Beam Dynamics Issues in SuperKEKB

Demin Zhou

Thanks to

KEK: T. Agoh, H. Fukuma, N. Iida, H. Ikeda, M. Kikuchi, H. Koiso, A. Morita, K. Ohmi, Y. Ohnishi, K. Oide, K. Shibata, Y. Suetsugu, H. Sugimoto, K. Yokoya, ...

SLAC: Y. Cai, G. Stupakov, L. Wang

BINP: E. Levichev, P. Piminov

The 18th KEKB Accelerator Review Committee, Mar. 04, 2013

Outline

- ➤ Introduction
- ➤ CSR
  - ● Instability analysis; Impedance calculation; MWI simulations
- ➤ Beam-beam
  - ● Tune scan; Crosstalk with lattice nonlinearities; Chromatic aberration
- ➤ Space charge
  - ● Linear tune shift; Crosstalk with beam-beam and lattice nonlinearities
- ➤ Fast ion
  - ● Simulations
- ➤ Summary and Future plan

1. Introduction: Scaling SuperKEKB/KEKB

	LER			HER		
	SKEKB	KEKB*	Factor	SKEKB	KEKB*	Factor
E(GeV)	4.0	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	11.5	240	0.048
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

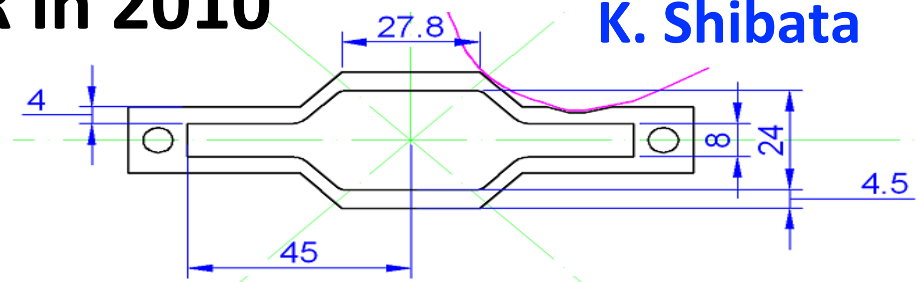
*Machine parameters on Jun.17, 2009

1. Introduction: Beam dynamics issues

- SuperKEKB: Low emit., small beam size, high current
- Effects comparable to KEKB
  - Long. single-bunch instability
  - Multi-bunch instability
  - CSR
  - HOM heating
  - … …
- Effects (possibly) significant in SuperKEKB
  - Intra-beam scattering, Touschek lifetime, DA
  - Beam-beam, beam-beam + Lat. nonlin.
  - Space charge, Space charge + beam-beam + Lat. nonlin.
  - Fast ion
  - Transverse impedance: TMCI, beam tilt
  - … …

2. CSR: DR

- **Found to be important in DR in 2010**
  - **Optics: CSR-optimized**
  - **Vacuum chamber and RF system**



K. Shibata

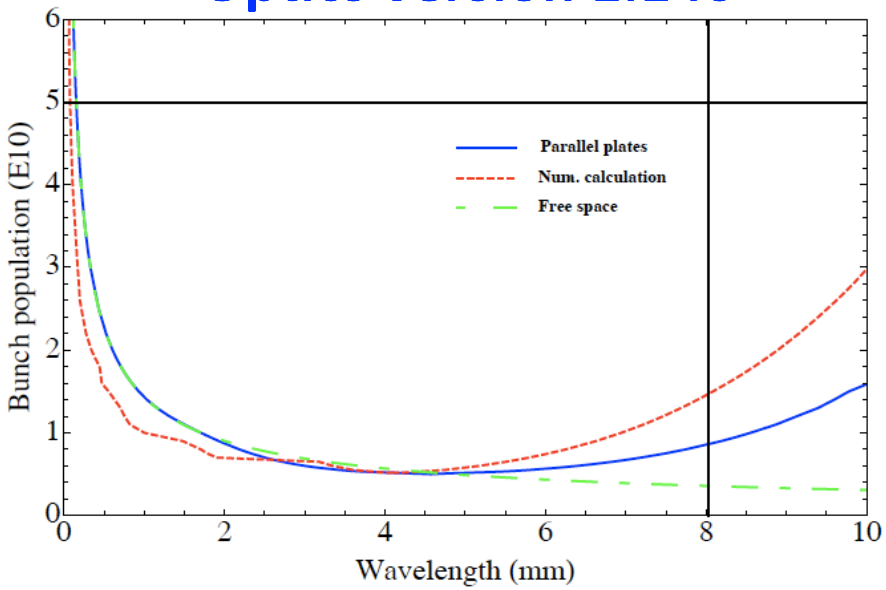
- **Collaboration**
  - **KEK: T. Agoh, H. Ikeda, M. Kikuchi, K. Ohmi, K. Oide, K. Shibata, K. Yokoya, D. Zhou**
  - **SLAC: Y. Cai, G. Stupakov, L. Wang**
  - **CERN: F. Zimmermann**
- **Intensive CSR impedance calculations**
  - **Benchmark: 5 codes (Agoh, Oide, Zhou, Stupakov, Wang)**
  - **Single-bend and multi-bend**
  - **Rectangular and arbitrary cross-section of chamber**
- **Intensive simulations of MWI**
  - **Macro-particle tracking: SAD**
  - **Vlasov solver: SAD, Cai-Warnock's code**

2. CSR: DR

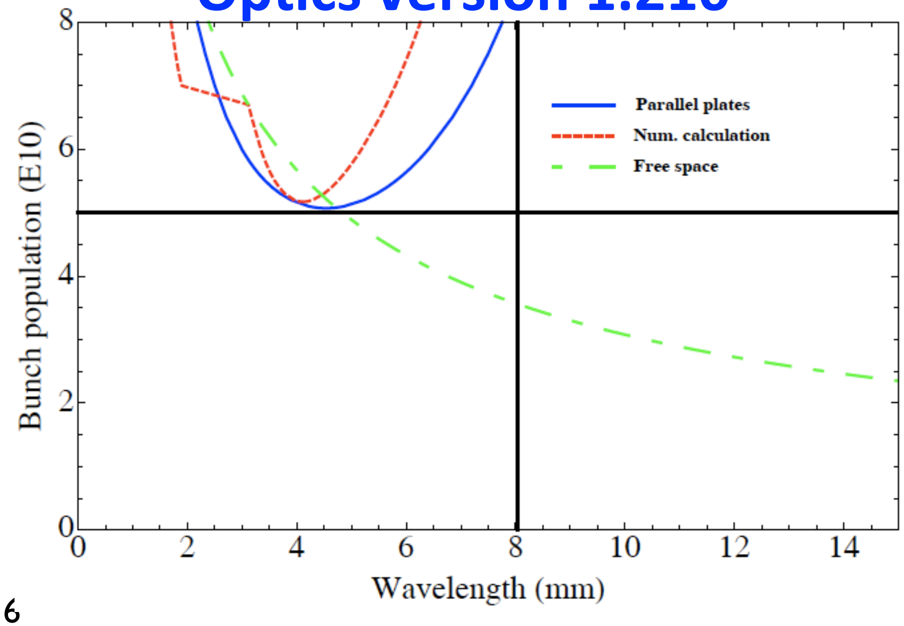
➤ Findings: General

- **CSR: High-frequency impedance in the mm wave regime; Overtaking self-fields**
- **Numerical noise in impedance calculation: Low/high in rectangular/arbitrary chamber cross-section**
- **Instability analysis(Stupakov-Heifets theory): a simple, but robust method for estimate of CSR effect**

Optics version 1.140



Optics version 1.210

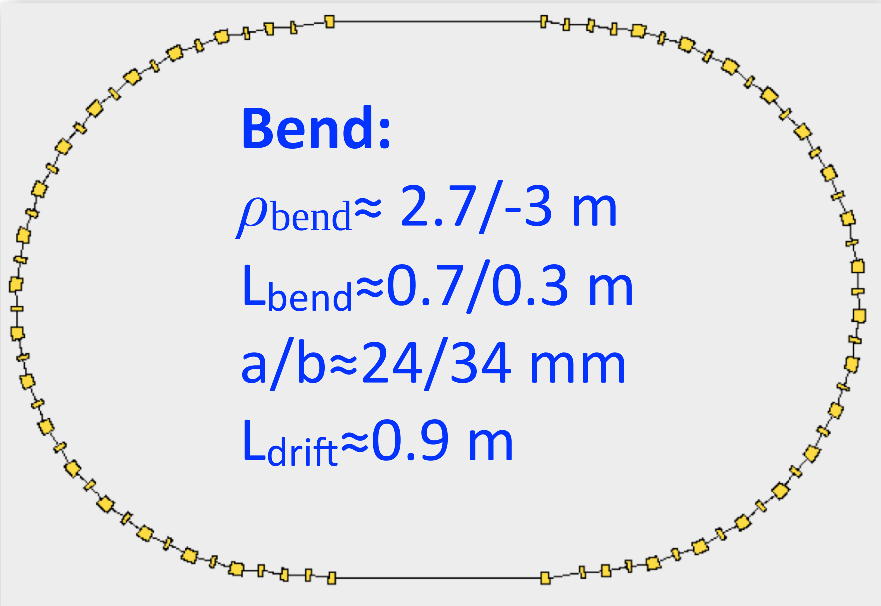


2. CSR: DR

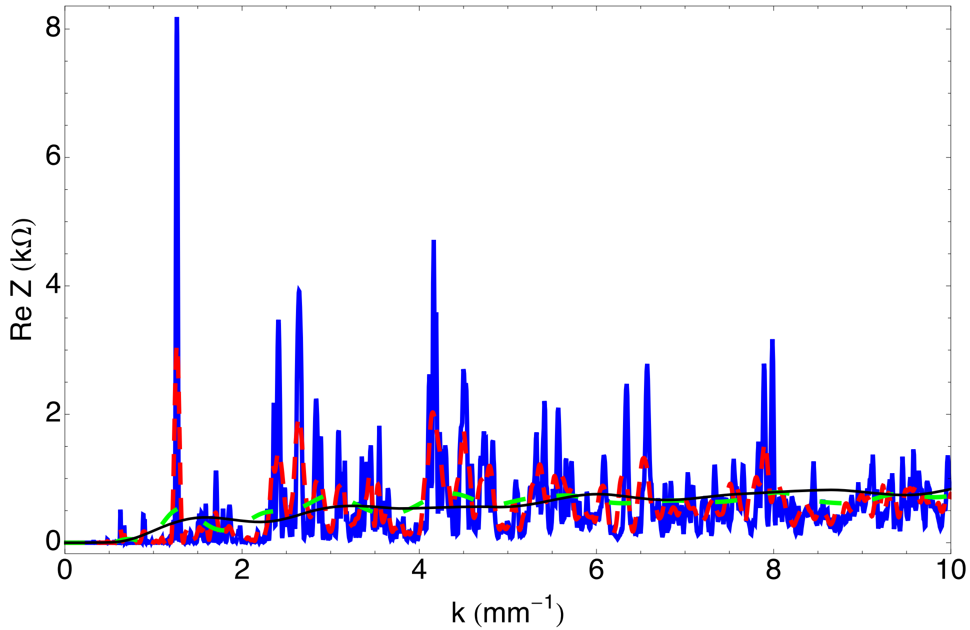
➤ Findings: Impedance

- CSR impedance: Forest of "narrow-band" spikes
- Multi-bend interference in CSR: Interesting but likely not important for both single- and multi-bunch instability

DR layout



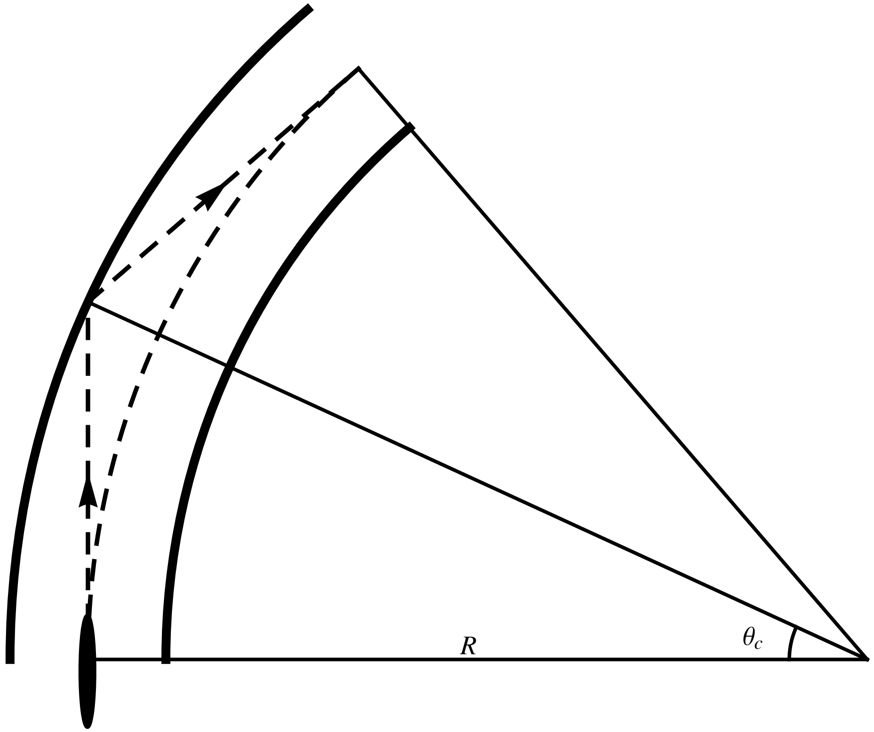
Impedance

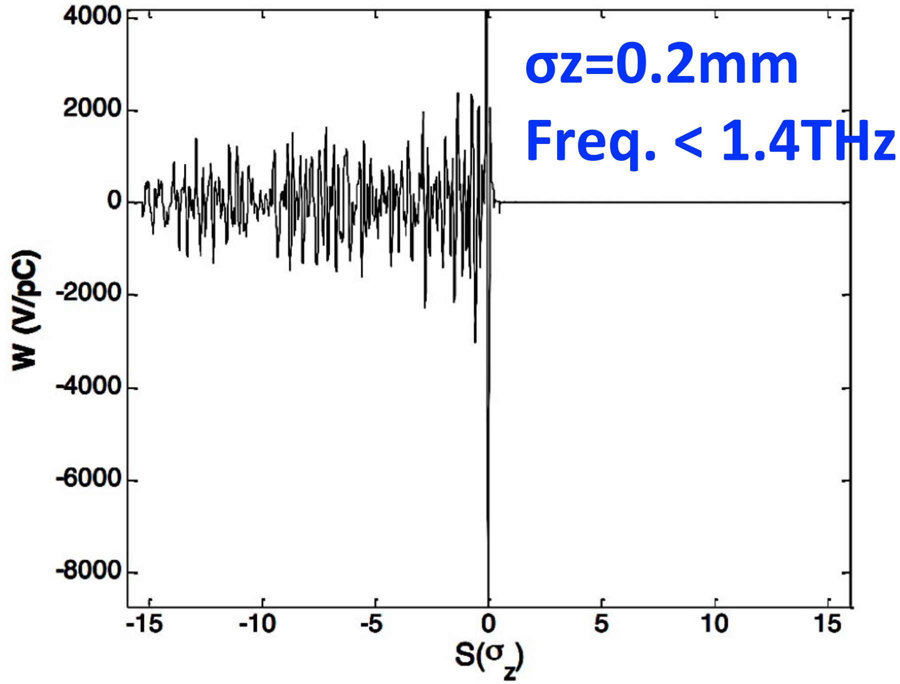


2. CSR: DR

➤ **Findings: Multi-bunch instability**

- **Long-range CSR wake extend to distance of ~0.1 m**
- **Not considered in CSR impedance calculation: Resistive wall and chamber discontinuities**
- **No multi-bunch CSR instability(?)**



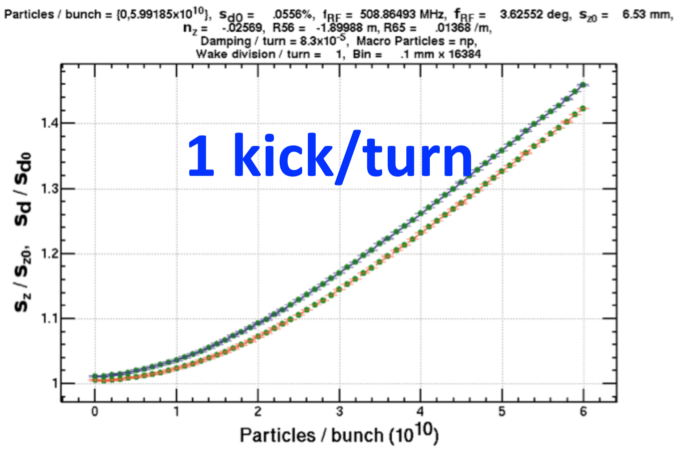


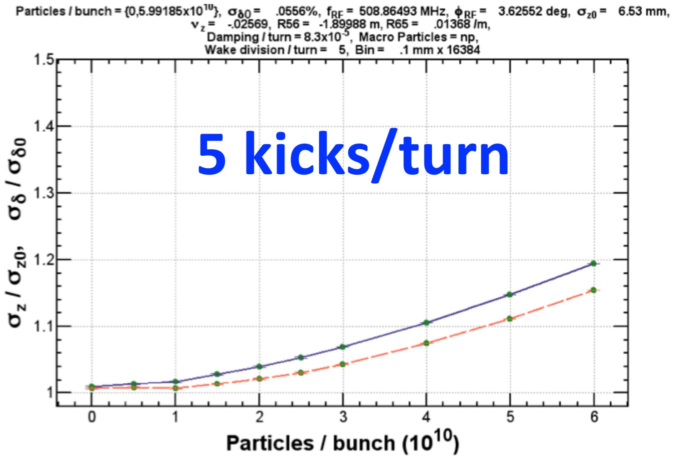
L. Wang and D. Zhou

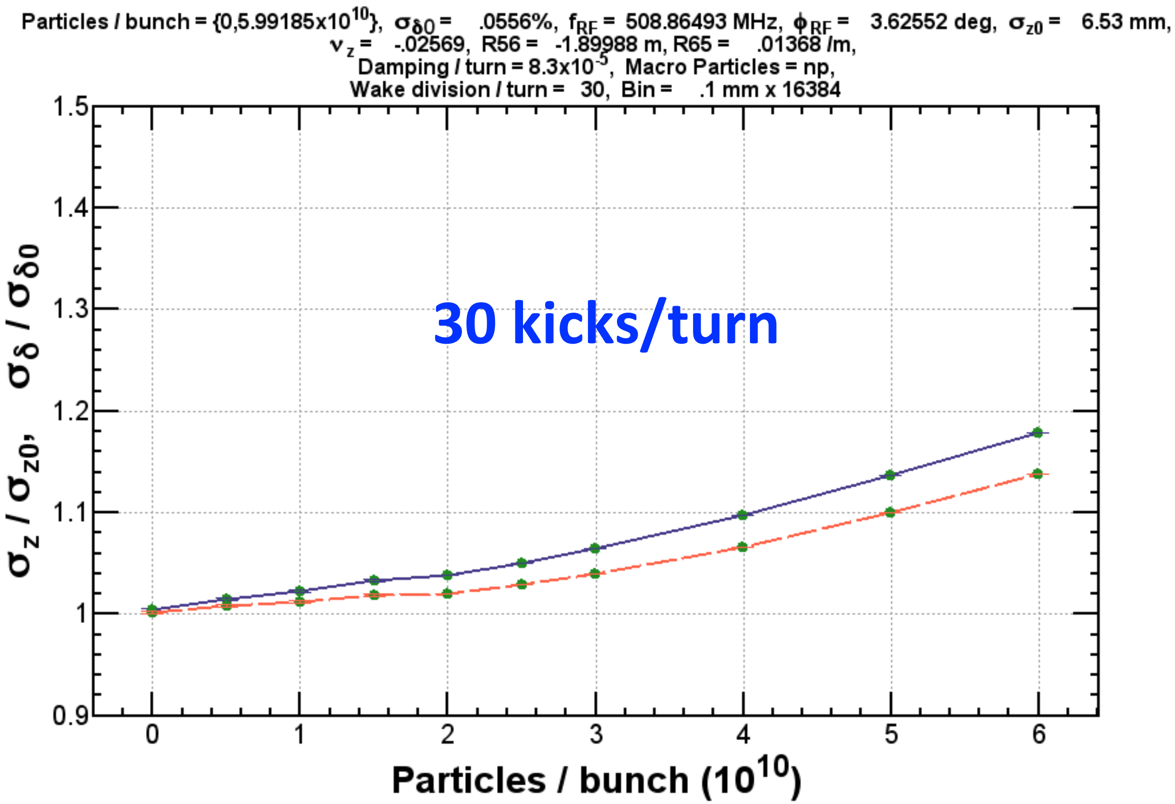
2. CSR: DR

➤ Findings: PIC tracking

- CSR instability is sensitive to number of kicks per turn
- Mesh size contribute to numerical noise
- Tracking always suffers from numerical noise







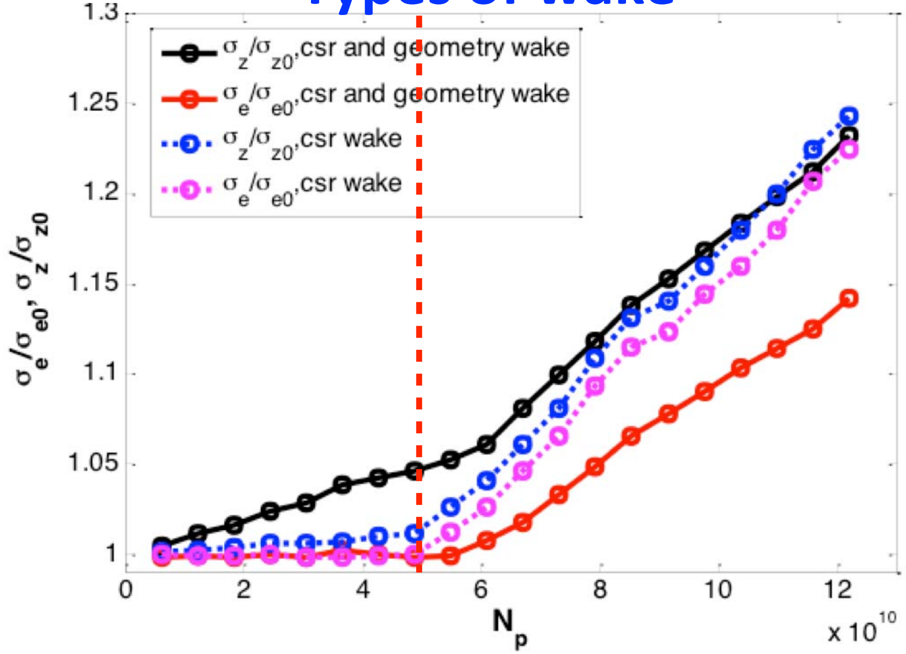
Courtesy of H. Ikeda

2. CSR: DR

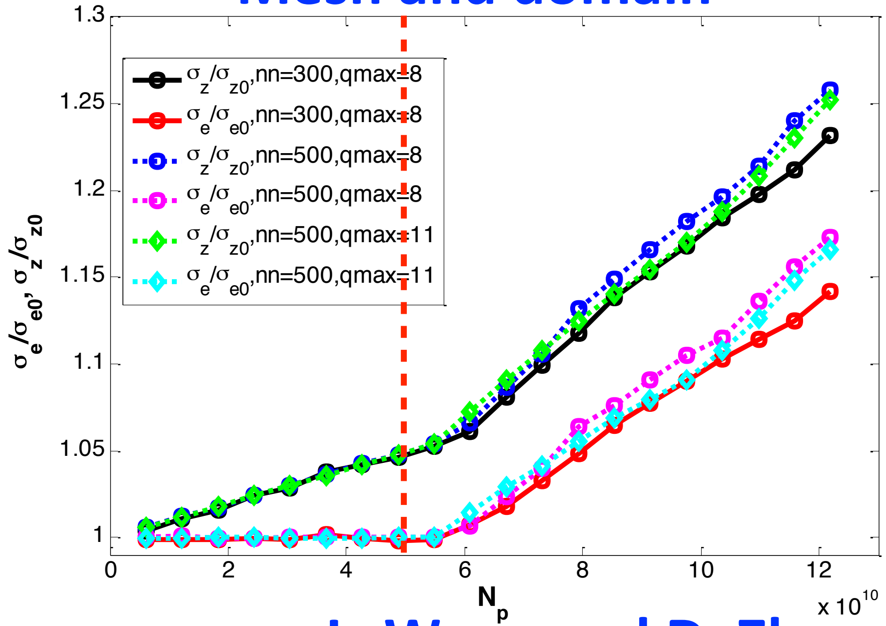
➤ **Findings: Vlasov solver**

- CSR instability is sensitive to number of kicks per turn
- Sizes of mesh and domain contribute to numerical noise
- Numerical noise significantly suppressed
- Typical: 1024 kicks per synch. period
- Almost no CSR instability below design bunch current
- Threshold(CSR) close to Stupakov-Heifets-Cai theory

Types of wake



Mesh and domain



L. Wang and D. Zhou

2. CSR: Summary

➤ **Instability threshold estimated by S-H-C theory**

- **All rings are safe from CSR instability**

	DR			LER	HER
E(GeV)	1.1			4.0	7.007
NP(10^{10})	5			9.04	6.53
b(mm)	24			90	52
R(m)	2.7/3			74.7	106
α_p(10^{-4})	141			3.25	4.55
σ_δ(10^{-4})	5.5			8.08	6.37
σ_z(mm)	6.6	7.8	11	6	5
N_{th}(10^{10})	4.4	5.2	7.6	8.8	19.3

$$N_{th} = \frac{CI_A}{ce} \frac{\alpha_p \gamma \sigma_\delta^2}{\sigma_z} \frac{\sigma_z^{4/3}}{R^{1/3}} \xi_{th}$$

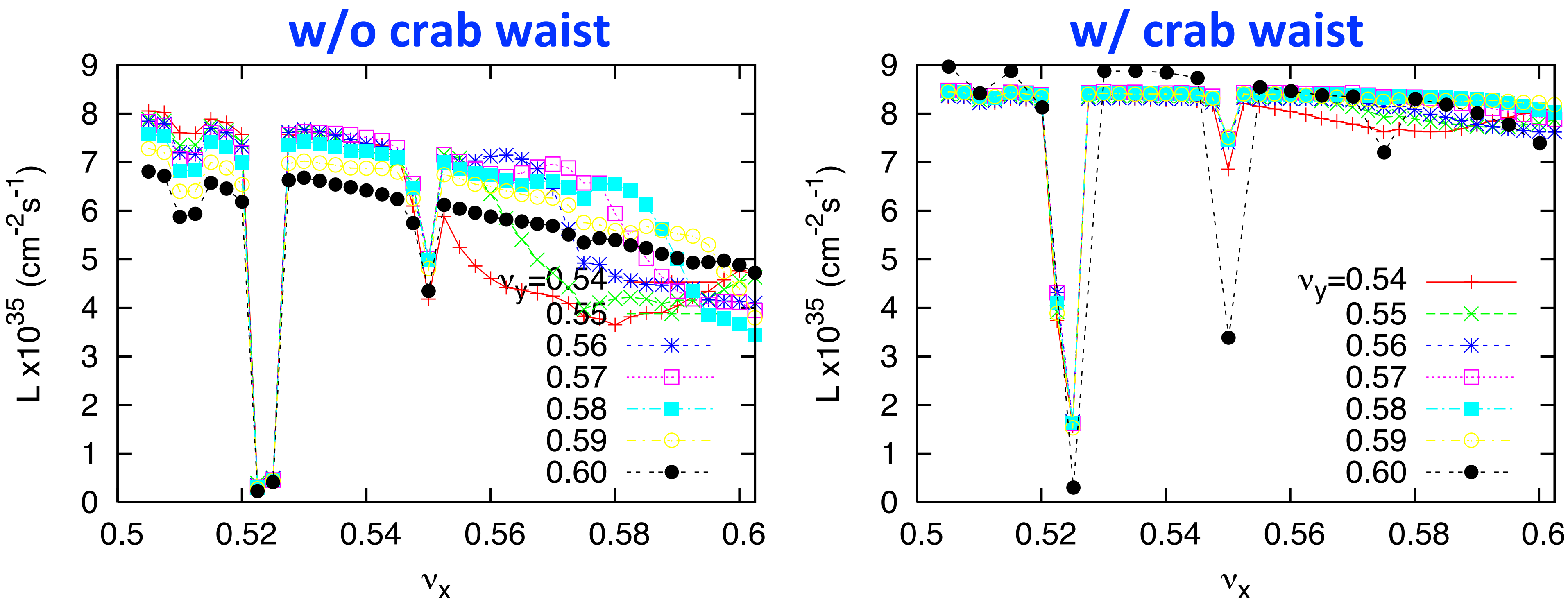
$$I_A = 4\pi\epsilon_0 \frac{m_e c^3}{e}$$

$$\xi_{th} = 0.5 + 0.34\chi$$

$$\chi = \sigma_z \sqrt{\frac{R}{b^3}}$$

3. Beam-beam: Tune scan(BBWS)

- ➤ Synchro-betatron resonance: $2\nu_x - n\nu_s$ = Int. due to x^2z^2 term in beam-beam force
- ➤ Present choice: $(\nu_x,\nu_y)=(*.53,*.57)$
- ➤ Tune closer to half integer is necessary?
- ➤ Lum. gain from crab waist: ~15%@Design



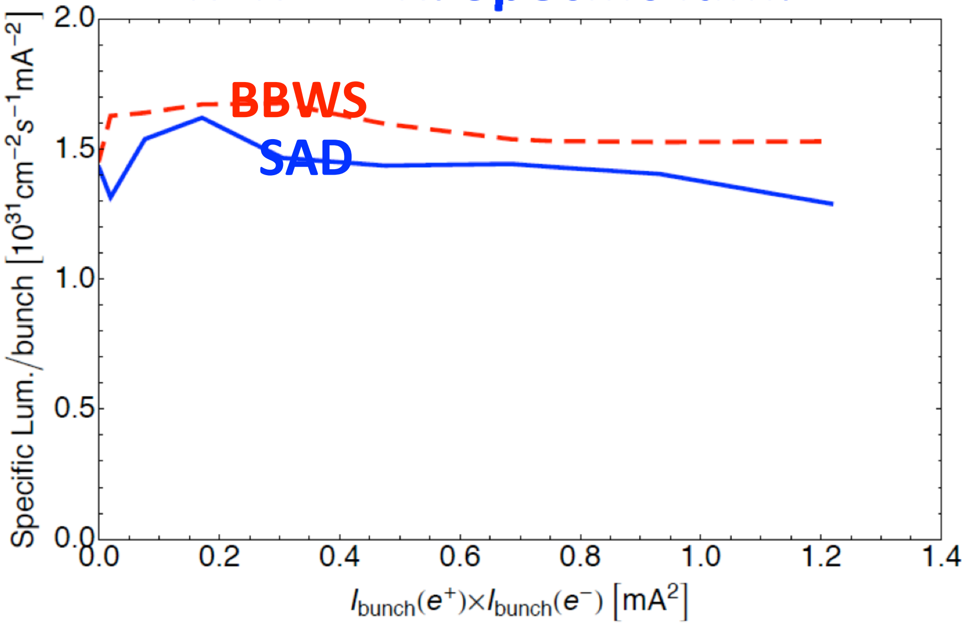
Courtesy of K. Ohmi

3. Beam-beam: Lattice nonlinearities

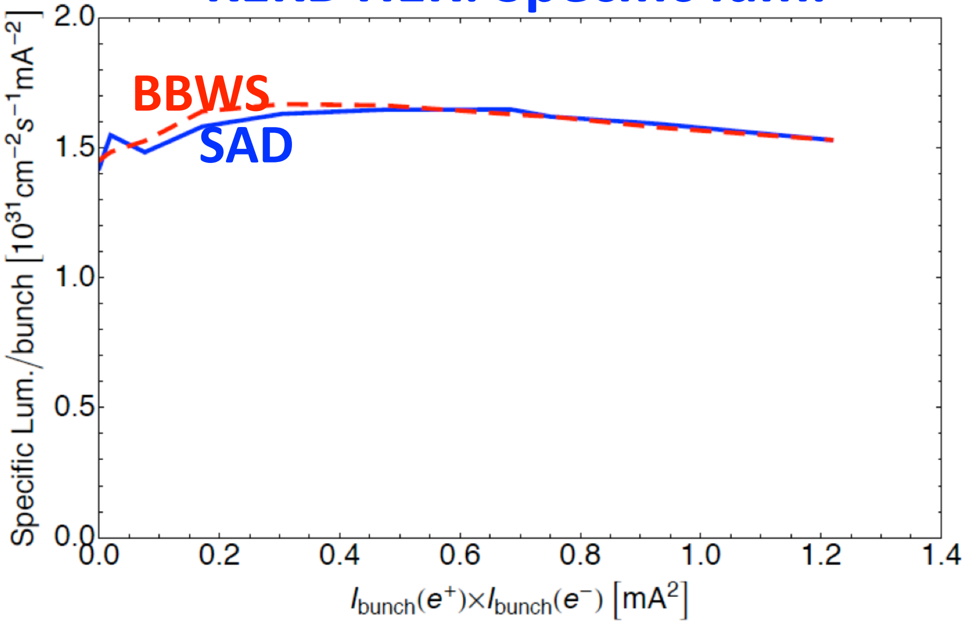
➤ **Lattice nonlinearities**

- **Low emit. => Strong lattice nonlinearities**
- **Crosstalk with beam-beam and space charge**
- **BB simulation(w/o crab cavity) => Not important in KEKB**

KEKB LER: Specific lum.



KEKB HER: Specific lum.

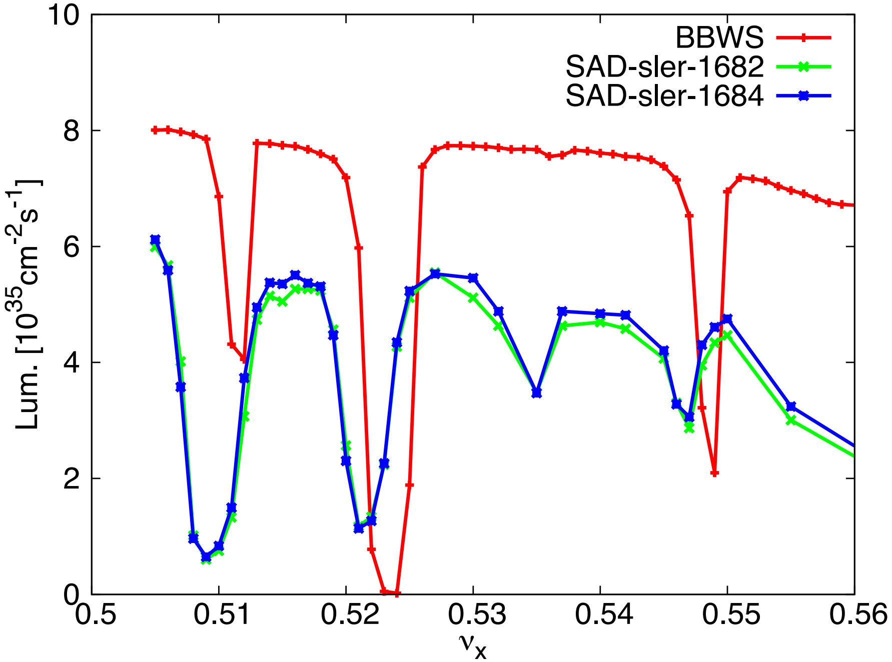


3. Beam-beam: Lattice nonlinearities

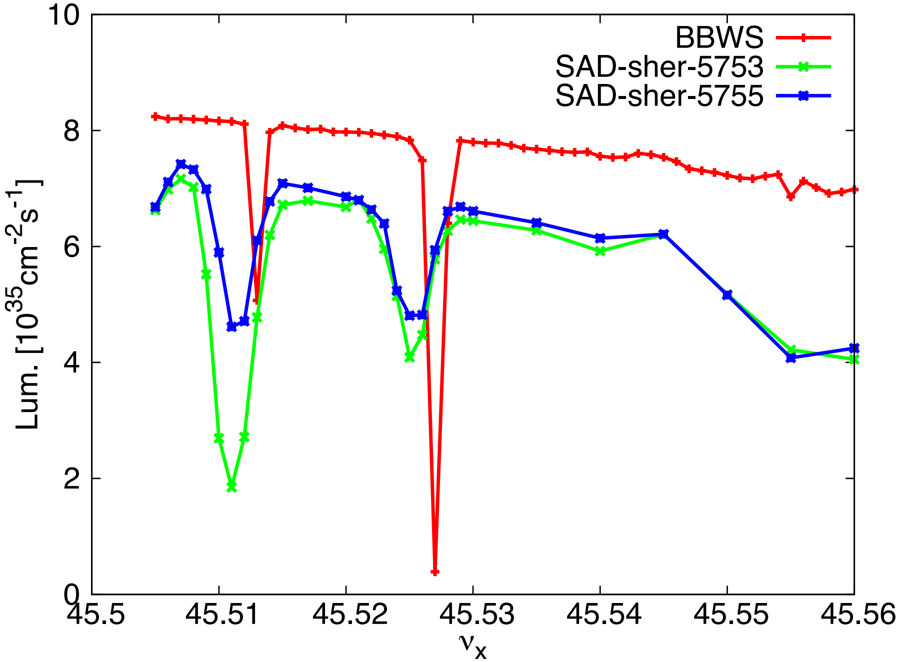
➤ **BB(weak-strong) + LN**

- **Simulation: BBWS(NP=10000), SAD(NP=1000)**
- **Significant lum. loss independent on hor. tune**
- **LN enhance synchro-betratron resonances**
- **Depend on optics**

LER: tune scan



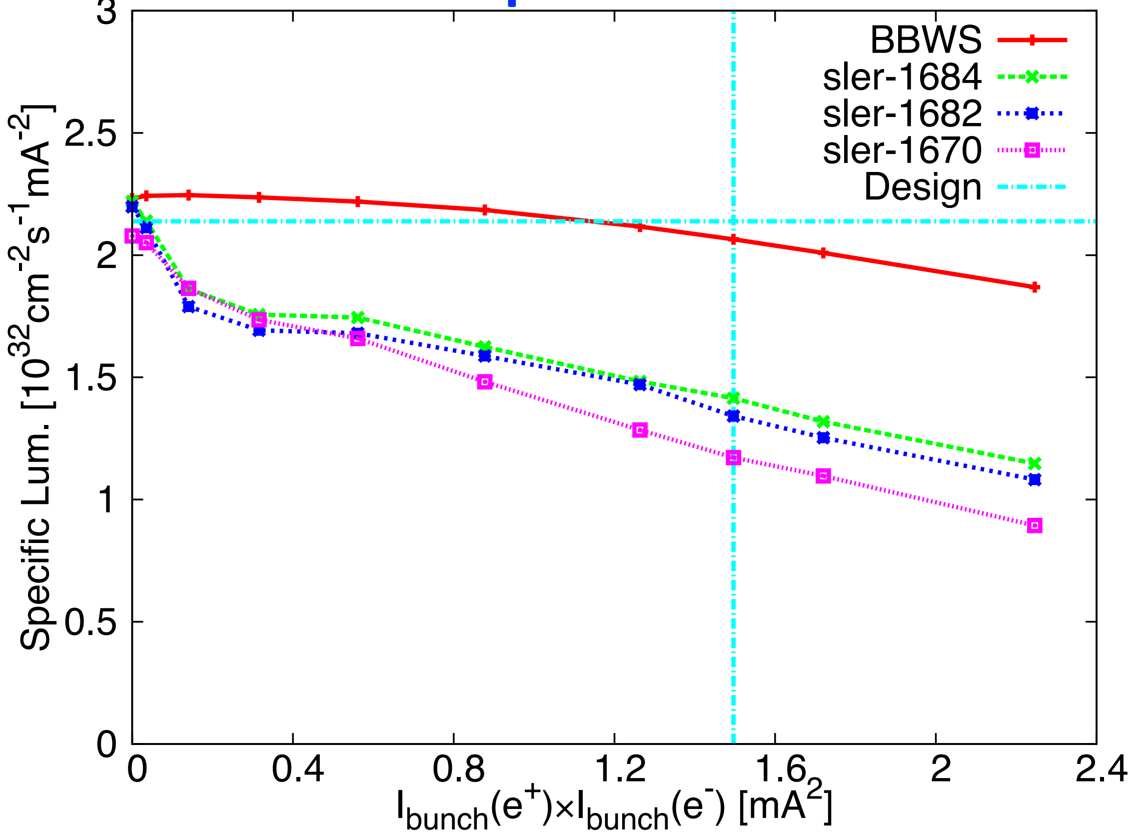
HER: tune scan



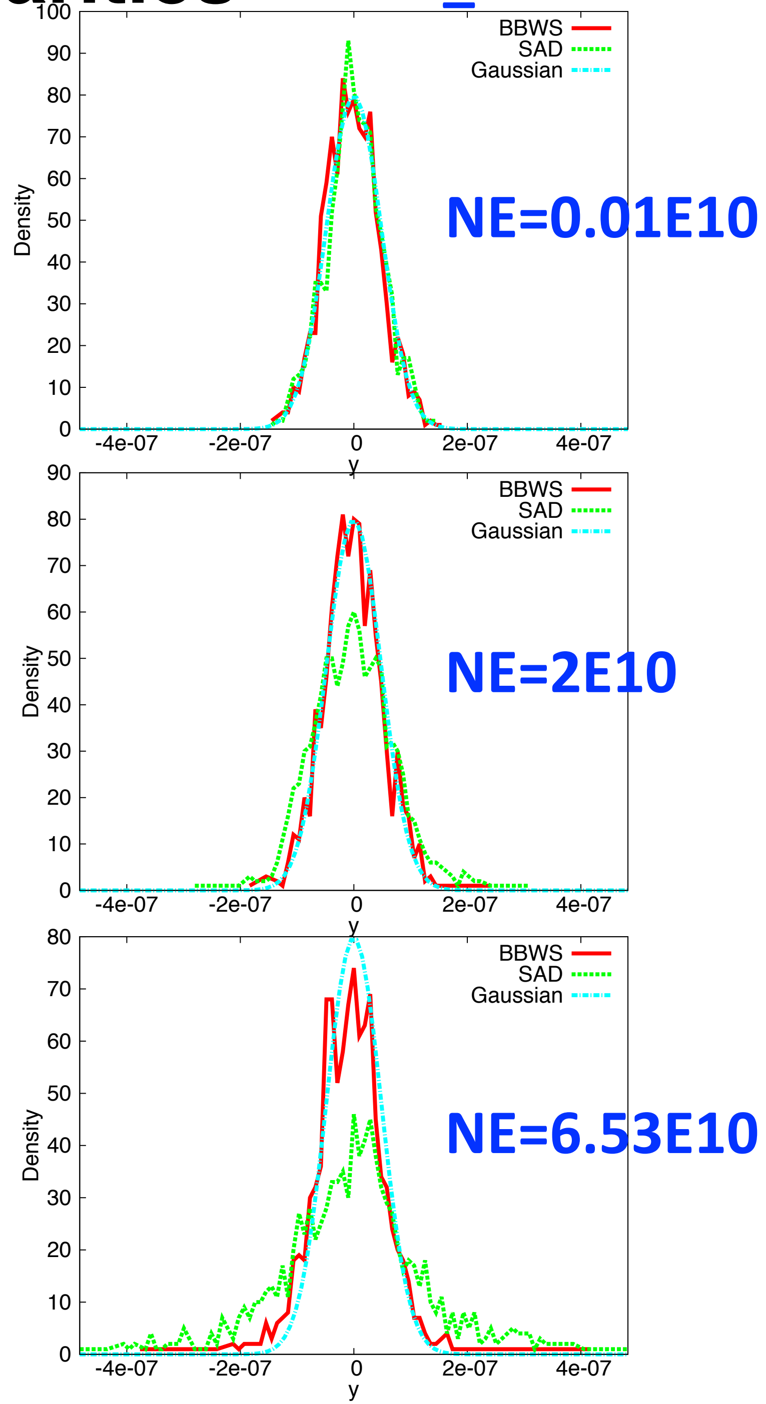
3. Beam-beam: Lattice nonlinearities

- **BB(weak-strong) + LN**
  - **Direct vert. emit. growth**
  - **Current dependent**
  - **Mechanism not well understood**

LER: specific lum.



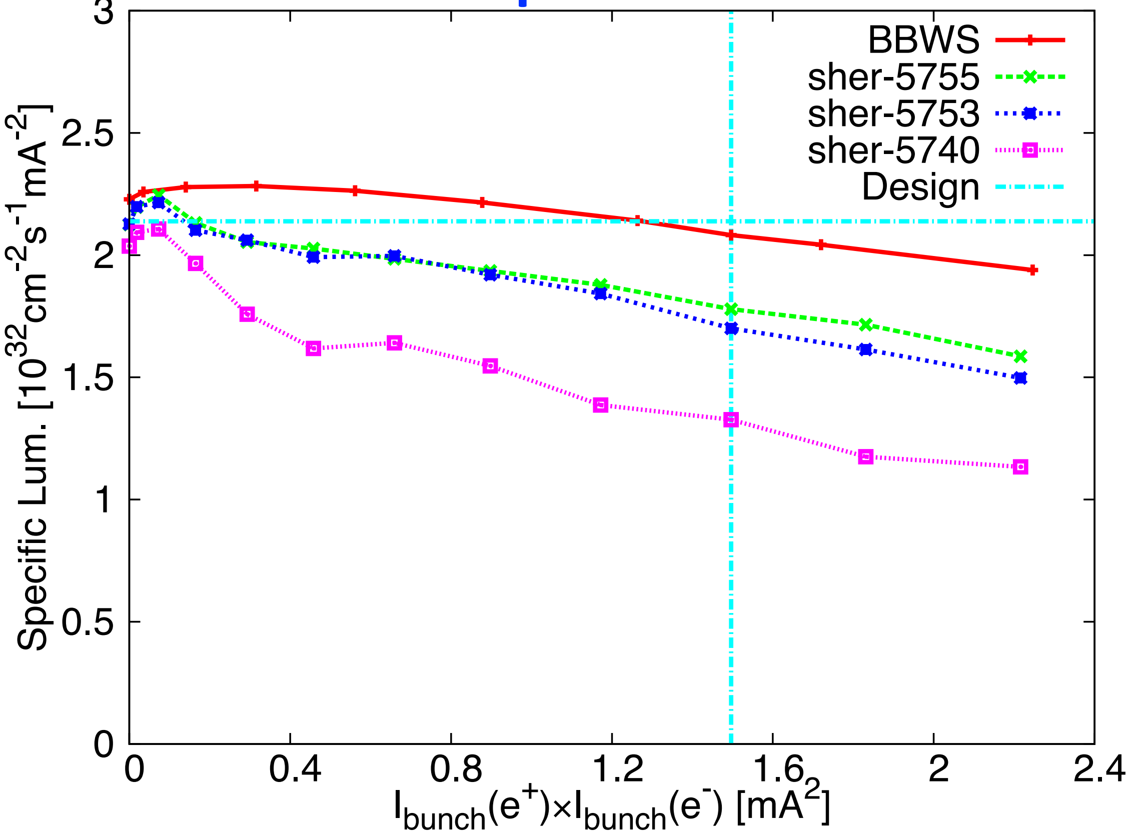
sler_1684



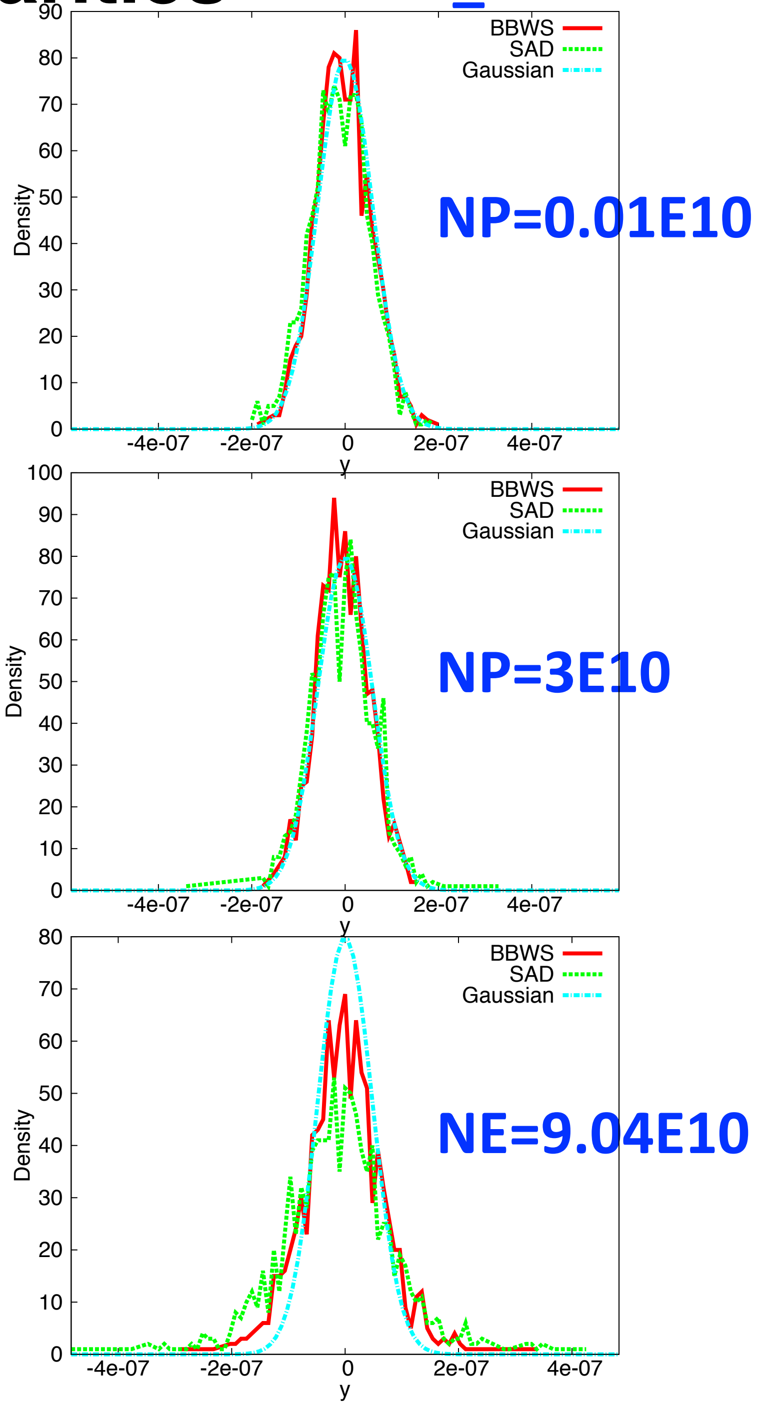
3. Beam-beam: Lattice nonlinearities

- ➤ **BB(weak-strong) + LN**
  - **Direct vert. emit. growth**
  - **Current dependent**
  - **Mechanism not well understood**

HER: specific lum.



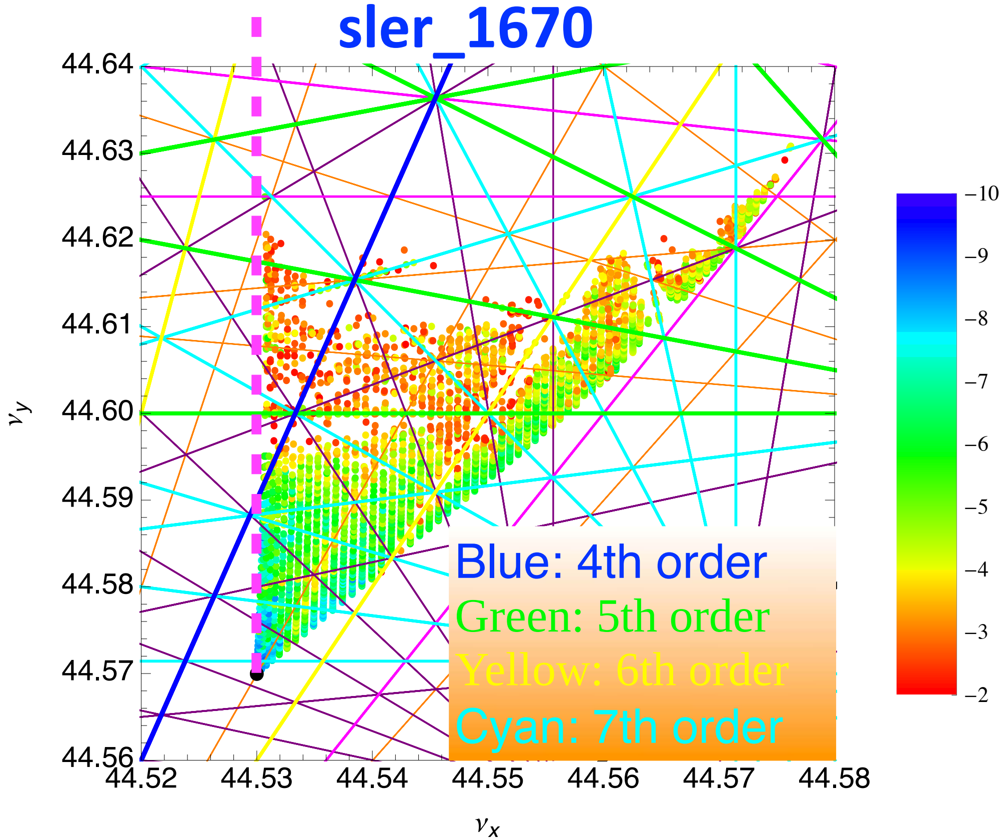
sher_5755

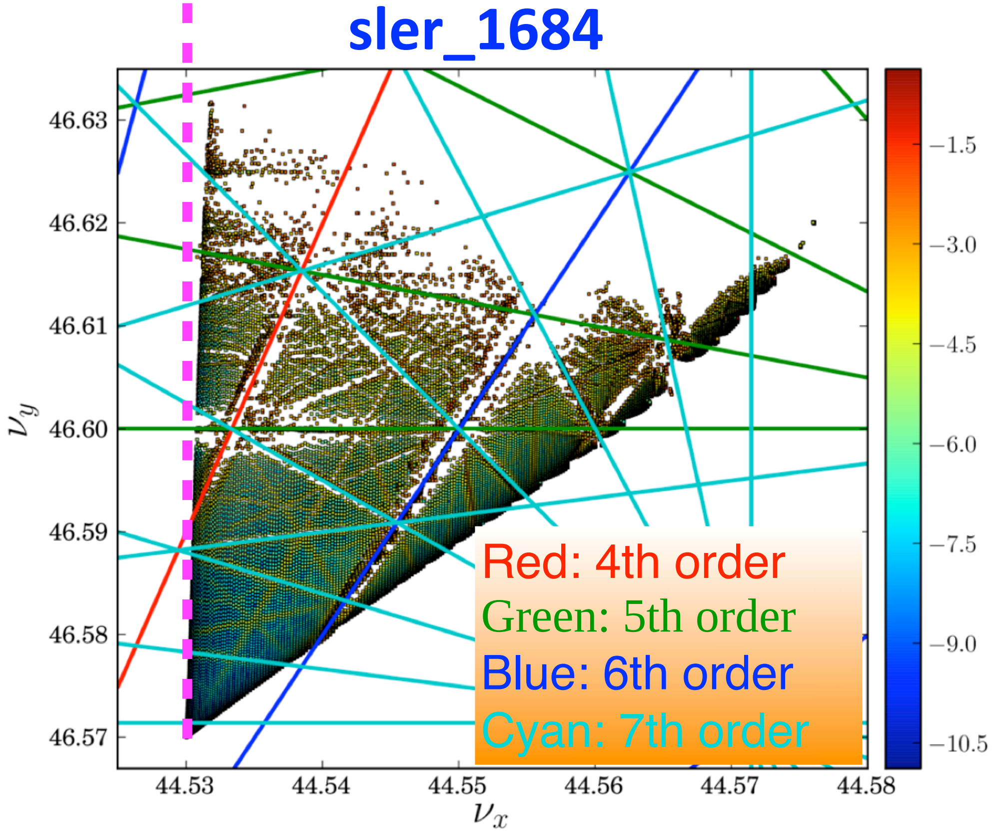


3. Beam-beam: Lattice nonlinearities

➤ FMA w/o BB: LER

- Footprints in tune space: on-momentum
- BB tune shift: $\Delta\nu_y \approx 0.09$
- Strong high-order resonances
- Improvement in DA leads to better lum. performance





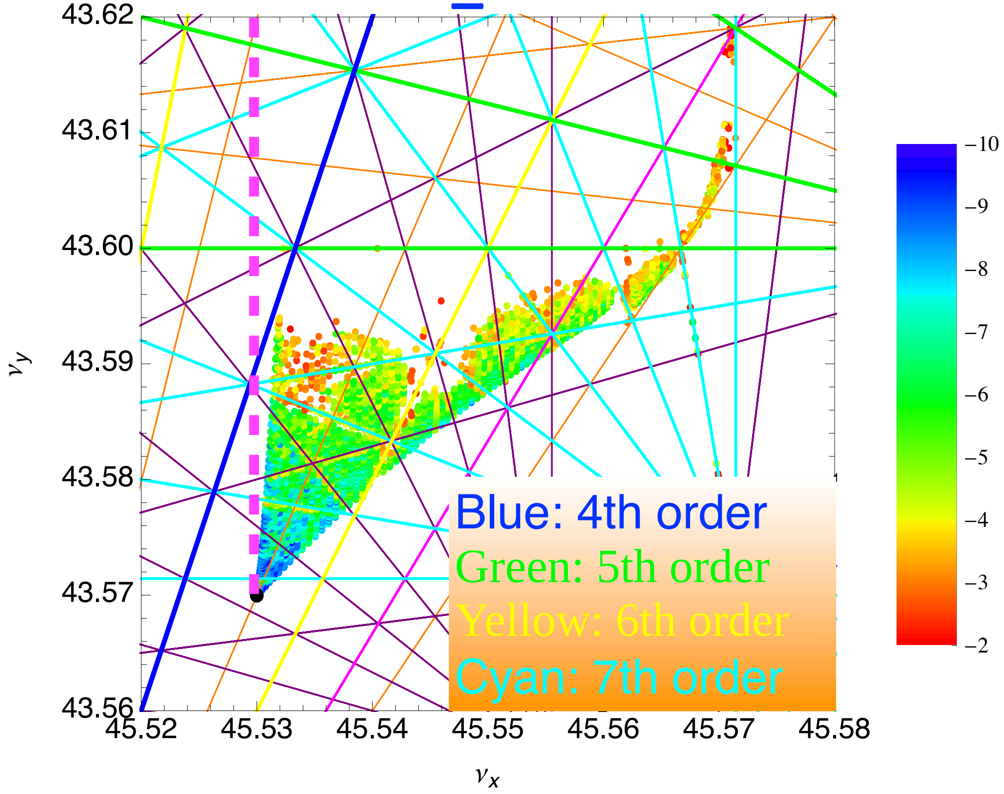
Courtesy of H. Sugimoto

3. Beam-beam: Lattice nonlinearities

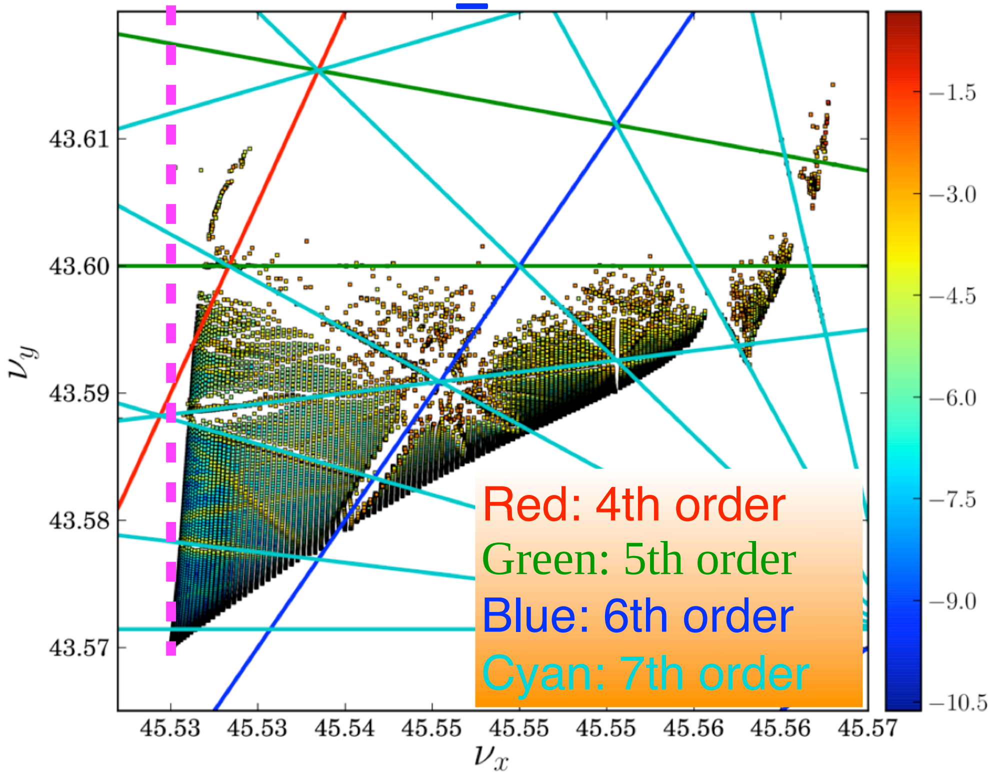
➤ FMA w/o BB: HER

- Footprints in tune space: on-momentum
- BB tune shift: $\Delta\nu_y \approx 0.08$
- Improvement in DA leads to better lum. performance
- Nonlin. motion by crossing resonances?

sher_5740



sher_5755

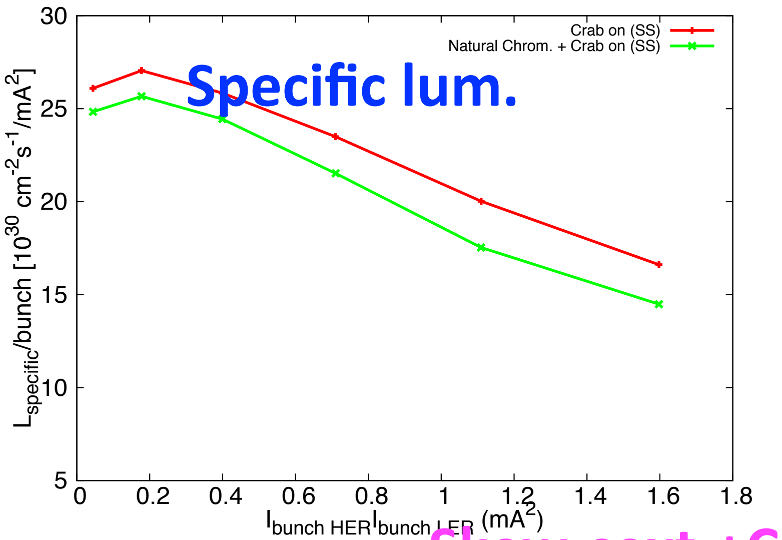


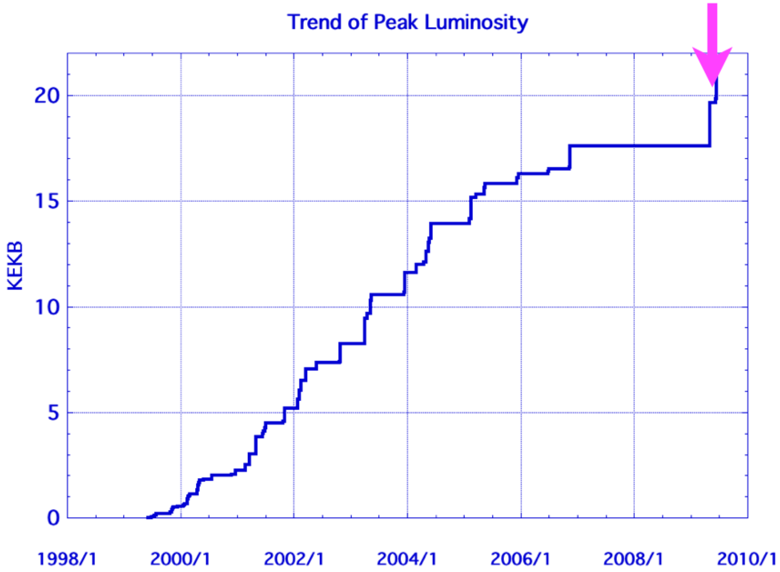
Courtesy of H. Sugimoto

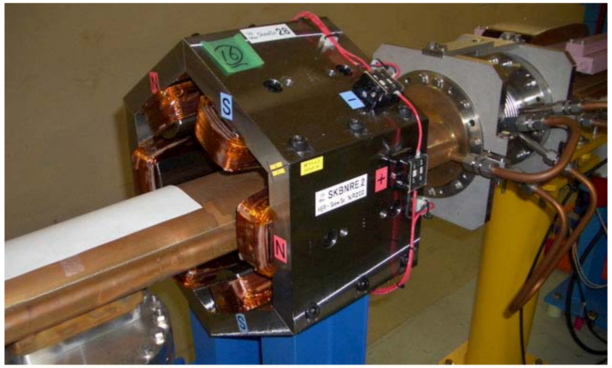
3. Beam-beam: Chromatic coupling

➤ KEKB

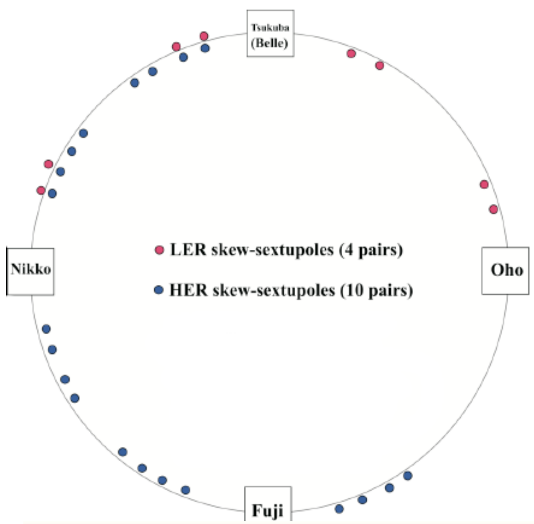
- **Important in both crab on and off**







Skew sext., Masuzawa et al.

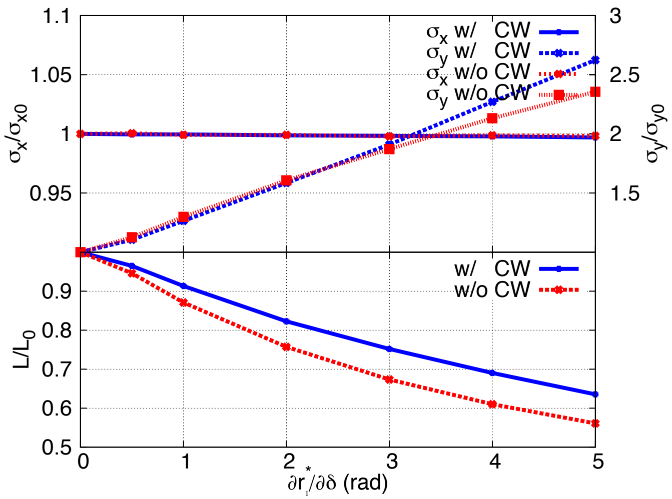


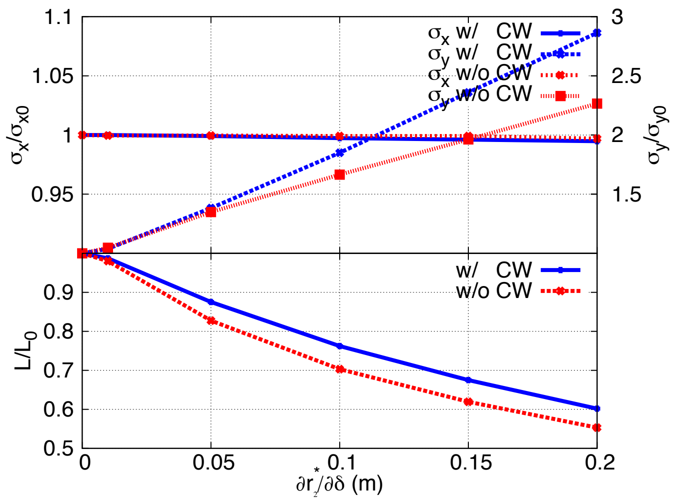
Optics, A. Morita et al.

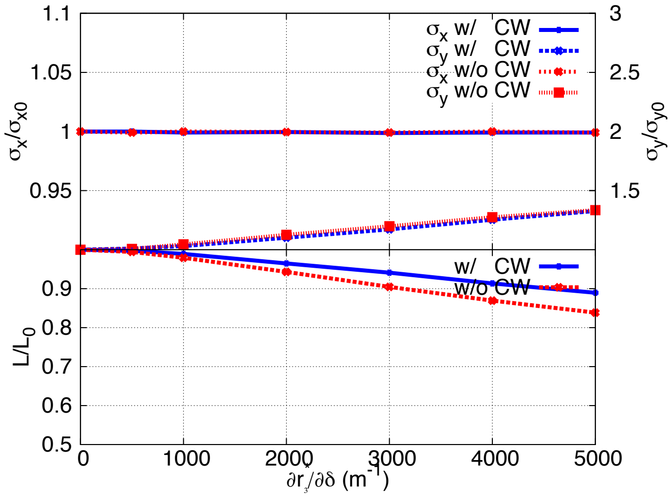
3. Beam-beam: Chromatic coupling

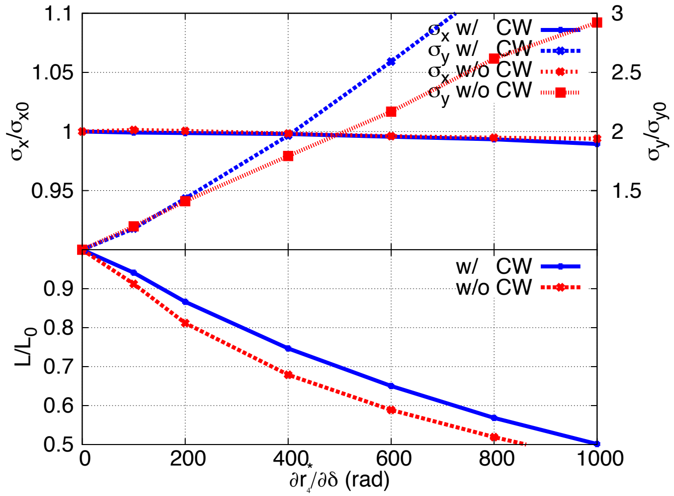
➤ SuperKEKB LER

- **Lum. more sensitive to chrom. coupling**
- **Chrom. coupling routinely minimized in optics design**









3. Beam-beam: Chromatic coupling

➤ **SuperKEKB LER**

- Tolerance for parameters with 10% lum. loss
- Better tolerance with crab waist
- Similar results for HER

Parameter	w/ crab waist	w/o crab waist
$\partial r_1^*/\partial\delta$ (rad)	1.1	0.8
$\partial r_2^*/\partial\delta$ (m)	0.04	0.03
$\partial r_3^*/\partial\delta$ (m^{-1})	4500	3000
$\partial r_4^*/\partial\delta$ (rad)	160	110

3. Beam-beam: Other parameters

➤ Old results for SuperKEKB(KEKB MAC11, K. Ohmi)

- **Tolerance for parameters with 20% lum. loss**

Parameter	w/ crab waist	w/o crab waist
r_1^* (mrad)	±5.3	±3.5
r_2^* (mm)	±0.18	±0.13
r_3^* (m^{-1})	±44	±15
r_4^* (rad)	±1.4	±0.4
$\partial r_1^* / \partial\delta$ (rad)	±2.4	±2.1
$\partial r_2^* / \partial\delta$ (m)	±0.086	±0.074
$\partial r_3^* / \partial\delta$ (m^{-1})	$\pm 1.0\times10^4$	±8400
$\partial r_4^* / \partial\delta$ (rad)	±400	±290
η_y^* (μm)	±62	±31
$\eta_y'^*$	±0.73	±0.23
Δx (μm) collision offset	10	10
Δs (μm) waist error	100	100
Δy,Δy'(μm,μrad) collision offset	0.02 (100)	
δx (μm) turn by turn noise	0.5	0.5
δy (nm)	4	4

The degradation is roughly quadratic

σx=6-10μm σy=50 nm

4. Space charge

- **SC effects**
  - **Linear/Nonlinear tune shift**
  - **Emittance growth**
  - **Crosstalk with B-B/Lat. nonlin.**
  - **Impact on injection**
- **Effect studied in detail for ILC damping ring**
  - **Codes: SAD and MaryLie/Impact**
  - **Emittance degradation: Cross lattice resonances; Amplify effects of lattice errors; Tune choices; ...**
- **Also studied for SuperB LER**
- **Differences from ILC DR**
  - **BB**
  - **No symmetry in lattice => Strong lat. nonlin.**

4. Space charge: Linear tune shift

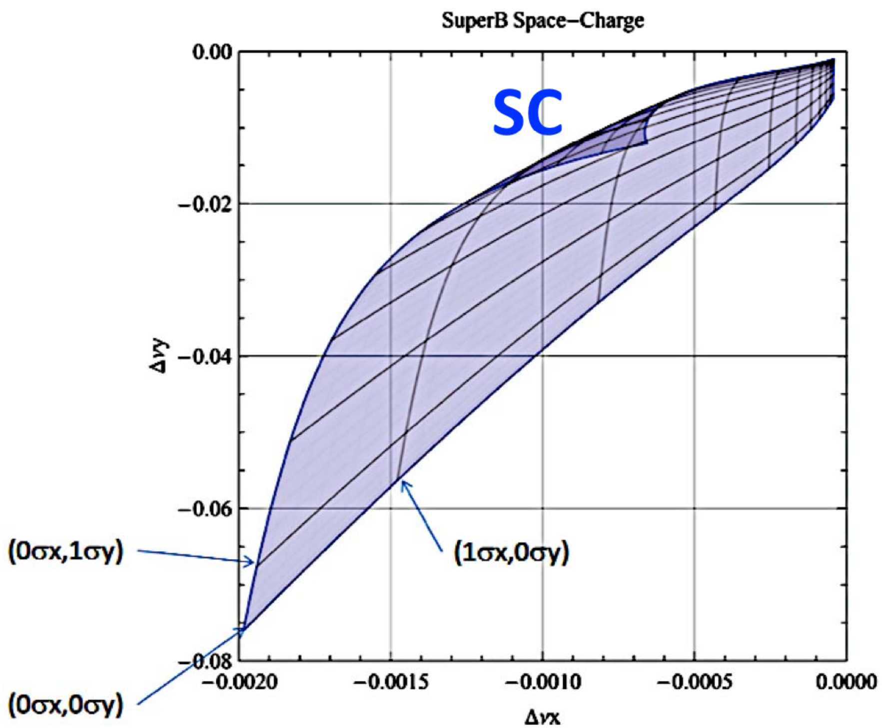
- **SuperKEKB LER**
  - **Tune shift: Same order for SC and BB**
  - **But have opposite signs**

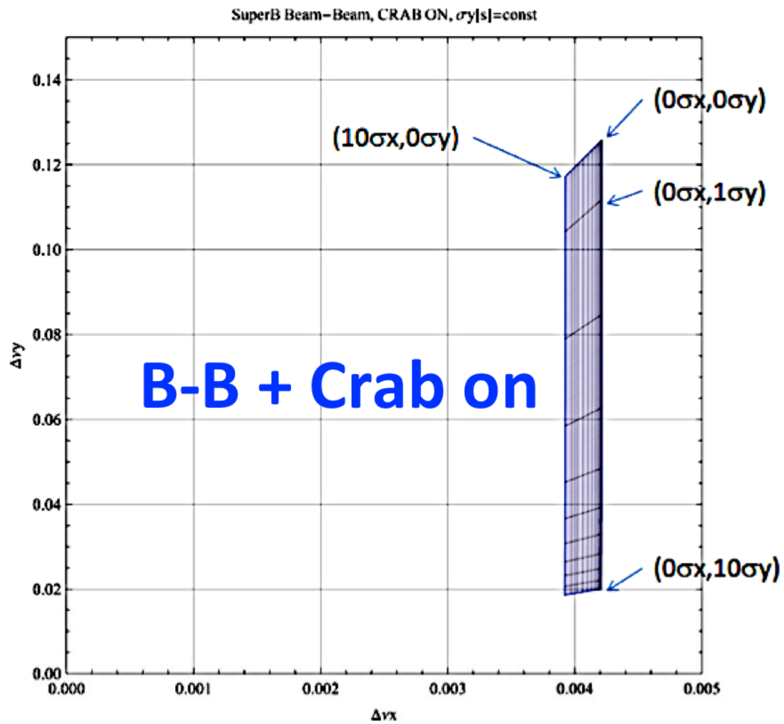
	SuperKEKB[1]		KEKB[4]	
	LER[2]	HER[3]	LER	HER
ε_x (nm)	3.2	4.6	18	24
ε_y (pm)	8.64	11.5	180	240
ξ_x	0.0028	0.0012	0.127	0.102
ξ_y	0.0881	0.0807	0.129	0.09
$\Delta\nu_x$	-0.0027	-0.0004	-0.0005	-3.00E-05
$\Delta\nu_y$	-0.0943	-0.0121	-0.0072	-0.0004

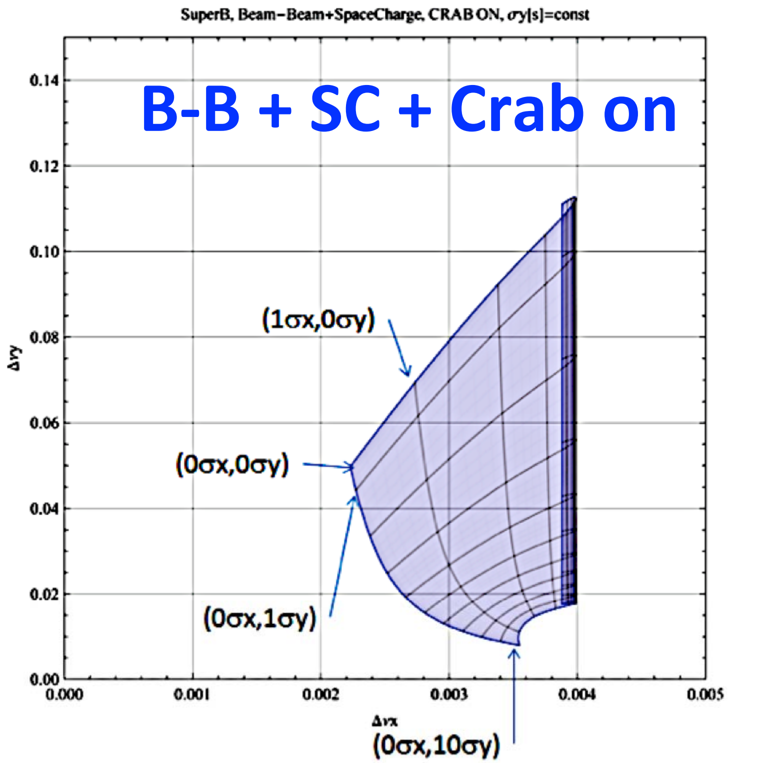
[1]Main paraperters from Y. Ohnishi et al., Prog. Theor. Exp. Phys. 2012;
[2]sler_1682; [3]sher_5753; [4]Lattice used on Jun.17, 2009.

4. Space charge: Tune shift

- **SuperB**
  - **Linear SC tune shift $\Delta\nu_y \approx -0.08$**
  - **Linear SC tune shift $\Delta\nu_y \approx 0.12$**





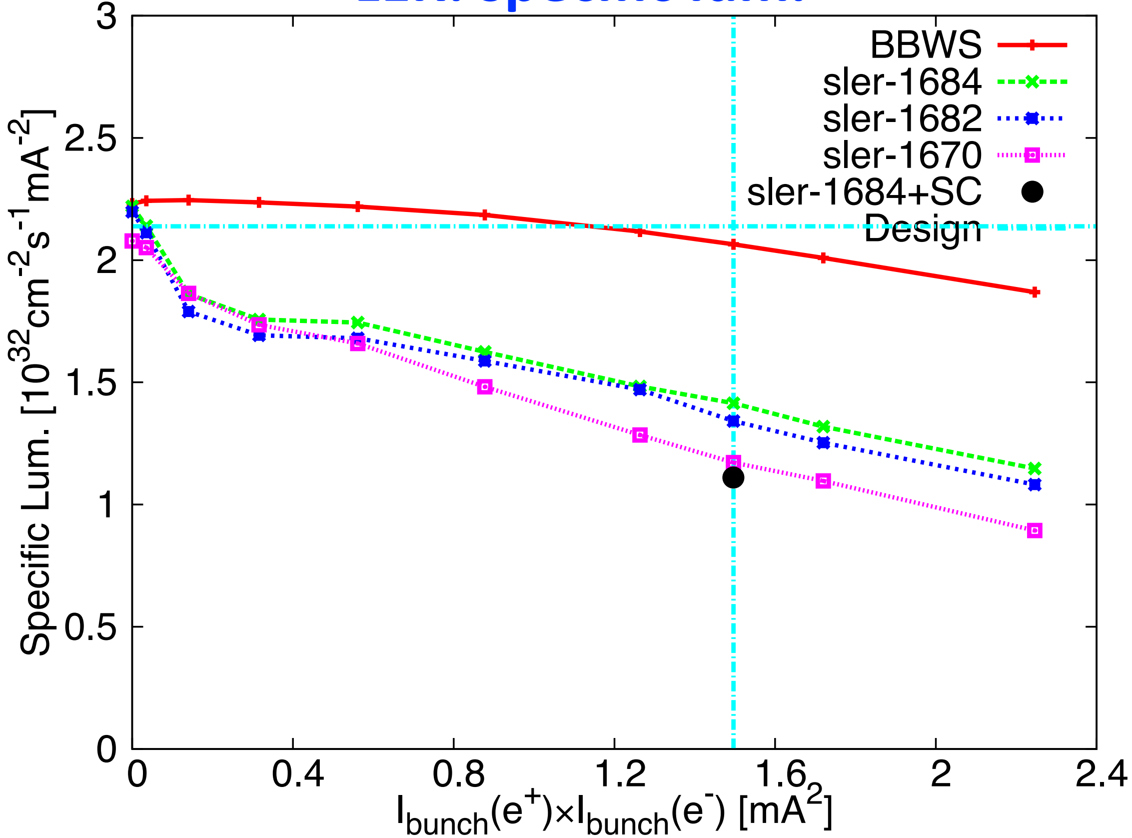


Courtesy of E. Levichev

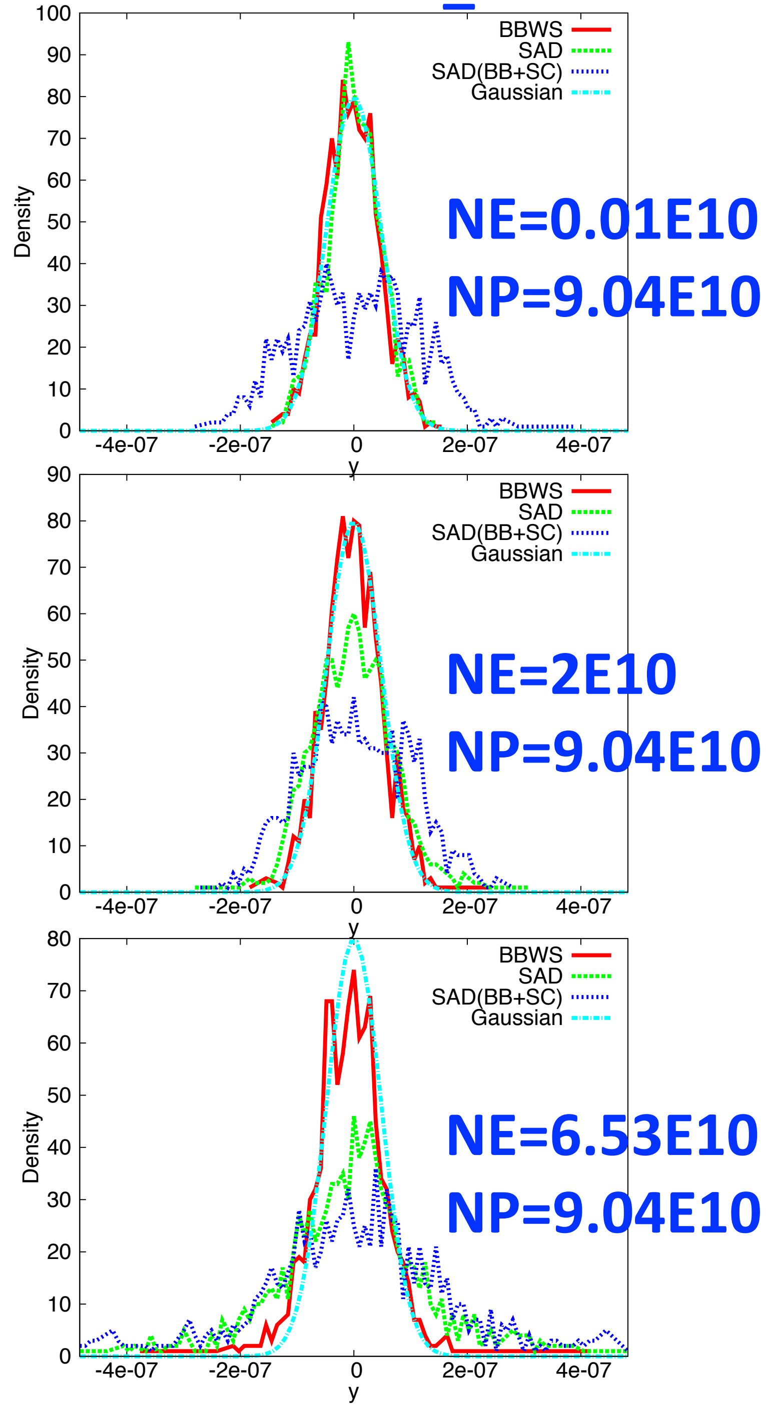
4. Space charge: Simulations

- ➤ **BB+LN+SC (Very preliminary!)**
  - **Lum. loss observed**
  - **Emit. growth due to SC**
  - **SC+BB: Compensation?**

LER: specific lum.



sler_1684



5. Fast ion: HER

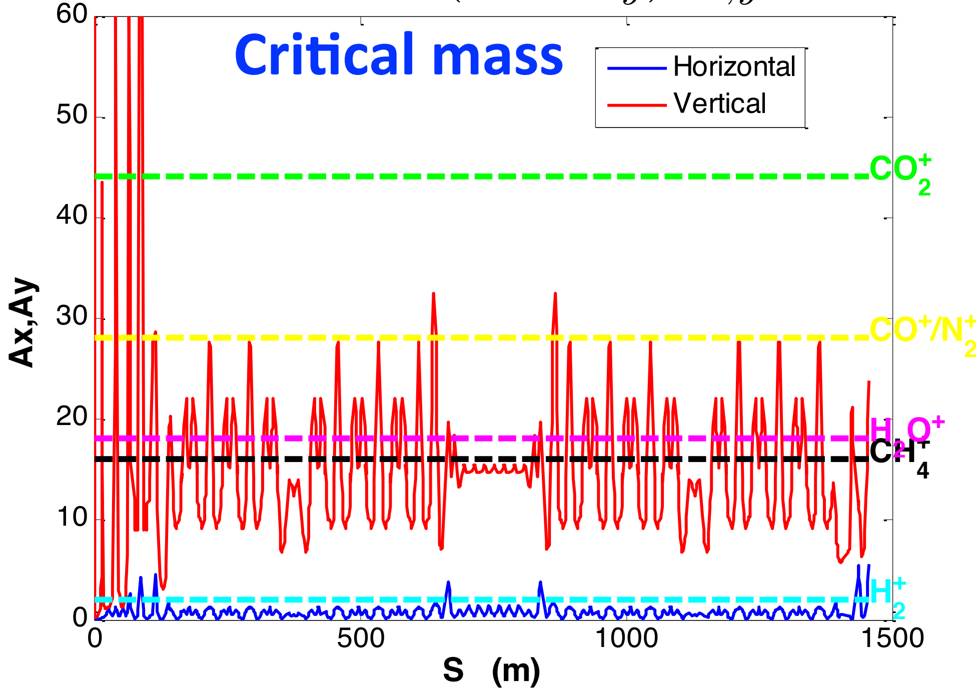
- KEKB achieved: $P_{tot} \approx$ 2-3x10^{-7}Pa(Arc section)
- SuperKEKB expected:

  $P_{tot}\approx$9(4.5)x10^{-7}Pa, P(CO)≈2(1)x10^{-7}Pa if photo-desorption coefficient η=1(0.5)x10^{-6}
- Critical mass: CO and CO_2 are most important

# of bunch/train	125
Bunch separation	2 RF buckets
Train gap	6 RF buckets
# of trains	20
Pressure	5x10^{-7} Pa(3.8 nTorr)
Ion*	50% CO 25% H_2
Coupling	0.28%

*Partial pressure is based on that at the beginning of KEKB operation

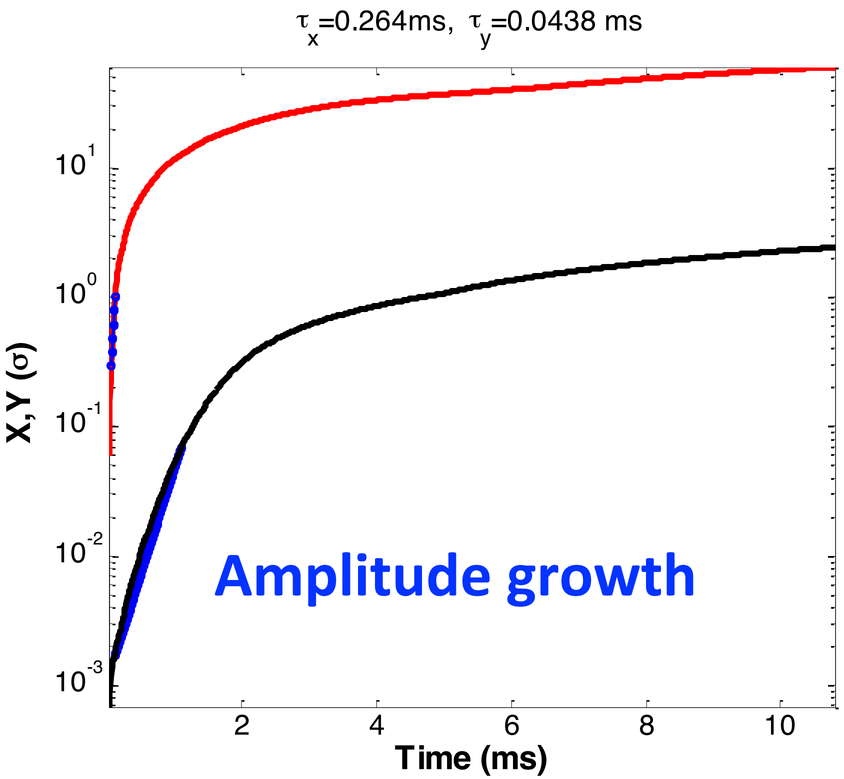
$$A_{x,y} = \frac{N_b r_p s_b}{3(\sigma_x + \sigma_y)\sigma_{x,y}}$$

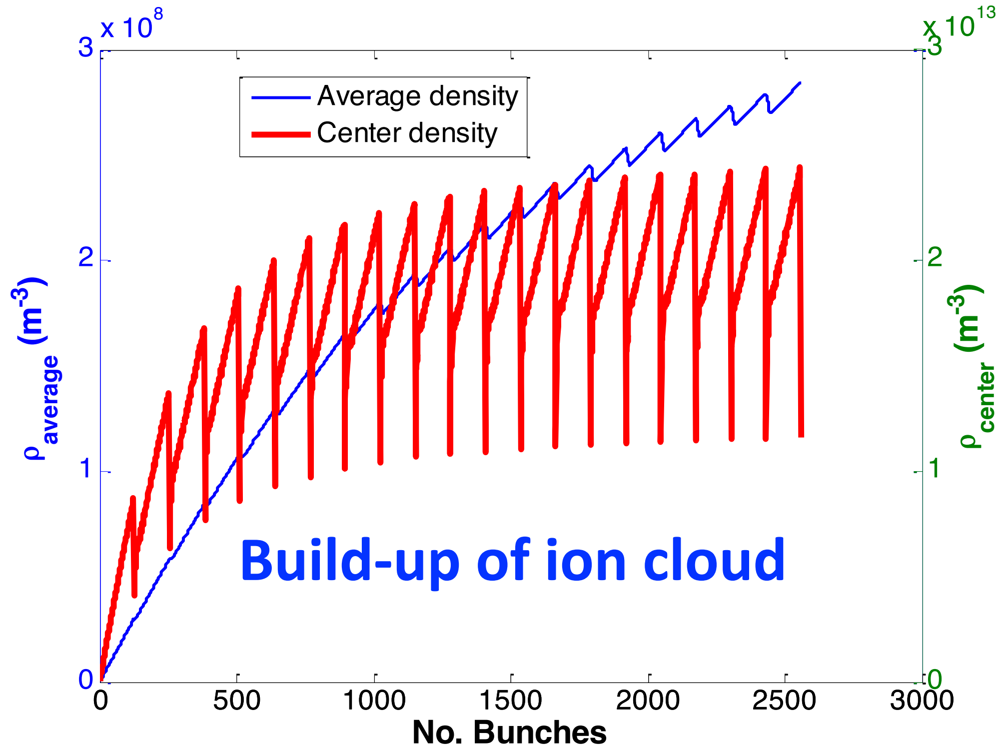


L. Wang and H. Fukuma

5. Fast ion: HER: Simulation results (L. Wang)

- ➤ Vertical growth time: τ_y = 44μs for P_{tot}=5x10^{-7}Pa
- ➤ If total pressure P_{tot}=1.3x10^{-7}Pa(1 nTorr), τ_y = 104μs
- ➤ If H_2 is dominant(e.g. 70%), as expected in long term operation, τ_y = 76μs (P_{tot}=5x10^{-7}Pa)



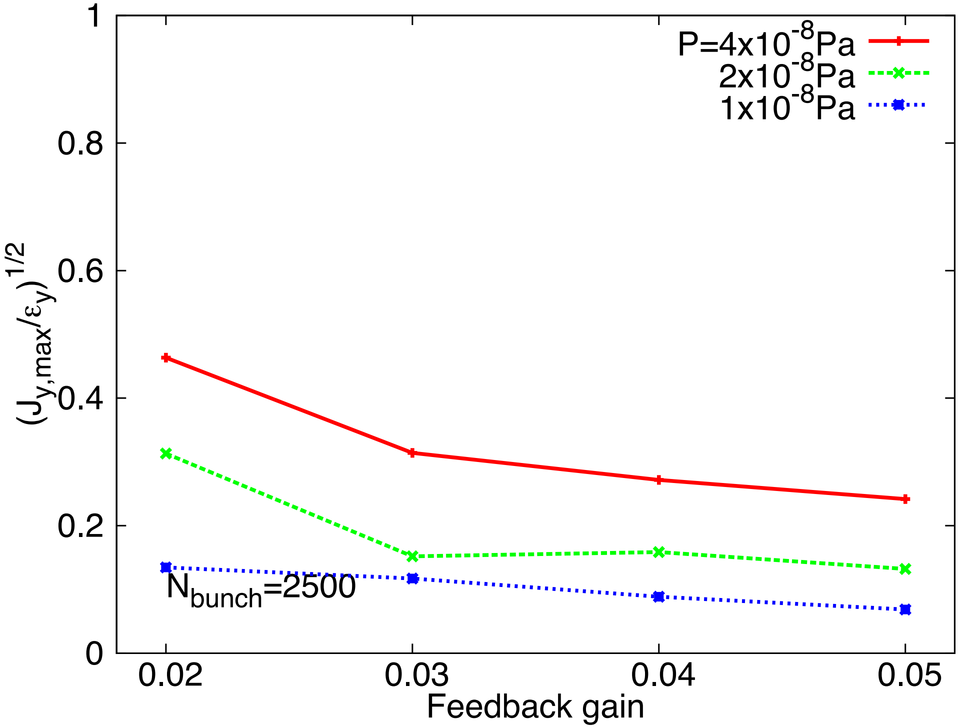


L. Wang and H. Fukuma

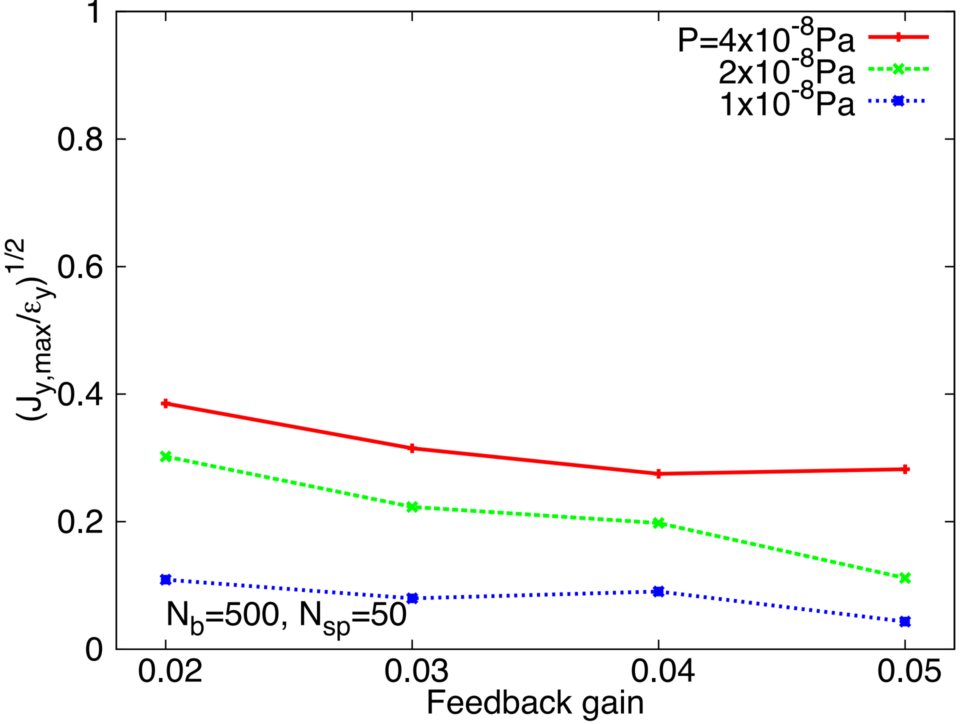
5. Fast ion: HER: Simulation results (K. Ohmi)

- **Amp. growth sensitive to partial gas pressure of CO**
- **Fast feedback necessary (G=0.05 ➟ 20 turns)**
- **Simulations: Only pressure of CO considered**

N_{bunch}=2500



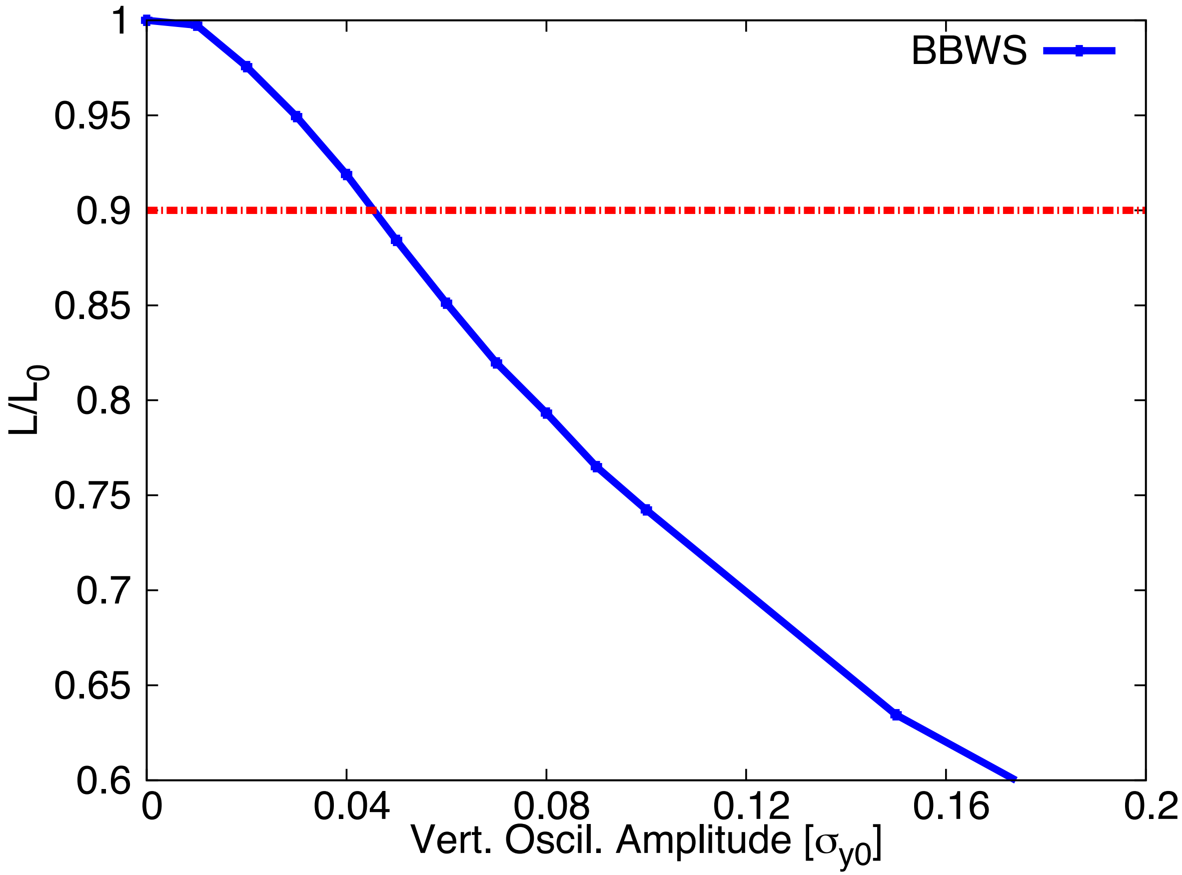
N_{bunch}=5x500, N_{sp}=50



K. Ohmi

5. Fast ion: HER: Future study

- **BBWS: Lum. loss < 10% ➠ DY/σ_{y0} < 5%**
- **Future study:**
  - **Optimum fill pattern**
  - **Expected pressure**
  - **Bunch feedback**



6. Summary

- **CSR unlikely to be important in SuperKEKB**
  - **Improvements in CSR calculation and MWI simulation**
  - **Study of CSR in linac is ongoing**
- **Beam-beam**
  - **Strong synchro-betatron resonances => Tune choice**
  - **Crosstalk with LN likely to be important => Need more study in detail; Benchmark work is preferred**
  - **Study of crosstalk with SC is ongoing**
  - **Tight control of chromatic coupling is necessary => Future work: To simulate all knob scans in the control room based on a virtual machine**
- **Space charge**
  - **Recognized most recently**
  - **Study in detail is underway**

6. Summary

- **Fast ion**
  - **Ongoing study: Fill pattern; Expected pressure; Feedback**
- **Not addressed issues**
  - **Single particle dynamics => H. Sugimoto's talk**
  - **Strong-strong beam-beam simulation => Time consuming; Challenges in parallelization of code**
  - **Ecloud => No new simulation results; Experiments**
  - **Impedance => Impedance database is under preparation (Longitudinal for MWI; Transverse for TMCI and beam tilt)**
- **Unrecognized issues???**
  - **Recommendations from the review committee are mostly appreciated!**
  - **Ideas from outside are welcome! SuperKEKB will be an excellent platform for accelerator physicists!**

7. Future plan

➤ **An international effort to study the beam dynamics issues in SuperKEKB**

- **BINP team: E. Levichev, P. Piminov, Shatilov, Koop, et al.**
- **SLAC team: Y. Cai, G. Stupakov, L. Wang, and others?**
- **INFN team: SuperB experiences?**
- **SuperKEKB team: ... ...**

➤ **Proposals by E. Levichev**

- **Polarization: Ivan Koop and Dmitry Schwarts**
- **BB+LN+SC: Pavel Piminov and Dmitry Shatilov**
- **DA, Crab waist, Lattice: Anton Bogomyagkov, Sergey Siniatkin, Pavel Piminov**

Thanks for your attention!