TUOAB02

Design Study of the SuperKEKB Interaction Region Optics

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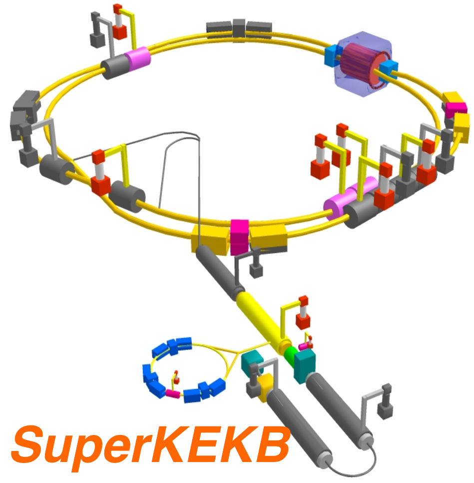
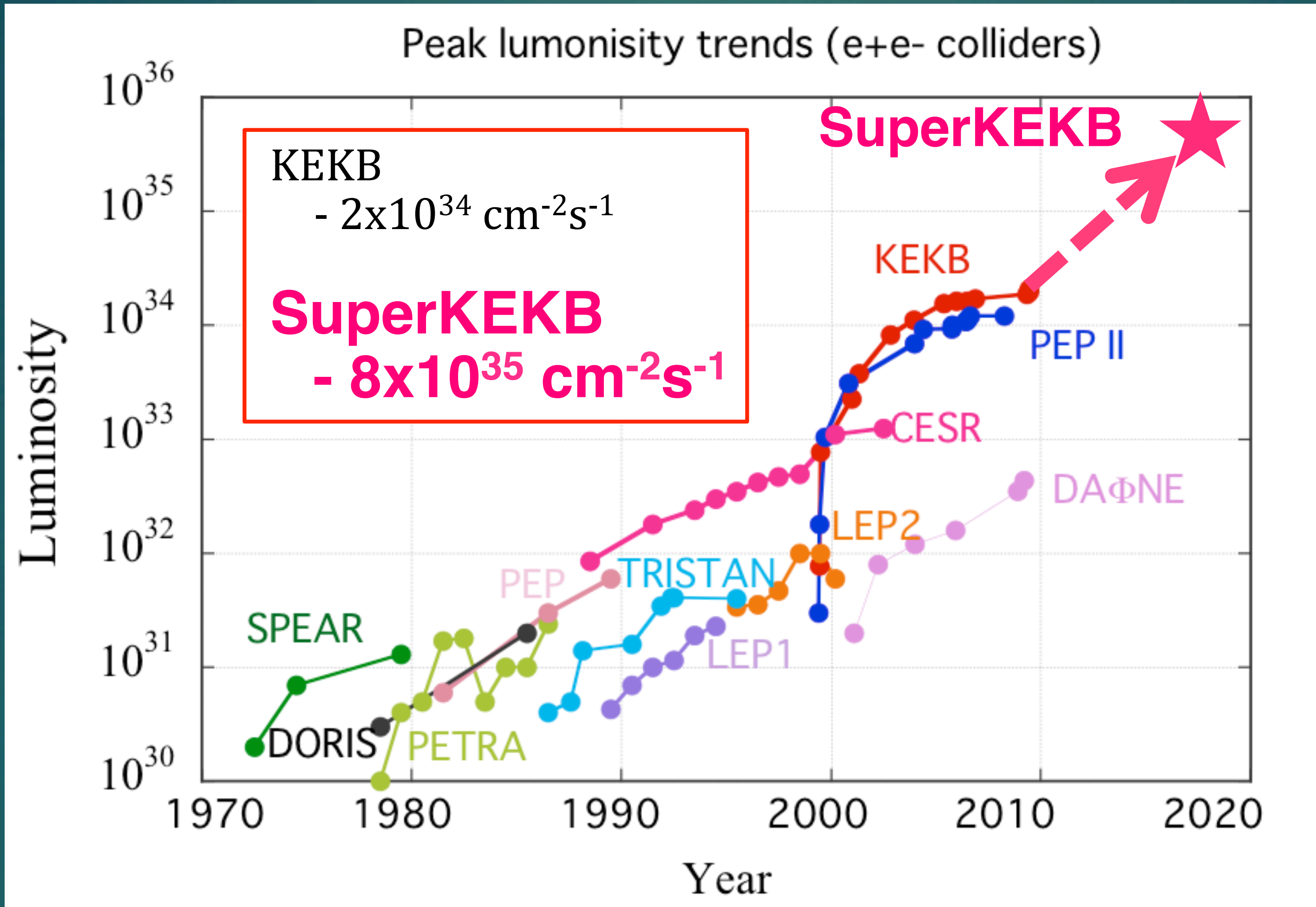
High Energy Accelerator Research Organization (KEK)

This Talk



- Background
  - SuperKEKB collider
  - Optics and beam dynamics requirements
- Design overview of the interaction region
  - Numerical modeling
  - Liner optics and dynamic aperture optimization
- A design study on an imperfection of final focus magnets
  - Numerical study
  - Corrector coil arrangement

A New Luminosity Frontier



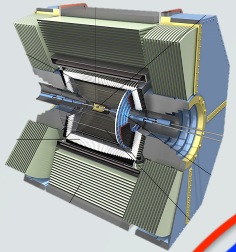
- SuperKEKB
  An upgrade project of KEKB for a new luminosity frontier.

SuperKEKB

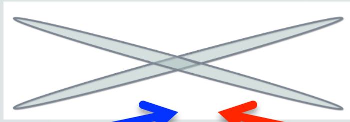
N. Ohuchi, et.al., WEOCA01

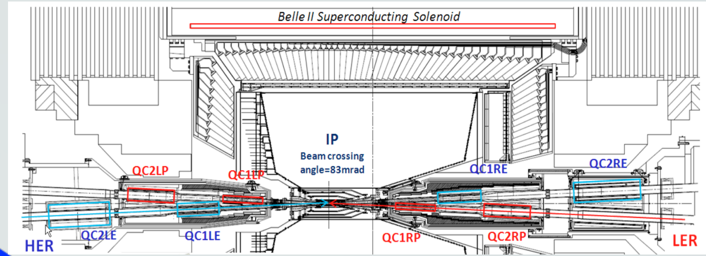
Beam commissioning will start 2015.

Upgrade to Belle II detector



Nano-beam scheme





New superconducting final focusing magnets near the IP

Redesign the lattice to squeeze the emittance (replace short dipoles with longer ones, increase wiggler cycles)

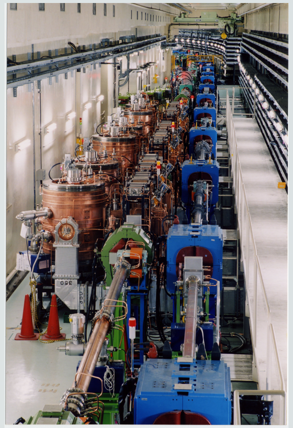
4GeV e+ 7GeV e-

SuperKEKB

New luminosity frontier

$L = 8 \times 10^{35}\ \mathrm{cm^{-2}s^{-1}}$

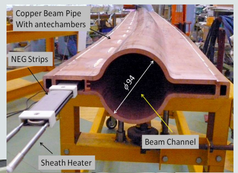
- Nano-Beam scheme
  extremely small β_y^*
  low emittance
- High beam current



Reinforce RF systems for higher beam currents

Improve monitors and control system

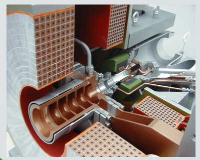
Replace beam pipes with TiN-coated beam pipes with antechambers



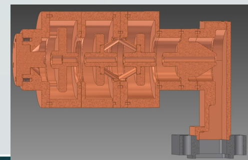
New e+ Damping Ring

Injector Linac upgrade

New capture section



RF electron gun



KEKB to SuperKEKB

$$L = \frac{\gamma_\pm}{2er_e}\left(1+\frac{\sigma_y^*}{\sigma_x^*}\right)\left(\frac{I_\pm \xi_{\pm y}}{\beta_y^*}\right)\left(\frac{R_L}{R_y}\right) = 8 \times 10^{35}\ \mathrm{cm^{-2}s^{-1}}$$

e^+ e^-

- Vertical β function at IP: 5.9 → 0.27/0.30 mm (× 20)
- Beam current: 1.7/1.4 → 3.6/2.6 A (× 2)
- Beam-beam parameter: .09 → .09 (× 1)
- Beam energy: 3.5/8.0 → 4.0/7.0 GeV

Requirements

- Extremely small beta functions

e^+ e^-

$\beta_x = 32 / 25$ mm $\beta_y = 0.27 / 0.30$ mm

- Low emittance beams

$\varepsilon_x = 3.2 / 4.6$ nm $\varepsilon_y = 8.6 / 12.9$ pm

- Sufficient Dynamic Aperture (DA)
  for Touschek lifetime > **600** sec

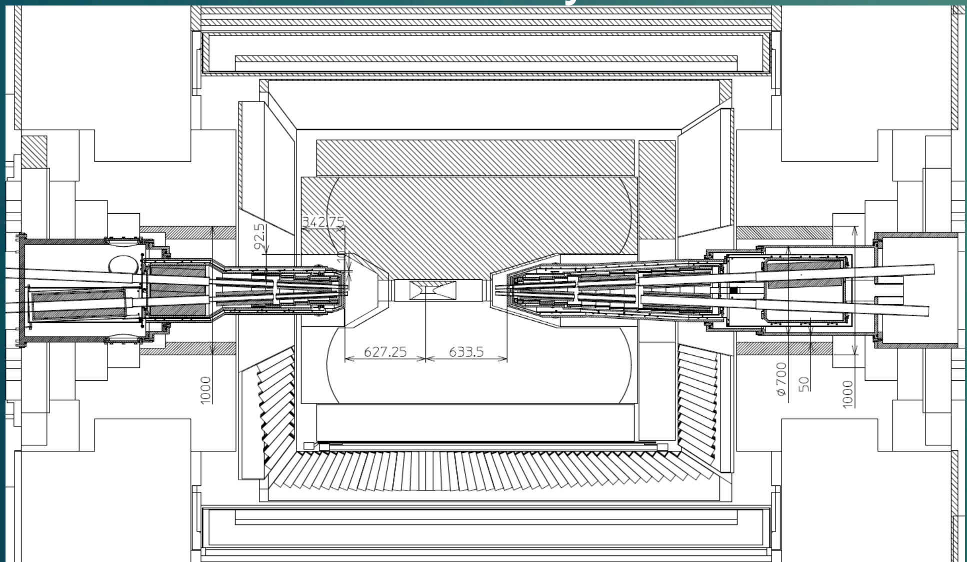
- Low beam background to the detector
- Fit in the existing KEKB tunnel

Interaction Region (IR)

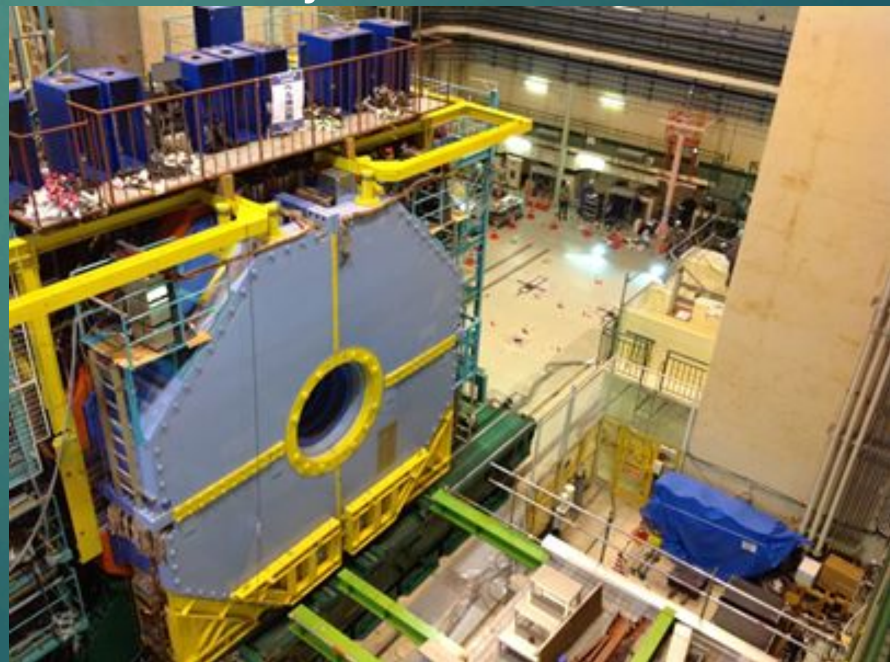
- Essential difference, compared to light-source rings
- Extremely strong focus and detector solenoid field

Huge chromaticity, kinematic term,
non-liner magnetic field, vertical emittance source,
X-Y coupling, etc.

Final focus system

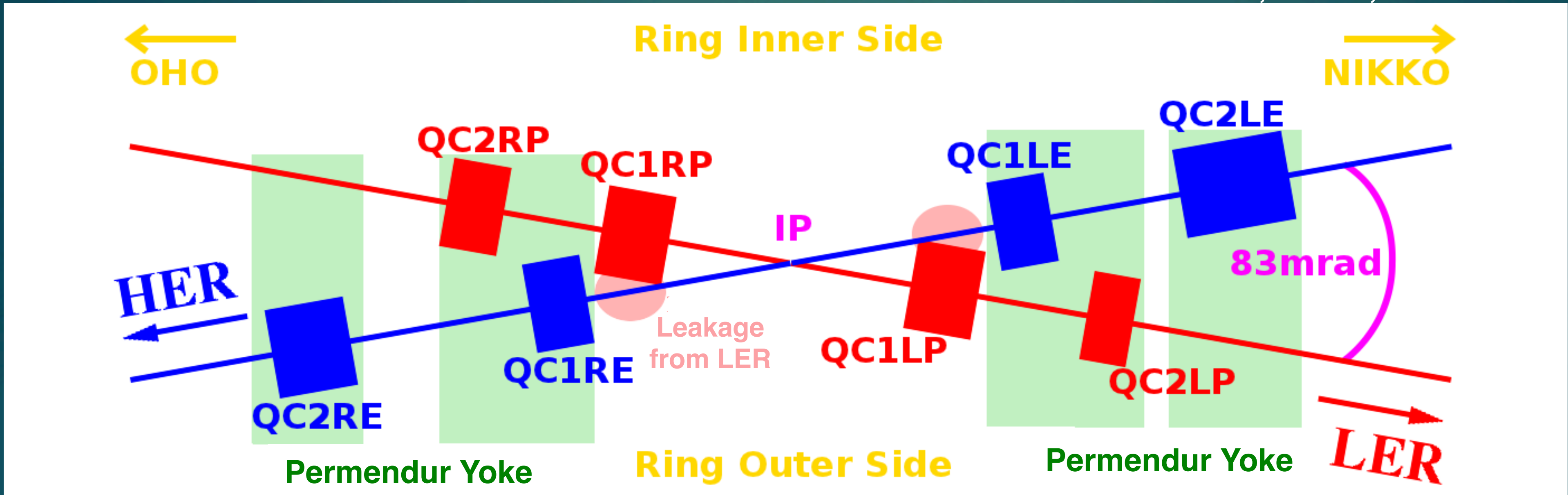


Physics detector



Final Focus System (QCS)

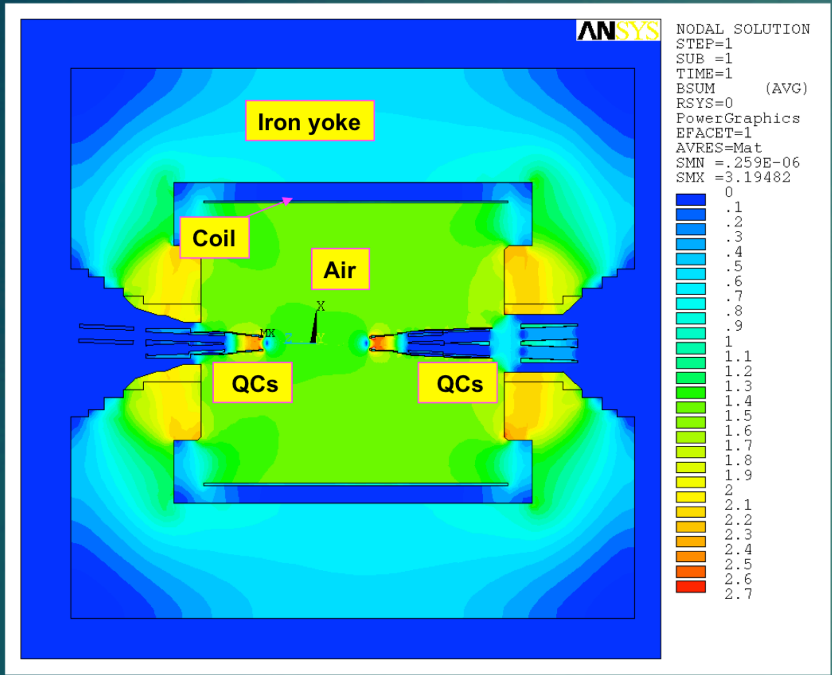
N. Ohuchi, et.al., WEPRI087



- All magnets except for QC1Ps have iron or permendur yoke for preventing leakage fields to the opposite beam line.
- Canceller coils are installed in the HER beam line to suppress the leakage fileds from QC1Ps.
- All magnets have superconducting corrector coils.
  - Normal&Skew Dipole, Skew Quad
- Octcupole and sextupole coils are also available.

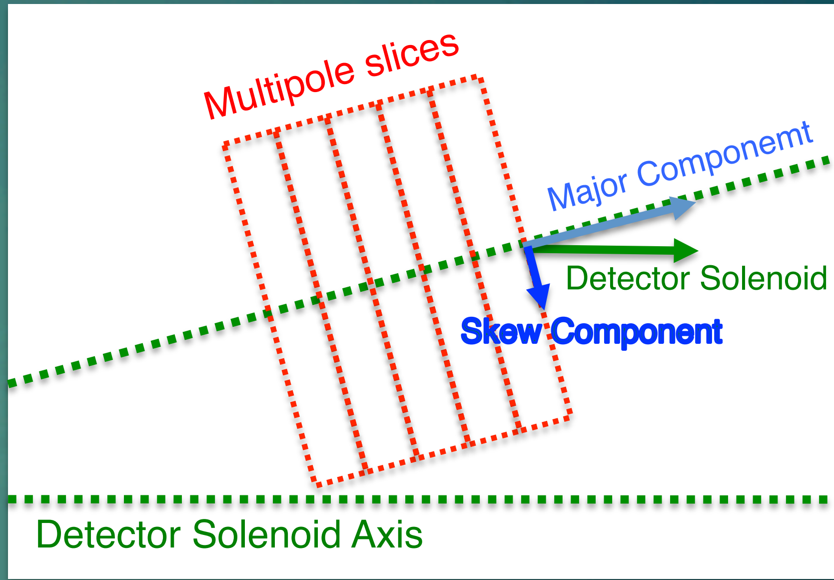
Numerical Modeling

3D Field Calculation (ANSYS)



Import

Optics Calculation (SAD)

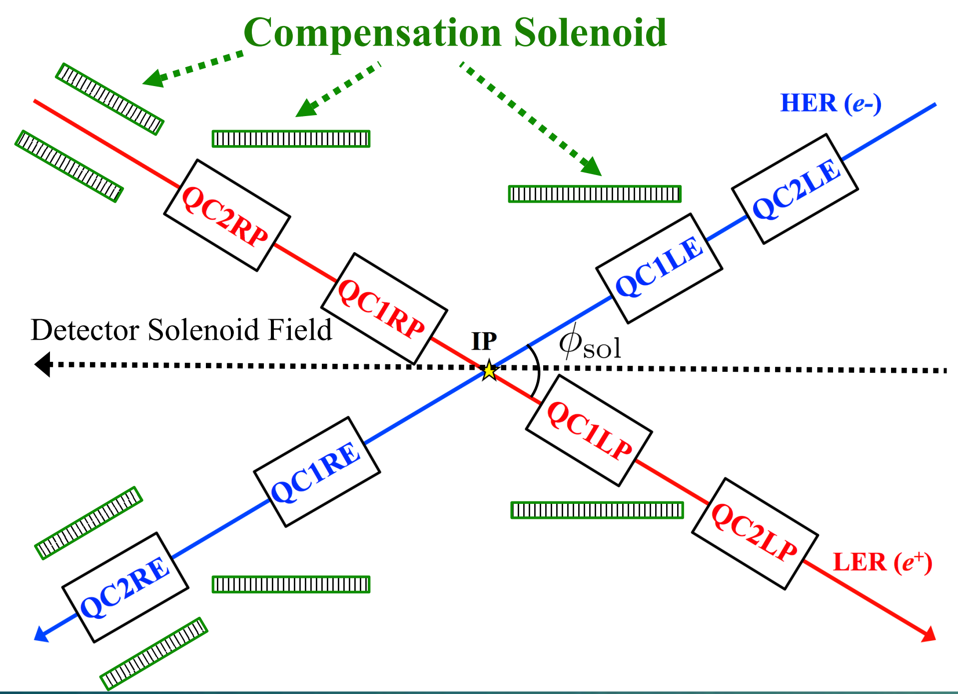


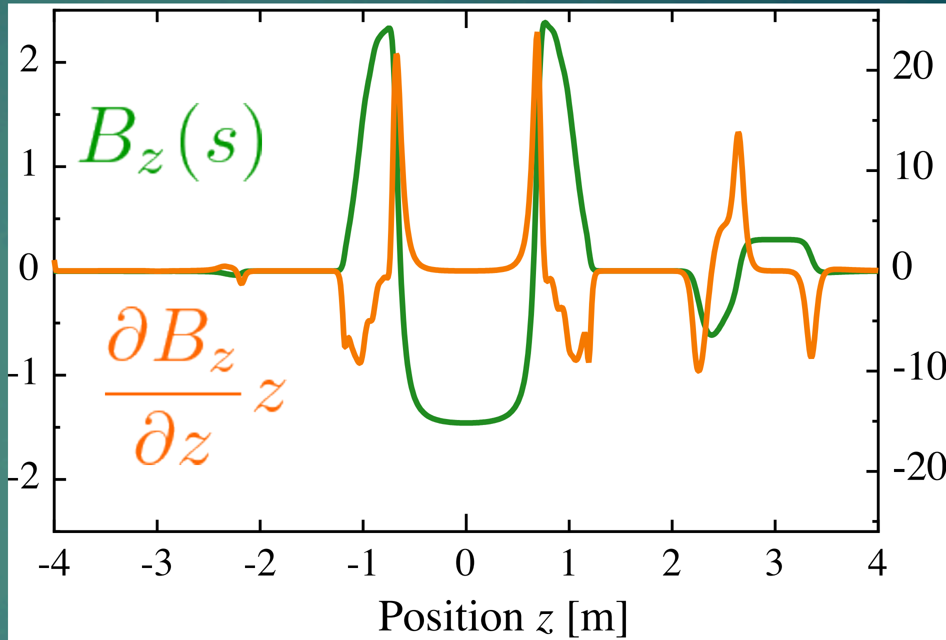
- Modeled by series of multipole slices attached to the beam line.
- Their strengths are obtained by 3D multipole expansion of the field data.

$$\boldsymbol{B} = \nabla\phi \qquad \phi(r,\theta,z) = \Im\left[\sum_{n=0}^{\infty} r^n e^{in\theta} \sum_{m=0}^{\infty} \frac{(-1)^m\, n!\, r^{2m}}{4^m m!\,(n+m)} \frac{d^{2m}}{dz^{2m}} d_n(z)\right]$$

Compensation Solenoid

- Install to mitigate the detector solenoid effect.





- $\int B_z dz \sim 0$ for mitigation of horizontal-vertical coupling.
- Suppress $\frac{\partial B_z}{\partial z} z$ to decrease vertical emittance.

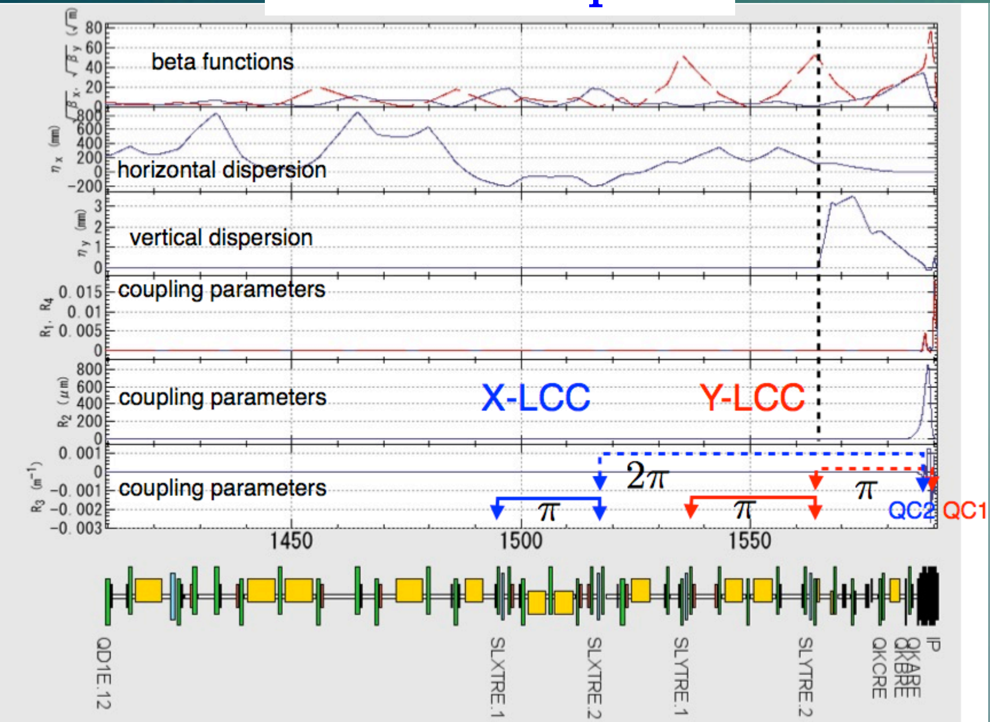
$$\because B_x \sim -\frac{1}{2}\frac{\partial B_z}{\partial z} x = -\frac{1}{2}\frac{\partial B_z}{\partial z} z \tan\phi_{\rm sol}$$

Local Chromaticity Correction (LCC)

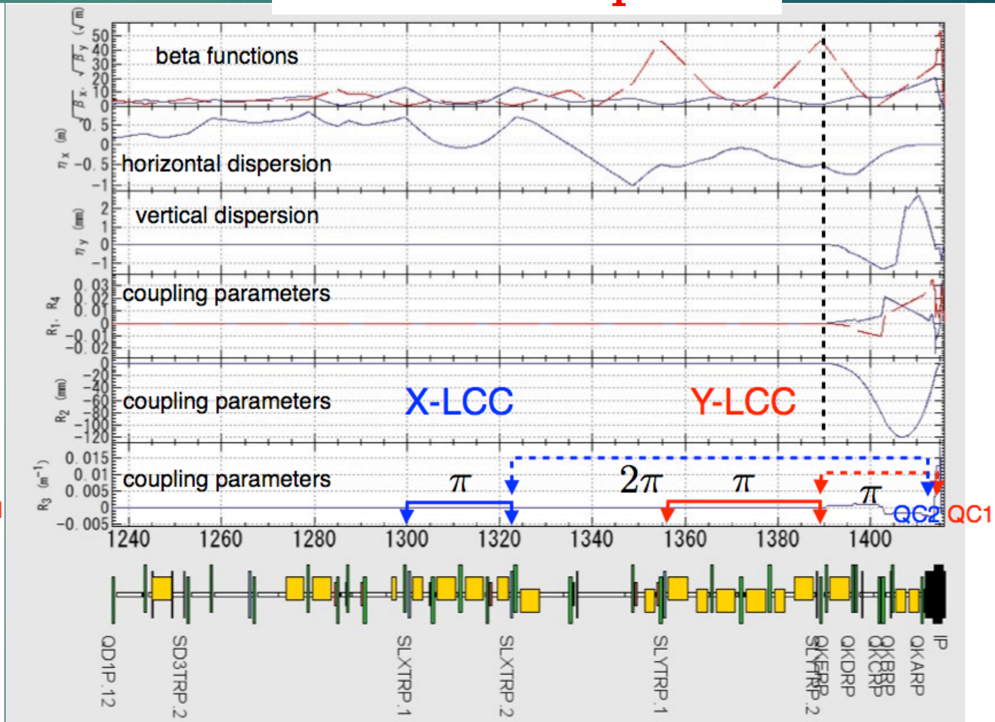
Natural chromaticity

	SuperKEKB		KEKB	
	LER	HER	LER	HER
Horizontal	-105	-171	-72	-70
Vertical	-776	-1081	-123	-124

HER LCC Optics



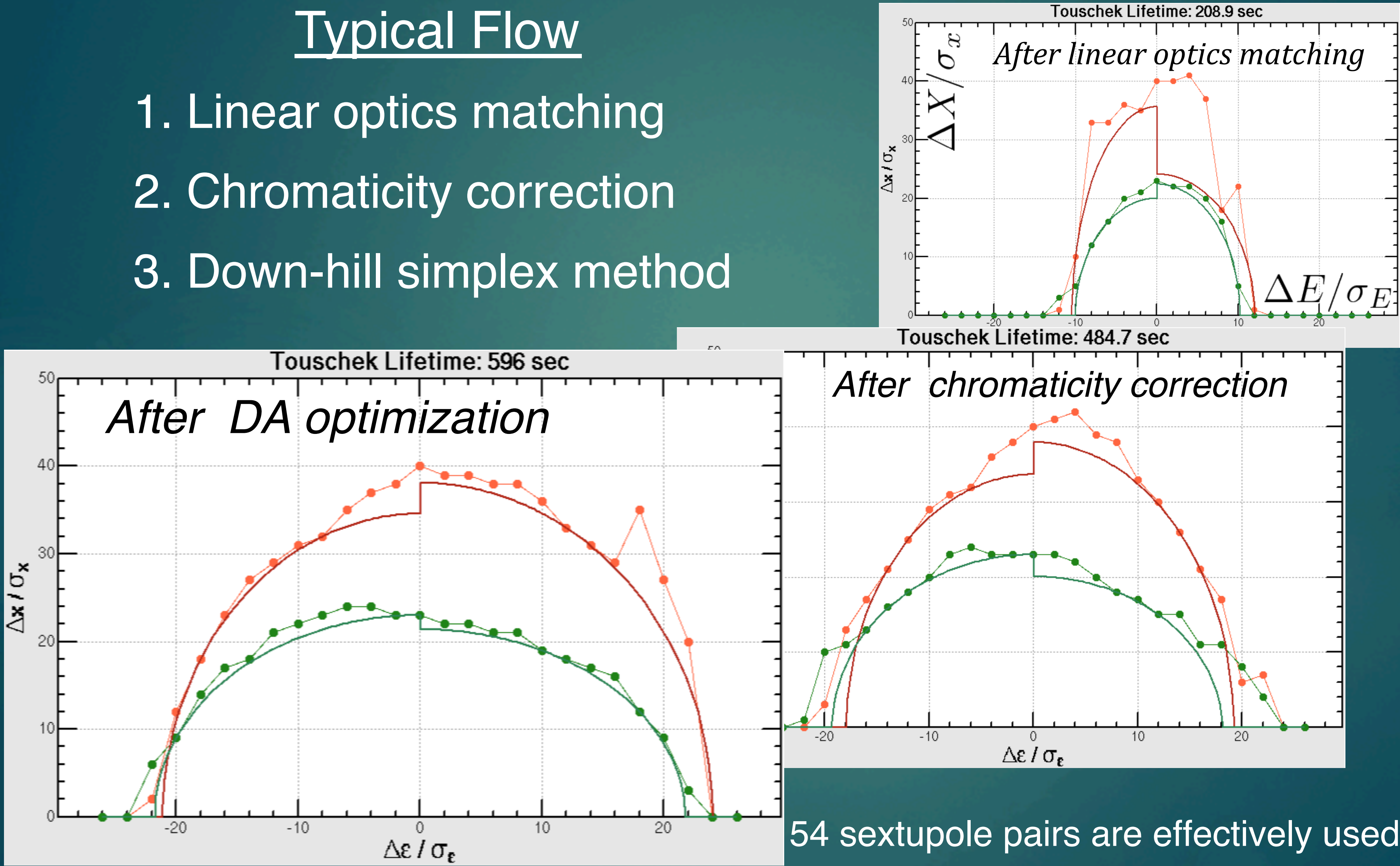
LER LCC Optics



Dynamic Aperture Optimization

Typical Flow

1. Linear optics matching
2. Chromaticity correction
3. Down-hill simplex method



54 sextupole pairs are effectively used.

Octupole Corrector

- Original purpose
  Cure the non-linear fringe of the final focus quadrupoles

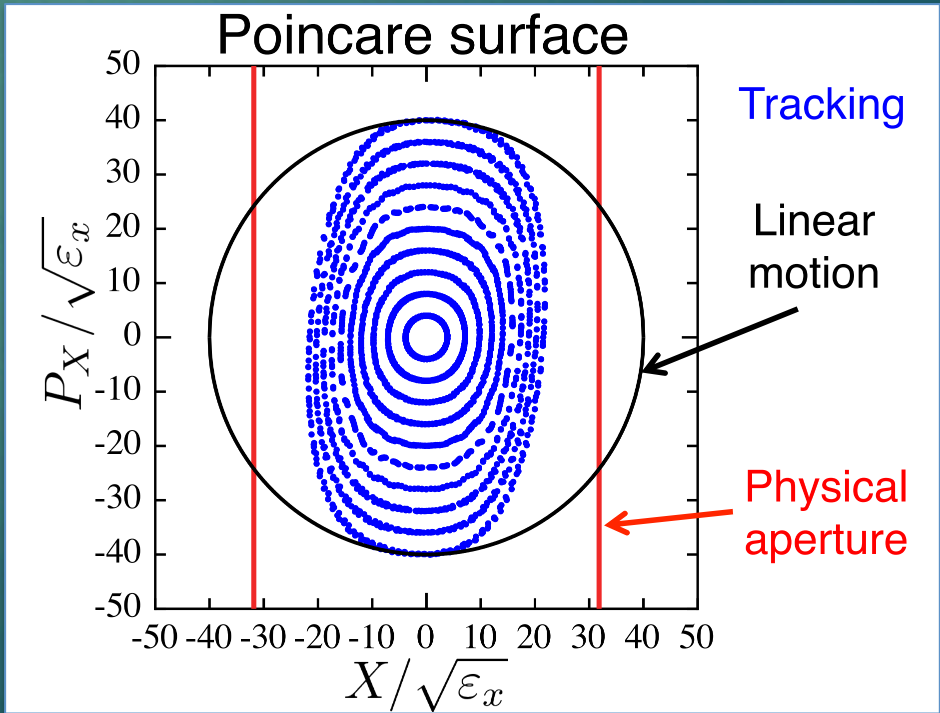
Fringe effect from a quadrupole magnet

$$x \to x \pm \frac{b_2}{12(1+\delta)}\left(x^3 + 3y^2x\right) \qquad y \to y \pm \frac{b_2}{12(1+\delta)}\left(y^3 + 3x^2y\right)$$

$$p_x \to p_x \pm \frac{b_2}{4(1+\delta)}\left(2xyp_y - x^2p_x - y^2p_x\right) \qquad p_y \to p_y \pm \frac{b_2}{4(1+\delta)}\left(2xyp_x - y^2p_y - x^2p_y\right)$$

- Actual usage
  Manipulate the Hamiltonian torus so that a particle with large action variable can pass through the IR physical aperture.

  Utilized especially in LER



Frequency Map Analysis

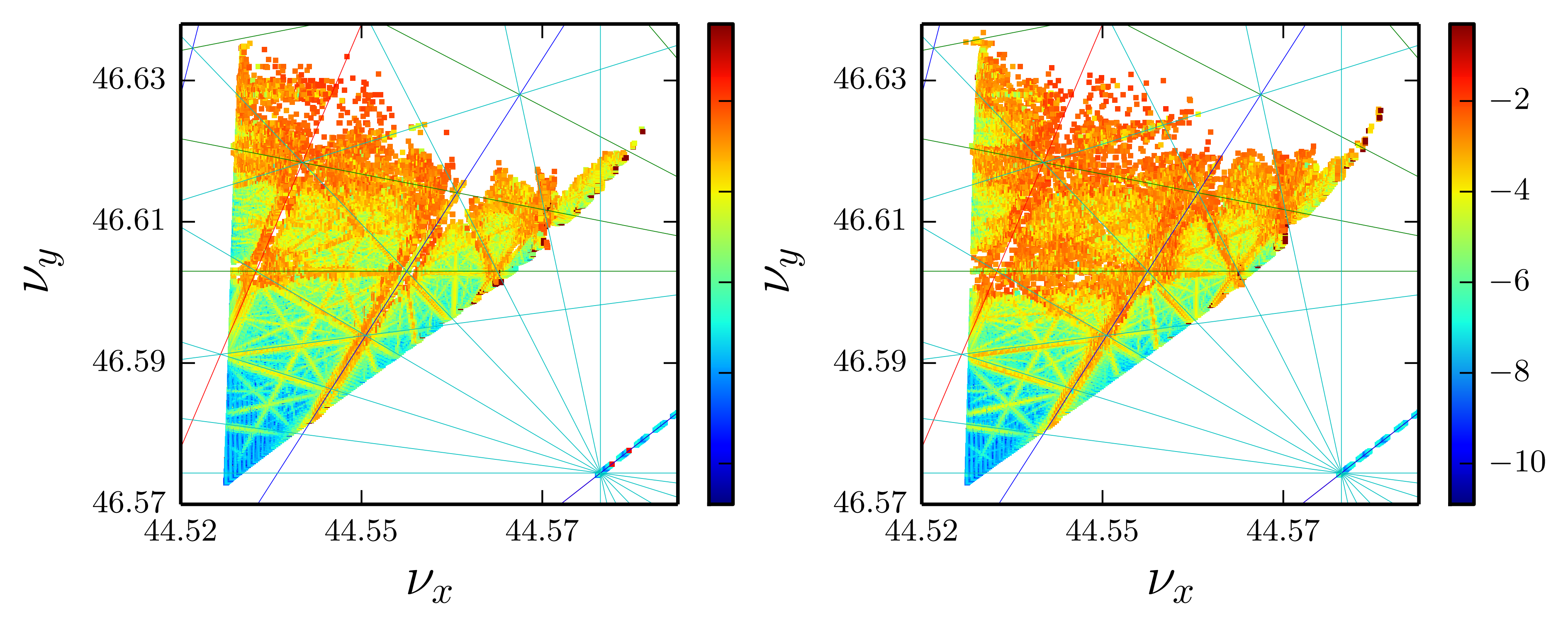
- Diffusion rate calculated from 2000 turn tracking data

$$\log_{10}\sqrt{(\nu_{x1}-\nu_{x2})^2+(\nu_{y1}-\nu_{y2})^2}$$

- LER footprints

4th order
5th order
6th order
7th order

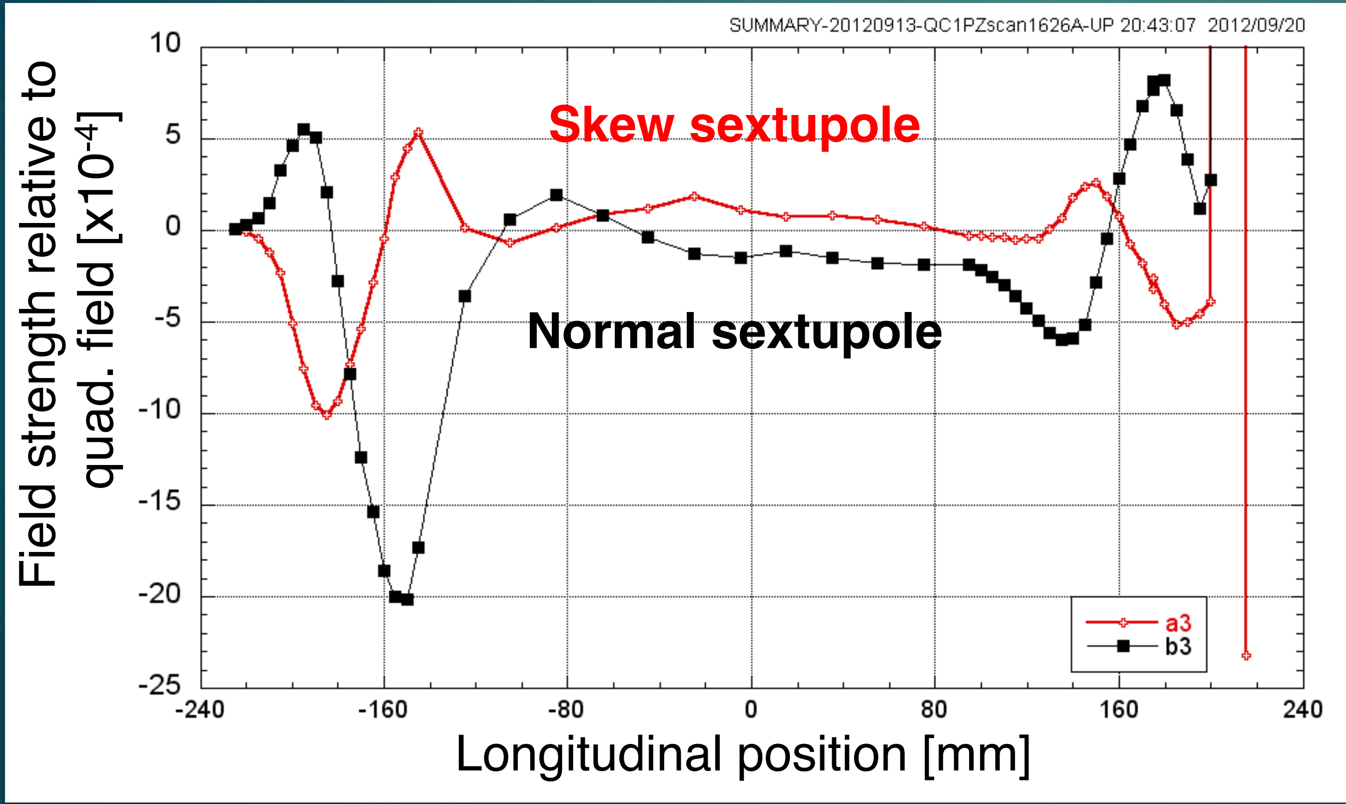
Nominal Lattice | **Lack of a corrector coil**



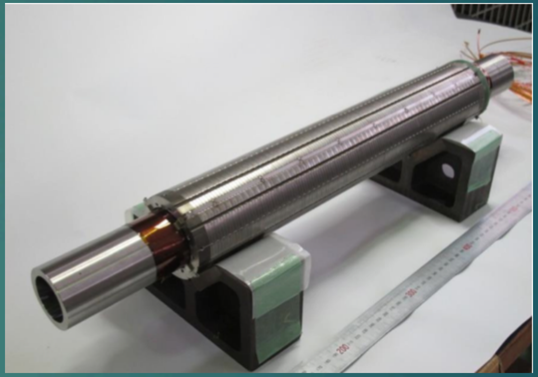
QCS Imperfection

- Unexpected normal and skew sextupole have been observed.
- Amplitude is ~0.1% of the quadrupole field.
- Likely due to misalignment of the main coils of a few tens of μm.

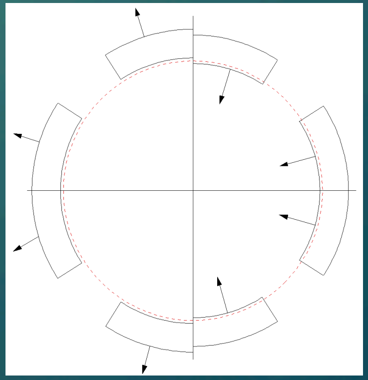
Field profile along QC1P prototype



QC1P Prototype



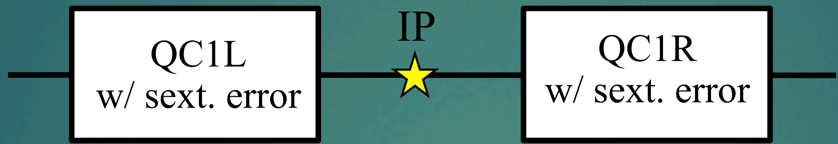
Coil misalignment model (Transverse plane)

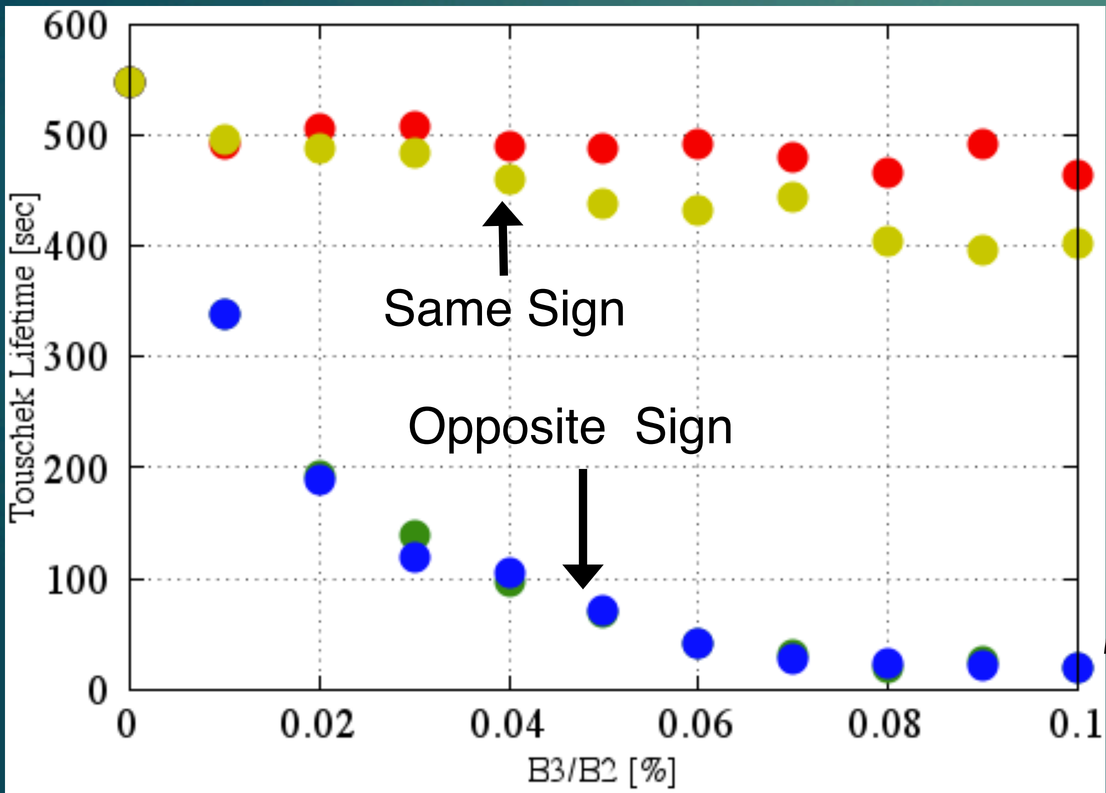


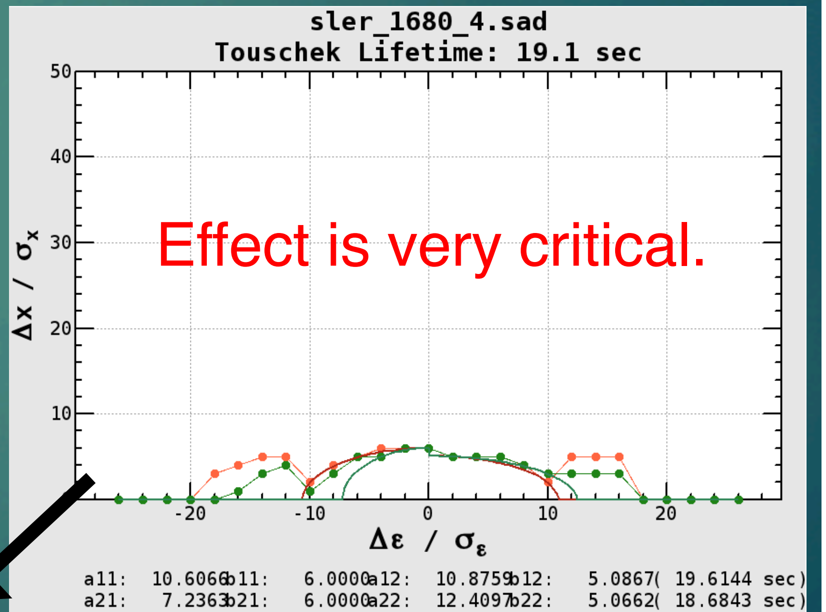
- How much impact on the dynamic aperture?

Numerical Study

- Thin lens sextupoles are inserted to QC1L and QC1R.
- Their magnitudes are identical, while signs are independent.
- Evaluate DA for 4 possible combinations of signs at each error amplitude.

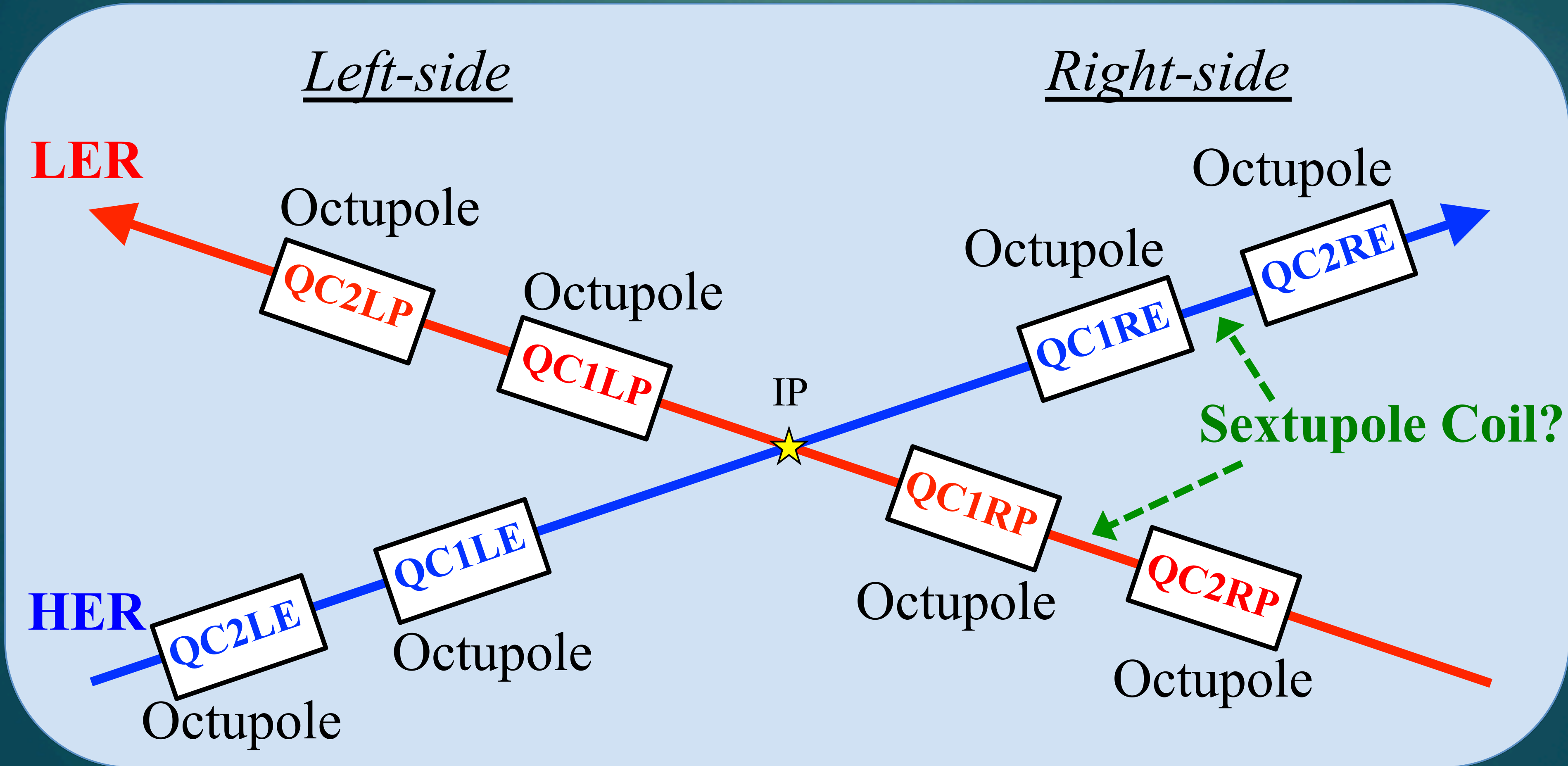






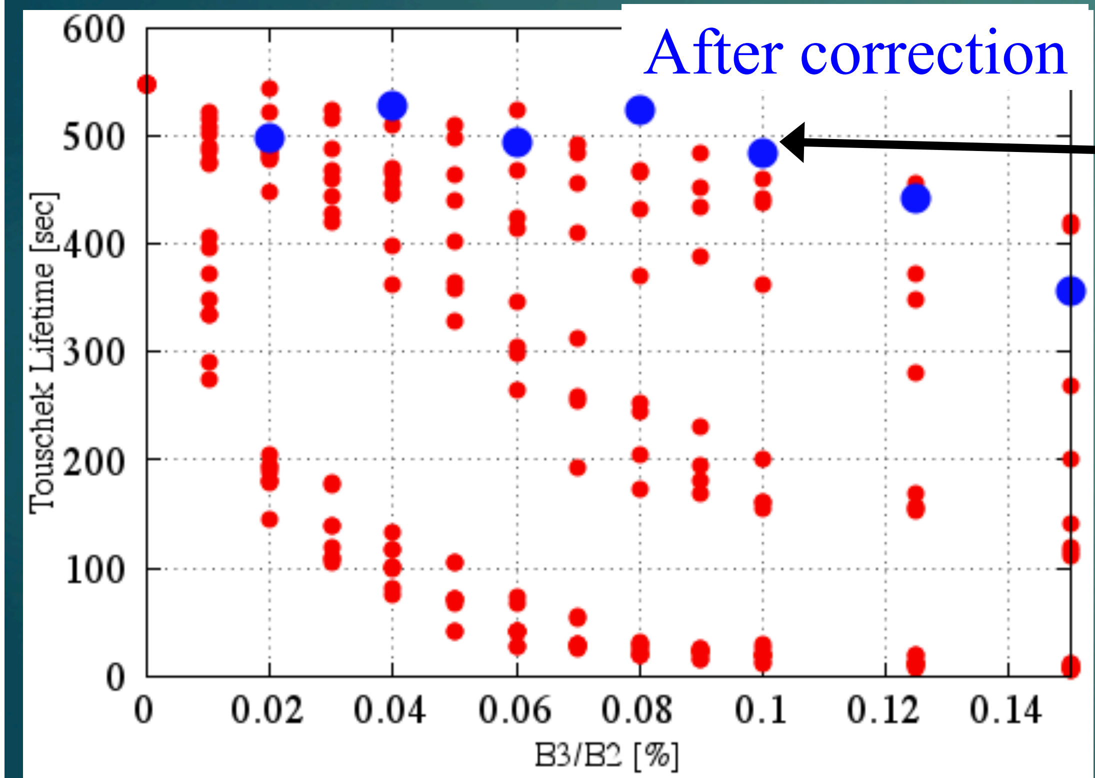
Install Sextupole Corrector?

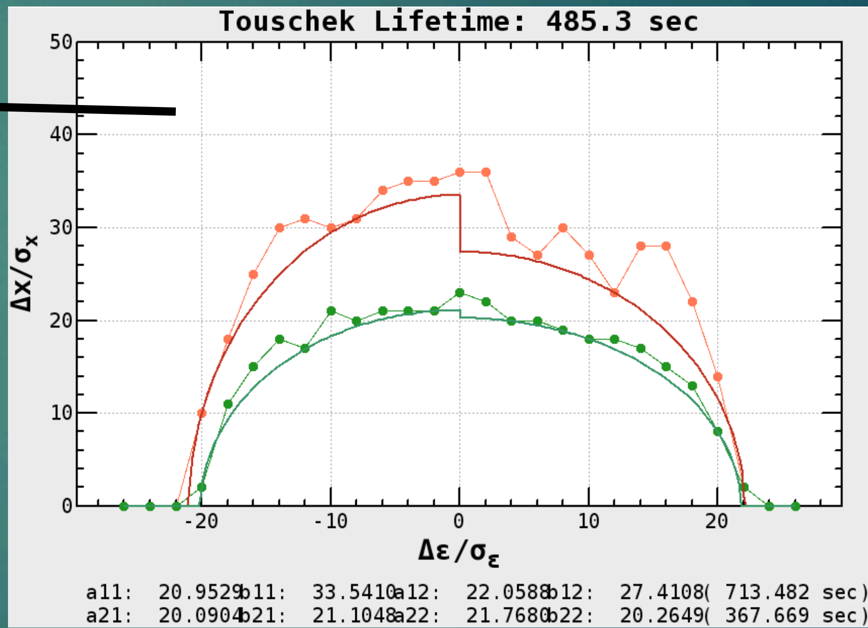
- Only right-side design can be changed. (Light-side has been fixed)
- The location between QC1 and QC2 considered to be a candidate.



DA Improvement by Corrector Coil

- Introduce sextupole error to ALL QCs.
- Check whether we can mitigate DA degradation by optimizing the corrector strength.

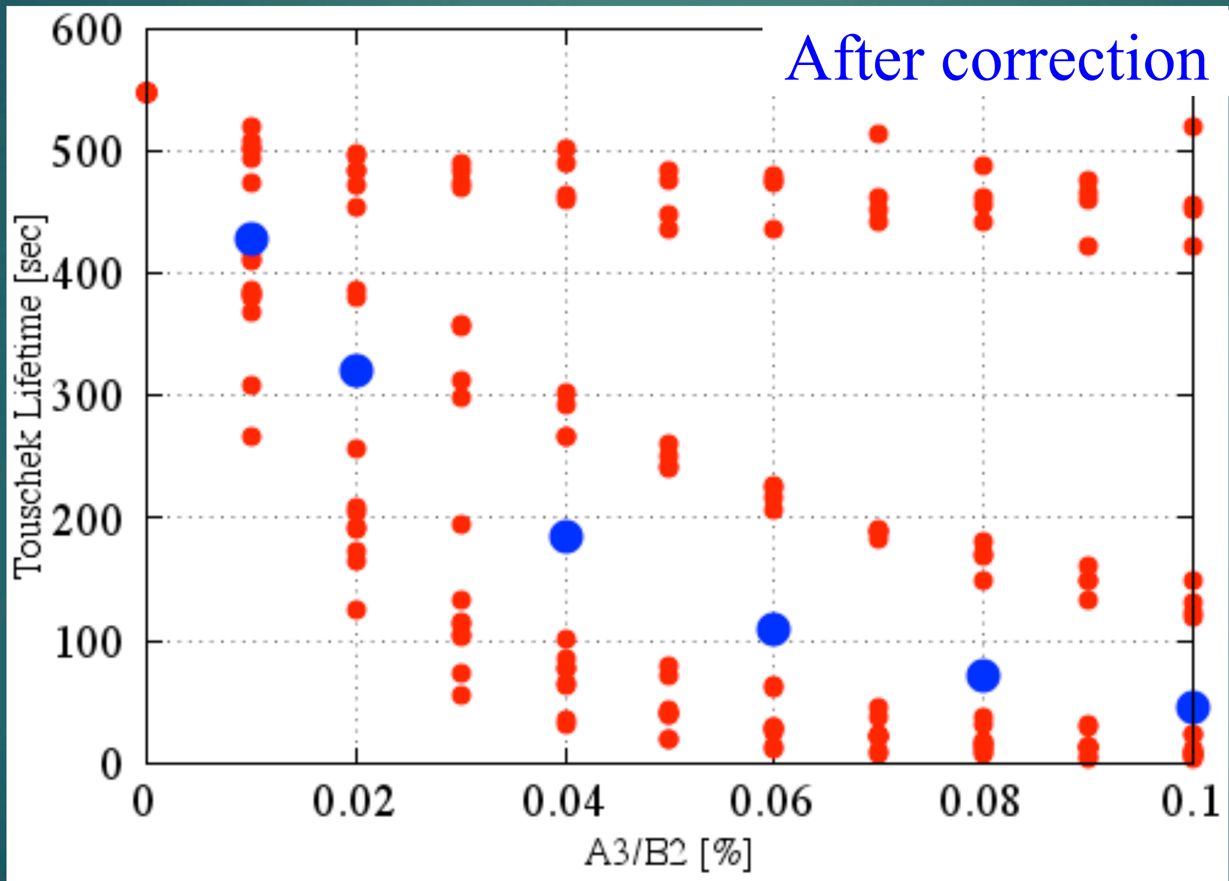




- DA degradation is improved, but B3/B2 < 0.1% is preferable.

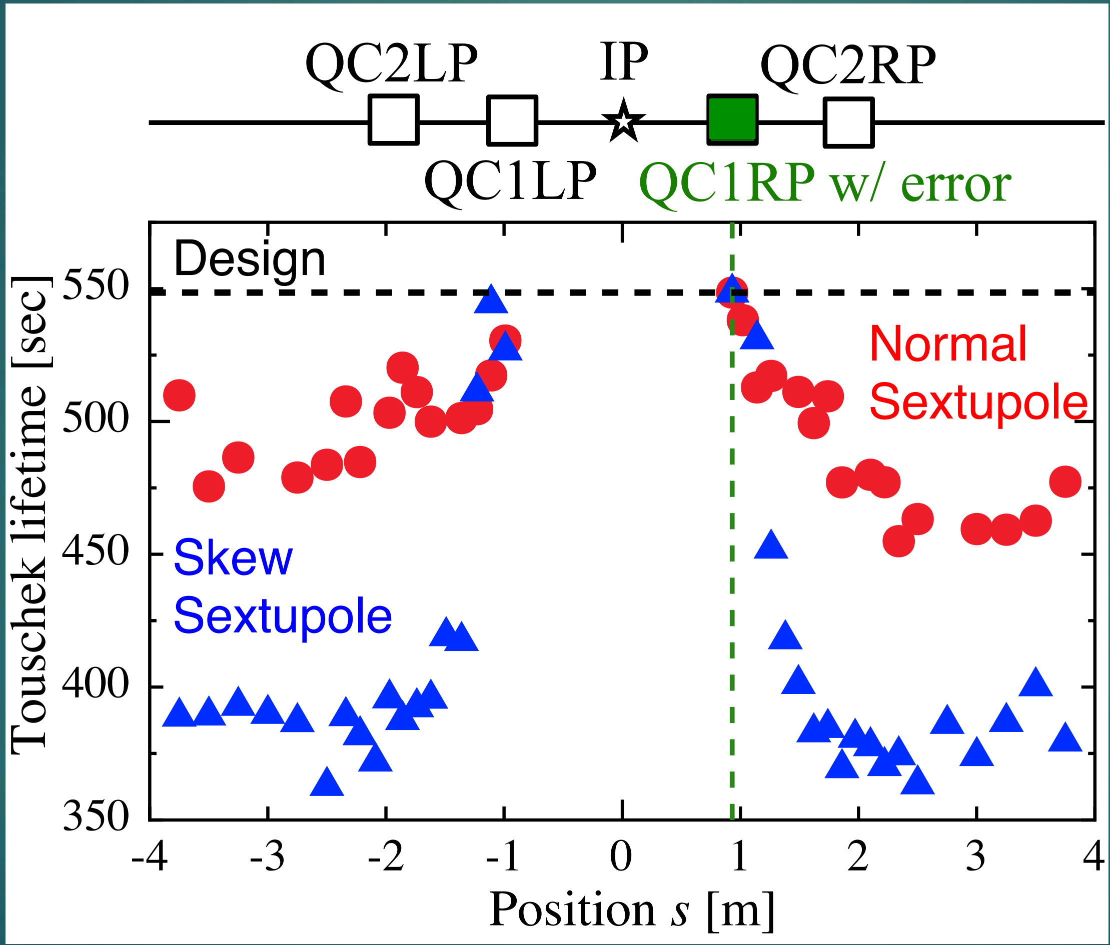
Skew Sextupole Error Field

- Similar calculation for skew sextupole error field.
- DA Improvement is not enough level compared to the sextupole case.



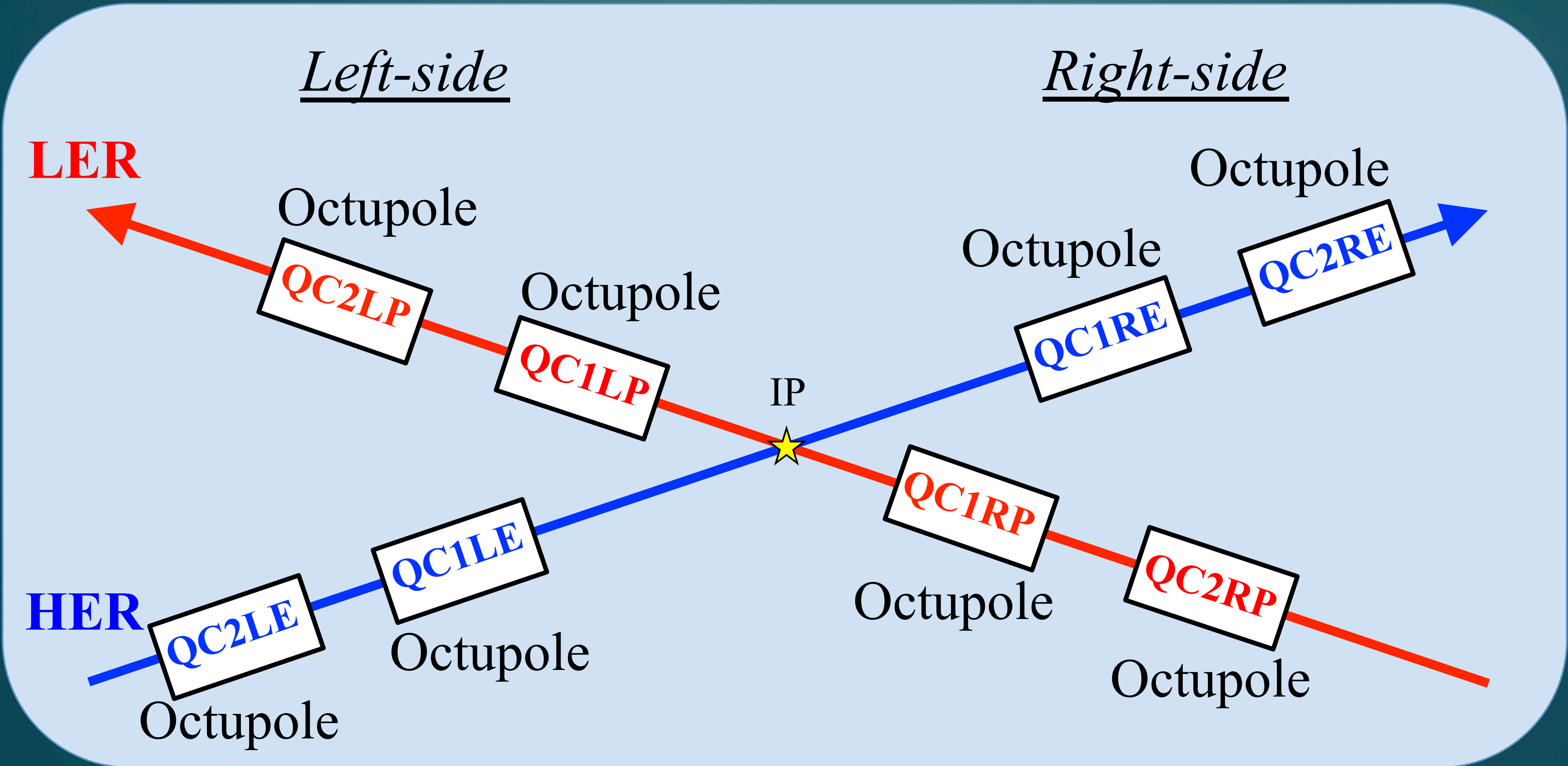
Lifetime and Corrector Coil Position

- DA survey with changing corrector position.
- Only QC1RP has skew sextupole error.



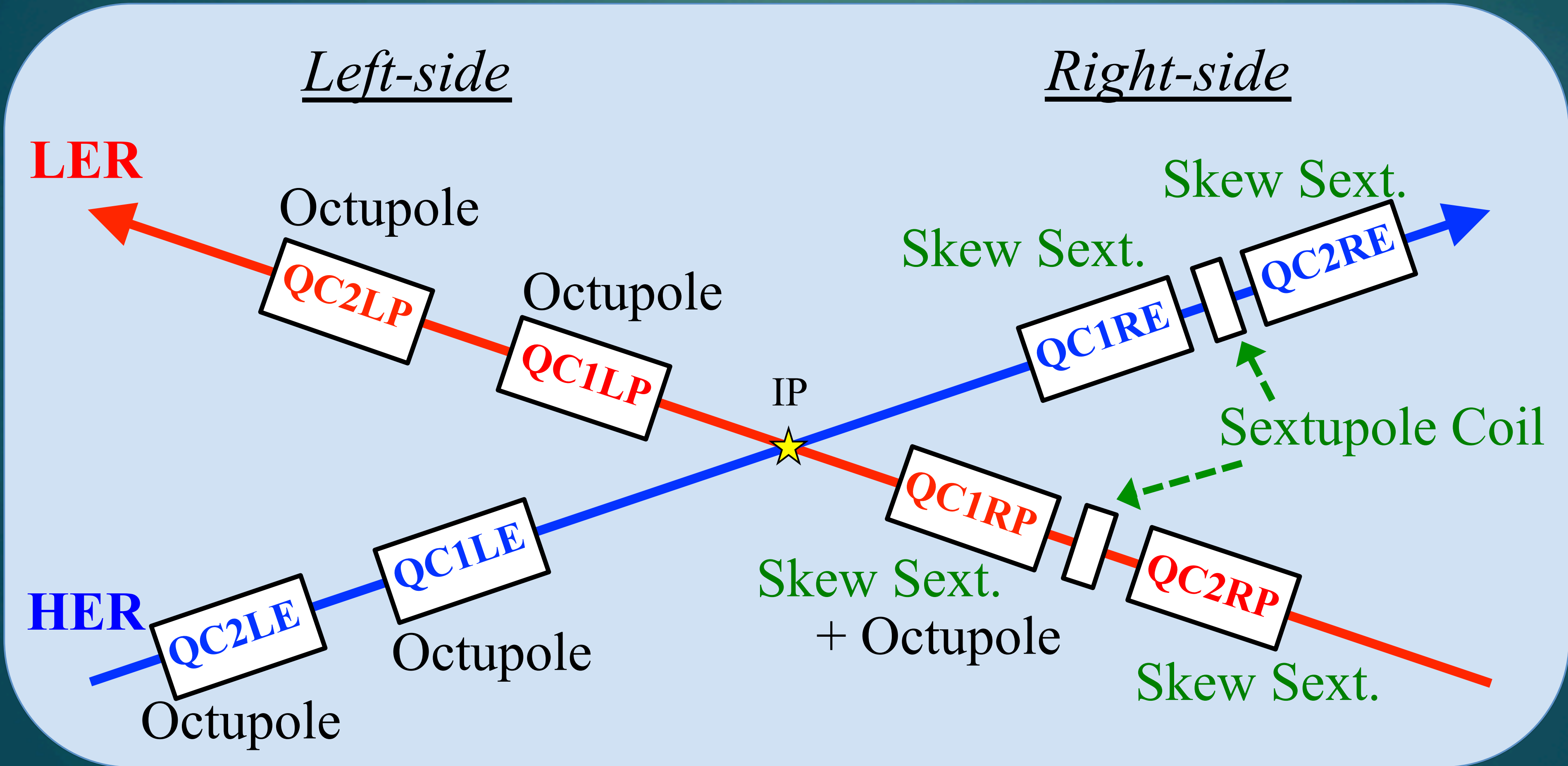
- ***Skew corrector must be installed to QC1.***

Original Design



Current Design

- Skew sextupole corrector is installed to two final focus magnets in the right-side.
- QC1RP still have octupole coil to avoid undesirable resonances.



Summary

- The SuperKEKB IR optics design has been finalized.

- Linear Optics
  - The solenoid field is optimized by minimizing X-Y coupling and vertical emittance.

- DA optimization
  - Chromaticity correction and the Down-hill simplex method.
    Knobs are
      54 pairs of sextupole magnets along the ring
      Octupole correctors (3/LER, 2/HER)

- Sextupole error field of QCs
  - Effect on DA is very critical.
  - Decided to install correctors with consideration on fabrication schedule and the space limitation.

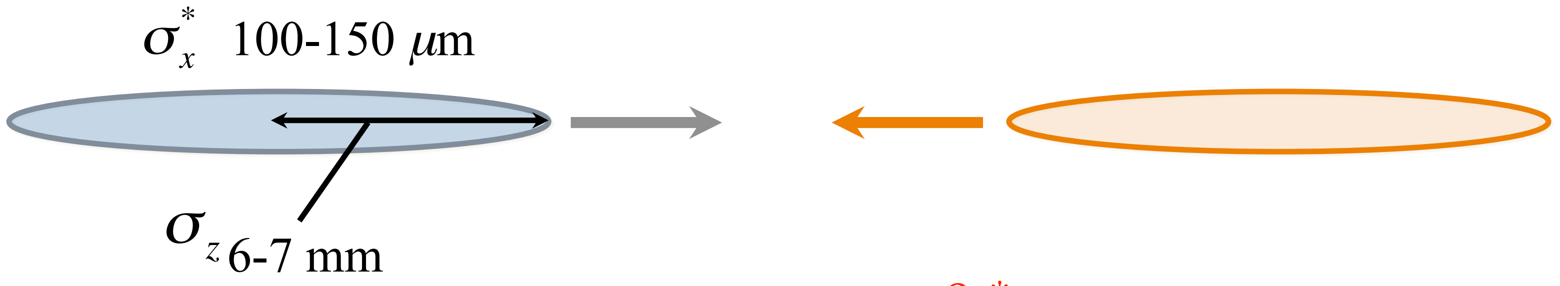
Backup

Machine Parameters

	LER	HER
Energy (GeV)	4.0	7.007
Current (A)	3.6	2.6
#of bunches	2500	2500
β_x^* (mm)	32	25
β_y^* (mm)	0.27	0.30
ε_x^* (nm)	3.2	4.6
ε_y^* (pm)	8.64	11.5
σ_z^* (mm)	6	5
ν_x , ν_y	44.53 , 46.57	45.53 , 43.57
ν_s	-0.0247	-0.0280
ξ_y	0.0881	0.0807
Luminosity (10^{34} cm^{-2} s^{-1})	8×10^{35}	

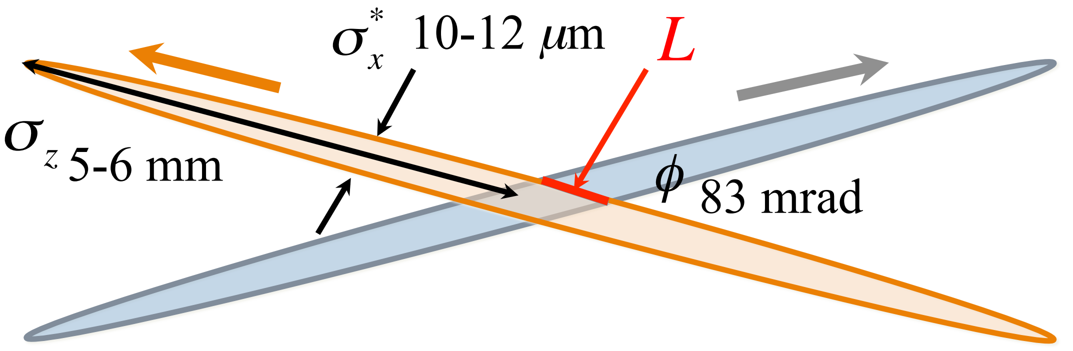
Collision Scheme

- **KEKB** head-on (crab crossing)



hourglass condition: $\beta_y^* >\sim \sigma_z$

- **Nano-Beam SuperKEKB**



hourglass condition: $\beta_y^* >\sim L$