Coherent beam-beam instability in SuperKEKB and CEPC

K. Ohmi,

CEPC workshop

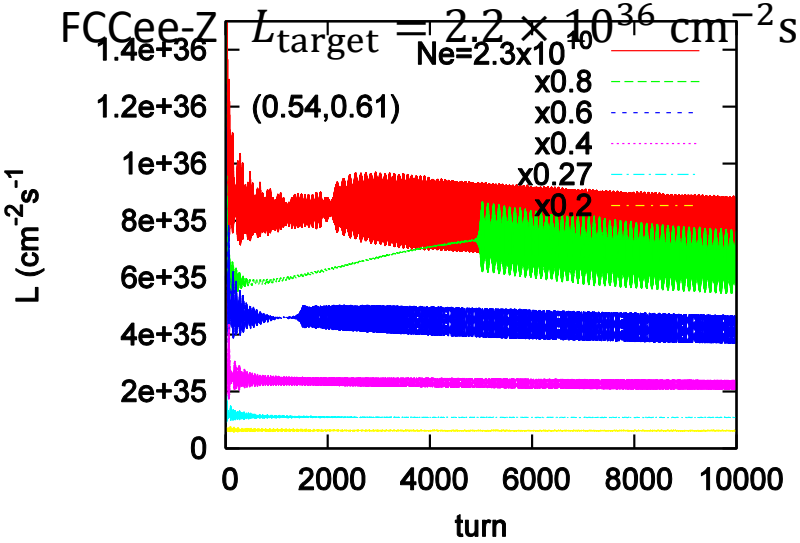
IHEP, Nov 12-14, 2018

Coherent beam-beam instability in collision with a large crossing angle

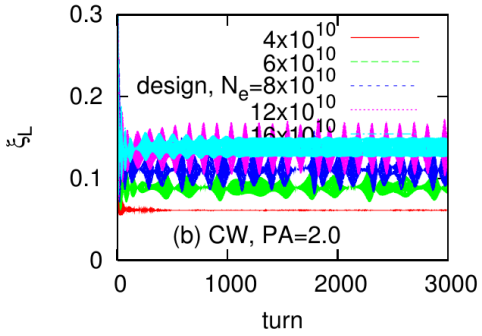
- Beam-beam instability in coupled horizontal head-tail mode is induced in collision with a large crossing angle.
- This instability is serious for future colliders based on crab waist scheme.

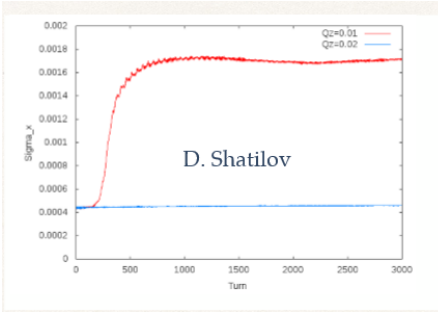
Strong-strong simulation

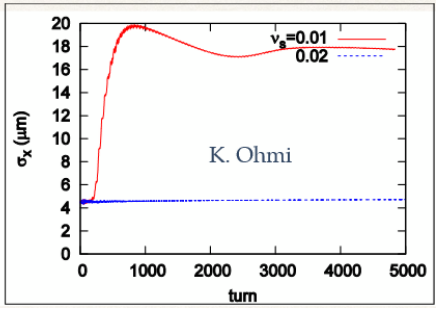
FCCee-Z $L_{\text{target}} = 2.2 \times 10^{36}\ \text{cm}^{-2}\text{s}^{-1}$



FCCee-H

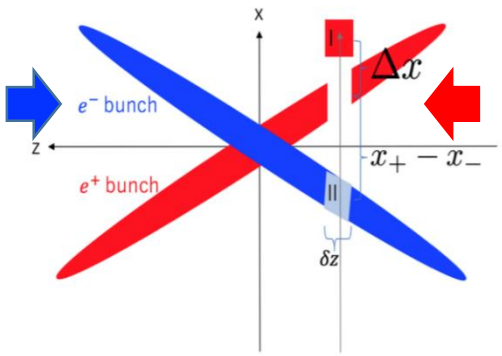






Coherent beam-beam instability in head-tail mode for collision with a large crossing angle

Mechanism of the instability- Cross wake force



- Usual wake force gives correlation between bunch head to tail. Head-tail instability is induced by synchrotron motion

$$\Delta p_x(z) = -\int_z^\infty W(z-z')\rho_x(z')dz'$$

- Cross wake field gives correlation of two colliding beam by convolution of each dipole moment.

$$\Delta p_{x,\mp}(z_\mp) = -\int_{-\infty}^{\infty} W_x^{(\mp)}(z_\mp - z'_\pm)\rho_x^{(\pm)}(z'_\pm)dz'_\pm$$

- Cross wake force induced by the beam-beam interaction is localized at IP.

CEPC Parameters

Y. Zhang, CEPC conference Nov. 2017, IHEP

	Higgs	***W***	***Z***
Number of IPs	2		
Energy (GeV)	120	80	45.5
Circumference (km)	100		
SR loss/turn (GeV)	1.68	0.33	0.035
Half crossing angle (mrad)	16.5		
Piwinski angle	2.75	4.39	10.8
N_e/bunch (10^{10})	12.9	3.6	1.6
Bunch number	286	5220	10900
Beam current (mA)	17.7	90.3	83.8
SR power /beam (MW)	30	30	2.9
Bending radius (km)	10.9		
Momentum compaction (10^{-5})	1.14		
β_{IP} x/y (m)	0.36/0.002		
Emittance x/y (nm)	1.21/0.0036	0.54/0.0018	0.17/0.0029
Transverse σ_{IP} (um)	20.9/0.086	13.9/0.060	7.91/0.076
ξ_x/ξ_y/IP	0.024/0.094	0.009/0.055	0.005/0.0165
RF Phase (degree)	128	134.4	138.6
V_{RF} (GV)	2.14	0.465	0.053
f_{RF} (MHz) (harmonic)	650		
Nature bunch length σ_z (mm)	2.72	2.98	3.67
Bunch length σ_z (mm)	3.48	3.7	5.18
HOM power/cavity (kw)	0.46 (2cell)	0.32(2cell)	0.11(2cell)
Energy spread (%)	0.098	0.066	0.037
Energy acceptance by RF (%)	2.06	1.48	0.75
Photon number due to beamstrahlung	0.25	0.11	0.08
F (hour glass)	0.93	0.96	0.986
L_{max}/IP ($10^{34}cm^{-2}s^{-1}$)	2.0	4.1	1.0

FCCee parameters

D. Shatilov,
Aug-Oct 2017

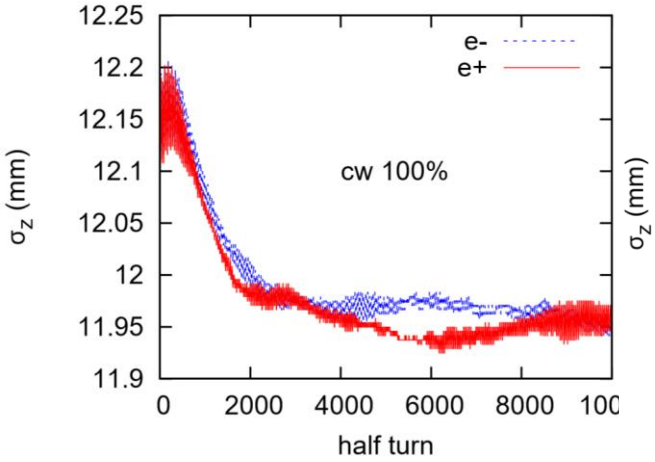
parameter	Z	W	H (ZH)	ttbar	ttbar
beam energy [GeV]	45.6	80	120	175	182.5
arc cell optics	60/60	90/90	90/90	90/90	90/90
momentum compaction [10^{-5}]	1.48	0.73	0.73	0.73	0.73
horizontal emittance [nm]	0.27	0.28	0.63	1.34	1.45
vertical emittance [pm]	1.0	1.0	1.3	2.7	2.9
horizontal beta* [m]	0.15	0.2	0.3	1	1
vertical beta* [mm]	0.8	1	1	2	2
length of interaction area [mm]	0.42	0.5	0.9	1.95	2.0
tunes, half-ring (x, y, s)	(0.569, 0.61, 0.0125)	(0.577, 0.61, 0.0115)	(0.565, 0.60, 0.0180)	(0.553, 0.59, 0.0343)	(0.553, 0.59, 0.0349)
longitudinal damping time [ms]	414	77	23	7.5	6.6
SR energy loss / turn [GeV]	0.036	0.34	1.72	7.8	9.21
total RF voltage [GV]	0.10	0.44	2.0	9.5	10.9
RF acceptance [%]	1.9	1.9	2.3	5.0	4.7
energy acceptance [%]	1.3	1.3	1.5	2.5	2.5
energy spread (SR / BS) [%]	0.038 / 0.132	0.066 / 0.153	0.099 / 0.151	0.147 / 0.192	0.153 / 0.195
bunch length (SR / BS) [mm]	3.5 / 12.1	3.3 / 7.65	3.15 / 4.9	2.45 / 3.25	2.5 / 3.3
Piwinski angle (SR / BS)	8.2 / 28.5	6.6 / 15.3	3.4 / 5.3	1.0 / 1.33	1.0 / 1.3
bunch intensity [10^{11}]	1.7	1.5	1.5	2.7	2.8
number of bunches / beam	16640	2000	393	48	39
beam current [mA]	1390	147	29	6.4	5.4
luminosity [10^{34} $cm^{-2}s^{-1}$]	**230**	**32**	**7.8**	**1.8**	**1.5**
beam-beam parameter (x / y)	0.004 / 0.133	0.0065 / 0.118	0.016 / 0.108	0.095 / 0.157	0.090 / 0.148
luminosity lifetime [min]	70	50	42	39	39
time between injections [sec]	122	44	31	32	32
allowable asymmetry [%]	±5	±3	±3	±3	±3
required lifetime by BS [min]	29	16	11	12	12
actual lifetime (w) by BS [min]	> 200	20	20	24	25

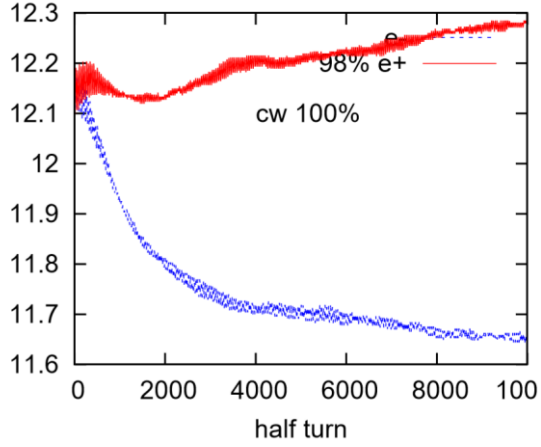
3D beam-beam effect D. Shatilov

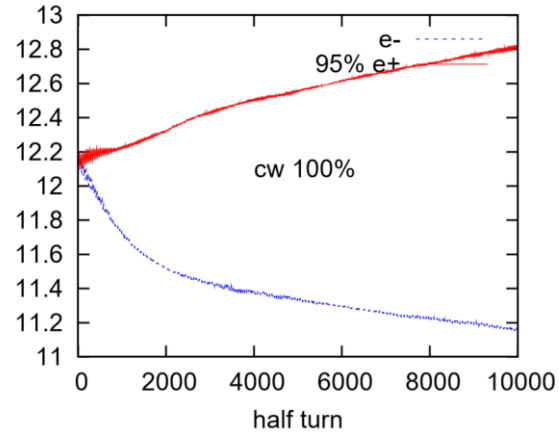
- Combined effect of the coherent beam-beam head-tail instability and Beamstrahlung
- Scenario
  1. Horizontal size increases due to the beam-beam instability.
  2. Vertical size increases due to hourglass effect enhanced by horizontal size increase.
  3. When vertical size of one beam is larger, beam-strahlung is enhanced, then bunch length increases.
- Very sensitive for current balance of e+e-.
- Parameters should be chosen so as to avoid the beam-beam instability under condition without beamstrahlung.

Collision with slightly asymmetric beam currents

- Equilibrium state exists when beam current balance is within 95%.
- The balance condition should be kept on the beam injection.



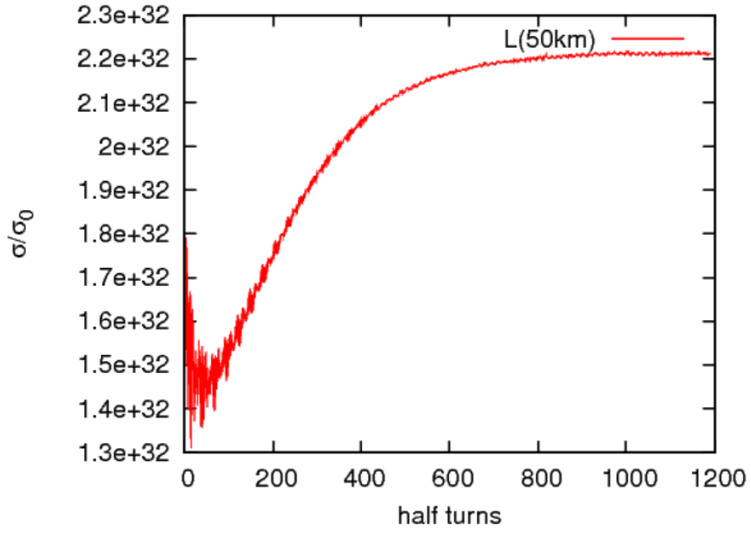


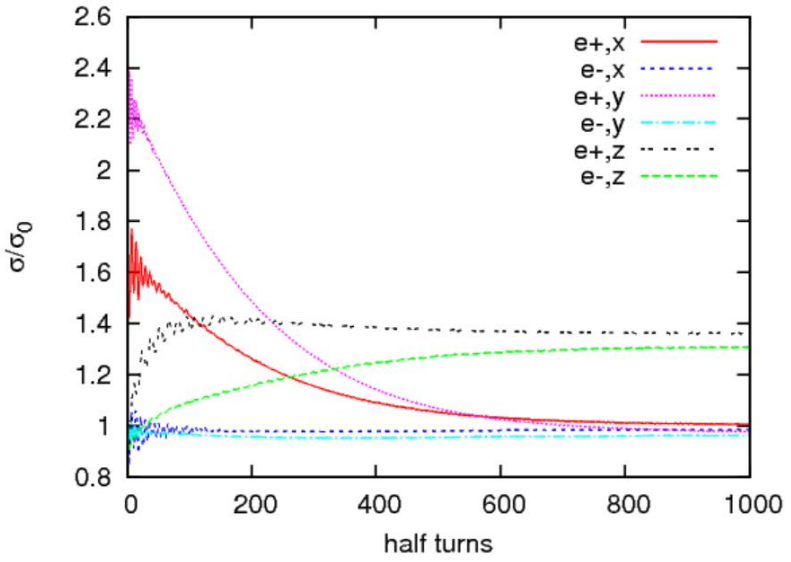


Simulation result (bbss)

- Stability for injected beam

	Injected Beam	Stored Beam
Circumference[km]	50	
Bunch Population	15×10^{10}	
Half Crossing Angle[mrad]	16.5	
Crab Waist Strength	100%	
ϵ_x[nmrad]	3.57	1.21
ϵ_y[pmrad]	17.8	3.1
σ_z[mm]	2.8	3.26
$\sigma_\delta[10^{-4}]$	9.4	9.94
$\nu_x/\nu_y/\nu_s$	0.555/0.61/0.035	
β_x^*/β_y^*[m]	0.36/0.0015	
Damping Decrement[x/y/z]	0.0035/0.0035/0.007	



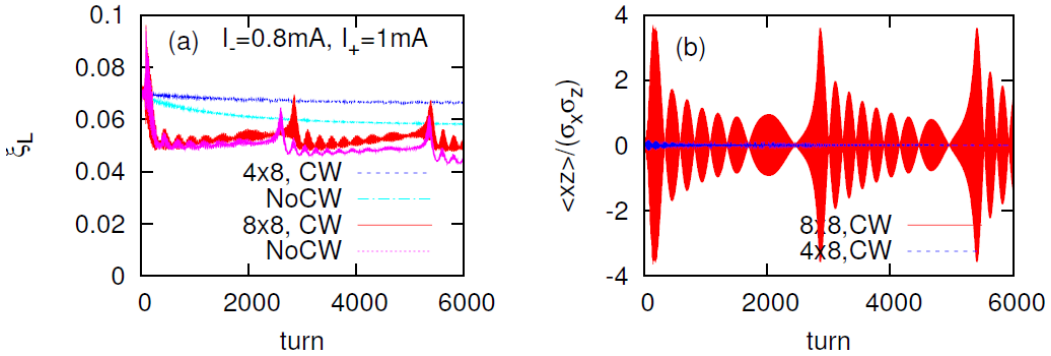


SuperKEKB as test machine for future colliders

- The design parameters of CEPC and FCC-ee are being almost converged.

- SuperKEKB
  - Is there any problem for collision with a large Piwinski angle?
  - Tolerance for optics aberration at IP is severe as β^* is squeezed.
  - The instability is really observed and how serious?

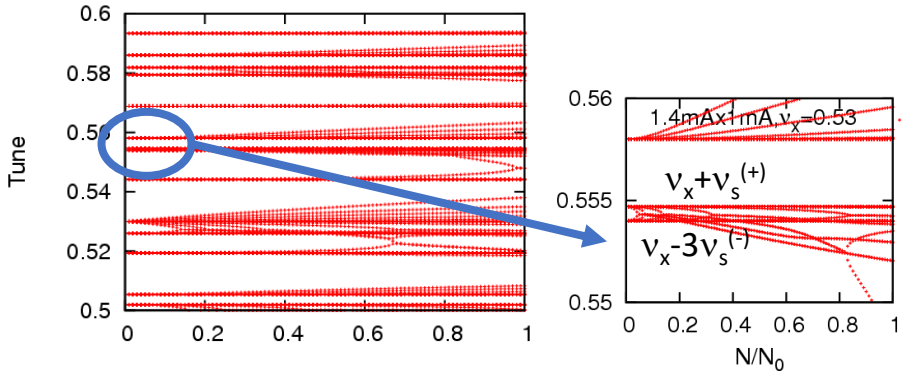
Coherent beam-beam Instability seen in strong-strong simulation (SuperKEKB)

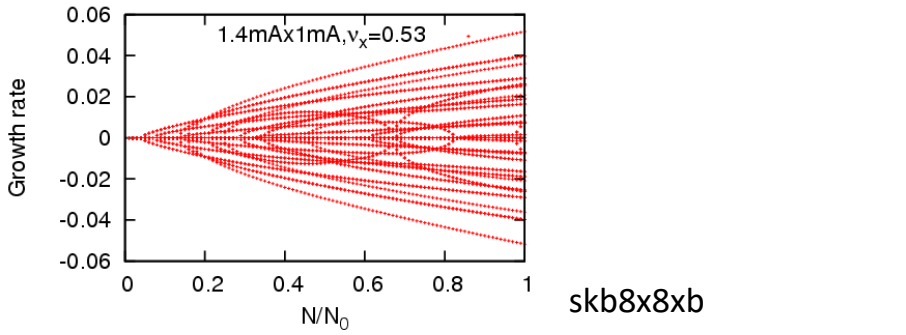


- Design parameters of SuperKEKB was stable.
- We squeeze β* step-by-step.
- Instability was seen in detuned β* (8x,8x).
- We plan to study this instability in Phase II commissioning this year.
- This instability is serious for FCC-ee design.

Eigen mode analysis for ν_x=0.53
ν_s(LER)=0.0247, ν_s(HER)=0.0280

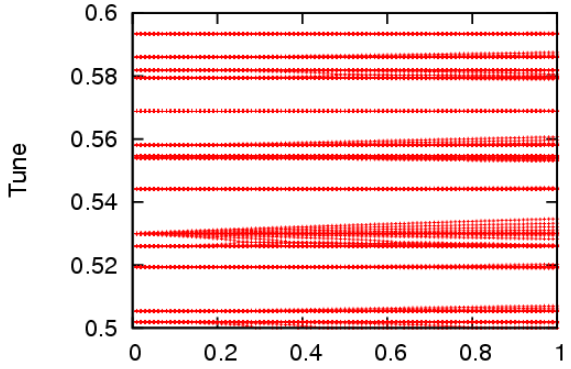
- 8x8x

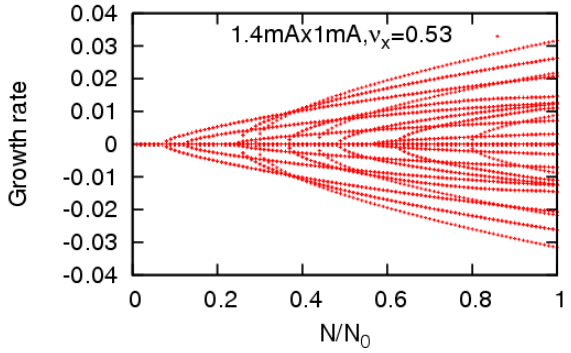




skb8x8xb

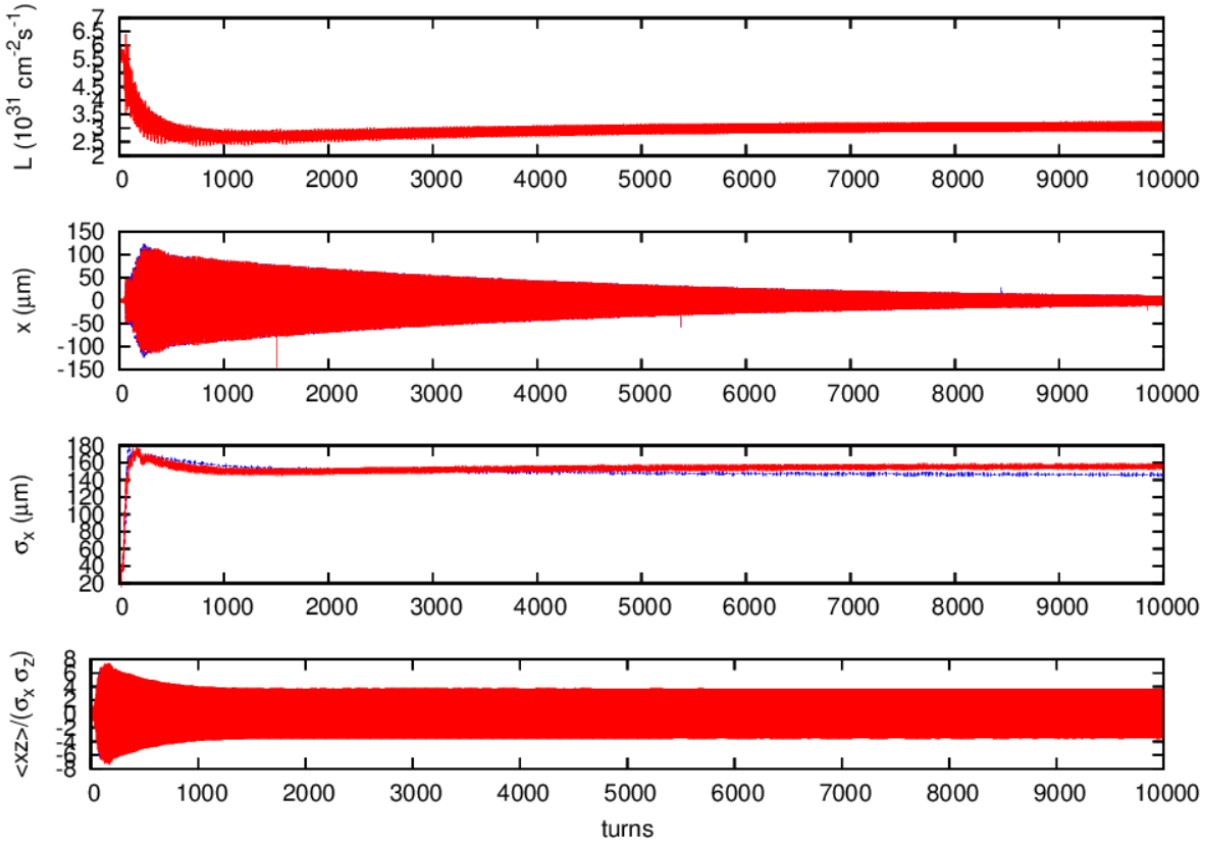
4x8x





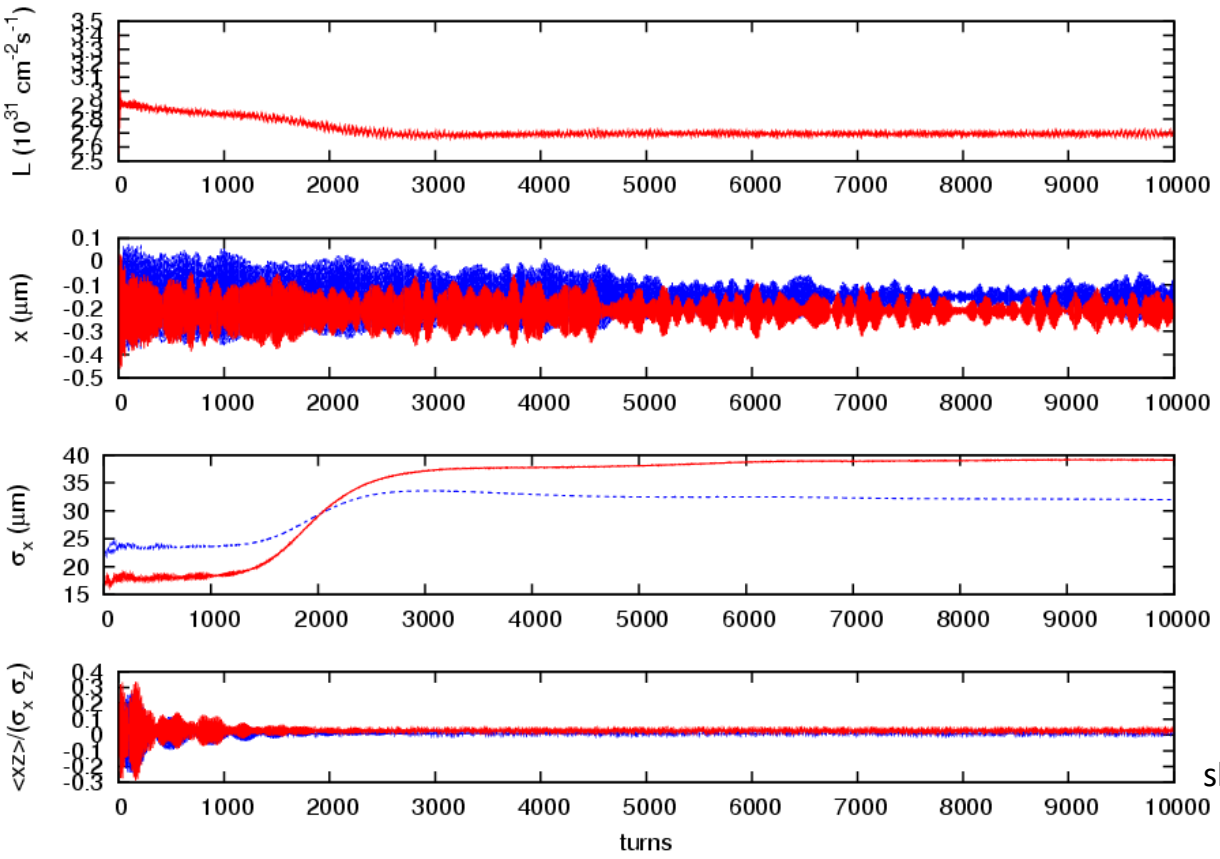
Low threshold with coupling $\nu_x+\nu_s^{(+)}$ and $\nu x-3\nu_s^{(-)}$.
For different νs, appearance of instability is complex.

Strong-strong beam-beam simulation 8x8x, 1.44mAx1.04mA, ν_x=0.53



skb2a

4x8x, 1mAx0.8mA , ν_x=0.53



skb21b

Summary of the strong-strong simulation

I=1.44mA x 1.04mA

ν_x	8x8x				4x8x			
	L/L_0,	σ_x/σ_{x0} (L & H)		osc.	L/L_0,	σ_x/σ_{x0} (L & H)		osc.
0.53 a	0.58-0.66	6.5	4.5		0.75-1.0	3.0-7.5	2.2-6.2	
0.535 g	0.70-0.95	2.5-6.2	1.4-4.0		1.04	1.2	1.0	
0.54 d	0.75-0.95	2.5-6.0	1.4-4.0		1.05	2.1	1.1	
0.545 f	0.83	7.2	1.2	no osc.	0.94	5.2	1.7	
0.55 e					0.75-0.77	8.6	3.5	

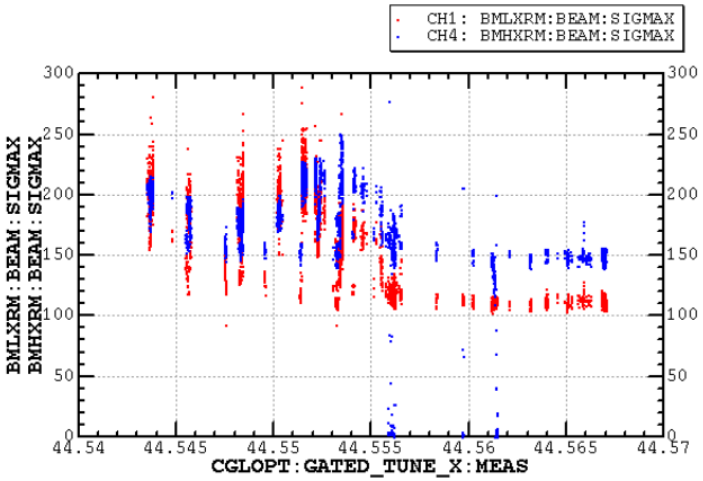
Horizontal emittance growth does not contribute luminosity drop in collision with a large crossing angle, when β_y is large.
Crab waist on in the simulation. CW-off may be serious for the horizontal emittance growth.

Instability study in Phase II

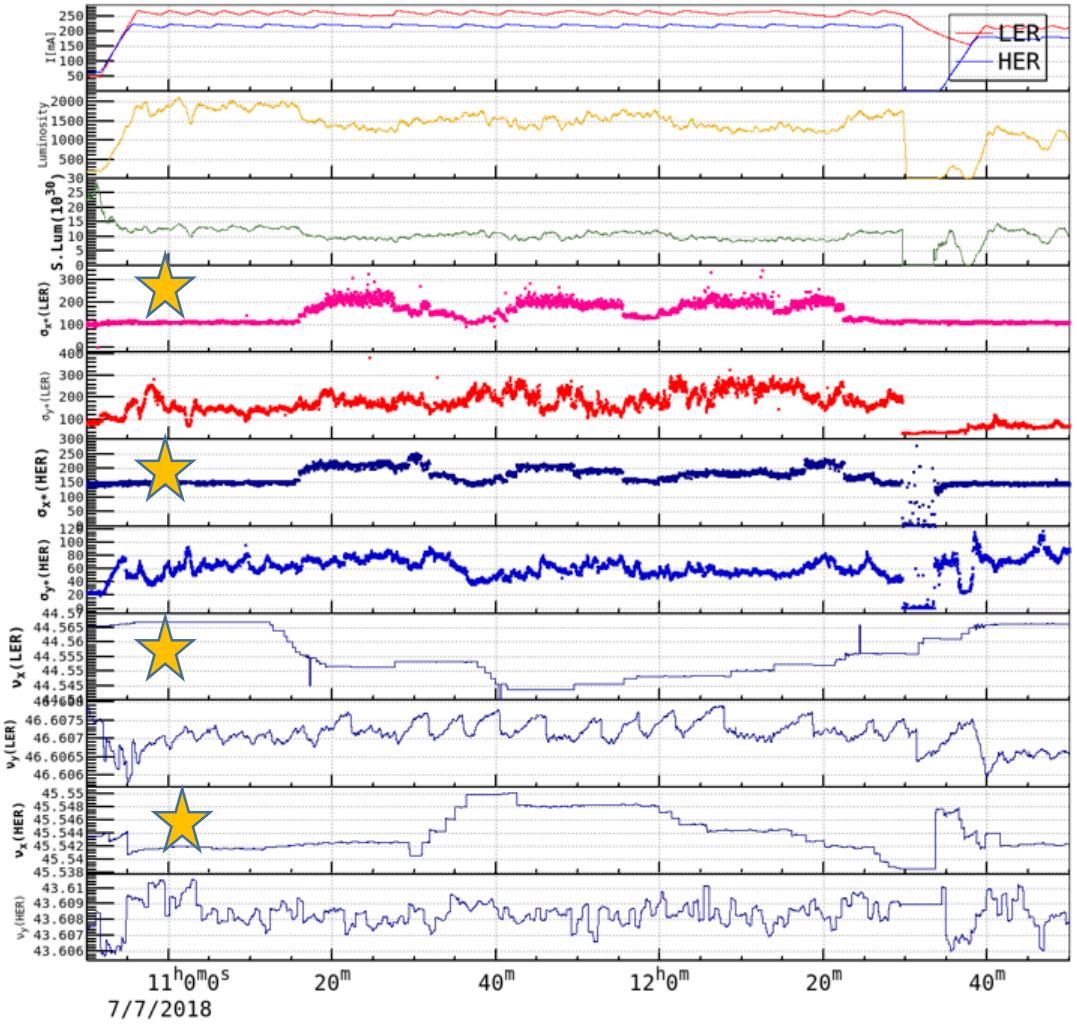
- Typical condition
- β_x=0.2m, 0.1m, β_y=3mm
- I_{tot}=270mA (e+)x 225mA (e-), Nb=395,
- I_b=0.68mAx0.57mA (design 1.44mAx1.04mA)
- Np=4.3×10^{10}, 3.6×10^{10}. (design 9.04×10^{10}x 6.53×10^{10})
- ν_s (e+)=0.022, ν_s (e-)=0.026

7/7 day time study

- 270mAx225mA, 10:50-12:30
- Search tune condition in which the instability appears.

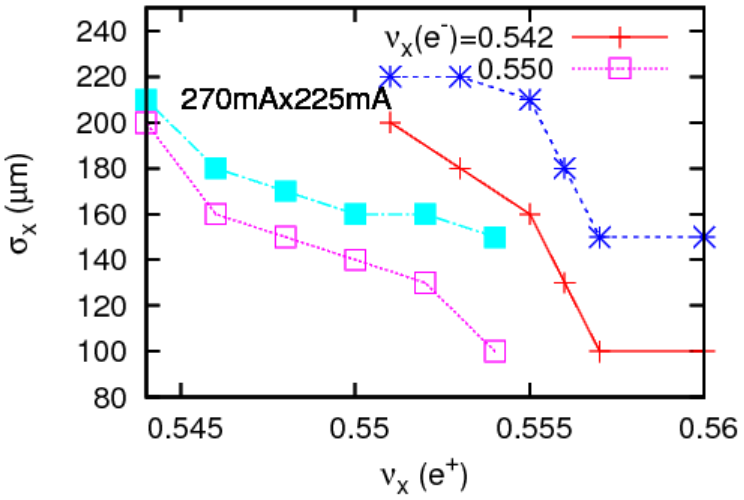


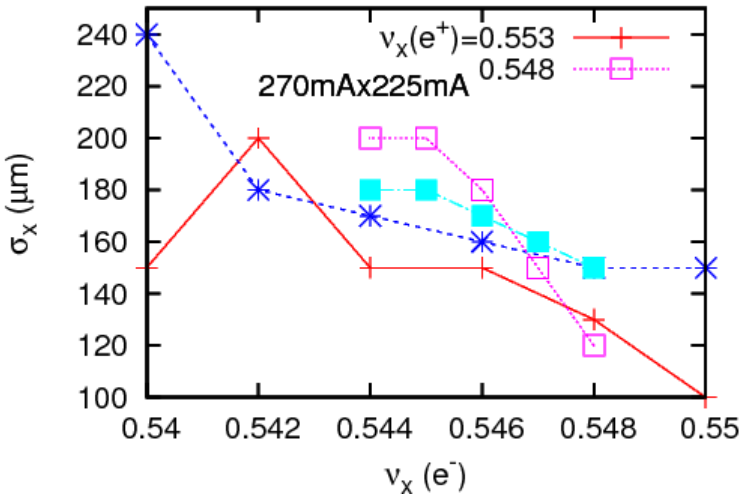
- ν_x(e-)をあげると安定になるが、ν_x(e+)を下げると不安定になる。



σ_x ($\nu_x(e^+)$, $\nu_x(e^-)$) at 270mAx225mA

- I_+I_-=0.39 mA^2, N_b=395
- We did not cross over the peak to avoid a beam abort.

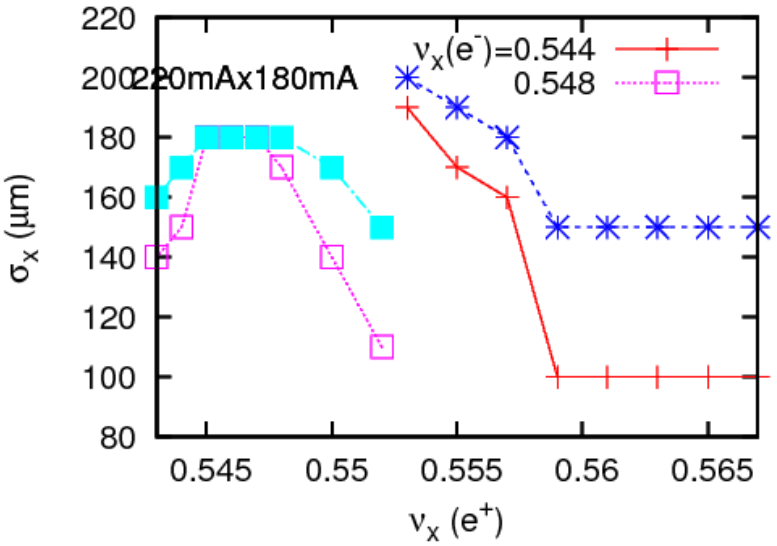


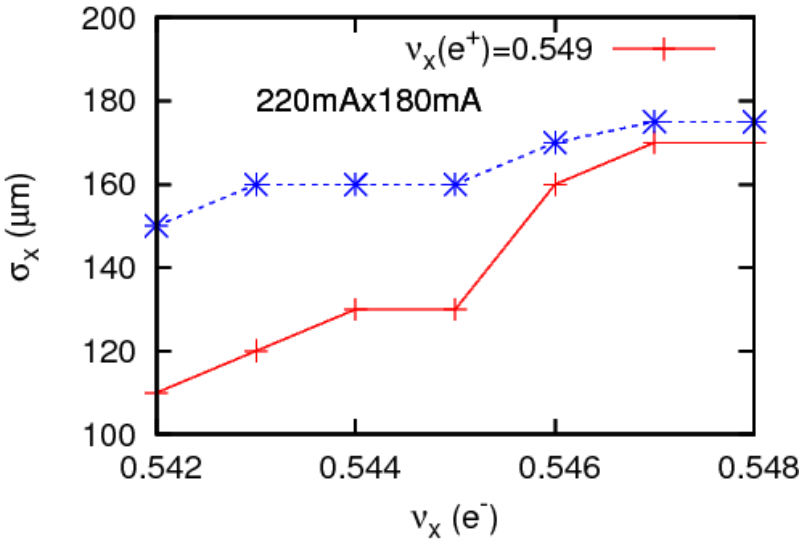


- The same tune condition in Red(e+) & blue(e-)
- Magenta(e+) & cyan(e-)

σ_x ($\nu_x(e^+)$, $\nu_x(e^-)$) at 220mAx180mA

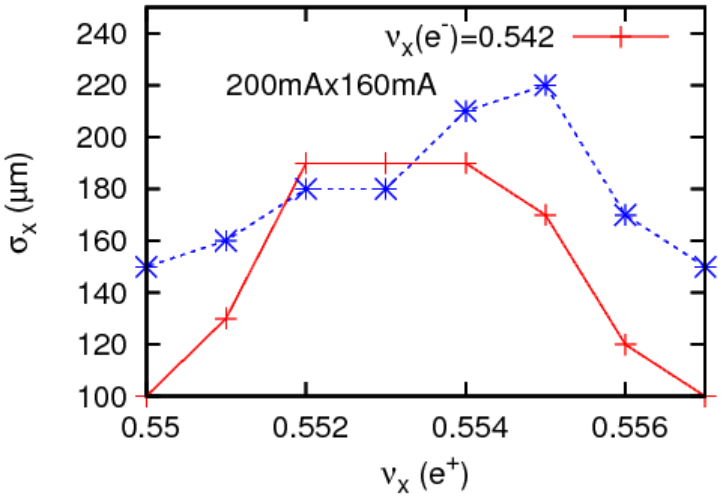
- I_+I_-=0.25 mA^2, N_b=395

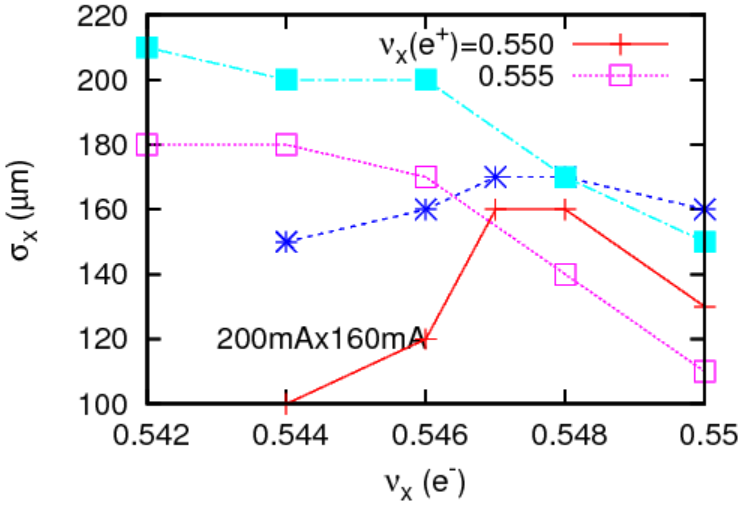




σ_x ($\nu_x(e^+)$, $\nu_x(e^-)$) at 200mAx160mA

- I_+I_-=0.21 mA^2, N_b=395
- Beam size blow-up somewhat weak. The resonance line was crossed over.

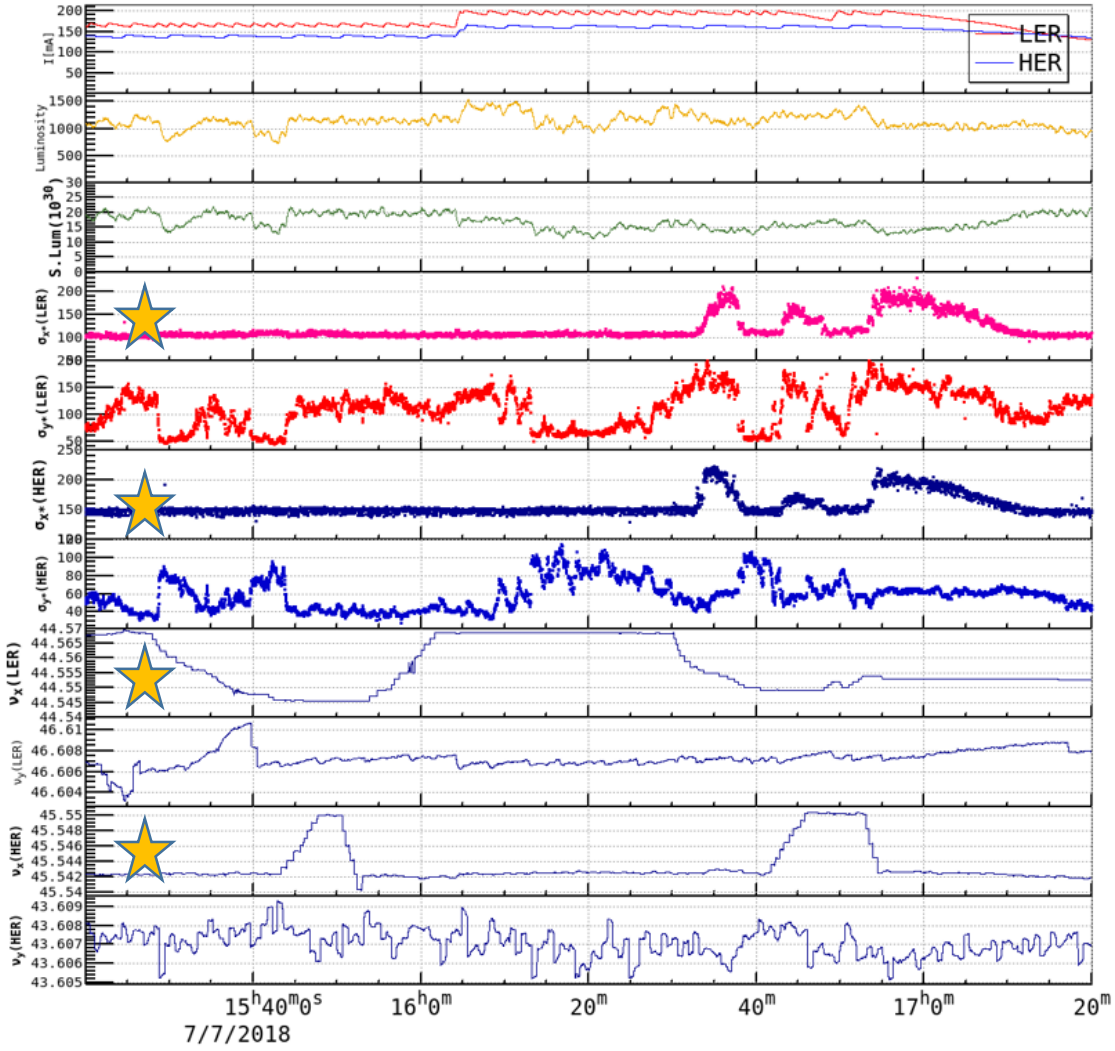




- Peak tune does not depend on bunch current.
- Stop-band may depend on?
- More study is necessary.

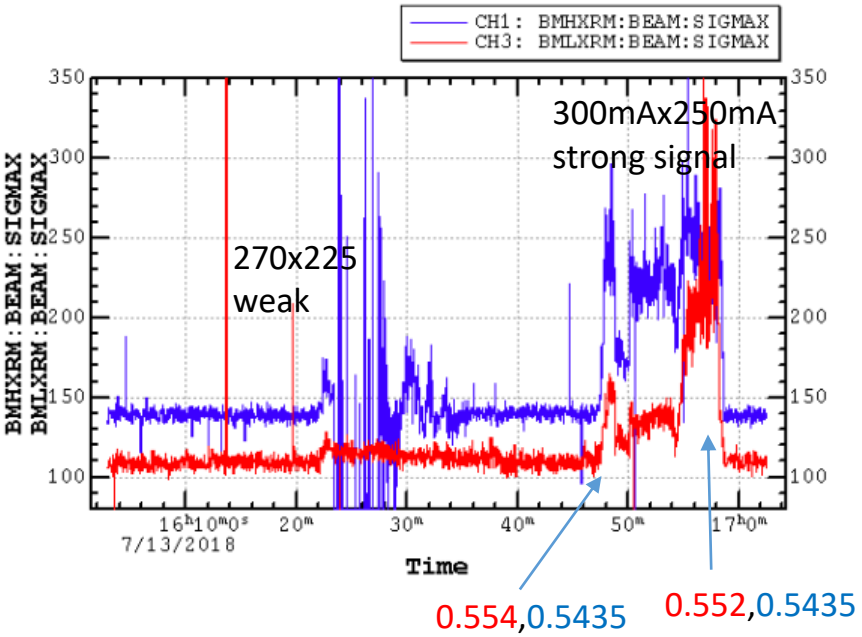
Threshold of the instability

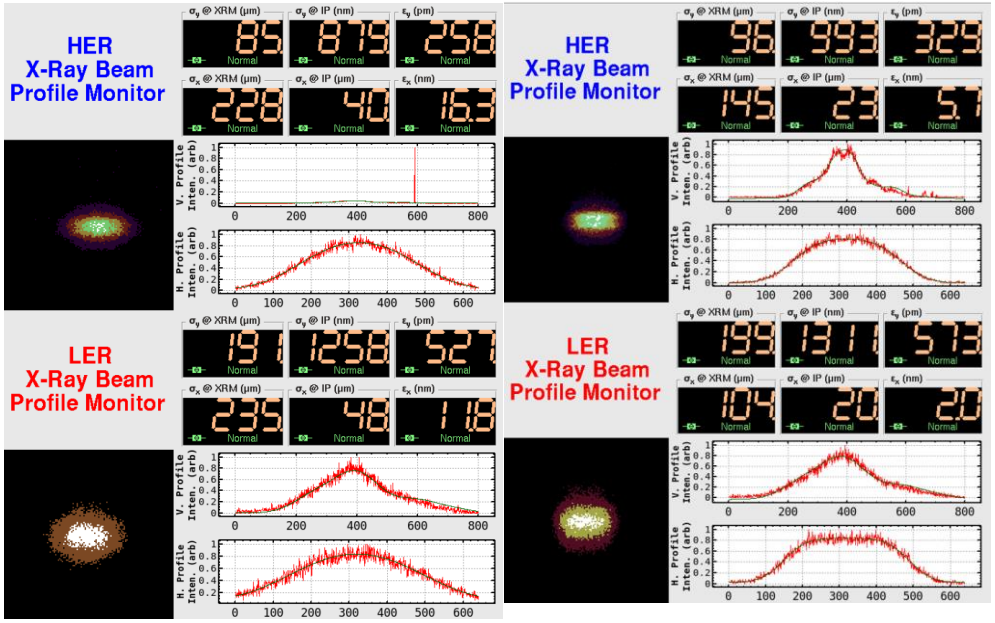
- 170mAx142mA, No σ_x blowup
- 200mAx160mA, blowup is seen.
- No blow-up in single beam tune scan.



Machine experiment at July 13, 2018

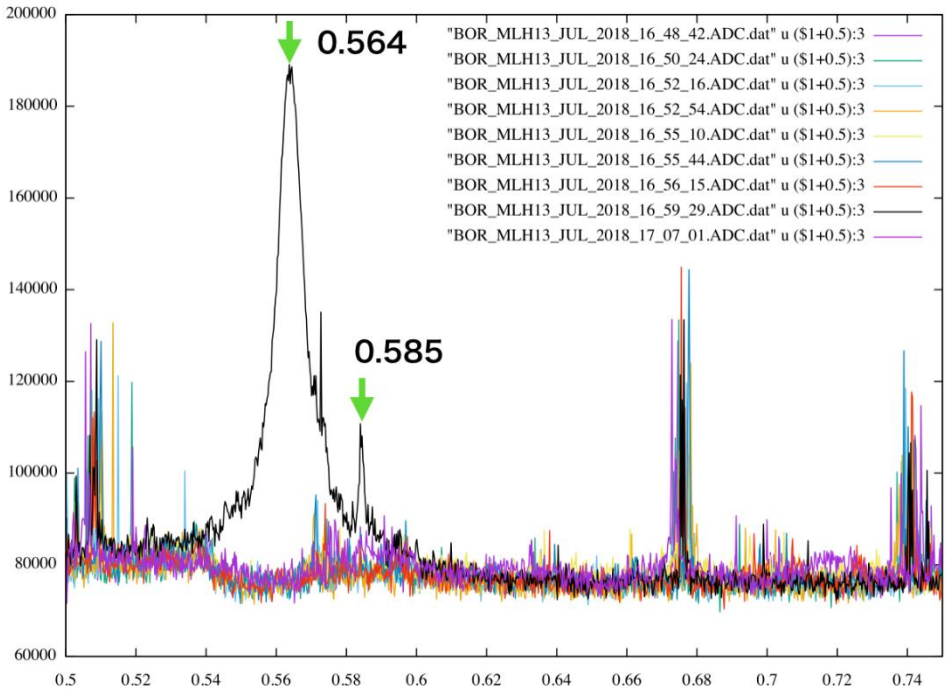
- 16:50 (instability start) & 16:57 (peak), data taking using streak camera x-z and BOR.
- ν_s (e+)=0.022, ν_s (e-)=0.026





Bunch Oscillation Recorder (LER)

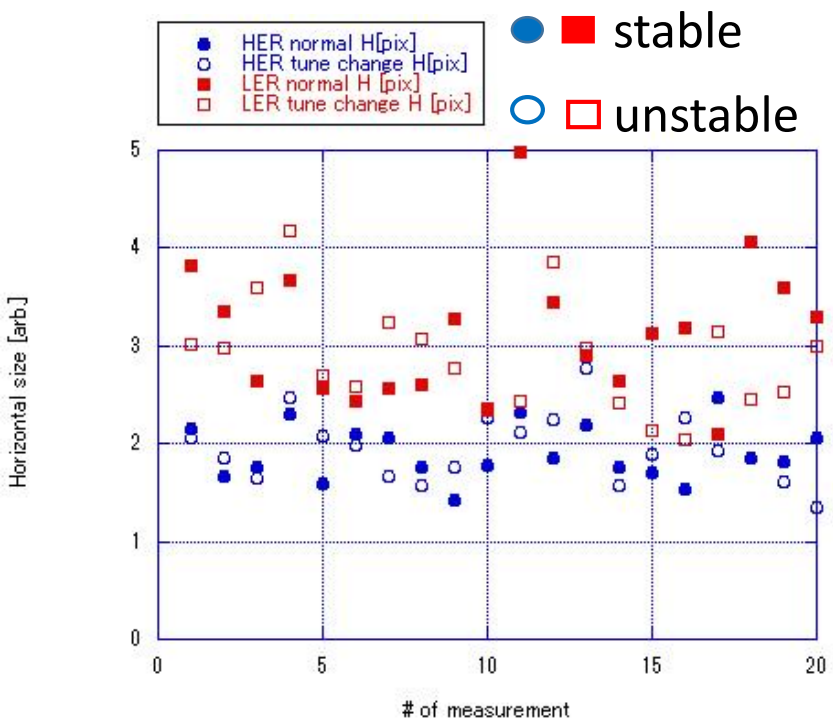
- Clear oscillation was seen in a data, which taken at strongest beam size blow-up.
- Background level of HER data was high, noisy.



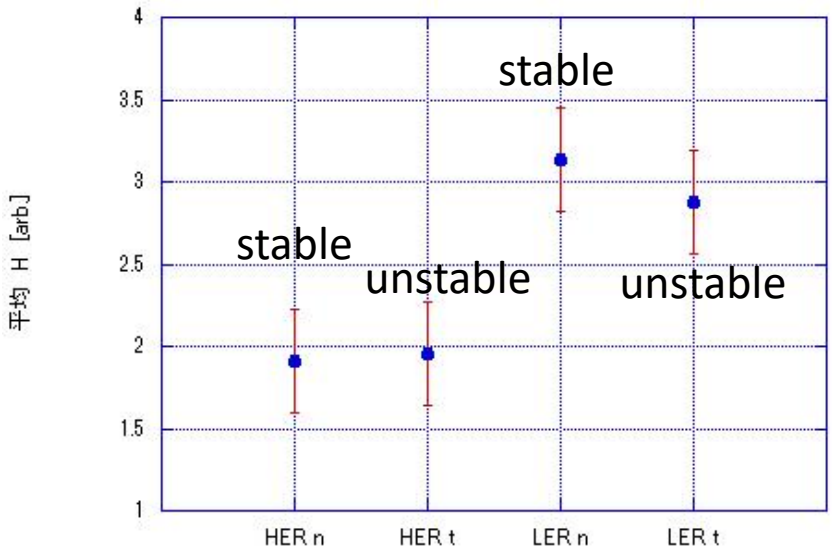
Horizontal beam size by streak camera

- No clear difference between stable and unstable
- Perhaps, lack of resolution.

Shot by shot



average



Possible instability condition

- ν_x(e+)=0.552, ν_x(e-)= 0.5435, ν_s (e+)=0.022, ν_s (e-)=0.026
- ν_x(signal)=0.563

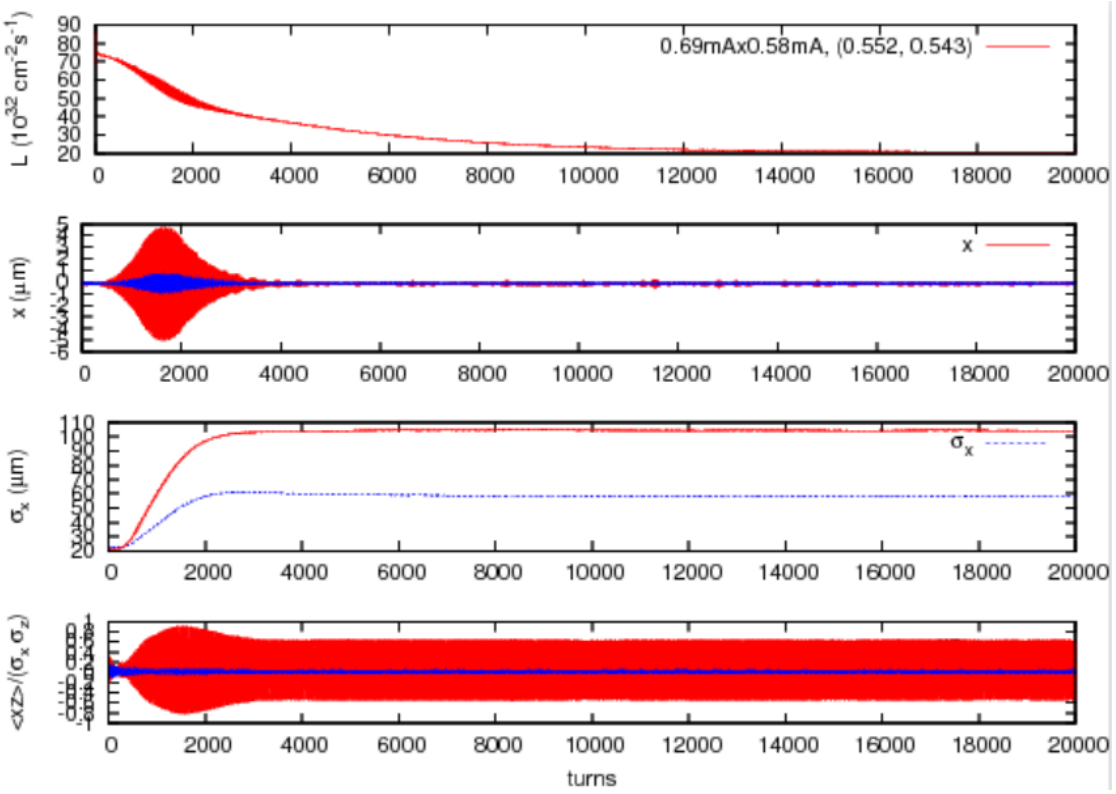
- ν_x(e-)+ ν_s (e-)= 0.5695, ν_x(e+)- 5ν_s (e+)= 1-0.558
  300mAx250mA: ξ_x(e+)=0.0073, ξ_x(e-)=0.0025
  Possible candidate: 0.563=(0.5695+0.558)/2
- ν_x(e-)- ν_s (e-)= 0.5175, ν_x(e+)-3 ν_s (e+)= 1-0.514
- ν_x(e-)+ ν_s (e-)= 0.5695, ν_x(e+)+ ν_s (e+)= 0.574

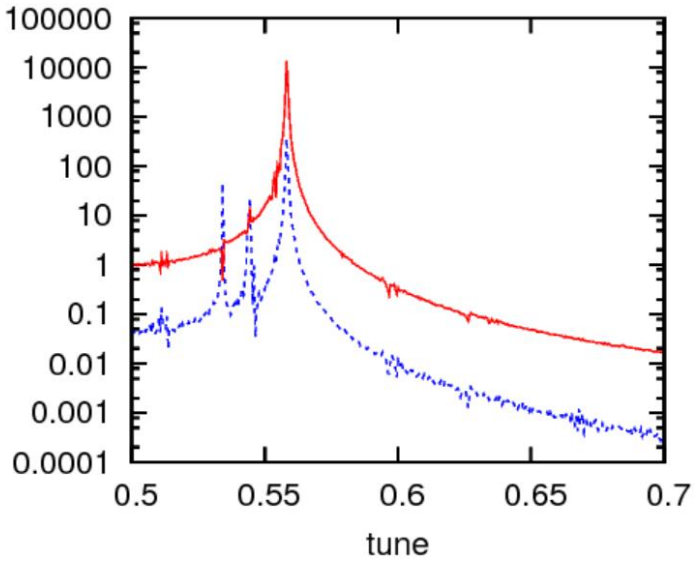
- ν_x(e-)+ν_s (e+)=0.5655,
  but no synchro-beta coupling mode.
- ν_x(e+)+ν_s (e-)=0.578

Simulation in the experimental condition

- FFT peak 0.558(simulation), not 0.564 (measured).
- ν_x(e+)=0.552, ν_s (e+)=0.0213, ν_x(e-)= 0.5435, ν_s (e-)=0.026

ambiguous





Summary

- Coherent beam-beam instability in head-tail mode has been predicted in strong-strong beam-beam simulation.
- Understanding this instability is very important for future colliders (CEPC/FCCee) based on crab waist scheme.
- The instability was observed in SuperKEKB commissioning as is predicted.
- Horizontal beam size blow-up has been observed depending on horizontal tunes of two beams.
- Bunch oscillation was detected, but streak camera did not show the signals of instability.
- Simulation in the experimental condition shows reasonable agreement. Probably mode coupling between +1(e^-) and -5(e^+) modes.
- More systematic tune scan, identify peak position.

Instability and Tune

- 7/6 0:00-0:40
- 7/2 stable unstable

  HER 45.5464 43.6109 0.5431 0.607

  LER 44.5594 46.6187 0.556 0.618

- 6/24 No instability

  HER .5437 0.607

  LER 0.5585 0.6143