Electron cloud effects in positron rings and LHC

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Electron cloud effects in positron rings

- Large yield of photo-emission,
- Flat beam,
- short bunch length

Parameters for e^+ machines

Table 1: Basic parameters of the positron rings

Lattice		KEKB	Cesr-TA	PETRA-III	SuperKEKB	Super B
Circumference	L (m)	3,016	768	2304	3016	1260
Energy	E (GeV)	3.5	2-5	6	4.0	6.7
Bunch population	$N_+(10^{10})$	8	2	0.5	9	5
Beam current	I_+ (A)	1.7	-	0.1	3.6	1.9
Emittance	ε_x(nm)	18	2.3	1	3.2	2
	ε_y(nm)	0.18	0.023	0.01	0.01	0.005
Momentum compaction	$\alpha(10^{-4})$	3.4	68	12.2	3.5	
Bunch length	σ_z(mm)	6	6.8	12	6	5
RMS energy spread	$\sigma_E/E(10^{-3})$	0.73	0.8		0.8	0.64
Synchrotron tune	ν_s	0.025	0.067	0.049	0.0256	0.0126
Damping time	τ_x(ms)	40	56.4	16	43	26

Table 2: Threshold of the B factories positron rings and others

		KEKB (no sol.)	KEKB (50 G sol.)	Cesr-TA	PETRA-III	SuperKEKB	SuperB
Bunch population	$N_+(10^{10})$	3	8	2		8	5
Beam current	I_+ (A)	0.5	1.7	-	0.1	3.6	1.9
Bunch spacing	ℓ_{sp}(ns)	8	7	4-14	8	4	4
Electron frequency	$\omega_e/2\pi$(GHz)	28	40	43	35	150	175
Phase angle	$\omega_e\sigma_z/c$	3.6	5.9	11.0	8.8	18.8	18.3
Threshold	ρ_e (10^{12} m^{-3})	0.63	0.38	1.7	1.2	0.27	0.54

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

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

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

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

- 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} depends on the nonlinear interaction.
- K characterizes cloud size effect and pinching.
- We use $K=\omega_e\sigma_z/c$ and $Q_{nl}=7$ for analytical estimation.

KEKB: measurement and simulation of fast head-tail instability

Beam size blow up observed, and simultaneously synchro-beta sideband observed.

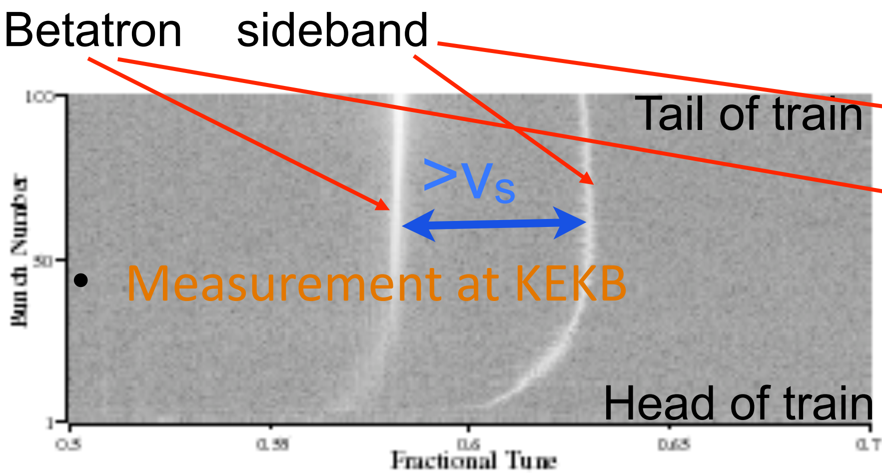
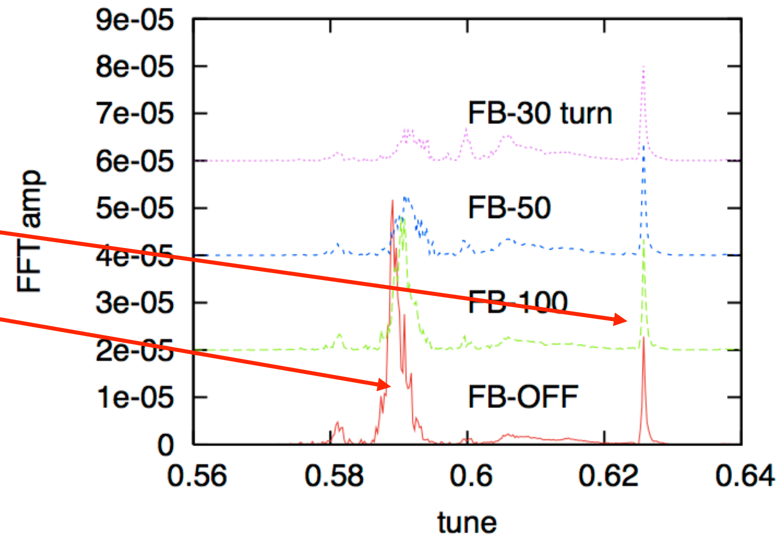
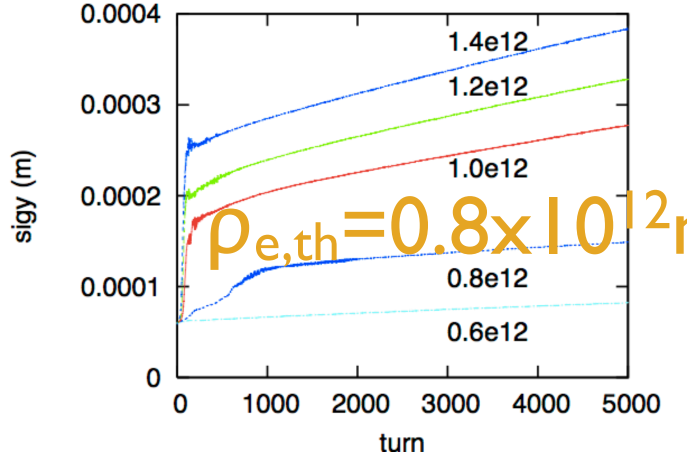


FIG. 1. Two-dimensional plot of vertical bunch spectrum versus bunch number. The horizontal axis is the fractional tune, from 0.5 on the left edge to 0.7 on the right edge. The vertical axis is the bunch number in the train, from 1 on the bottom edge to 100 on the top edge. The bunches in the train are spaced 4-rf buckets (about 8 ns) apart. The bright, curved line on the left is the vertical betatron tune, made visible by reducing the bunch-by-bunch feedback gain by 6 dB from the level usually used for stable operation. The line on the right is the sideband.

Simulation (PEHTS)

HEADTAIL gave similar results (E. Beneditto showed large cloud gave nice sideband signal)





$\rho_{e,th}=0.8\times10^{12}\,m^{-3}$

Bunch by bunch Feedback does not suppress the sideband

Bunch by bunch feedback suppress only betatron amplitude.

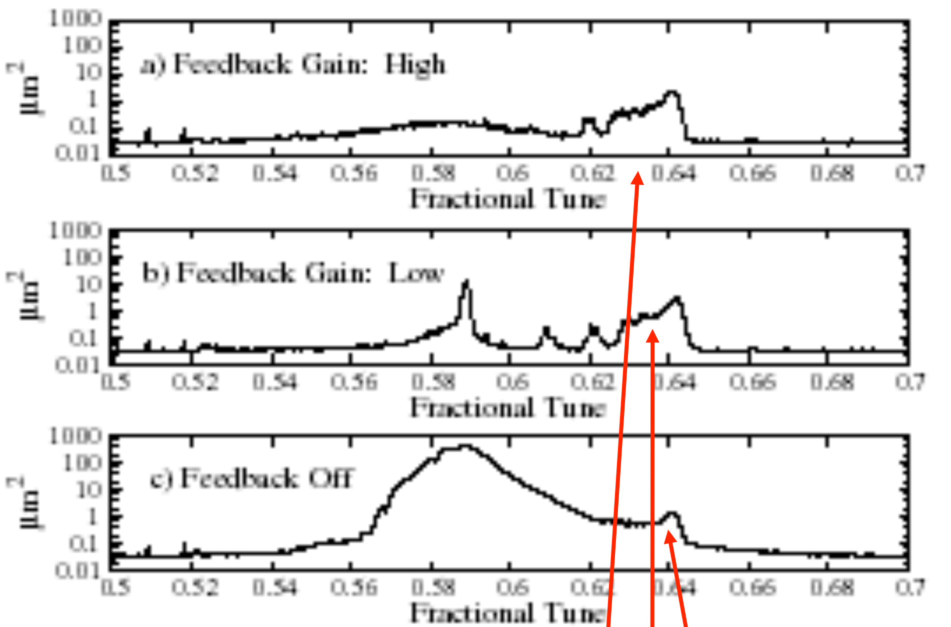
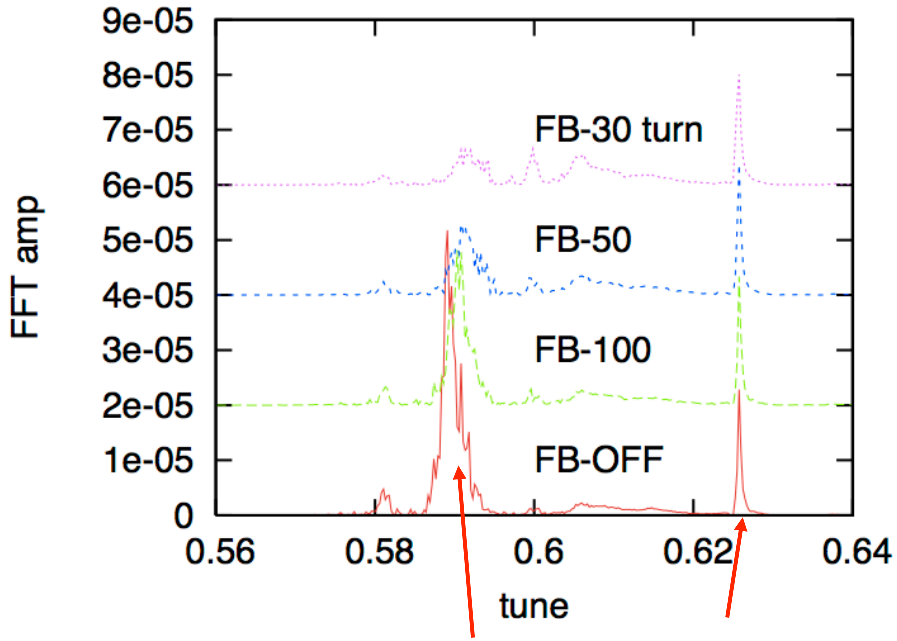


FIG. 2. Averaged spectra of all bunches with the feedback gain (a) high, (b) low, and (c) set to zero. The vertical betatron peak is visible at 0.588, and the sideband peak can be seen around 0.64.

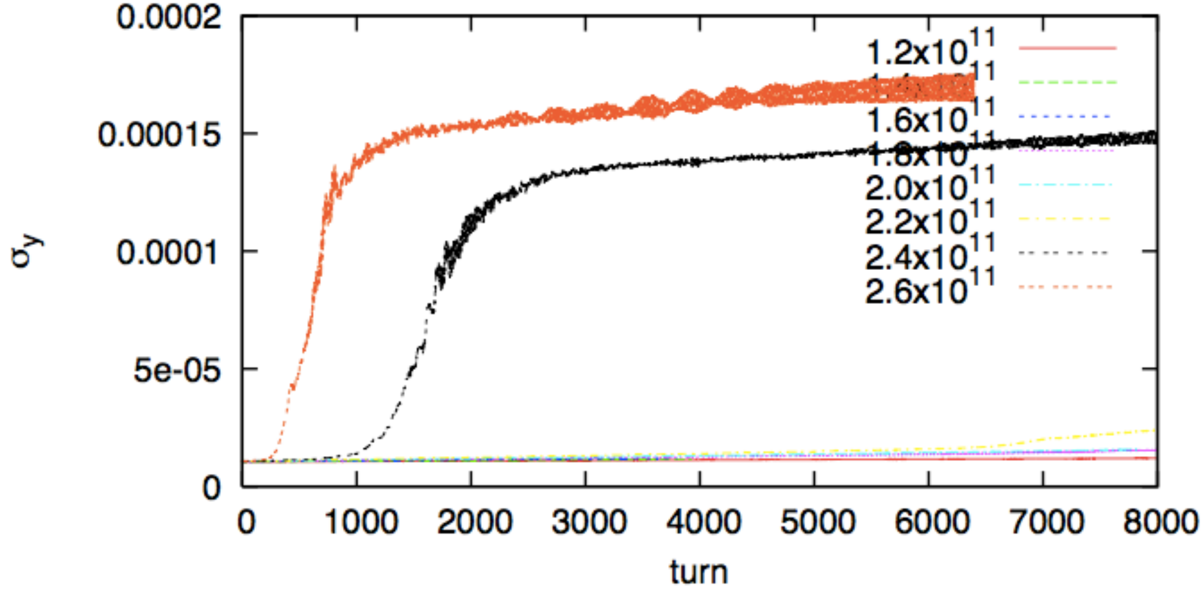


Betatron sideband

Simulation (PEHTS)

Sideband signal is Integrated over the train

SuperKEKB

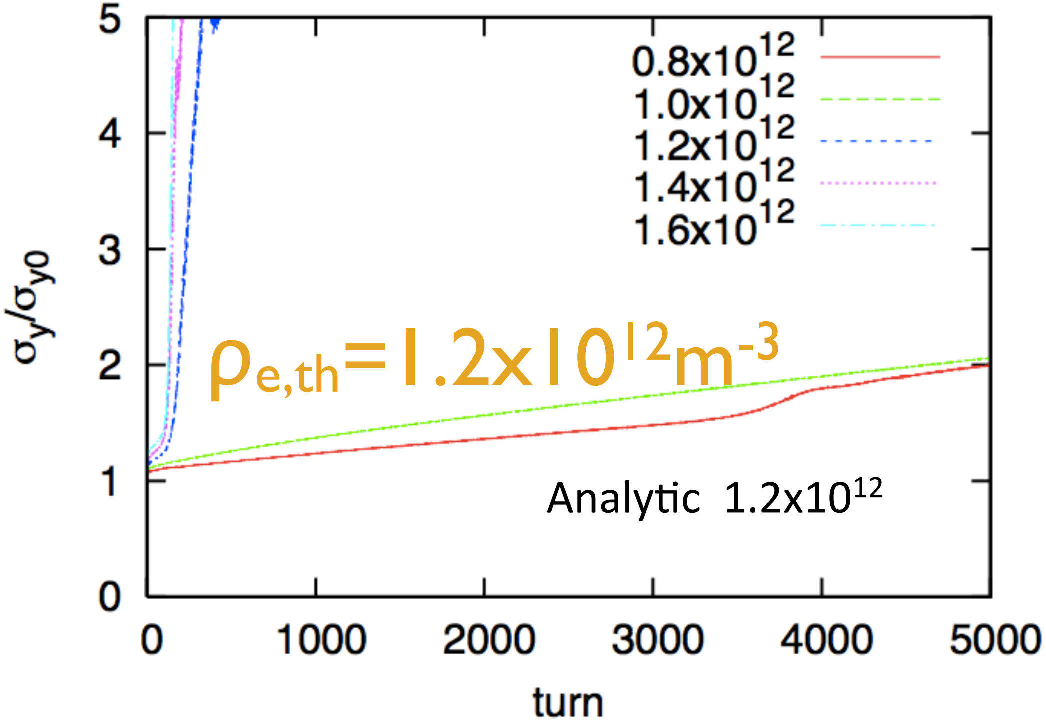


- Simulation ρ_{th}=2.2x10^{11} m^{-3}.
- Analytic ρ_{th}=2.7x10^{11} m^{-3}.
- Take care of high β section. Effects are enhanced.

Vacuum system designed to be ρ_e=1x10^{11} m^{-3}

$$\oint \rho_e \beta_y ds/L = 10^{11} \times 10 \text{ m}^{-2}$$

PETRA-III

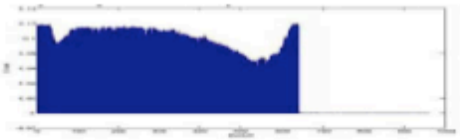


- No ante-chamber.
- The threshold current is very low. $N_{+}=0.5\times10^{10}$/bunch.
- Upper sideband like KEKB has been observed.

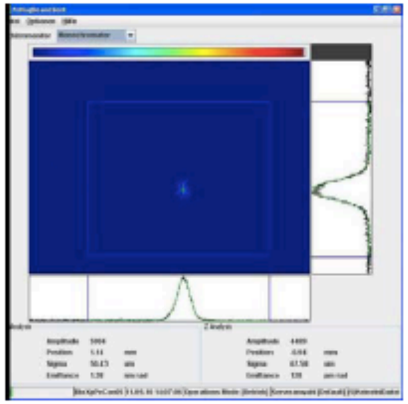
Vertical emittance blow up (640 bunches)

640 bunches, 8 ns bunch spacing + gap
639 x 8 ns = 5112 ns, gap 2568 ns

Bunch current:

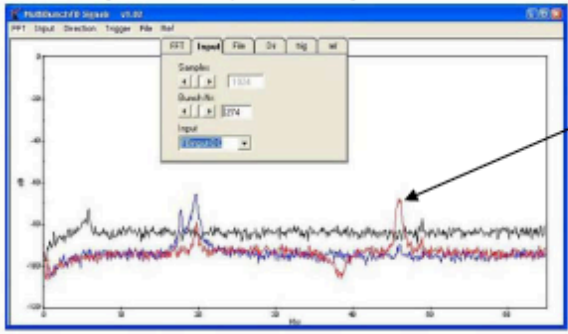


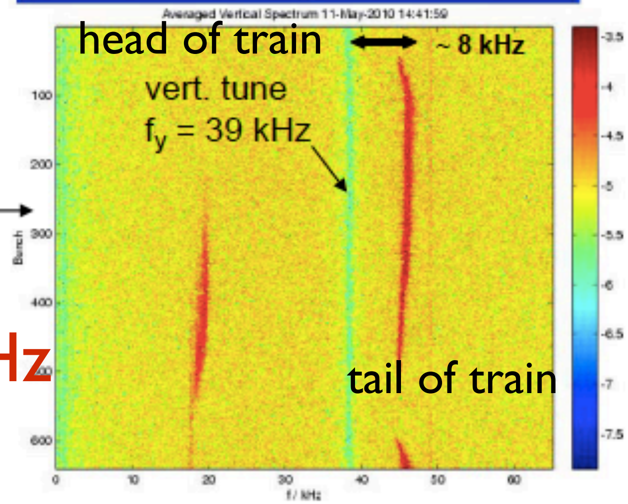
Harmonic number: h = 3840
Revolution time: 7.68 micro sec
Bunch positions: 960 (8 ns bunch spacing)



measured emittance on May 11, 2010
Horz. 1.38 nm, total current 65 mA
Vert. 128 pm

Tune spectrum, bunch position #274



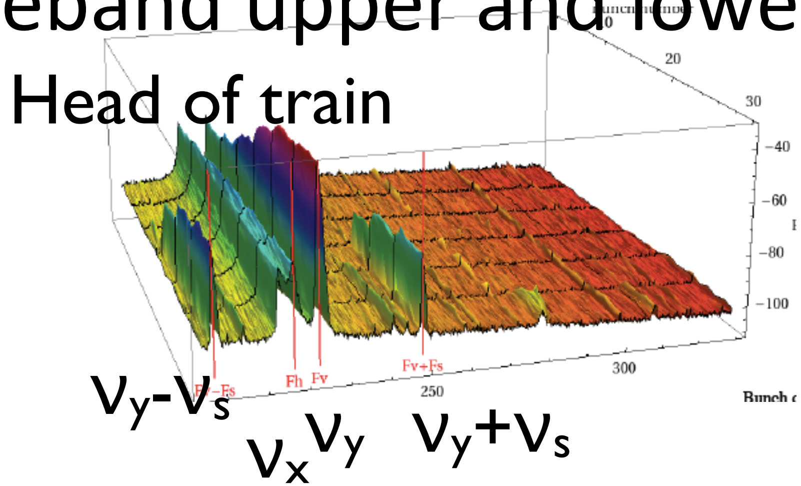


Courtesy of R. Wanzenberg

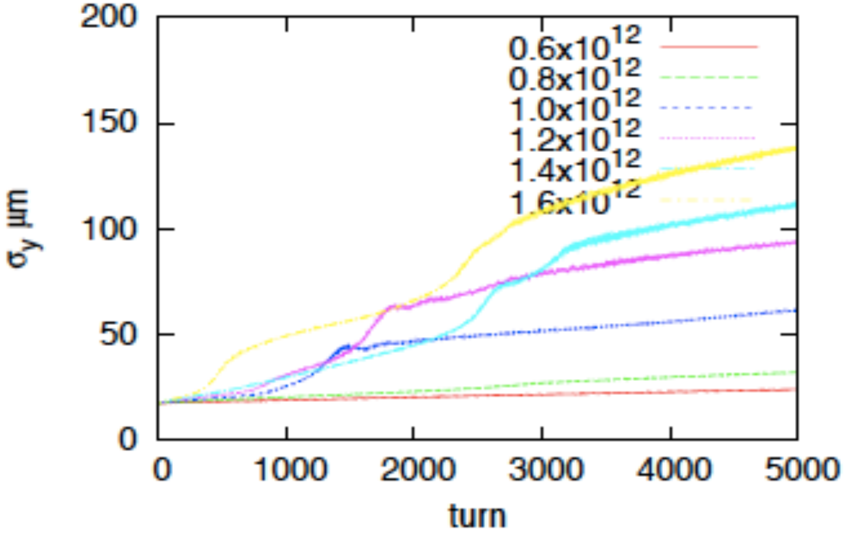
Cesr-TA

- 5 GeV high emittance 40nm, $\omega_e \sigma_z / c = 3.2$
- 2GeV low emittance 2nm, $\omega_e \sigma_z / c = 11$

- Threshold of the instability is $\rho_e = 1 \times 10^{12}$ m^{-3} in CesrTA 2GeV experiment (ECLOUD10, G. Dugan)
- Both sideband upper and lower are seen.

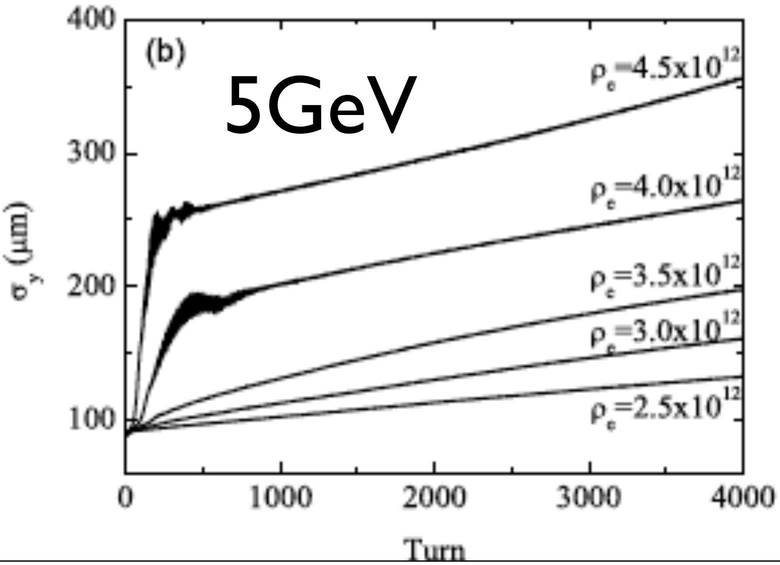


CesrTA 2 and 5 GeV



ρ_{th}=0.8x10^{12} cm^{-3}

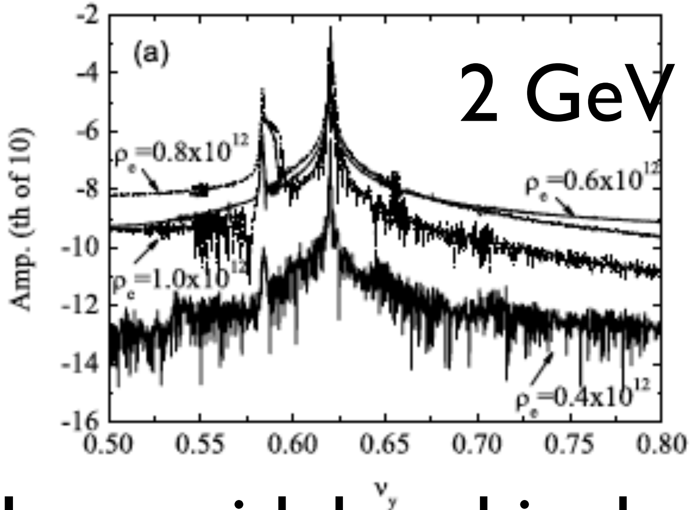
- High(2GeV) and low(5GeV) $\omega_e \sigma_z/c$.



ρ_{th}=4x10^{12} cm^{-3}

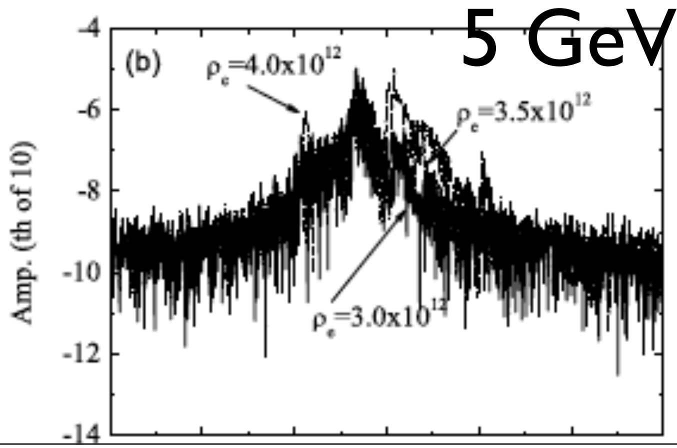
Simulated Unstable spectra

- Lower sideband is dominant for high $\omega_e\sigma_z/c$ (low emittance).

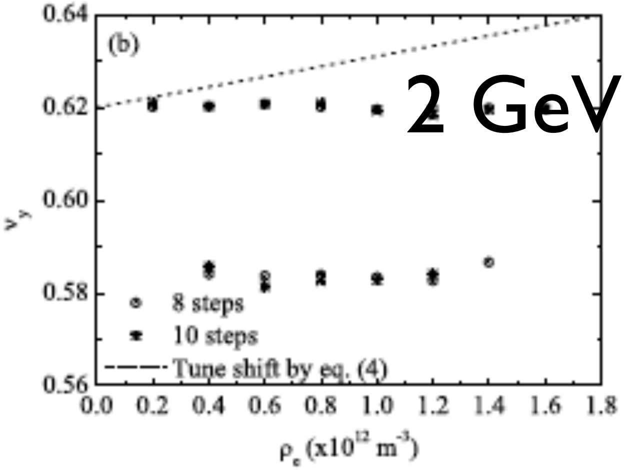


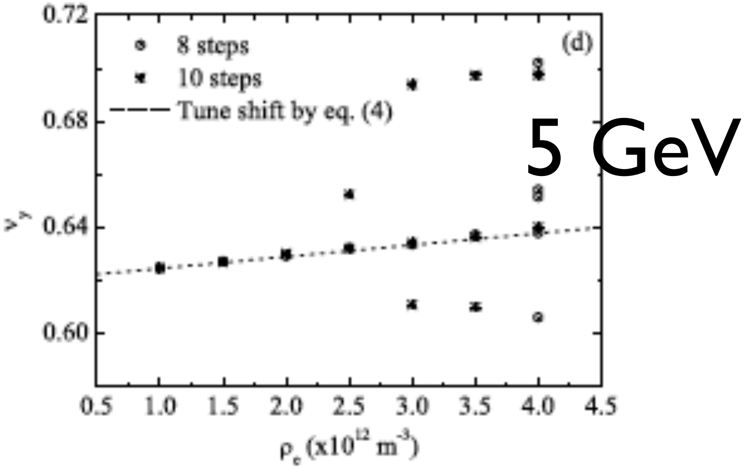
H. Jin et al., JJAP, 50, 026401(2011)

- Upper sideband is dominant for 5GeV



Simulated beam spectra

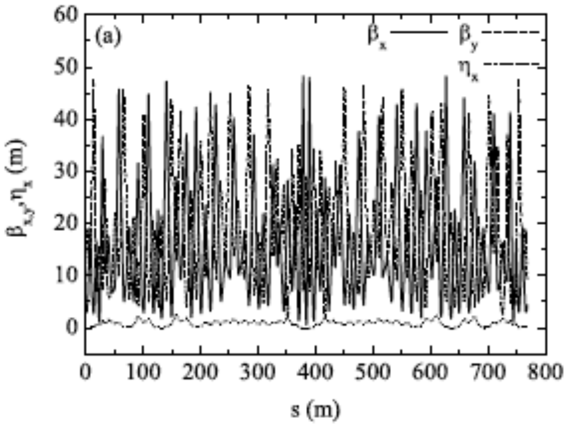


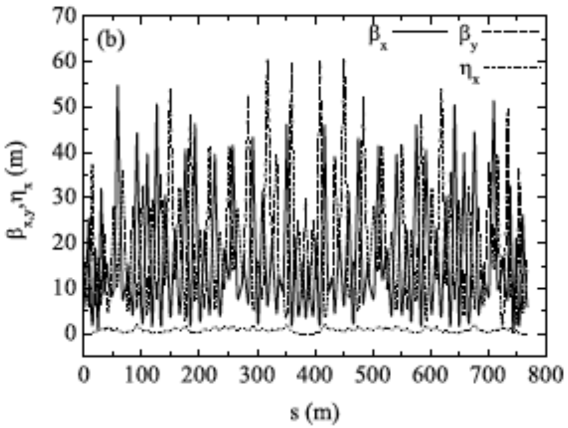


- Lower sideband is seen for high $\omega_e\sigma_z/c$, 2GeV.
- Upper sideband is seen for low $\omega_e\sigma_z/c$, 5 GeV.

Incoherent effect in CesrTA

- Emittance growth due to nonlinear interaction with electron cloud





- Nonlinearity of beam-cloud interaction
- Integrated the nonlinear terms with multiplying β function and cos (sin) of phase difference

$$M = e^{-:\phi_1:}\, e^{-:F_{12}:}\, e^{-:\phi_2:}\, e^{-:F_{23}:}\, e^{-:\phi_3:}\, e^{-:F_{34}:}\, e^{-:\phi_4:}\, e^{-:F_{45}:}\, e^{-:\phi_5:} \ldots e^{-:F_{n1}:}$$

$$\approx e^{-:F_{11}:} \exp\left(-: \sum_{i=1}^{n} \phi_i (e^{-:F_{1i}:} \mathbf{x}) : \right)$$

F: (non)linear lattice transformation

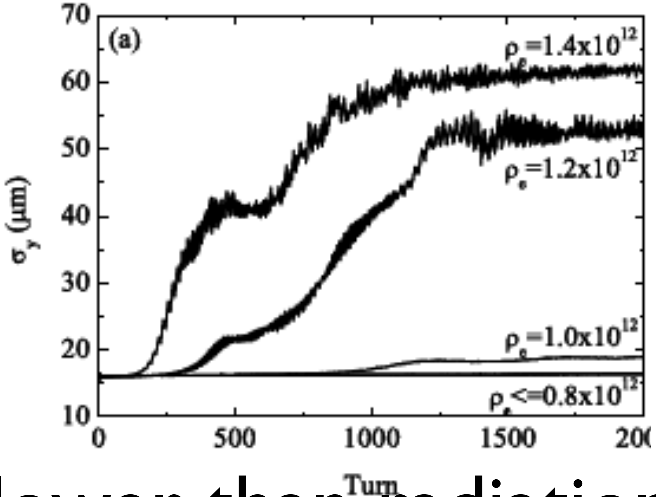
φ: cloud interaction

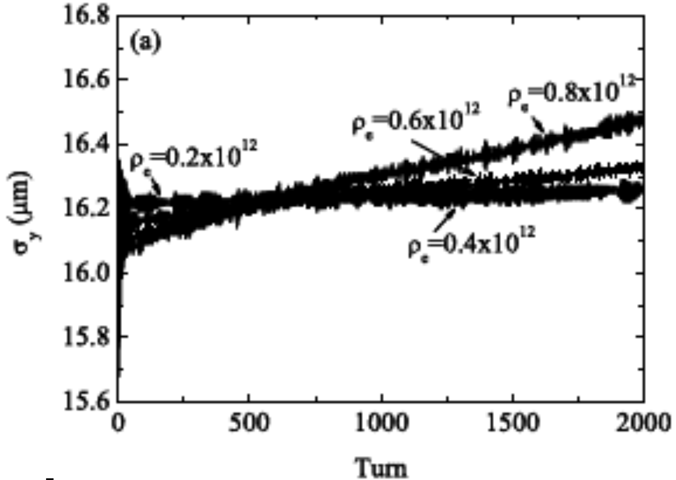
$$kx^m \Rightarrow k \beta_i^{m/2} J^{m/2} \cos(m \Delta \psi_{1i})$$

Slow growth lower than the threshold

2GeV

$\rho_{th}=1.2\mathrm{x}10^{12}$

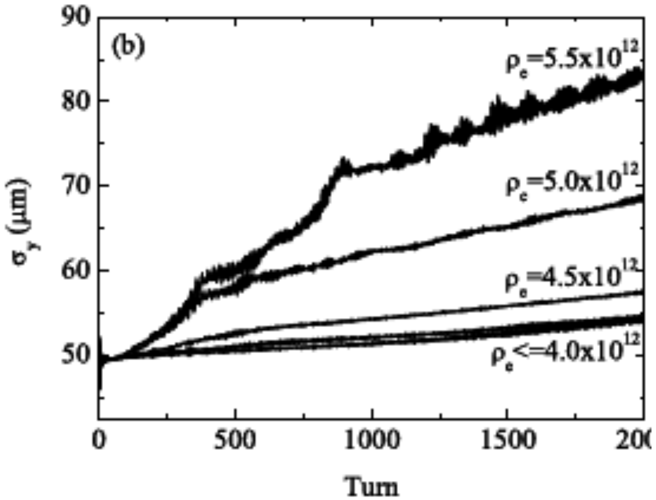


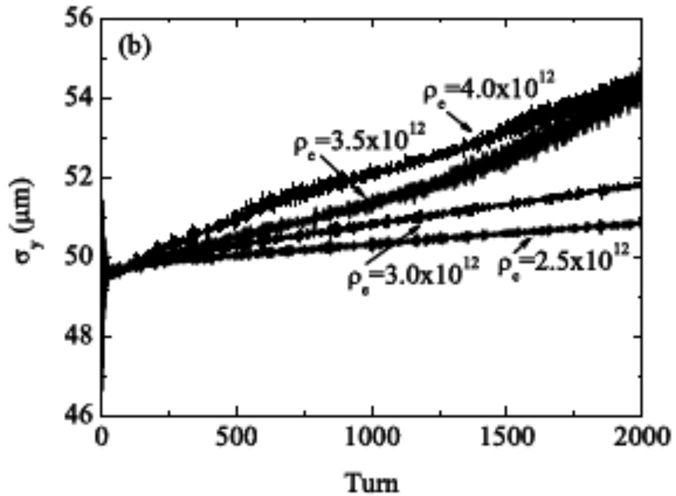


Slower than radiation damping time

5GeV

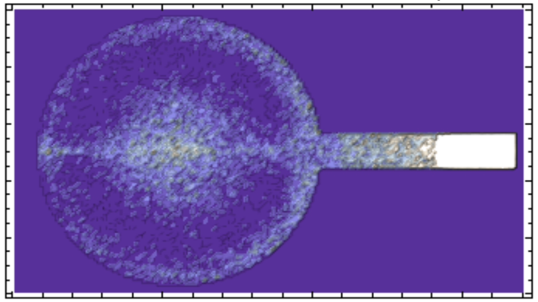
$\rho_{th}=5\mathrm{x}10^{12}$

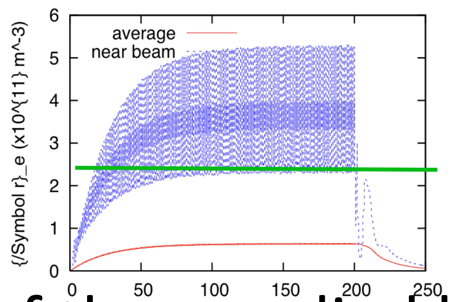




Estimation of cloud density and coupled bunch instability in SuperKEKB

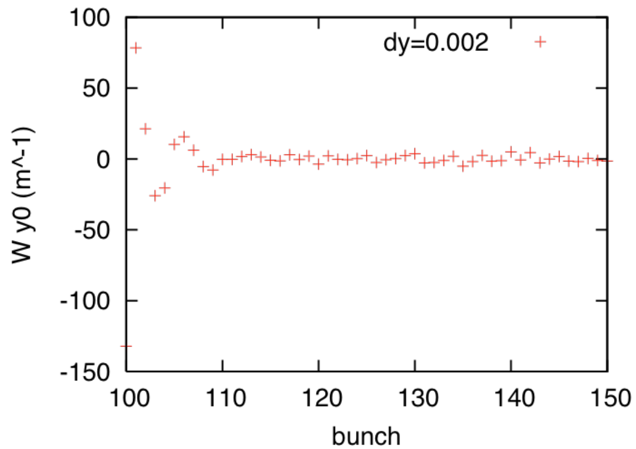
- Ante-chamber, $\delta_{2,max}$=1.2 without special structure like groove

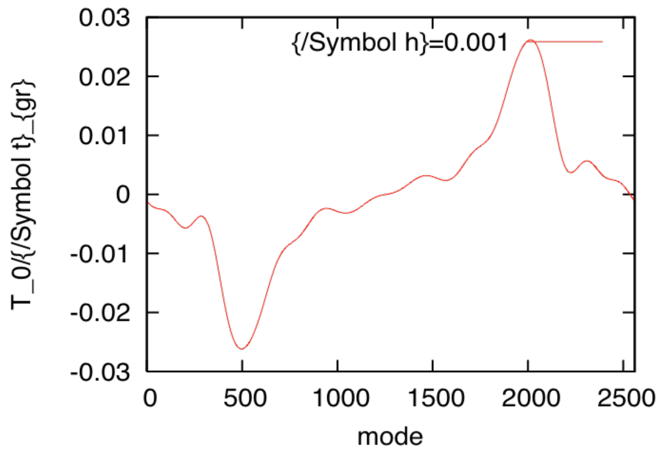




$\rho_e = 2.2 \times 10^{11}\ m^{-3}$

- Wake field and growth rate of the coupled bunch instability.





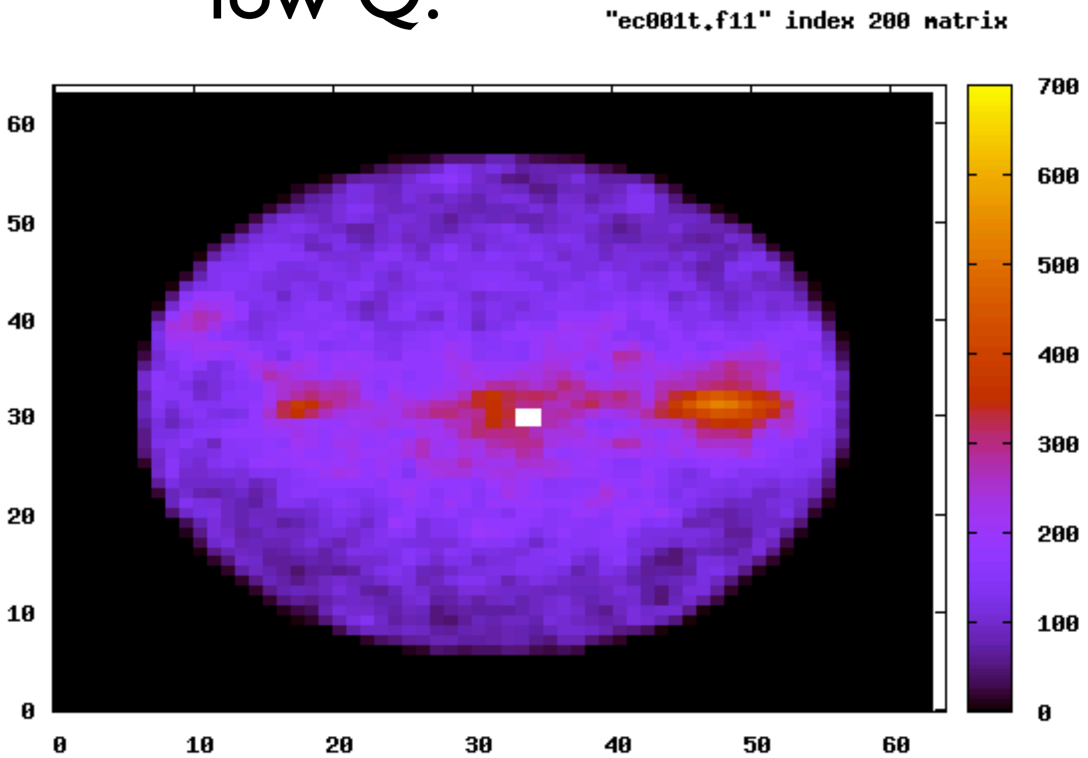
Growth time is 40 turns. It should be suppressed at $\rho_e = 1 \times 10^{11}\ m^{-3}$.

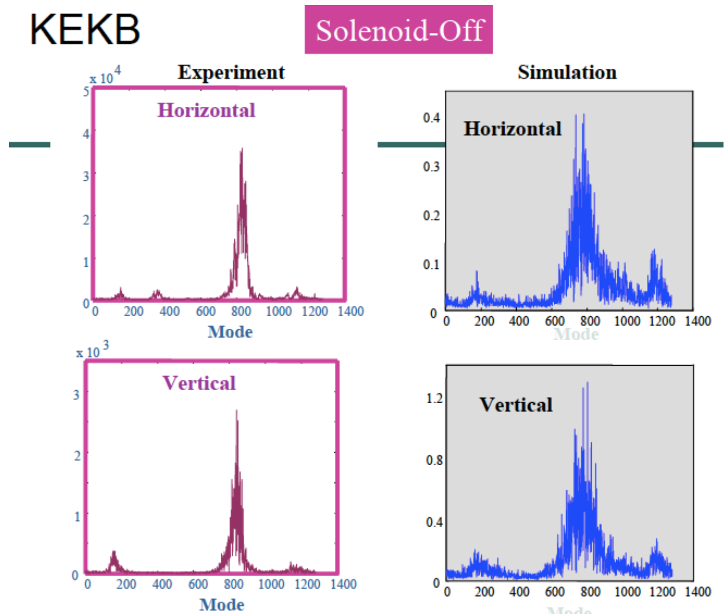
- Suetsugu-san estimates the density based on measurements and is designing the chamber to achieve density.

Multi-bunch instability in KEKB

Beam dancing with electron cloud

- Drift space
- Electrons move one way
- Bunch by bunch correlation is short, very low Q.

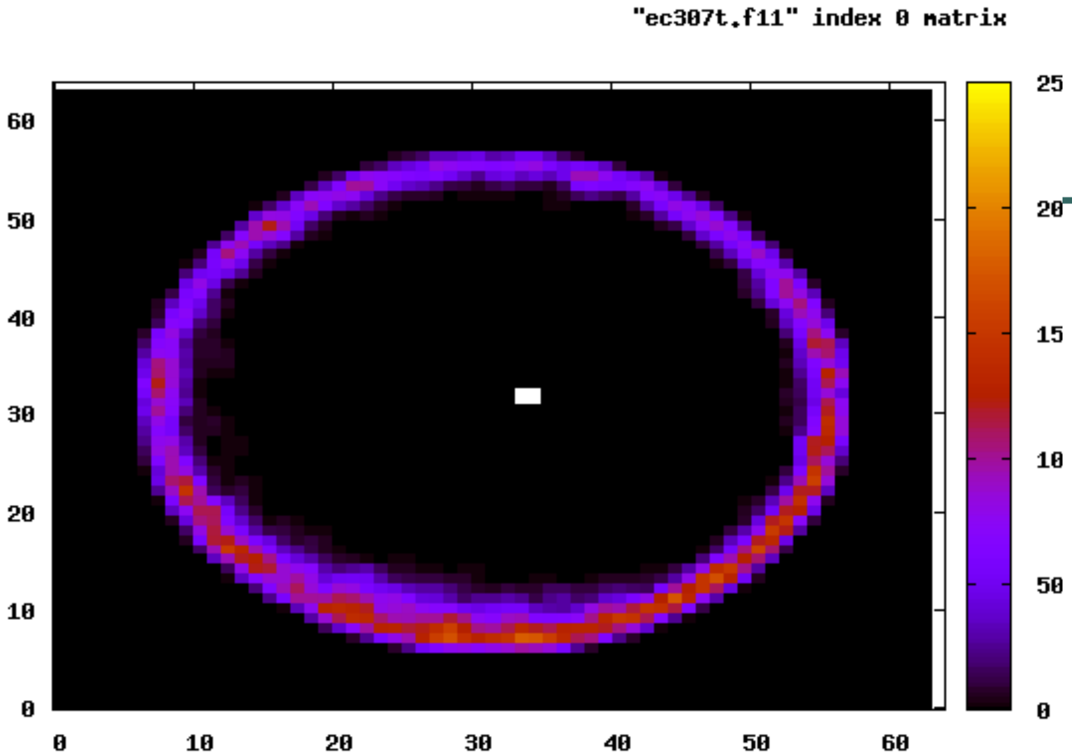


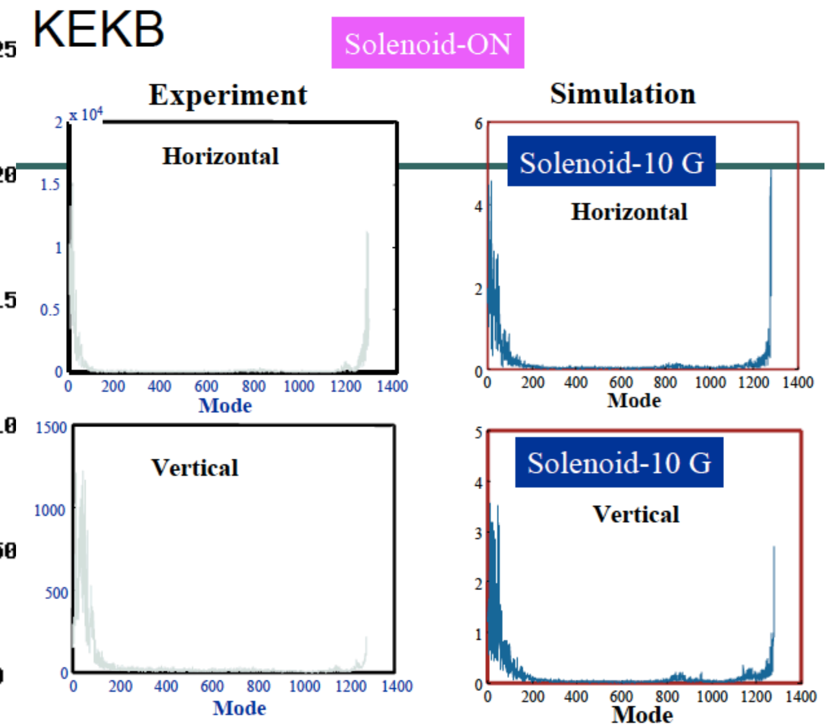


Multi-bunch instability in KEKB

Beam dancing with electron cloud

- In solenoid magnets
- Electrons move along the chamber surface.



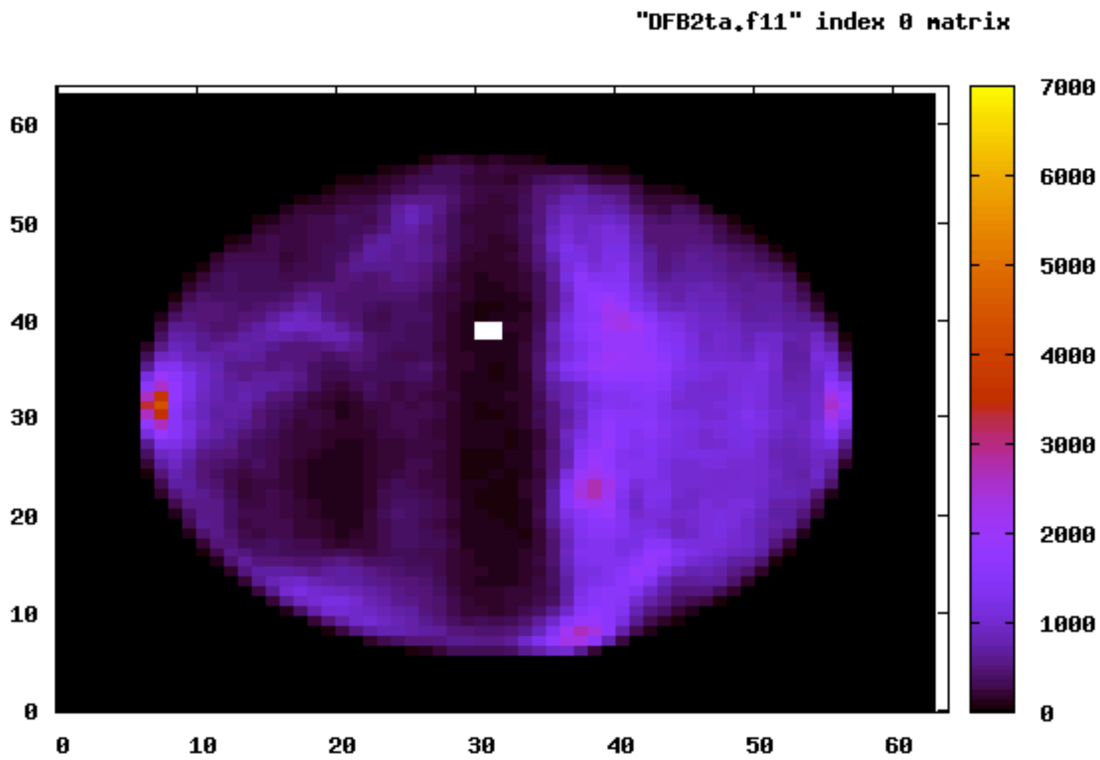


Multi-bunch instability in DAFNE

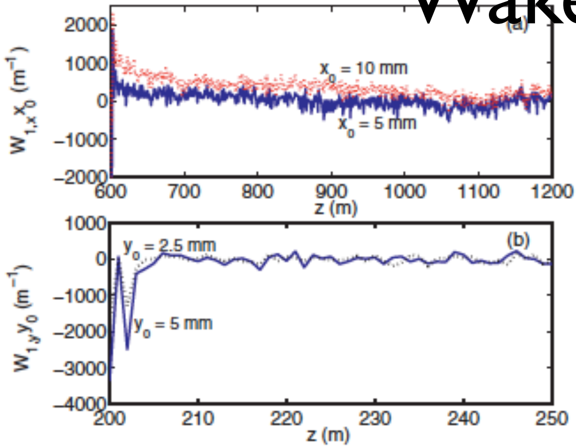
Beam dancing with electron cloud

- Electron cloud in bending magnet

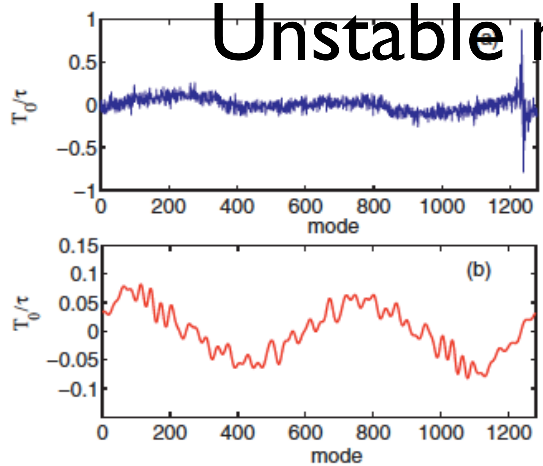
- Does beam dance with electron cloud pillar?



Wake



Unstable mode



Summary for positron rings

- Electron cloud effects have been seen many positron rings. All machines are photo-emission dominant.
- Synchrotron sideband due to electron cloud instability has been observed in many machines. The behaviors well agree with simulations.
- Coupled bunch instability has observed many rings and analyzed in detail. The behaviors well agree with simulations.

Electron cloud effects in LHC

Table 1: Parameter list of LHC.

	injection	top
Beam Energy (TeV)	0.45	7
Circumference (m)	26,658	26,658
Bunch population	1.15×10^{11}	1.15×10^{11}
Emittance x/y (m)	7.3×10^{-9}	5.1×10^{-10}
Bunch length (m)	0.112	0.0755
Energy spread (10^{-4})	3.06	1.13
Synchrotron tune ν_s	0.0055	0.0019
Bending field (T)	0.535	8.33
Bunch spacing (ns)	25	25

		injection	top
$\omega_e\sigma_z/c$		3.4	11
Analytic	$\rho_{e,th}$ (m^{-3})	2.2×10^{11}	5.7×10^{11}
Simulation (bend)	$\rho_{e,th}$ (m^{-3})	6×10^{11}	3×10^{12}
Simulation (drift)	$\rho_{e,th}$ (m^{-3})	3×10^{11}	1×10^{12}

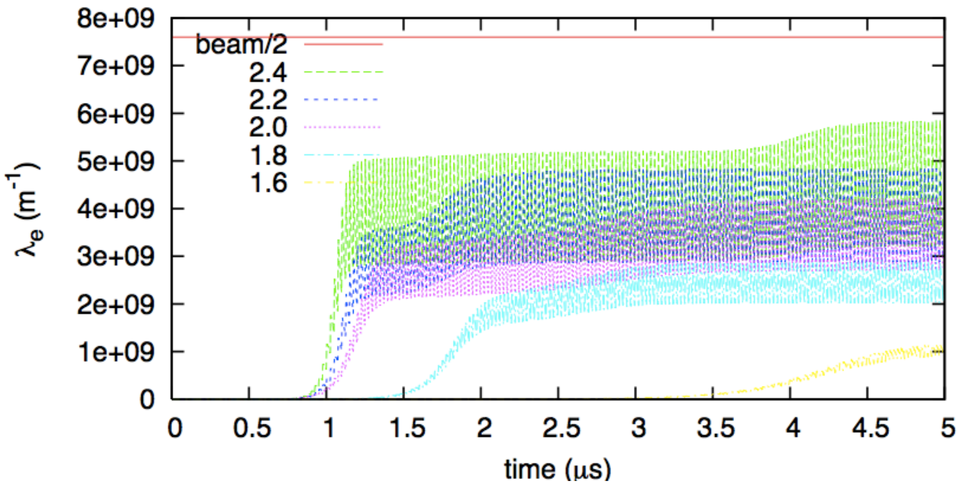
Simulations are showed letter

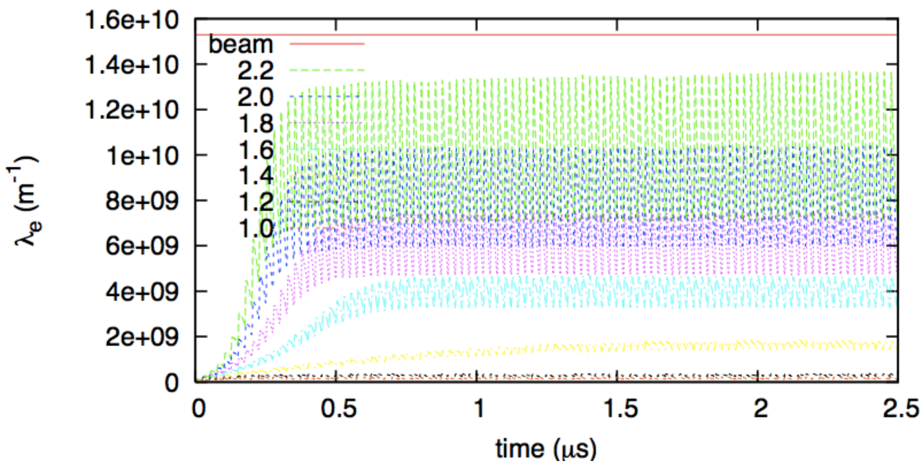
Electron source

- Ionization, 2×10^{-7} Pa, $N_{pe}/L=8\times10^{-9}$ m^{-1} at injection
- Photo-emission $\gamma=7463$, $N_{pe}/L=0.0019$ m^{-1}, $u_c=30$ eV at top energy
- Cyclotron motion in bending magnet.
  - ⋆ Inj 0.535 T, $\omega_c\sigma_z/c=35$, $\rho_c/\sigma_x=0.12$ (300eV)
  - ⋆ Top 8.33T, $\omega_c\sigma_z/c=369$, $\rho_c/\sigma_x=0.03$ (300eV)
  - ⋆ Neglect cyclotron motion in this presentation, electrons move along magnetic flux line.

Electron line density

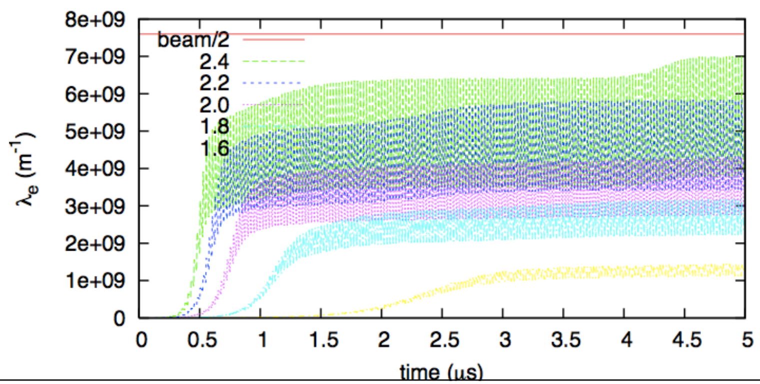
- injection   top energy





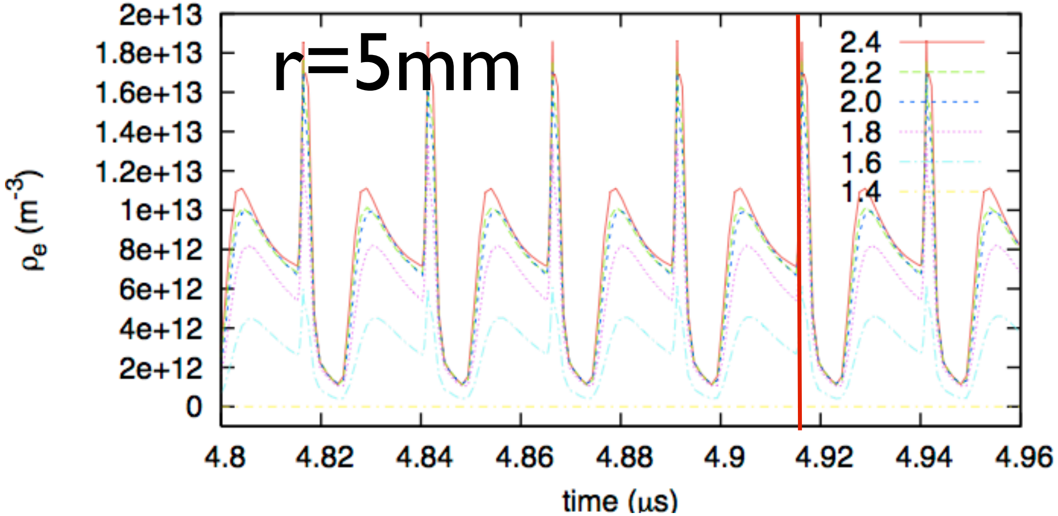
Used cylindrical pipe r=2cm

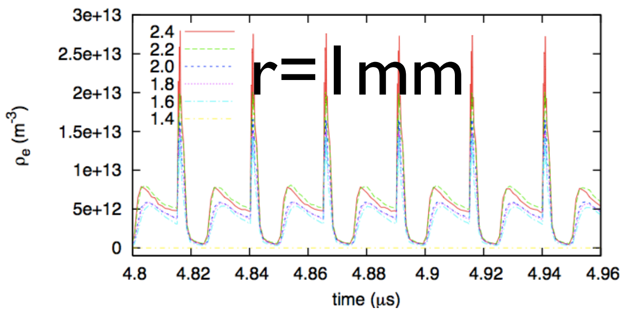
- 100 time worse vacuum



Since multipacting is dominant in injection, the density is almost independent of initial yield

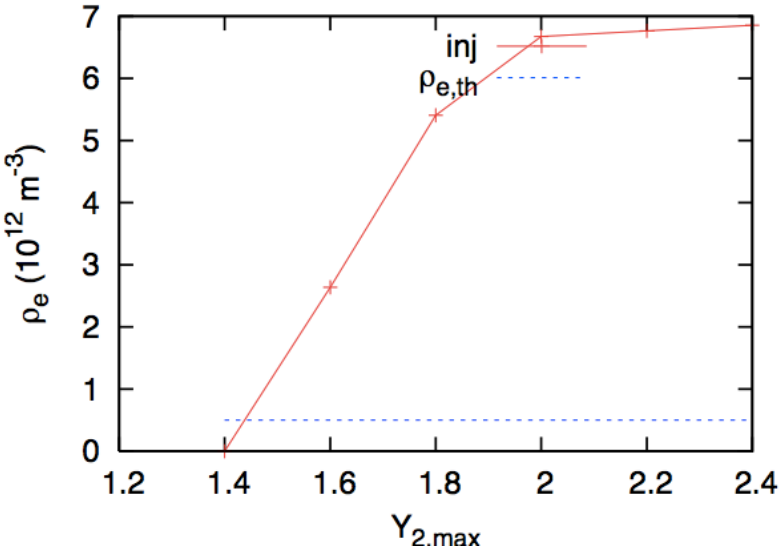
Electron density at injection





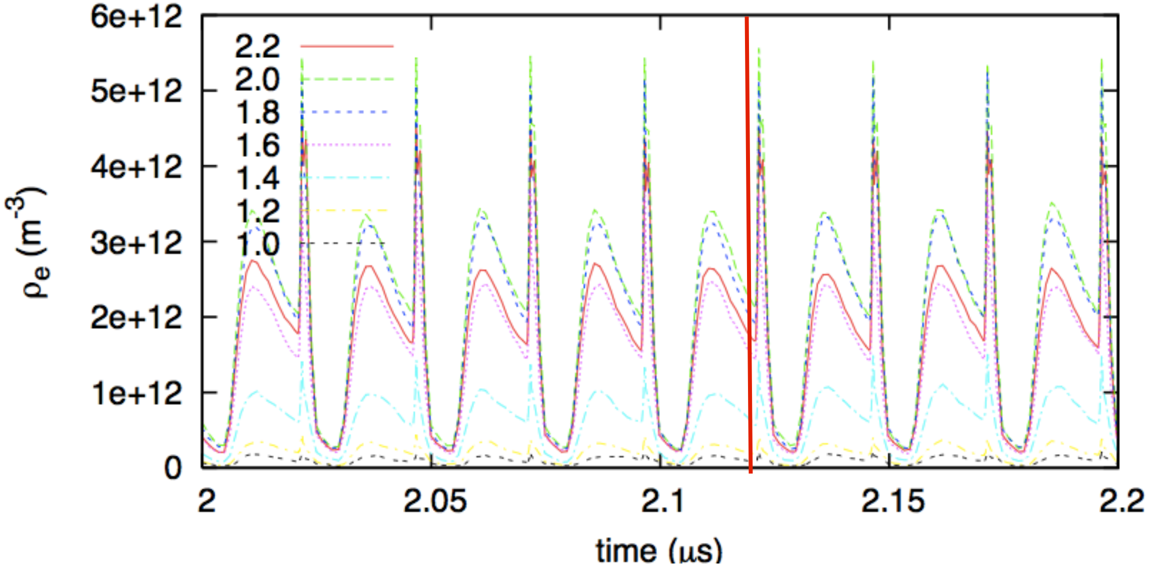
The density r=1mm slightly different

- Density just interacting with beam

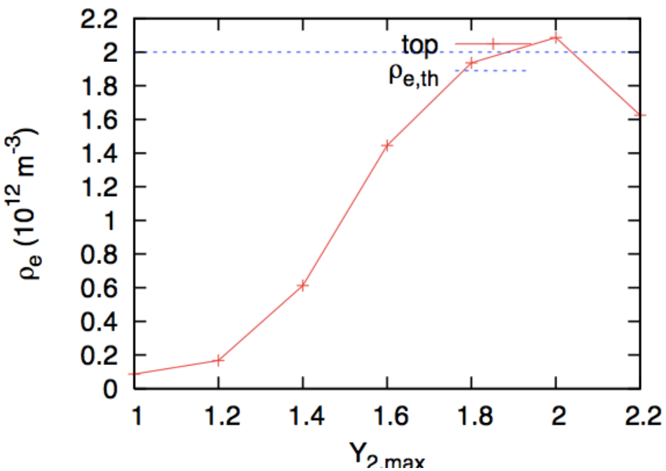


$\rho_{e,th}$=6x10^{11}m^{-3} is determined by simulation in next slides

Electron density at top energy



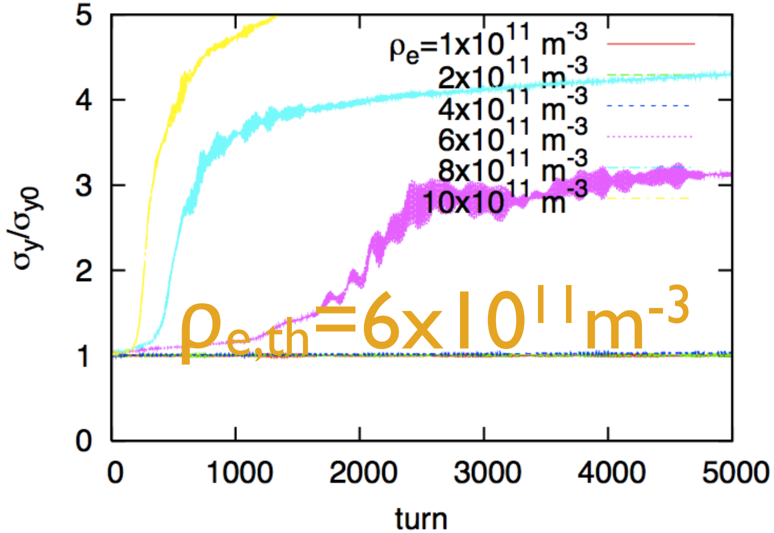
- Density just interacting with beam

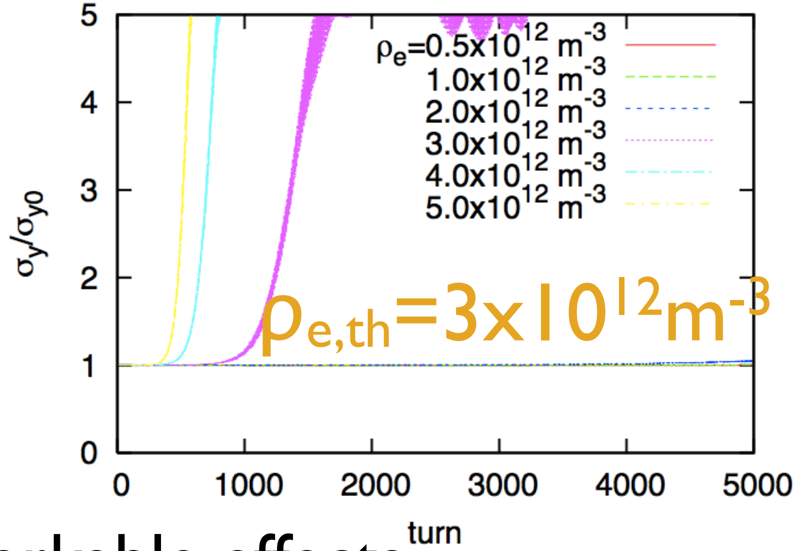


$\rho_{e,th}=2\times10^{12}m^{-3}$ is determined by simulation in next slides

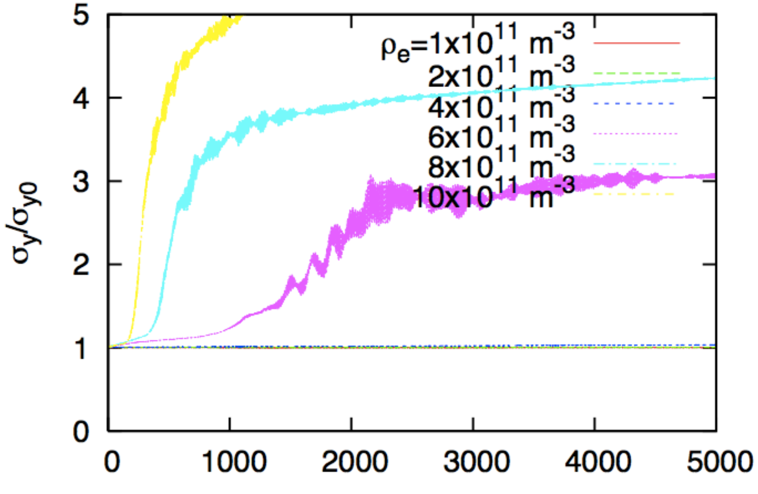
Simulation results (PEHTS)

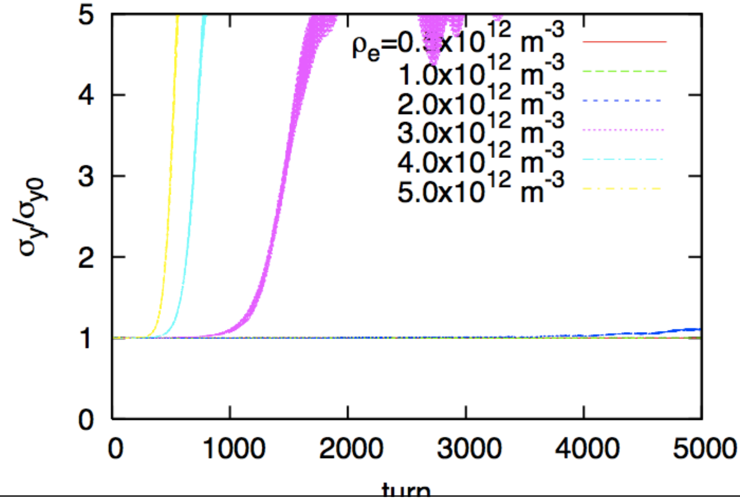
- injection — top energy



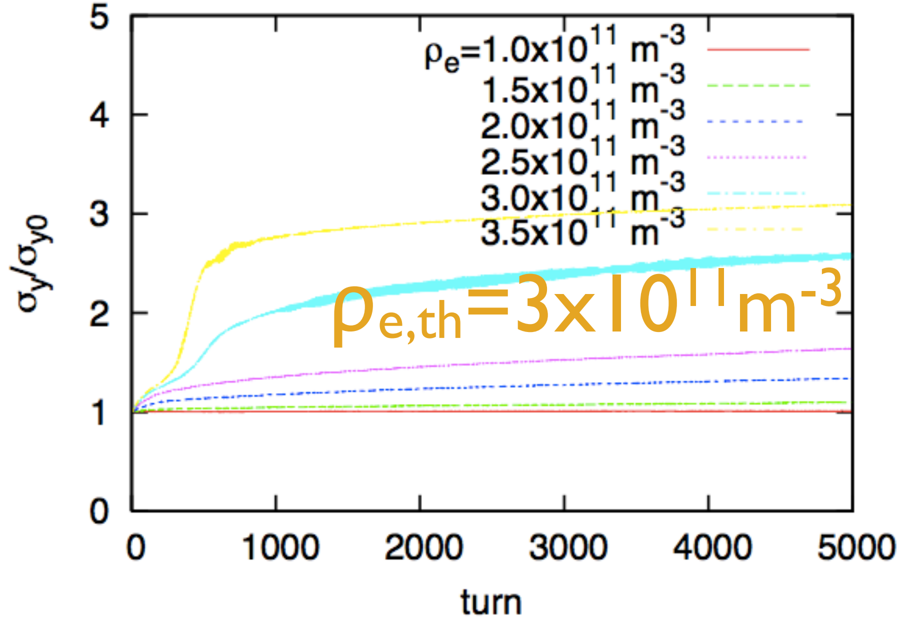


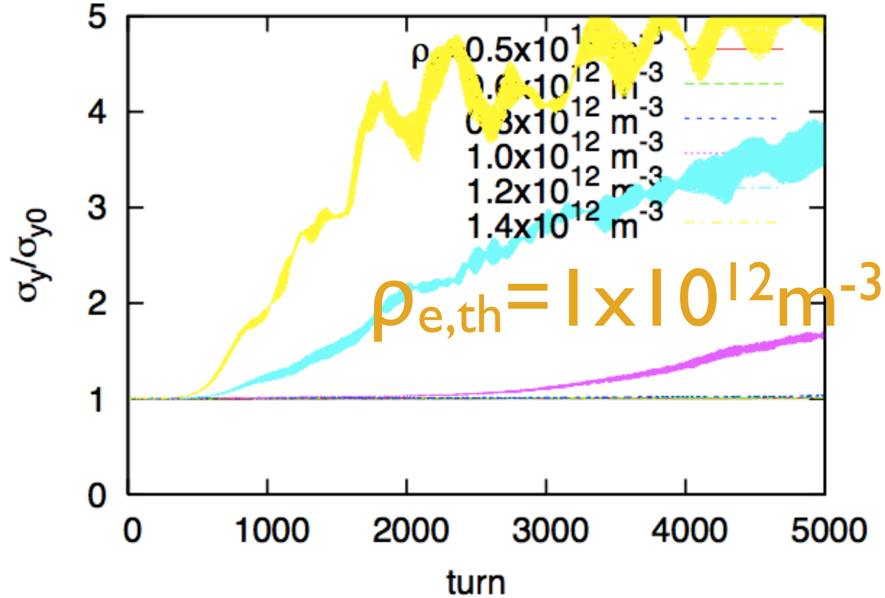
- dispersion 1.5m, no remarkable effects

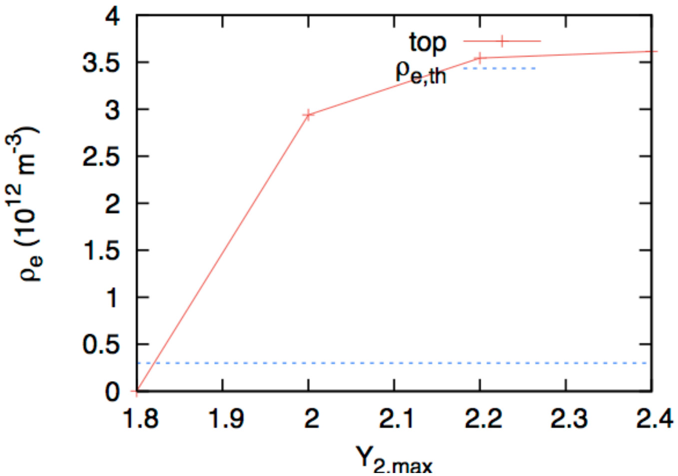


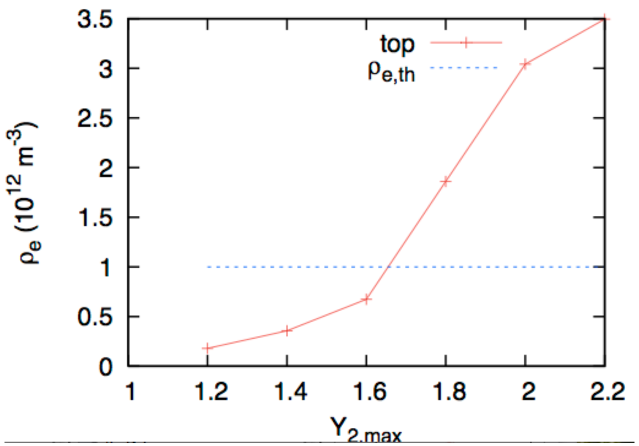


Simulations in Drift space





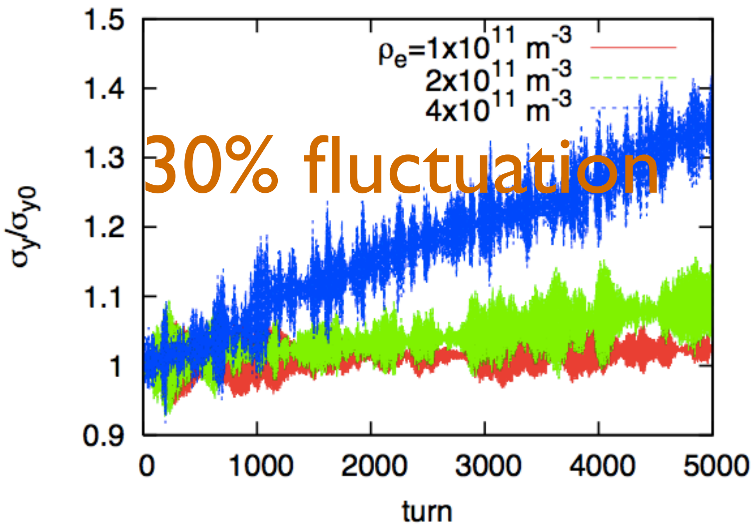


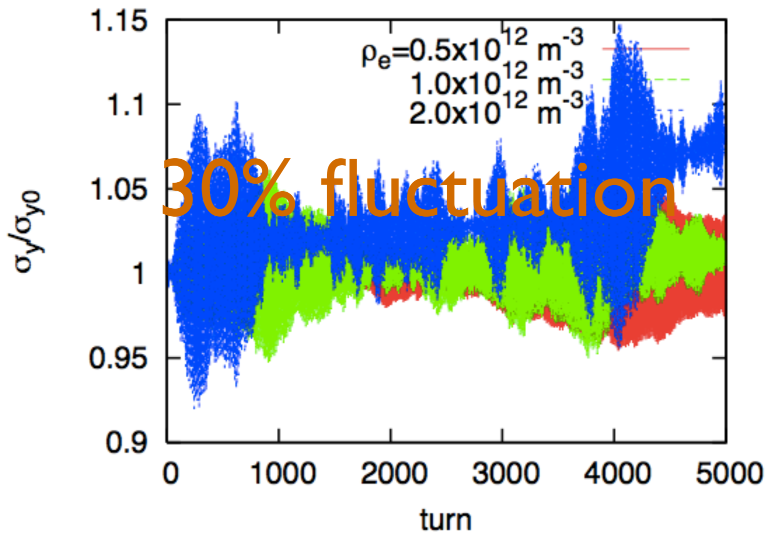


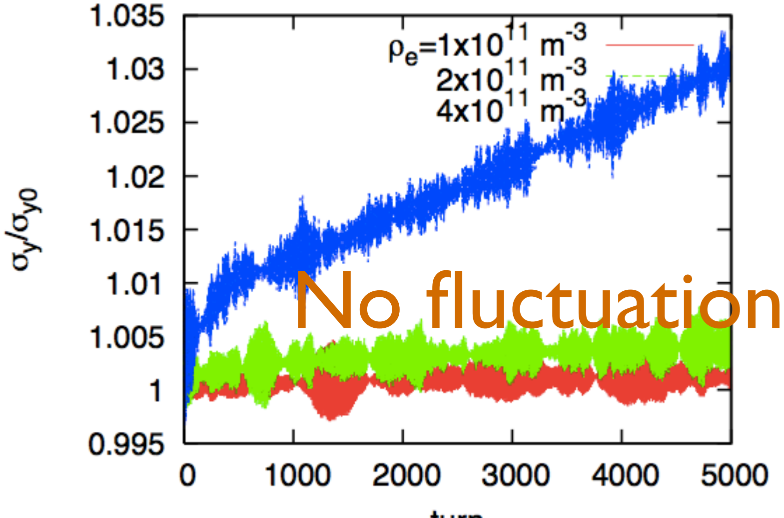
Cloud density fluctuation

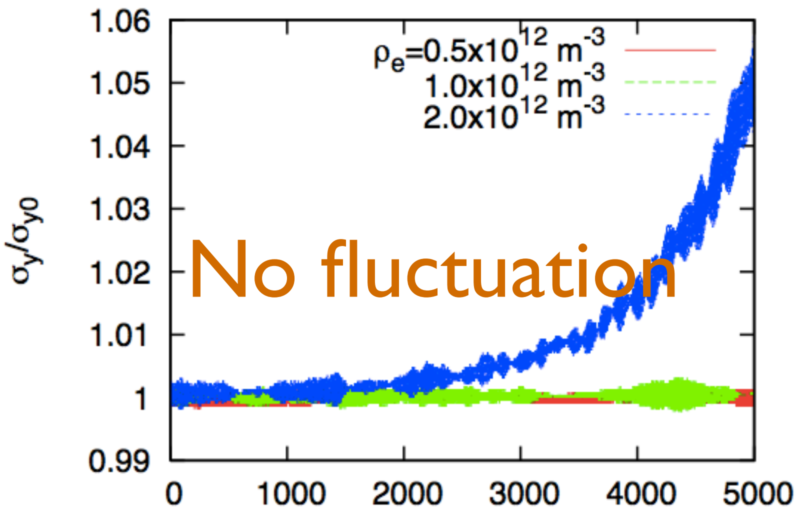
- injection

top energy









The slow growth is artifact, but the differences have meaning.

Summary for LHC electron cloud

- Electron cloud density and threshold for fast head-tai instability was estimated.
- The threshold densities are $\rho_{e,th}$=3x10^{11}m^{-3} (drift) and 6x10^{11}m^{-3} (bend) for injection, and 1x10^{12} (drift) and 3x10^{12} (bend) for top energy.
- The densities of onset of instability in drift agree with analytical estimates.
- Fluctuation of cloud density may be serious for emittance growth.
- Scrubbing to achieve Y_{2max}=1.6 is necessary for operation with 25 ns spacing.