Beam-beam and electron cloud effects in FCC-ee

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Thanks to W. Chou, K. Oide, D. Shatilov, Y. Zhang, D. Zhou, F. Zimmermann

Introduction

- Beam-beam simulations
  - Strong-strong simulations for luminosity prediction
  - Coherent instability
  - Collective emittance growth
- Study of electron cloud effects
  - FCC-ee TLEP-Z,W,H,t
- Study of ion instability
  - FCC-ee TLEP-Z

Parameters for FCC-ee's; CEPC and TLEP

		CEPC	TLEP-Z	TLEP-W	TLEP-H	TLEP-t
Circumf	C (km)	54	100	100	100	100
Energy	E (GeV)	120	45.5	80	120	175
No. bunches	N_b	49	90300	5162	770	78
Bunch pop	N_e (10^{11})	3.8	0.33	0.6	0.8	1.7
emittance	ε_x(nm)/ε_y(pm)	6.1/18	0.09/1	0.27/1	0.61/1.2	1.3/2.5
Beta at IP	β_x(m)/β_y (mm)	0.8/1.2-3	1/2	1/2	1/2	1/2
Synchro. tune	ν_s	0.18	0.015	0.037	0.056	0.075
Bunch length	$\sigma_{z,SR}/\sigma_{z,tot}$(mm)	2.3/2.6	2.7/5.0	2.0/3.0	2.0/2.4	2.1/2.5
Energy spread	$\sigma_{\delta,SR}/\sigma_{\delta,tot}$($10^{-4}$)	13/15	3.7/6.8	6.5/10	10/12	14/17
Crossing angle	ϕ_c (half angle)	-	15	15	15	15
Piwinski angle	$\phi_c\sigma_{z,tot}/\sigma_x$	-	7.9	2.7	1.5	1.0
Damping time	τ_z/T_0	40	1520		71	25
Luminosity	L (10^{34} $cm^{-2}s^{-1}$)	2	62		5.2	1.4

Luminosity is calculated by ws code BBWS.

Simulation of beam-beam collision

- Luminosity evaluation using simplified lattice, in which arc transformation is represented by 6x6 transfer matrix. Effect of lattice is discussed later.
- Weak-strong (WS) simulation
  - One (strong) beam is fixed charge distribution (Gaussian).
  - The other (weak) beam is represented by macro-particles.
- Strong-strong (SS) simulation
  - Two beams are represented by macro-particles.
  - Equilibrium charge distribution of two beams are determined self-consistently.
  - Coherent instability can be treated.
  - Noise due to statistics for macro-particle number. The statistical noise should be smaller than radiation excitation.

$$N_{mp} \gg 2T_0/\tau_{x,y}$$

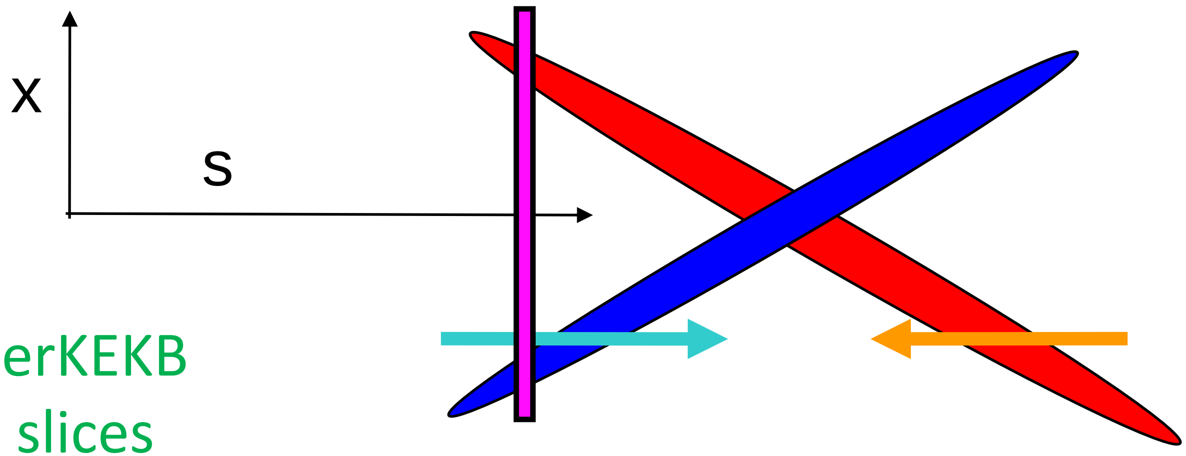
Strong-strong simulation using BBSS code

- Arbitrary beam distribution is treated using Particle In Cell Poisson solver.
- Available for very flat beam, using integrated Green function.
- Longitudinal slice and potential interpolation
- Beamstrahlung
- Shifted Green function for collision with large separation, collision between head of one beam and tail of the other beam.

- 50x50x4(TLEP-Z) collision solving Poisson equation per beam-beam crossing.

- Other choice for collision simulation: Gaussian approximation, combination of PIC and Gaussian collision

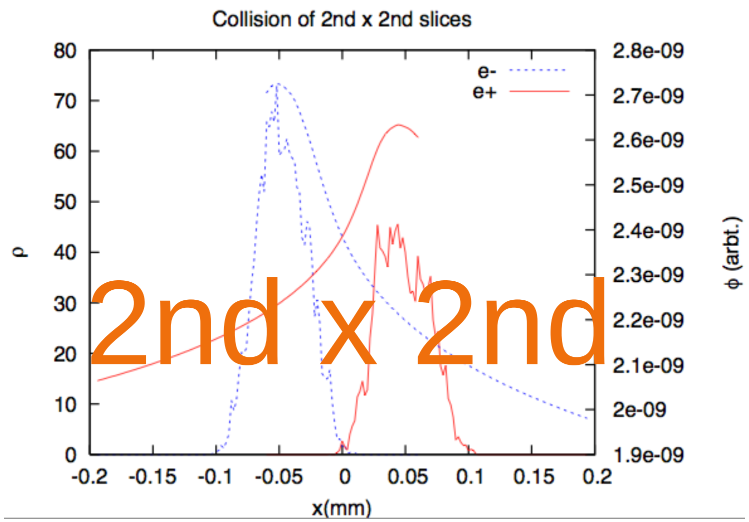
Shifted Green function
Beam distribution and potential

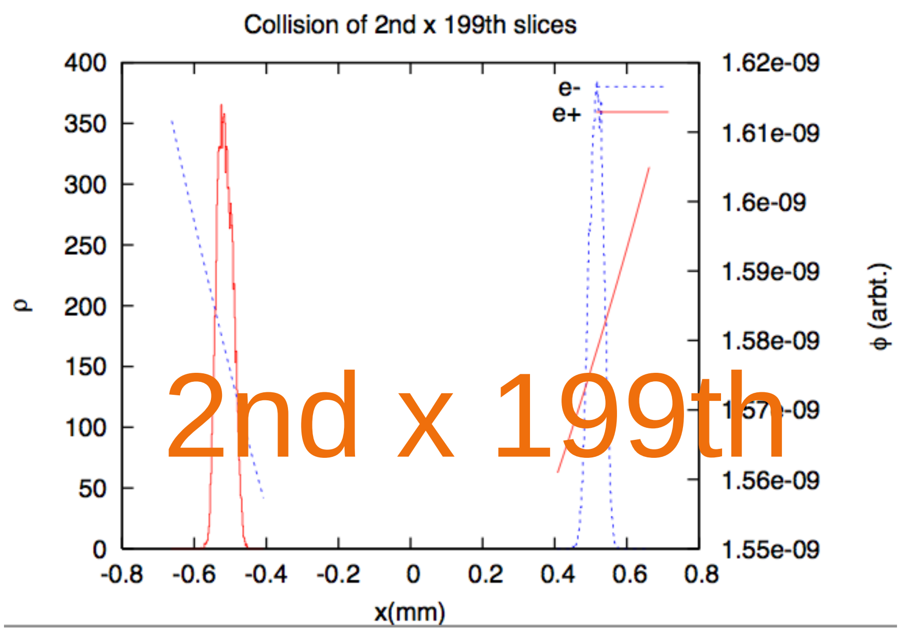


Neglect parallel translation to x

$\sigma_{z+} > \sigma_{z-}$

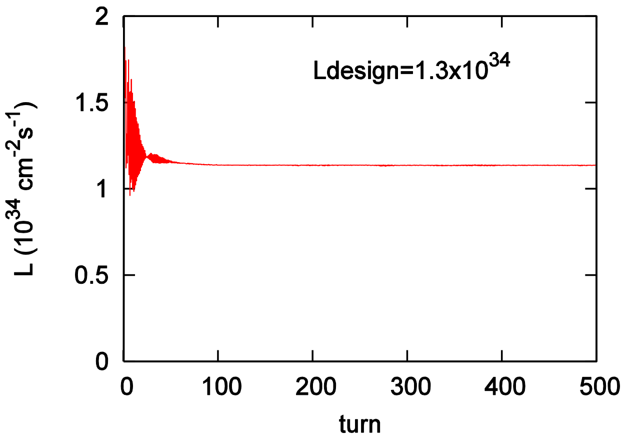
SuperKEKB
200 slices

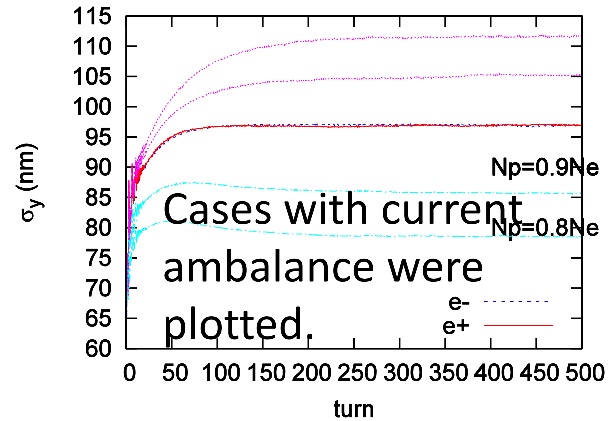




TLEP-t (strong-strong sim.)

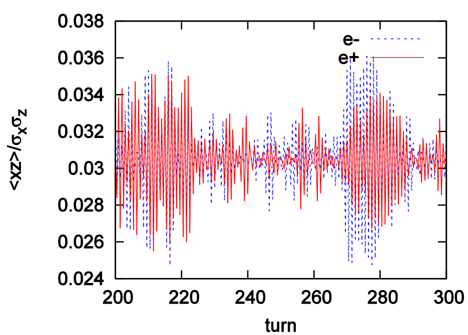
- Evolution of Lum and beam sizes, σ_y, σ_z.

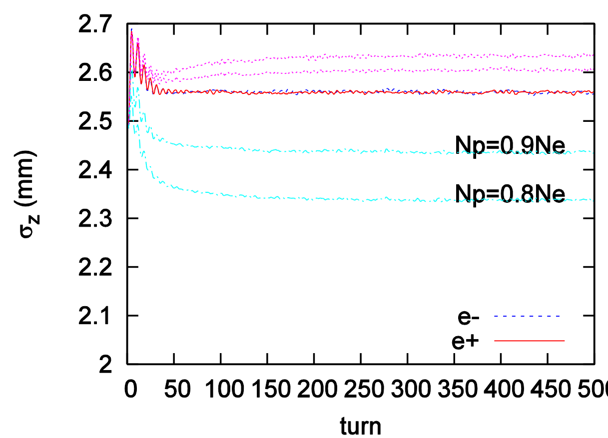




Cases with current ambalance were plotted.

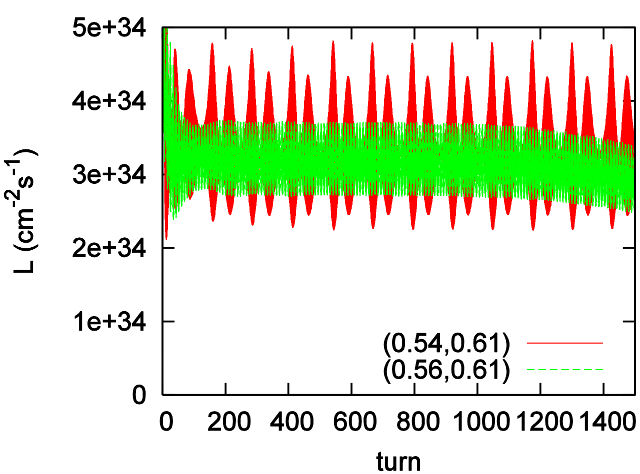
- No oscillation in <xz>. Dynamic <xz> due to BB is seen.

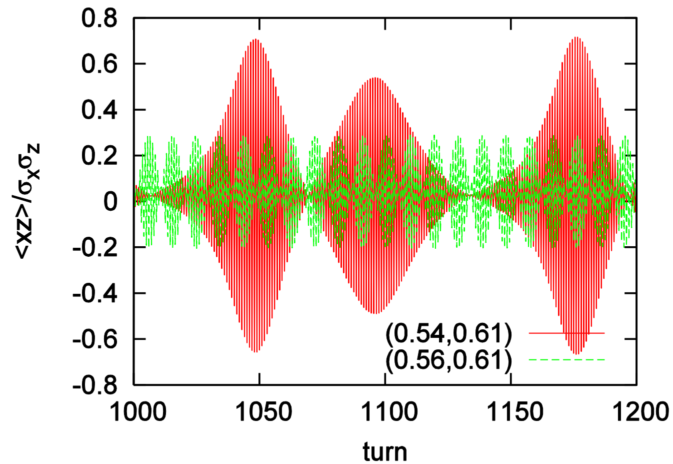


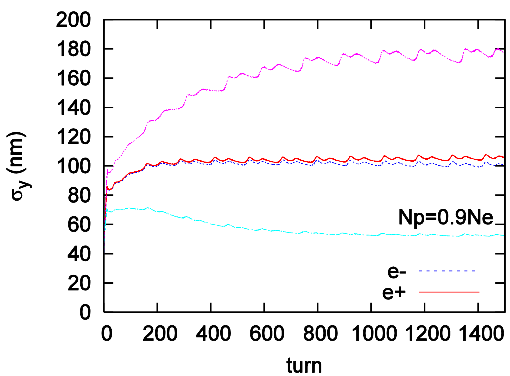


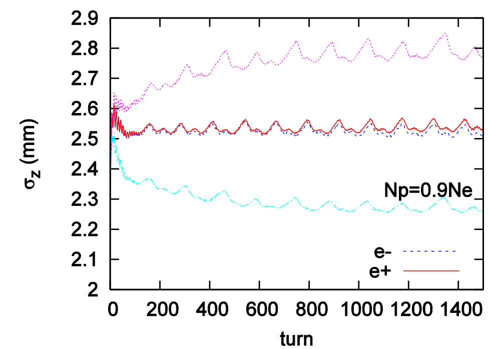
TLEP-H (strong-strong simulation)

- Evolution of Lum and beam sizes, σ_y, σ_z.
- Fluctuations in Lum. and beam sizes are seen.
- Fluctuation of <xz> is the origin.



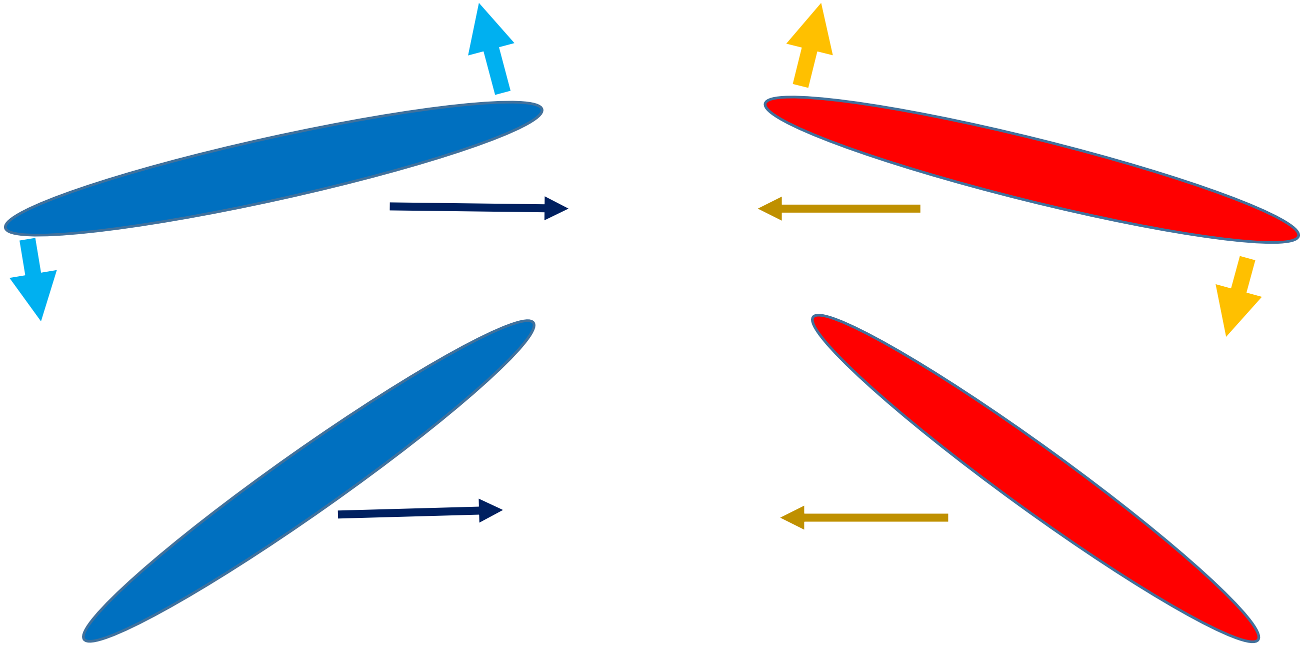






Coherent motion in <xz> at tune $(\nu_x, \nu_y)=(0.54,0.61)$

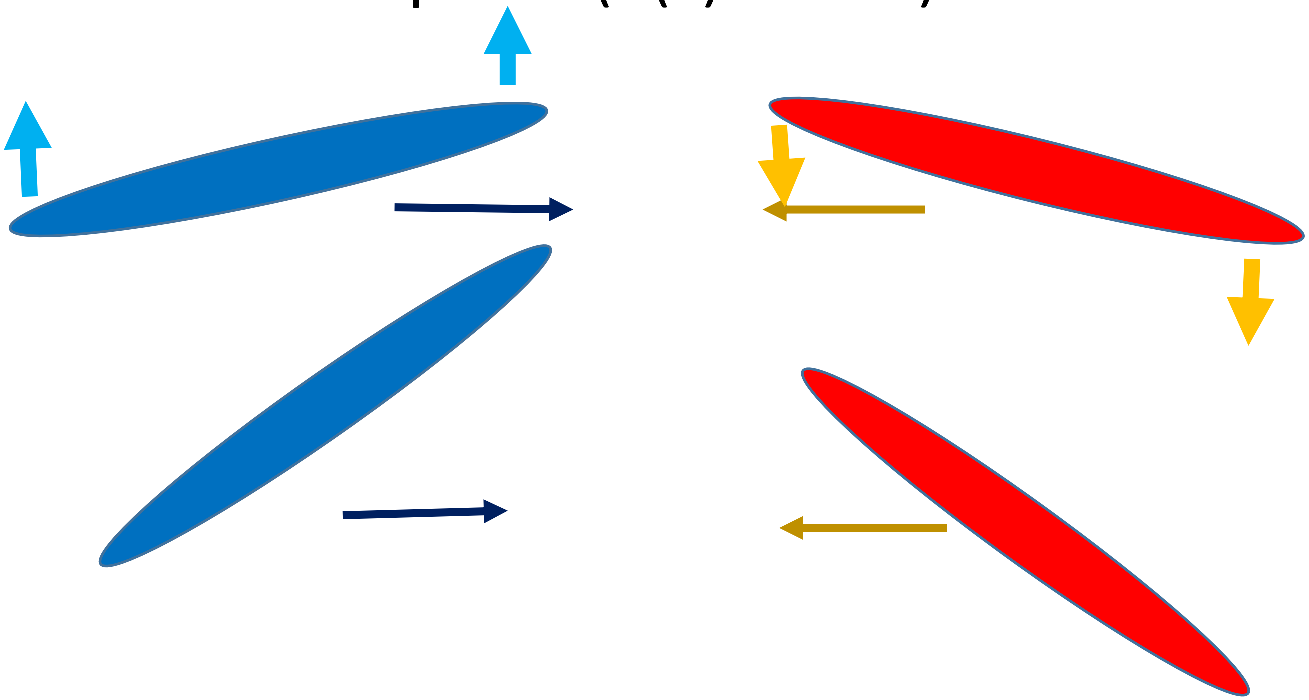
- <xz> oscillate in-phase (σ(xz) mode) for e^- and e^+ beam.



- Luminosity degradation is not very strong in H, but the motion is bad sign.
- Gaussian strong-strong gave similar results.

Coherent motion in <x> at tune $(\nu_x, \nu_y)=(0.51,0.57)$

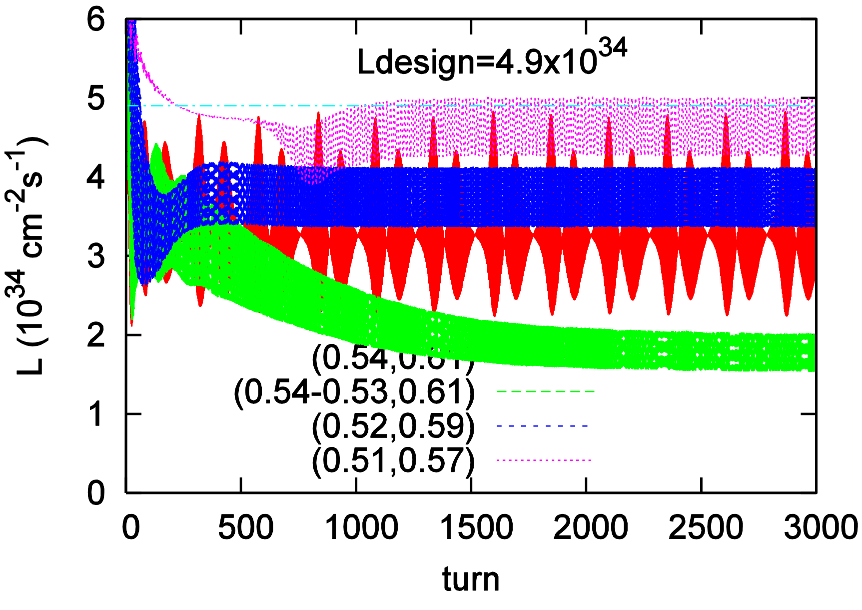
- <x> oscillate out-phase (π(x) model) for e^- and e^+ beam.

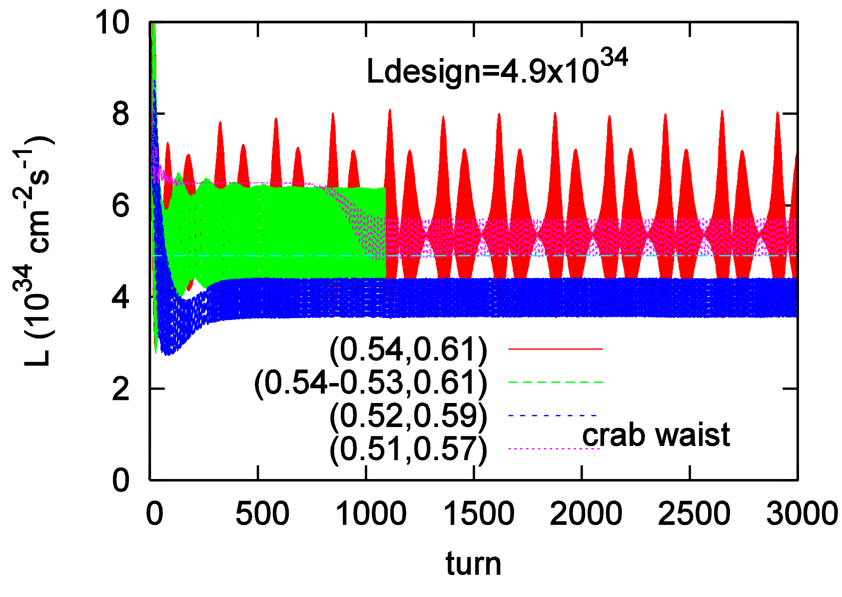


- Luminosity degradation is not very strong in H, but the motion is bad sign.
- Both of π(x) and σ(xz) modes are seen in (0.52,0.59).
- Gaussian strong-strong gave similar results.

Trials with several tune operating points

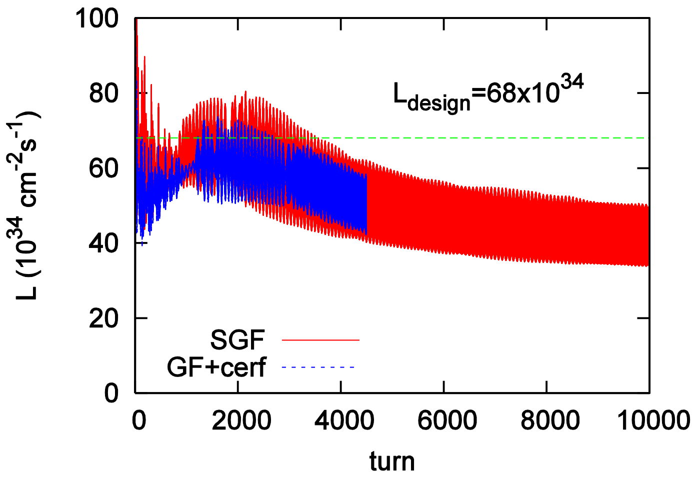
- The coherent motion is not recovered by choice of tune.
- The motion has not seen in KEKB nor SuperKEKB simulations. ξ~0.1 for finite crossing angle.
- Separation of ν_x (0.53-0.54) did not work.
- $\xi \sim 0.15$ of TLEP may be too high.





TLEP-Z (strong-strong sim.)

- High Piwinski angle $\phi_c\sigma_{z,tot}/\sigma_x$=7.9
- Shifted Green function is used for potential calculation for collision between separated slices
- The coherent motion is seen for TLEP-Z. Lum. is degraded by the motion



Simulation using shifted Green function and combination of ordinary Green function and complex error function ($\Delta x>5\sigma_x$)

- Coherent motion in <xz>/σ_z~σ_x is seen.

Summary for beam-beam studies using strong-strong simulation

- Coherent motion (instability) is seen H and Z, probably in W.
- Collision with crossing angle and high beam-beam parameter may induce the coherent motion.
- The coherent motion is bad sign.
- The coherent motion is not seen in simulations of KEKB and SuperKEKB.

Electron cloud effects in FCC-ee

- Photons are emitted by positron/electron beam.

  Number of photon per revolution $N_\gamma = \frac{5\pi}{\sqrt{3}}\alpha\gamma$

  Critical energy $u_c = \frac{3\hbar c}{2}\frac{\gamma^3}{\rho_{bend}}$

- Electrons are produced at the chamber wall due to photo-emission. Quantum efficiency Y_1=0.1-0.2.
- Electron production by a bunch per m passage.

  $n_{e,pri} = N_\gamma Y_1 N_p \ (m^{-1})$

- Secondary electron

Synchrotron radiation

- Number of photon per meter, proton

$$N_\gamma = \frac{5\alpha}{2\sqrt{3}} \frac{\gamma}{\rho_{Bend}}$$ ρ_{bend}=11.3km(TLEP), 6km(CEPC)

- Critical energy

$$E_c = \frac{3\hbar c}{2} \frac{\gamma^3}{\rho_{Bend}}$$

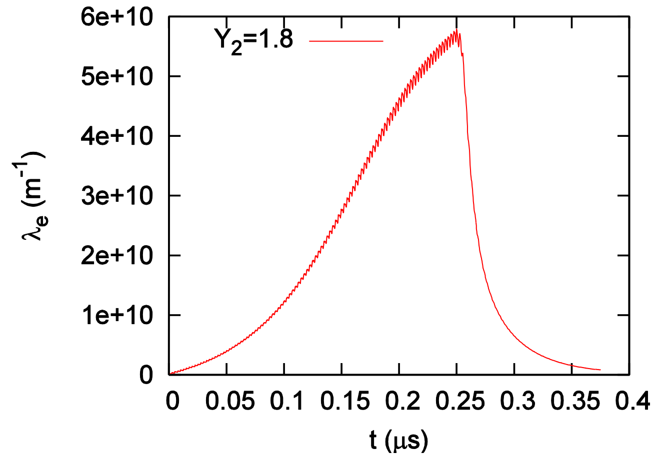
- Quantum efficiency of electron production, Y_1=0.1-0.2
- Electron production by a bunch per m passage.

  $n_{e,pri} = N_\gamma \, Y \, N_p \, (m^{-1})$

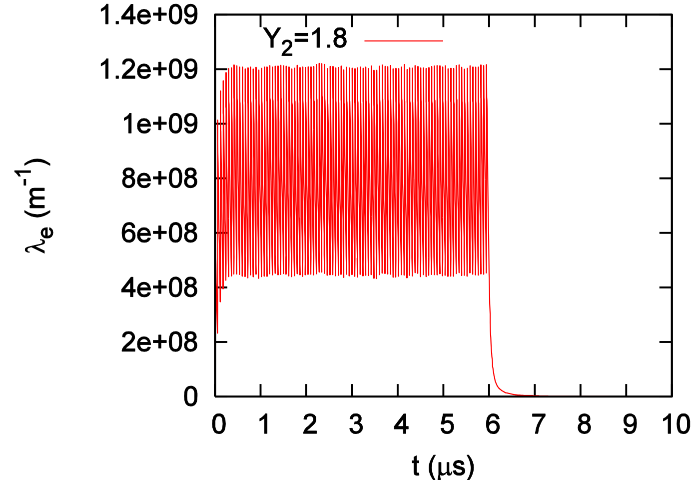
- Chamber cross section 0.005 m^{-2} (tentative)
- Electron density exceeds $\rho_{e,th}=7.8\times10^9\ m^{-3}$ even in a bunch passage.
- Antechamber and other cures are necessary.

Simulation of electron cloud build up in TLEP

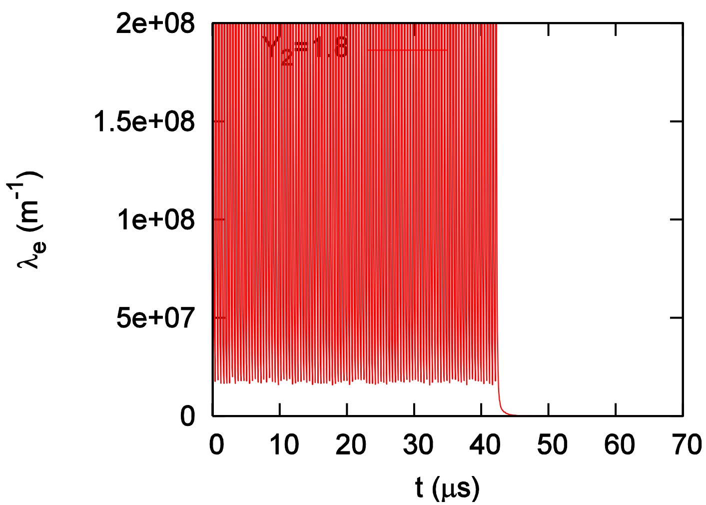
TLEP-Z



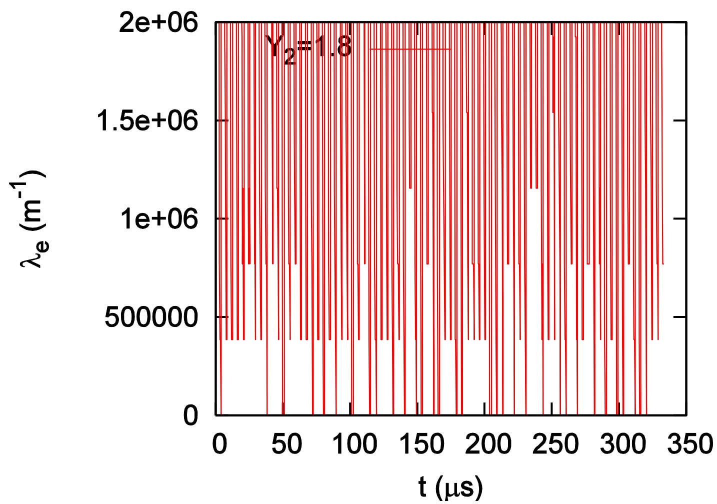
TLEP-W



TLEP-H

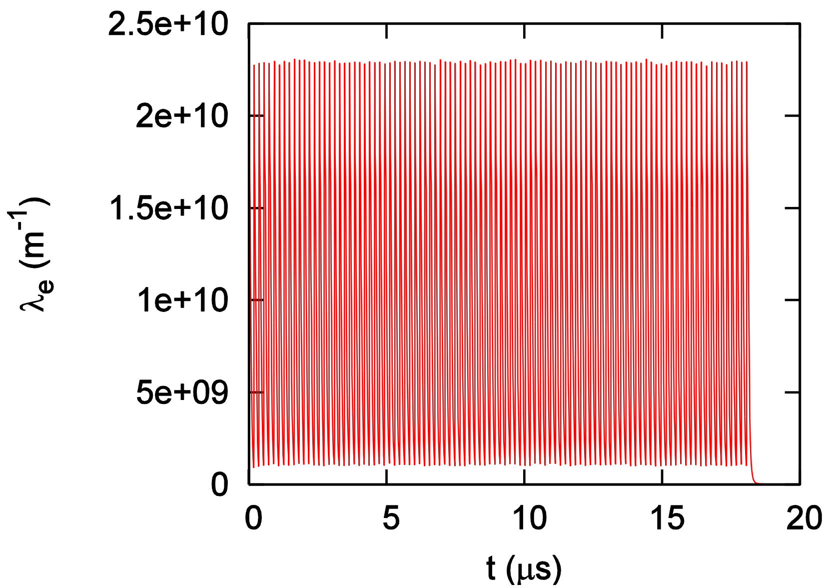


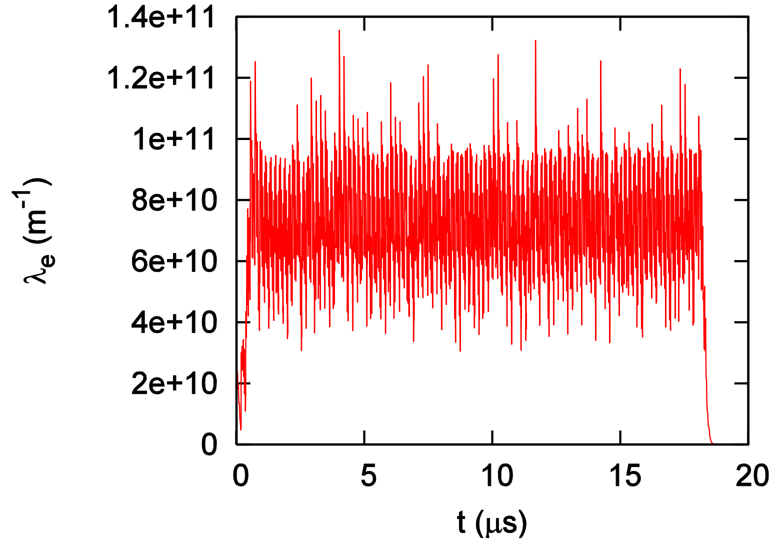
TLEP-t



CEPC electron cloud build-up for partial double ring scheme

- Bunches are injected in 3000m area in circum. 50km. Bunch spacing is about 50m for 50 bunches.
- Electron cloud density for δ_{2max}=1.8 and 2.2.





ρ_e can be threshold 1×10^{12} m^{-3}.

Electron cloud effects in FCC-ee

- TLEP-Z
- N_b=90300, $L_{b\text{-}b}$=1.1m
- $N_p=3.3\text{x}10^{10}$, $\langle\beta\rangle$=100m, σ_x=95μm, σ_y=10μm

$$\omega_e = \sqrt{\frac{\lambda_p r_e c^2}{\sigma_y(\sigma_x + \sigma_y)}}$$

- $\omega_e = 2\pi\text{x}127$GHz, $\omega_e\sigma_x/c=13$

$$\rho_{e,th} = \frac{2\gamma\nu_s\omega_e\sigma_z/c}{\sqrt{3}KQr_0\beta L}$$

$$K = \omega_e\sigma_z/c$$
$$Q = \min(\omega_e\sigma_z/c, 7)$$

- $\rho_{e,th}=7.8\text{x}10^9$ m^{-3}. Threshold is very weak density.
- KEKB $5\text{x}10^{11}$, SuperKEKB $1\text{x}10^{11}$

Parameters related to EC instabilitiy

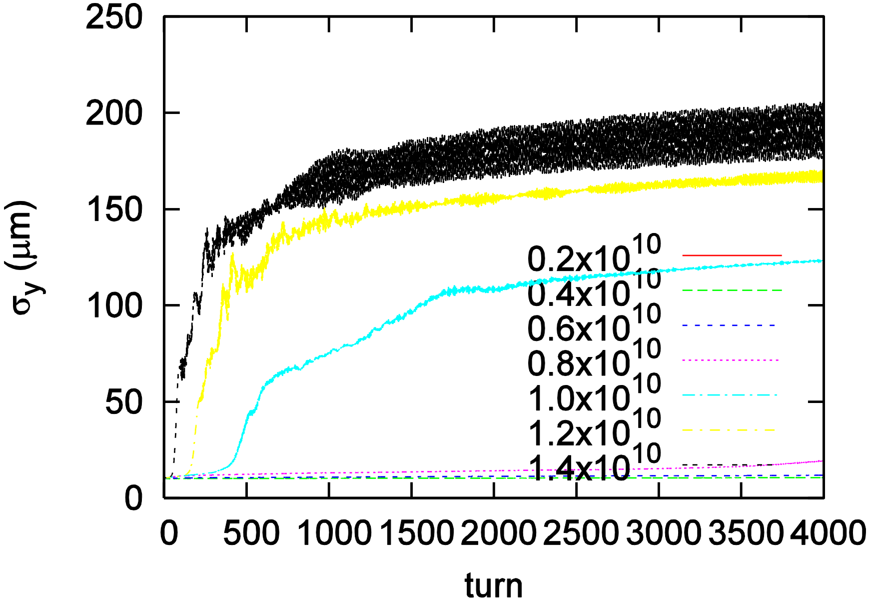
		CEPC	TLEP-Z	TLEP-W	TLEP-H	TLEP-t
Circumf	C (km)	54	100	100	100	100
Energy	E (GeV)	120	45.5	80	120	175
No. bunches	N_b	49	90300	5162	770	78
Bunch pop	N_p (10^{11})	3.8	0.33	0.6	0.8	1.7
Beam l-density	λ ($10^{10}m^{-1}$)	0.74	3.0	0.3	0.06	0.0013
Beam size (av.)	σ_x/σ_y (μm)	583/32	95/10	164/10	247/11	360/16
Bunch length	$\sigma_{z,tot}$(mm)	2.6	5.0	3.0	2.4	2.5
Synch. tune	ν_s	0.18	0.015	0.037	0.056	0.075
γ prod. rate	N_γ (/m/e^+)	0.28	0.059	0.10	0.16	0.23
e^- prod. rate	$n_{e,prod}$ ($10^{10}m^{-1}$)	1.1	0.020	0.062	0.12	0.39
Electron freq.	$\omega_e/2\pi$ (GHz)	137	127	171	174	171
Electron osci.	$\omega_e\sigma_{z,tot}/c$	7.5	13	11	8.7	9.0
Thr. density	$\rho_{e,th}$ ($10^{10}m^{-3}$)	104	0.78	3.4	7.7	15
Tune shift	$\Delta\nu$ at $\rho_{e,th}$	0.034	0.0025	0.0061	0.0092	0.012

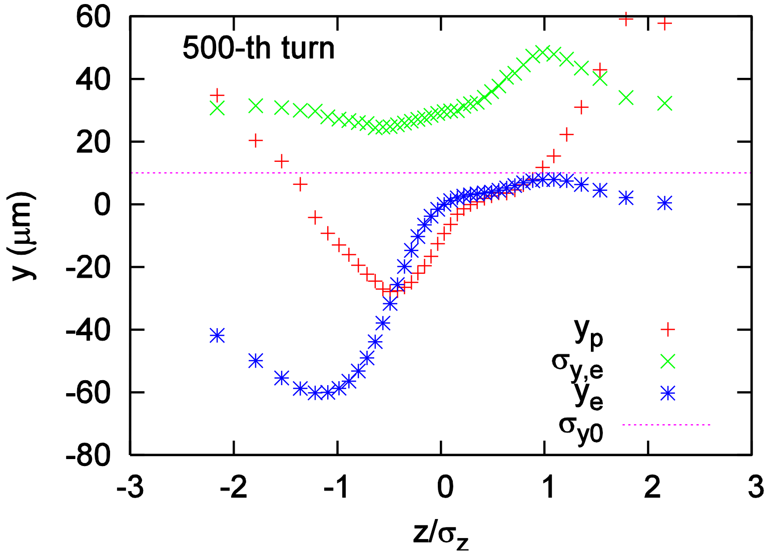
Simulation for TLEP-Z

- Growth of emittance

Coherent motion in

$y_+(z)$, $y_-(z)$, $\sigma_{y+}(z)$





Threshold is $\rho_{e,th}$=0.8x10^{10} m^{-3} , agree with the analytic formula 0.78x10^{10}.

Ion instability in FCC-ee (TLEP-Z)

- N_b=90300, L_{sp}=0.75m(2.5 ns)
- N_e=3.3x10^{10},<β>=50m, σ_x=67μm, σ_y=7μm
- Dispersion increases σ_x , assume $2^{1/2}$ times controlled by ε_x in simulation.
- ε_x =0.09nm, ω_i=2πx103MHz, $\omega_e L_{sp}$/c=1.61<- critical for trap in the bunch train,

  ε_x =0.18nm, ω_i=2πx88MHz, $\omega_e L_{sp}$/c=1.38

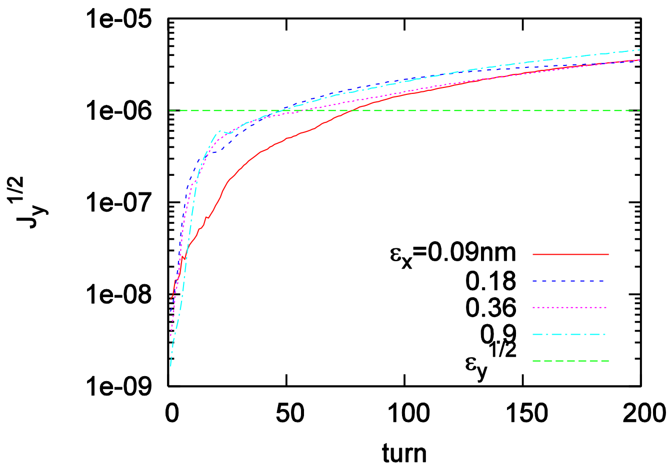
- Ion production rate for CO, n_i =0.045 Ne P(Pa),

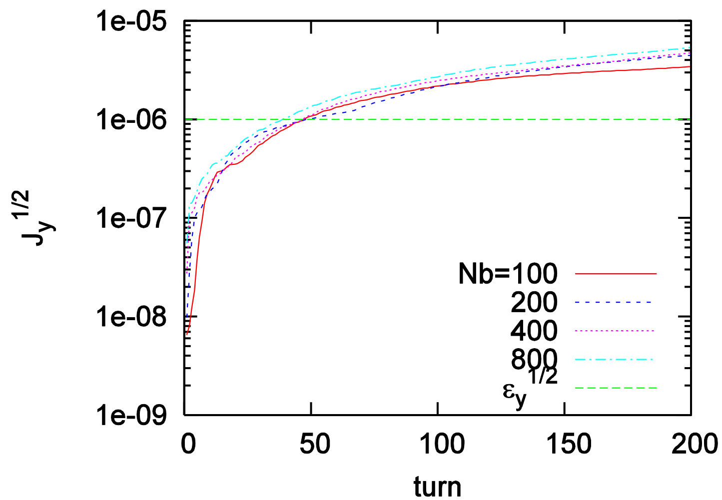
  n_i (10^{-8} Pa)= 14.9 (/(m.e^-)).

Simulation results for P=10^{-8} Pa

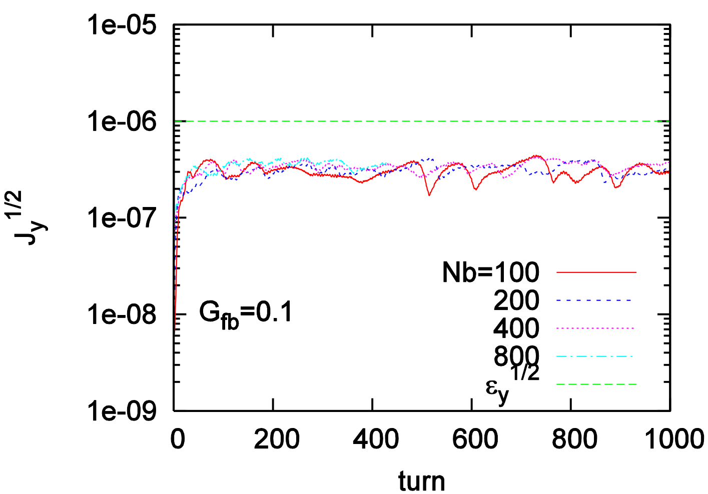
Ions are trapped partially for ε_x=0.09nm

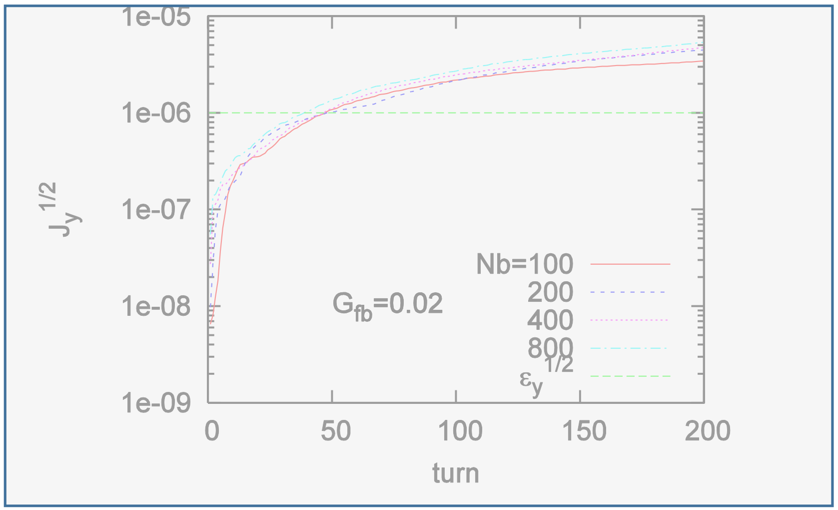
Growth does not depend on train length.





Bunch-by-bunch Feedback G=0.1(10 turn) is necessary.

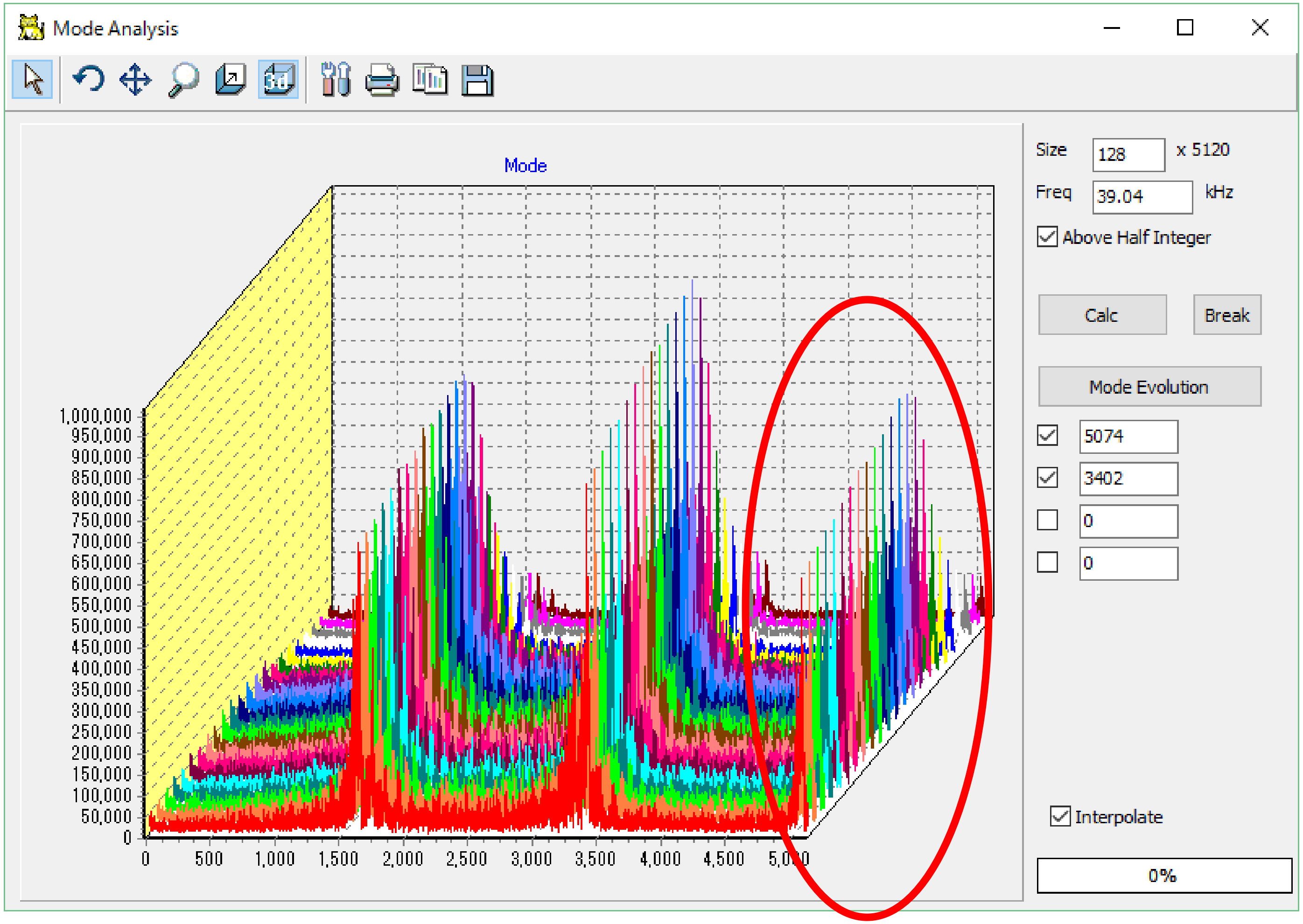




Coupled bunch instability observed in SuperKEKB

- SuperKEKB started from Feb. 2016. (no collsion)
- I(e+)=260mA, I(e-)=200mA in early April.
- e+ beam is unstable only in the early stage (Mar16), but is stable in Apr. Antechamber works well.
- Ion instability is observed in e- beam. The growth becomes weak gradually.

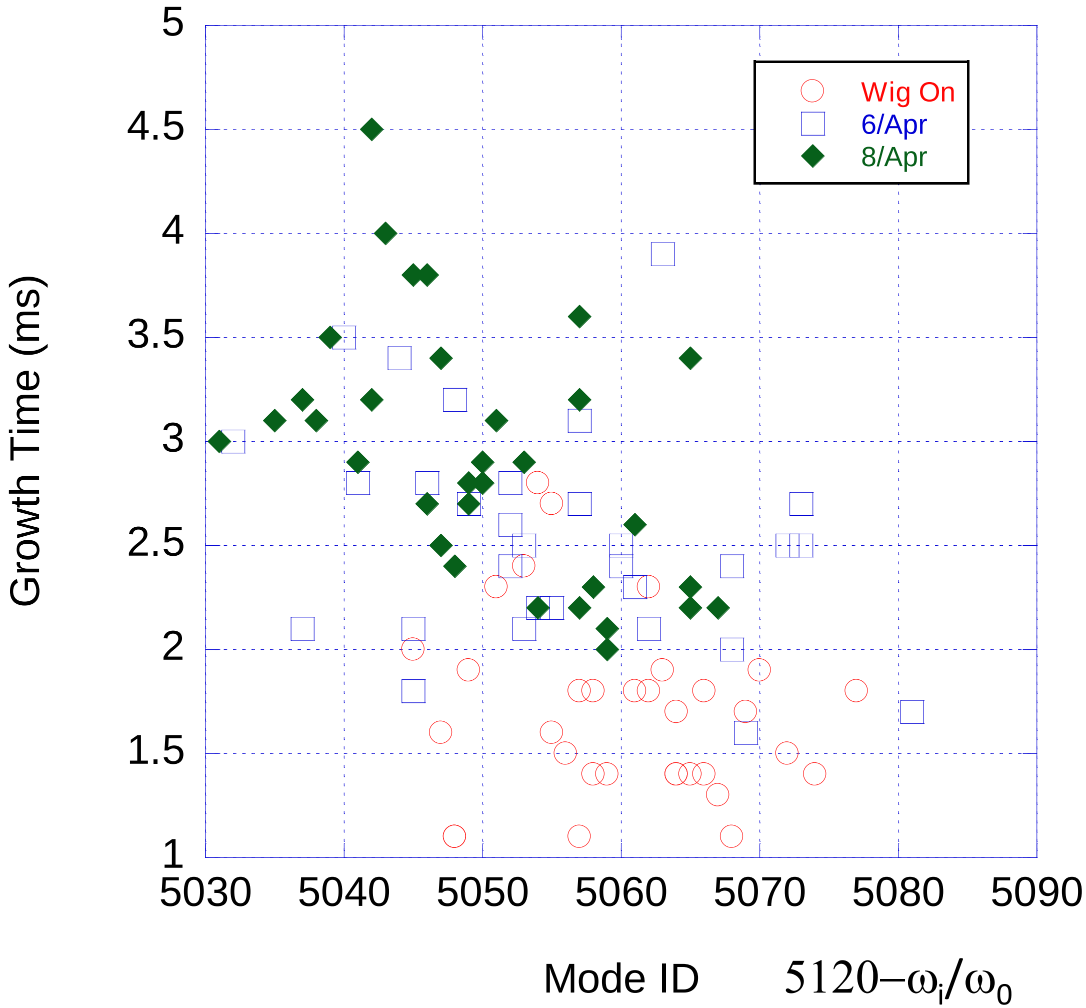
Mode analysis (Tobiyama)



Correspond to $5120-\omega_i/\omega_0$

Vertical beam size seems several times higher than the design at present.

Growth and mode change slightly day-by-day



- ω_i/ω_0=140 for the design beam size
- ω_i/ω_0=70-80 at present.
- ω_i~$(\sigma_x\sigma_y)^{1/2}$. σ_y is 4 times of design.

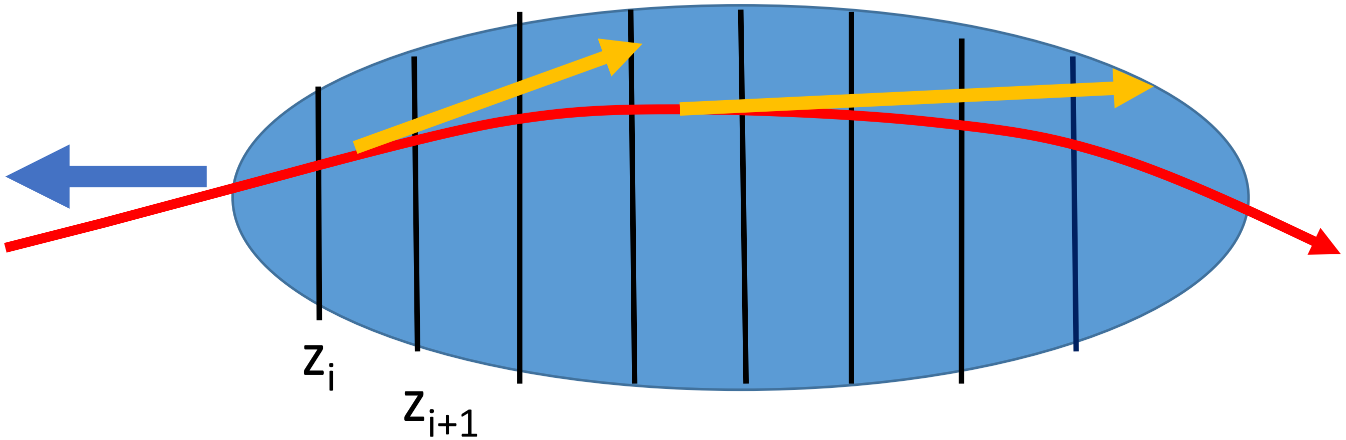
Summary

- Beam-beam effects and luminosity expectation have been studied for FCC-ee’s, CEPC and TLEP.
- Beamstrahlung and lifetime issue are evaluated.
- Design tools for beam-beam study are ready.
- Design parameters are achieved in weak-strong simulation, but are not in strong-strong simulations, because beam-beam coherent instability in <xz> is seen in H and Z.
- Electron cloud and ion instabilities in TLEP-Z are challenging issues.
- Threshold of electron density was given for FCCee’s.
- Required vacuum pressure and feedback power were given preliminary.

Thank you for your attention

Schematic view of the simulation

- Calculate trajectory interacting with colliding beam.
- Particles emit synchrotron radiation due to the momentum kick dp/ds.



$$ds = \frac{z_i - z_{i+1}}{2}$$

$$\langle \delta \rangle = dn_\gamma \langle u \rangle = \frac{2 r_e \gamma^3}{3 \rho^2} ds$$

$$\frac{1}{\rho_{x,y}} = \frac{dp_{x,y}}{ds}$$

$$\langle \delta^2 \rangle = dn_\gamma \langle u^2 \rangle = \frac{55}{24\sqrt{3}} \frac{r_e \hbar \gamma^5}{mc\rho^3} ds$$