Crab crossing in KEKB and nano-beam scheme in SuperKEKB

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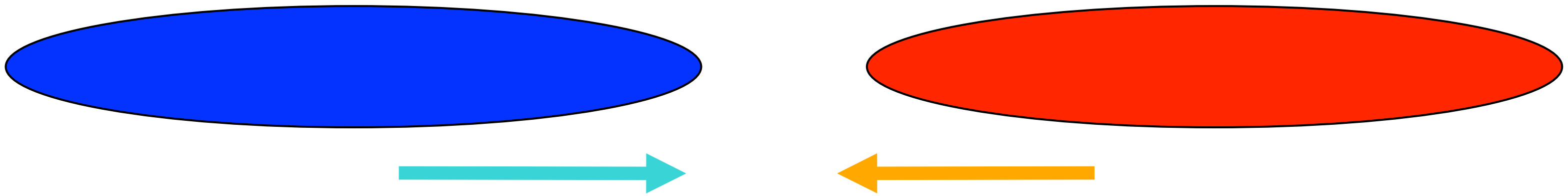
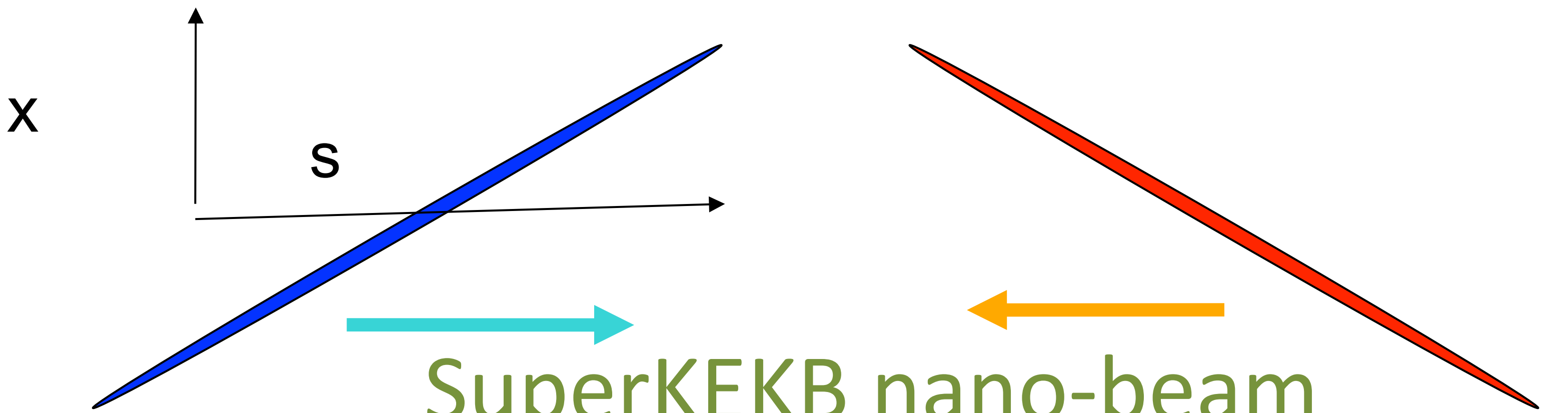
Crab crossing at KEKB

- High current, high beam-beam parameter.

KEKB crab crossing, 2008-2010



- Low emittance, low beta, low current, so-called super bunch collision



SuperKEKB nano-beam

Comparison of two approach

High curent $\frac{\sqrt{\varepsilon_x \beta_x}}{\theta \sigma_z} > 1$ or $\theta = 0$

$$L \sim \frac{N^2}{\sqrt{\varepsilon_x \beta_x \varepsilon_y \beta_y}}$$

$$\xi_x \sim \frac{N}{\varepsilon_x}$$

$$\xi_y \sim N \sqrt{\frac{\beta_y}{\varepsilon_x \beta_x \varepsilon_y}}$$

$$\beta_y > \sigma_z$$

θ: half crossing angle

Low emittance $\frac{\sqrt{\varepsilon_x \beta_x}}{\theta \sigma_z} < 1$

Overlap factor

$$L \sim \frac{N^2}{\theta \sigma_z \sqrt{\varepsilon_y \beta_y}}$$

$$\xi_x \sim \frac{N}{\theta \sigma_z} \sqrt{\frac{\beta_x}{\varepsilon_x}}$$

$$\xi_y \sim \frac{N}{\theta \sigma_z} \sqrt{\frac{\beta_y}{\varepsilon_y}}$$

$$\beta_y > \frac{\sqrt{\varepsilon_x \beta_x}}{\theta}$$

ξ_x is smaller due to cancellation of tune shift along bunch length

High current approach

$$L \sim \frac{N^2}{\sqrt{\varepsilon_x \beta_x \varepsilon_y \beta_y}}$$

$$\xi_x \sim \frac{N}{\varepsilon_x}$$

$$\xi_y \sim N\sqrt{\frac{\beta_y}{\varepsilon_x \beta_x \varepsilon_y}}$$

$$\beta_y > \sigma_z$$

Keep ε_x, β_x and $\sqrt{\frac{\beta_y}{\varepsilon_y}}$.

$$\varepsilon_y \beta_y \to 0$$

$$L \to \infty$$

$\beta_y > \sigma_z$ limits luminosity

- High current, Small coupling
- Choice of operating point

$$\nu_x \to +0.5 \quad \xi_y \to \infty \quad N \to \infty$$

$\theta=0$

$$L \to \infty$$

How ξ_y can be large

- $\nu_x \rightarrow 0.5$, the horizontal motion is integrated independent of y, because horizontal beam-beam force weakly depends on y.
- z independent for $\theta_c=0$.
- Nonlinear y motion (1 dim) is slowly modulated by x motion (externally).

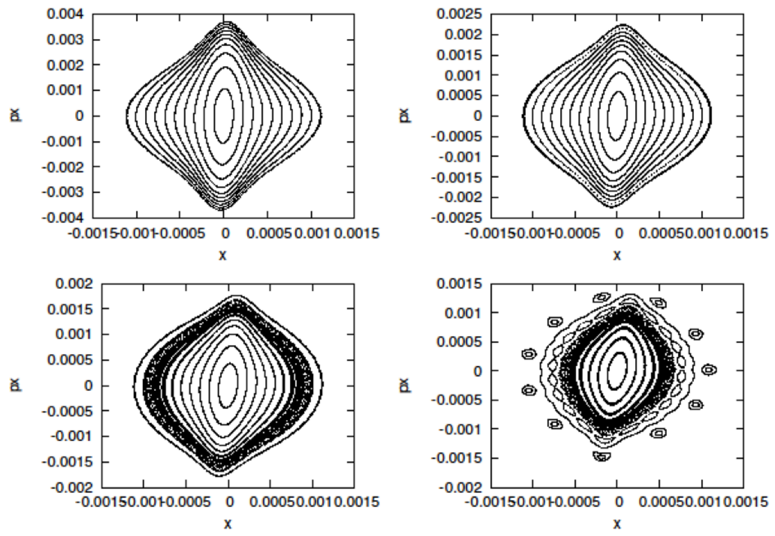
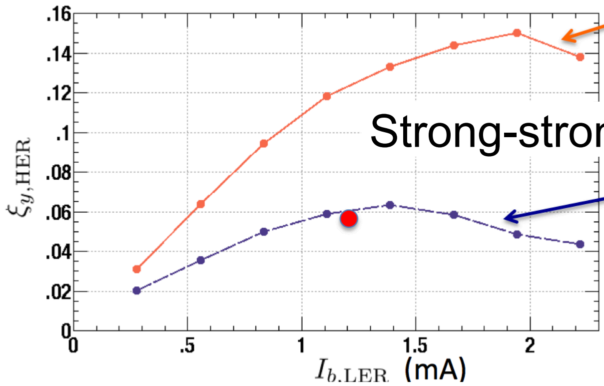
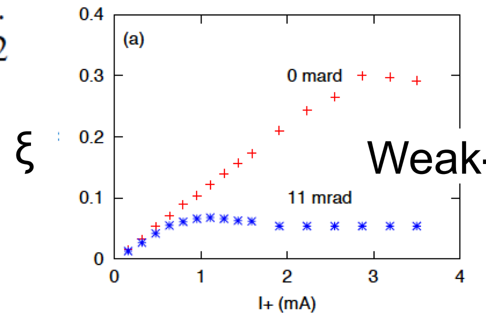


Figure 3: Phase space plot in $x - p_x$. $y_0 = 2\mu$ m$\approx 3\sigma_y$. plots (a), (b), (c) and (d) is given for ν_x =0.503,0.51,0.52 and 0.54, respectively.



Head-on
ν_x =.508 } → ξ_y ~0.15



Weak-strong: ξ=0.3

Limitation of crab and $\nu_x \rightarrow 0.5$ scheme

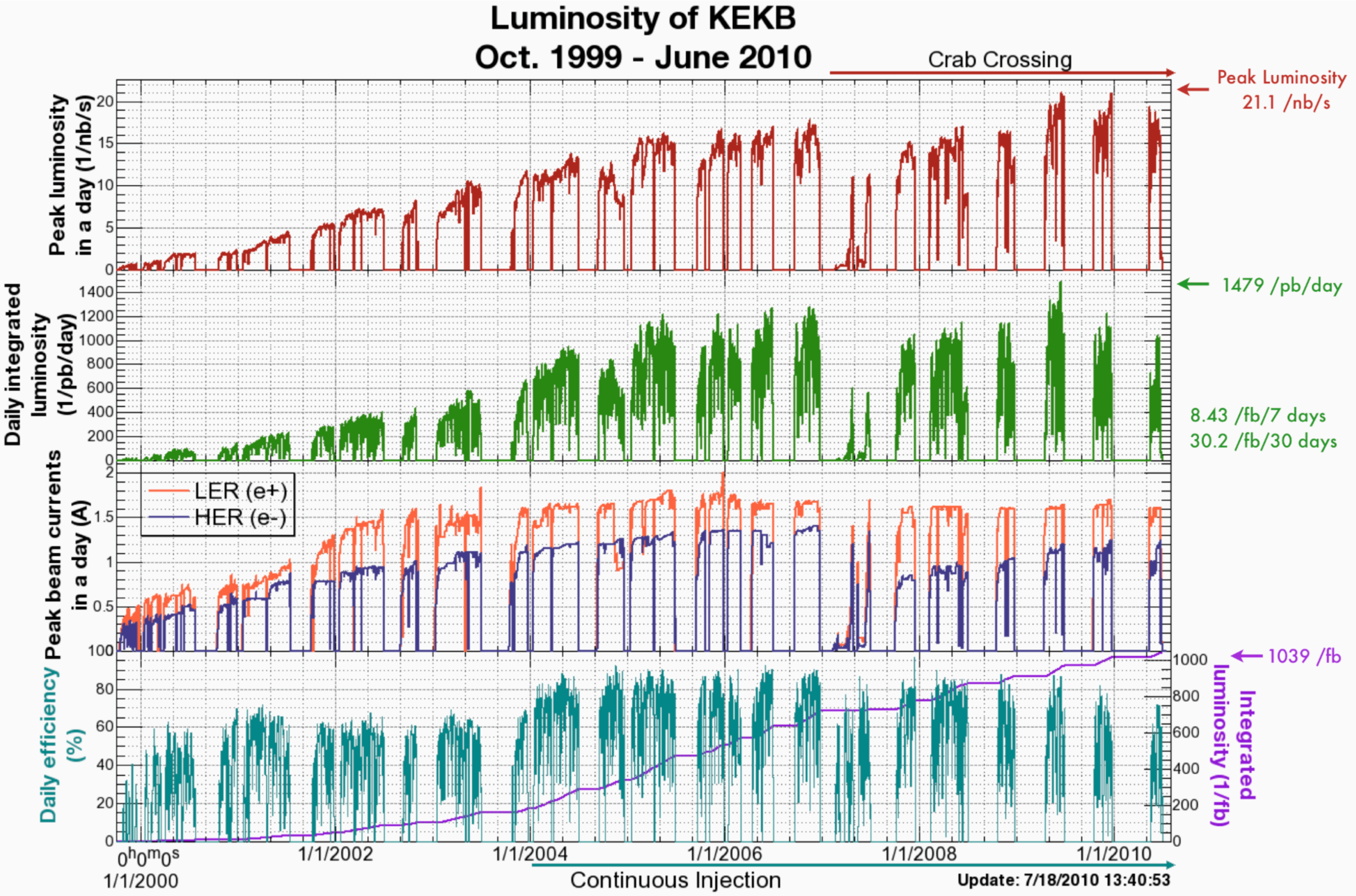
- Dynamic beta in horizontal works demerit.
- Aperture issue appears other place of IR, especially at the crab cavity. Crab β_x is reduced.
- Low crab β_x requires high crab voltage, while high IR β_x degrades luminosity.
- Crossing angle relaxes the dynamic beta ironically, $\sigma_x=(\varepsilon_x\beta_x+\theta\sigma_z{}^2)^{1/2}$.
- We had to find the middle ground.
- Limitation of beam current for crab cavity trip.

The crab crossing works fairly well, though it is not perfect.

Machine parameters (before/after crab)

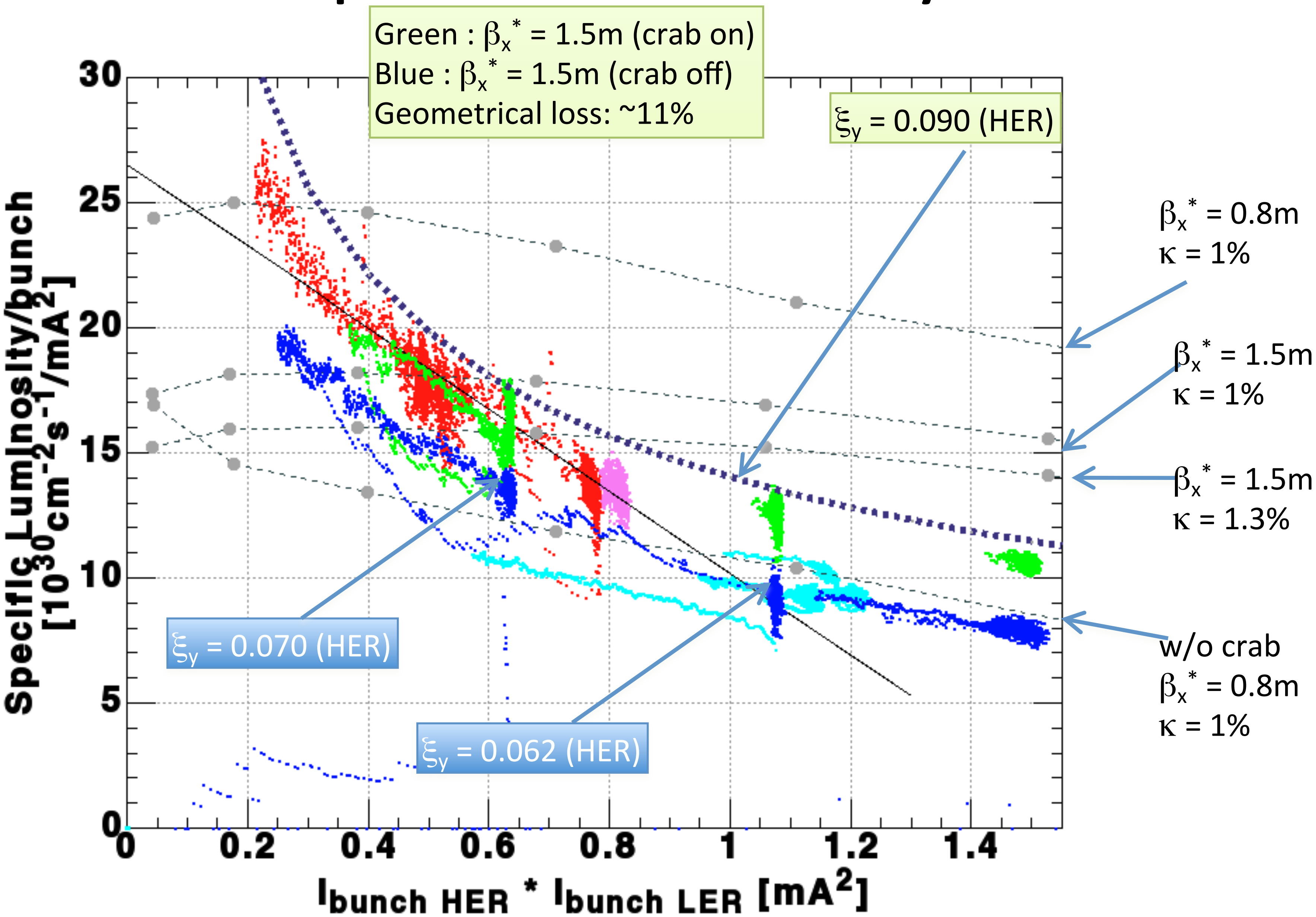
Date	Nov.15 2006 before crab		Jun. 17 2009 with crab		
	LER	HER	LER	HER	
Current	1.65	1.33	1.64	1.19	A
Bunches	1389		1584		
Bunch current	1.19	0.96	1.03	0.750	mA
spacing	2.10		1.84		mA
emittance ε_x	18	24	18	24	nm
β_x^*	59	56	120	120	cm
β_y^*	6.5	5.9	5.9	5.9	mm
σ_x @IP	103	107	147	170	μm
σ_y @IP	1.8	1.8	0.94	0.94	μm
ν_x	45.505	43.509	45.506	44.511	
ν_y	44.534	41.565	43.561	41.585	
ν_s	-0.0246	-0.0226	-0.0246	-0.0209	
beam-beam ξ_x	0.117	0.070	0.127	0.102	
beam-beam ξ_y	0.108	0.058	0.129	0.090	
Luminosity	17.6		21.08		$10^{33}cm^{-2}s^{-1}$

7



Luminosity of KEKB
Oct. 1999 - June 2010
Crab Crossing
Peak Luminosity
21.1 /nb/s
1479 /pb/day
8.43 /fb/7 days
30.2 /fb/30 days
1039 /fb
Peak luminosity in a day (1/nb/s)
Daily integrated luminosity (1/pb/day)
Peak beam currents in a day (A)
LER (e+)
HER (e-)
Daily efficiency (%)
Integrated luminosity (1/fb)
1/1/2000
1/1/2002
1/1/2004
1/1/2006
1/1/2008
1/1/2010
Continuous Injection
Update: 7/18/2010 13:40:53

Specific luminosity



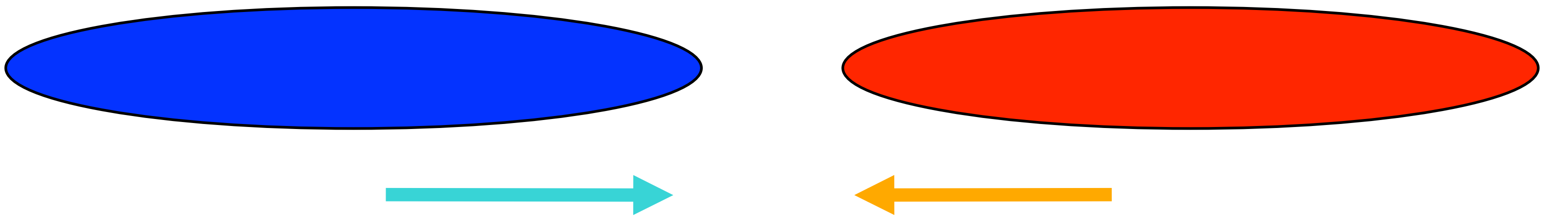
Summary for KEKB crab crossing

- Beam Crabbing was realized without problems.
- Strong Dynamic beta at crab cavity.
- Tuning knobs increase, optics parameters at crab cavity, in addition of those at IP. X-y coupling at crab cavity induces y-z tilt at IP.
- Correction of chromatic coupling at IP was efficient.
- Luminosity 2.11×10^{34} $cm^{-2}s^{-1}$ was achieved. $\xi_y \sim 0.09$.
- Expectation was 3×10^{34}, $\xi_y > 0.1$.
- Chromatic aberration between crab cavity and IP may affect the luminosity performance.

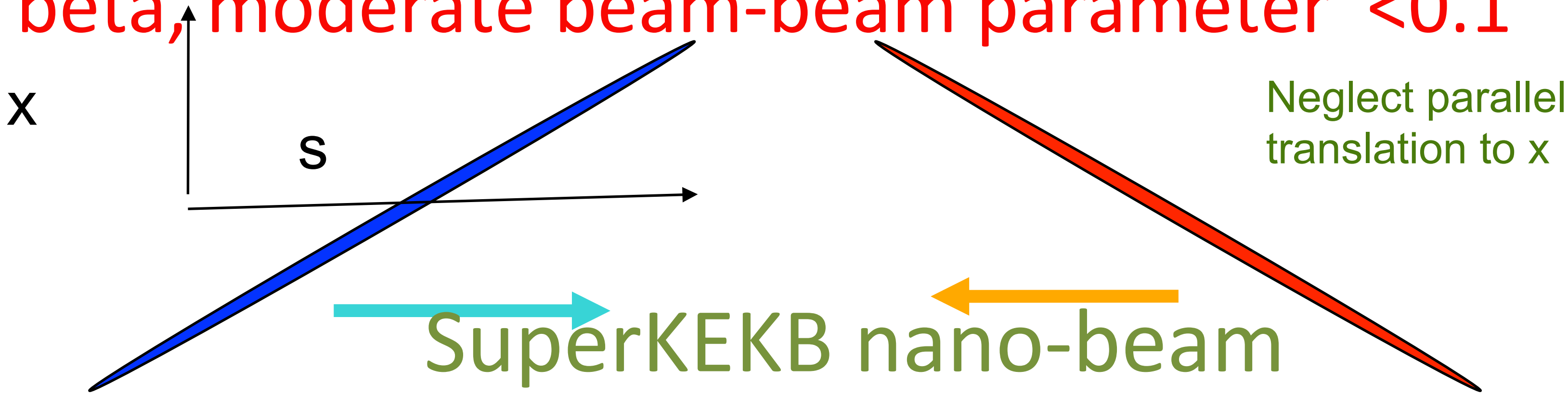
Nano-beam scheme

- KEKB with crab cavity targeted a high beam-beam parameter >0.1.

KEKB crab crossing



- SuperKEKB goes toward Low emittance, low beta, moderate beam-beam parameter <0.1



SuperKEKB nano-beam

Low emittance approach

Φ: half crossing angle

$$\sigma_x/\phi < \sigma_z$$

$$\sigma_x/\phi < \beta_y$$

$$L \propto \frac{N^2}{\phi\sigma_z\sqrt{\varepsilon_y\beta_y}}$$

$$\xi_x \propto \frac{N\beta_x}{(\phi\sigma_z)^2}$$

$$\xi_y \propto \frac{N}{\phi\sigma_z}\sqrt{\frac{\beta_y}{\varepsilon_y}}$$

Keep $\sqrt{\frac{\beta_y}{\varepsilon_y}}$ and σ_x/β_y

Then take limit $\varepsilon_y\beta_y \to 0$

$$L \to \infty$$

- Bunch length is free.
- Small beta and small emittance are required.

Super KEKB

ε_x=3/5 nm, ε_y=3/5 pm

β_x=32/25 mm, β_y=0.3mm

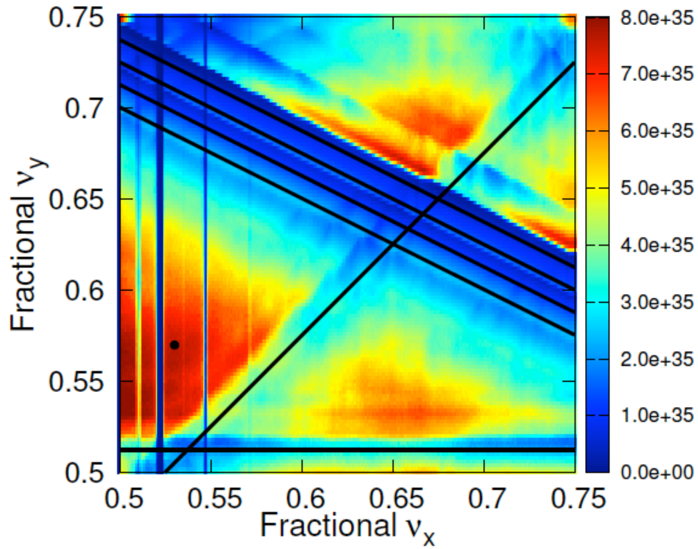
Machine Parameters

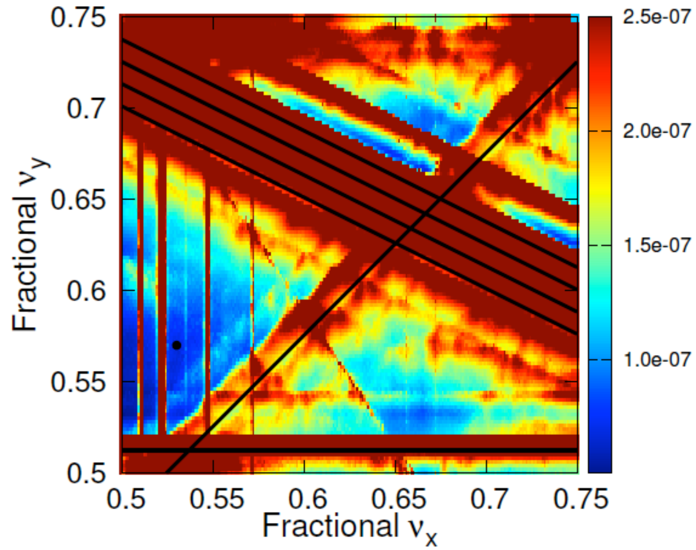
2011/July/20	LER	HER	unit	
E	4.000	7.007	GeV	
I	3.6	2.6	A	
Number of bunches	2,500			
Bunch Current	1.44	1.04	mA	
Circumference	3,016.315		m	
$\varepsilon_x/\varepsilon_y$	3.2(1.9)/8.64(2.8)	4.6(4.4)/11.5(1.5)	nm/pm	():zero current
Coupling	0.27	0.28		includes beam-beam
β_x^*/β_y^*	32/0.27	25/0.30	mm	
Crossing angle	83		mrad	
α_p	3.25×10^{-4}	4.55×10^{-4}		
σ_δ	$8.08(7.73)\times10^{-4}$	$6.37(6.31)\times10^{-4}$		():zero current
V_c	9.4	15.0	MV	
σ_z	6.0(5.0)	5(4.9)	mm	():zero current
ν_s	-0.0247	-0.0280		
ν_x/ν_y	44.53/44.57	45.53/43.57		
U_0	1.87	2.43	MeV	
$\tau_{x,y}/\tau_s$	43.1/21.6	58.0/29.0	msec	
ξ_x/ξ_y	0.0028/0.0881	0.0012/0.0807		
Luminosity	8×10^{35}		$cm^{-2}s^{-1}$	

2. Beam-beam and luminosity: LER

➤ Lum. tune scan for LER (by BBWS: weak strong with linear arc)

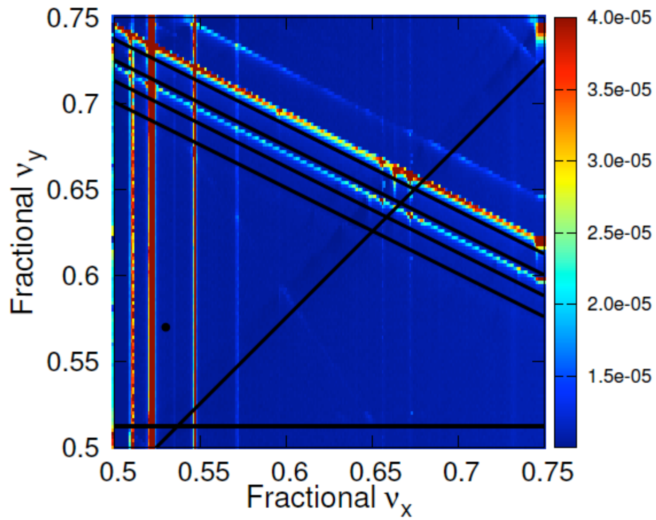
$\mathcal{L}$





σ_y

σ_x

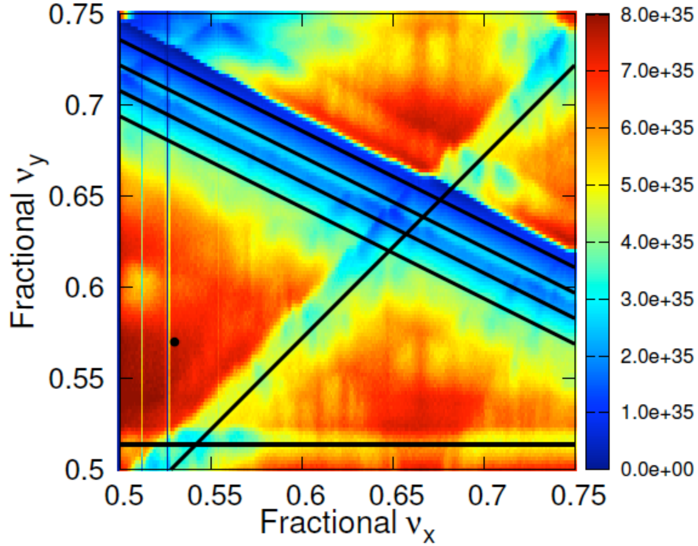


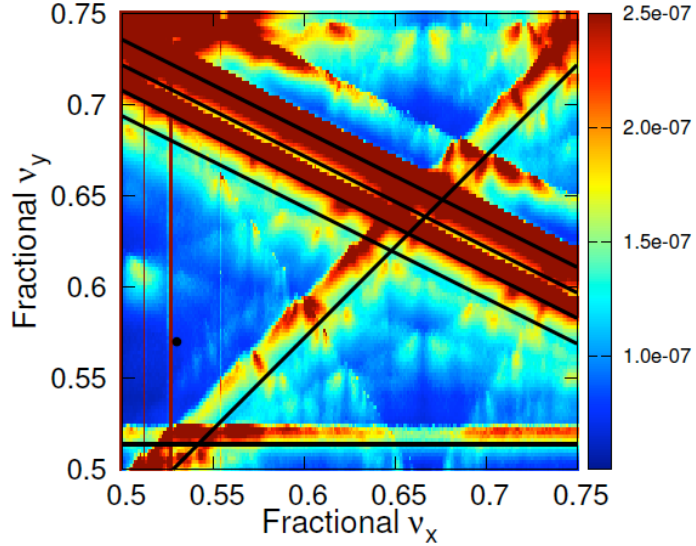
Choice of tune operating point
ν_x near half integer, keep away from synchrobeta resonance
ν_x ,ν_y=0.53,0.57

2. Beam-beam and luminosity: HER

➤ Lum. tune scan for HER (by BBWS: weak strong with linear arc)

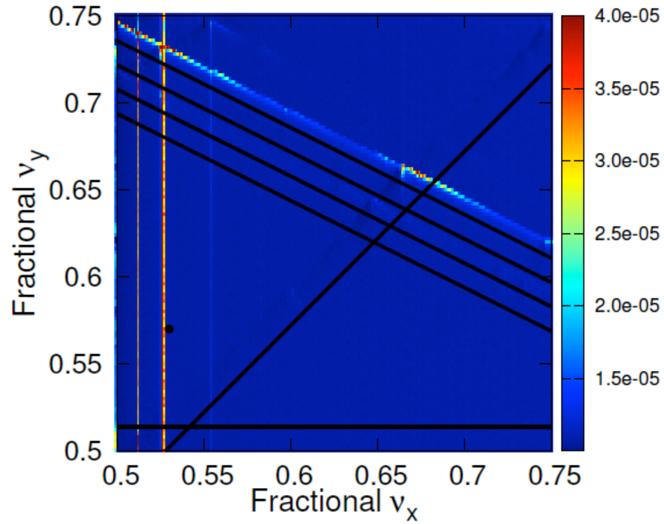
$\mathcal{L}$





σ_y

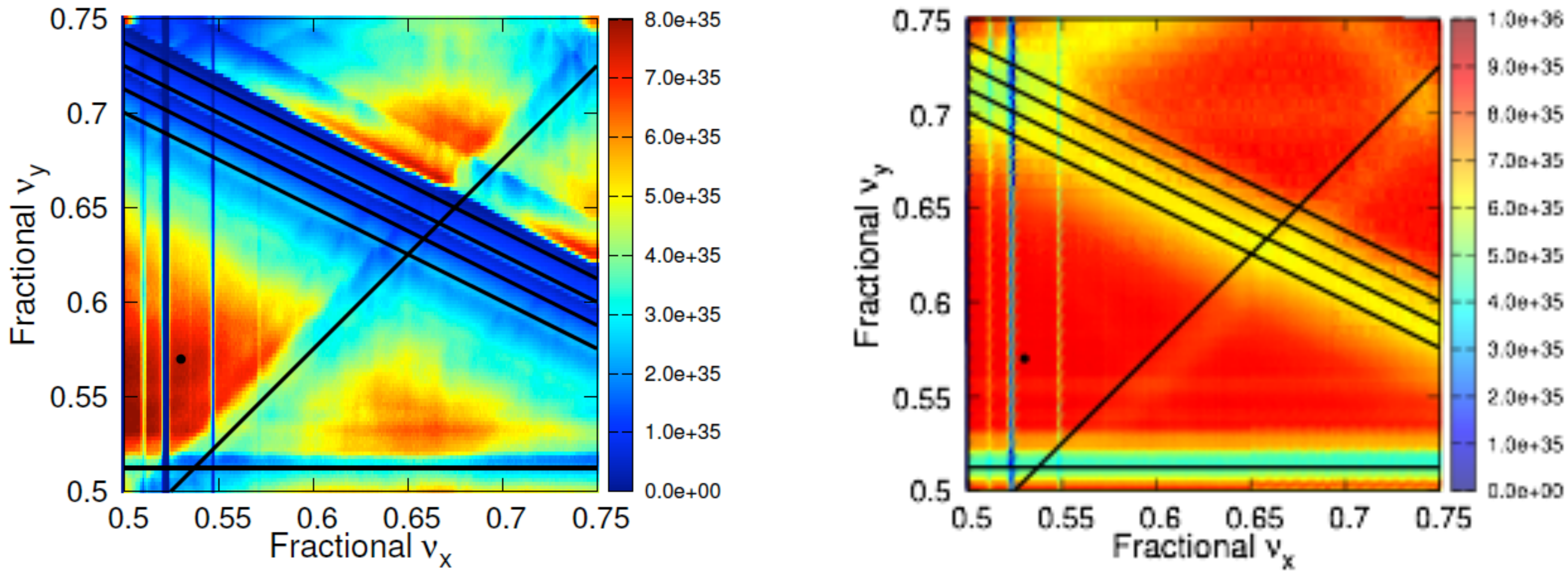
σ_x



σ_z

2. Beam-beam and luminosity: LER

➤ Lum. scan w/o and w/ crab waist for LER (by BBWS)



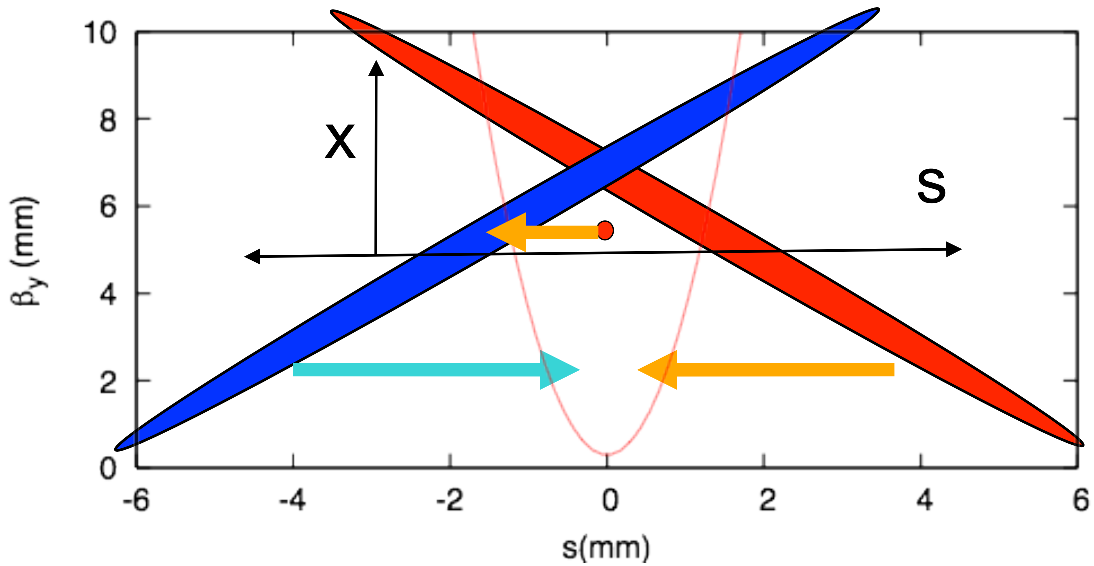
$$H_I^* = \pm \frac{1}{2\phi} x p_y^2$$

ϕ: half crossing angle

The crab waist is very powerful.
Degradation of dynamic aperture is inevitable, because nonlinearity between IP and crab waist sextupole is not transparent. See later.

Characteristics of the collision

- βy is small only interaction area
  - ✤ Beam particles with a large horizontal amplitude collide high beta region
  - ✤ Issues on injection, collision offset, Touschek life time
  - ✤ Crab waist recovers the issues, but…

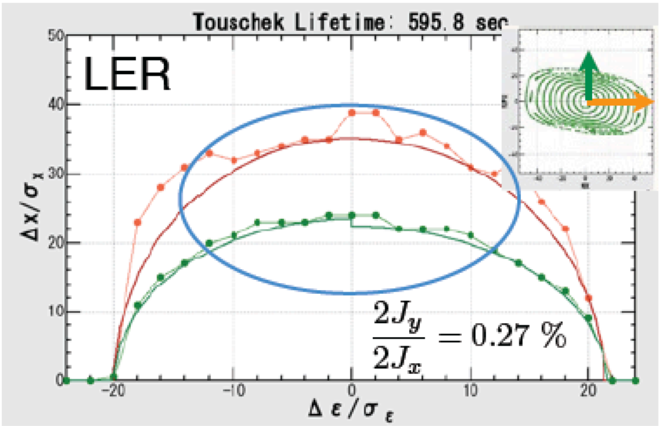


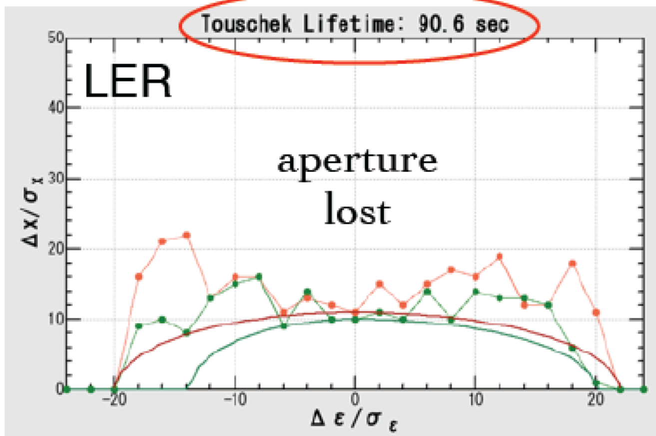
Neglect parallel translation to x

Dynamic aperture and Touschek life time

- Dynamic aperture with beam-beam is quite narrow.
- Touschek event-> betatron amplitude -> over the aperture

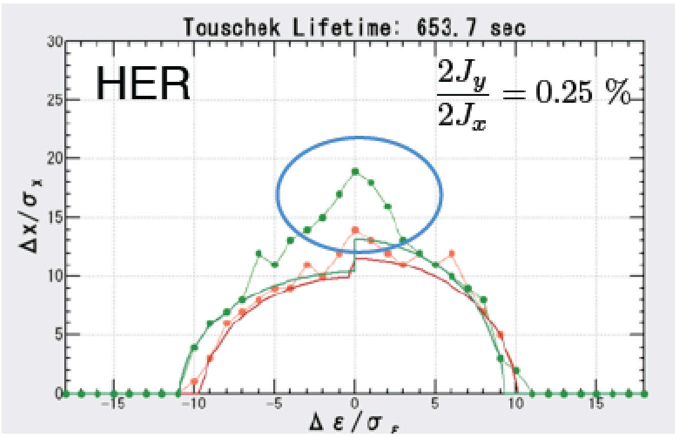
w/o beam-beam **with beam-beam (W-S)**

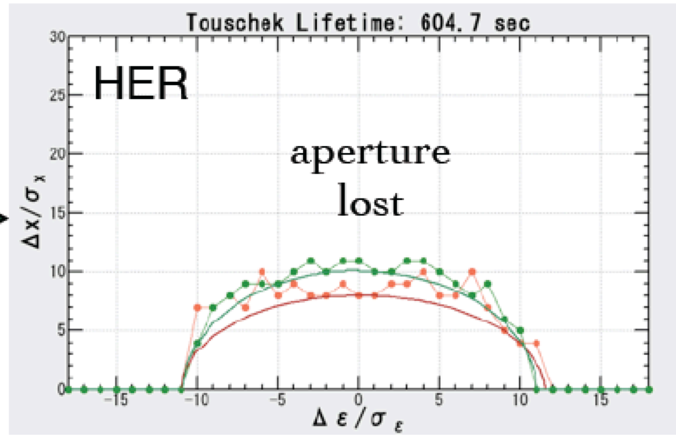




Transverse aperture is reduced significantl

Y. Ohnishi et al.





Crab waist

- Transformation of Effective Crab waist at IP.

$$H_I^* = \pm \frac{1}{2\phi} x p_y^2$$

ϕ: half crossing angle

+: before collision

-: after collision

- The nonlinearity is completely cancelled without beam-beam, when the transformation is applied at IP.
- Particles with a horizontal amplitude collide with another beam at their vertical waist.
- The aperture issue with beam-beam is recovered, but

$$\bar{y} = y \pm \frac{x}{2\phi} p_y \quad \bar{p}_x = p_x \mp p_y^2/2\phi$$

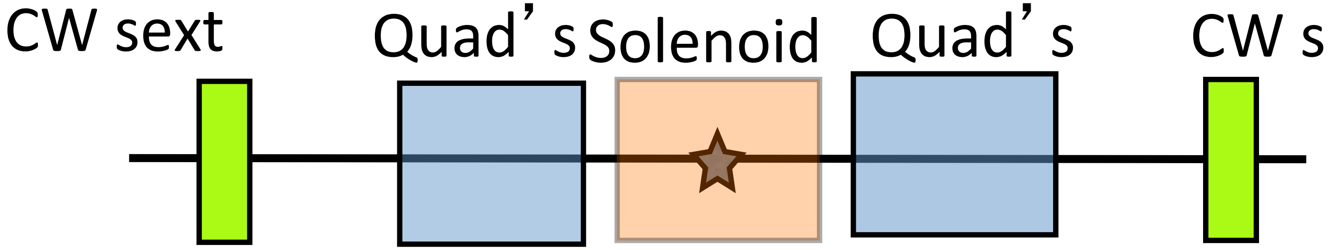
-> next slide

$$M_y = \begin{pmatrix} 1 & x/2\phi \\ 0 & 1 \end{pmatrix}$$

$$M_y^{-1} M_{BB} M_y$$

Waist shift: x/2ϕ

Crab waist and IR nonlinearity



$$\mathcal{M}_{IR} = e^{-axy^2} e^{-H_{Q's}} e^{-H_{Sol}} e^{-H_{BB}} e^{-H_{Sol}} e^{-H_{Q's}} e^{-axy^2}$$

crab waist sext — crab waist sext

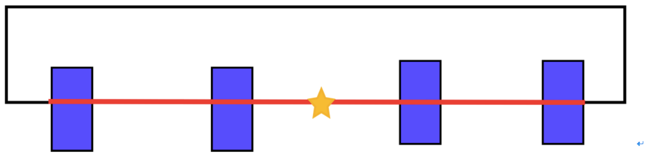
$$\neq$$

ideal crab waist — ideal crab waist

$$e^{-H_{Q's}} e^{-H_{Sol}} e^{-xp_y^2/2\phi} e^{-H_{BB}} e^{-xp_y^2/2\phi} e^{-H_{Sol}} e^{-H_{Q's}}$$

- Severe dynamic aperture degradation is seen by crab sextupole installation in SAD (H. Koiso).
- We do not know how to handle the nonlinear terms of Q’s and Solenoid located at very high β.
- Crab waist is not base in Super KEKB.

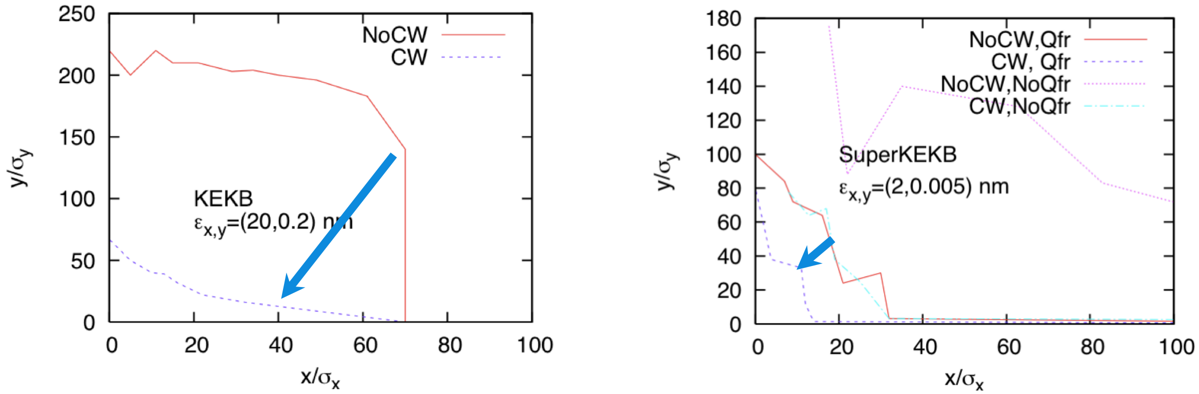
Study with a simple model



- Strong nonlinearity in drift space, chromatic effects.
- Quadrupole edge at very high β

$$\mathcal{M}_{IR} = e^{-H_{QF}} e^{-H_{L1}} e^{-H_{QD}} e^{-H_{L0}} e^{-H_{L0}} e^{-H_{QD}} e^{-H_{L1}} e^{-H_{QF}}$$

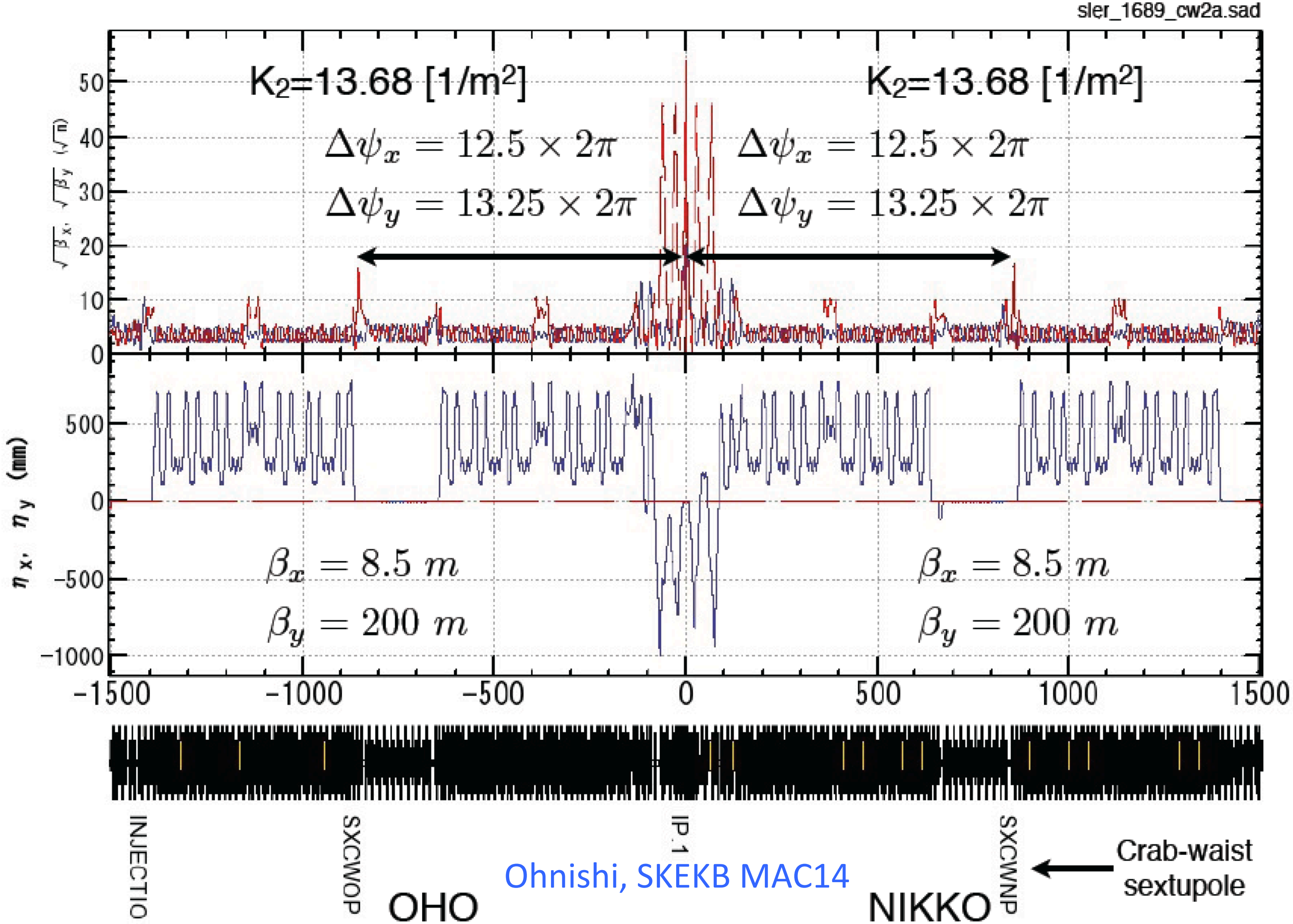
$$\mathcal{M}_{rev} = \mathcal{M}_{IR} \mathcal{M}_{arc}$$



- Dynamic aperture is strongly degraded by installation of crab waist sextupoles.
- More nonlinear components in IR actually.

Realistic crab waist

Crab-waist optics in LER

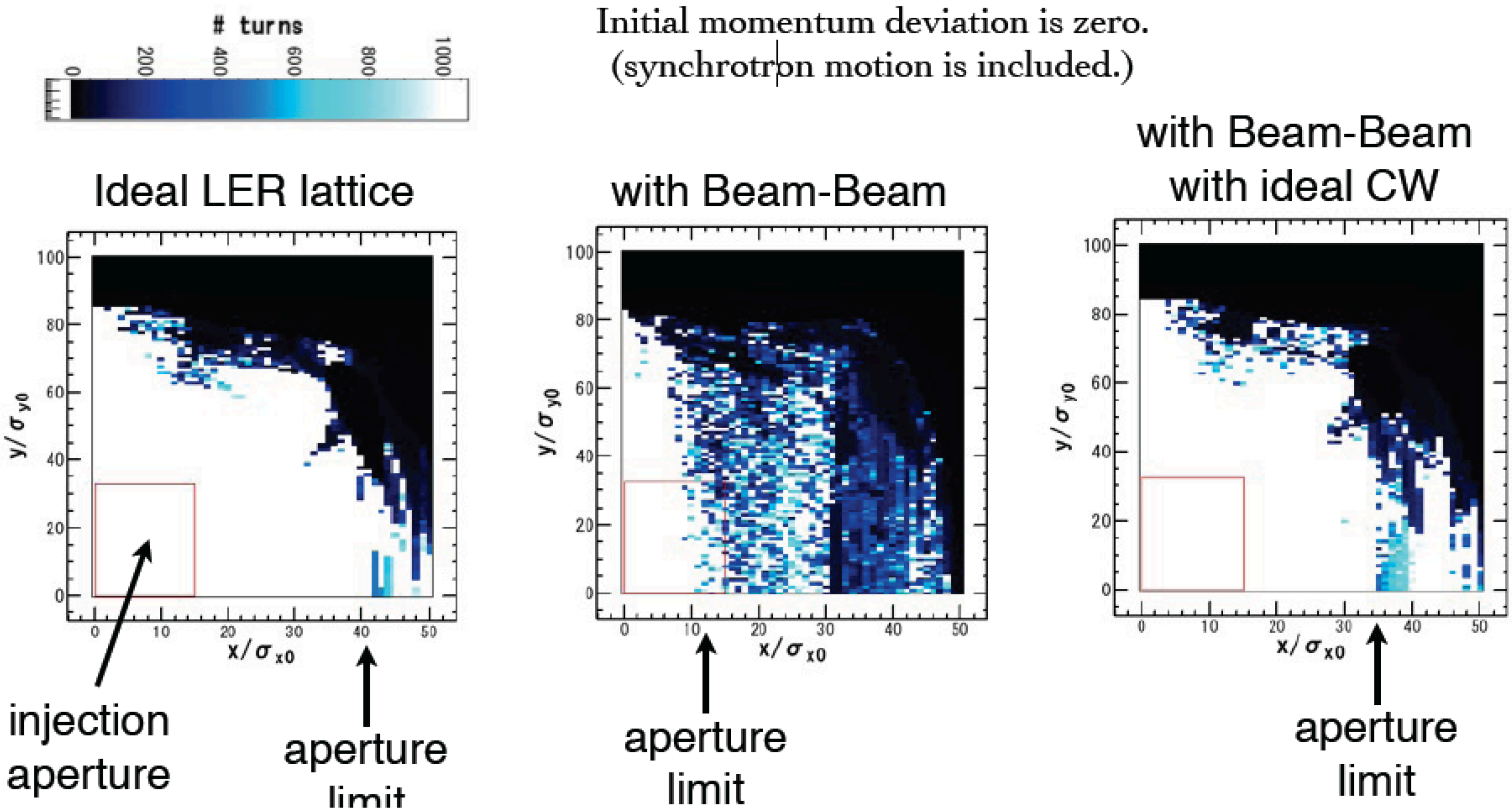


Ohnishi, SKEKB MAC14

Dynamic aperture using SAD

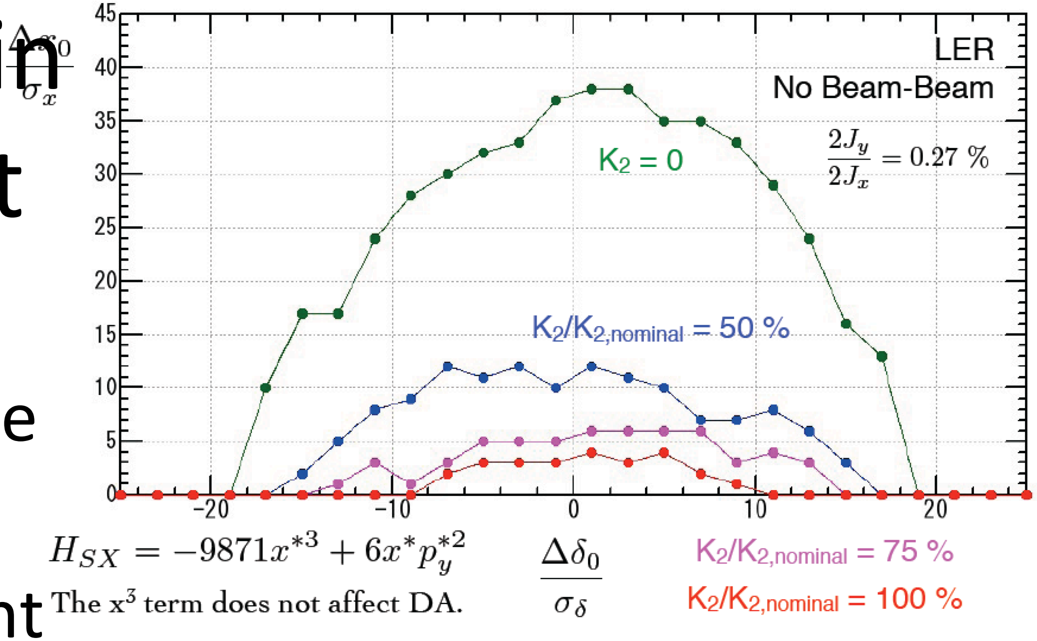
- On momentum aperture

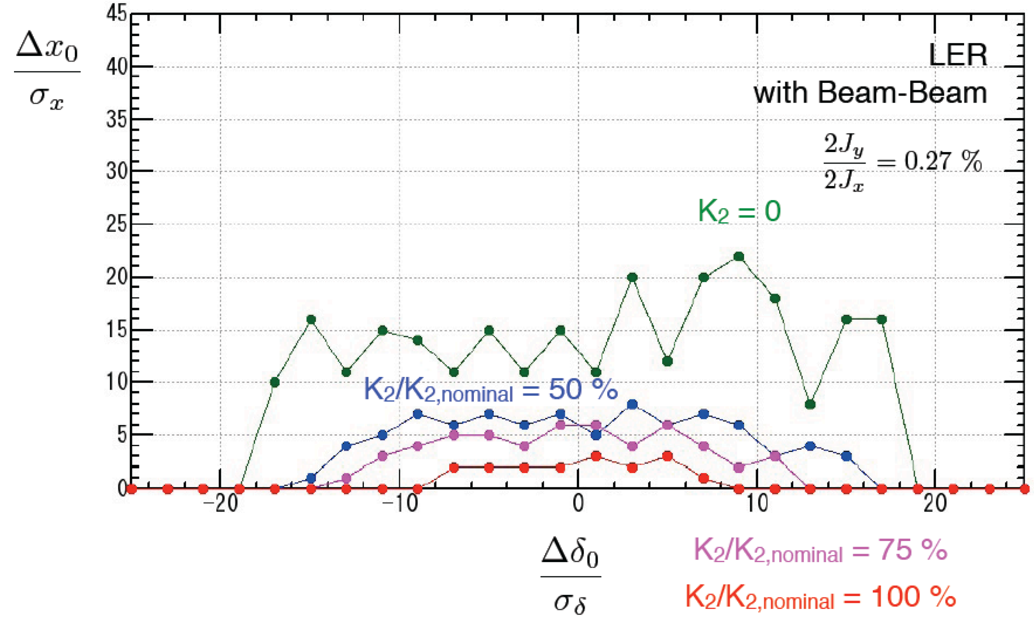
Ohnishi, SKEKB MAC14



Dynamic aperture in realistic crab waist

- Crab waist sextupole reduces dynamic aperture significantly.
- The results is independent of (effective) crab sextupole location outside of IR (A. Morita).





Strategy for crab waist in SuperKEKB

- We understand efficiency of the crab waist on luminosity in simple model.
- However the side effect, which reduces dynamic aperture, is too severe in very low β^* IP.
- Crab waist scheme is not adopted in SuperKEKB at present.
- Efforts to enlarge dynamic aperture with crab waist sextupole are continued. (BINP collaboration)

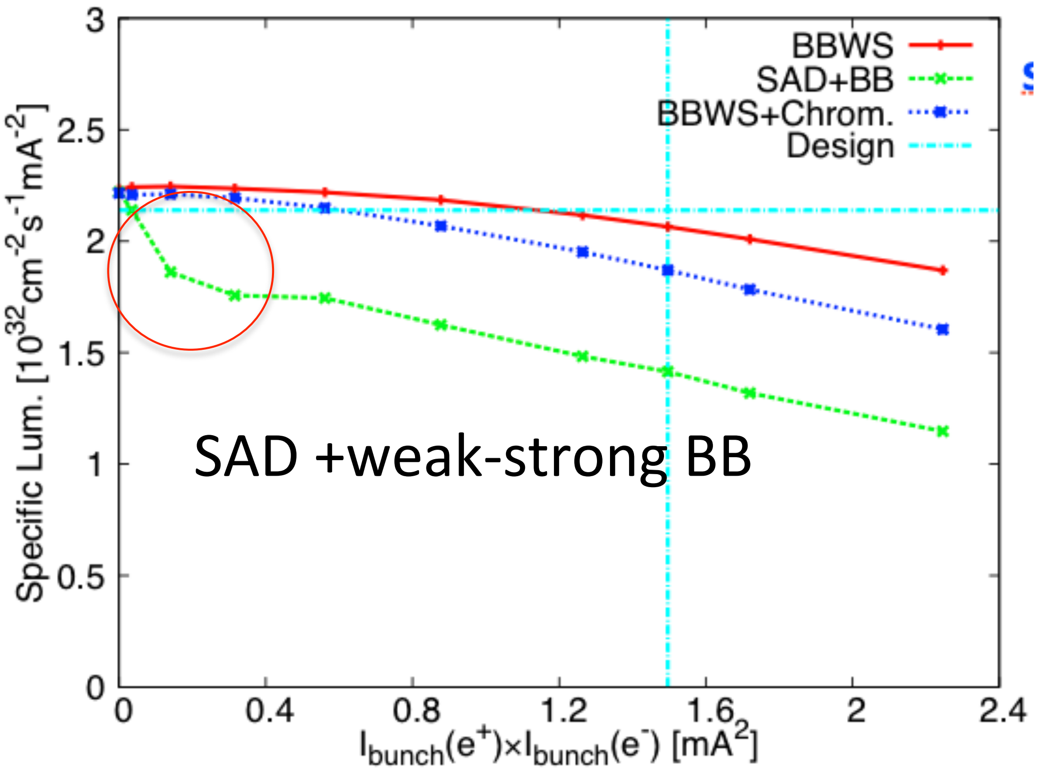
Luminosity simulation in realistic lattice

- Weak-strong beam-beam simulation using SAD.

- Crosscheck is began using other codes, Acceleraticum (Levichev,Piminov in BINP), BMAD(Sagan), SCTR (K.Ohmi).

Weak-strong Simulation for LER lattice

- Even low current, luminosity loss ~20% is seen.
- 30% loss at the design current.
- Chromatic effect can not explain the lum. Loss.



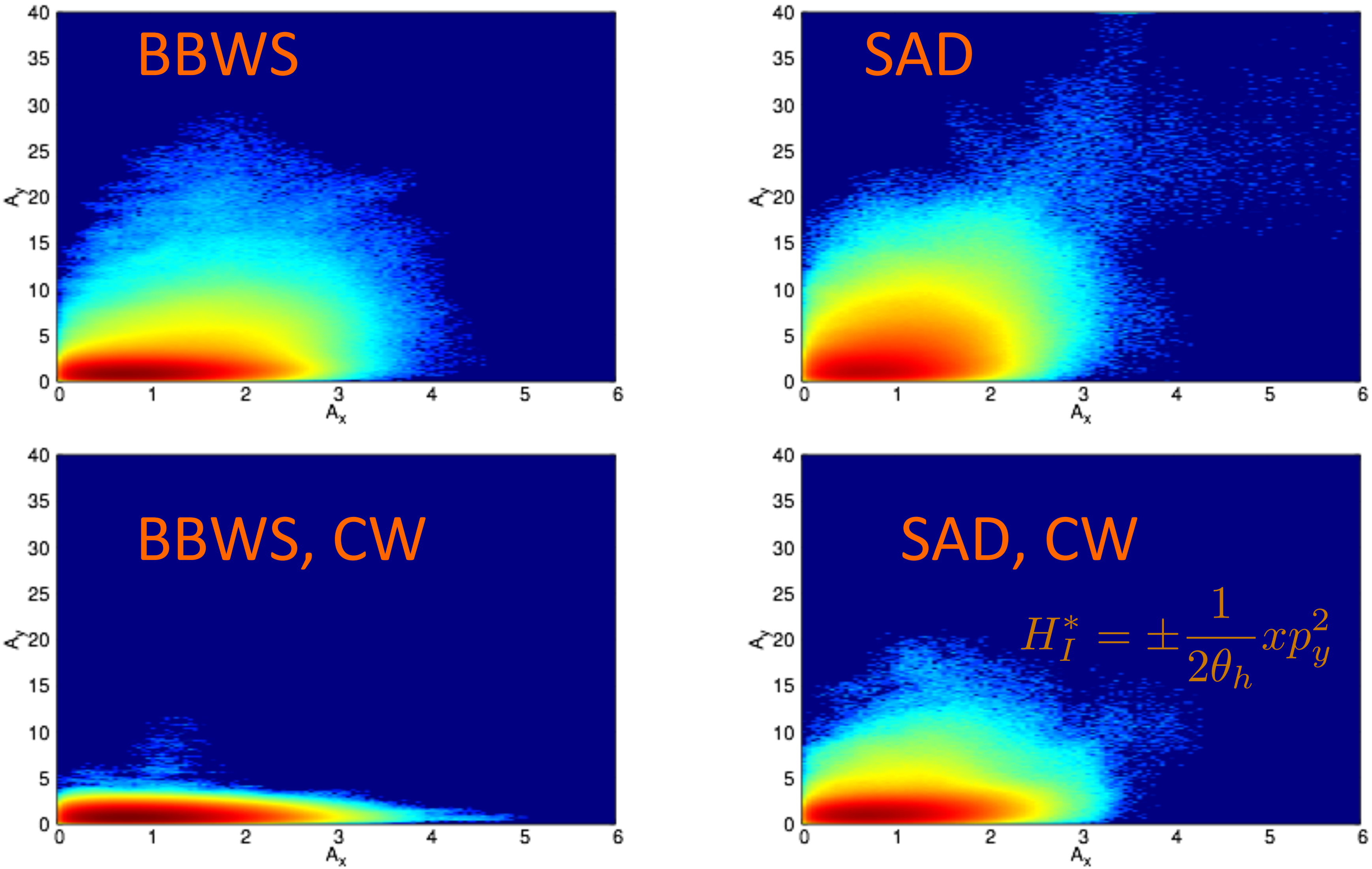
sler_1684

IR solenoid is taken into account

Beam tail distribution LER, A=J/ε

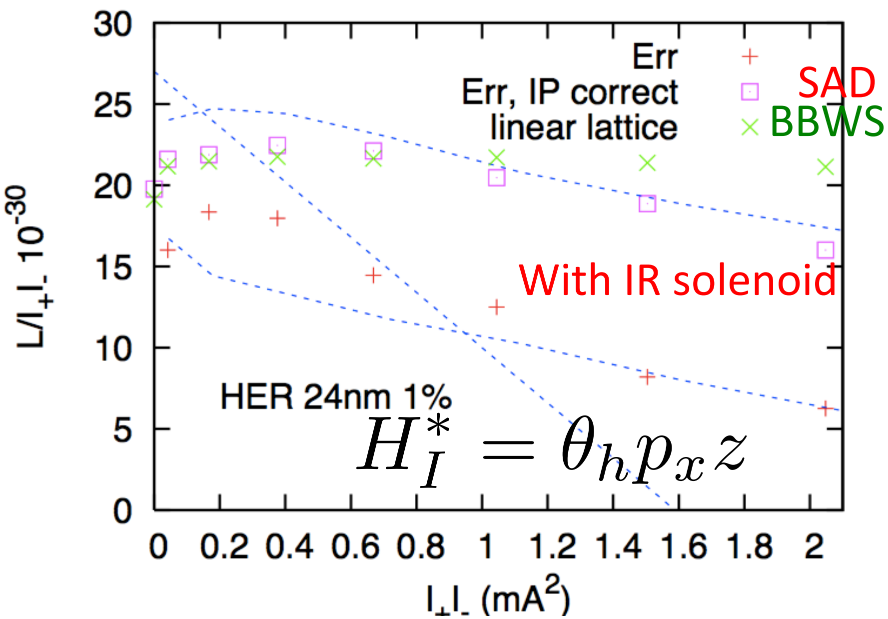
- Ne=6.53x10^{10},

SAD +weak-strong BB

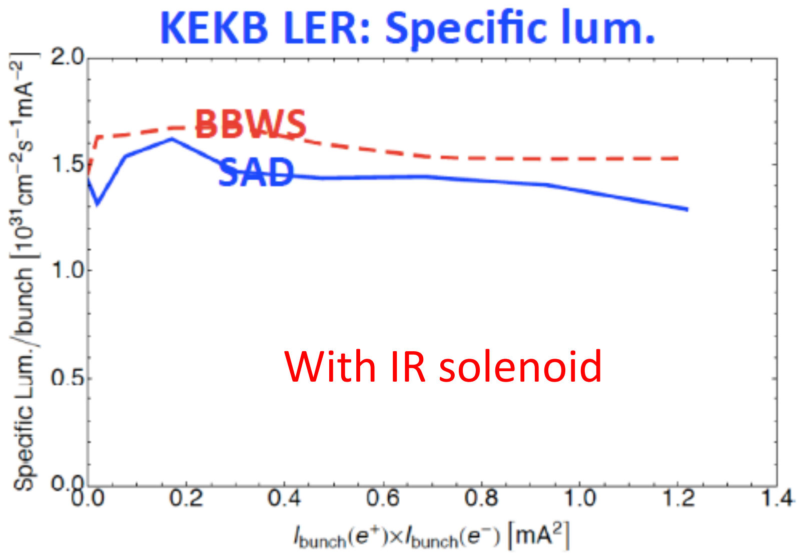


Other experiences on beam-beam in realistic lattice

KEKB crab, EPAC08



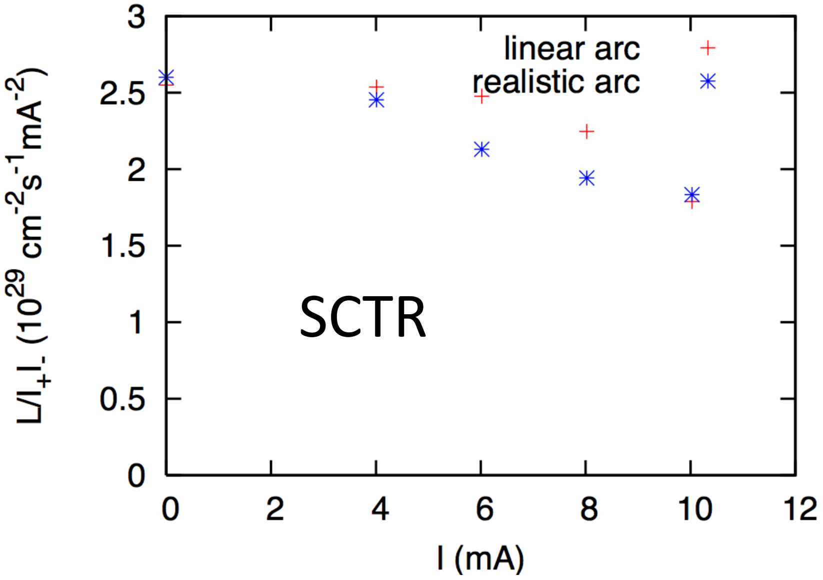
No crab

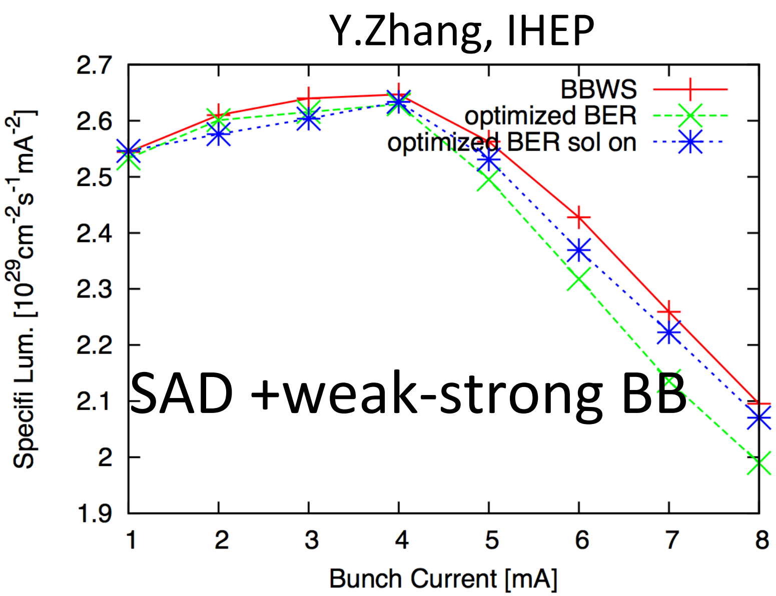


- No clear degradation due to lattice nonlinearity is seen in KEKB, except high beam-beam parameter.

BEPC-II

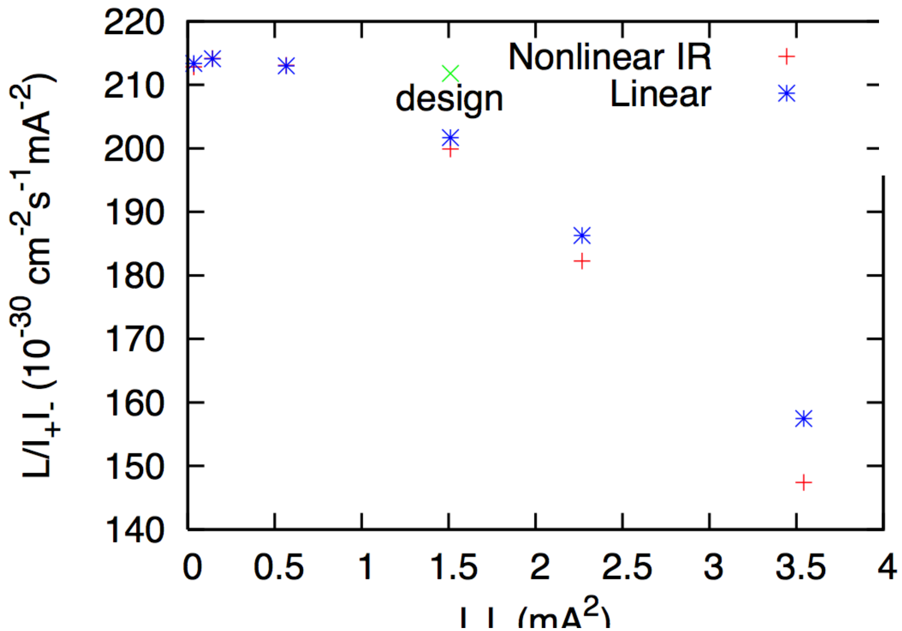
- SCTR code showed 15% loss at 6 & 8 mA.
- SAD does not show clear difference

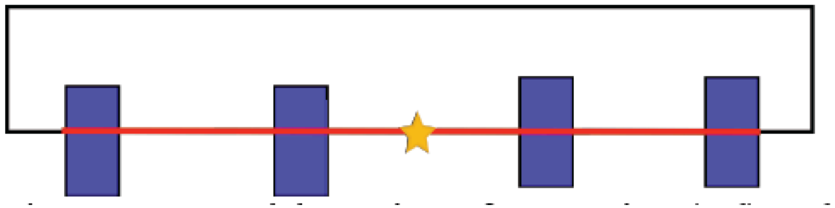




SuperKEKB

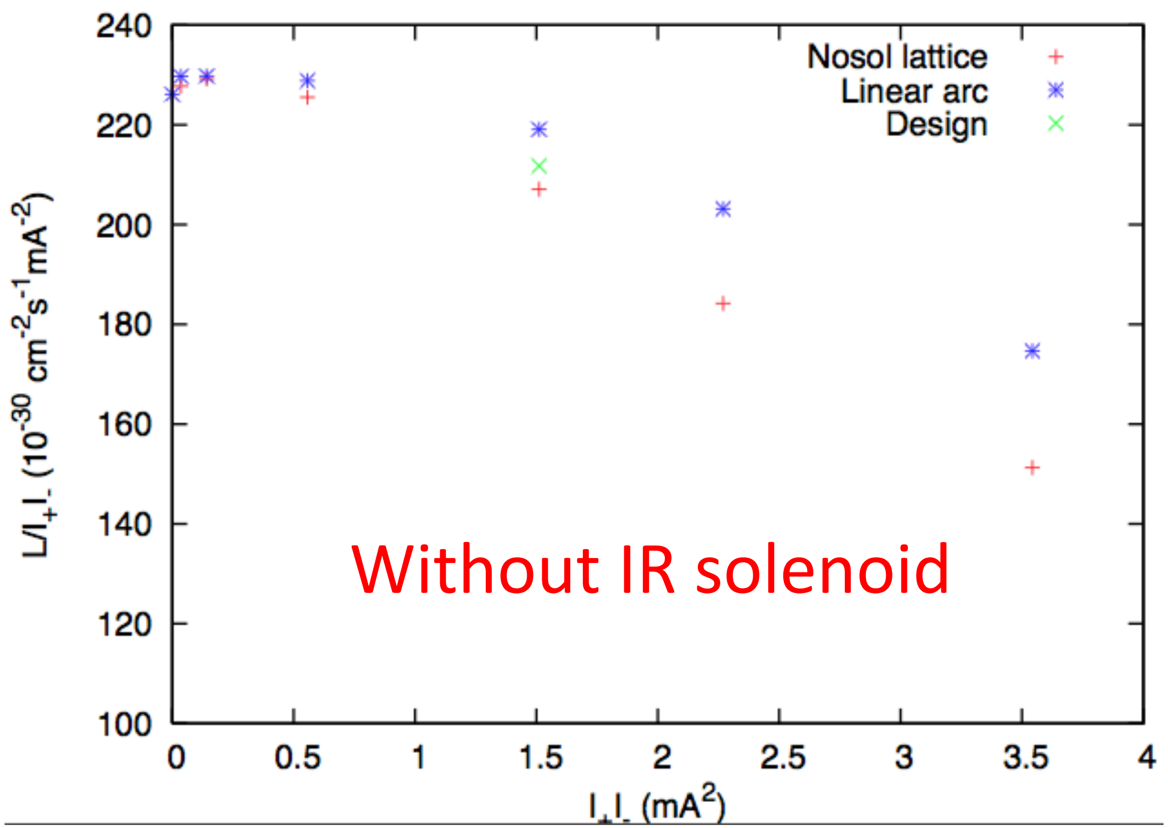
- Simplified IR model for SuperKEKB

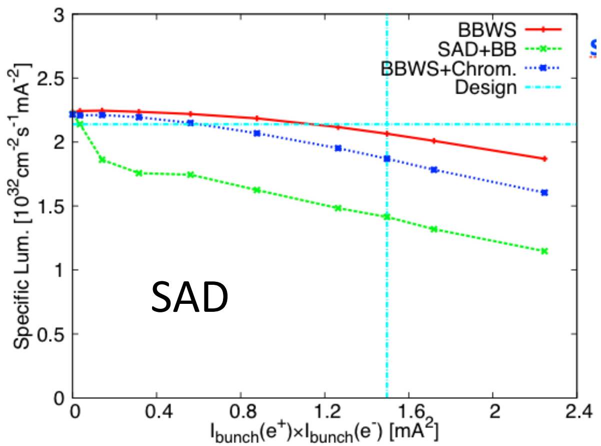




IR solenoid is not taken into account

SCTR Including WS Beam-beam



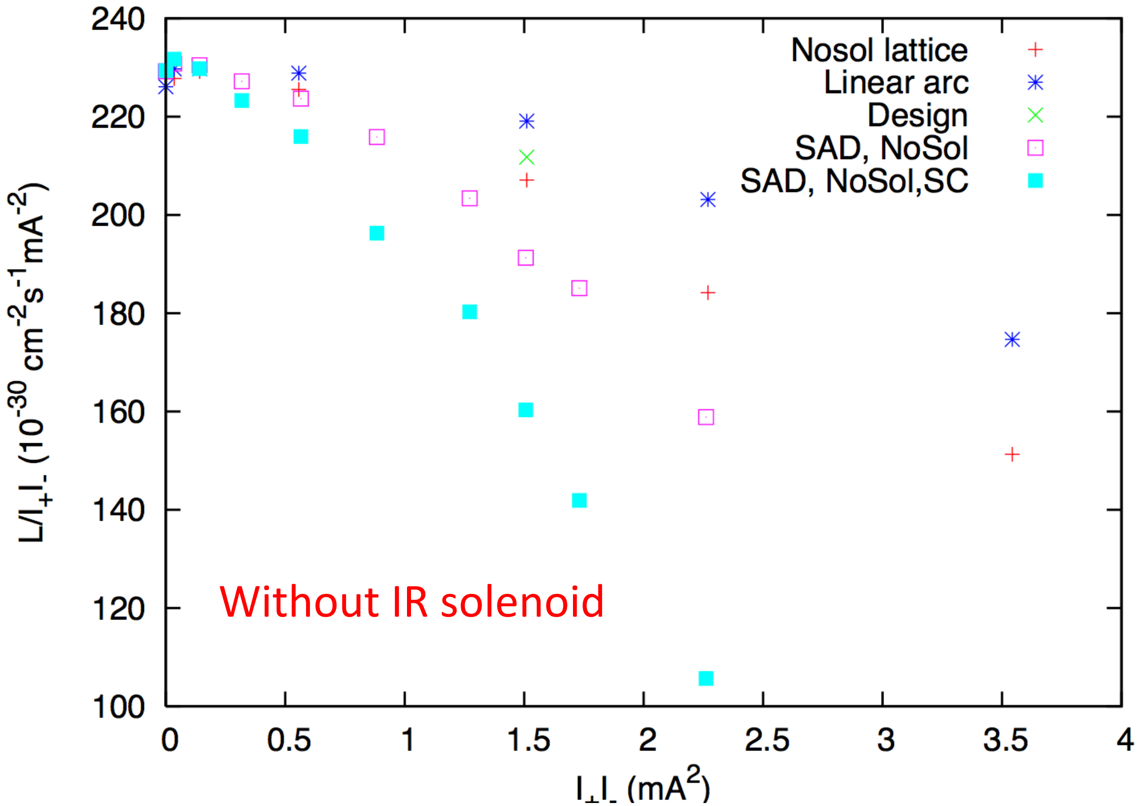


With IR solenoid

- Note: bunch length 5.3mm (design 6mm)

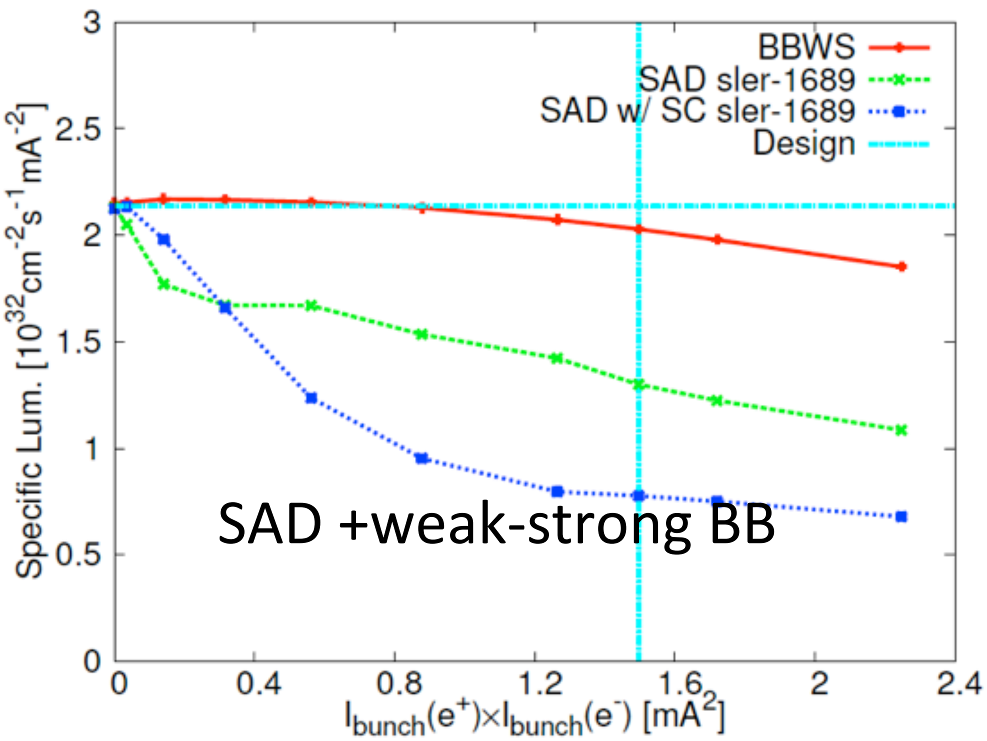
Include Space charge

- No sol



Space charge: LER

- ➤ Weak-strong model for space charge
- ➤ "Strong" beam: Emittance growth due to IBS included
- ➤ Remarkable luminosity loss is seen (65%).



With IR solenoid

Summary for SuperKEKB studies

- Touschek life time is severe when beam-beam interaction is taken into account.
- Crab waist degrade the dynamic aperture due to IR strong nonlinearity.
- Beam-beam effect in realistic Lattice has been studied using weak-strong & SAD.
- Clear luminosity loss (30%) has been seen.
- In KEKB, BEPC, the loss is small.
- Crosscheck is began using several codes. Understanding of mechanism will be performed.
- Solenoid and IR complex may degrade the luminosity. (preliminary)
- Further loss (60-70%) is seen in taking account of space charge. Crosscheck and understanding will be performed.