Electron cloud simulations for SuperKEKB

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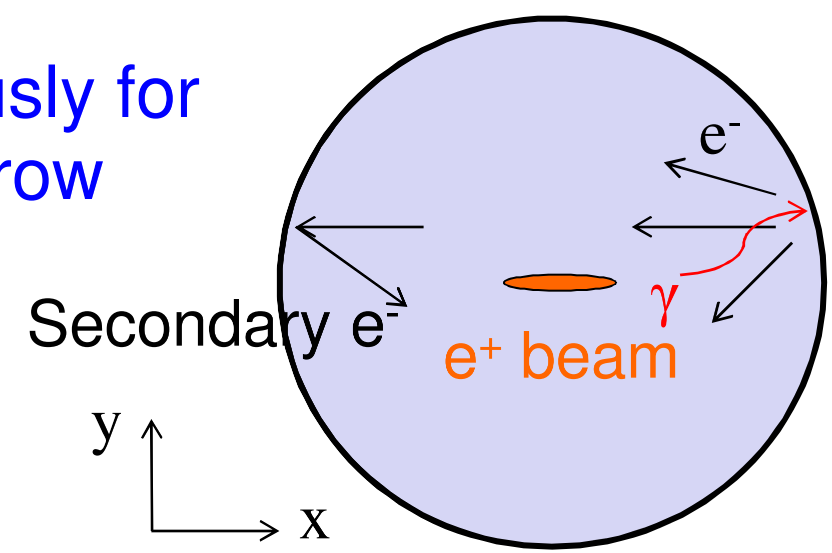
Low Emittance Rings 2010, CERN

Electron cloud built-up

K.Ohmi, Phys.Rev.Lett,75,1526 (1995)

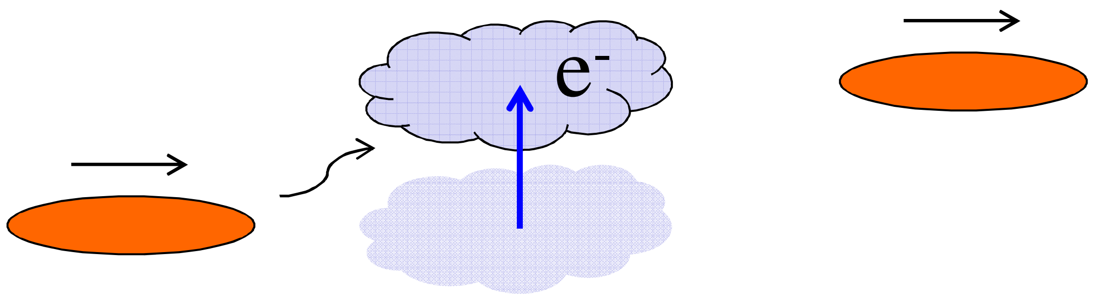
1. Positron beam emits synchrotron radiation
2. Electrons are produced at the chamber wall by photoemission
3. Electrons are attracted and interact with the positron beam
4. Electrons are absorbed at the chamber wall after several 10 ns
   - Secondary electrons are emitted according the circumferences
5. Electrons are supplied continuously for multi-bunch operation with a narrow spacing



⇨ Electron cloud is built up

Coherent instabilities due to electron cloud

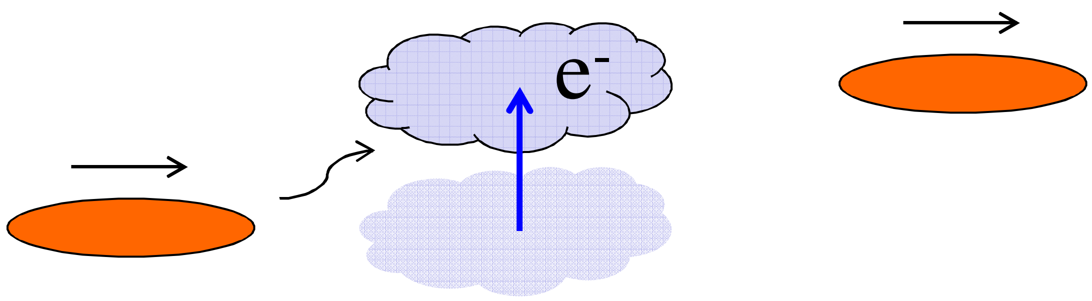
- Wake field is left behind in the electron cloud by advanced bunches
- The wake field induced by the electron cloud affect backward bunches



- Coherent instability occurs when there is resonance between the wake field and the backward bunches
  - Coupled bunch instability
  - Single bunch instability

Coupled bunch instability

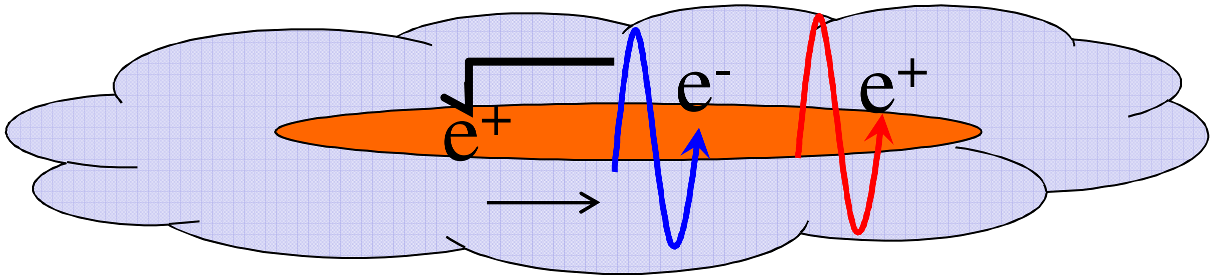
- The wake filed causes correlation among bunches



- Threshold is determined by balance with some damping effects
- Independent of emittance, momentum compaction
- Depends on electron cloud density, distribution and motion

Single bunch instability

- The wake filed causes correlation among positrons within a single bunch



- Threshold is determined by the balance with Landau damping due to the momentum compaction factor
- Depends on emittance
- Depends on only local electron cloud density

List of parameters

	Unit	SuperKEKB LER	SuperB LER
E+	GeV	4	4
I+	Amp	3.6	2.70
Np	$\times 10^{10}$	6.25	4.53
Nbun		2500	1740
I_{bunch}	mA	1.4	1.6
β x,y ave	m	12	12
ν_s	Hz	0.012	
ε_x	nm	3.2	2.8
ε_y	pm	33	7
σ_x	mm	0.2	0.18
σ_y	µm	20	9.1
σ_z	mm	6	
L	m	3016	1400
radiation damping time	ms(turn)	60(6000)	

Number of produced electrons

- Number of the photon emitted by one positron per unit meter

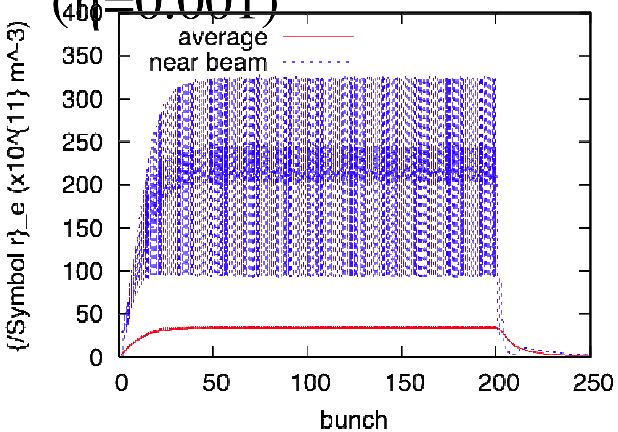
$$Y_\gamma = \frac{5\pi}{\sqrt{3}} \frac{\alpha\gamma}{L}$$ α= 1/137 (fine structure const.)

  - SuperKEKB-LER γ=8000 → Y_γ=0.17 m^{-1}
- Bunch population
  - SuperKEKB-LER design (3.6A) Np=10^{11}
- Quantum efficiency for photoelectron ($n_{p.e.}/n_\gamma$) η=0.1
- Energy distribution 10±5 eV
- Number of electrons produced by one positron per unit meter
  - SuperKEKB-LER $Y_{p.e}$=0.017 m^{-1}
- $Y_{p,e}N_p$=1.7x10^9 m^{-1}
- Quantum efficiency for secondary electrons $\delta_{2,max}$=1.0-1.2

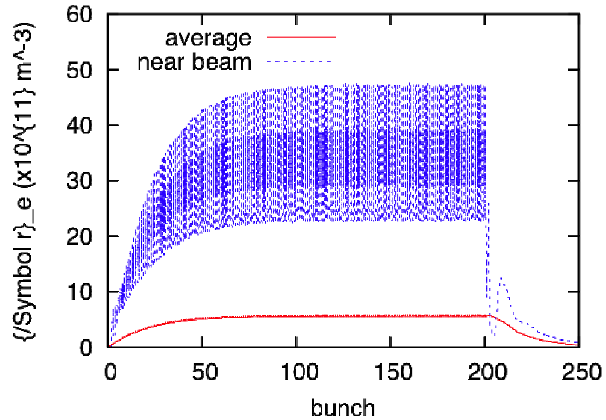
Increase of electron density ρ_e with multi-bunch (simulation results)

- $\delta_{2,max}$=1.2

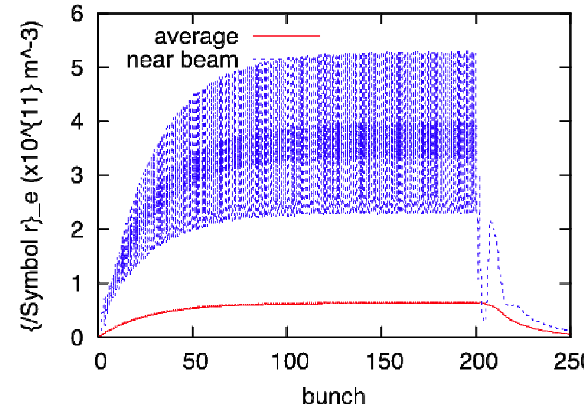
$Y_{p,e}N_p = 1.7\times10^9$ (η=0.1)



$Y_{p,e}N_p = 1.7\times10^8$ (η=0.01)

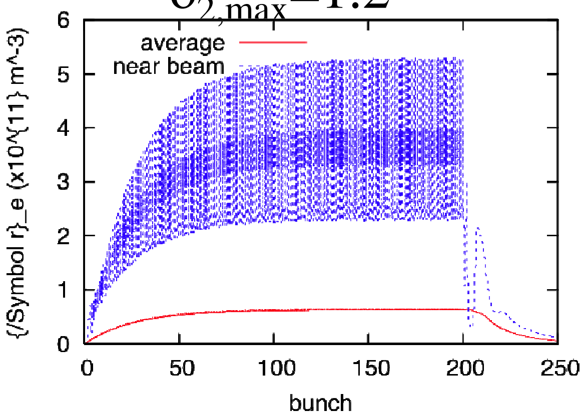


$Y_{p,e}N_p = 1.7\times10^7$ (η=0.001)

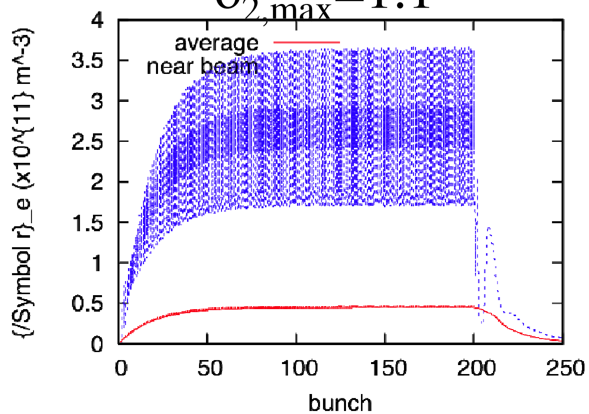


- $Y_{p,e}N_p = 1.7\times10^7$ (η=0.001)

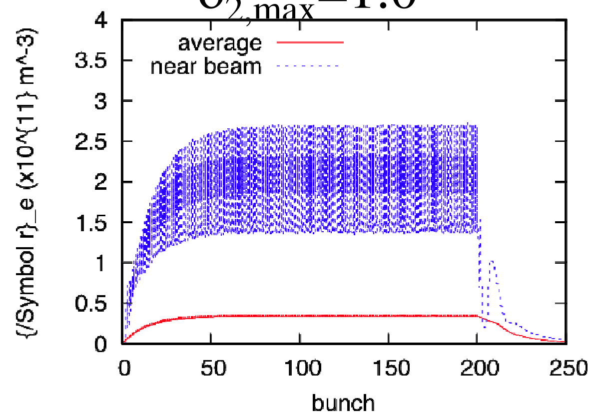
$\delta_{2,max}$=1.2



$\delta_{2,max}$=1.1

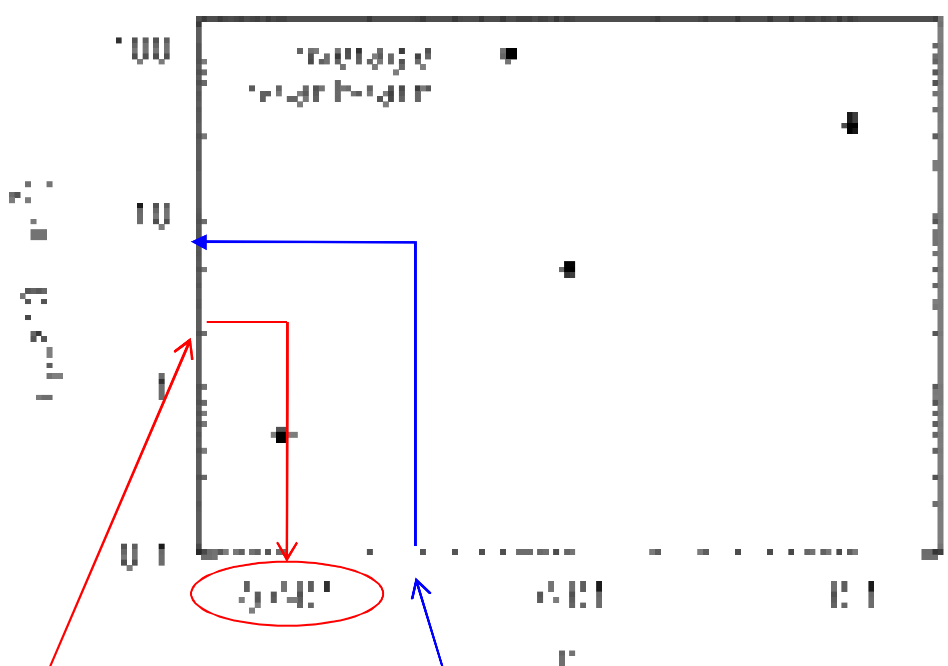


$\delta_{2,max}$=1.0



Electron density ρ_e as functions of quantum efficiencies (η and $\delta_{2,max}$)

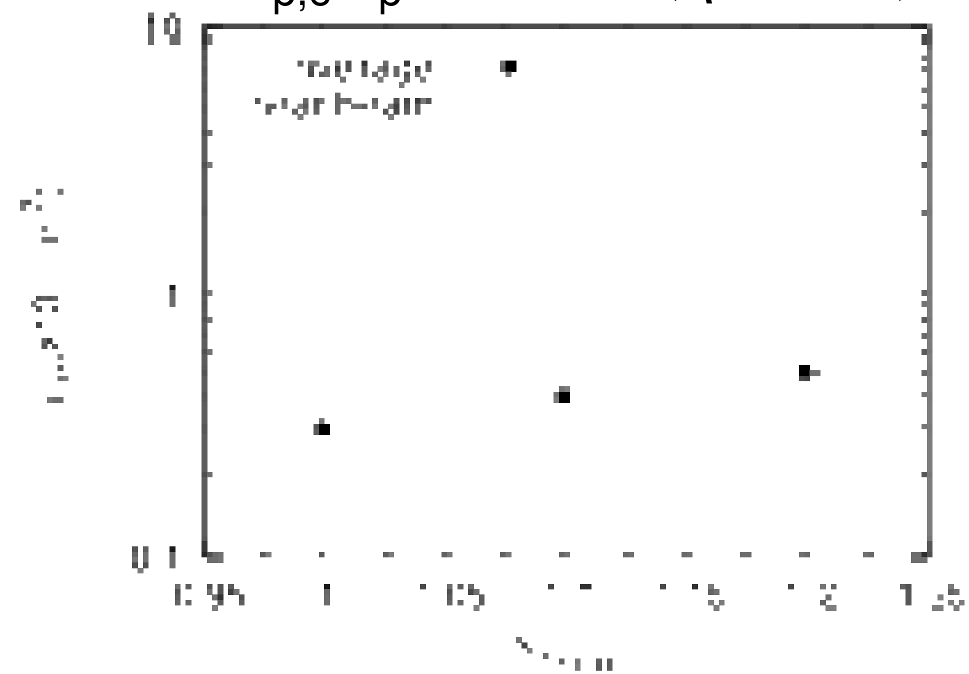
$\delta_{2,max}=1.2$



$\rho_{eth}=1.1\times10^{11}m^{-3}$

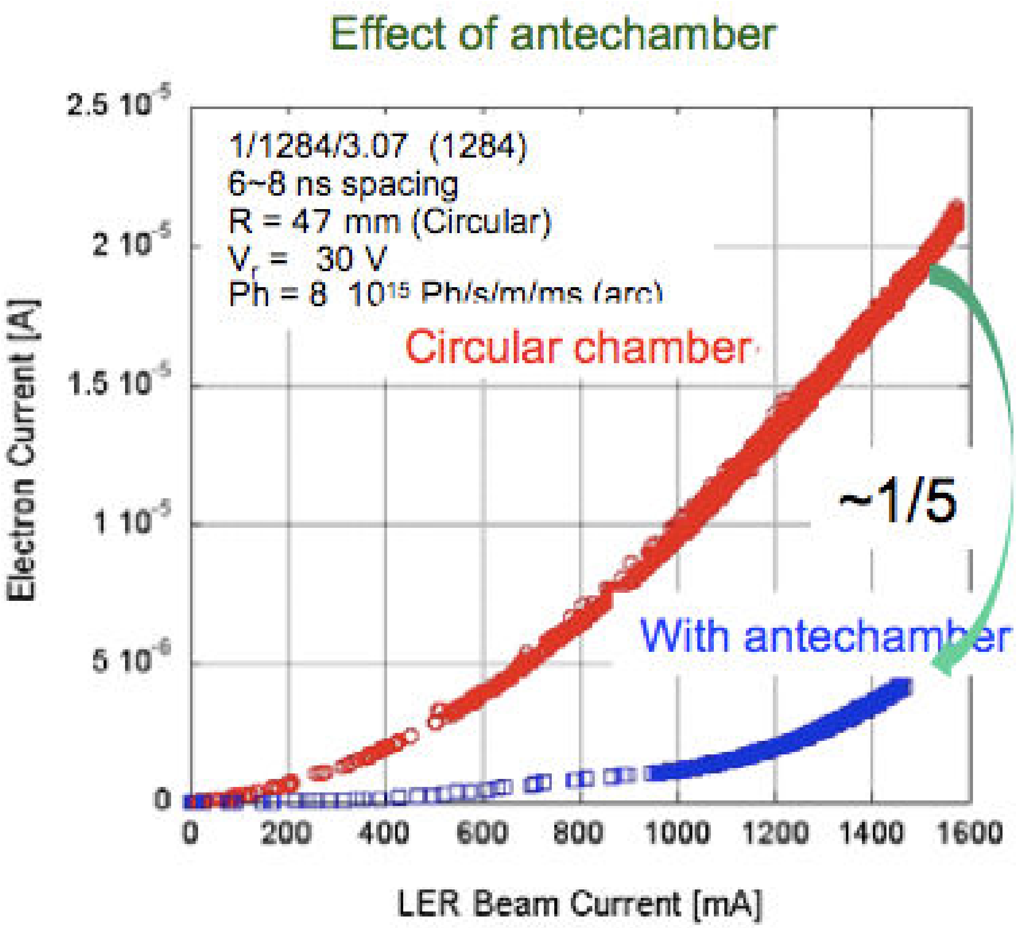
$\eta=0.003$ w/ antechamber

$Y_{p,e}N_p=1.7\times10^7$ ($\eta=0.001$)



Together with solenoid it is expected to reduce η to 0.001 (Suetsugu)

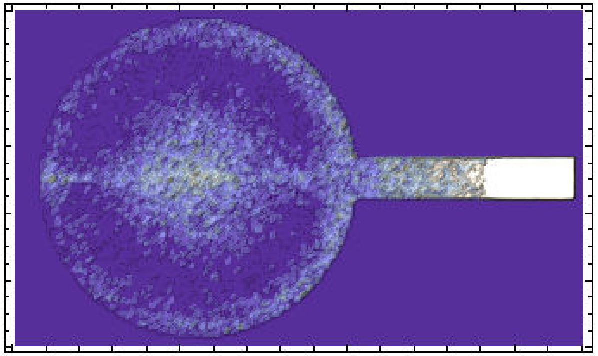
Antechamber

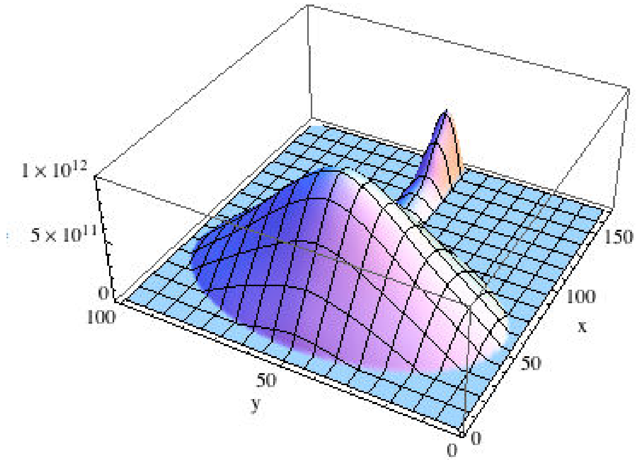


©Suetsugu

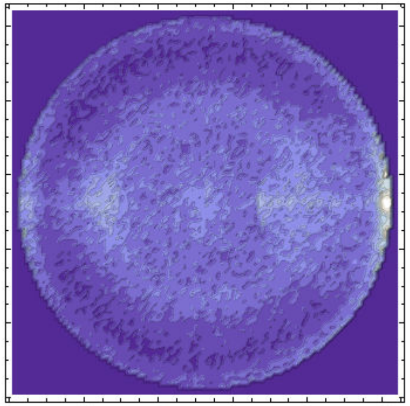
Electron distribution and electric potential with $\delta_{2,max}$=1.2

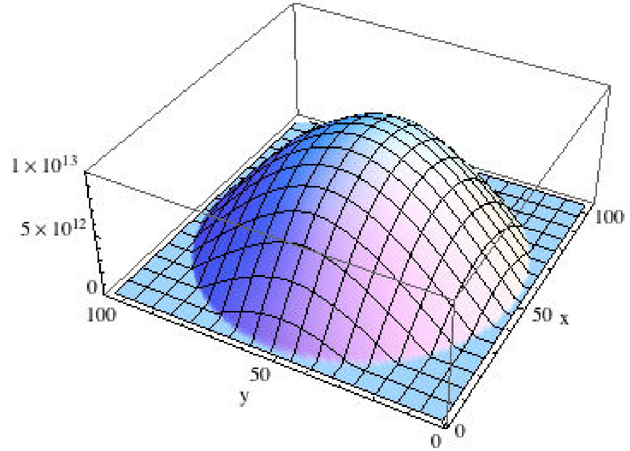
- Antechamber





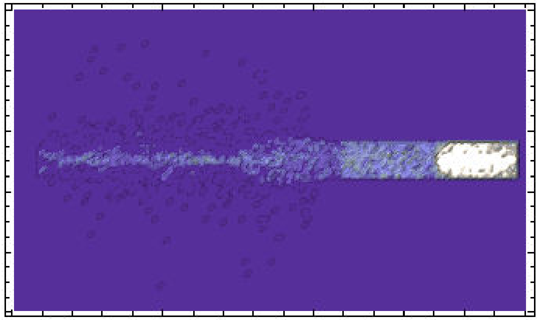
- Cylindrical chamber

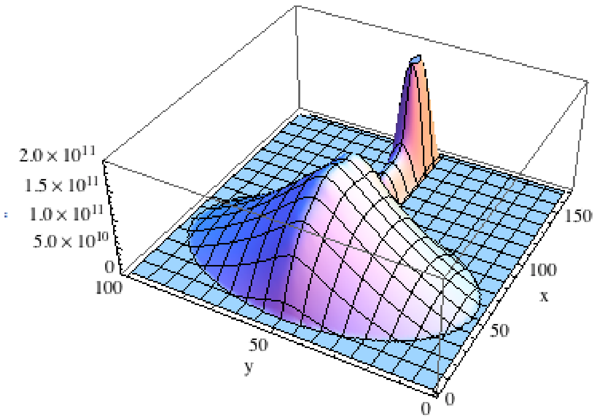




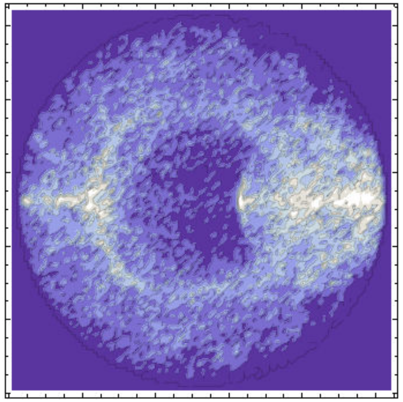
Electron distribution and electric potential with $\delta_{2,max}=0$

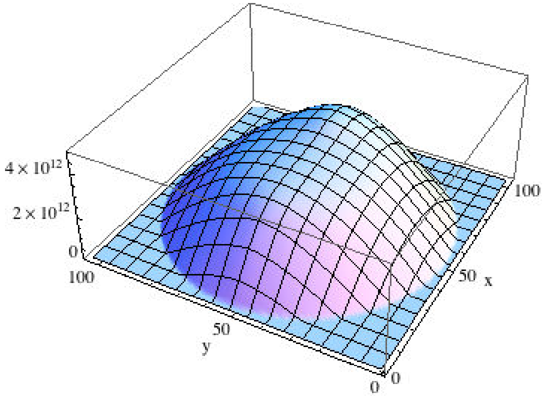
- Antechamber





- Cylindrical chamber

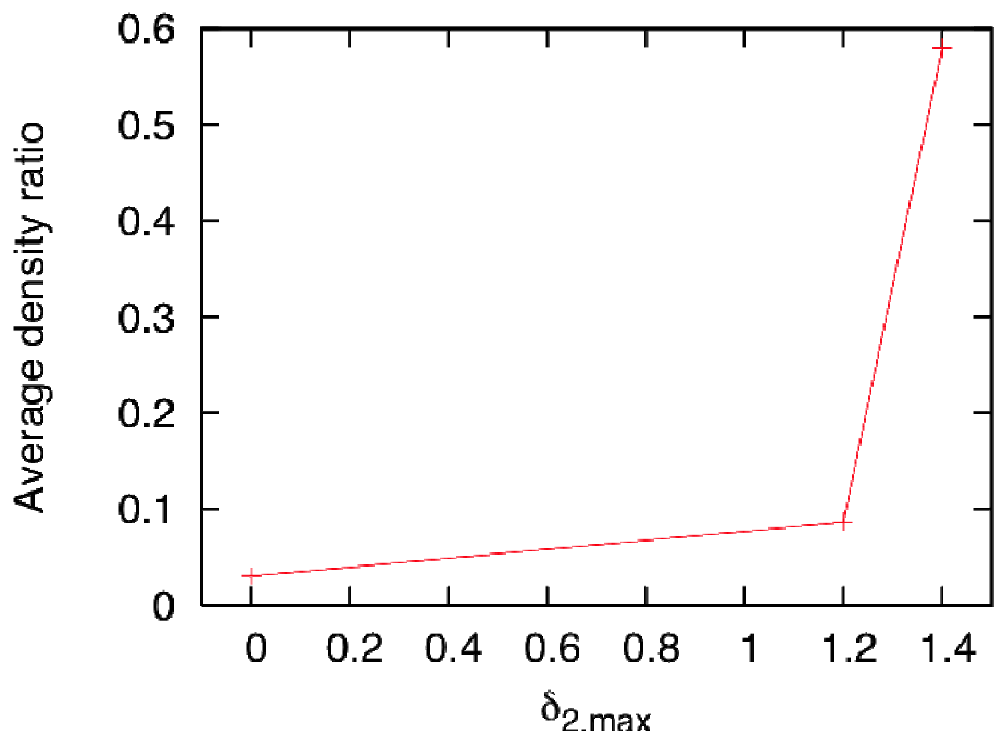




Reduction factor
Averaged electron density

- Ratio of the densities at the beam pipe of ante-chamber and cylindrical-chamber
- The ratio ≈0.03 for $\delta_{2,max}$=0

➔The antechamber reduces η in 3% effectively



Wake field induced by electron cloud and beam stability

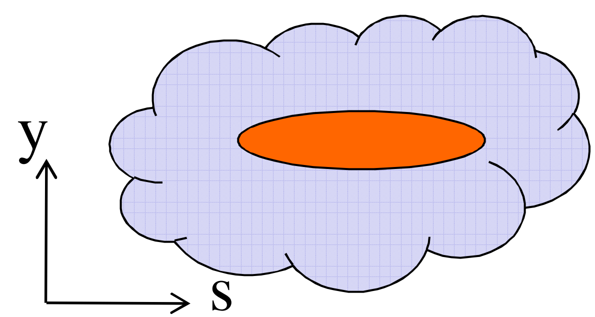
- EOM for the beam and the cloud in the y direction (coasting beam model)

$$\left(\frac{\partial}{\partial t}+c\frac{\partial}{\partial s}\right)^2 y_b(s,t)+\omega_\beta^2 y_b(s,t)=-\frac{2n_c r_b c^2}{\gamma}F\big(y_b(s,t)-y_c(s,t)\big)$$

$$\frac{d^2 y_c(s,t)}{dt^2}=-2n_b r_c c^2 F\big(y_c(s,t)-y_b(s,t)\big)$$

- *F* becomes linear near the beam

$$F(y)=\frac{y}{\sigma_y\left(\sigma_x+\sigma_y\right)}$$



Wake field induced by electron cloud and beam stability

- The eq. for the cloud can be solved as

$$y_c = \omega_c \int_{t_0}^{t} y_b(s,t')\sin\omega_c(t-t')dt'$$

wake field

- The eq. for the beam becomes

$$\left(\frac{\partial}{\partial t} + c\frac{\partial}{\partial s}\right)^2 y_b(s,t) + \tilde{\omega}_\beta^2 y_b(s,t) = \omega_b^2\omega_c \int_{t_0}^{t} y_b(s,t')\sin\omega_c(t-t')dt'$$

wake force

$$\tilde{\omega}_\beta^2 = \omega_\beta^2 + \omega_b^2$$

Wake field induced by electron cloud and beam stability

- Fourier trans. of the eq. for the beam leads

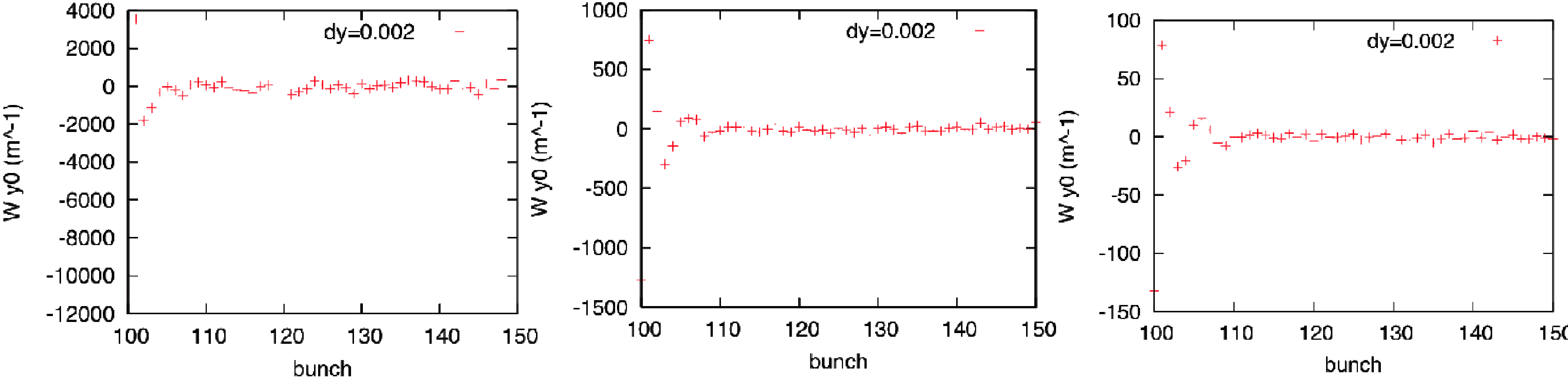
$$-(\omega - m\omega_0)^2 + \omega_\beta^2 = \frac{n_b r_b c^2}{\gamma T_0} Z_\perp(\omega)$$

$$Z_\perp(\omega) = i \int_{-\infty}^{\infty} W(t) \exp(-i\omega t) dt$$

- Growth rate of instability = Im ω

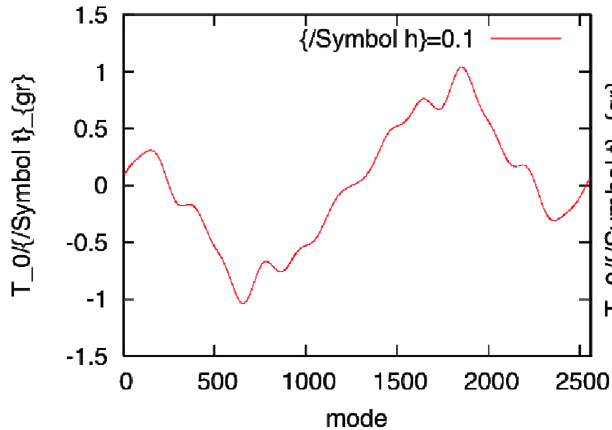
Wake for bunch correlation

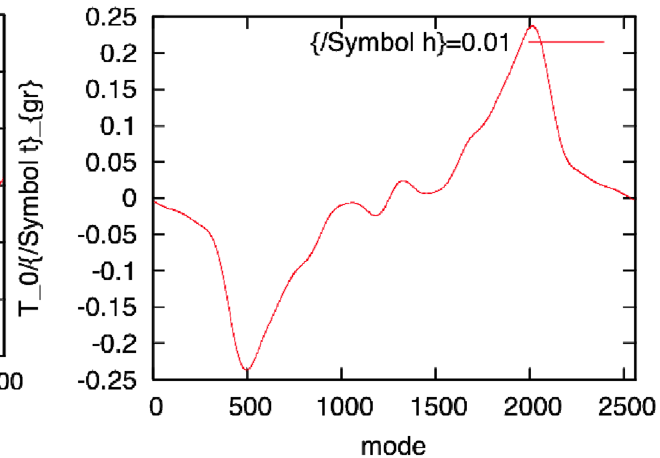
$Y_{1e}N_p$=1.7×10^9 m^{-1}(η=0.1)   1.7×10^8 m^{-1}(η=0.01)   1.7×10^7 m^{-1}(η=0.001)

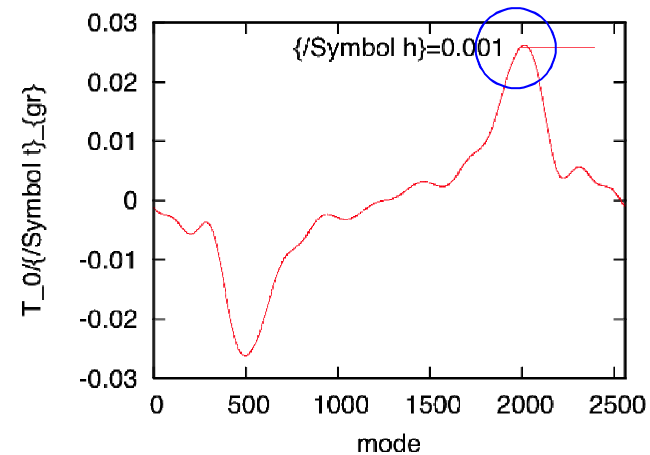


Unstable modes and growth rate

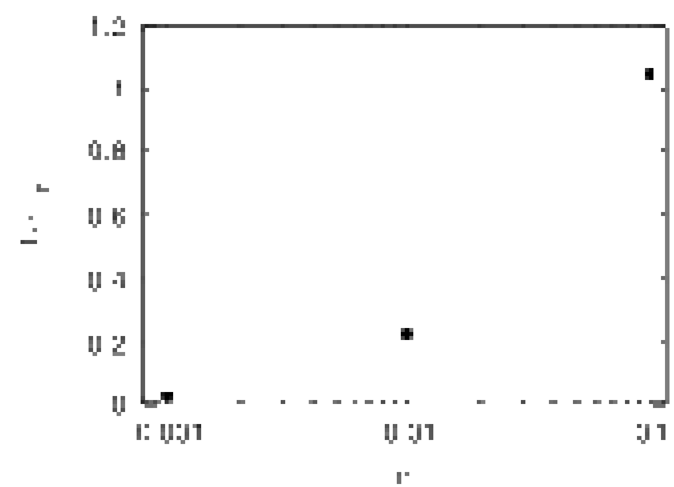
$Y_{1e}N_p=1.7\times10^9\ \mathrm{m}^{-1}(\eta=0.1)$ $1.7\times10^8\ \mathrm{m}^{-1}(\eta=0.01)$ $1.7\times10^7\ \mathrm{m}^{-1}(\eta=0.001)$







- Growth rate for η
  - Growth rate is 0.02 for η=0.001
  - not so severe that it could be controlled by the feedback



corresponding to the threshold of the SBI

Stability condition for the single bunch instability

- Landau damping

Coherence of the transverse oscillation is weakened by the longitudinal oscillation associated with momentum compaction

- Stability condition for $\omega_e \sigma_z / c > 1$
  - Balance of growth and Landau damping

$$\mathrm{Im}\,\omega_e < 0 \Rightarrow U = \frac{\sqrt{3}\lambda_p r_0 \beta}{\nu_s \gamma \omega_e \sigma_z / c} \frac{\left|Z_\perp(\omega_e)\right|}{Z_0} < 1$$

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

Threshold of the single bunch instability

- Threshold of the electron cloud density

$$\rho_{e,th} = \frac{2\gamma\nu_s\omega_e\sigma_z/c}{\sqrt{3}KQr_0\beta L} \qquad Q = \min\left(Q_{nl}, \omega_e\sigma_z/c\right)$$

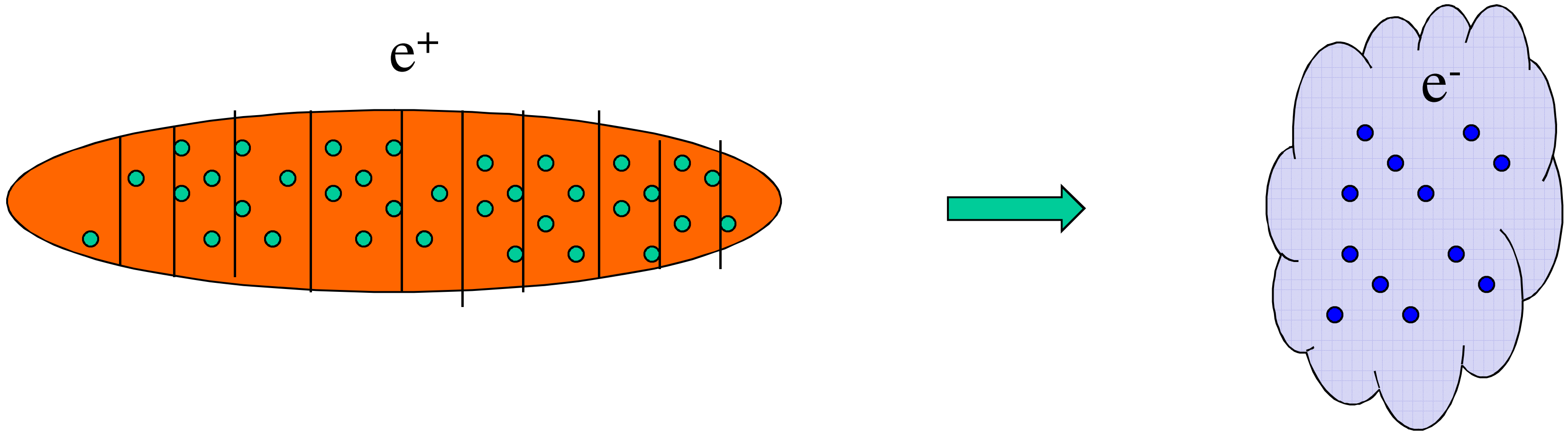
  - Q_{nl} depends on the nonlinear interaction
  - K characterizes cloud size effect and pinching
  - $\omega_e\sigma_z/c>10$ for low emittance rings
  - We use $K=\omega_e\sigma_z/c$ *and* $Q_{\mathrm{nl}}=7$ for analytical estimation

Threshold for SuperKEKB and SuperB

	Unit	SuperKEKB LER	SuperB LER
L	m	3016	1400
γ		8000	8000
I+	Amp	3.6	2.70
Np	$\times 10^{10}$	6.25	4.53
I_{bunch}	mA	1.4	1.6
β x,y ave	m	12	12
ν_s	Hz	0.012	
σ_x	mm	0.2	0.18
σ_y	µm	20	9.1
σ_z	mm	6	
Q		7	
$\omega_e \sigma_z / c$		10.9	
ρ_e threshold	$\times 10^{11} m^{-3}$	1.13	

Simulation with Particle In Cell Method for the single bunch instability

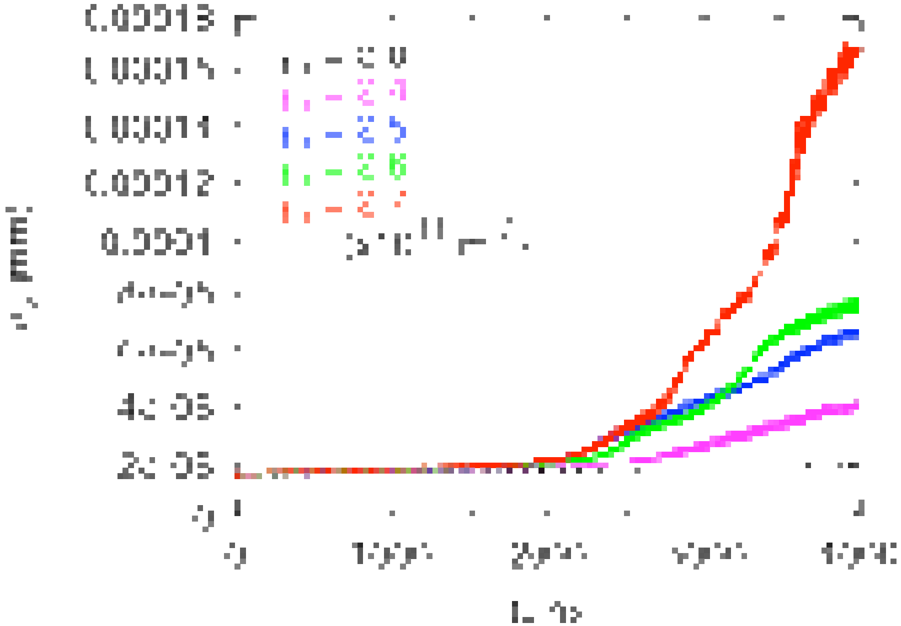
- Electron clouds are put at several positions in a ring
- Beam-cloud interaction is calculated by solving two-dimensional Poisson equation on the transverse plane
- A bunch is sliced into 20-30 pieces along the longitudinal direction



Simulations for instability threshold for SuperKEKB

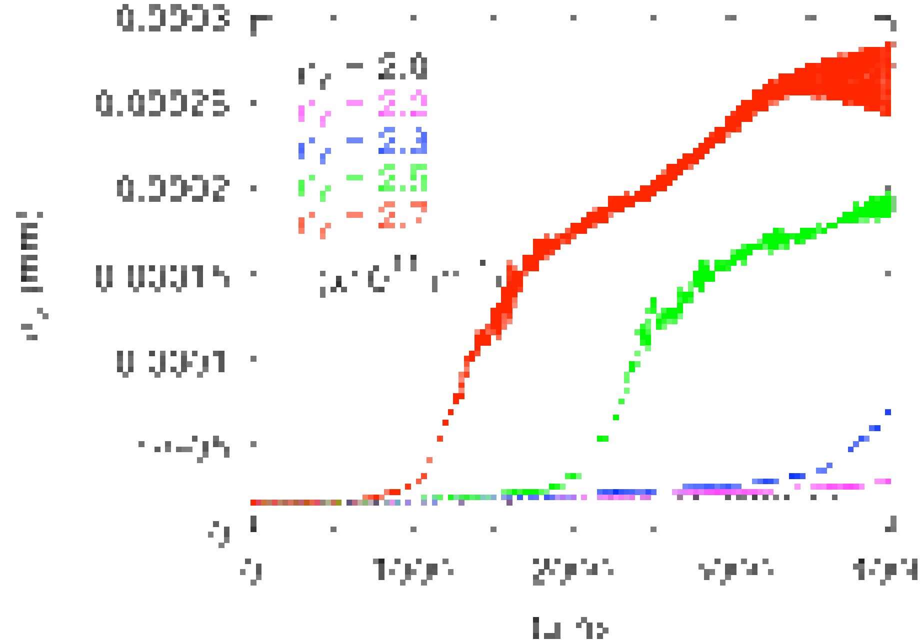
- Profiles of the beam size

η_y=0



$\rho_{e,th} \approx 2.4\times10^{11} m^{-3}$

η_y=0.2

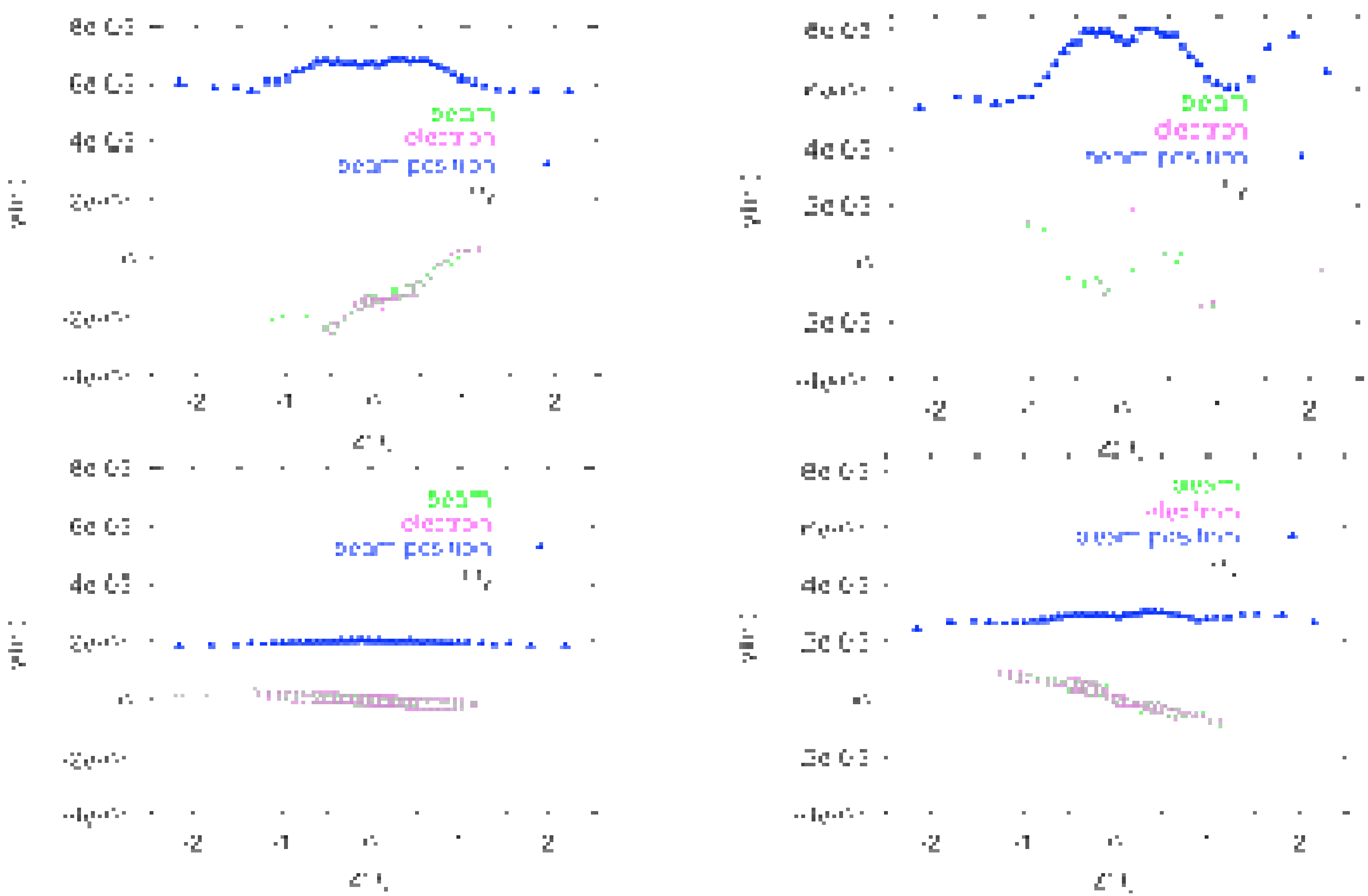


$\rho_{e,th} \approx 2.2\times10^{11} m^{-3}$

Coherent motions (SuperKEKB)

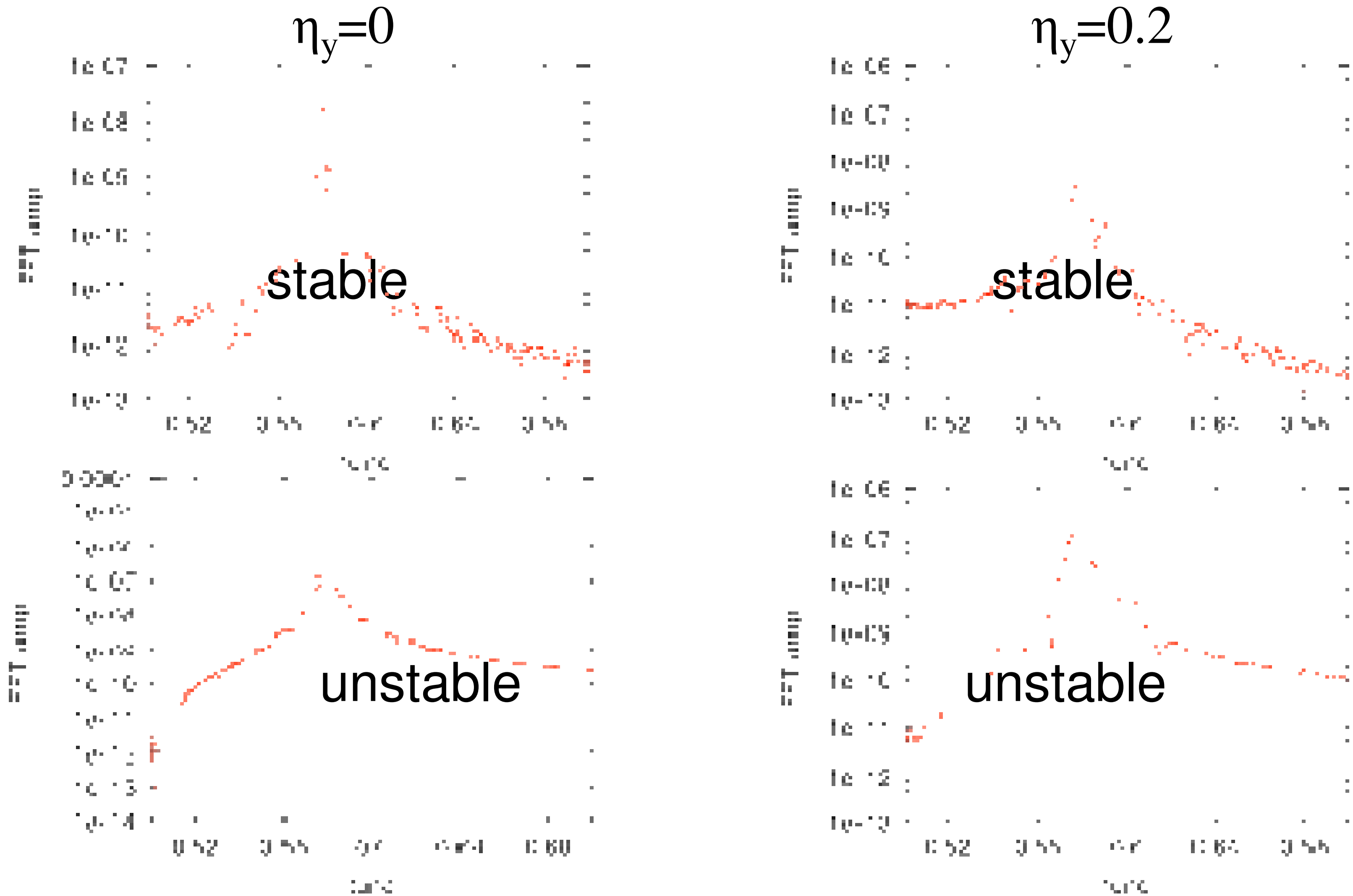
- Bunch and e-cloud profiles at 4000 turn

$\eta_y=0$ $\eta_y=0.2$



Unstable modes of the instability (SuperKEKB)

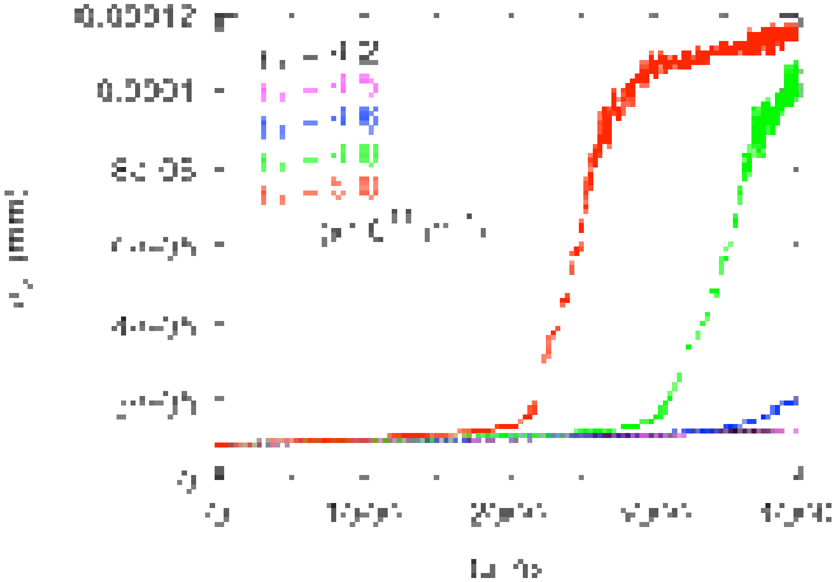
- FFT spectra below and above the threshold



Simulations for instability threshold for SuperB

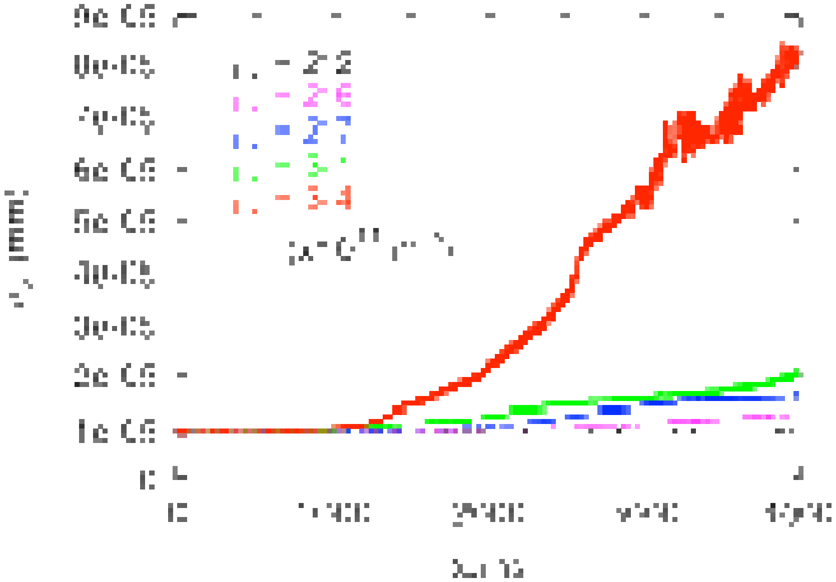
- Profiles of the beam size

η_y=0



$\rho_{e,th} \approx 4.4\times10^{11} m^{-3}$

η_y=0.2

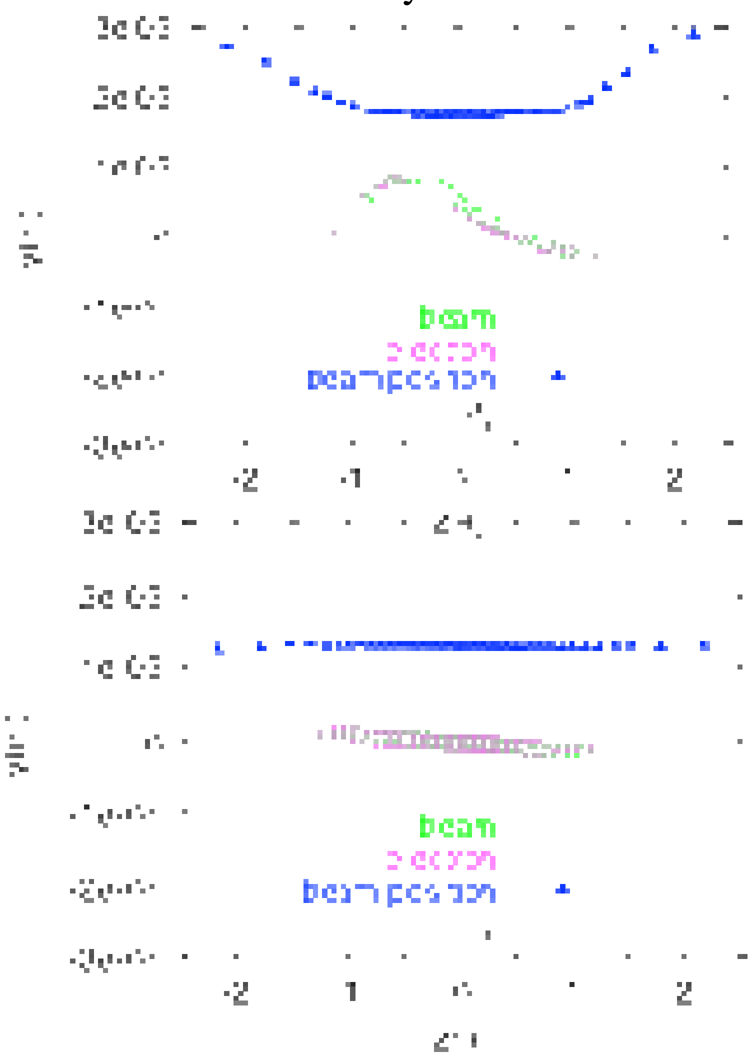


$\rho_{e,th} \approx 2.6\times10^{11} m^{-3}$

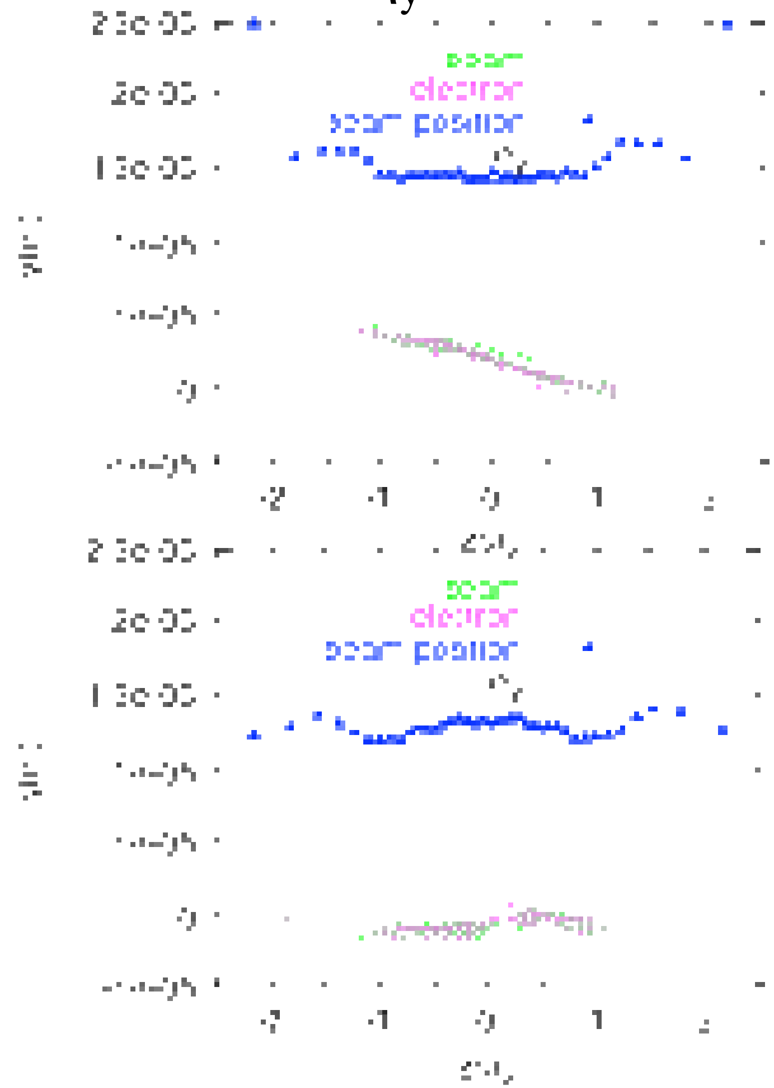
Coherent motions (SuperB)

- Bunch and e-cloud profiles at 4000 turn

$\eta_y=0$

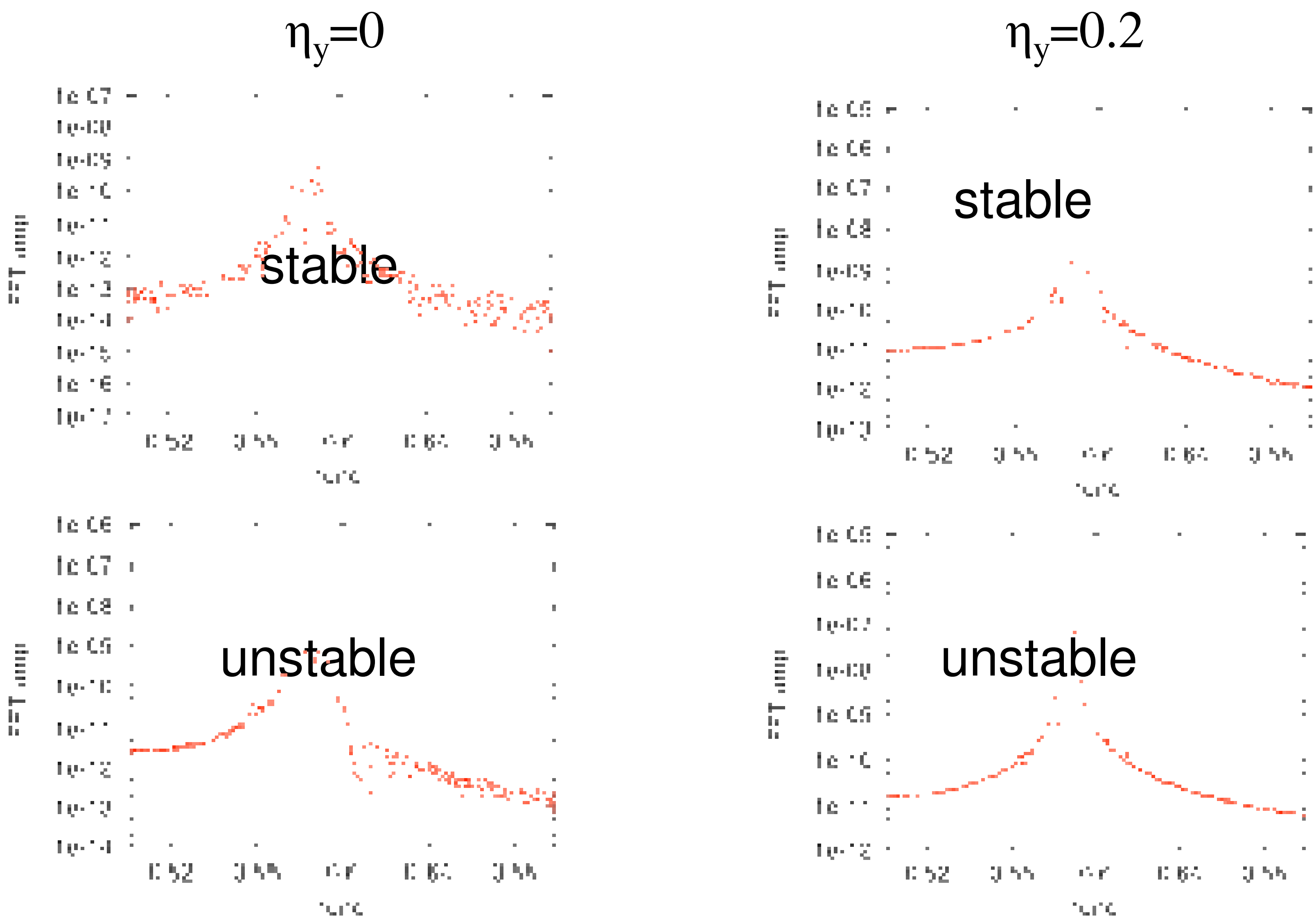


$\eta_y=0.2$



Unstable modes of the instability (SuperB)

- FFT spectra below and above the threshold



Summary

- Multi-bunch numerical simulation
  - The effective quantum efficiency η should be reduced to 0.001
  - The antechember alone seems not to be sufficient for achieving η=0.001, but together with solenoid it is expected to cure the situation (Suetsugu)
  - The CBI seems not to be severe with η=0.001

- Single bunch numerical simulation
  - The threshold of the electron cloud density for the stability has been estimated for SuperKEKB, SuperB