Beam-beam effects in SuperKEKB Phase II commissioning

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SuperKEKB MAC 2018

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Thanks to E. Forest, Y. Funakoshi, N. Iida, H. Koiso, N. Kuroo, A. Morita,
Y. Ohnishi, N. Ohuchi, K. Oide, D. Sagan, H. Sugimoto, Y. Zhang

SuperKEKB

- Luminosity upgrade strategy changes the crab cavity to the large crossing angle scheme.
- Extremely low β IP optics, β_x^*=3cm β_y^*=0.3mm.
- Large Piwinski angle,

- Commissioning with collision starts with detuned beta*.
- IP beta is squeezed step by step,

$(8x\beta_x^*,8x\beta_y^*)$, $(4x\beta_x^*,8x\beta_y^*)$, $(4x\beta_x^*,4x\beta_y^*)$,…, (β_x^*,β_y^*)

Two subjects are discussed,

1. IR nonlinearity, chromatic Twiss (β and coupling)
2. Coherent beam-beam instability

Machine Parameters

SuperKEKB can exceed the peak luminosity of KEKB when we achieve $\xi_y > 0.05$

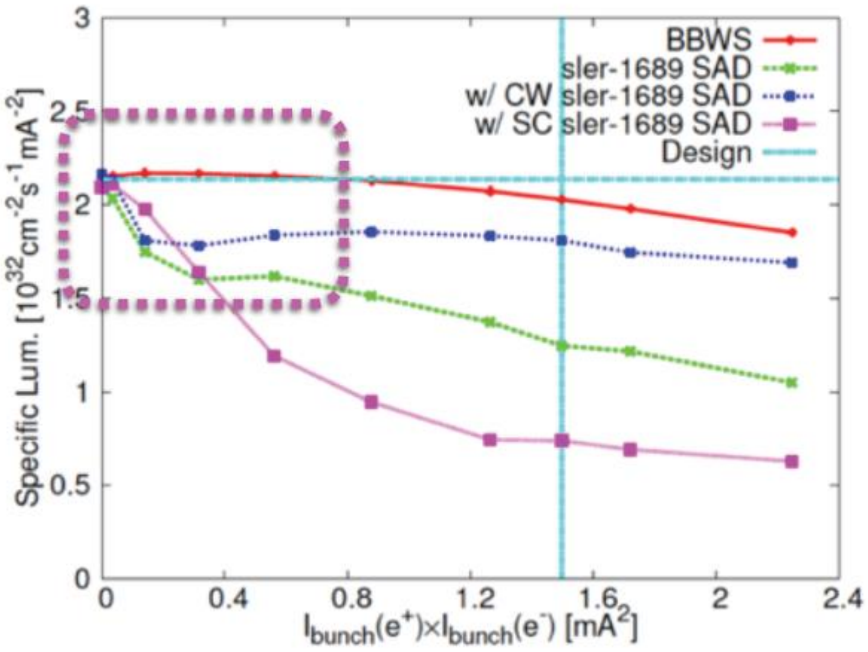
	Phase 2.3 (4x8)				Phase 2.4 (4x4)		Phase 3 (1x1)	
	LER	HER	LER	HER	LER	HER	LER	HER
I_L x I_H, n_b	**1 A x 0.8 A, 1576 bunches (3-bucket spacing)**						**3.6 A 2500**	**2.6 A 2500**
β_x^* [mm]	128	100	128	100	128	100	32	25
β_y^* [mm]	2.16	2.4	2.16	2.40	1.08	1.20	0.27	0.30
$\varepsilon_y/\varepsilon_x$ [%]	**5.0**		**1.4**		**0.7**		**0.27**	**0.28**
ξ_x	0.0052	0.0020	0.0053	0.0021	0.0053	0.0021	0.0028	0.0012
ξ_y	0.0257	0.0264	0.0484	0.0500	0.0496	0.0505	0.0881	0.0807
I_{bunch} [mA]	0.64	0.51	0.64	0.51	0.64	0.51	1.44	1.04
L [$cm^{-2}s^{-1}$]	**1 x 10^{34} (tentative target)**		2 x 10^{34}		4 x 10^{34}		8 x 10^{35}	
L_{sp} [$cm^{-2}s^{-1}/mA^2$]	1.97 x 10^{31}		3.94 x 10^{31}		7.88 x 10^{31}		2.14 x 10^{32}	

Y. Ohnishi,
Dec. 2017

IR magnets and their nonlinearity

- There are many nonlinear field components in IR magnets.
- Chromatic coupling
  - ➤ **Realistic lattice: lum. drops at low beam currents**
  - ➤ **Crab-waist:**
    - **To cancel beam-beam driven resonances**
    - **Work well at high currents, but not well at low currents**

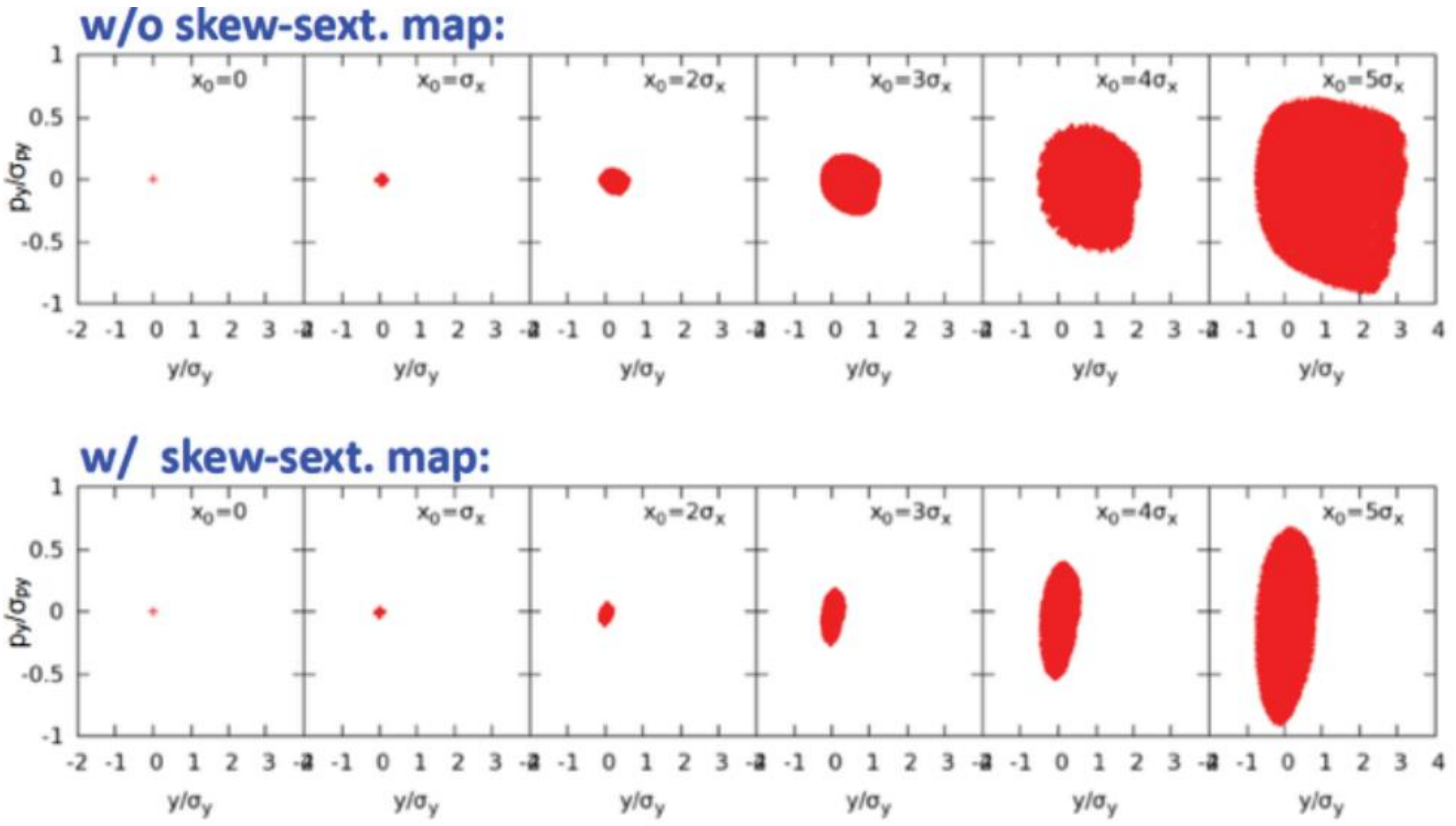
D. Zhou, SKEKB
MAC 2015



BBWS : arc expressed by simple transfer matrix
SAD: complex lattice structure

Y. Zhang's (IHEP) work at KEK

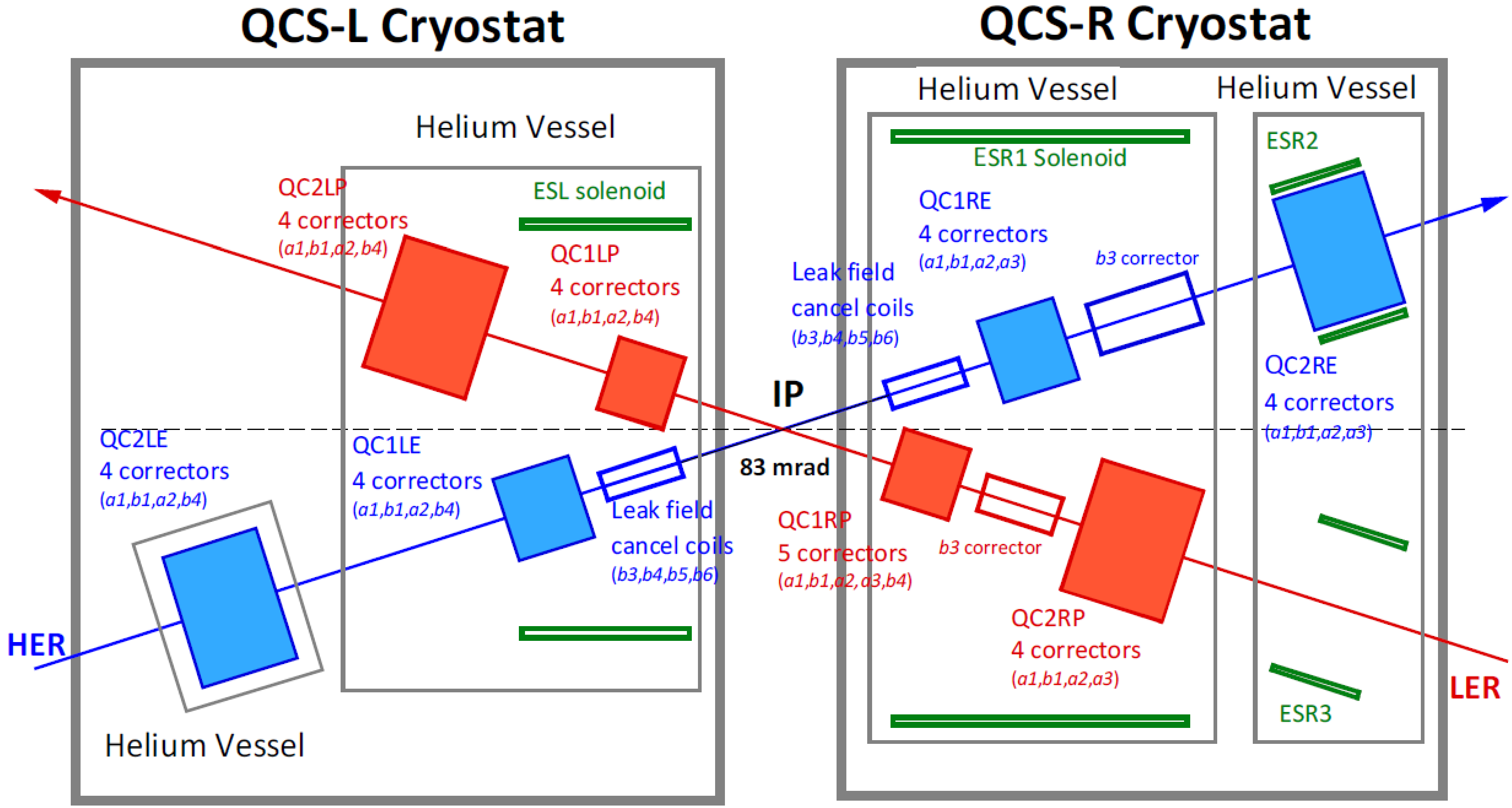
- Vertical orbit is induced by a large horizontal betatron oscillation.
- Skew sextupole term at IP, x^2y, is suspected for the luminosity degradation.



From Y. Zhang

QCS superconducting magnet system

N. Ohuchi et al.



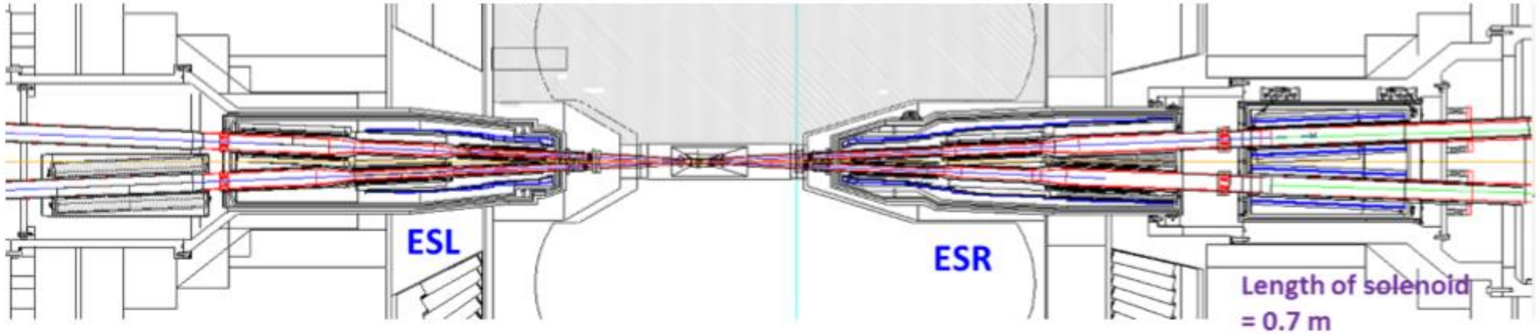
超伝導4極電磁石：4台
超伝導補正磁石（ a1, b1, a2, b4 ）:16台
QC1LP漏れ磁場キャンセル磁石（ b3, b4, b5, b6 ）:4台
超伝導補正ソレノイド：1台

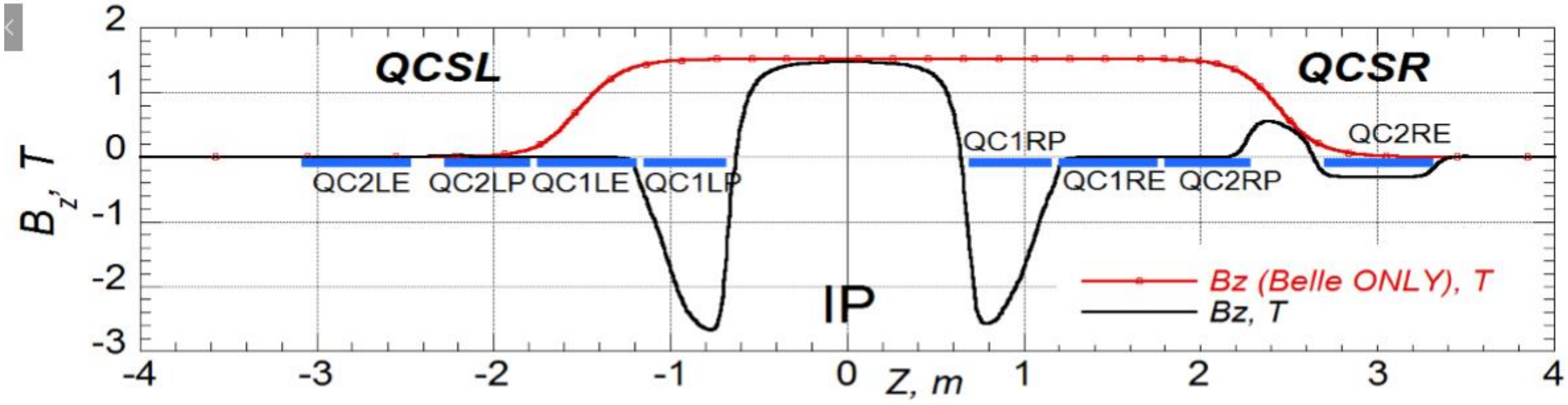
超伝導4極電磁石：4台
超伝導補正磁石（ a1, b1, a2, a3, b3, b4 ）:19台
QC1RP漏れ磁場キャンセル磁石（ b3, b4, b5, b6 ）:4台
超伝導補正ソレノイド：3台

Overview of IR magnets

N. Ohuchi et al.

- Compensation solenoids [ESL, ESR1, ESR2 and ESR3]

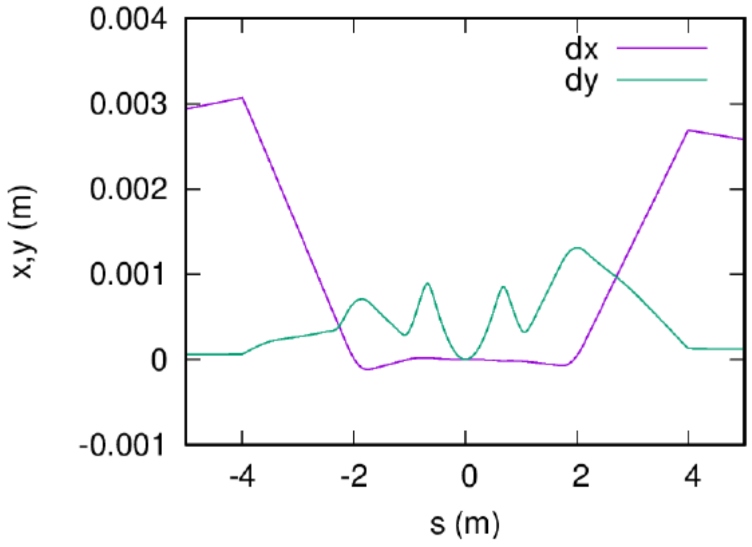




- In the left cryostat, one solenoid (12 small solenoids) is overlaid on QC1LP and QC1LE.
- In the right cryostat, the 1st solenoid (15 small solenoids) is overlaid on QC1RP, QC1RE and QC2RP.
  - The 2nd and 3rd solenoids on the each beam line in the QC2RE vessel.

Evaluation of nonlinear term

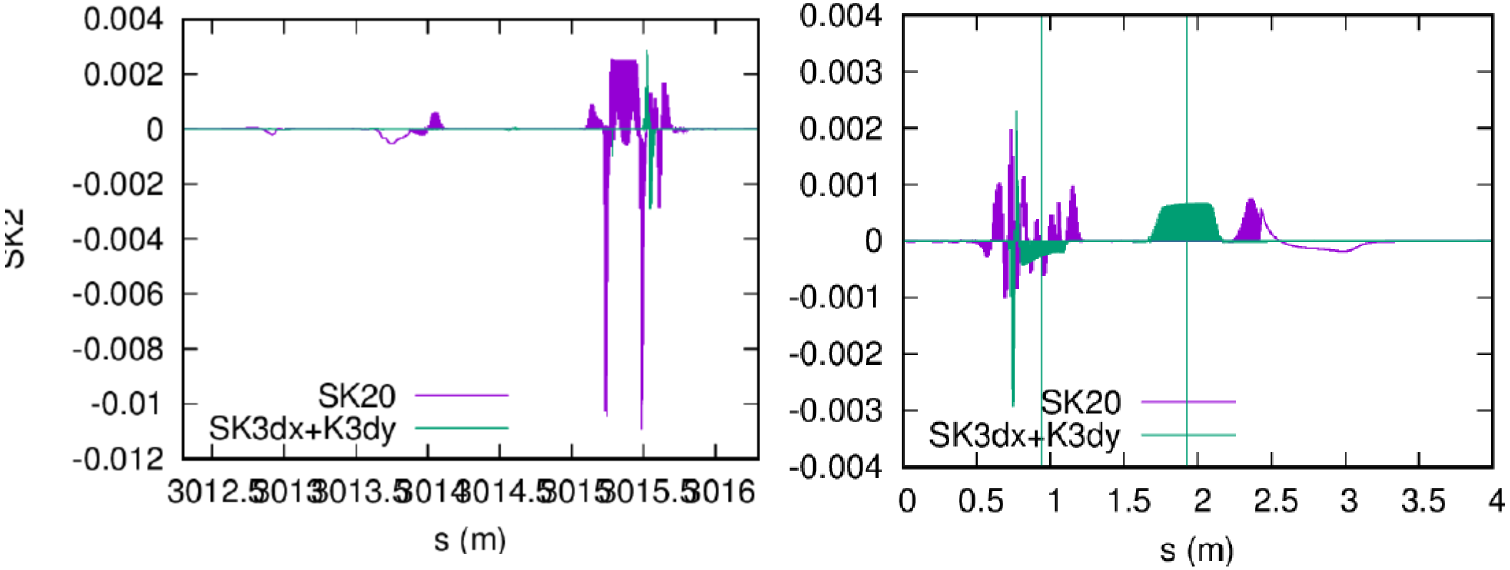
- Focus on skew sextupole component.
- Reference axes in solenoid is chosen as a straight line with half crossing angle.
- Magnet components are defined on the reference orbit.
- Beam orbit deviate from the reference orbit.
- Skew sextupole component is induced by Skew sextupole and octupole with a vertical orbit.



Skew sextupole component

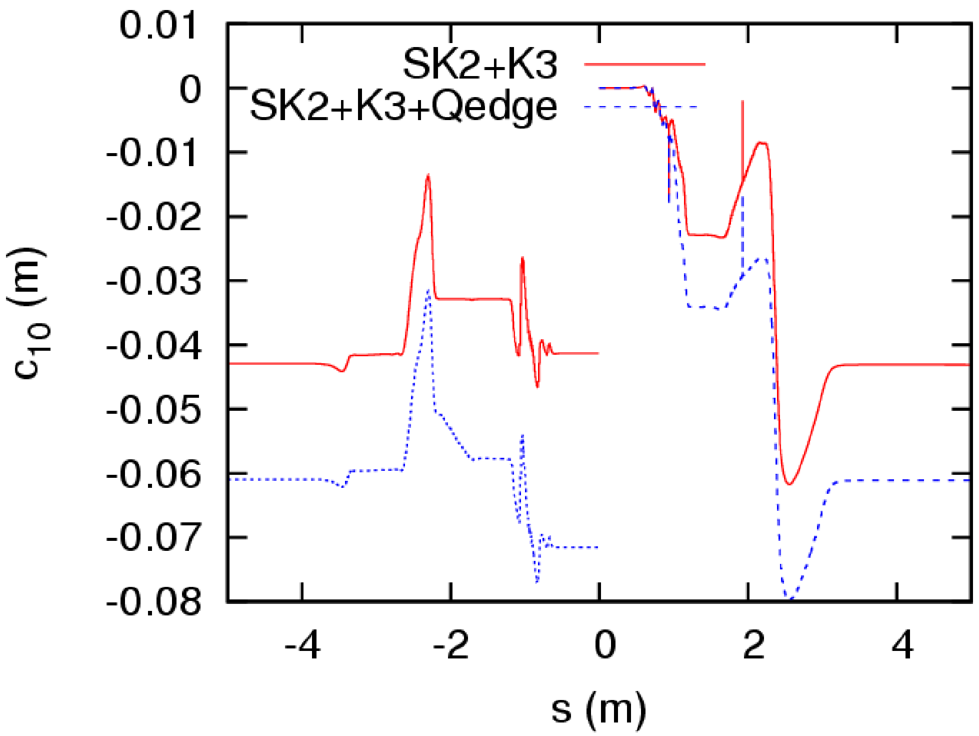
upstream of IP

downstream



C_{10} from SK2 and K3+yCOD

- Contribution to SK2 is coming from explicit Skew Sext $SK2_0$ and octupole, K3+COD
- No contribution from higher order than K3.



There are 10 skew components.

$$y^3, y^2p_y, yp_y^2, p_y^3$$

$$x^2y, x^2p_y, xp_xy, xp_xp_y, p_x^2y, p_x^2p_y$$

$$H = c_{10}p_x^2p_y$$

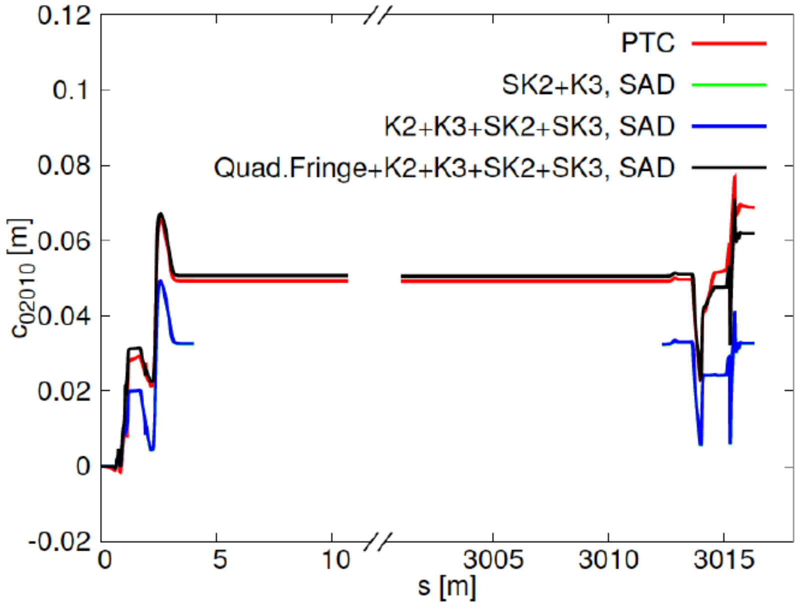
$$\begin{aligned}\mathcal{M}(s) &= \prod_{i=0}^{N-1} e^{-\mathcal{H}(x,s_i)} M(s_i, s_{i+1}) \\ &= \left\{\prod_{i=0}^{N-1} M^{-1}(s_i, s) e^{-\mathcal{H}(x,s_i)} M(s_i, s)\right\} M(s) \\ &= \left\{\prod_{I=0}^{N-1} e^{-\mathcal{H}(M(s,s_i)x,s_i)}\right\} M(s) \\ &\approx \underline{e^{-\oint \mathcal{H}(M(s,s')x,s')ds'} M(s)}\end{aligned}$$

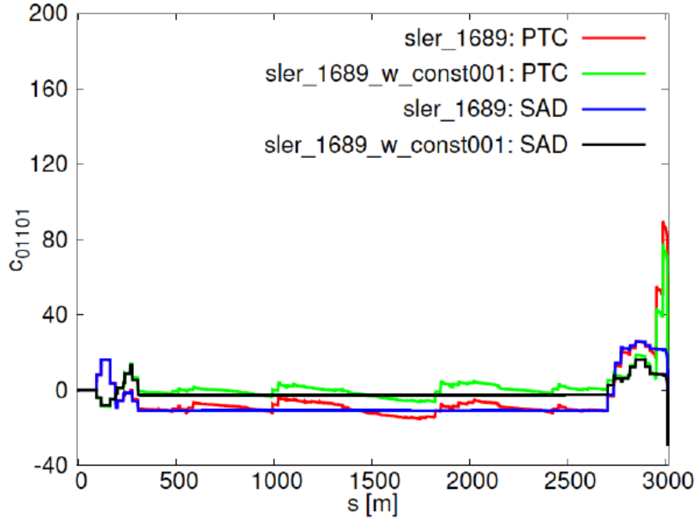
- Skew sextupole coming from higher order nonlinearity is small.

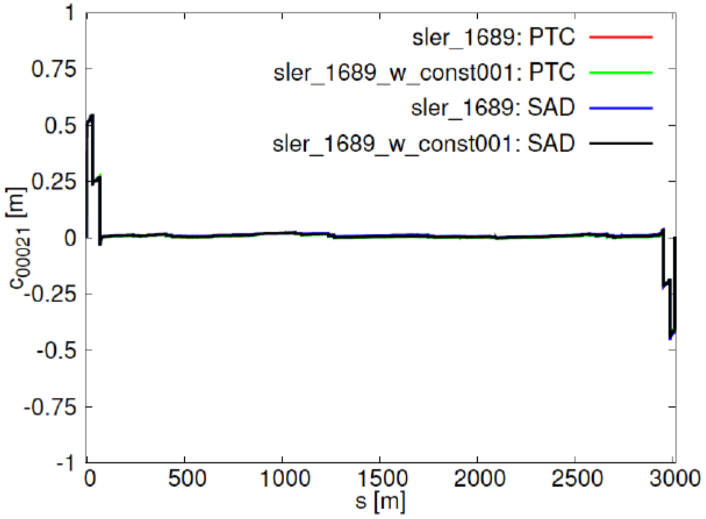
Comparison with PTC

D. Zhou

- **$p_x^2 p_y$ term**
  - **Hard-edge fringe fields of final focus quads are important sources**

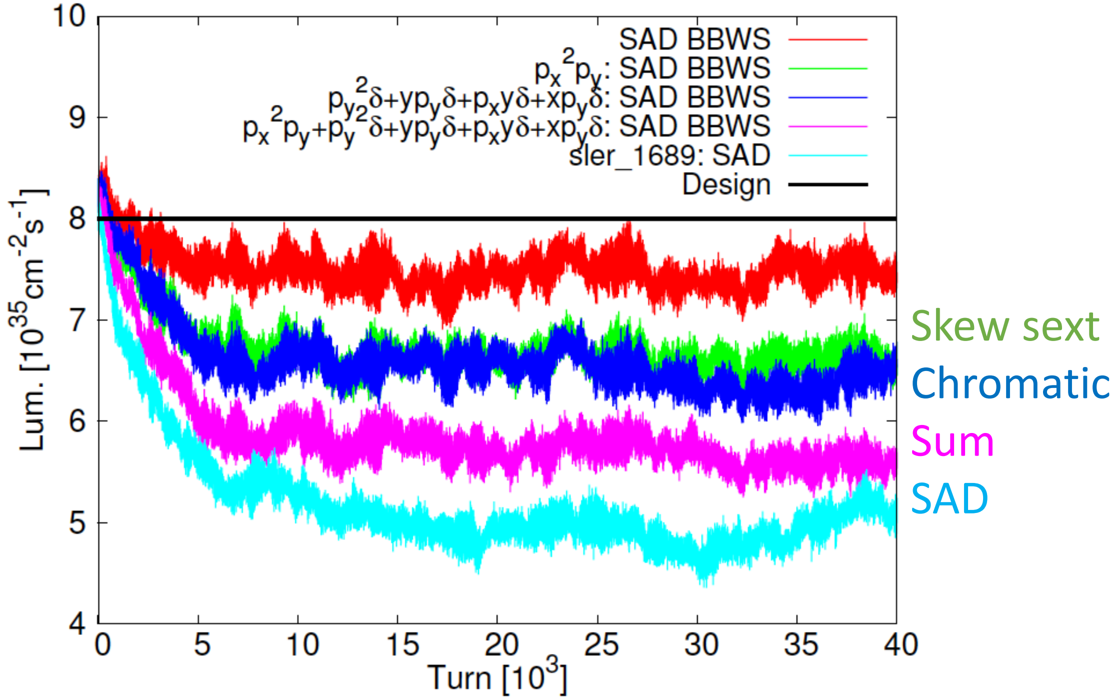


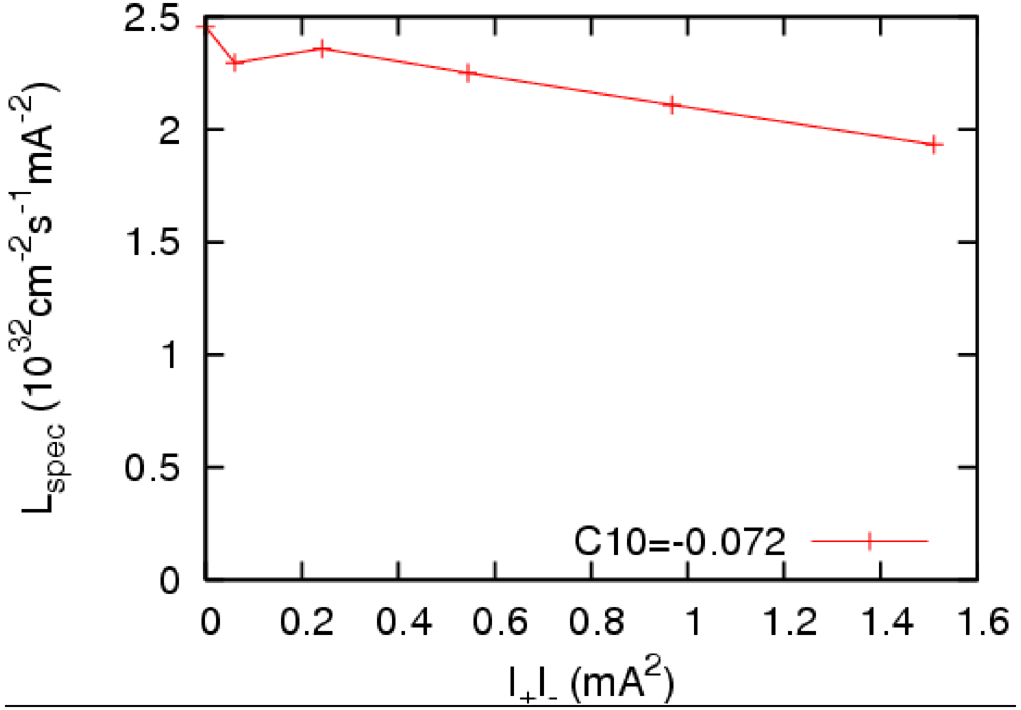


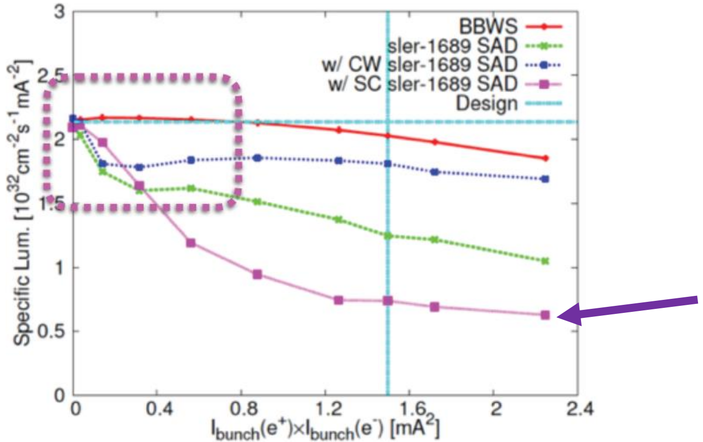


- “SAD” means to do integration of the nonlinearity using SAD script.

Luminosity for $H=c_{10}p_x^2p_y$ and chromatic Twiss







- The luminosity degradation due to Skew sext component and chromatic Twiss almost explains that of beam-beam simulation with SAD.
- Study of Space charge force is next.

Detuning β*

- c_{10}=0.072 m is kept for β*change, because IR magnets are fixed in SuperKEKB.
- For normalized coordinates, $P_i = \sqrt{\beta_i} p_i, X_i = x_i / \sqrt{\beta_i}$

$$C_{10} = \frac{c_{10}}{\beta_x^* \sqrt{\beta_y^*}} \qquad H = c_{10} p_x^2 p_y \qquad H_N = C_{10} P_x^2 P_y$$

- C_{10}=136.9 $m^{-1/2}$ for β_x*=3.2cm, β_y*=0.27mm
- Normalized C_{10} directly affects the beam dynamics. $\Delta Y = C_{10} P_x^2$

$$\Delta Y = C_{10} P_x^2 \approx 136.9 \varepsilon_x \approx 0.15 \sqrt{\varepsilon_y}$$

for β_x*=3.2cm, β_y*=0.27mm

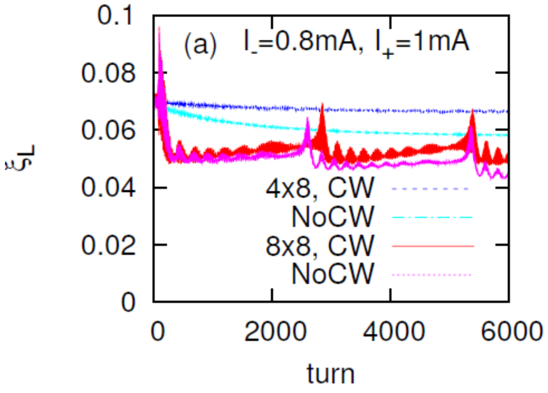
- The effect is reduced by Detune of β*.
- C_{10} is 4.4% for 8x8, 8.8% for 4x8.
- C_{10} can be canceled by Octupole coils, but are not compatible with dynamic aperture.

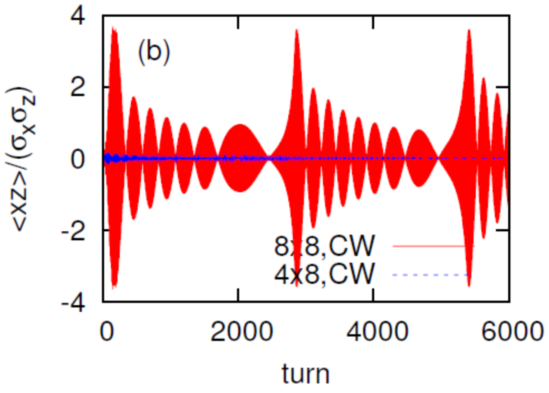
Measurement of the Coherent beam-beam instability

Y. Ohnishi,
Dec. 2017

- Beam-beam instability should be observed at detuned lattice (8x8x) in commissioning of Phase-II (this year).
- Design parameters of SuperKEKB was stable.

	KEKB (2006)		Phase 2.2		Phase 2.3		Phase 2.4		Phase 3	
	LER	HER	LER	HER	LER	HER	LER	HER	LER	HER
β_x [mm]	590	560	256	200	128	100	128	100	32	25
β_y [mm]	6.5	5.9	2.16	2.40	2.16	2.40	1.08	1.2	0.27	0.30
ε_x [nm]	18	24	2.1	4.6	2.1	4.6	2.1	4.6	3.2	4.6
$\varepsilon_y/\varepsilon_x$ [%]	**3**	**2.5**	**5.0**		**1.4**		**0.7**		**0.27**	**0.28**
σ_x^* [μm]	103	116	23.2	30.3	16.4	21.4	16.4	21.4	10.1	10.7
σ_y^* [nm]	1900	1900	476	743	252	393	126	197	48	62
σ_z [mm]	7	7	6	5	6	5	6	5	6	5
ϕ_x [mrad]	11		41.5		41.5		41.5		41.5	
Φ	**0.75**	**0.66**	**10.7**	**8.2**	**15.2**	**9.7**	**15.2**	**9.7**	**24.7**	**19.4**
Remark	1.72×10^{34} cm^{-2}s^{-1}		10^{34} cm^{-2}s^{-1}		2×10^{34} cm^{-2}s^{-1}		4×10^{34} cm^{-2}s^{-1}		8×10^{35} cm^{-2}s^{-1}	

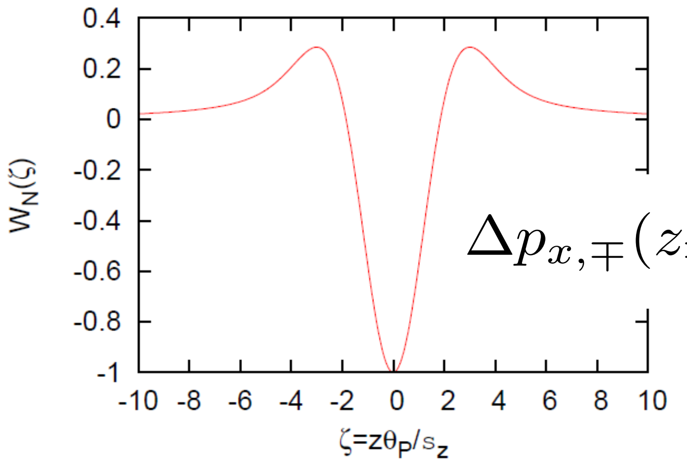




Beam-beam effects in nano-beam collision-Accelerator physics activity

KEK-CERN-BINP-SLAC-BNL-Fermilab

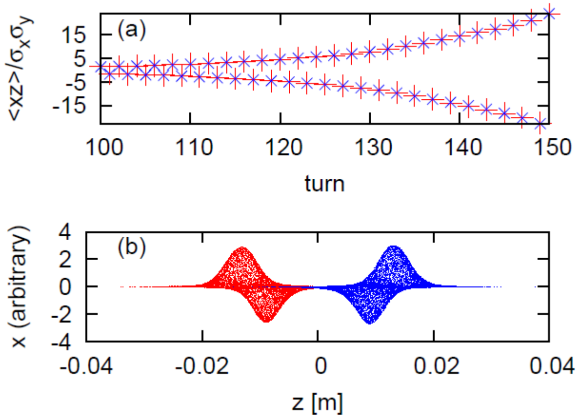
- Coherent beam-beam instability in collisions with a large crossing angle is caused by cross wake force, which gives correlation between two beams

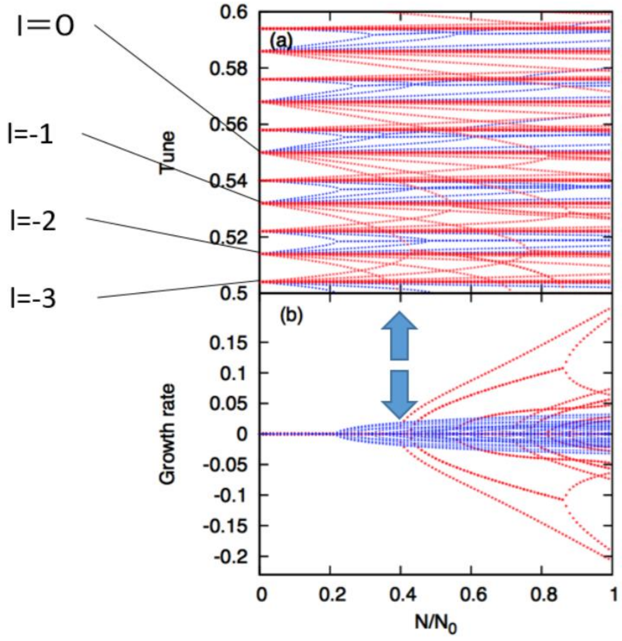


$$W_x^{(-)}(z) = -\frac{N^{(+)} r_e}{\gamma^{(-)} \bar{\sigma}_x^2}\left[1 - \frac{\sqrt{\pi}\theta_P z}{2\bar{\sigma}_z}\,\mathrm{Im}\; w\left(\frac{\theta_P z}{2\bar{\sigma}_z}\right)\right]$$

$$\Delta p_{x,\mp}(z_\mp) = -\int_{-\infty}^{\infty} W_x^{(\mp)}(z_\mp - z'_\pm)\rho_x^{(\pm)}(z'_\pm)\,dz'_\pm$$

- Mode coupling instability can occur in collision with a large crossing angle.





Analysis of the instability

- Beam-beam eigenmode analysis. Solve eigenvalues of 1000x1000 matrix.
- Eigen tune is $\nu=\nu_x$+-Lν_s. Mode coupling or synchro-beta resonance is casued.
- Synchrotron tune, ν_s(LER)=0.0247, ν_s(HER)=0.0280.
- Number of Sidebands increases. More unstable.

- strong-strong beam-beam simulation.

- Vector $\quad \boldsymbol{x}_{kl} = (x_{kl}^{(+)}, p_{kl}^{(+)}, x_{kl}^{(-)}, p_{kl}^{(-)})$ length=4(k_{max}+1)(2l_{max}+1)
- Betatron

$$M_\beta = \begin{pmatrix} \cos\mu_x^{(+)} & \sin\mu_x^{(+)} & 0 & 0 \\ -\sin\mu_x^{(+)} & \cos\mu_x^{(+)} & 0 & 0 \\ 0 & 0 & \cos\mu_x^{(-)} & \sin\mu_x^{(-)} \\ 0 & 0 & -\sin\mu_x^{(-)} & \cos\mu_x^{(-)} \end{pmatrix}$$

- Synchrotron

$$M_s = \begin{pmatrix} e^{-2\pi i l \nu_s^{(+)}} & 0 \\ 0 & e^{-2\pi i l \nu_s^{(-)}} \end{pmatrix}$$

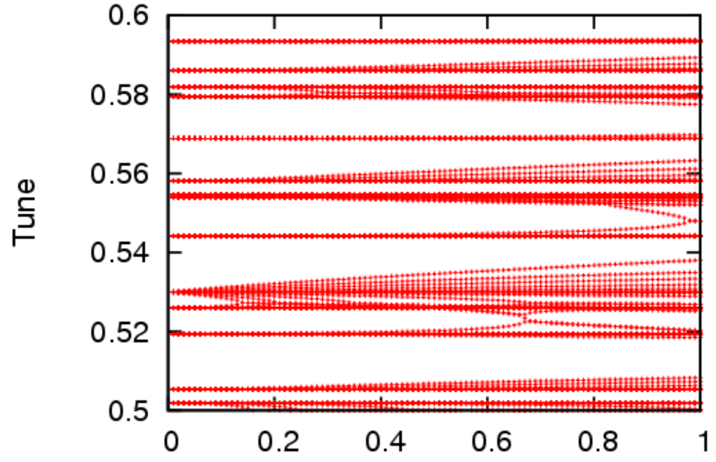
- Wake force

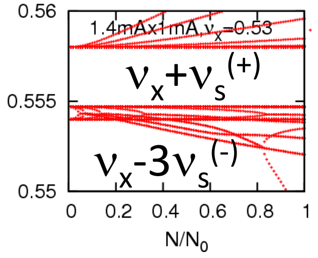
$$M_W = \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & -2M_{klk'l'}^{(+)} & 0 \\ 0 & 0 & 1 & 0 \\ -2M_{klk'l'}^{(-)} & 0 & 0 & 1 \end{pmatrix}$$

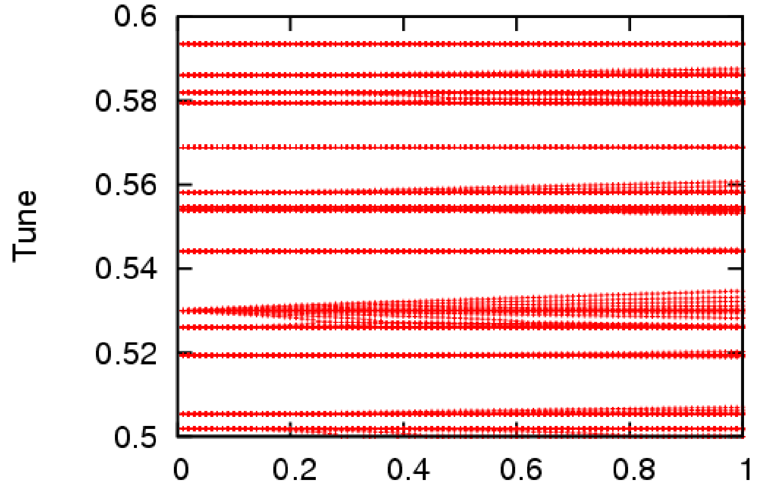
- Revolution matrix, $M_W M_s M_\beta$
- Solve Eigenvalue problem

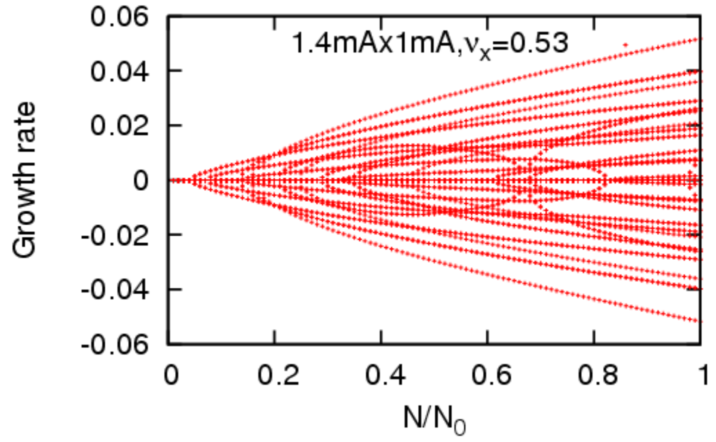
Eigen mode analysis for ν_x=0.53

- 8x8x 4x8x

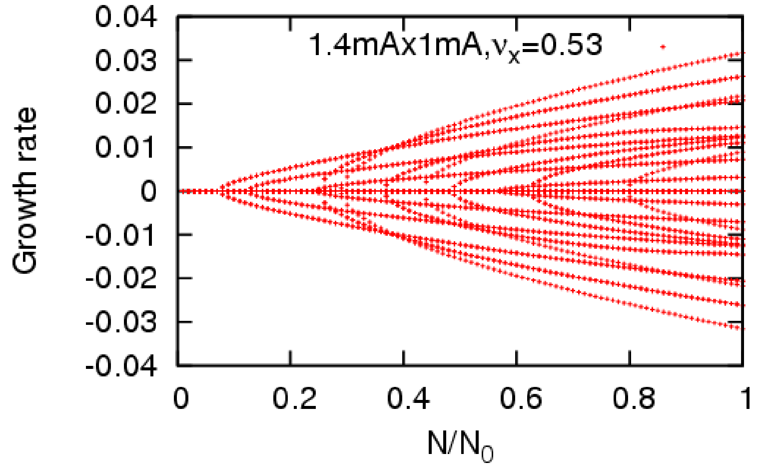






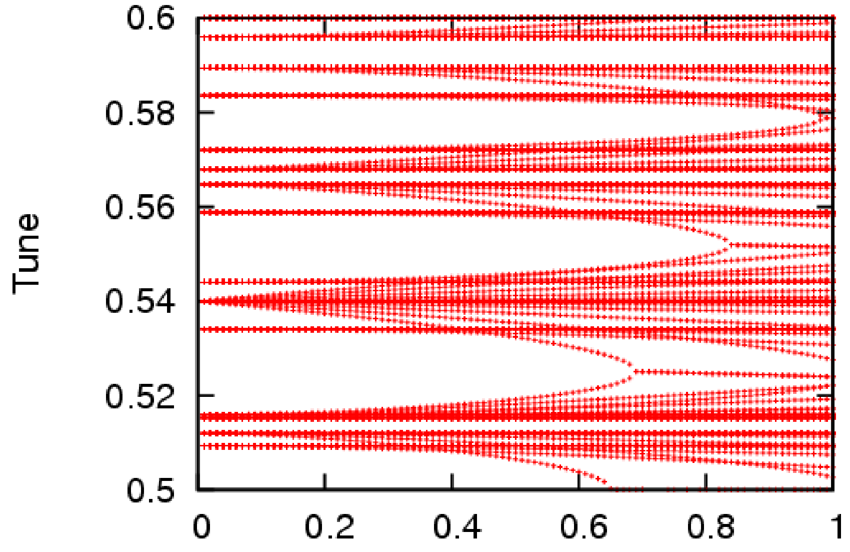


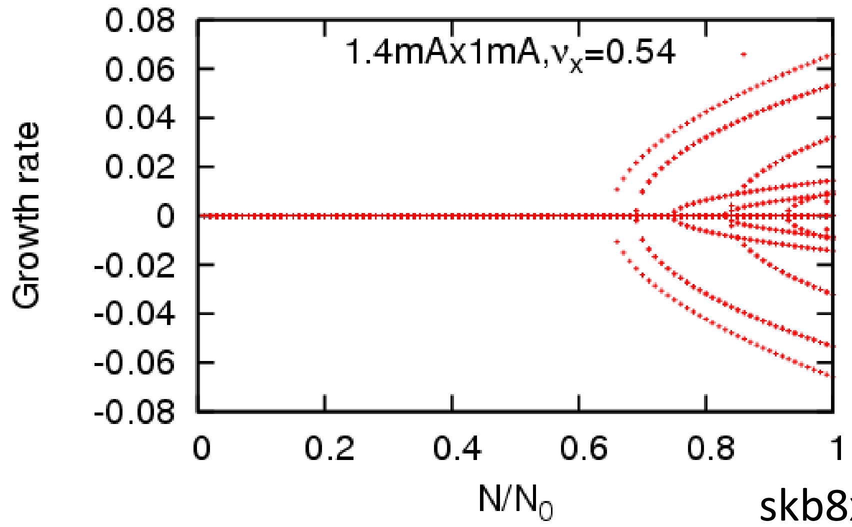
skb8x8xb



Eigen mode analysis for $\nu_x=0.54$

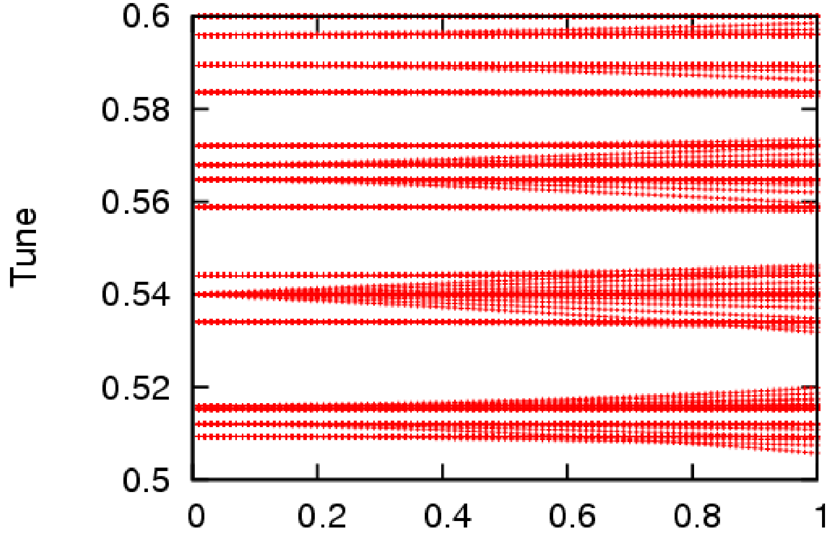
- 8x8x

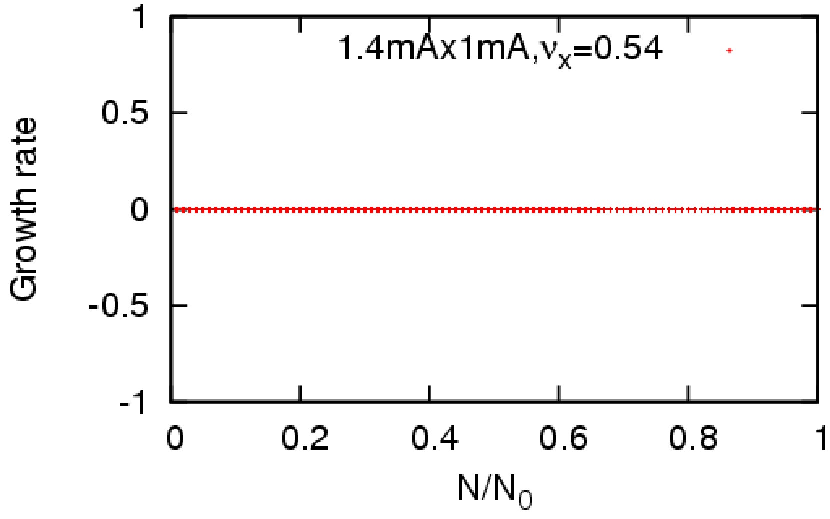




skb8x8xc

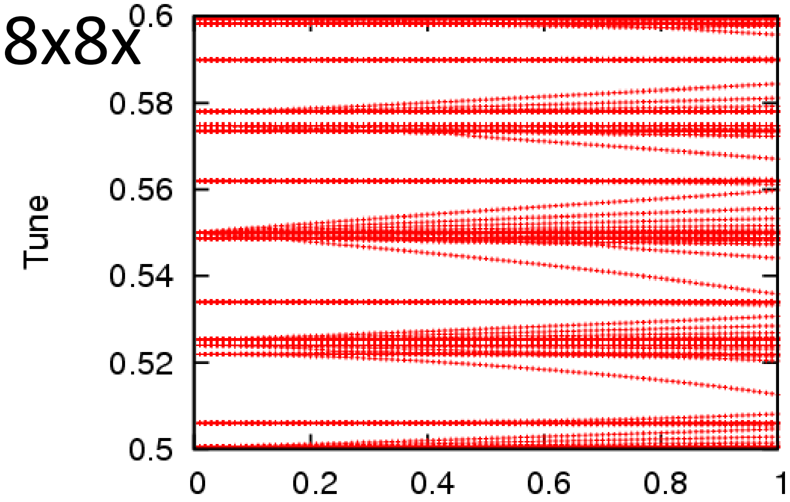
4x8x

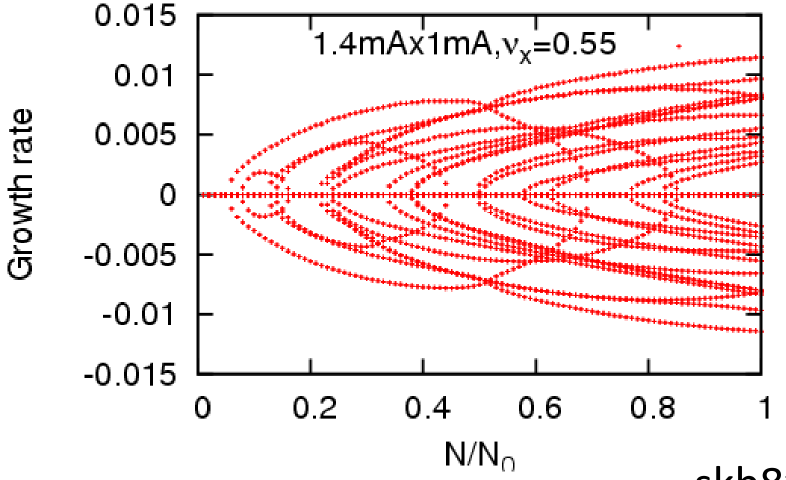




Eigen mode analysis for ν_x=0.55

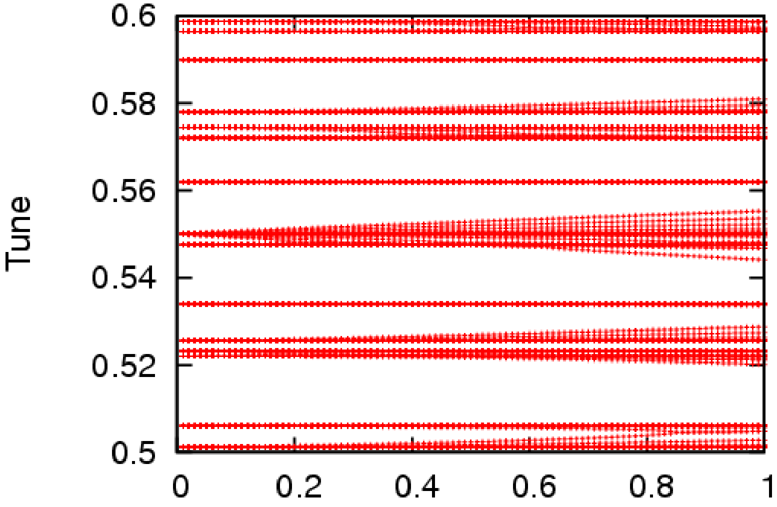
- 8x8x

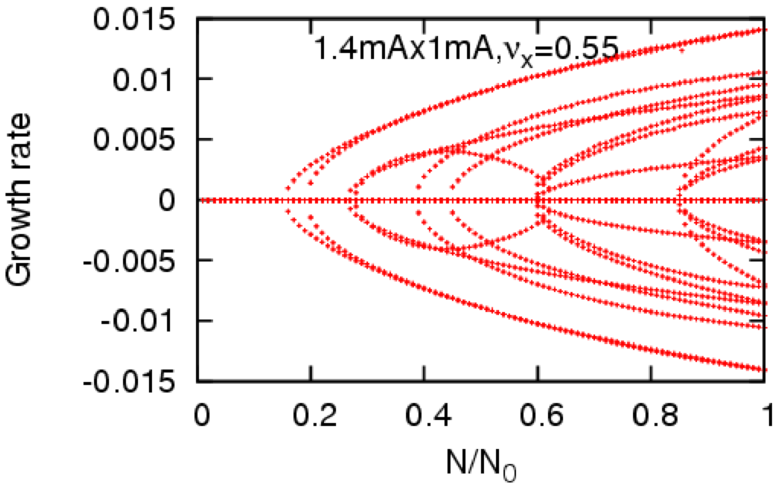




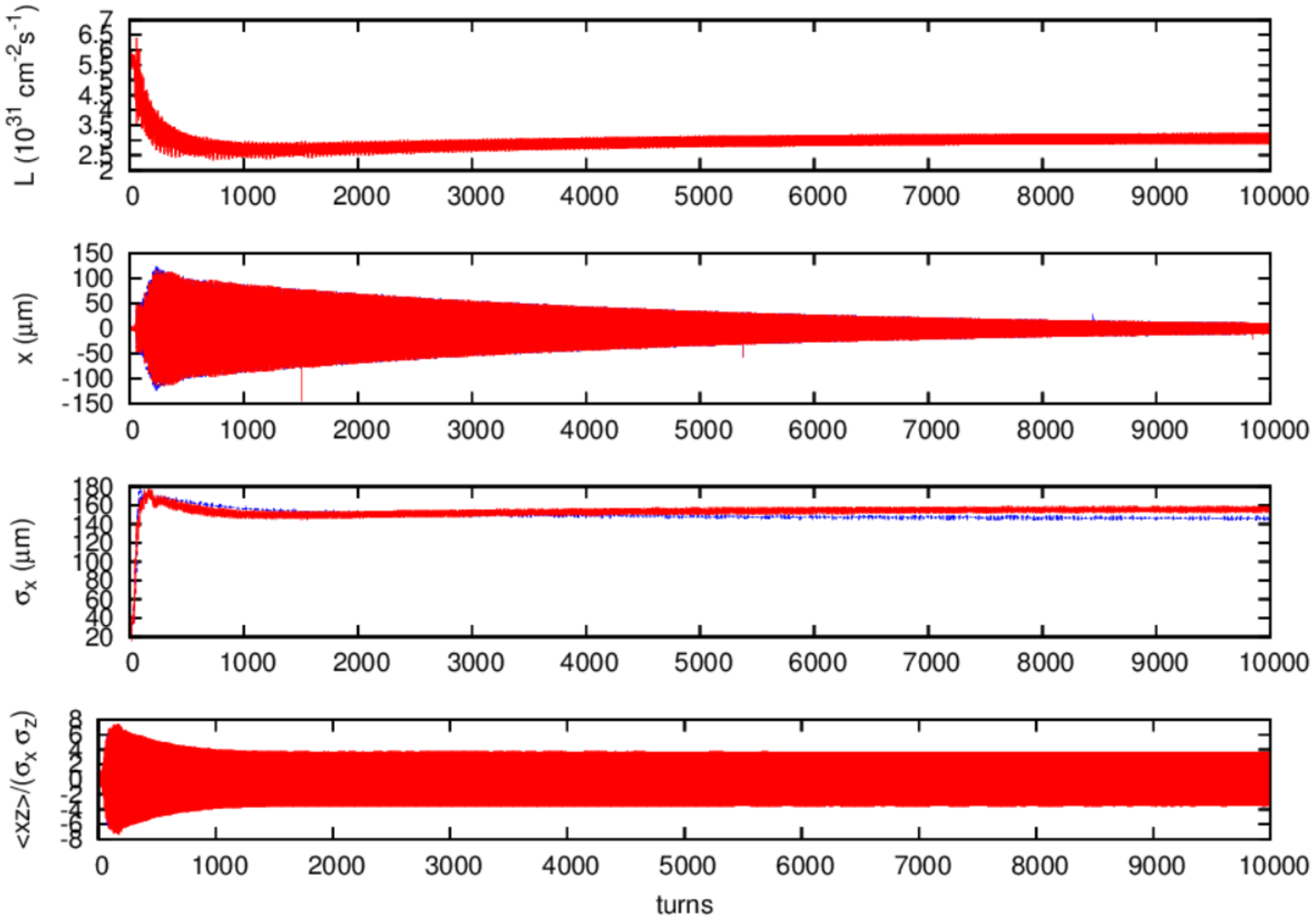
skb8x8xd

4x8x



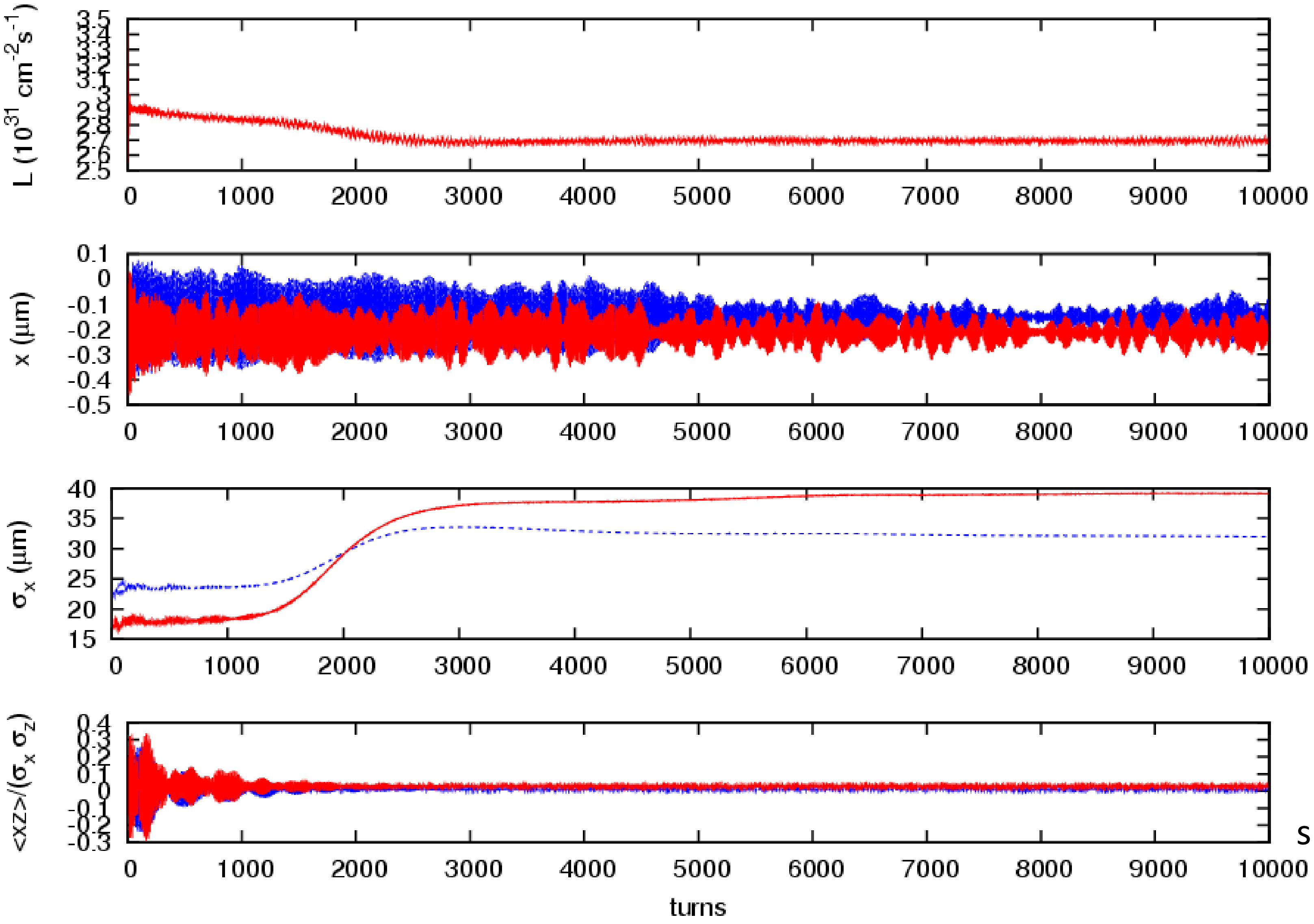


Strong-strong beam-beam simulation 8x8x, 1.44mAx1.04mA, ν_x=0.53



skb2a

4x8x, 1mAx0.8mA , ν_x=0.53



skb21b

Summary of the strong-strong simulation

I=1.44mA x 1.04mA

ν_x	8x8x				4x8x			
	L/L_0,	σ_x/σ_{x0} (L & H)		osc.	L/L_0,	σ_x/σ_{x0} (L & H)		osc.
0.53 a	0.58-0.66	6.5	4.5		0.75-1.0	3.0-7.5	2.2-6.2	
0.535 g	0.70-0.95	2.5-6.2	1.4-4.0		1.04	1.2	1.0	
0.54 d	0.75-0.95	2.5-6.0	1.4-4.0		1.05	2.1	1.1	
0.545 f	0.83	7.2	1.2	no osc.	0.94	5.2	1.7	
0.55 e					0.75-0.77	8.6	3.5	

Horizontal emittance growth does not contribute luminosity drop in collision with a large crossing angle, when β_y is large.
Crab waist on in the simulation. CW-off may be serious for the horizontal emittance growth.

Summary

- SuperKEKB collision starts now, Mar 2018 (Phase II).
- Beta function is squeezed step-by-step.
- From the beam dynamics, these two issues are focused now.

  1. IR nonlinearity. This becomes serious for squeezing beta*. Tuning using IR multipole knob. Measurement of IR (chromatic) optics.

  2. Coherent beam-beam in head-tail mode. Instability is seen in detuned beta, but disappears squeezing beta*. The experiment is important for future collider designs, and is good exercise for the commissioning.

Also studies to be continued

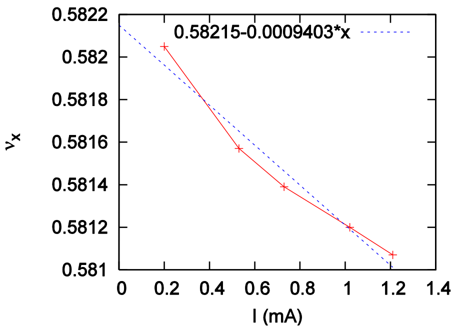
3. Electron cloud/ion

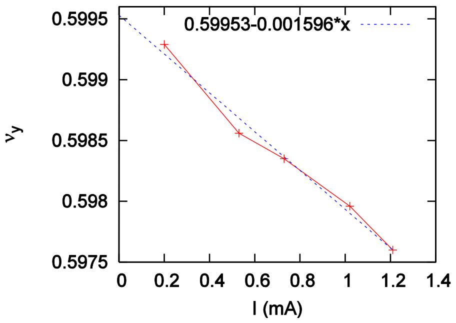
4. Impedance issues

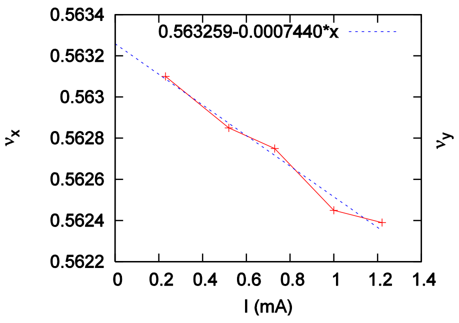
Impedance estimation- transverse

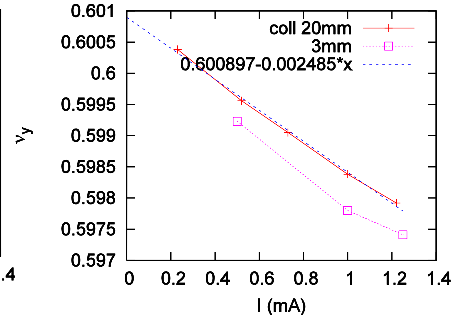
- Tune shift as function of bunch current

$$\Delta\nu_x = \frac{1}{4\pi^{3/2}}\frac{Nr_e}{\gamma}\frac{L}{\nu_x\sigma_z}\frac{iZ_{eff}}{Z_0} \qquad iZ_{eff}(k\Omega) = 33.3\frac{\Delta\nu_x}{I(mA)}\ \text{LER} \qquad = 58.2\frac{\Delta\nu_x}{I(mA)}\ \text{HER}$$



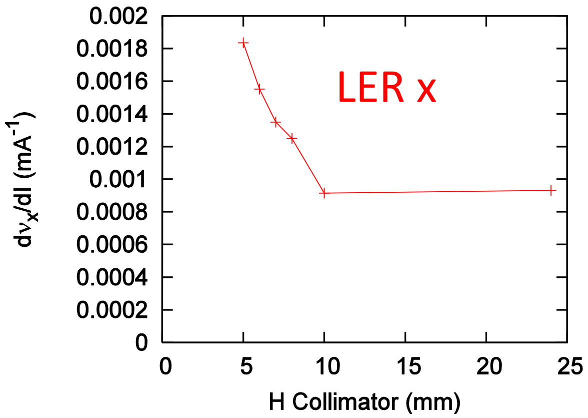


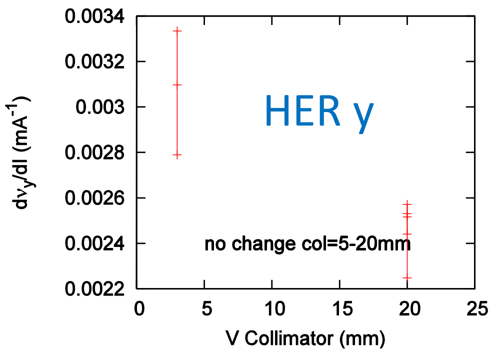




$iZ_{eff} = 31\ (x) \quad 53\ (y)\ \ k\Omega/m$

$iZ_{eff} = 43\ (x) \quad 145\ (y)\ \ k\Omega/m$





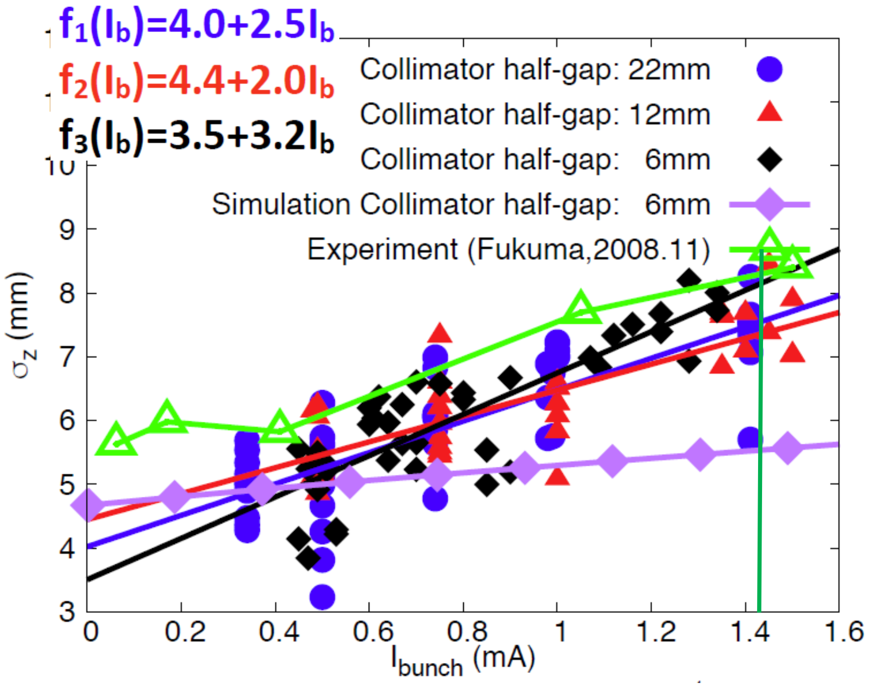
Collimator dependence

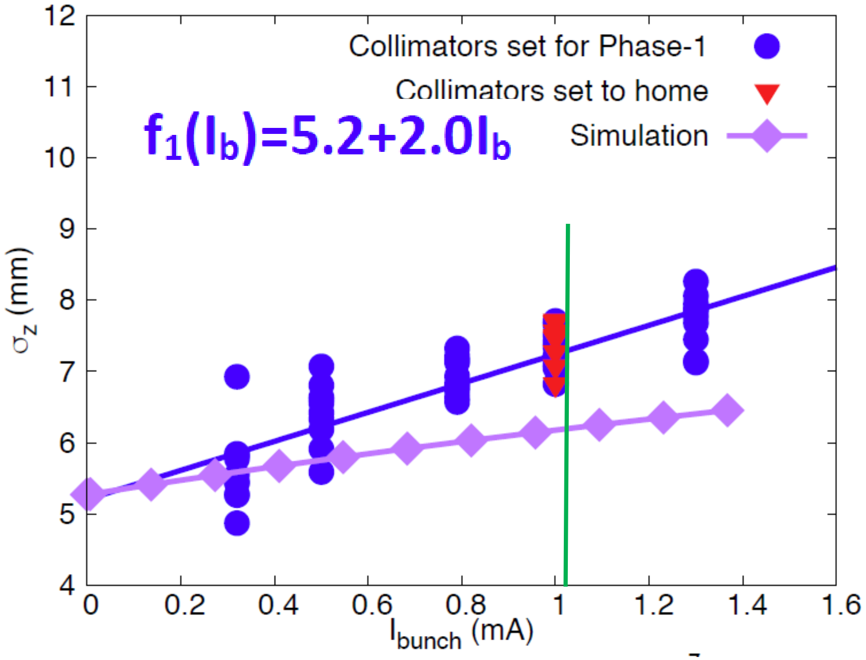
KEKB-LER: -0.0034mA^{-1}, 81kΩ/m

coll. open 33-46 kΩ/m T. Ieiri, EPAC00

Longitudinal impedance issue- Bunch length measurement

- L





Measured by a Streak camera

The behaviors are similar as KEKB for both of LER and HER.
Bunch lengthening is stronger than that of simulation.

KEKB impedance model, Y. Cai

TABLE I. Parameters of the *LRC* impedance model for both rings.

Parameter	Description	LER	HER
L (nH)	Inductance	116.7	109.1
R (KΩ)	Resistance	22.9	12.5
C (fF)	Capacitor	0.22	0.69

➤ Simulations of MWI with SuperKEKB Phase-3 parameters

- **Note that impedance model (Collimators, IR, …) and machine parameters are different from Phase-1**