

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

Outline

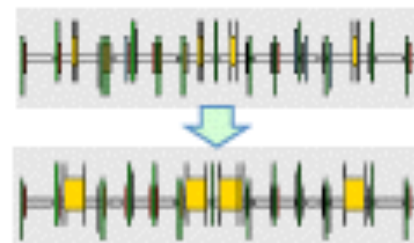
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1. Introduction

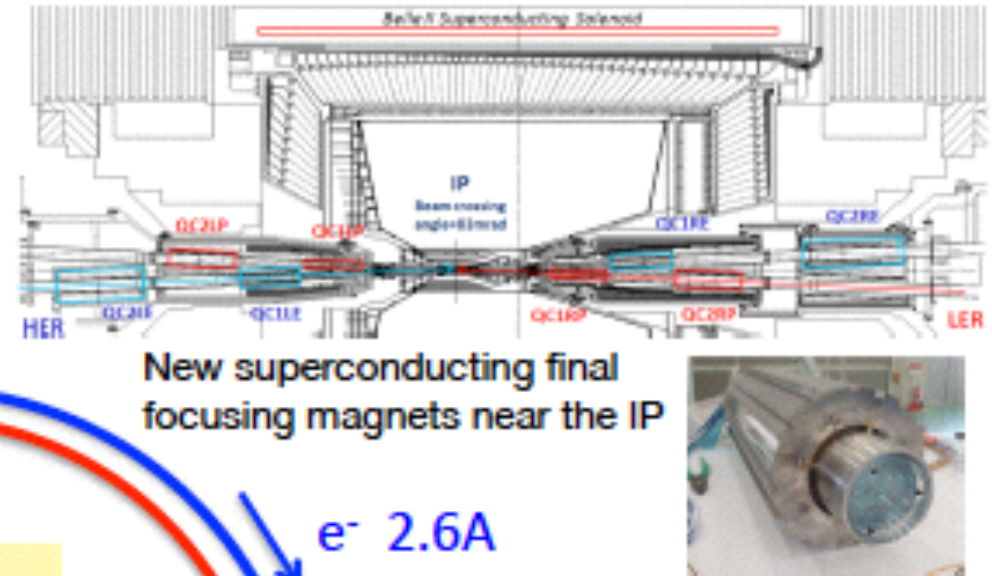
T. Miura, TUYB1



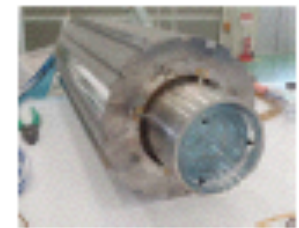
Redesign the lattice to squeeze the emittance (replace short dipoles with longer ones, increase wiggler cycles)



Colliding bunches



New superconducting final focusing magnets near the IP



$e^+ 3.6A$

$e^- 2.6A$

SuperKEKB

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

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

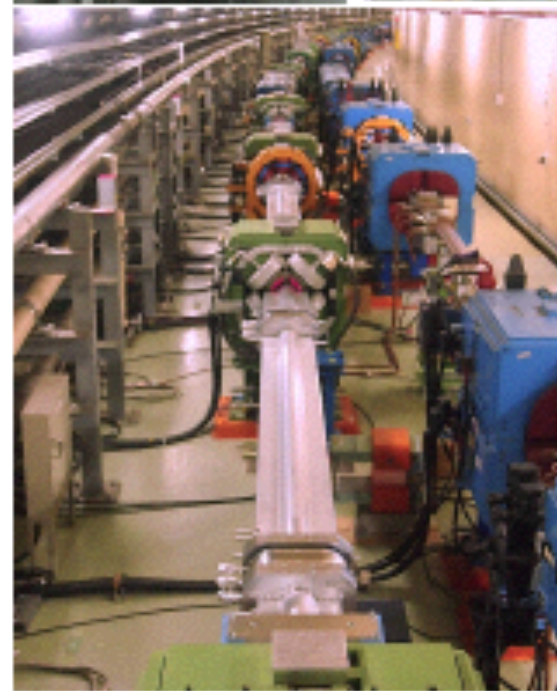
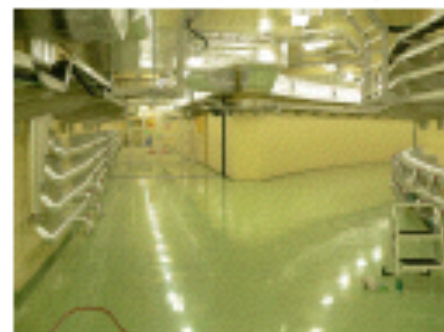
40 times higher luminosity
 $2.1 \times 10^{34} \rightarrow 8 \times 10^{35} \text{ cm}^{-2} \text{ s}^{-1}$

Improve monitors
and control system

Injector Linac upgrade
● RF electron gun
● improve e^+ source

Injector Linac upgrade

New e^+ Damping Ring



Replace beam pipes with TiN-coated
antechamber-type ones



Wiggler sections upgrade



Reinforce RF systems for
higher beam currents

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
α _p (10 ⁻⁴)	3.25	3.31	0.98	4.55	3.43	1.33
σ _δ (10 ⁻⁴)	8.08	7.73	1.11	6.37	6.3	0.96

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2. Beam dynamics issues: BB

➤ Lum. tune scan for LER by BBWS

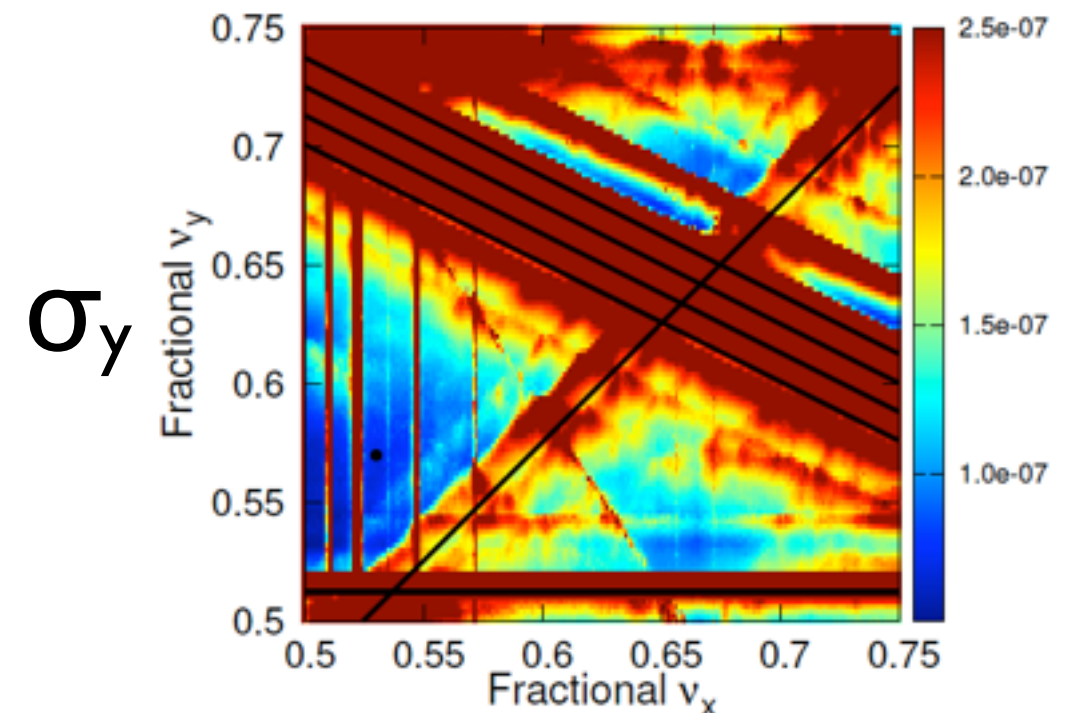
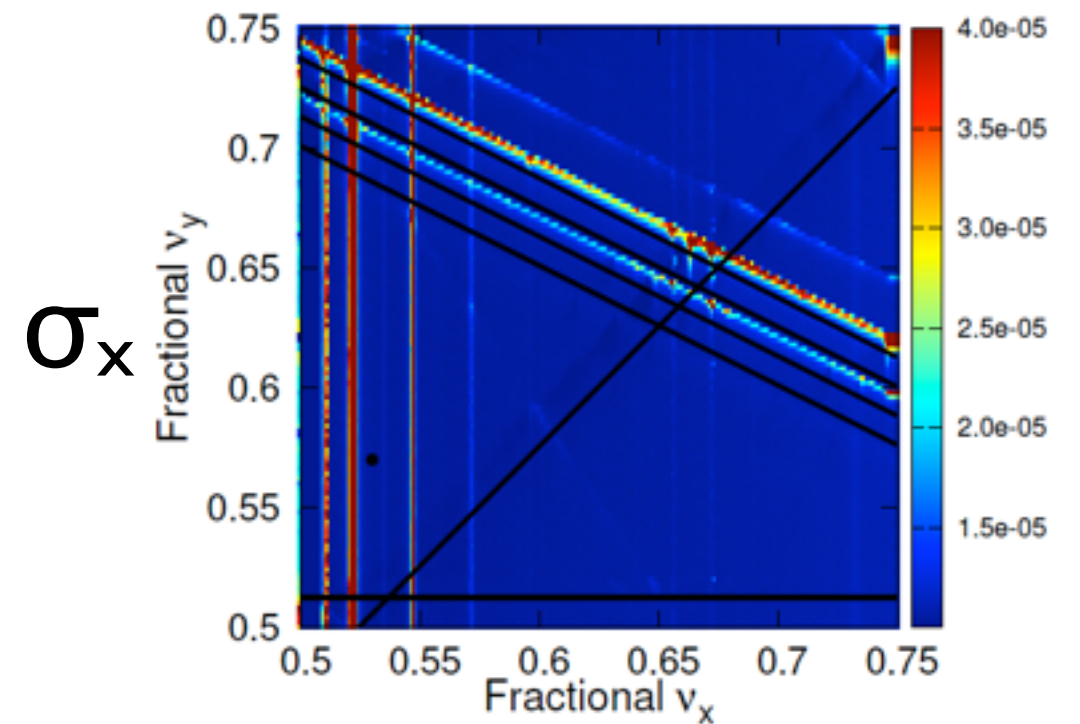
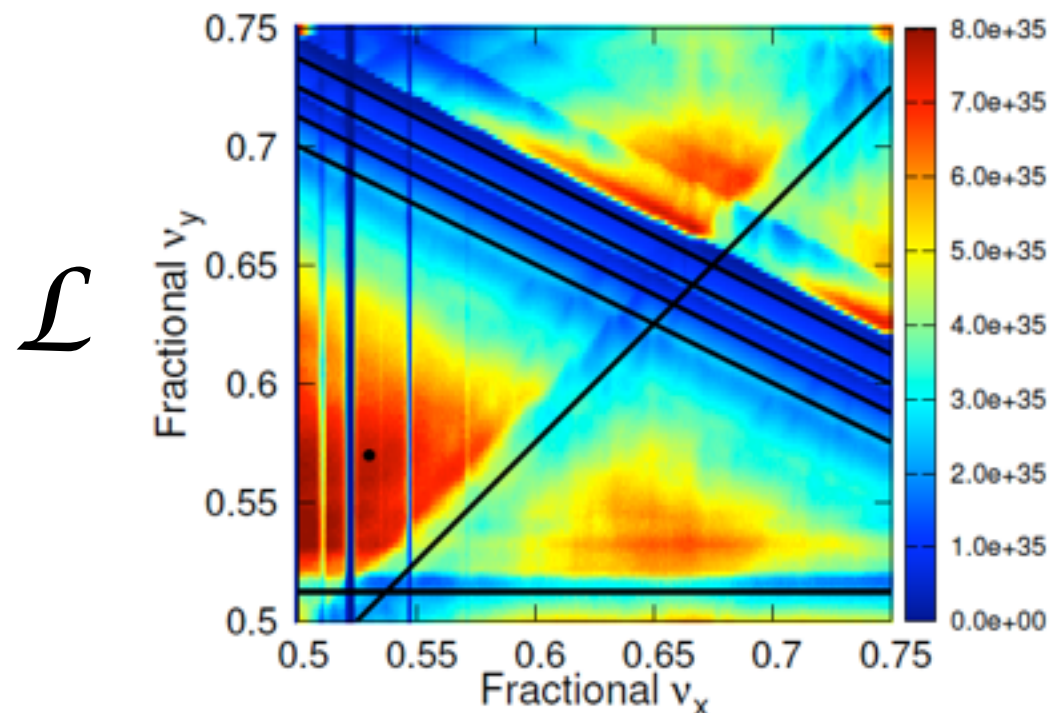
- By BBWS (weak-strong) w/o crab waist
- 'Sweet spot' close to half-integer
- Isolated islands for working point
- Important BB resonances:

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

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

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

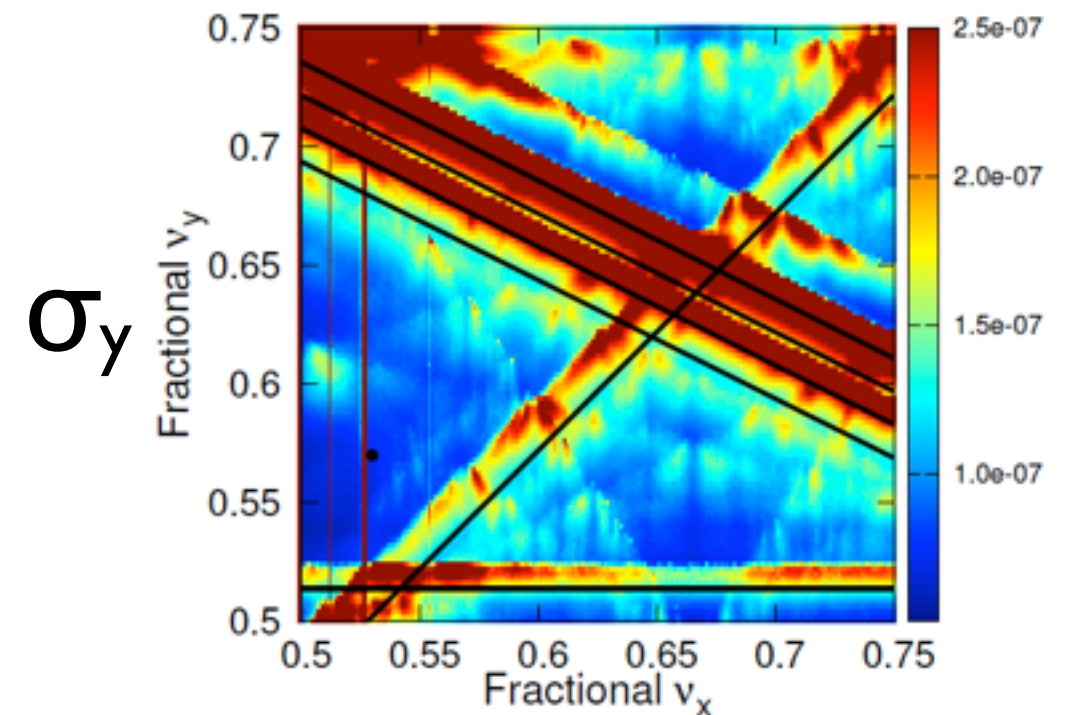
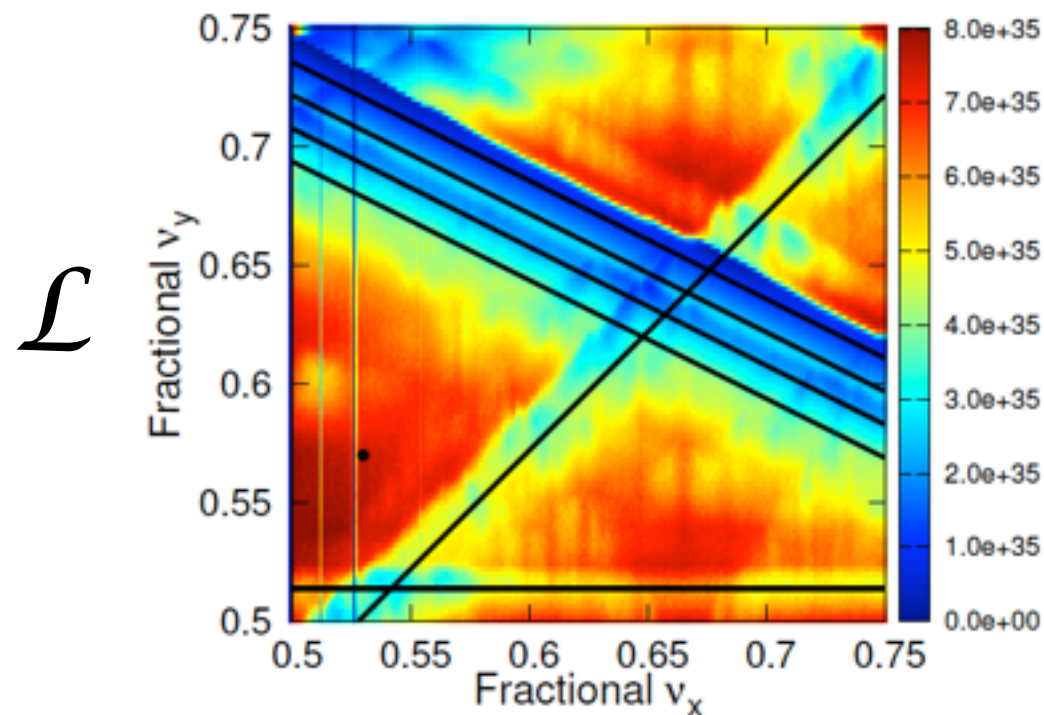
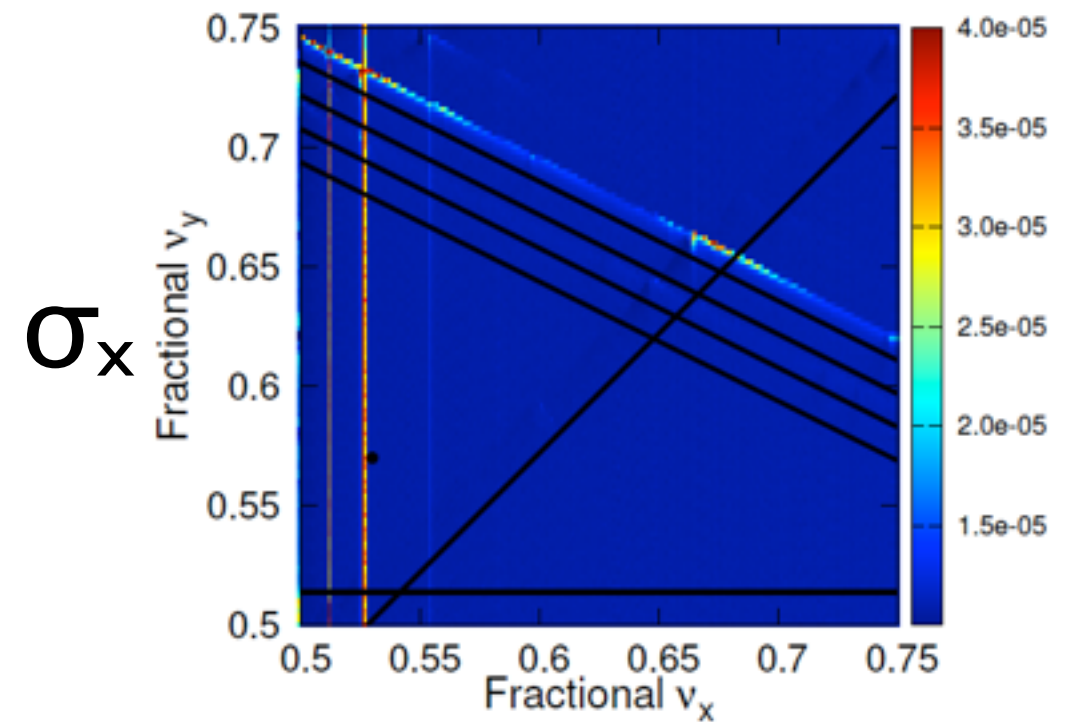
$$2\nu_y - \nu_s = \text{Integer}$$



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



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 ($\theta=0.083$) => 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)

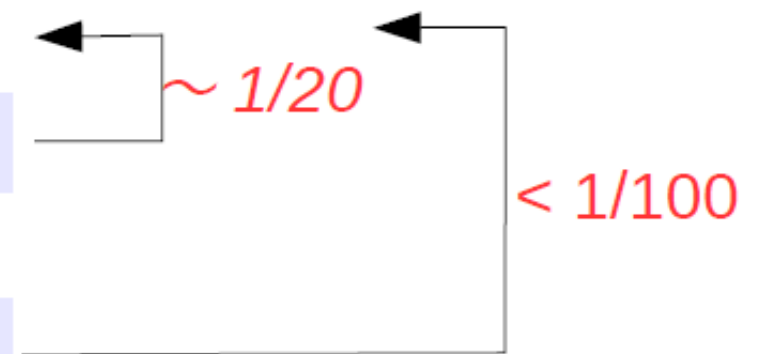
K. Ohmi and H. Koiso, IPAC'10 (2010)

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

- FF quad. fringes of SuperKEKB are very strong and comparable to kinematic terms

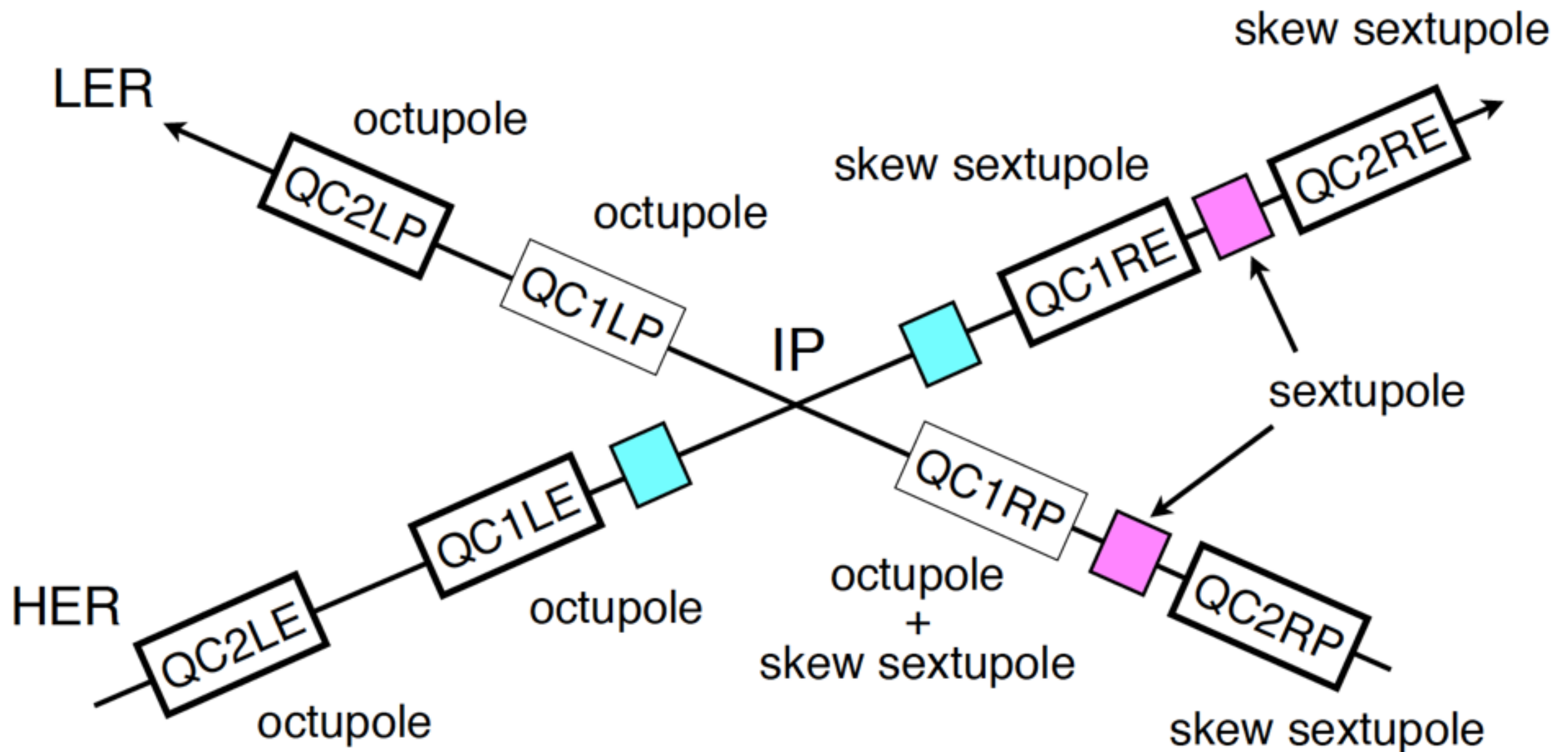
- β_y^* is the key parameter for DA

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



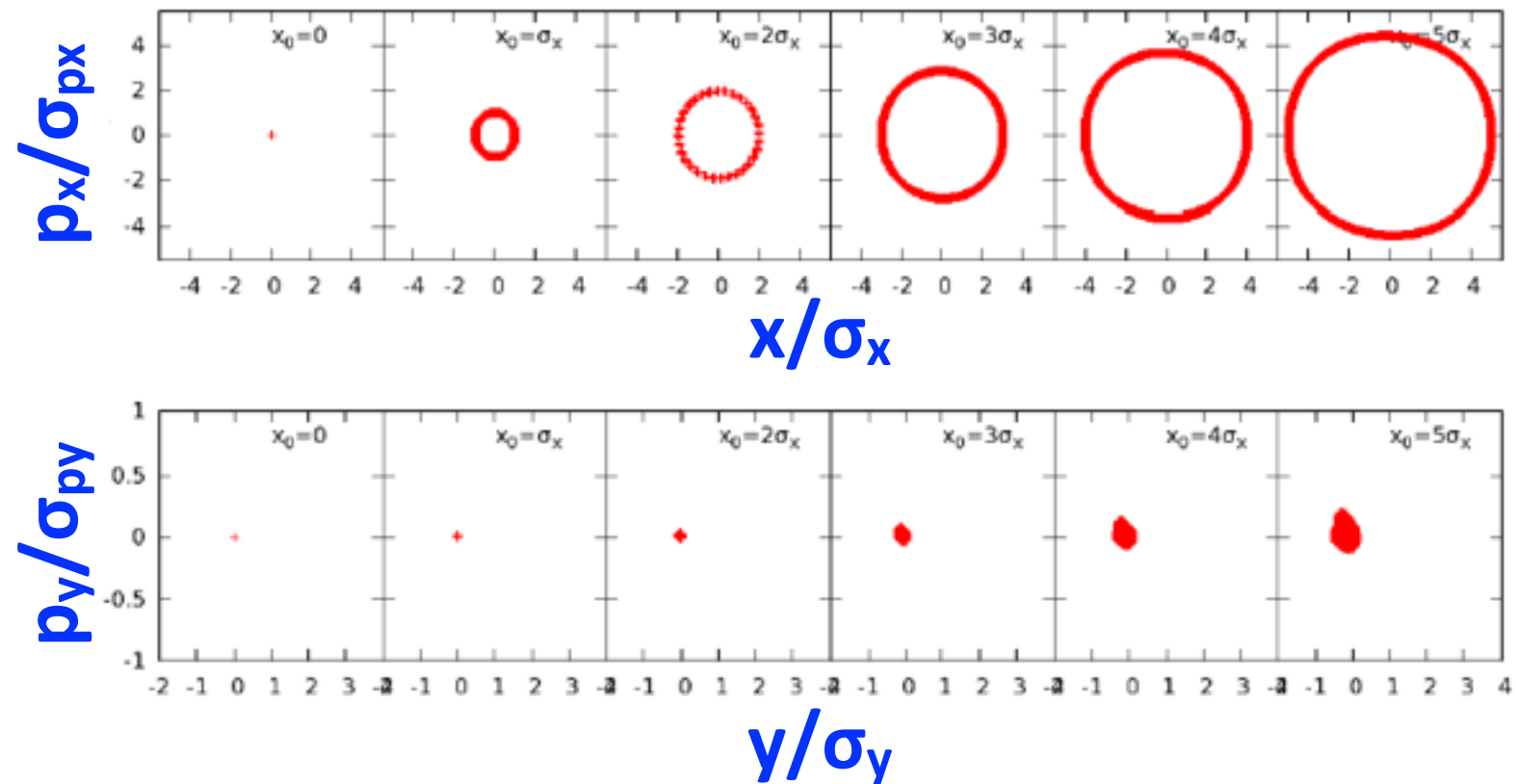
2. Beam dynamics issues: LN

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



2. Beam dynamics issues: LN

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

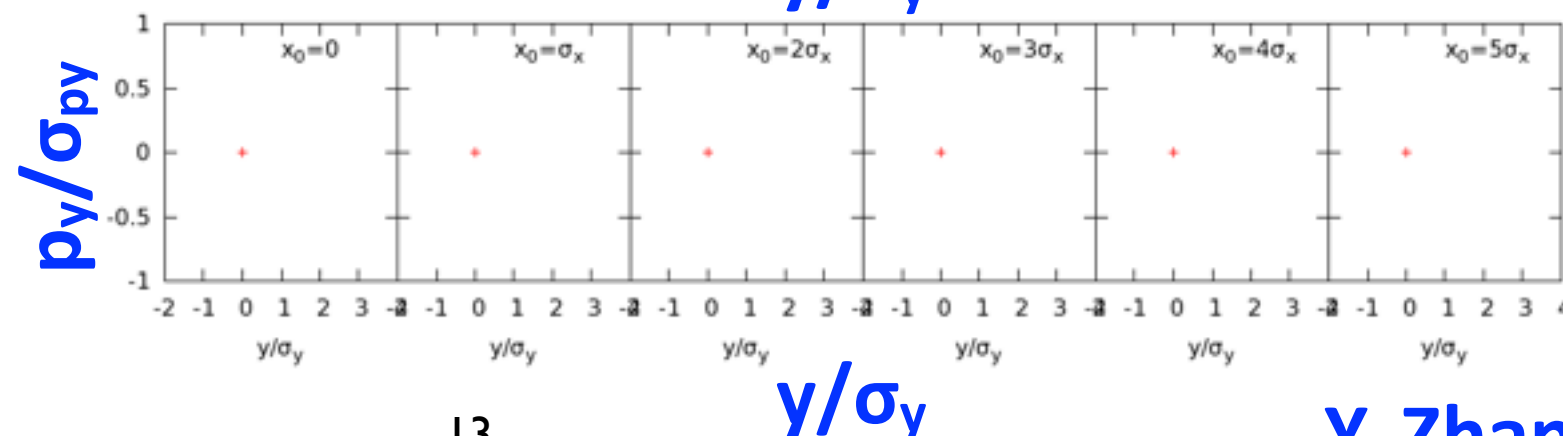
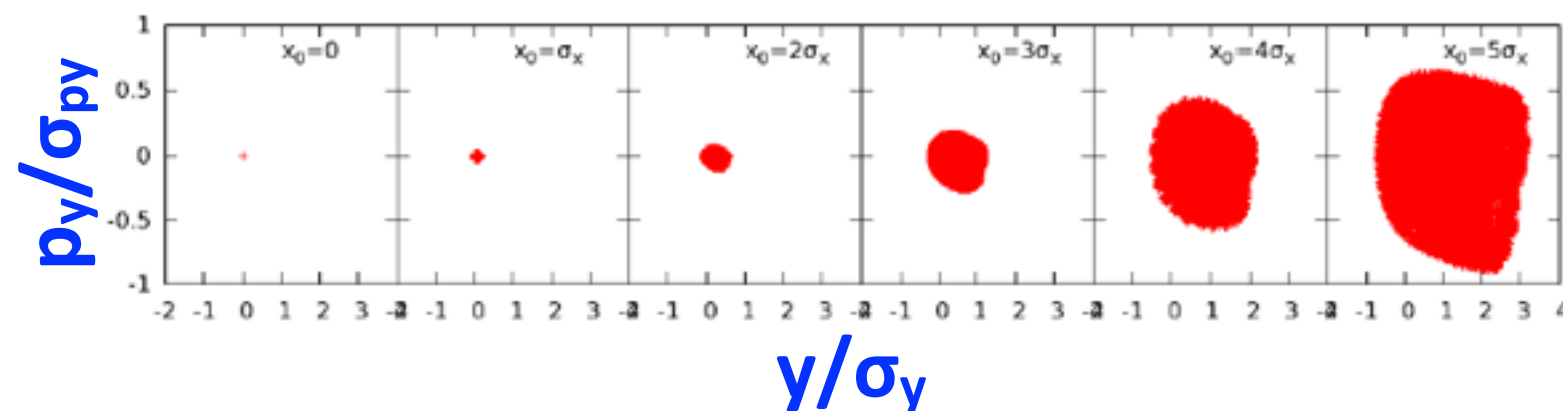
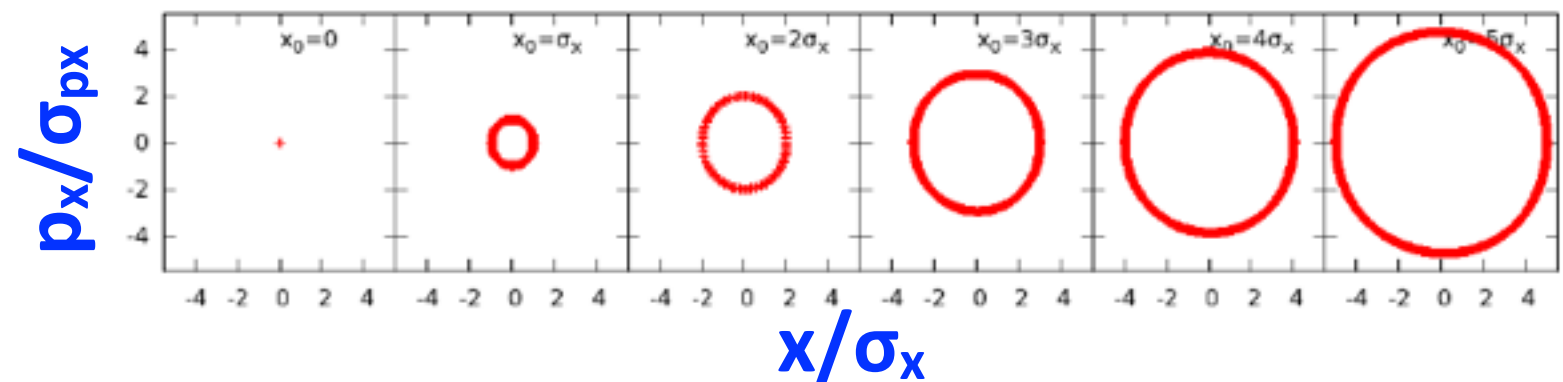


Baseline lattice



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



2. Beam dynamics issues: SC

➤ Linear tune shift

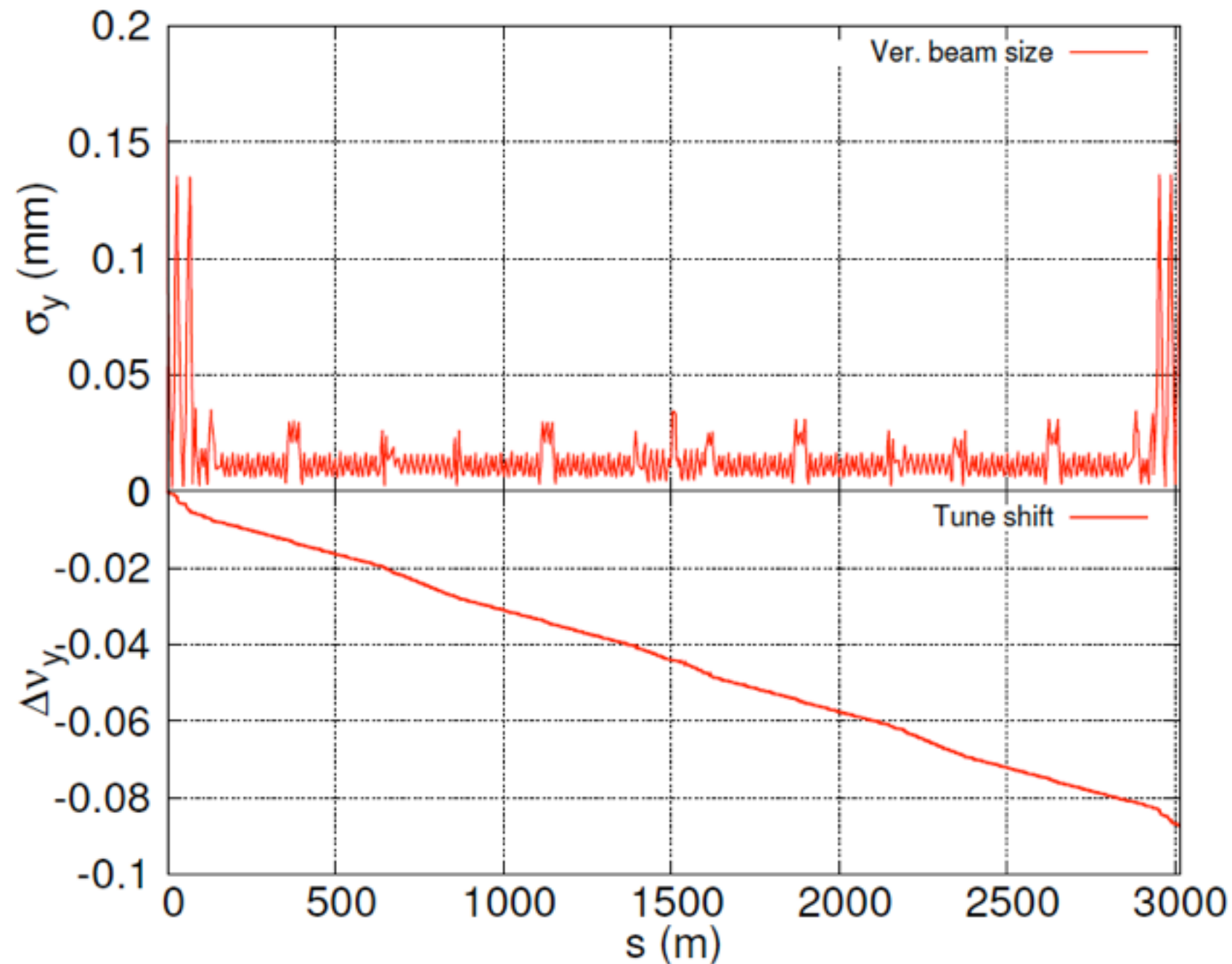
- Same level for SC and BB
- But have opposite signs

	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

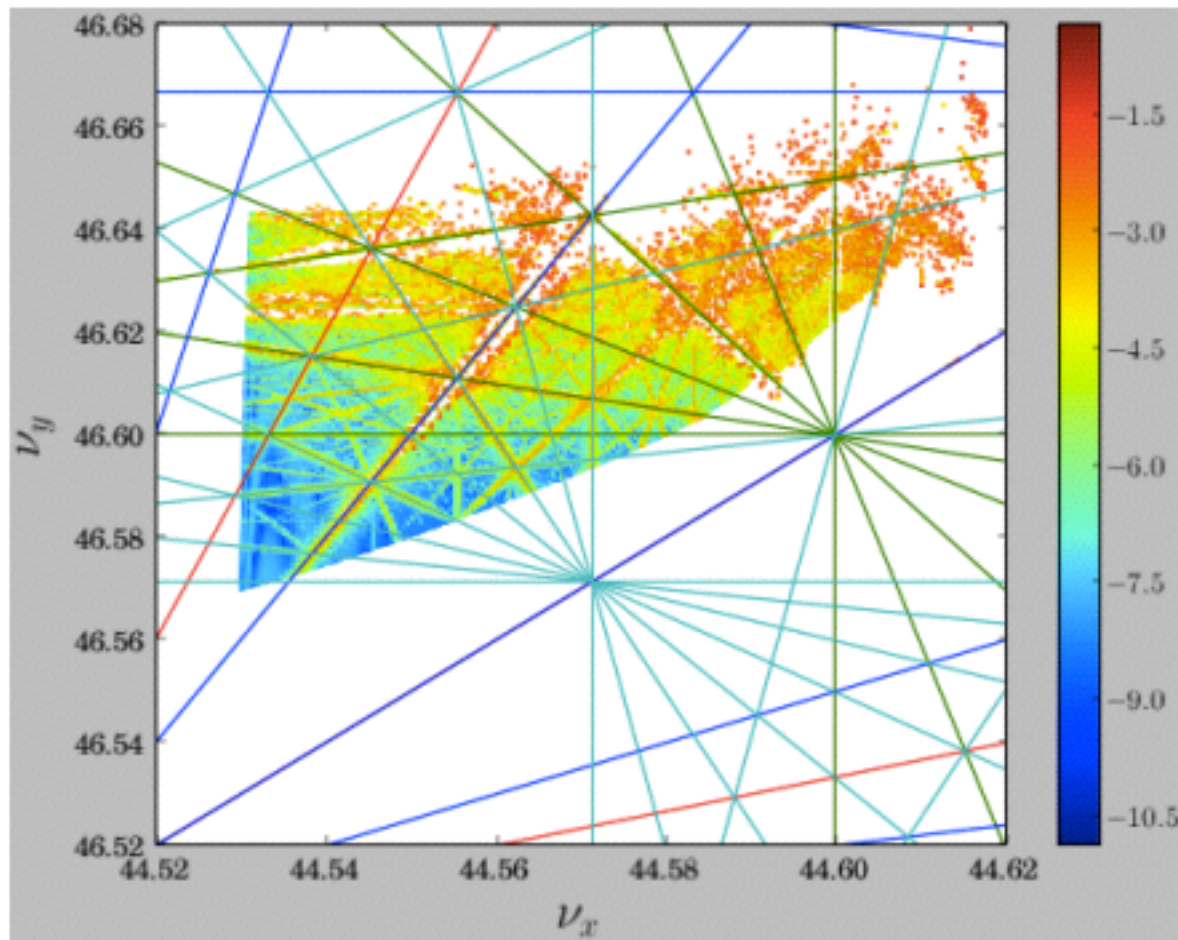


2. Beam dynamics issues: SC

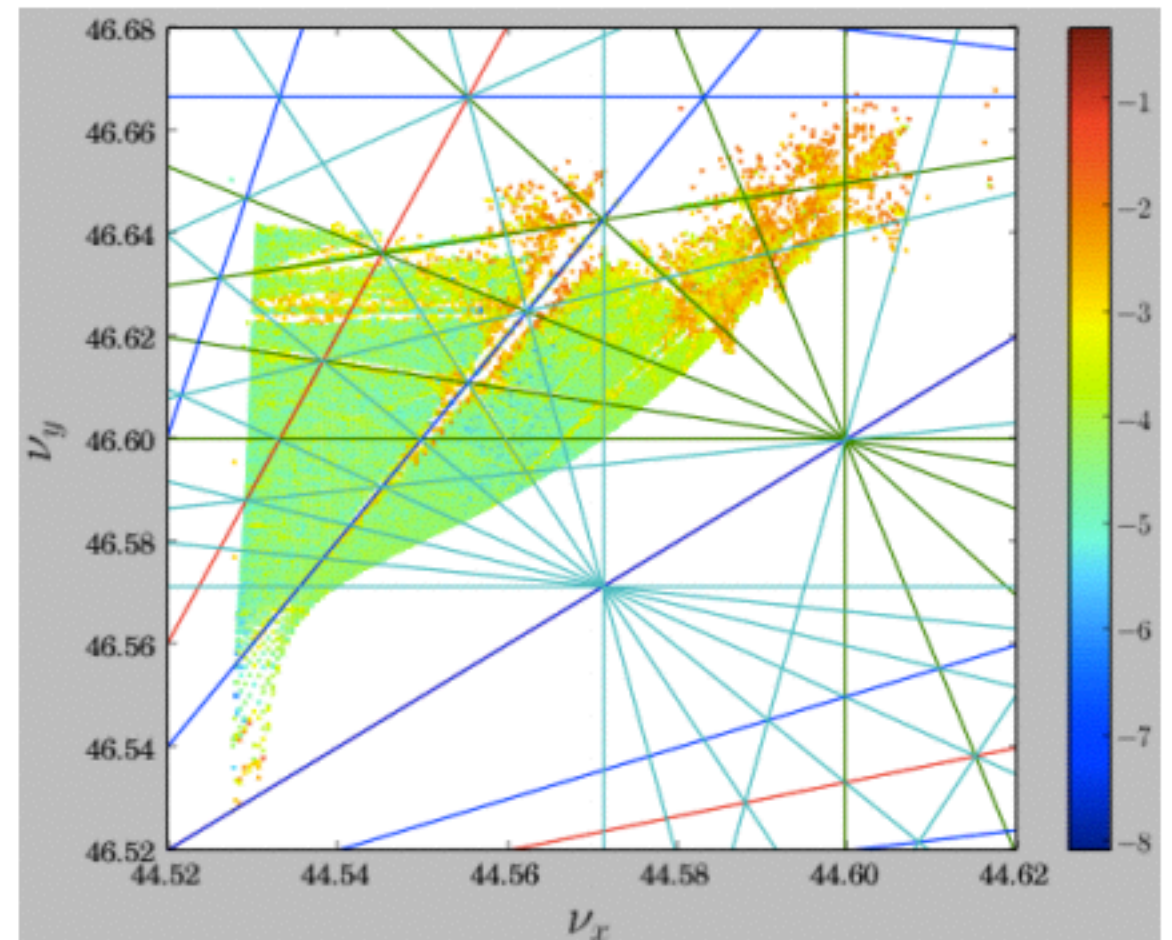
➤ FMA: SC drives the particles close to half-integer

- Weak-strong model for SC

W/O SCE



W/ SCE



4th order

5th order

6th order

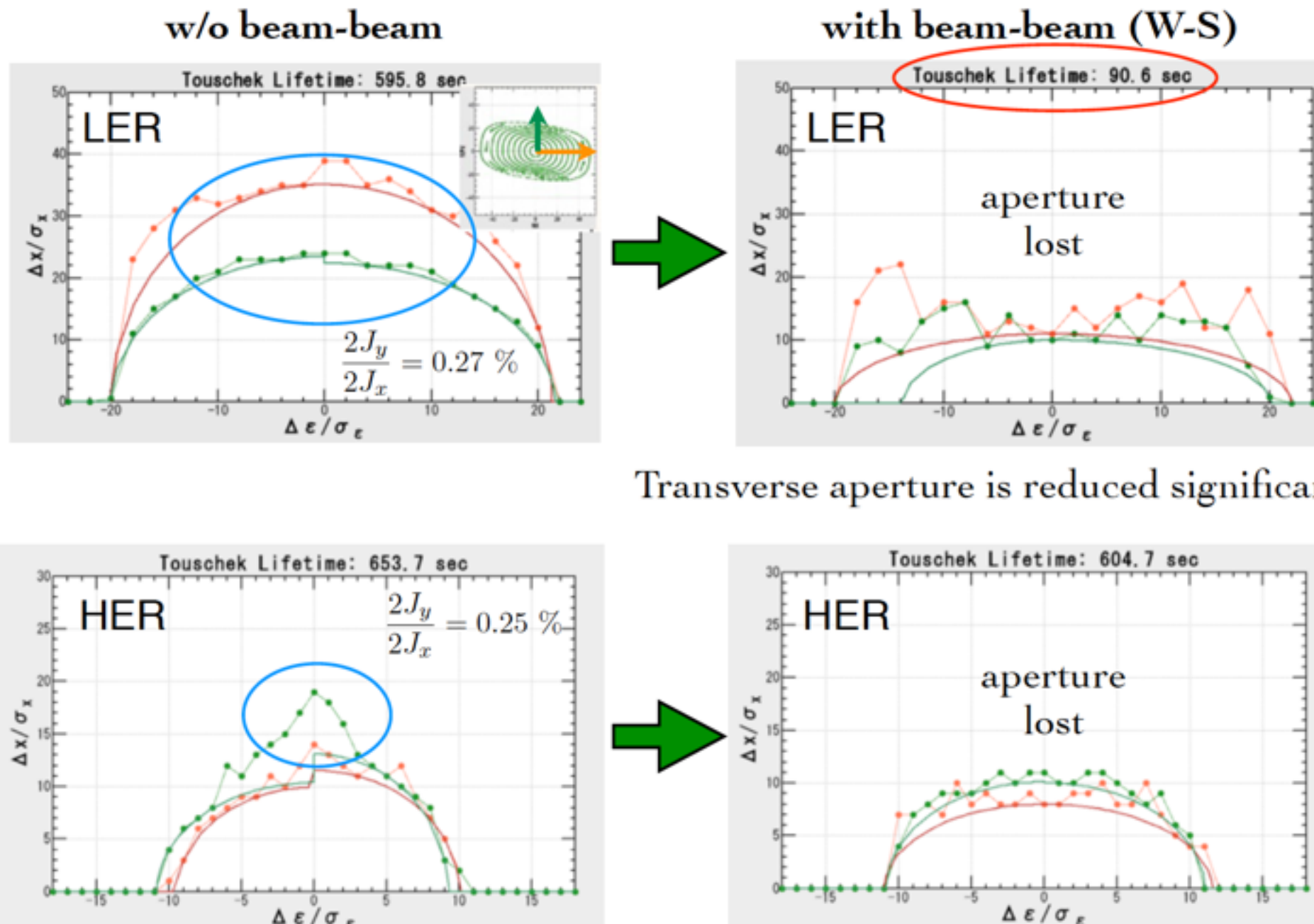
7th order

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

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

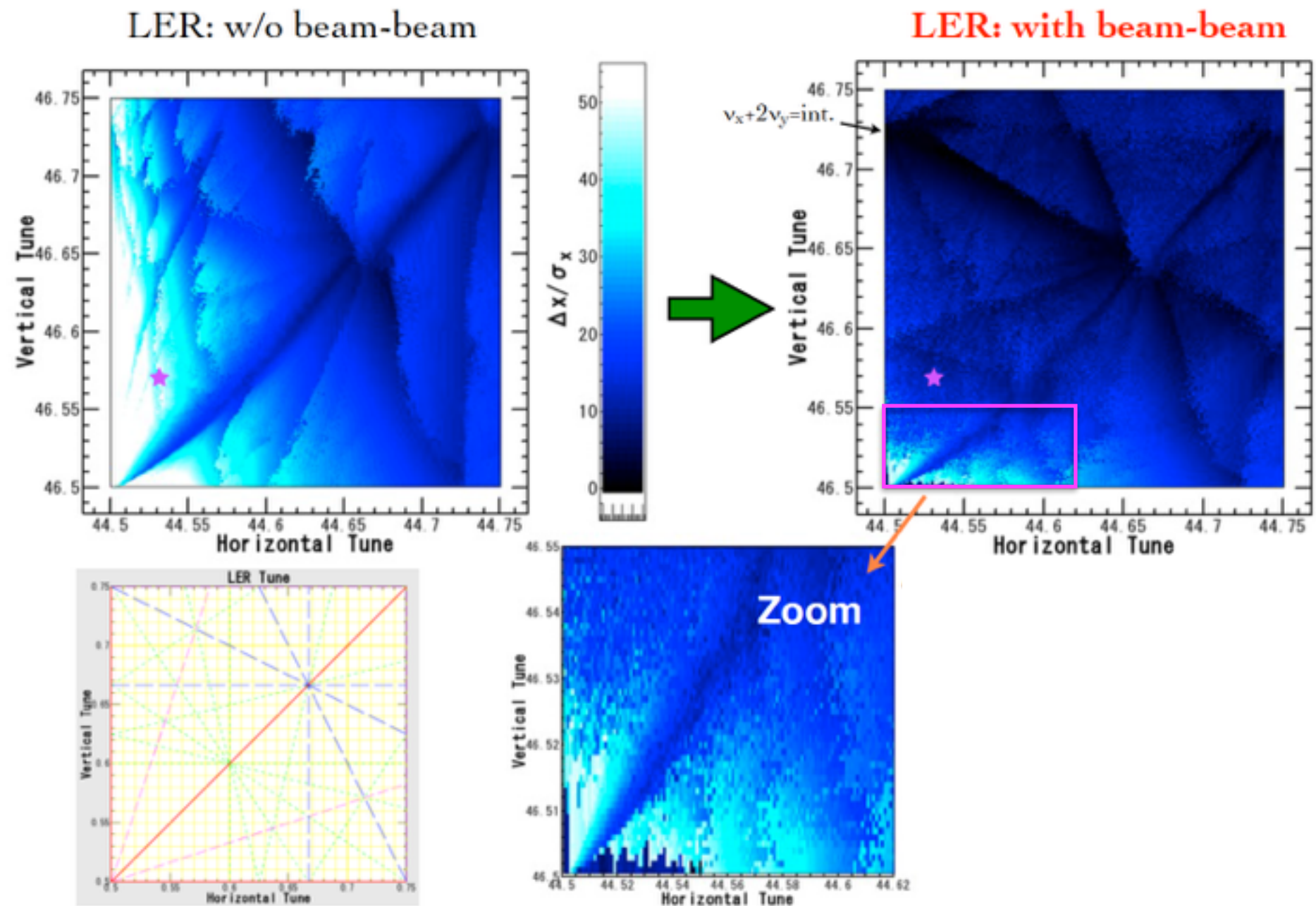


Transverse aperture is reduced significantly.

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

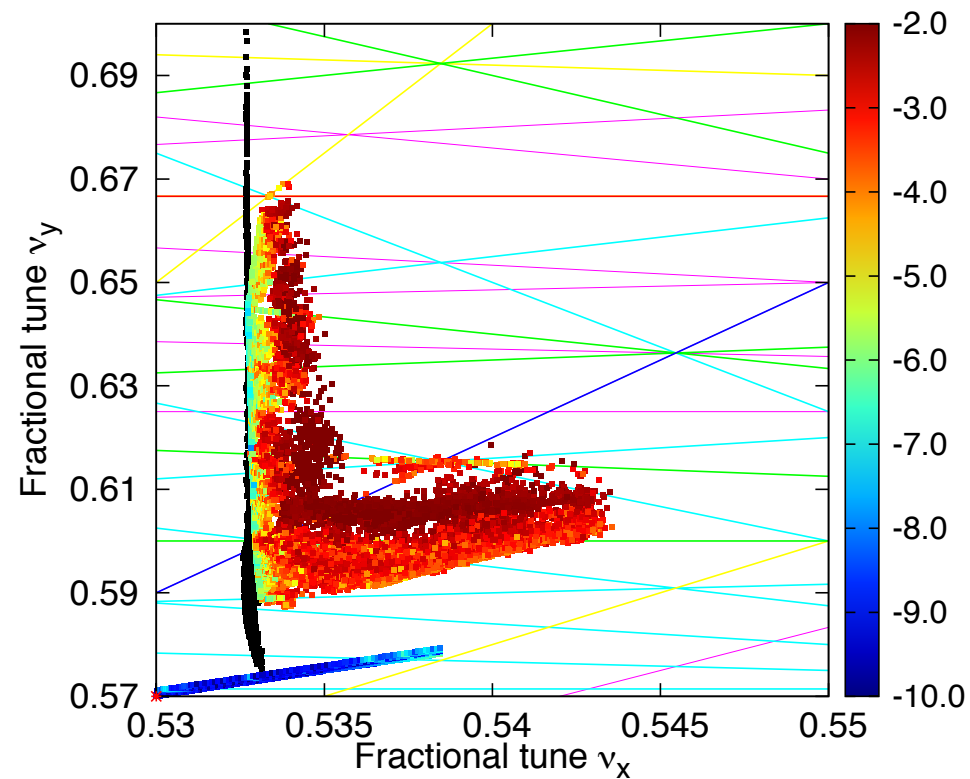


3. Interplay: Baseline lattice: **BB+LN**

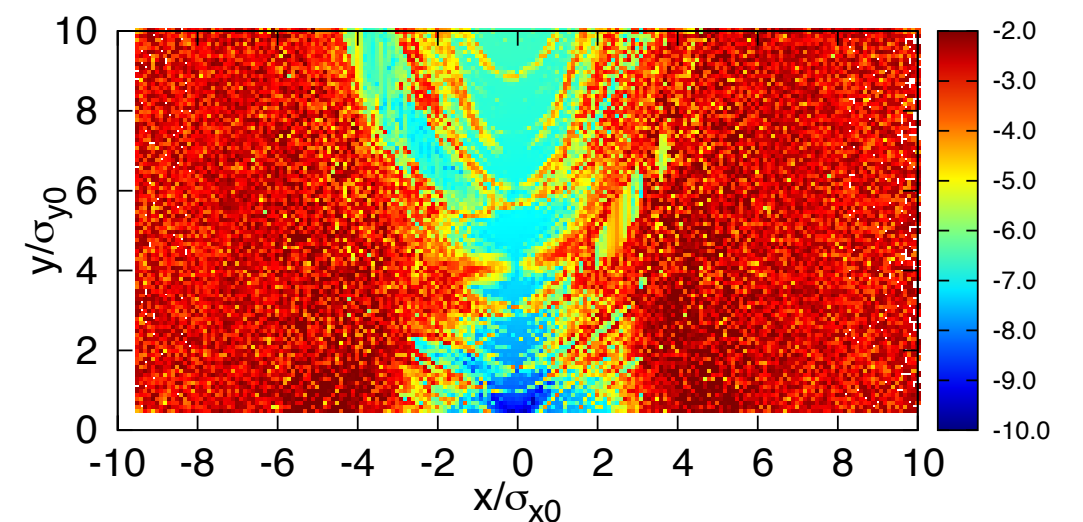
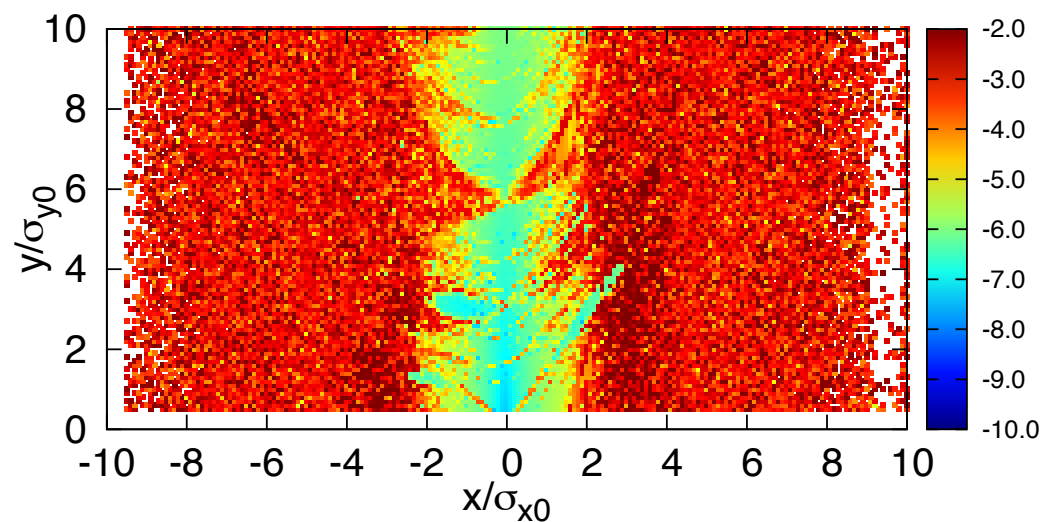
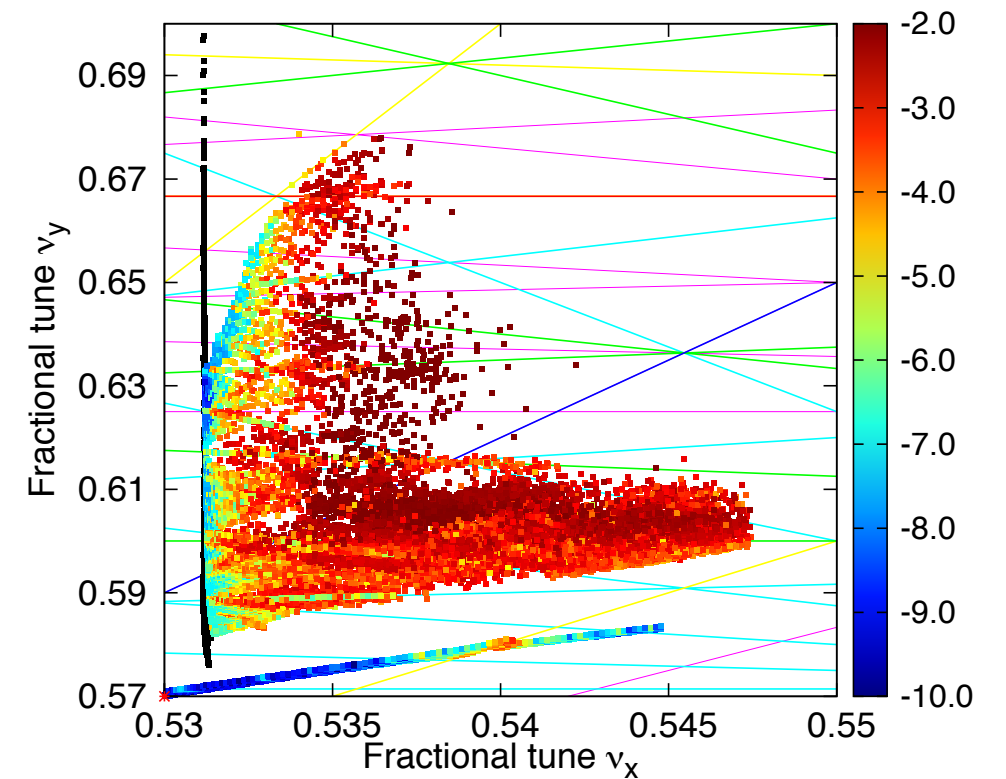
➤ FMA with beam distribution: $10\sigma_x \times 10\sigma_y$

- Footprint in the tune space extended

BB+LN (LER)



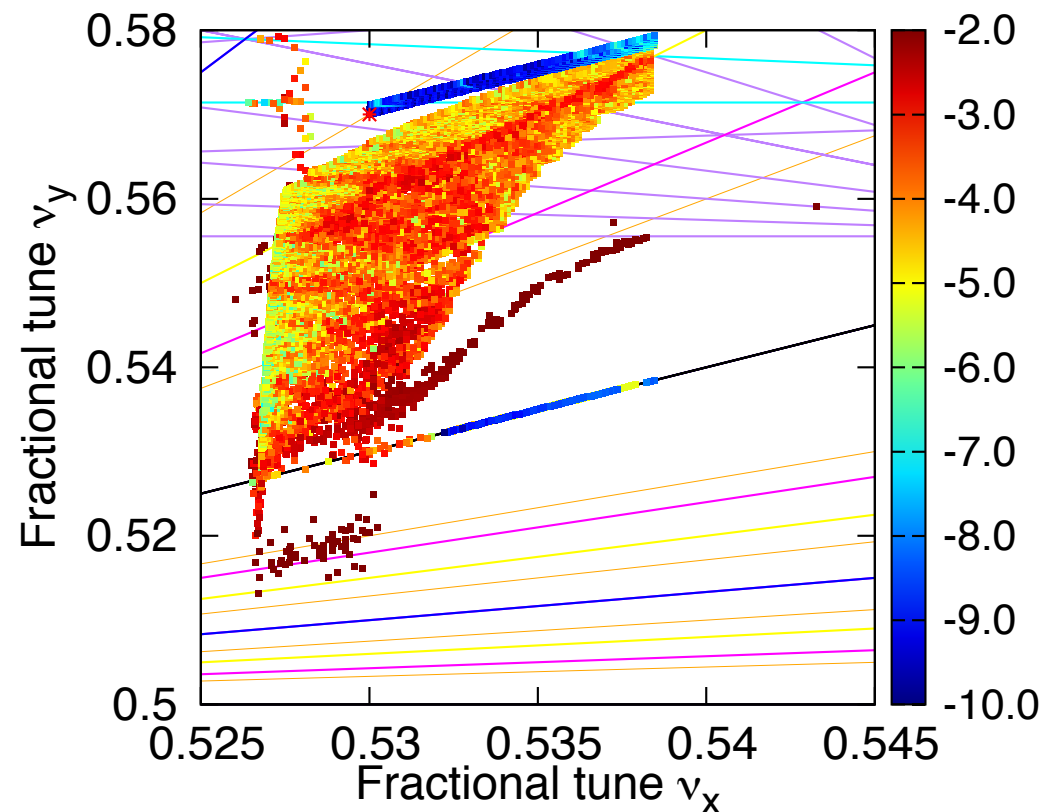
BB+LN (HER)



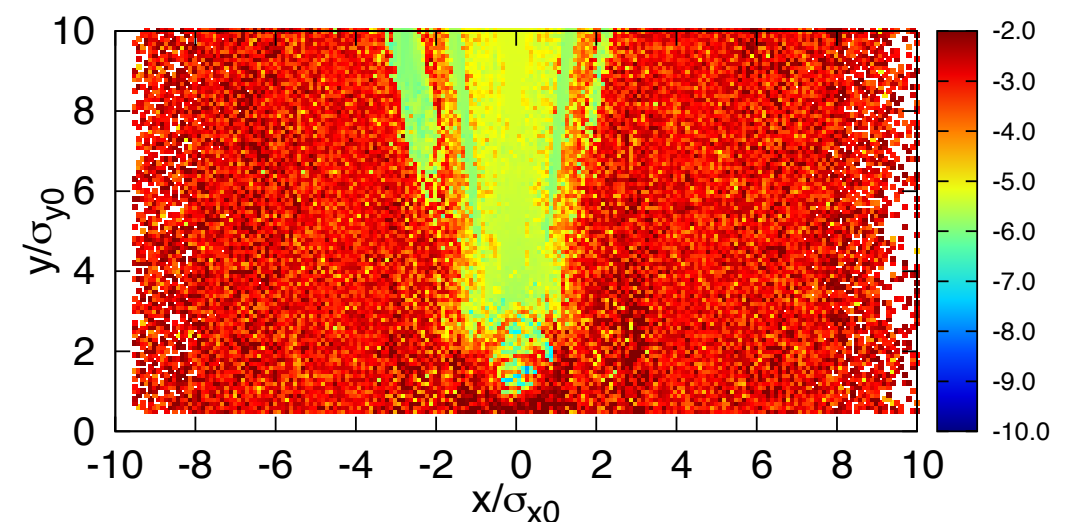
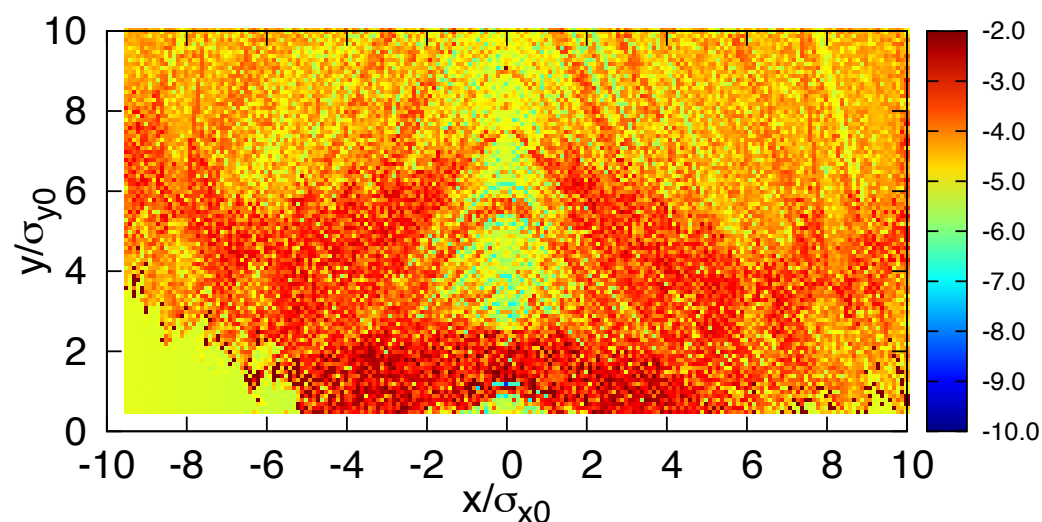
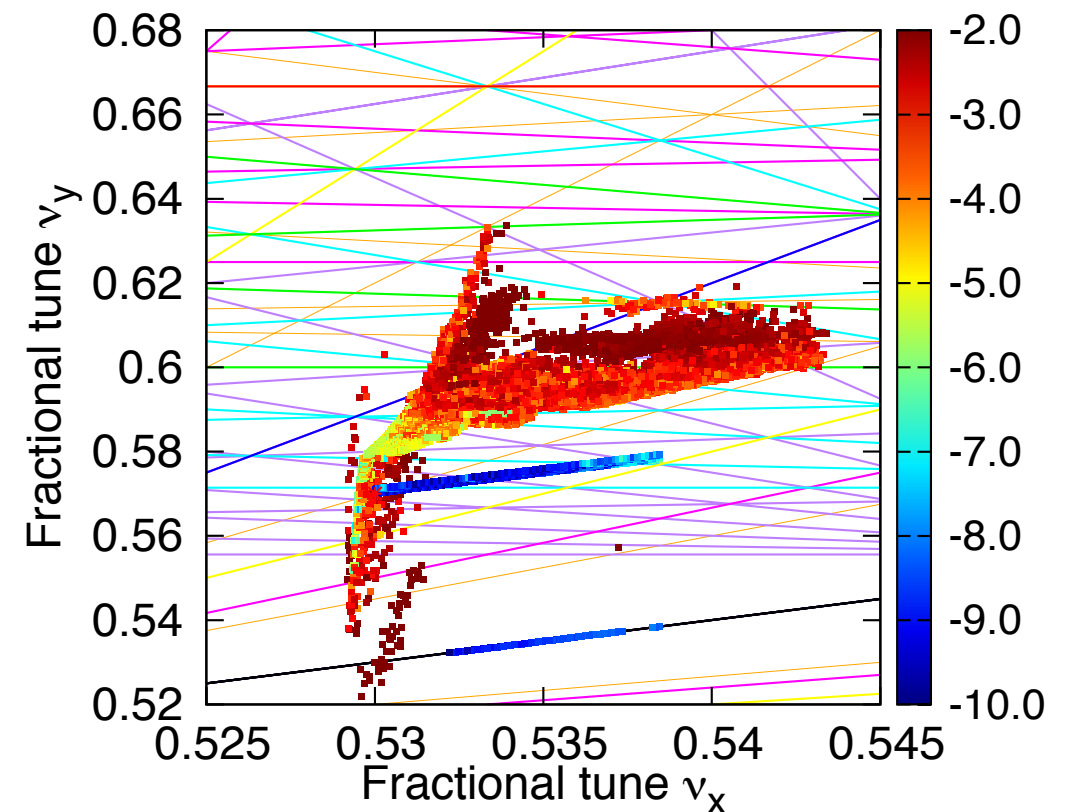
3. Interplay: Baseline lattice: **BB+LN+SC**

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

SC+LN (LER)

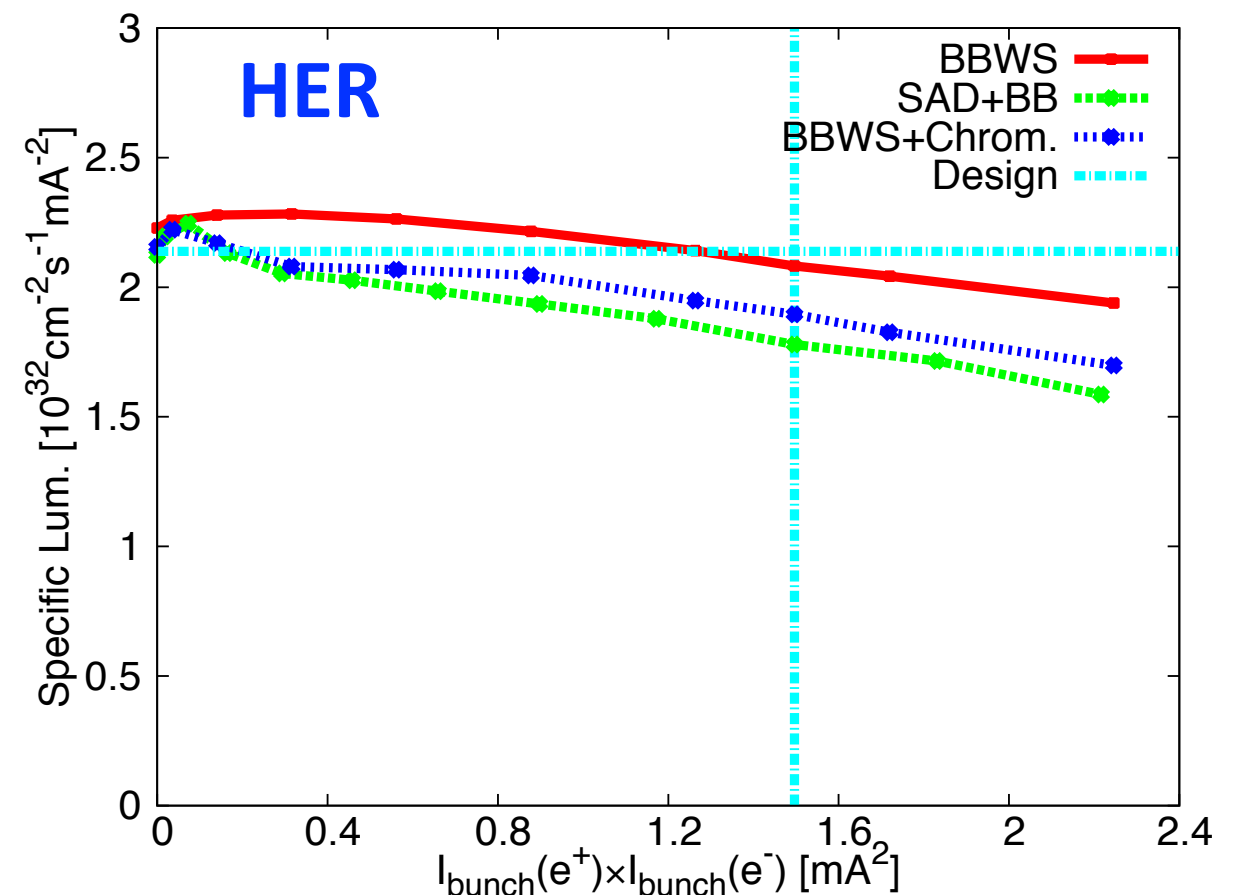
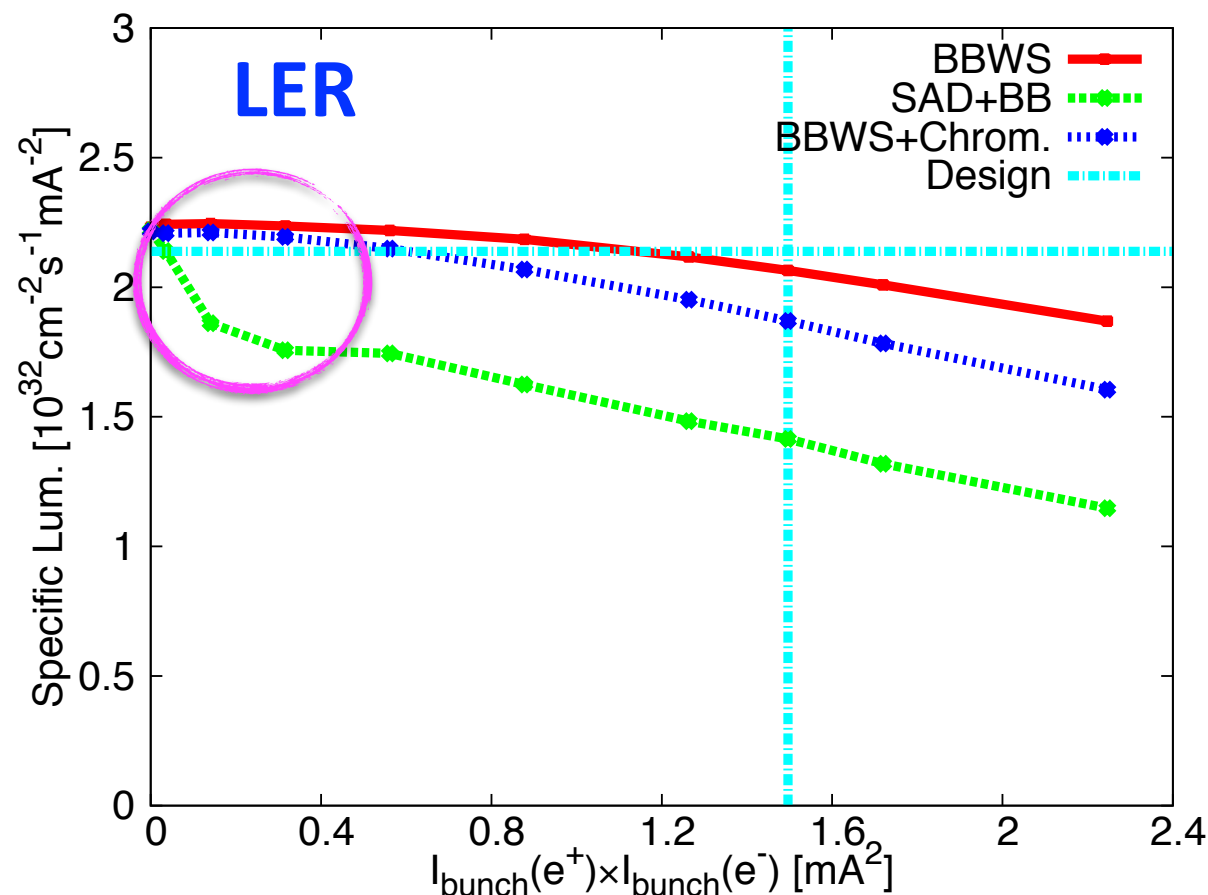


BB+LN+SC (LER)



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

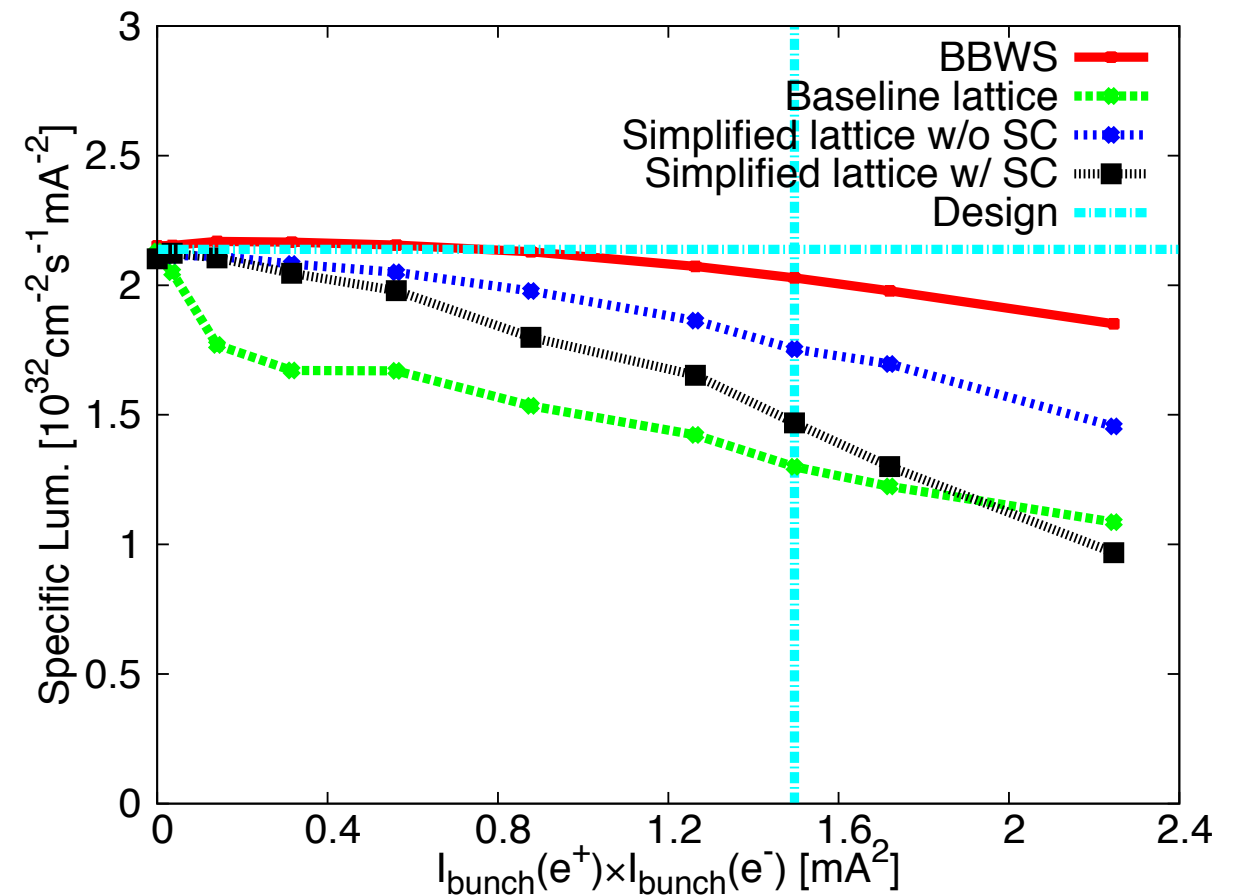
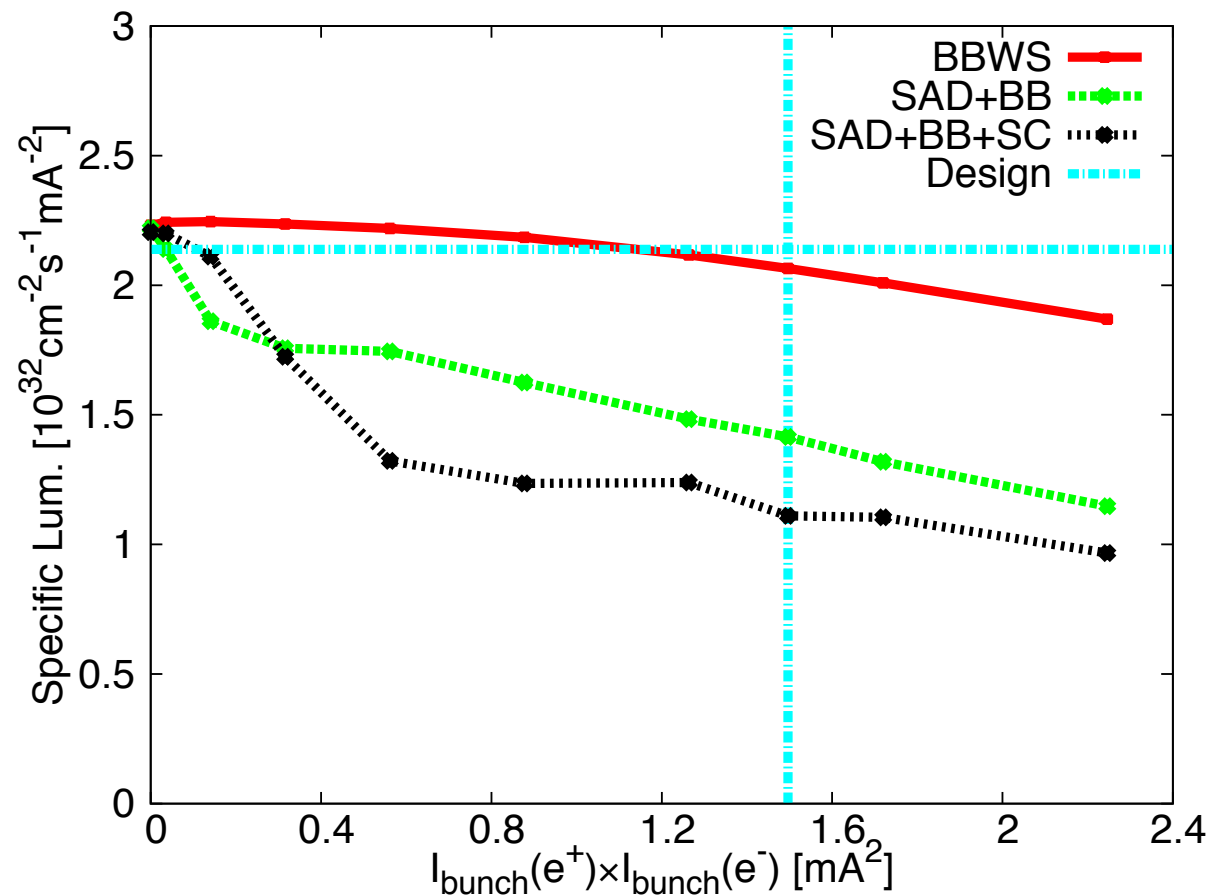
- BB+LN cause significant lum. loss
- LER: Lum. loss is attributed to amplitude-dependent nonlin.
 - Vertical emittance is very sensitive to beam-beam perturbation
 - Hard to suppress
 - Lum. loss starts from low currents (due to solenoids)
- HER: Lum. loss is attributed to chromatic nonlin.
 - Controllable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

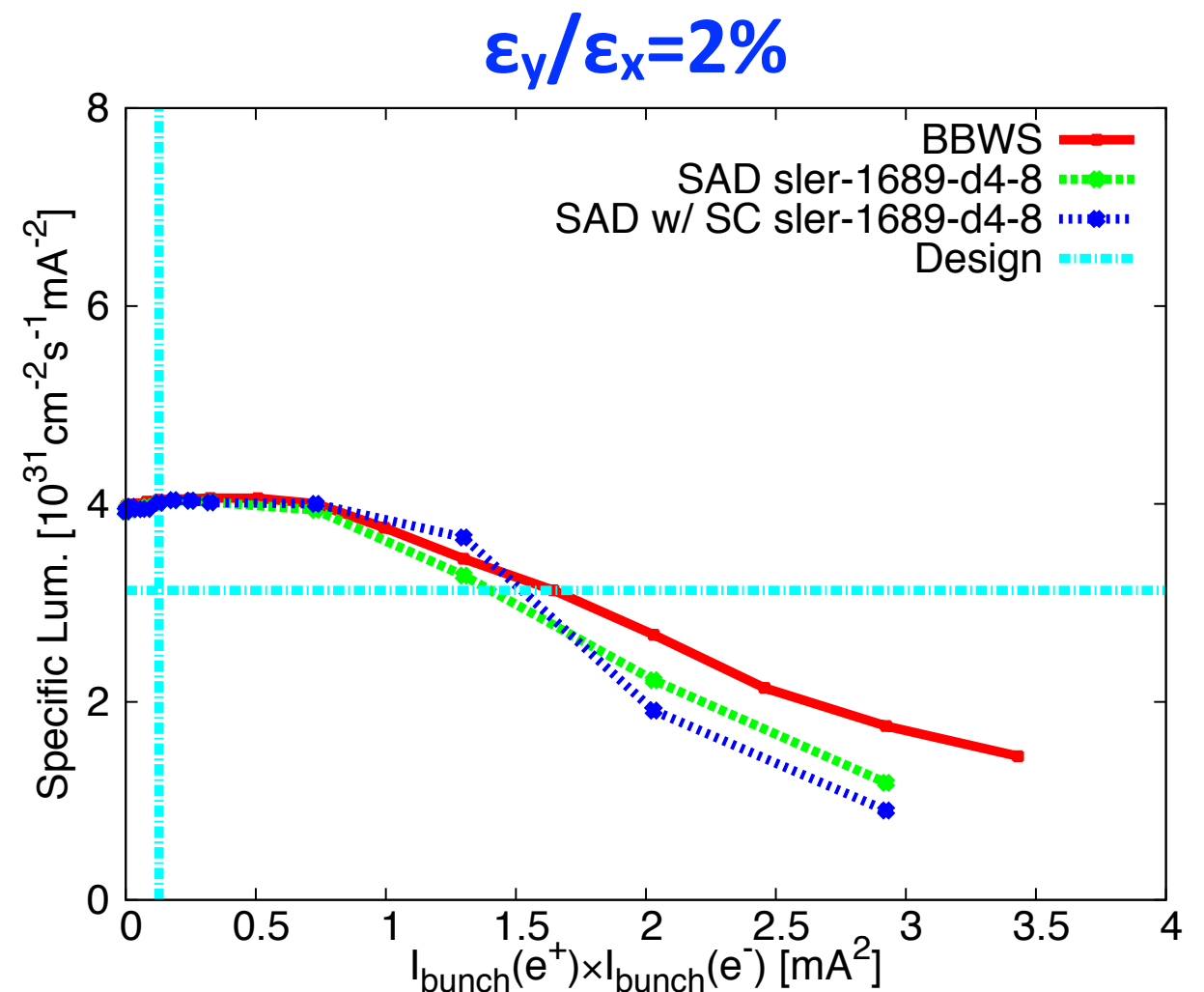
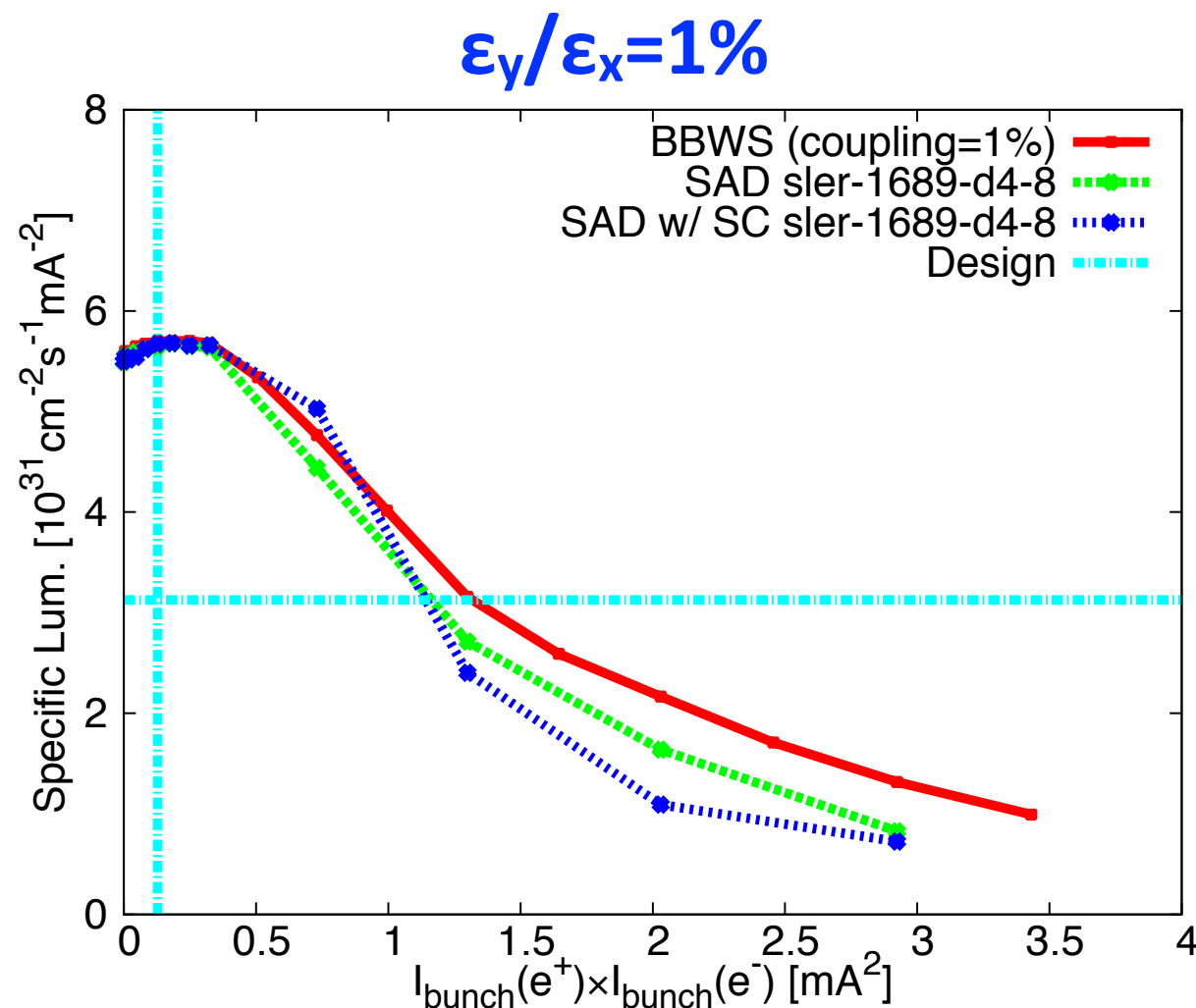
► Detuned lattice for **Phase 2** of SuperKEKB

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

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	ϵ_y/ϵ_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	1×10^{34}		8×10^{35}		$\text{cm}^{-2}\text{s}^{-1}$

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
- $L=1 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$ is promising
- $L=10 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$ is possible by increasing beam currents



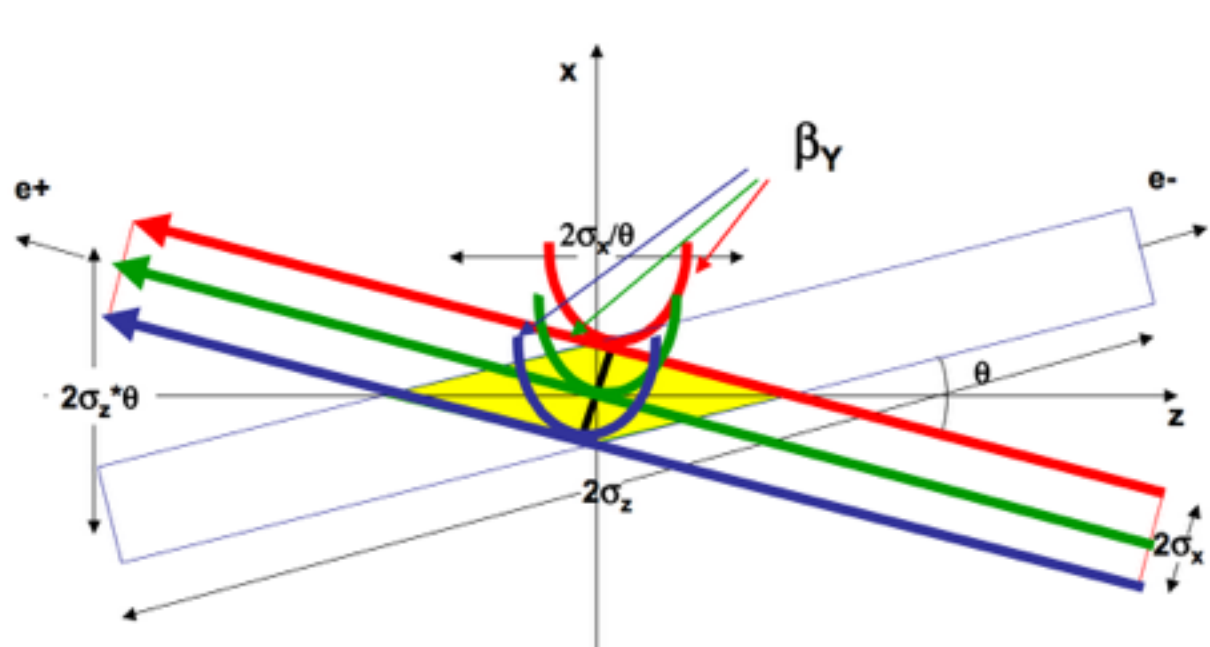
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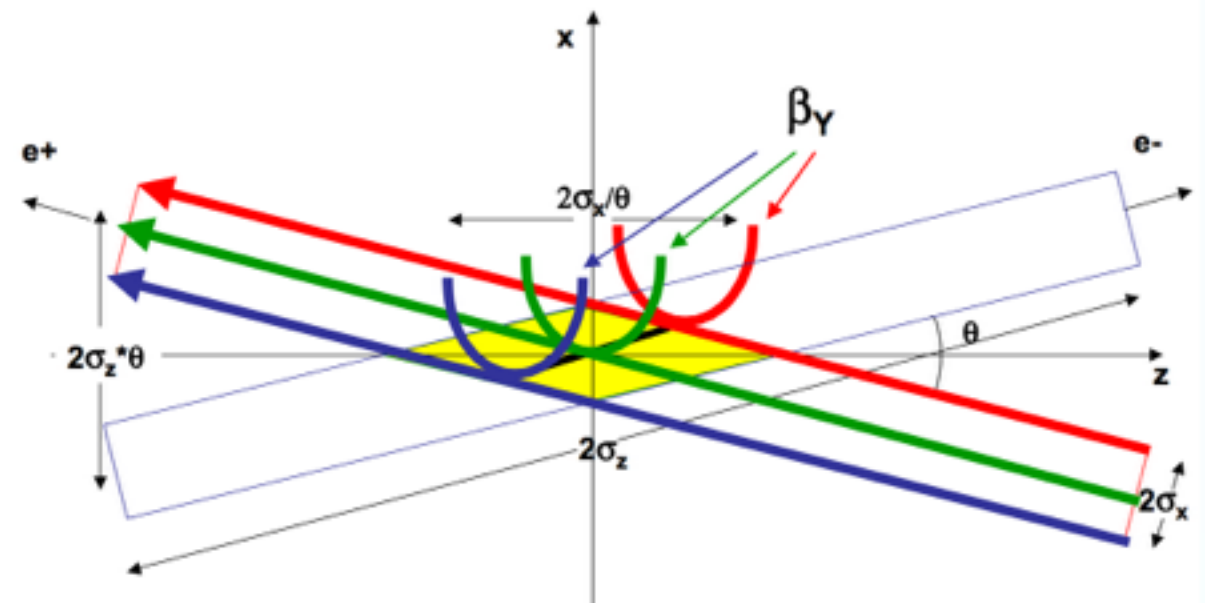
4. Mitigation schemes: CW

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

w/o CW



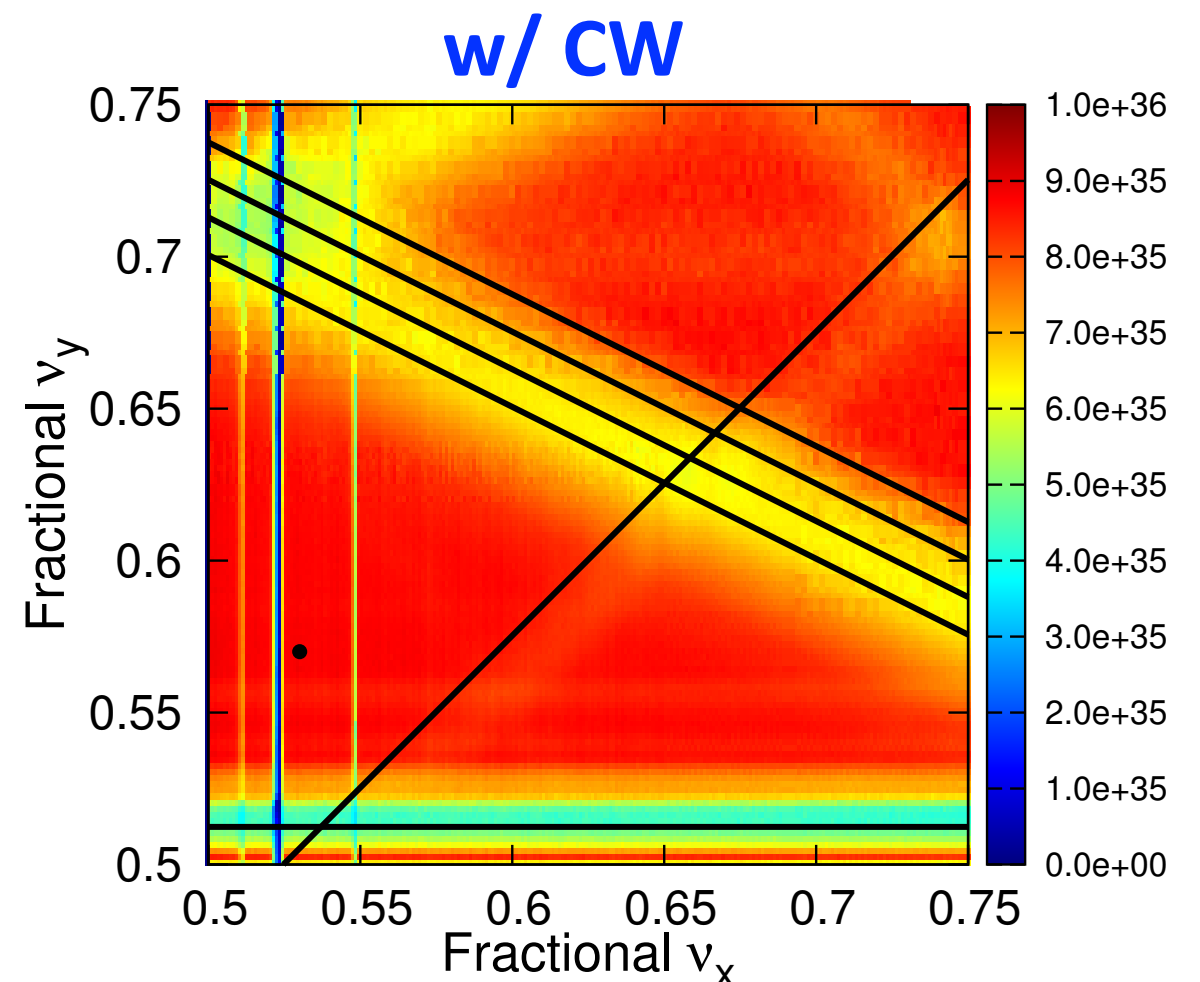
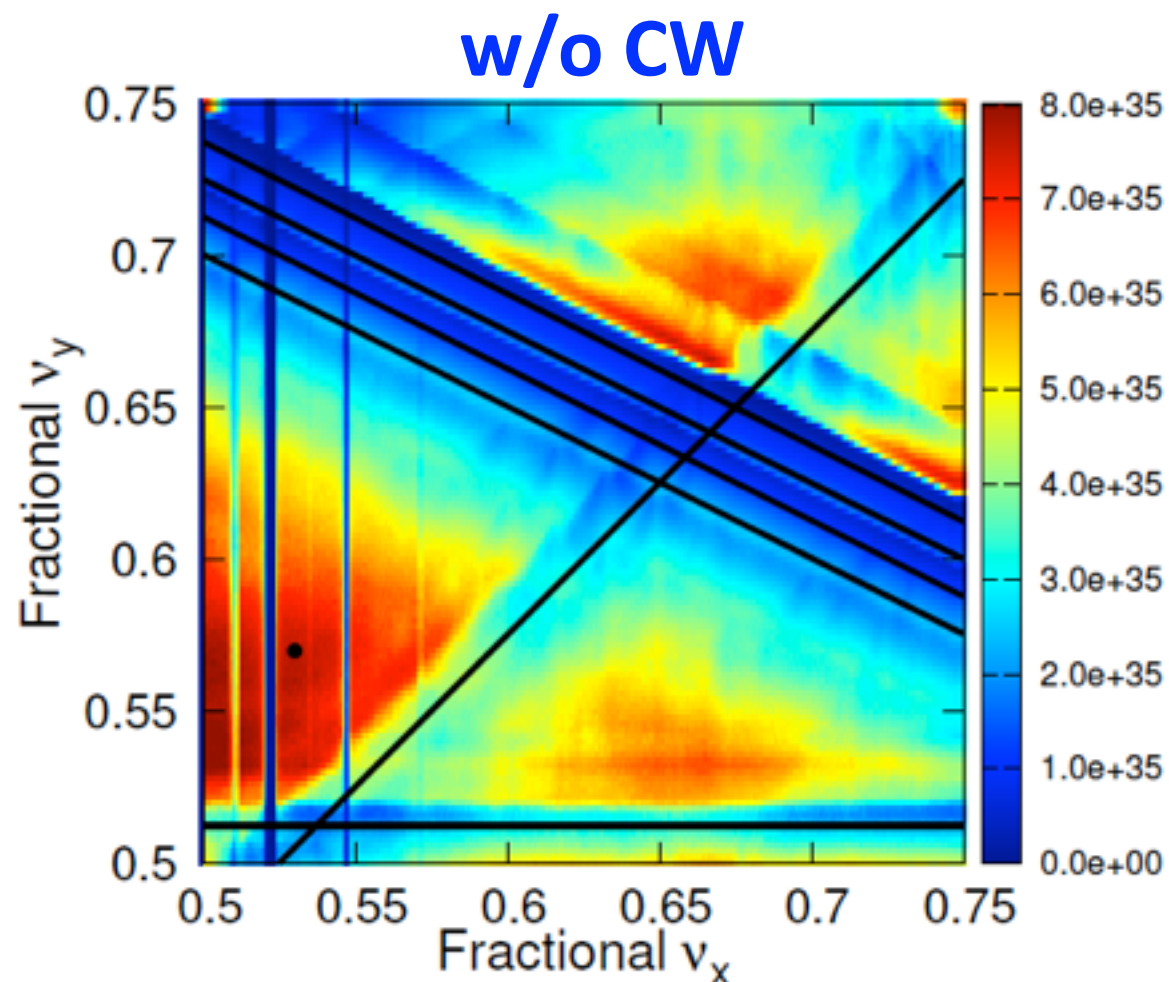
w/ CW



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

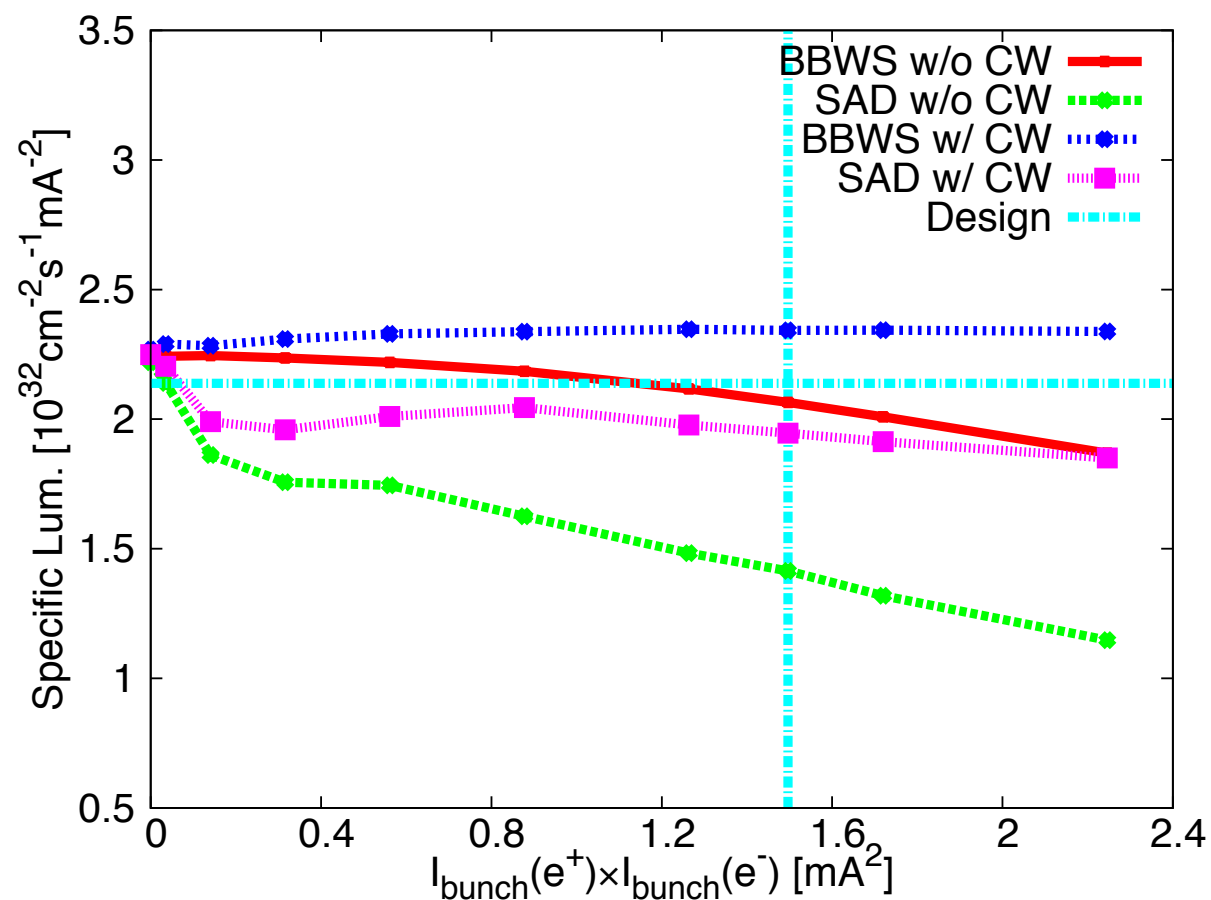
➤ Ideal CW ($M=M_{CW}M_{BB}M_{CW}^{-1}$):

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

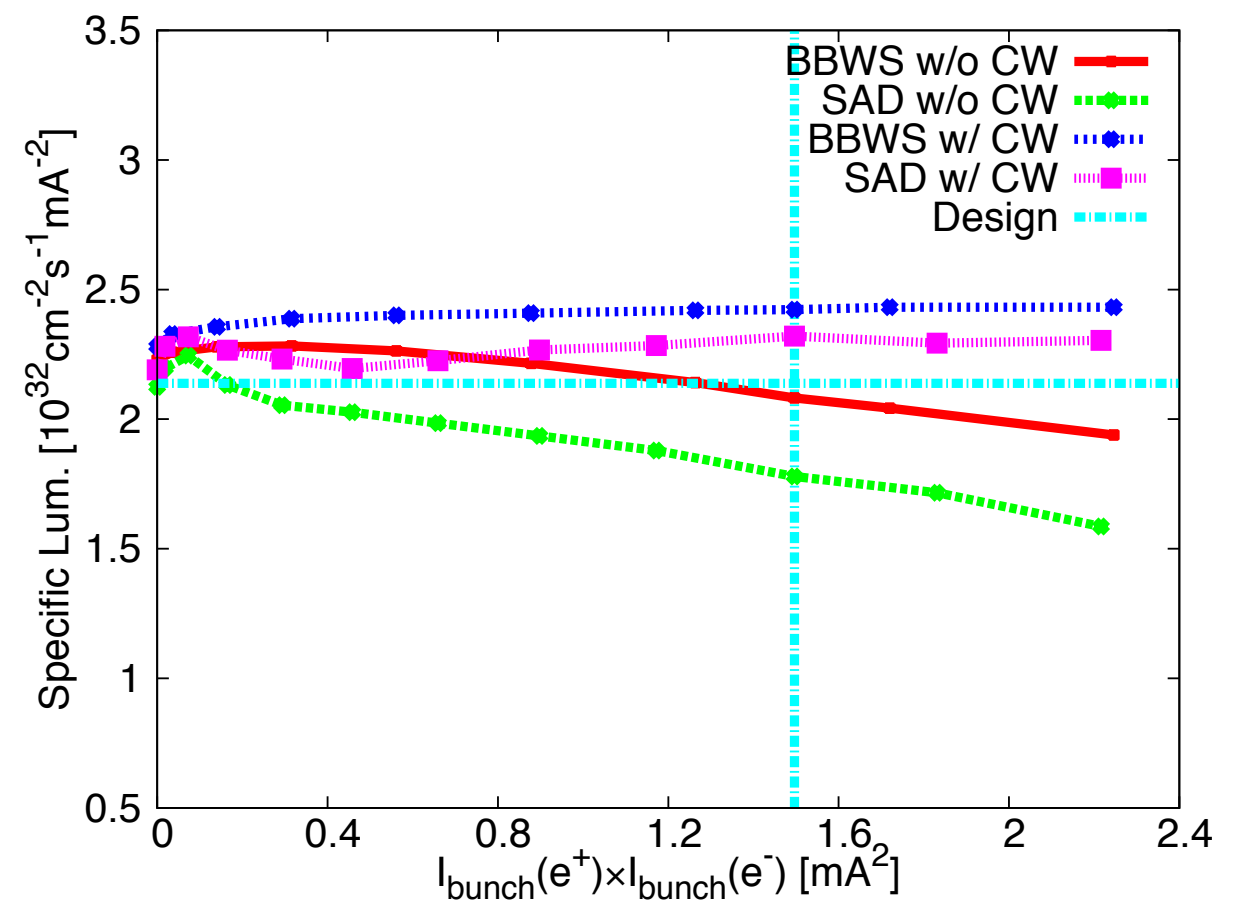
➤ Real lattice w/ ideal CW:

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

LER



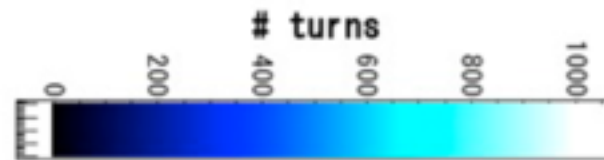
HER



4. Mitigation schemes: CW: DA

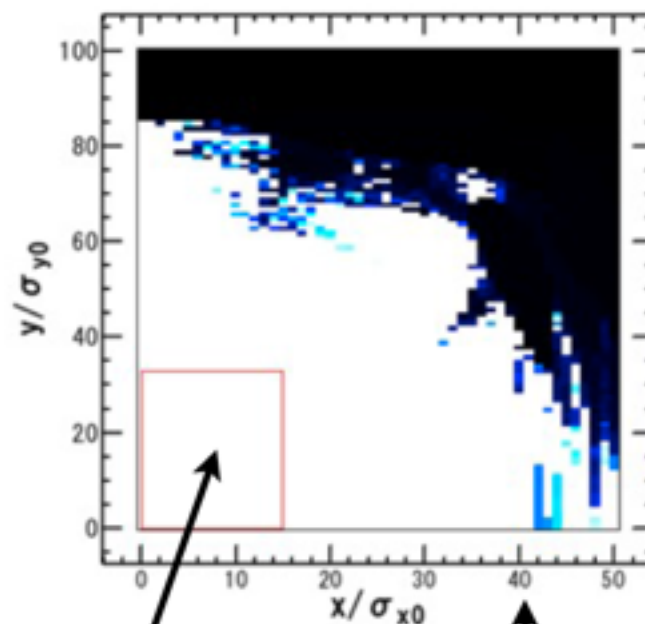
➤ DA: BB + ideal CW: LER

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



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

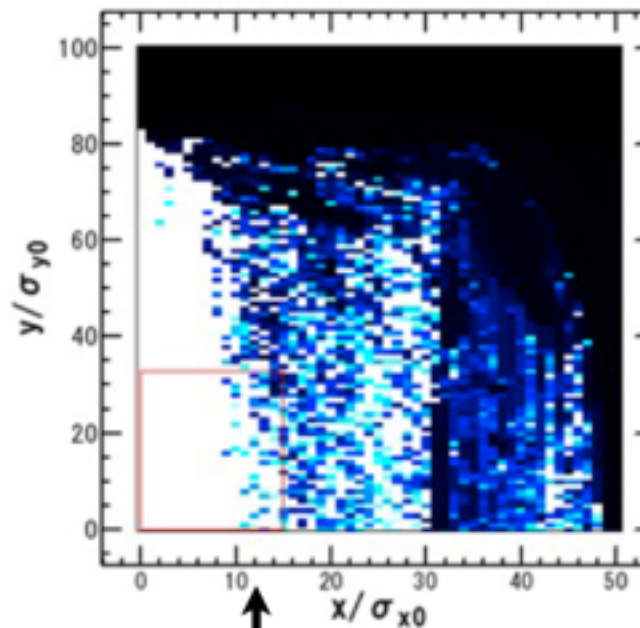
Ideal LER lattice



injection
aperture

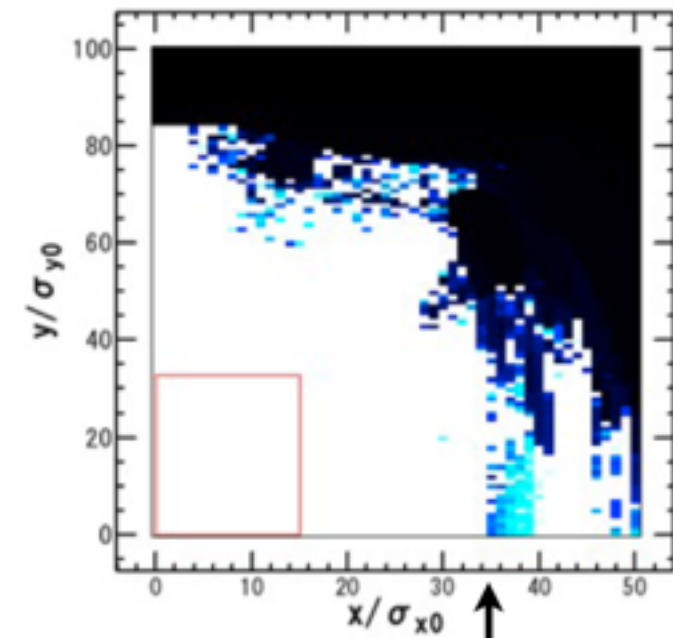
aperture
limit

with Beam-Beam



aperture
limit

with Beam-Beam
with ideal CW



aperture
limit

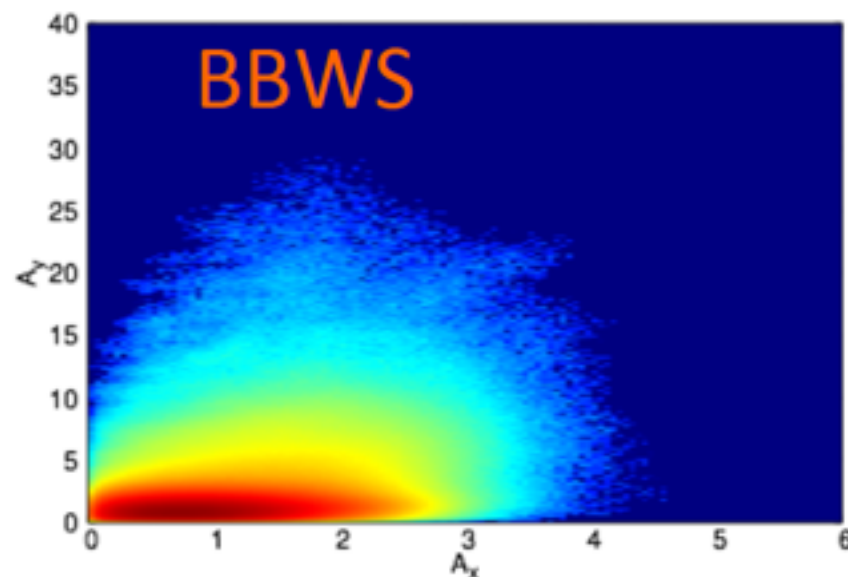
Ideal crab-waist is a map of $f_{BB} \rightarrow f_{CW}(+\lambda)f_{BB}f_{CW}(-\lambda)$ $\lambda = \frac{1}{\tan 2\phi_x}$
 $f_{CW}(\lambda) : p_x \rightarrow p_x + \frac{\lambda}{2}p_y^2, y \rightarrow y - \lambda xp_y$

4. Mitigation schemes: CW: Beam tail

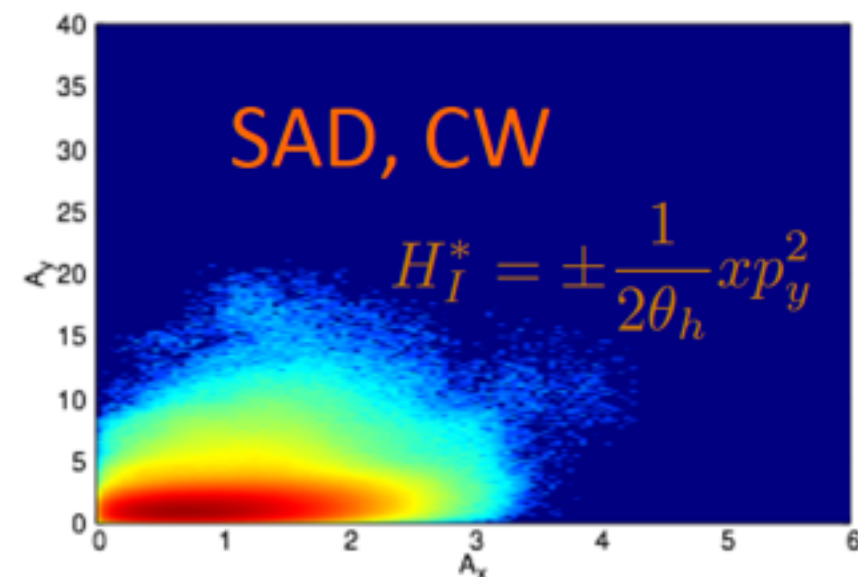
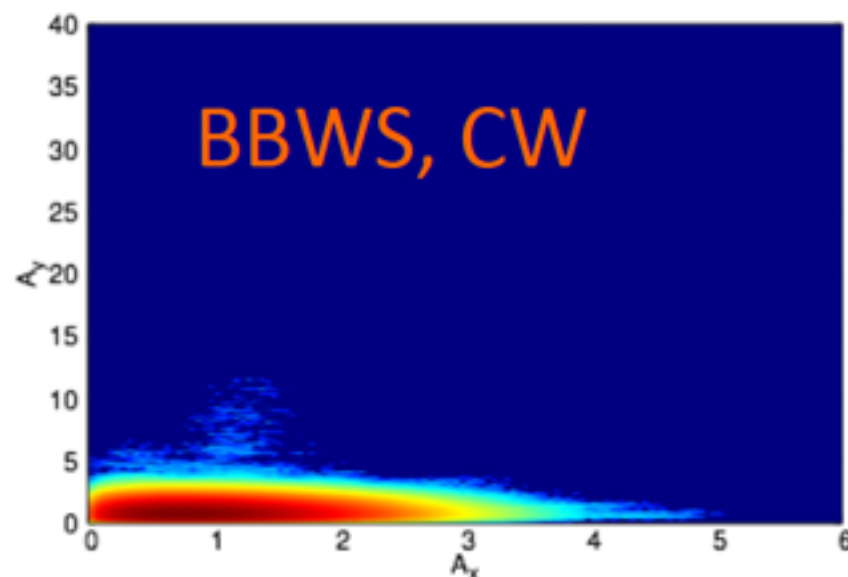
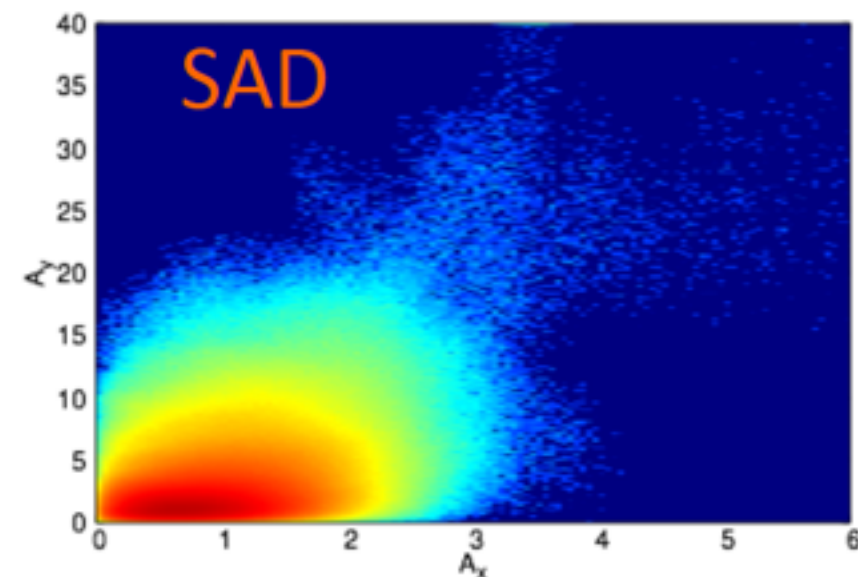
➤ Beam tail distribution: Ideal CW: LER

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

- $N_e = 6.53 \times 10^{10}$,



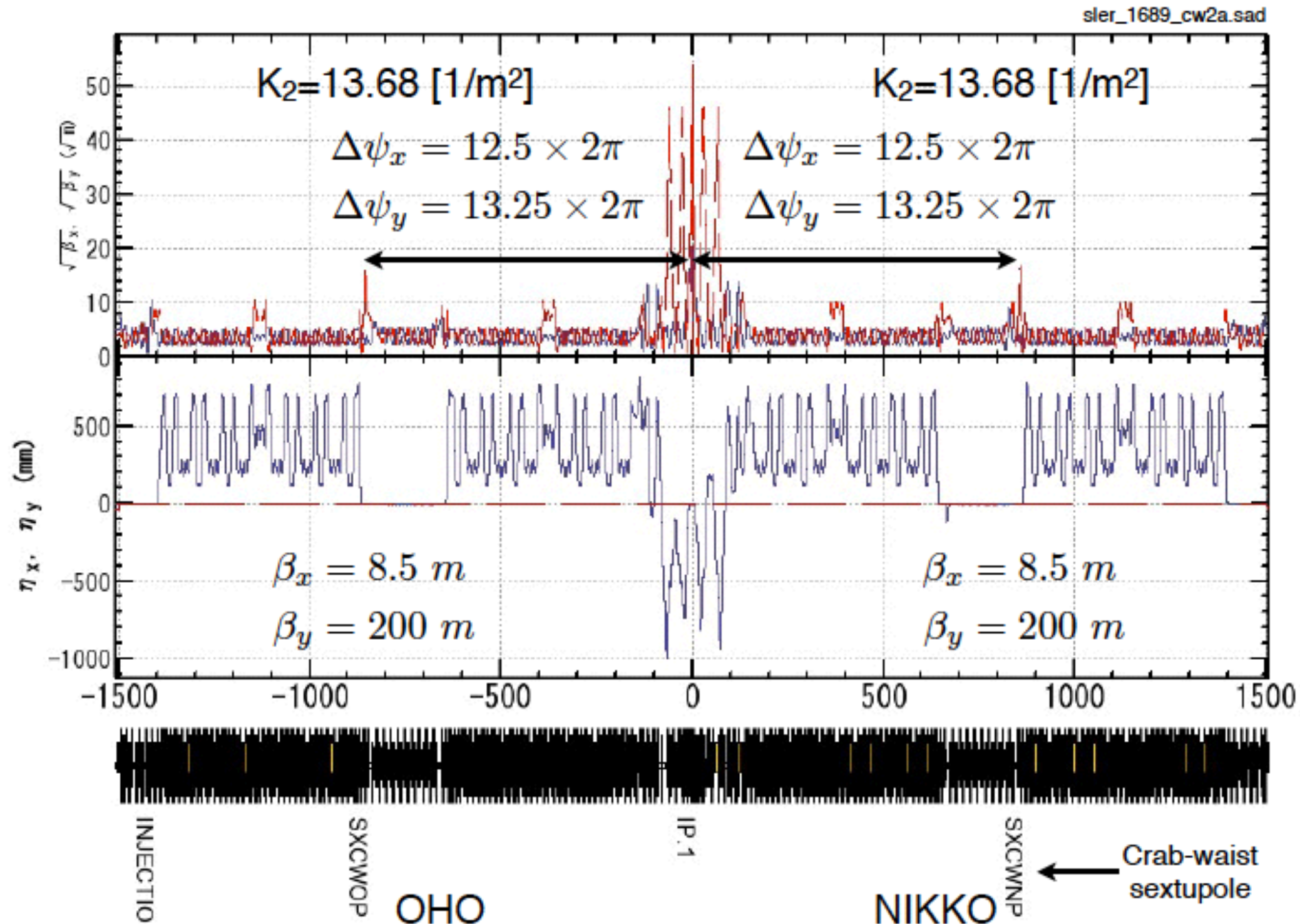
SAD +weak-strong BB



4. Mitigation schemes: CW: DA

➤ CW: Real lattice: LER

- Thin-lens model for CW sextupoles

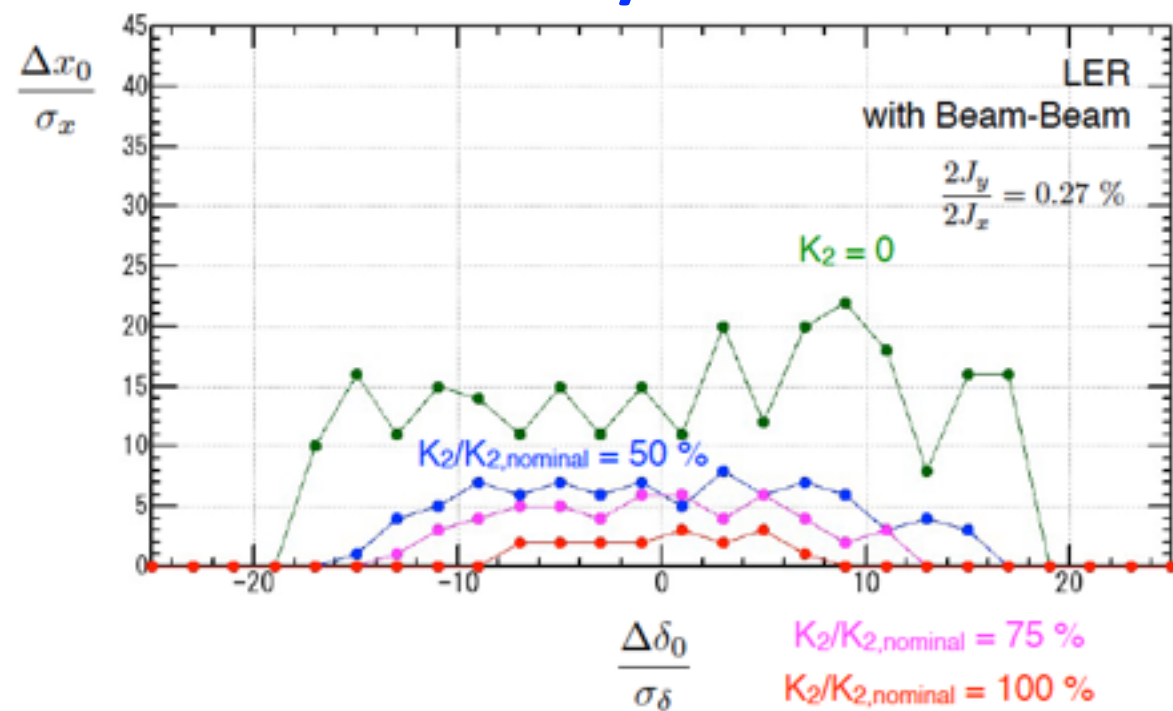


4. Mitigation schemes: CW: DA

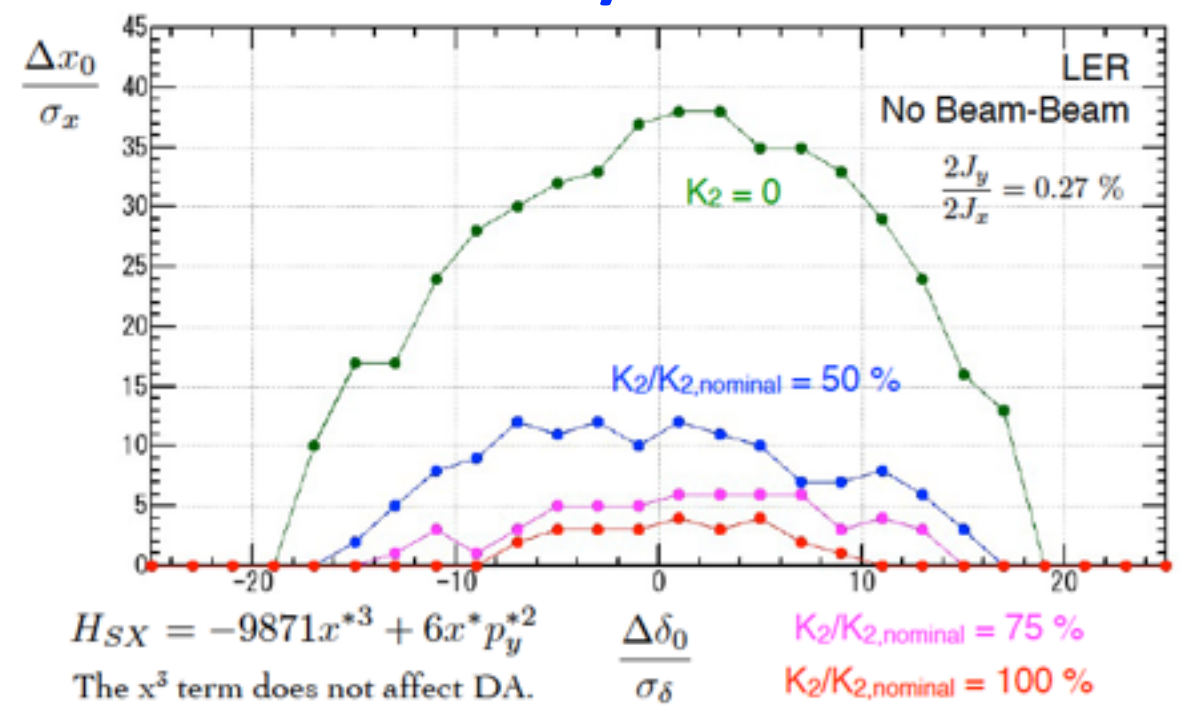
➤ CW: Real lattice: LER

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

w/ BB



w/o BB



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

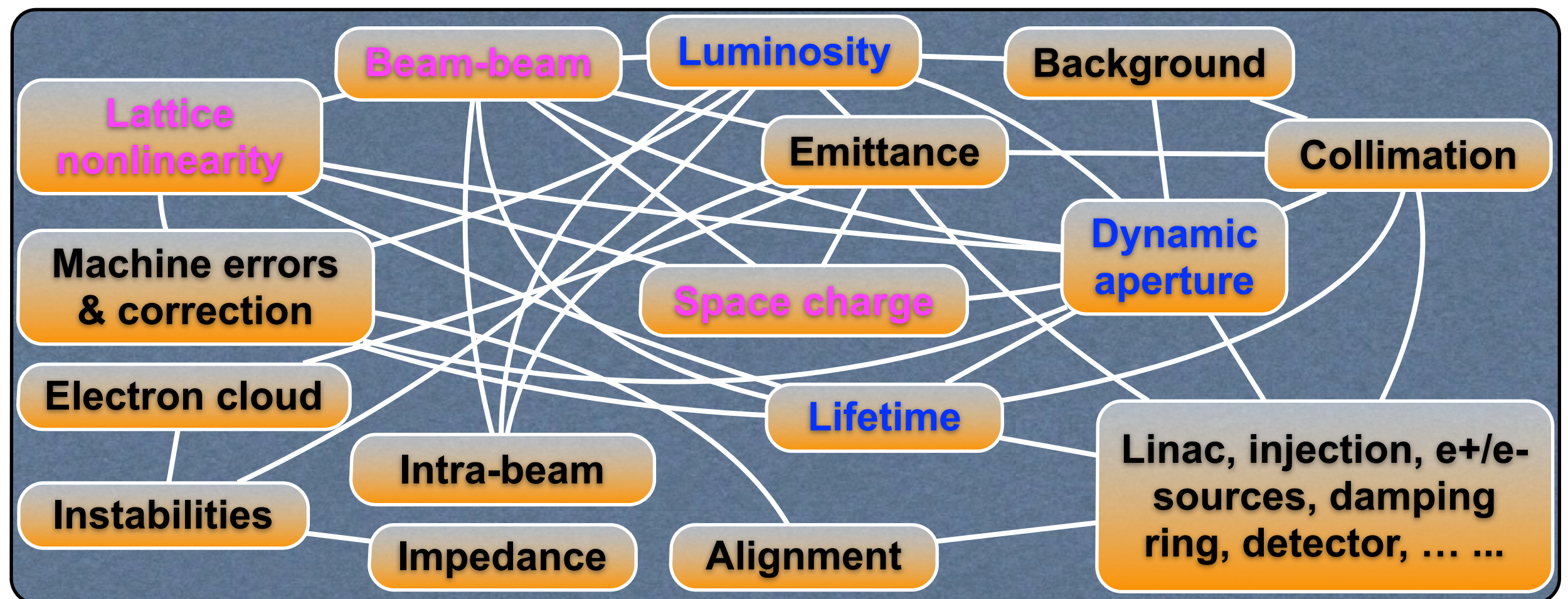
Outline

- 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** $\leq$ Emittance $\leq$ Beam-beam, Lattice nonlinearity, Space charge, Impedances, Electron cloud, Intra-beam scattering, etc.
- BB+LN+SC+... $\Rightarrow$ **Dynamic aperture and lifetime** $\Rightarrow$ Beam commissioning $\Rightarrow$ Injection, Detector back ground, Alignments, etc. $\Rightarrow$ Tolerances for hardwares $\Rightarrow$...



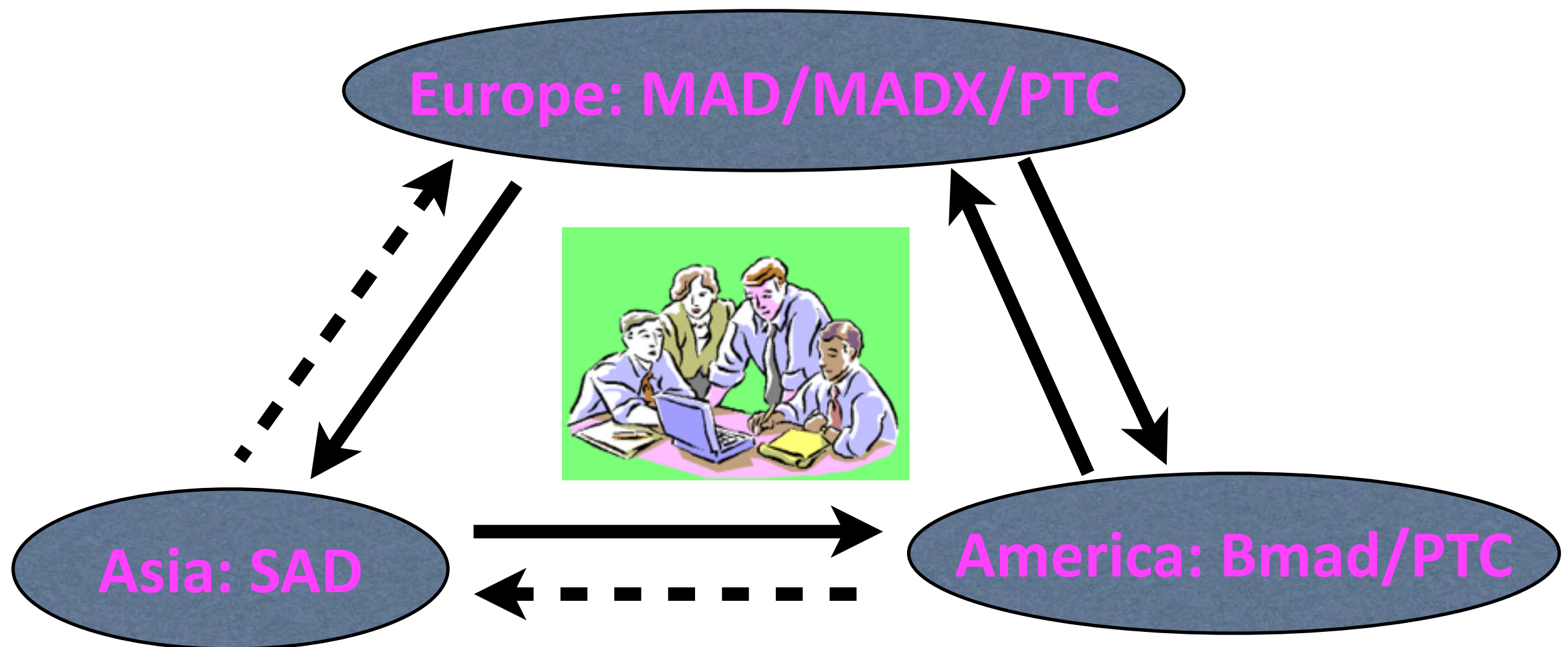
6. Future plans

- 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

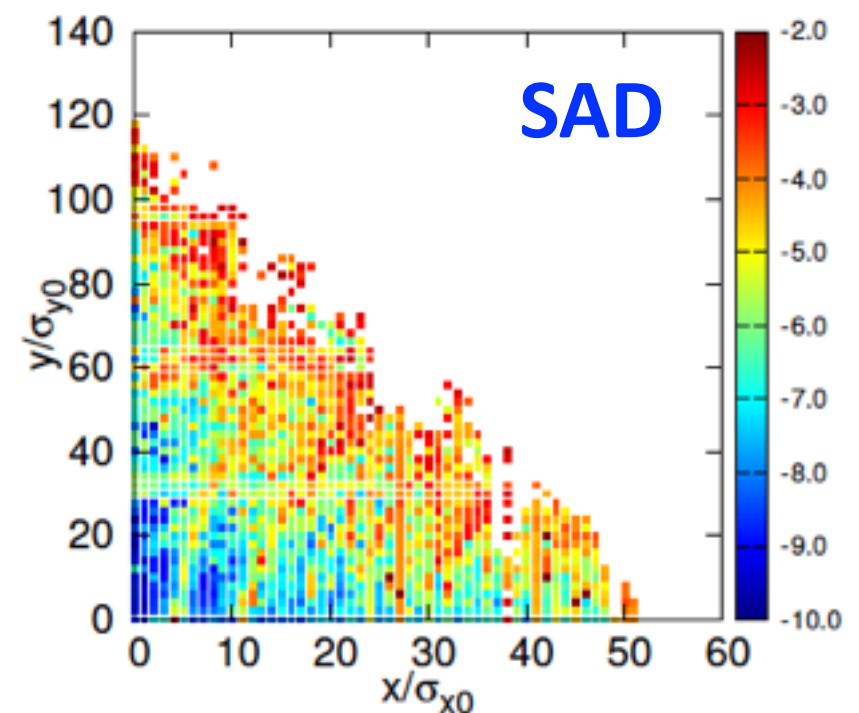
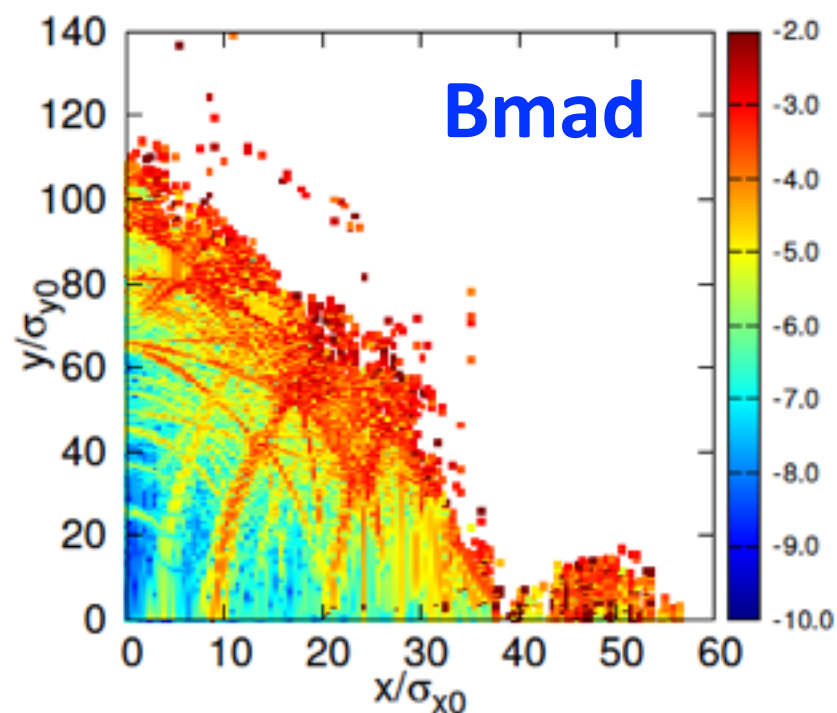
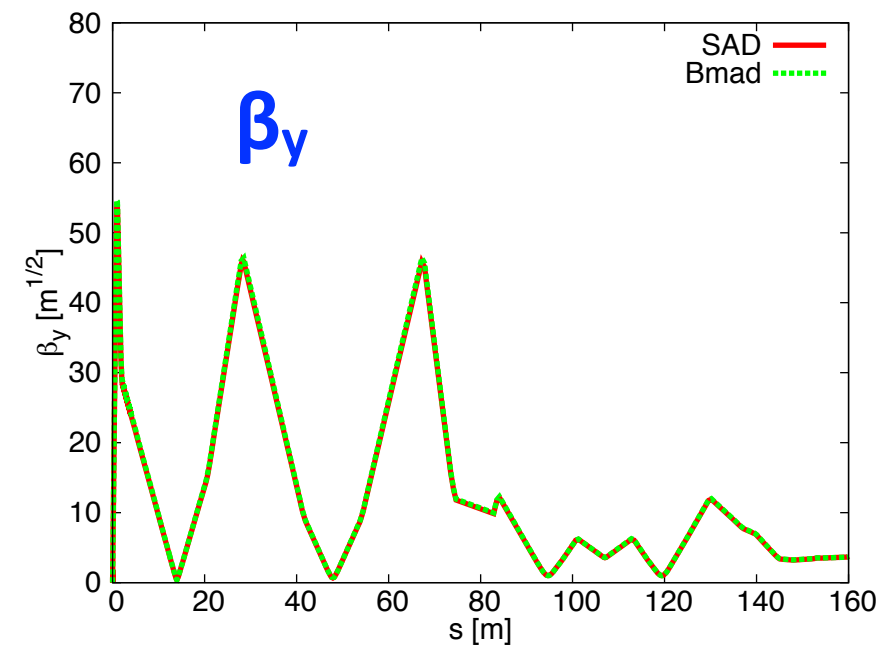
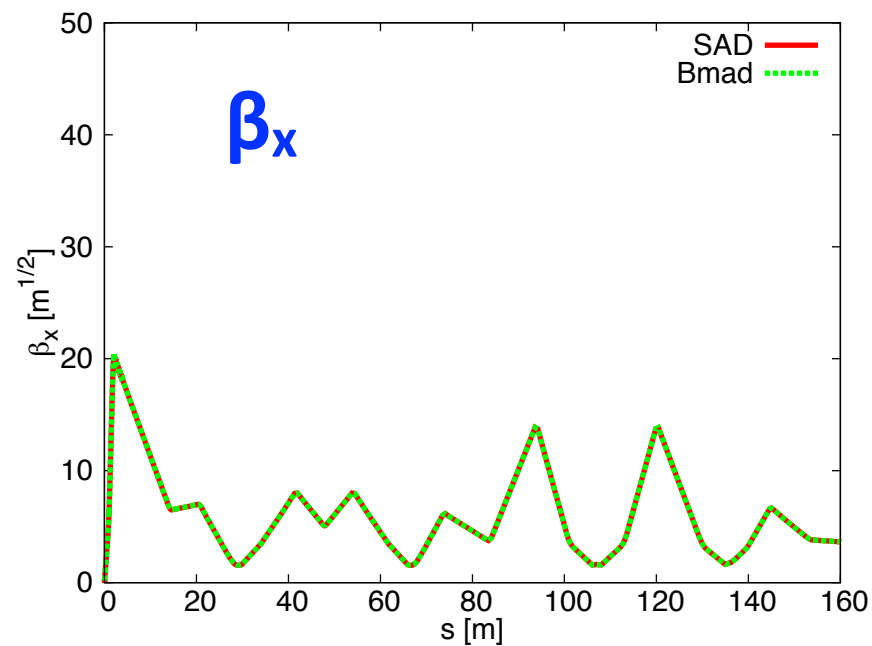
- **SAD**: TRISTAN, KEKB, SuperKEKB, J-PARC, ...
- **Bmad**: CESR, ERL, ...
- **MAD/MADX**: LHC, FCCs, DAΦNE, Super τ -charm, ...



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!