Electron cloud effect in ILC damping ring

K. Ohmi and X. Dong (KEK)

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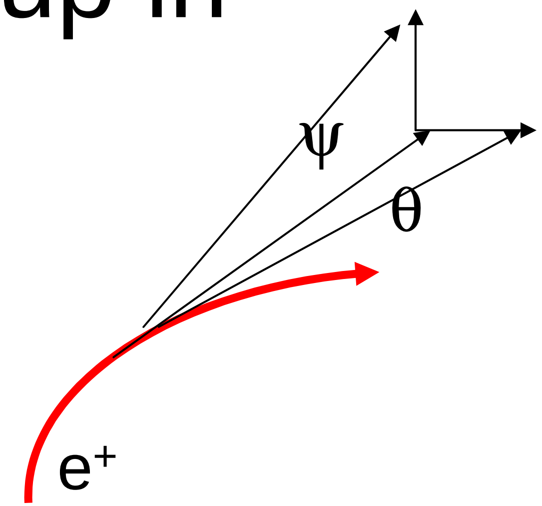
Studies for damping ring

- Photoelectron build-up in an antechamber
- Coupled bunch instability
- Single bunch instability
- Incoherent emittance growth

Electron cloud build-up in antechambers



- Photon emission for unit bending angle θ of one positron

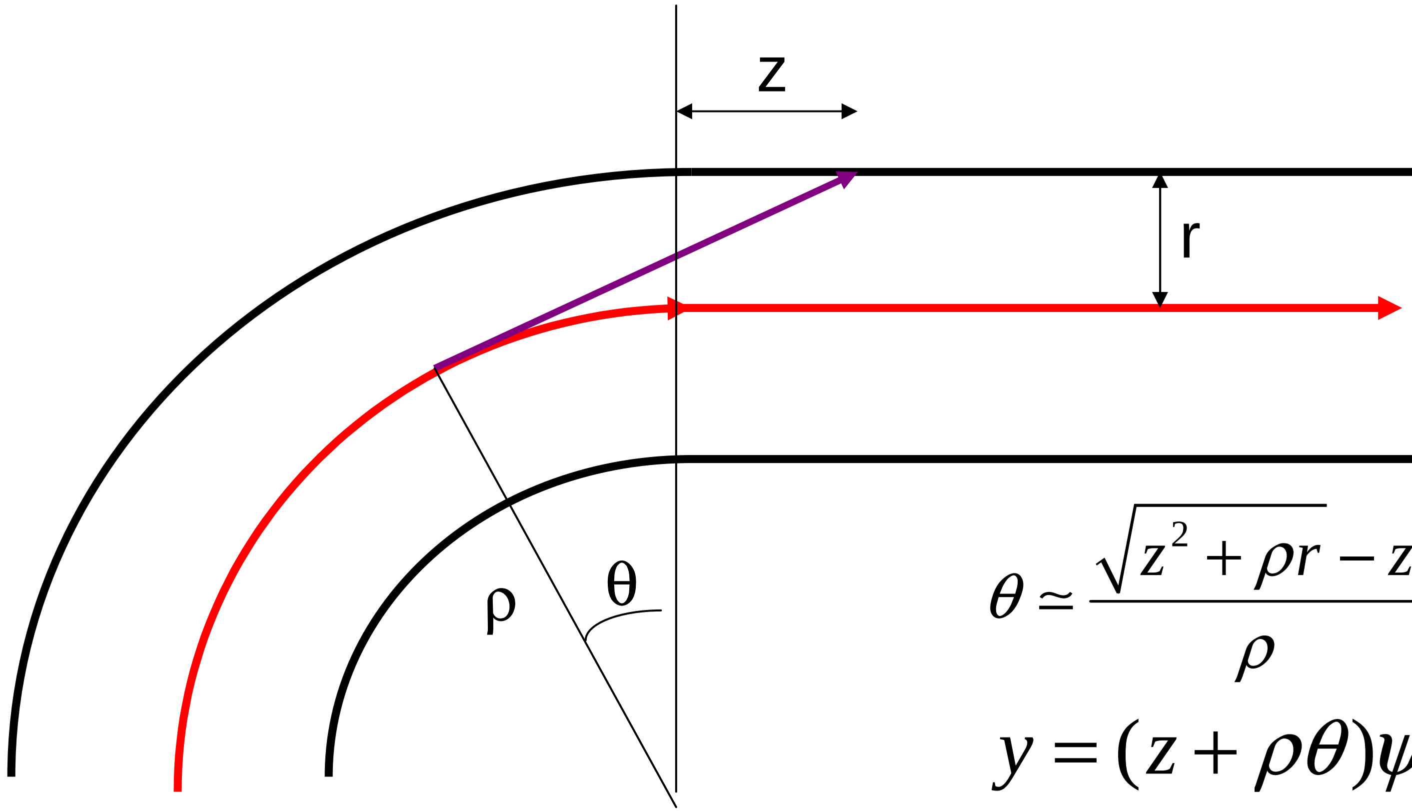
$$N_\gamma = N_\sigma + N_\pi$$

$$\frac{d^2 N_\sigma}{d\psi d\theta} = \frac{3\alpha}{4\pi^2}\gamma^2\left(\frac{\omega}{\omega_c}\right)^2\left\{1+(\gamma\psi)^2\right\}^2 K_{2/3}(\eta)^2\,\frac{\Delta\omega}{\omega}$$

$$\frac{d^2 N_\pi}{d\psi d\theta} = \frac{3\alpha}{4\pi^2}\gamma^2\left(\frac{\omega}{\omega_c}\right)^2\left\{1+(\gamma\psi)^2\right\}(\gamma\psi)^2 K_{1/3}(\eta)^2\,\frac{\Delta\omega}{\omega}$$

$$\alpha = \frac{1}{4\pi\varepsilon_0}\frac{e^2}{\hbar c} \approx \frac{1}{137} \qquad \omega_c = \frac{3}{2}\frac{c}{\rho}\gamma^3 \qquad \eta = \frac{1}{2}\frac{\omega}{\omega_c}\left\{1+(\gamma\psi)^2\right\}^{3/2}$$

Geometry of photon emission



$$\theta \simeq \frac{\sqrt{z^2 + \rho r} - z}{\rho}$$

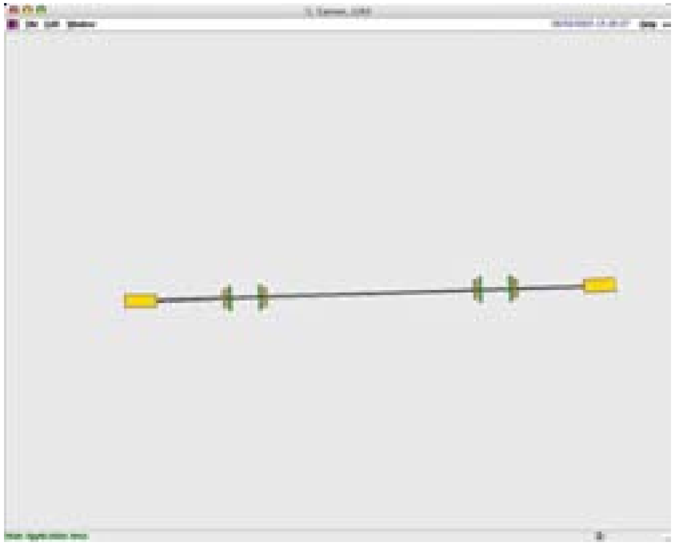
$$y = (z + \rho\theta)\psi$$

$$\frac{d^2 N_\gamma}{dy dz} = \frac{d^2 N_\gamma}{d\psi d\theta} \left| \frac{d(\psi,\theta)}{d(y,z)} \right|$$

$$\left| \frac{d(\psi,\theta)}{d(y,z)} \right| = \frac{\theta}{z^2 + \rho r}$$

Arc lattice

OTW

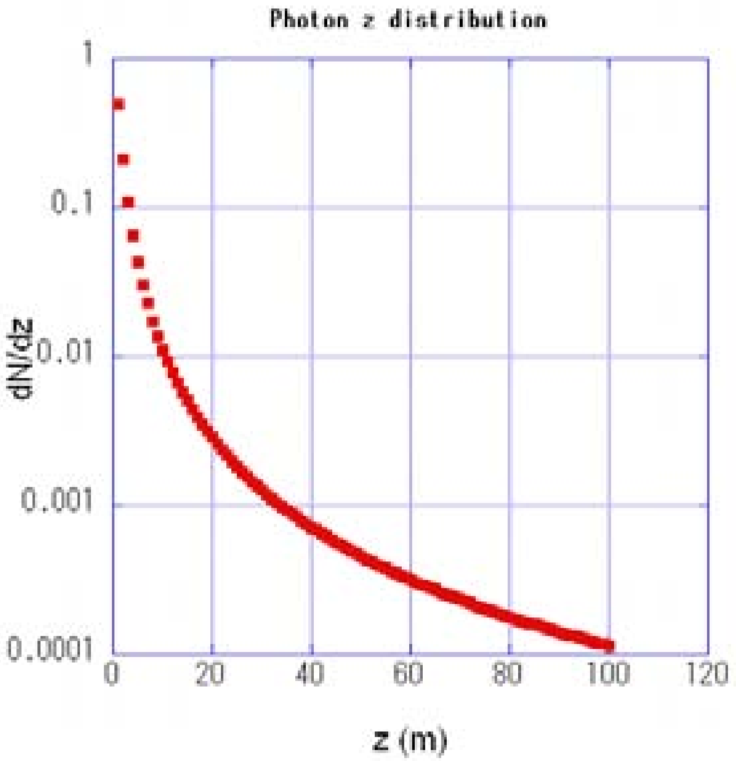


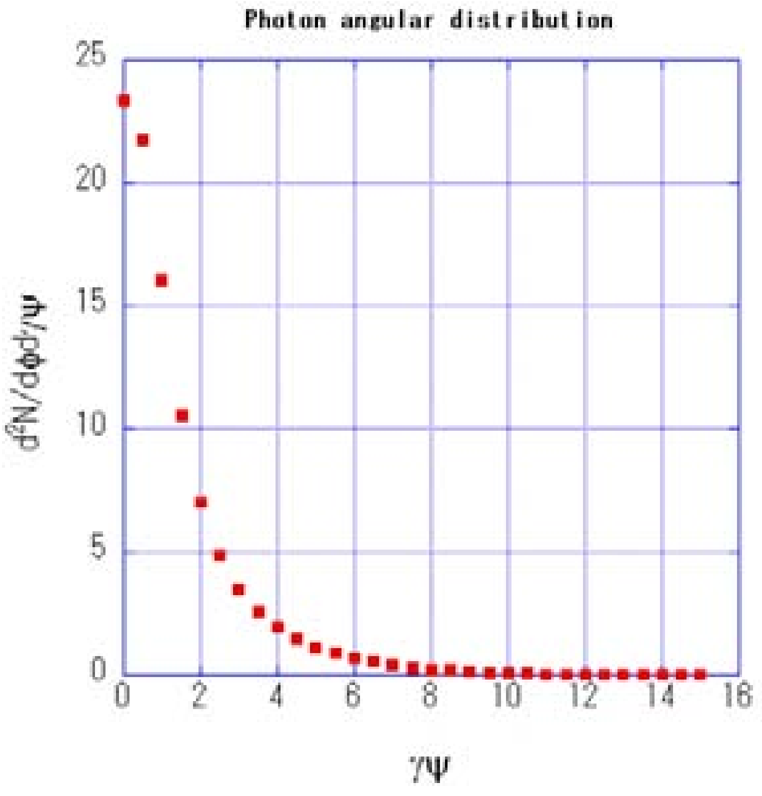
OCS

TESLA

Photon distribution

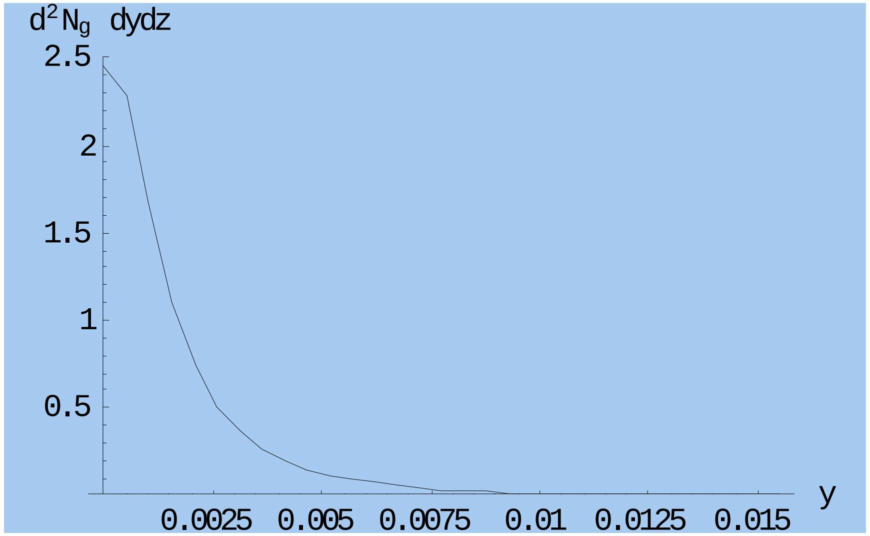
- Z distribution, and angular distribution





Photoelectron production rate

Z (m)	Ne (e$^-$/m)	Ne(|y|>5 mm)
1	0.097	
5	0.0045	$1.3x10^{-5}$
10	0.0011	$5.2x10^{-5}$
50	$4.5x10^{-5}$	$2.4x10^{-5}$



Photoelectron production rate at Injection

Large emittance $\gamma\varepsilon$=0.01 m,

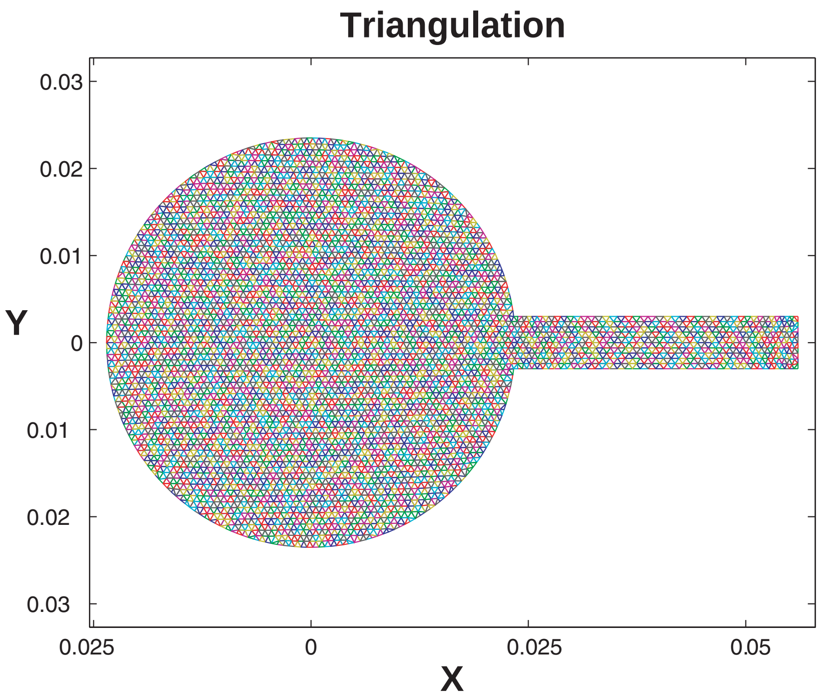
$\delta x'$=0.3 mrad for β=10 m (F.Z)

Z (m)	Ne (e^-/m)	Ne(|y|>5 mm)
1	0.097	5.6×10^{-8}
3	0.0124	0.0012
5	0.0045	0.0014
10	0.0011	0.00066
50	4.5×10^{-5}	4.1×10^{-5}

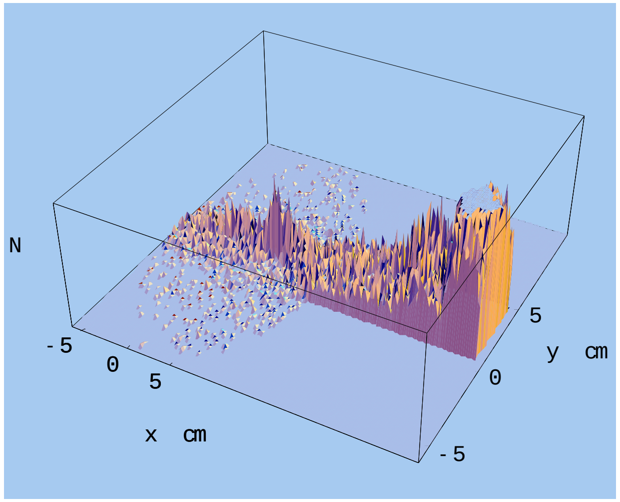
Coupled bunch instability may be serious.

Poisson solver with the Finite Element Method

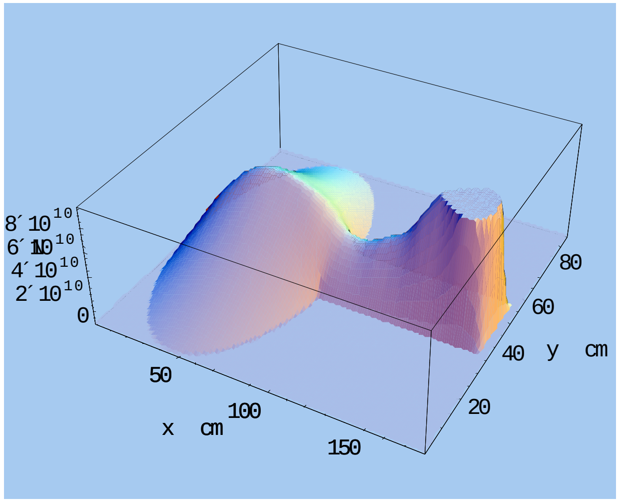
- Mesh



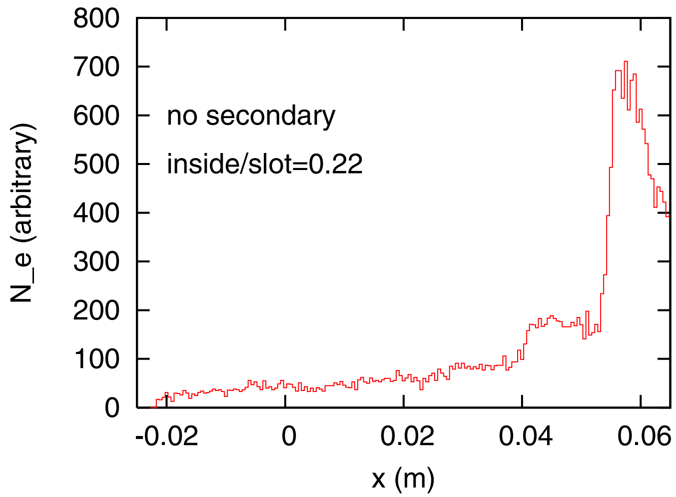
ρ_e



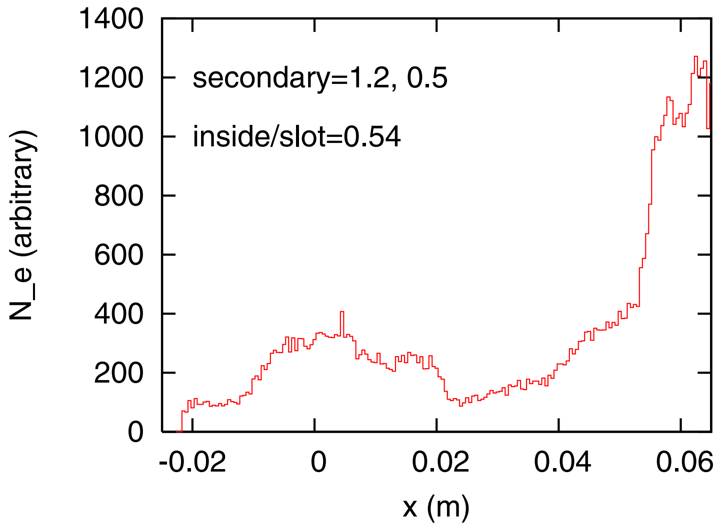
ϕ_{cloud}

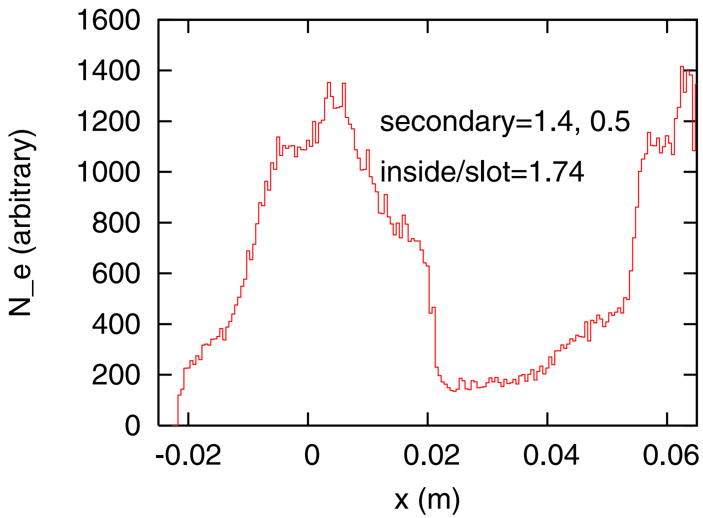


Typical Electron distribution (OTW) in the antechamber

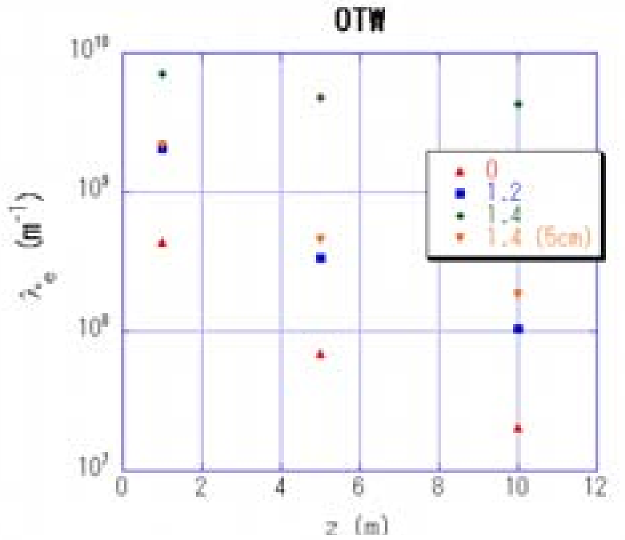


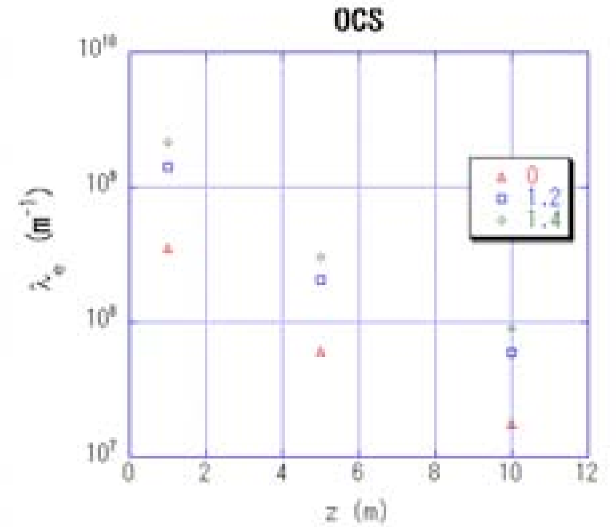
Cloud density at cylindrical part increases for high secondary rate

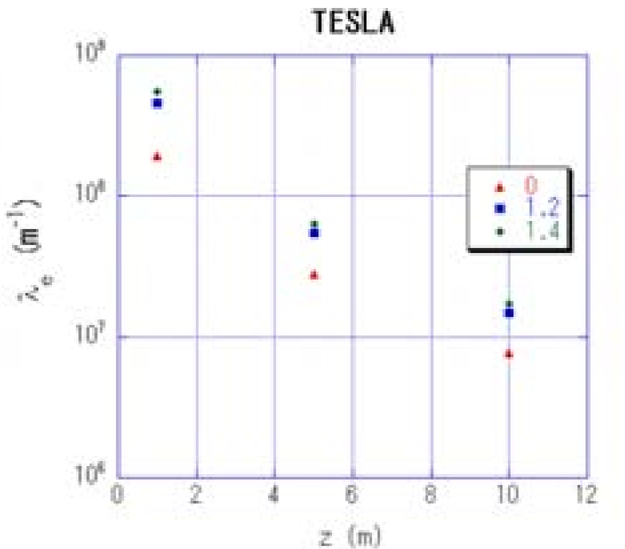




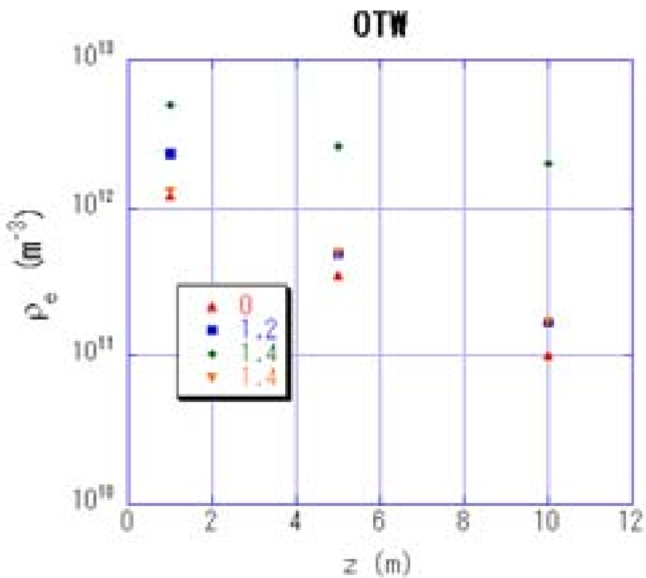
Cloud line density along z

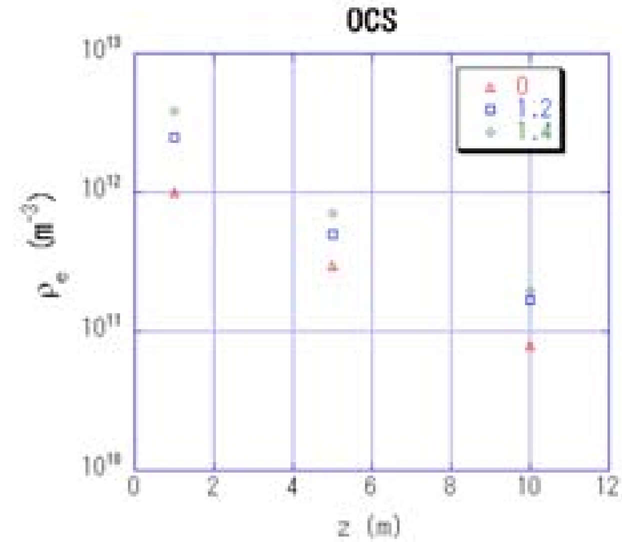


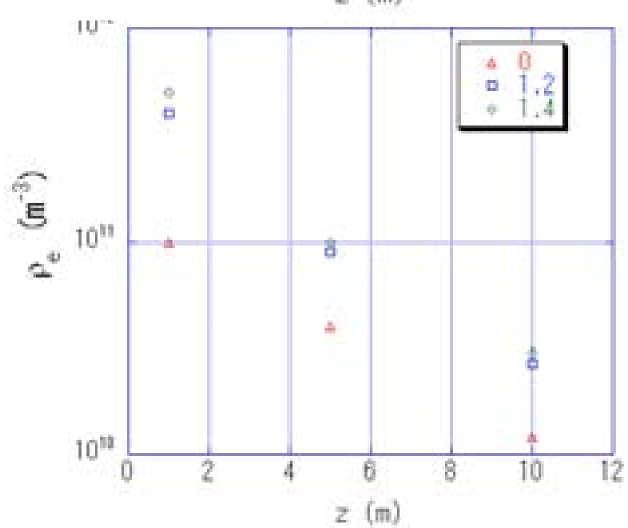




Cloud density (r=1mm) along z







Multipacting occurs for OTW 2.2cm chamber, but does not occur for 4.5cm (KEKB type) chamber.

Effect of antechamber

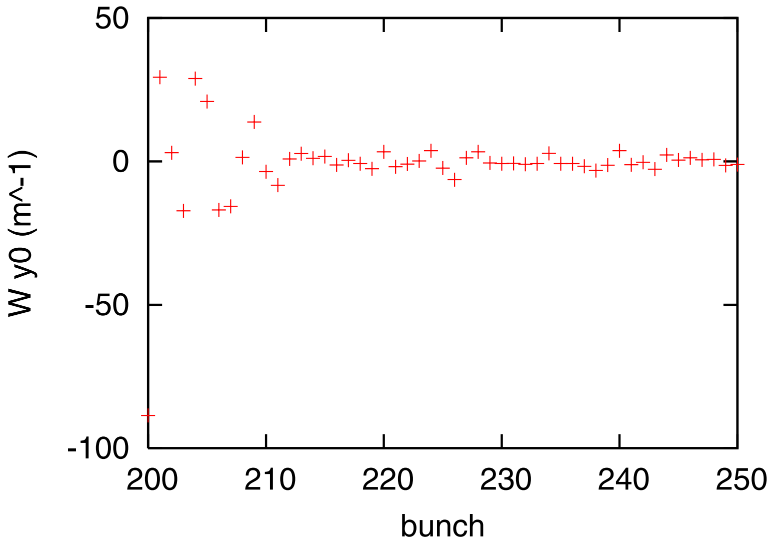
- Antechamber suppress the cloud line density with several % level (5-10m downstream), if multipacting can be avoided.
- Electron accumulation in magnets may be relatively important, when their effective length exceed several % of the ring.
- Wiggler, Quad… Mauro is estimating.

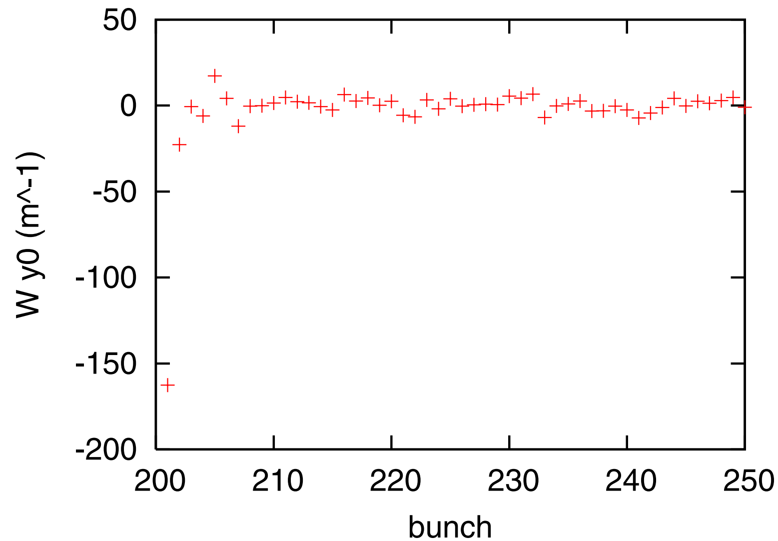
Photon reflection

- Bending magnets almost cover arc-section in OTW and TESLA.
- Electrons produced at the direct illuminated point do not seem to contribute the build-up.
- Photon reflection may be important.
- No experimental data?

Coupled bunch instability

- Wake force induced by electron cloud
- $\lambda_e = 7x\ 10^7\ m^{-1}$ (OTW) $5x10^7\ m^{-1}$ (OCS)
- This line density corresponds to that at 10 m down stream.
- The wake is 5 times stronger at 5 m downstream.
- At Injection, the wake is 10-20 times stronger.

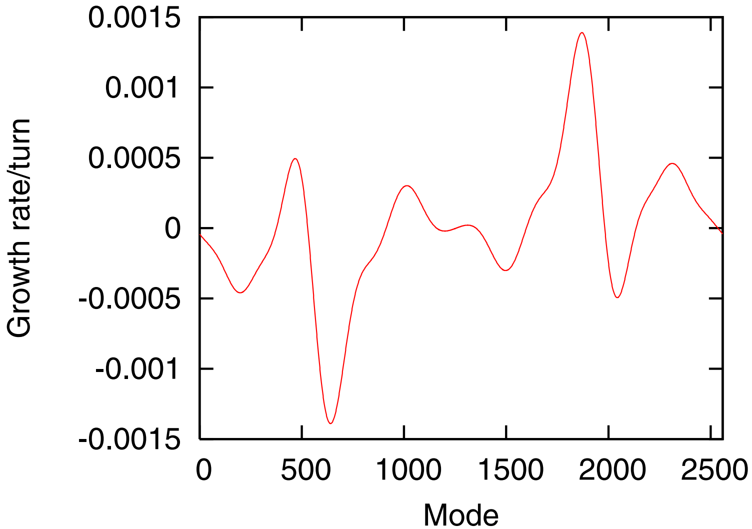




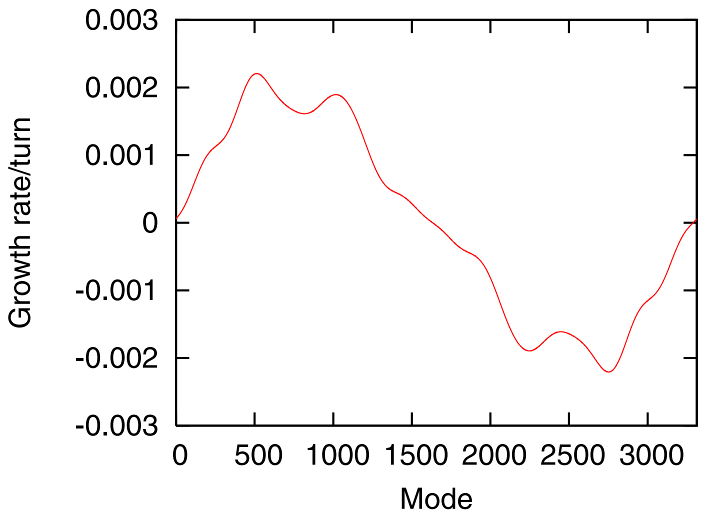
Growth rate of the coupled bunch instability

- Slow growth rate (τ~1000 turn), if the conditions (average density =10m down stream) are kept.
- At injection, growth rate increases 10-20 times, (τ~50-100 turn)
- If someone study mode spectra for wiggler and quad, they can be used to diagnose whether electrons exist in the magnets.

OTW



OCS



Single bunch instability

- Electrons oscillate in a bunch with a frequency, ω_e.

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

- $\omega_e \sigma_z / c > 1$ for vertical.
- Vertical wake force with ω_e was induced by the electron cloud causes strong head-tail instability, with the result that emittance growth occurs.

- Linear theory
- Simulation based on the strong-strong model.

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

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

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

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

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

- $Q=\min(Q_{nl}, \ \omega_e\sigma_z/c)$

  Q_{nl}=5-10? Depending on the nonlinear interaction
- K~3 Cloud size effect.
- $\omega_e\sigma_z/c$~12-15 for damping rings.

Threshold cloud density given by the linear theory

	KEKB	OTW	OCS	TESLA
E (GeV)	3.5	5	5	5
L (m)	3016	3223	6,114	17,000
Np	3.30E+10	2.20E+10	2.00E+10	2.00E+10
$\omega \sigma_z / c$	2.5	14.7	14.1	12.4
ν_s	0.018	0.0418	0.0337	0.066
σ_x (μm)	420	110	110	103
σ_y (μm)	60	7.3	7.3	7.3
σ_z (mm)	5	6	6	5.5
ρ_{th}	5.40E+11	1.82E+12	7.36E+11	4.50E+11

$Q = \mathrm{Min}(\omega_e \sigma_z / c, 5)$

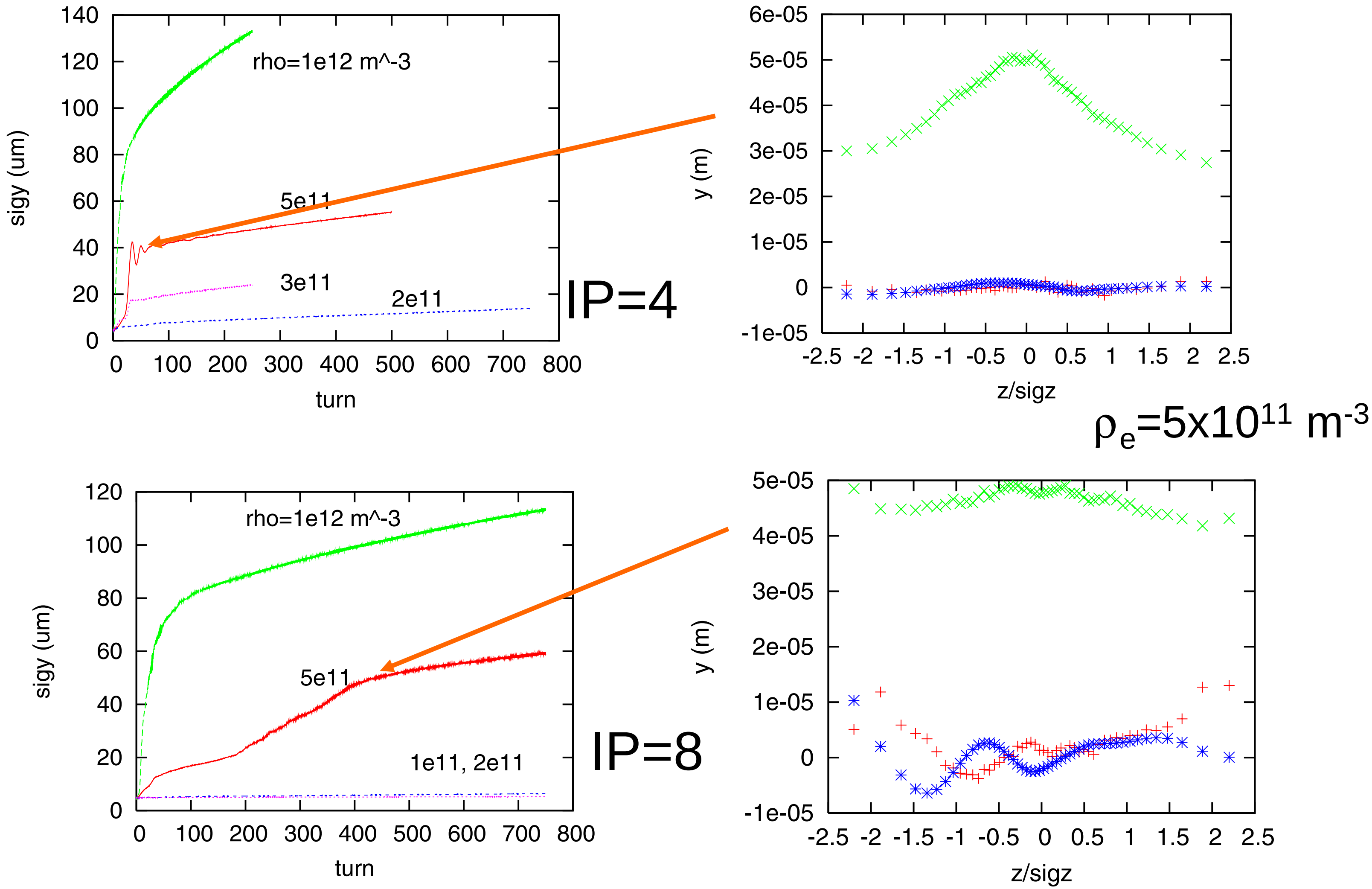
Simulation

- Strong-strong type of simulation. Interaction of macro-positron and macro-electron.
- Beam interacts with electron cloud several interaction point (considered as integration step) in this model.

Simulation result for OTW

Emittance growth

beam (red) and electron profile (blue, green) along z

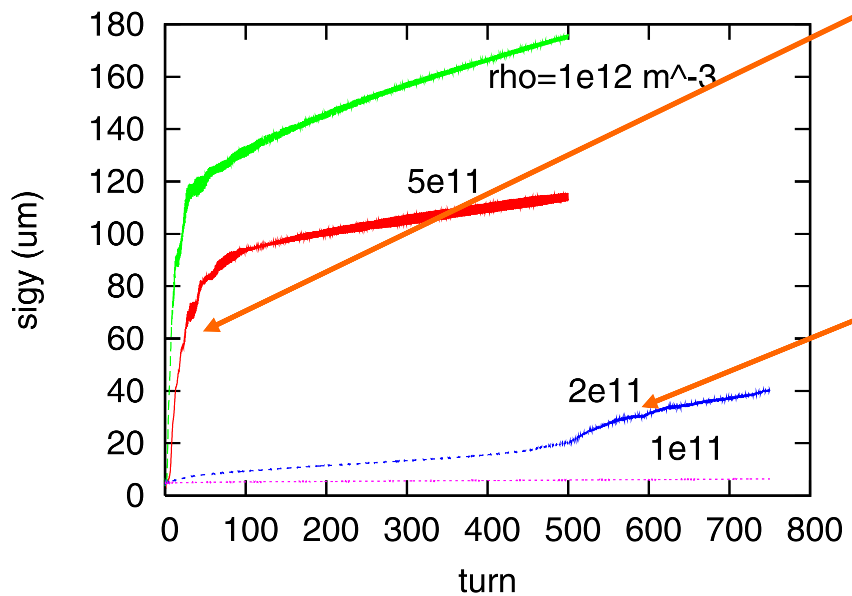


Threshold of the strong head-tail instability in OTW

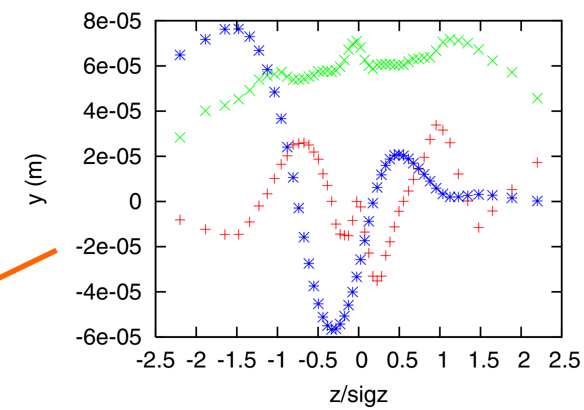
- Growth behavior for IP=4 is different from that for IP=8.
- In both case, beam amplitude in the profile is smaller than emittance growth. No signal for IP=4, and a small signal for IP=8.
- Instability at ρ_e=5x10^{11} m^{-3} is weak and critical. Threshold is $\rho_{e,th}$=5x10^{11} m^{-3}.
- We have to take care of the fact that the result depend on IP. This feature was not remarkable for KEKB simulation. Strong pinching of electron cloud may be essential as is discussed later.

OCS

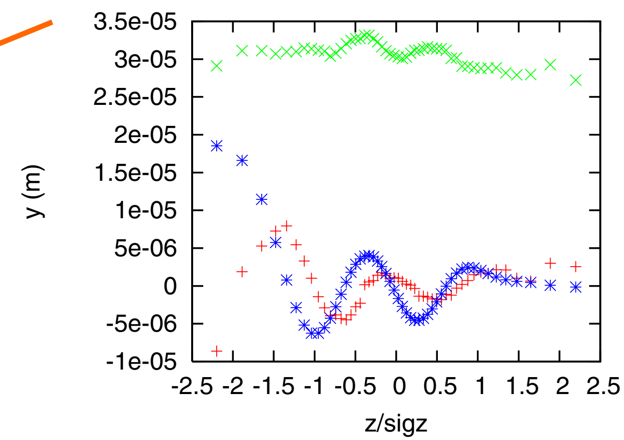
- Clear head-tail signal was observed $\rho_e=2\times10^{11}\ m^{-3}$ and more.
- Threshold $\rho_{e,th}=2\times10^{11}\ m^{-3}$



$\rho_e=5\times10^{11}\ m^{-3}$

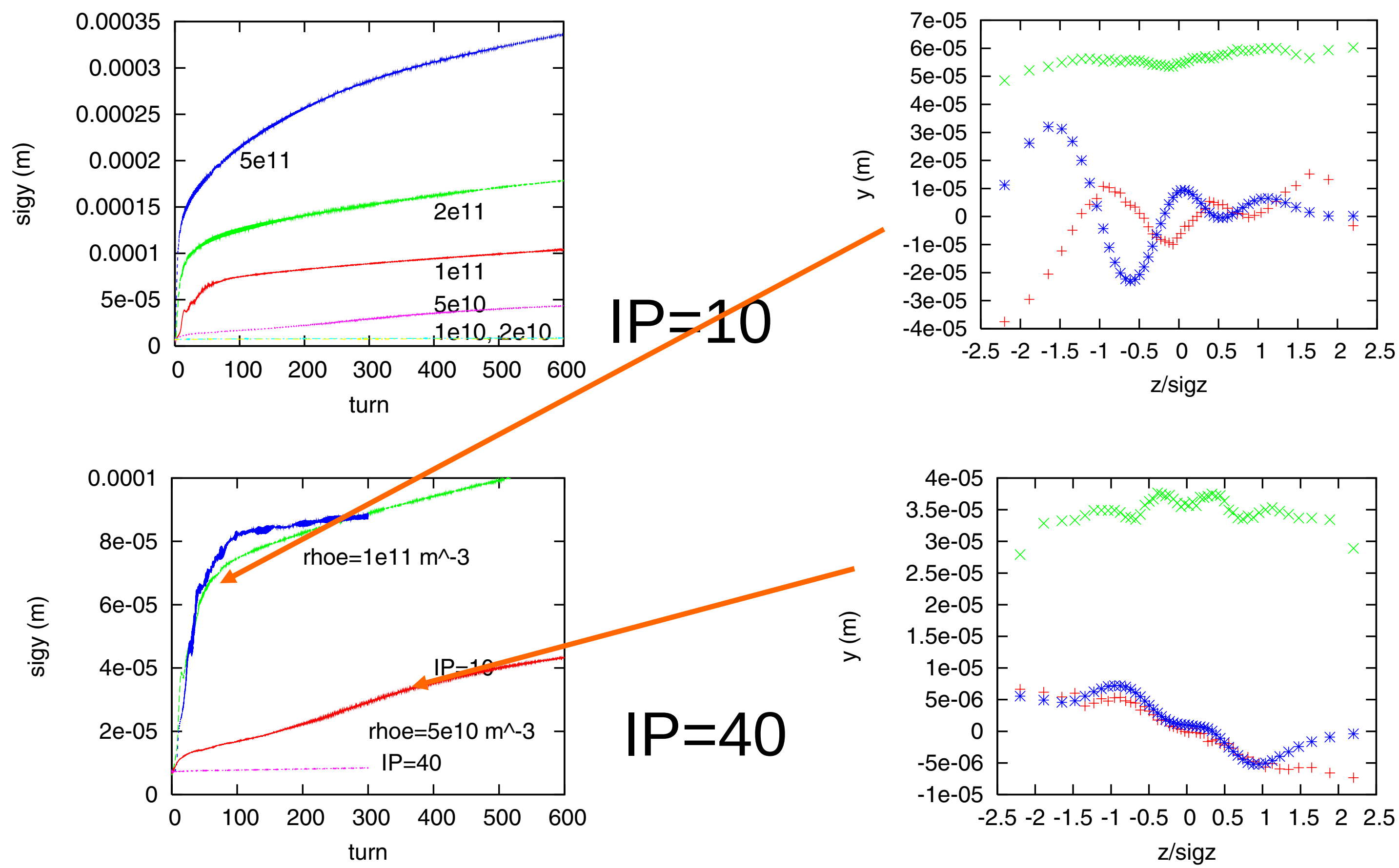


$\rho_e=2\times10^{11}\ m^{-3}$



TESLA

- Threshold $\rho_{e,th}$=1x10^{11} m^{-3}



Above or below the threshold?

- The threshold density

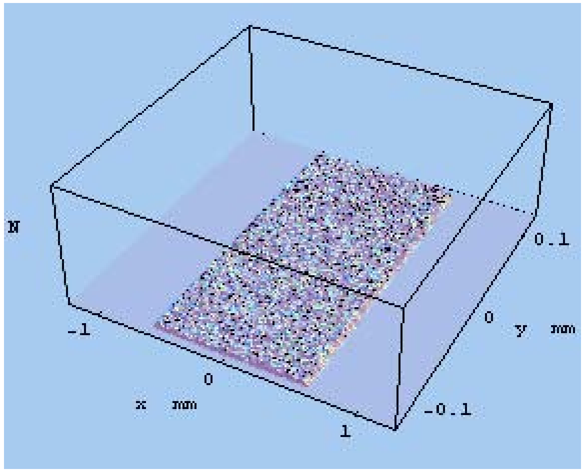
		simulation	linear theory
OTW	$\rho_{e,th}$	$=5 \times 10^{11}\ m^{-3}$	(1.8×10^{12})
OCS		$=2 \times 10^{11}\ m^{-3}$	(7.4×10^{11})
TESLA		$=1 \times 10^{11}\ m^{-3}$	(4.5×10^{12})

- The systematic difference (3-4x) between simulation and linear theory may be due to the cloud pinching.
- Simulations are accurate because the pinching is taken into account.
- To make lower density, multipacting should be avoided.
- Cloud density has been estimated with considering photoelectron production and antechamber geometry.
- Detailed density estimation along the ring gives an answer.

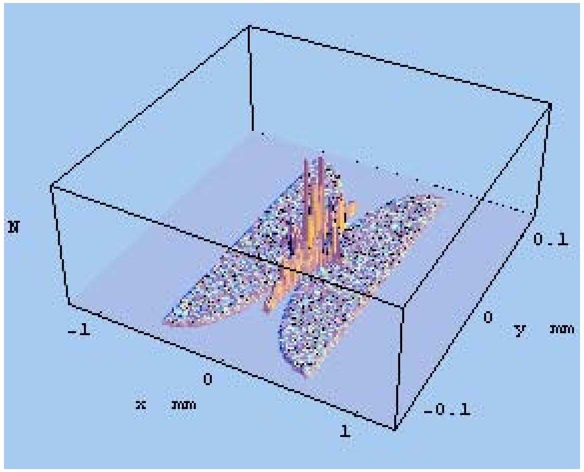
Incoherent emittance growth due to nonlinear interaction

- Electron cloud near beam is strongly squeezed by the beam force.
- Large tune shift for very small region, $\sim\sigma_y/10$.
- The strong nonlinear force causes emittance growth due to the chaotic diffusion like the beam-beam and space charge effects.
- The indication has already seen in simulations for the head-tail effect.
- The growth in the simulation is not accurate, since exact lattice information is not included.
- This work should be done soon.

Electron distribution during collision with the beam

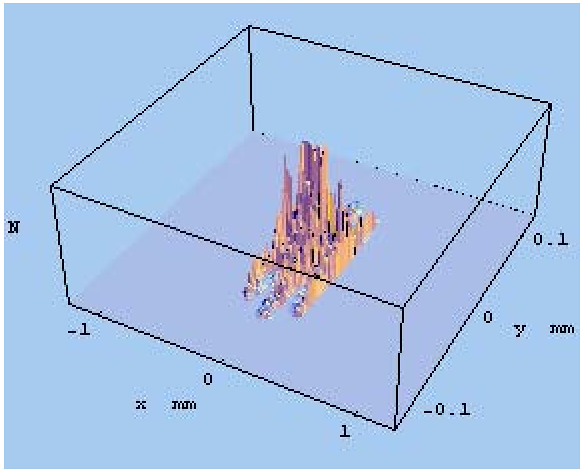


1-st slice

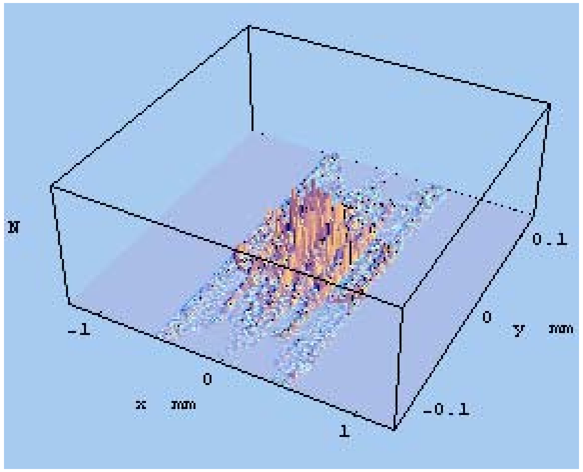


5/50-th

25/50-th $\rho(1)$x40

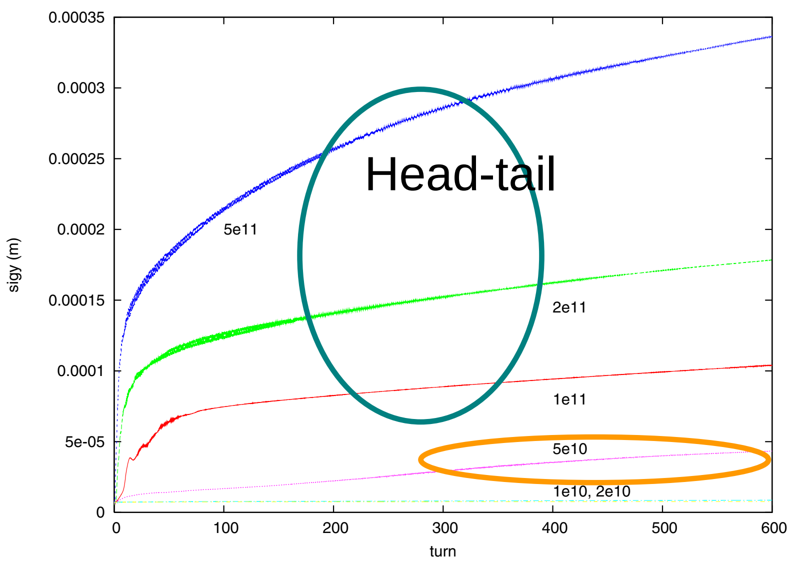


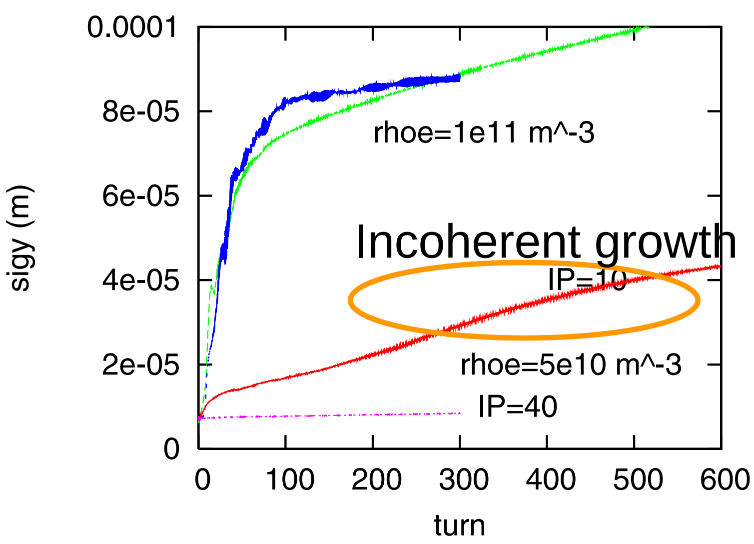
45/50-th slice



Simulation

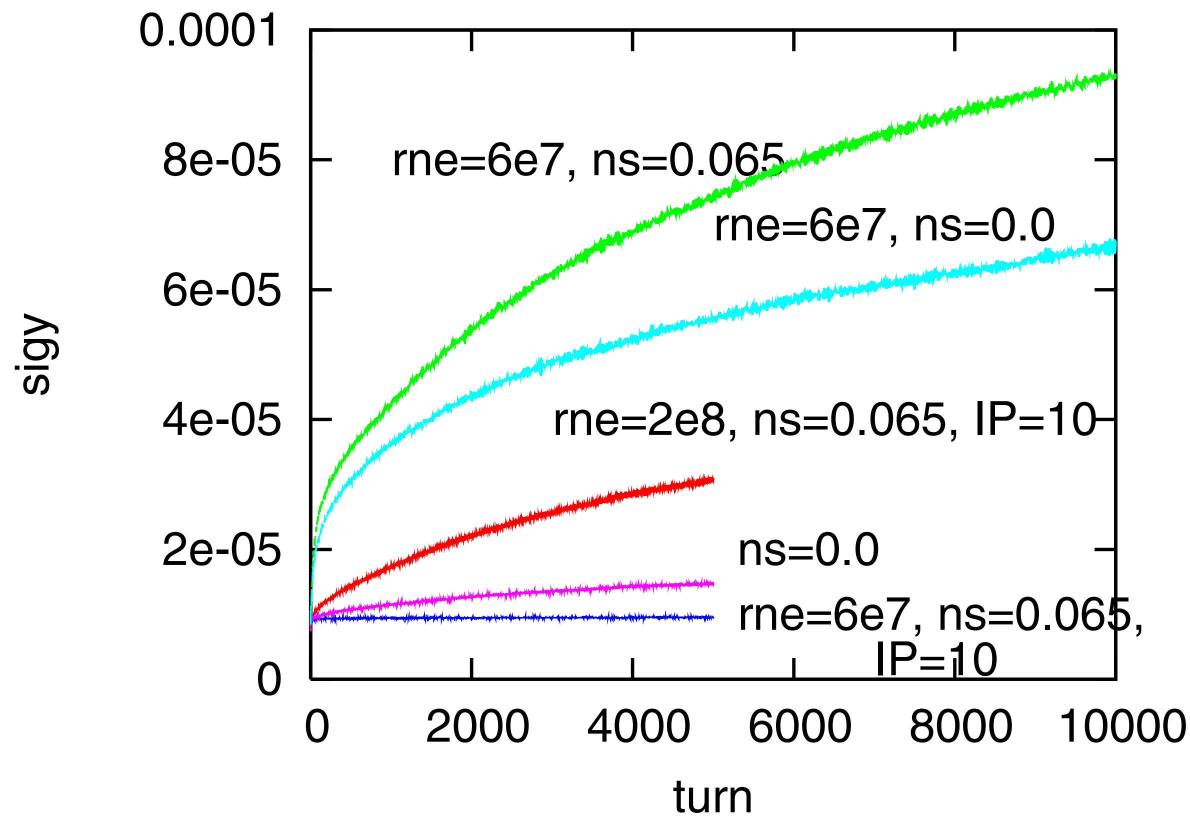
- Threshold of the head-tail instability is between ρ_e=5x10^{10}-1x10^{11} m^{-3}.
- The emittance growth for 5x10^{10} m^{-3} strongly depends on the number of interaction points





Simplified model

- This phenomenon is basically weak-strong effect.
- Emittance growth by a weak-strong simulation is consistent with head-tail (strong-strong) simulation.



Importance of Lattice

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

$$M = \mathrm{e}^{-:K_{1N}:}\,\mathrm{e}^{-:F_{12}:}\,\mathrm{e}^{-:K_{2N}:}\,\mathrm{e}^{-:F_{23}:}\,\mathrm{e}^{-:K_{3N}:}\,\mathrm{e}^{-:F_{34}:}\,\mathrm{e}^{-:K_{4N}:}\,\mathrm{e}^{-:F_{45}:}\,\mathrm{e}^{-:K_{5N}:}\ldots\mathrm{e}^{-:F_{n1}:}$$

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

F: linear transformation

K: nonlinear kick

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

Nonlinear term should be evaluated with considering the beta function and phase of position where electron cloud exists.

Unphysical cancel of nonlinear term may be caused by simple increase of interaction point.

Summary

- Antechamber suppress electron cloud.
- Detail estimation of photon reflection and cloud in magnets has been done and is continued.
- Coupled bunch instability can be cured by feedback system.
- The cloud density is below the threshold of strong head-tail instability, if the average density is that at 5-10 m downstream.
- We need some more time to conclude.