Interplay of Beam-beam, Lattice Nonlinearity, and Space Charge Effects in the SuperKEKB Collider

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Outline

- Introduction
- Beam dynamics issues
  - Beam-beam (BB)
  - Lattice nonlinearity (LN)
  - Space charge (SC)
- Interplay of BB, LN and SC
  - Baseline lattice
  - Detuned lattice
- Mitigation schemes
  - Crab waist (CW)
  - Nonlinear optimization
- Summary and Future plans

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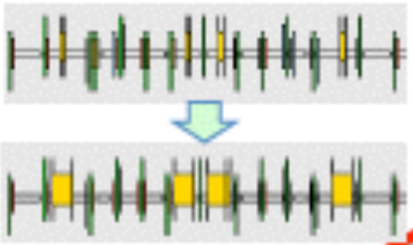
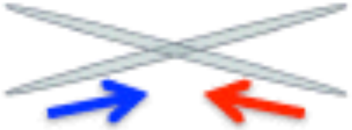
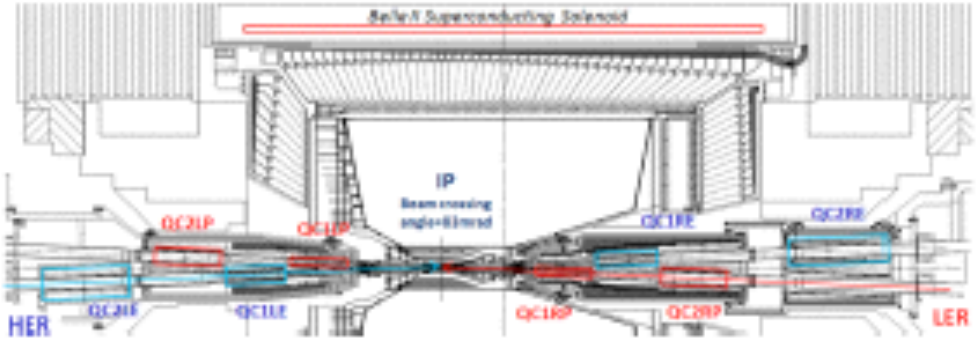
1. Introduction

T. Miura, TUYB1

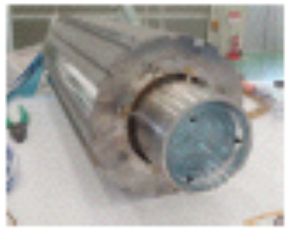
Redesign the lattice to squeeze the emittance (replace short dipoles with longer ones, increase wiggler cycles)

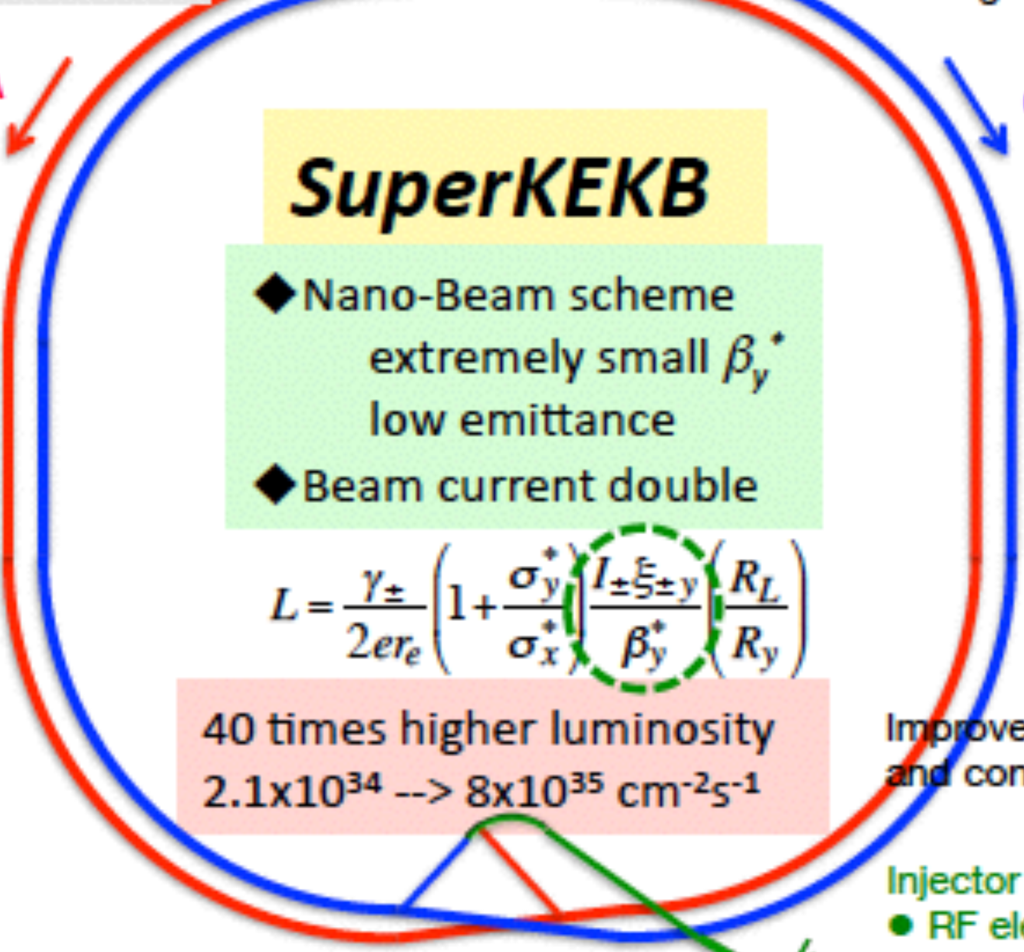



Colliding bunches



New superconducting final focusing magnets near the IP





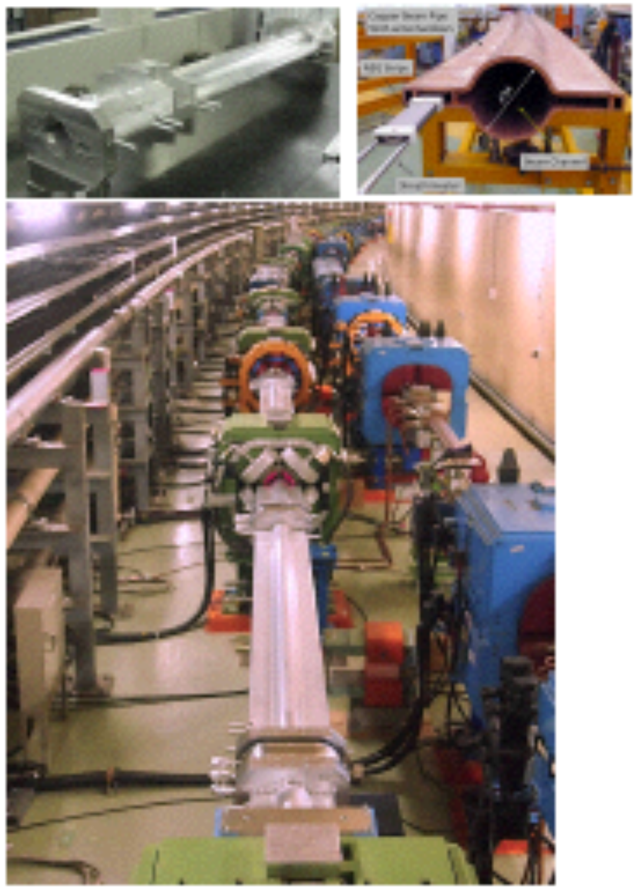
SuperKEKB

- ◆Nano-Beam scheme
  - extremely small β_y^*
  - low emittance
- ◆Beam current double

$$L = \frac{\gamma_\pm}{2er_e}\left(1+\frac{\sigma_y^*}{\sigma_x^*}\right)\left(\frac{I_\pm\xi_{\pm y}}{\beta_y^*}\right)\left(\frac{R_L}{R_y}\right)$$

40 times higher luminosity
2.1×10^{34} --> 8×10^{35} cm^{-2}s^{-1}


Wiggler sections upgrade

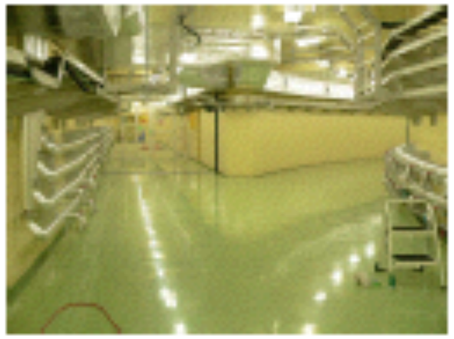

Replace beam pipes with TiN-coated antechamber-type ones

Improve monitors and control system

Injector Linac upgrade
- RF electron gun
- improve e+ source

Injector Linac upgrade

New e+ Damping Ring




Reinforce RF systems for higher beam currents

K. Akai

1. Introduction: Scale SuperKEKB/KEKB

➤ **Luminosity performance of SuperKEKB will be very sensitive to various imperfections/perturbations**

- **Lattice nonlinearity, machine errors, collective effects, etc.**

	LER			HER		
	SKEKB	KEKB*	Factor	SKEKB	KEKB*	Factor
E(GeV)	4	3.5	1.14	7.007	8	0.876
I_b(mA)	1.44	1.03	1.4	1.04	0.75	1.4
ε_x(nm)	3.2	18	0.18	4.6	24	0.19
ε_y(pm)	8.64	180	0.048	12.9	240	0.054
β_x^*(m)	0.032	1.2	0.027	0.025	1.2	0.021
β_y^*(mm)	0.27	5.9	0.046	0.3	5.9	0.051
$\alpha_p(10^{-4})$	3.25	3.31	0.98	4.55	3.43	1.33
$\sigma_\delta(10^{-4})$	8.08	7.73	1.11	6.37	6.3	0.96

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  - Detuned lattice
- Mitigation schemes
  - Crab waist (CW)
  - Nonlinear optimization
- Summary and Future plans

2. Beam dynamics issues: BB

➤ Lum. tune scan for LER by BBWS

- By BBWS (weak-strong) w/o crab waist
- ‘Sweet spot’ close to half-integer
- Isolated islands for working point
- Important BB resonances:

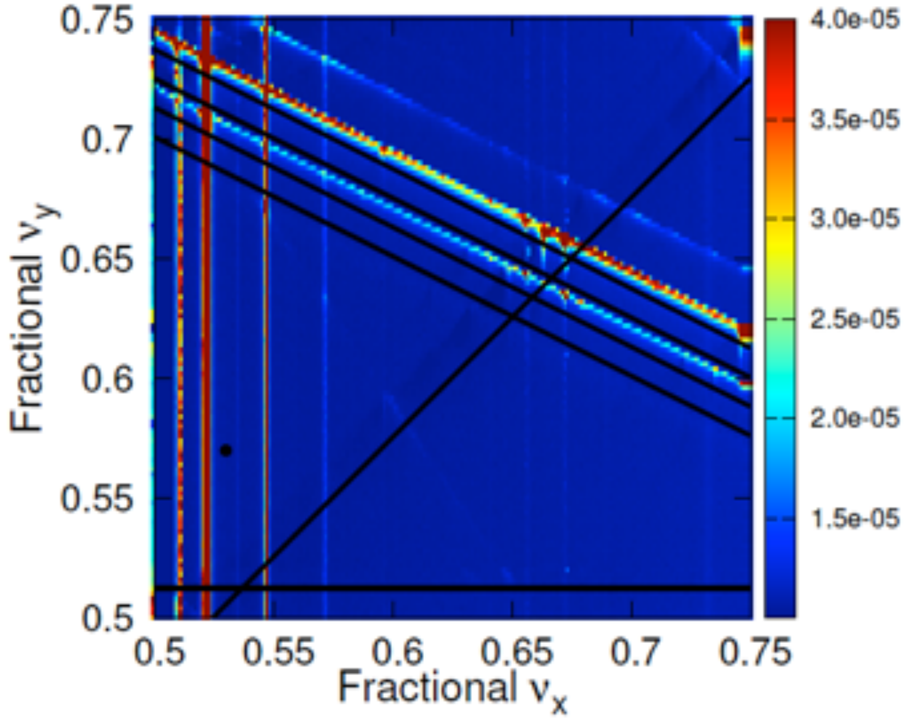
$$2\nu_x - N\nu_s = \text{Integer}$$

$$\nu_x + 2\nu_y + N\nu_s = \text{Integer}$$

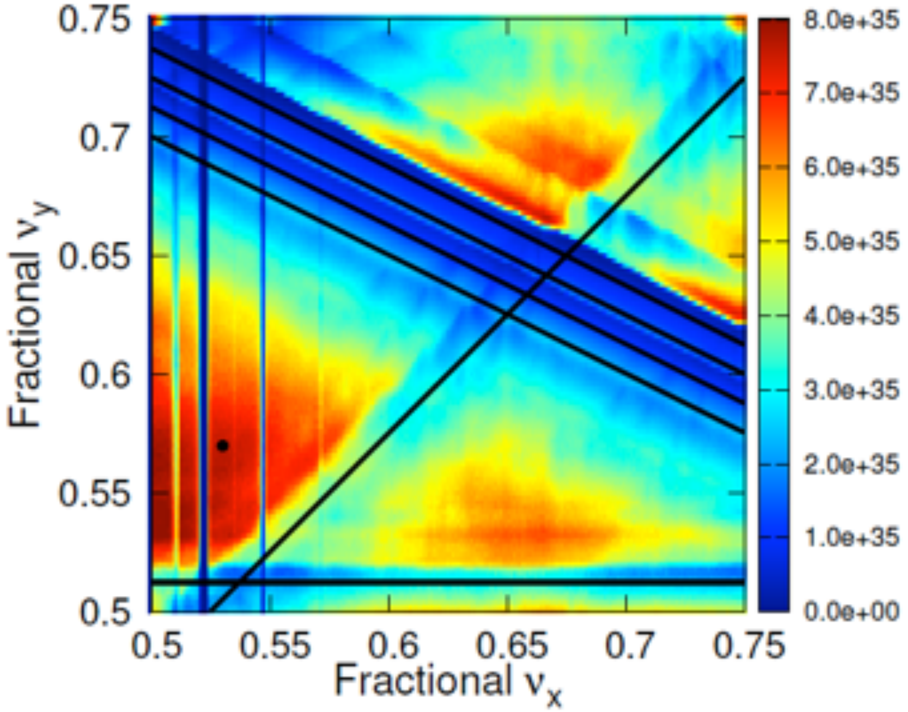
$$\nu_x - \nu_y - \nu_s = \text{Integer}$$

$$2\nu_y - \nu_s = \text{Integer}$$

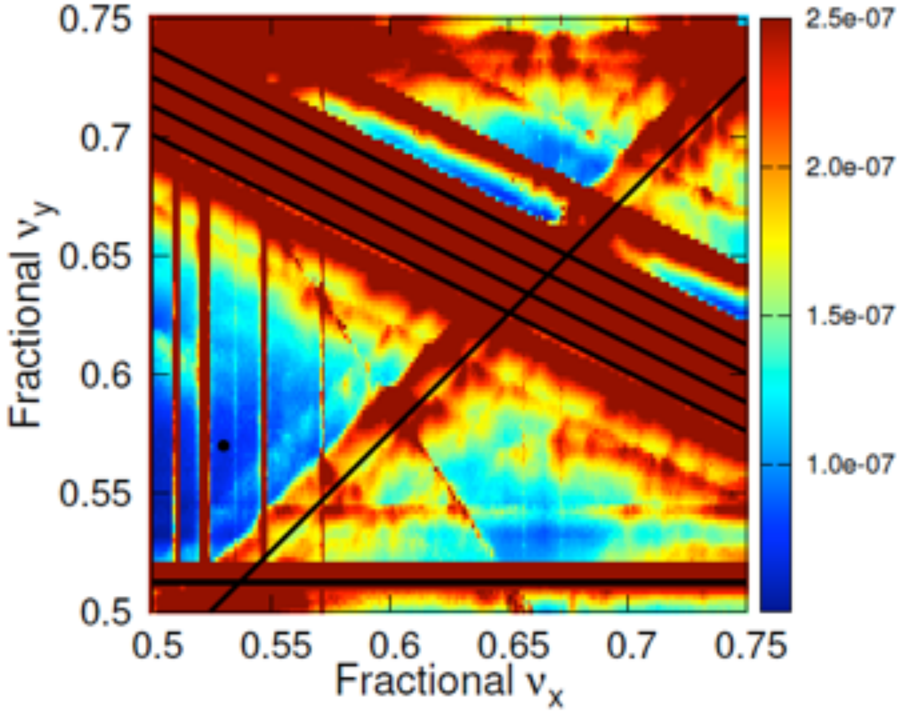
σ_x



$\mathcal{L}$



σ_y

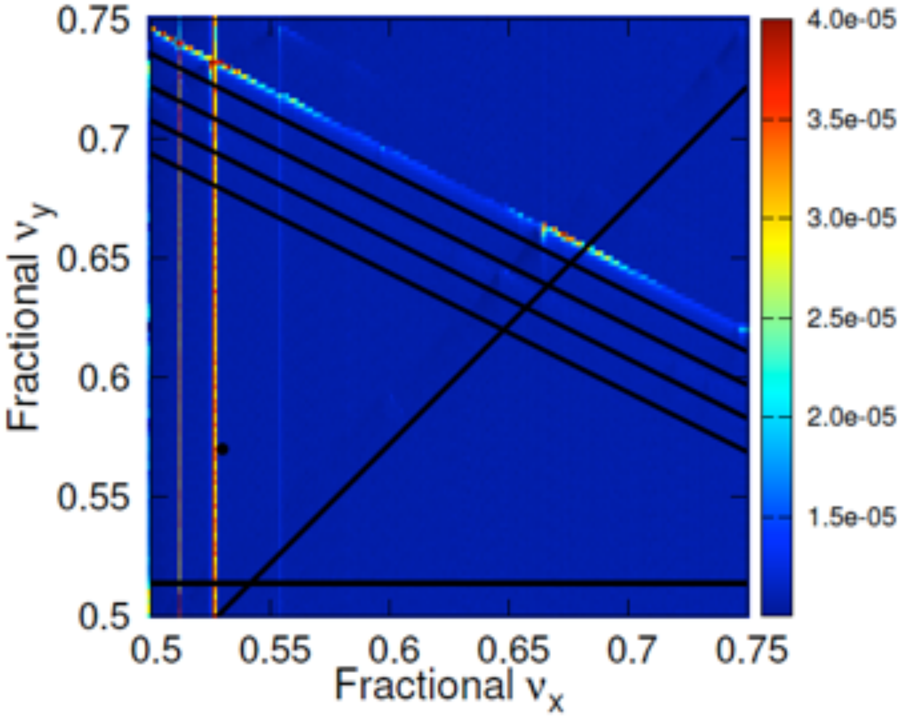


2. Beam dynamics issues: BB

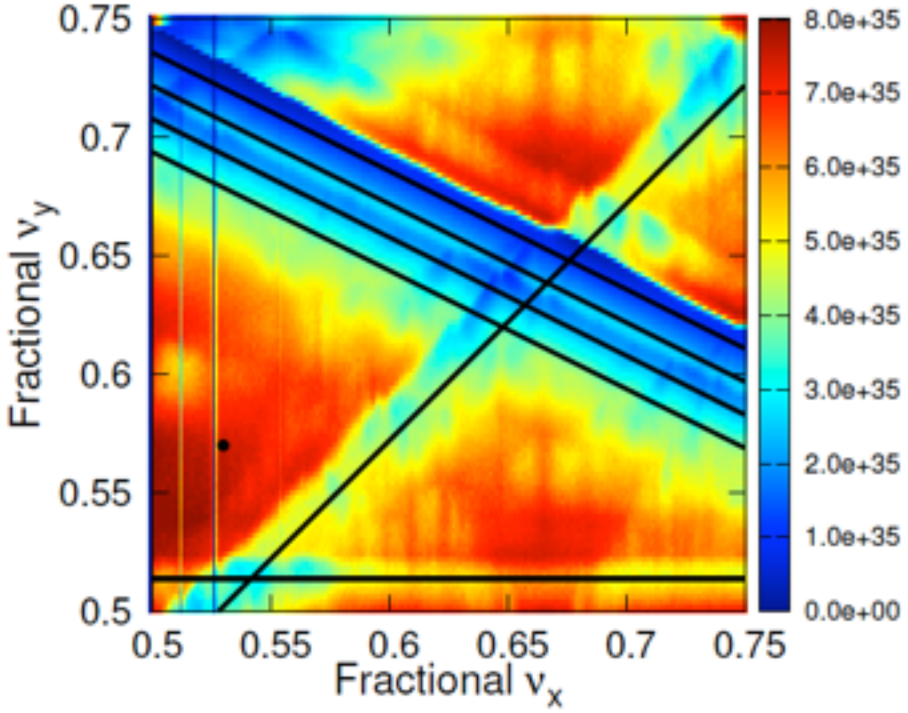
➤ Lum. tune scan for HER

- By BBWS (weak-strong) w/o crab waist
- Better situation for HER
- Island areas shrinks due to machine imperfections

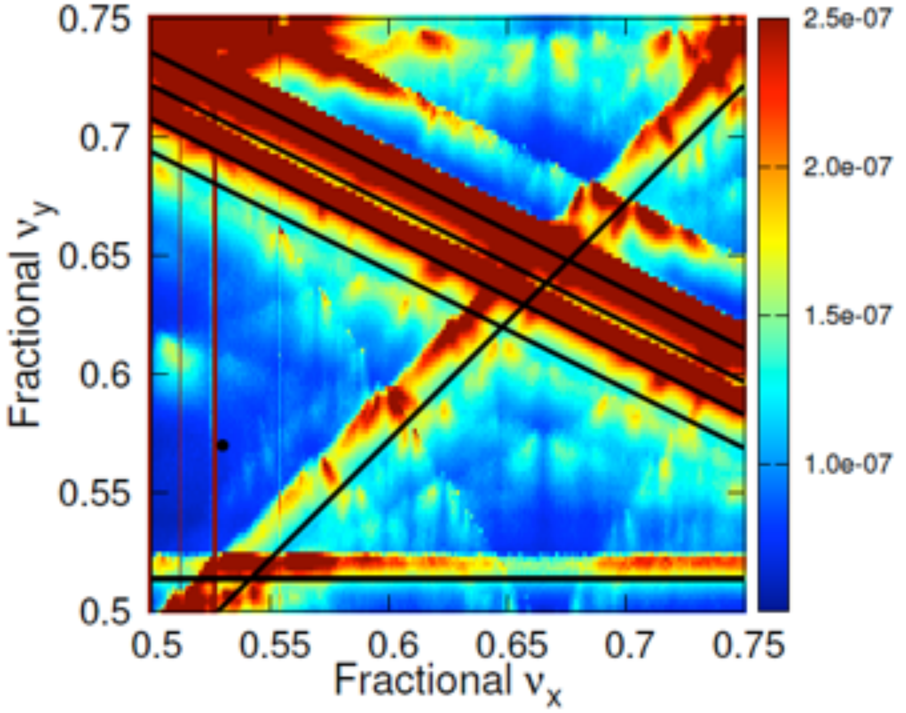
σ_x



$\mathcal{L}$



σ_y



2. Beam dynamics issues: LN

➤ **For SuperKEKB, most of the “intrinsic” LN are attributed to the IR resulting from extremely small $\beta^*_{x,y}$ and low emittances**

- **Nonlinear drift space near IP:**

$$H = 1 + \delta - \sqrt{(1+\delta)^2 - p_x^2 - p_y^2}$$

- **Fringe fields of final focus (FF) quadrupoles**
- **Large crossing angle (θ=0.083) => Deviation of solenoid axis from beam axis => Solenoid fringe fields**
- **Shift of FF quadrupoles downside to compensate dipole term from solenoid fields**
- **Rotation of FF quadrupoles around the beam axis to minimise the vertical dispersions and the X-Y couplings**
- **Chromaticity correction sextupoles**
- **Leakage fields to the HER from LER**

2. Beam dynamics issues: LN

➤ **DA limited by kinematic terms and FF quad. fringes:**

- **K. Oide and H. Koiso, Phys. Rev. E47 (1993)**
  K. Ohmi and H. Koiso, IPAC'10 (2010)

$$J_y \leq \frac{\beta_y^{*2}}{(1+2|K|L^{*3}/3)L^*} A(\mu_y)$$

- **FF quad. fringes of SuperKEKB are very strong and comparable to kinematic terms**
- **β^*_y is the key parameter for DA**

Ring	β_y^* [μm]	$K=k_1$ [m^{-2}]	L^* [m]	J_y/A [μm]
SuperKEKB HER	300	-3.1	1.22	0.018
SuperKEKB LER	270	-5.1	0.76	0.032
CEPC	1200	-0.176	1.5	0.76
TLEP(BINP design)	1000	-0.16	0.7	1.36
KEKB	5900	-1.779	1.762	4.22

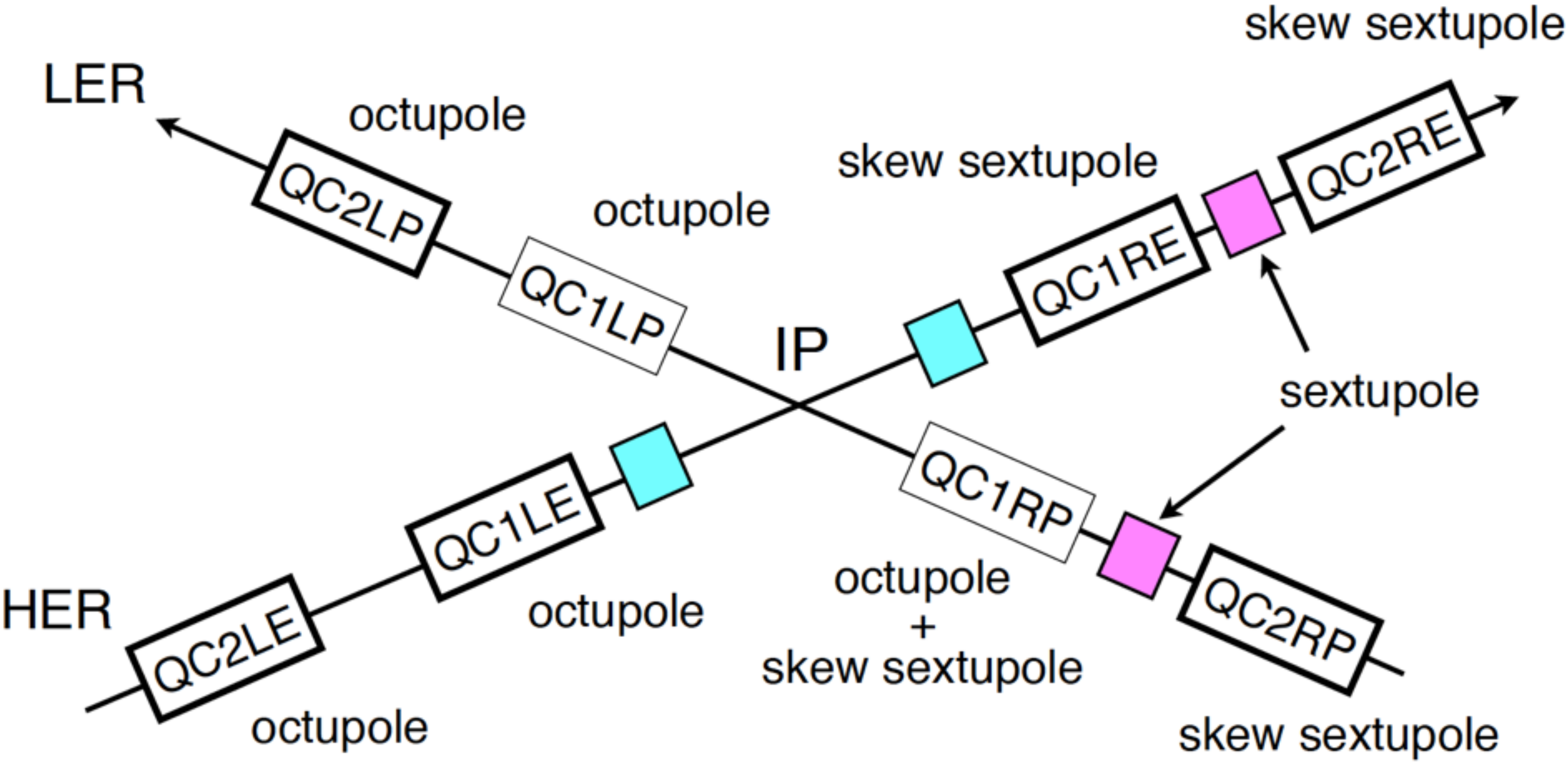
~ 1/20

< 1/100

Y. Ohnishi

2. Beam dynamics issues: LN

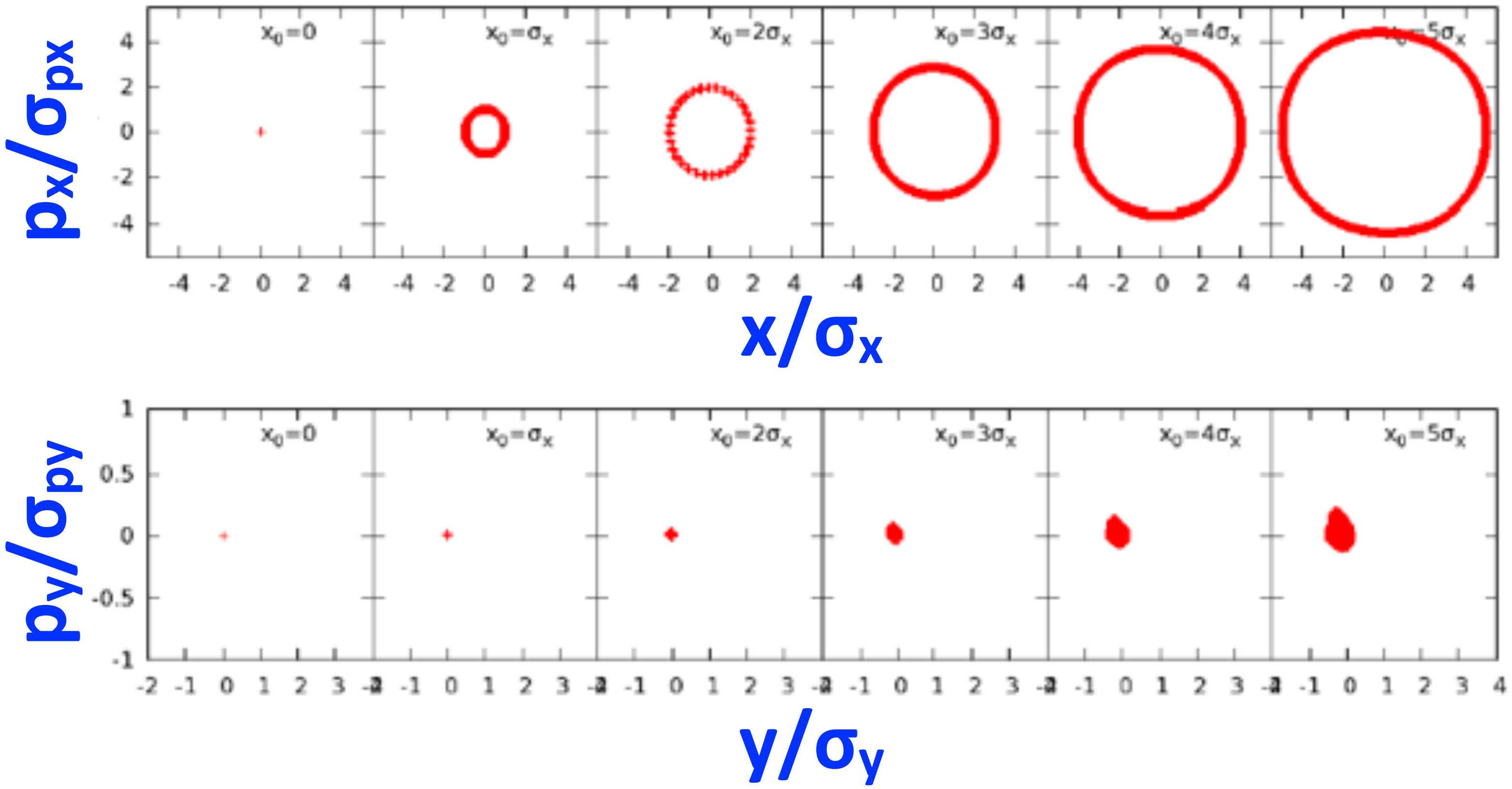
- **High-order correctors added to each SC magnet**
- **IR is not transparent for off-momentum and large-amplitude particles**



Y. Ohnishi

2. Beam dynamics issues: LN

- ➤ **Poincare maps at IP**
- ➤ **Baseline lattice: HER w/ solenoids**
  - Evidence of nonlinear X-Y coupling

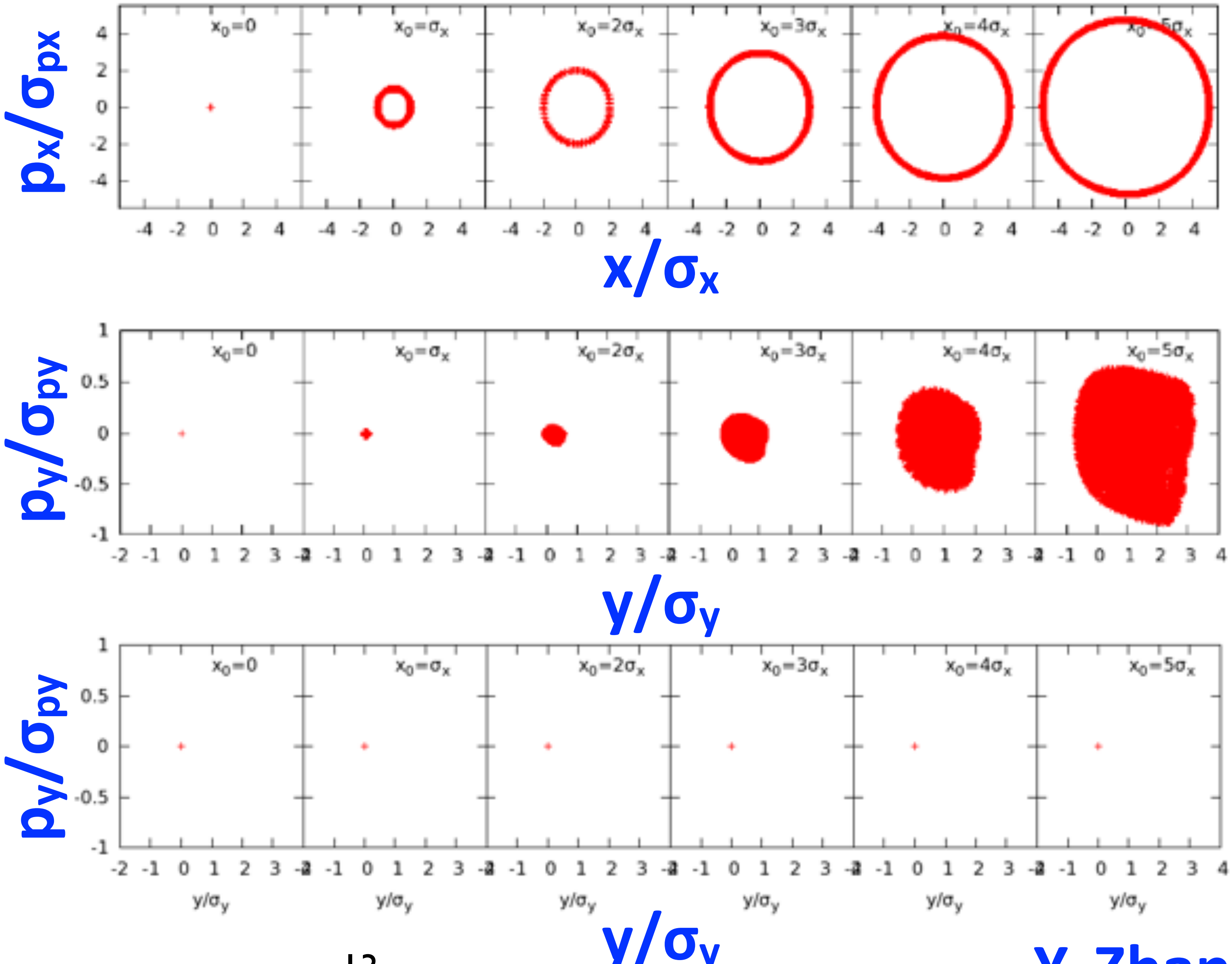


Baseline lattice →

Y. Zhang

2. Beam dynamics issues: LN

- ➤ Poincare maps at IP
- ➤ Baseline lattice: LER w/ solenoids
- ➤ Simplified lattice: LER w/o solenoids, FF magnets simplified: no offset, no rotation, dipole and skew-quad removed



Baseline lattice →

Simplified lattice →

Y. Zhang

2. Beam dynamics issues: SC

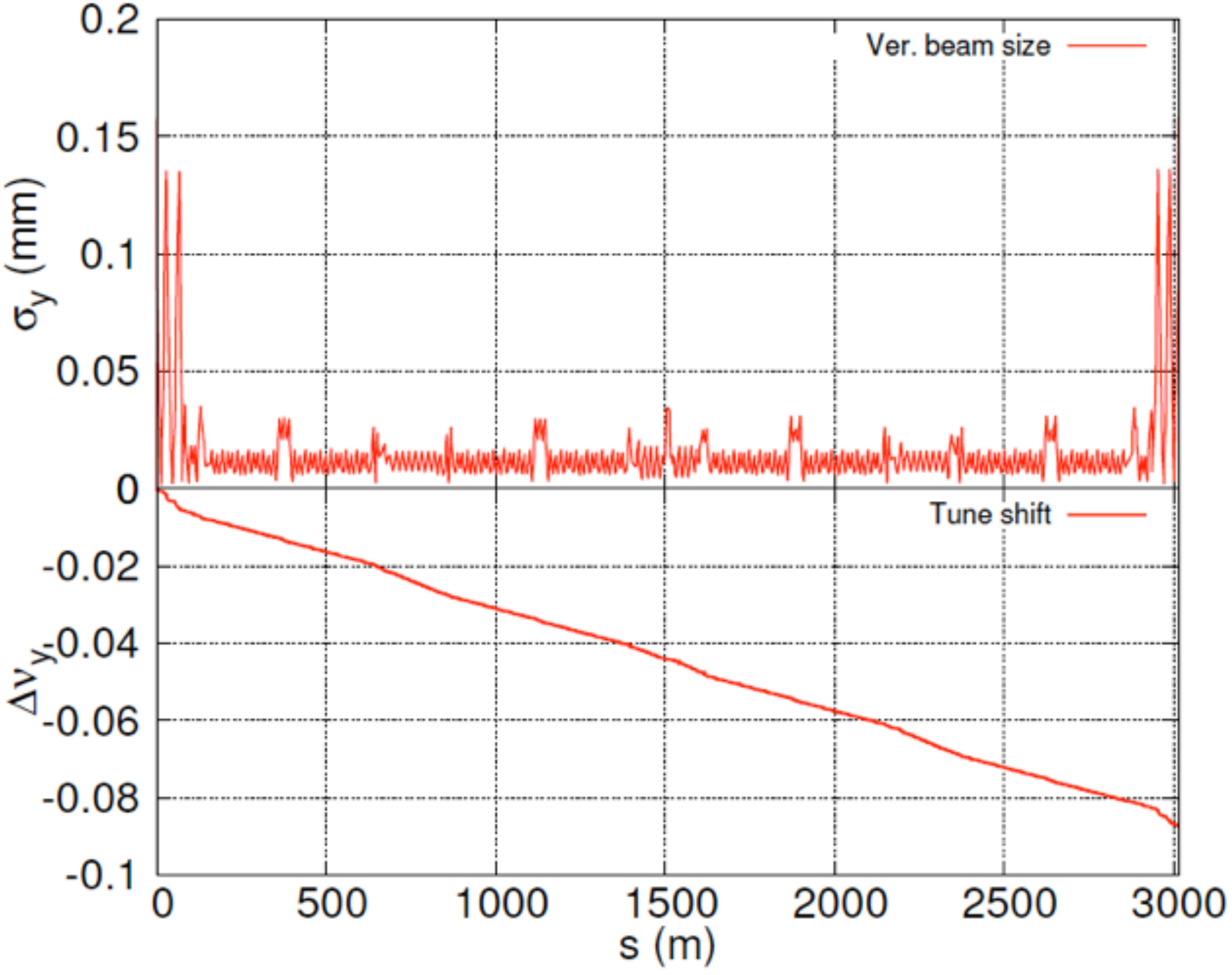
- **Linear tune shift**
  - Same level for SC and BB
  - But have opposite signs

	SuperKEKB		KEKB	
	LER	HER	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	0.088	0.081	0.129	0.09
$\Delta\nu_x$	-0.0027	-0.0004	-0.0005	-3E-05
$\Delta\nu_y$	-0.094	-0.012	-0.0072	-0.0004

2. Beam dynamics issues: SC

➤ **Vertical beam size and tune shift along the ring: LER**

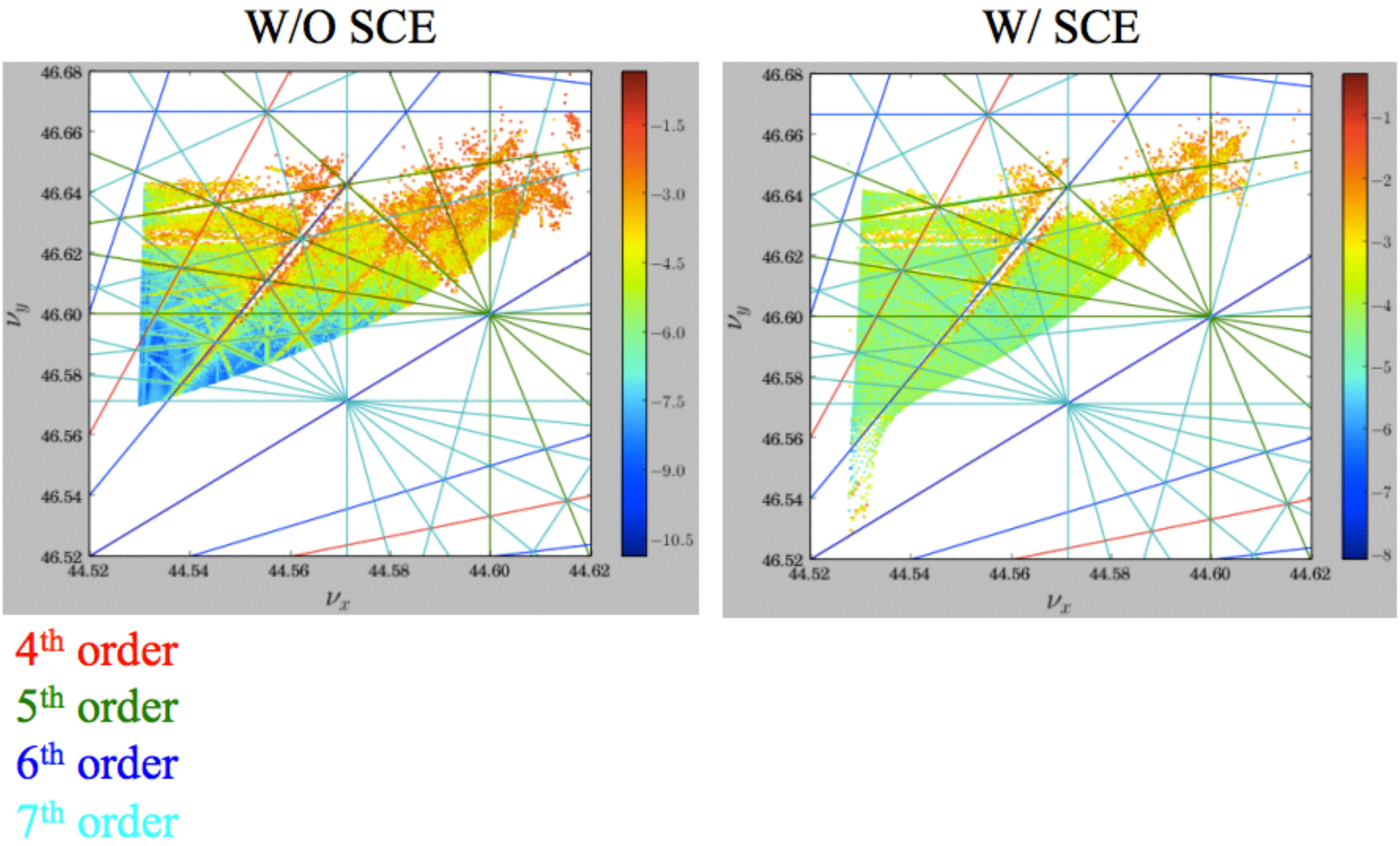
- **Uniform distribution of tune shift**
- **Influence on matching conditions for optics design**



2. Beam dynamics issues: SC

➤ **FMA: SC drives the particles close to half-integer**

- **Weak-strong model for SC**



H. Sugimoto

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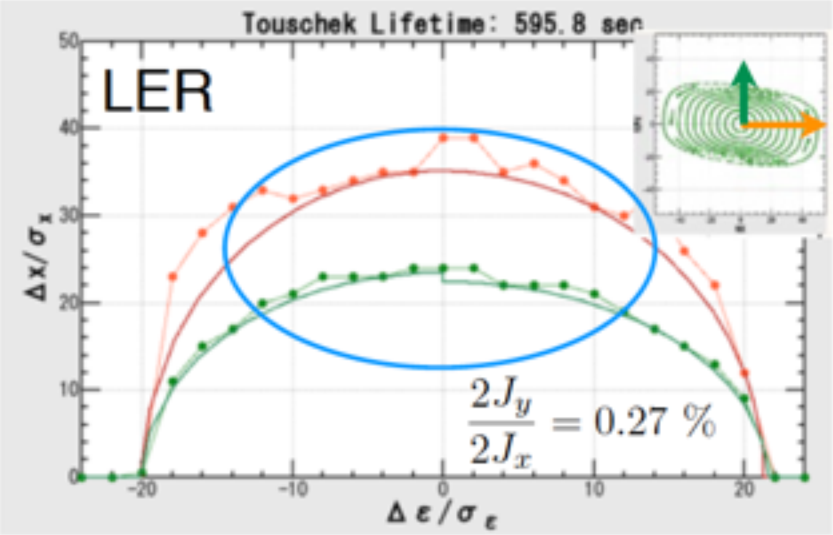
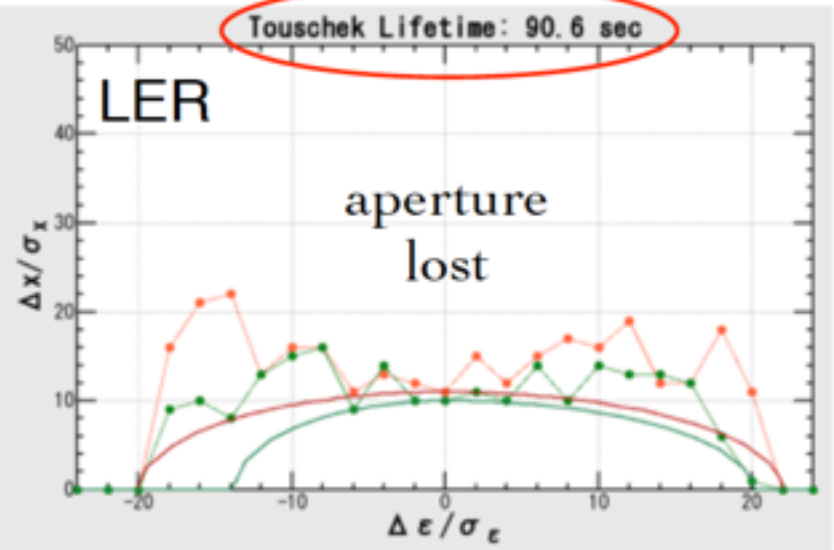
3. Interplay: Baseline lattice: BB+LN

- **DA and lifetime are sensitive to beam-beam interaction**
  - **Target Tousheck lifetime: 600 s for injection**
  - **LER: Significant loss of DA, 600 s => 90 s w/o optics optimization**

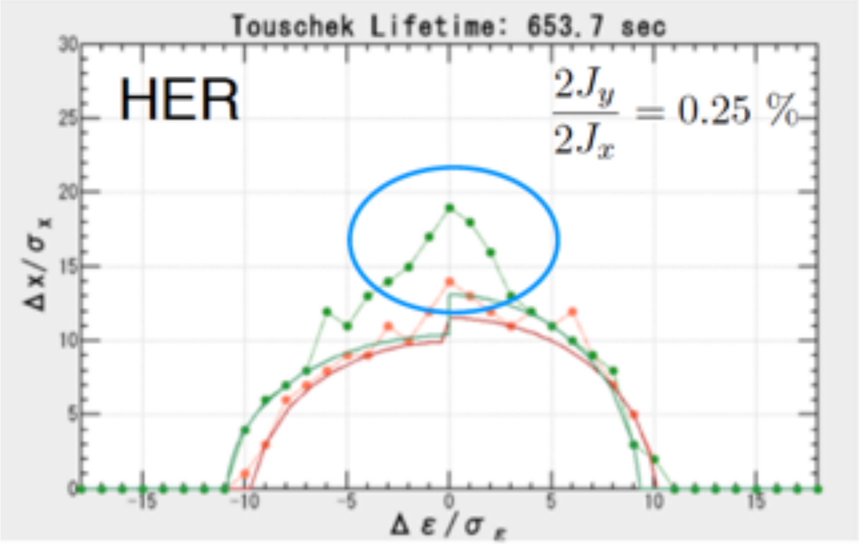
w/o beam-beam

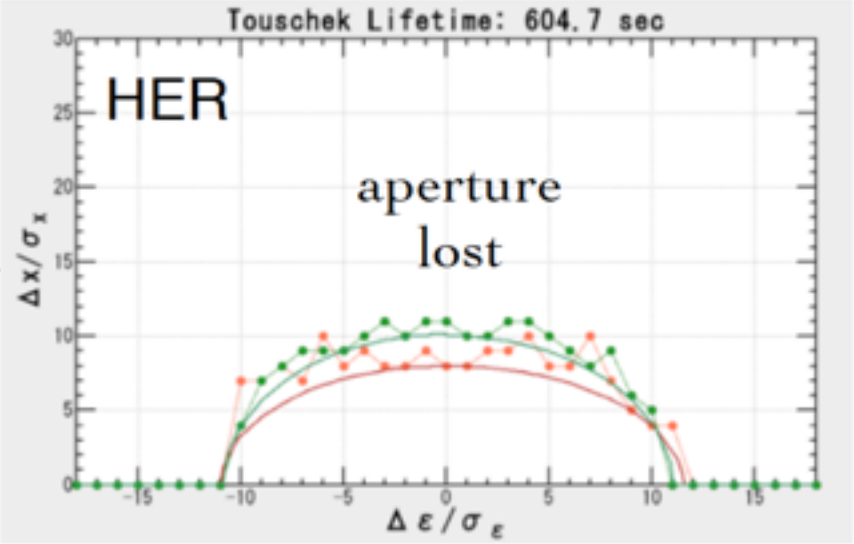
with beam-beam (W-S)





Transverse aperture is reduced significantly.



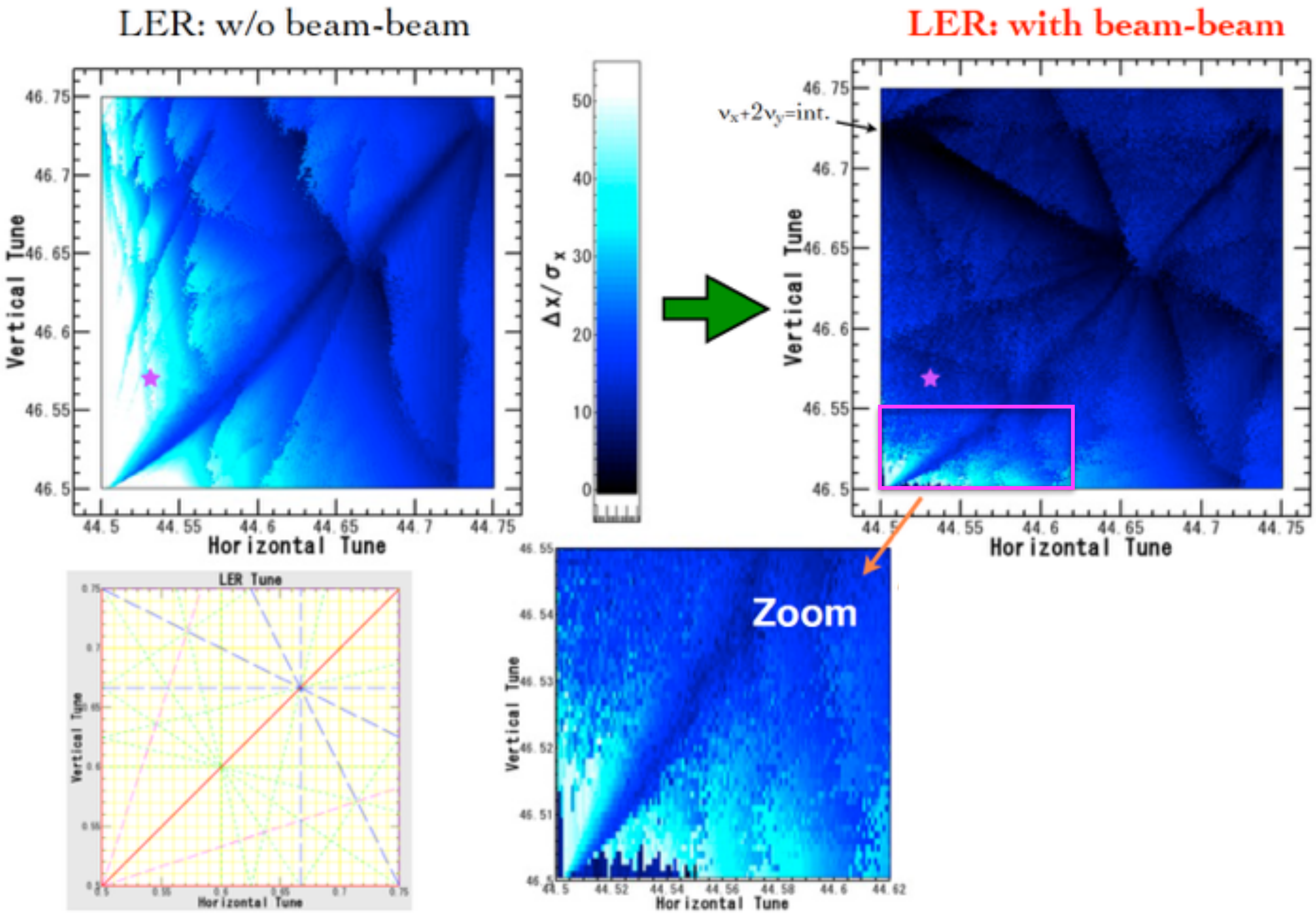


Y. Ohnishi

3. Interplay: Baseline lattice: BB+LN

➤ Tune survey of DA: LER

- Good region near half-integer
- Chromaticity correction is very challenging with tune close to half-integer

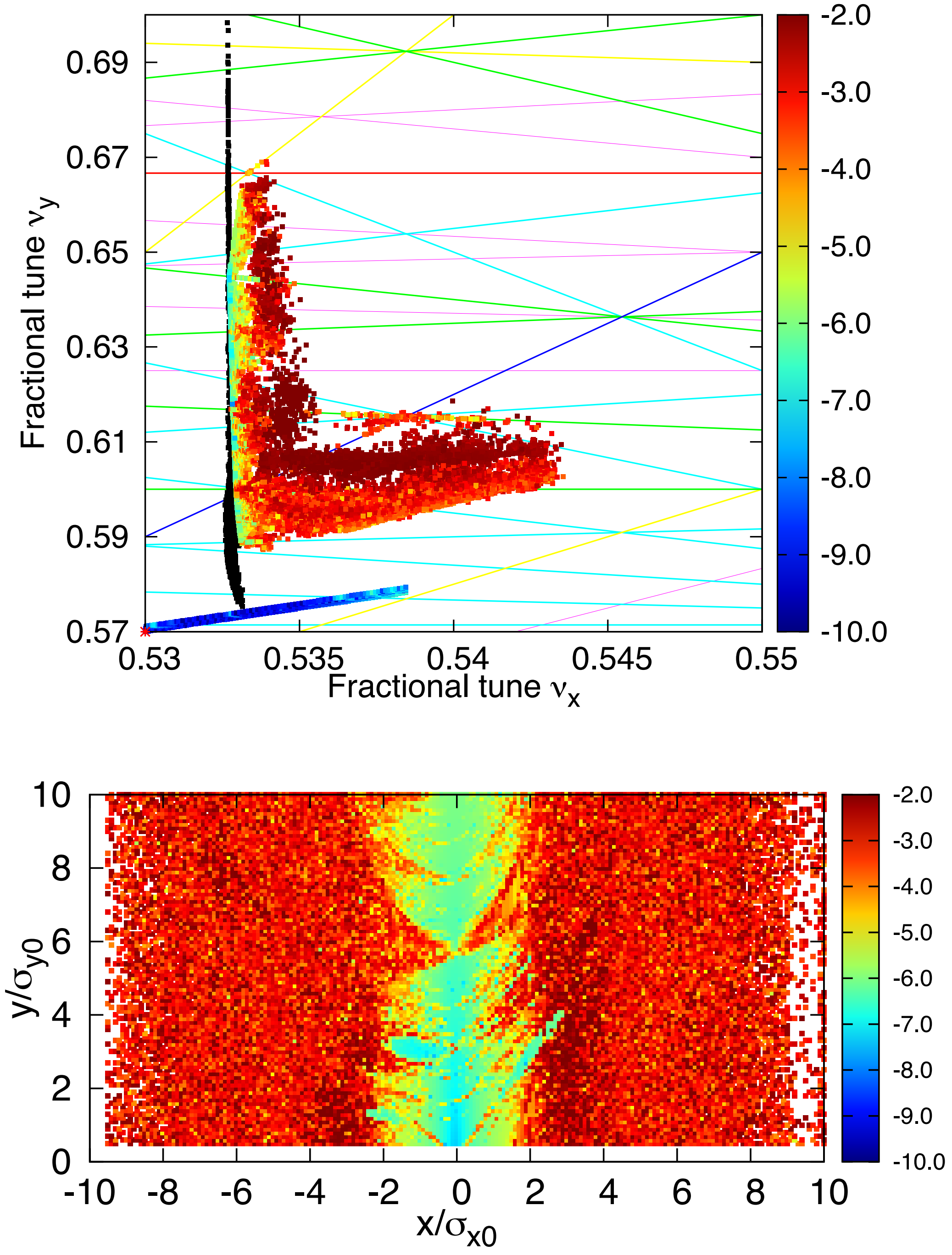


Y. Ohnishi

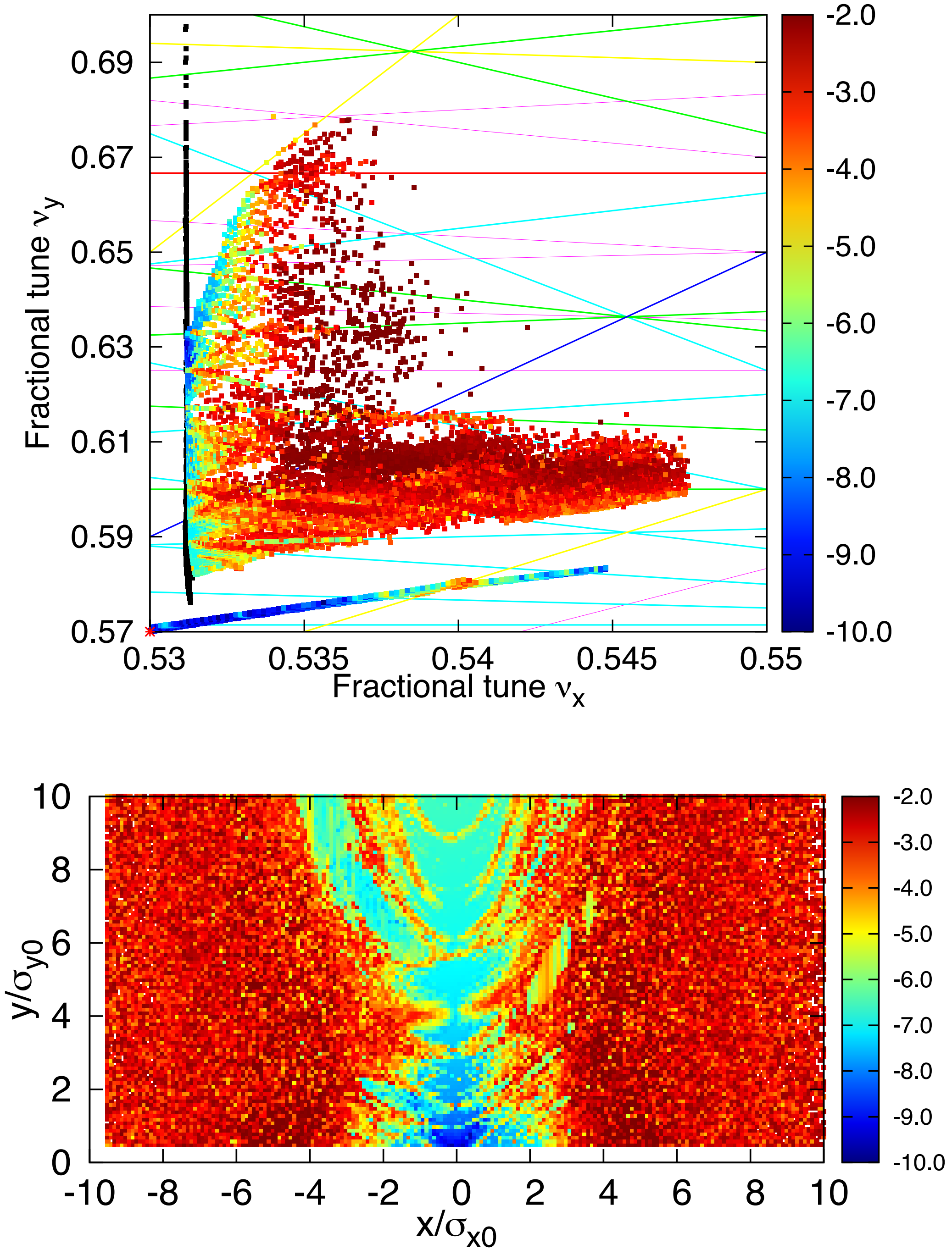
3. Interplay: Baseline lattice: BB+LN

- **FMA with beam distribution: $10\sigma_x \times 10\sigma_y$**
  - **Footprint in the tune space extended**

BB+LN (LER)



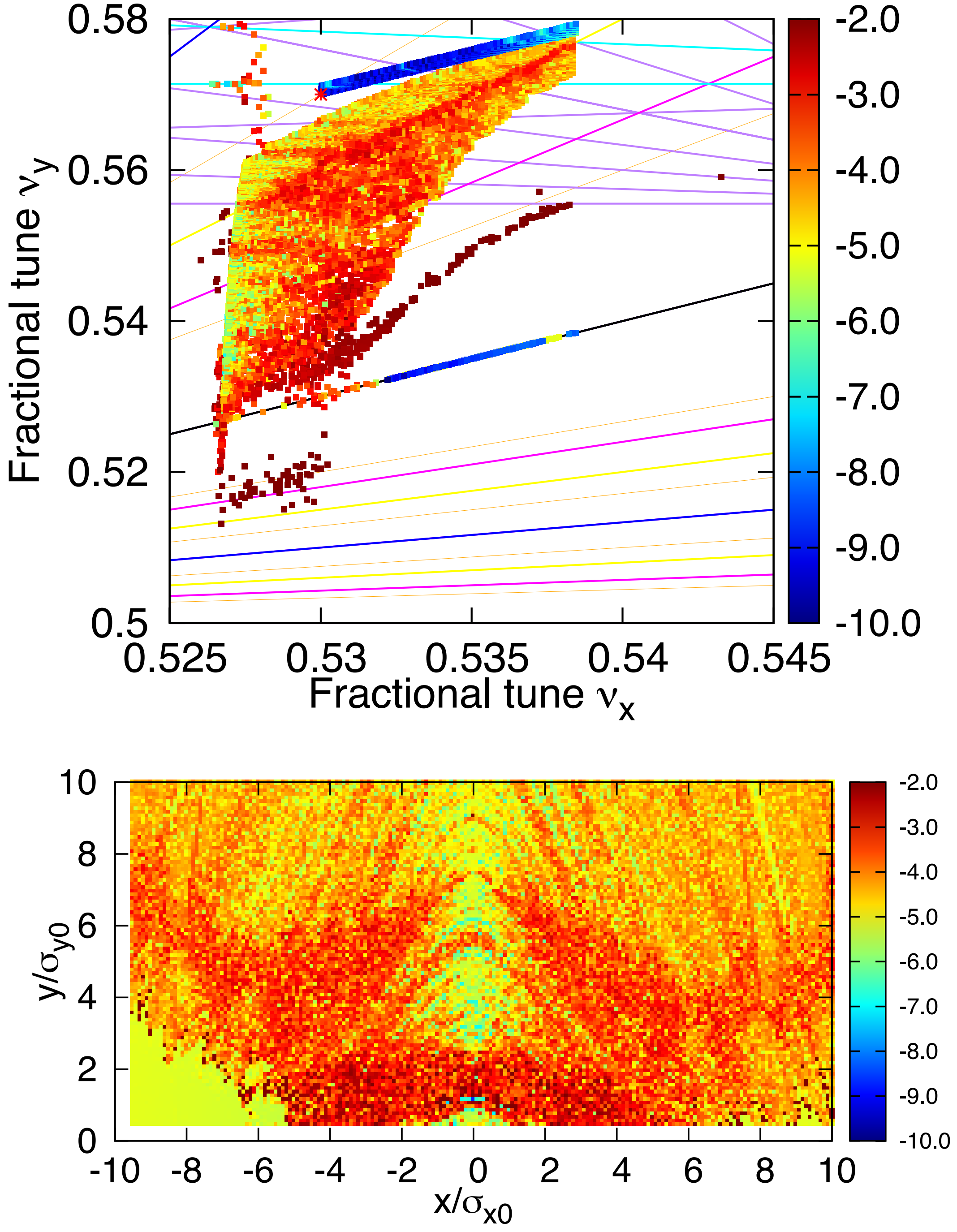
BB+LN (HER)



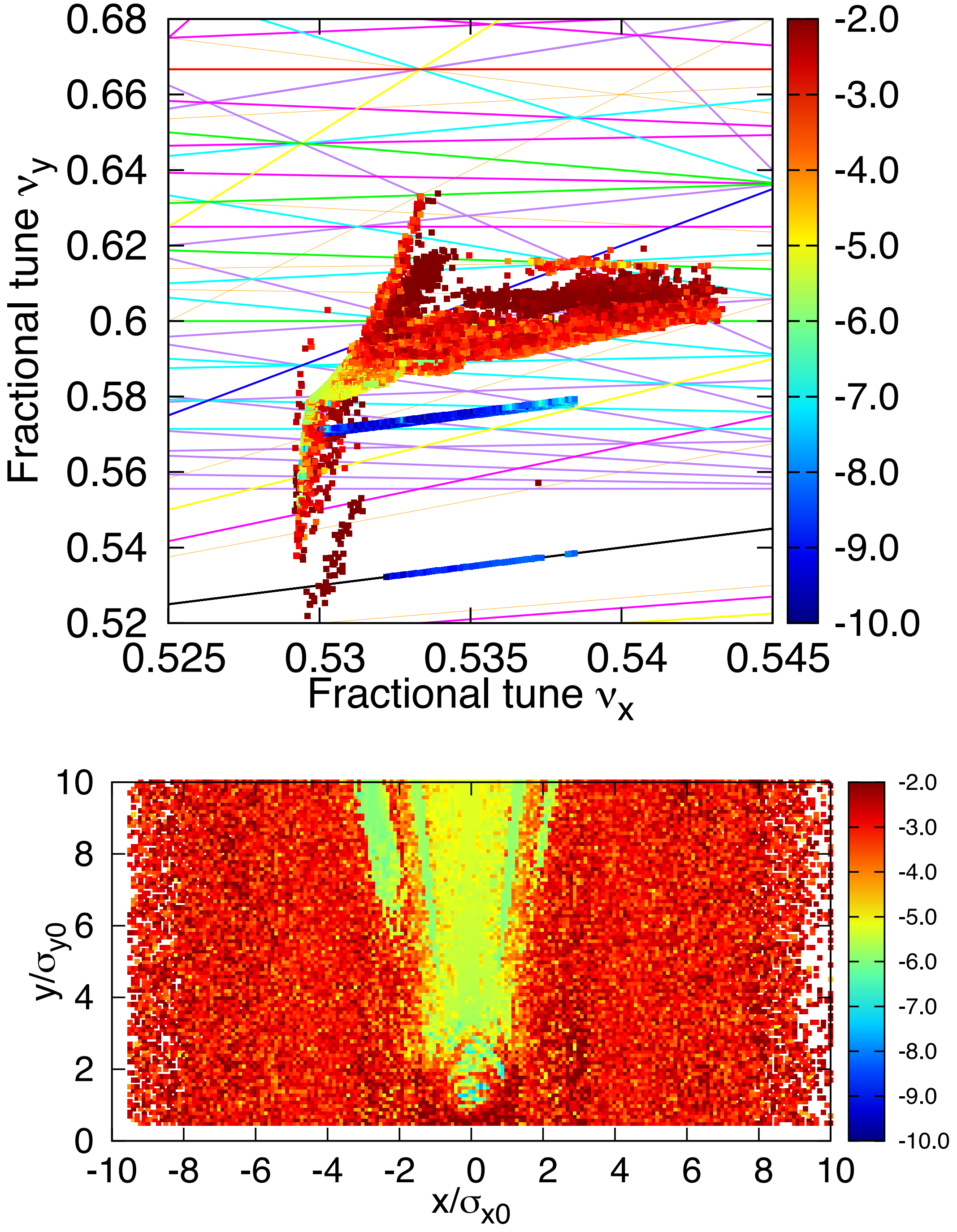
3. Interplay: Baseline lattice: BB+LN+SC

- **FMA with beam distribution: $10\sigma_x \times 10\sigma_y$**
  - **Footprint in the tune space strongly distorted**

SC+LN (LER)

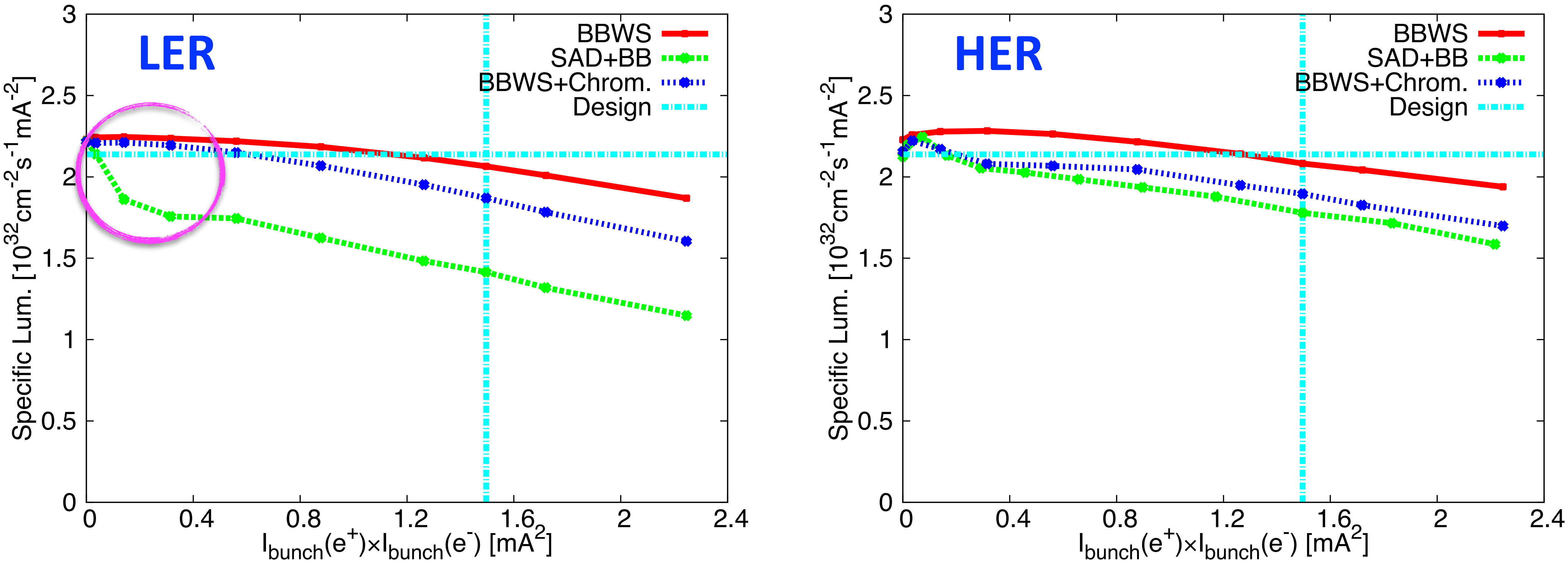


BB+LN+SC (LER)



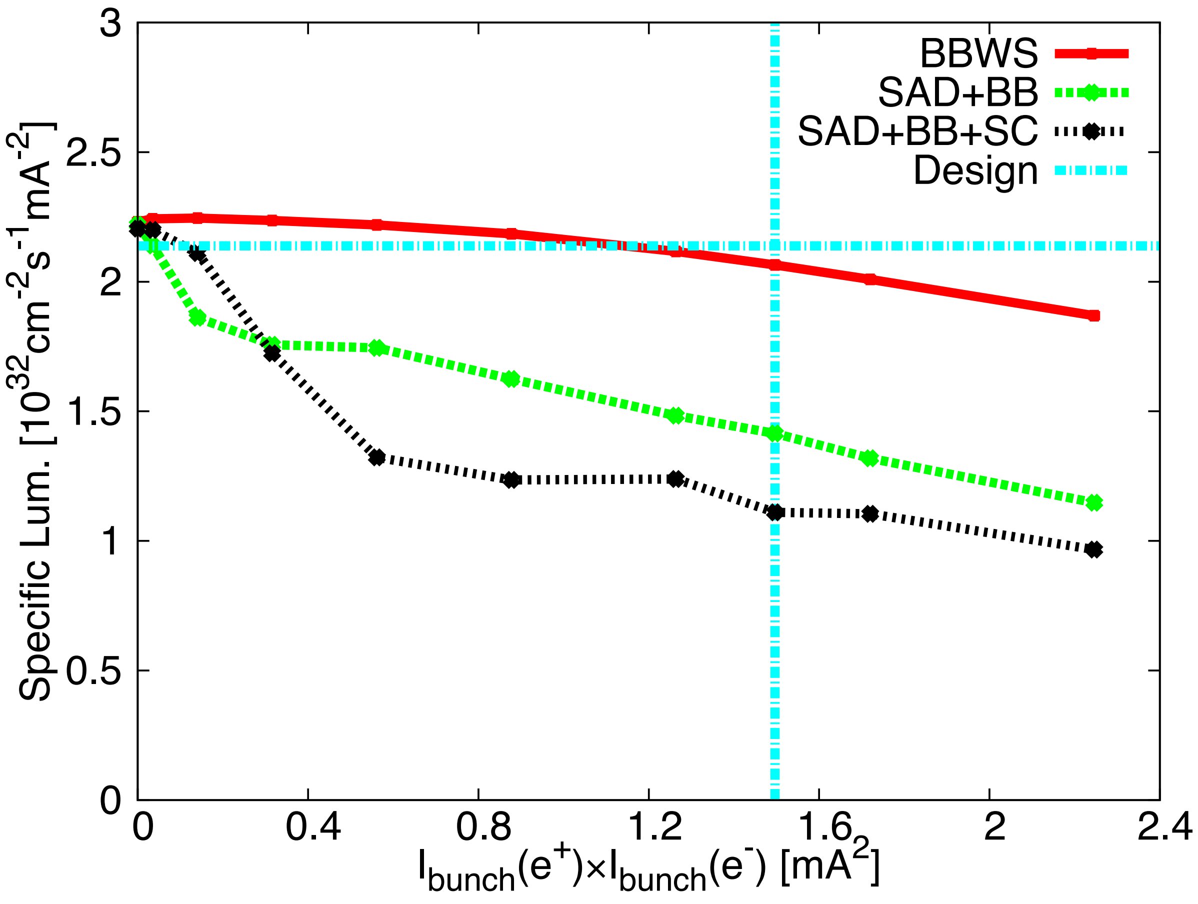
3. Interplay: Baseline lattice: BB+LN

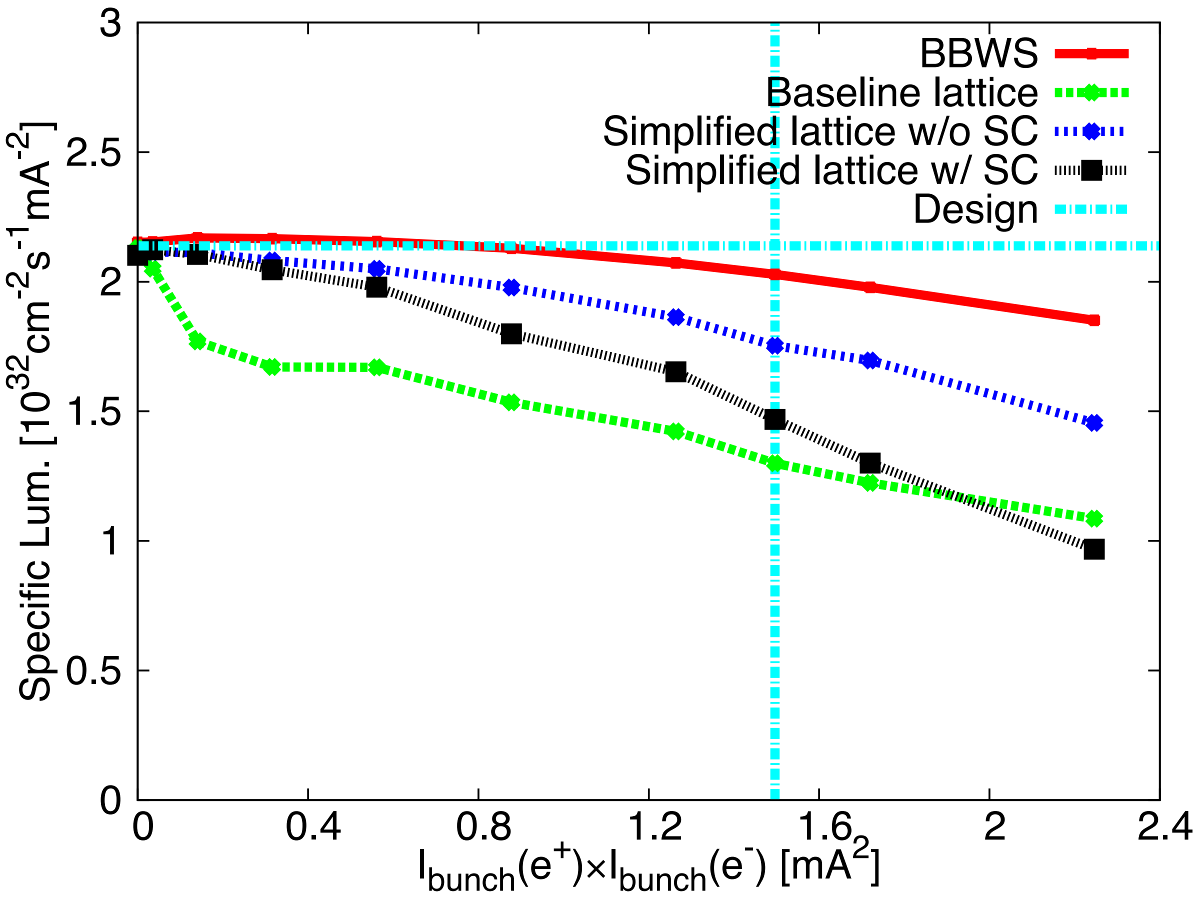
- ➤ BB+LN cause significant lum. loss
- ➤ LER: Lum. loss is attributed to amplitude-dependent nonlin.
  - Vertical emittance is very sensitive to beam-beam perturbation
  - Hard to suppress
  - Lum. loss starts from low currents (due to solenoids)
- ➤ HER: Lum. loss is attributed to chromatic nonlin.
  - Controllable if skew-sextupoles installed (KEKB experience)



3. Interplay: Baseline lattice: BB+LN+SC

- **LER**
  - **SC causes lum. loss, and loss rate depends on lattice design**
  - **SC compensates BB effects at low currents**
  - **Nonlinear fields from solenoids play an important role**

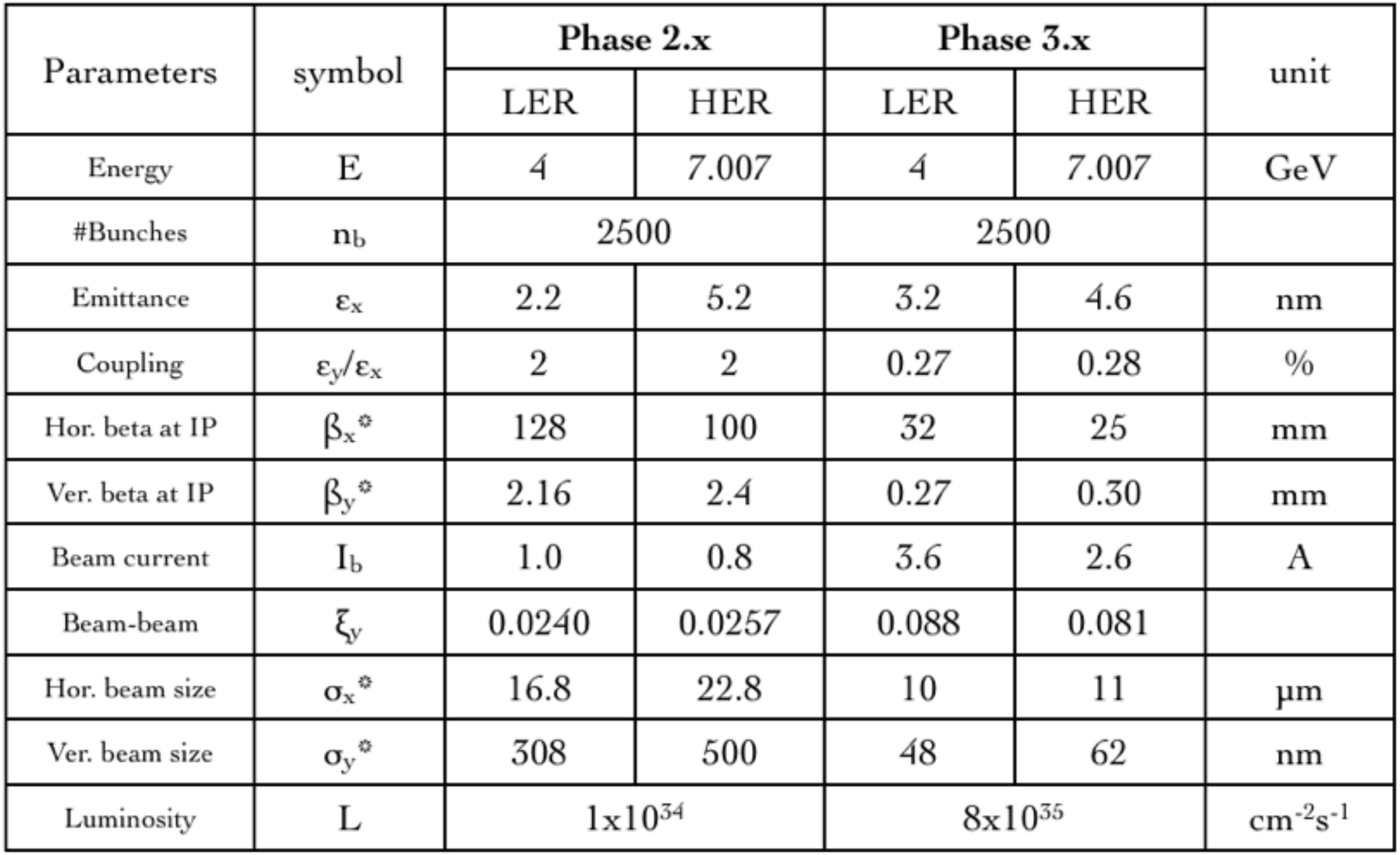




3. Interplay: Detuned lattice

➤ Detuned lattice for Phase 2 of SuperKEKB

- $\beta_x^* \times 4$ and $\beta_y^* \times 8$ for both LER and HER
- Emittance coupling $\varepsilon_y/\varepsilon_x$=1-2%



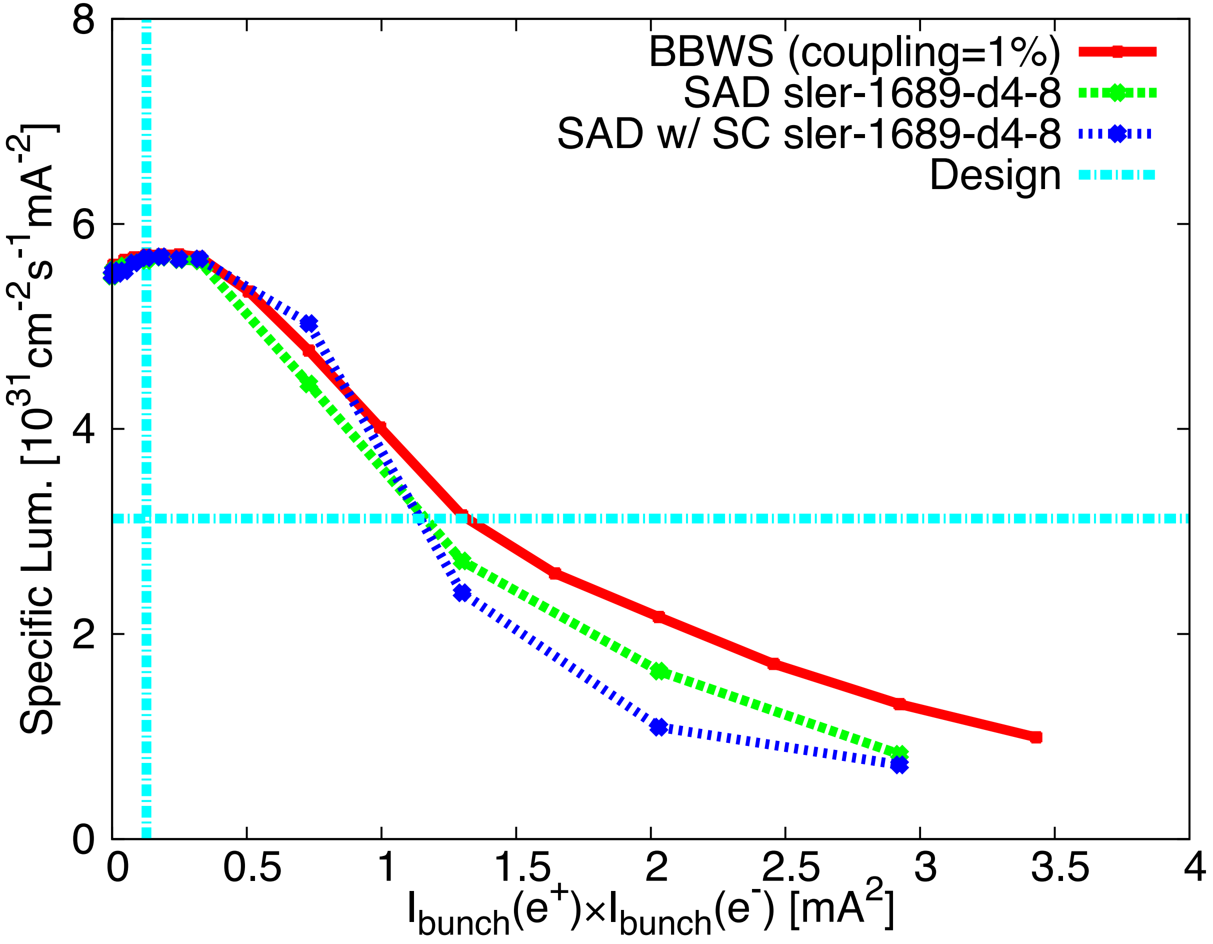
Parameters	symbol	Phase 2.x		Phase 3.x		unit
		LER	HER	LER	HER	
Energy	E	4	7.007	4	7.007	GeV
#Bunches	n_b	2500		2500		
Emittance	ε_x	2.2	5.2	3.2	4.6	nm
Coupling	$\varepsilon_y/\varepsilon_x$	2	2	0.27	0.28	%
Hor. beta at IP	β_x^*	128	100	32	25	mm
Ver. beta at IP	β_y^*	2.16	2.4	0.27	0.30	mm
Beam current	I_b	1.0	0.8	3.6	2.6	A
Beam-beam	ξ_y	0.0240	0.0257	0.088	0.081	
Hor. beam size	σ_x^*	16.8	22.8	10	11	μm
Ver. beam size	σ_y^*	308	500	48	62	nm
Luminosity	L	$1\text{x}10^{34}$		$8\text{x}10^{35}$		$\text{cm}^{-2}\text{s}^{-1}$

Y. Ohnishi

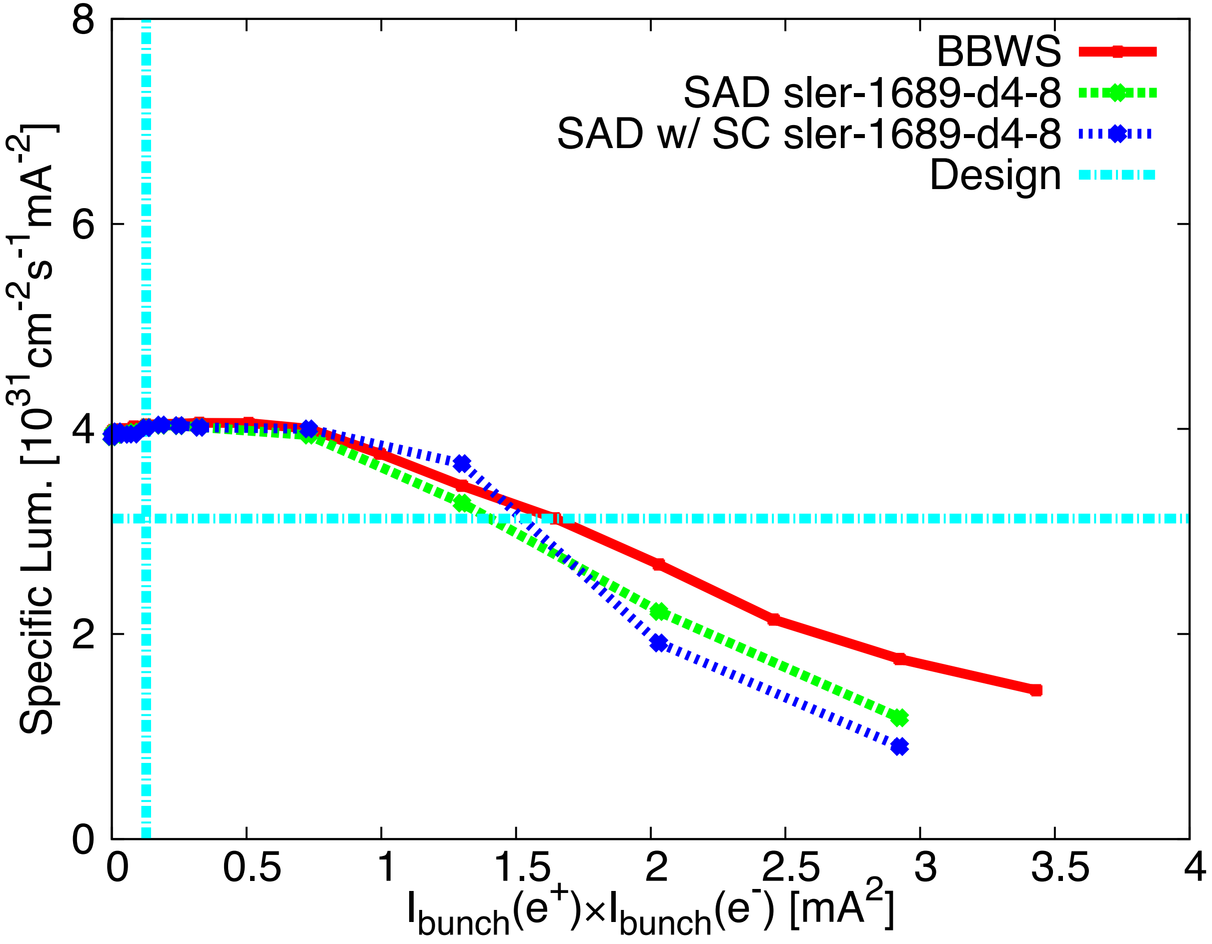
3. Interplay: Detuned lattice: BB+LN+SC

- ➤ **Space-charge is not important**
  - **SC compensates BB effects at low currents**
- ➤ **Lattice nonlinearity is not very important**
- ➤ **L=1×10^{34}cm^{-2}s^{-1} is promising**
- ➤ **L=10×10^{34}cm^{-2}s^{-1} is possible by increasing beam currents**

$\varepsilon_y/\varepsilon_x$=1%



$\varepsilon_y/\varepsilon_x$=2%



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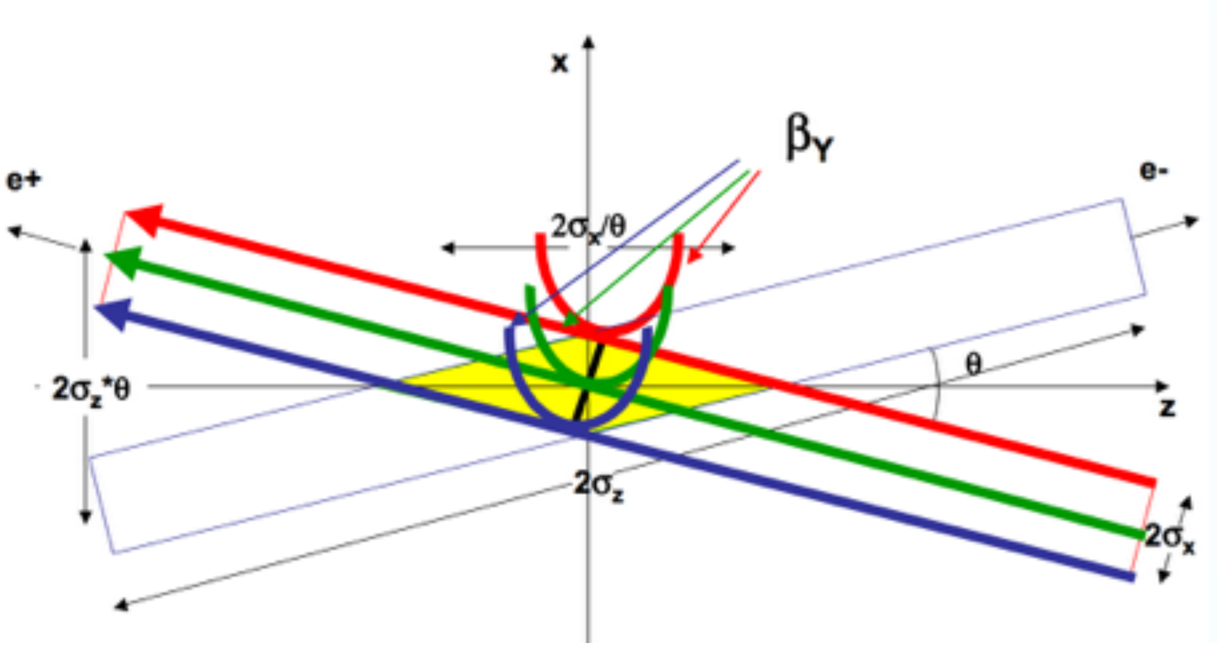
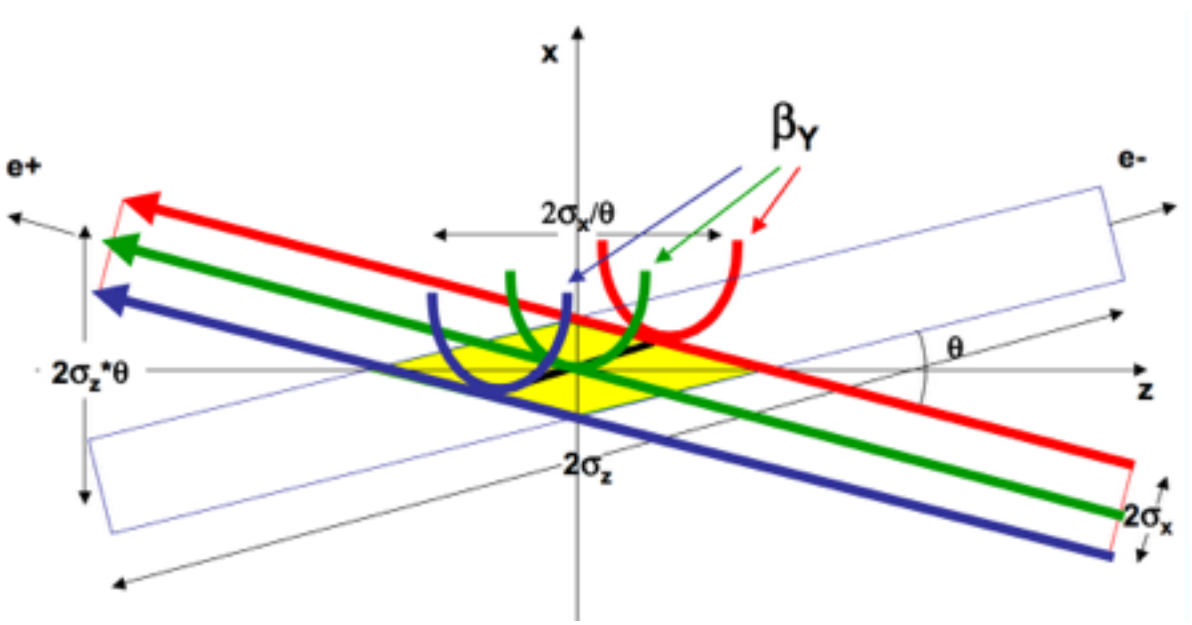
4. Mitigation schemes: CW

- **CW for large crossing angle collision**
  - To mitigate the hourglass effects in x-direction

w/o CW



w/ CW

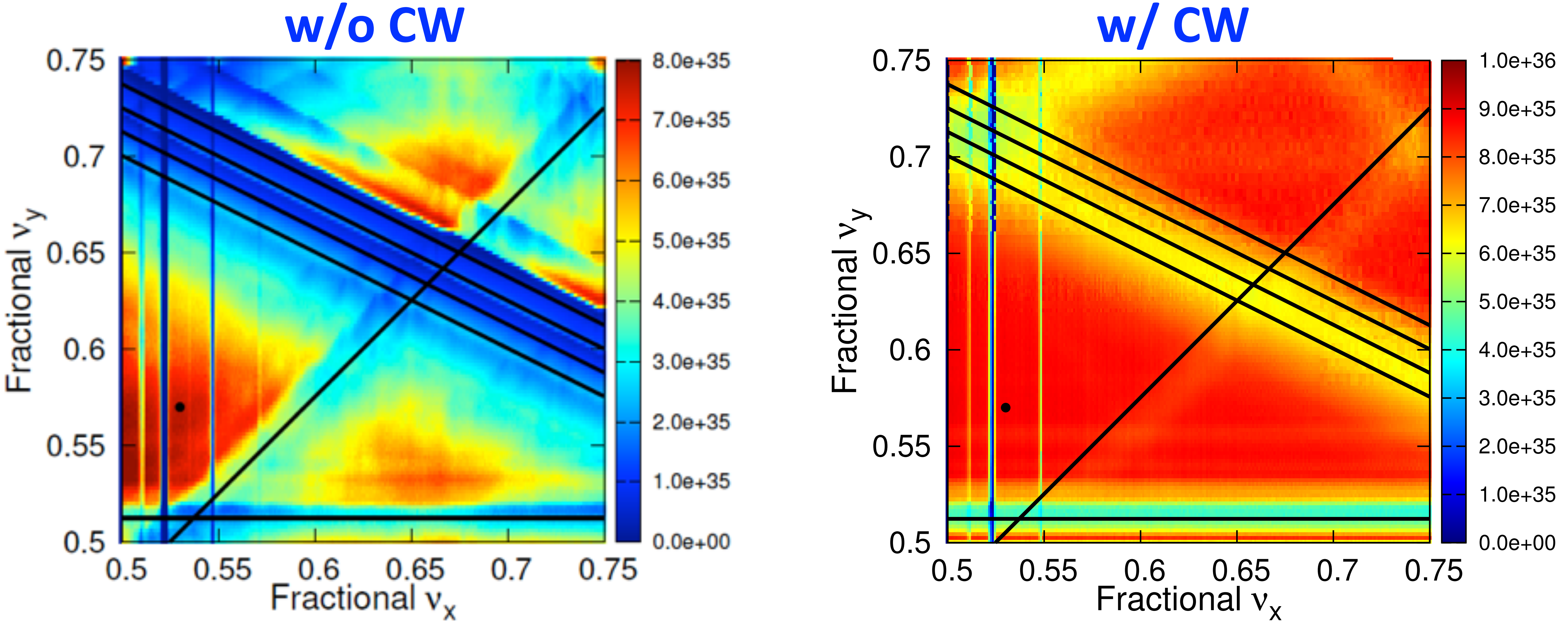


M. Zobov, Phys. Part. Nucl. 42 (2011) 782-799

4. Mitigation schemes: CW: Luminosity

➤ **Lum. tune scan for LER by BBWS w/o and w/ CW**

- CW is the most promising scheme to suppress BB resonances
- 'Sweet spot' for high lum. enlarged tremendously
- Easy choice for working point
- But CW causes loss of DA due to LN …



4. Mitigation schemes: CW: Luminosity

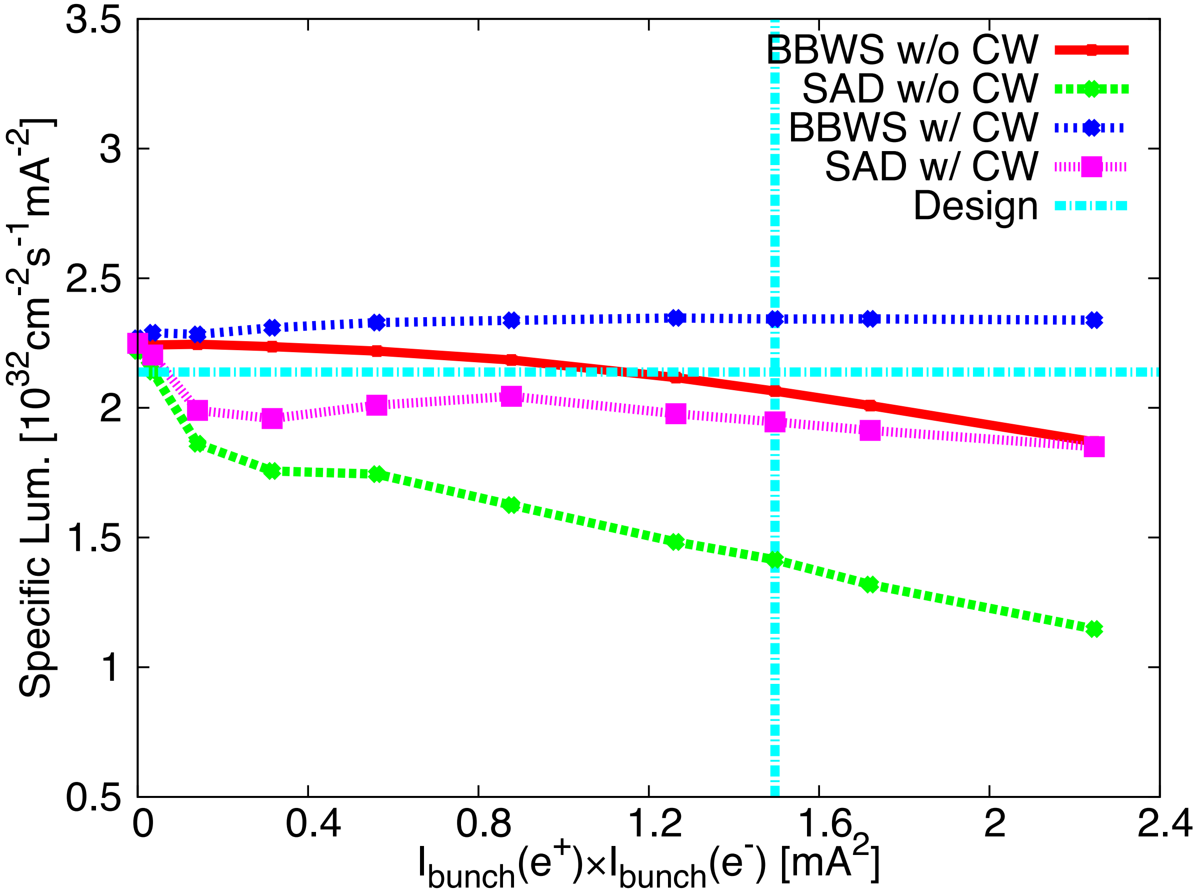
➤ **Ideal CW** ($M=M_{CW}M_{BB}M_{CW}^{-1}$):

- **In the ideal case, CW causes lum. gain of ~10% for SuperKEKB**
- **Its power is to sppress beam-beam driven resonances**

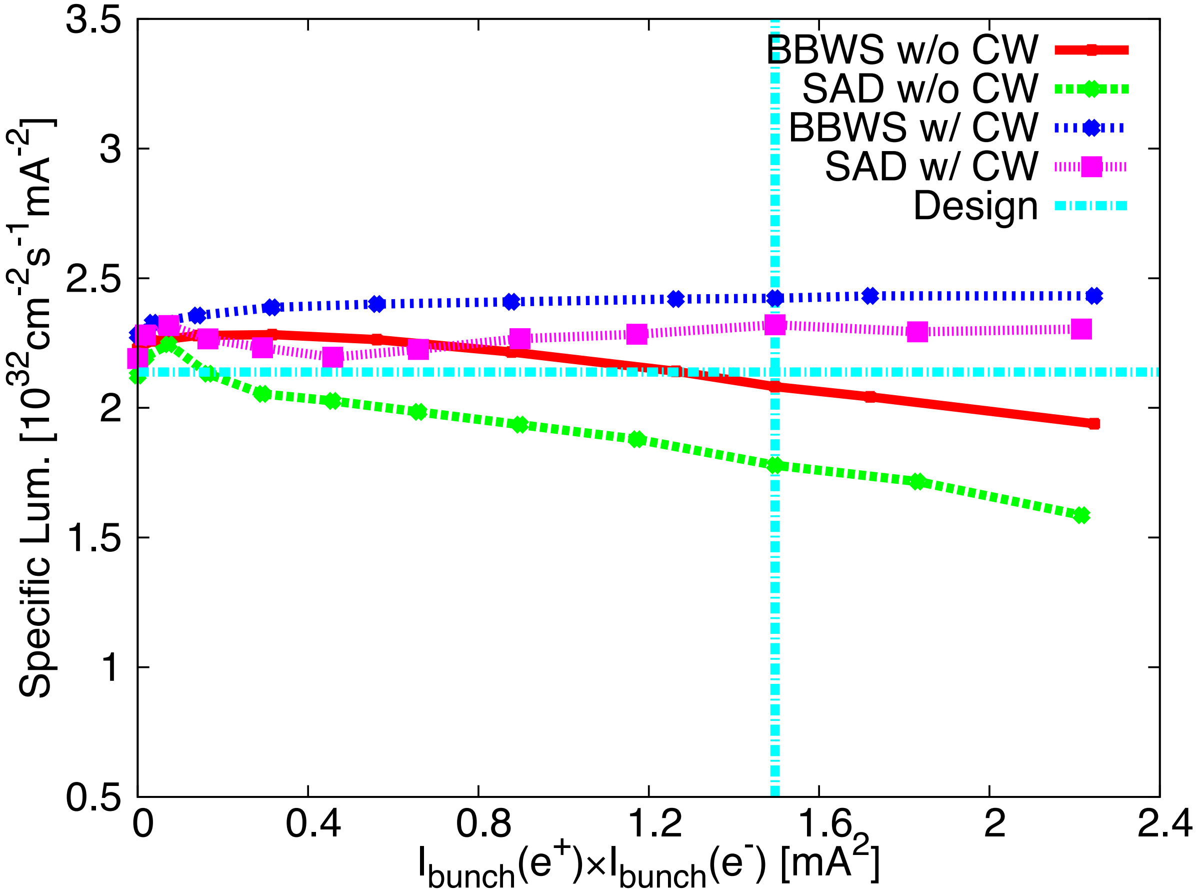
➤ **Real lattice w/ ideal CW:**

- **Work at high currents, but not well at low currents**

LER



HER

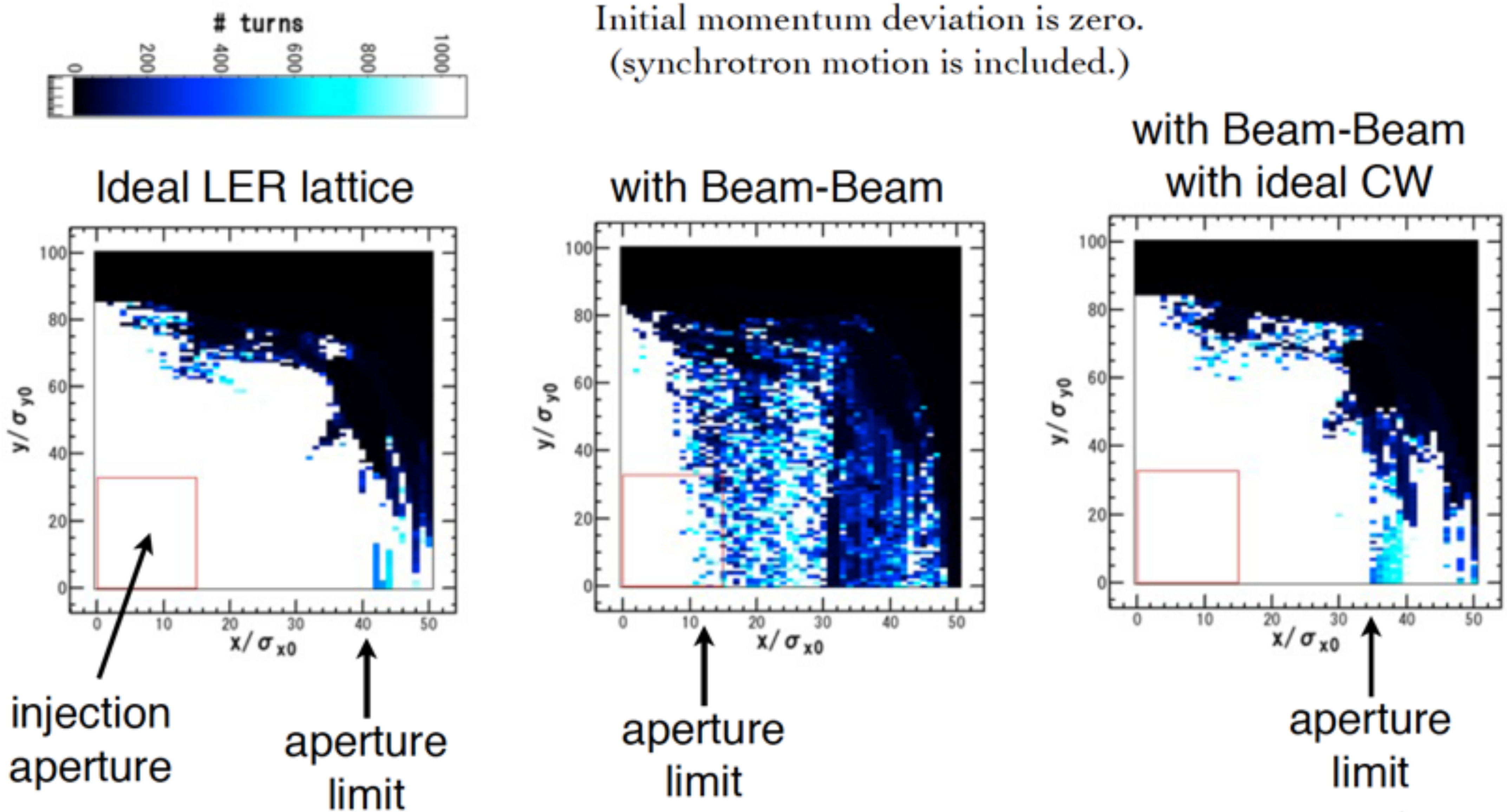


4. Mitigation schemes: CW: DA

➤ DA: BB + ideal CW: LER

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

Initial momentum deviation is zero.
(synchrotron motion is included.)



Ideal LER lattice

with Beam-Beam

with Beam-Beam
with ideal CW

injection aperture

aperture limit

aperture limit

aperture limit

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

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

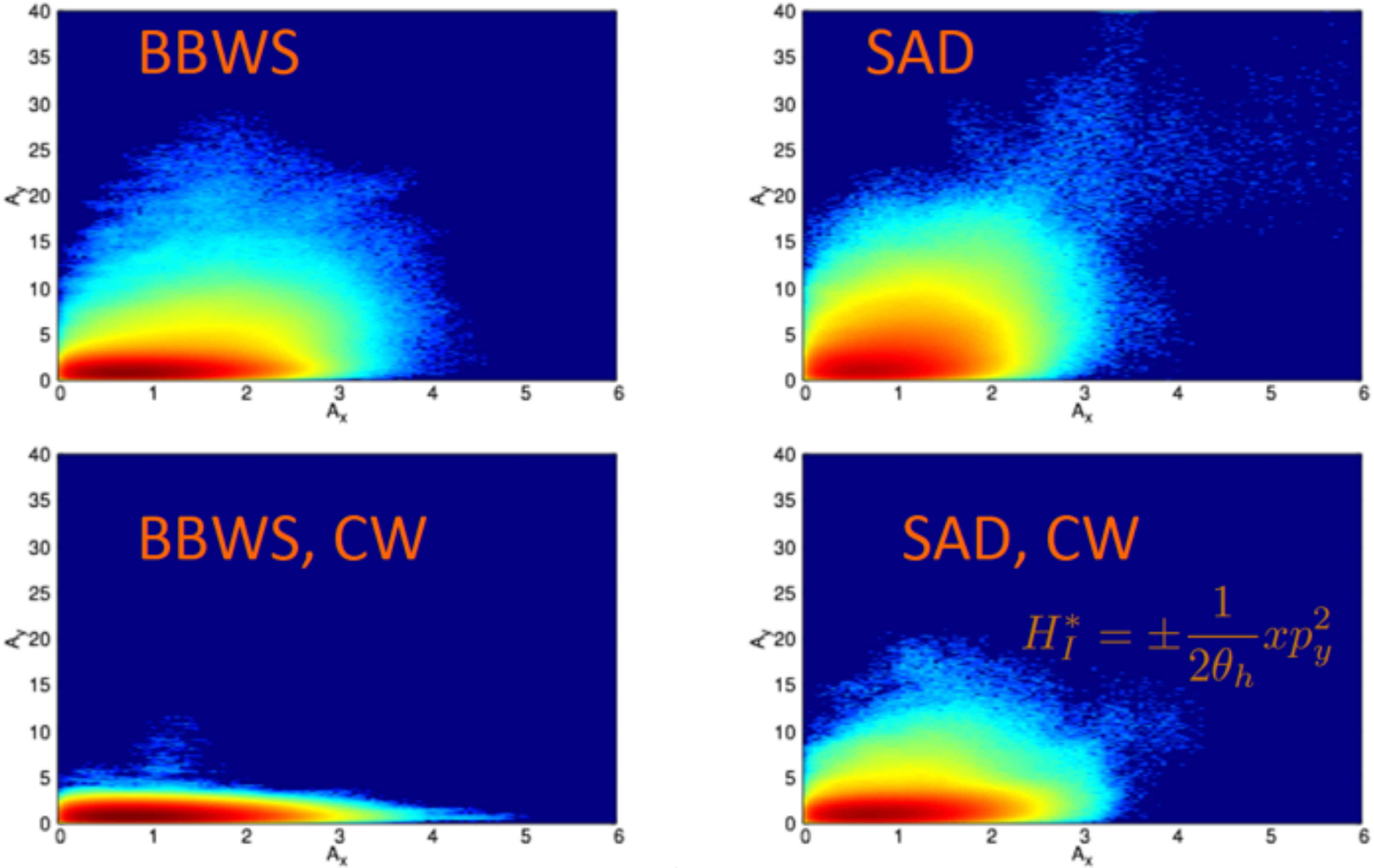
Y. Ohnishi

4. Mitigation schemes: CW: Beam tail

➤ **Beam tail distribution: Ideal CW: LER**

- CW not suppress beam tail well when LN exists
- Beam tail => Detector background => Collimation => Impedance budget => Instability => Commissioning

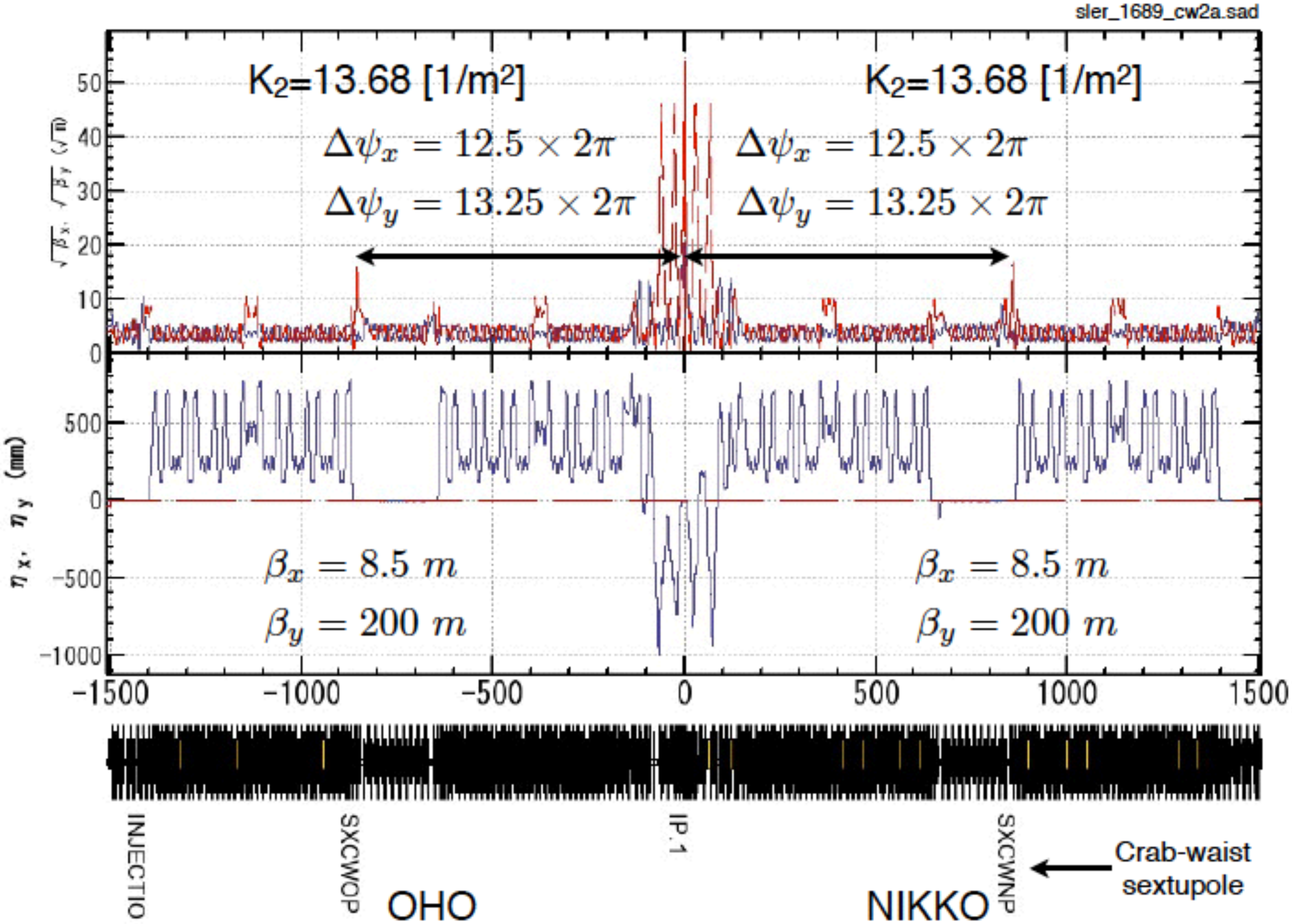
- $Ne=6.53x10^{10}$, SAD +weak-strong BB



4. Mitigation schemes: CW: DA

➤ CW: Real lattice: LER

- **Thin-lens model for CW sextupoles**



Crab-waist sextupole

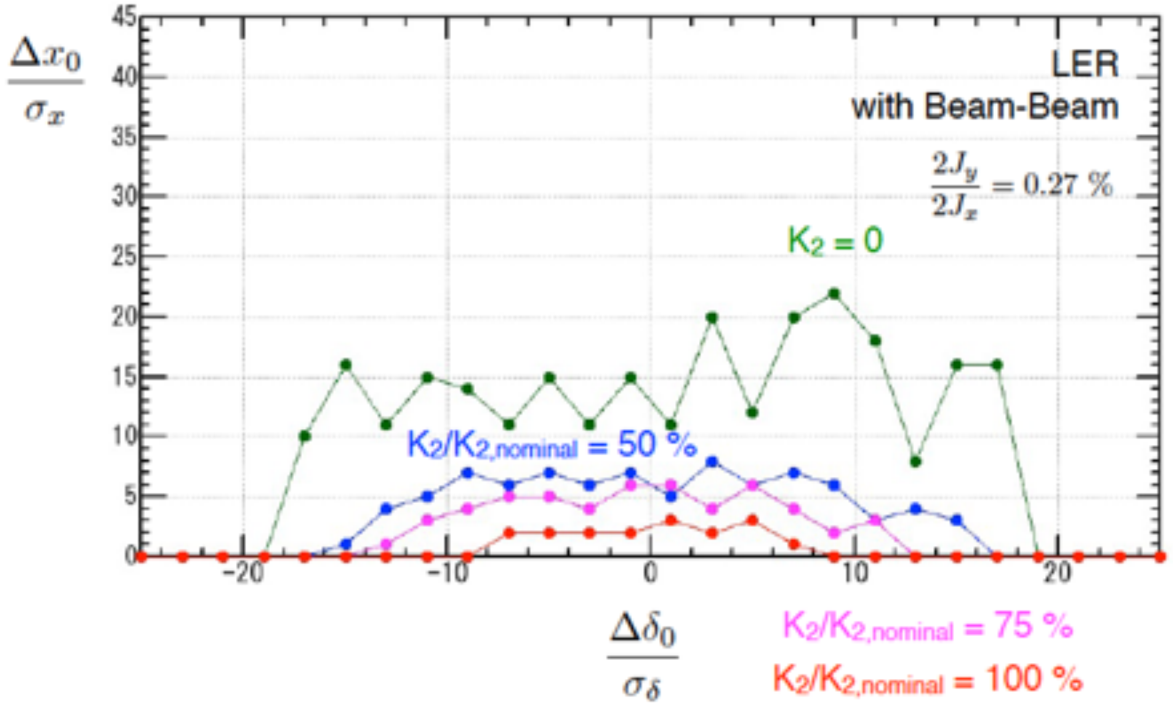
Y. Ohnishi

4. Mitigation schemes: CW: DA

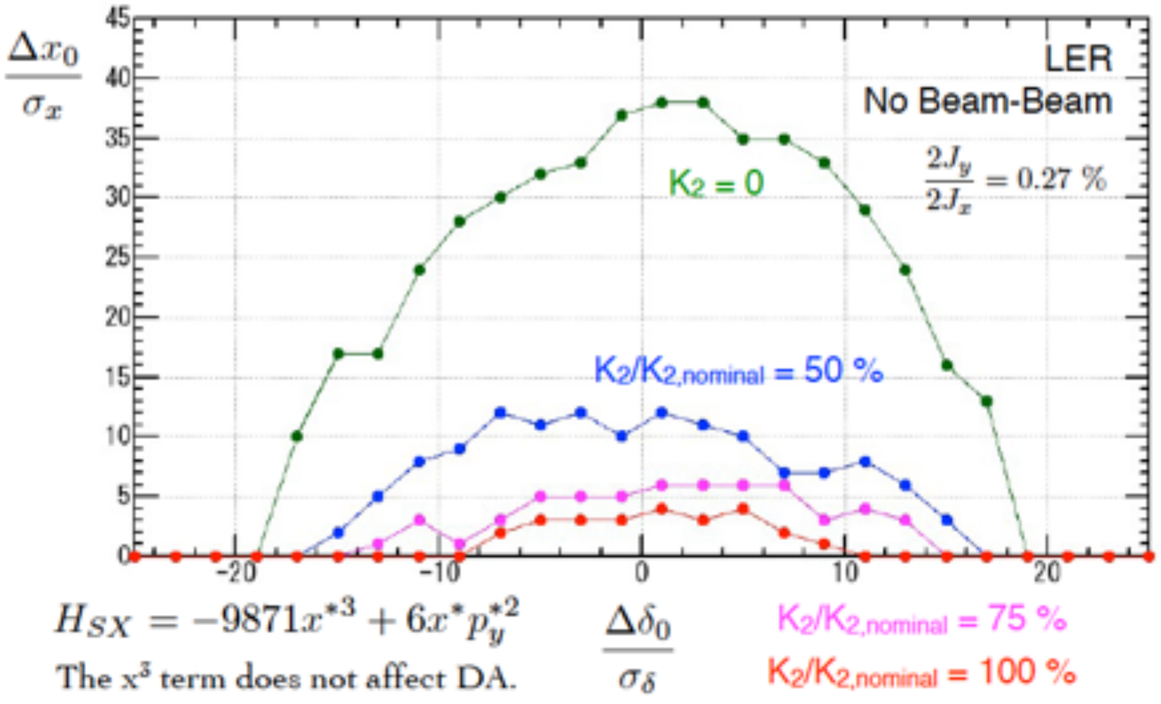
➤ CW: Real lattice: LER

- DA decreases when CW sextupole strength increases
- Nonlinearity between IP and CW sextuple breaks CW condition

w/ BB



w/o BB



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

The x^3 term does not affect DA.

Y. Ohnishi

4. Mitigation schemes: Nonlinear optimization

- Nonlinear optimisation is a must for successful CW scheme
  - Up to now, not very successful yet
  - Advanced nonlinear analysis techniques are necessary
  - An international collaboration program initiated
- SC compensation
  - Linear tune shift compensation is not enough
  - Amplitude-dependent tune shift also needs to be compensated: installation of dedicated octupoles is a candidate

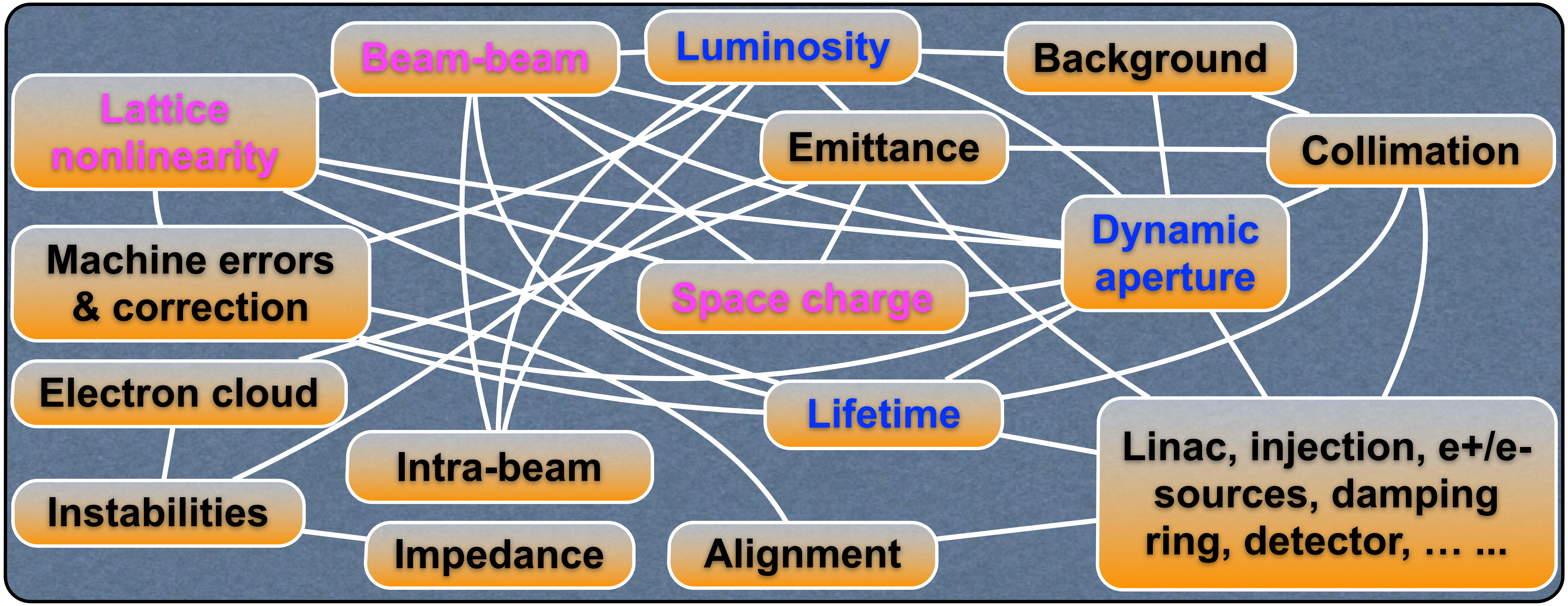
Outline

- ➤ Introduction
- ➤ Beam dynamics issues
  - Beam-beam (BB)
  - Lattice nonlinearity (LN)
  - Space charge (SC)
- ➤ Interplay of BB, LN and SC
  - Baseline lattice
  - Detuned lattice
- ➤ Mitigation schemes
  - Crab waist (CW)
  - Nonlinear optimization
- ➤ **Summary and Future plans**

5. Summary

➤ Interplay of various issues

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



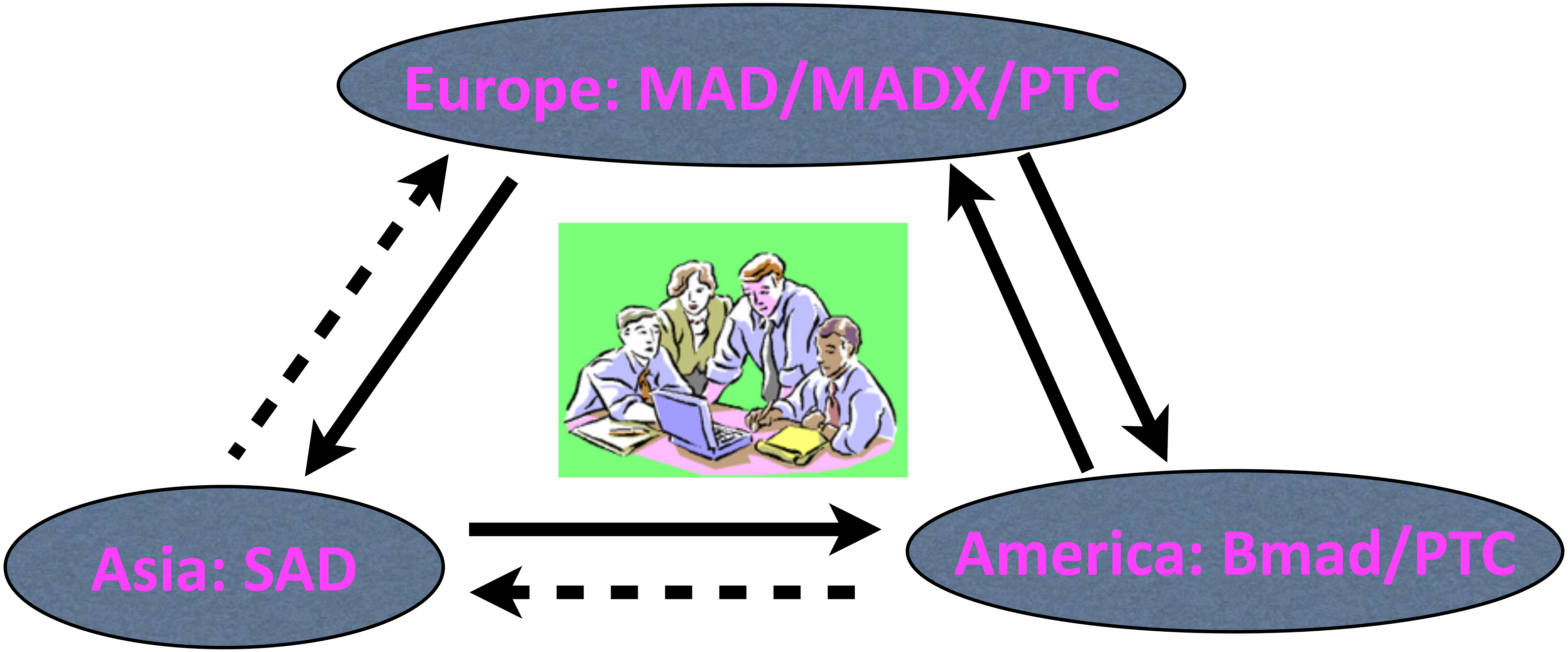
6. Future plans

- **Detailed analysis of lattice nonlinearity under an international collaboration program**
  - **Cornell Univ., IHEP, INFN, KEK, SLAC**
- **Collaboration with CEPC and FCC-ee teams**
  - **FCCs share similar accelerator physics challenges with SuperKEKB**
- **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**
  - **… …**

6. Future plans

➤ **A recently initiated project: Benchmark studies for accelerator design codes**

- **SAD: TRISTAN, KEKB, SuperKEKB, J-PARC, …**
- **Bmad: CESR, ERL, …**
- **MAD/MADX: LHC, FCCs, DAϕNE, Super τ-charm, …**



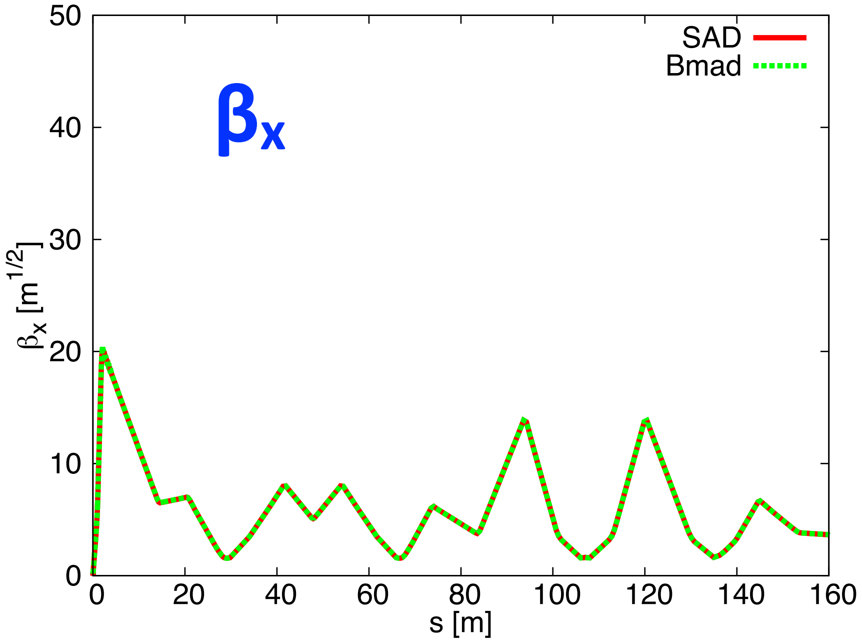
Europe: MAD/MADX/PTC

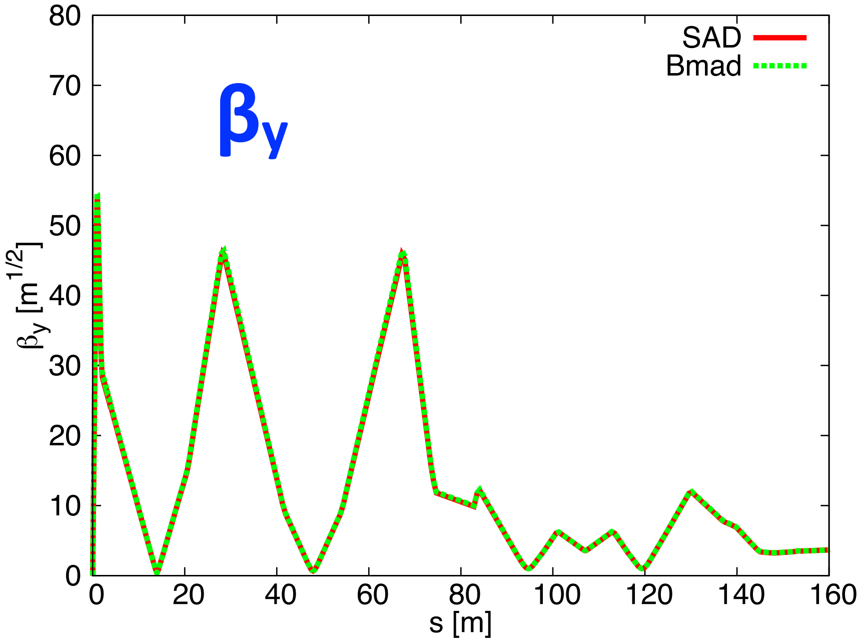
Asia: SAD

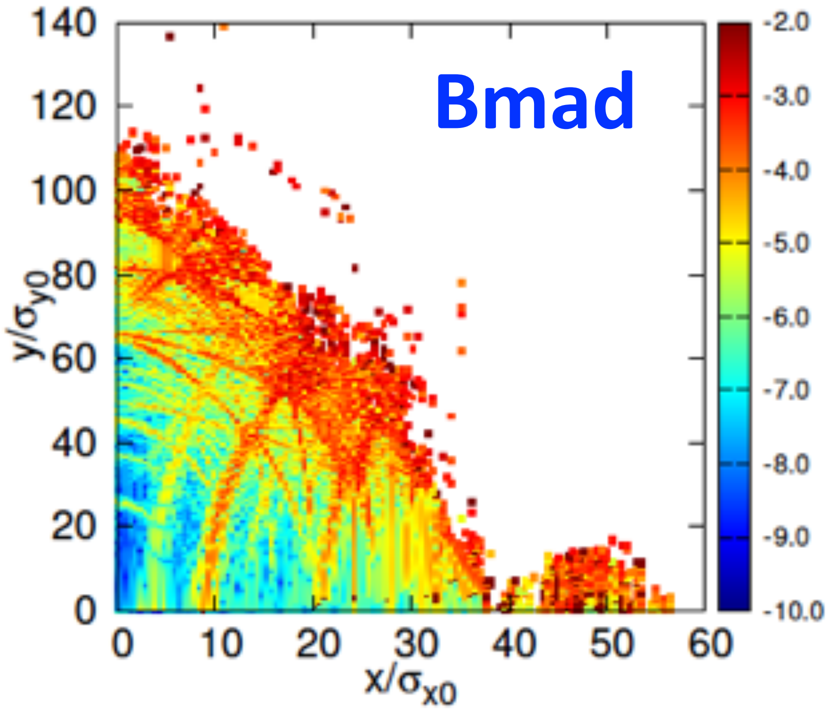
America: Bmad/PTC

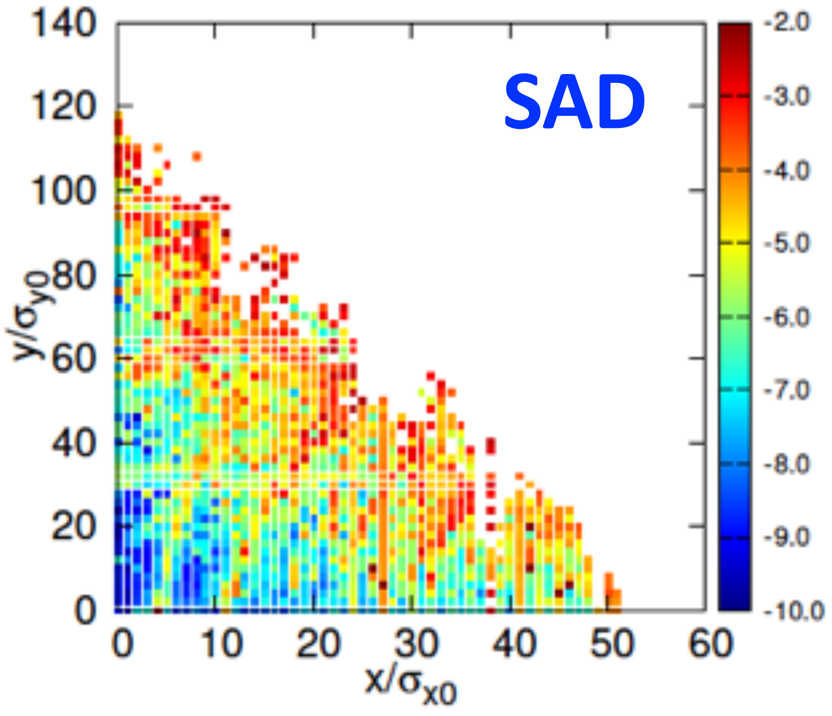
6. Future plans

- **A good step for benchmark of SAD and Bmad**
  - Twiss function and FMA for SuperKEKB LER









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Thanks for your attention!