Beam instabilities at the SuperKEKB

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1. Resistive wall instability
2. Closed orbit instability
3. Electron cloud instability
4. Ion instability

1. Resistive wall instability

Growth rate

$$g = \frac{cI}{4\pi\nu_\beta E} \sum_{p=-\infty}^{\infty} \mathrm{Re}\, Z((pM + \mu + N_\beta)\omega_0 + \delta\nu_\beta)$$

$$\mathrm{Re}\, Z = sign(\omega) \cdot \frac{Z_0 \cdot R}{b^3} \cdot \delta, \quad \delta = \sqrt{\frac{2c}{Z_0 \sigma |\omega|}}$$

Z_0=377Ω, δ:skin depth, b:chamber radius

M:number of bunches, μ:mode no.

$N_\beta, \delta\nu_\beta$:integer and fractional part of tune

Using

M=5120 (uniform fill),

b=25mm(HER),45mm(LER),

I=4.1A(HER), 9.4A (LER),

Growth rate

HER(horizontal/vertical)	959/1096 (s^{-1})
LER(horizontal/vertical)	843/ 919 (s^{-1})

Damping time of a bunch by bunch feedback system 5000 s^{-1}

⇩

Instability will be suppressed by the bunch by bunch feedback system.

2. Closed orbit instability

Recently V. Danilov et al. pointed out that the closed orbit may experience an unstable drift due to a long-range wake field such as a resistive wall wake.

Closed orbit distortion → Accumulation of wake

Unstable drift of closed orbit

Dispersion equation of closed orbit y(s)

$$y(s) = \frac{iNr_0}{2\gamma T sin\pi\nu_\beta} \oint ds' \tilde{Z}_\perp(s',\Omega)\sqrt{\beta(s)\beta(s')}\cos[\pi\nu - \psi(s,s')]\cdot y(s')$$

$\tilde{Z}_\perp(s',\Omega)$: linear density of impedance

N:the number of particles, T:revolution time

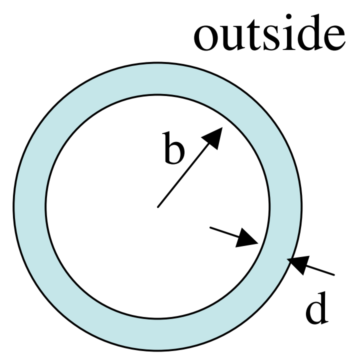
If $\beta(s)$ and $\tilde{Z}_\perp(s',\Omega)$ are uniform,

$$-n^2\omega^2 + \omega_\beta^2 = i\frac{Nr_0c^2}{\gamma C}Z_\perp(\Omega)$$ C: ring circumference

At threshold, Ω=0, n=integer part of ν_β ⟹ N_{th}

Resistive wall impedance

(A. Chao, S. Heifets and B. Zotter, Phys. Rev. ST-AB, 5, 111001 (2002),
Y. Shobuda and K. Yokoya, Phys. Rev. E, 66, 056501 (2002),
A. Burov and V. Levedev , EPAC2002, 1452)



Skin depth $\delta = c/\sqrt{2\pi\sigma\Omega}$ >> wall thickness d

Model by A. Burov and V. Levedev

$$\tilde{Z}_{\perp}(\Omega) = -i\frac{Z_0}{\pi b^2}\frac{1}{2+\kappa\cdot tanh(\kappa d)}$$ Vacuum outside

$$\tilde{Z}_{\perp}(\Omega) = -i\frac{Z_0}{\pi b^2}\frac{1}{1+\kappa\cdot tanh(\kappa d)}$$ Ideal magnetic material outside

$Z_0 = 377\Omega$, b: chamber radius (b>>d) , $\kappa = (1-i)/\delta$

$$\tilde{Z}_{\perp}(\Omega) = \frac{Z_0}{\pi b^2}\frac{g\lambda}{\Omega + i\lambda} \quad \delta >> d$$

($\tilde{Z}_{\perp}(\Omega) = \propto \frac{1}{\sqrt{-i\Omega}}$ $|\delta| << d$)

g=1/2 : Vacuum outside, g=1 : Ideal magnetic material outside

Threshold intensity of the instability

$$N_{th} = \frac{2\pi^2 b^2 \gamma \nu_\beta \delta\nu_\beta}{r_0 C g}$$

$\delta\nu_\beta$: fractional part of tune

N_{th}: the number of particles at the threshold of instability

1) SuperKEKB LER

C=3016m, ν =43.55, γ =7000, b=45x10^{-3}m, g=1

⇨ N_{th}=7.7 x 10^{14} > design 5.9 x 10^{14}

2) SuperKEKB HER

C=3016m, ν =41.57, γ =16000, b=36.5x10^{-3}m(ave.), g=1

⇨ N_{th}=5.0 x 10^{14} > design 2.6 x 10^{14}

3. Electron cloud instability

Estimation for HER

Cloud buildup

Simulation by CLOUDLAND (developed by L.F.Wang)

3D PIC code to calculate electron cloud formation

Assumption

- Ante-chamber will be installed.
- Shape of chamber : round
- Uniform production of electrons on chamber wall.
- Primary electrons

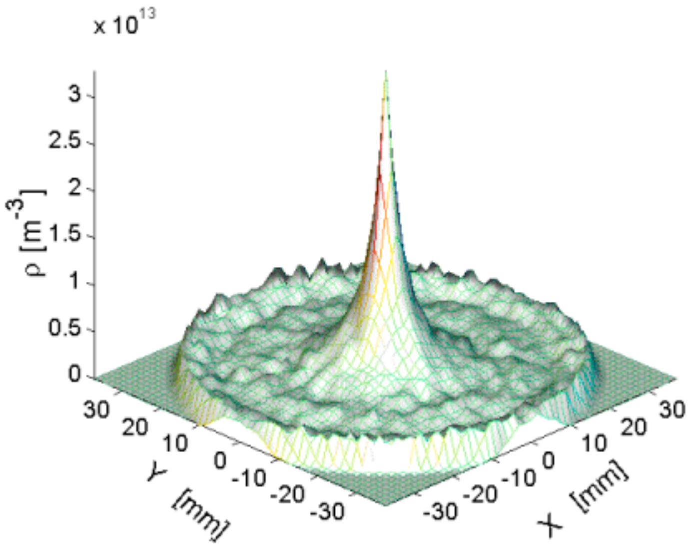
  Primary electron yield of 0.01 is artificially used in order to take into account of the reduction of electron yield by the ante-chamber.

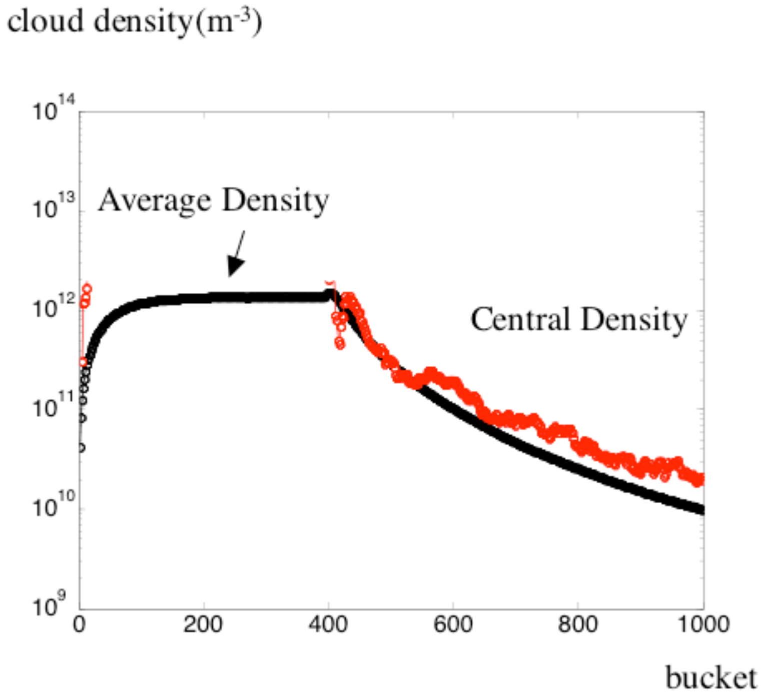
Parameters used in a simulation of electron cloud buildup

Beam energy(GeV)	8
Bunch spacing(ns)	2
Number of particles in a bunch	$5.2\ 10^{10}$
Chamber radius(mm)	37
Maximum secondary emission yield	1.5
Energy of maximum secondary yield	250eV
Number of bunches	200
Number of train	1
Primary electron yield	0.01
rms bunch length(mm)	3
Horizontal emittance(m)	$2.4\ 10^{-8}$
Vertical emittance(m)	$4.8\ 10^{-10}$
Average horizontal beta function (m)	10
Average vertical beta function (m)	10

Distribution of electron cloud

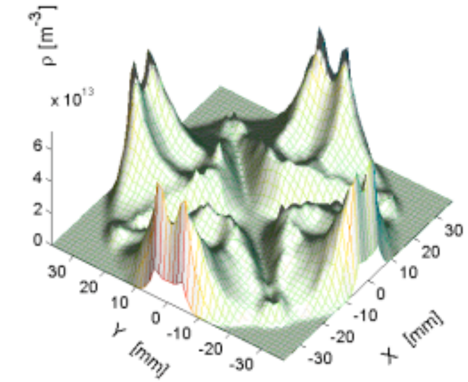
1) Drift space



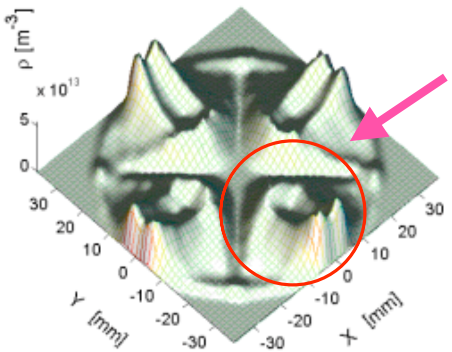


Very high central density of electrons.

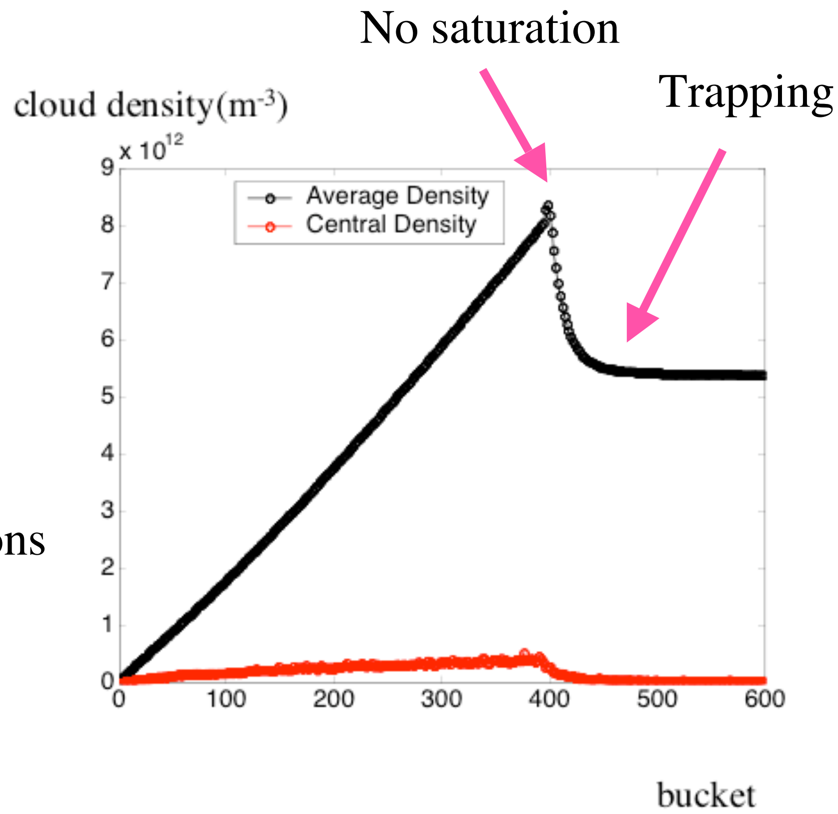
2) Quadrupole magnet



At the end of bunch train

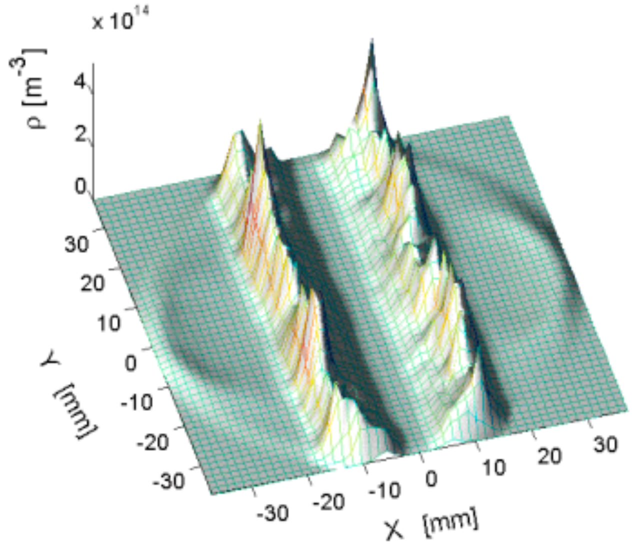


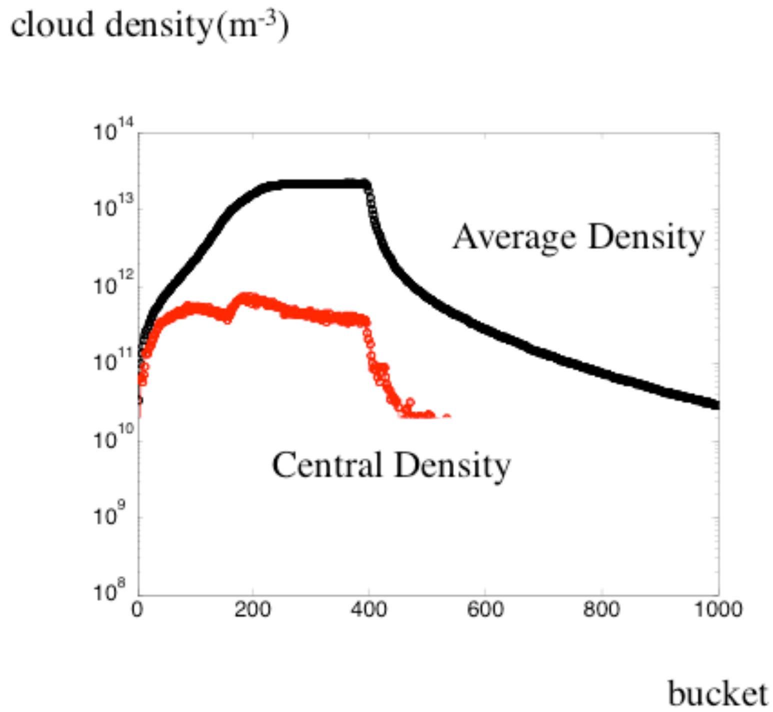
At a bunch gap (40ns after the last bunch in the train)



Trapping of electrons.

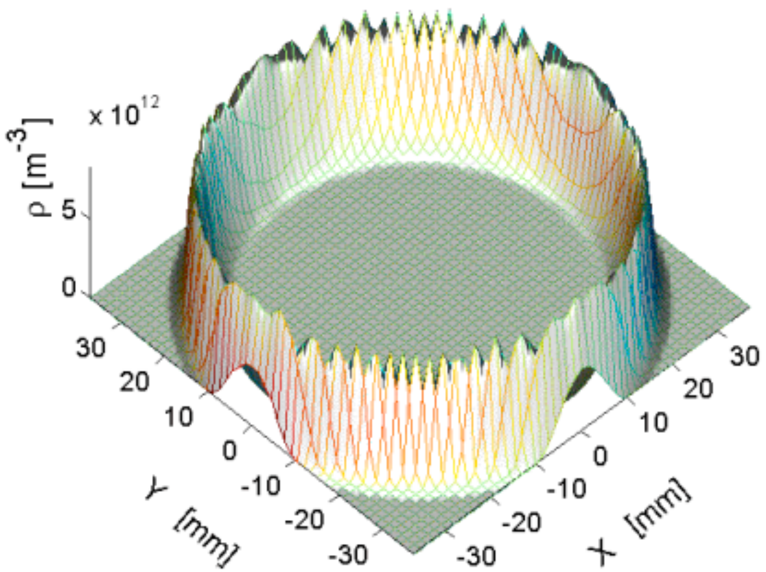
3) Dipole magnet

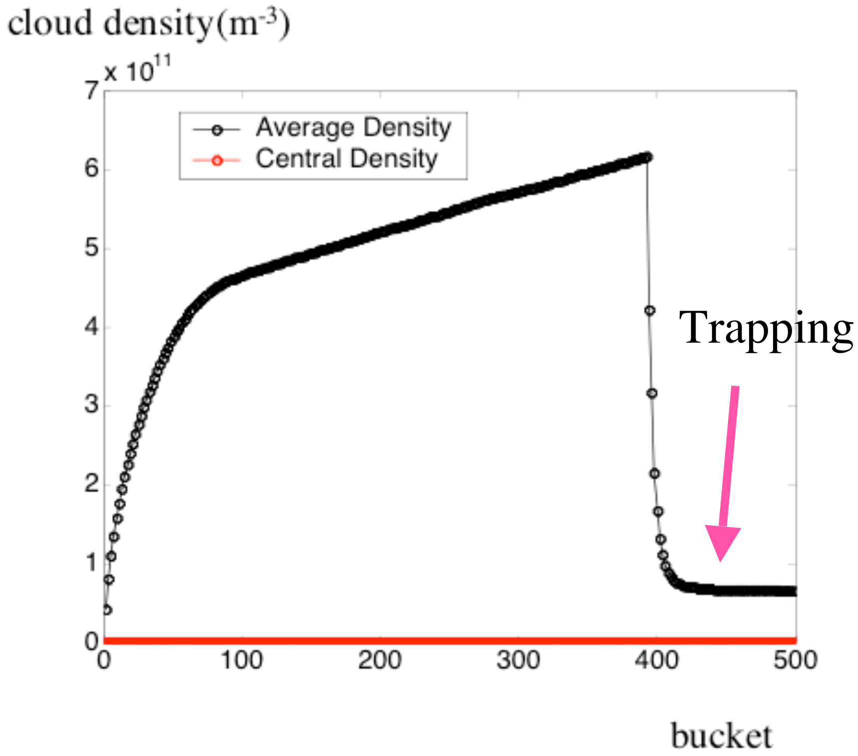




Very strong multipacting.

4) Uniform solenoid field of 60G





60 G is enough to suppress the electron cloud near the beam.

Average electron volume density and electron volume density at a pipe center in various magnetic fields

	Field strength	average ($10^{12}m^{-3}$)	at pipe center ($10^{12}m^{-3}$)
Drift space	-	1.0	10
Dipole	0.25(T)	20.0	0.6
Quadrupole	10.3(T/m)	8.4	0.46
Solenoid	60(G)	0.61	0.0

Solenoid field of 60G is very effective.

Electron cloud remains inside bending and quadrupole magnets.

Threshold of strong head-tail instability

(K. Ohmi and F. Zimmermann)

Instability occurs if

$$\int \rho \cdot ds > \frac{2\gamma\nu_s}{\pi r_0 \beta_y}$$

ρ:density of electrons, s:orbit length
β_y:beta function, ν_s:synchrotron tune

$0.6 \times 10^{15} m^{-2}$ (left-hand side) $4.5 \times 10^{15} m^{-2}$ (right-hand side)

(by using ρ from simulation)

Solenoid system

Solenoid will be installed on ante-chambers.

	LER		HER
Field strength(G)		60	
Current(A)		3.8	
Diameter of wire(mm)		1.6	
Layers of winding		2	
Total length of solenoid(m)	2470		1850
Total turns of winding(10^4)	309		231
Resistance of wire(kΩ)	13.1		9.1
Dissipated power(kW)	189		131

Main parameters of solenoid system

Simulation shows

1) Solenoid field of 60G is very effective to reduce the electron density at the center of a chamber.

2) Substantial electron cloud stays inside bending and quadrupole magnets.

3) Simulated electron density is below the threshold of the strong head-tail instability.

We need further experimental and simulation study to obtain more reliable estimation.

- Refinement of input parameters for simulations,
  - the number and distribution of primary electrons in the ante-chamber,
  - secondary emission coefficient etc..
- Understanding of behavior of electrons inside magnets.

4. Ion instability

In SuperKEKB the electron beam is stored in LER after LINAC upgrade.

Comparing with KEKB,

beam energy : 8 ⇨ 3.5 GeV

beam current :1.1 ⇨ 9.4A

Ion instability would be strong enough to degrade the luminosity.

Simulation (by Ohmi's code)

2 dimensional model

Beam : rigid Gaussian, ions : macro particles

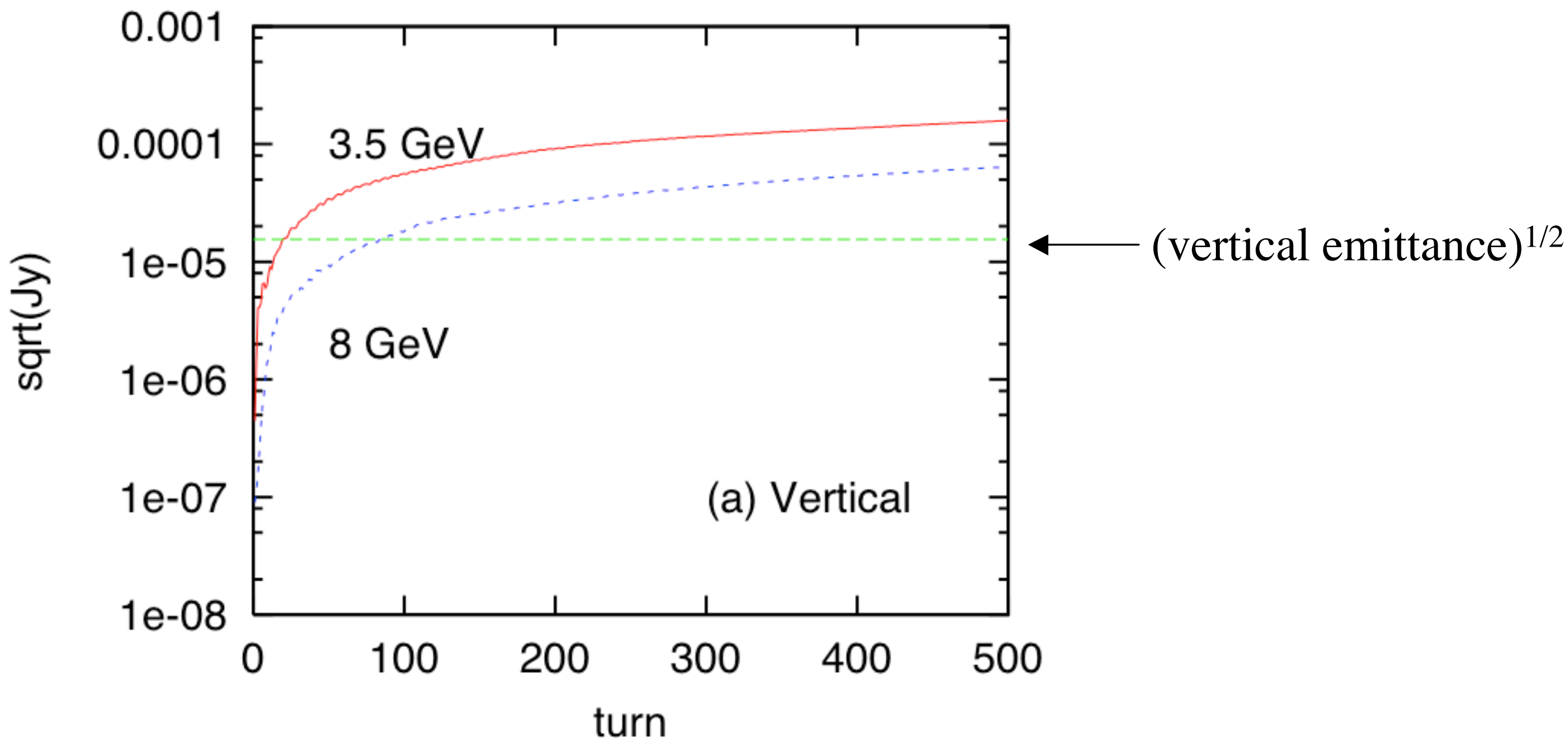
Beam-ion force by Basetti-Erskine formula

One ionization point in a ring

Parameters used in a simulation of ion instability

Beam energy(GeV)(LER/HER)	3.5/8
Bunch spacing(ns)	2
Number of particles in a bunch(LER/HER)	$11.7\ 10^{10}/5.1\ 10^{10}$
Number of bunches	5000
Number of train	1
Vacuum pressure(Pa)	$1\ 10^{-7}$
rms bunch length(mm)	3
Horizontal emittance(m)	$2.4\ 10^{-8}$
Vertical emittance(m)	$4.8\ 10^{-10}$
Ion	CO^+

5 times smaller than design value



The amplitude grows rapidly up to about vertical beam size then almost saturates.

growth time at 10^{-7} Pa < 10 turns (rapid growth region)

560 turns (saturated region)

damping time of the bunch-by-bunch feedback: 20 turns

The ion instability may not cause a beam loss. Bunch by bunch feedback will suppress the beam oscillation in saturated region.

However, it may cause a dipole oscillation whose amplitude is order of the beam size and may lead to a loss of luminosity.

The ion instability would be an issue of SuperKEKB.

Unknowns which may mitigate the instability

Feedback system and noise

Beam-beam force...

⇨ Simulation and experimental study is needed.

If the electron beam is stored in the HER,

the growth time is 50 turns in the rapid growth region in 1×10^{-7} Pa.

Electron storage in the HER is preferable to that in the LER from the view point of the ion instability.

Summary

- Resistive wall instability

  will be cured by the bunch by bunch feedback system.

- Closed orbit instability

  Threshold is above the design intensity both in LER and HER.

  In LER, threshold is near the design intensity. Detailed analysis may be necessary.

- Electron cloud instability

  In the present stage of the simulation , threshold of strong head-tail instability will not be reached in HER.

  In the simulation, strong multipacting in a dipole magnet and trapping of electrons in a quadrupole were found.

  To understand the behavior of electrons inside magnets may be important to estimate the electron cloud instability more accurately.

- Ion instability

  Simulation assuming the vacuum of 1×10^{-7} Pa shows that

  growth time is shorter than the damping time of the bunch by bunch feedback system τ_g(F.B.) in case of electron storage in LER,

  growth time is longer than τ_g(F.B.) in case of electron storage in HER.

  ⇨ Electron storage in HER is preferable from the view point of the ion instability.

  (For the design pressure of 5×10^{-7}Pa, the growth time will be larger than τ_g(F.B.) even in HER.)

Backup

Effect of beam energy on electron cloud instability (SuperKEKB)

Electron cloud density in drift space

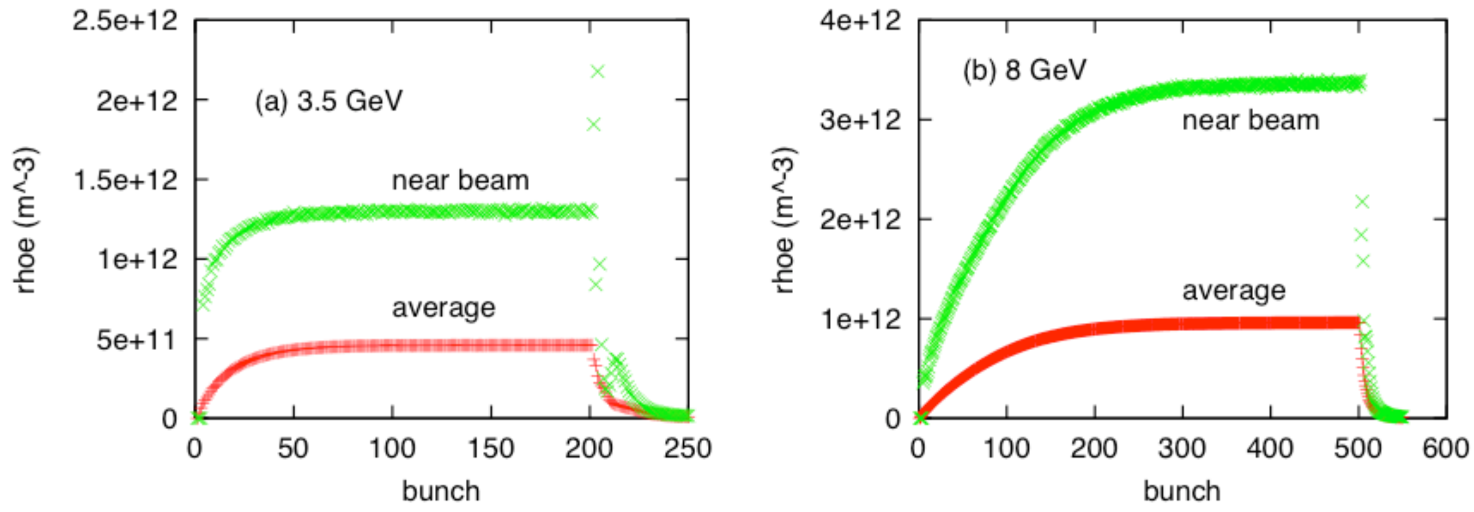


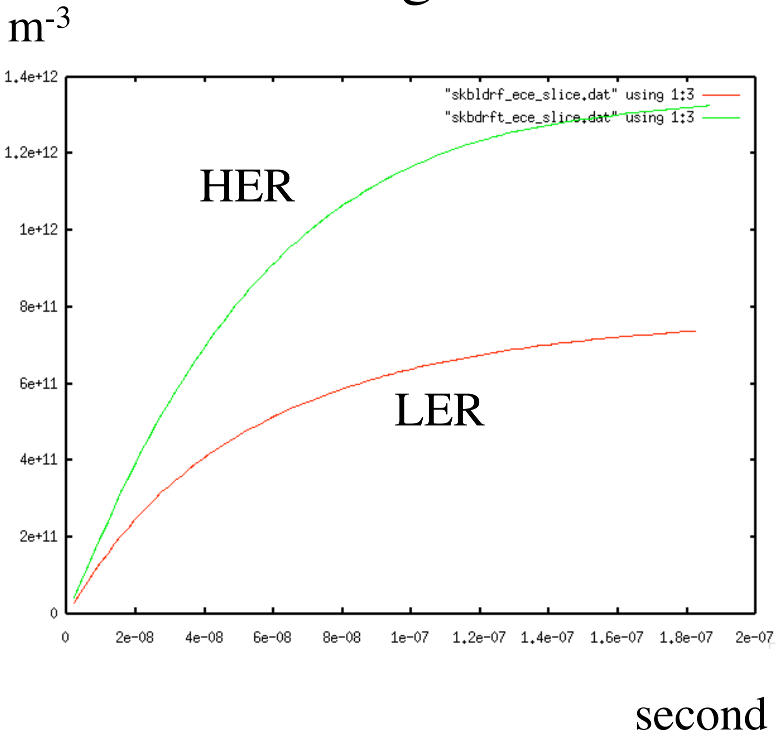
Figure 3: Electron cloud density for 3.5 GeV and 8 GeV cases.

(K. Ohmi, PAC03)

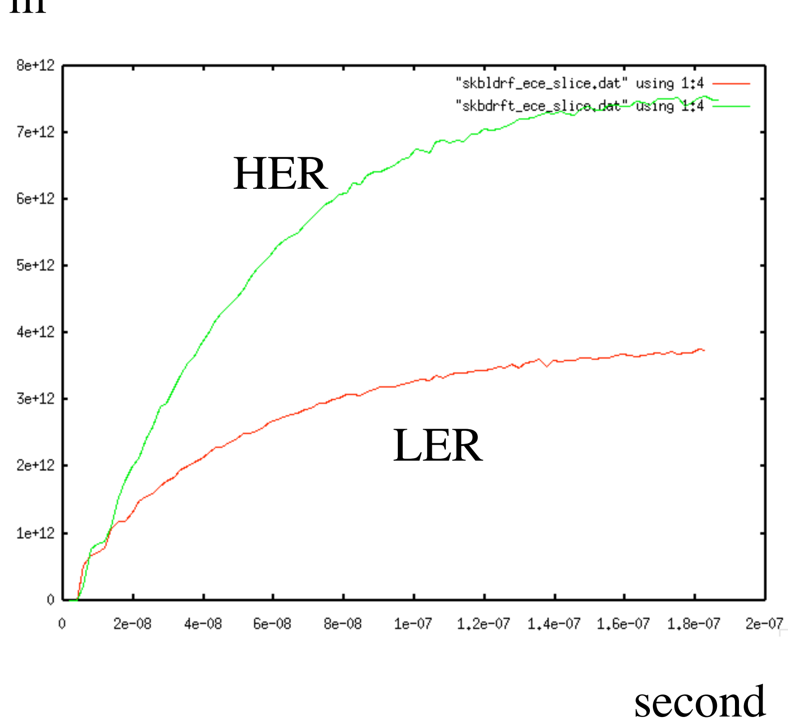
Simulation by code PEI

preliminary

average



near beam



Simlation by code CLOUDLAND

Electron density

HER : LER $\approx$ 2 to 3 :1

Energy

HER : LER $\approx$ 2.3 : 1

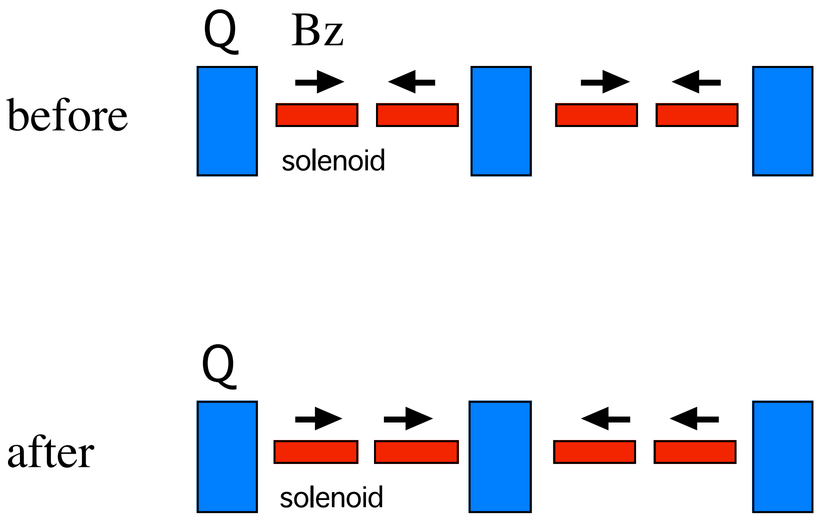
Growth rate $\propto$ electron density / energy

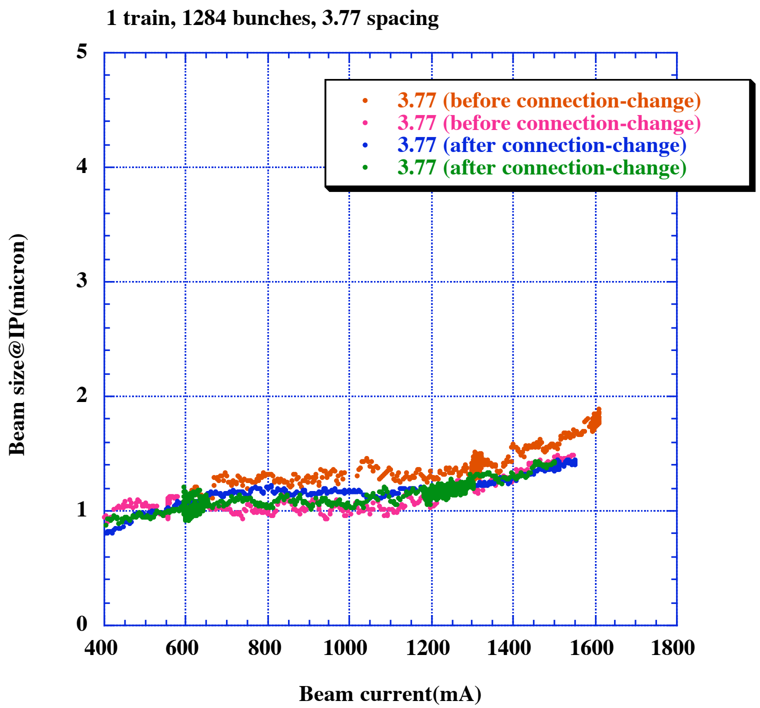
In drift space, effect of electron density and energy tend to cancel each other. HER and LER have comparable growth rates.

Inside magnets, solenoid ??

LER Blowup in 2003

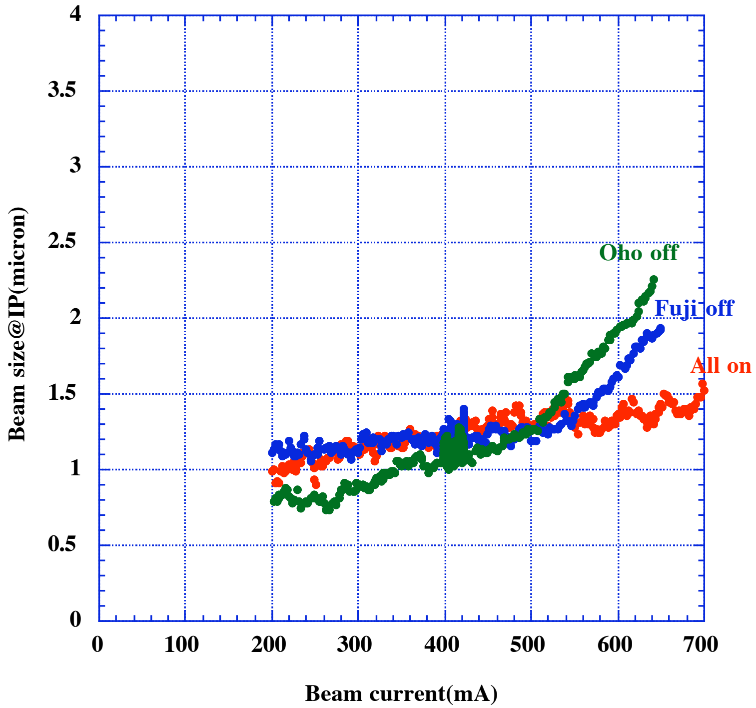
1) Change of connection of solenoid





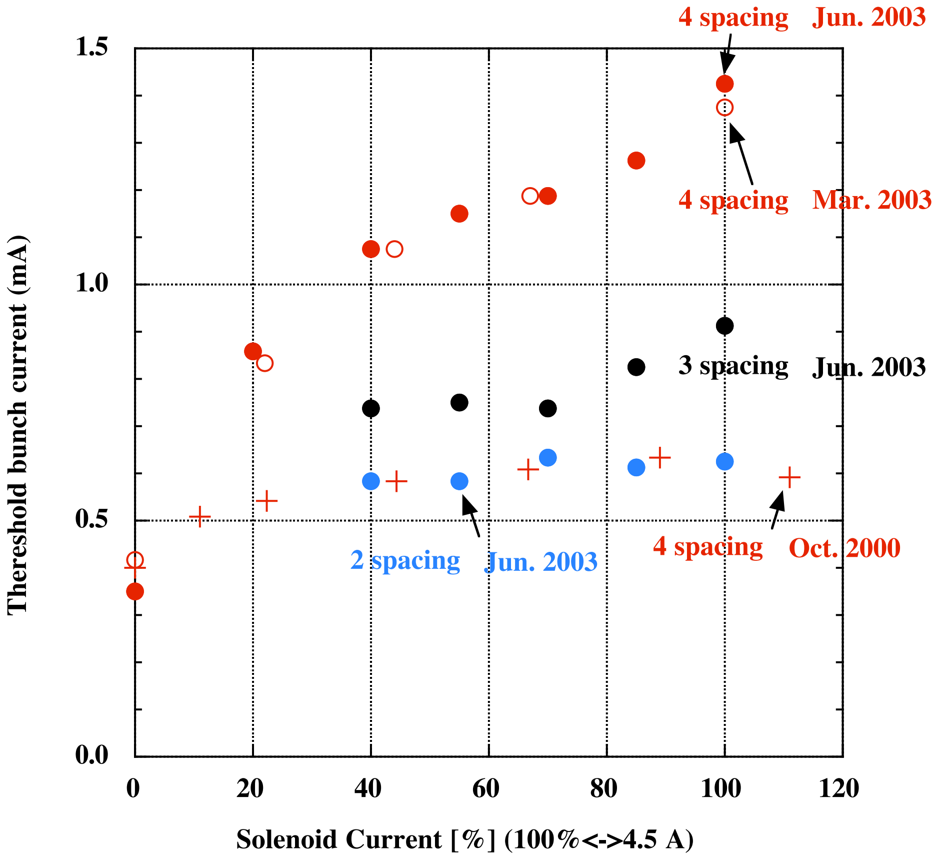
Almost no improvement was observed.

2) Solenoids in long four straight sections have an effect on the blowup.



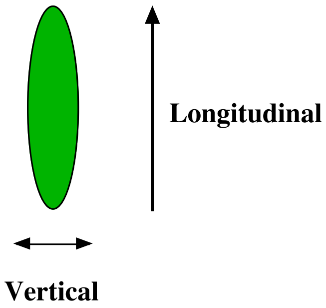
Putting more solenoids in Fuji straight section is underway.

3) Field strength vs. Threshold bunch current of blowup



Stronger field will be helpful for raising the threshold if bunch spacing is larger than 3 buckets.

4) Attempt to detect head-tail motion by streak camera (preliminary)

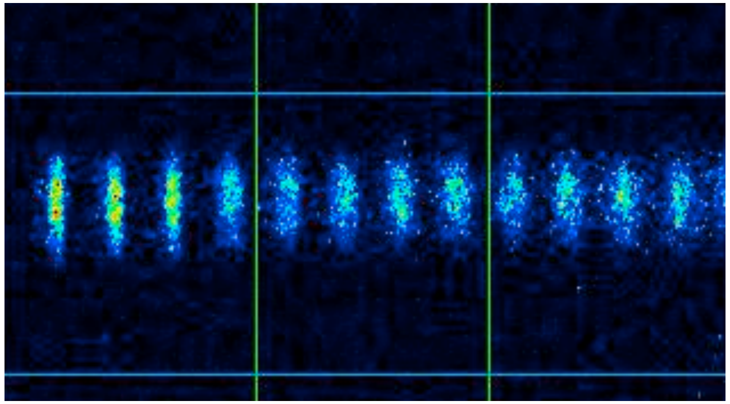


Solenoid off

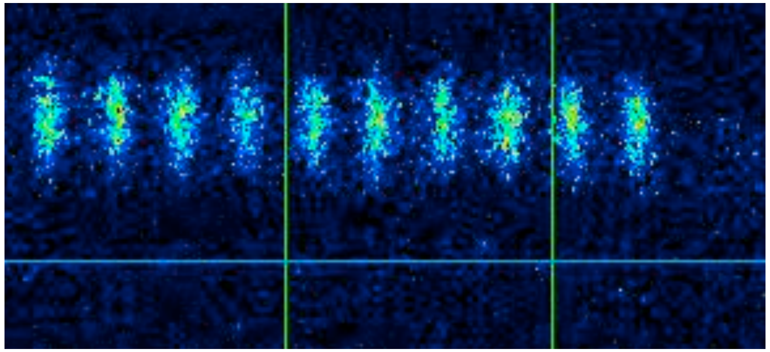
1000 bunches, 4 bucket spacing

Train head

Tail



893mA



900mA

Vertical beam size starts to increase at 3 or 4th bunch.

Clear tilt of bunch is not observed.

Plan in 2004

1) More solenoids

Fuji straight sections : about 40m

2) Study electron cloud in magnets