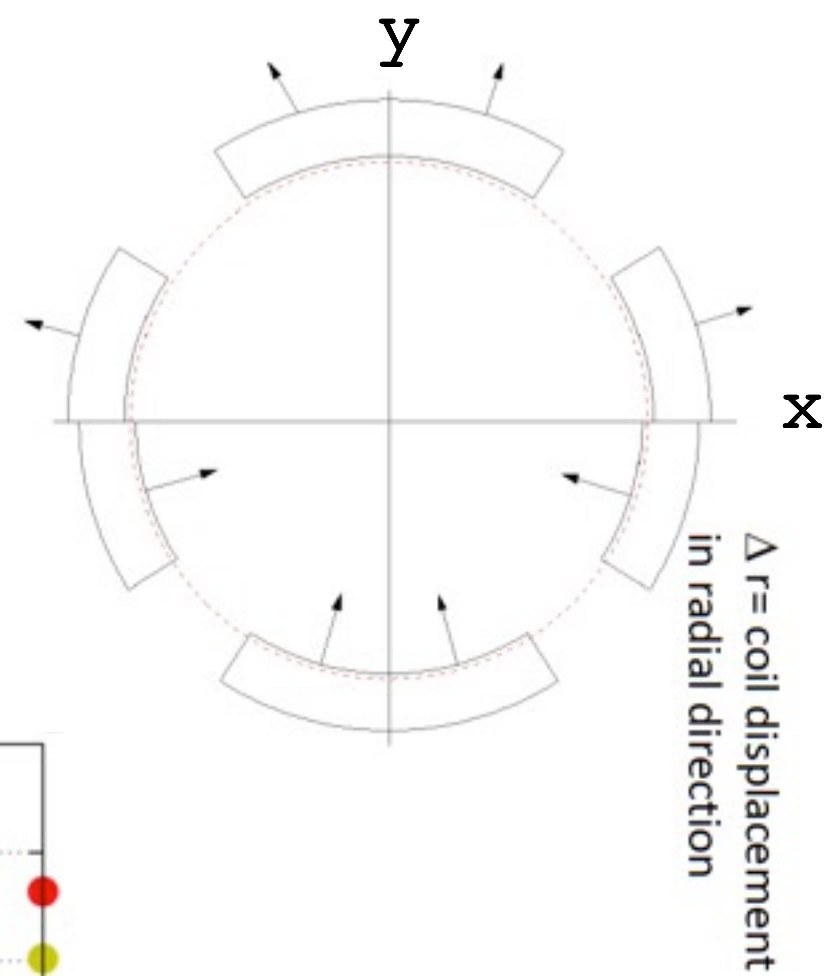
$$N_+ = 9.04 \times 10^{10}$$
$$N_- = 6.53 \times 10^{10}$$
$$n_b = 2500$$

Misalignment of quadrupole coils in QC1 and QC2

Sextupole field



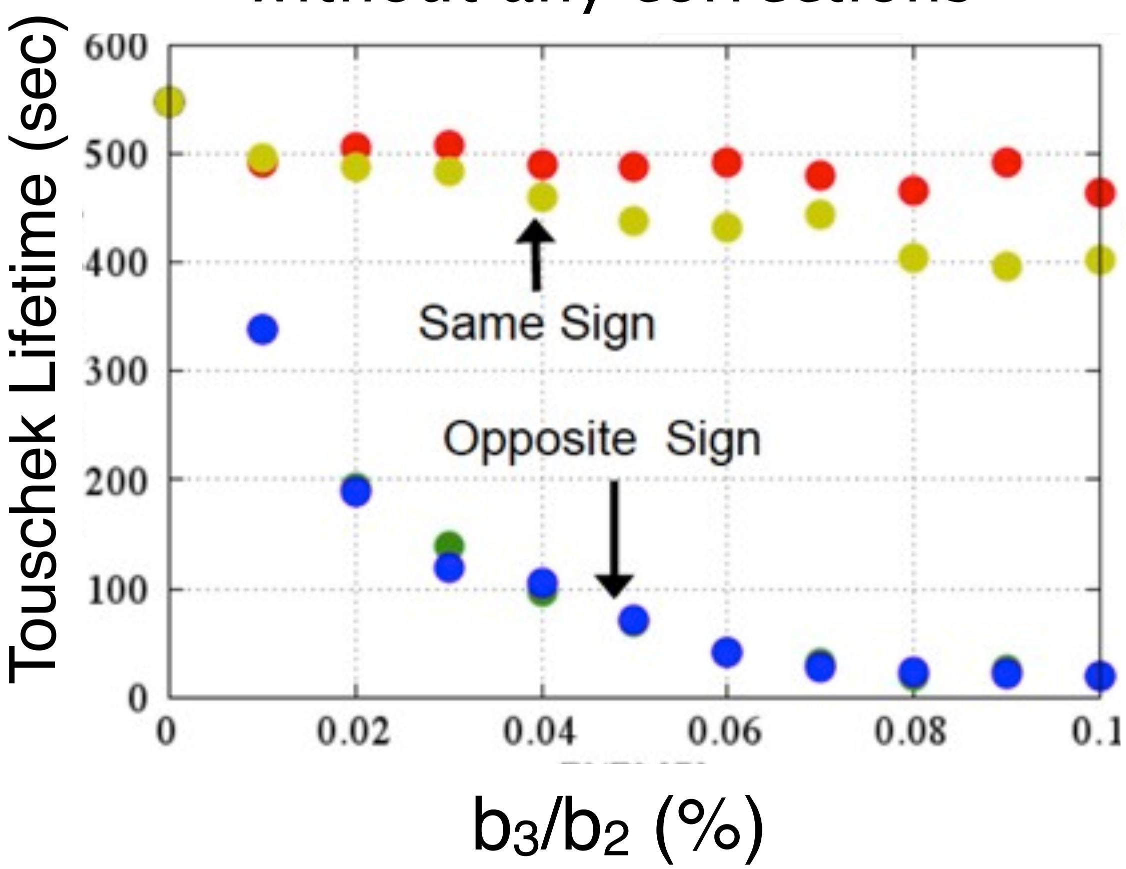
Skew sextupole field

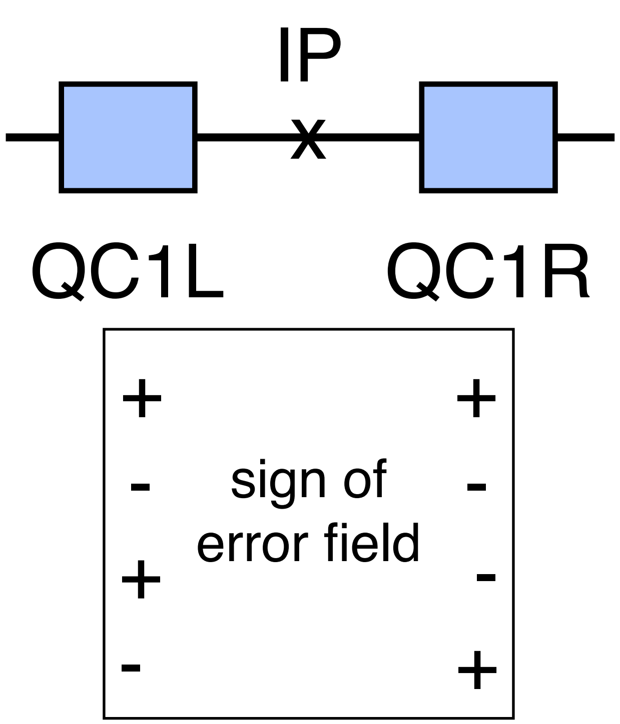


Δr=35 μm induces 0.1 % of b_3/b_2.

b_3 ~7 Gauss

without any corrections

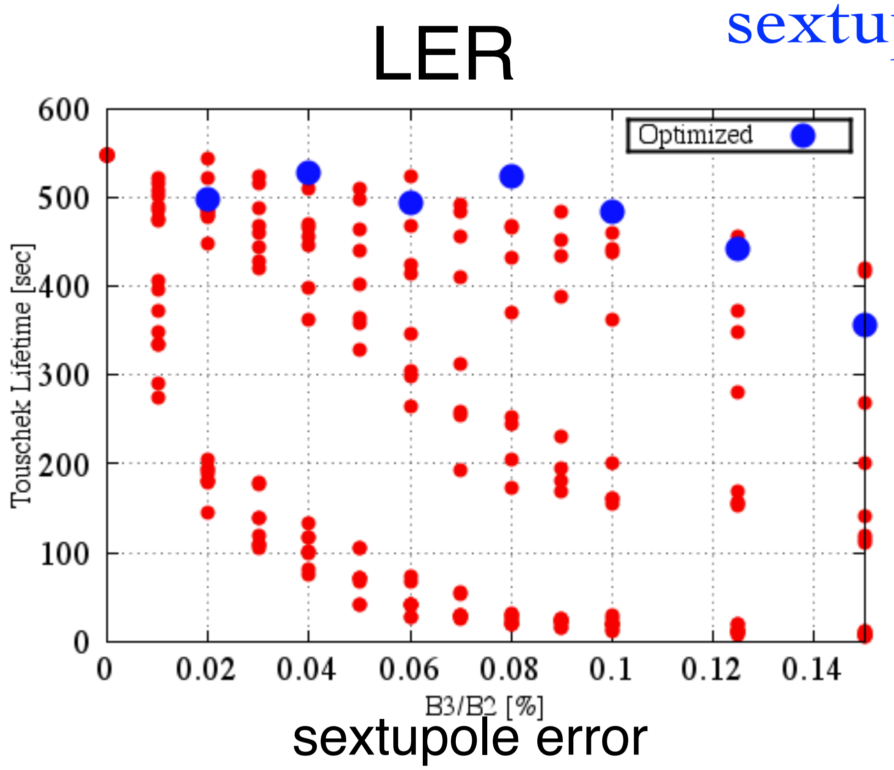


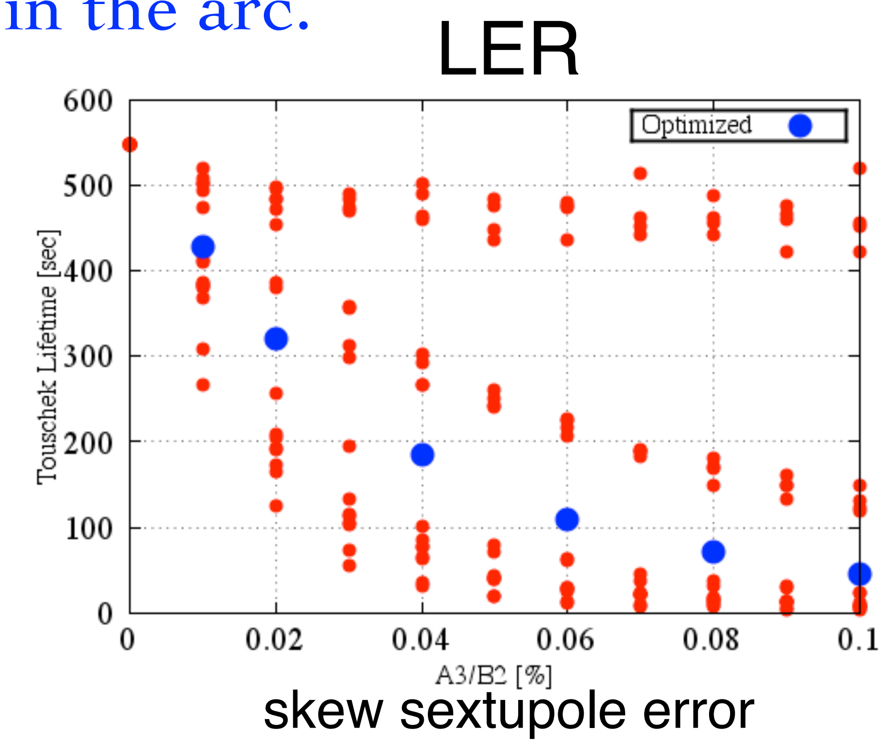


Sextupole error field: normal and skew

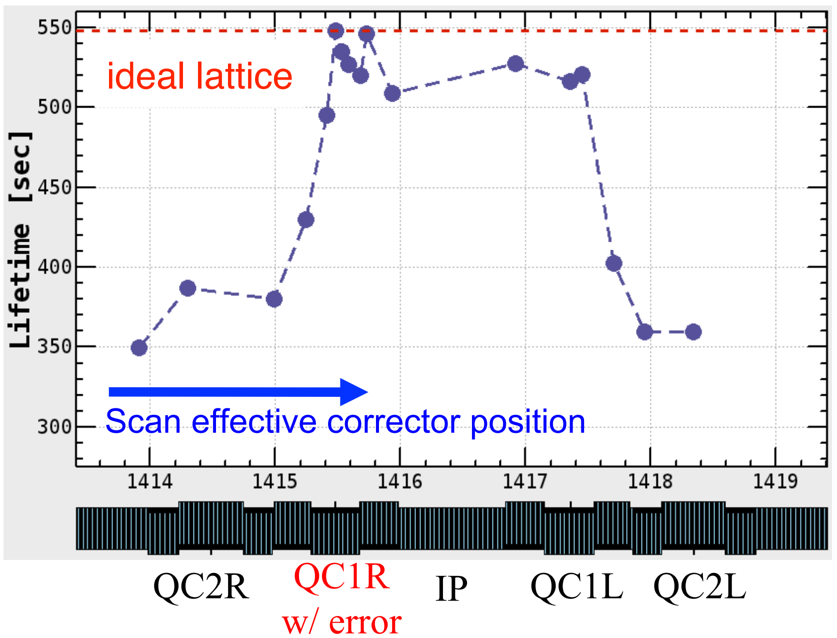
Touschek lifetime for 16 combinations of field error in 4 QCs

Dynamic aperture is optimized by using normal sextupoles(108) and skew sextupoles(24) in the arc.





Sextupole error can be recovered by using normal sextupoles(in the arc), however, skew sextupoles error can not be corrected for enough level.

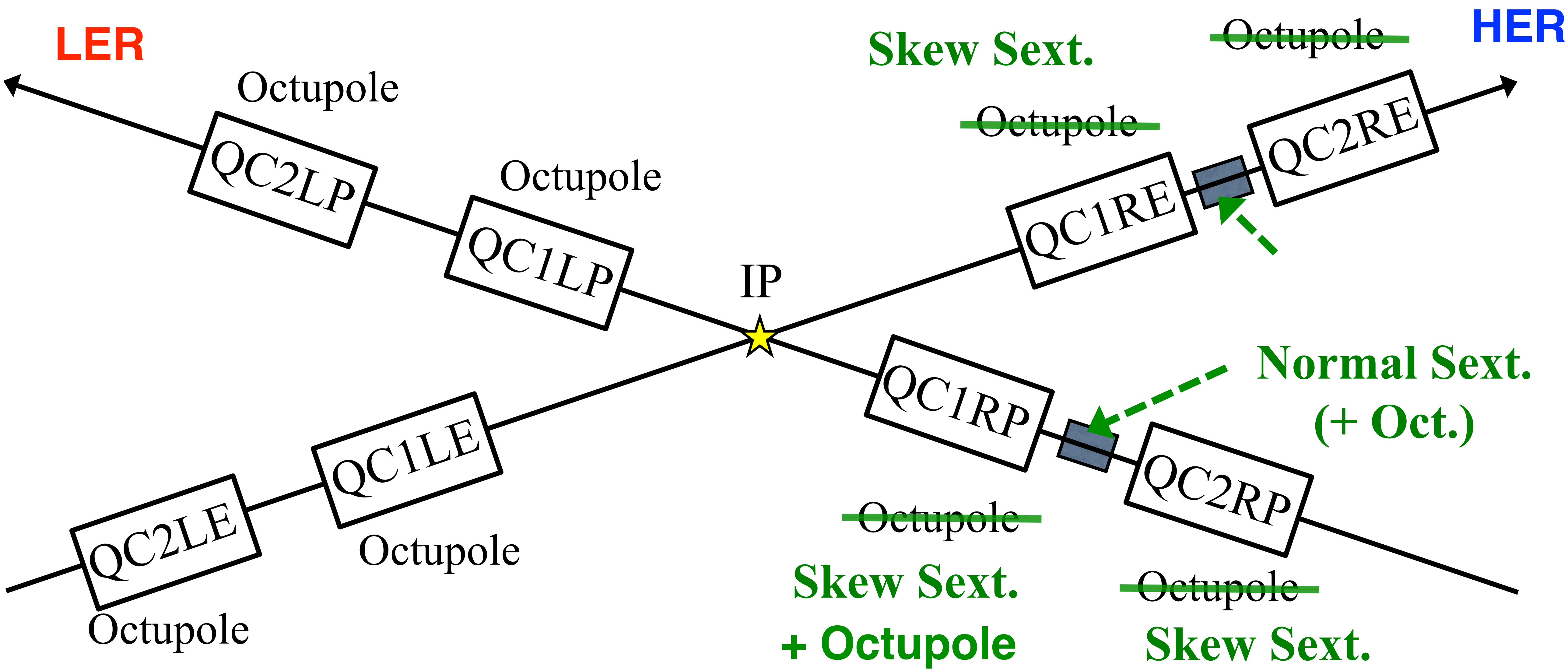


Position dependence of the skew corrector coil is stronger than that of normal.

Skew sextupole corrector must be installed in the vicinity of the error source.

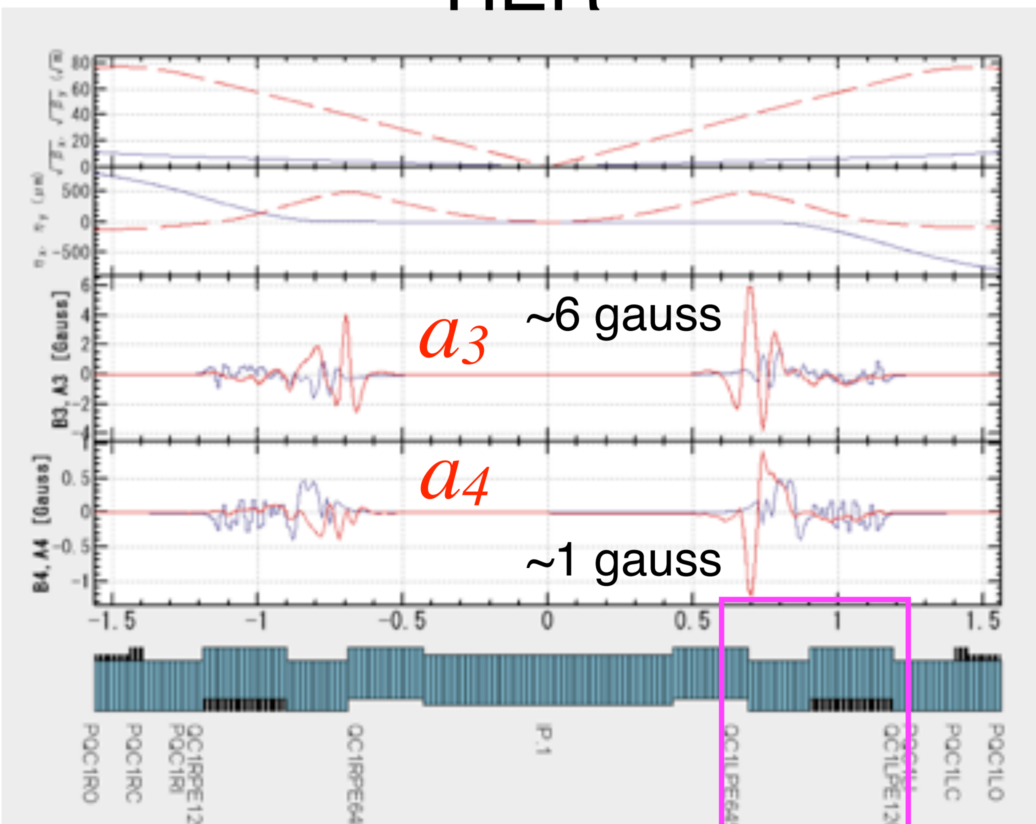
Design change after consideration of QC error

QC1L and QC2L have already been constructed and can not change the design.
Possible change is to replace octupoles with skew sextupoles since the space is limited (4-layer is maximum).
Octupoles in the left-side can provide enough Touschek lifetime.

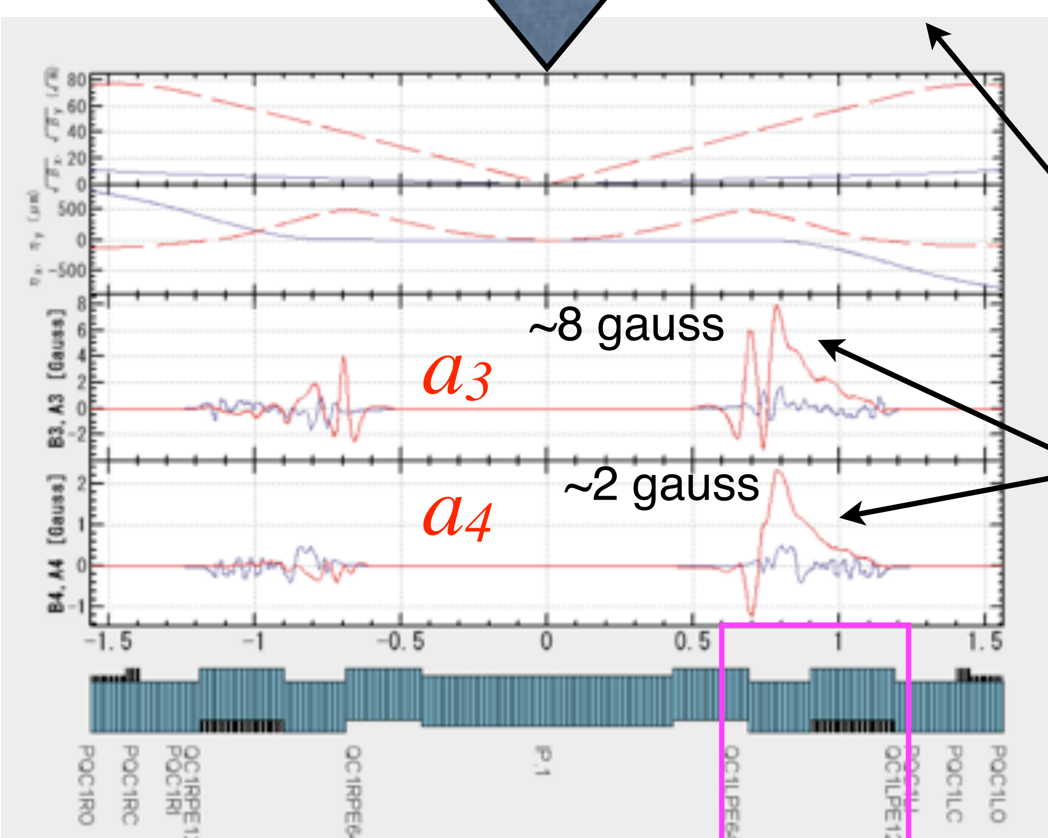


Rotation error of cancel coil in HER

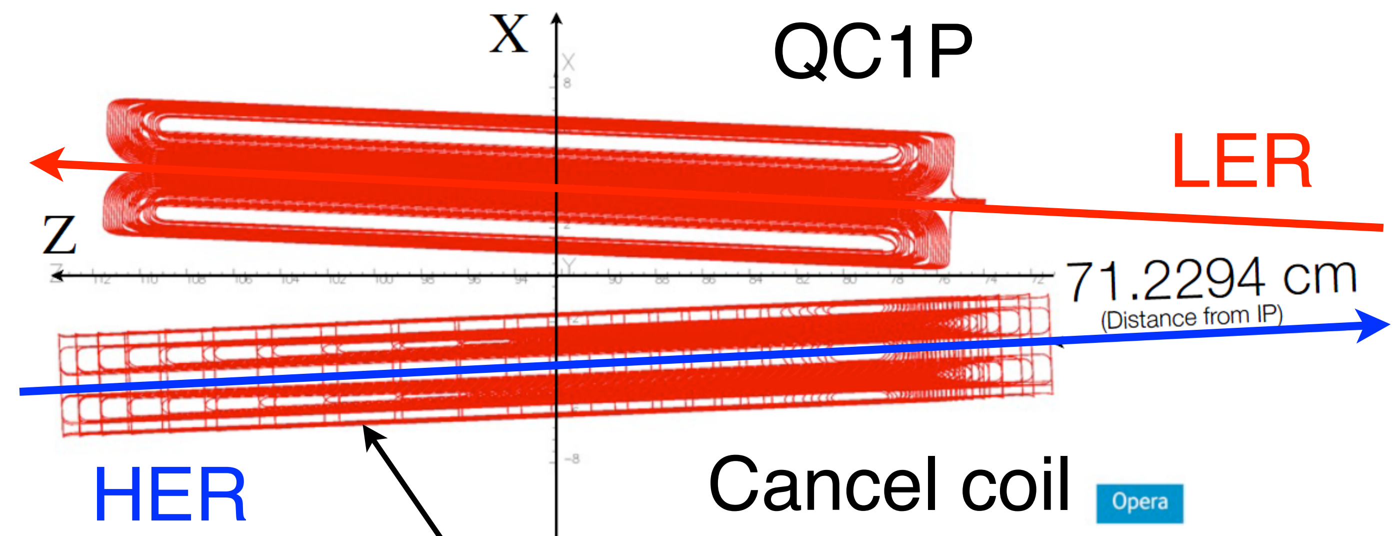
HER



cancel coil ⇩ cancel coil



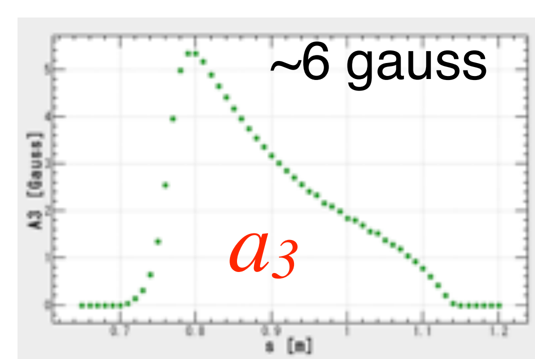
Cancel coil to compensate leakage field from QC1P(LER) in HER



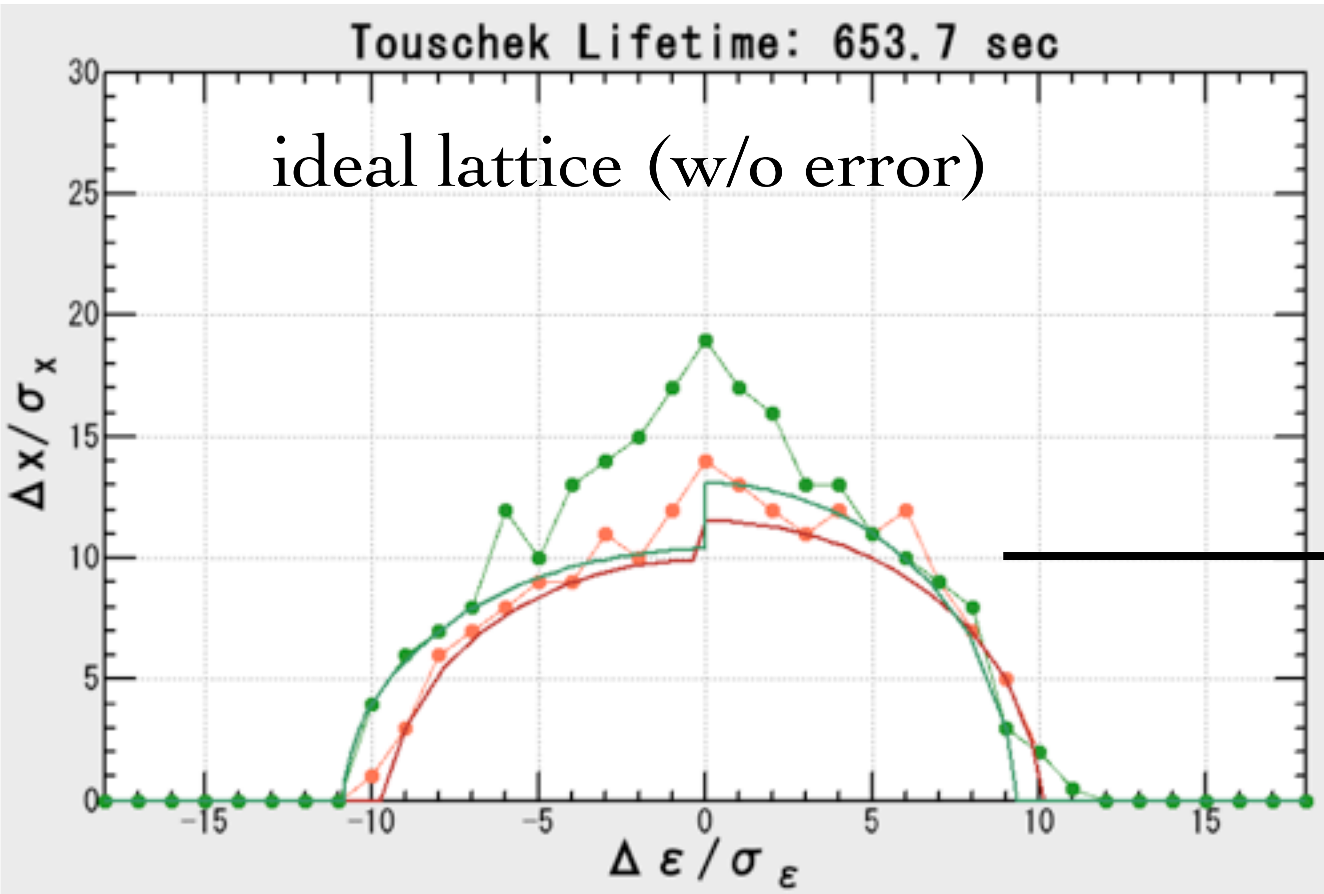
Cancel coil consists of b_3, b_4, b_5, b_6 coils (b_1 and b_2 are involved in the optics design.)

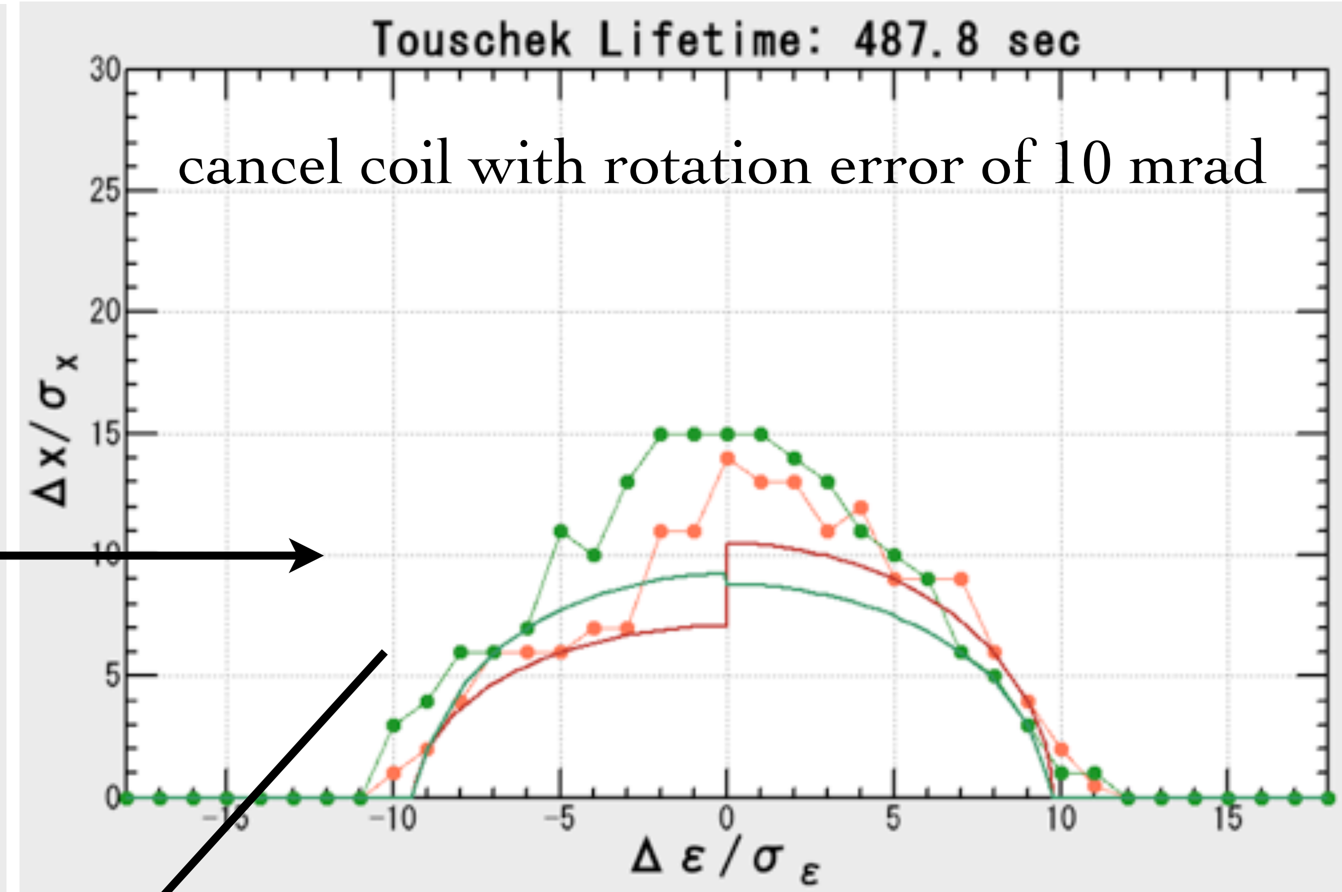
10 mrad rotation around the beam axis is expected due to magnet construction error.

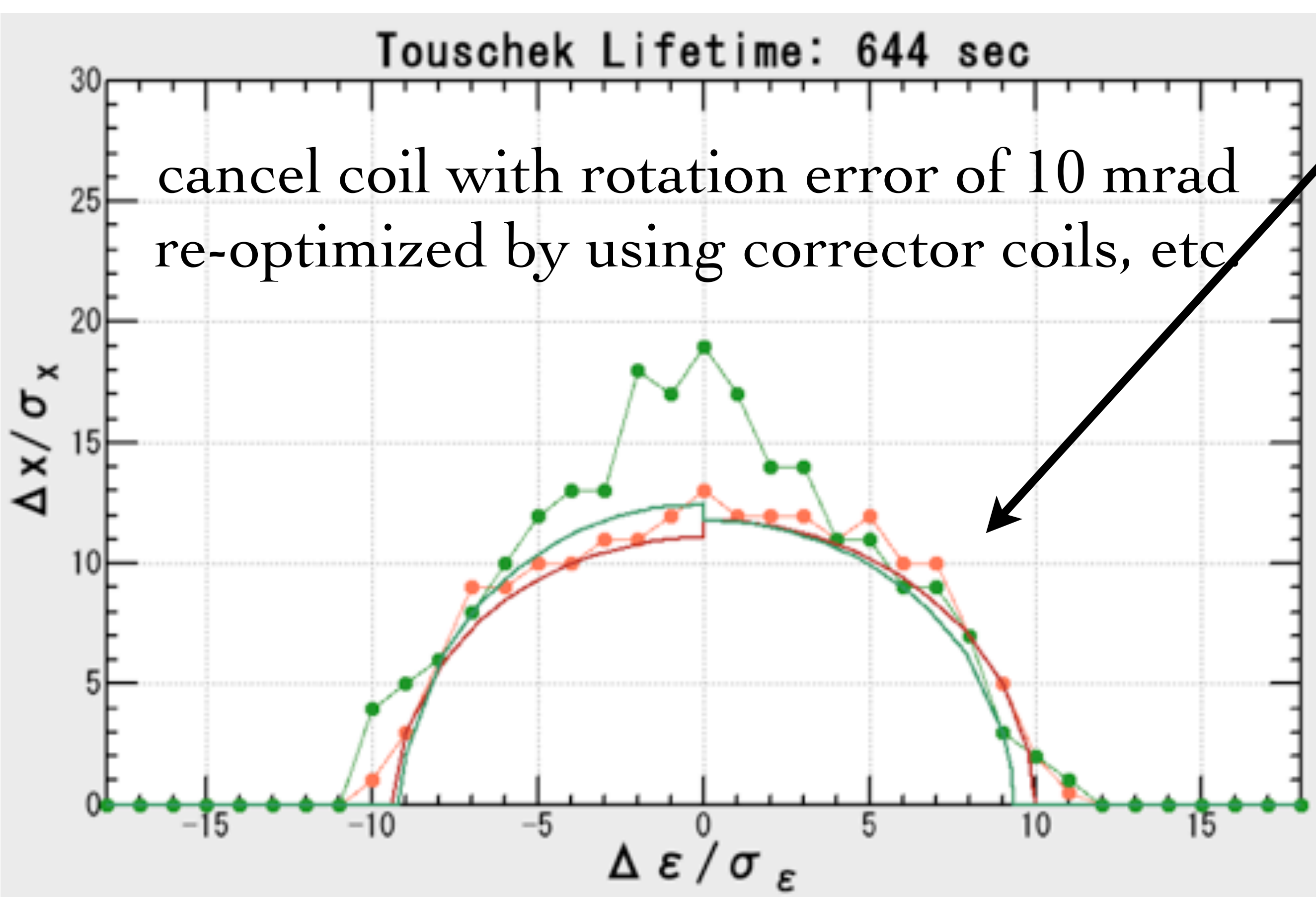
Skew sextupole(a_3) and skew octupole(a_4) are induced.

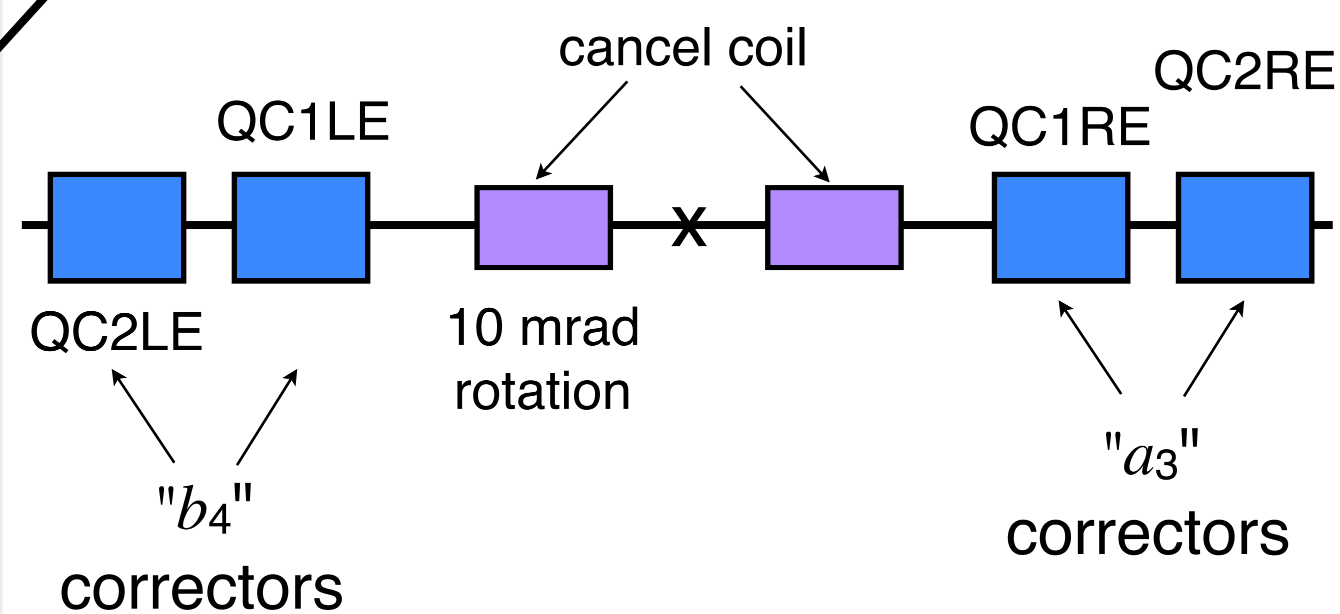


Rotation error of cancel coil in HER









Summary

- SuperKEKB is an e-e+ collider to achieve **40** times luminosity of KEKB. The vertical beta at IP is squeezed down to 1/**20** which is available in the "Nano-beam scheme". The beam current is **twice** of KEKB.

"Luminosity Frontier Machine"

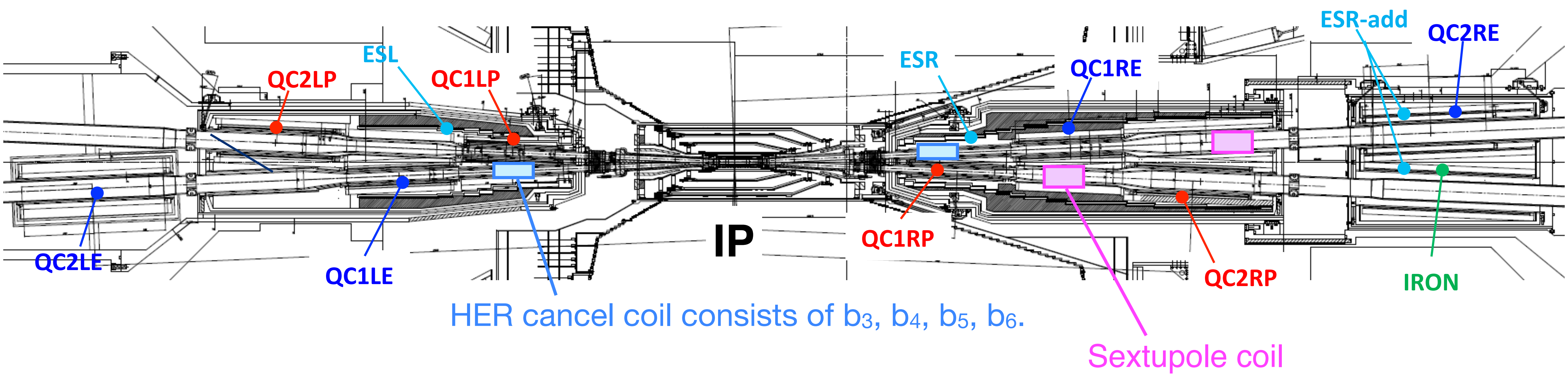
- The error of the final focus system affects the optics performance significantly.
- Especially, multipole fields such as sextupole and skew sextupole error reduce the dynamic aperture.
- The level of a several-gauss field in IR limits the optics performance.
- We have to consider magnet imperfections due to a misalignment of coils as well as a gradient error and should put appropriate correctors to recover them.

Appendix

Machine parameters

2013/July/29	LER	HER	unit	
E	4.000	7.007	GeV	
I	3.6	2.6	A	
Number of bunches	2,500			
Bunch Current	1.44	1.04	mA	
Circumference	3,016.315		m	
$\varepsilon_x/\varepsilon_y$	3.2(1.9)/8.64(2.8)	4.6(4.4)/12.9(1.5)	nm/pm	():zero current
Coupling	0.27	0.28		includes beam-beam
β_x^*/β_y^*	32/0.27	25/0.30	mm	
Crossing angle	83		mrad	
α_p	$3.18\text{x}10^{-4}$	$4.53\text{x}10^{-4}$		
σ_δ	$8.10(7.73)\text{x}10^{-4}$	$6.37(6.30)\text{x}10^{-4}$		():zero current
V_c	9.4	15.0	MV	
σ_z	6.0(5.0)	5(4.9)	mm	():zero current
ν_s	-0.0244	-0.0280		
ν_x/ν_y	44.53/46.57	45.53/43.57		
U_0	1.86	2.43	MeV	
$\tau_{x,y}/\tau_s$	43.2/21.6	58.0/29.0	msec	
ξ_x/ξ_y	0.0028/0.0881	0.0012/0.0807		
Luminosity	$8\text{x}10^{35}$		$cm^{-2}s^{-1}$	

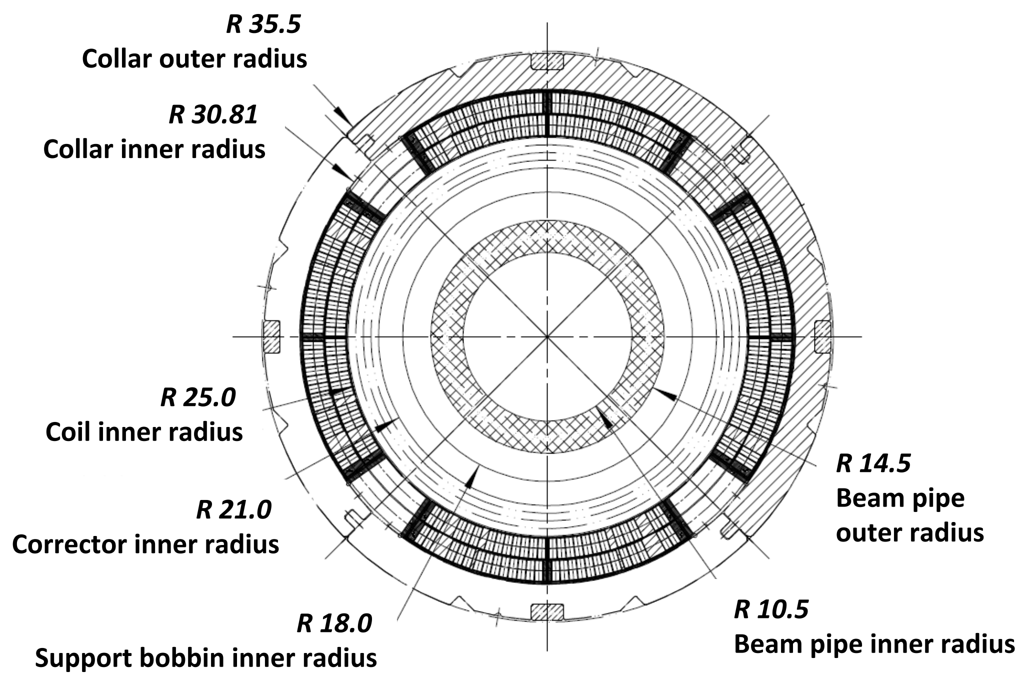
Final focus quadrupoles



Design param.	Dipole	Skew dipole	Quad	Skew quad	Sextupole	Skew sext	Octupole
	b_1L (Tm)	a_1L (Tm)	b_2L/r_0 (T)	a_2L/r_0 (T)	b_3L/r_0^2 (T/m)	a_3L/r_0^2 (T/m)	b_4L/r_0^3 (T/m^2)
QC1LP(no shield)	0.004	-0.002	-22.96	-9.50E-05			-27.0
QC2LP	-0.0217	0.022	11.48	0.0095			48.2
QC1RP(no shield)	0.0050	-0.0086	-22.96	1.92E-05		0.0	-26.7
QC2RP	-0.0023	0.0214	11.54	-6.30E-06		0.0	
QC1RP-QC2RP					0.0		
QC1LE	0.030	0.0092	-26.94	-0.0729			8.9
QC2LE	0.000	-0.0016	15.27	0.0271			23.6
QC1RE	-0.0305	0.0053	-25.39	0.0653		0.0	
QC2RE	0.000	-0.0022	13.04	0.0559		0.0	
QC1RE-QC2RE					0.0		

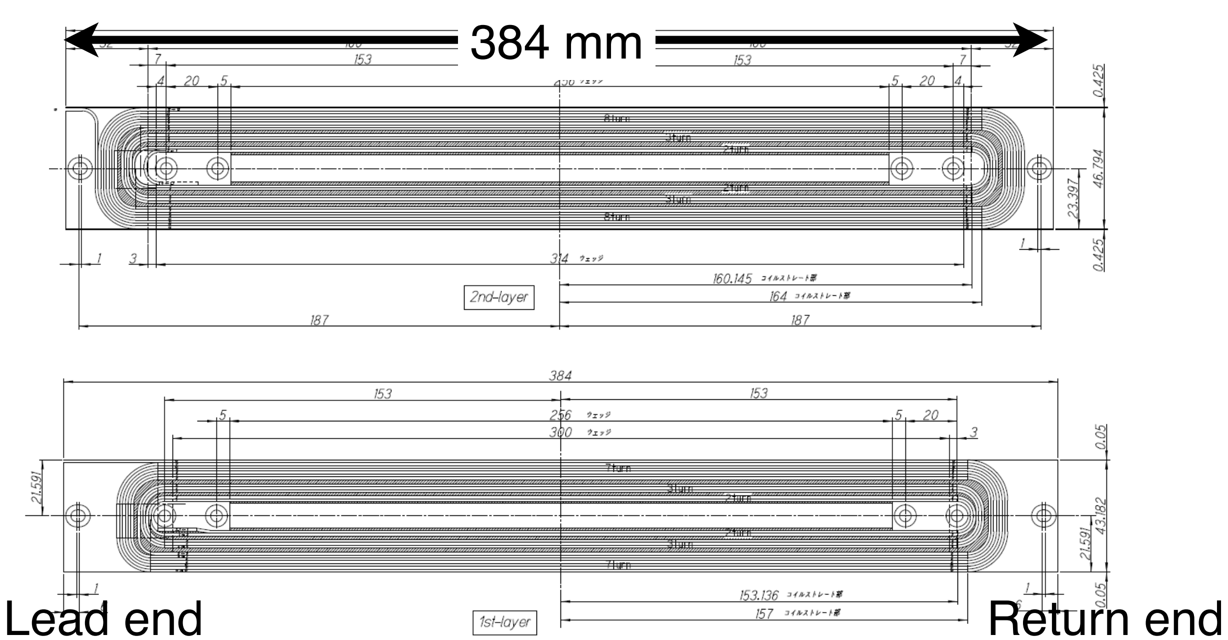
QC2LP, QC2RP, QC1LE, QC1RE: permendur yoke
QC2LE, QC2RE: iron yoke

QC1P

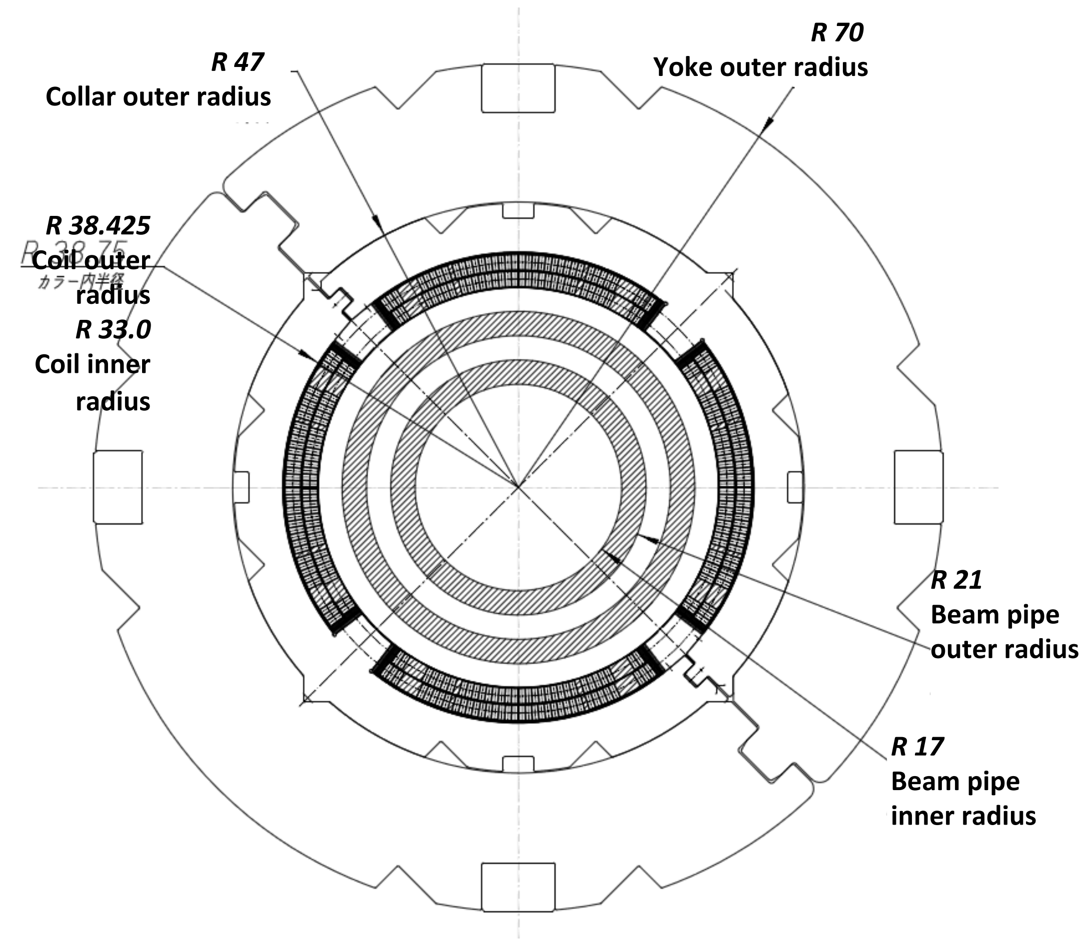


a_2, b_1, a_1 inside of the magnet bore

b_4, a_3 outside of the magnet collar



QC1E



a_2, b_1, a_1 inside of the magnet bore

b_4, a_3 inside of the magnet bore