Beam Dynamics Issues in SuperKEKB

D. Zhou

With contributions from

KEK: T. Ishibashi, K. Ohmi, K. Oide, Y. Ohnishi, K. Shibata, H. Sugimoto, ...

Cornell Univ.: D. Sagan

IHEP: Y. Zhang

SLAC: Y. Cai

The 20th KEKB Accelerator Review Committee, Feb. 23, 2015

Outline

- ➢ **Impedance issues - updates**
- ➢ **Interplay of beam-beam(BB) and lattice nonlinearity(LN)**
- ➢ **Space charge(SC) effects in LER**
- ➢ **Luminosity calculation for detuned lattices**
- ➢ **Benchmark of SAD**
- ➢ **Summary and Future plan**

Outline

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- ➤ Interplay of beam-beam(BB) and lattice nonlinearity(LN)
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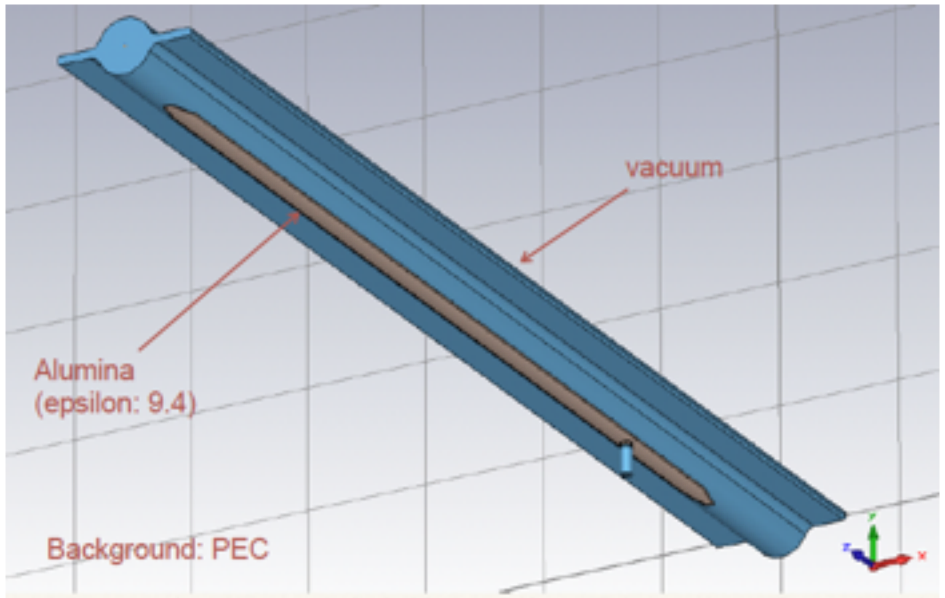
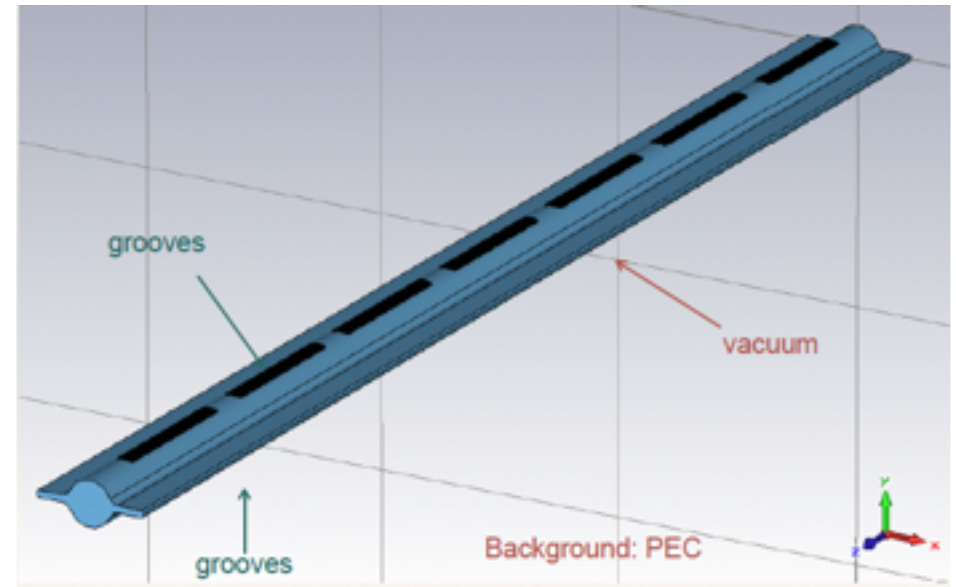
- ➤ Summary and Future plan

1. Impedance issues: LER

Clearing electrode



Grooved surfaces



From T. Ishibashi

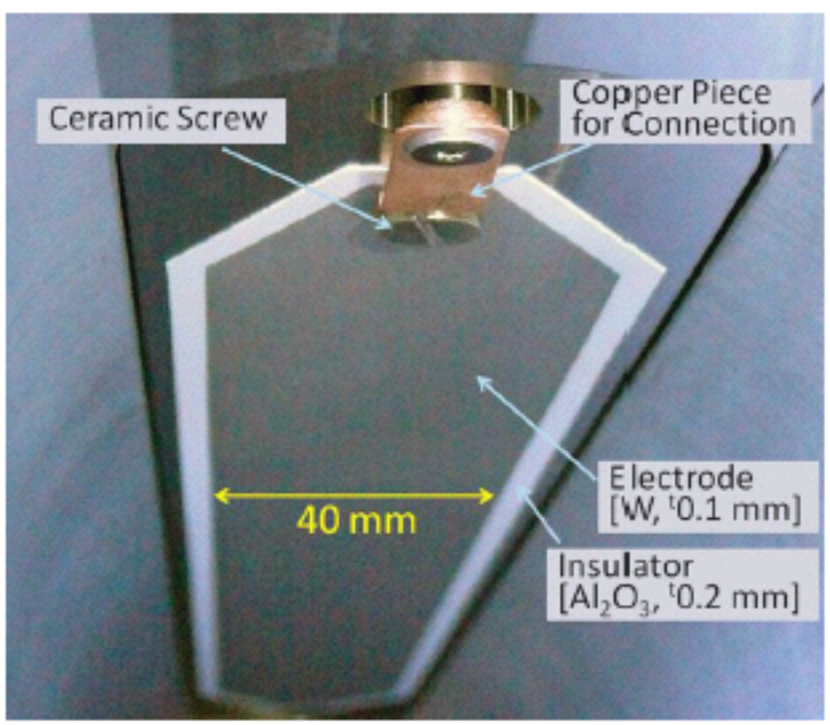


Fig. 2 Clearing electrode installed in test chamber. The electrode and the feed-through are connected by small piece of copper.

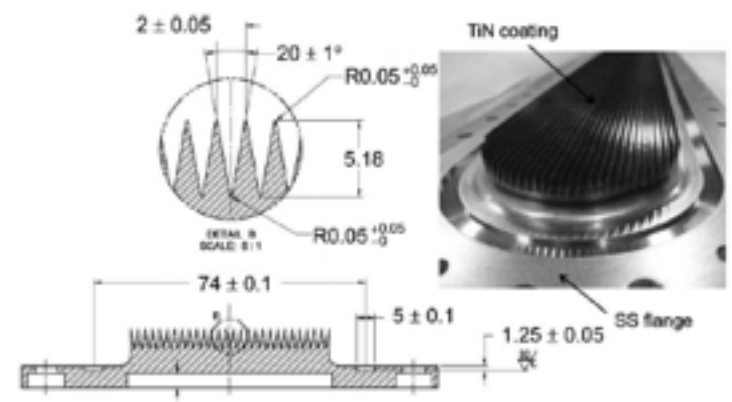


Fig. 1. Insertion with TiN-coated groove surface.

Tested in KEKB

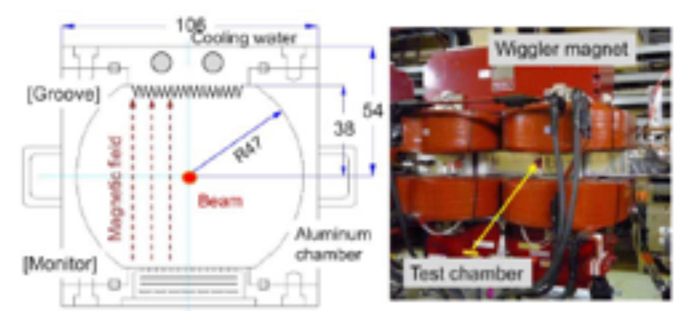


Fig. 2. Cross-section of the test chamber and the experimental setup in a wiggler magnet section in the KEKB positron ring.

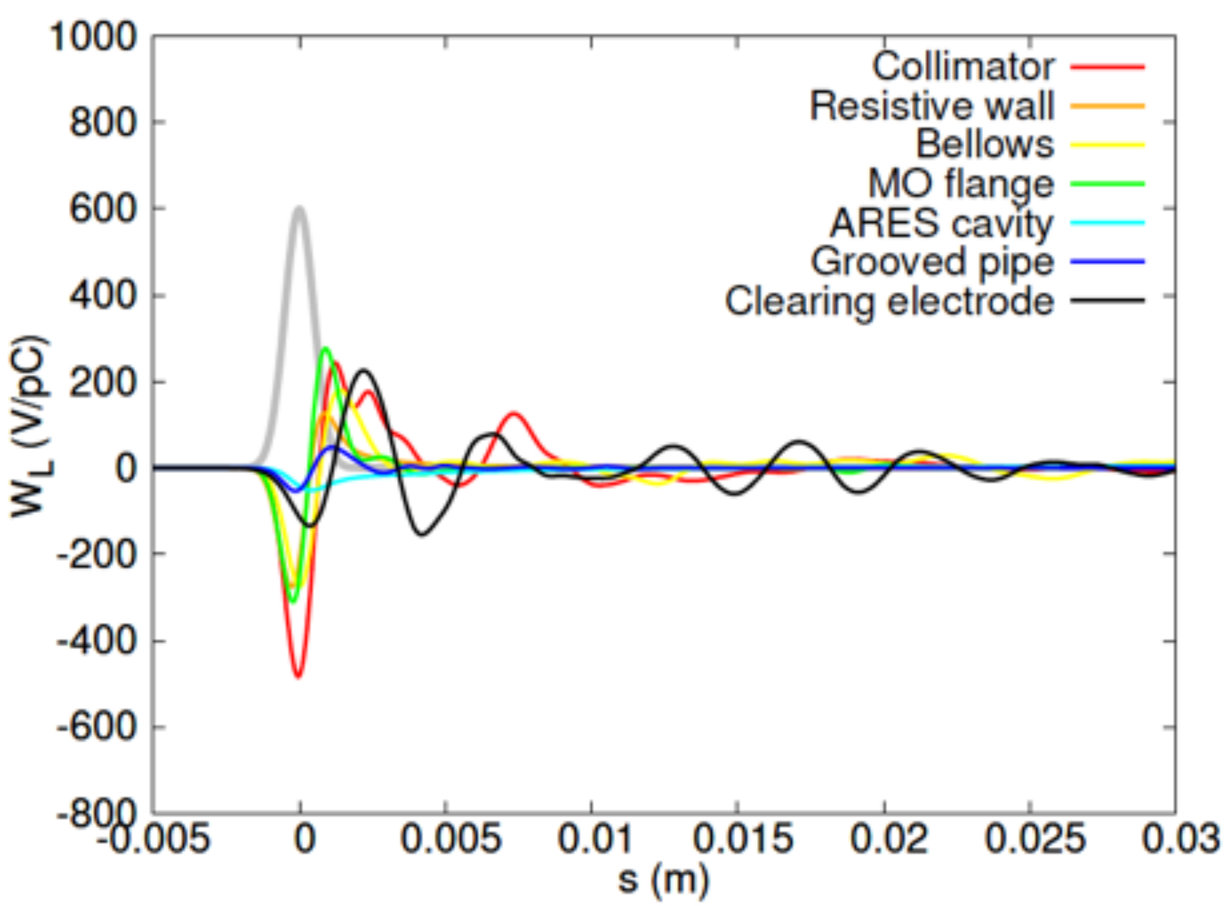
Ref. Y. Suetsugu et al., NIMA 598 (2009)

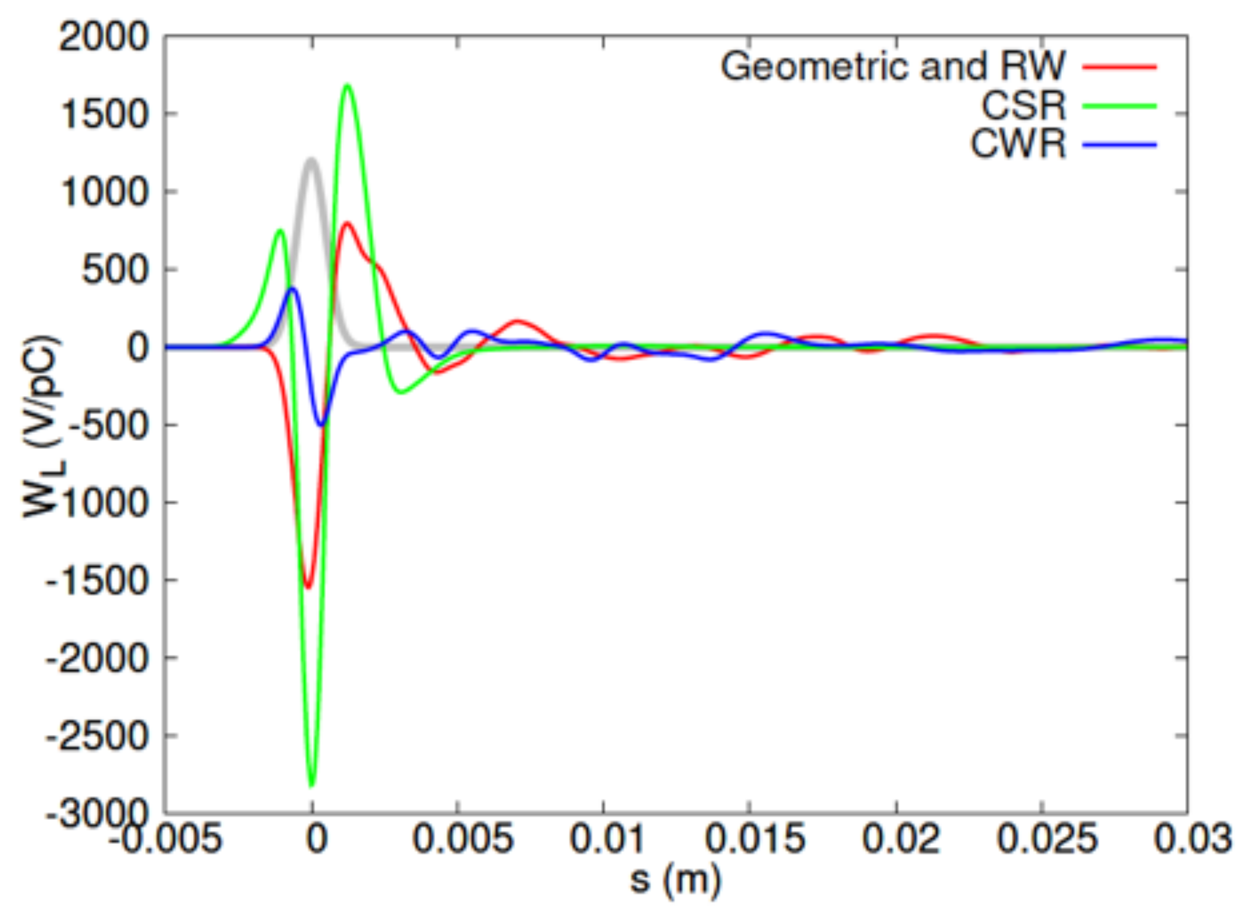
Ref. Y. Suetsugu et al., NIMA 604 (2009)

1. Impedance issues: LER

➤ Pseudo-Green wake function

- σ_z=0.5mm
- Pumping ports and SR masks are negligible sources because of antechamber
- CSR and CWR (Wiggler radiation): CSRZ code with rectangular chamber

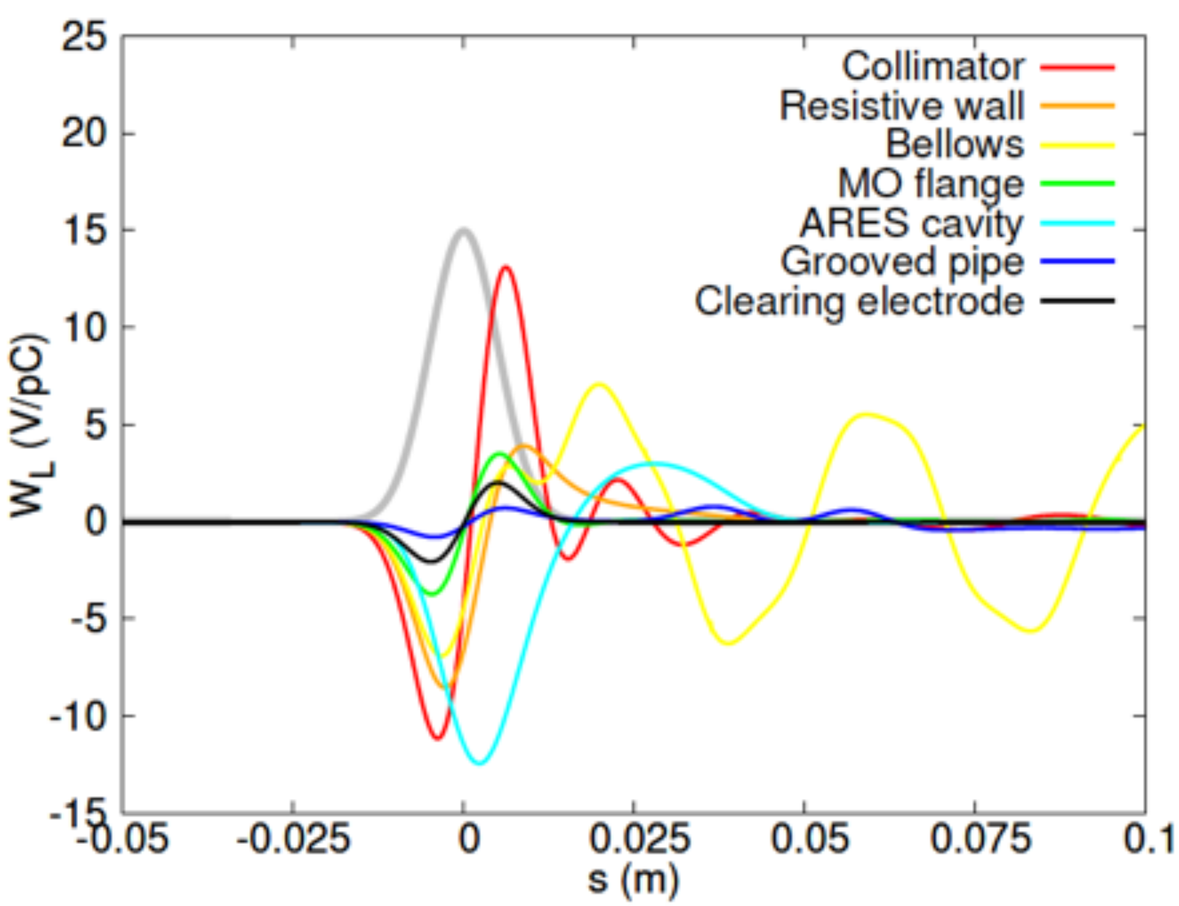


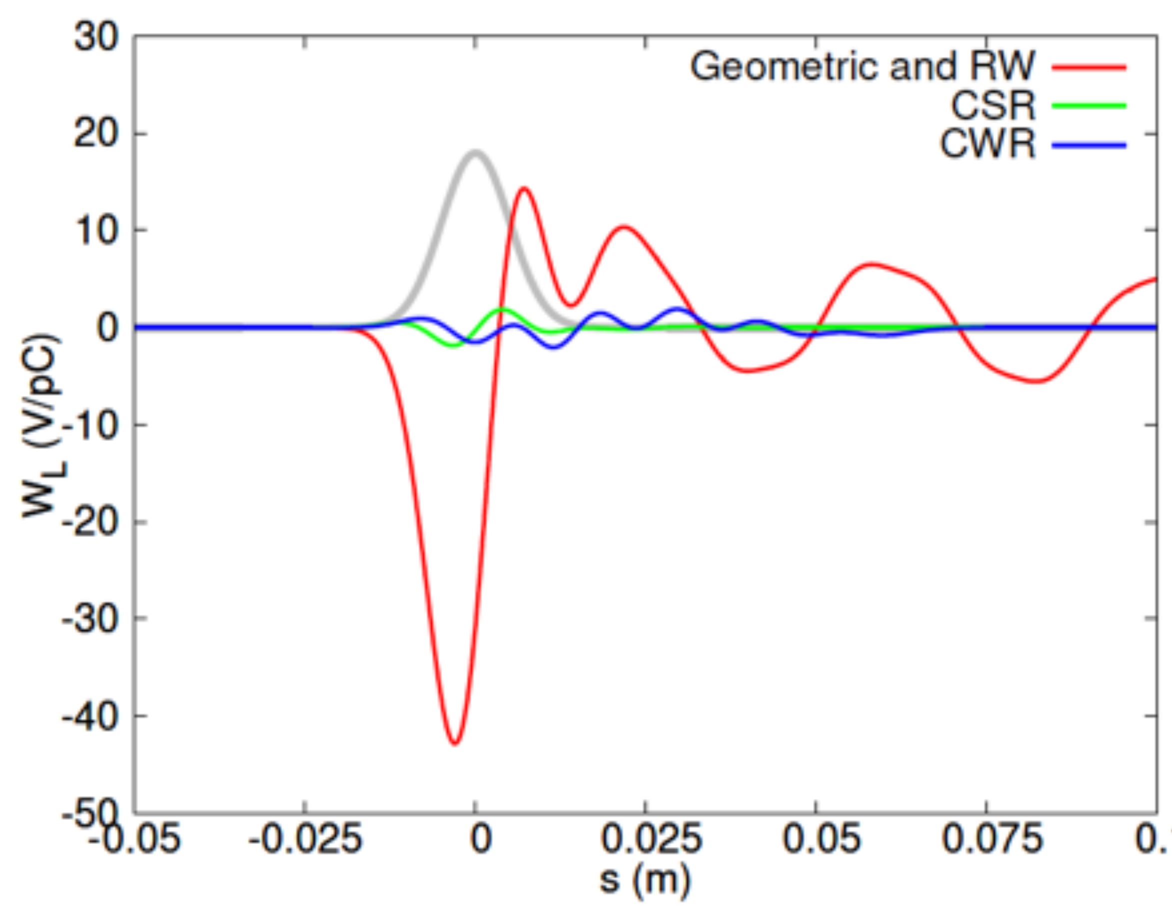


1. Impedance issues: LER

➤ **Wake potential with nominal bunch length**

- **σ_z=5mm**
- **Main sources: Collimators, Resistive wall, ARES cavity, Bellows, MO flanges, Clearing electrodes**
- **CSR and CWR are not strong if no microbunching happens**





1. 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 2: Key parameters of SuperKEKB main rings for MWI simulations.

Parameter	LER	HER
Circumference (m)	3016.25	3016.25
Beam energy (GeV)	4	7.007
Bunch population (10^{10})	9.04	6.53
Nominal bunch length (mm)	5	4.9
Synchrotron tune	0.0244	0.028
Long. damping time (ms)	21.6	29.0
Energy spread (10^{-4})	8.1	6.37

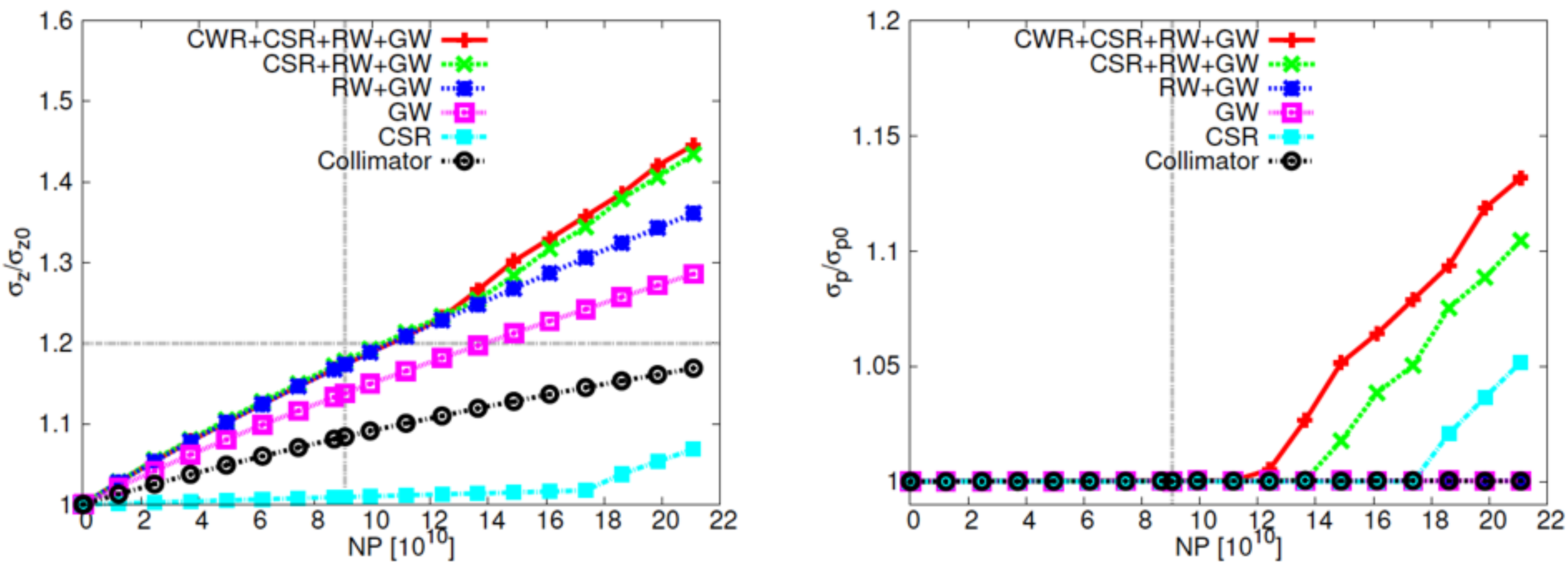
Component	LER			HER		
	$k_{\|\|}$	R	L	$k_{\|\|}$	R	L
ARES cavity	8.9	524	-	3.3	190	-
SC cavity	-	-	-	7.8	454	-
Collimator	1.1	62.4	13.0	5.3	309	10.8
Res. wall	3.9	231	5.7	5.9	340	8.2
Bellows	2.7	159	5.1	4.6	265	16.0
Flange	0.2	13.7	4.1	0.6	34.1	19.3
Pump. port	0.0	0.0	0.0	0.6	34.1	6.6
SR mask	0.0	0.0	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

1. Impedance issues: MWI: LER

➤ **Simulations with input of Pseudo-Green wake:**

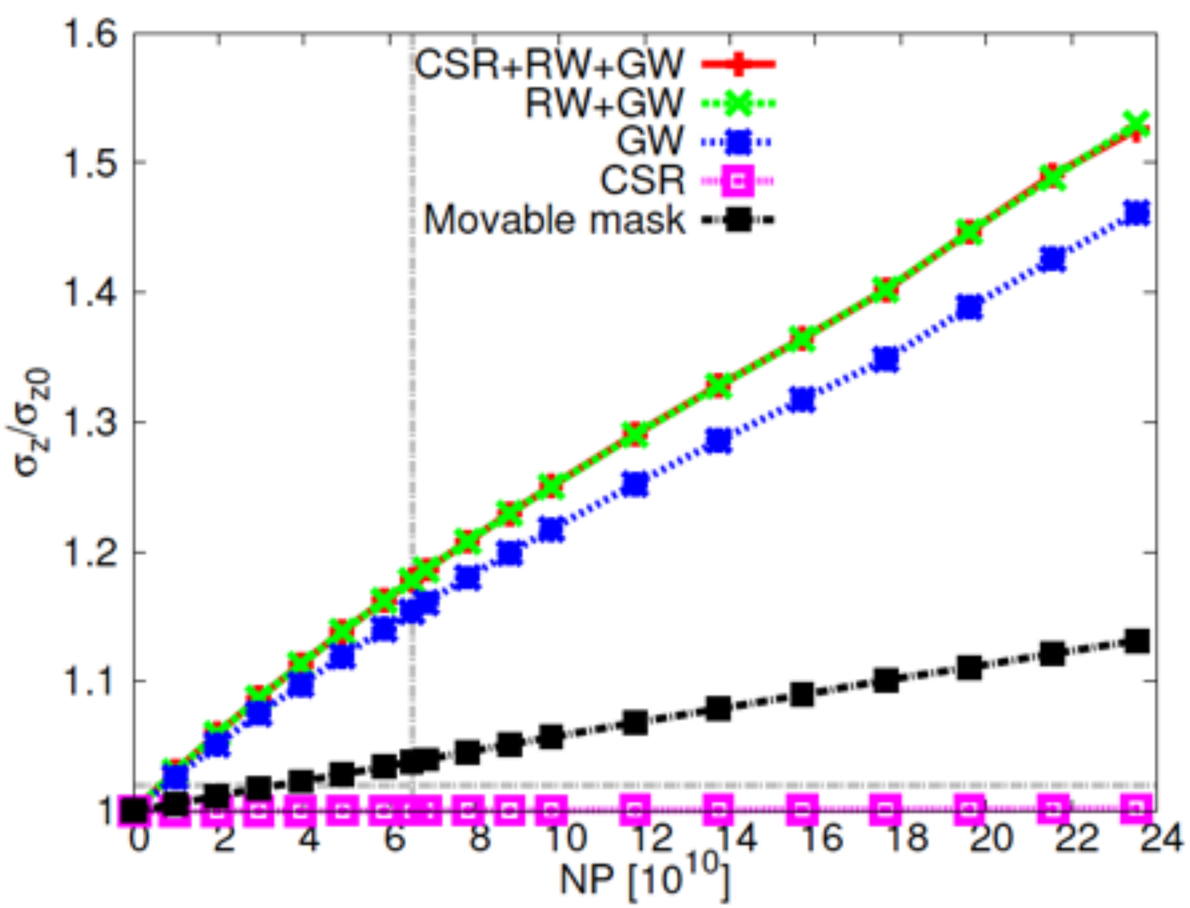
- Use Warnock-Cai's VFP solver
- Collimators are important sources in bunch lengthening
- Simulated $\sigma_z \approx 5.9$mm @Design bunch current
- Simulated MWI threshold is around NP_{th}=1.2E11
- Interplay between CSR and conventional wakes?

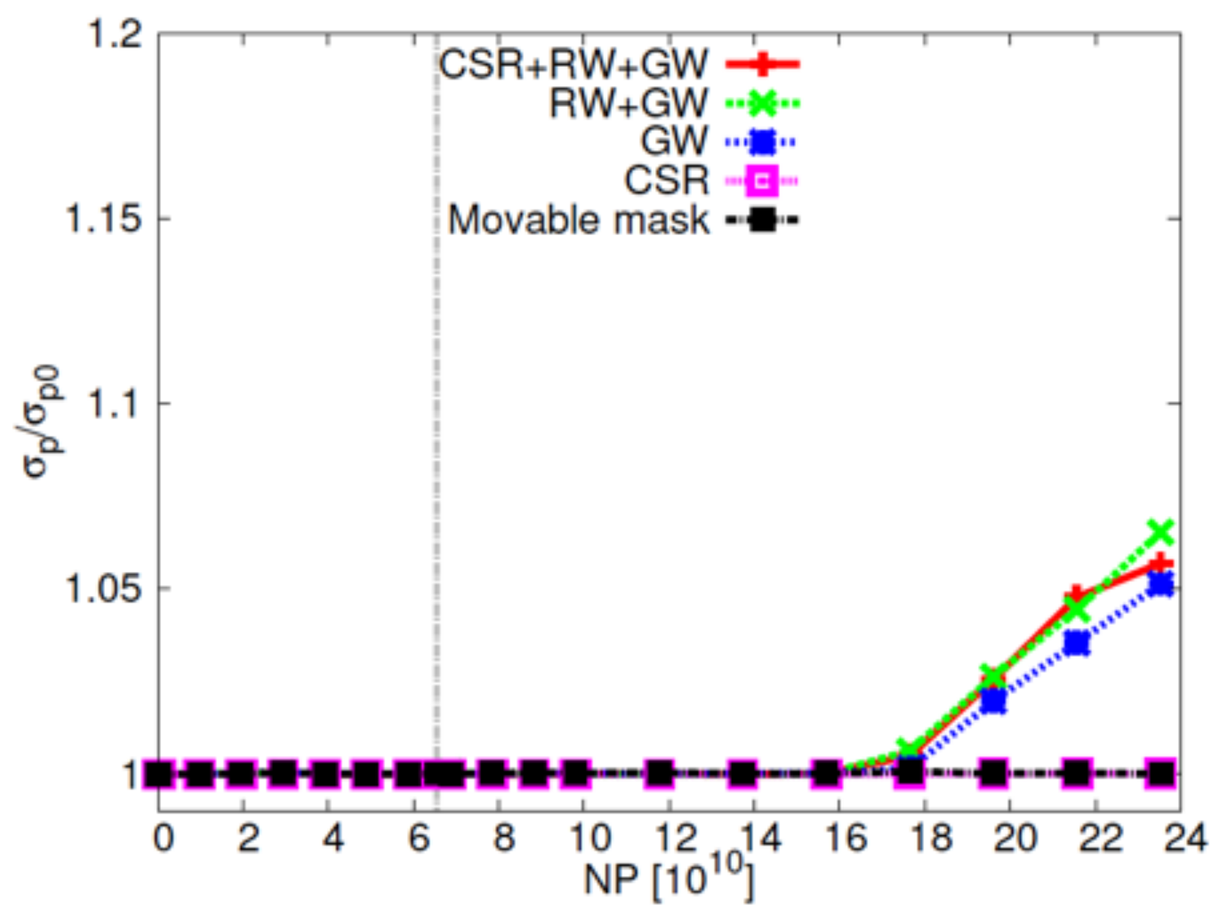


1. Impedance issues: MWI: HER

➤ **Simulations with input of Pseudo-Green wake:**

- **Use Warnock-Cai's VFP solver**
- **Simulated $\sigma_z \approx 5.8$mm @Design bunch current**
- **Simulated MWI threshold is around NP_{th}=1.7E11**
- **Y. Cai's comment: CSR should not be important in SuperKEKB (consider shielding and long bunch).**





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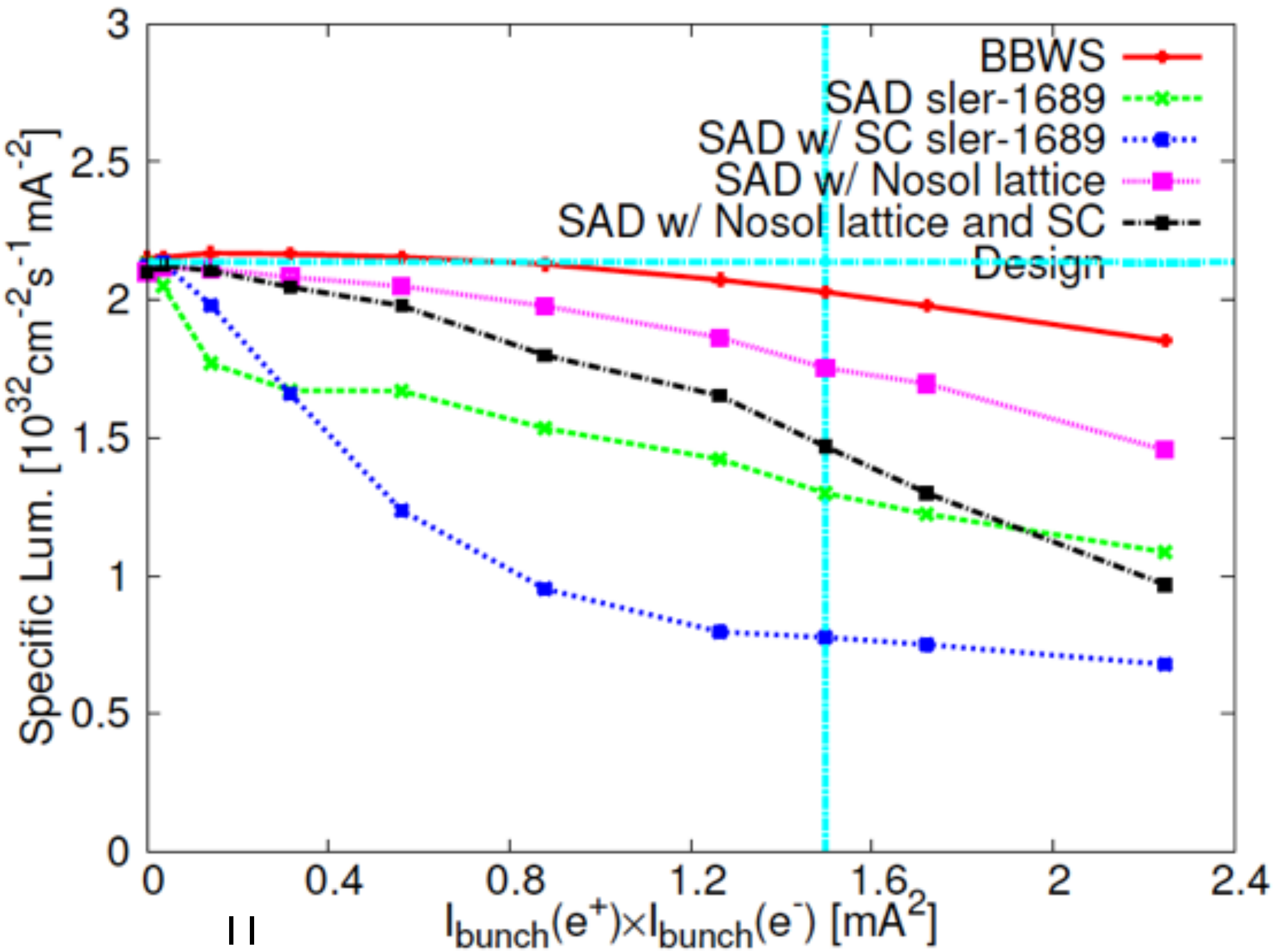
2. BB+LN: LER: Simplified IR

➤ Simplified lattice (sler_simple001.sad) by H. Sugimoto

- No solenoid
- QC* magnets simplified: no offset, dipole and skew-quad correctors removed

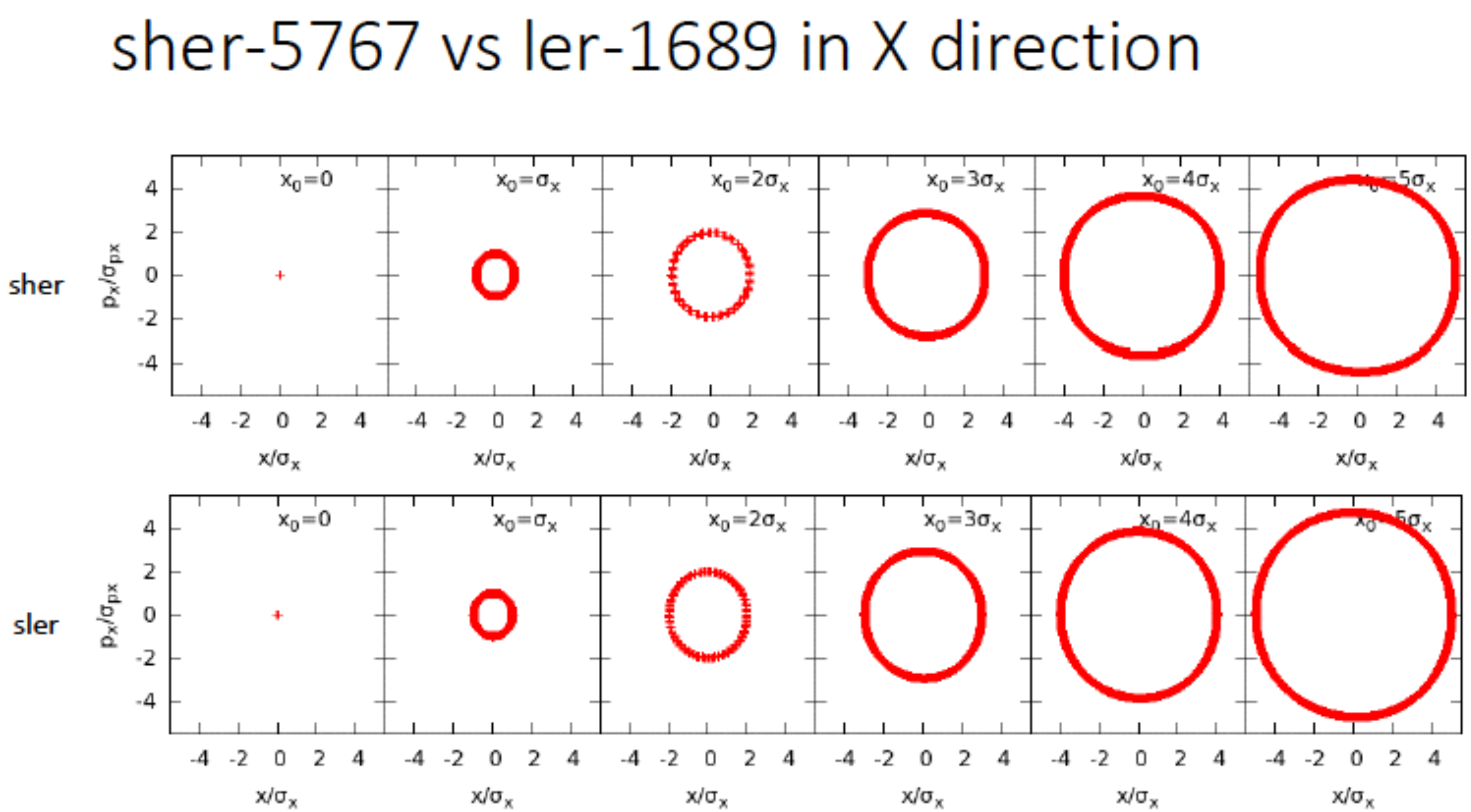
➤ No significant lum. degradation at low current

➤ Solenoid and high-order terms in QC* are the main sources of lattice nonlinearity



2. BB+LN: Nonlin. X-Y coupling

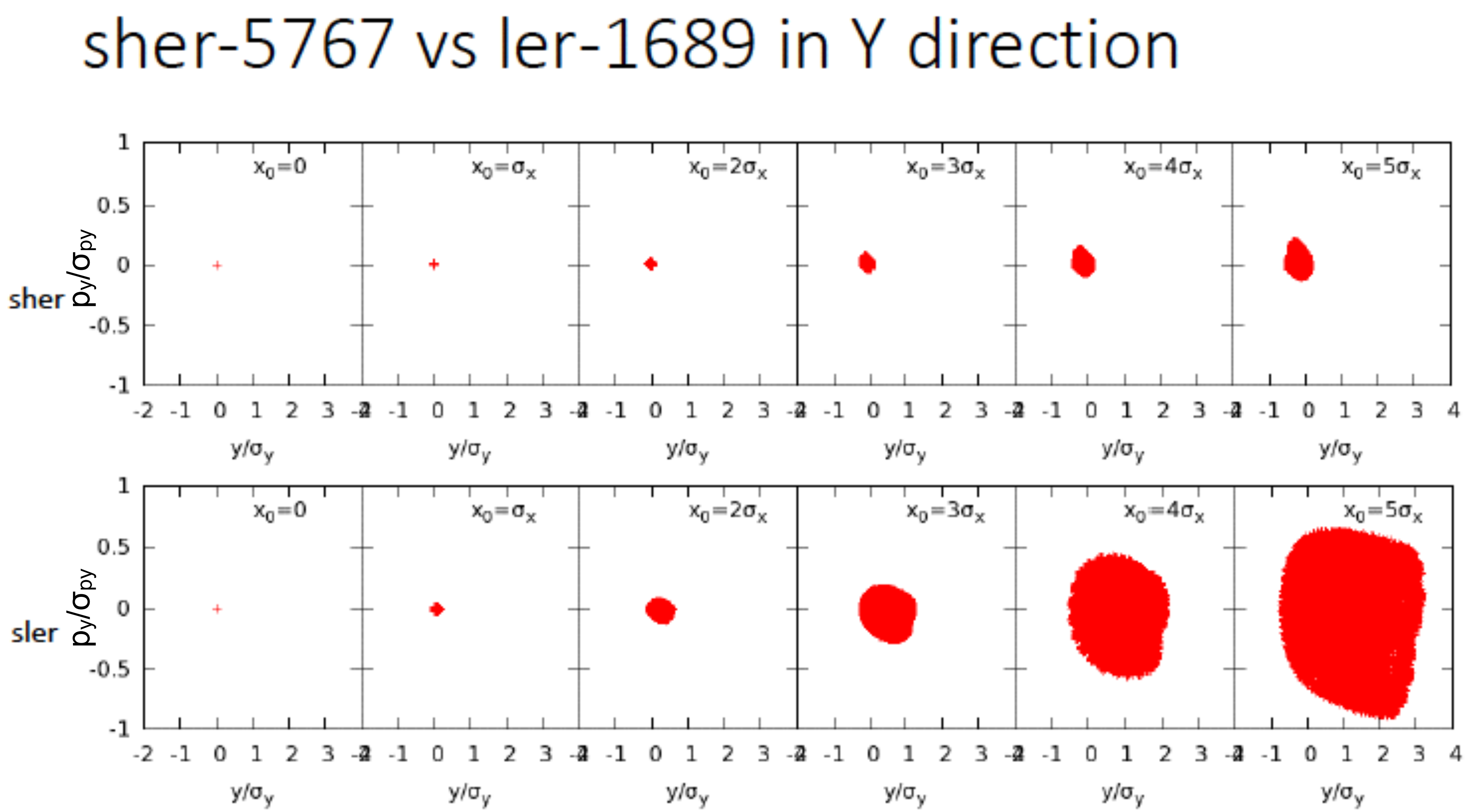
- **Realistic lattice**
- **Y. Zhang's idea: Look at the nonlinear X-Y coupling**



From Y. Zhang

2. BB+LN: Nonlin. X-Y coupling

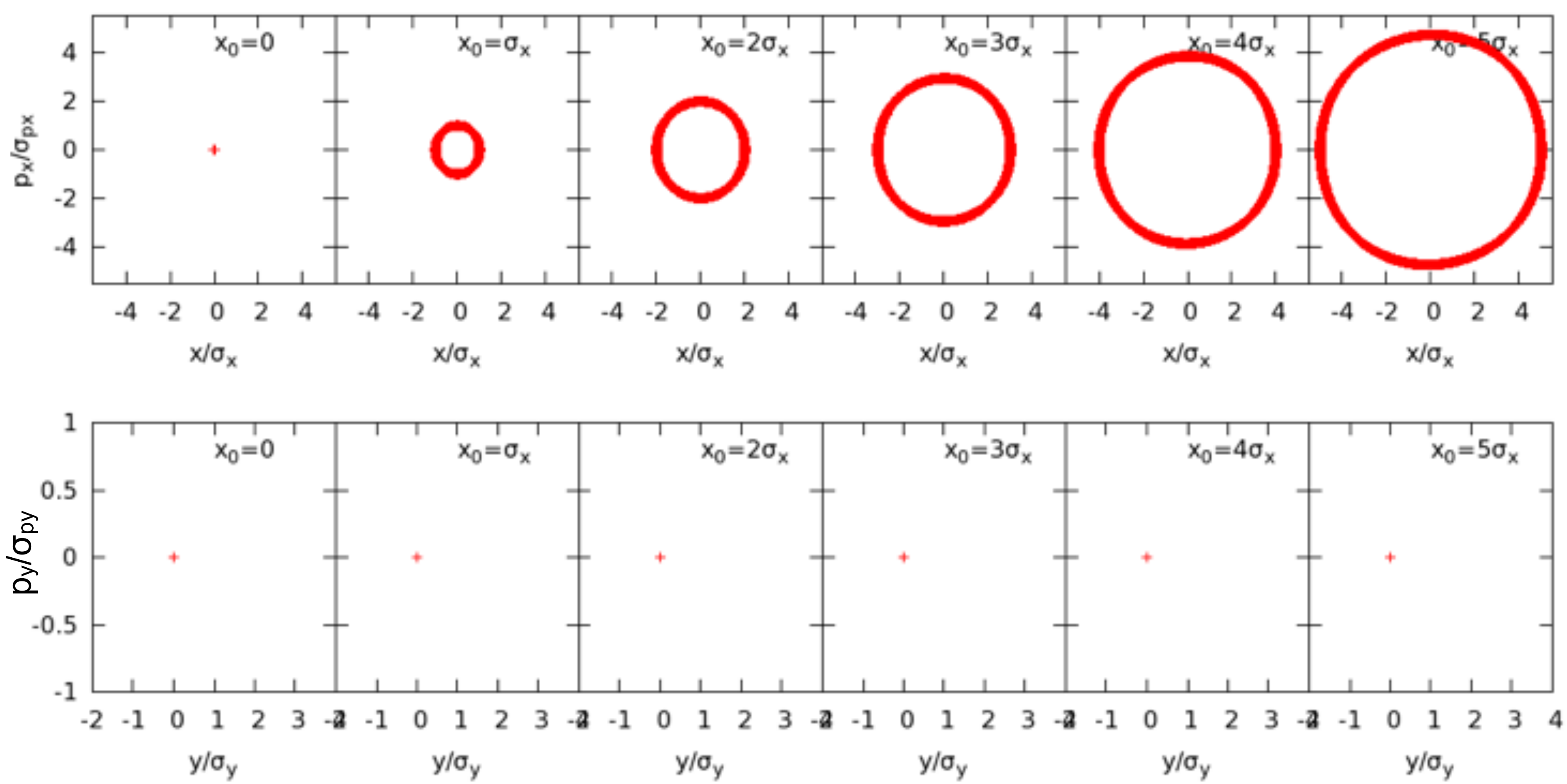
- Realistic lattice
- Poincare map in y direction as function of X offset
- Strong nonlinear X-Y coupling in LER



From Y. Zhang

2. BB+LN: Nonlin. X-Y coupling

- ➤ **Simplified LER lattice (From H. Sugimoto)**
- ➤ **Confirm: solenoid and high-order terms in QC* magnets cause nonlinear X-Y coupling**



From Y. Zhang

2. BB+LN: Nonlin. X-Y coupling

➤ **Test by inserting a map of $H=K*x^2y$ into the LER lattice**

```
GetMAIN["/ldata/SuperKEKB/Lattice/LER/sler_1689.sad"];
USE ASC;
b=ExtractBeamLine[];
b=Prepend[Drop[b,2],BeamLine[IP,BMBMP,SKEWSEXT]];
```

```
!!! Define external maps of skew sextupole (from Y. Zhang)
lambda=-66.6;
cosx = Cos[-1.571];
sinx = Sin[-1.571];
cosy = Cos[-1.351];
siny = Sin[-1.351];
 ExternalMap["TRACK",LINE["POSITION","SKEWSEXT"],nt_,x_]:=(
  normalx = x[[1]]/Sqrt[32e-3];
  normalpx = x[[2]]*Sqrt[32e-3];
  normaly = x[[3]]/Sqrt[0.27e-3];
  normalpy = x[[4]]*Sqrt[0.27e-3];

  xxsext = cosx * normalx + sinx * normalpx;
  pxsext =-sinx * normalx + cosx * normalpx;
  yysext = cosy * normaly + siny * normalpy;
  pysext =-siny * normaly + cosy * normalpy;

  xx=xxsext;
  px=pxsext - 6*lambda * xxsext * yysext;
  yy=yysext;
  py=pysext - 3*lambda * xxsext * xxsext;
```

← **Phase advance from IP**

← **Normalized coordinates**

← **Phase shift**

← **skew-sext. kick**

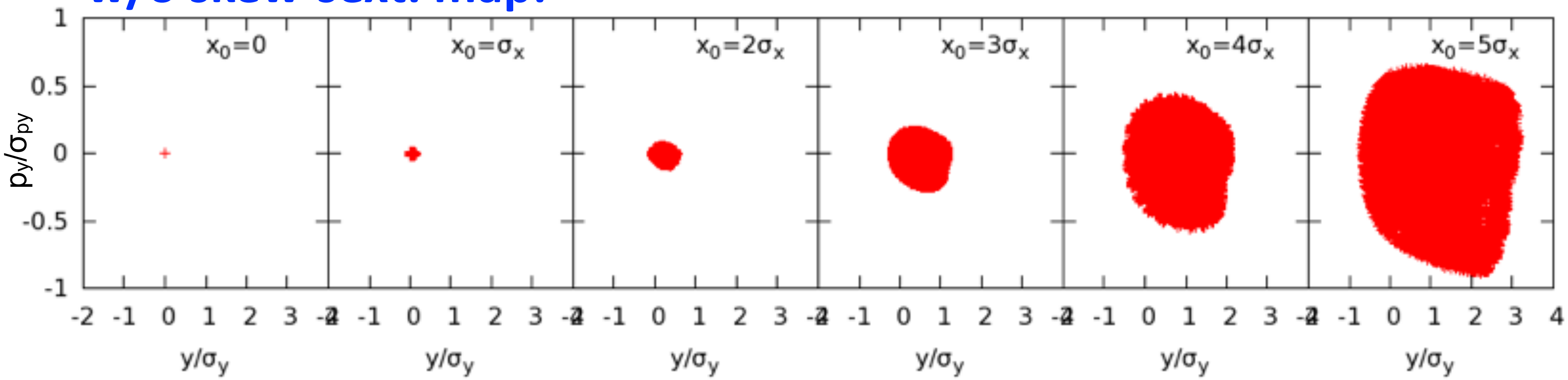
```
  normalx  = cosx * xx - sinx * px;
  normalpx = sinx * xx + cosx * px;
  normaly  = cosy * yy - siny * py;
  normalpy = siny * yy + cosy * py;

  xx = normalx*Sqrt[32e-3];
  px = normalpx/Sqrt[32e-3];
  yy = normaly*Sqrt[0.27e-3];
  py = normalpy/Sqrt[0.27e-3];

  zz=x[[5]];
  dd=x[[6]];
  fl=x[[7]];
  Return[{xx,px,yy,py,zz,dd,fl}];
 );
```

From Y. Zhang

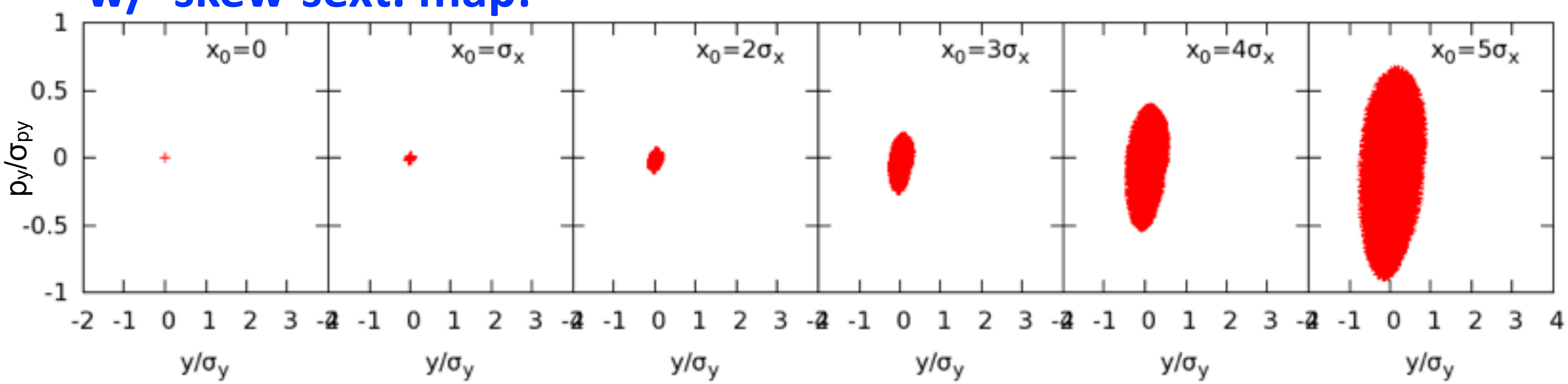
2. BB+LN: Nonlin. X-Y coupling

- ➤ Test by inserting a map of $H=K*x^2y$ into the LER lattice
- ➤ COD and oscillation amplitude in y are well suppressed as expected

w/o skew-sext. map:



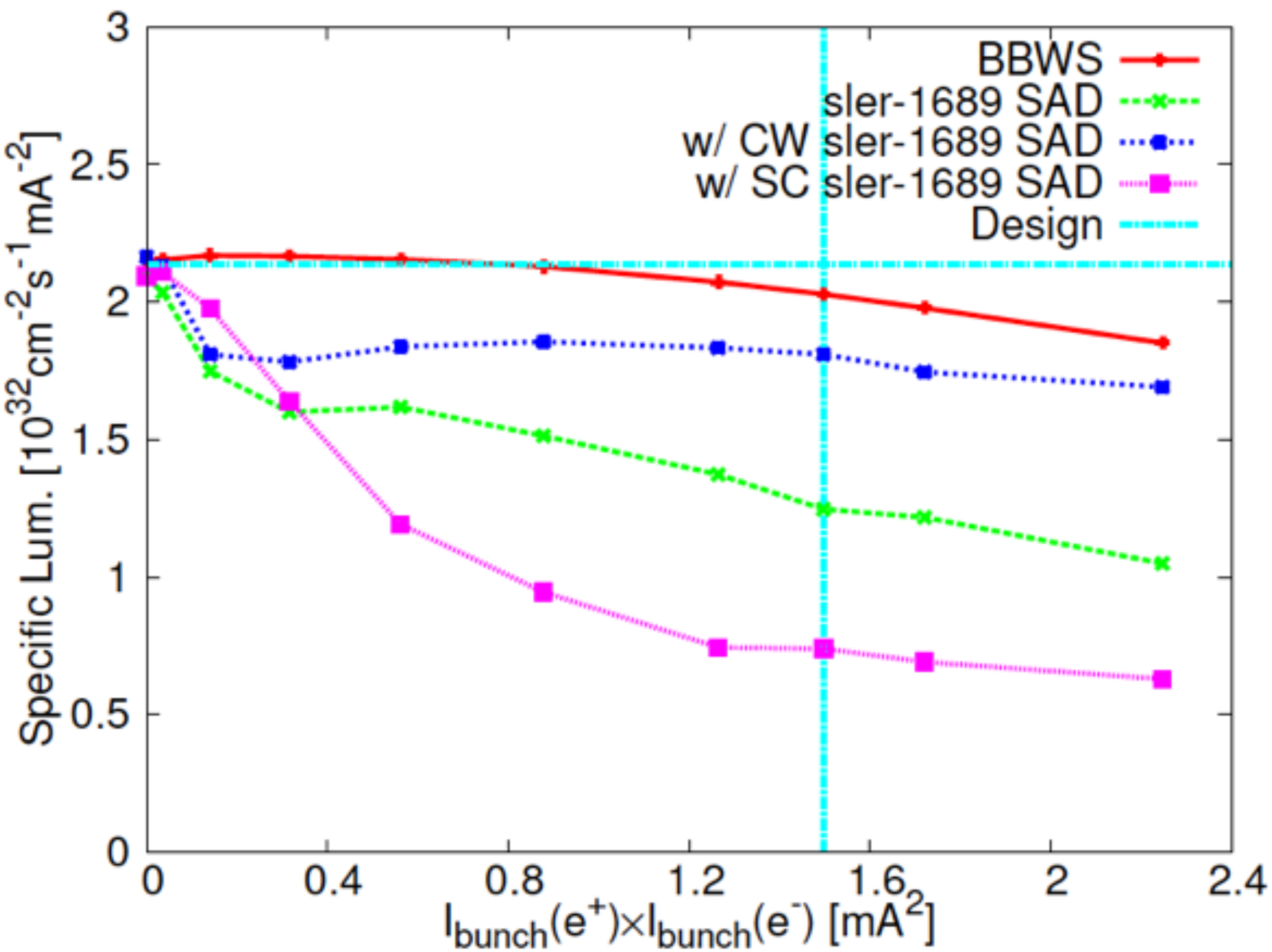
w/ skew-sext. map:



From Y. Zhang

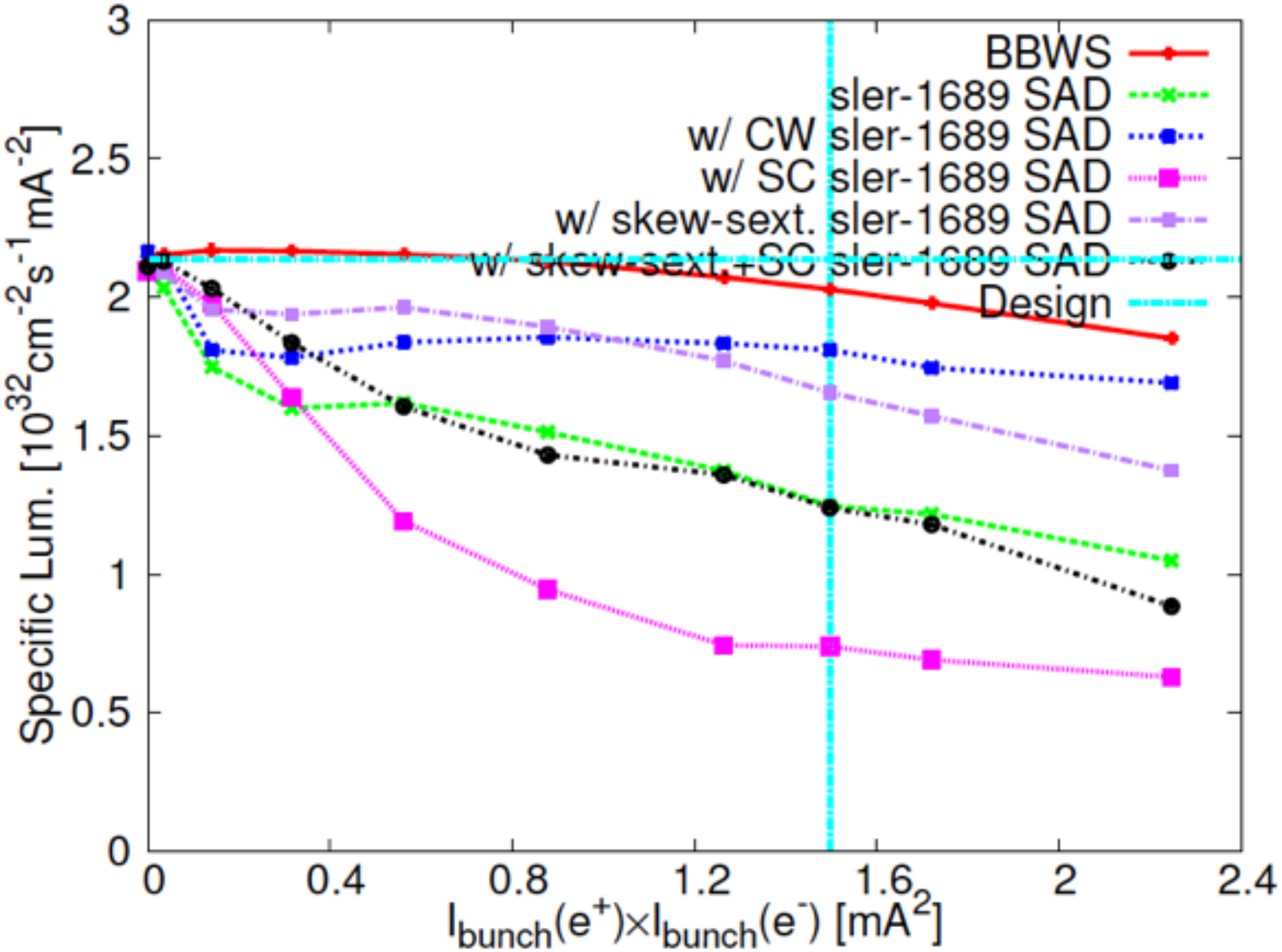
2. BB+LN: Luminosity: LER

- **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**



2. BB+LN: Luminosity: LER

- **Test by inserting a map of $H=K^*x^2y$ into the LER lattice**
- **Skew-sext. map:**
  - **To cancel the nonlinear terms from solenoid and QC***
  - **Work well at both low and high currents**
  - **Interplay of SC and lattice nonlin. also mitigated partially**

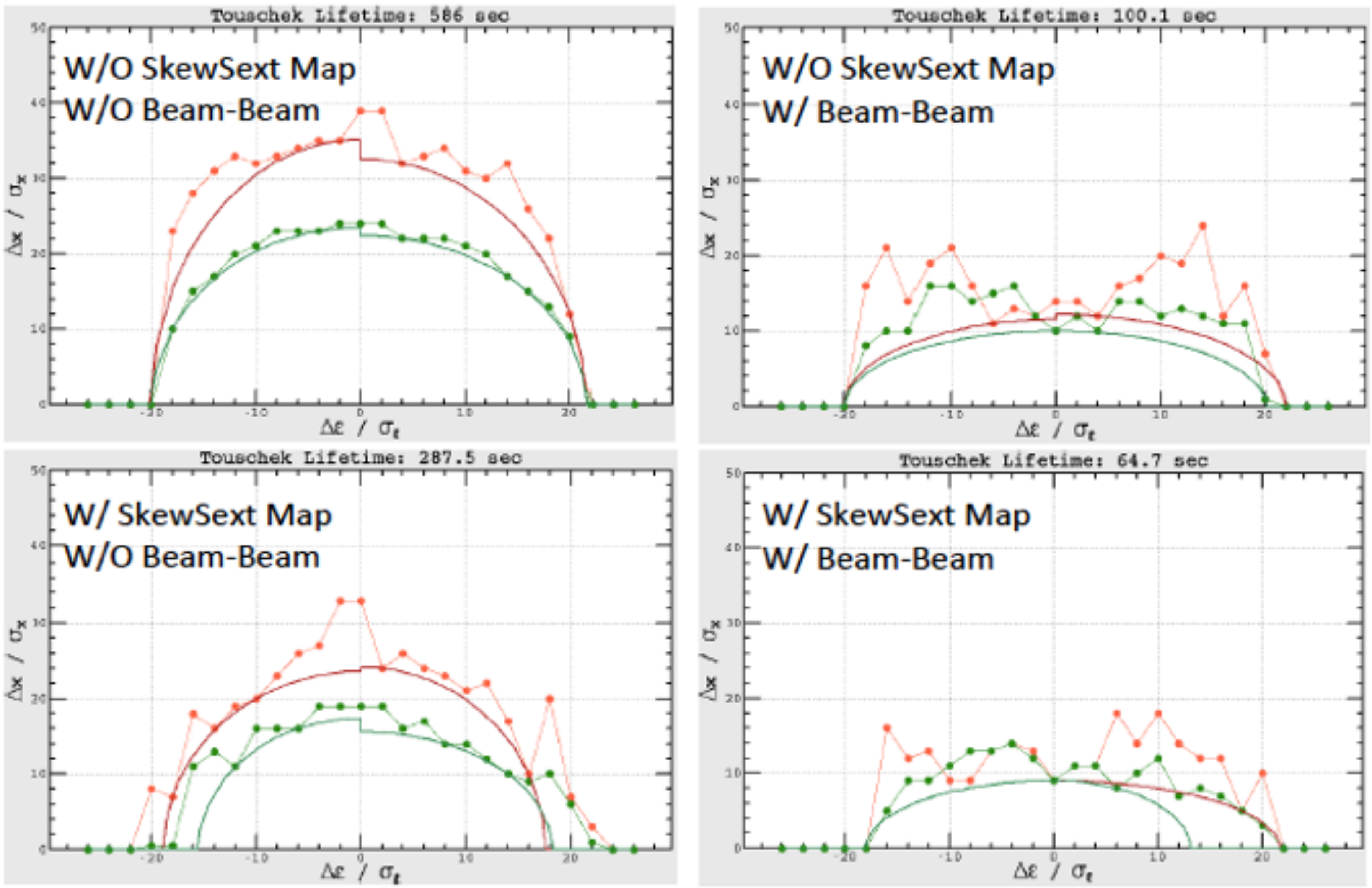


2. BB+LN: LER: DA and lifetime

- **Test by inserting a map of $H=K*x^2y$ into the LER lattice**
- **Skew-sext. map:**
  - cause loss in DA and lifetime
  - not perfect

sler_1689

DA and Lifetime



From H. Sugimoto

2. BB+LN: Quasi-strong-strong simulation

Condition

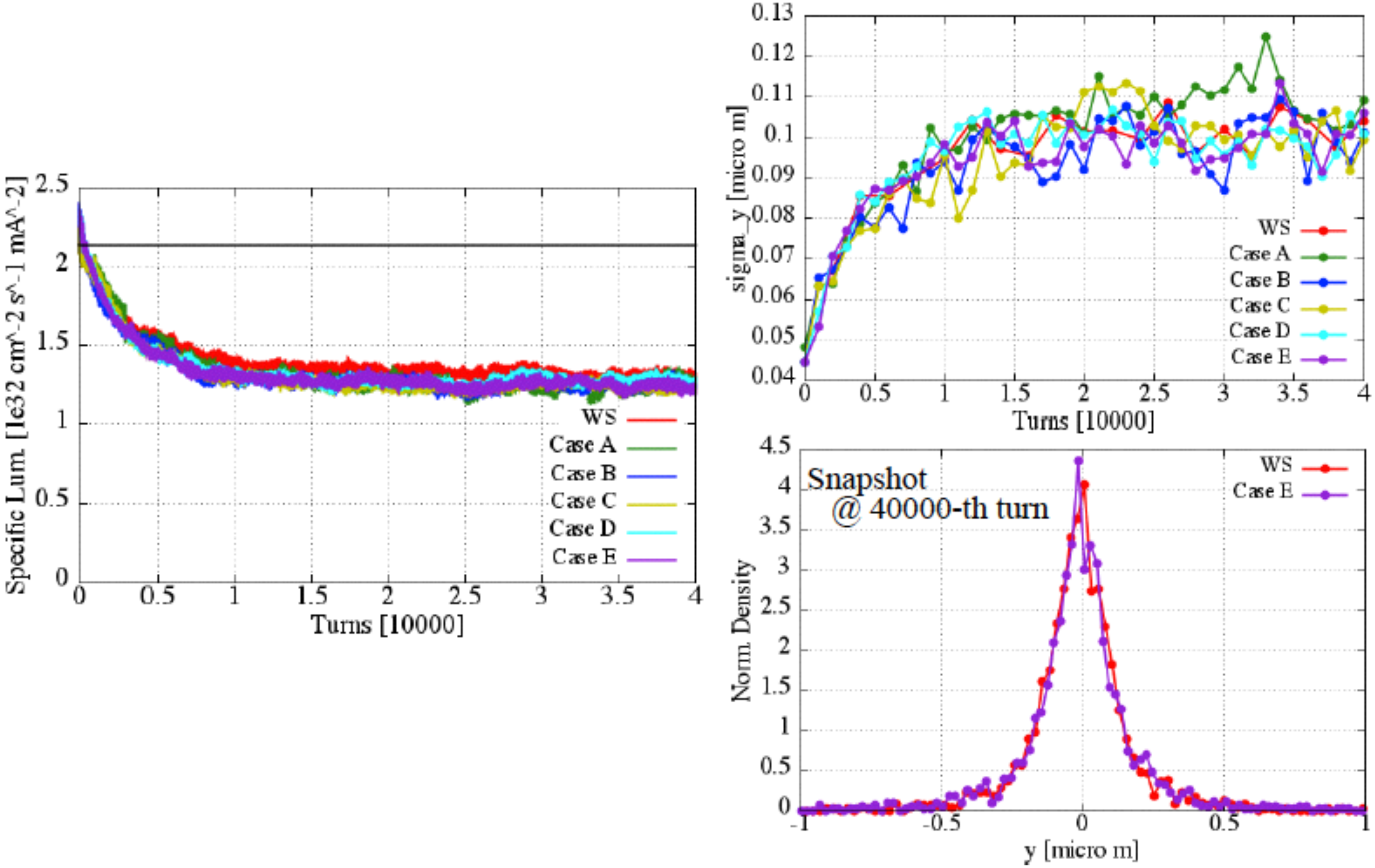
- Assumption
  - Phase space distribution is upright during collisions.
    (i.e. alphax=0, alphay=0, etax=0, …)
- Fitting procedure
  - Gaussian fit is done for x, px, y, py, z, delta independently.
  - EMITX, EMITY, BX, BY, SIGZ, DP are obtained the fitting.
- The beambeam element is updated with the above 6 parameters.
- # of particles = 2000
- Case A: Update interval is 1000 turns
  Case B: Update interval is 10 turns, average of the last 10 turns
  Case C: Update interval is 1000 turns, exponentially weighted average of the all past data with damping rate of 1000 turns
  Case D: Case C with interval = 1 turn
  Case E: Case D with damping rate = 200 turns

From H. Sugimoto

2. BB+LN: Quasi-strong-strong simulation

sler_1689.sad

LER

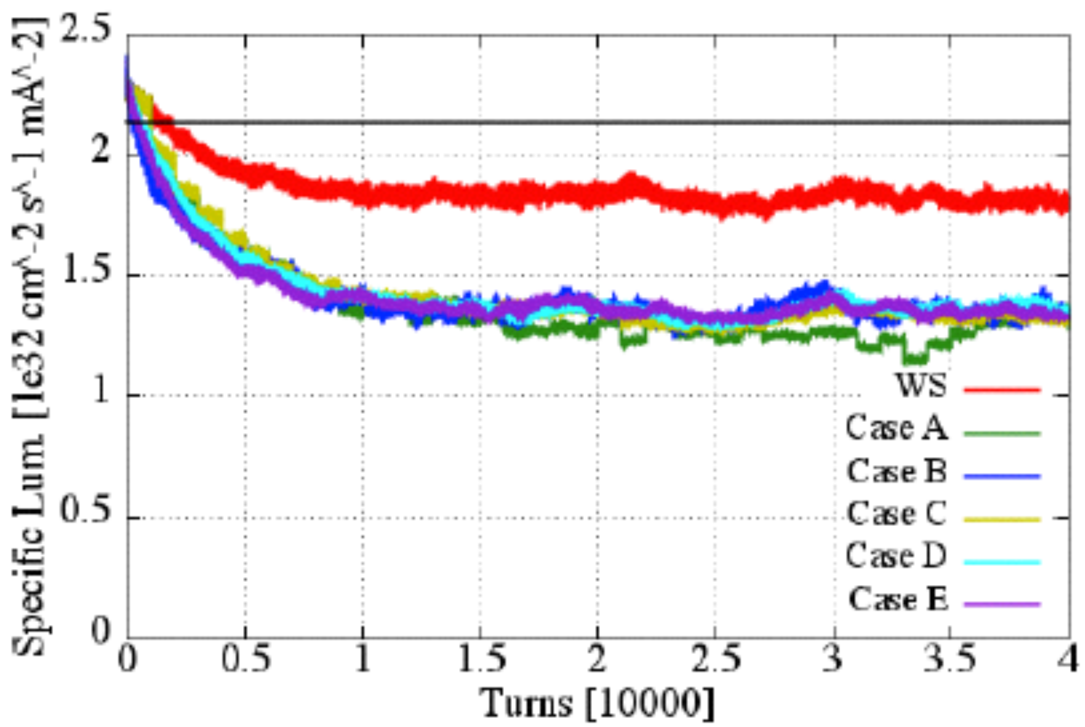


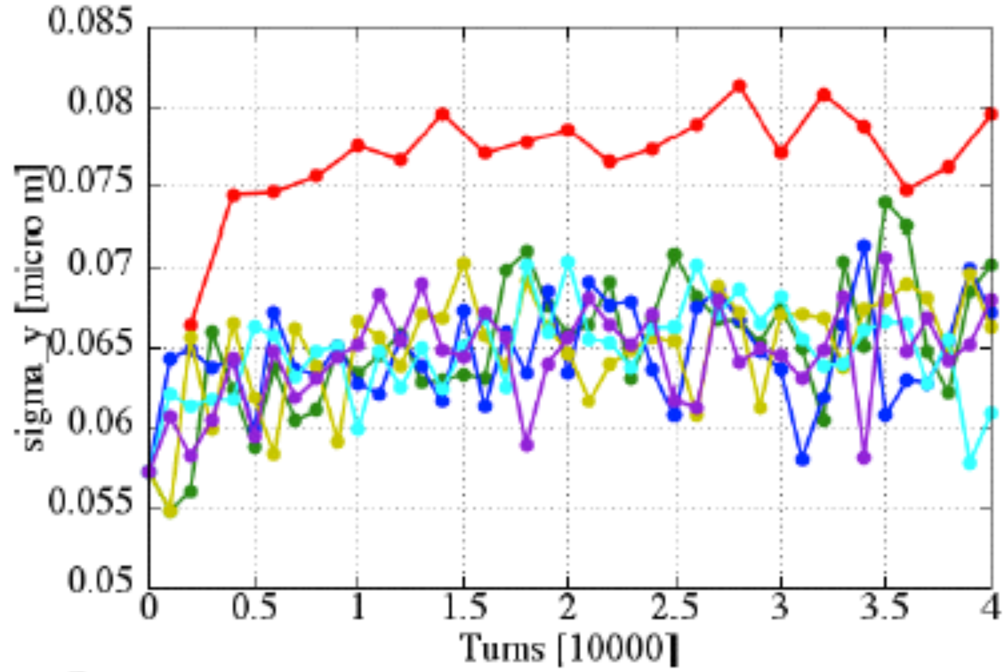
From H. Sugimoto

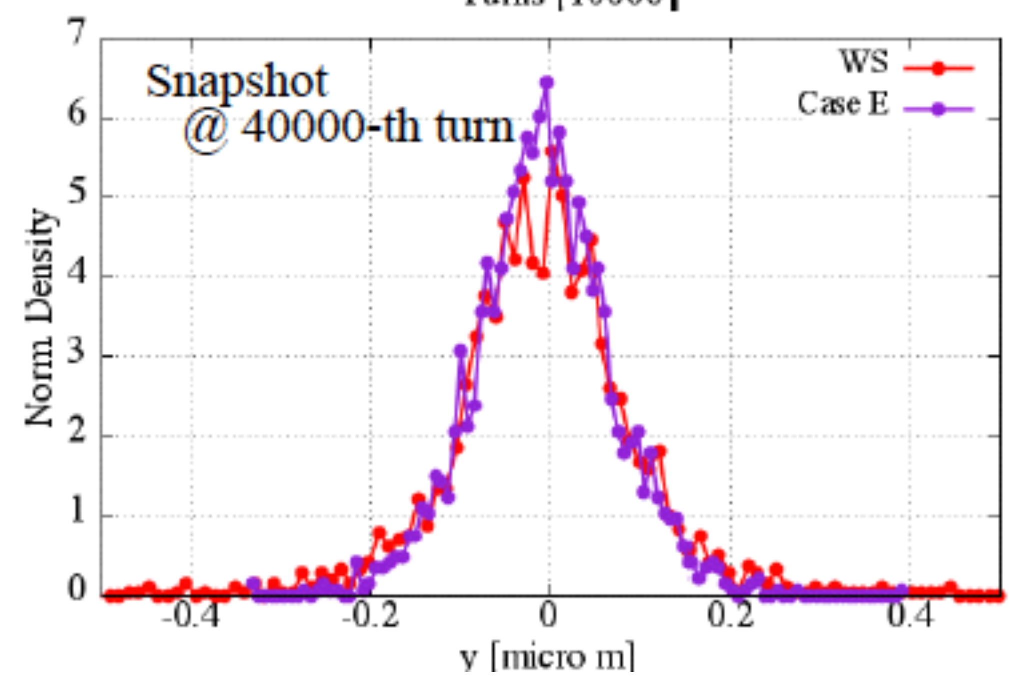
2. BB+LN: Quasi-strong-strong simulation

sher_5769.sad

HER







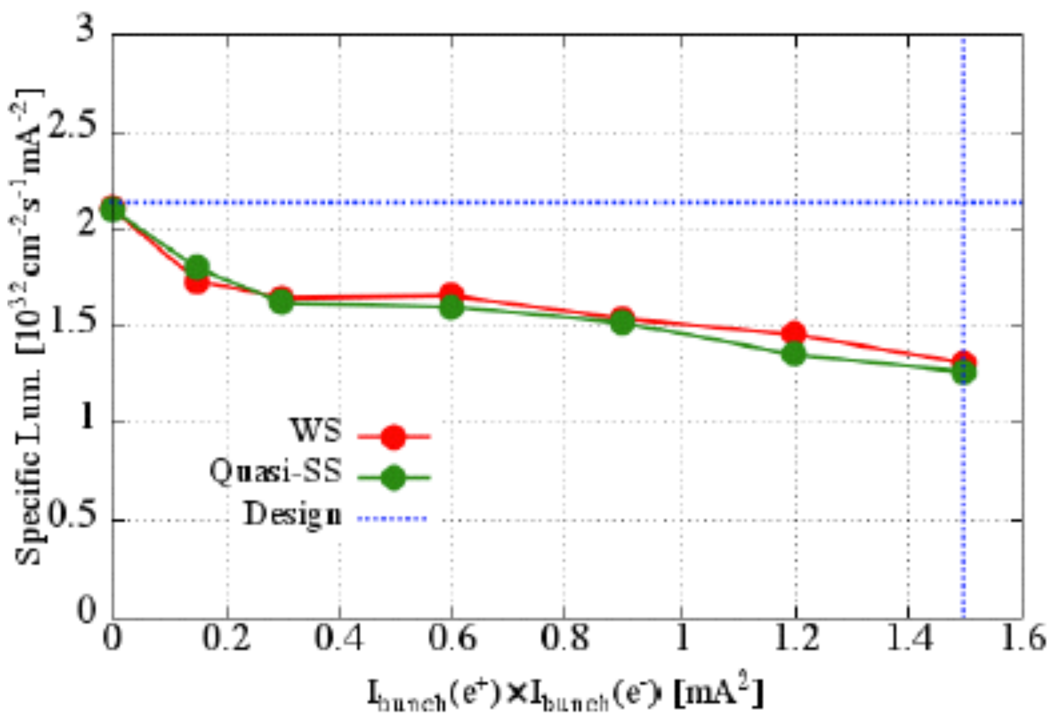
From H. Sugimoto

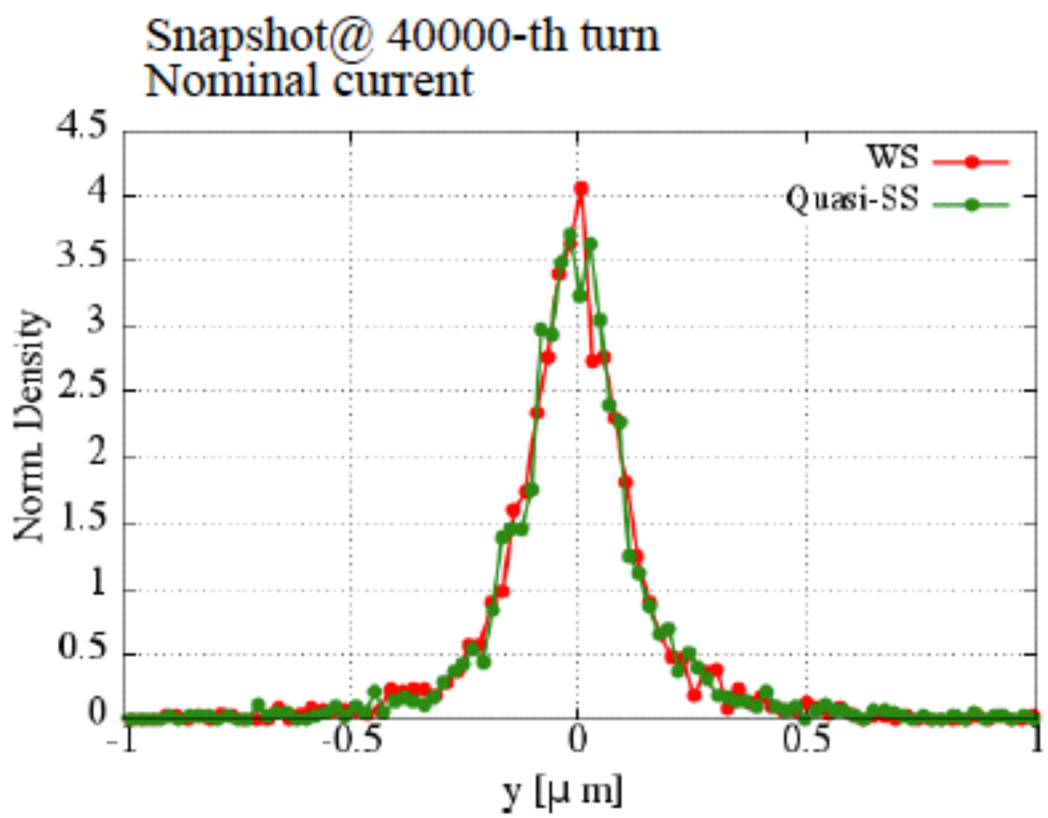
2. BB+LN: Quasi-strong-strong simulation

sler_1689.sad

Luminosity vs. Beam Current(LER)

- Done with the parameters of Case D.





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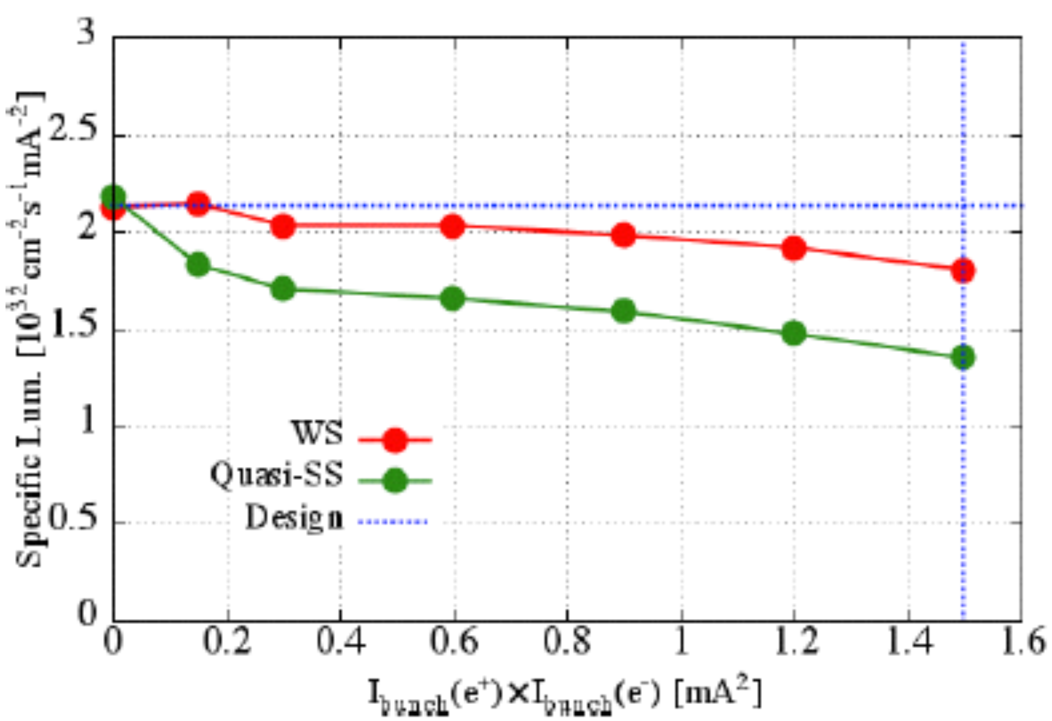

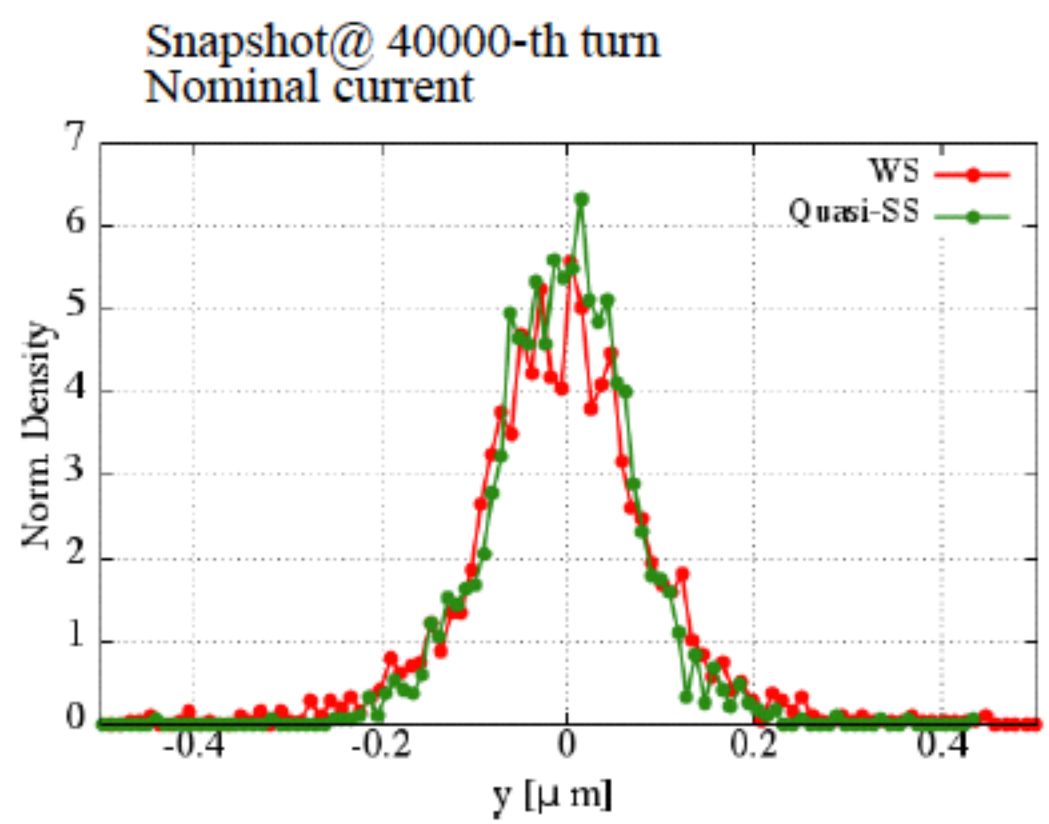

From H. Sugimoto

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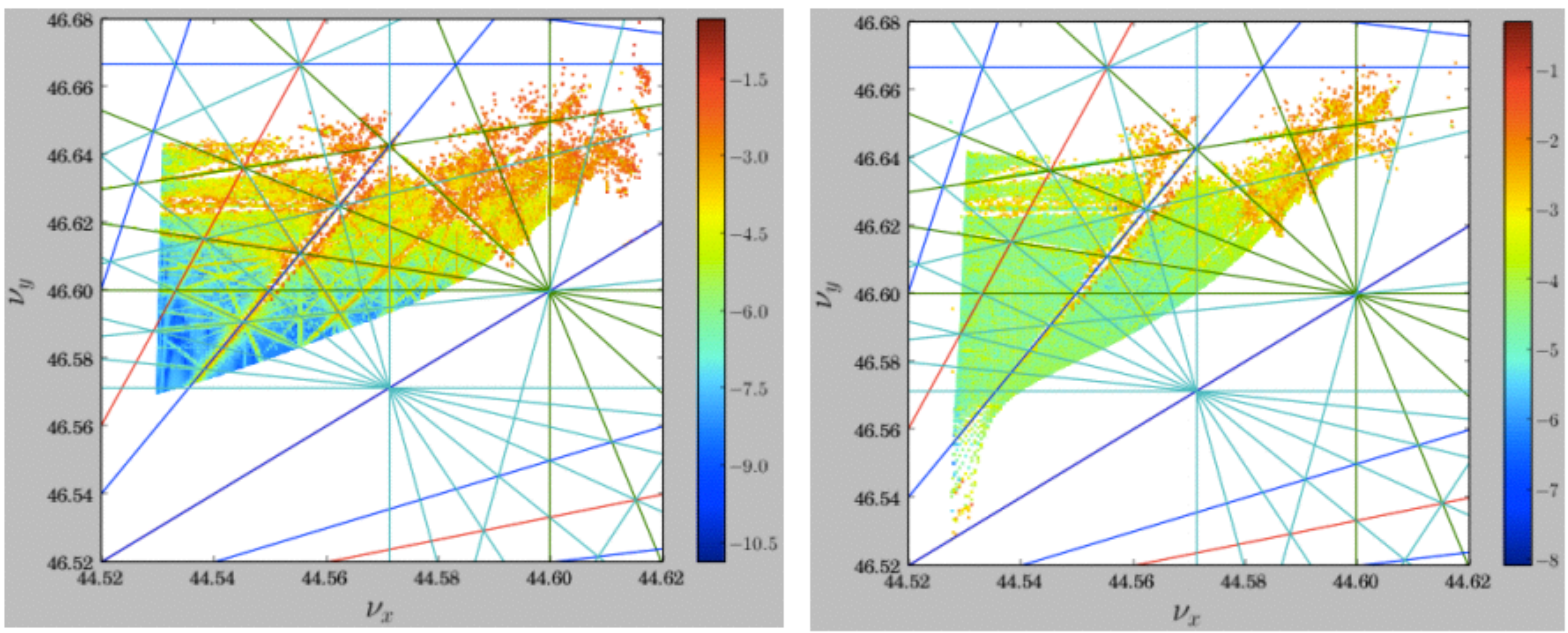
3. SC effects: LER

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

W/O SCE W/ SCE



4^{th} order
5^{th} order
6^{th} order
7^{th} order

Detailed Studies are now ongoing.
- Optics matching
- Checking simulation code including SAD code itself.

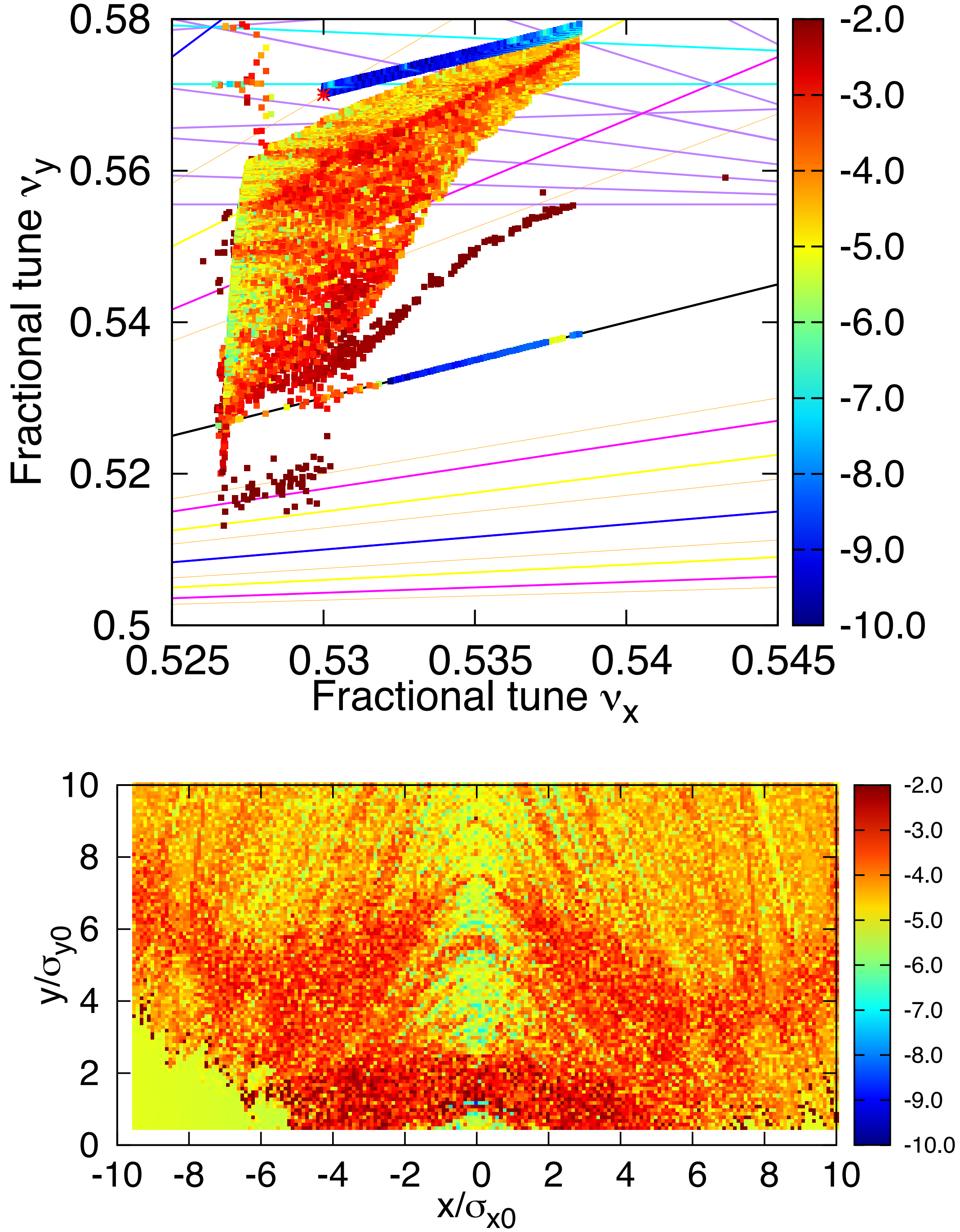
From H. Sugimoto

3. SC effects: LER

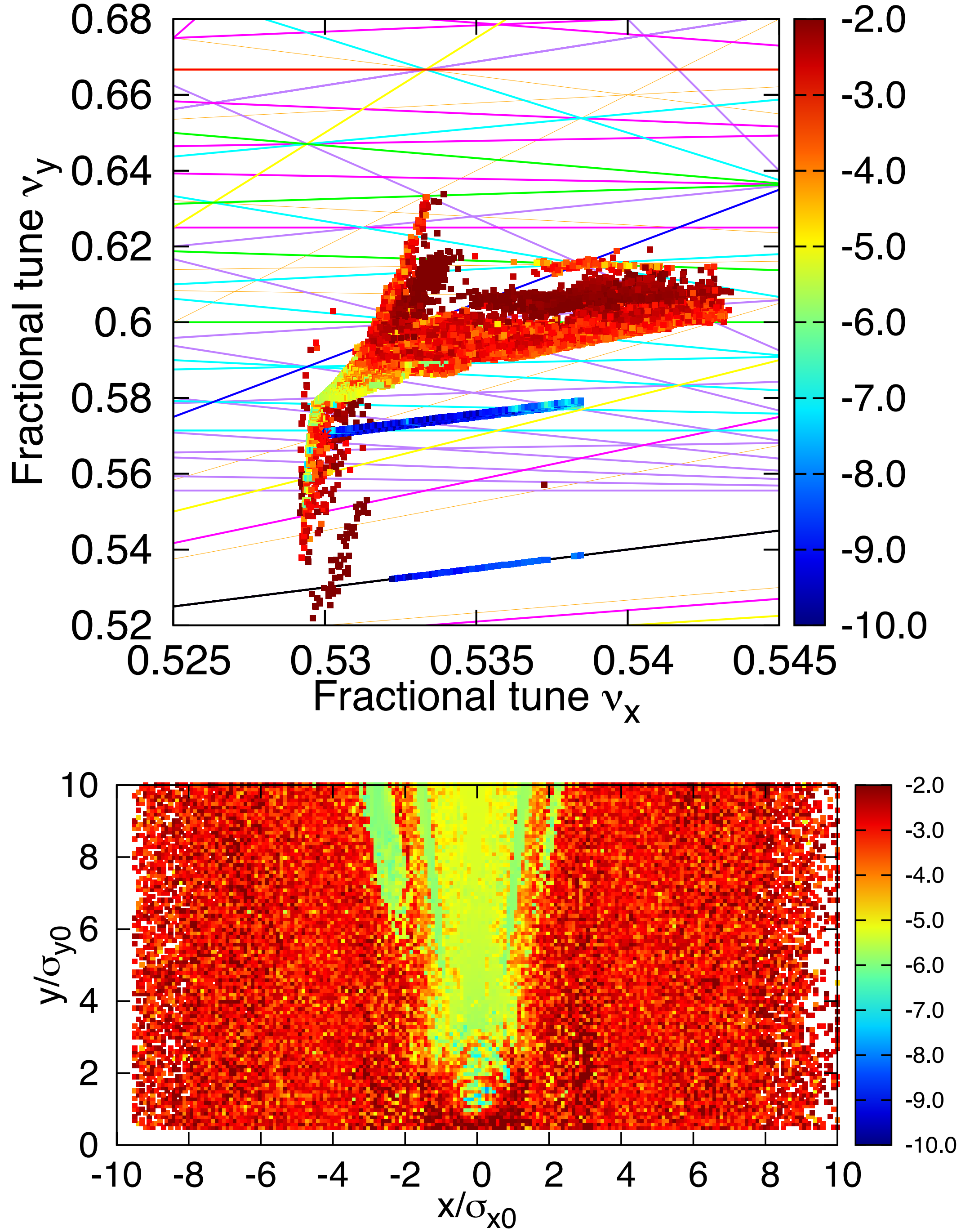
➤ FMA with beam distribution: $10\sigma_x \times 10\sigma_y$

sler_1684

LN + SC

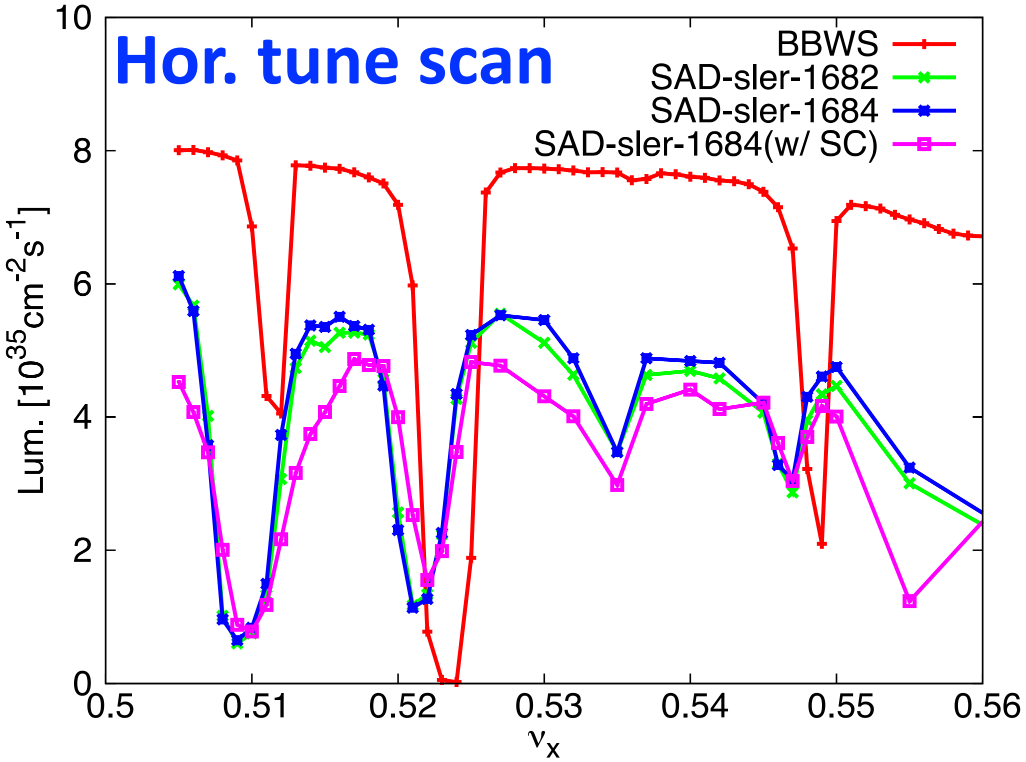


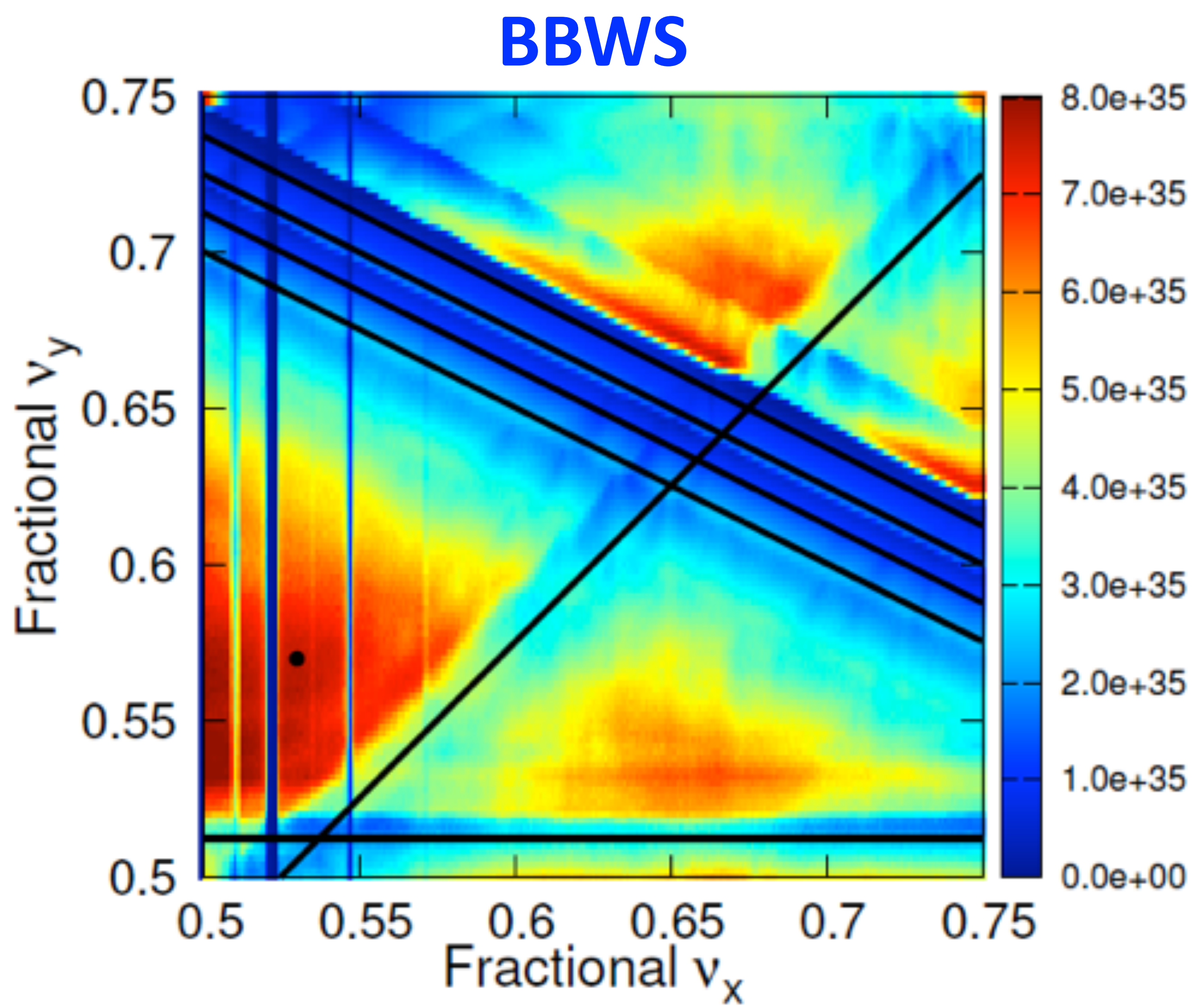
LN + SC + BB

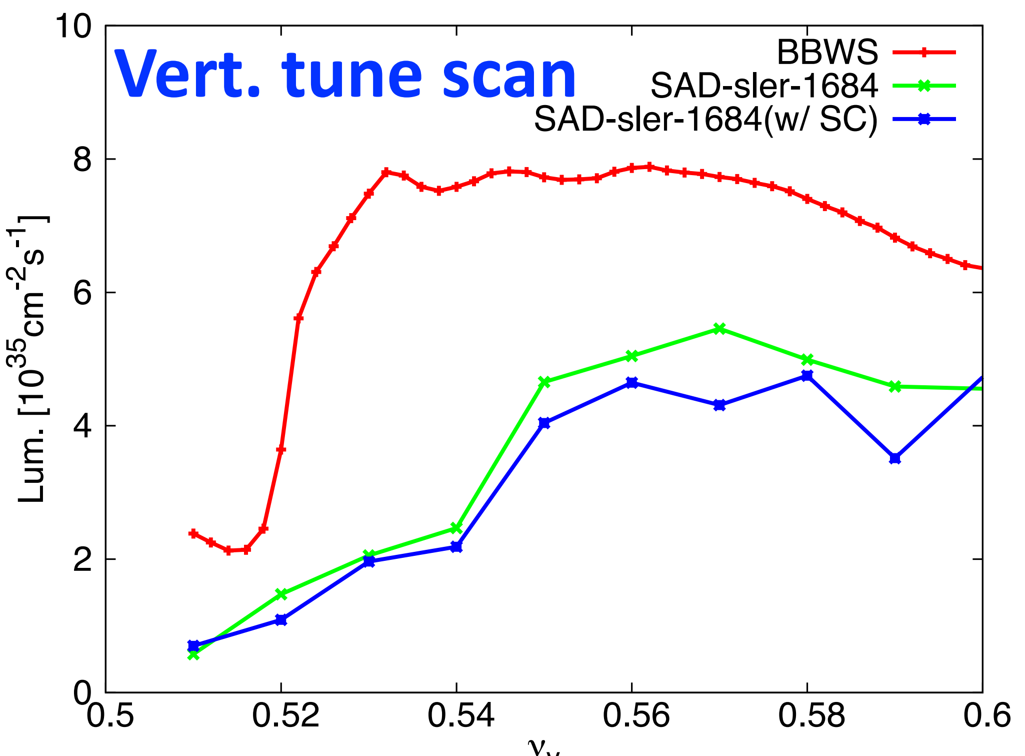


3. SC effects: LER

➤ Luminosity: Tune scan w/ and w/o SC



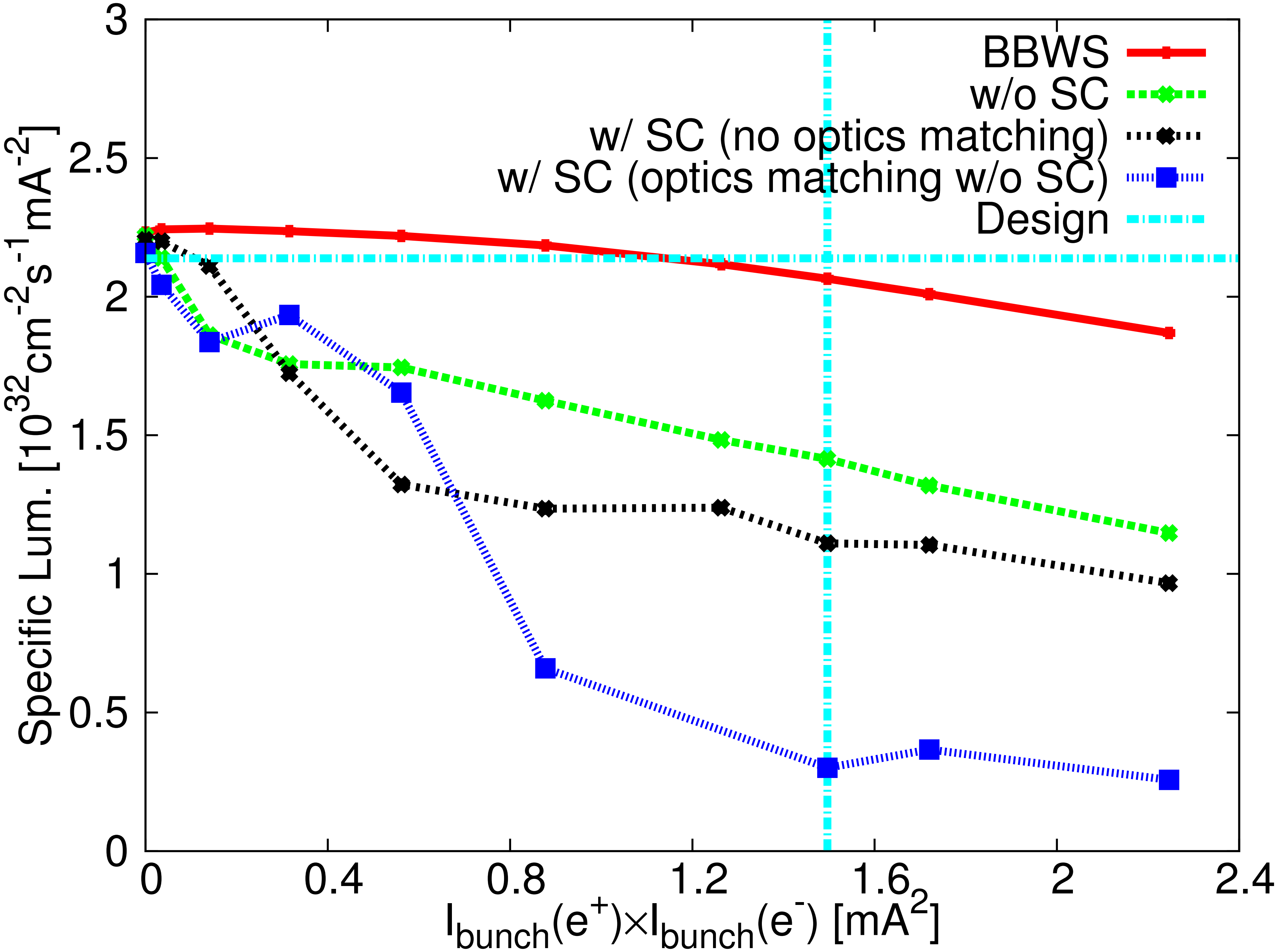




3. SC effects: LER

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

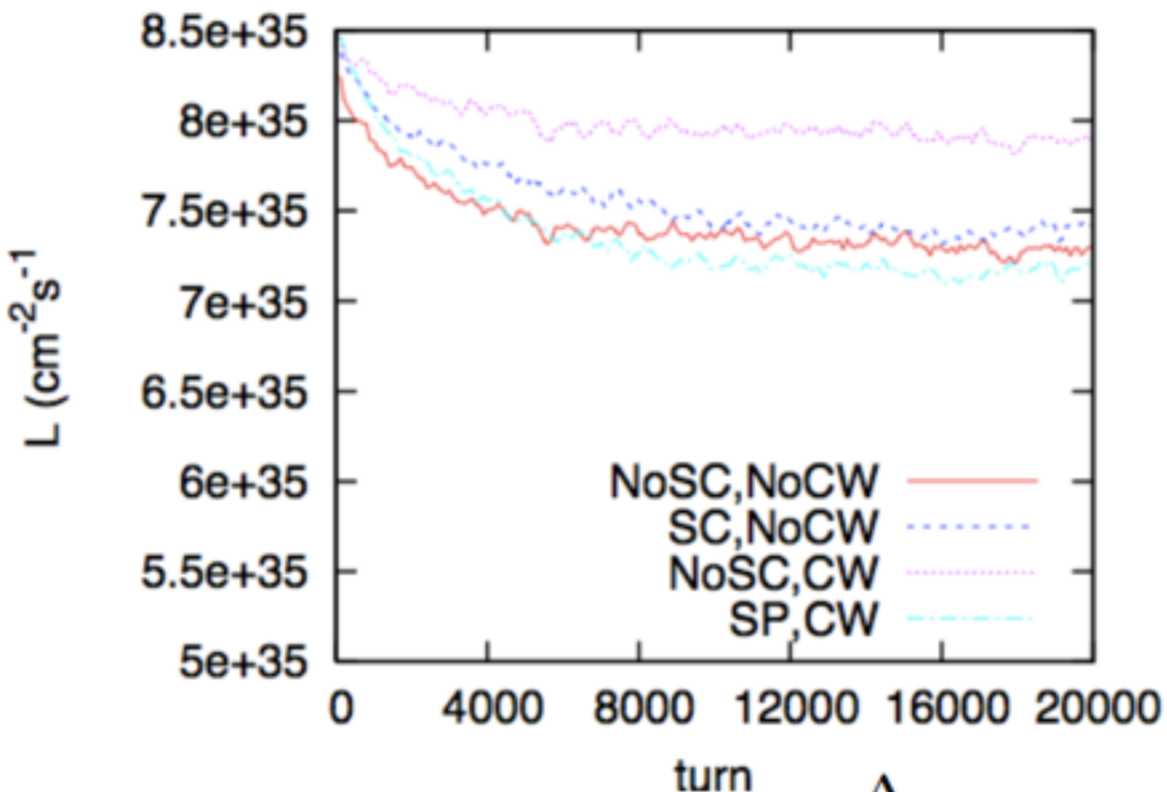
sler_1684

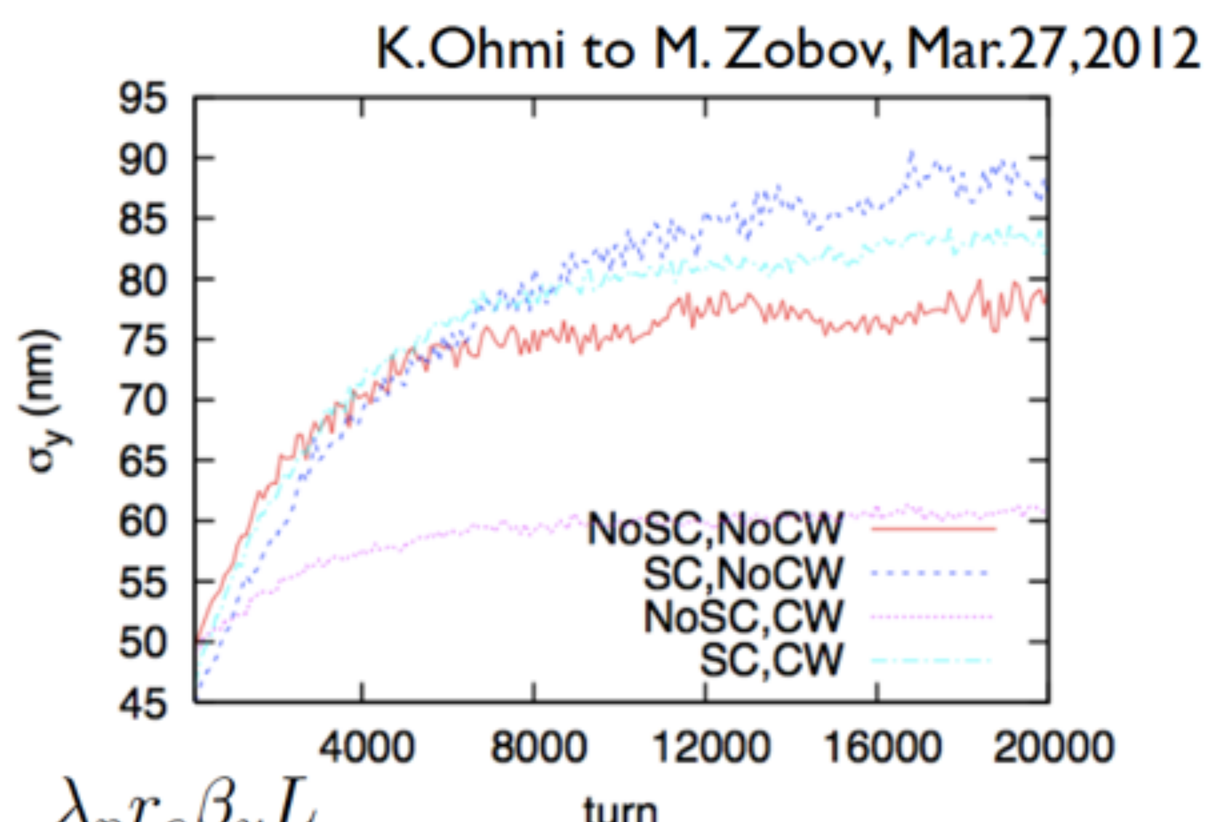


3. SC effects: LER

➤ **Independent simulation (BBWS+SC) showed SC effects are not serious, but:**

- **No lattice nonlinearity**
- **Simple model for SC (Only consider tune spread due to SC)**





$$\Delta\nu_y = \frac{\lambda_p r_e \beta_y L}{2\pi\gamma_p^3 \sigma_y(\sigma_x + \sigma_y)} \approx -0.11$$

From K. Ohmi

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4. Lum. calculation: Detuned lattice

➤ **Detuned lattice: sler_1689_d4-8/sher_5767_d4-8**

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	1×10^{34}		8×10^{35}		$cm^{-2}s^{-1}$

LER

β_x at IP	128	mm
β_y at IP	2.16	mm
I_b	1	A
n_b	2500	
ε_x	1.75	nm
$\varepsilon_y/\varepsilon_x$	2	%

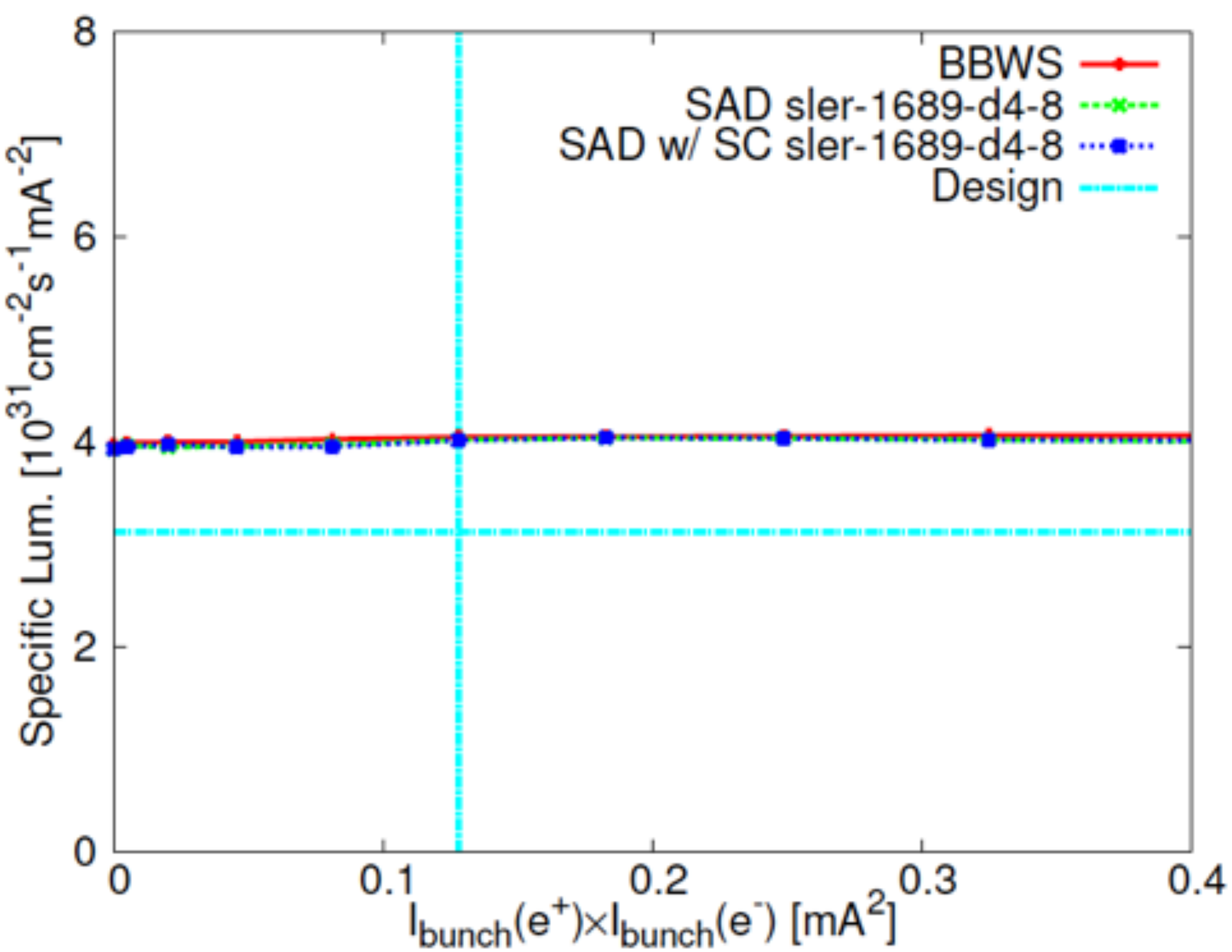
HER

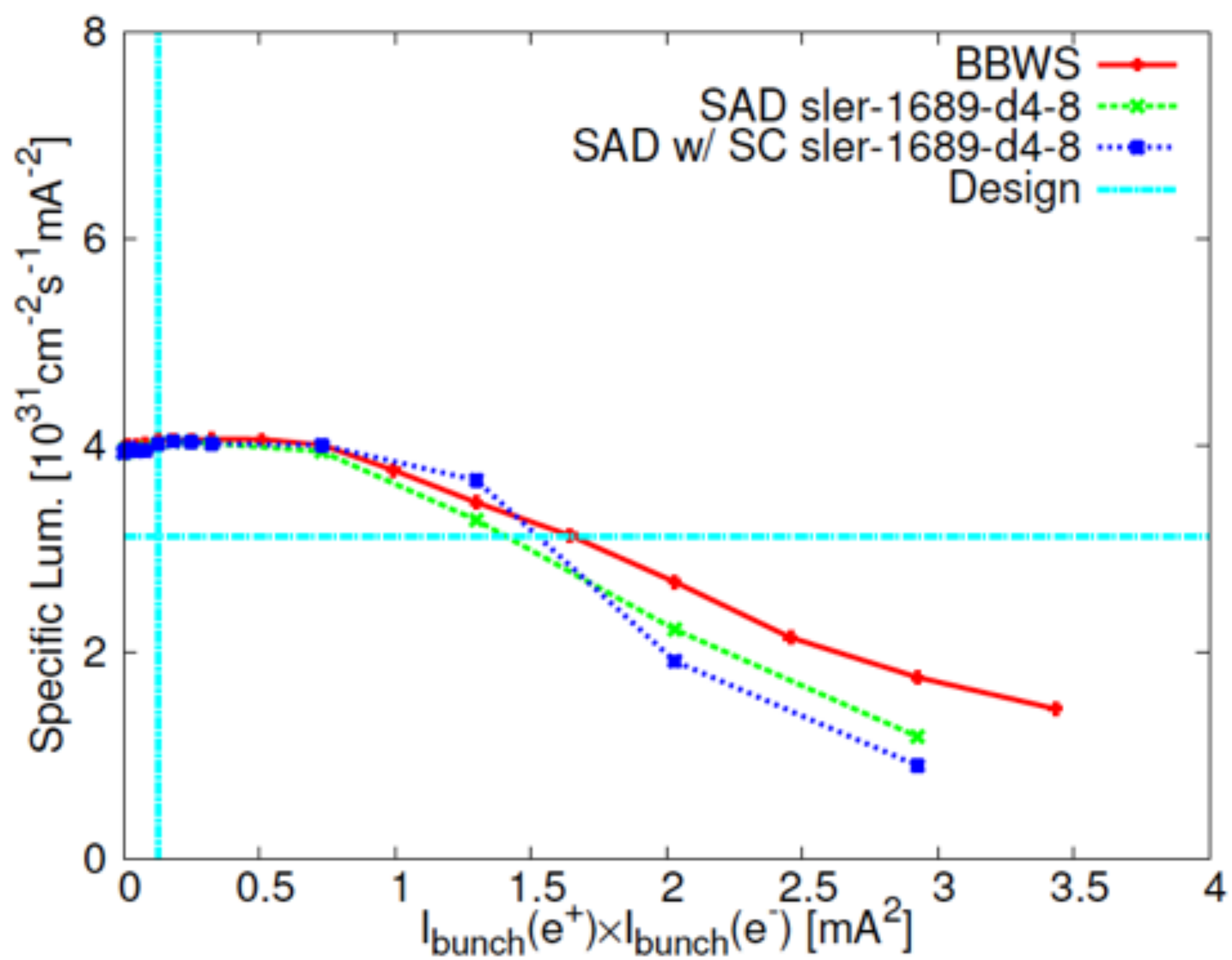
β_x at IP	100	mm
β_y at IP	2.40	mm
I_b	0.8	A
n_b	2500	
ε_x	4.5	nm
$\varepsilon_y/\varepsilon_x$	2	%

From Y. Ohnishi

4. Lum. calculation: Detuned lattice

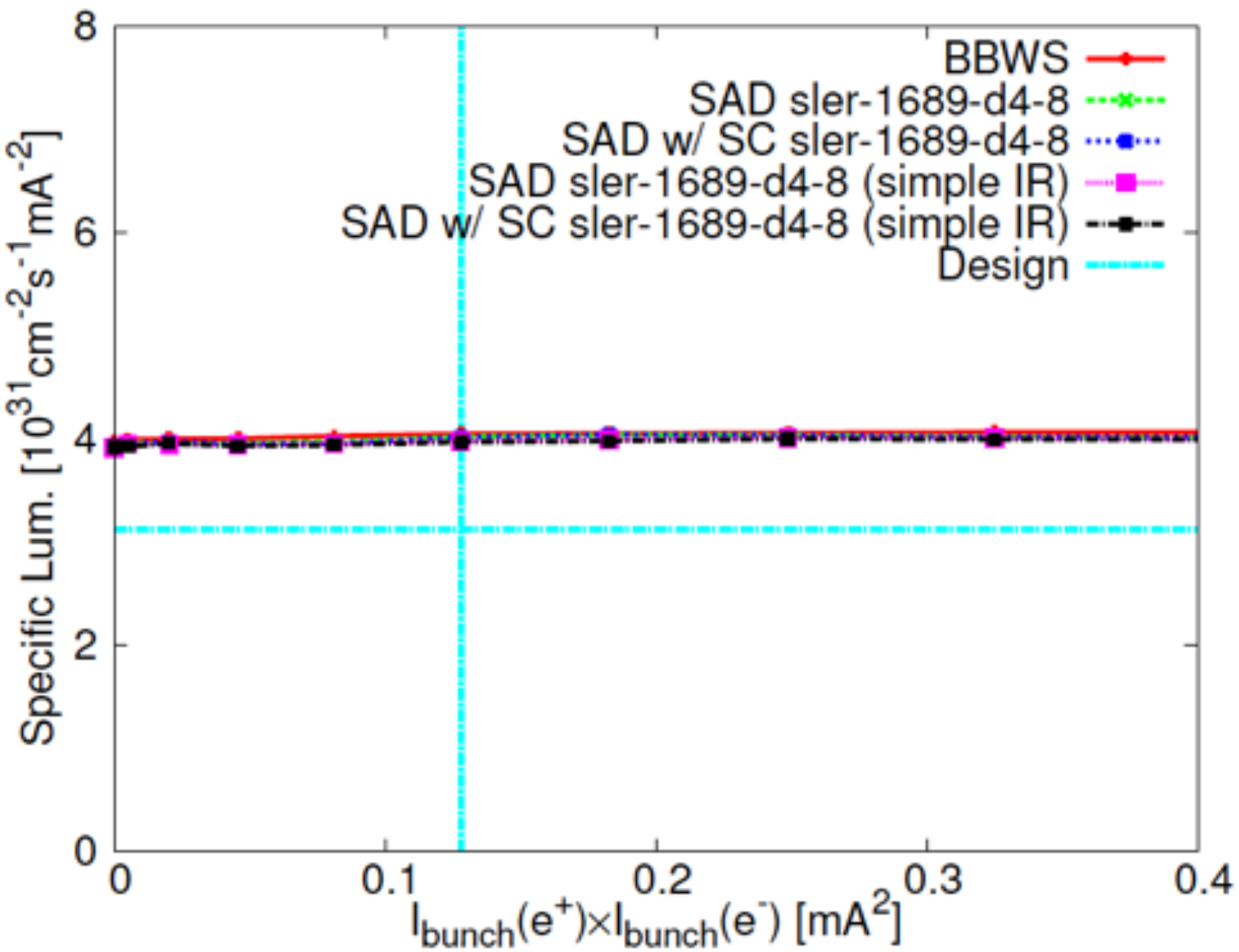
- **Assume: ε_x=1.75nm, coupling = 2%**
- **Space-charge is not important**
- **Lattice nonlinearity is not very important**
- **L=1×10^{34}cm^{-2}s^{-1} is promising**
- **L=10×10^{34}cm^{-2}s^{-1} is possible by increasing beam currents**

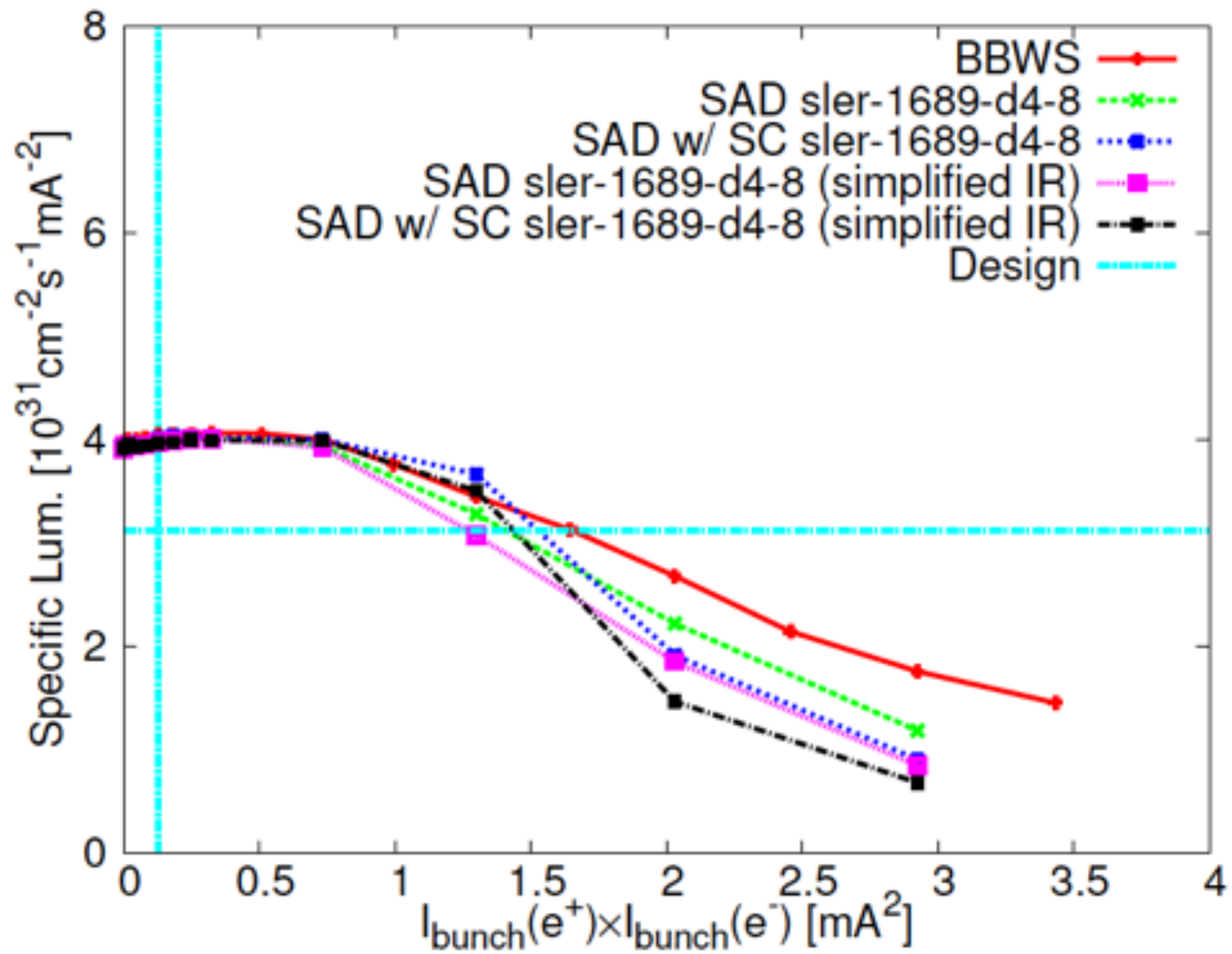




4. Lum. calculation: Detuned lattice

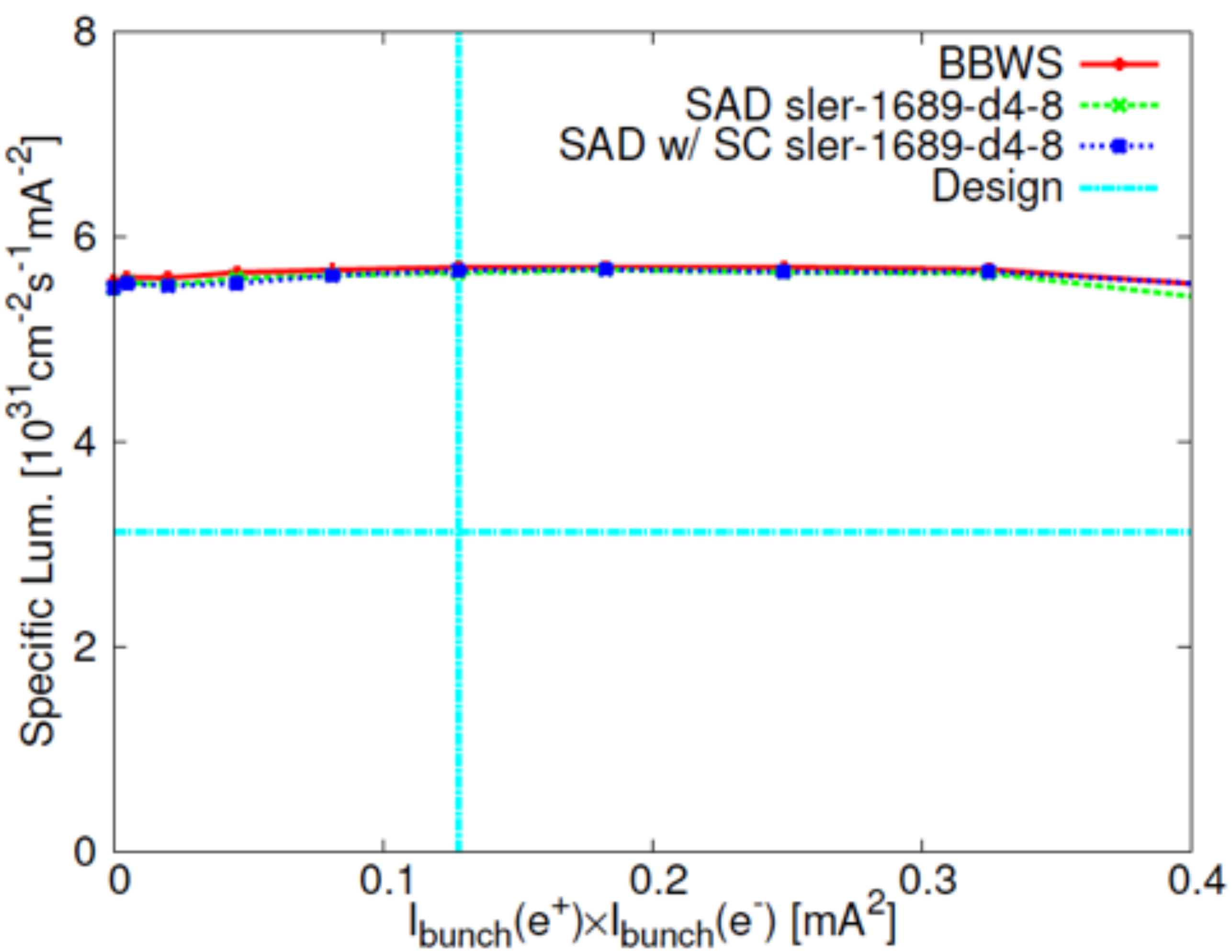
- Assume: ε_x=1.75nm, coupling = 2%
- Compare with the case of simplified IR
- Solenoid not to cause lum. loss

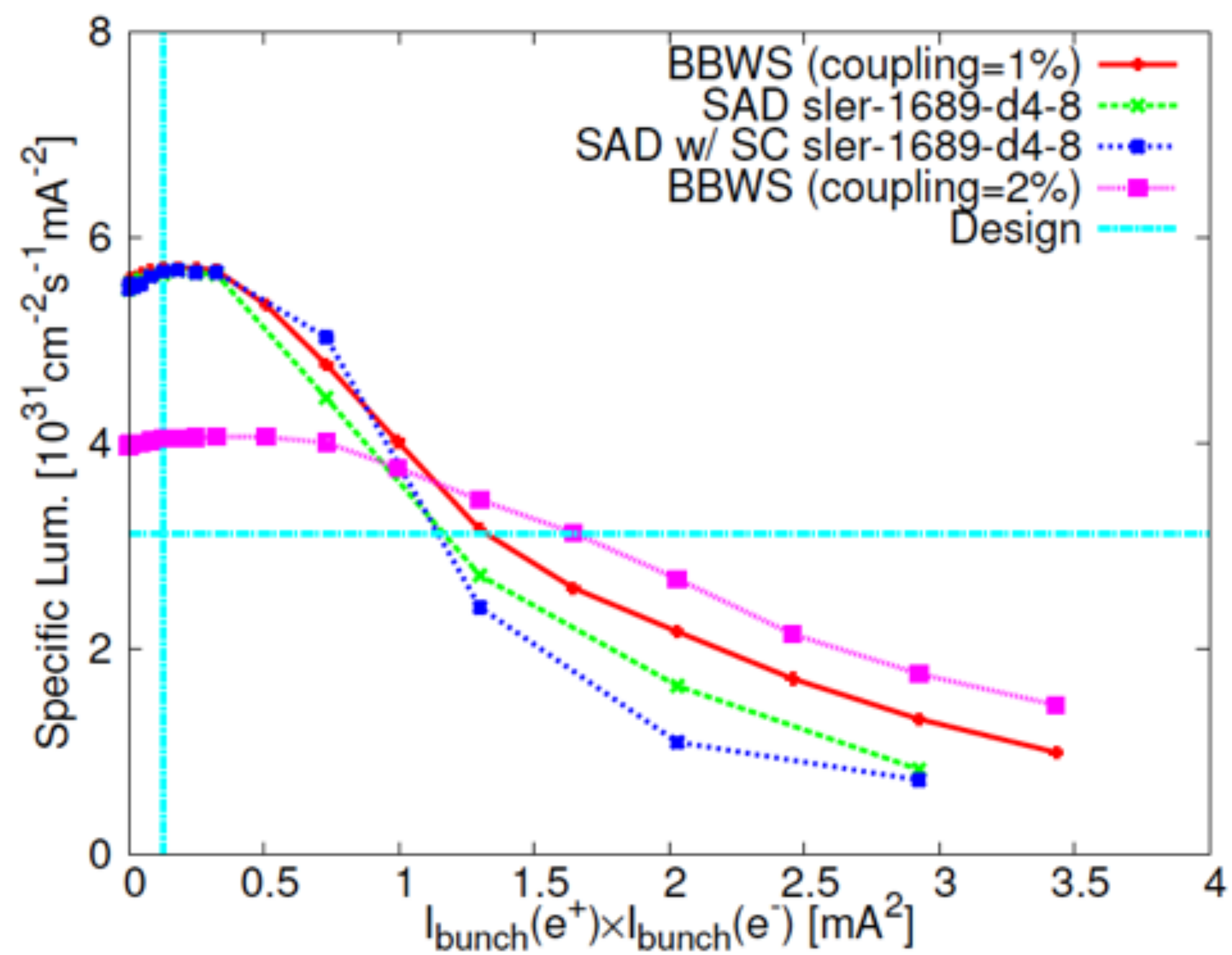




4. Lum. calculation: Detuned lattice

- 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





4. Lum. calculation: Detuned lattice

➤ **LER: Tolerance for errors in various optics parameters at IP (Assume 10% of lum. loss)**

$\varepsilon_y/\varepsilon_x$, β_y^*	2%, 2.2mm	1.5%, 1.1 mm	0.28%, 0.3 mm
Δx (μm)	77	30	7.2
Δy (μm)	0.35	0.2	0.025
R1 (mrad)	18	8.2	1.5
R2 (mm)	2.3	1.6	0.06
R3(m^{-1})	50	7.9	4.9
R4(rad)	3.7	0.93	0.21
η_y (mm)	0.33	0.23	0.017
η'_y (mrad)	1	0.44	0.08

From K. Ohmi

Outline

- ➤ Impedance issues - updates
- ➤ Interplay of beam-beam(BB) and lattice nonlinearity(LN)
- ➤ Space charge(SC) effects in LER
- ➤ Luminosity calculation for detuned lattices
- ➤ **Benchmark of SAD**
- ➤ Summary and Future plan

5. Benchmark of SAD: sher_5764

➤ **Optics parameters at IP with δ=0**

- **In general, Bmad agrees well with SAD**

Bmad:

β_x=0.02498209m, α_x=-4.959E-5, ν_x=45.5299896,
D_x=-4.E-8m, D'_x=-8.16E-6,
β_y=2.941E-4m, α_y=-6.791E-5, ν_y=43.56852721,
D_y=-4.55E-9, D'_y=-2.4E-7,

SAD:

β_x=0.025m, α_x=-1.34E-12, ν_x=45.53,
D_x=-1.03E-13m, D'_x=-3.11E-13,
β_y=3.E-4m, α_y=-3.545E-13, ν_y=43.57,
D_y=2.963E-15, D'_y=-1.616E-12,

5. Benchmark of SAD: sher_5764

➤ **Optics parameters at IP with δ=0.002**

- **In general, Bmad agrees well with SAD**

Bmad:

β_x=0.32635028E-01m, α_x=0.65882408E-01, ν_x=45.536646,
D_x=-0.47815350E-03m, D'_x=-0.11870747E-01,
β_y=0.31470442E-03m, α_y=0.13545109E-01, ν_y=43.577108,
D_y=0.64778741E-06, D'_y=0.23488780E-02,

SAD:

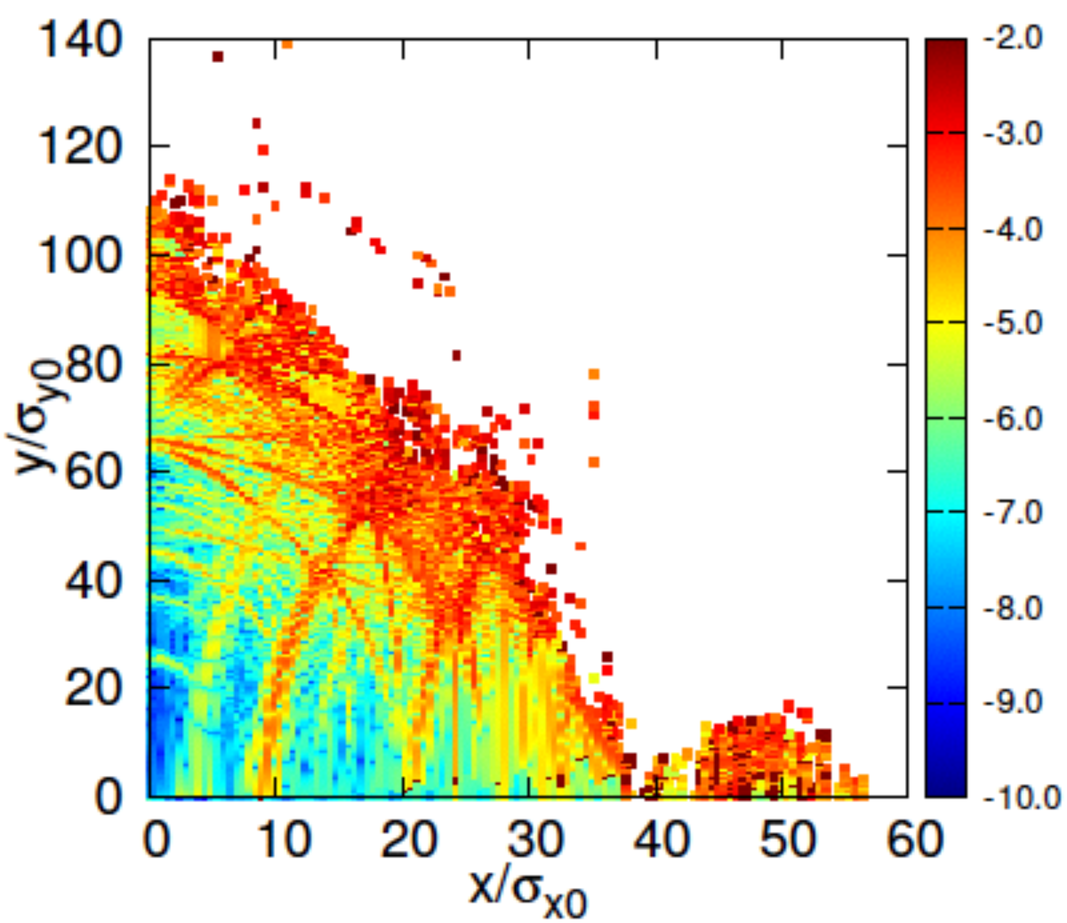
β_x=.032642757m, α_x=.0658513493, ν_x=45.536688655,
D_x=-.0004781727, D'_x=-.01190317,
β_y=.00032006m, α_y=.01341448, ν_y=43.57852356,
D_y=6.27523687e-07, D'_y=.0022601526,

5. Benchmark of SAD: FMA: sler_1684

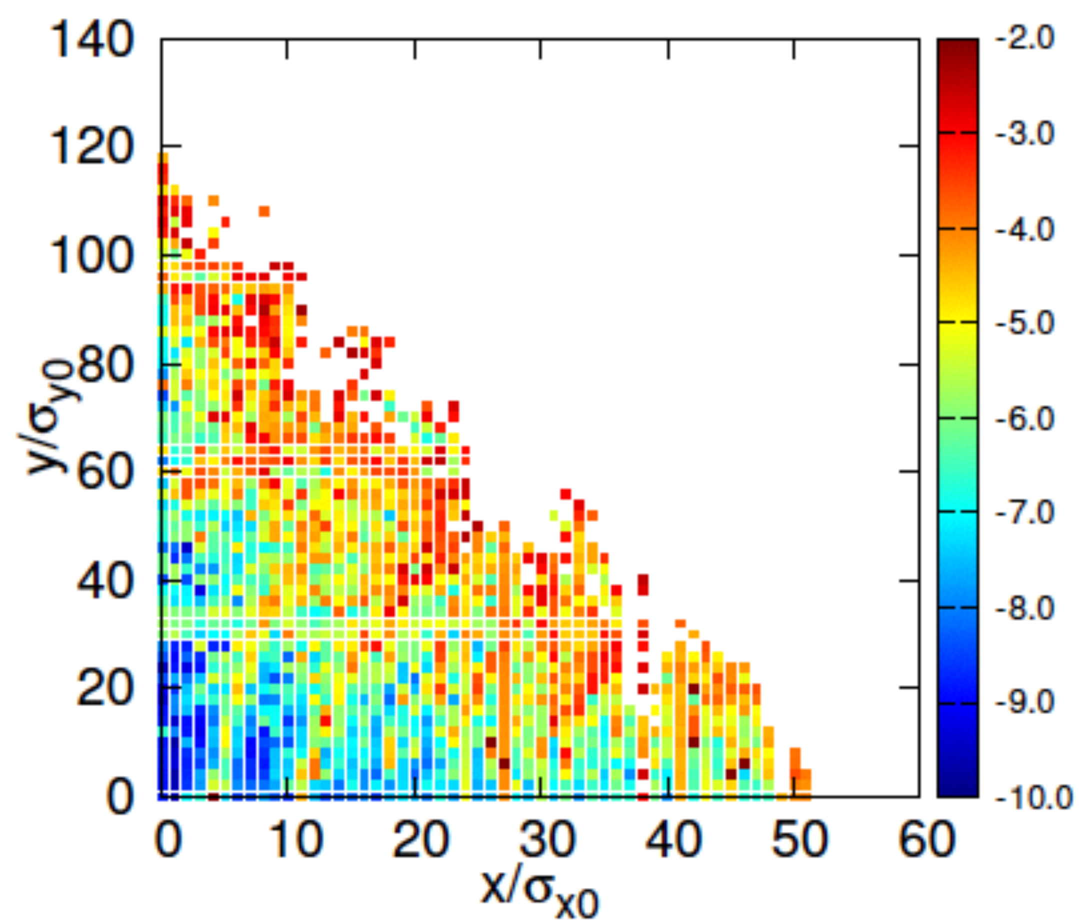
➤ **X-Y space**

- **Bmad and SAD give similar DA in size**
- **Discrepancy is due to use of different maps for high-order nonlinear terms in elements such as solenoid**

Bmad



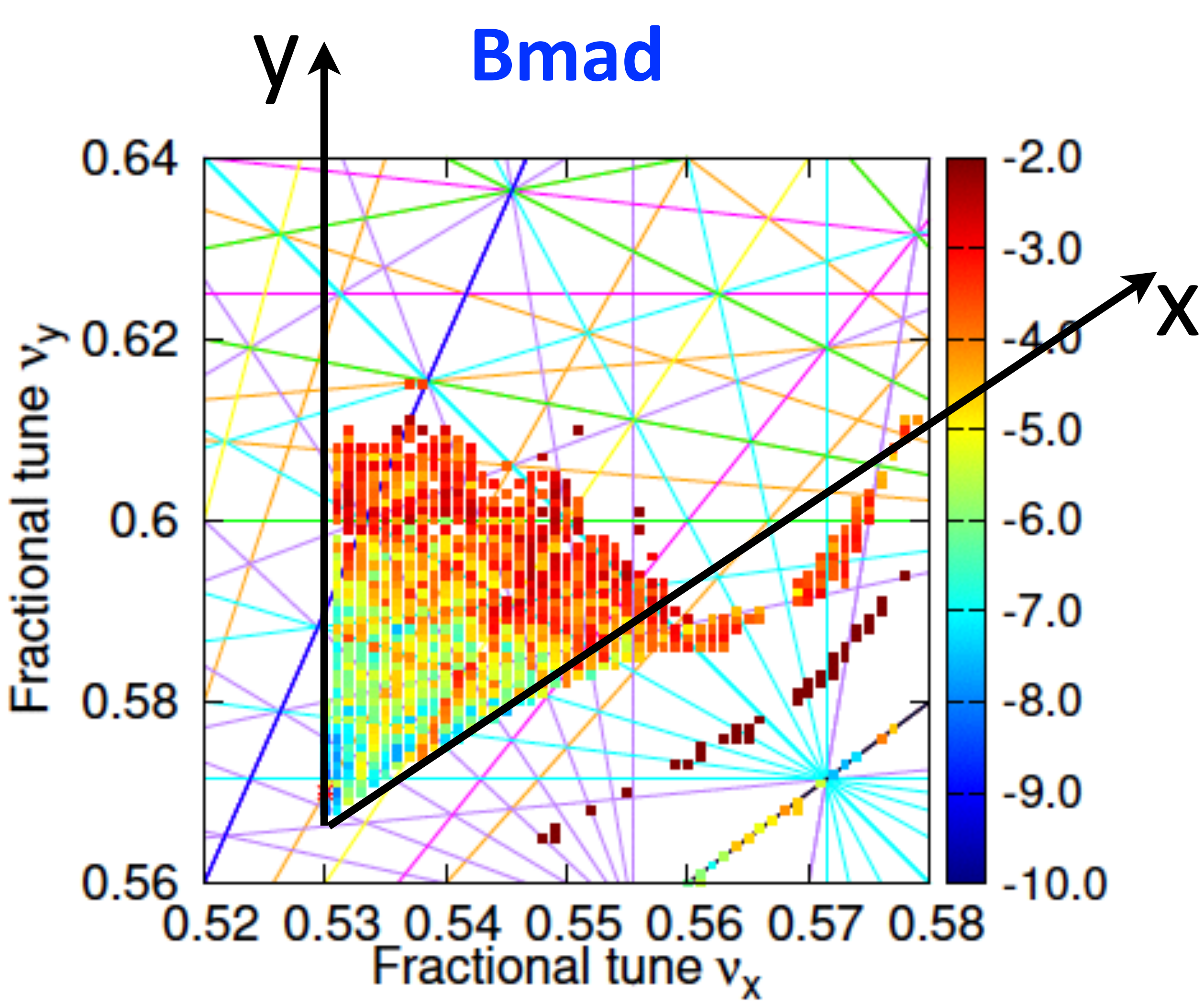
SAD

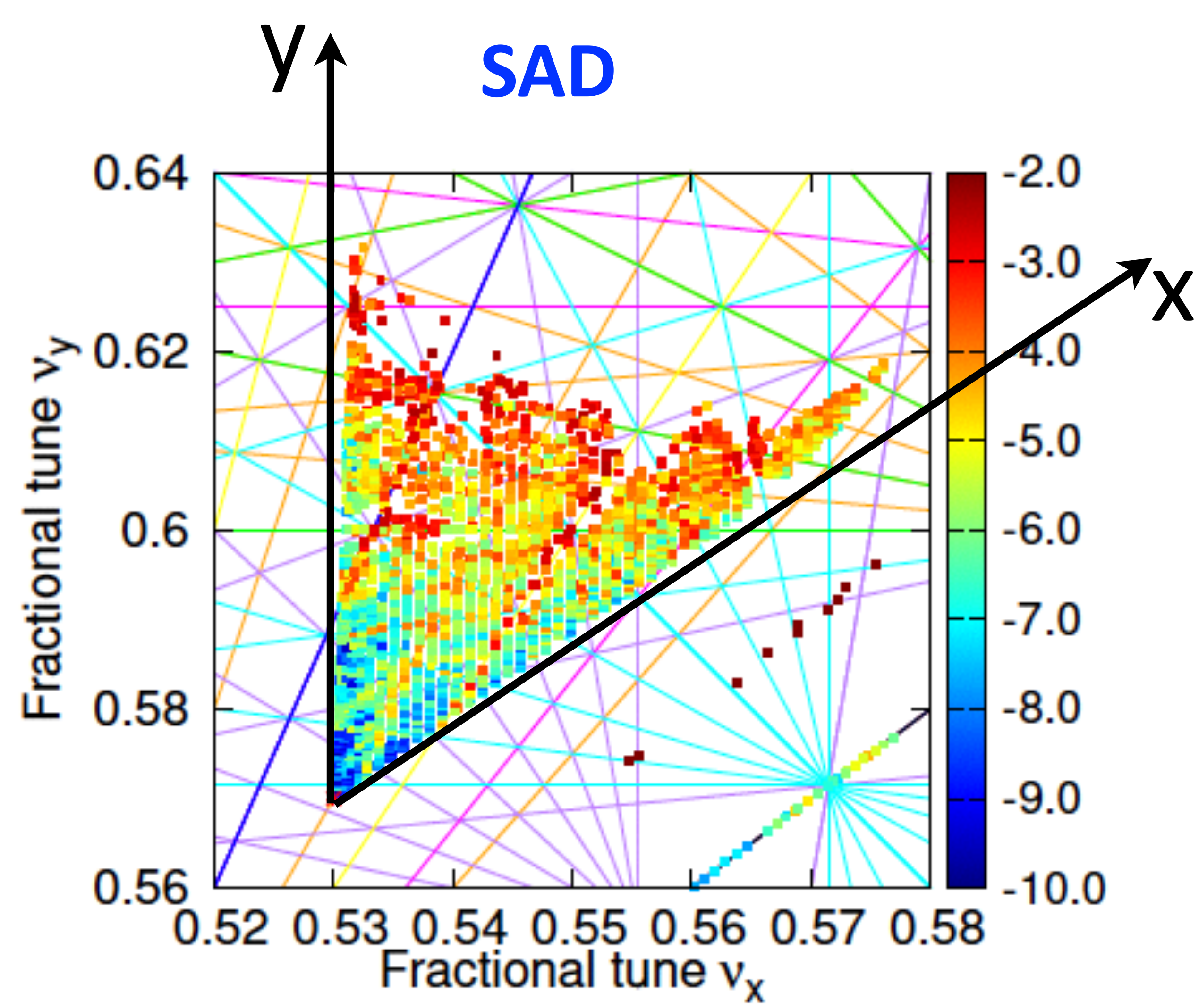


5. Benchmark of SAD: FMA: sler_1684

➤ Tune space

- **Discrepancy is due to use of different maps for high-order nonlinear terms in elements such as solenoid**

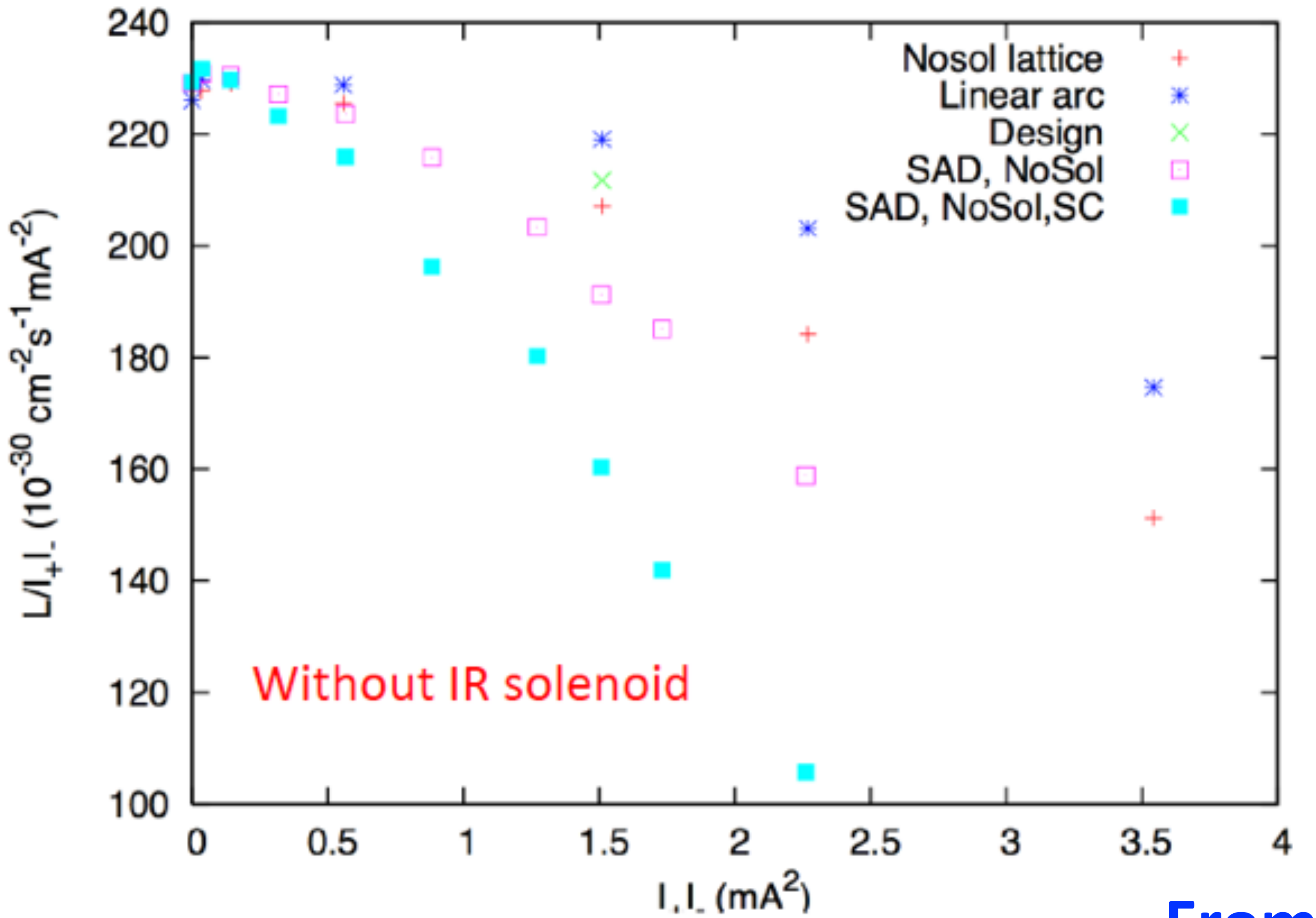




5. Benchmark of SAD: luminosity calculation

➤ **Compare with SCTR code (by K. Ohmi)**

- **Test on simplified lattice (sler_simple001.sad)**
- **Discrepancy observed**
- **Need to compare in detail the nonlinear maps used in SAD, SCTR and Bmad.**



From K. Ohmi

Outline

- ➤ Impedance issues - updates
- ➤ Interplay of beam-beam(BB) and lattice nonlinearity(LN)
- ➤ Space charge(SC) effects in LER
- ➤ Luminosity calculation for detuned lattices
- ➤ Benchmark of SAD and Bmad
- ➤ **Summary and Future plan**

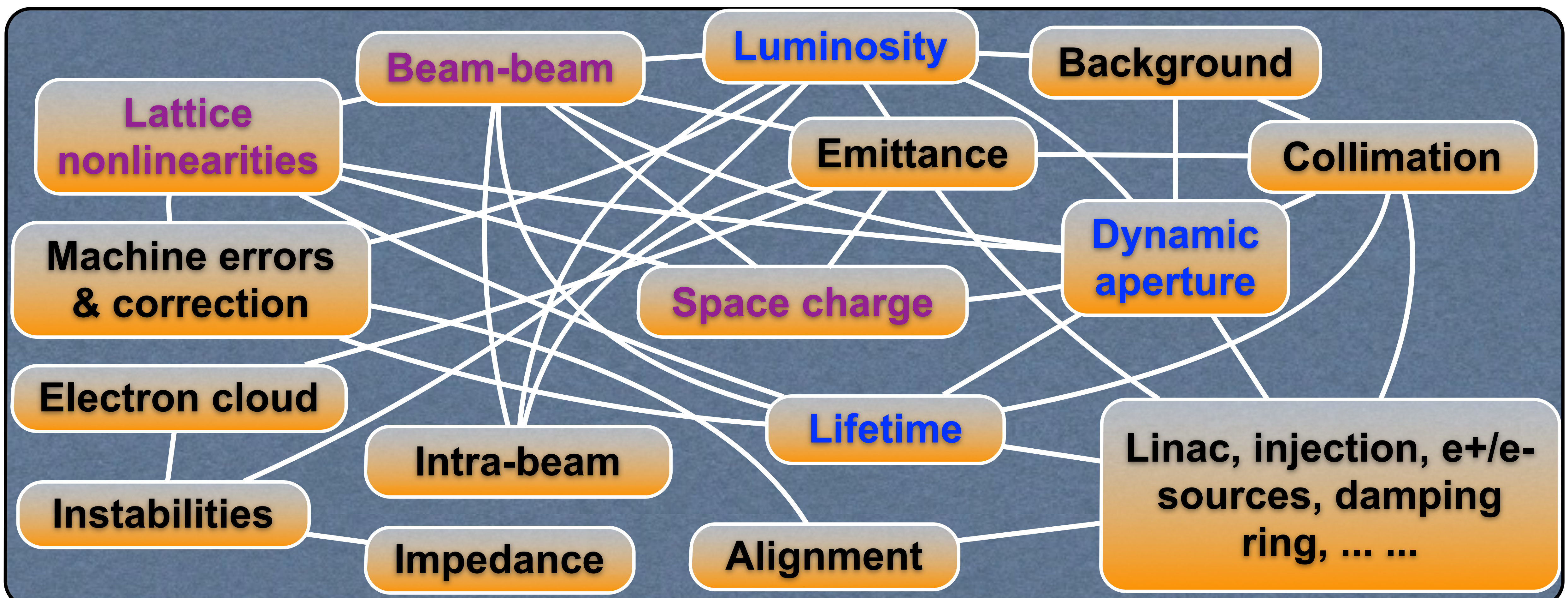
6. Summary

- **Impedance issues**
  - **Impedance model updated**
  - **MWI simulation updated**
- **BB+LN**
  - **Nonlinear amplitude-dependent X-Y coupling identified**
  - **Solenoid and high-order terms in QC* magnets are the main sources of LN**
  - **Mitigation methods to be investigated**
- **Space charge**
  - **To be investigated**
  - **Optics matching with SC (need to upgrade SAD?)**
- **Lum. calculation for detuned optics**
  - **SC and LN likely not to cause lum. loss**
  - **$L=1\times10^{34}cm^{-2}s^{-1}$ is promising, $L=10\times10^{34}cm^{-2}s^{-1}$ is possible**
- **Benchmark of SAD**
  - **Successful and need more efforts**

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. => Tolerance 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/FCC-ee teams

➤ High-priority tasks:

- Global or local correction schemes for latt. nonlin.
- SC compensation schemes
- Better understand beam-beam physics for nano-beam scheme
- More benchmark studies for SAD
- … …

➤ Recommendations are welcome!

Thanks for your attention!