Super KEKB

http://www-superkekb.kek.jp

Status of SuperKEKB

Y. Ohnishi

JOINT BELLE II & SUPERB BACKGROUND MEETING

VIENNA, AUSTRIA 9-10 FEBRUARY 2012

SuperKEKB Accelerator

- SuperKEKB is a double-ring, asymmetric energies collider:
  - LER e+ @ 4 GeV, HER e- @ 7 GeV
  - Nano-beam(large Piwinski angle) scheme
  - ***No crab waist at the baseline design***
  - ***No longitudinally polarized electron beam***
  - Target luminosity of $8x10^{35}$ $cm^{-2}s^{-1}$ at Y(4S)
  - No realistic consideration for tau/charm threshold so far
- Re-use of KEKB hardware as much as possible
- SuperKEKB DOES NOT consider "Light Source " usage because we think very difficulties of the simultaneous operation.

Machine Parameters

	SupeKEKB LER	SuperKEKB HER	SuperB LER	SuperB HER	unit
E	4.000	7.007	4.180	6.700	GeV
I	3.6	2.6	2.447	1.892	A
Number of bunches	2,500		978		
#Particles/bunch	9.04	6.53	6.56	5.08	10^{10}
Circumference	3,016.315		1,258.400		m
$\varepsilon_x/\varepsilon_y$	3.2(1.9)/8.64(2.8)	4.6(4.4)/11.5(1.5)	2.46(1.82)/6.15	2.0(1.97)/5.0	nm/pm
Coupling	0.27	0.28	0.25	0.25	
β_x^*/β_y^*	32/0.27	25/0.30	32/0.205	26/0.253	mm
Crossing angle	83		66		mrad
α_p	3.25	4.55	4.05	4.36	10^{-4}
σ_δ	$8.08(7.73)\mathrm{x}10^{-4}$	$6.37(6.31)\mathrm{x}10^{-4}$	$7.34\mathrm{x}10^{-4}$	$6.43\mathrm{x}10^{-4}$	
V_c	9.4	15.0			MV
σ_z	6.0(5.0)	5(4.9)	5.0(4.29)	5.0(4.69)	mm
ν_s	−0.0247	−0.0280	−0.0129	−0.0135	
ν_x/ν_y	44.53/44.57	45.53/43.57	42.575/18.595	40.575/17.595	
U_0	1.87	2.43	0.865	2.11	MeV
$\tau_{x,y}/\tau_s$	43.1/21.6	58.0/29.0	40.6/20.3	26.7/13.4	msec
ξ_x/ξ_y	0.0028/0.0881	0.0012/0.0807	0.0033/0.0971	0.0021/0.0970	
Luminosity	$8\mathrm{x}10^{35}$ (P_{tot} = 71 MW)		10^{36} (P_{RF} = 17 MW)		$cm^{-2}s^{-1}$

Beam Energy

- ***Electron beam is 7 GeV.***
  - Ion effect becomes serious for lower energy.
  - Ion speed is very slow, the beam is influenced by only electric field

$$\Delta\nu \propto \frac{F_r}{\gamma} \propto \frac{1}{\gamma} \qquad F_r = eE_r + evB_\theta$$

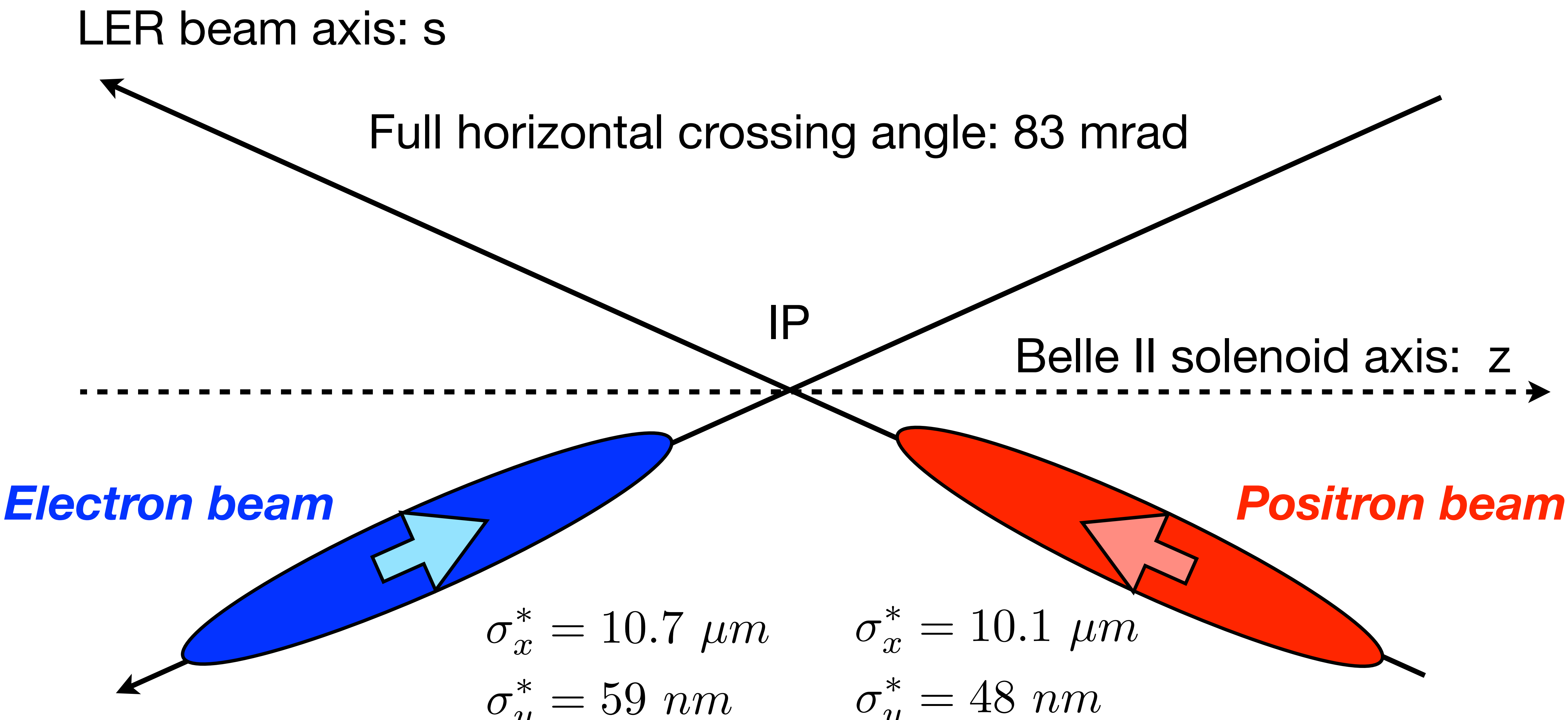
- ***Positron beam is 4 GeV.***
  - Photoelectron remains stationary. The beam is influenced by only electric field. Density of photoelectron is proportional to the beam energy. Therefore, tune shift is

$$\Delta\nu \propto \frac{F_r}{\gamma} \propto \frac{\rho}{\gamma} \propto 1$$

If the dominant source is multipacting, there is another argument.

  - It is difficult to make positrons having higher energy than electrons at the present injector scheme.

Colliding Beams at SuperKEKB



LER beam axis: s

Full horizontal crossing angle: 83 mrad

IP

Belle II solenoid axis: z

Electron beam

Positron beam

$\sigma_x^* = 10.7\ \mu m$

$\sigma_y^* = 59\ nm$

Piwinski angle: 19.4

$\sigma_x^* = 10.1\ \mu m$

$\sigma_y^* = 48\ nm$

Piwinski angle: 24.6

HER beam axis: s

(sometimes flips in case of tracking simulation)

Low Emittance Optics

- Nano-beam scheme needs low emittance.
  - 1/10 of KEKB for LER and 1/5 for HER
- Emittance (in simple case):

$$\varepsilon_x = \frac{C_\gamma \gamma^2}{J_x} \frac{1}{2\pi\rho_0^2} \oint_{bend} H(s) ds$$

$$H(s) = \gamma_x(s)\eta_x(s)^2 + 2\alpha_x(s)\eta_x\eta_{px} + \beta_x(s)\eta_{px}^2$$

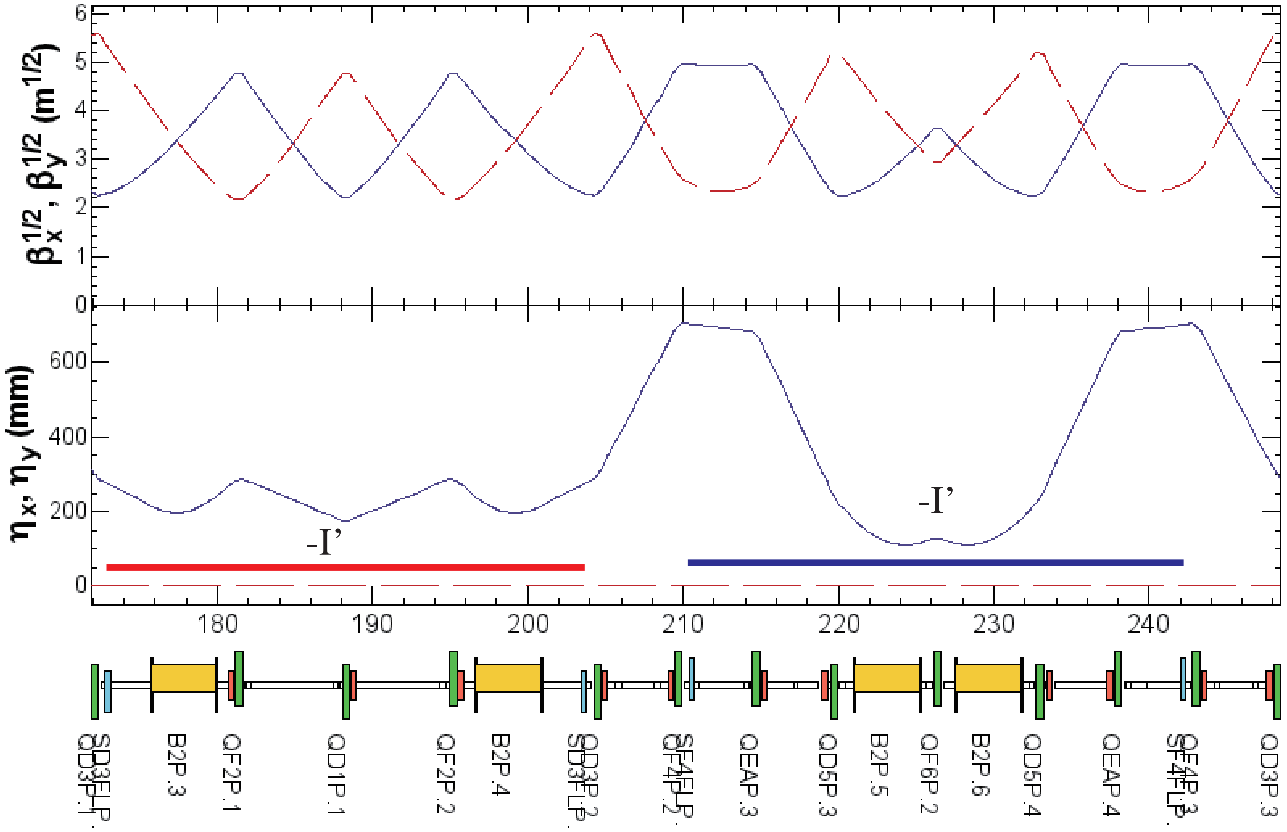
- In order to reduce emittance:

1. larger bending radius (long magnet) → ***LER (replace magnet: 0.9→4.2 m)***
2. smaller H(s) in bending magnet → ***HER (Twiss parameters)***
3. larger damping partition number (J_x) ← *Frequency shift*

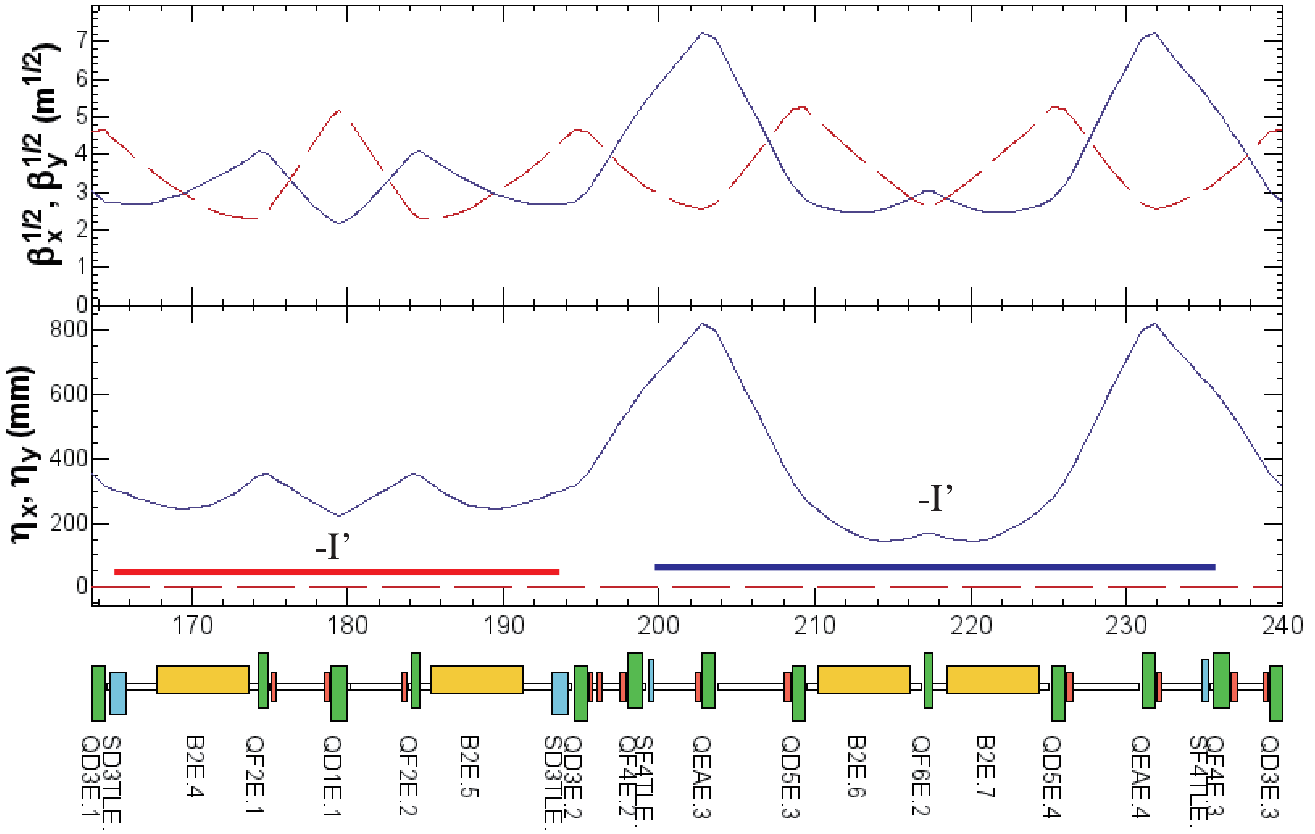
Arc Cells

- 2.5 π non-interleaved sextupole correction (24 normal cells)

LER



HER

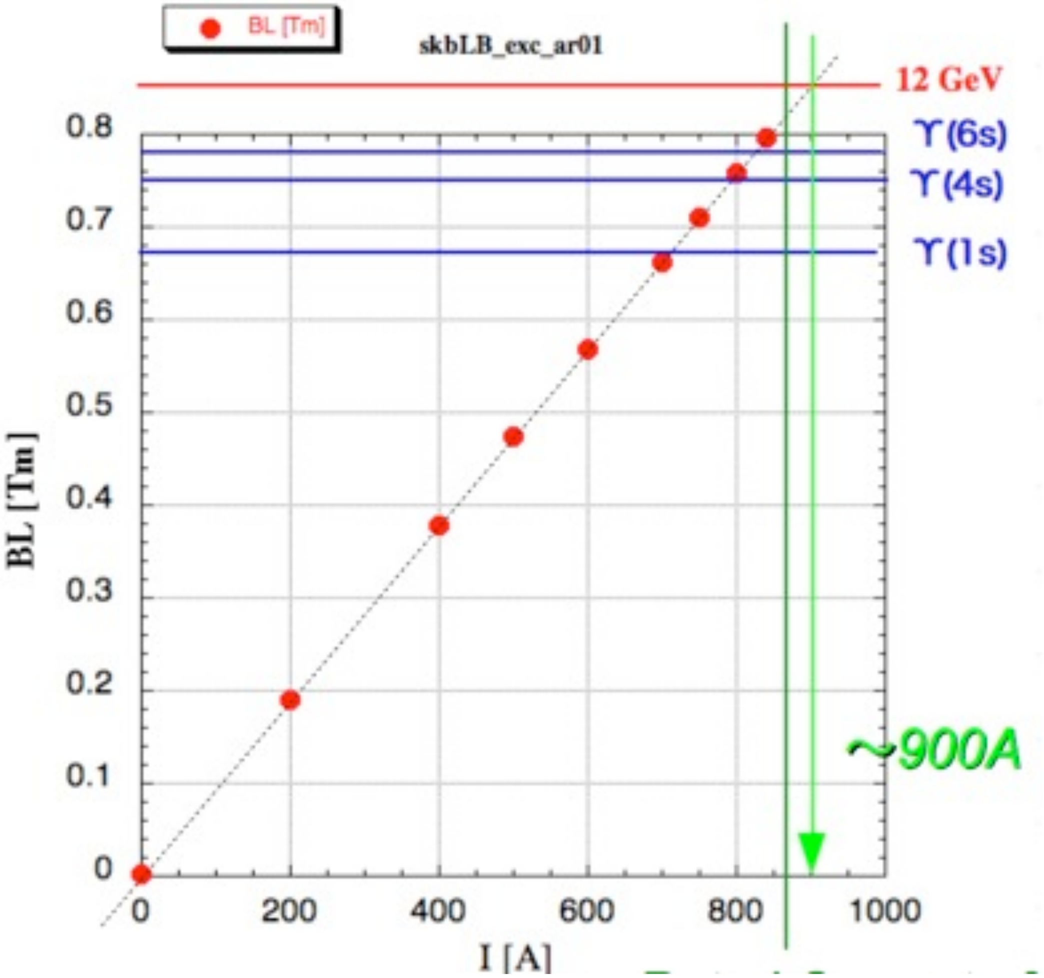


Positron →

← Electron

5.7 m length for dipole magnets

New Main Bending Magnet in LER



Anchor bolt for base plate
(new 4.2 m bending magnet)

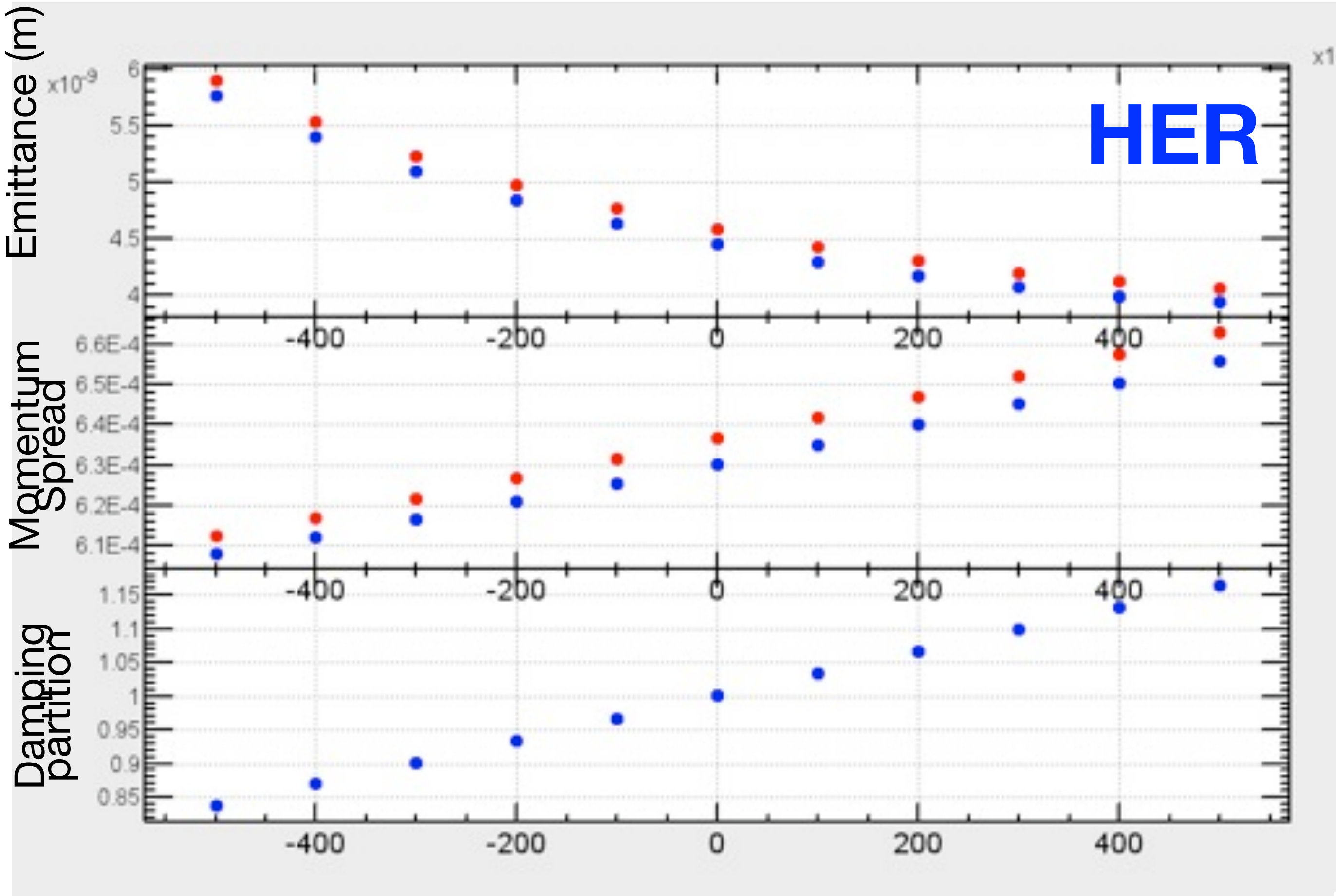
← ***Preliminary field measurement***
Y(6S) could be achieved within the rated current.
12 GeV operation with keeping boost factor is risky.

Hot News !

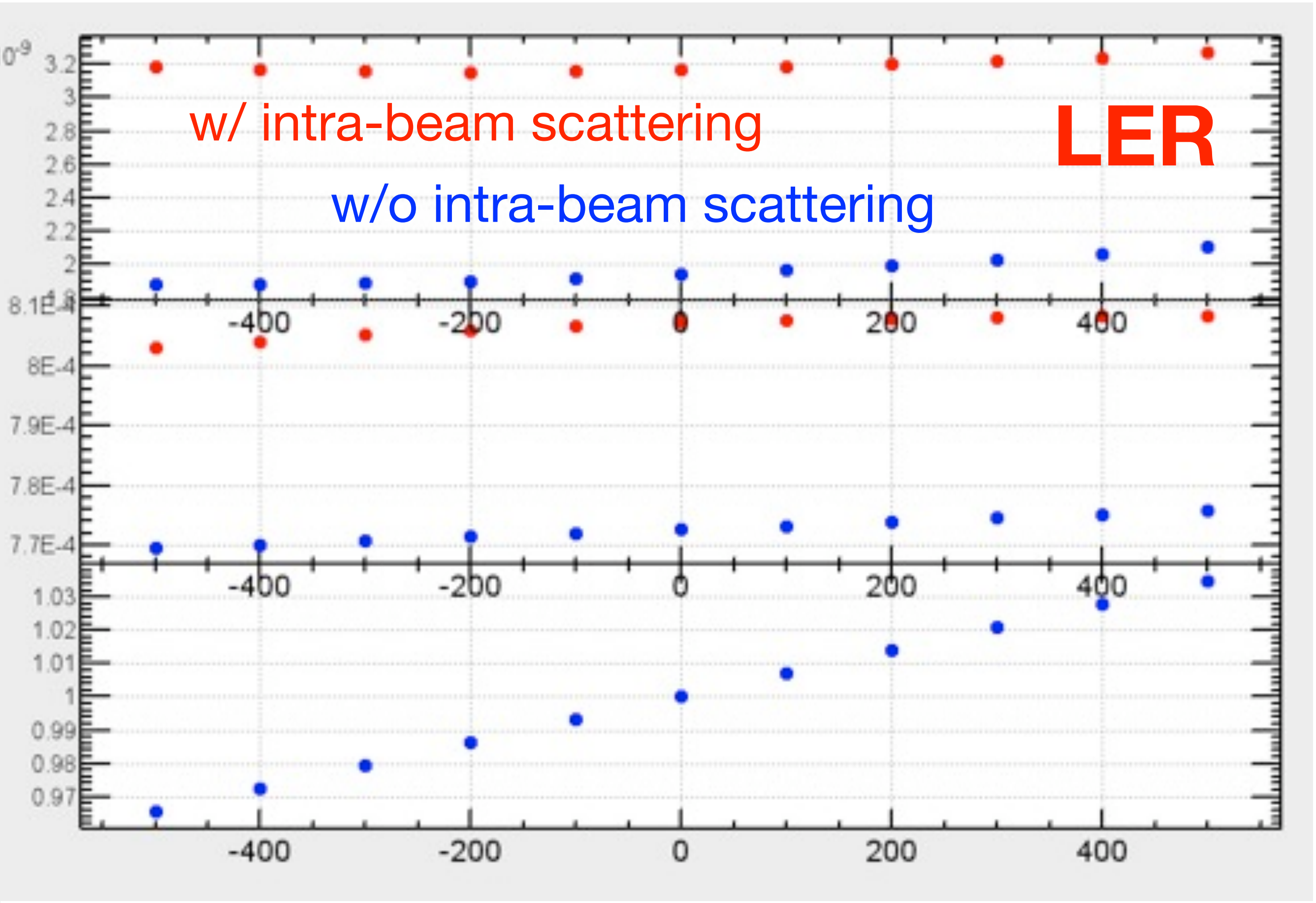
For the first time, a new main bending magnet was installed in LER.

Feb. 7, 2012

Frequency Shift



frequency shift (Hz)



frequency shift (Hz)

No gain for LER

10 % reduction in HER incase of +400 Hz: ΔC = -2.4 mm

Energy spread becomes large. Bad mass resolution ?

Dynamic aperture ?

We don’t use this technique.

Ref: SLAC Pub-7954 September 1998
CERN SL-99-031 AP

Five Big Issues (FBI)

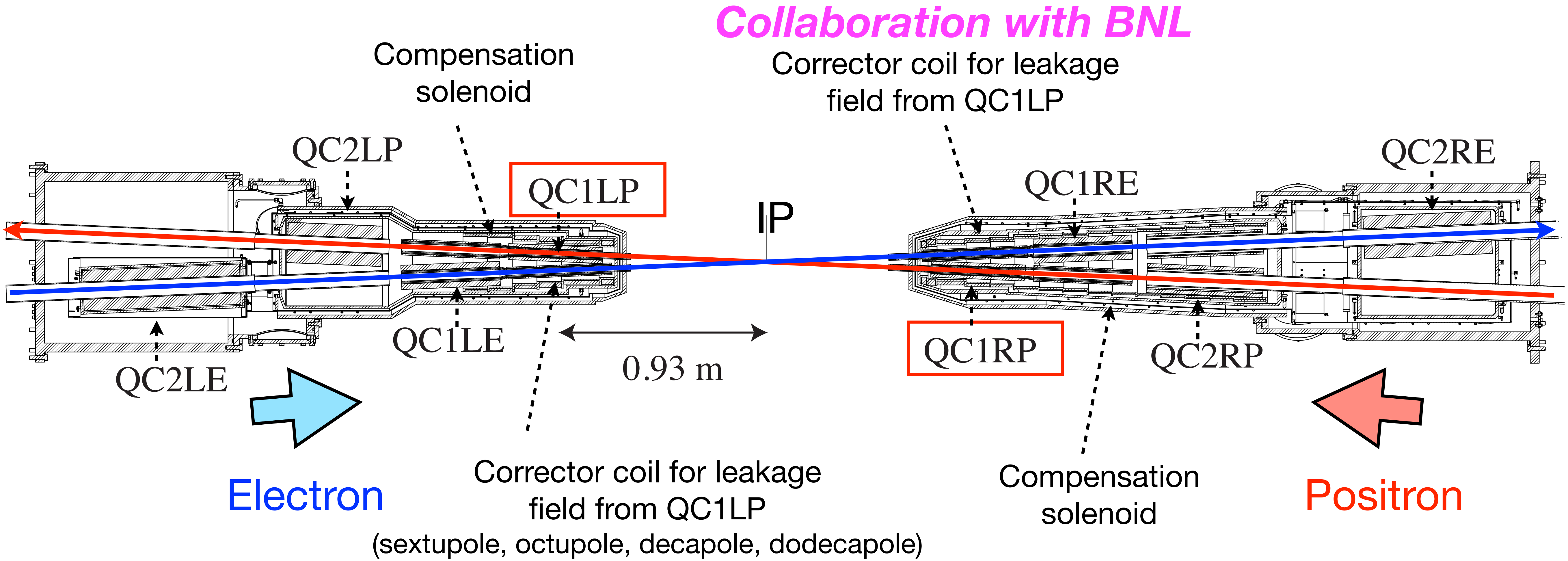
- Dynamic Aperture (Touschek lifetime)
- Machine Error and Orbit/Optics Correction
- Injection with Beam-Beam effect
- Detector Background and Collimator
- Beam Energy (variable range)

Dynamic Aperture

- Dynamic aperture is very sensitive to the IR design.
- Touschek lifetime and injection efficiency are determined by a dynamic aperture.
- Dynamic aperture is restricted by a nonlinear filed such as multipoles and fringes from the solenoid magnet, the final focusing magnets, and the sextupole magnets, and so on.
- ***Higher order multipoles for QC1/QC2: K2-K21, SK2-SK21***
- ***SK2-SK9 for solenoid field (in case of 3D field calculation)***

Layout of IR Magnets

- Each QC1/QC2 has an iron shield except for QC1LP/QC1RP in LER.



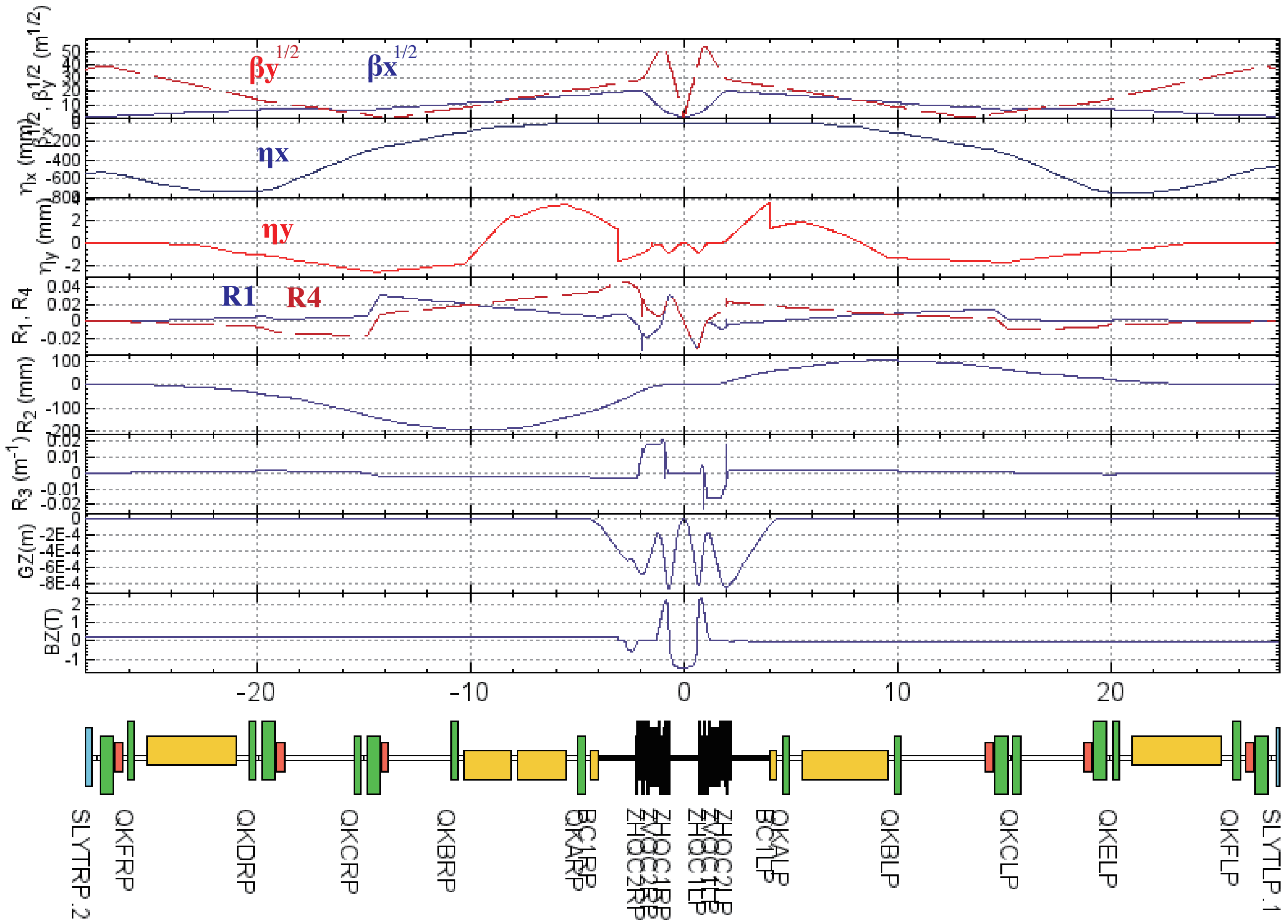
- Superconducting magnets have dipole, skew dipole, skew quadrupole, and octupole correction coils.

- Even though dipole and quadrupole leakage field from QC1LP/QC1RP exists in HER, we take an horizontal offset(~700 μm) of QC1/QC2 in HER and dipole corrector of QC1 to adjust design orbit and use quadrupole field for focusing force.

IR Optics Design

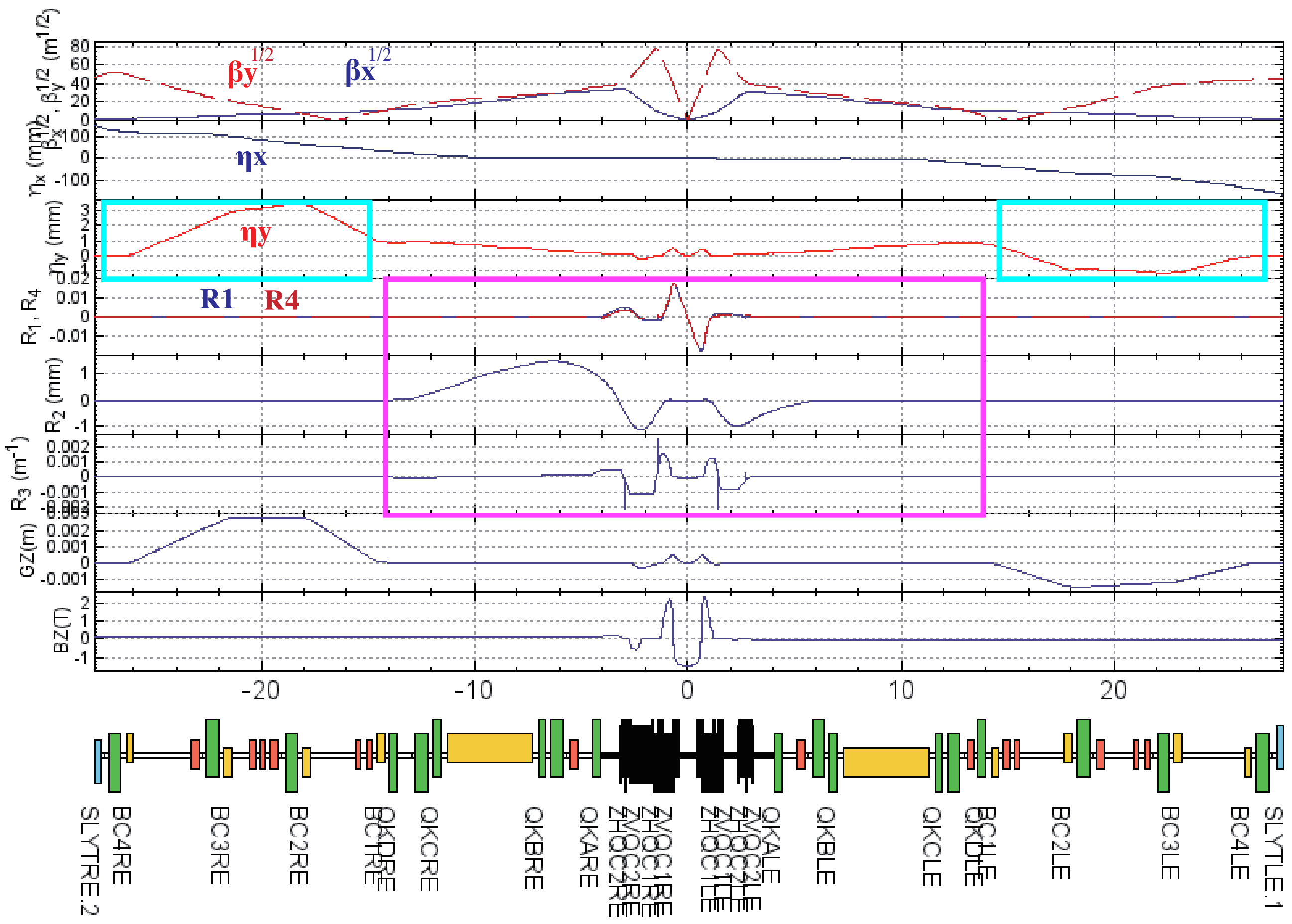
- LER: X-Y couplings and vertical dispersions are corrected by skew dipoles in QC1/QC2, rotation of QC1/QC2 around the beam axis, and skew quadrupoles before the local chromaticity correction.
- HER: X-Y couplings and vertical dispersions are separated for their correction.

LER



Positron

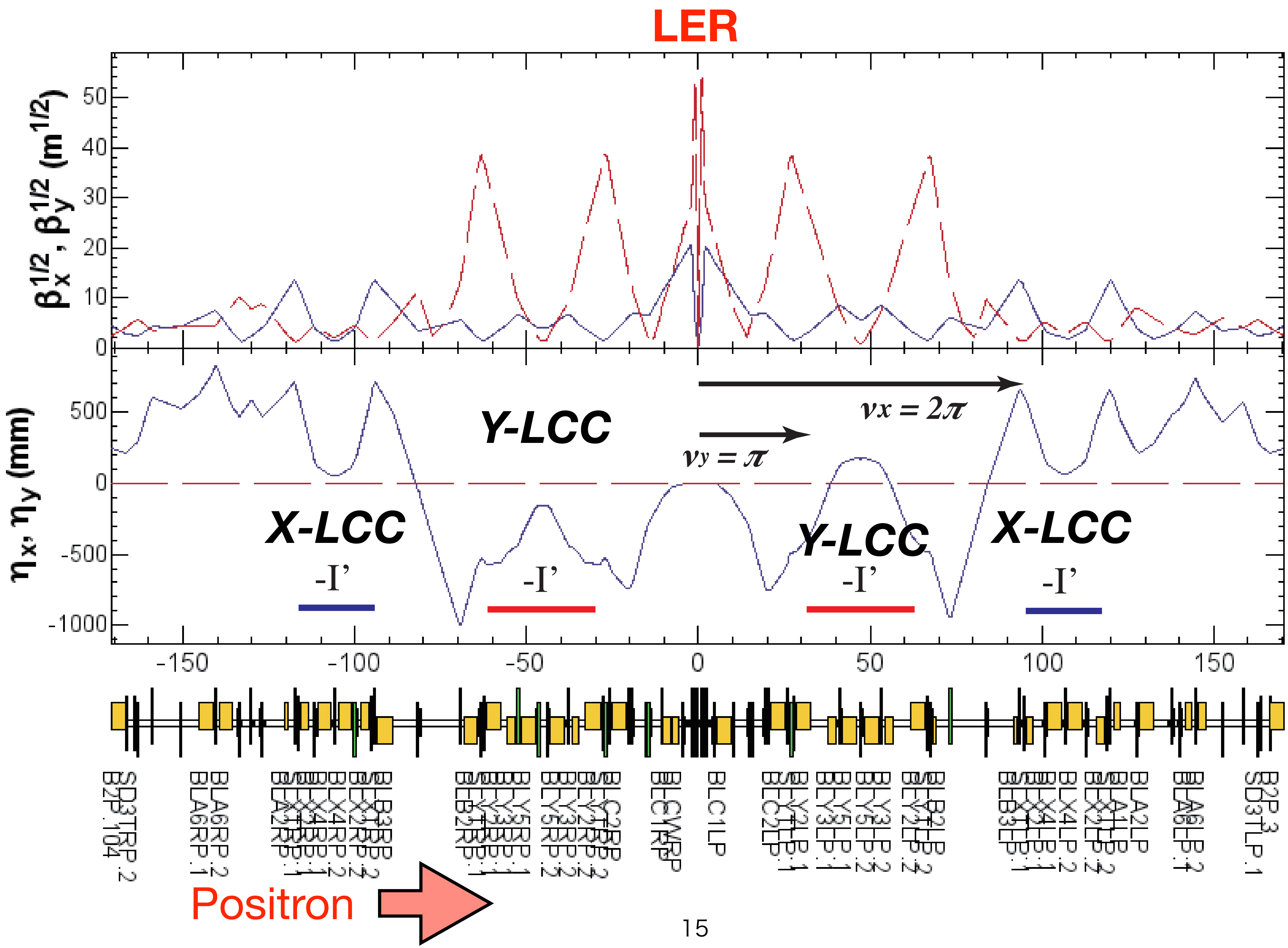
HER



Electron

IR Optics Design in LER

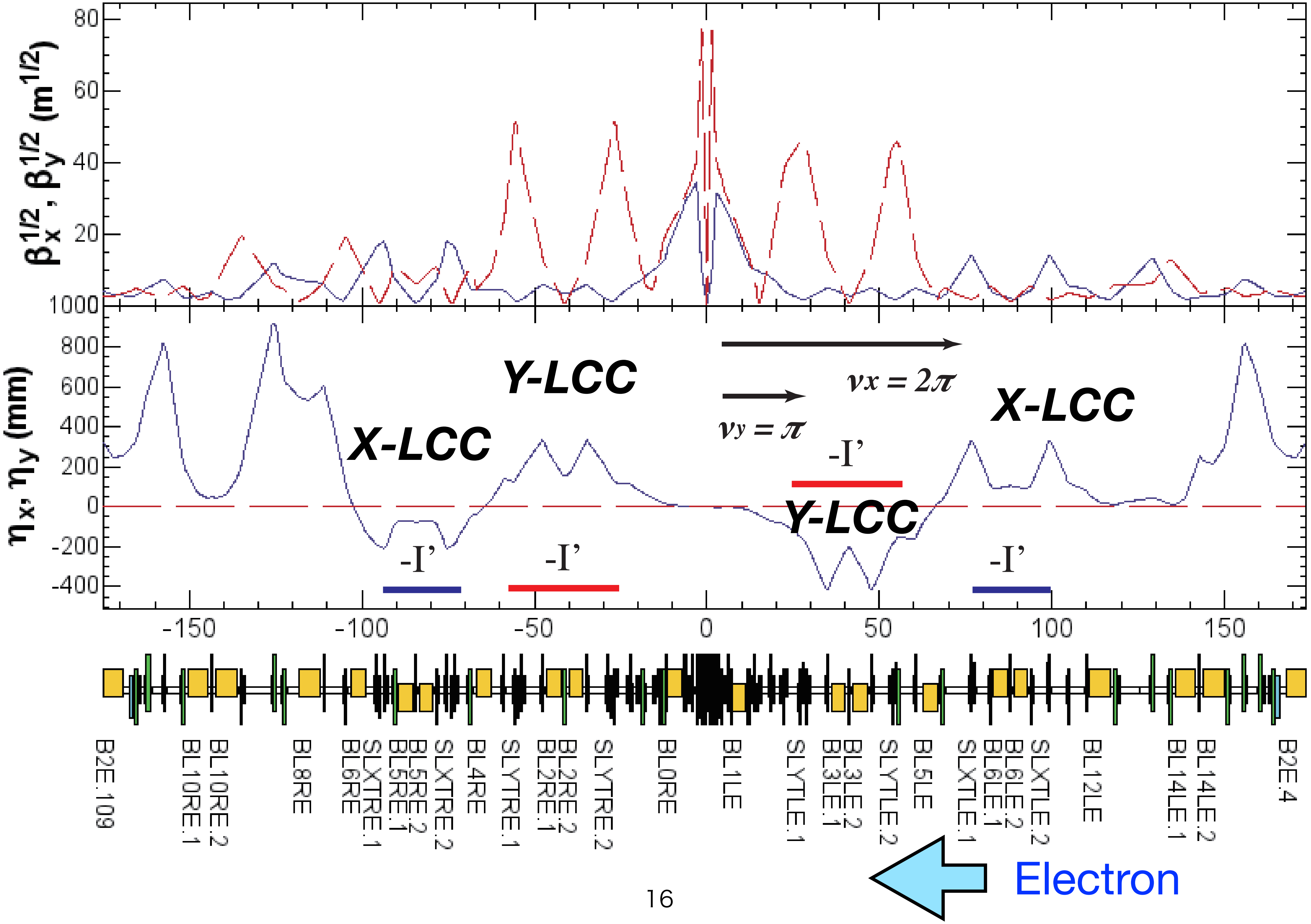
- Local chromaticity corrections (Y-LCC, X-LCC)



IR Optics Design in HER

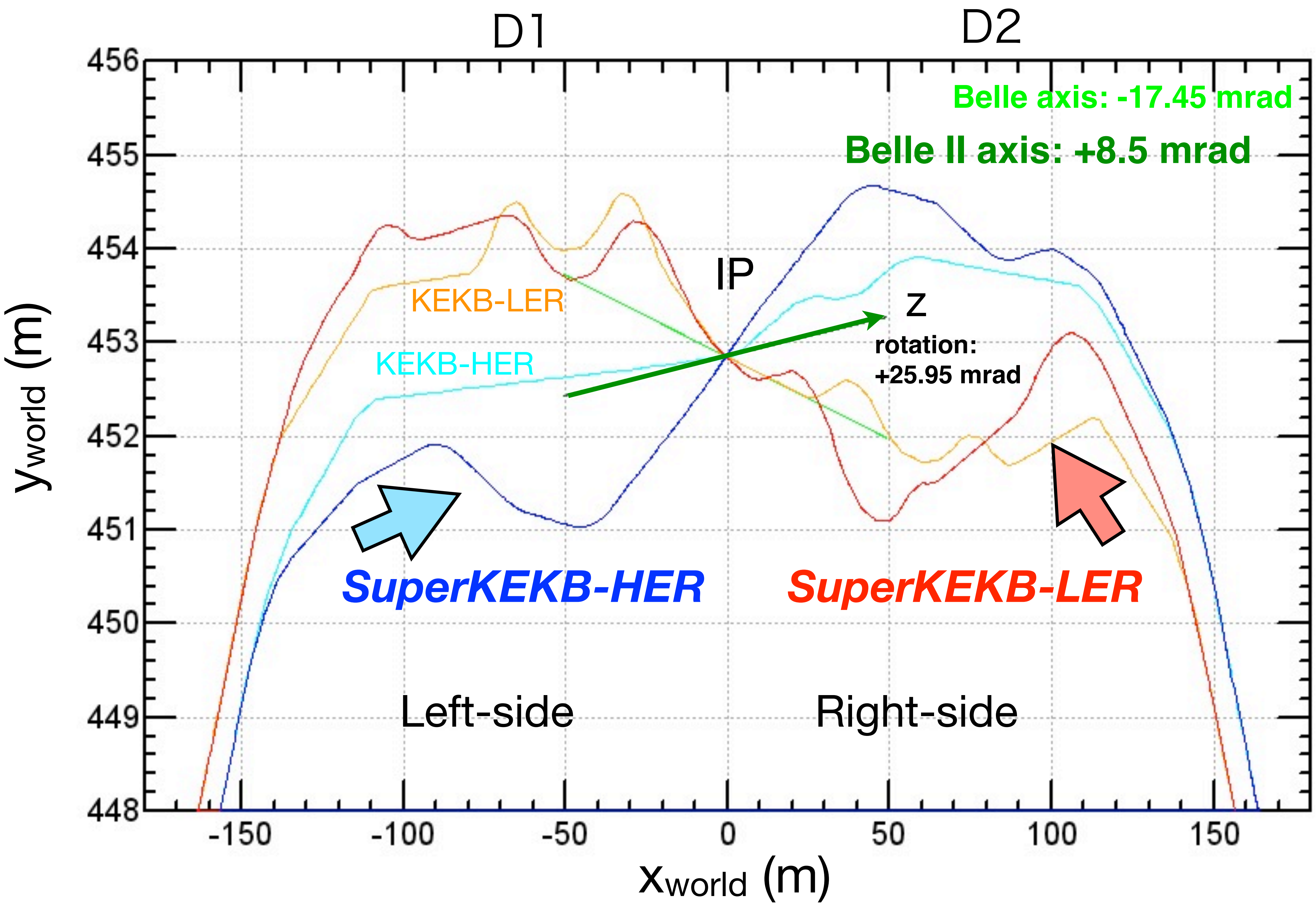
- Local chromaticity corrections (Y-LCC, X-LCC)

HER



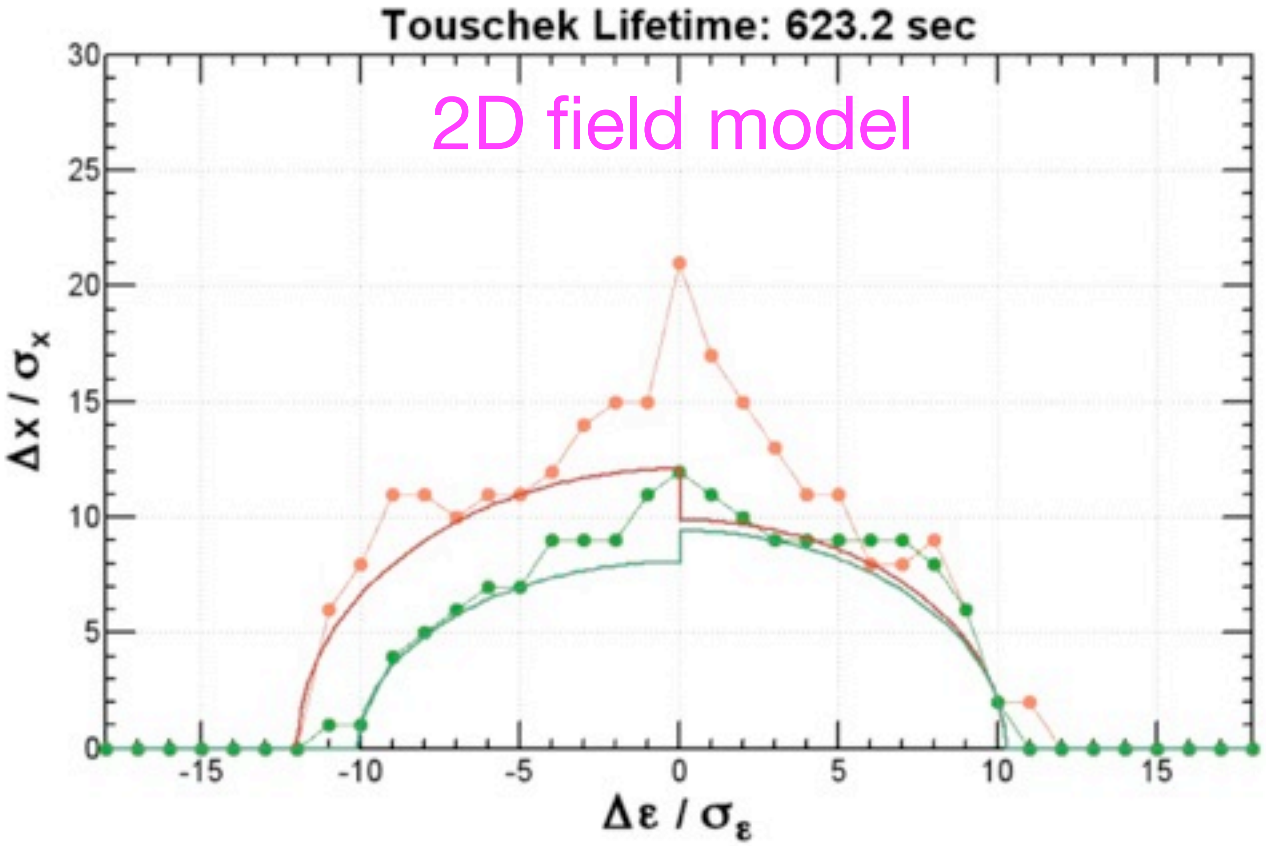
Design Orbit in IR

- *Orbit is NOT SIMPLE !*

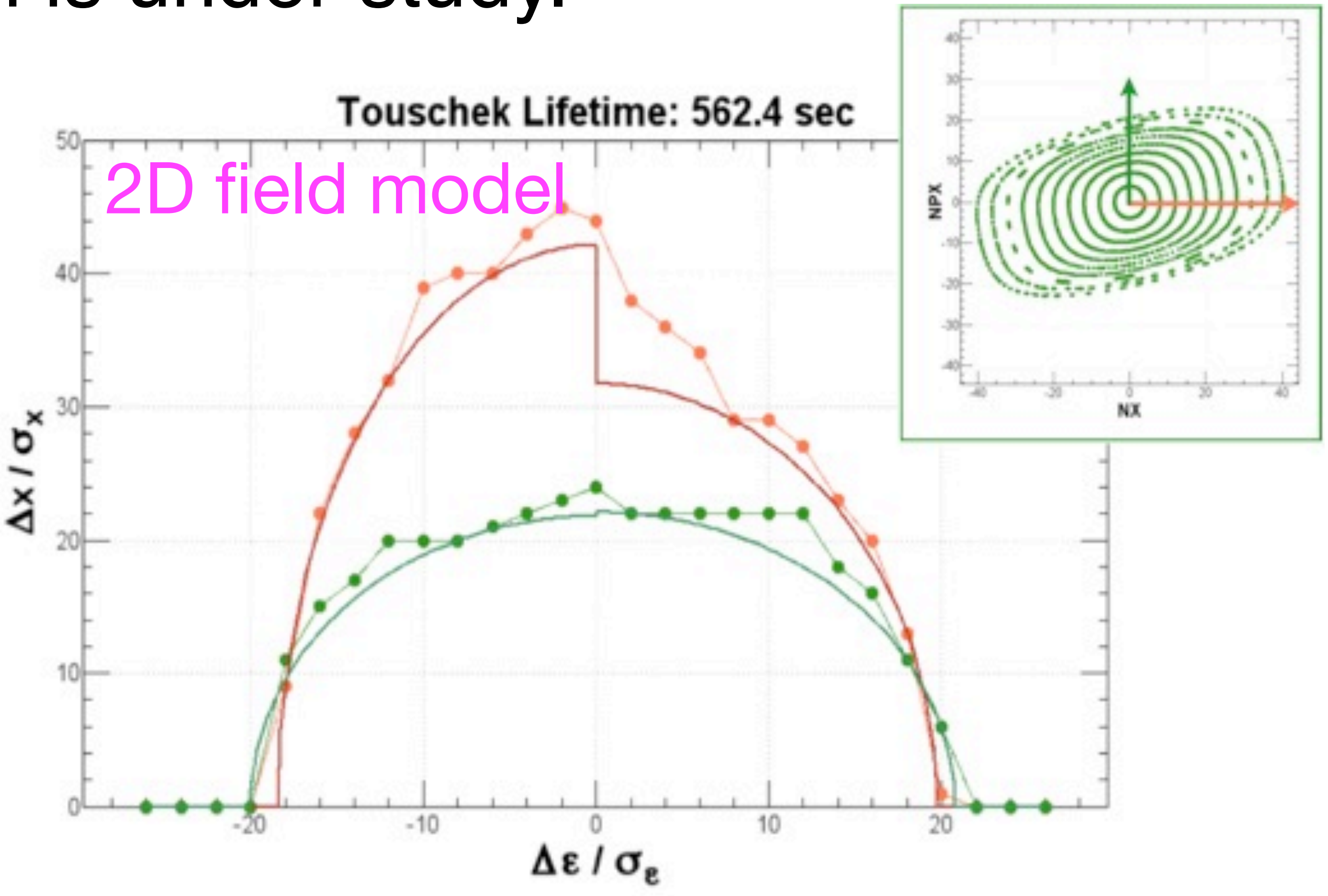


Touschek Lifetime

- Target lifetime is 600 sec.
- In case of ***IR model based on 2D*** solenoid field calculation, the target is almost achieved. However, 2D is less prediction power.
- ***IR model with 3D*** calculation is under study.



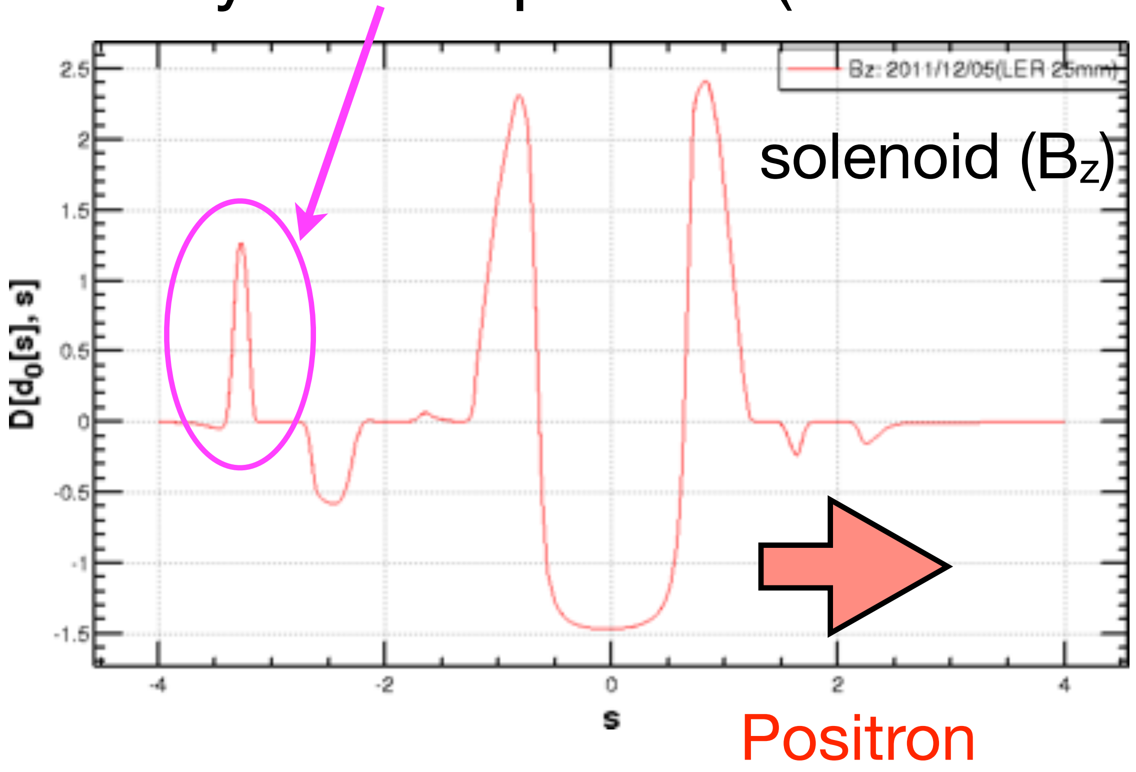
a11: 12.0000 b11: 12.1004 a12: 10.2111 b12: 9.8869 (751.468 sec)
a21: 10.0778 b21: 8.0623 a22: 10.2336 b22: 9.4136 (532.355 sec)

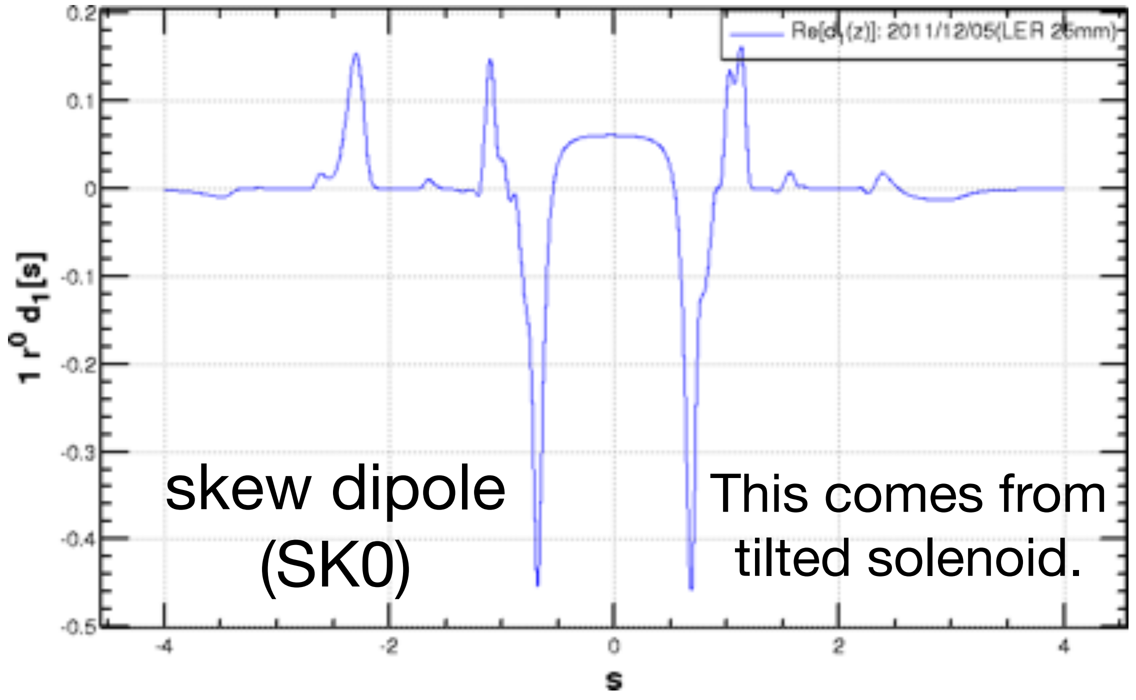


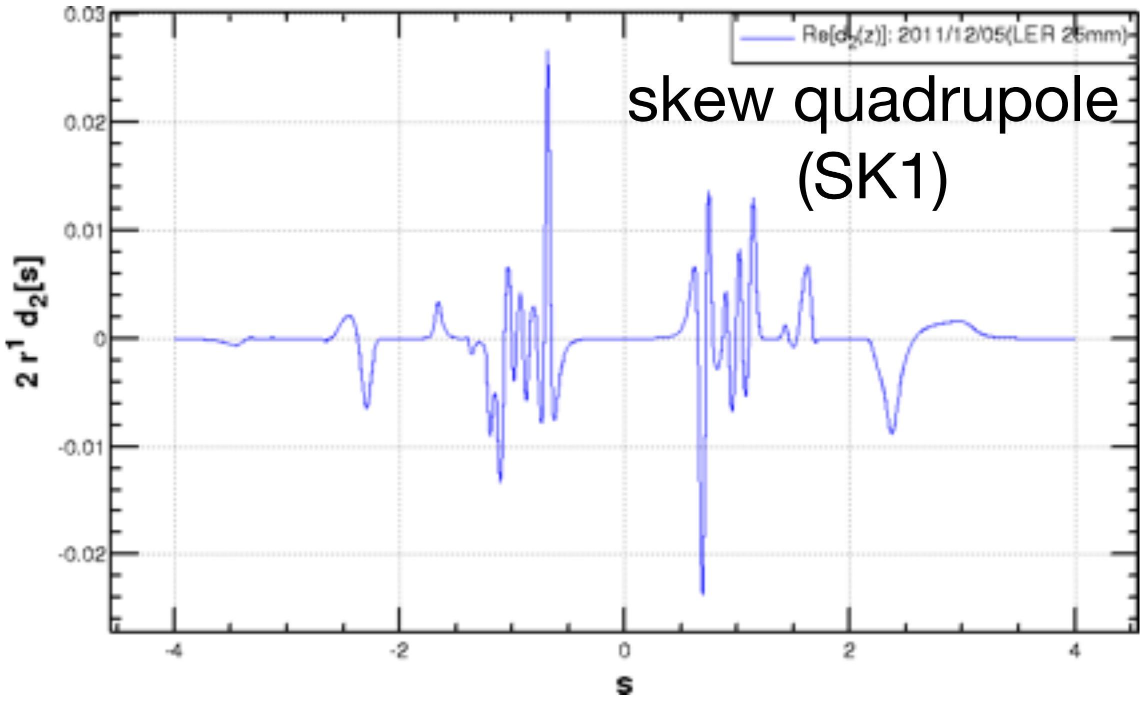
a11: 18.4245 b11: 42.1711 a12: 19.7329 b12: 31.7241 (815.260 sec)
a21: 20.0000 b21: 21.8218 a22: 20.7525 b22: 22.1029 (429.311 sec)

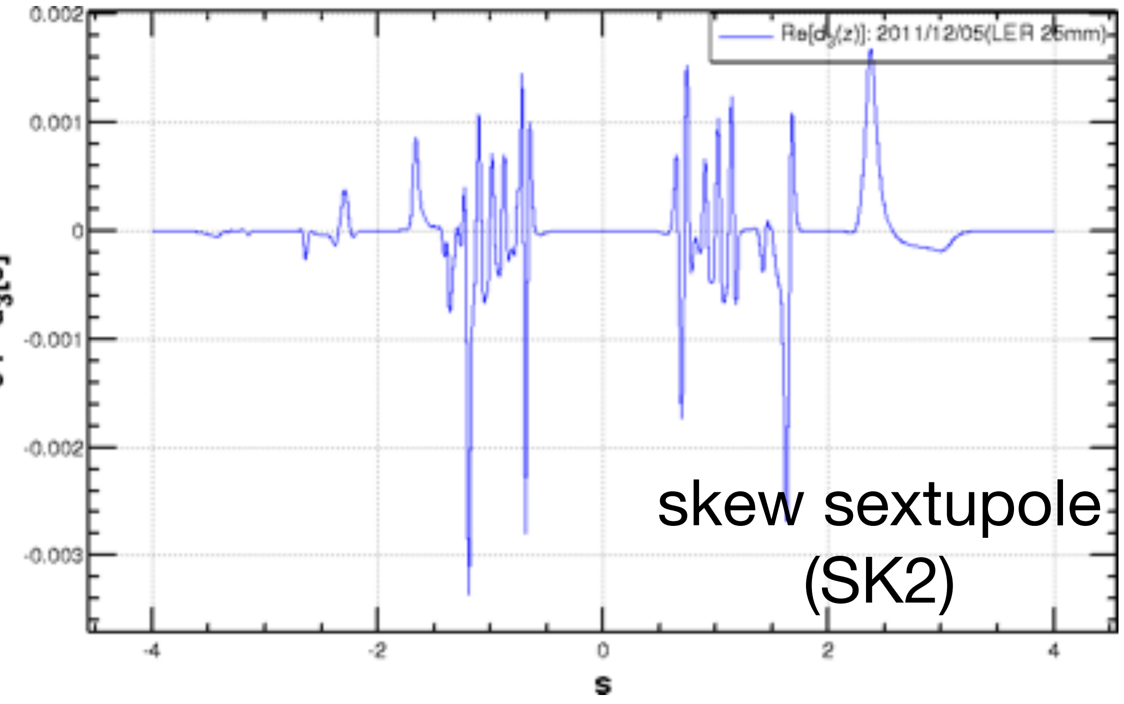
Solenoid Field Calculation in 3D

- Model of solenoid field includes SK0 - SK9 (*skew icosapole*).
- Bz of upper stream of IP will be modified to reduce bump since this affects dynamic aperture (~400 sec → > 540 sec with reduction of QC1 fringe).

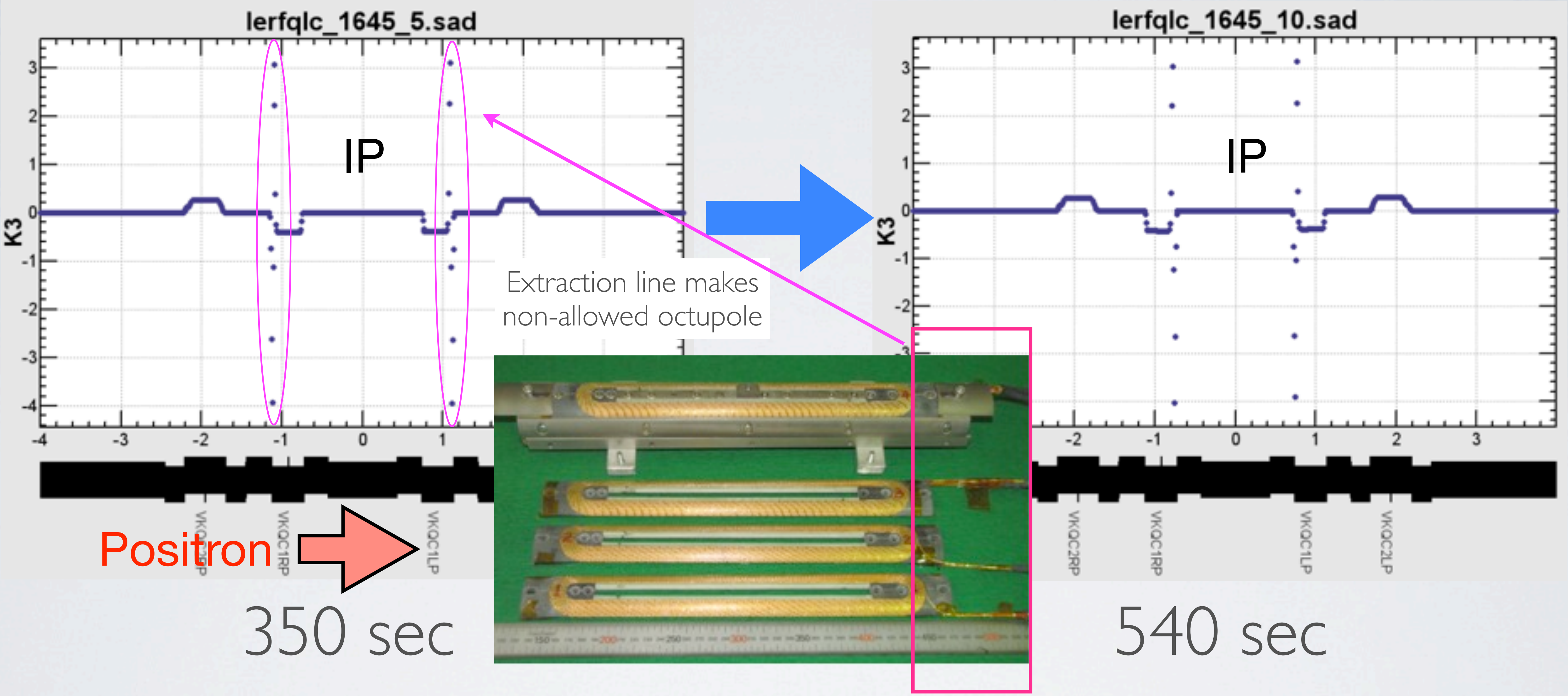








Change the Orientation of QC1



Extraction line makes
non-allowed octupole

Positron

350 sec

540 sec

By swapping the orientation of QC1, the lifetime has recovered to 540 sec, keeping the magnitudes of the nonlinearity Kn:K1! ***The difference is the beta functions.***

Solenoid:V10.5.1, QCS: 20111219

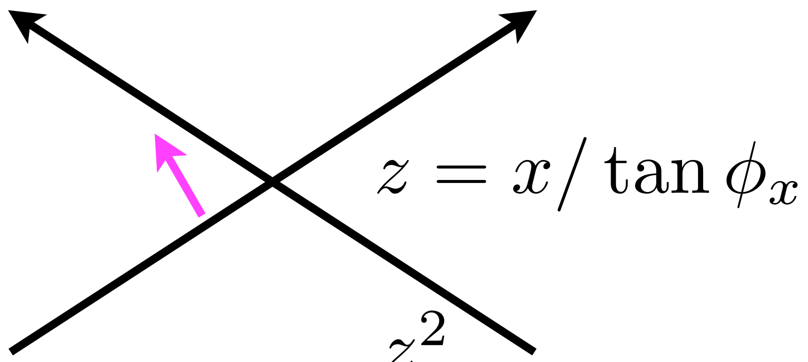
K. Oide

Five Big Issues (FBI)

- Dynamic Aperture (Touschek lifetime)
- Machine Error and Orbit/Optics Correction
- Injection with Beam-Beam effect
- Detector Background and Collimator
- Beam Energy (variable range)

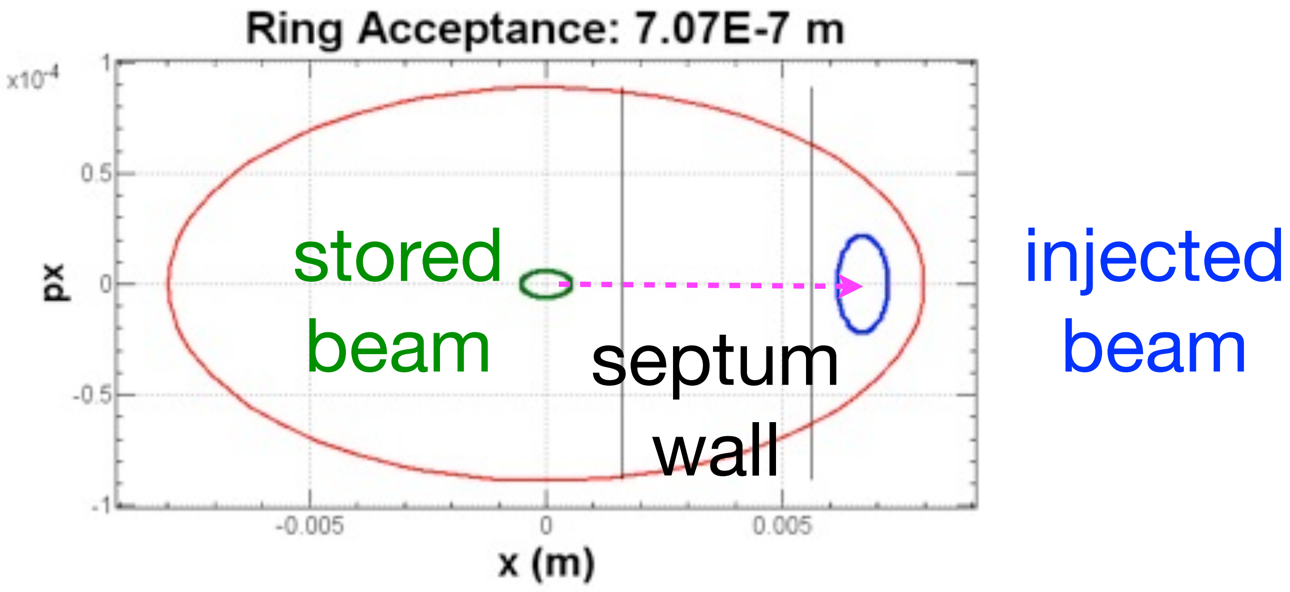
Why injected beam is influenced by BB ?

- An injection scheme for SuperKEKB is a "continuous injection" (top-up injection) with keeping a beam collision.
- An injected beam has a finite coherent oscillation in the horizontal direction while it merges into a stored beam although a local bump orbit between two injection kickers makes the oscillation as small as possible.
- The horizontal beam position is translated into the longitudinal displacement of the collision point due to the large horizontal crossing angle between two colliding beams. This implies the injected beam collides with the opposite beam at a large vertical beta function, which comes from the hourglass effect, receiving a large vertical kick.

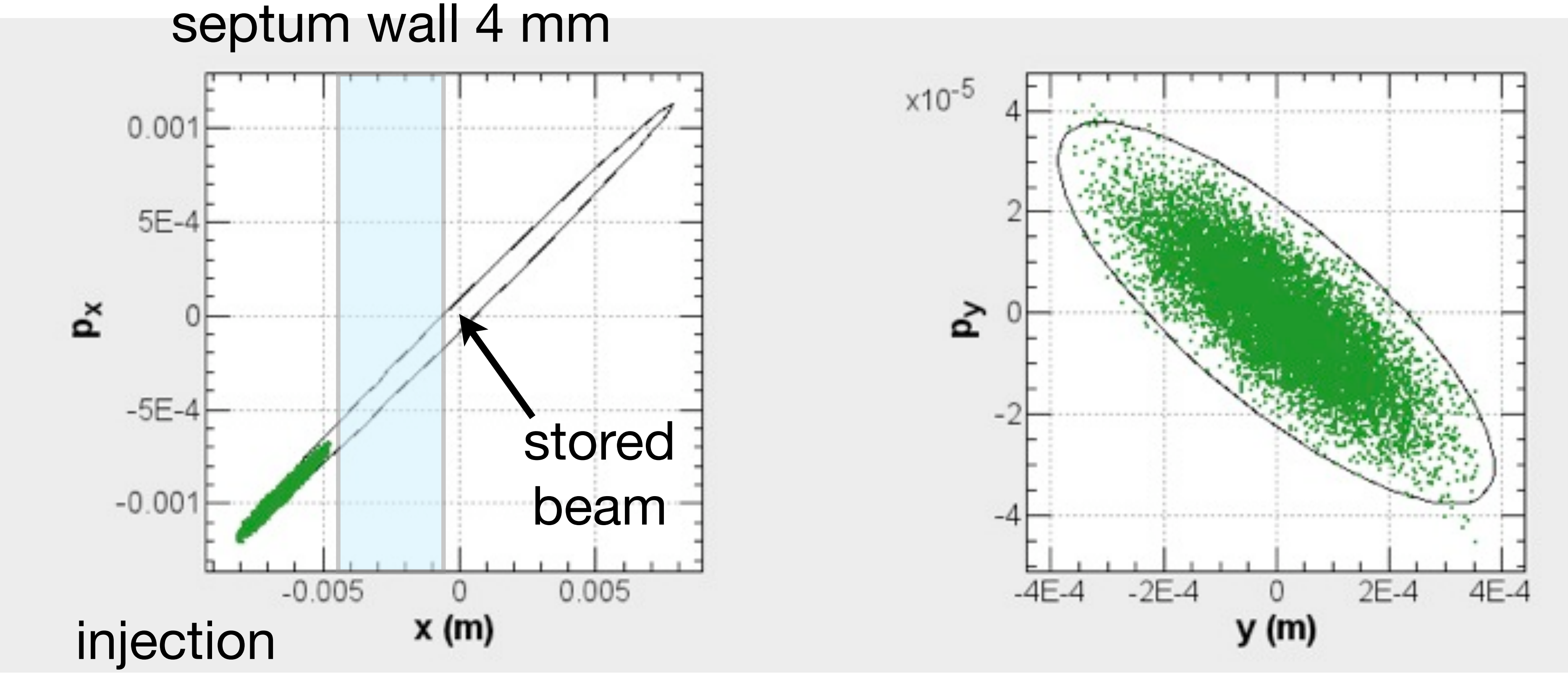


$$z = x / \tan\phi_x$$

$$\beta_y = \beta_y^* + \frac{z^2}{\beta_y^*}$$



Positron Distribution from Linac+DR+BT



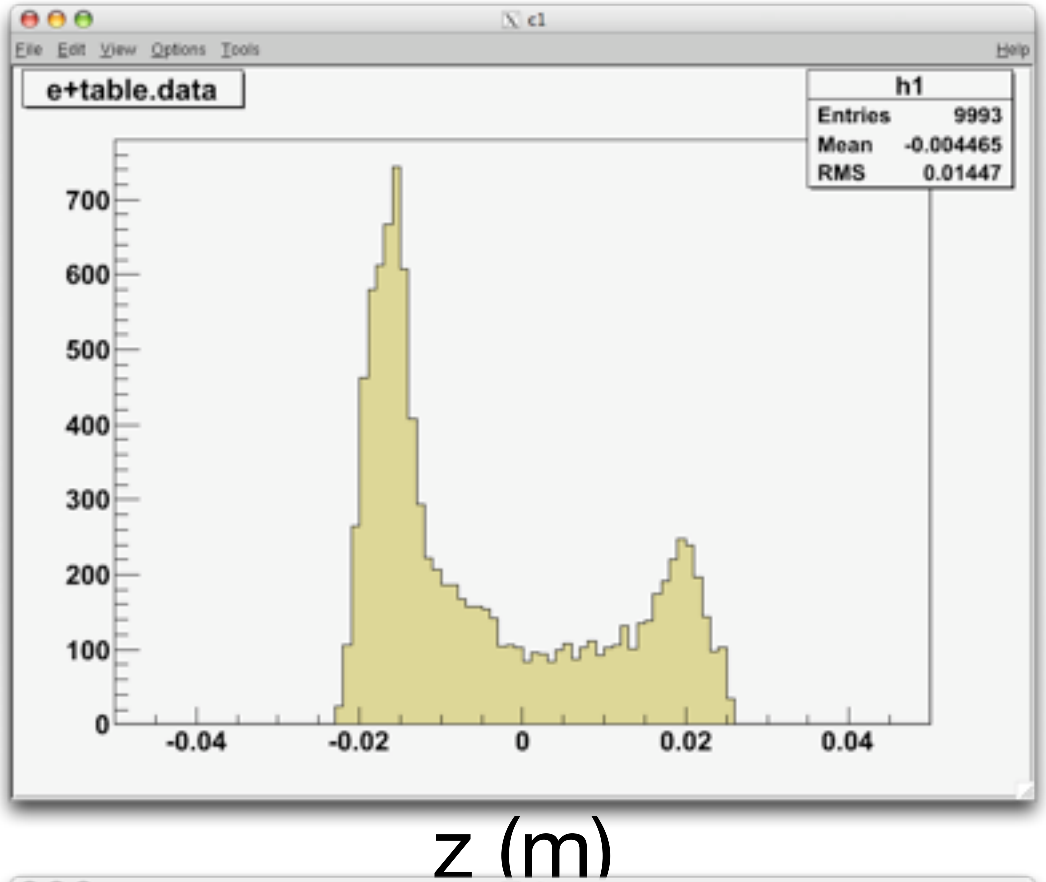
septum wall 4 mm

stored beam

injection beam

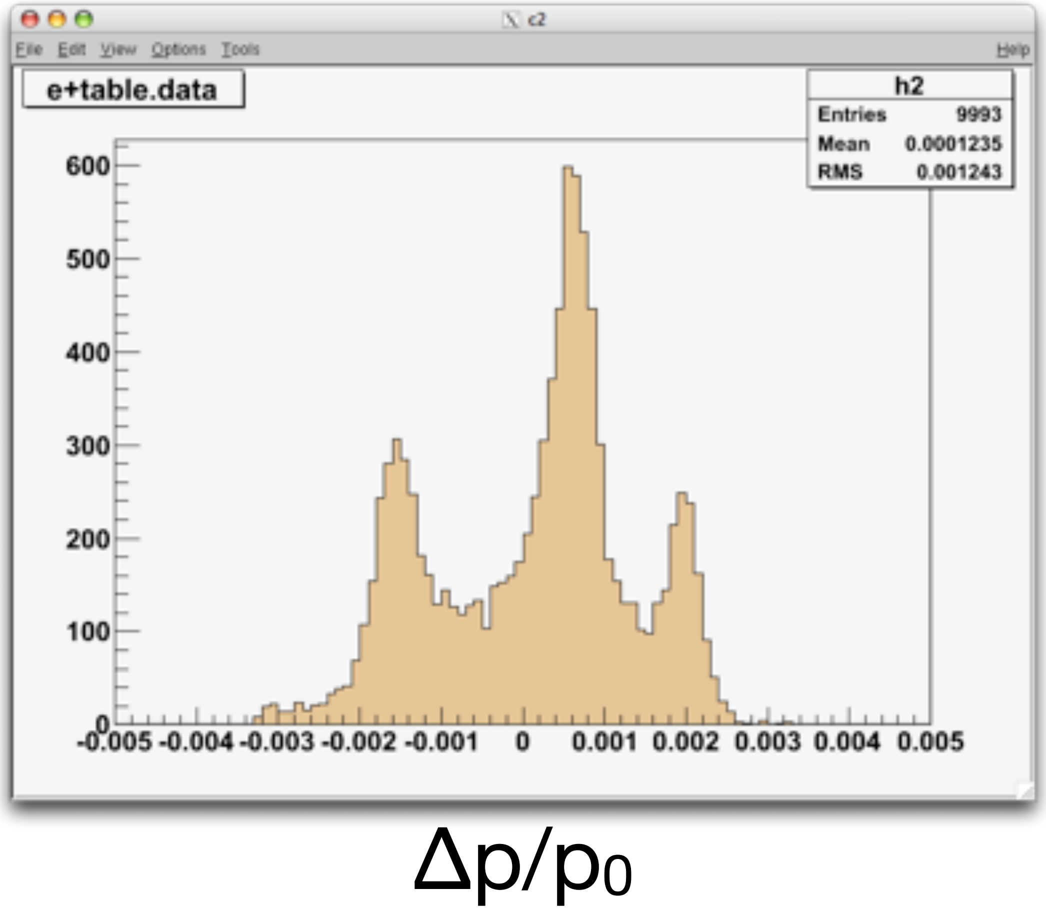
injection beam		
ε_x	11.7	nm
ε_y	0.87	nm
β_x	27.60	m
$2J_{x0}$	0.467	µm

Positron Distribution from BT



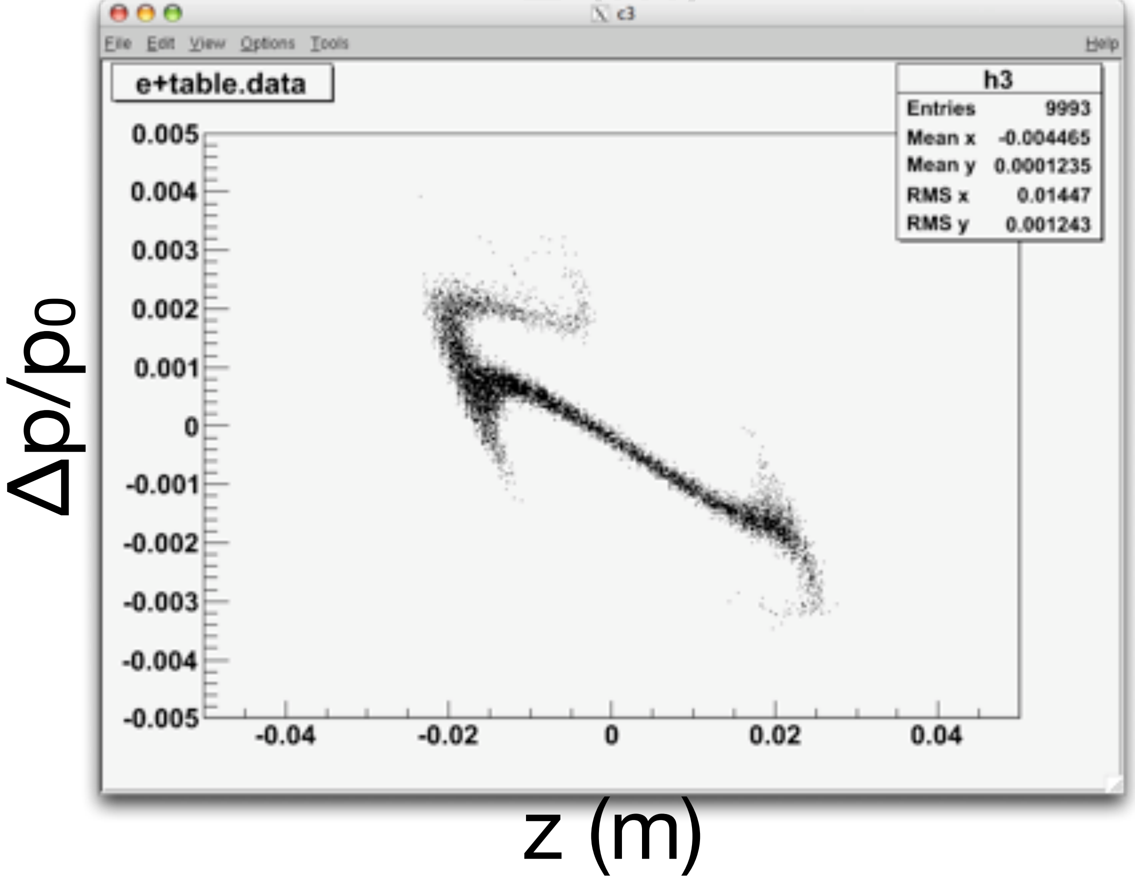
h1

Entries	9993
Mean	-0.004465
RMS	0.01447



h2

Entries	9993
Mean	0.0001235
RMS	0.001243



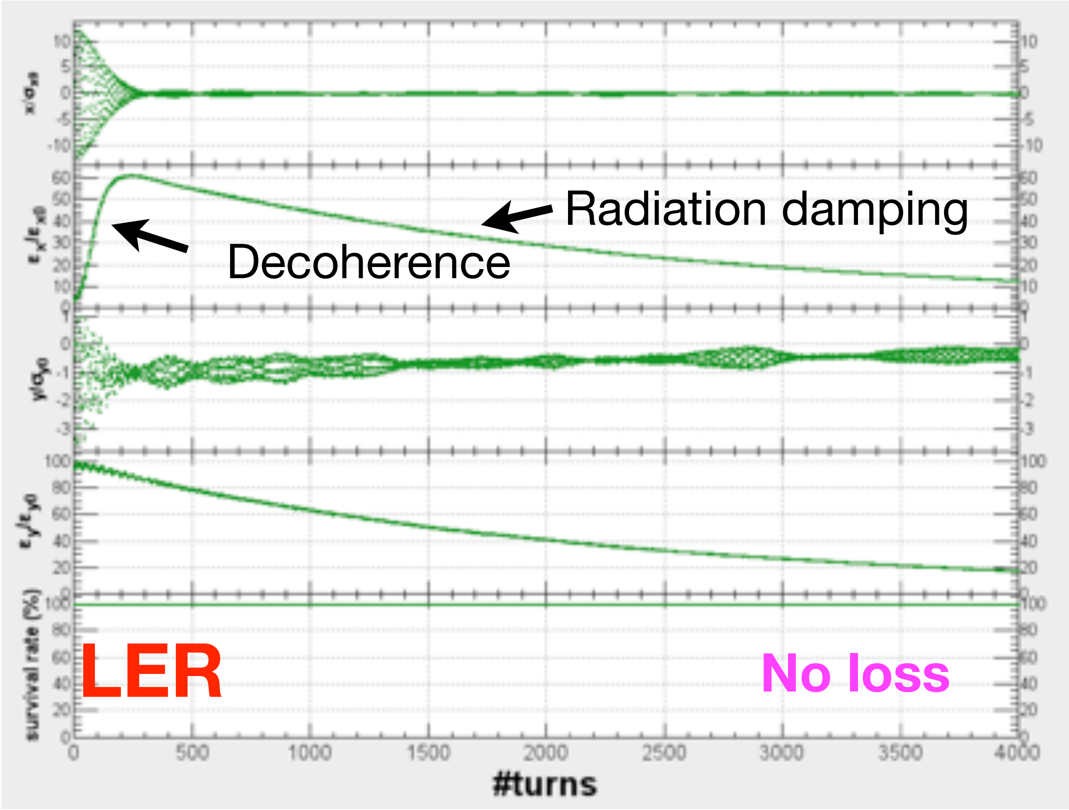
h3

Entries	9993
Mean x	-0.004465
Mean y	0.0001235
RMS x	0.01447
RMS y	0.001243

injection beam	Hard Edge	
σ_z	22	mm
σ_δ	0.3	%

Tracking Simulation

Weak-Strong model is used for Beam-Beam interaction.



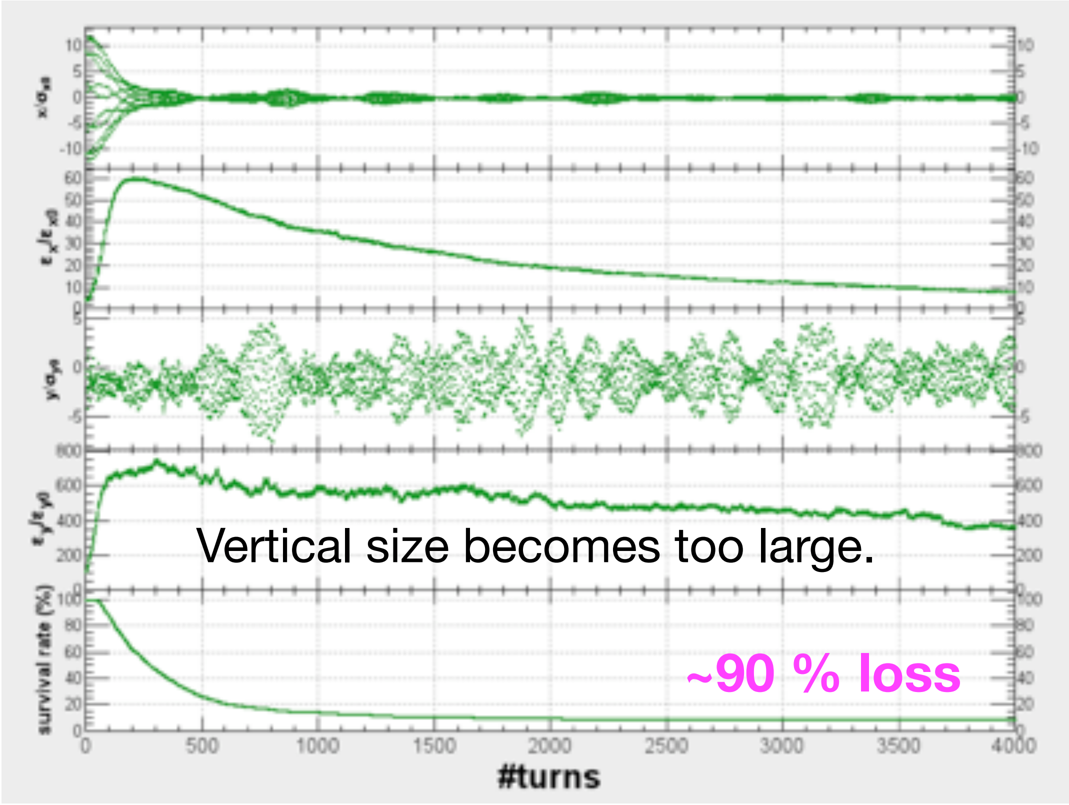
Radiation damping

Decoherence

LER

No loss

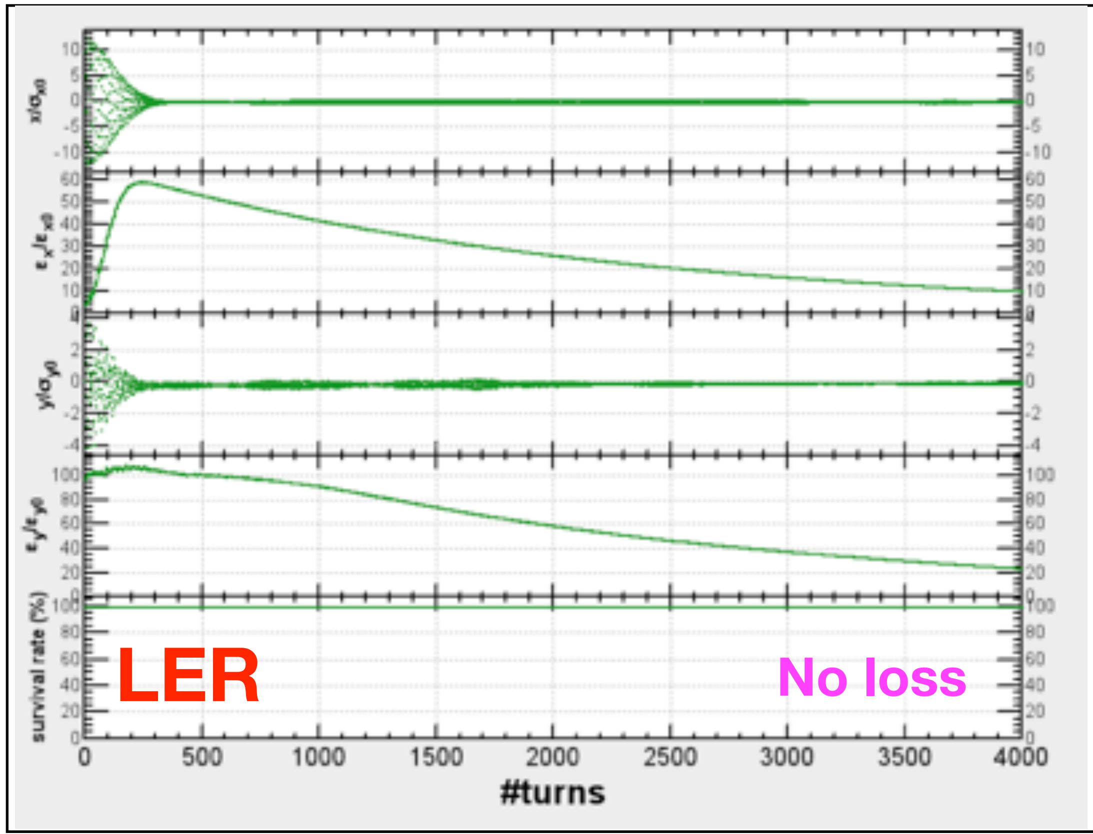
Bad
Lattice



Vertical size becomes too large.

~90 % loss

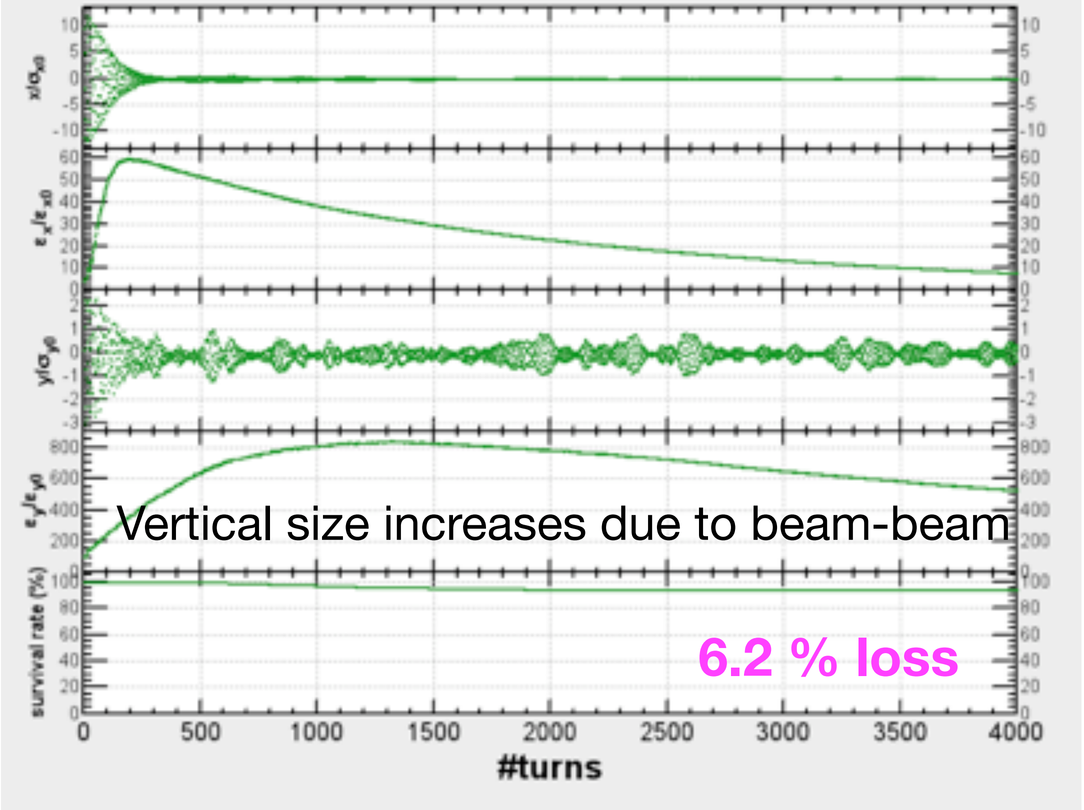
Beam-Beam



LER

No loss

Good
Lattice



Vertical size increases due to beam-beam

6.2 % loss

Injection Loss due to Beam-Beam

- There are several cures :-)
- Synchrotron phase-space injection
  - Need modification of injection optics
- Crab-waist scheme (heroic drug)
  - Dynamic aperture is reduced by crab-waist sextupoles (side effect)
- Vertical phase-space tuning
  - Reduce nonlinearity of vertical direction of a particle motion by optimizing octupole coil of final focusing quadrupoles(QC1/QC2).

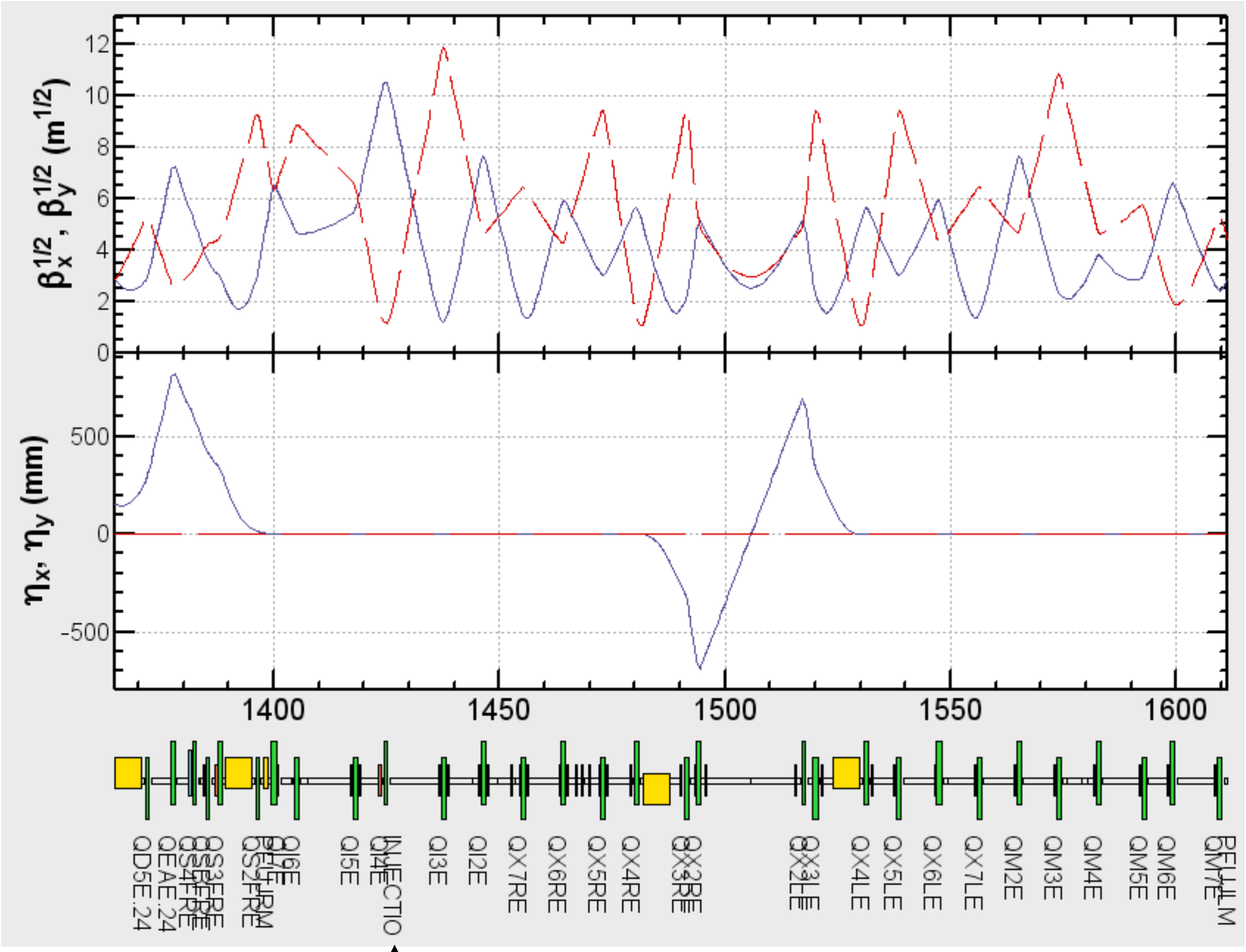
Synchrotron phase-space Injection

Transverse oscillation exchanges longitudinal oscillation.

$(x, p_x) = (\eta_x, \eta_{px})\delta_{inj}$. δ_{inj}: energy deviation of injected beam.

HER

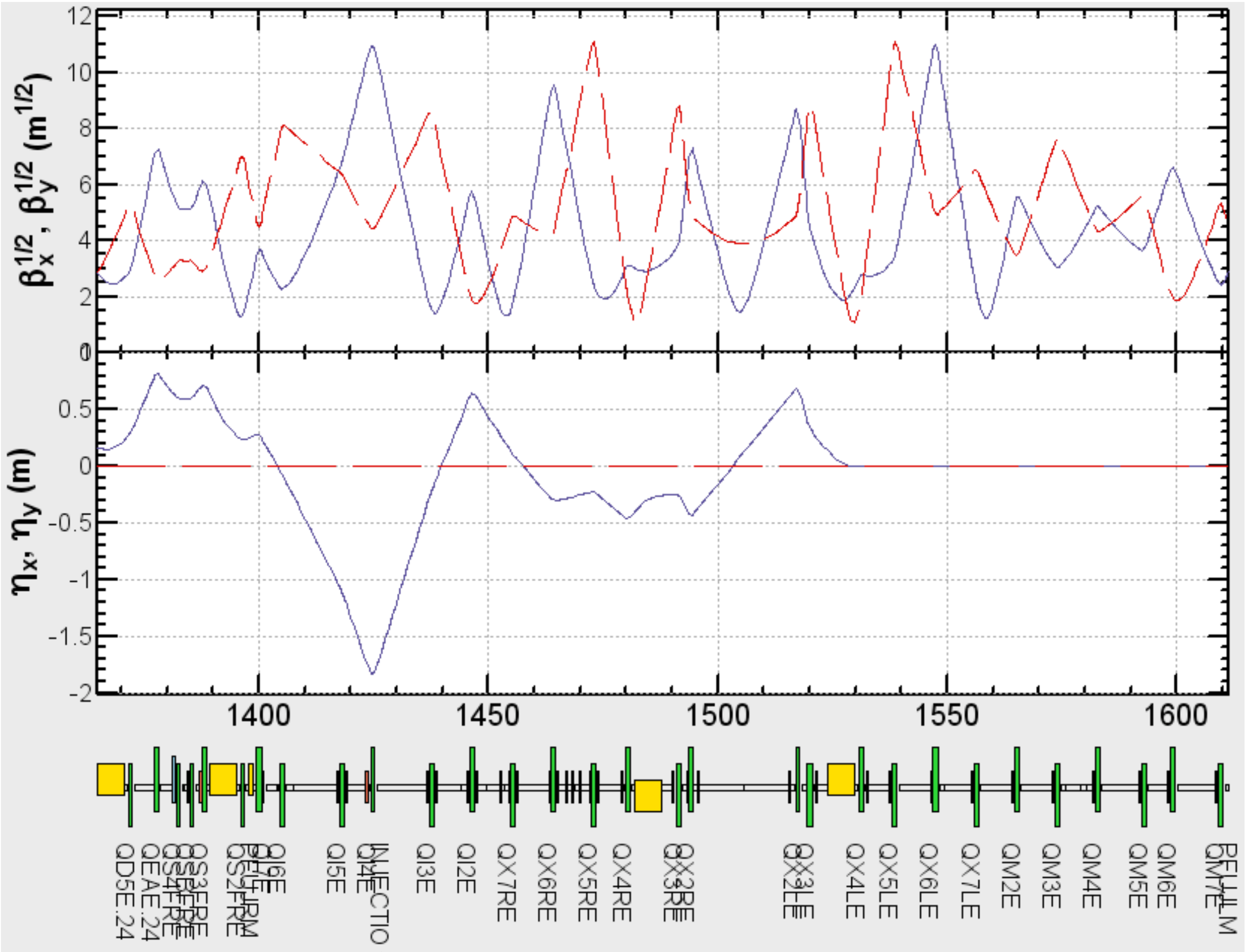
Betatron phase-space injection



injection point

HER

Synchrotron phase-space injection



dispersion = -1.75 m

injection point

Lifetime and Injection Power

unit in sec	LER	HER
Touschek lifetime	562	623
Luminosity lifetime	1800	1300
Beam-Gas lifetime	2240	3260
Total lifetime	360	373
Injection limit (25 Hz)*	181	104

*Injection efficiency is assumed to be 100 %

Summary

- The IR lattice design is almost fixed. We are ready to make the final focusing magnets, anti-solenoids, corrector coils. The 3D magnetic field calculation becomes reliable now. The IR model can be more accurate rather than 2D model since each magnet has an iron shield to avoid leakage field to opposite beam(except for QC1P).
- We expect that Touschek lifetime of 600 sec can be obtained after a few iterative procedure of the hardware design and the lattice optimization.
- We have begun to install hardwares, for example LER dipole magnet, and the construction of vacuum pipes.
- The beam commissioning will be started from 2015 after 3 years upgrade. This is on schedule.

Appendix

Lower Emittance due to Frequency Shift

- Emittance

$$\varepsilon_x = C_q \gamma^2 \frac{I_5}{I_2 - I_4} = C_q \gamma^2 \frac{I_5}{I_2 J_x}$$

- Damping partition number

$$J_x = 1 - \frac{I_4}{I_2}$$

$$I_2 = \oint \frac{ds}{\rho^2}$$

$$I_4 = \oint \frac{1}{\rho^2} \left(\frac{1}{\rho} + 2\rho K_1 \right) \eta_x ds$$

non-combined bend: ρK₁ = 0

$$\Delta I_4 = \oint 2 K_1^2 \eta_x^2 \frac{\Delta p}{p} ds$$

$$= \oint 2 K_1^2 \eta_x \Delta x ds$$

frequency shift

$$\frac{1}{\rho} = K_1 \Delta x = K_1 \eta_x \frac{\Delta p}{p}$$

positive frequency shift -> low momentum -> inner orbit -> J_x increase

- Damping wigglers degrade the effect of frequency shift since I_2 is large.

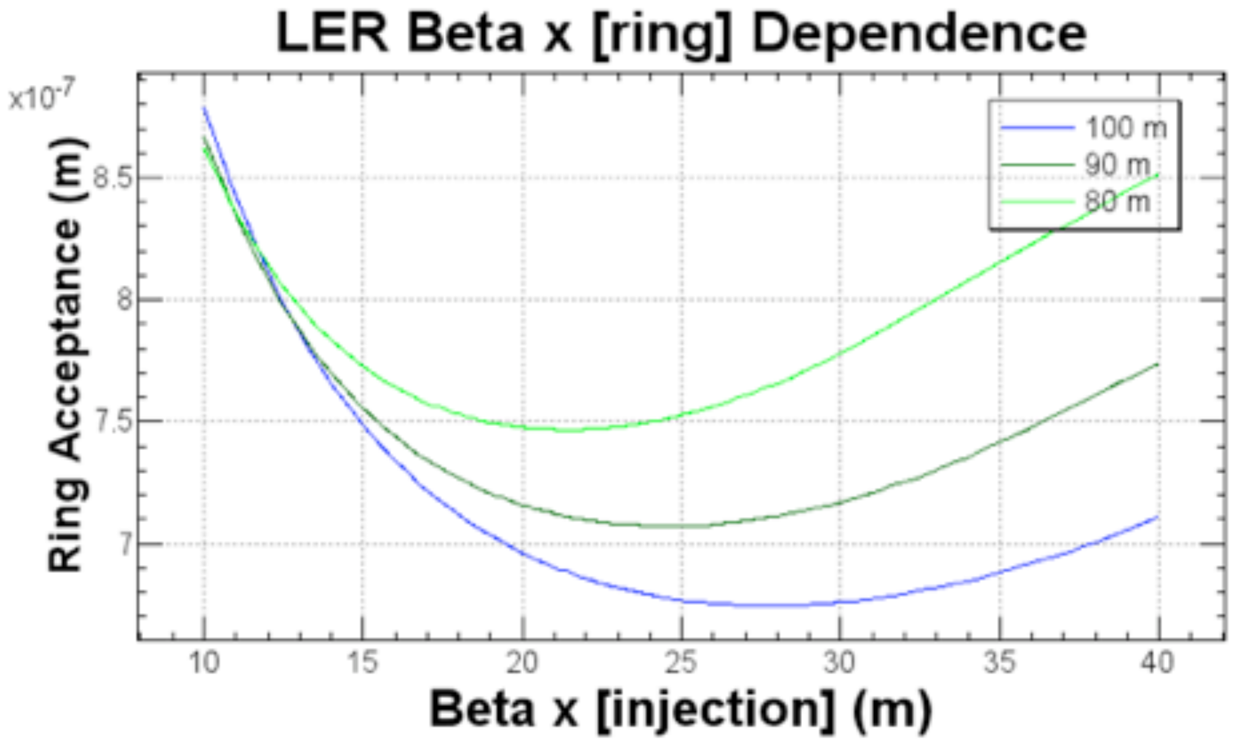
Parameters of e^+ Injection Beam

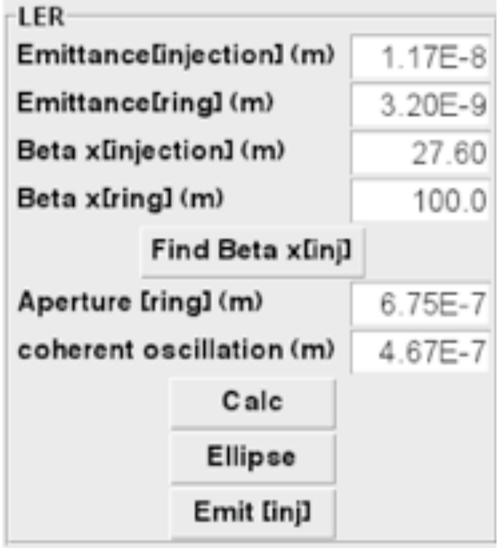
		emittance (x) (nm)	emittance (y) (nm)	bunch length (mm)	σ_δ (%)	P (GeV)
Before DR	Before ECS	1400	1400	±8 (hard edge)	±5 (hard edge)	1.1
	After ECS	1400	1400	±35 (hard edge)	±1.5 (hard edge)	1.1
After DR	Before BCS	42.9	3.12	8.80	7.4x10^{-4}	1.1
	After BCS	42.9	3.12	0.83	8.5x10^{-3}	1.1
Injection point		11.8	0.86	±27.3 (hard edge)	±0.4 (hard edge)	4.0

Parameters of e^- Injection Beam

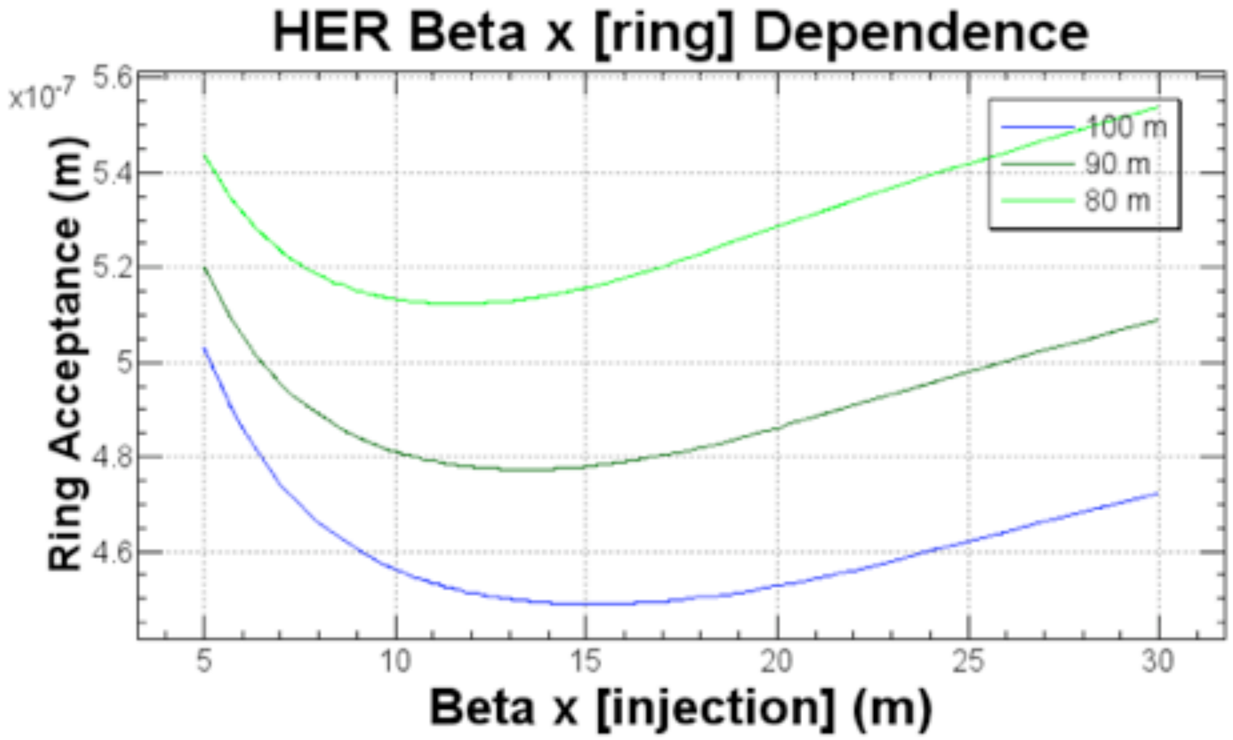
	emittance (x) (nm)	emittance (y) (nm)	bunch length (mm)	σ_δ (%)	P (GeV)
Linac end	1.46	1.46	1.3		7.0
Injection point (betatron)	1.46	1.46	4.6	±0.25 (hard edge)	7.0
Injection point (synchro.)	1.46	1.46		0.047	7.0

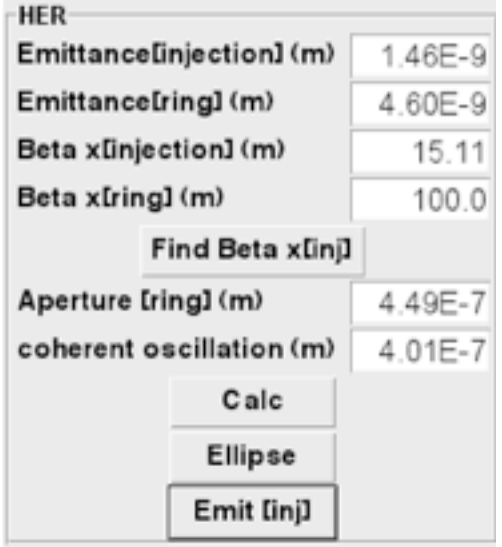
Injection Condition (Betatron)




LER

Emittance[injection] (m)	1.17E-8
Emittance[ring] (m)	3.20E-9
Beta x[injection] (m)	27.60
Beta x[ring] (m)	100.0
Aperture [ring] (m)	6.75E-7
coherent oscillation (m)	4.67E-7

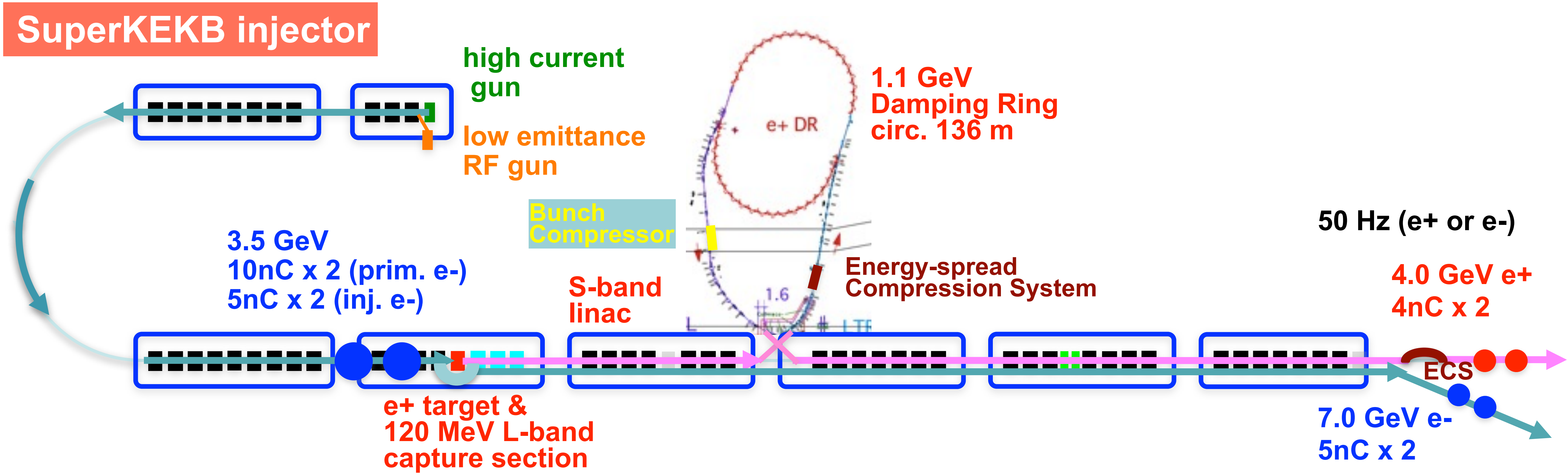



HER

Emittance[injection] (m)	1.46E-9
Emittance[ring] (m)	4.60E-9
Beta x[injection] (m)	15.11
Beta x[ring] (m)	100.0
Aperture [ring] (m)	4.49E-7
coherent oscillation (m)	4.01E-7

Injectors

SuperKEKB injector



high current gun

low emittance RF gun

1.1 GeV
Damping Ring
circ. 136 m

e+ DR

Bunch Compressor

Energy-spread Compression System

50 Hz (e+ or e-)

3.5 GeV
10nC x 2 (prim. e-)
5nC x 2 (inj. e-)

S-band linac

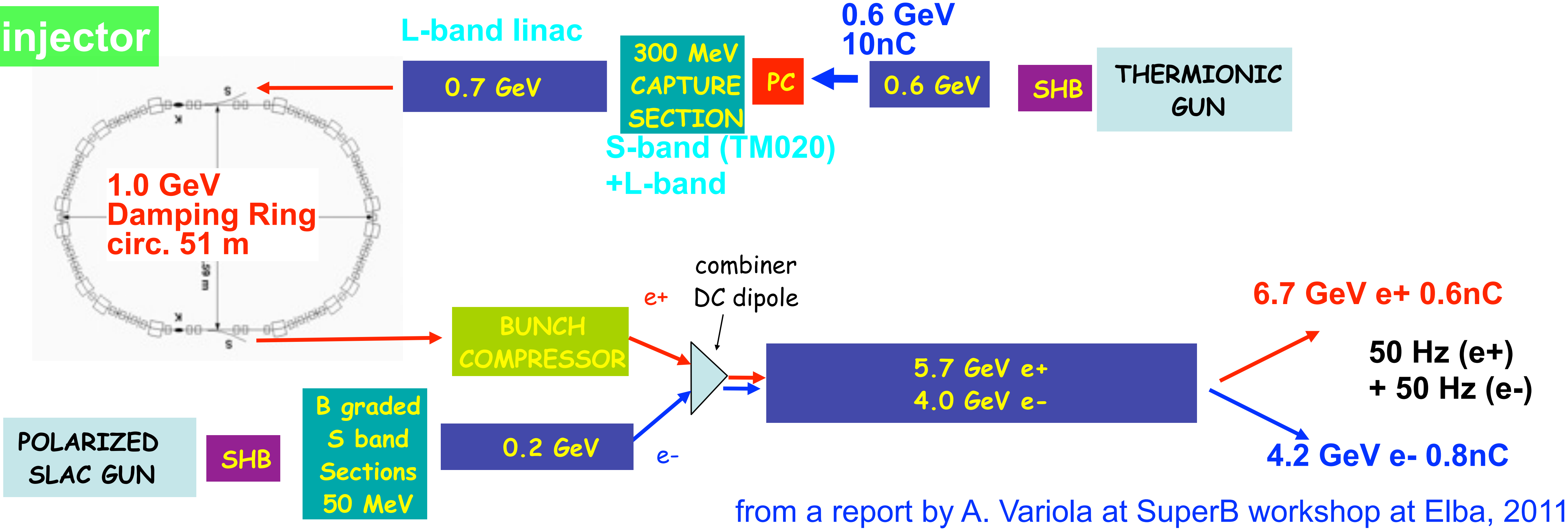
4.0 GeV e+
4nC x 2

ECS

e+ target &
120 MeV L-band
capture section

7.0 GeV e-
5nC x 2

SuperB injector



L-band linac

0.7 GeV

300 MeV CAPTURE SECTION

PC

0.6 GeV
10nC

0.6 GeV

SHB

THERMIONIC GUN

S-band (TM020)
+L-band

1.0 GeV
Damping Ring
circ. 51 m

combiner
DC dipole

e+

6.7 GeV e+ 0.6nC

BUNCH COMPRESSOR

5.7 GeV e+
4.0 GeV e-

50 Hz (e+)
+ 50 Hz (e-)

POLARIZED SLAC GUN

SHB

B graded S band Sections 50 MeV

0.2 GeV

e-

4.2 GeV e- 0.8nC

from a report by A. Variola at SuperB workshop at Elba, 2011

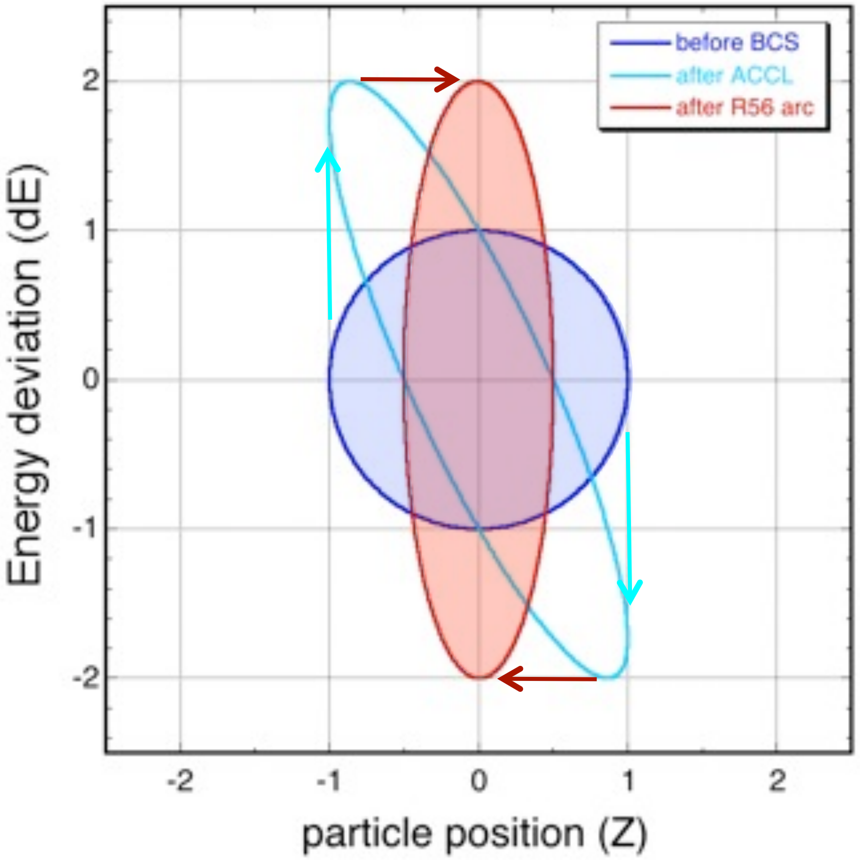
ECS & BCS (SuperKEKB)

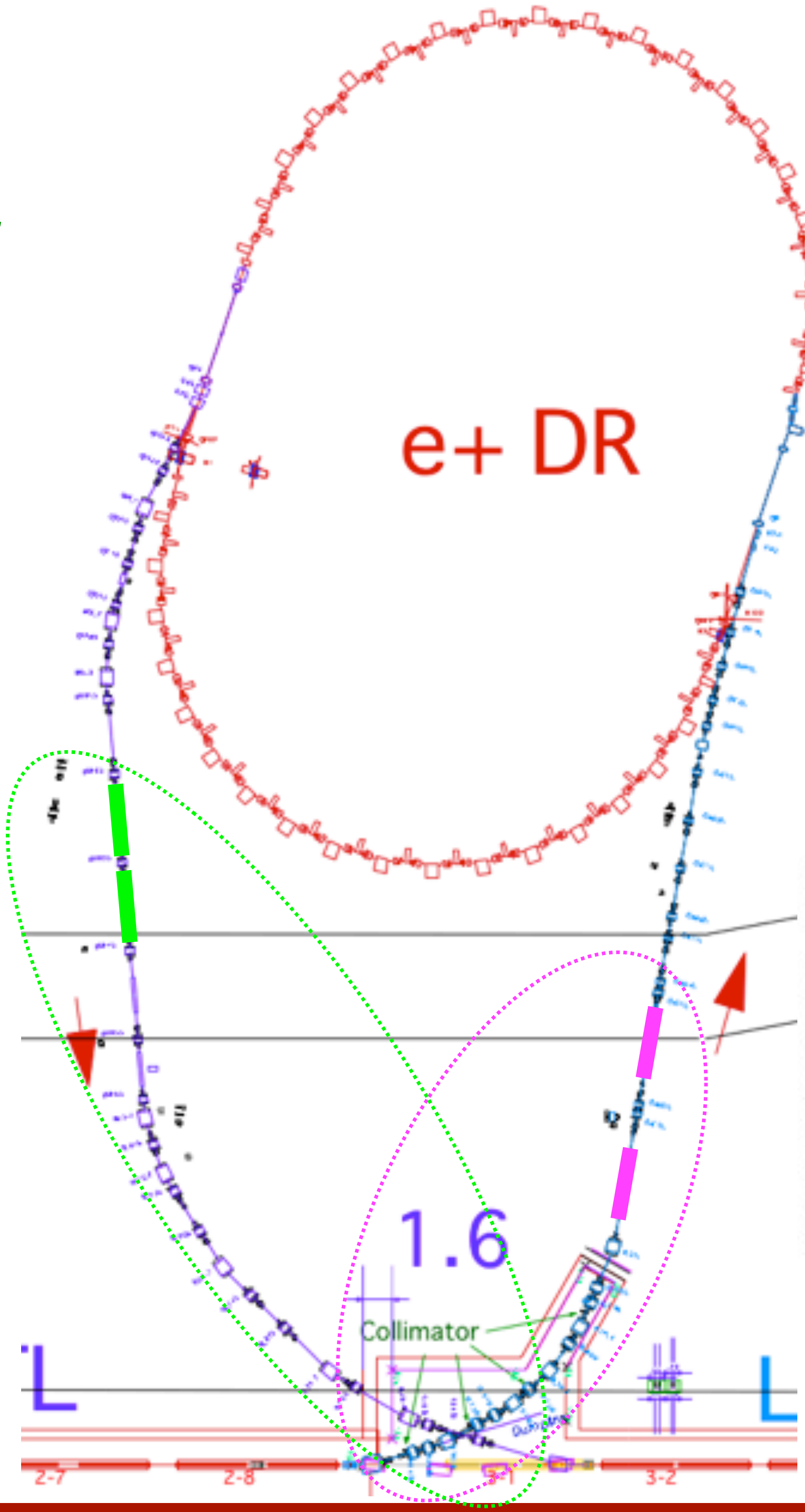
Bunch
Compression
System

BCS reduce bunch-length of e+ extracted from DR

energy gradient by RF field
+ non-isochronous arc

Vc = 37 MV (L-band)
R_{56} = -1.05 m
compression 1/9



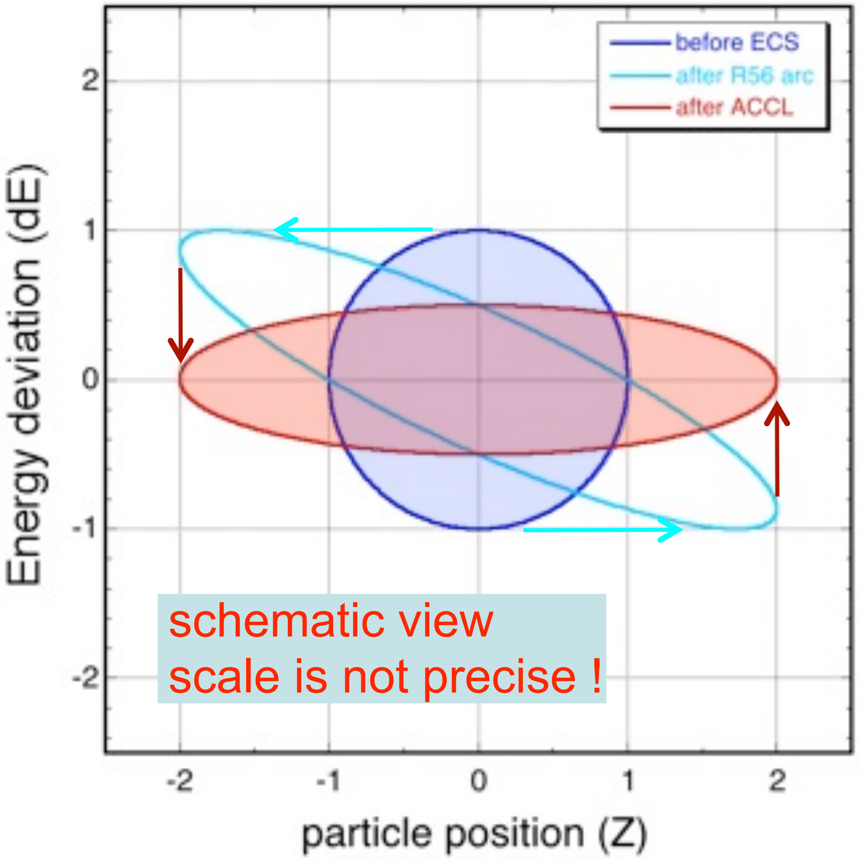


Energy-spread
Compression
System

ECS reduce energy-spread of e+ entering DR

non-isochronous arc +
energy correction by RF field

R_{56} = -0.61 m
Vc = 41 MV (S-band)
compression 1/3



schematic view
scale is not precise !