The Simulation of the Electron Cloud Instability in BEPCII and CSNS/RCS

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Outline

(1) Electron cloud build up

- Physical model
- Simulation recipe
- Results for BEPCII

(2) Coupled bunch instability

- turn-by-turn method to calculate the multi-bunch instability

(3) Single bunch instability

- Head tail model for simulation
- Application for BEPCII

(4) Bunch lengthening caused by longitudinal wake field of electron cloud

(5) Electron cloud instability in CSNS (China Spallation Neutron Source)

Electron Build Up in the chamber

electron production

- The number of photons emitted from synchrotron radiation of one positron during one revolution

$$N_\gamma = \frac{5\pi}{\sqrt{3}}\alpha\gamma \approx 244$$

- Photoelectron number

$$N_e = YN_\gamma(1+R+R^2+R^3+\cdots) = \frac{Y}{1-R}N_\gamma = Y'N_\gamma$$

basic yield Y, reflectivity R, quantum efficiency Y'

In the simulation, Y and R are input parameters

- secondary electron emission

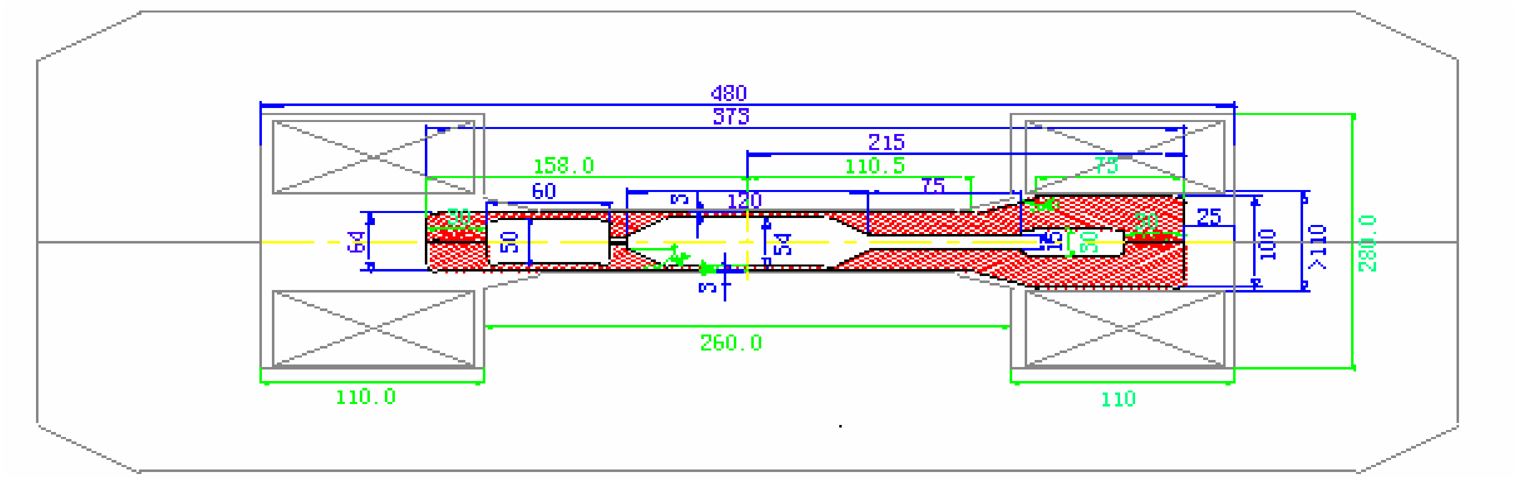
$$\delta(E,\theta) = \delta_{\max} \cdot 1.11 \cdot \left(\frac{E}{E_{\max}}\right)^{-0.35} \cdot \left\{1 - \exp\left[-2.3 \cdot \left(\frac{E}{E_{\max}}\right)^{1.35}\right]\right\} / \cos\theta$$

Incident angle θ, maximal secondary yield $\delta_{\max}$,

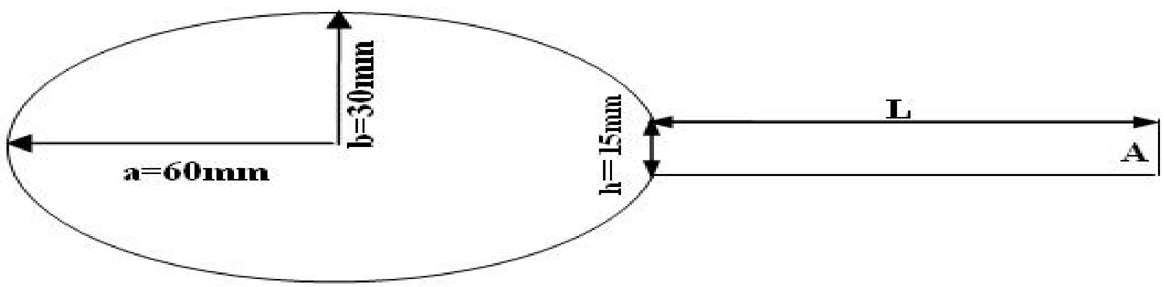
$E_{\max}$ is electron incident energy responding to $\delta_{\max}$

With TiN coating in the chamber, $\boxed{\delta_{\max} \approx 1.06}$

Without TiN coating, $\boxed{\delta_{\max} \approx 1.8}$

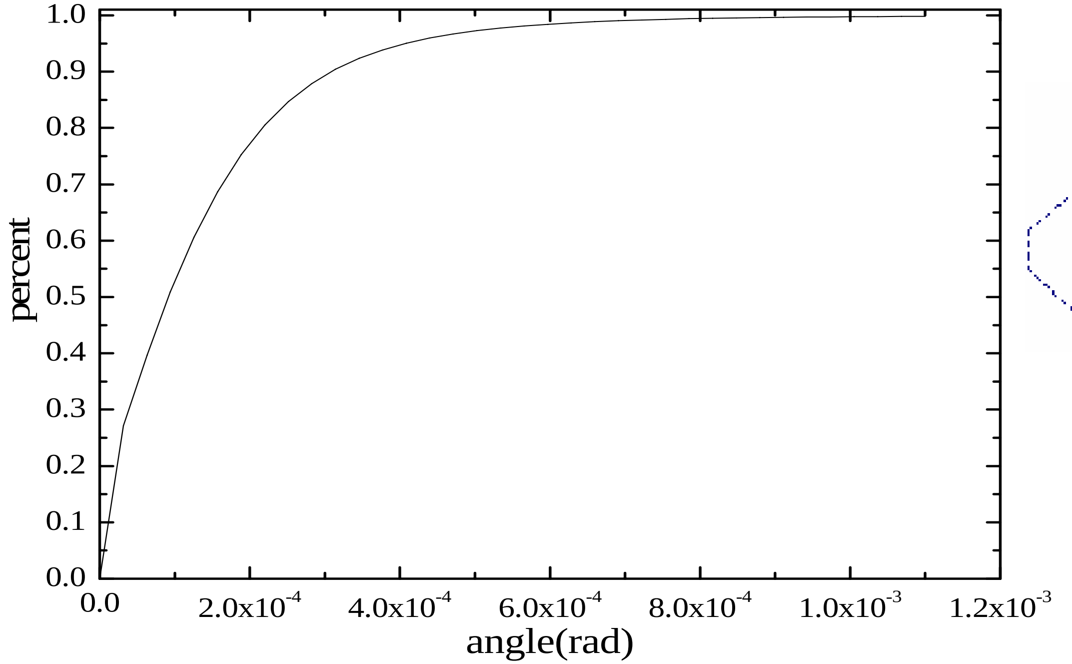


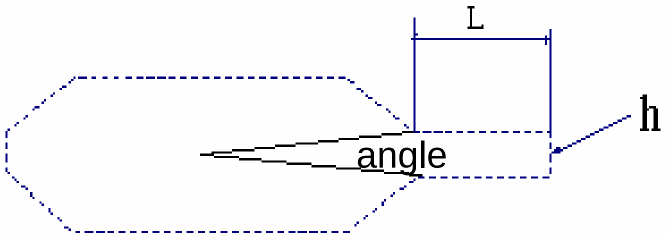
chamber in the Dipoles of BEPCII



chamber structure in the simulation

- Photon in the antechamber

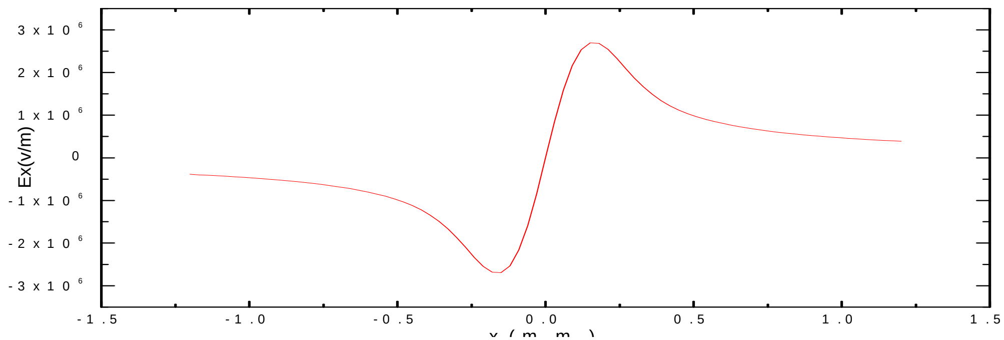




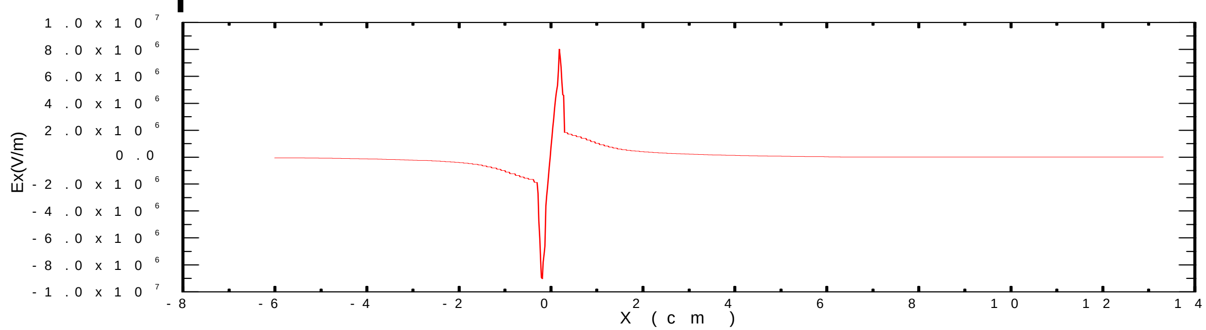
99.5% photons will be produced in the antechamber

The beam field in the pipe of BEPCII

- In central region of beam $(10\sigma_x, 10\sigma_y)$,the beam field is presented by Basseti-Erskine formula.



- Out of the central region, the beam field is the solver of Poission-Superfish.



Simulation recipe for the ecloud build up

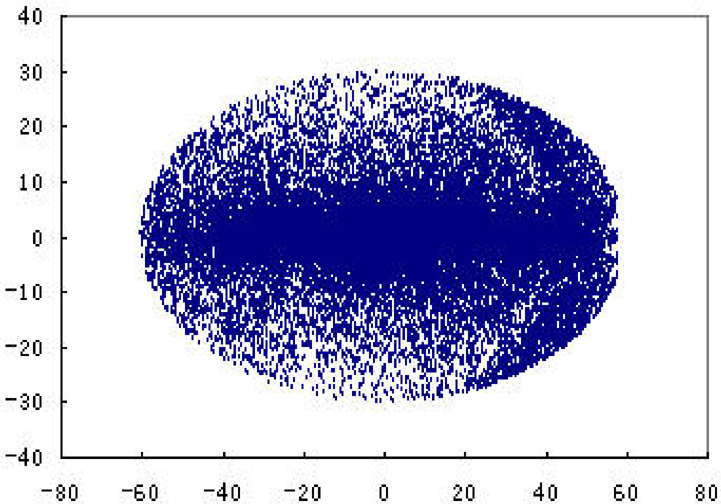
- Present e- with macro-particles(10^4 e- for a bunch passing)
- For every bunch, e- will be produced in the pipe and antechamber
- e- will be accelerated in the beam field
- If e- hit the boundary of the pipe, secondary electron will be produced.
- e- will move between the bunches in the field of the ecloud space force and clearing electrode field
- If there is a photon absorber in the antechamber, the yield Y and reflectivity R will be much smaller.

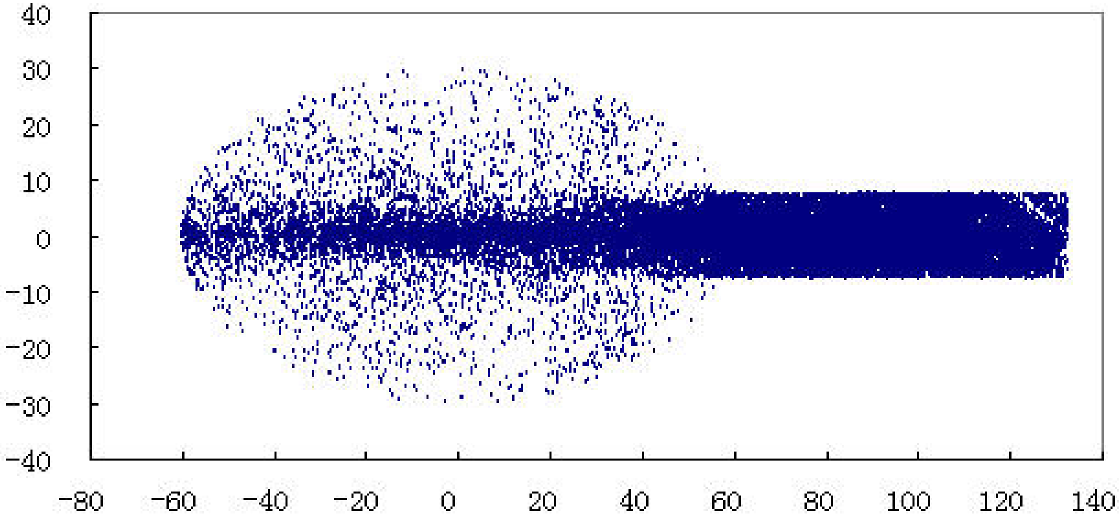
Main Parameters of BEPCII

Energy E(GeV)	1.89	Energy spread(10^{-4}) σ_e	5.16
Circumference C(m)	237.53	Momentum compact α_p	0.0235
Rev. frequency f_0 (MHz)	1.2621	Bunch length σ_z(cm)	1.5
Harmonic number h	396	Emittance $\varepsilon_x/\varepsilon_y$(nm)	144/2.2
RF frequency f_{rf}(MHz)	499.8	β_x/β_y(m)	10/10
RF Voltage V_{rf}(MV)	1.5	σ^*_x/σ^*_y(μm)	380/5.7
Energy loss/turn U_0(keV)	121	$\nu_x/\nu_y/\nu_z$	6.57/7.61/0.033
Damping time $\tau_x/\tau_y/\tau_z$(ms)	25/25/12.5	ν'_x/ν'_y	-11.9/-25.4
Total current/beam I(A)	0.91	Crossing angle ϕ^*(mrad)	±11
SR Power P(kW)	110	Piwinski angle Φ(rad)	0.435
Bunch number N_b	93	Bunch spacing S_b(m)	2.4
Bunch current I_b(mA)	9.8	Beam-beam parameter ξ	0.04/0.04
Particle number N_t	4.84×10^{10}	Luminosity($10^{33}cm^{-2}s^{-1}$) L_0	1.0

Simulation for the ecloud density

- Ecloud distribution in the pipe with or without antechamber

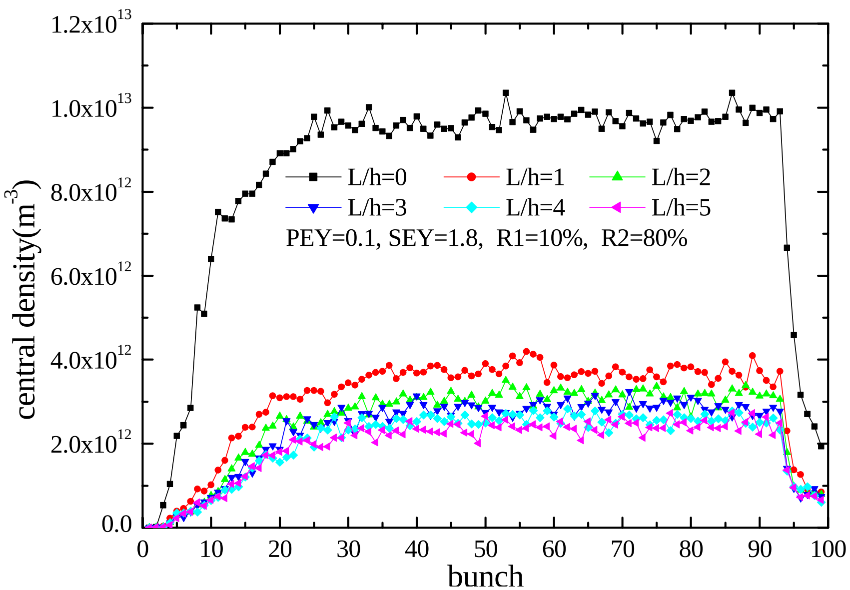


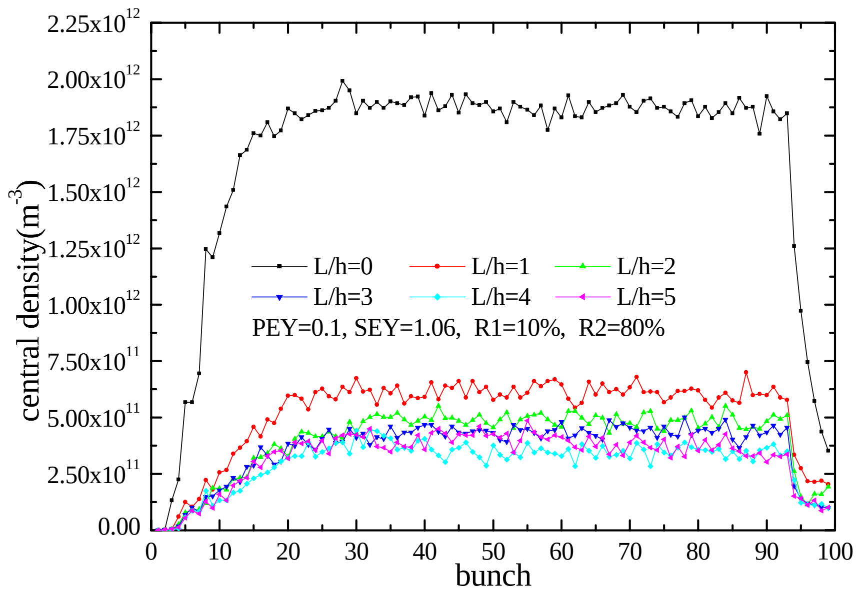


(the length of the antechamber is 5 times of its height L=5h)

Much of the electrons will be produced in the antechamber.

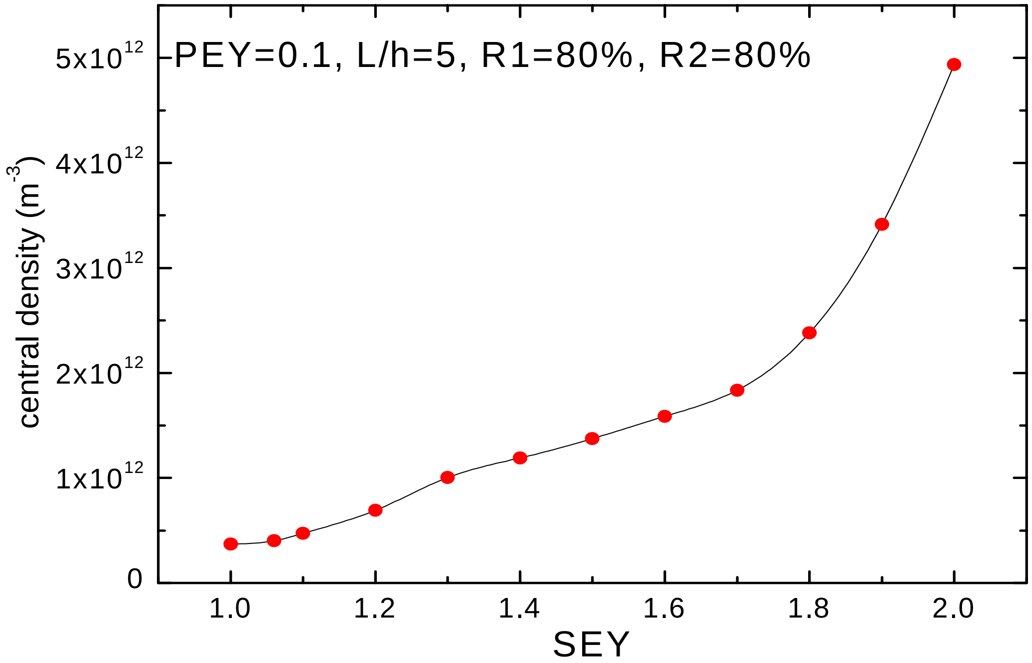
- Ecloud density in different length of antechamber





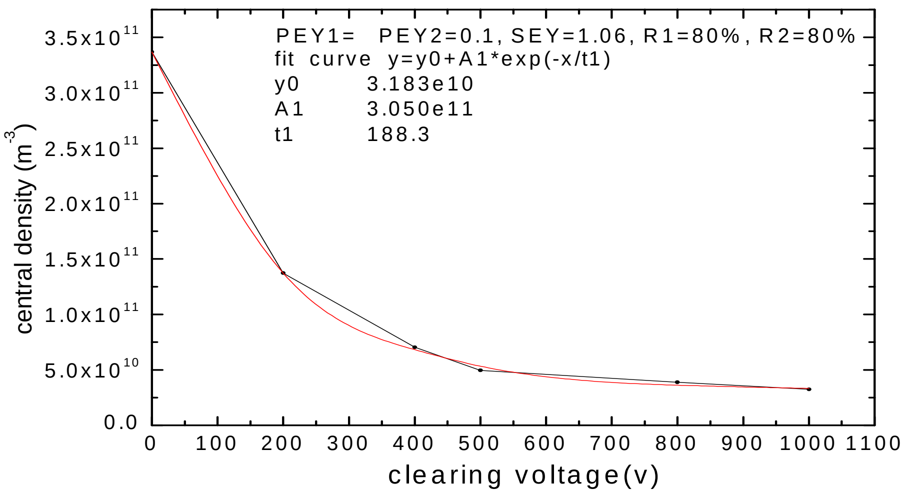
With the antechamber, the central density can be reduced about 5 times.

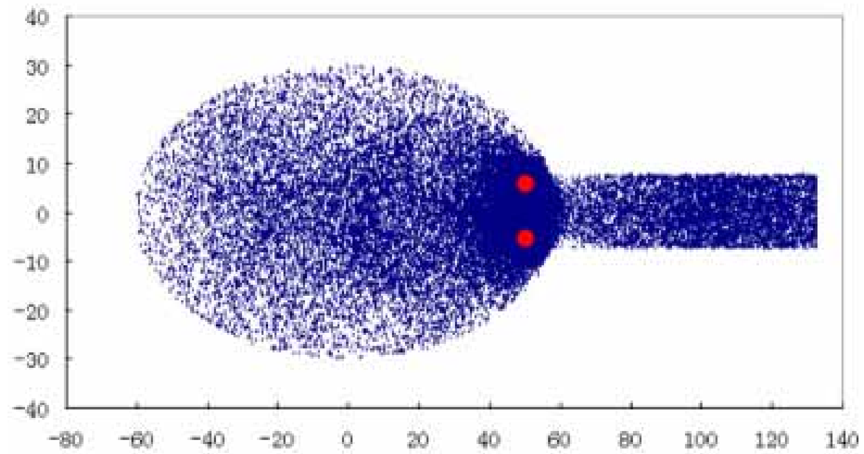
- Ecloud density with different secondary yield



After SEY>1.6, ecloud density increased quickly.

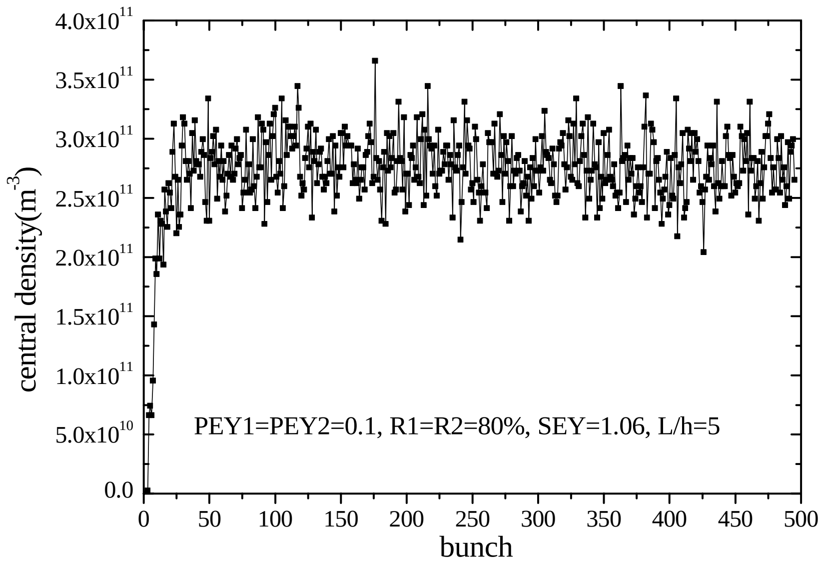
- Ecloud density with clearing electrodes in the pipe



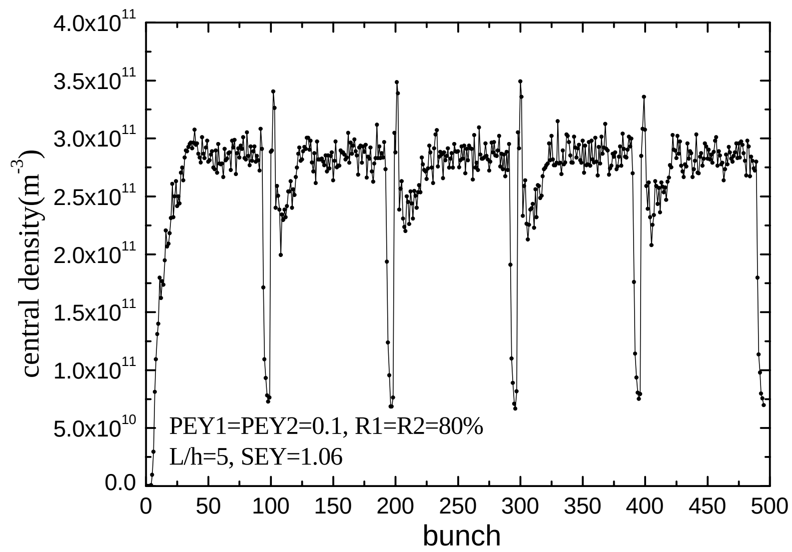


Much of the electrons will surround the electrodes.

- Ecloud density with a bunch train in many turns



without train gap



train gap: 48ns

Summary of the ecloud density in different restraining methods

Restraining methods	L/h	PEY(Y)	R	SEY	ρ (m^{-3})
None	0	0.1	80%	1.8	1.03×10^{13}
Antechamber only	5	0.1	80%	1.8	2.22×10^{12}
TiN coating only	0	0.1	80%	1.06	1.85×10^{12}
antechamber and TiN coating	5	0.1	80%	1.06	3.26×10^{11}
antechamber and photon absorber	5	0.02	10%	1.8	7.18×10^{11}
antechamber, photon absorber and TiN	5	0.02	10%	1.06	1.35×10^{11}
antechamber and clearing electrodes	5	0.1	80%	1.8	3.74×10^{11}
antechamber, clearing electrodes and TiN	5	0.1	80%	1.06	3.33×10^{10}

Electron cloud in different magnetic fields

- the force of the magnetic field

$$F_B = e V_e \times B$$

In dipole magnetic field region without considering the fringe field, the magnetic field is only in vertical direction.

$$B = B_y$$

the electrons in the cloud are confined to move in tight vertical helices whose radius is typically a few microns, and whose cyclotron frequency is $f = eB/2\pi m$, B=8000Gs, $f = 22.3$GHz. The main consequence of the cyclotron motion of the electrons is the severe suppression of the horizontal component of the velocity of the electrons in the cloud.

- in quadrupole magnetic field, ***B*** can be expressed by

$$B_x = k_1 y$$

$$B_y = k_1 x$$

k_1 is gradient of the magnetic field

- in sextupole magnetic field, B can be expressed by

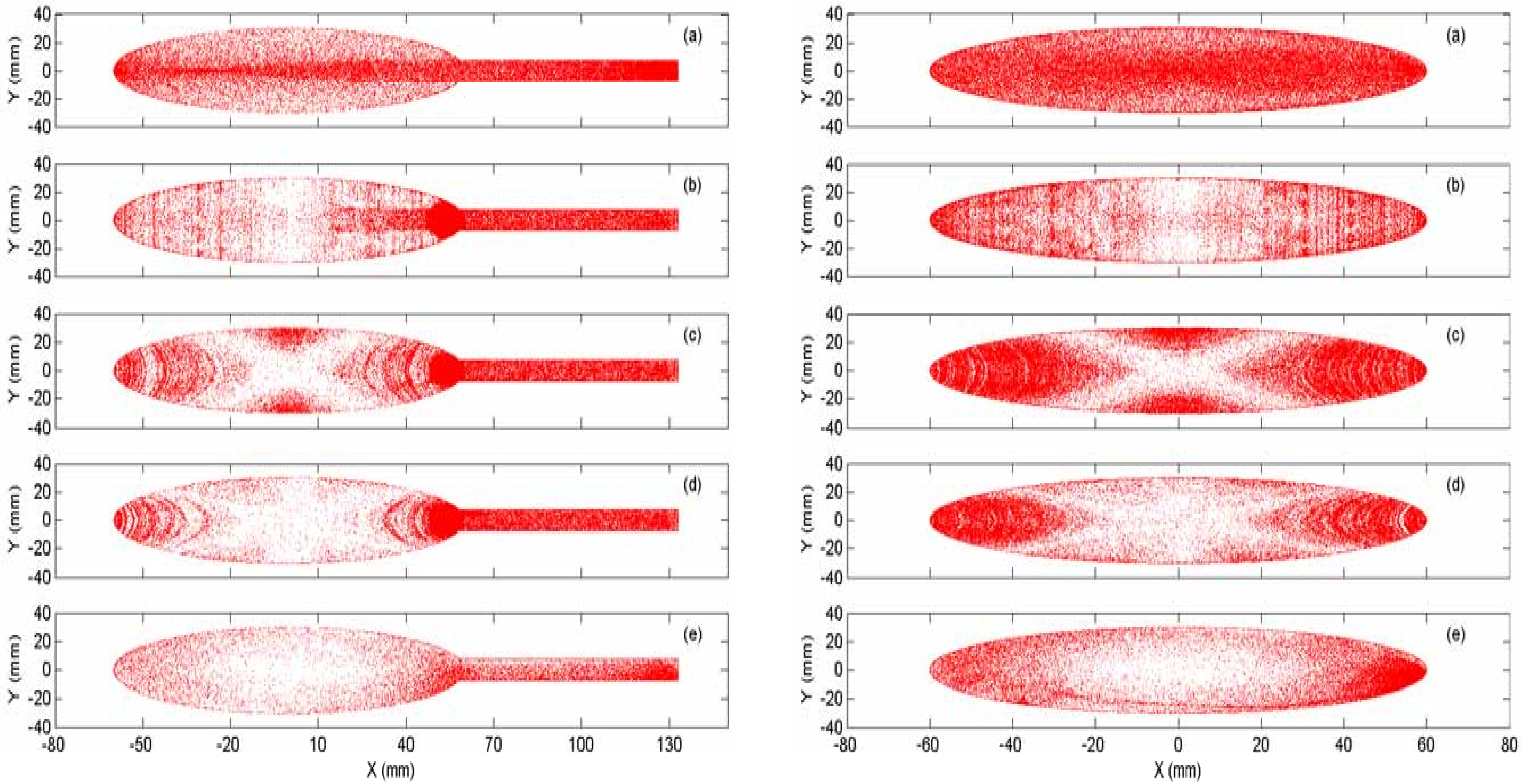
$$B_x = k_2 xy$$

$$B_y = \frac{1}{2} k_2 (x^2 - y^2)$$

- In uniform solenoid field, the magnetic field is only in longitudinal direction.

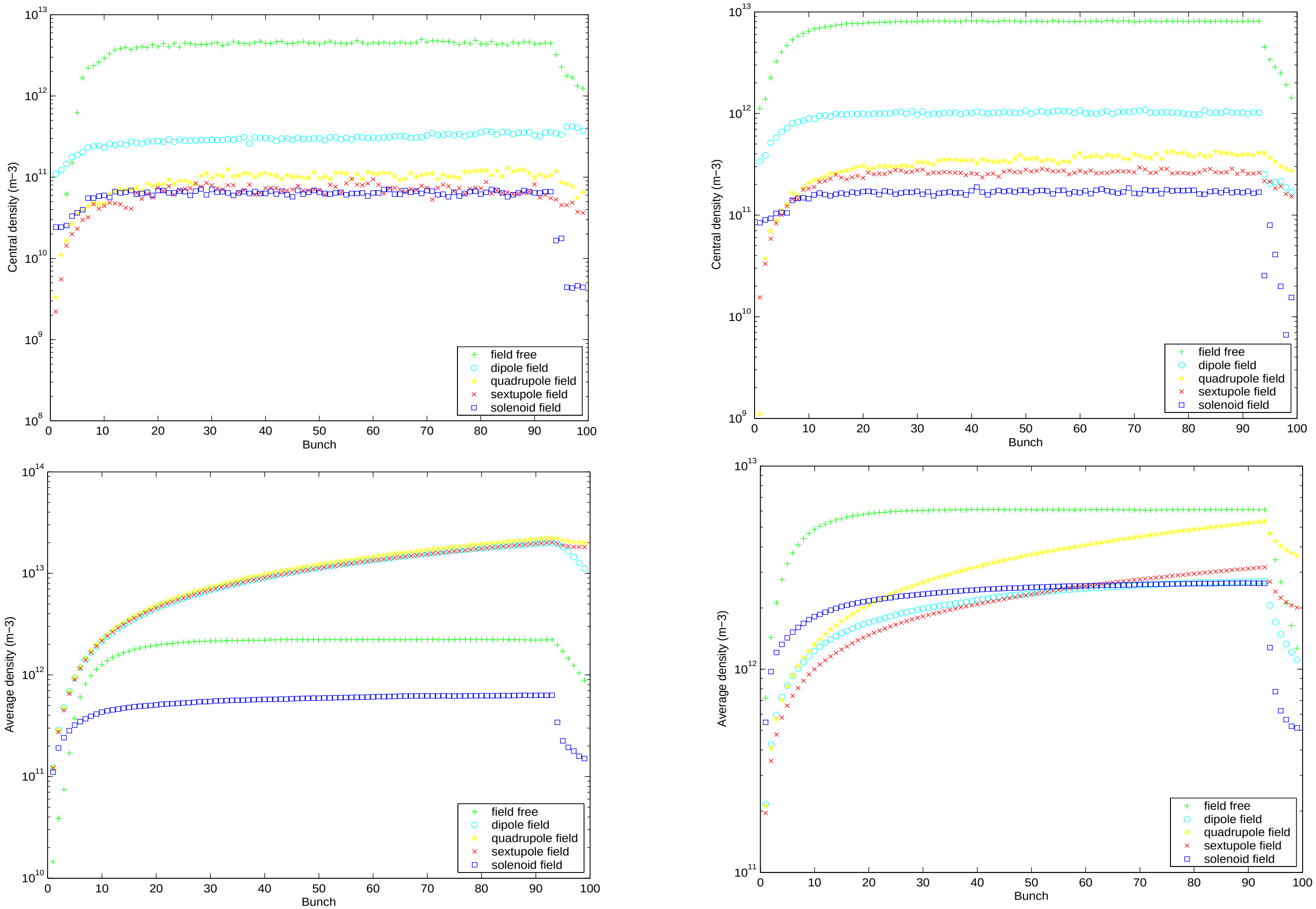
$$B = B_z$$

Electron cloud distribution in magnetic fields



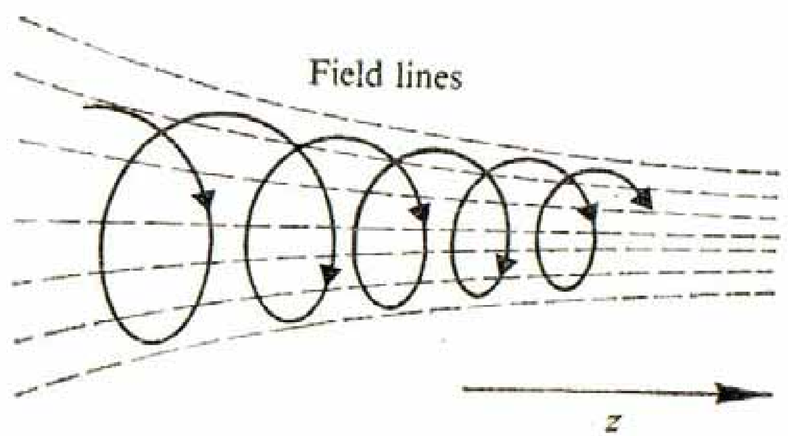
Distribution of electron cloud in various kinds of magnetic field
left: chamber with antechamber; right: elliptic chamber)
(a: free field region; b: dipole field; c: quadrupole field; d: sextupole field; e: solenoid field *Bz*=10Gs)

Electron cloud density in elliptic and antechamber vacuum chamber



(left: antechamber; right: elliptic chamber)

The distribution of electron cloud in the quadupole and sextupole magnetic fields can be explained with the magnetic mirror trap in the plasma physics . The motion of the electron in the magnetic field can be regarded as the superposition of the gyration motion around the guiding center and the motion of the guiding center. The gyration motion of the electron is a rapid rotation around the magnetic field line. The motion of the guiding center is the average motion over the gyration motion.

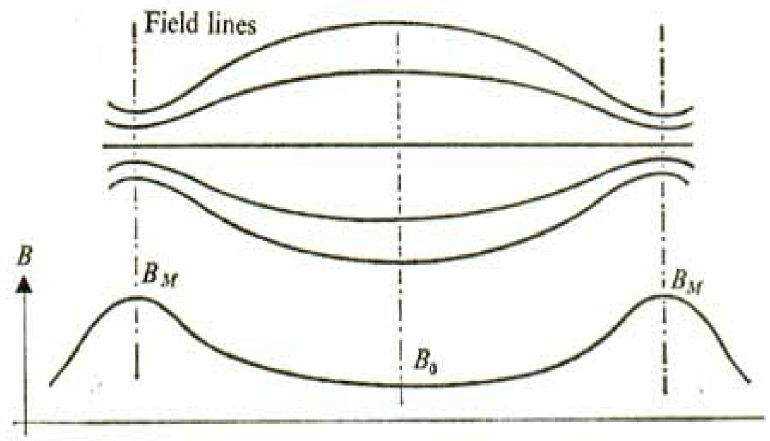


In magnetic fields, the total energy of the electrons will be a constant. That is expressed by

$$\frac{1}{2}mV_{//}^{2} + \mu B = const \qquad \mu = \frac{1}{2}mV_{\perp}^{2} / B$$

μ is the magnetic moment, $V_{\perp}$ is the gyration motion of electrons
$V_{//}$ is the parallel or longitudinal velocity, which is parallel to the magnetic field

The magnetic field is a mirror field in the quadrupole and sextupole magnets, in which the magnetic field is weaker at the center and is stronger at both ends of the field lines. Thus, the same trap effect will happen in quadrupole and sextupole magnetic fields.

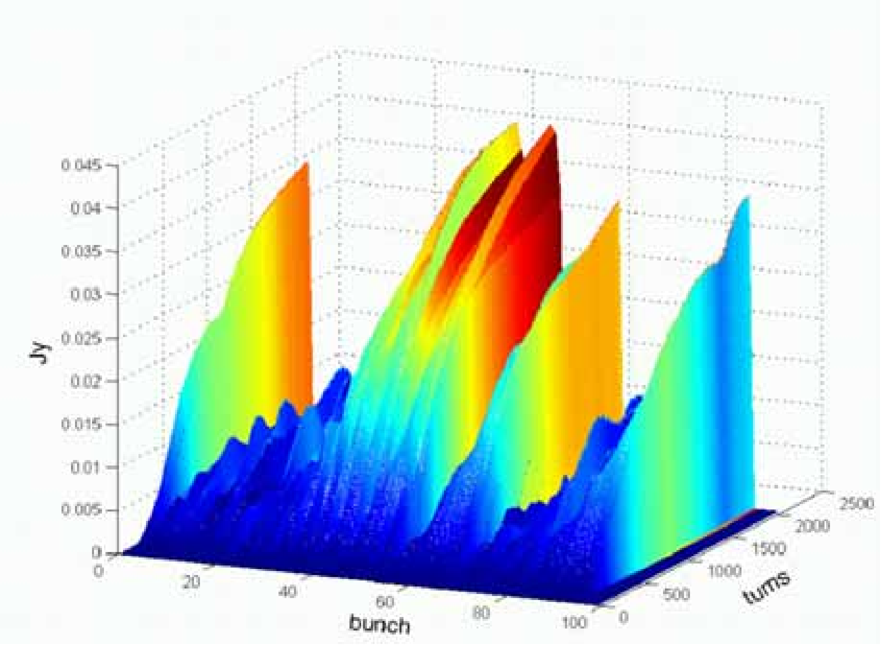


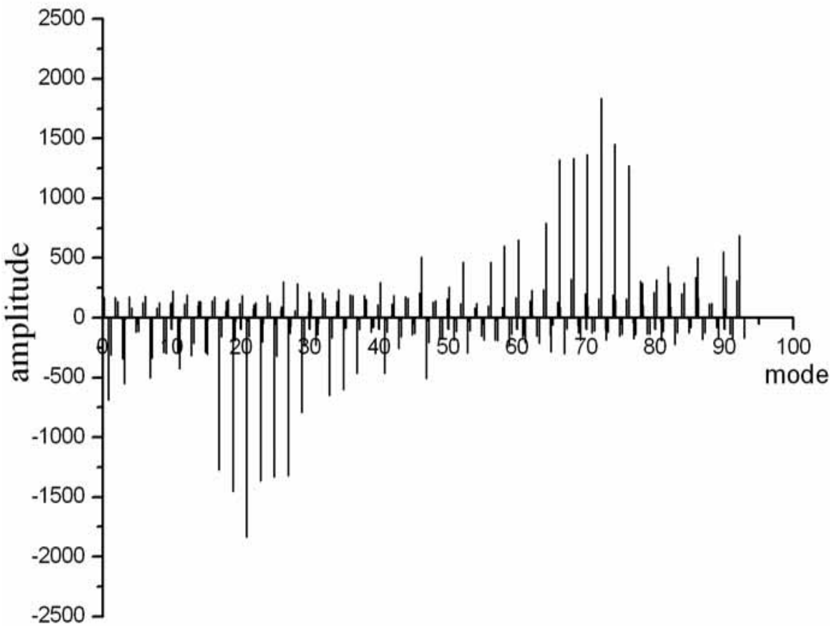
Coupled bunch instability

- The turn by turn method was used to track the motion of 93 bunches in a train.
- In every circle the positions of 93 bunches will be recorded.
- The oscillation can be transferred to the spectrum by FFT.

- The tracking results

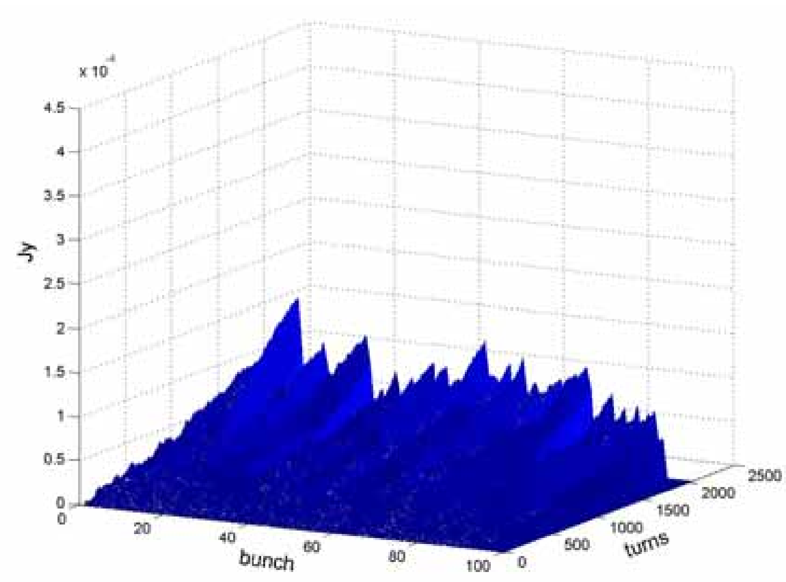
Elcoud density $1.03\times10^{13}m^{-3}$

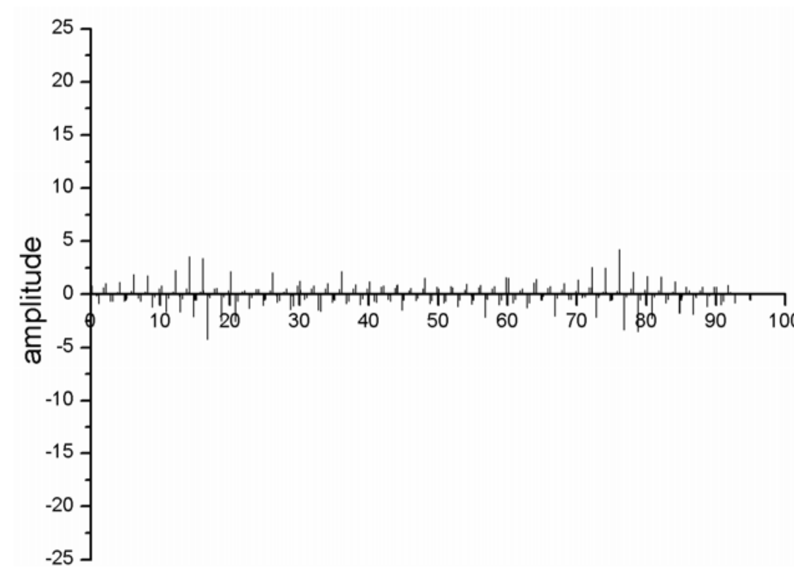




Growth time $\tau \approx 0.08ms$

电子云密度$1.35\times 10^{11}\,m^{-3}$



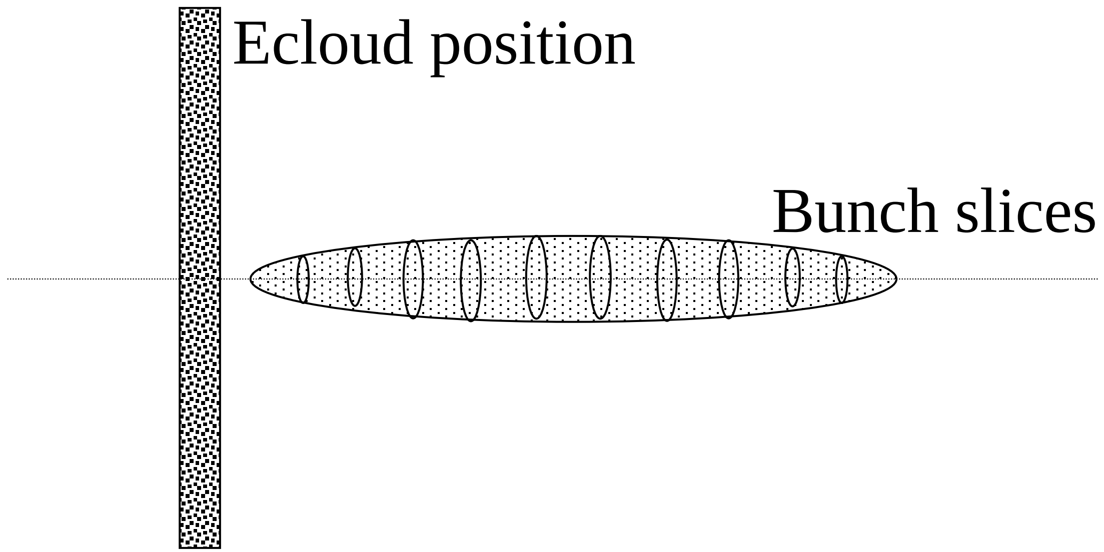


Growth time $\tau \approx 4.3ms$

Single bunch instability

- e- are accumulated near the beam center during bunch passage
- if there is a displacement between head and tail particles, the tail experiences a ‘wake’ force
- effective short-range wake field in region of the bunch length
- Strong head tail theory can be use to estimate the threshold of the blow up
- Positive chromaticity can restrain the bunch blow up

Simulation approach for single bunch instability



- ✓ Concentrate e− cloud at one location of the ring
- ✓ Represent bunch and e- with macro-particles

- ✓ compute electric force between bunch macro-particles and ecloud macro-particles
- ✓ For bunch macro-particles, there is a change in x’ and y’
- ✓ For ecloud macro-particles, their position (x_e,y_e) will change between two slices
- ✓ Between turns, beam macro-particles can change longitudinal position Z due to synchro-motion

- The force between positron and electron

$$\frac{d^2 \boldsymbol{X}_{\boldsymbol{p,i}}}{ds^2} + K(s)\boldsymbol{X}_{\boldsymbol{p,i}} = \left(\frac{2r_e}{\gamma}\right) \cdot \sum_{j=1}^{n_e} \boldsymbol{F}(\boldsymbol{X}_{\boldsymbol{p,i}} - \boldsymbol{X}_{\boldsymbol{e,j}})$$

$$\frac{d^2 \boldsymbol{X}_{\boldsymbol{e,i}}}{dt^2} = -2r_e c^2 \cdot \sum_{i=1}^{n_b} \boldsymbol{F}(\boldsymbol{X}_{\boldsymbol{p,i}} - \boldsymbol{X}_{\boldsymbol{e,j}})$$

$$\boldsymbol{F} = -\frac{\boldsymbol{X}}{|\boldsymbol{X}|^2}\delta(s)$$

$$M(s) = \begin{pmatrix} \cos(2\pi\nu_{x,y}) & \bar{\beta}\sin(2\pi\nu_{x,y}) \\ -\frac{\sin(2\pi\nu_{x,y})}{\bar{\beta}} & \cos(2\pi\nu_{x,y}) \end{pmatrix}$$

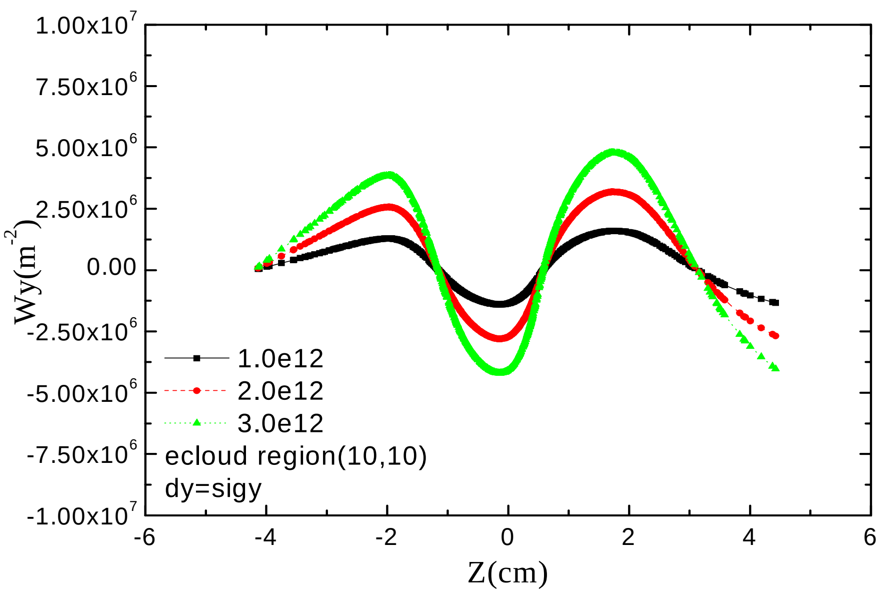
M(s) is transfer matrix of the ring

Simulation results

- Ecloud short-wake field

Head particles distance $\Delta y = \sigma_y$

the short wake expressed as: $W(z_j, z_i) = \frac{N_p \gamma}{N_b r_e} \frac{\delta y'_{p,j}}{\Delta y_{p,i}}$

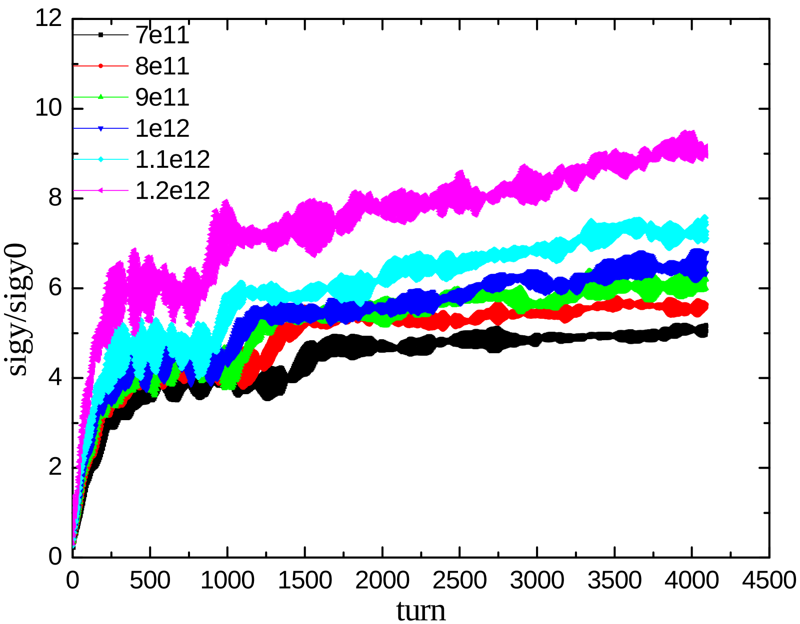


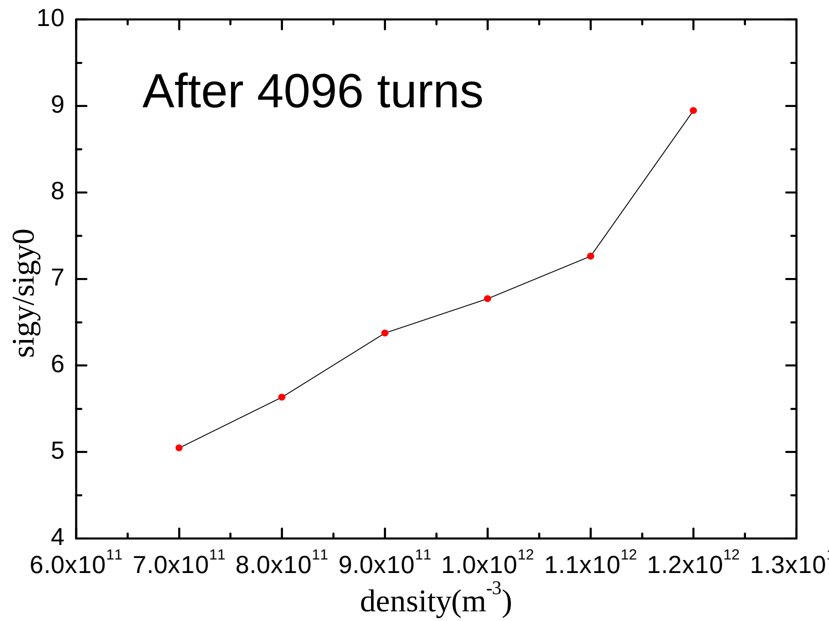
•Strong head-tail instability threshold

$$\Gamma = \frac{N_b r_e \,|\, W_y(0) \,|\, \bar{\beta}_y}{16 \gamma \nu_s} \leq 1$$

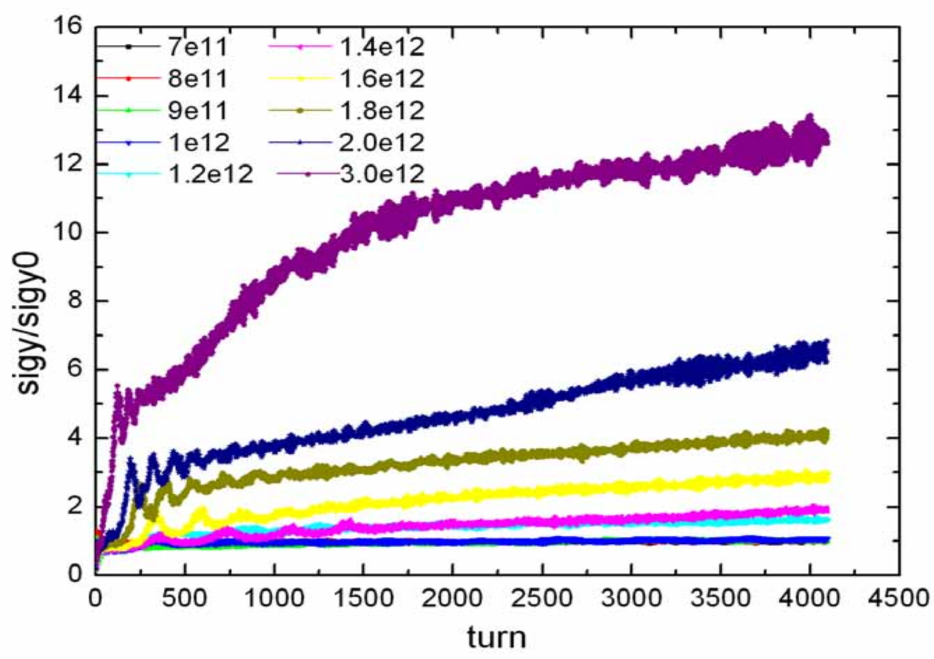
According the formula, the wake field threshold is $1.47 \times 10^6 m^{-2}$ corresponding to the ecloud density $9.2 \times 10^{11} m^{-3}$. So there will be a single bunch instability threshold in $9.2 \times 10^{11} m^{-3}$.

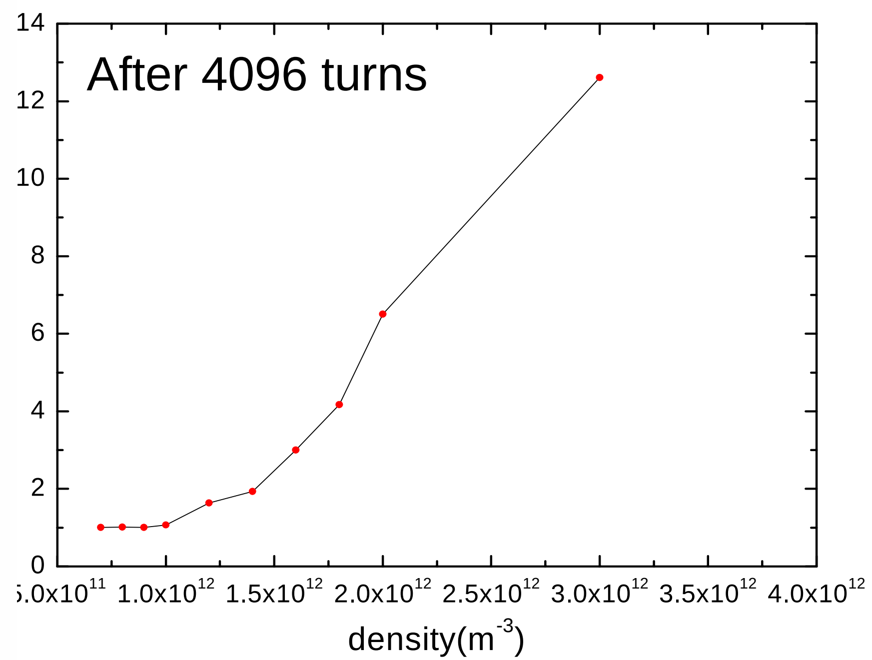
- Increase of bunch size in different ecloud density
(without considering the synchrotron motion)





- Increase of bunch size in different ecloud density (considering the synchrotron motion ,chromaticity (0,0))





- Effect of chromaticity on the beam size

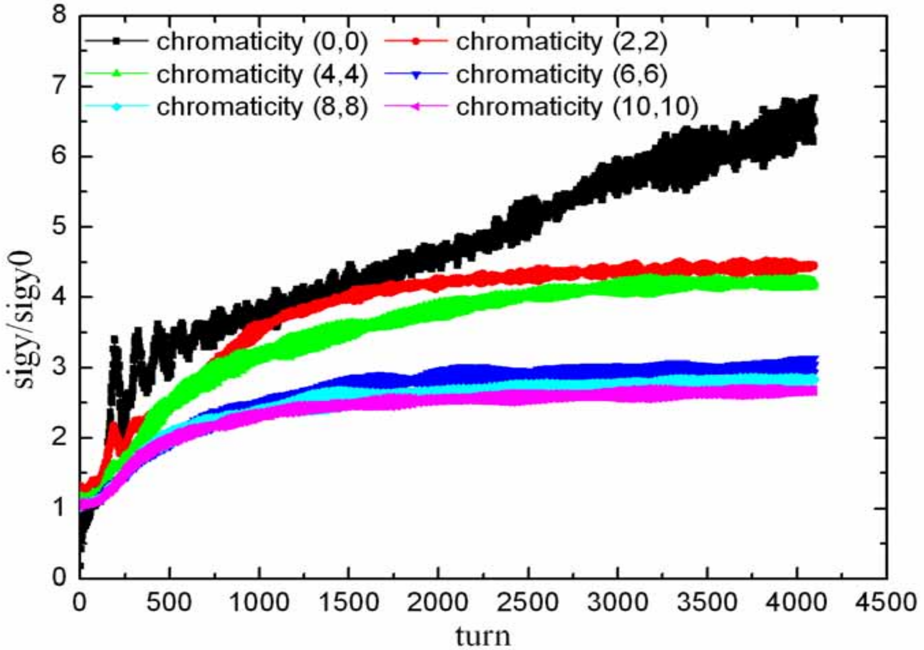
Considering the Energy error, the tune will change in different particles.

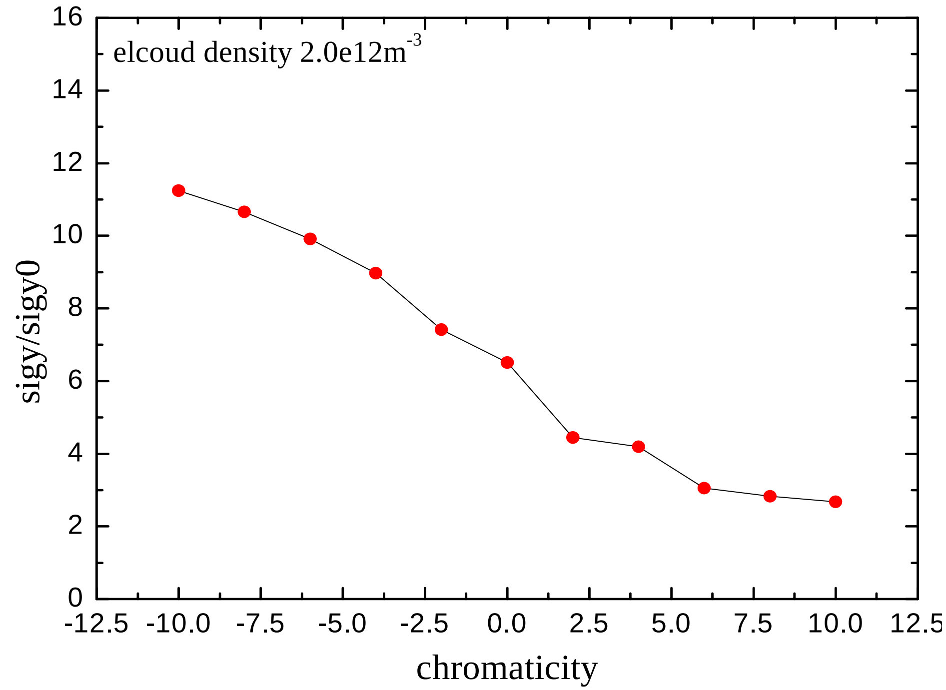
$$\nu_{x,y} = \nu_{0x,0y} + \xi_{x,y} \left(\frac{\Delta P}{P}\right)_{x,y}$$

$$\varphi_{x,y} = \varphi_{0x,0y} + \frac{\omega_0 \xi_{x,y}}{c} \int_C \left(\frac{\Delta P}{P}\right)_{x,y} ds$$

The betatron and synchrotron motions are coupled by chromaticity. Positive chromaticity can restrain the bunch blow up.

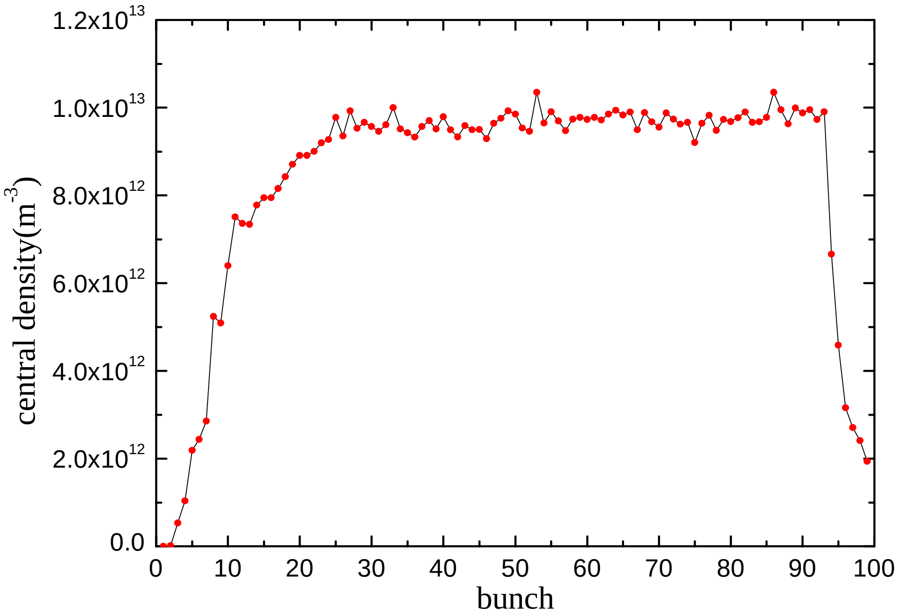
- Results for different chromaticity



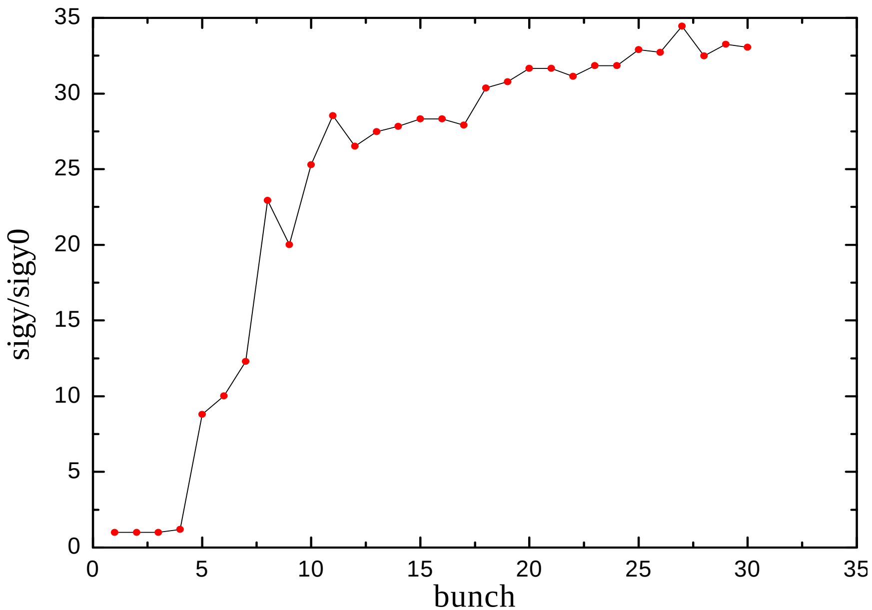


- # Blow up in bunch train

According to the ecloud density, the bunches size change in the train can be simulated.



The ecloud density in BEPCII (without any restrain methods)



The bunches size in a train

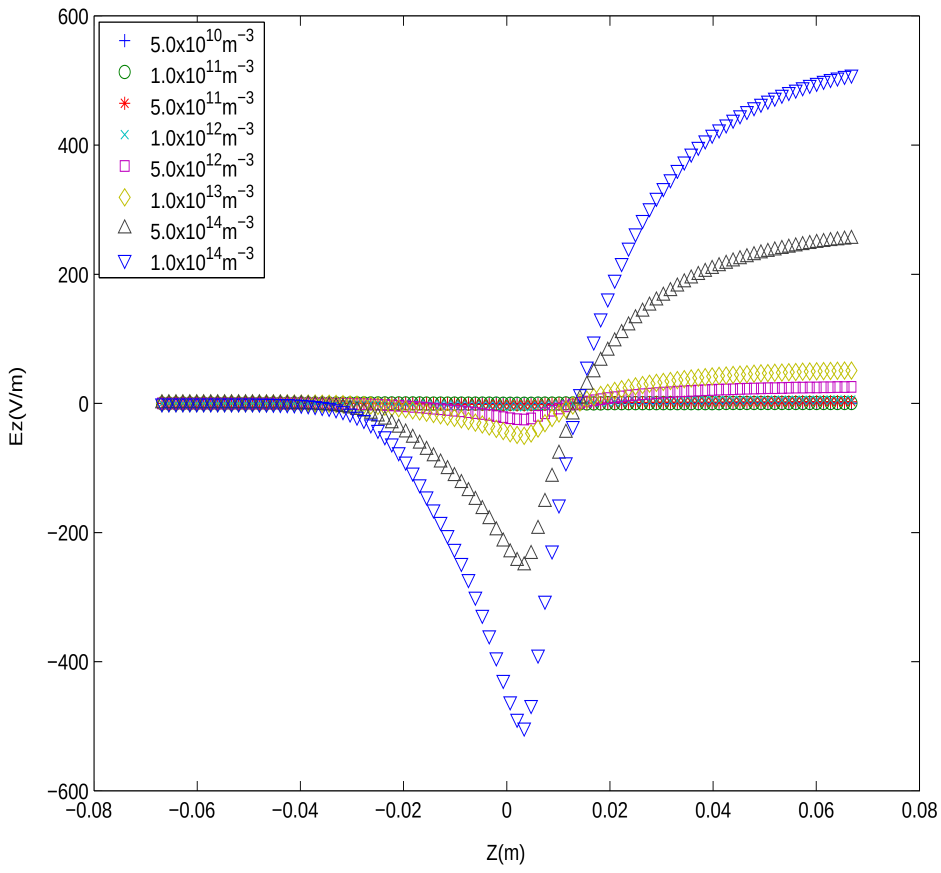
Bunch lengthening caused by longitudinal wake field of electron cloud

Physical model for the longitudinal wake field of electron

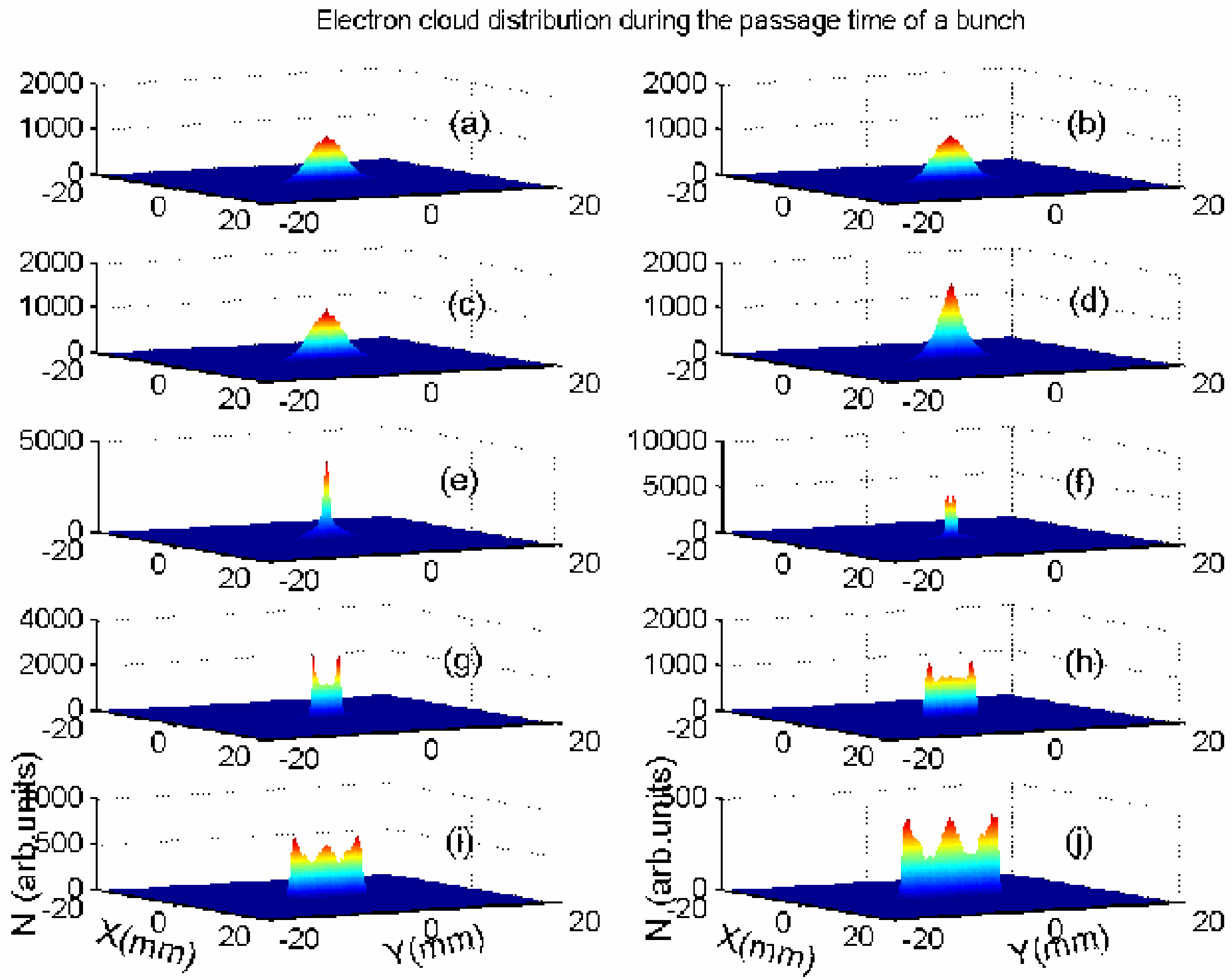
During the passage of a bunch through the electron cloud, the electrons are attracted by the beam electric field and accumulate around the positron beam. The positron bunches have to lose some mount of their kinetic energy to build the electron cloud during the interaction with the electrons. The energy variation inside the bunch can be seen as a longitudinal wake. The bunch particles have an additional energy spread due to the longitudinal wake from the electron cloud. the longitudinal electric field of the electron cloud is expressed as,

$$E_z = Z_0 \int_r^a j_r dr$$

Z_0 the impedance in free space and j_r is transverse current density of electron cloud.



During the passage of a positron bunch the transverse distribution of the electron cloud also has some significant change as displayed in the following figure.

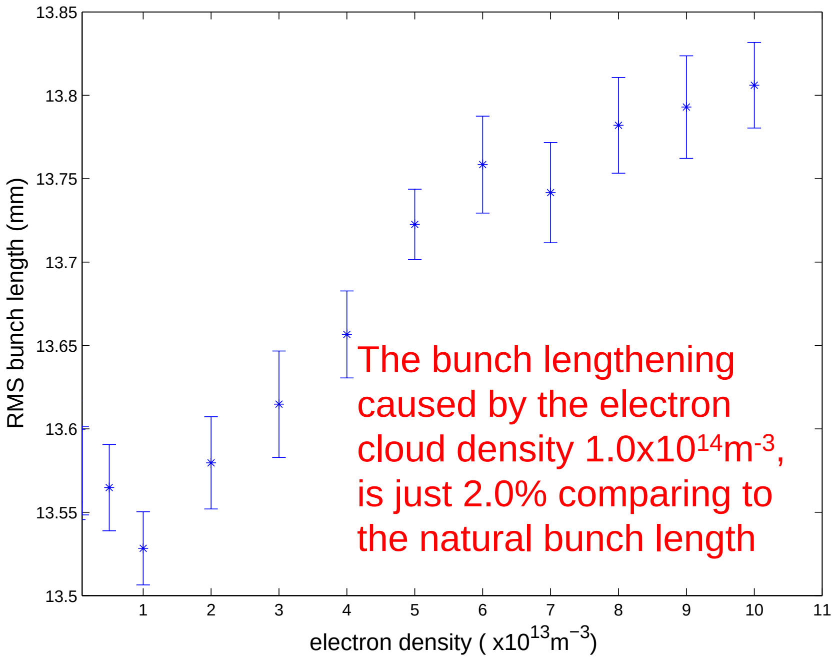


A normal method to simulate the process of bunch lengthening is to track the motions of many macro-particles presenting the bunch. The motion of macro-particles is described in the longitudinal phase by

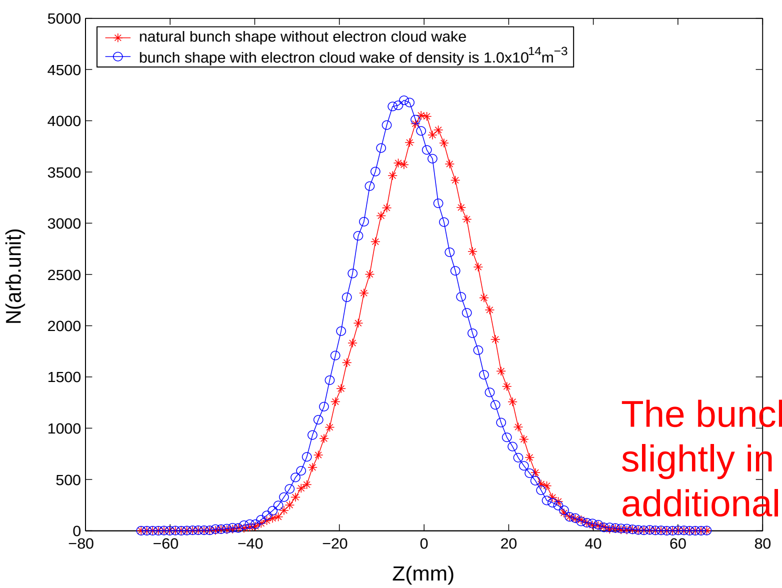
$$z_i(n) = z_i(n-1) + \frac{\alpha c T_0}{E}\varepsilon_i(n)$$

$$\varepsilon_i(n) = \varepsilon_i(n-1) - \frac{2T_0}{\tau_\varepsilon}\varepsilon_i(n-1) + 2\sigma_{\varepsilon 0}\sqrt{\frac{T_0}{\tau_\varepsilon}}R_i(n) - U_0 +$$

$$V\cos(\phi_s + \frac{2\pi h}{C}z_i(n)) + V_i[z_i(n)].$$

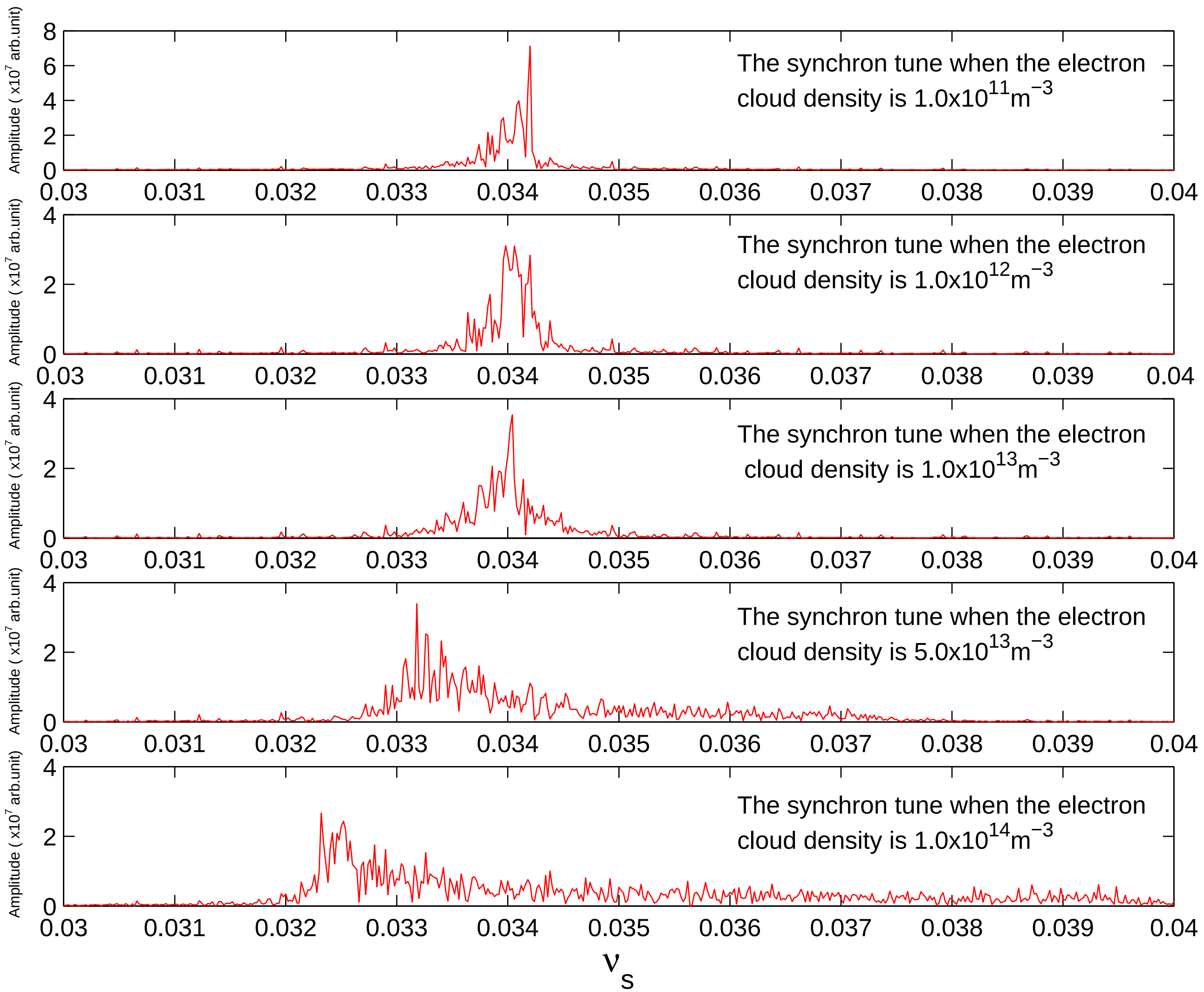


The bunch lengthening caused by the electron cloud density 1.0x10^{14}m^{-3}, is just 2.0% comparing to the natural bunch length



The bunch initial Gaussian distribution is shifted slightly in the forward direction for compensating the additional energy loss to the electron cloud

Synchrotron Tune shift caused by electron cloud



the synchrotron tune shift is only 5% of the undisturbed tune

Source of the electrons

(1)Proton losses incident the vacuum chamber

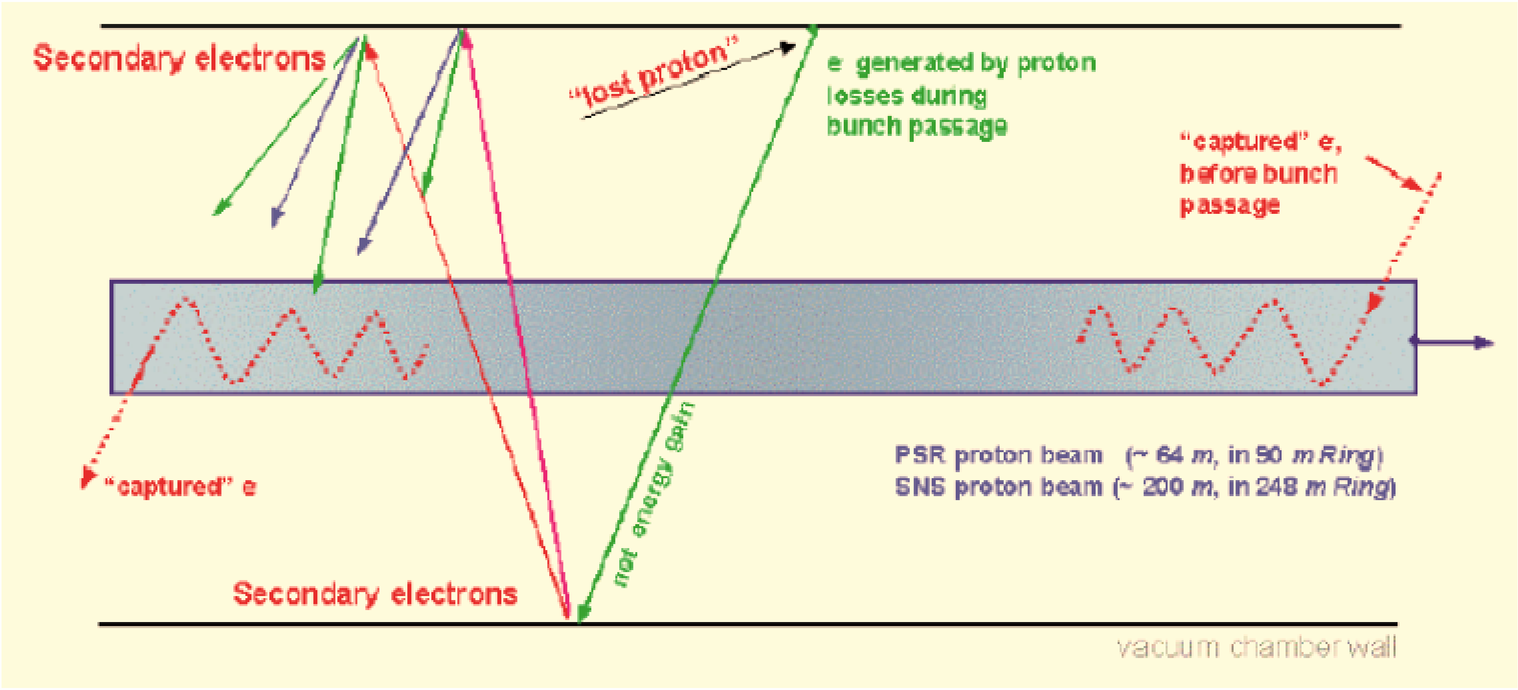
(2)Residual gas ionization

(3)Secondary electron emission

- *Elastically back-scattered electrons*
- *Re-diffused electrons*
- *True-secondary electrons*

Electron – proton instability in China Spallation Neutron Source

Electron multiplication mechanism in long proton bunches [1]



[1] M.T.F. Pivi and M.A. Furman, Phys. Rev. ST Accel. Beams 6, 034201 (2003)

Simulation on Electron-Proton instability

Bunch slicing

particle exchange between adjacent slices

take into account bunch size variation

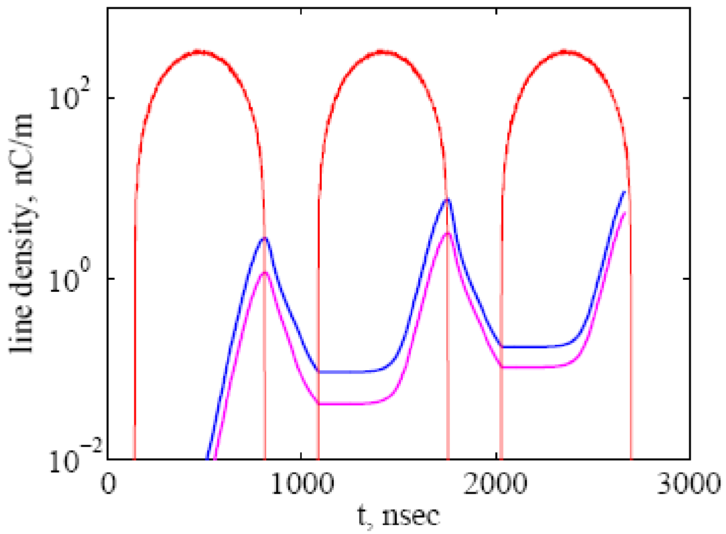
Energy ramping

one RF acceleration node

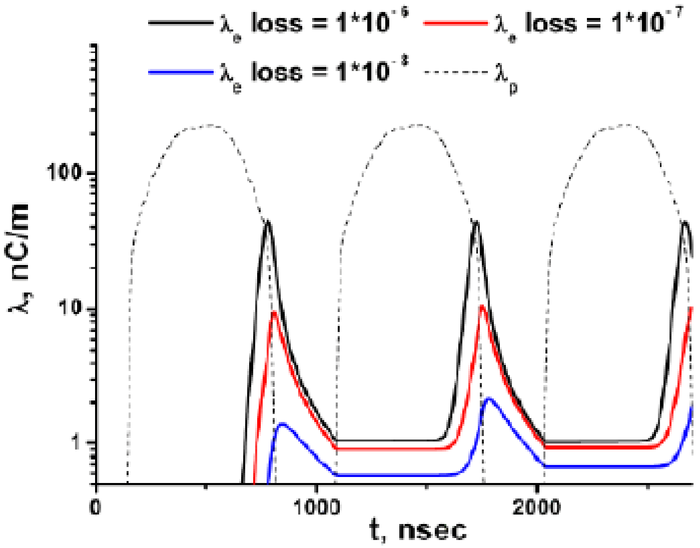
$$\Delta E = V_{rf} \sin(\phi + \phi_{rf})$$ ⟵ *dichotomic method*

Benchmark

- ***Electron development simulation of the SNS***



(a)



(b)

(a) Simulation result (Red: bunch density, Blue: p_{loss}=1×10^{-7}, Pink: p_{loss}=1 ×10^{-8})

(b) ORBIT code (A. Shishlo et al, in Proc. of the EPAC'06, p2832)

Both of the results show maximum electron density at the bunch tail, and the electron density keep almost unchanged at the bunch head.

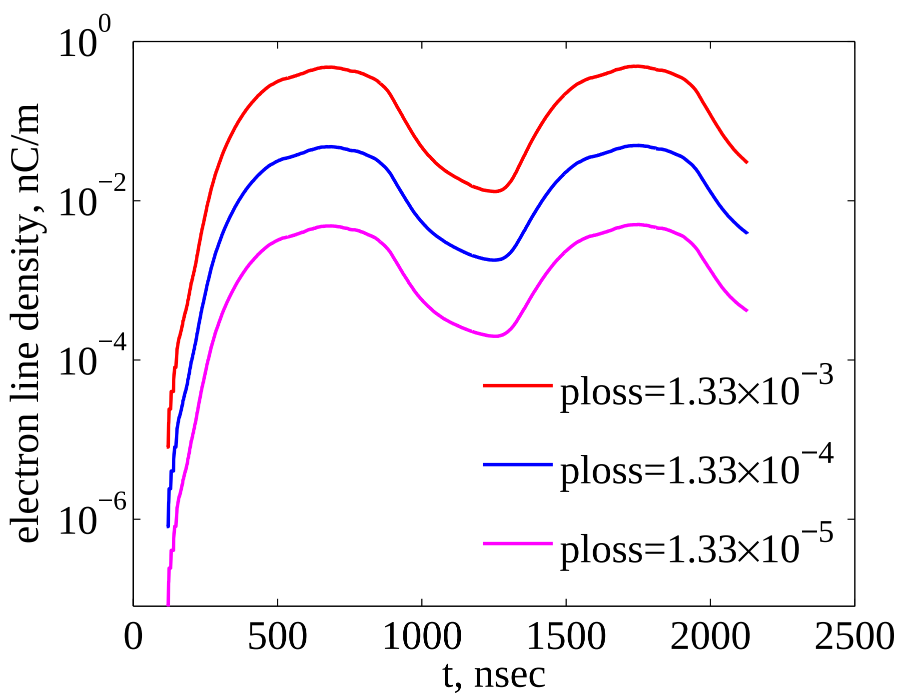
The peak density for p_{loss}=1 ×10^{-8} of (a) is a little higher.

Simulation result for the CSNS/RCS

Simulation parameters

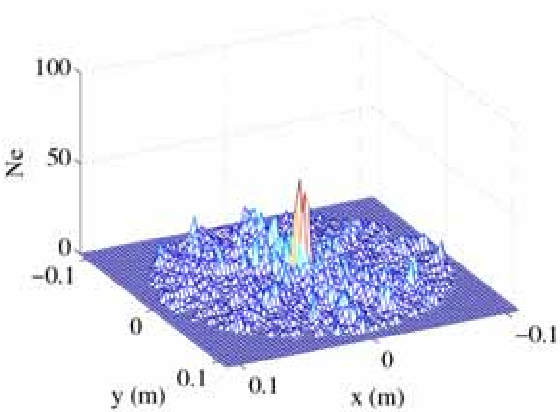
Parameters	Symbol, unit	Value
Inj./Ext. Energy	E_{in}/E_{ext}, GeV	0.08/1.6
Circumference	C, m	248
Bunch population	N_p, $\times 10^{12}$	9.4
Harmonic number	H	2
Repetition freq.	f_0, Hz	25
Betatron tune	ν_x/ν_y	5.86/5.78
Beam pipe radii	a/b, cm	10
Proton loss rate	P_{loss}, turn^{-1}	1.33×10^{-4}
Proton e^- yield	Y_p, e^-/p/loss	100
Ionization e^-	Y_i, e^-/p/loss	1.31×10^{-5}

Electron line density for different proton loss

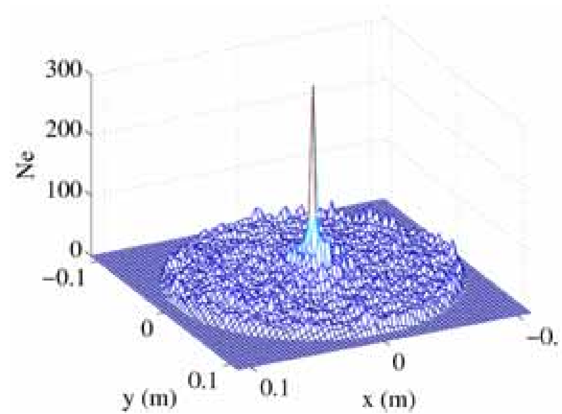


Simulation result

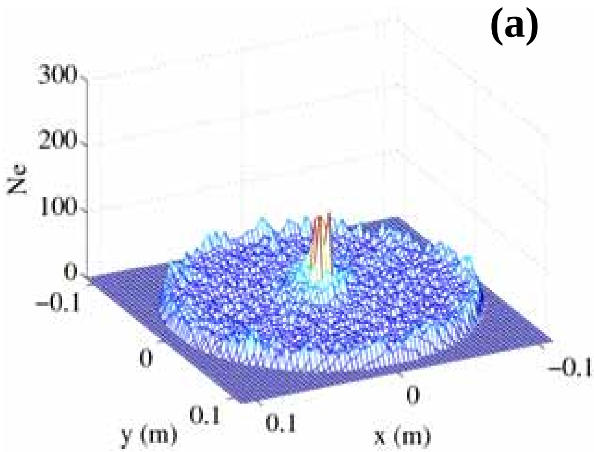
Electron distribution in transverse section



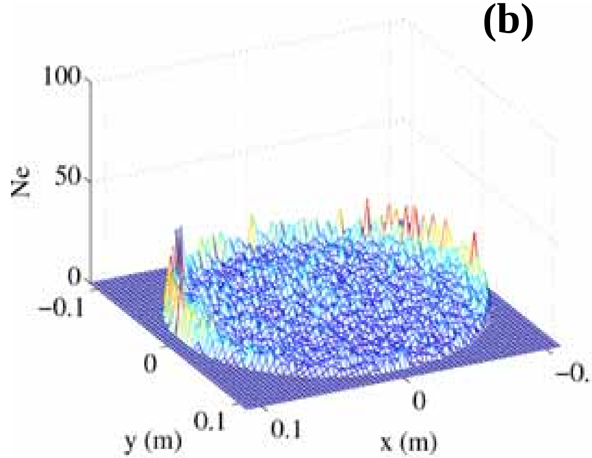
(a)



(b)



(c)

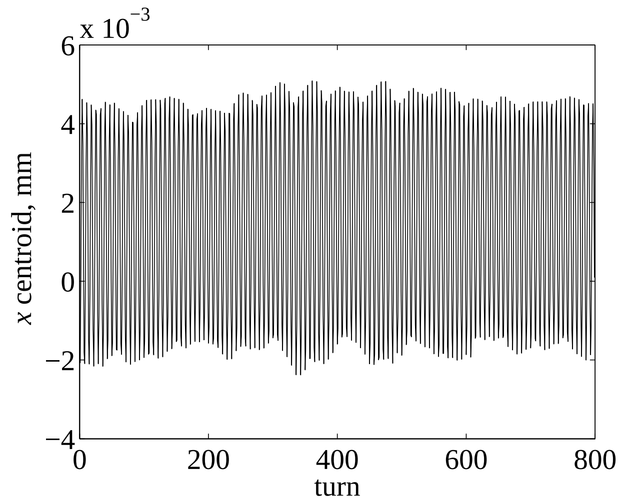


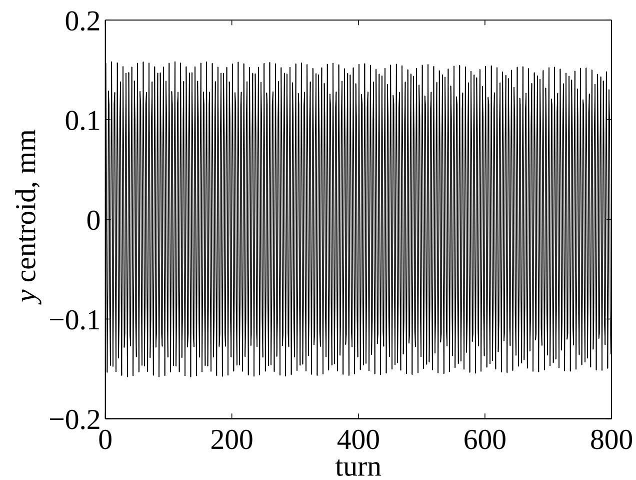
(d)

(a) bunch head (b) bunch center (c) Electron density peak (d) bunch tail

E-P instability

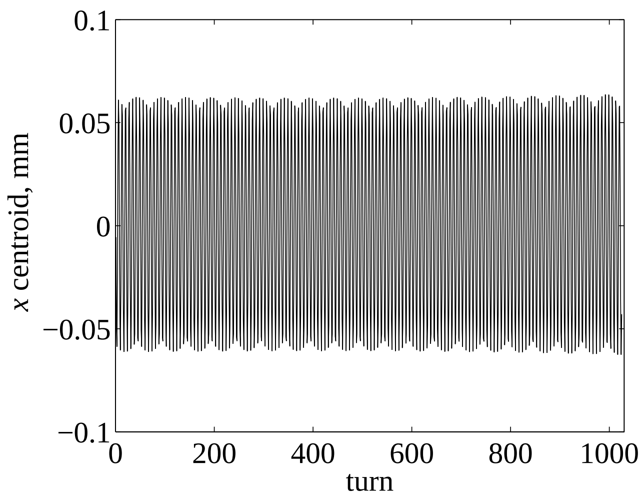
- *with RF acceleration*

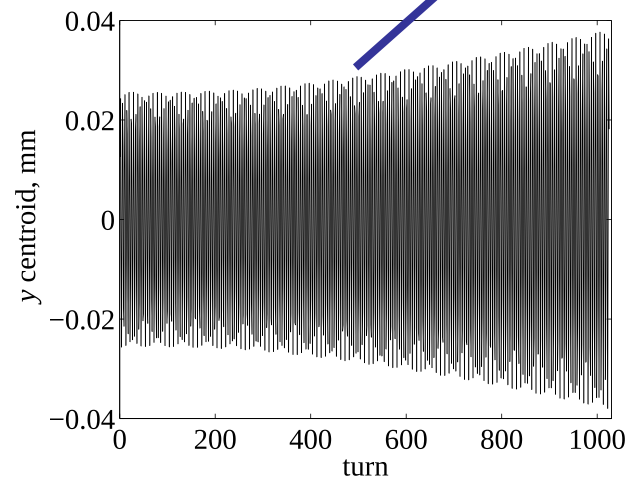




- *without RF acceleration*

with growth time of 2.1ms





Simulation summary

- Antechamber and TiN coating can reduce the ecloud density dramatically.
- It will be dangerous for single bunch instability in BEPCII when the ecloud density exceed $1.0\times10^{12}m^{-3}$.
- The coupled bunch instability may occur without ecloud density restraining method.
- The solenoid field is the most effective way to restrict the central density
- The electrons may be trapped in the quadrupole and sextupole magnetic fields
- The bunch lengthening due to electron cloud can be neglect in positron ring.
- Electron cloud is not a serious problem in CSNS/RCS

Thank you for attention