Study of Coherent instabilities due to electron cloud at CesrTA and KEKB

K. Ohmi, J. Flanagan

Coherent instabilities due to electron cloud

Single bunch instability

- Threshold is determined by balance with Landau damping due slippage (momentum compaction) factor.
- Dependent on emittance
- Depend only on local electron cloud density

Coupled bunch instability

- Threshold is determined by balance with other damping effects.
- Independent on emittance.
- Independent on momentum compaction.
- Depend on electron cloud density, distribution and motion.

Threshold of the strong head-tail instability (Balance of growth and Landau damping)

- Stability condition for $\omega_e\sigma_z/c>1$

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

$$U=\frac{\sqrt{3}\lambda_p r_0\beta}{\nu_s\ \ \gamma\ \ \omega_e\sigma_z/c}\frac{\left|Z_\perp(\omega_e)\right|}{Z_0}=\frac{\sqrt{3}\lambda_p r_0\beta}{\nu_s\ \ \gamma\ \ \omega_e\sigma_z/c}\frac{KQ}{4\pi}\frac{\lambda_e}{\lambda_p}\frac{L}{\sigma_y(\sigma_x+\sigma_y)}=1$$

- Since $\rho_e=\lambda_e/2\pi\sigma_x\sigma_y$,

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

Origin of Landau damping is momentum compaction

$$\nu_s\sigma_z=\alpha\sigma_\delta L$$

- Q=min(Q_{nl}, $\omega_e\sigma_z/c$)
  Q_{nl}=5-10?, depending on the nonlinear interaction.
- K characterizes cloud size effect and pinching.
- $\omega_e\sigma_z/c$~12-15 for damping rings.
- We use K=$\omega_e\sigma_z/c$ and Q_{nl}=7 for analytical estimation.

Threshold for various rings

	KEKB	KEKB	KEKB-DRt	CESR chess	CesrTA	ILC-OCS	PEPII
L	3016	3016	3016	768.44	768.44	6695	2200
gamma	6849	6849	4501	10372	3914	9785	6067
Np	3.30E+10	7.60E+10	2.00E+10	1.12E+11	2.00E+10	2.00E+10	8.00E+10
ex	1.80E-08	1.80E-08	1.50E-09	1.11E-07	2.30E-09	5.60E-10	4.80E-08
bx	10	10	10	10	10	30	10
ey	2.16E-10	2.16E-10	6.00E-12	1.11E-09	1.50E-12	2.00E-12	1.50E-09
by	10	10	10	10	10	30	10
sigx	4.24E-04	4.24E-04	1.22E-04	1.05E-03	1.52E-04	1.30E-04	6.93E-04
sigy	4.65E-05	4.65E-05	7.75E-06	1.05E-04	3.87E-06	7.75E-06	1.22E-04
sigz	0.006	0.007	0.009	0.0173	0.009	0.006	0.012
nus	0.024	0.024	0.011	0.0487	0.098	0.067	0.025
Q	3.6	5.9	7	4.7	7	7	3.7
omegae	1.79E+11	2.51E+11	5.29E+11	8.20E+10	6.84E+11	6.31E+11	9.20E+10
phasee	3.6	5.9	15.9	4.7	20.5	12.6	3.7
K	3.6	5.9	12.5	4.7	20.5	12.6	3.7
rhoeth	6.25E+11	3.81E+11	1.22E+11	5.73E+12	2.92E+12	1.91E+11	7.67E+11

Tune shift

- Single bunch instability depends on local electron cloud density near the beam.
- Incoherent tune shift can be an indicator of the single instability.

- Tune shift should linearly increase for every bunch passage, because a certain numbers of photoelectrons are supplied by every bunch.
- Tune shift saturates after several 10 bunches passage, because of space charge limit or dynamic balance of creation and absorption of electrons.

Tune shift at CESR

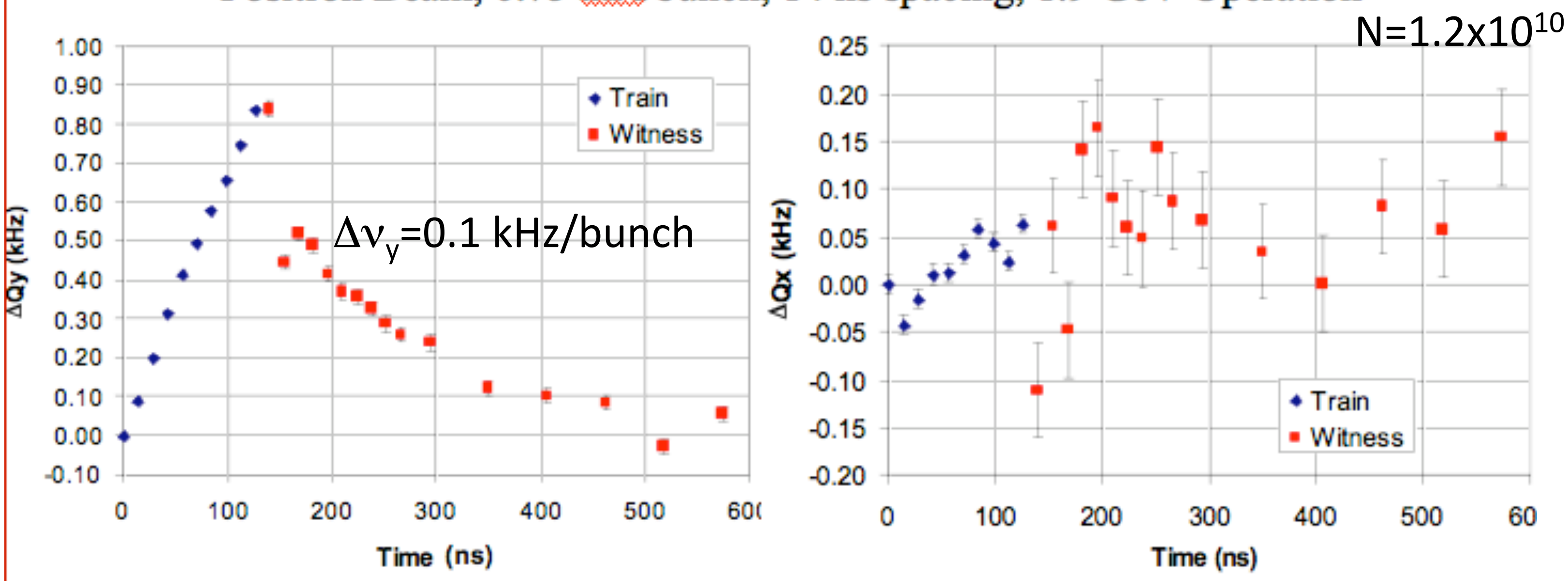
$$\Delta\nu_x + \Delta\nu_y = \frac{r_e}{\gamma}\oint \rho_e \beta ds$$

Cornell University
Laboratory for Elementary-Particle Physics

Witness Bunch Studies – e^+ Vertical Tune Shift

- Initial train of 10 bunches ⇨ generate EC
- Measure tune shift and beamsize for witness bunches at various spacings
- Bunch-by-bunch, turn-by-turn beam position monitor

Positron Beam, 0.75 mA/bunch, 14 ns spacing, 1.9 GeV Operation



Error bars represent scatter observed during a sequence of measurements

1 kHz ⇨ $\Delta\nu$=0.0026
$\rho_e \sim 1.5 \times 10^{11}\ m^{-3}$
Ohmi, etal, APAC01, p.445

β=30m

Preliminary

Tune shift at KEKB

(T. Ieiri, Proceedings of Ecloud07)

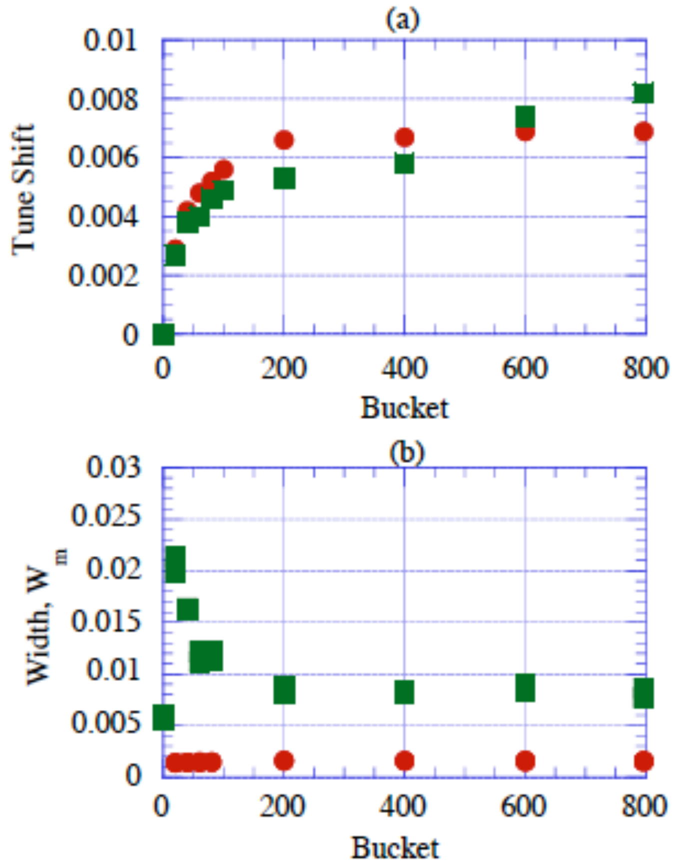


Figure 4: Tune shift (a) and spectrum width (b) along a train. The red dots (horizontal) and green squares (vertical) are measured at a bunch current of 0.5 mA. The tune of the head bunch of the train is used as the reference.

Without solenoid

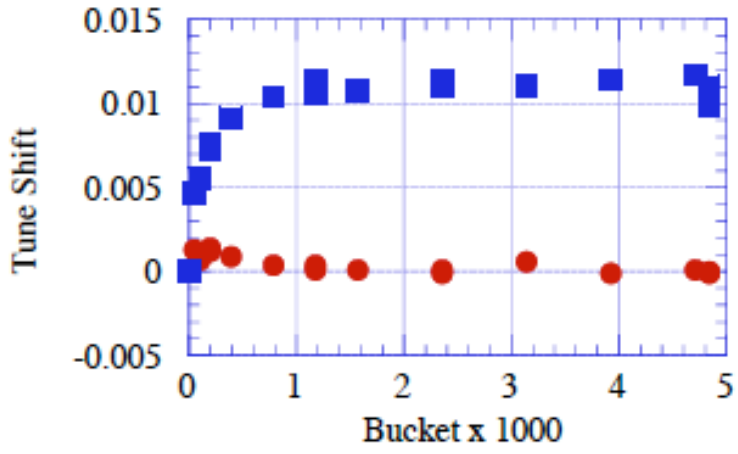


Figure 11: Horizontal (red dots) and vertical (blue squares) tune-shifts along the bunch-train. The bunch current is 1.0 mA with an average spacing of 7 ns.

With solenoid

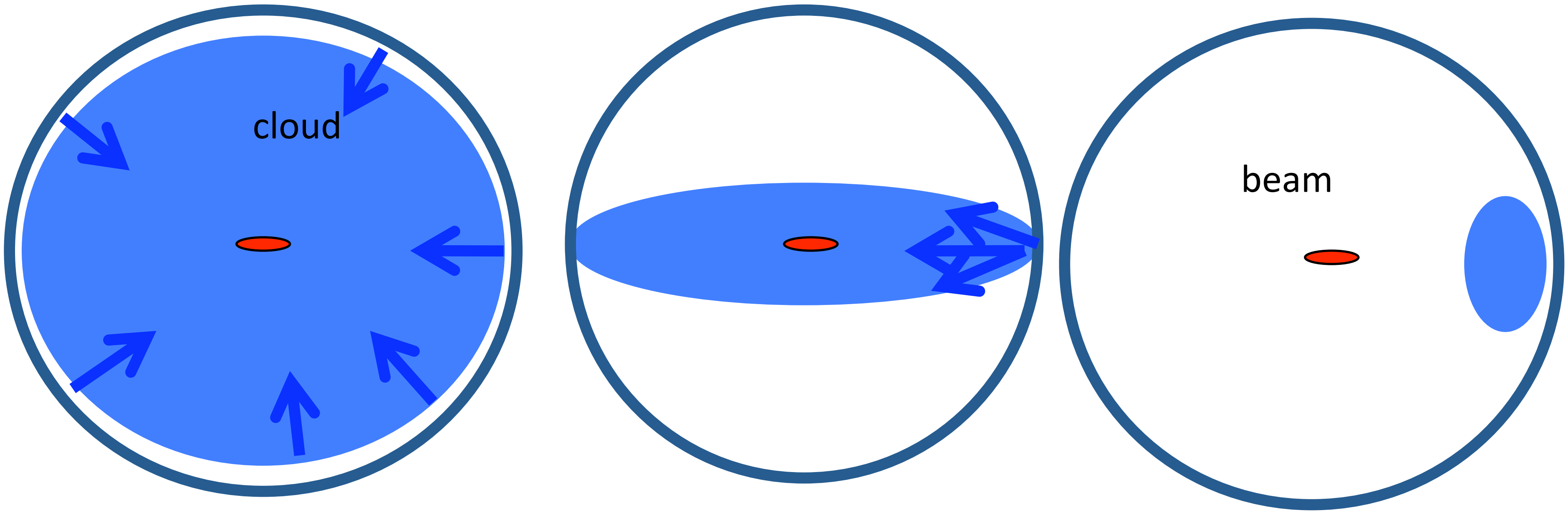
- Both showed similar density because of $\nu_x+\nu_y$=0.015 and 0.012.
- Round cloud for no solenoid and flat cloud for solenoid. How do we think?

Typical cloud distribution and tune shift

- Tune shift is determined by the electron distribution.
- Electron distribution depends on the initial condition and magnetic filed

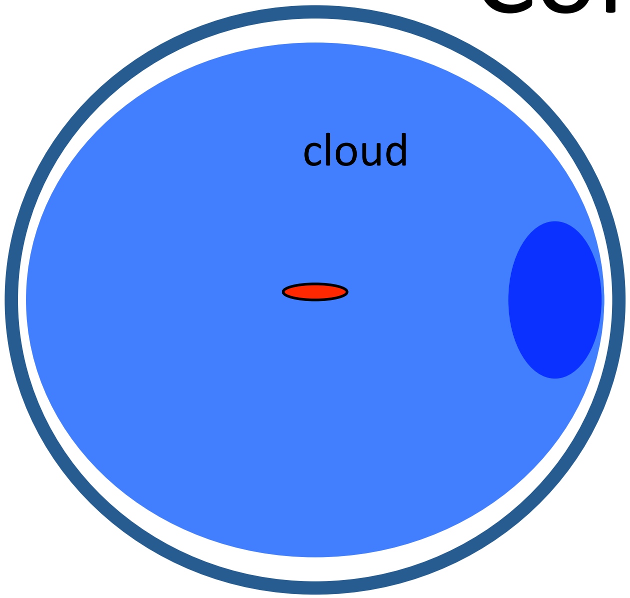
$$\mathrm{div}\mathbf{E} = \frac{\rho_e}{\varepsilon_0} \longrightarrow \Delta\nu_x + \Delta\nu_y = \frac{r_e}{\gamma}\oint \rho_e \beta ds$$

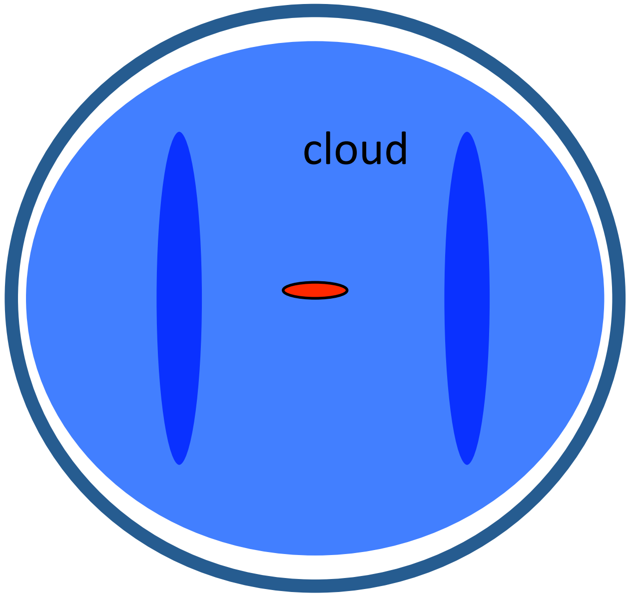
Straight section — Magnetic field section



$\Delta\nu_y \sim \Delta\nu_x$ — $\Delta\nu_y > 0$ $\Delta\nu_x = 0$ — $\Delta\nu_y \sim -\Delta\nu_x > 0$

Combination





- $\Delta\nu_y$ >0 $\Delta\nu_x$~0 can be realized, if $\Delta\nu_x$ is cancelled in two distributions.

Number of produced electrons

Number of photon emitted by a positron par unit bending angle.

$$\frac{dY_{pe}}{d\theta} = \frac{5}{2\sqrt{3}}\alpha\gamma \times 0.1(/\text{rad})$$

Quantum eff.=0.1

- CESR 5GeV γ=10000 → Y_{pe}=0.086/m, Ec=3 keV
- Cesr-TA 2GeV (arc) =4000 → Y_{pe}=0.034/m, Ec=100 eV
- KEKB 3.5 GeV =7000 → Y_{pe}=0.015/m,

- Bunch population
  $N_p=1.2\times10^{10}$ (0.75mA) 3.3×10^{10} (KEKB)
- electrons created by a bunch passage in a meter
  $N_p \times Y_{pe}=1.0\times10^{9}$ (5GeV) 4.0×10^{8} (2GeV) 4.9×10^{8} (KEKB)
- Increase of volume density per bunch ($\Delta\rho$[$m^{-3}bunch^{-1}$])
  2.0×10^{11} (5GeV) 8.1×10^{10}(2GeV) 6.2×10^{10} (KEKB)
- Tune shift per bunch
  0.00045 (5GeV) 0.00045 (2GeV) 0.00077 (KEKB)
- Beam line density $N_p/4.2=2.9\times10^{9}$ (Cesr) 1.4×10^{10} (KEKB)

Tune shift at the space charge limit

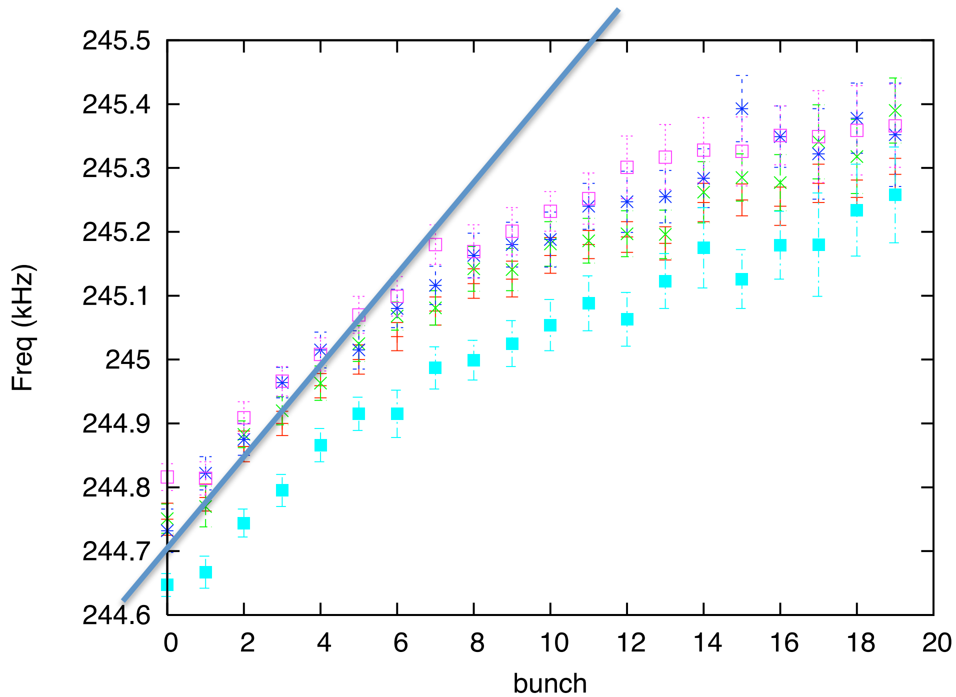
		Cesr 14 ns	Cesr 14 ns	KEKB 8ns
Bunch popu.	Np	1.2e10	2.0e10	3.3e10
Spacing	Lsp (m)	4.2	4.2	2.4
Line density	λp (m^{-1})	2.9e9	4.8e9	1.4e10
Neutralized density	ρ_e(m^{-3})	5.7e11	9.5e11	1.7e12
Tune shift	$\Delta\nu$	0.0032	0.0053	0.021

Tune shift at the threshold

	KEKB	KEKB	KEKB-DRt	Cesr chess	CesrTA	ILC-OCS	PEPII
L	3016	3016	3016	768.44	768.44	6695	2200
gamma	6849	6849	4501	10372	3914	9785	6067
Np	3.30E+10	7.60E+10	2.00E+10	1.12E+11	2.00E+10	2.00E+10	8.00E+10
ρ_{eth}	6.25E+11	3.81E+11	1.22E+11	5.73E+12	2.92E+12	1.91E+11	7.67E+11
$\Delta\nu_x+_y$@th	0.0078	0.0047	0.0023	0.0120	0.0162	0.0111	0.0078
DampT-xy	40	40	75	22	56.4	26	40
DampR-xy	2.51E-04	2.51E-04	1.34E-04	1.16E-4	4.54E-05	8.58E-04	1.83E-04

Tune shift at Cesr Chess

- 0.75mAx20bunches, 14ns
- $\Delta\nu_y$=0.0002/bunch(=0.07-0.08kHz/bunch), saturate 10-20 bunches, $\Delta\nu_y$=0.002=0.7kHz.



Threshold of cloud density as a function of bunch population (Cesr Chess)

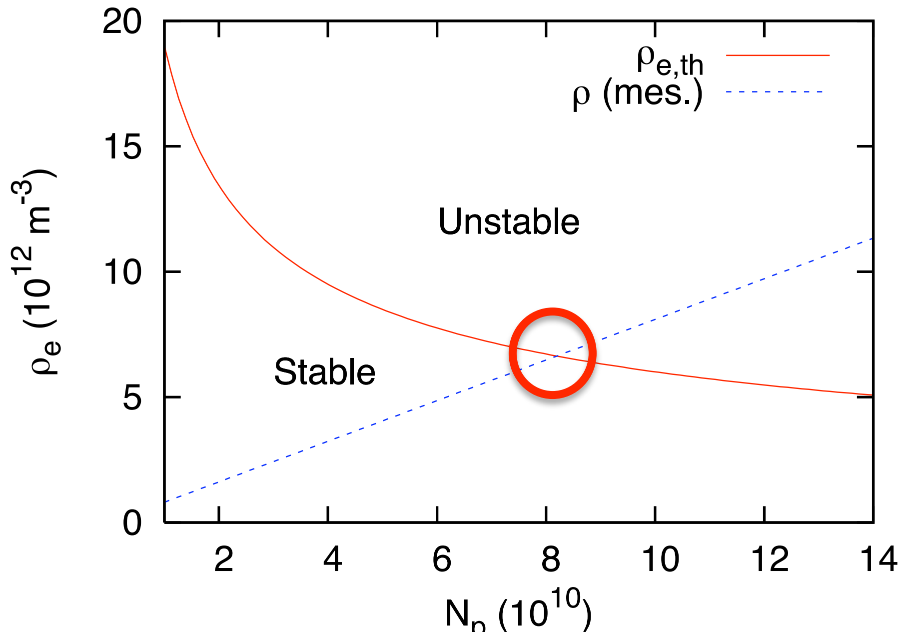
$$\rho_{e,th} = \frac{2\gamma\nu_s\omega_e\sigma_z/c}{\sqrt{3}KQr_0\beta L} = \frac{2\gamma\nu_s}{\sqrt{3}r_0\beta L\omega_e\sigma_z/c} = \frac{2\gamma\nu_s}{\sqrt{3}r_0\beta L}\sqrt{\frac{2\pi\sigma_x\sigma_y}{N_p r_e\sigma_z}}$$

$$\sqrt{N_p}\,\rho_{e,th} = 1.9\times10^{18}\,\mathrm{m}^{-3}$$

$$\rho_e = \frac{\gamma}{r_0\beta L}\left(\Delta\nu_x + \Delta\nu_y\right)$$

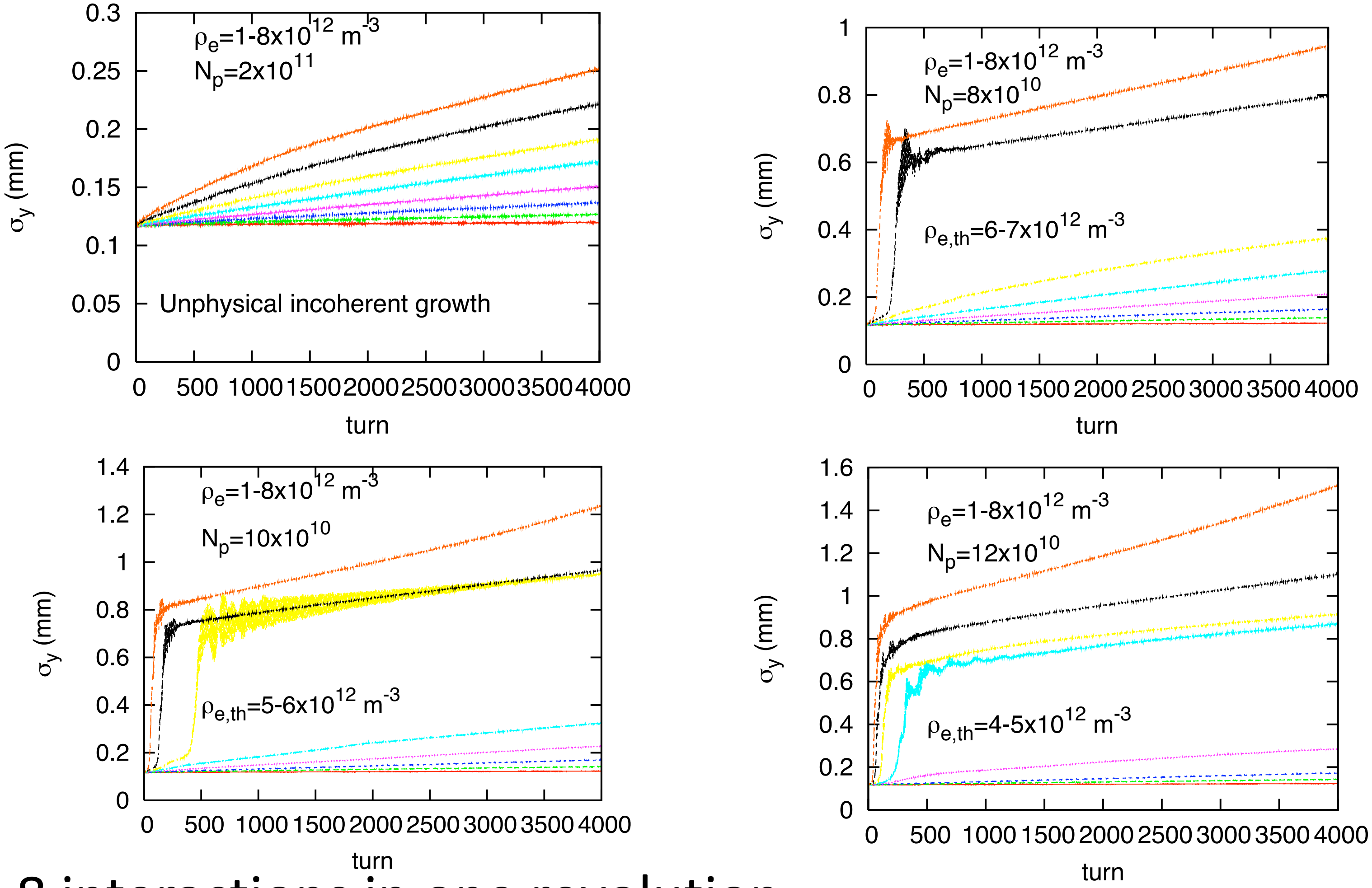
$$\Delta\nu = 0.0027 I_b(\mathrm{mA})$$

$$\rho_e[\mathrm{m}^{-3}] = 81 N_p$$



Fast head-tail instability should be observed at the bunch population more than 8×10^{10}.

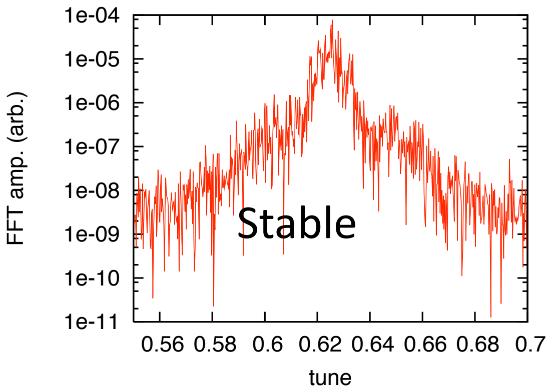
Simulations for instability threshold

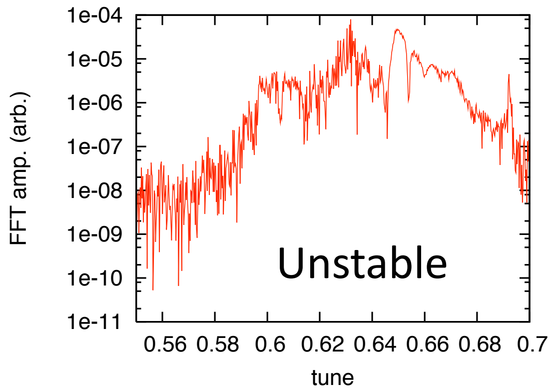


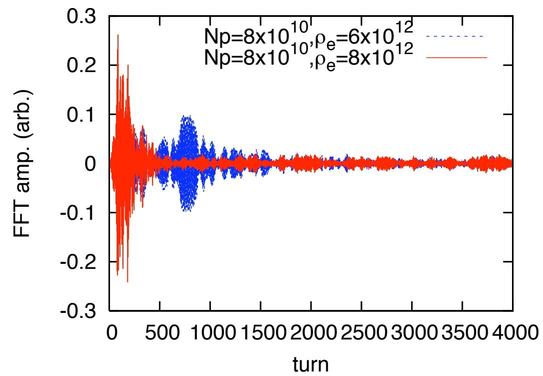
- 8 interactions in one revolution.
- No magnetic field

Unstable mode of the instability

- FFT spectra under and over the threshold
- $\nu_{y0}=0.6$, $\nu_s=0.0486$

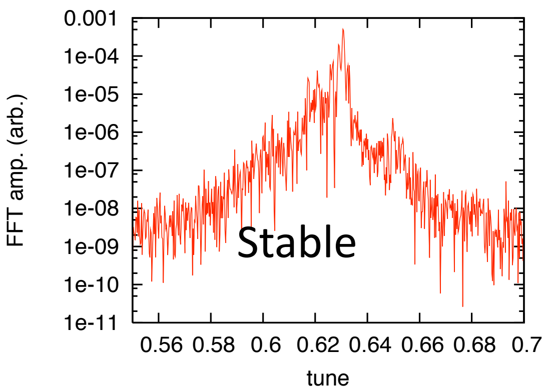


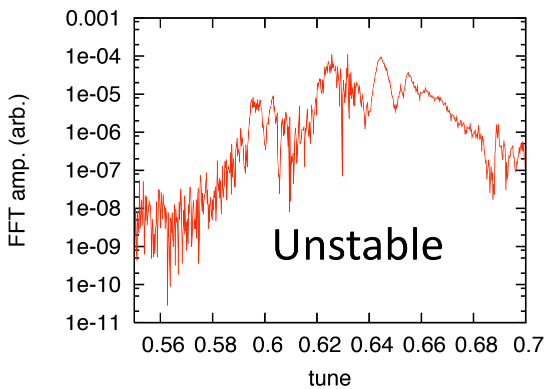




$Np=6\times10^{10}$, $\rho_e=6\times10^{12}$ m^{-3}, $\rho_e=8\times10^{12}$

Maybe signal near $\nu_\beta+\nu_s$ is observed.

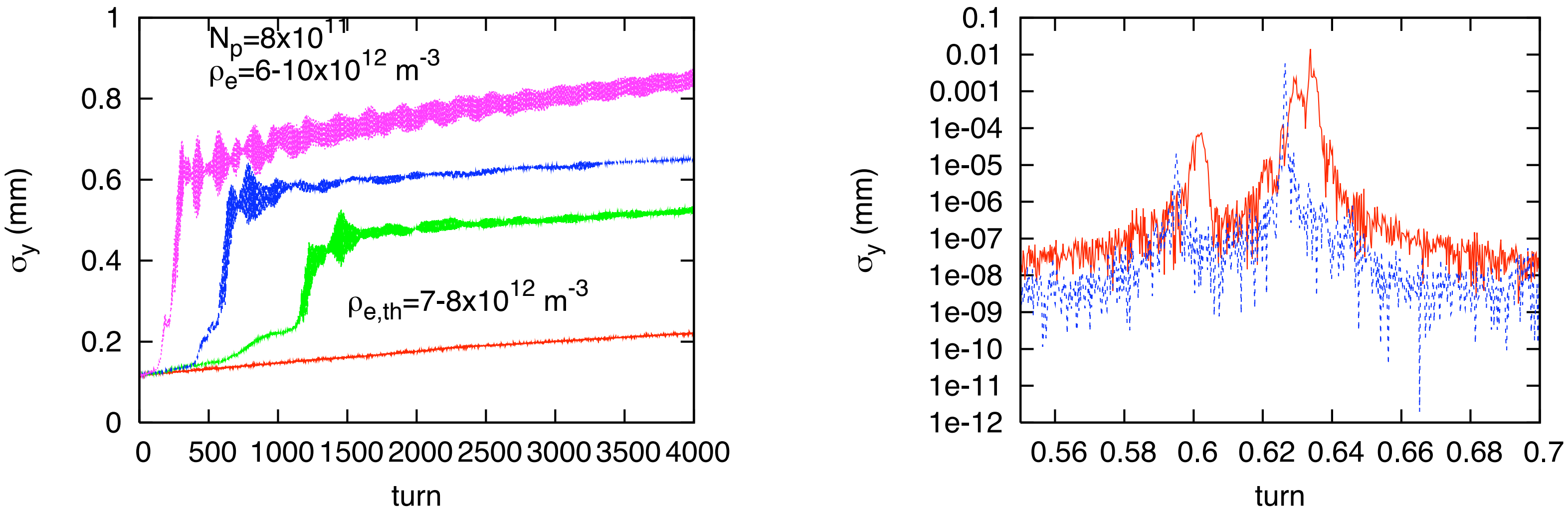




$Np=8\times10^{10}$, $\rho_e=6\times10^{12}$ m^{-3}, $\rho_e=8\times10^{12}$

Simulations in a strong bending field

- When electrons in bending or wiggler magnets are dominant, the threshold somewhat goes higher, because electron pinch is prevented in horizontal.
- Frequency spectrum is somewhat different from that for free electron motion.



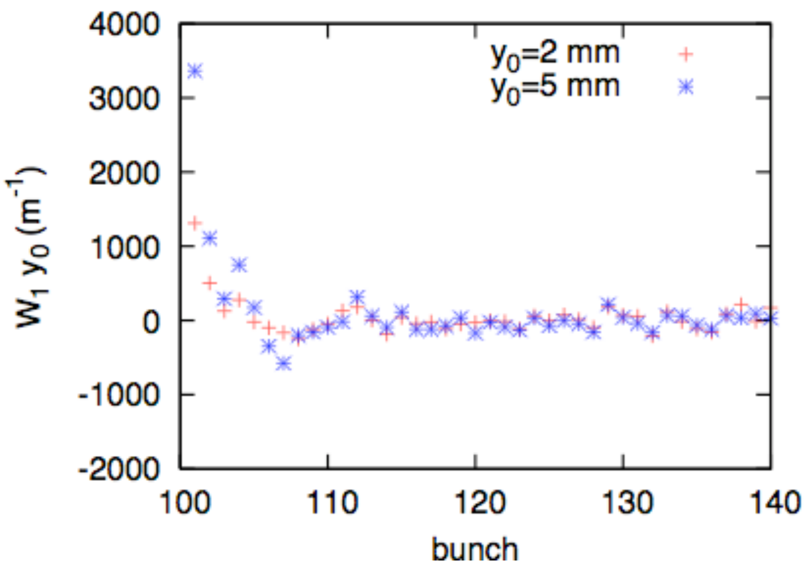
Proposal of experiments II
Coherent instability in CesrTA

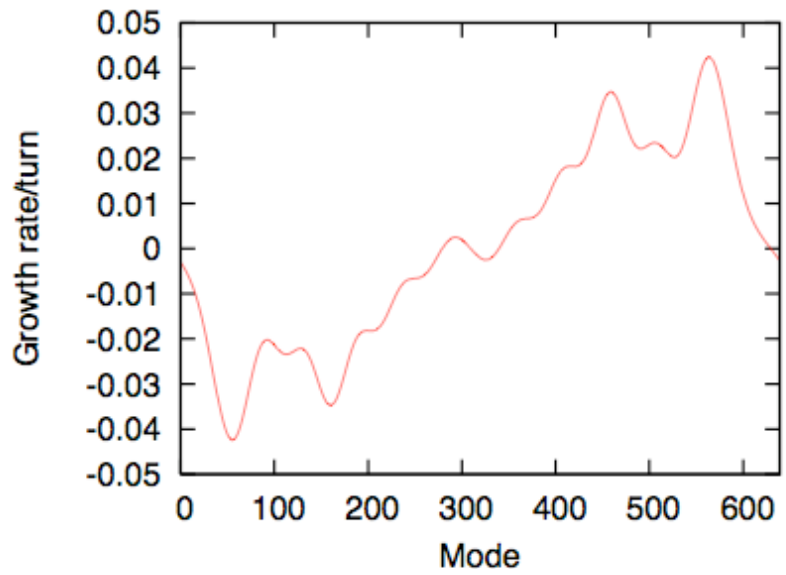
Measurement of the fast head-tail instability

- Cesr Chess optics can be used for the present.
- Higher current and longer bunch train. 7mA/bunch, 10 bunch train, 14ns may be satisfied to the instability condition.
- Coupled bunch instability or coherent dipole motion should be controlled in the measurements.
- Measure the bunch by bunch position and beam size turn by turn. Longer bunch train has an advantage for statistics; more bunches are unstable.

Measurement of electron cloud induced Coupled bunch instability

- Np=1x10^{10}, 4 ns spacing uniformly for example. Number of bunch is 640. It is possible to do 14 ns, 90 bunches.
- Cut off the feed back power and measure the positions of all bunches turn by turn.
- Growth time ~25 turn, 64 μsec for this condition.





This spectrum is given for free electron motion. If bending magnet is dominant, different spectrum is obtained.