Accelerator Physics Challenges for the SuperKEKB

D. Zhou

With contributions from

KEK: K. Akai, K. Ohmi, Y. Ohnishi, N. Ohuchi, H. Sugimoto, ...

IHEP: Y. Zhang

Theory club, FEL & Beam Physics Department, SLAC

Mar. 13, 2015

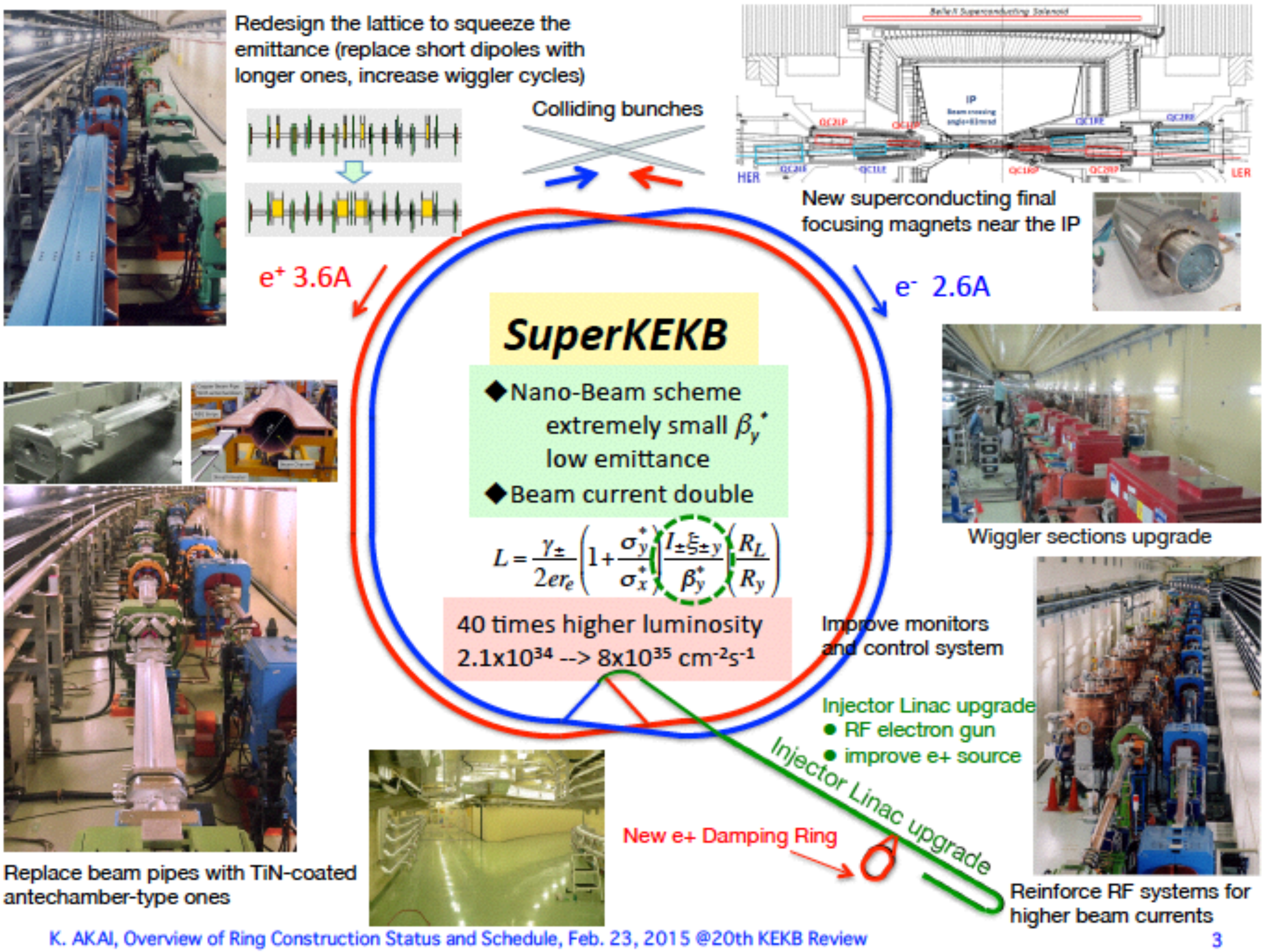
Outline

- ➤ Introduction
- ➤ Lattice nonlinearity (LN)
- ➤ Beam-beam (BB) effects
  - Crab waist (CW)
  - Interplay of BB and LN
- ➤ Space charge (SC) effects in LER
  - Interplay of BB, SC and LN
- ➤ Impedance issues
- ➤ Summary and Future plan

Outline

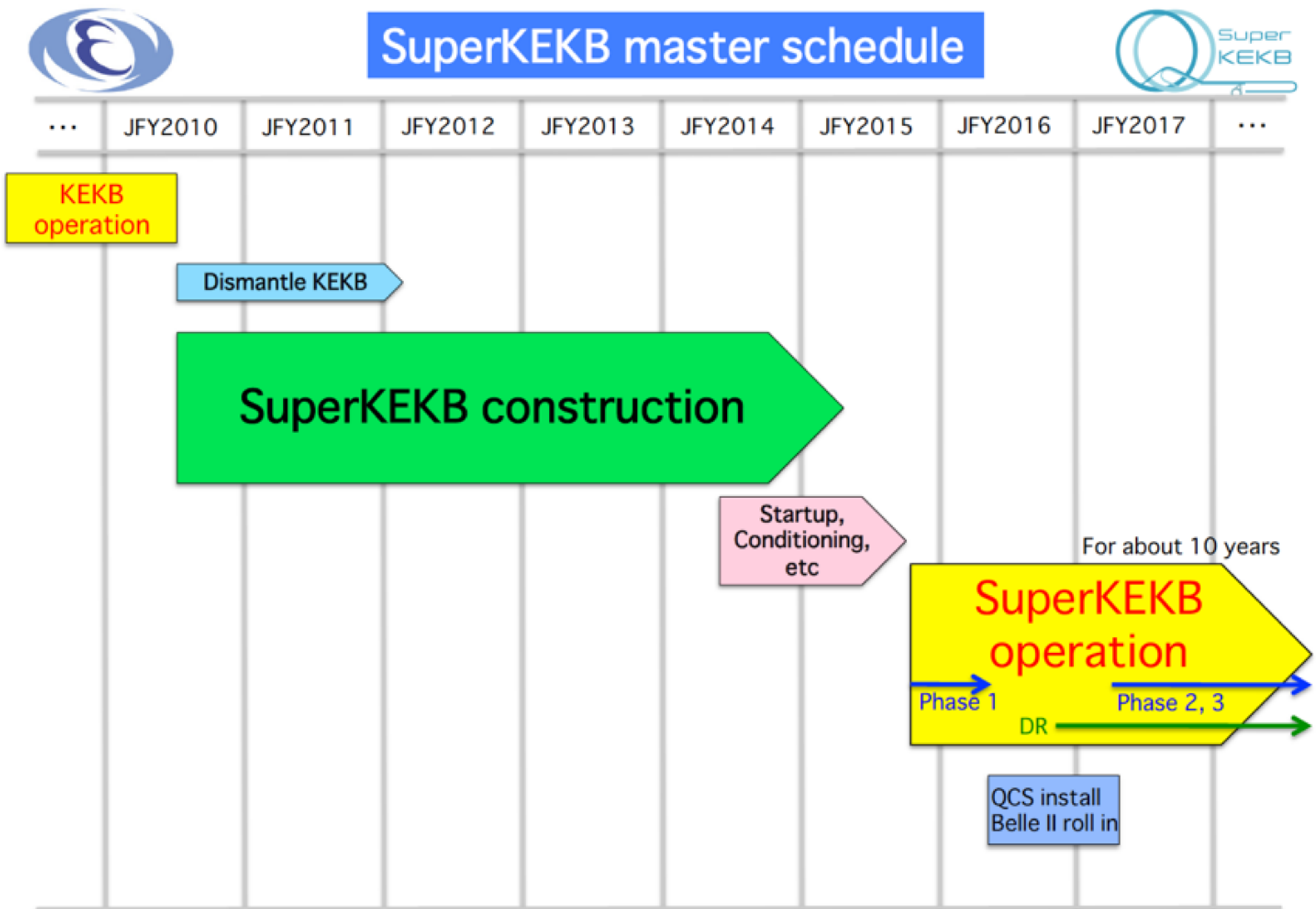
- **Introduction**
- Lattice nonlinearity (LN)
- Beam-beam (BB) effects
  - Crab waist (CW)
  - Interplay of BB and LN
- Space charge (SC) effects in LER
  - Interplay of BB, SC and LN
- Impedance issues
- Summary and Future plan

1. Introduction



From K. Akai, KEKB ARC 2015

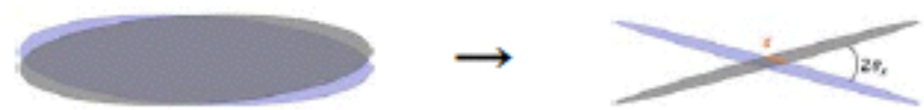
1. Introduction



From K. Akai, KEKB ARC 2015

1. Introduction: Expected lum. gain

- Increase the luminosity by 40 times based on “Nano-Beam” scheme



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

- Vertical β function at IP : 5.9 → 0.27/0.30 mm (× 20)

KEKB SuperKEKB Luminosity Gain

- Beam current : 1.7/1.4 → 3.6/2.6 A (× 2)
- Vertical beam–beam parameter : 0.09 → 0.09 (× 1)
- Beam energy: 3.5/8.0 → 4.0/7.0 GeV

LER : Longer Touschek lifetime and mitigation of emittance growth due to the intra–beam scattering

HER : Lower emittance and lower SR power

From N. Ohuchi, IPAC14, WEOCA01

1. Introduction: 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
Coupling	0.27	0.28	
β_x^*/β_y^*	32/0.27	25/0.30	mm
Crossing angle	83		mrad
α_p	3.18×10^{-4}	4.53×10^{-4}	
σ_δ	$8.10(7.73)\times10^{-4}$	$6.37(6.30)\times10^{-4}$	
V_c	9.4	15.0	MV
σ_z	6.0(5.0)	5(4.9)	mm
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	8×10^{35}		$cm^{-2}s^{-1}$

- HOM heating
- Impedance-driven instability
- Electron cloud

- Error tolerances
- Intra-beam scattering
- Space charge

- Beam-beam
- Dynamic aperture, Lifetime
- Lattice nonlinearity
- Background

- Beam-beam
- IR optics

- Impedance budget

 See http://www-superkekb.kek.jp/index.html for details

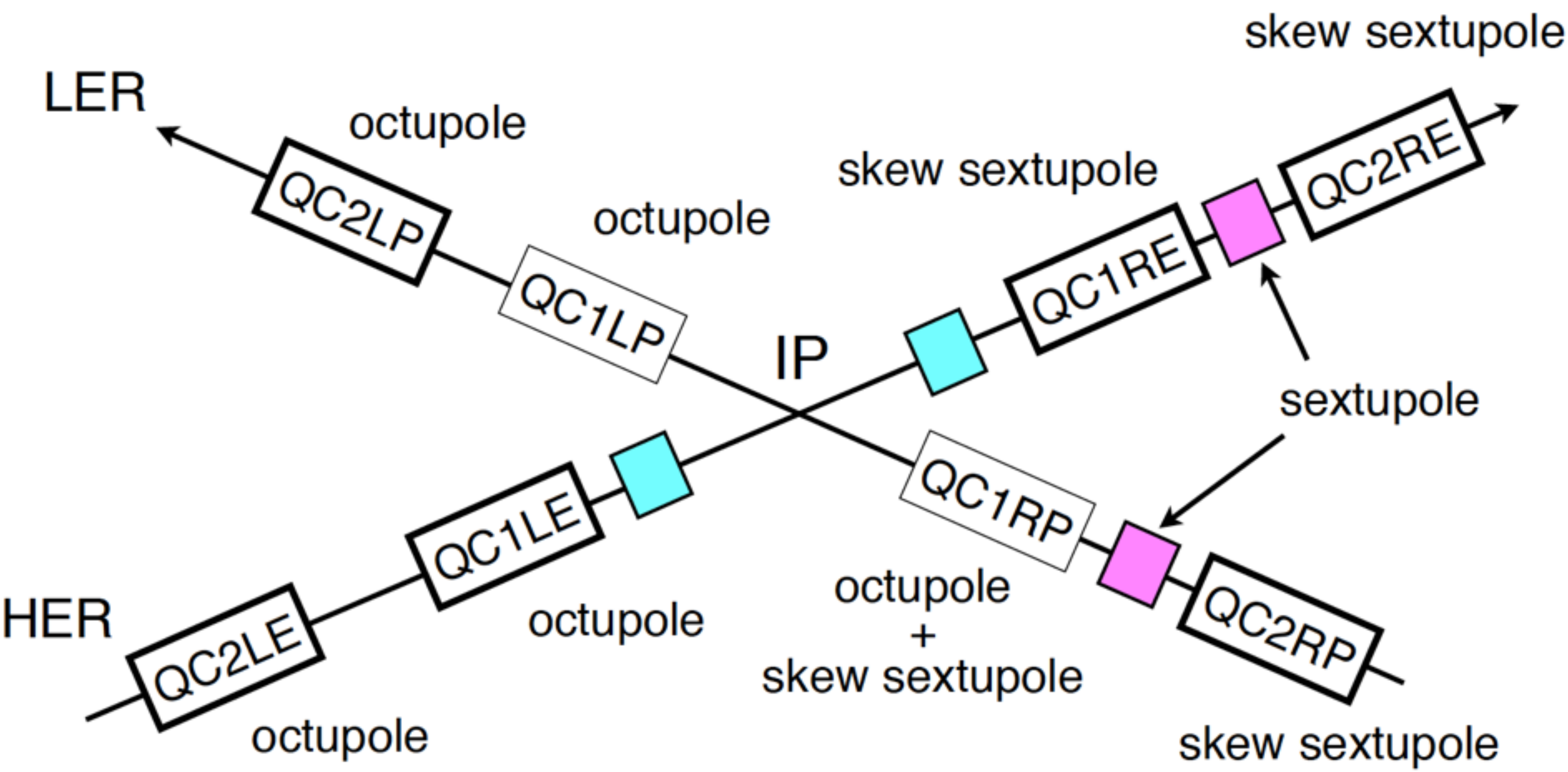
Outline

- Introduction
- **Lattice nonlinearity (LN)**
- Beam-beam (BB) effects
  - Crab waist (CW)
  - Interplay of BB and LN
- Space charge (SC) effects in LER
  - Interplay of BB, SC and LN
- Impedance issues
- Summary and Future plan

2. Lattice nonlinearity

➤ **High-order correctors added to each SC magnet**

➤ **Linear optics is OK, but IR is not transparent for off-momentum and large-amplitude particles**

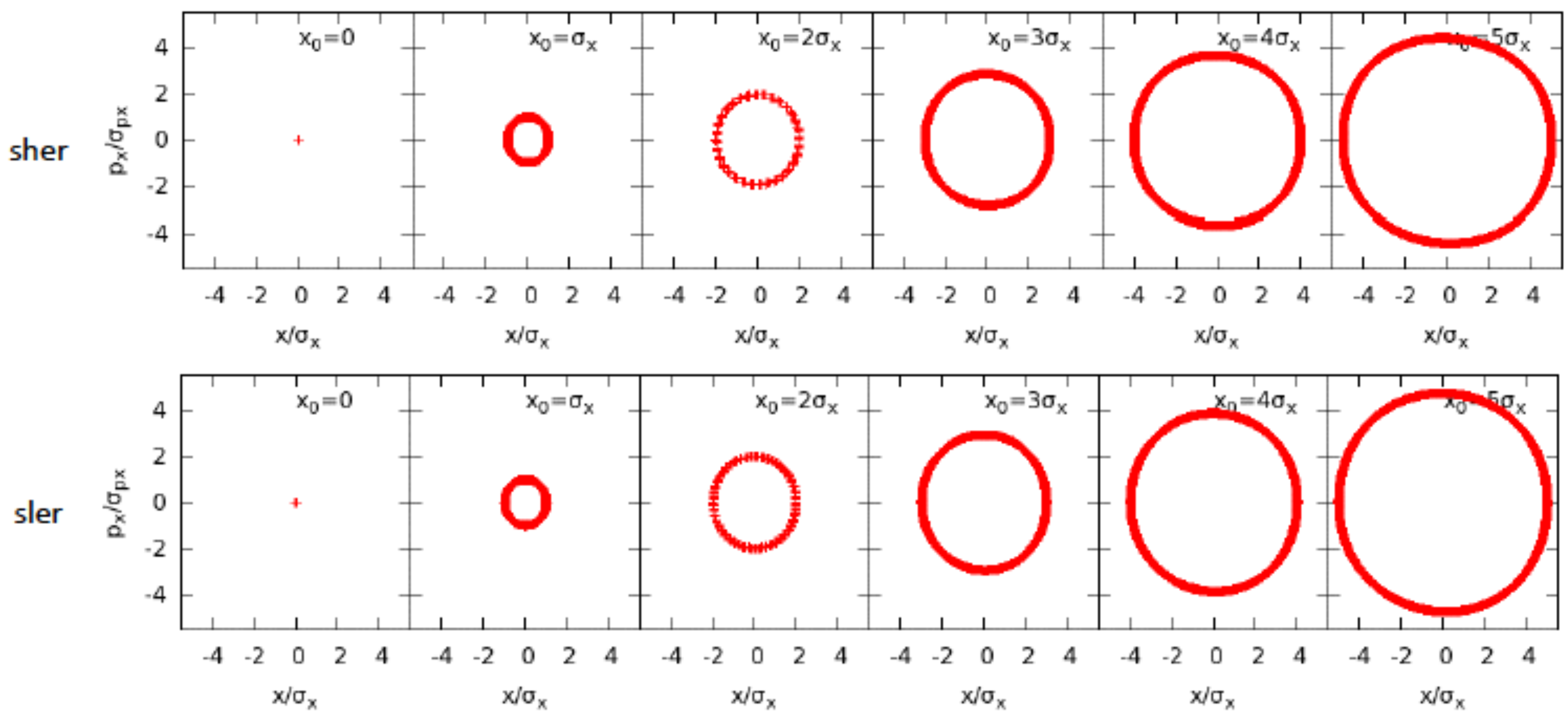


From Y. Ohnishi

2. Lattice nonlinearity

- **Realistic lattice**
- **Poincare map in y direction as function of X offset**

sher-5767 vs ler-1689 in X direction

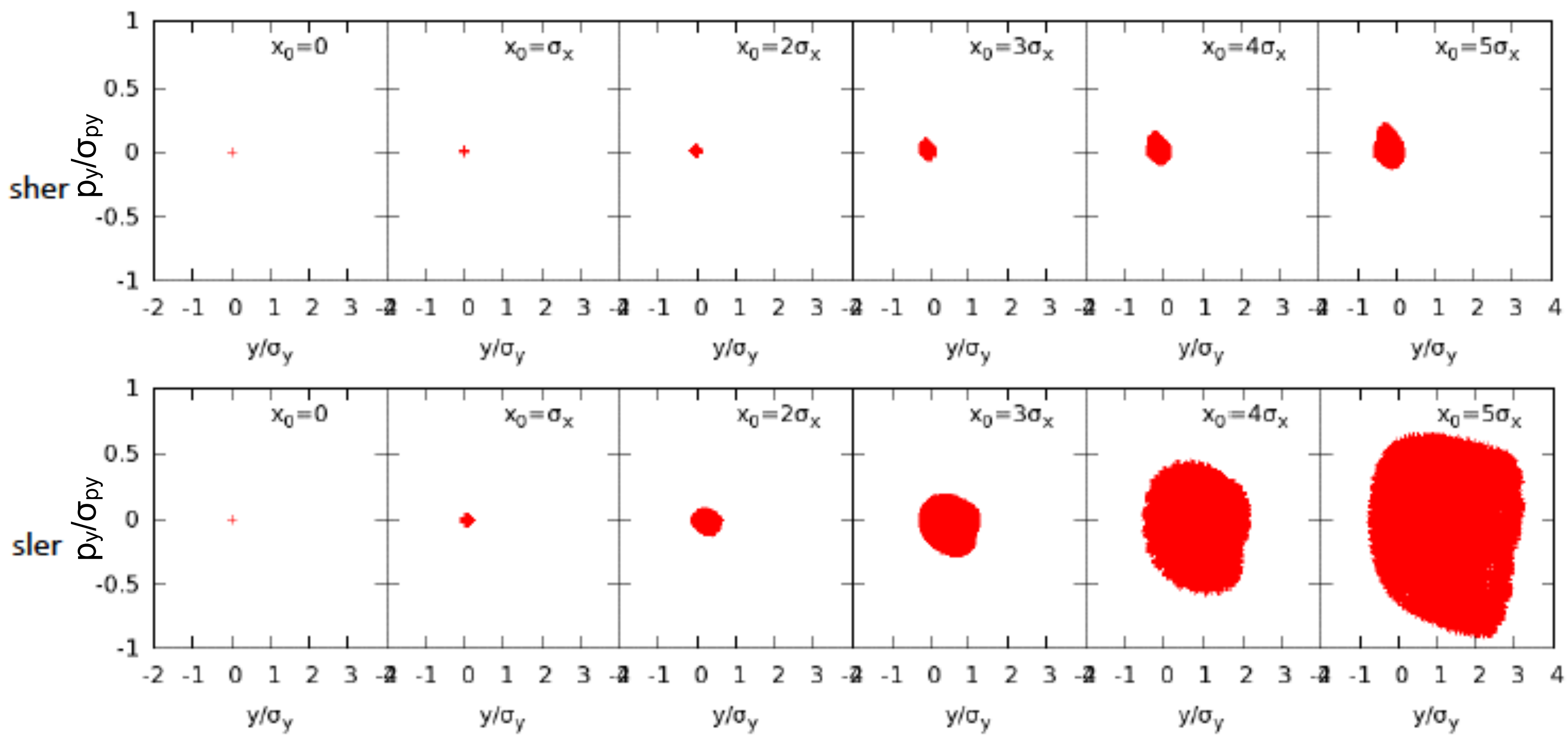


From Y. Zhang

2. Lattice nonlinearity

- ➤ **Realistic lattice**
- ➤ **Strong nonlinear X-Y coupling in LER**

sher-5767 vs ler-1689 in Y direction

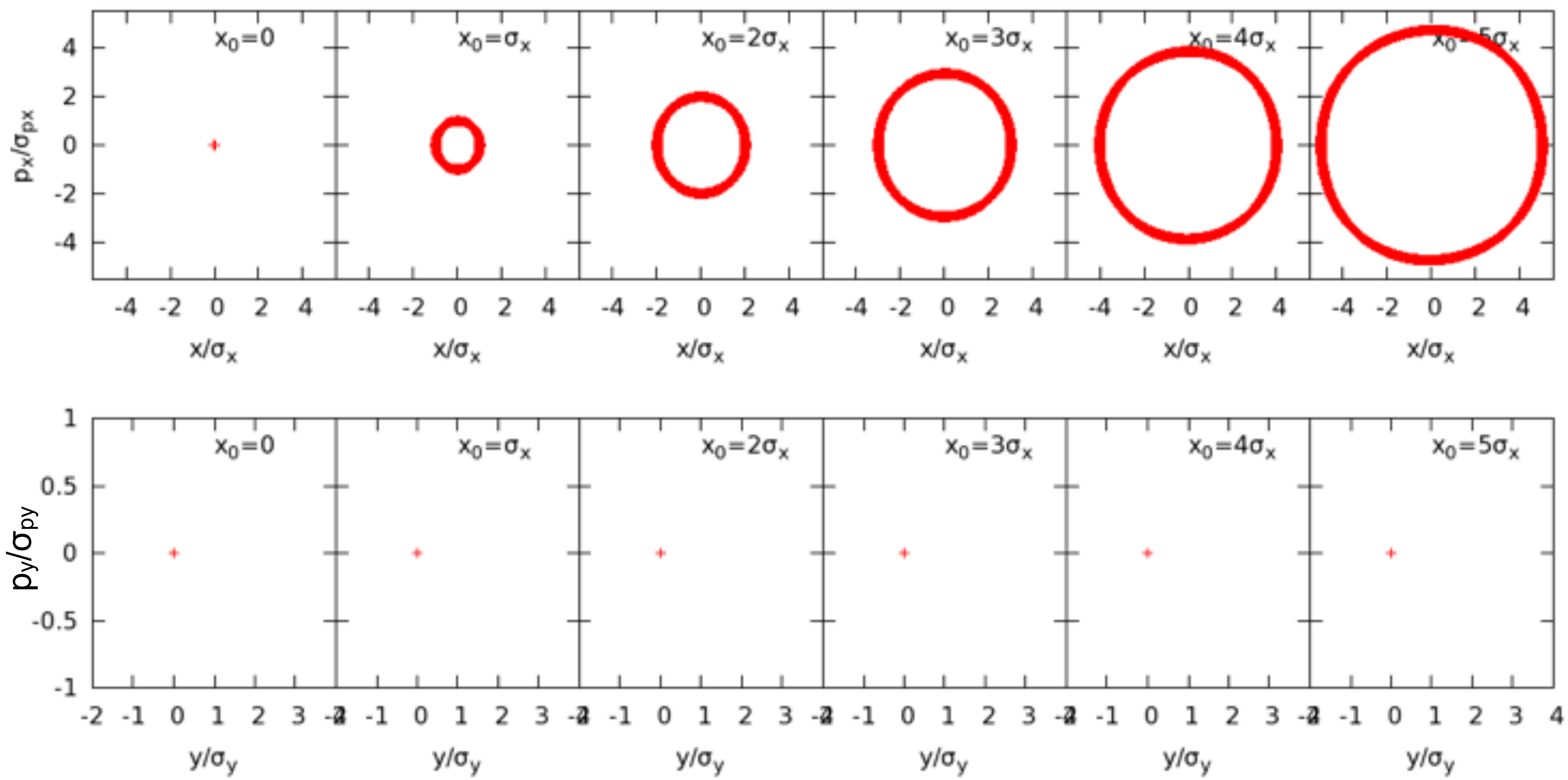


From Y. Zhang

2. Lattice nonlinearity: LER

➤ **Simplified LER lattice [No solenoid, QC* magnets simplified: no offset, dipole and skew-quad correctors removed]**

➤ **Confirmed: solenoid and high-order terms in QC* magnets cause nonlinear X-Y coupling**



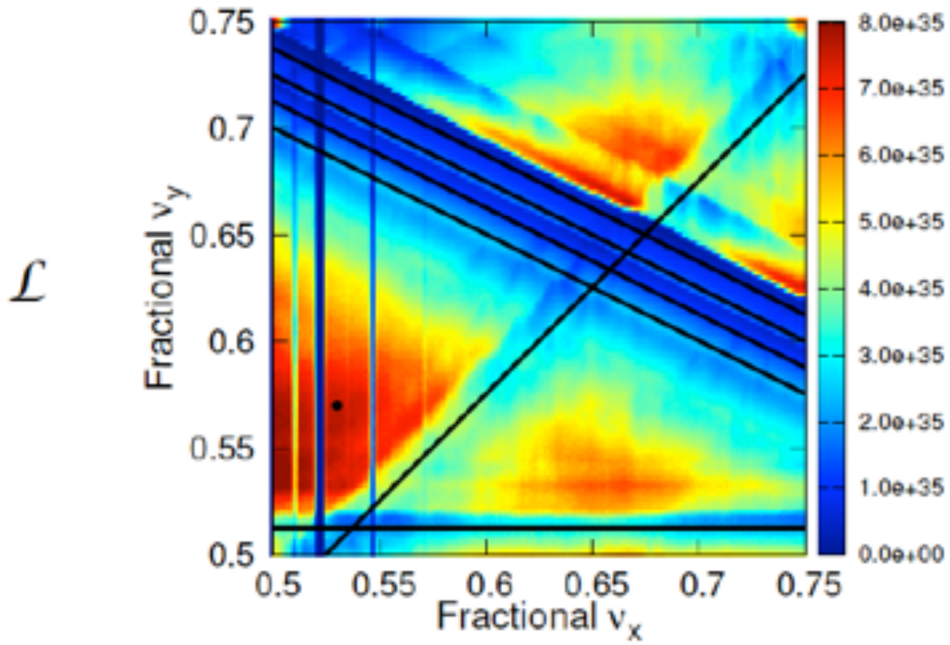
From Y. Zhang

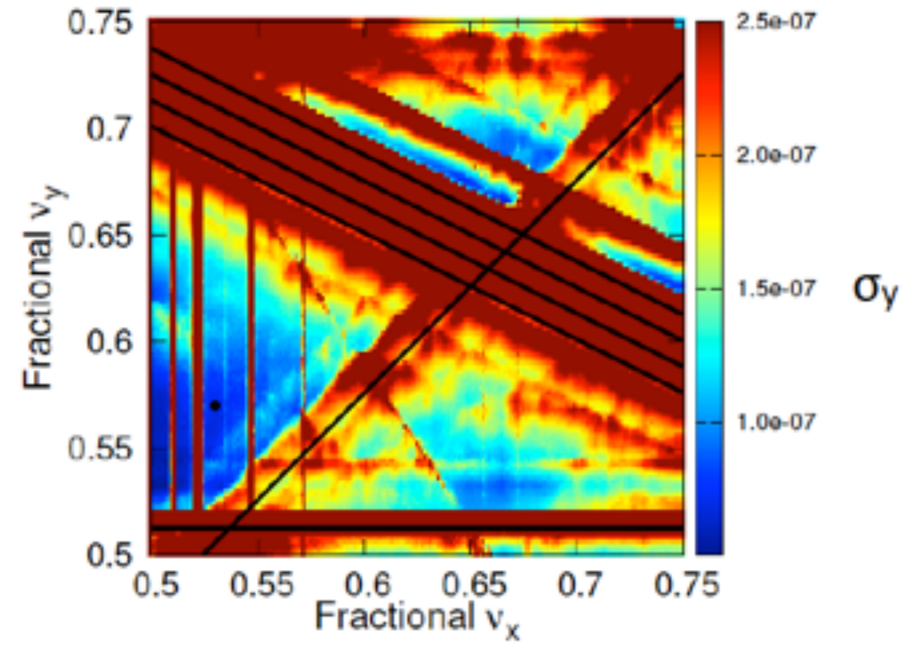
Outline

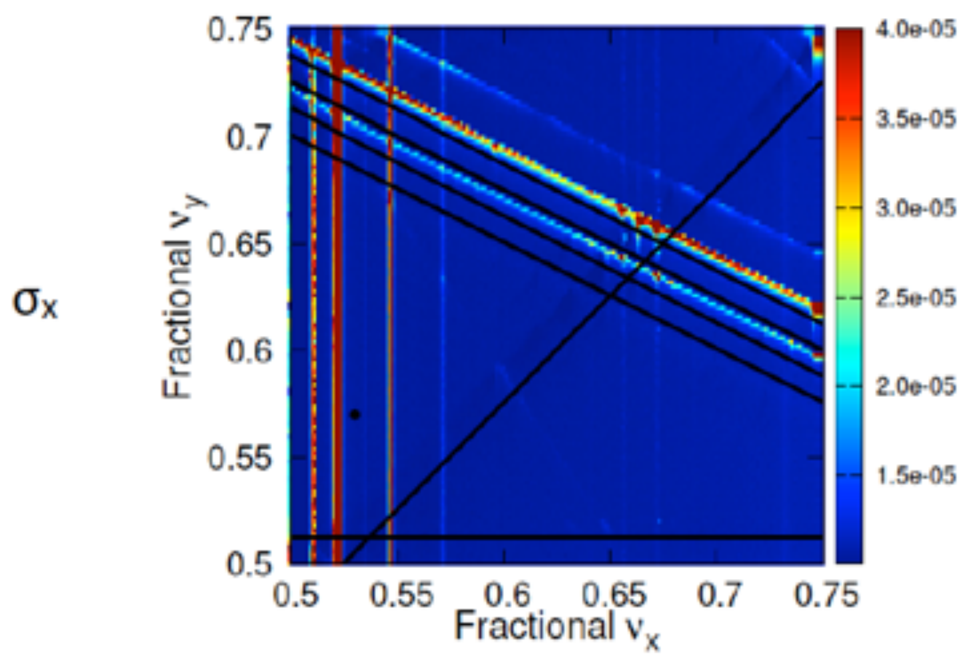
- Introduction
- Lattice nonlinearity (LN)
- **Beam-beam (BB) effects**
  - **Crab waist (CW)**
  - **Interplay of BB and LN**
- Space charge (SC) effects in LER
  - Interplay of BB, SC and LN
- Impedance issues
- Summary and Future plan

3. Beam-beam effects

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



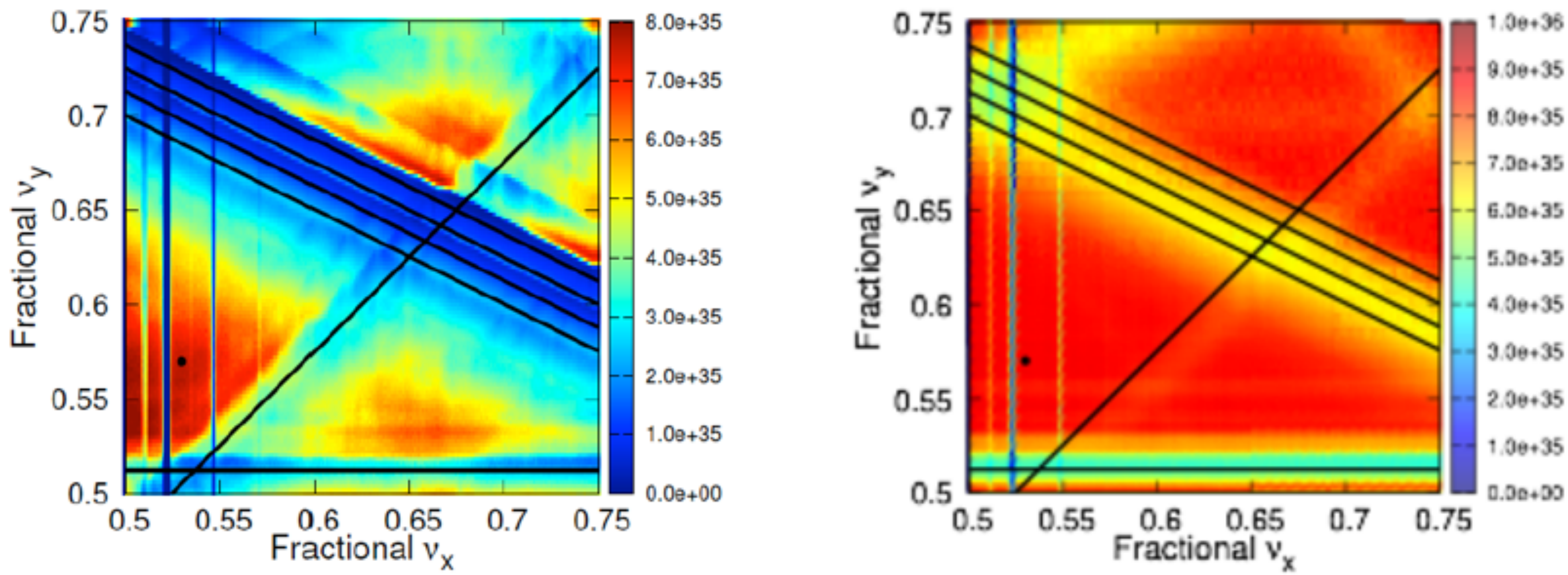




Choice of tune operating point
ν_x near half integer, keep away from synchrobeta resonance
ν_x ,ν_y=0.53,0.57

3. Beam-beam effects

➤ **Lum. tune scan for LER by BBWS: w/o and w/ crab waist**



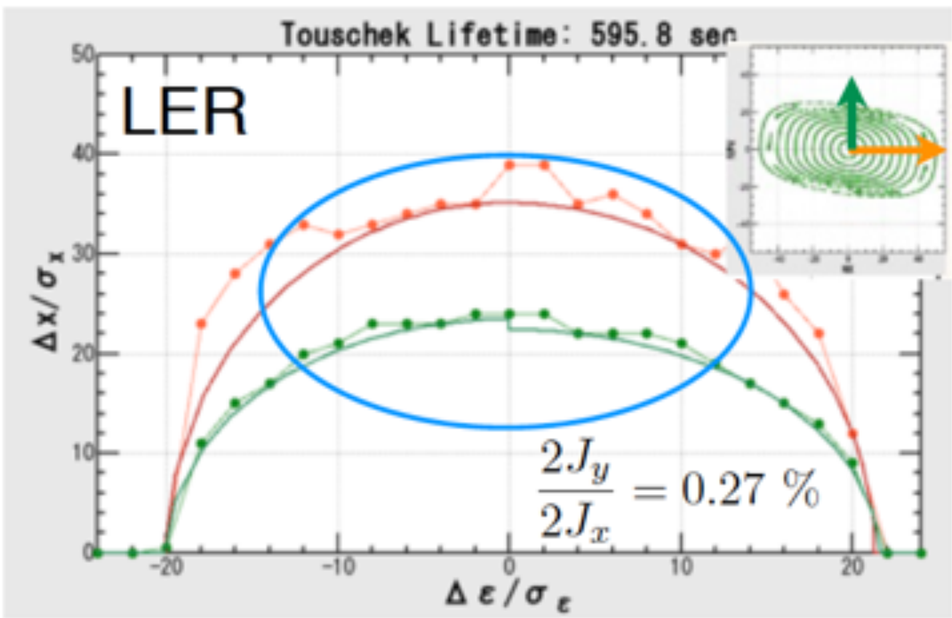
$$H_I^* = \pm \frac{1}{2\theta_h} x p_y^2$$

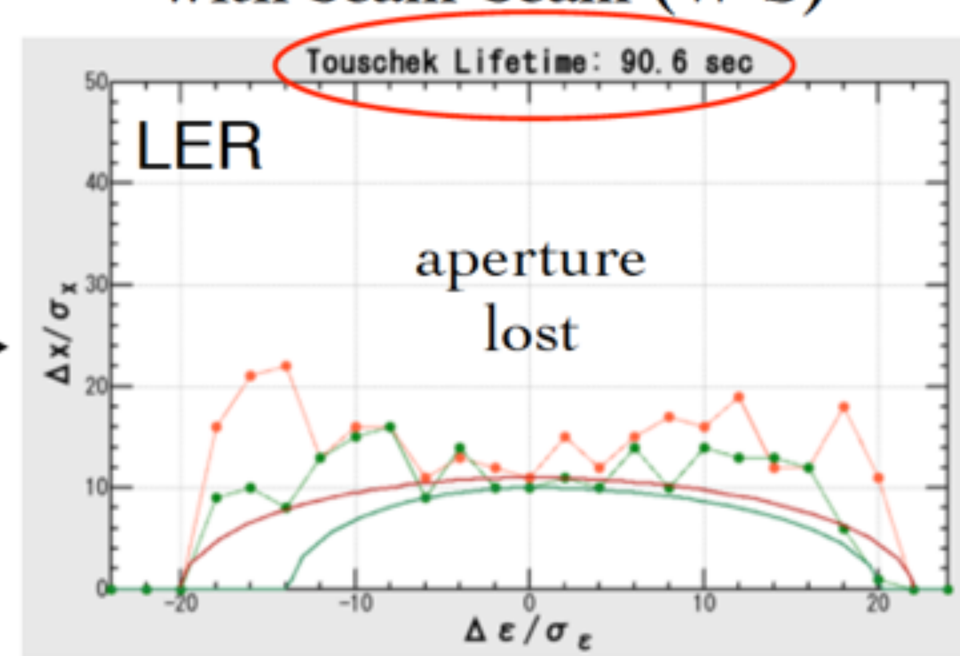
The crab waist is very powerful.
Degradation of dynamic aperture is inevitable, because nonlinearity between IP and crab waist sextupole is not transparent.

3. Beam-beam effects: DA and lifetime

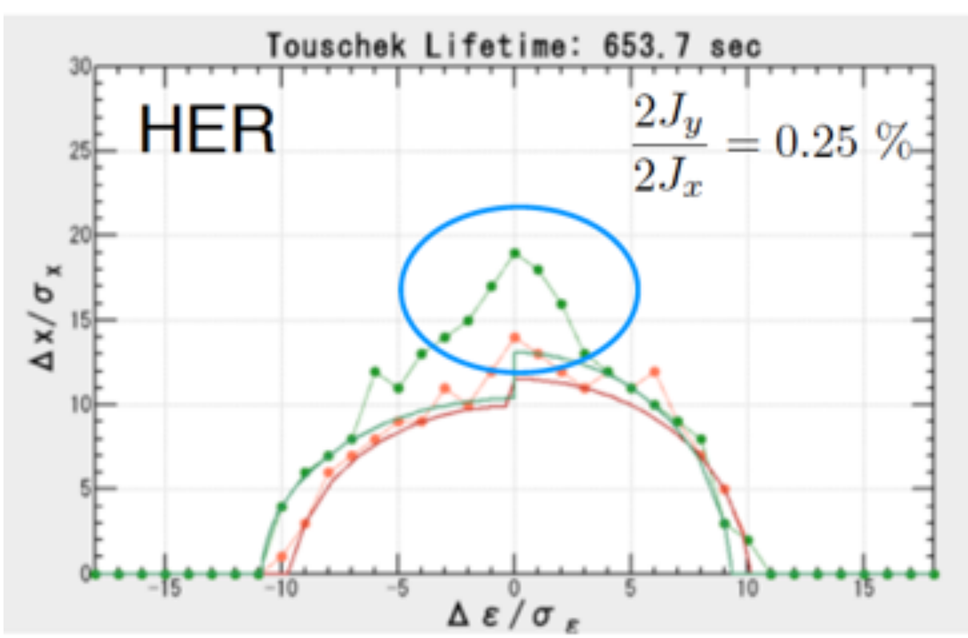
➤ **DA and lifetime are sensitive to beam-beam interaction**

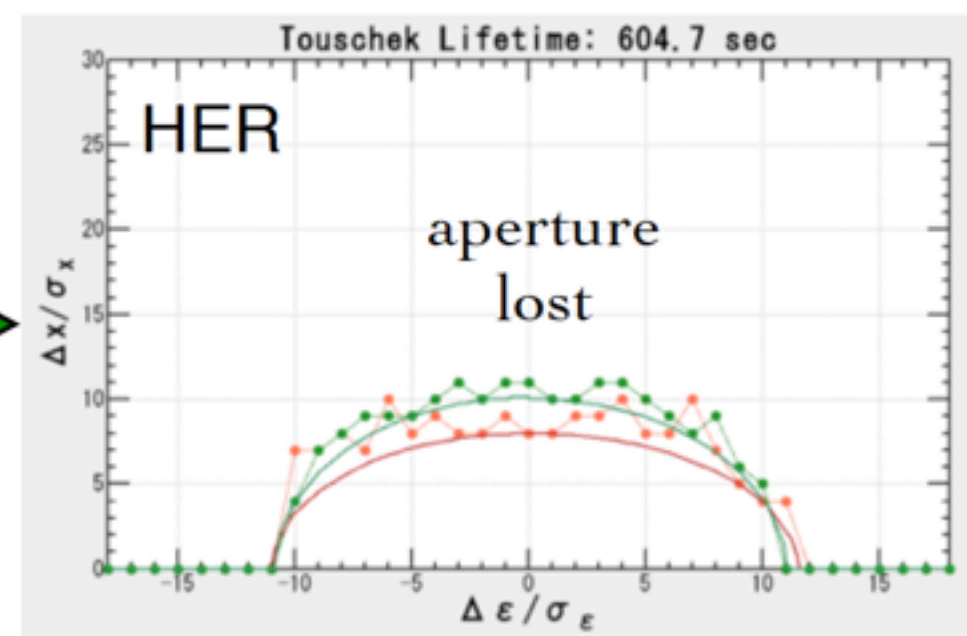
w/o beam-beam | with beam-beam (W-S)





Transverse aperture is reduced significantly.





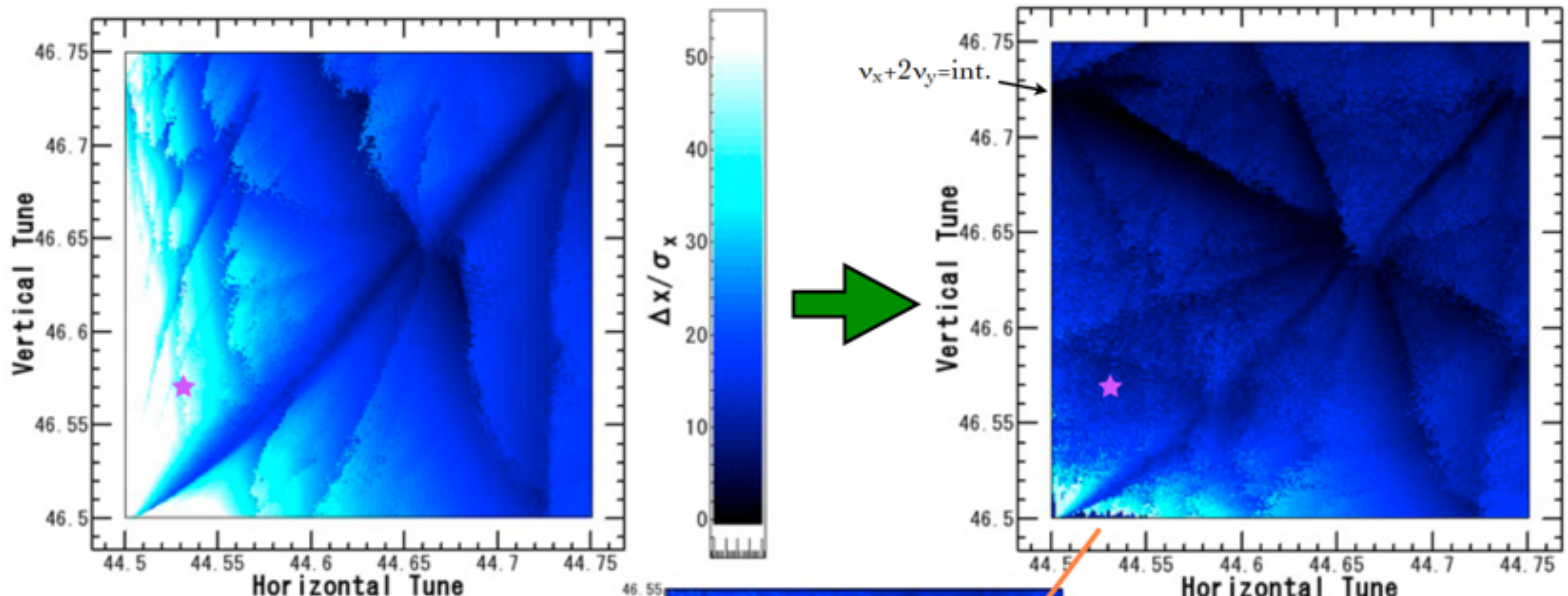
From Y. Ohnishi

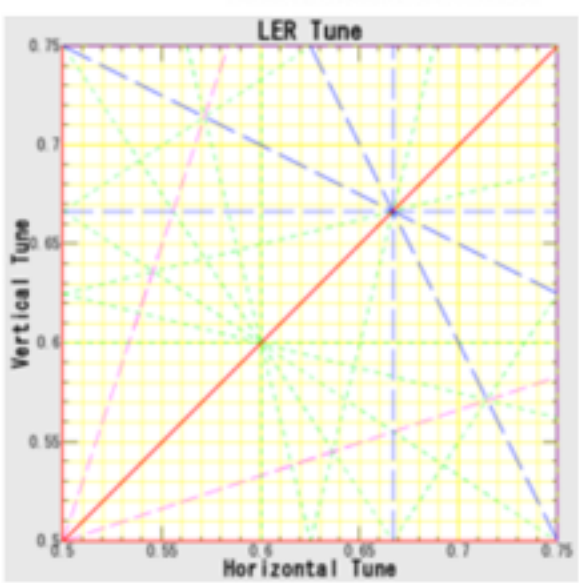
3. Beam-beam effects: DA and lifetime

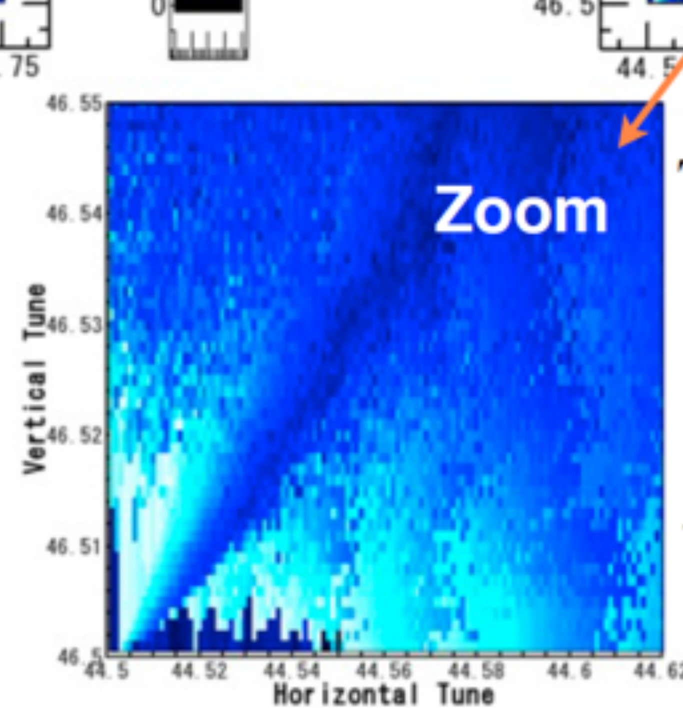
➤ Tune survey of DA

LER: w/o beam-beam

LER: with beam-beam







There is a good region near half integer resonance for the vertical tune.

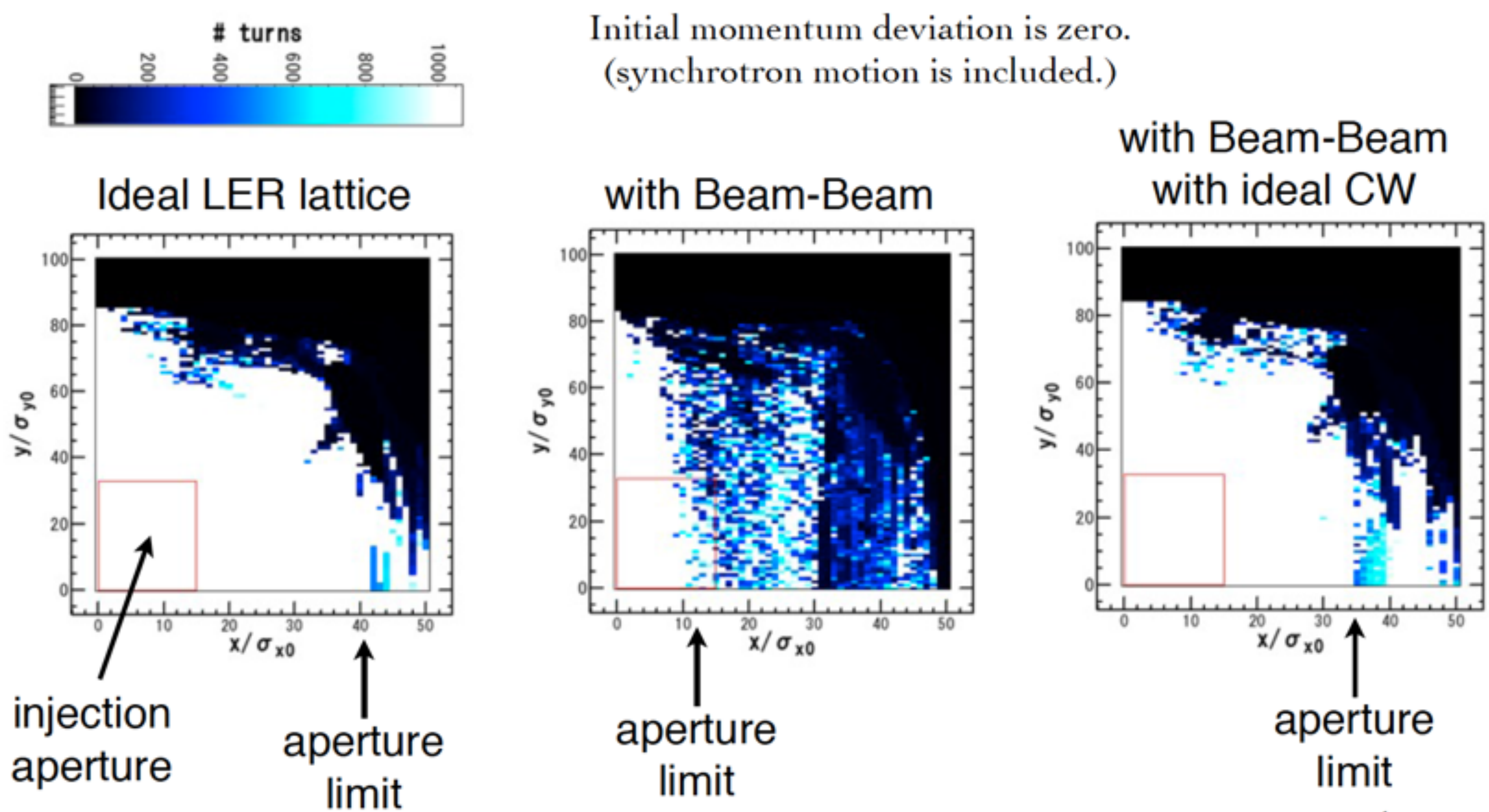
Chromaticity correction becomes very difficult near half integer.

From Y. Ohnishi

3. Beam-beam effects: DA and lifetime

➤ DA with BB and ideal CW

Stability of an initial amplitude in the horizontal and vertical plane.



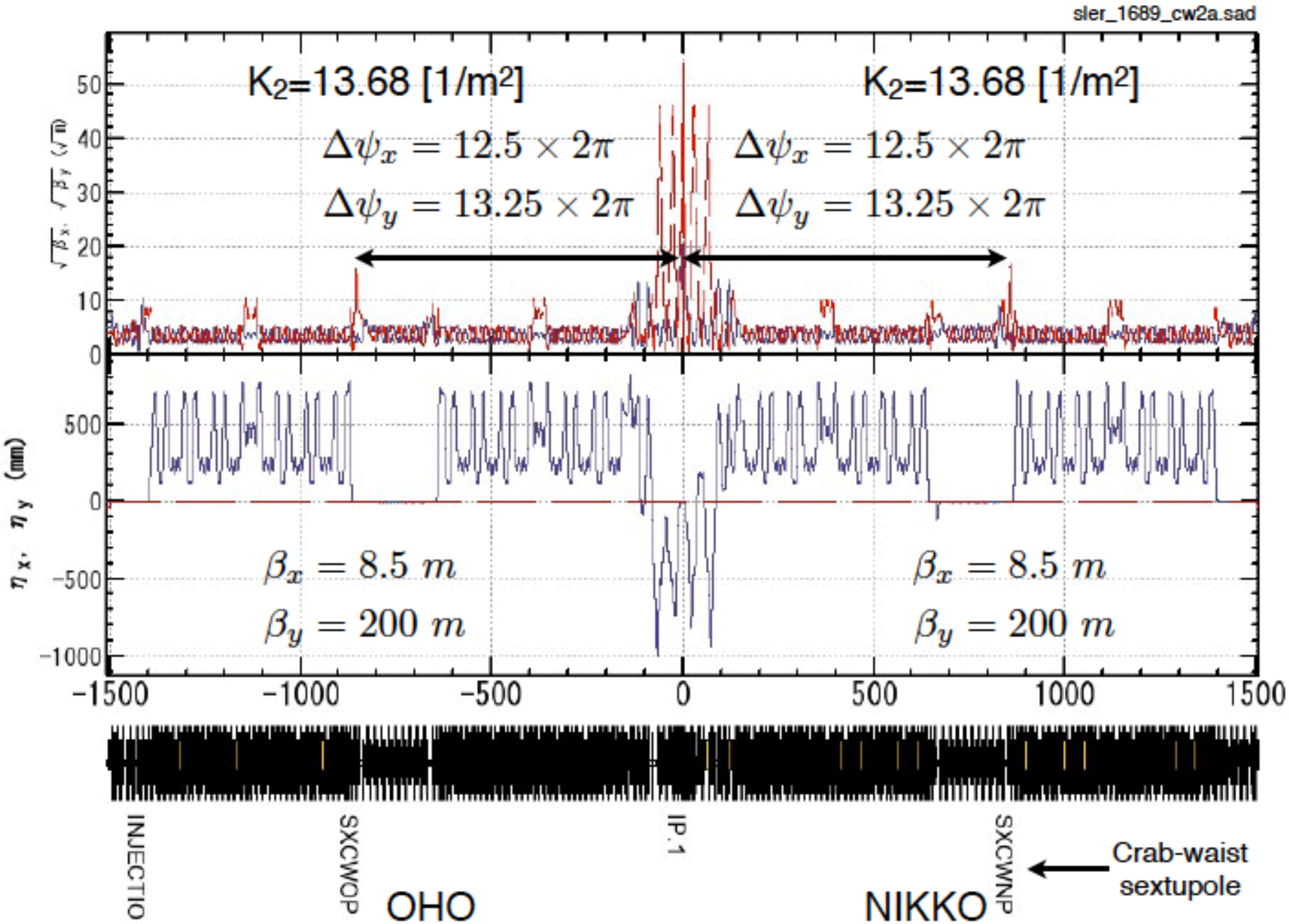
Ideal crab-waist is a map of $f_{BB} \to f_{CW}(+\lambda) f_{BB} f_{CW}(-\lambda)$ $\lambda = \dfrac{1}{\tan 2\phi_x}$

$$f_{CW}(\lambda) : p_x \to p_x + \frac{\lambda}{2} p_y^2, \; y \to y - \lambda x p_y$$

From Y. Ohnishi

3. Beam-beam effects: DA and lifetime

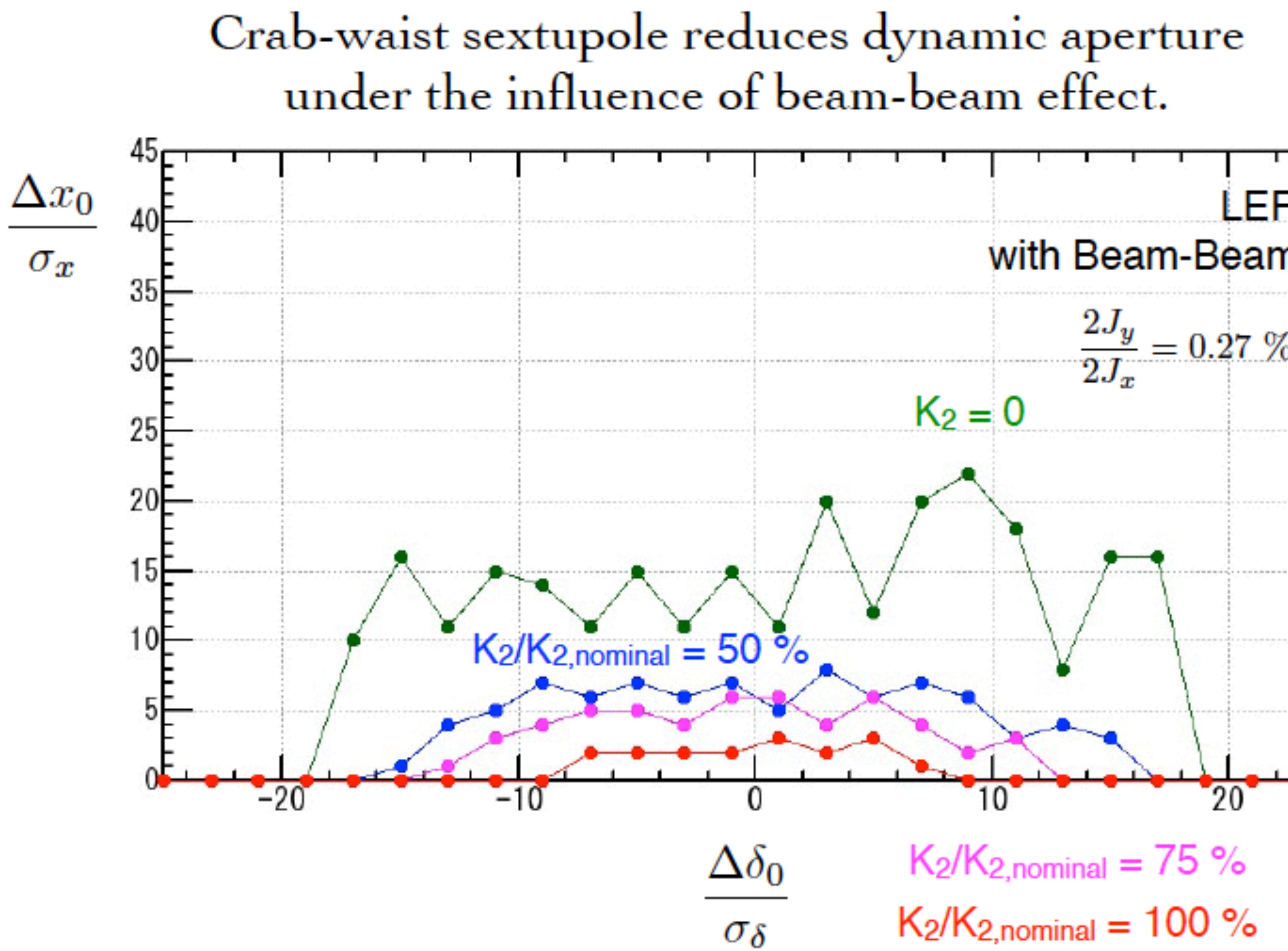
➤ **CW optics**



From Y. Ohnishi

3. Beam-beam effects: DA and lifetime

➤ **CW optics**

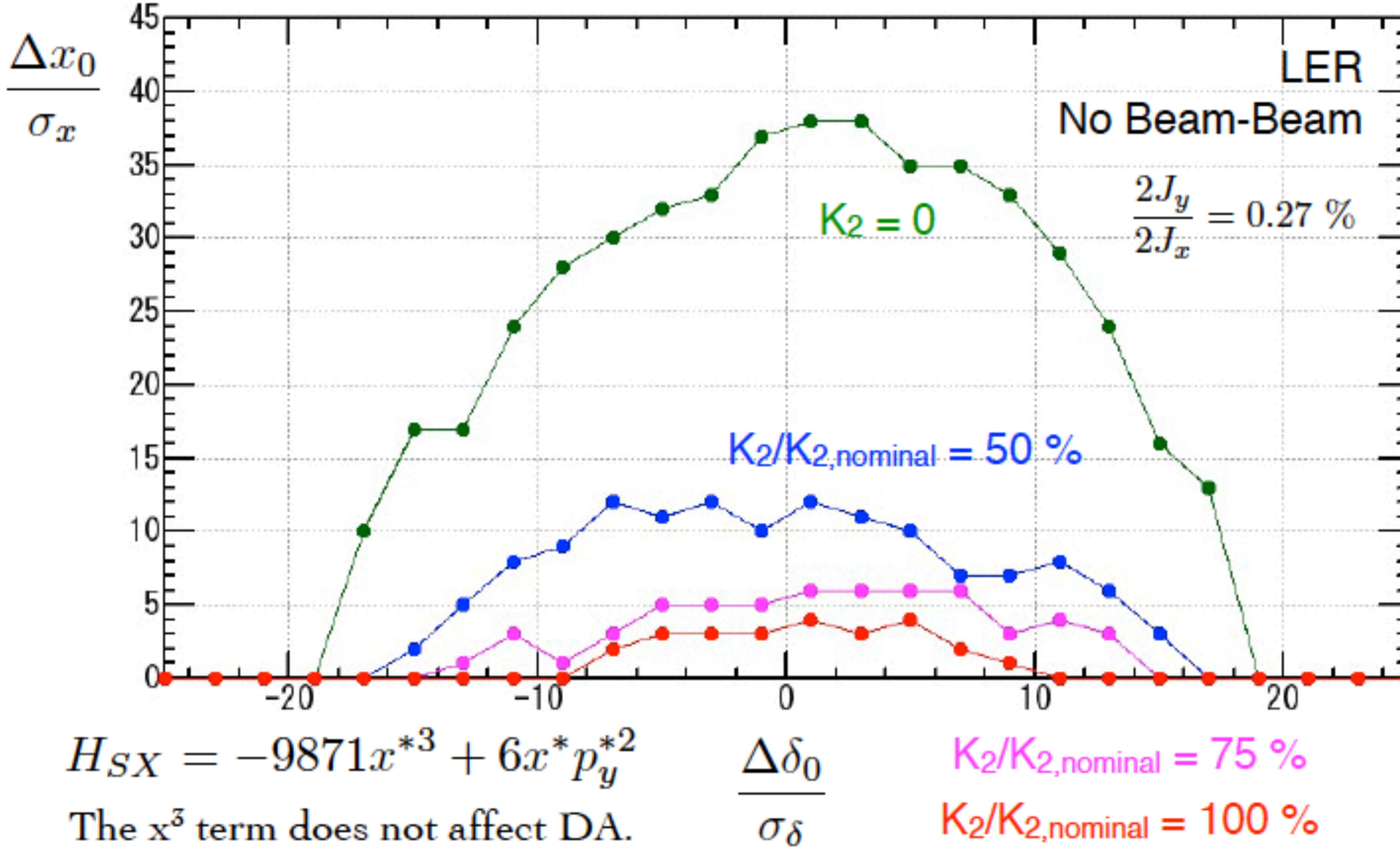


From Y. Ohnishi

3. Beam-beam effects: DA and lifetime

➤ **CW optics**

Crab-waist sextupole reduces dynamic aperture without beam-beam effect significantly.



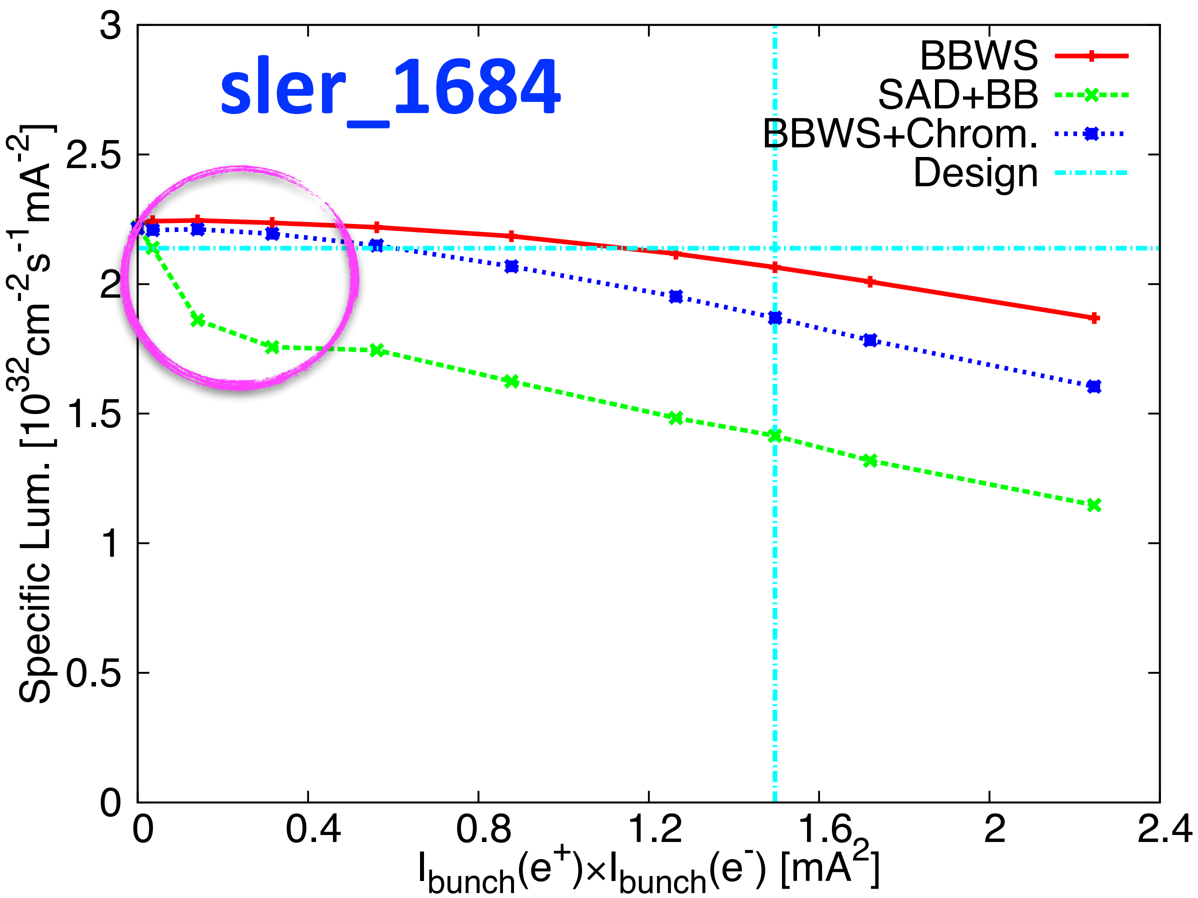
$$H_{SX} = -9871x^{*3} + 6x^{*}p_y^{*2}$$

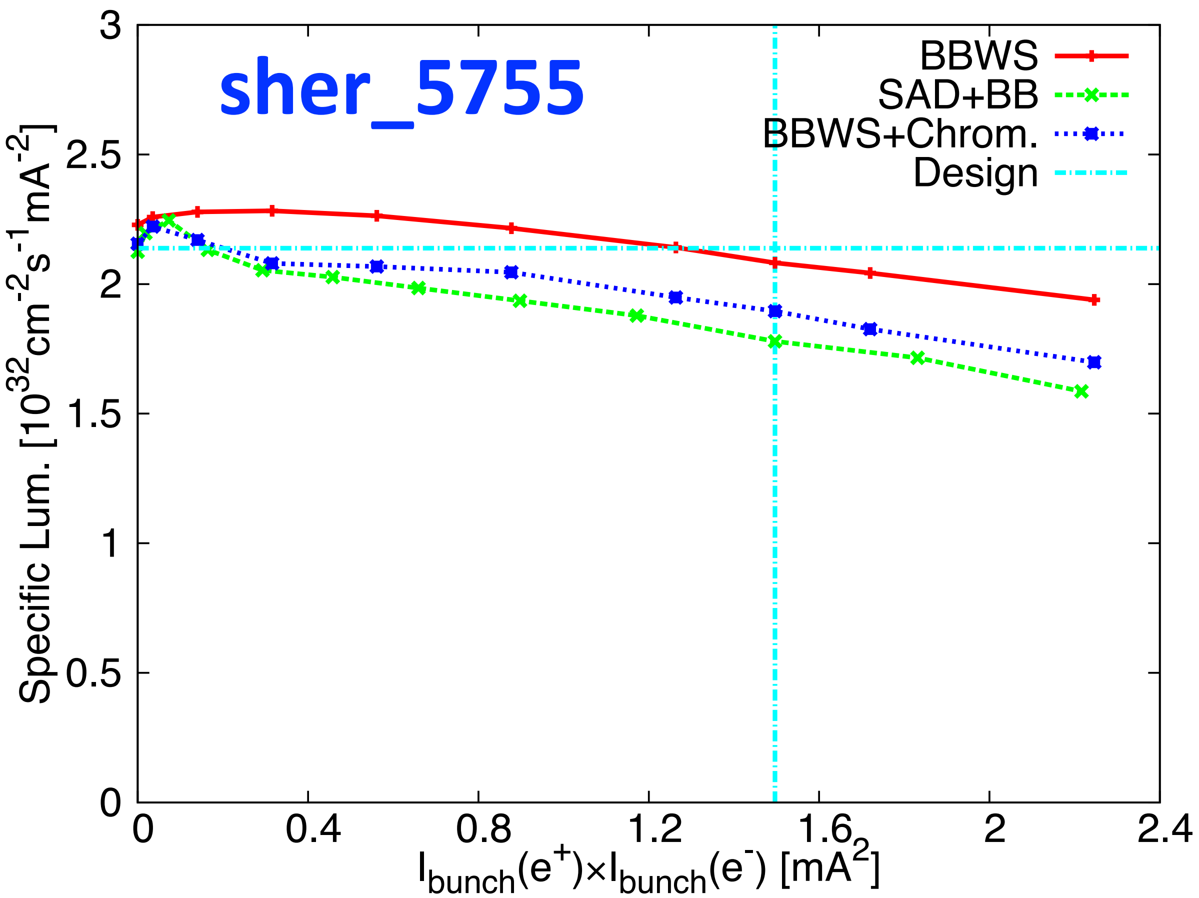
The x^3 term does not affect DA.

From Y. Ohnishi

3. Beam-beam effects: BB+LN

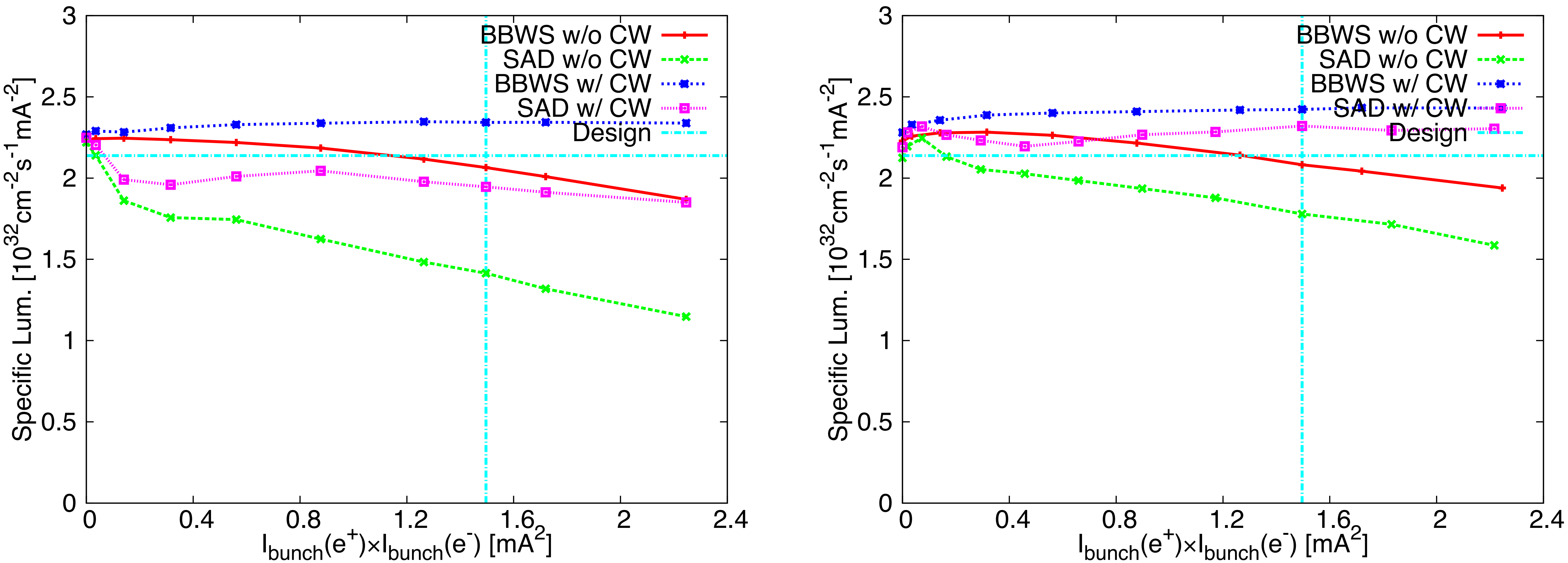
- ➤ **Interplay of BB and LN causes significant lum. loss**
- ➤ **LER: Lum. loss is attributed to amplitude-dependent nonlin.**
  - **Vertical emittance is very sensitive to beam-beam perturbation**
  - **Hard to suppress**
- ➤ **HER: Lum. loss is attributed to chromatic nonlin.**
  - **Controllable if skew-sextupoles installed**





3. Beam-beam effects: BB+LN

- **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**



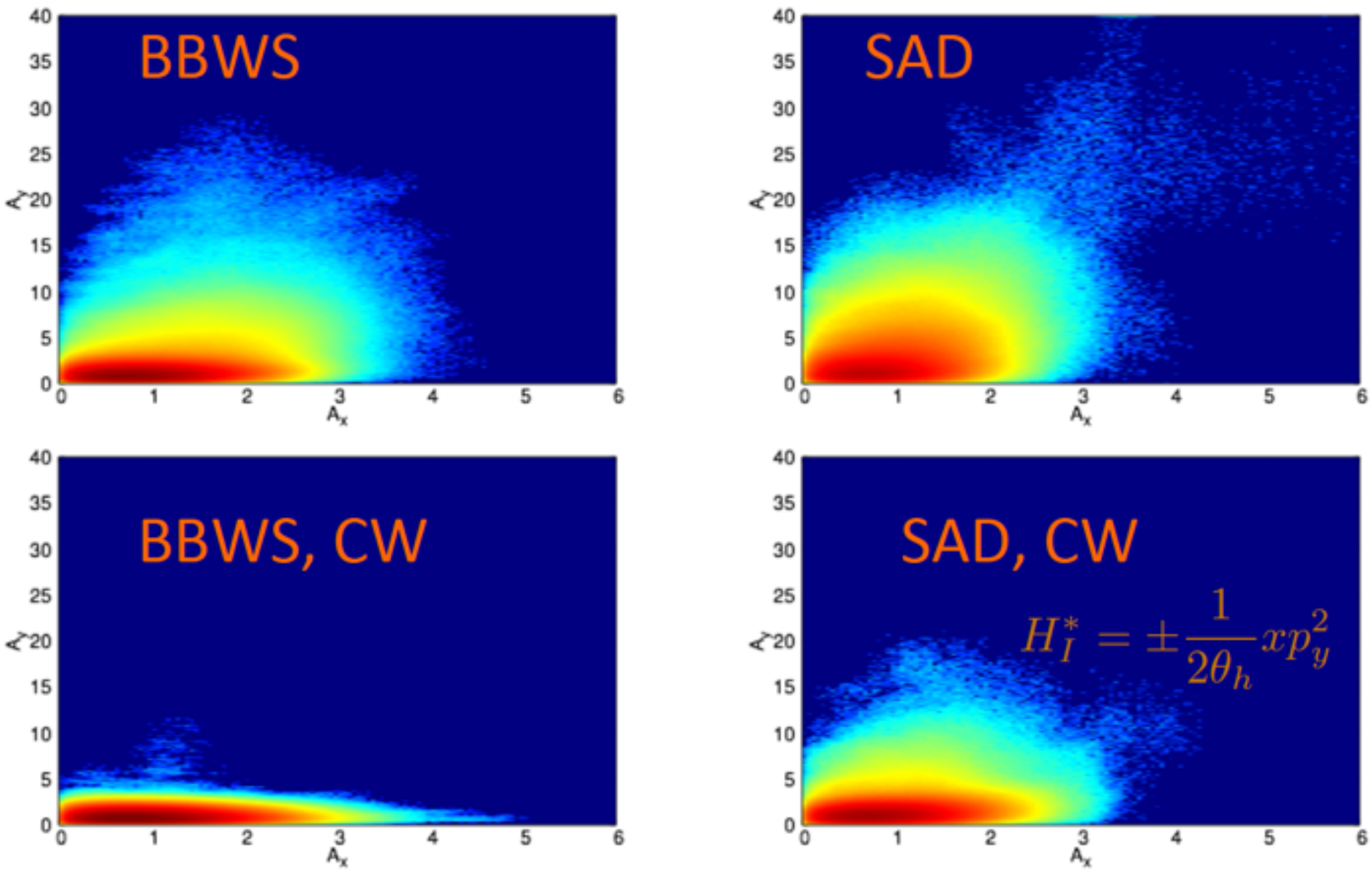
3. Beam-beam effects: BB+LN: LER

➤ **Beam tail distribution for LER**

- **CW not work well when LN exists**
- **Beam tail => Collimation => Impedance budget => Instability => commissioning**

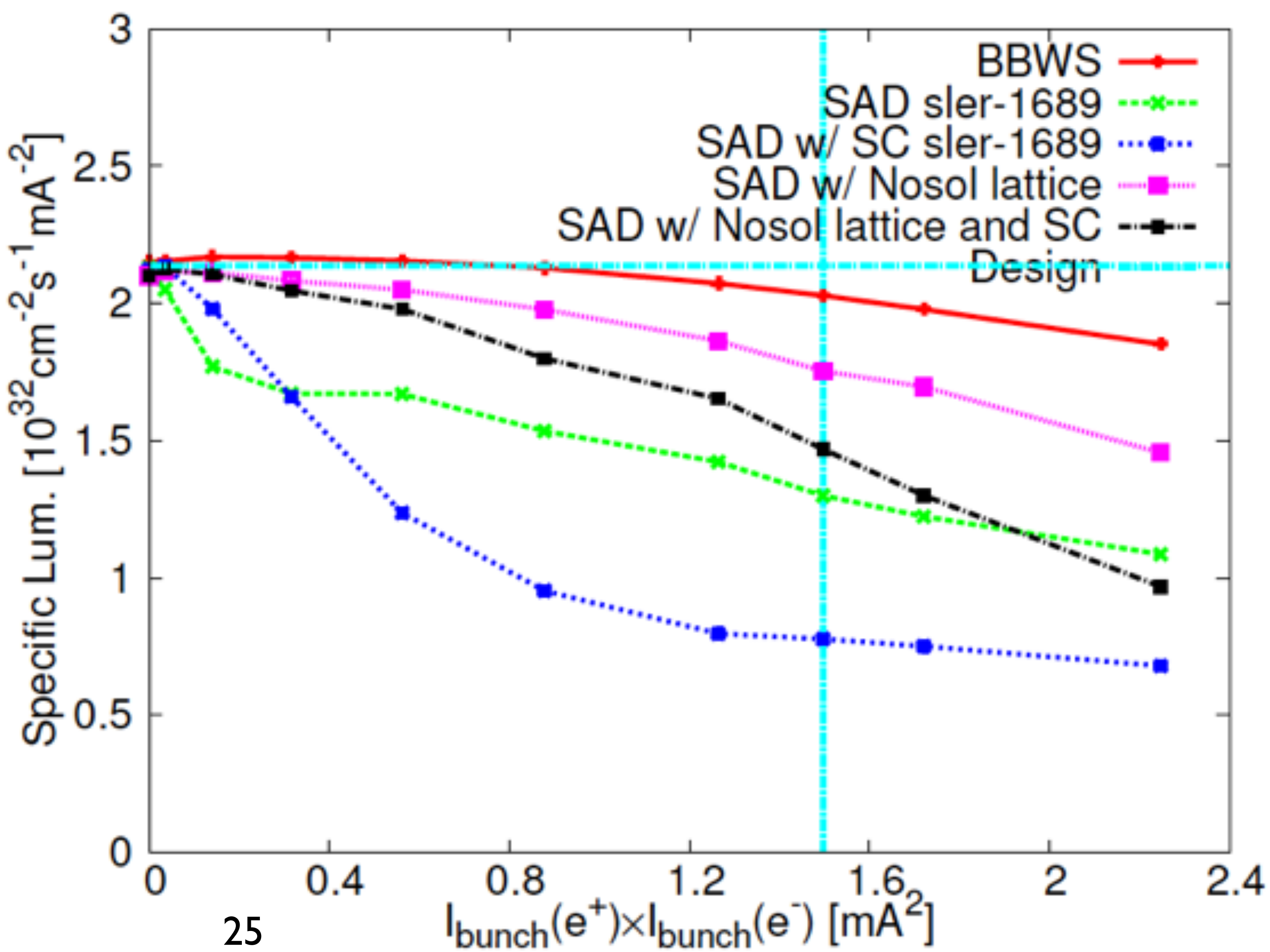
- $Ne=6.53\times10^{10}$,

SAD +weak-strong BB



3. Beam-beam effects: BB+LN: LER

- ➤ Simplified lattice
  - • No solenoid
  - • QC* magnets simplified: no offset, dipole and skew-quad correctors removed
- ➤ No significant lum. degradation at low current
- ➤ Solenoid and high-order terms in QC* are the main sources of lattice nonlinearity



Outline

- ➤ Introduction
- ➤ Lattice nonlinearity (LN)
- ➤ Beam-beam (BB) effects
  - Crab waist (CW)
  - Interplay of BB and LN
- ➤ **Space charge (SC) effects in LER**
  - **Interplay of BB, SC and LN**
- ➤ Impedance issues
- ➤ Summary and Future plan

4. SC effects: LER

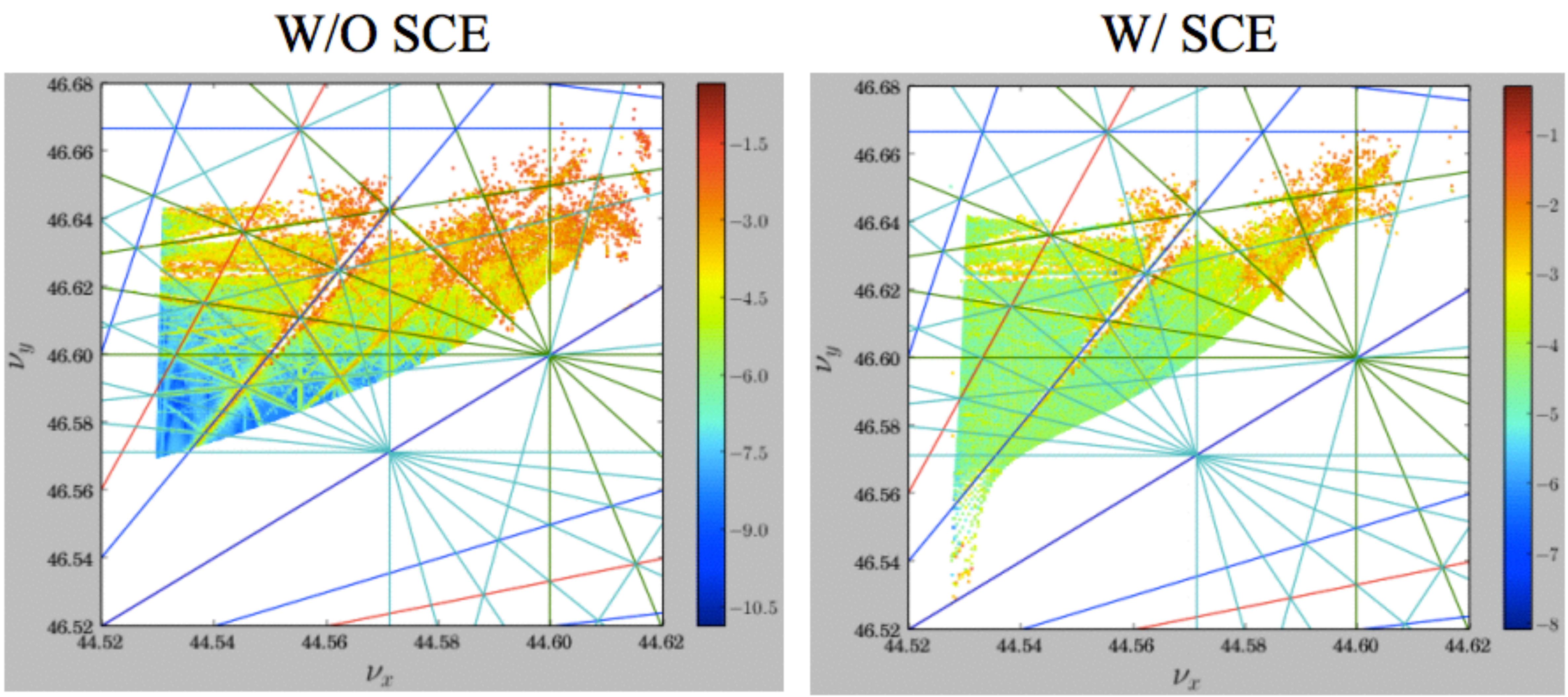
- **Linear tune shift**
  - Same order for SC and BB
  - But have opposite signs

	SuperKEKB[1)]		KEKB[4)]	
	LER[2)]	HER[3)]	LER	HER
ε_x (nm)	3.2	4.6	18	24
ε_y (pm)	8.64	11.5	180	240
ξ_x	0.0028	0.0012	0.127	0.102
ξ_y	0.0881	0.0807	0.129	0.09
$\Delta\nu_x$	-0.0027	-0.0004	-0.0005	-3E-05
$\Delta\nu_y$	-0.0943	-0.0121	-0.0072	-0.0004

[1)] Main paraperters from Y. Ohnishi et al., Prog. Theor. Exp. Phys. 2012;
[2)] sler_1682; [3)] sher_5753; [4)] Lattice used on Jun.17, 2009.

4. SC effects: LER

➤ **FMA shows betatron tunes of particles at the beam core are close to half-integer with only SC considered.**



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

Detailed Studies are now ongoing.

- Optics matching
- Checking simulation code including SAD code itself.

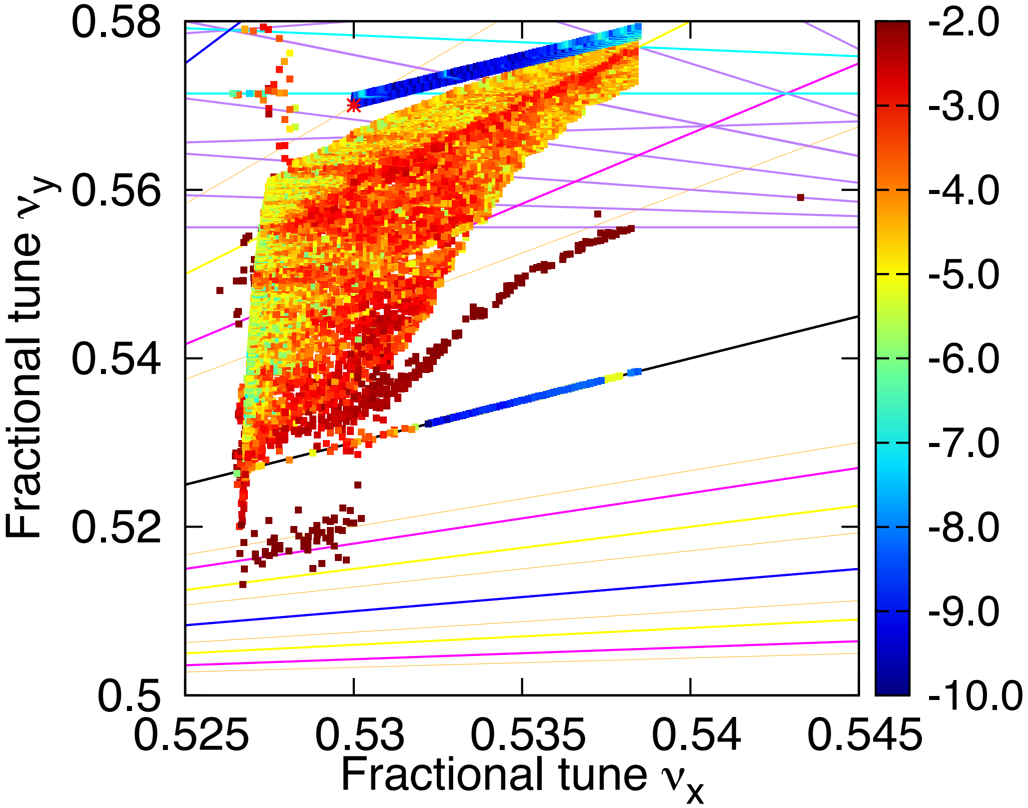
From H. Sugimoto

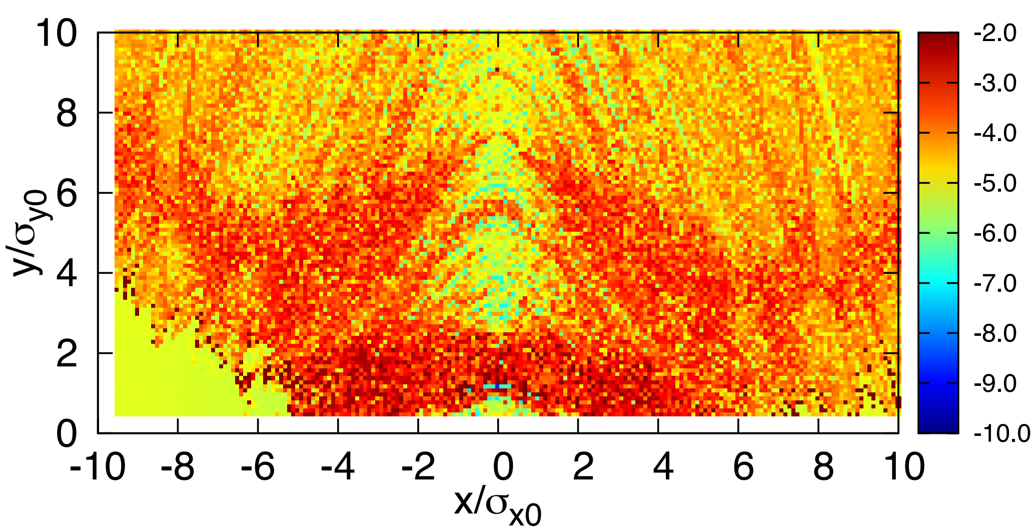
4. SC effects: LER

➤ **FMA with beam distribution: $10\sigma_x \times 10\sigma_y$**

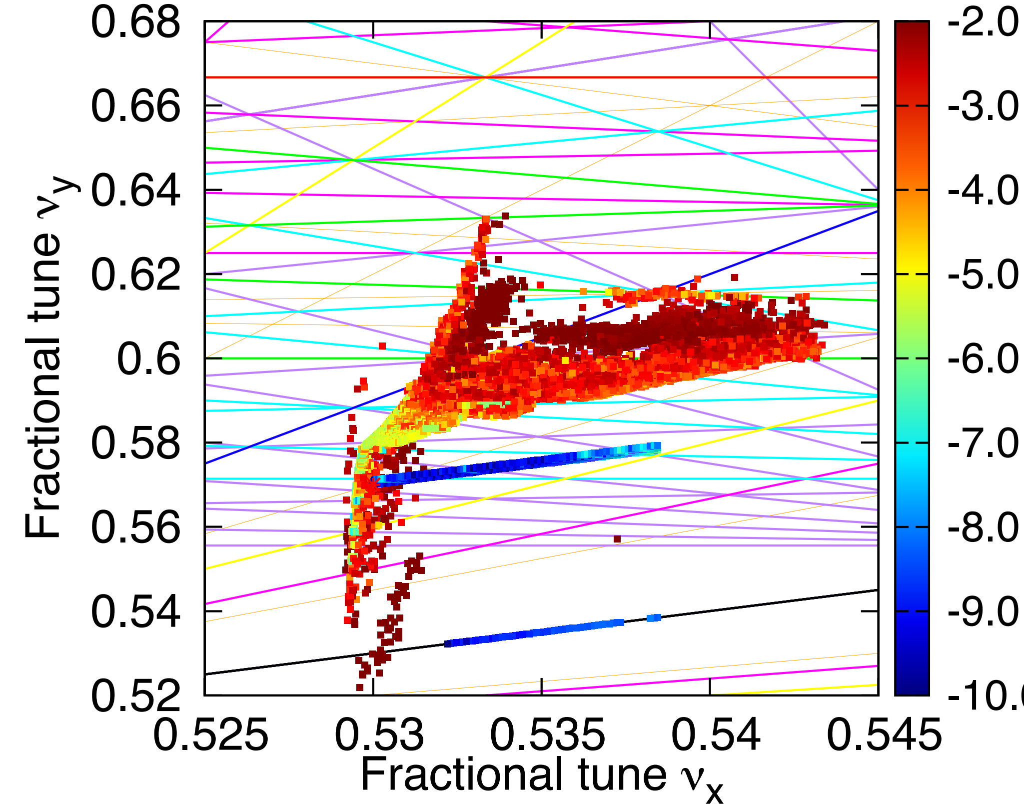
sler_1684

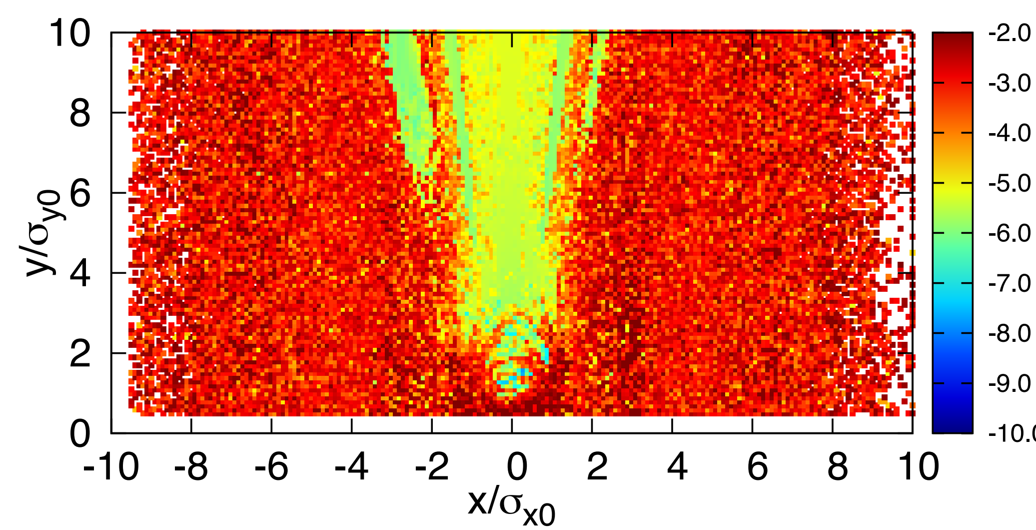
LN + SC





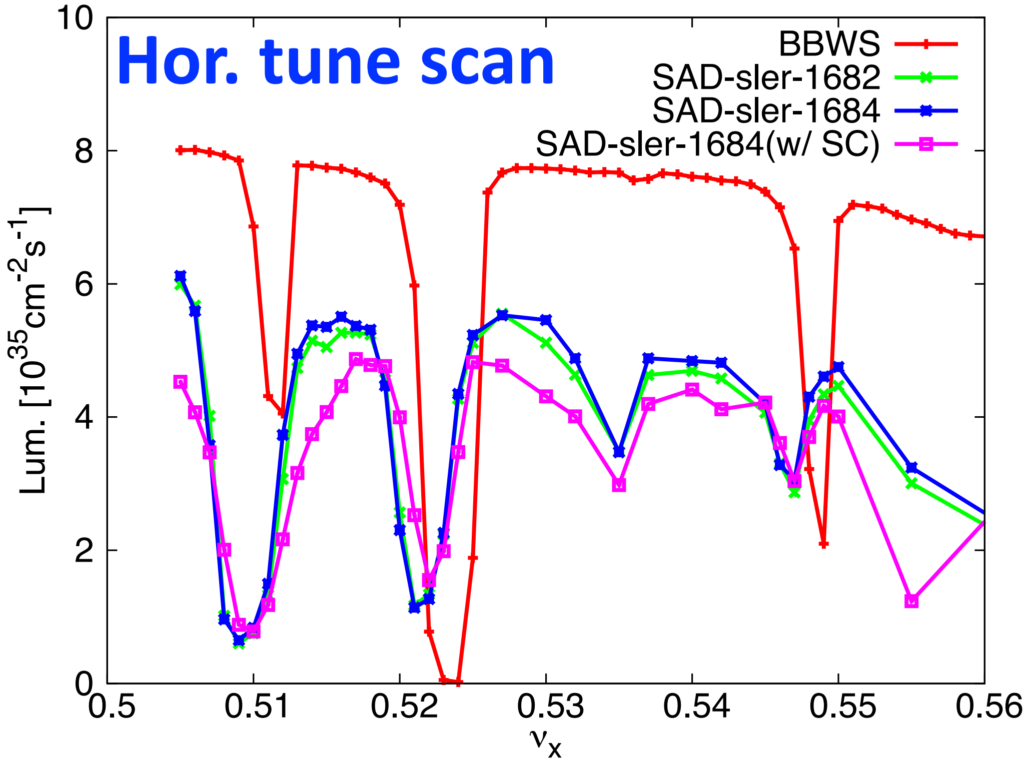
LN + SC + BB

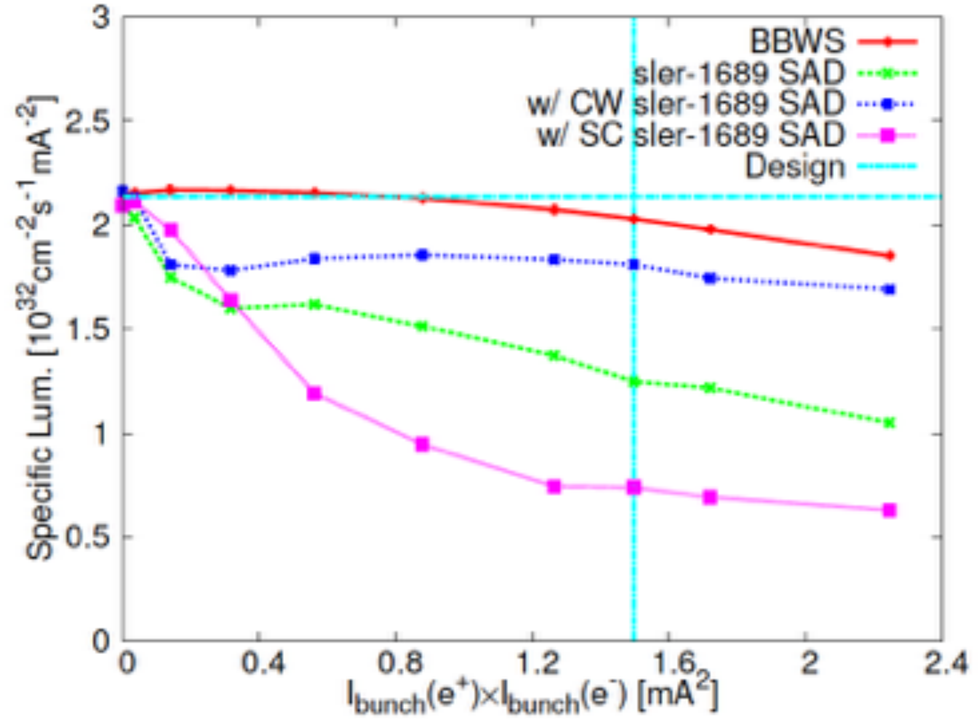


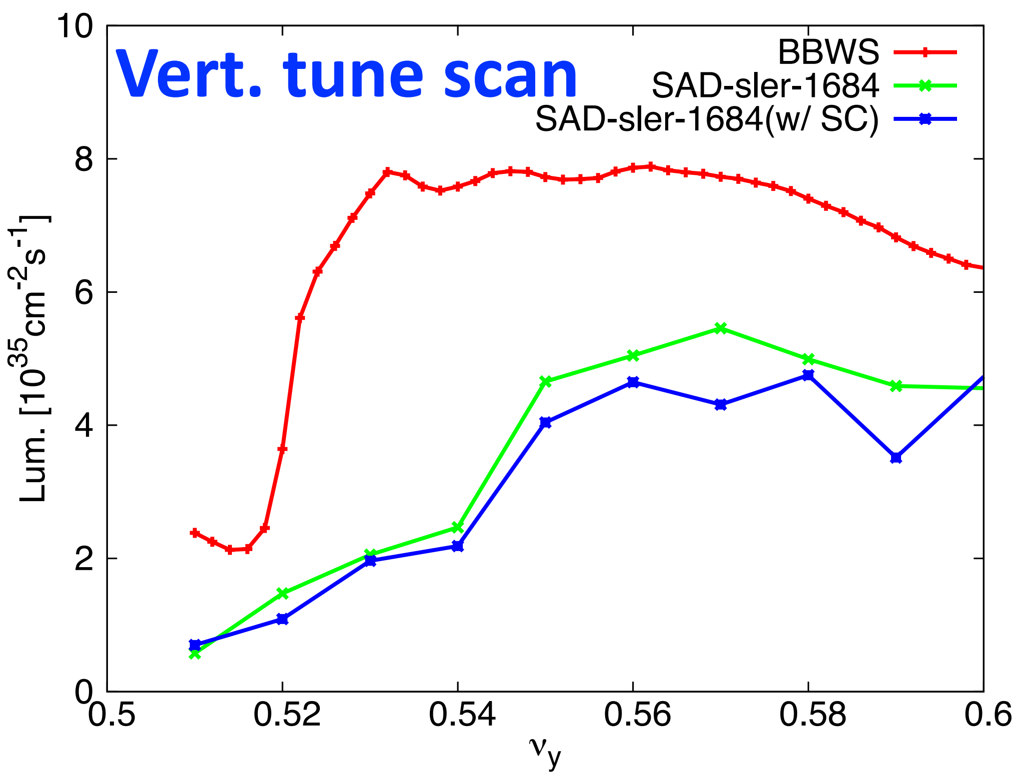


4. SC effects: LER

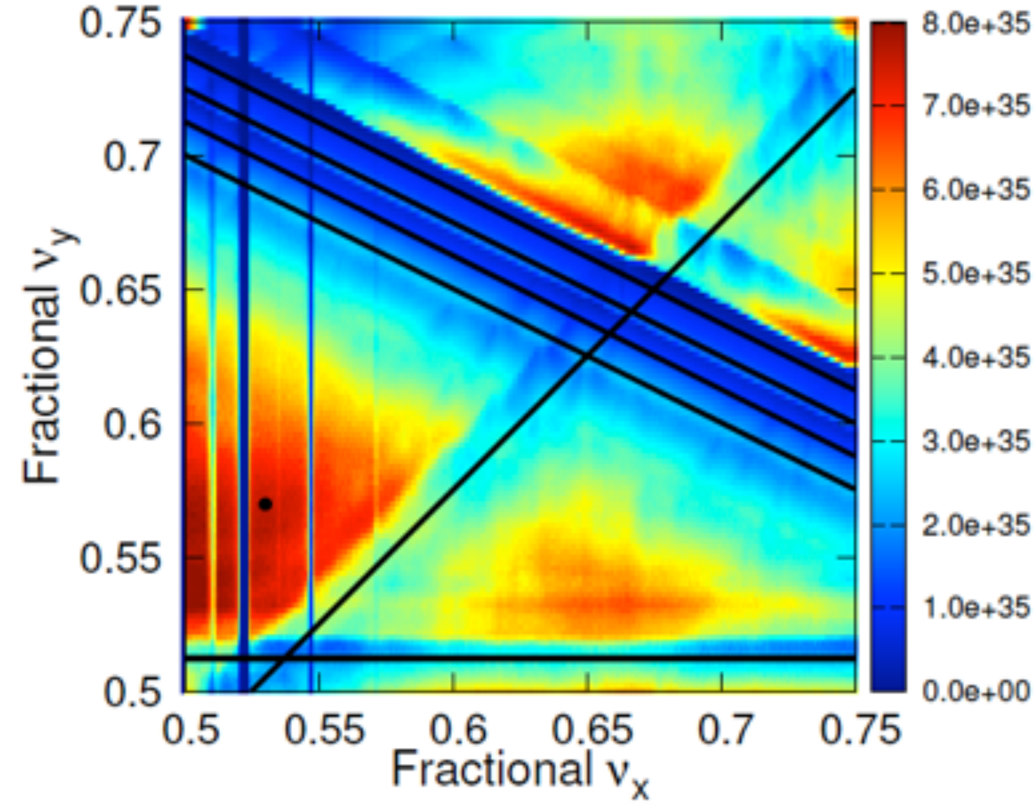
➤ Luminosity: Tune scan w/ and w/o SC







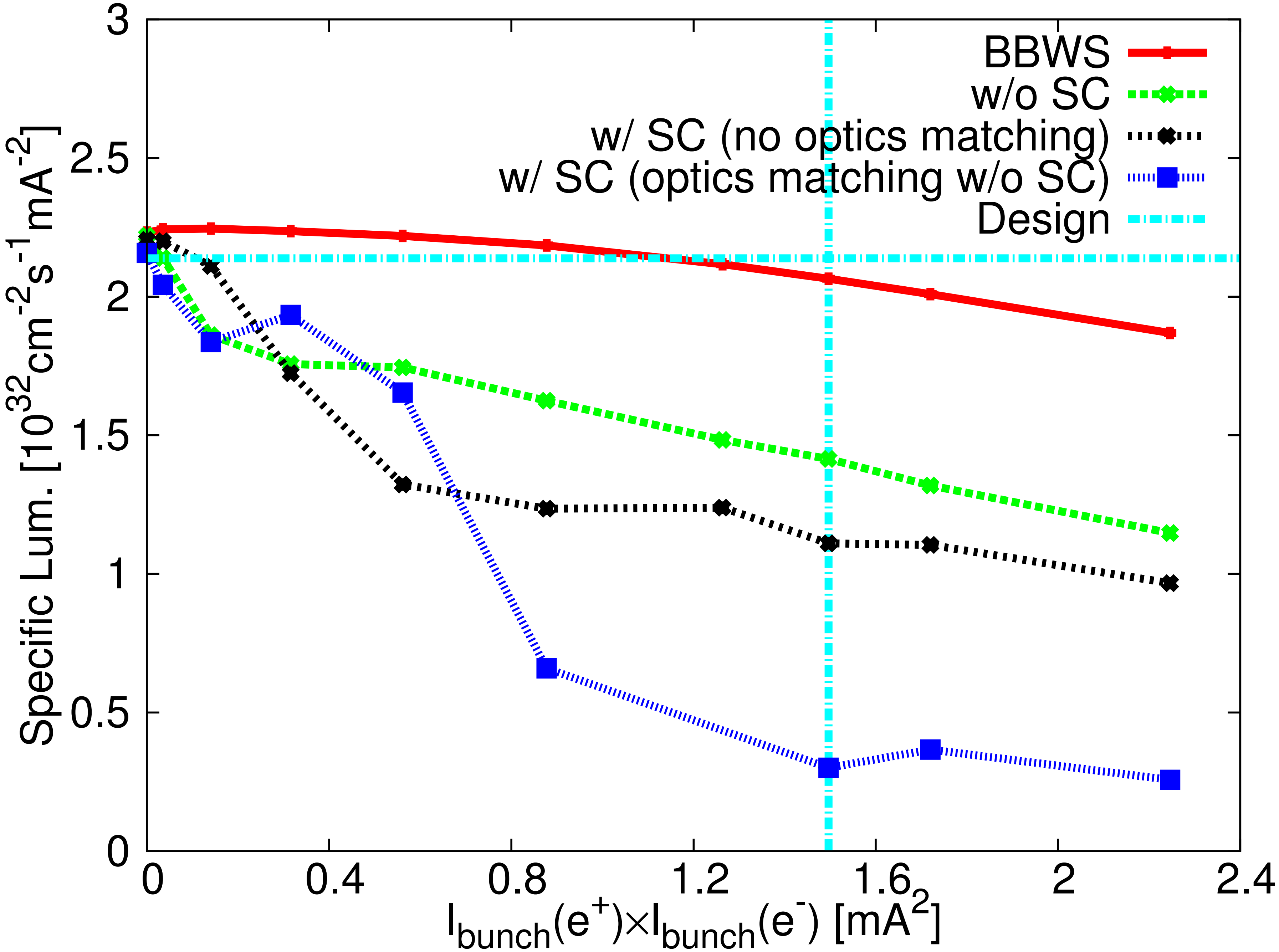
BBWS



4. SC effects: LER

- **First try:** **optics matching w/o SC**
- **Compensate linear SC tune shift => Not successful**
- **Next try:** **optics matching w/ SC** **=> Ongoing**

sler_1684



Outline

- Introduction
- Lattice nonlinearity (LN)
- Beam-beam (BB) effects
  - Crab waist (CW)
  - Interplay of BB and LN
- Space charge (SC) effects in LER
  - Interplay of BB, SC and LN
- **Impedance issues**
- Summary and Future plan

5. Impedance issues: Impedance budget

➤ **Impedance budget with σ_z=5/4.9mm:**

- **Loss factors, resistance and inductance are calculated at nominal bunch lengths**
- **Bellows, flanges and pumping ports contribute more impedance in HER than in LER**

Table 1. The PEP-II HER inductive impedance

Parameter	L (nH)	k_l (V/pC)
Dipole screens	0.10	
BPM	11.	0.8
Arc bellow module	13.5	1.41
Collimators	18.9	0.24
Pump slots	0.8	
Flange/gap rings	0.47	0.03
Tapers oct/round	3.6	0.06
IR chamber	5.0	0.12
Feedback kickers	29.8	0.66
Injection port	0.17	0.004
Abort dump port	0.23	0.005
Total	83.3	3.4

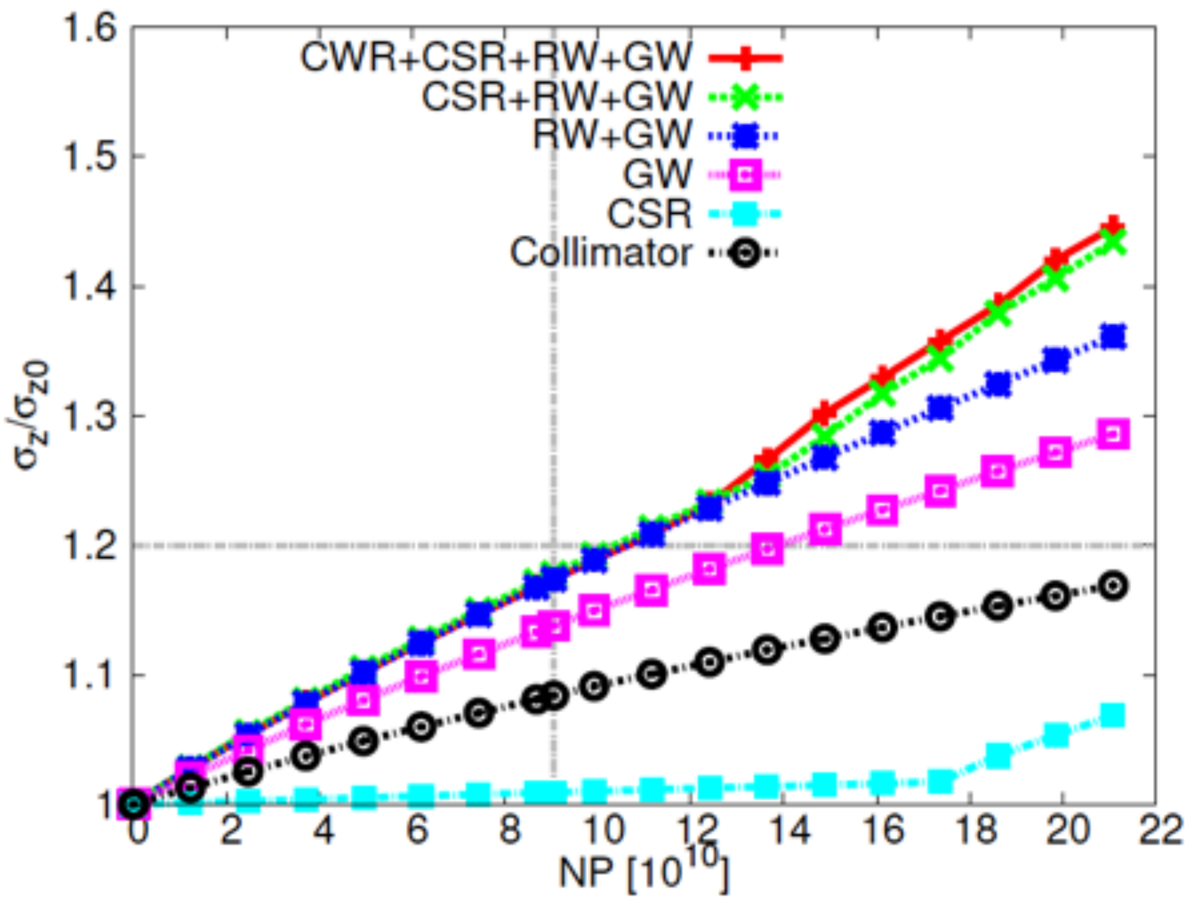
From slac-pub-6798

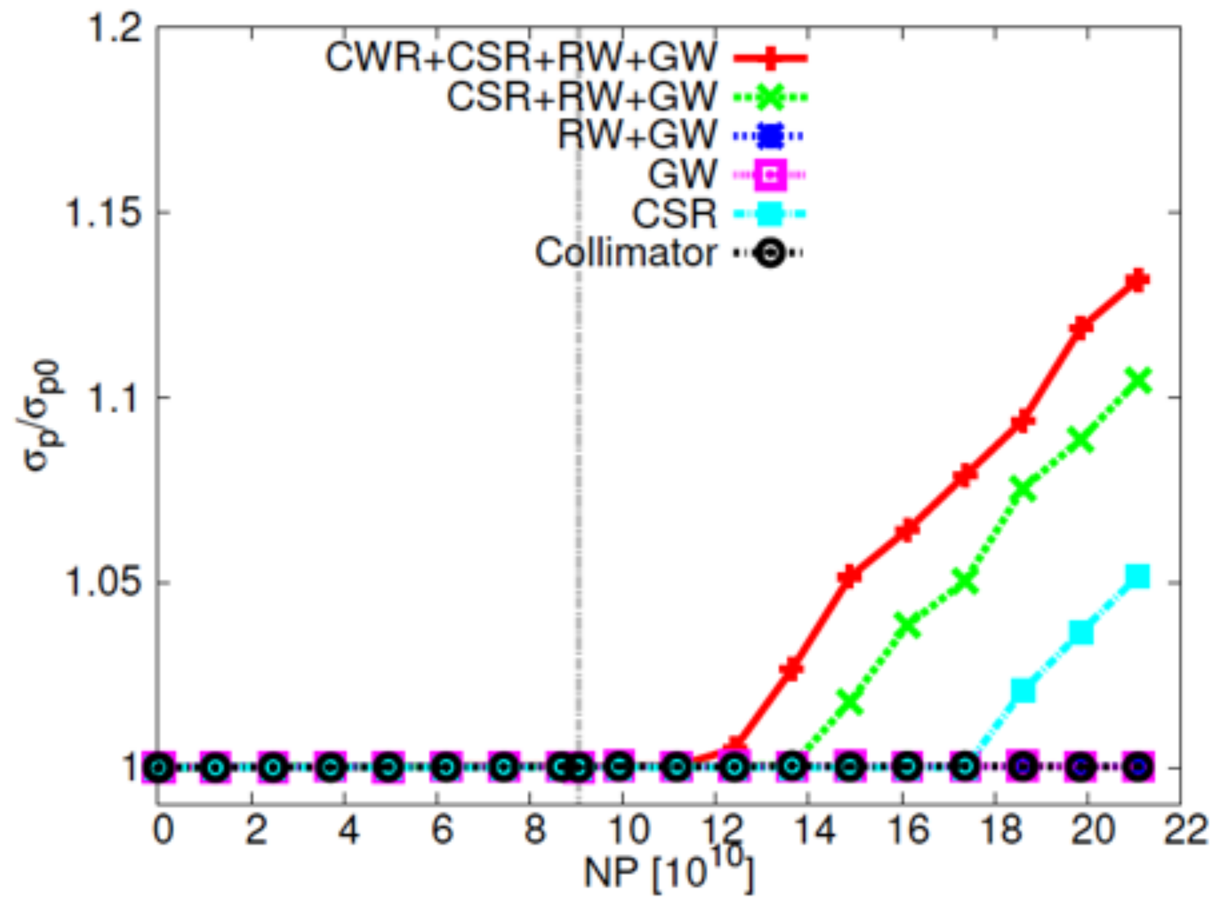
Component	LER			HER		
	$k_{\|\|}$	R	L	$k_{\|\|}$	R	L
ARES cavity	8.9	524	-	3.3	190	-
SC cavity	-	-	-	7.8	454	-
Collimator	1.1	62.4	13.0	5.3	309	10.8
Res. wall	3.9	231	5.7	5.9	340	8.2
Bellows	2.7	159	5.1	4.6	265	16.0
Flange	0.2	13.7	4.1	0.6	34.1	19.3
Pump. port	0.0	0.0	0.0	0.6	34.1	6.6
SR mask	0.0	0.0	0.0	0.4	21.4	0.7
IR duct	0.0	2.2	0.5	0.0	2.2	0.5
BPM	0.1	8.2	0.6	0.0	0.0	0.0
FB kicker	0.4	26.3	0.0	0.5	26.2	0.0
FB BPM	0.0	1.1	0.0	0.0	1.1	0.0
Long. kicker	1.8	105	1.2	-	-	-
Groove pipe	0.1	5.7	0.9	-	-	-
Electrode	0.0	2.2	2.3	-	-	-
Total	19.2	1141	33.4	29.0	1677	62.1

Ref. D. Zhou et al., IPAC14, TUPRI021

5. Impedance issues: MWI: LER

- **Simulations with input of Pseudo-Green wake:**
  - **Use Warnock-Cai's VFP solver**
  - **Collimators are important sources in bunch lengthening**
  - **Simulated $\sigma_z \approx 5.9$mm @Design bunch current**
  - **Simulated MWI threshold is around NP_{th}=1.2E11**
  - **Interplay between CSR and conventional wakes?**





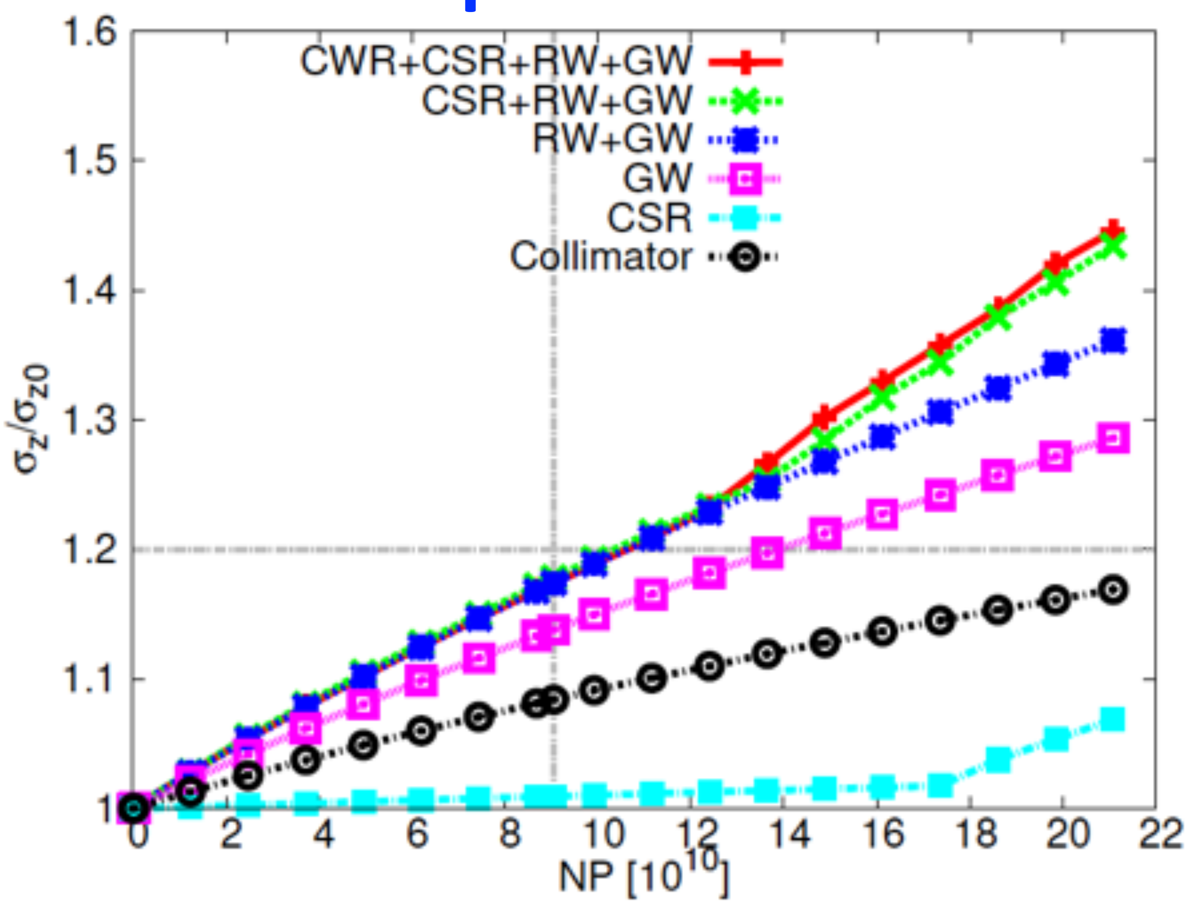
5. Impedance issues: MWI: LER

➤ **Concern of MWI in LER:**

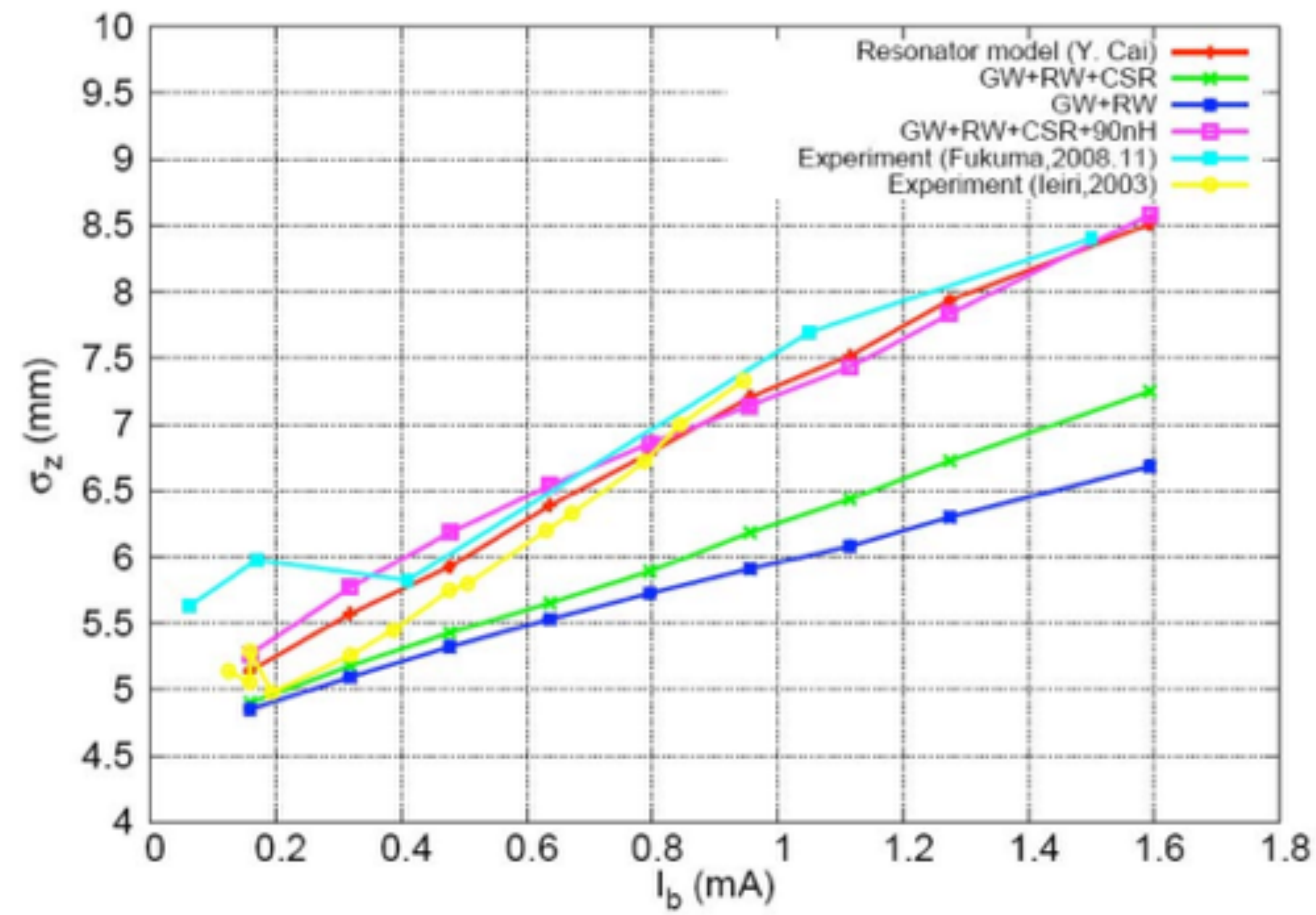
- **Unknown impedance source in KEKB LER**
- **Lum. inversely proportional to bunch length for SuperKEKB**

$$L = L_0 R_{H\theta} \qquad L_0 = \frac{N_e N_p f_0 N_b}{2\pi\sqrt{\sigma_{xe}^{*2}+\sigma_{xp}^{*2}}\sqrt{\sigma_{ye}^{*2}+\sigma_{yp}^{*2}}} \qquad R_{H\theta} \approx \frac{1}{\sqrt{1+\frac{\sigma_{ze}^2+\sigma_{zp}^2}{\sigma_{xe}^2+\sigma_{xp}^2}\tan^2\frac{\theta}{2}}}$$

SuperKEKB LER



KEKB LER



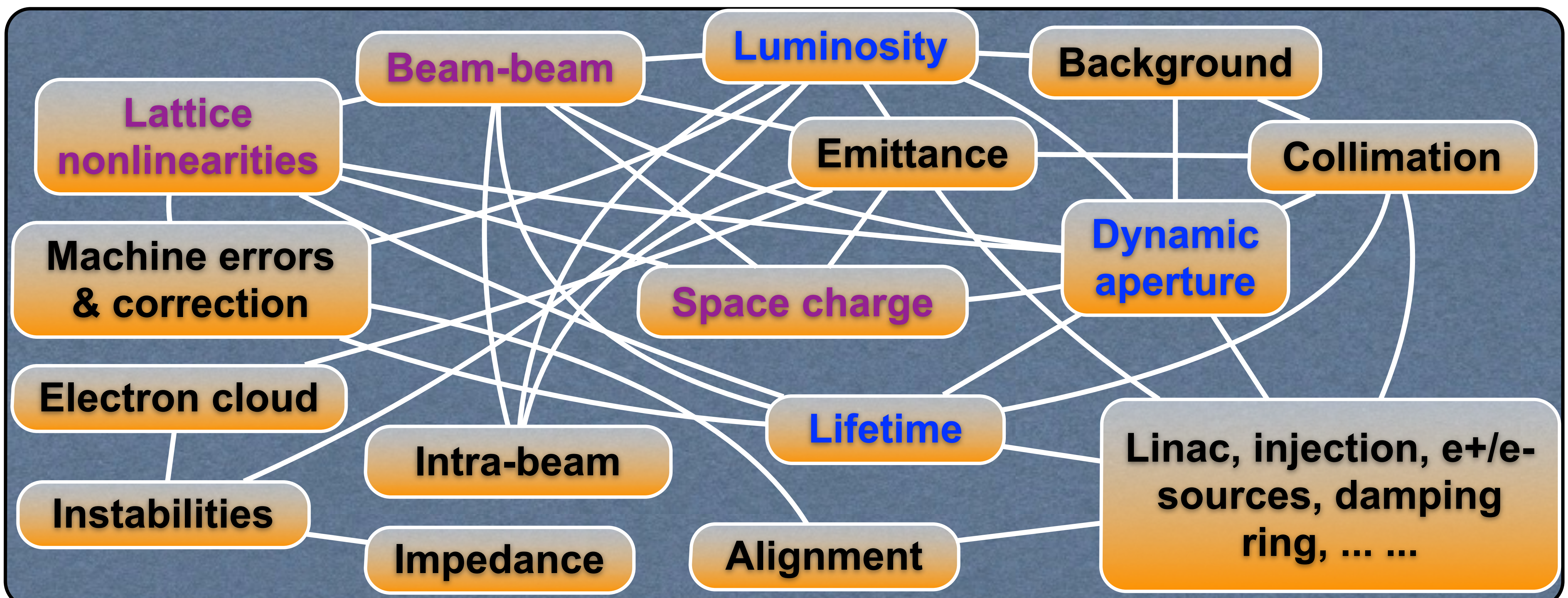
Outline

- Introduction
- Lattice nonlinearity (LN)
- Beam-beam (BB) effects
  - Crab waist (CW)
  - Interplay of BB and LN
- Space charge (SC) effects in LER
  - Interplay of BB, SC and LN
- Impedance issues
- **Summary and Future plan**

6. Summary

➤ **Interplay of various issues**

- Luminosity <= Emittance <= Beam-beam, Lattice nonlinearity, Space charge, Impedances, Electron cloud, Intra-beam scattering, etc.
- => Dynamic aperture and lifetime => Beam commissioning => Injection, Detector back ground, Alignments, etc. => Tolerances for hardwares => …



7. Future plan

➤ **Detailed analysis of lattice nonlinearity under an international collaboration program**

- **Cornell Univ.: D. Sagan (Bmad+PTC)**
- **SLAC: Y. Cai**
- **IHEP: Y. Zhang**
- **KEK: E. Forest, A. Morita, K. Ohmi, Y. Ohnishi, K. Oide, H. Sugimoto, D. Zhou, etc.**

➤ **Collaboration with CEPC and FCC-ee teams**

➤ **High-priority tasks:**

- **Global or local correction schemes for latt. nonlin.**
- **SC compensation schemes**
- **Better understand the interplay of BB and LN**
- **More careful study for crab waist scheme**
- **… …**

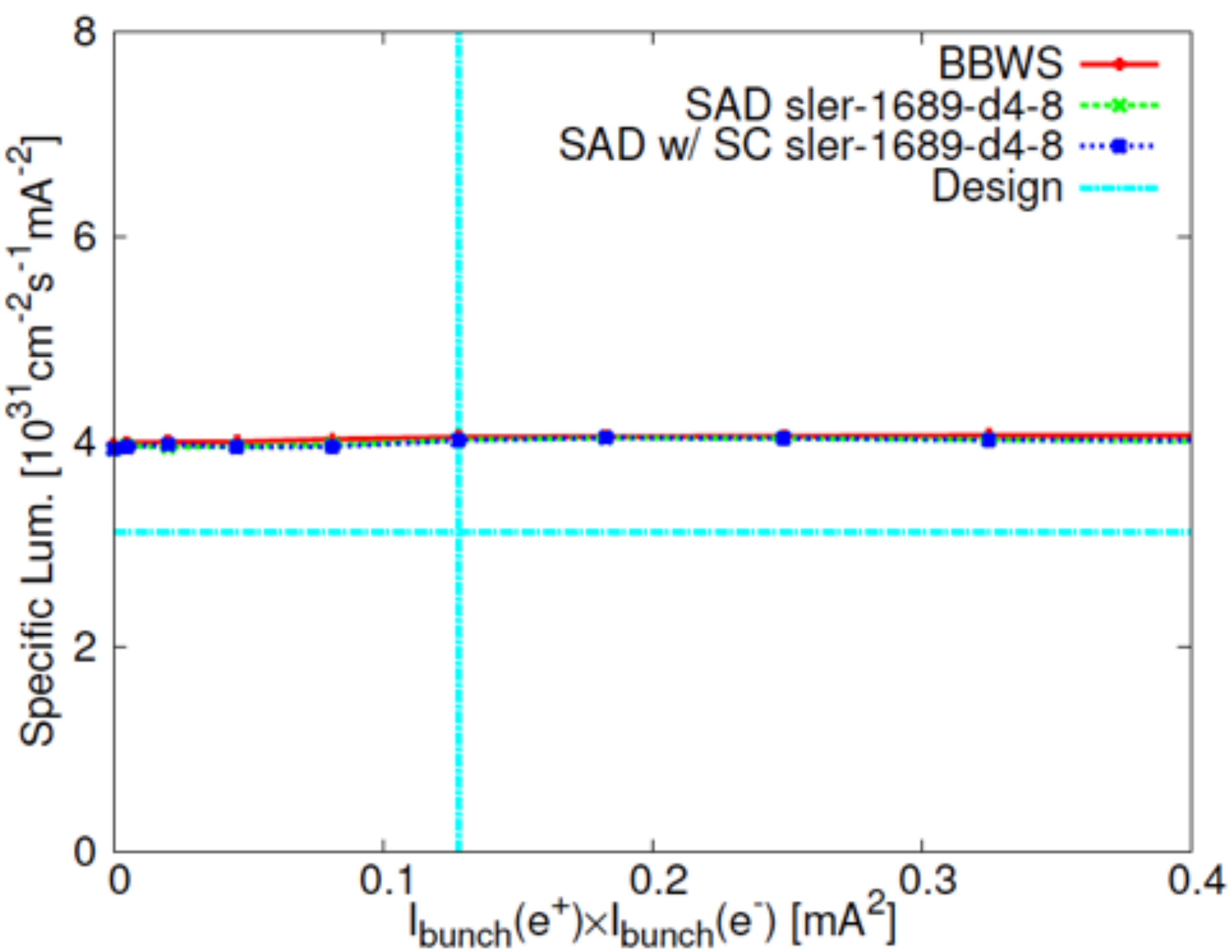
➤ **Recommendations are welcome!**

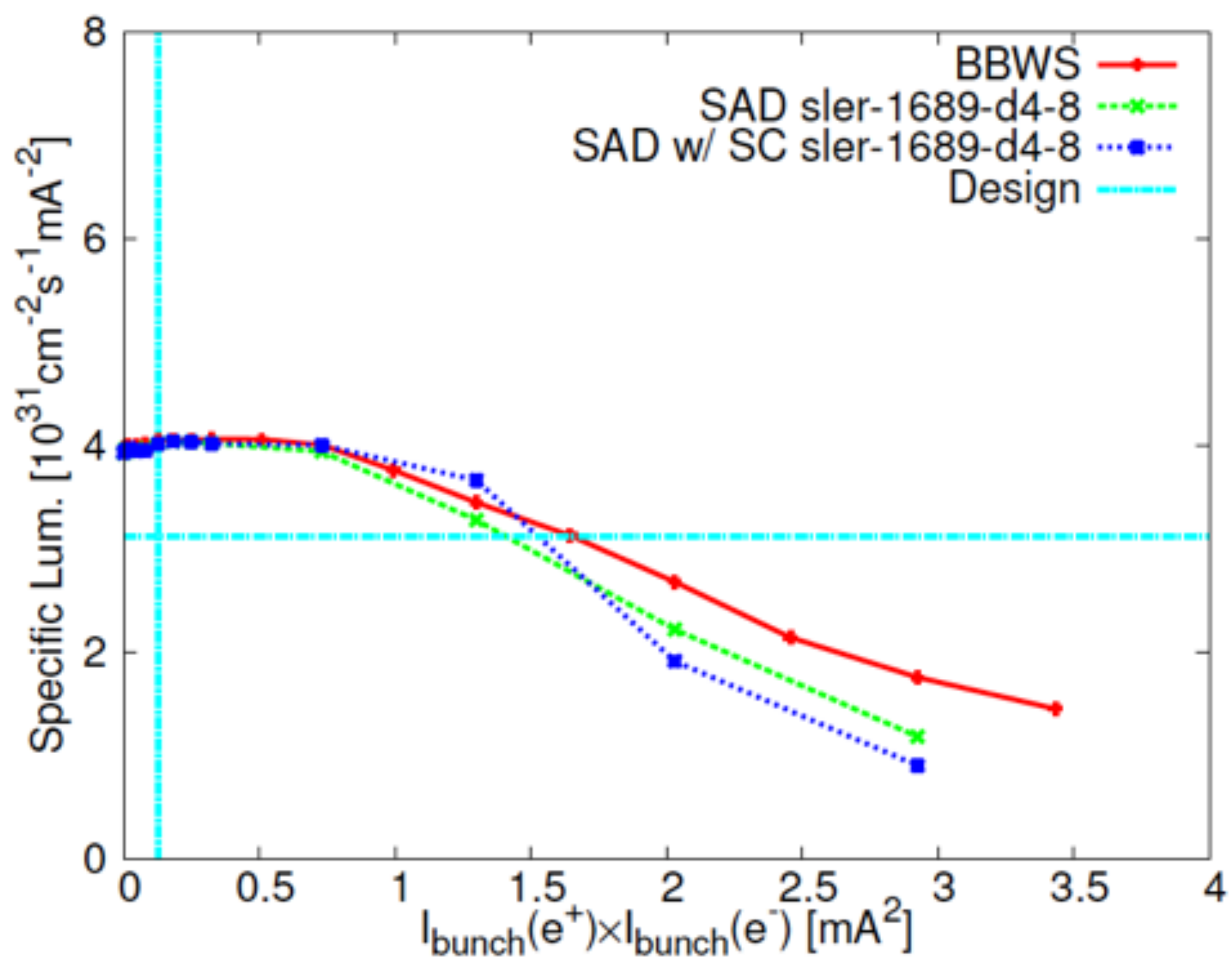
Thanks for your attention!

Backup

Lum. calculation: Detuned lattice

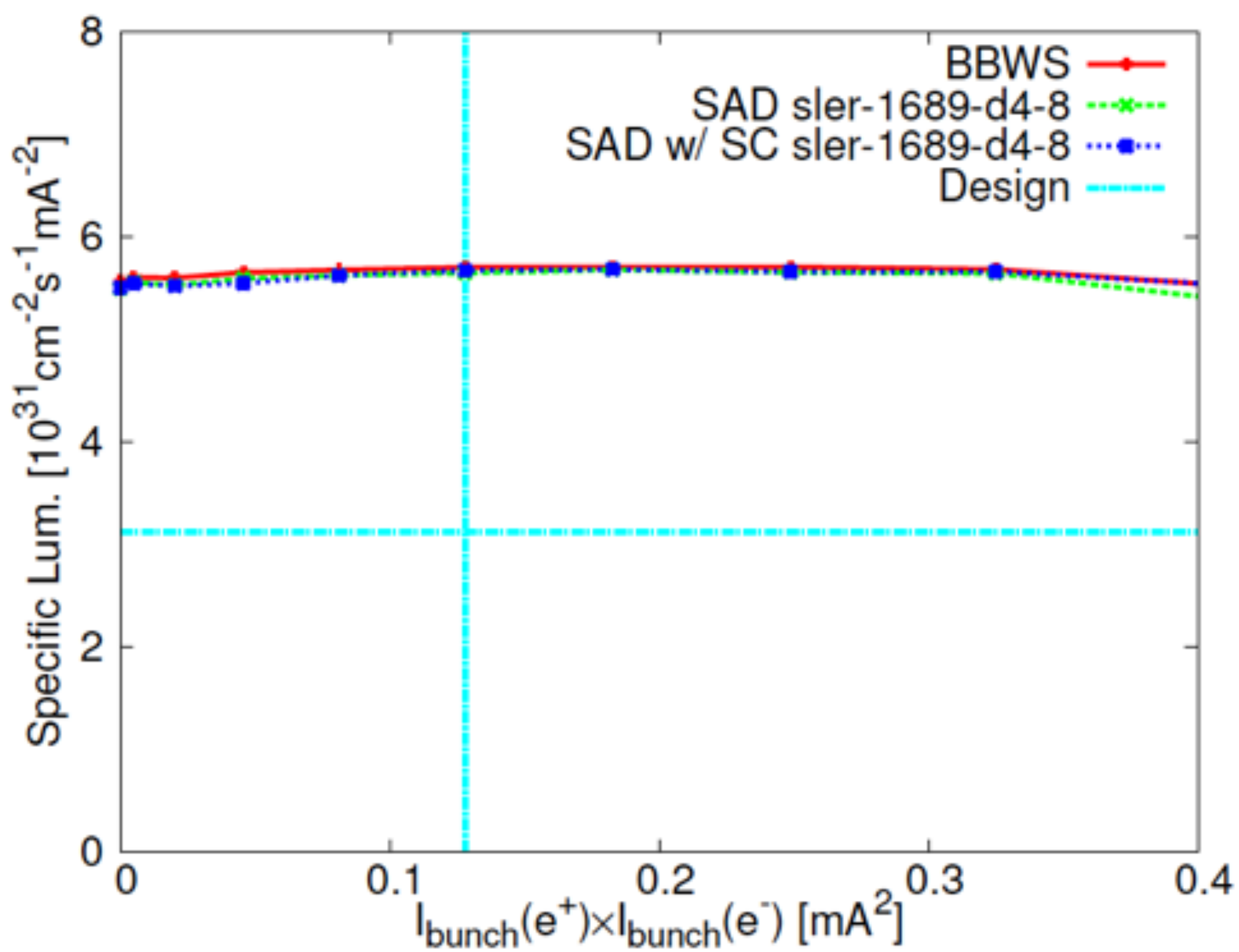
- Assume: ε_x=1.75nm, coupling = 2%
- Space-charge is not important
- Lattice nonlinearity is not very important
- L=1$\times 10^{34}$cm^{-2}s^{-1} is promising
- L=10$\times 10^{34}$cm^{-2}s^{-1} is possible by increasing beam currents

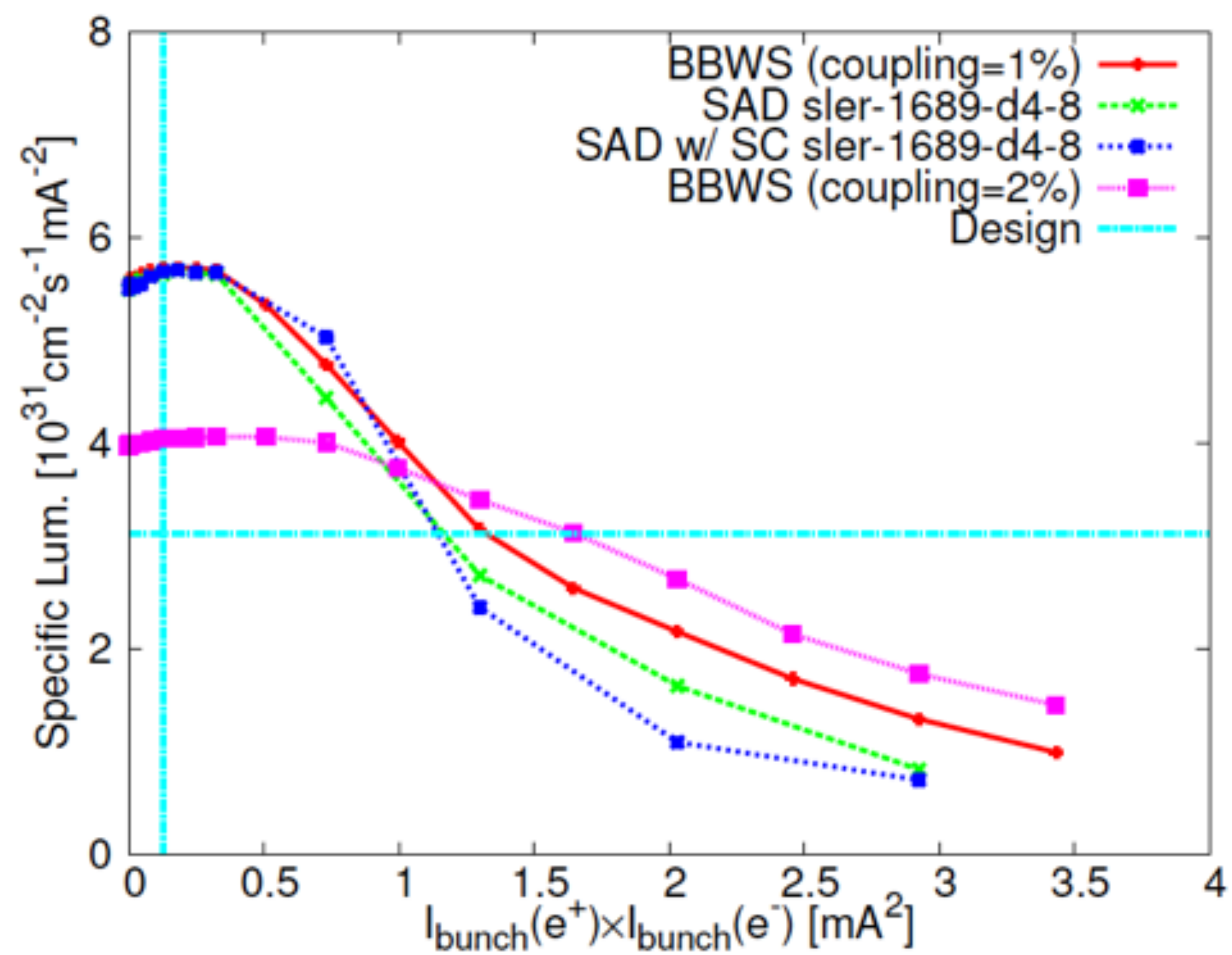




Lum. calculation: Detuned lattice

- Assume: ε_x=1.75nm, coupling = 1%
- Space-charge is not important at low currents
- Lattice nonlinearity is not very important
- Decreasing coupling => Lum. gain but beam-beam limit appears at lower beam currents

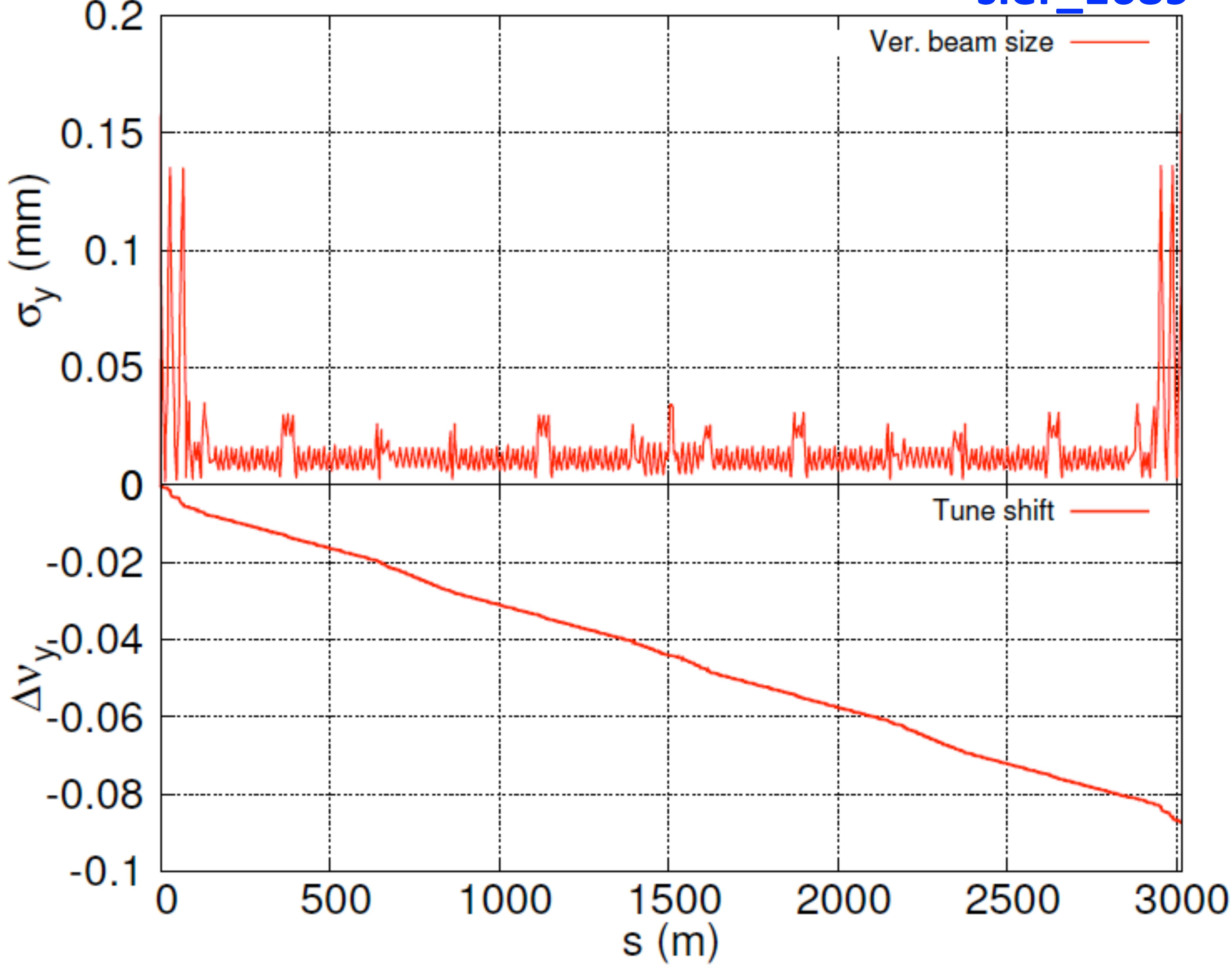




Space charge: LER: Tune shift

➤ **Linear SC tune shift along the ring**

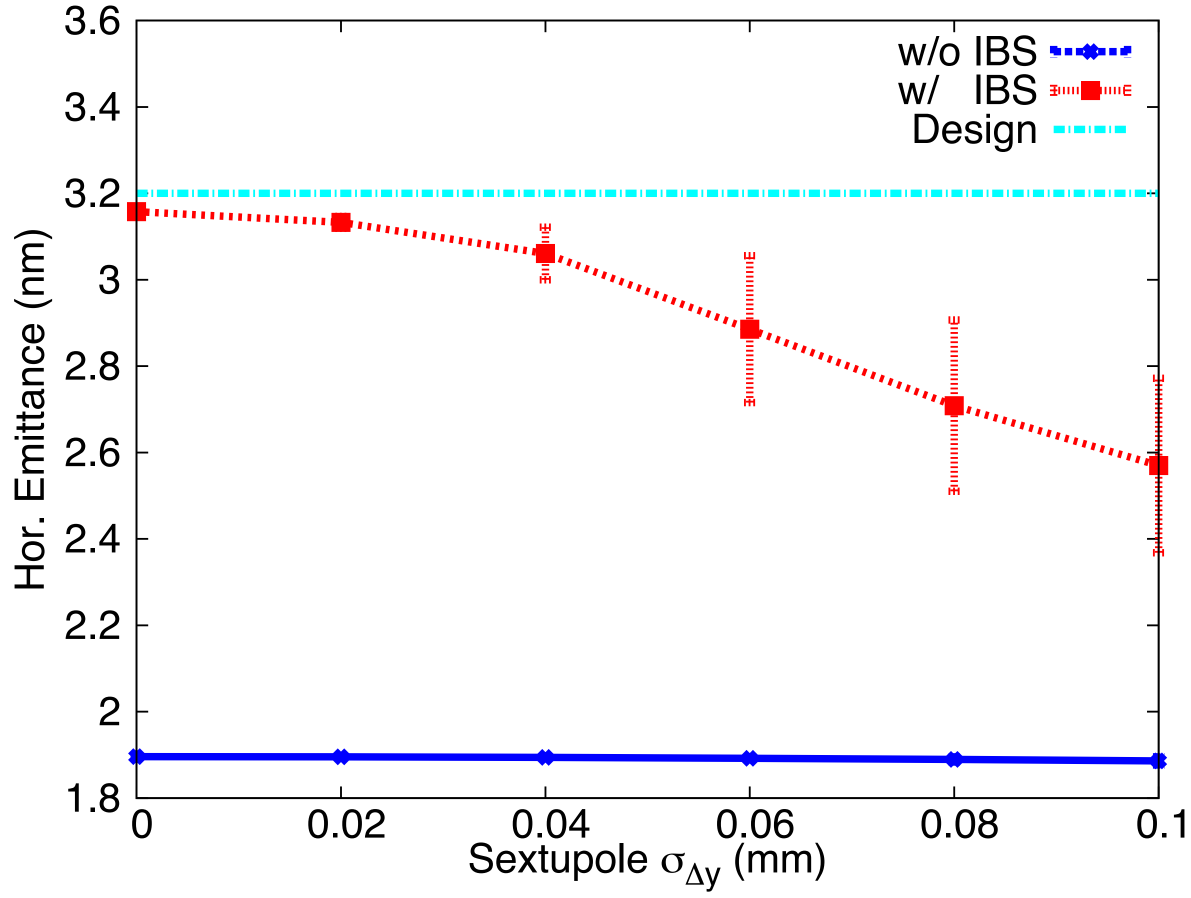
sler_1689

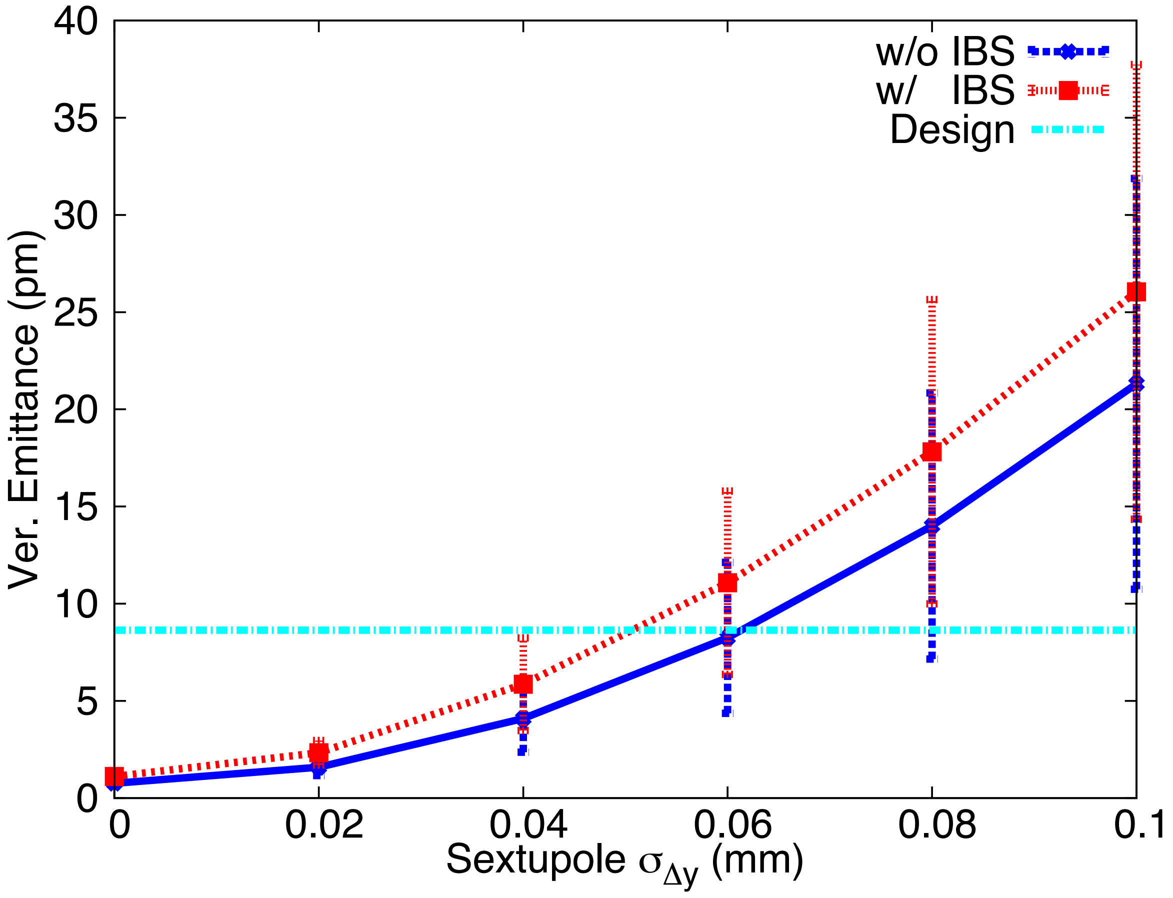


Intra-beam scattering: LER: SAD simulation

➤ **Emittance growth due to IBS (w/ errors in sext.)**

- **ε_x decrease with increasing errors in sext.**
- **Tolerance: $\sigma_{\Delta y}$ < 0.06 mm w/o IBS, $\sigma_{\Delta y}$ < 0.05 mm w/ IBS**

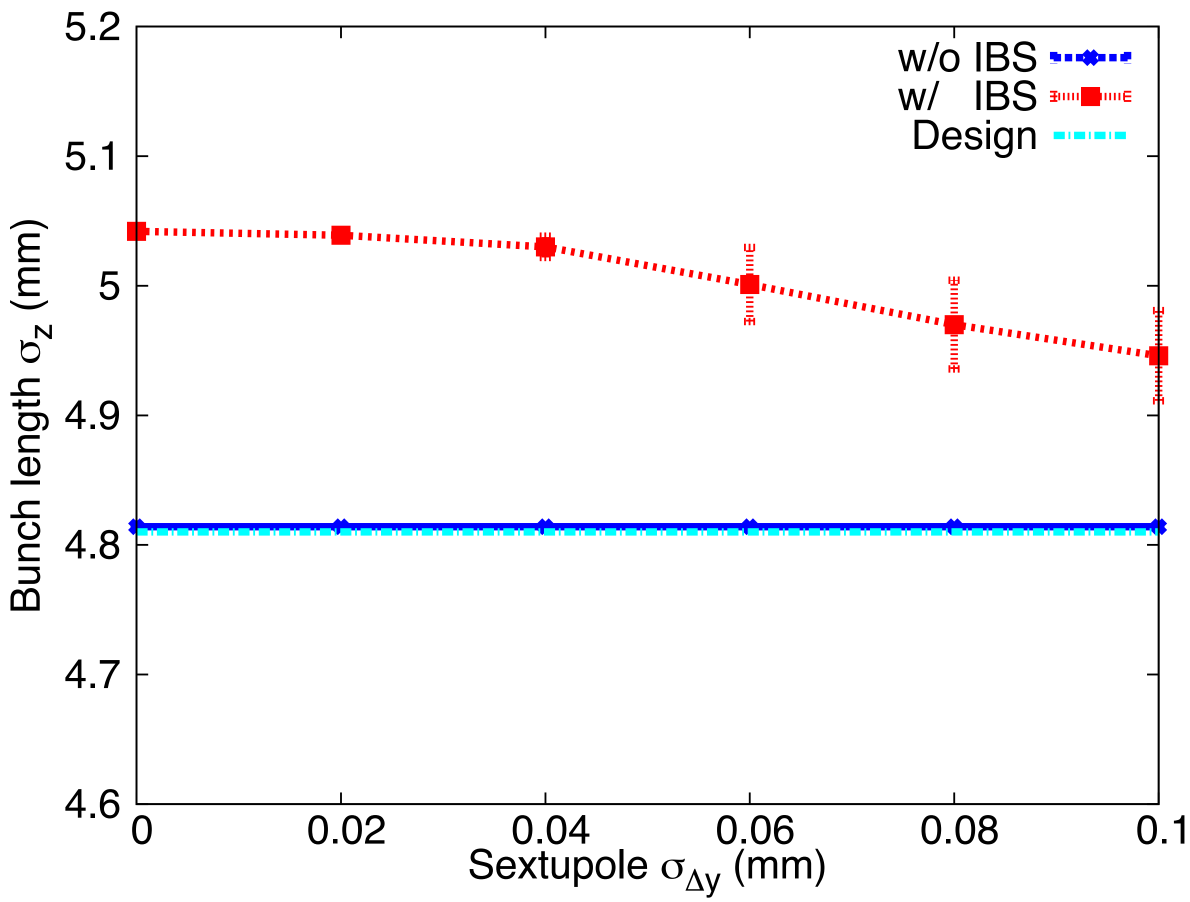


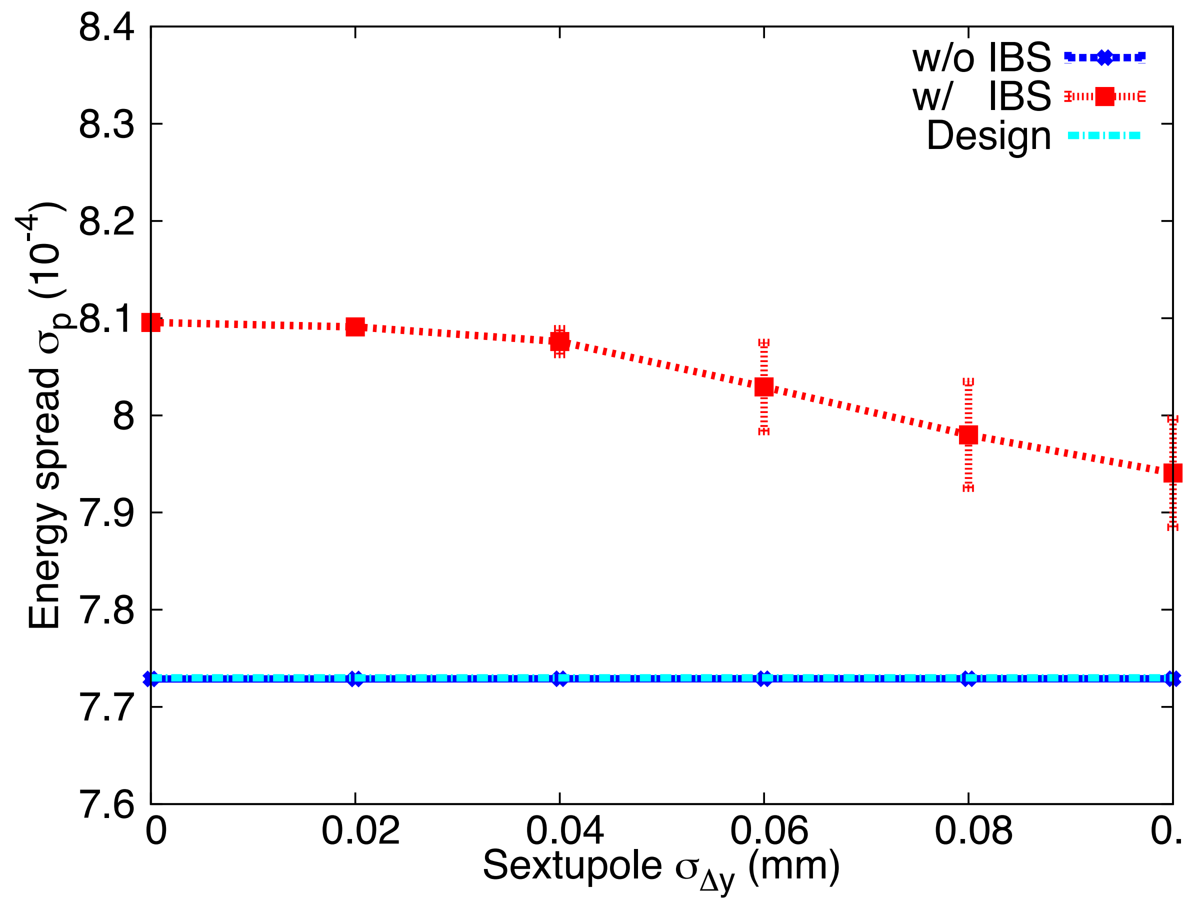


Intra-beam scattering: LER: SAD simulation

➤ **Bunch lengthening and energy spread increase due to IBS (w/ errors in sext.)**

- **Both σ_z and σ_z slightly increase due to IBS**
- **Not negligible in LER**





Bellows

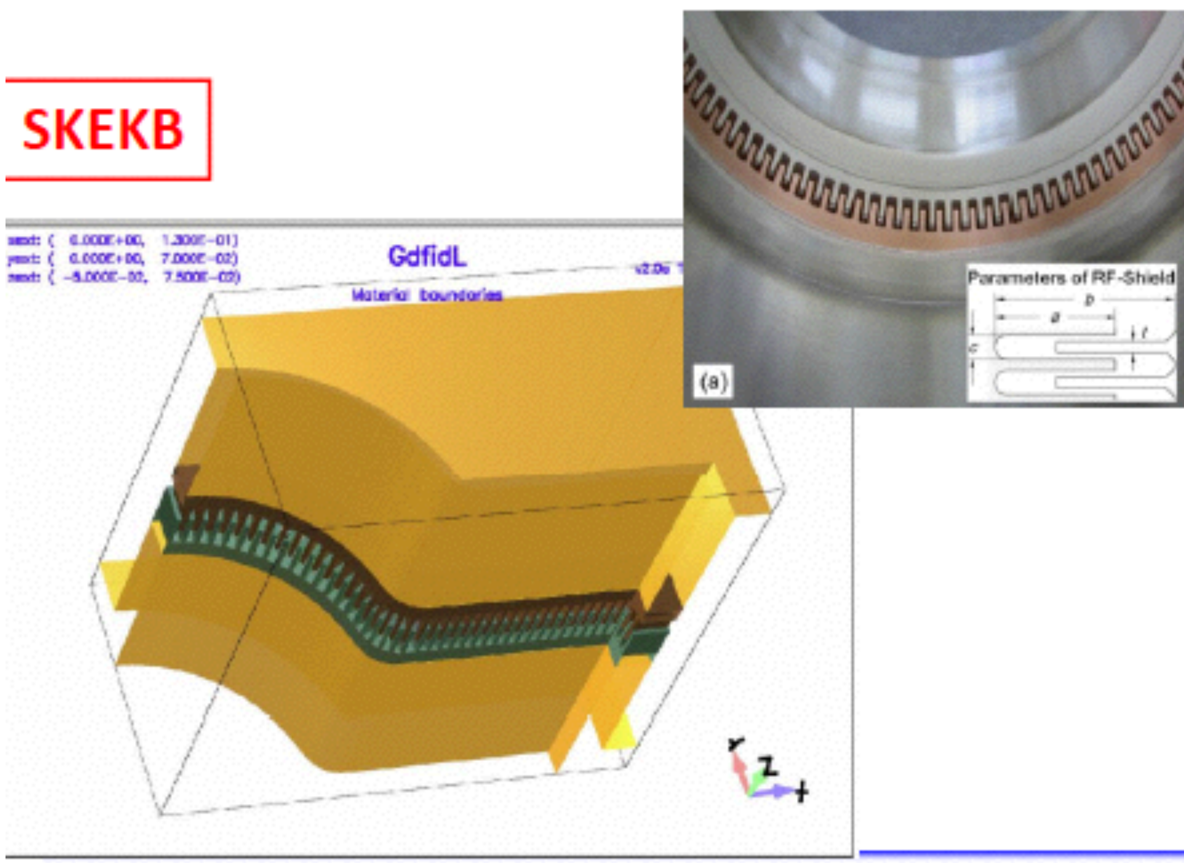
- Bellows chamber with comb-type RF shield will be used in SKEKB.
  - There is no radial step on the inner surface.

    (There is a small step (~1 mm) in a conventional bellows chamber.)
  - RF is shielded by nested comb teeth.

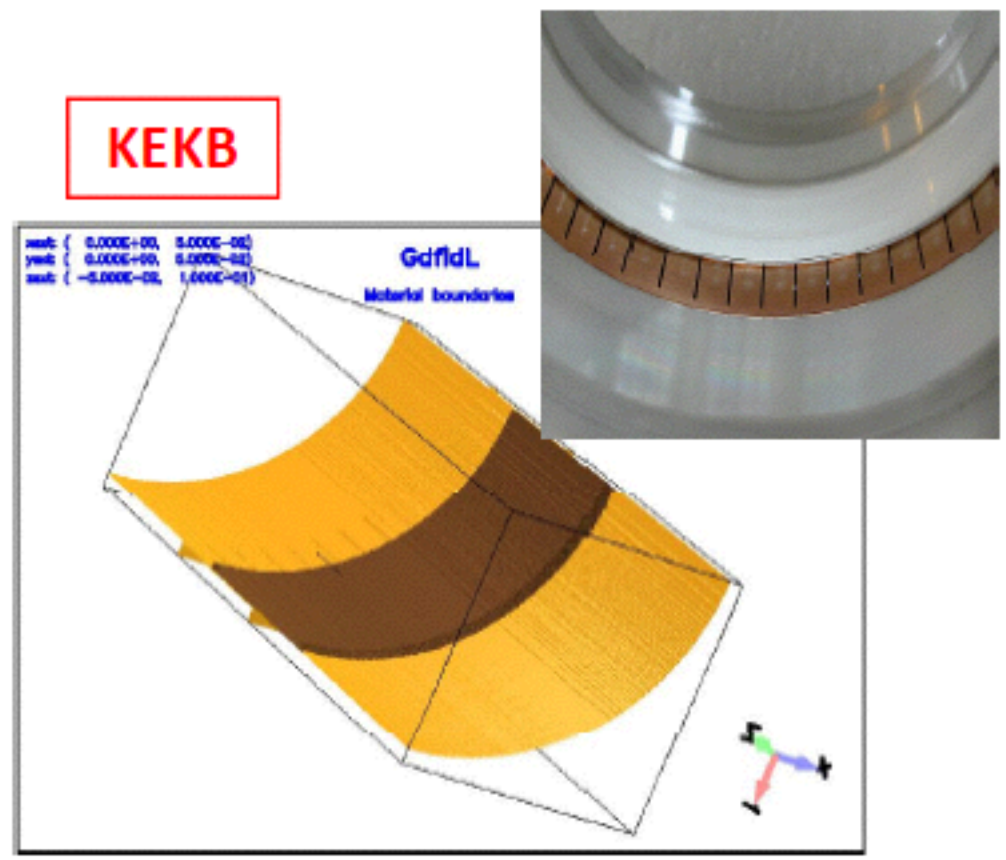
    length : 10 mm

    radial thickness : 10 mm

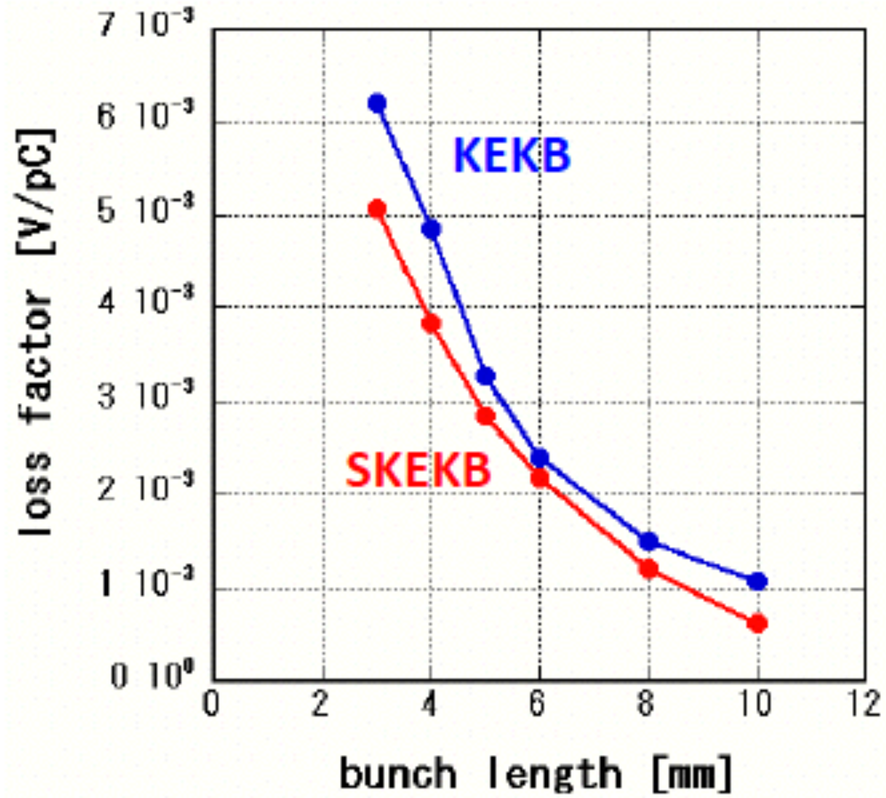
SKEKB

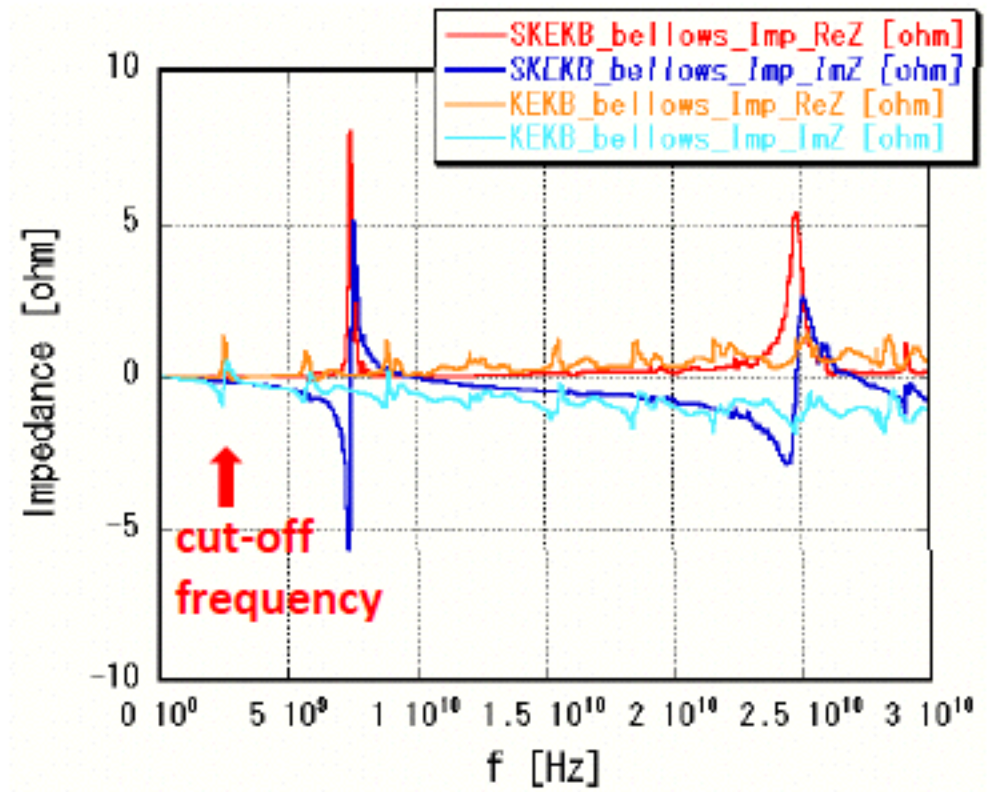


KEKB



Bellows





- Loss factor (σ_z = 6 mm)

  $k = 2.2\times10^{-3}$ V/pC

  ⇩ 1000 pieces in one ring

  ***k*_total = 2.2 V/pC**

- Impedance

  It was found that there are trapped modes at 7.5 GHz and 25 GHz (over cut-off frequency (2.5GHz)).

  Effects of these trapped modes on the beams will be investigated.

- TMCI in LER (pointed out in last KEKB Review)
  - We estimated the threshold of the Transverse Mode Coupling Instability using actual β value at location of each collimator with σ_z = 6 mm.
  - D02V1 is the main impedance source because it would be used with the narrow aperture (d = ±2 mm).
  - The threshold is about 1.71 mA/bunch (Design value: 1.44 mA/bunch) in the latest collimator design.

TMC threshold (mA/bunch)

	All Closed	Actual apertures		Bunch current (design)
Horizontal	1.41	13.15	>	1.44 mA/bunch
Vertical	1.32	1.71		

$$I_{thresh} = \frac{C_1 f_s E/e}{\sum_i \beta_i \kappa_{\perp i}(\sigma_z)}$$

C_1 : constant ≈8
f_s : synchrotron frequency
E : beam energy
β : beta function
$k_\perp$: kick factor

Collimator Aperture List (mm)

D06H1	-16.0/+17.0	D03H1	-21.0/+20.0	D02H1	-10.6/+12.0
D06H2	-16.0/+16.0	D03H2	-18.0/+20.0	D02H2	-16.0/+20.0
D06H3	-16.0/+15.0	D03V1	-9.0/+9.0	D02H3	-18.0/+21.0
D06H4	-13.0/+13.0	D03V2	-9.0/+9.0	D02H4	-13.0/+9.0
				D02V1	-2.0/+2.0