Electron cloud effects in positron and proton rings

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Fermilab

Thanks to Y. Alexahin, A. Valishev, R. Zwaska and V. Shiltsev

Electron cloud effects in positron rings

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

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

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

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

$$U_i \equiv \frac{\sqrt{3}r_p c\beta_i\lambda_e KQL}{4\pi\gamma\nu_s\omega_e\sigma_z\sigma_i(\sigma_x+\sigma_y)} = \frac{\sqrt{3}r_p c\beta_i\lambda_e KQ}{2\gamma\omega_e\eta\sigma_{\Delta p/p}\sigma_i(\sigma_x+\sigma_y)} = 1$$

- 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

$$2\pi\nu_s\sigma_z = \eta\sigma_{\Delta p/p}L$$

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

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

KEKB: measurement and simulation of fast head-tail instability

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

Simulation (PEHTS)

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

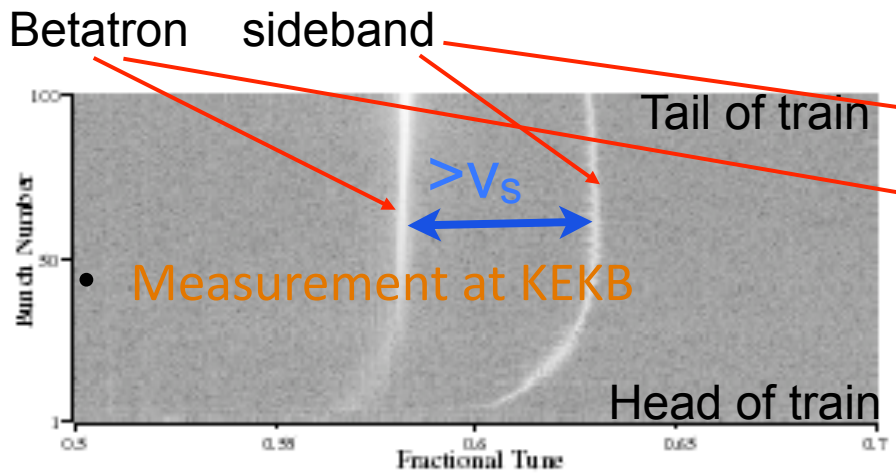
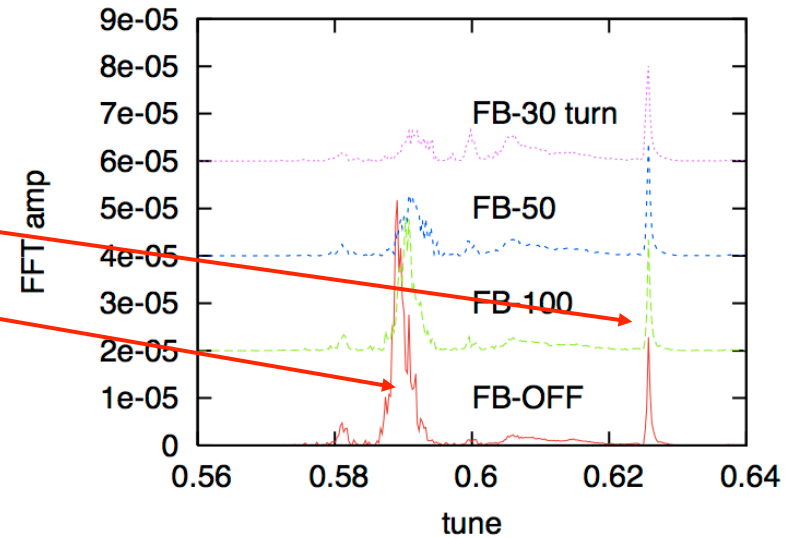
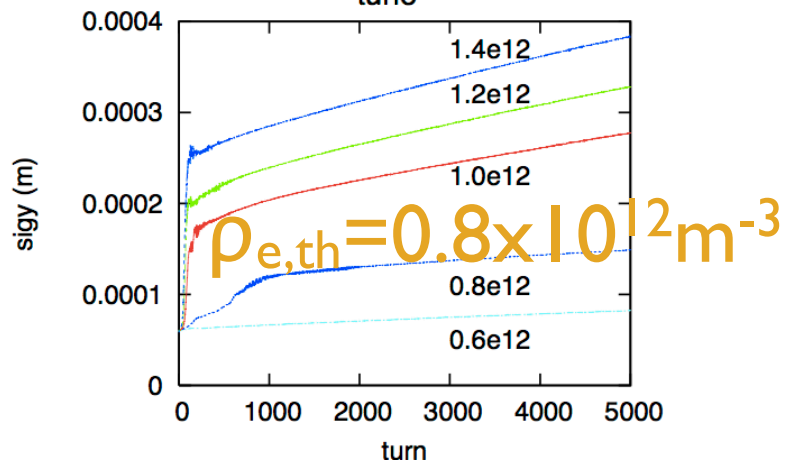


FIG. 1. Two-dimensional plot of vertical bunch spectrum versus bunch number. The horizontal axis is the fractional tune, from 0.5 on the left edge to 0.7 on the right edge. The vertical axis is the bunch number in the train, from 1 on the bottom edge to 100 on the top edge. The bunches in the train are 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.





Bunch by bunch Feedback does not suppress the sideband

Bunch by bunch feedback suppress only betatron amplitude.

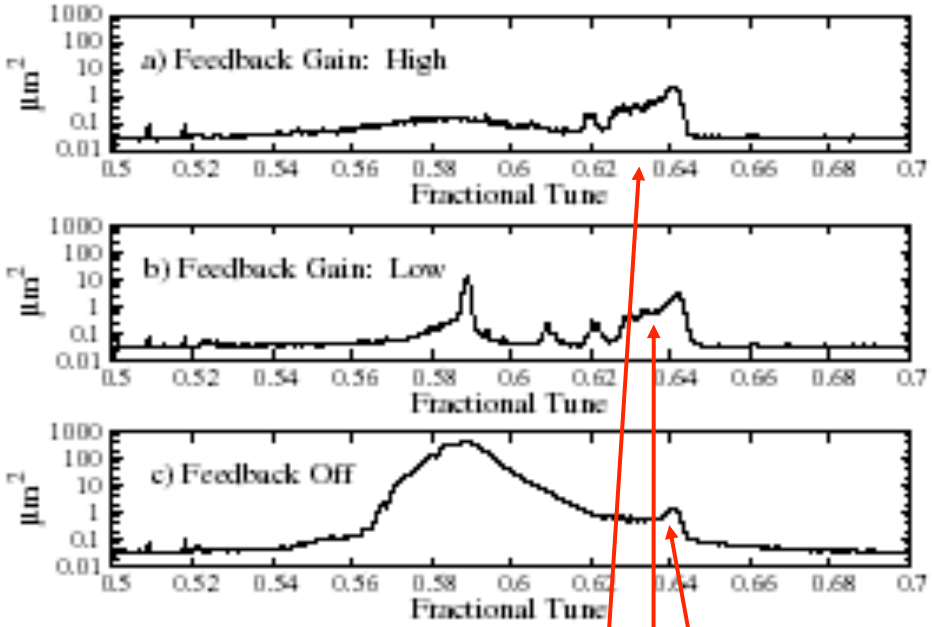
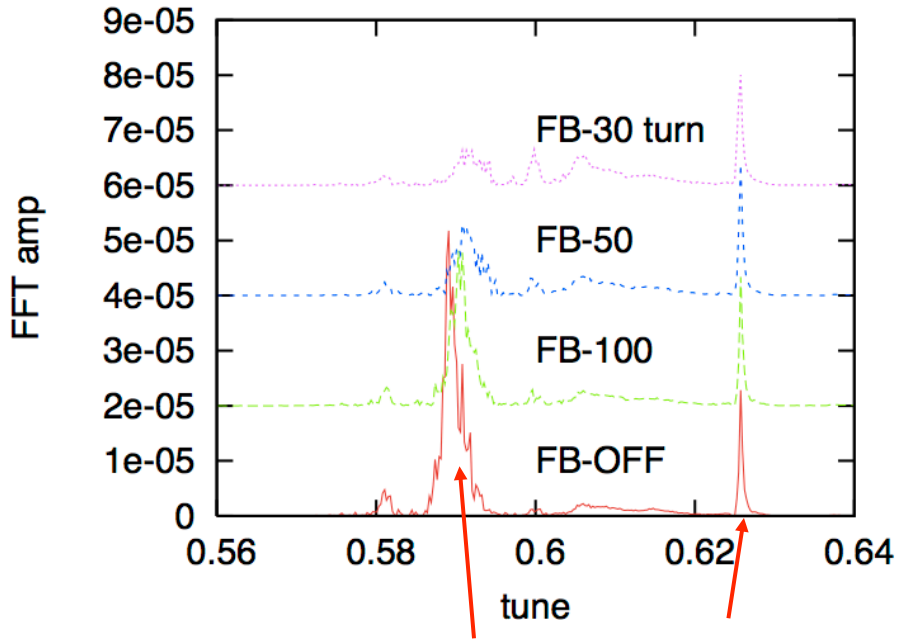


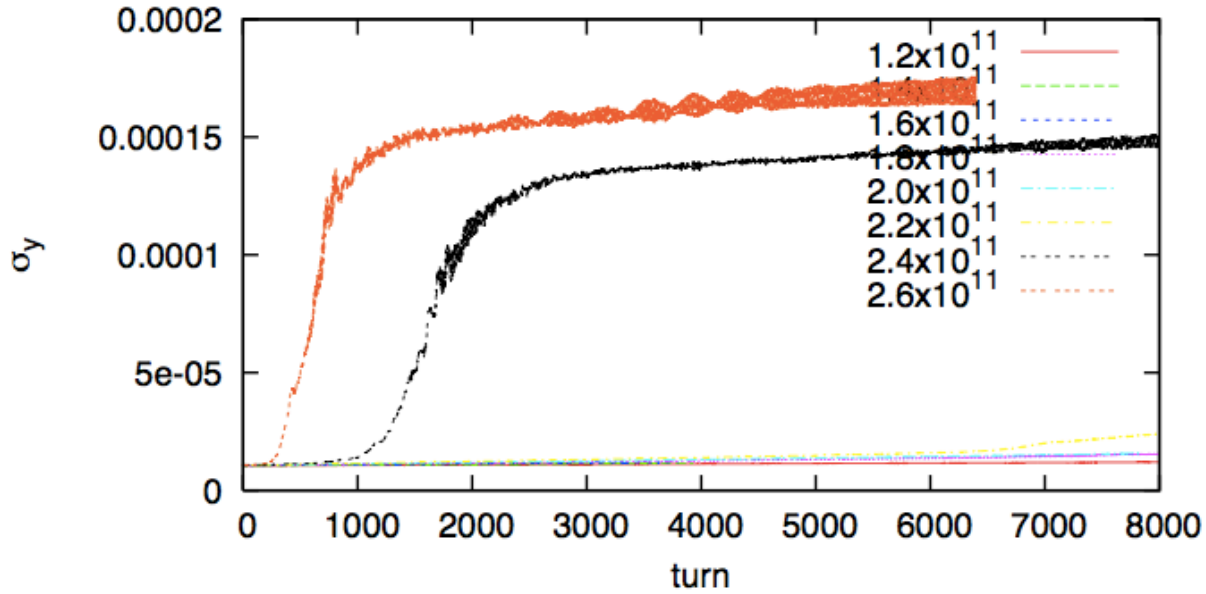
FIG. 2. Averaged spectra of all bunches with the feedback gain (a) high, (b) low, and (c) set to zero. The vertical betatron peak is visible at 0.588, and the sideband peak can be seen around 0.64.

Sideband signal is Integrated over the train



Simulation (PEHTS)

SuperKEKB

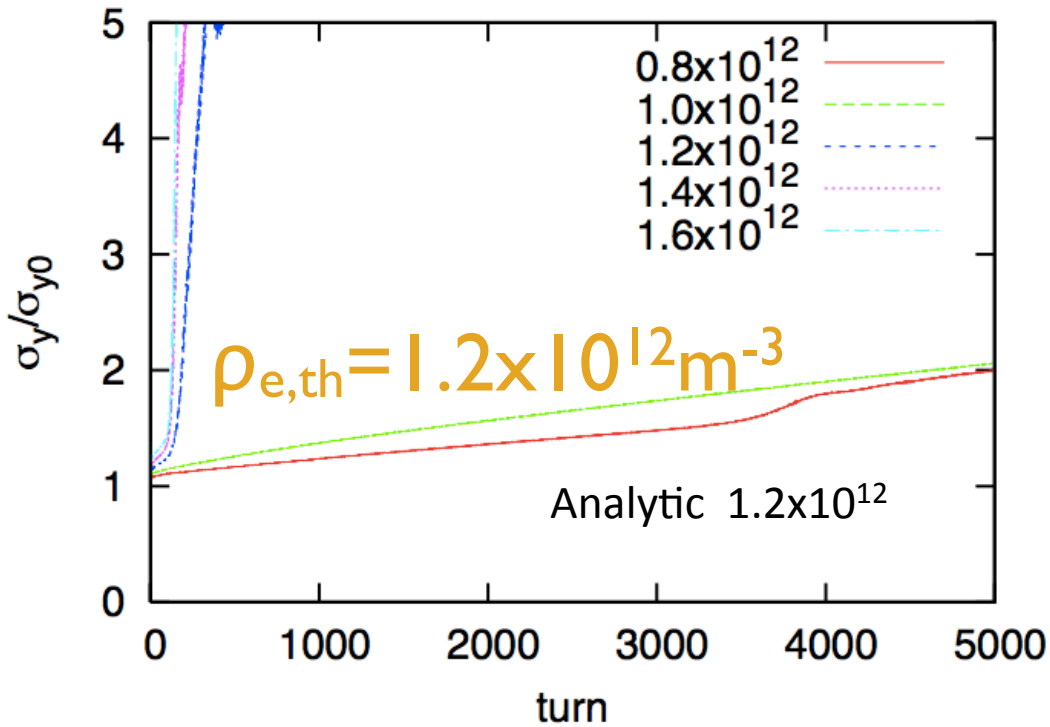


- Simulation $\rho_{th}=2.2\times10^{11}$ m^{-3}.
- Analytic $\rho_{th}=2.7\times10^{11}$ m^{-3}.
- Take care of high β section. Effects are enhanced.

Vacuum system designed to be $\rho_e=1\times10^{11}$ m^{-3}

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

PETRA-III

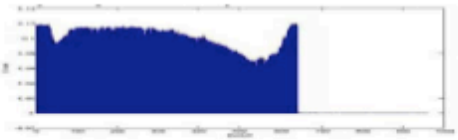


- No ante-chamber.
- The threshold current is very low. $N_+=0.5\times10^{10}$/bunch.
- Upper sideband like KEKB has been observed.

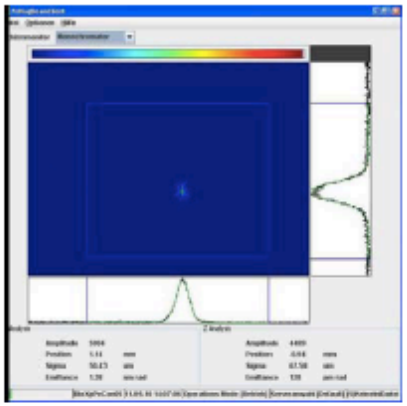
Vertical emittance blow up (640 bunches)

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

Bunch current:

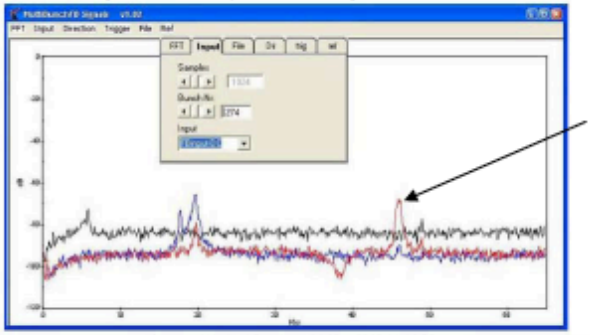


Harmonic number: h = 3840
Revolution time: 7.68 micro sec
Bunch positions: 960 (8 ns bunch spacing)

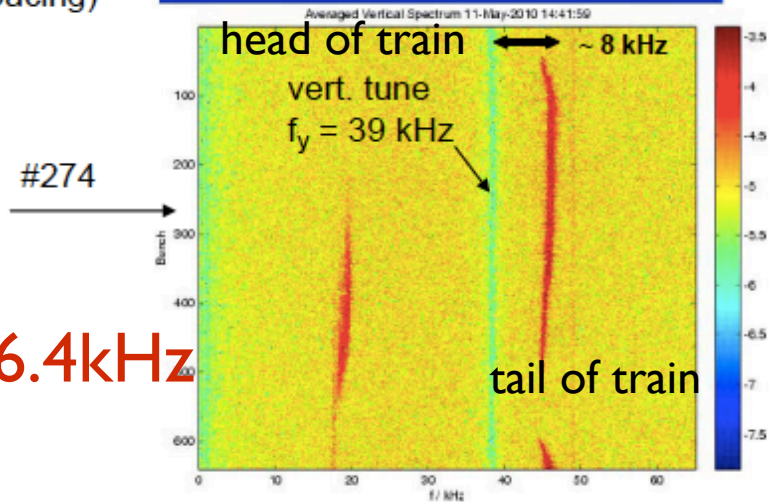


measured emittance on May 11, 2010
Horz. 1.38 nm, total current 65 mA
Vert. 128 pm

Tune spectrum, bunch position #274



upper side band



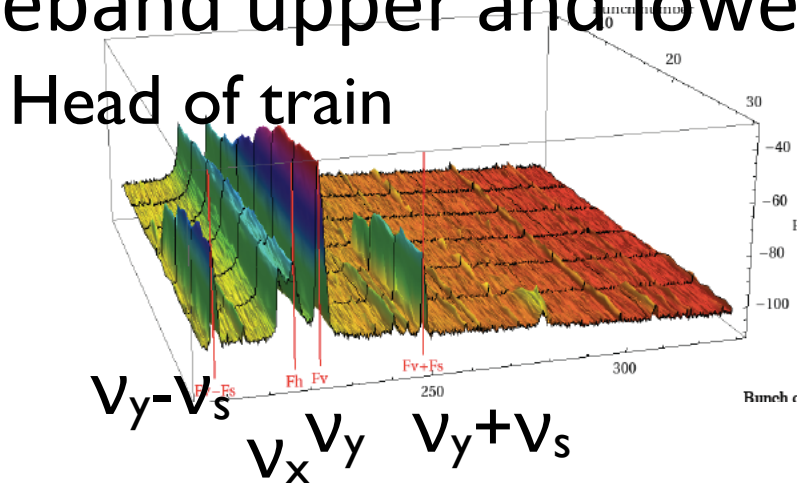
Rainer Wanzenberg | PETRA III | Oct., 2010 | Page 9

Courtesy of R. Wanzenberg

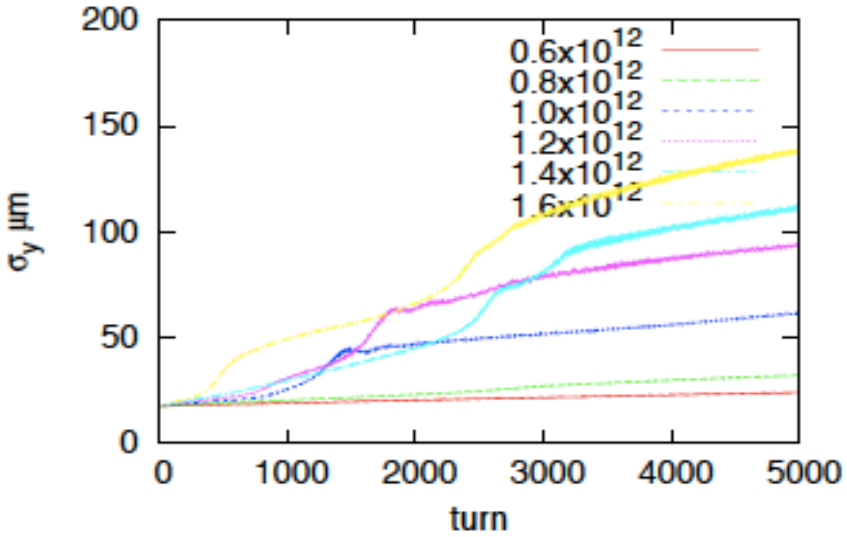
Cesr-TA

- 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 $\rho_e=1x10^{12}$ m^{-3} in CesrTA 2GeV experiment (ECLOUD10, G. Dugan)
- Both sideband upper and lower are seen.

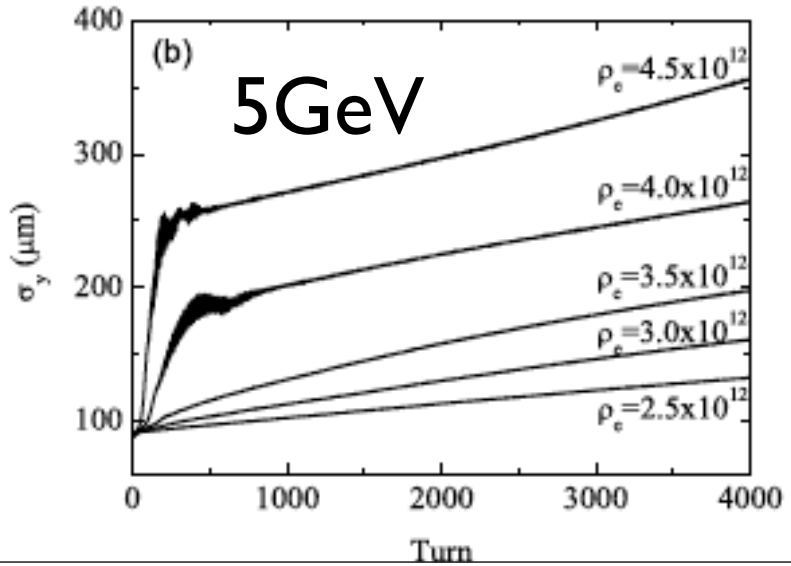


CesrTA 2 and 5 GeV



$\rho_{th}=0.8\times10^{12}$ cm^{-3}

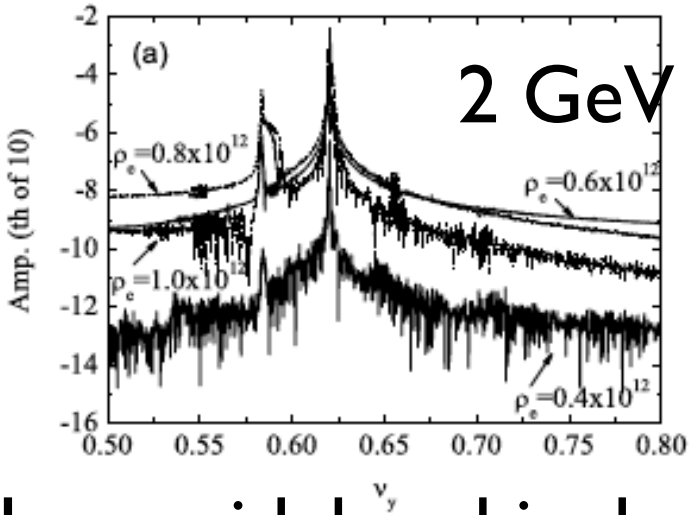
- High(2GeV) and low(5GeV) $\omega_e\sigma_z/c$.



$\rho_{th}=4\times10^{12}$ cm^{-3}

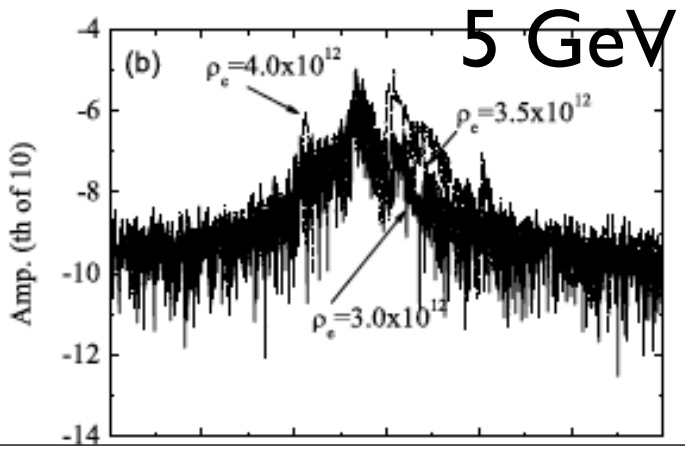
Simulated Unstable spectra

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



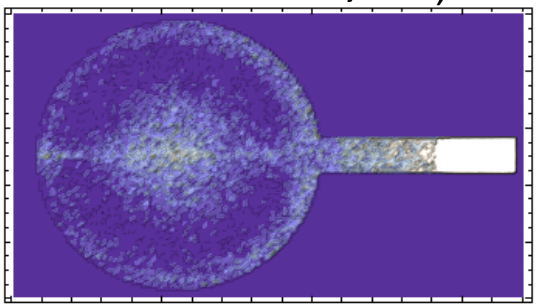
H. Jin et al., JJAP, 50, 026401(2011)

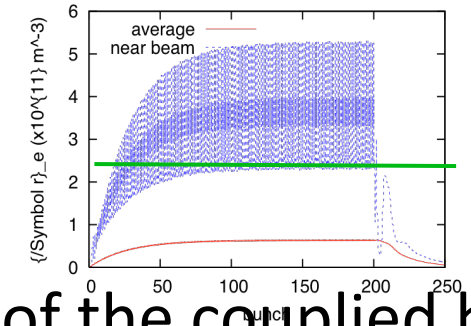
- Upper sideband is dominant for 5GeV



Estimation of cloud density and coupled bunch instability in SuperKEKB

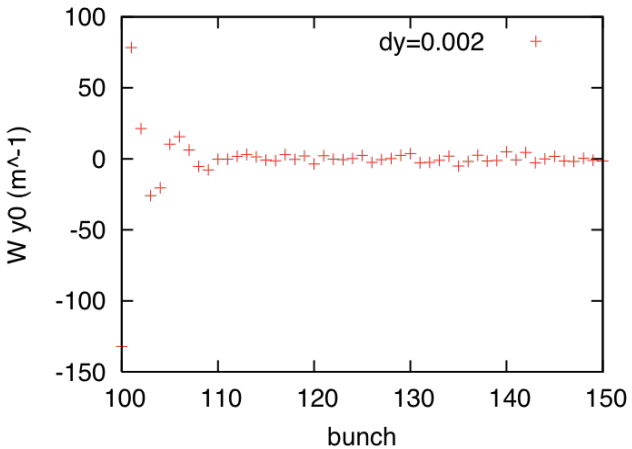
- Ante-chamber, $\delta_{2,max}$=1.2 without special structure like groove

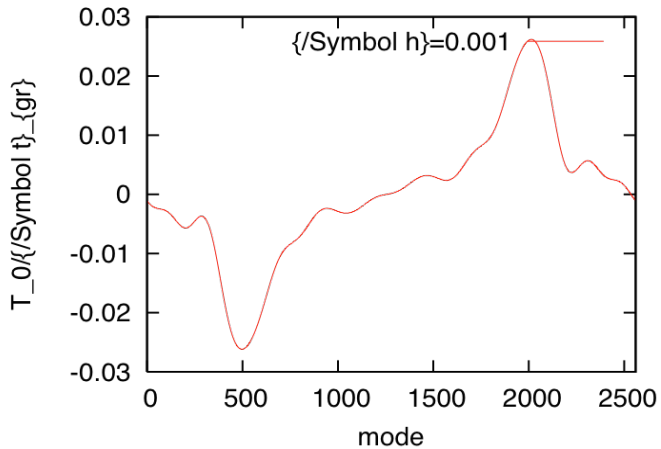




ρ_e=2.2x10^{11} m^{-3}

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





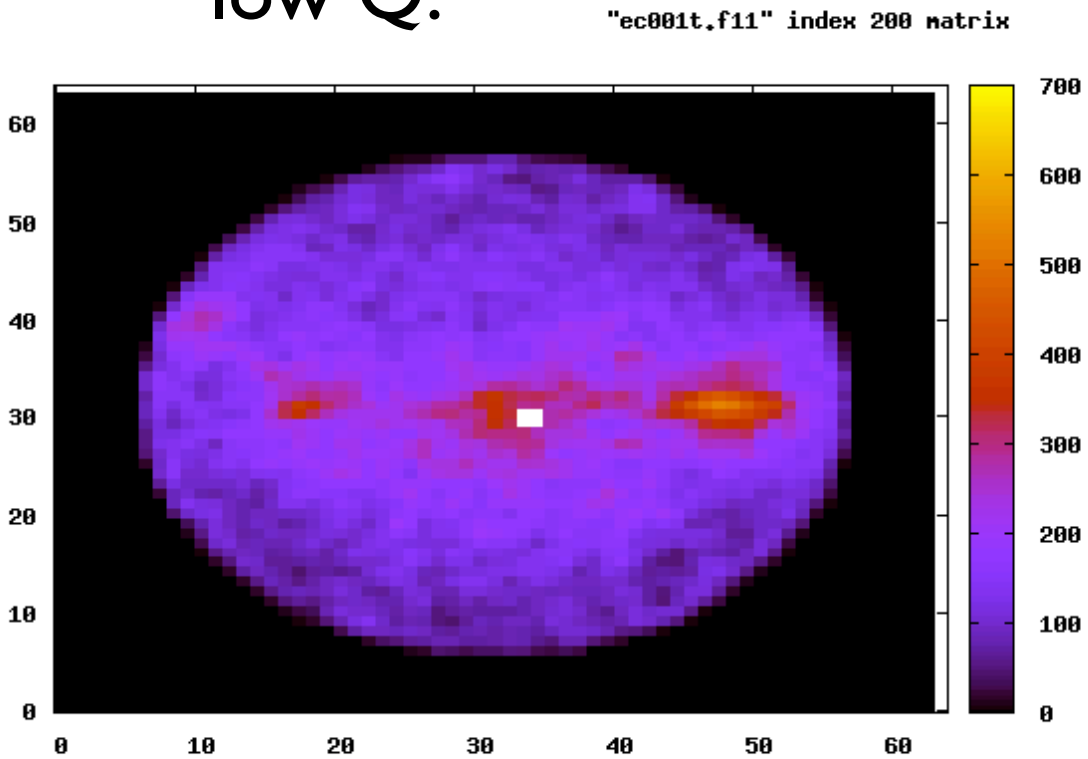
Growth time is 40 turns. It should be suppressed at ρ_e=1x10^{11} m^{-3}.

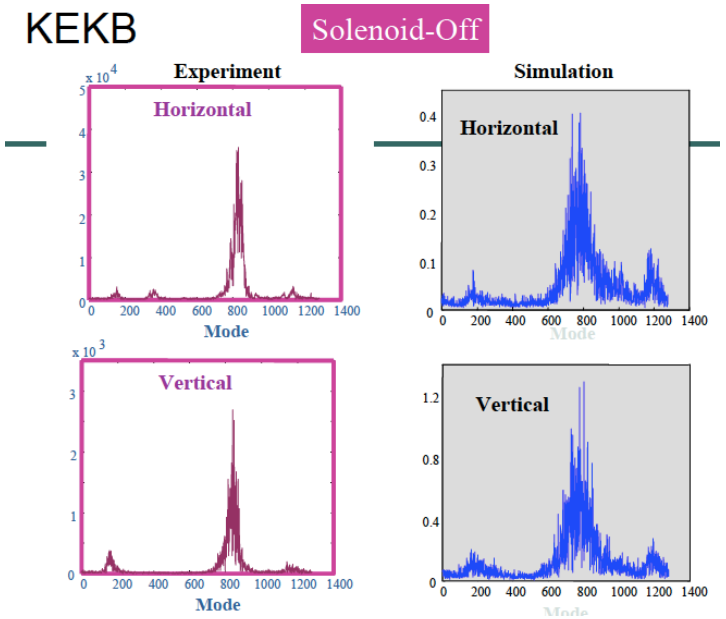
- Suetsugu-san estimates the density based on measurements and is designing the chamber to achieve density.

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.

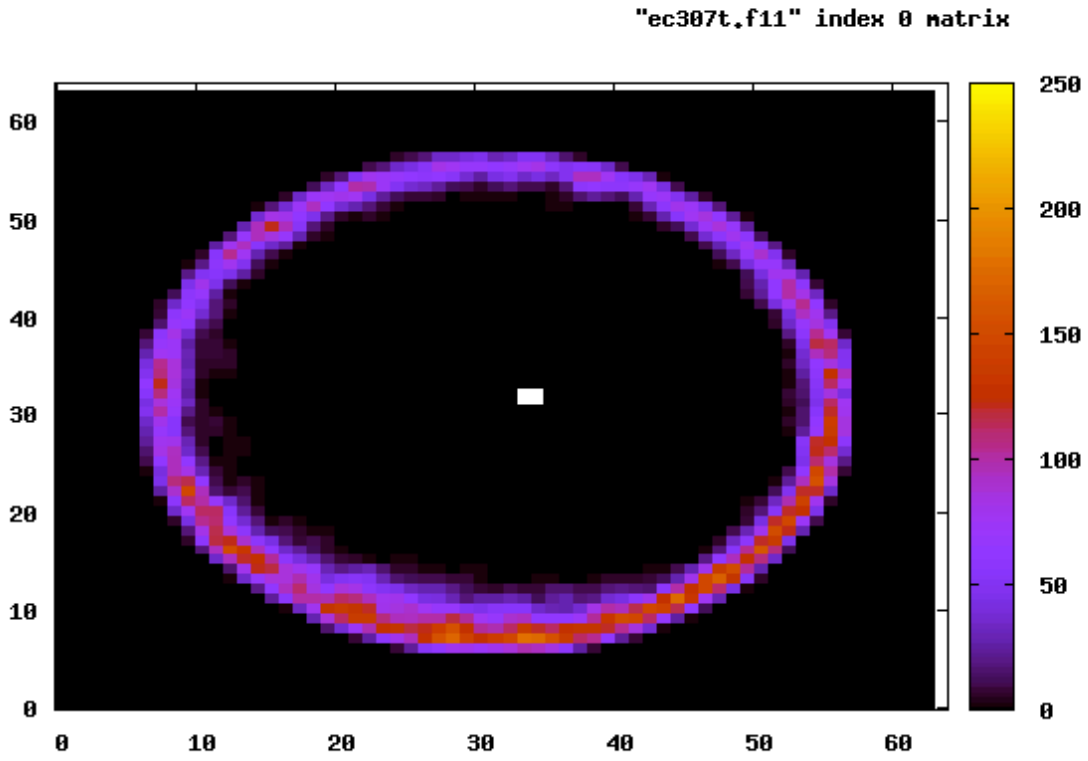


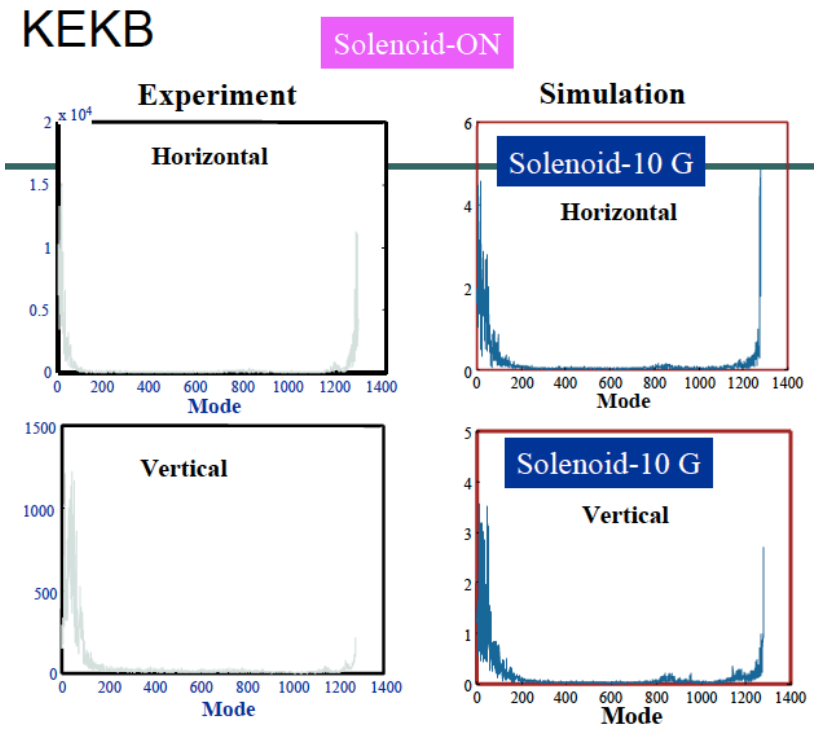


Multi-bunch instability in KEKB

Beam dancing with electron cloud

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





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.
- Simulations for SuperKEKB should be reliable.
- The vacuum cahmber is designed to satisfy the requirement $\rho_e \sim 1 \times 10^{11} m^{-3}$ in SuperKEKB.

Proton rings

- LHC, SPS

- J-PARC and neutron sources
- Proton machines in Fermilab

Electron source

- Ionization $Y_i=10^{-8}$/proton.meter

- Proton loss 100/proton loss

  PSR $Y_L=10^{-6}$/proton.meter

  J-PARC MR (1kW) $Y_L=10^{-8}$/proton.meter

- Photo-emission LHC $Y_e=10^{-3}$/proton.meter

  KEKB $Y_e=10^{-2}$/positron.meter

- Field emission...

Threshold of the strong head-tail instability LHC, SPS, Fermi MI

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

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

$$U_i \equiv \frac{\sqrt{3} r_p c \beta_i \lambda_e K Q L}{4\pi\gamma\nu_s \omega_e \sigma_z \sigma_i (\sigma_x + \sigma_y)} = \frac{\sqrt{3} r_p c \beta_i \lambda_e K Q}{2\gamma\omega_e \eta \sigma_{\Delta p/p} \sigma_i (\sigma_x + \sigma_y)} = 1$$

i=x,y

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

$$\rho_{e,th} = \frac{2\gamma\nu_s \omega_e \sigma_z / c}{\sqrt{3} K Q r_0 \beta L}$$

Origin of Landau damping is momentum compaction

$$2\pi\nu_s\sigma_z = \eta\sigma_{\Delta p/p} L$$

The same formula as positron machine

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

Threshold of the strong head-tail instability J-PARC and neutron sources

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

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

$$U_i \equiv \frac{\sqrt{3} r_p c \beta_i \lambda_e Q L}{4\pi\gamma\nu_s\omega_e\sigma_z\sigma_i(\sigma_x+\sigma_y)} = \frac{\sqrt{3} r_p c \beta_i \lambda_e Q}{2\gamma\omega_e\eta\sigma_{\Delta p/p}\sigma_i(\sigma_x+\sigma_y)} = 1$$

- i=x,y

$$2\pi\nu_s\sigma_z = \eta\sigma_{\Delta p/p} L$$

- λ_e is now electron line density, since all electrons are gathered near the beam.

- $Q = Q_{nl} = 7$
- Threshold for the neutralization factor

$$f_{th} = \frac{\lambda_e}{\lambda_p} = \frac{2\gamma\omega_e\eta\sigma_{\Delta p/p}\sigma_i(\sigma_x+\sigma_y)}{\sqrt{3} r_p c \lambda_p \beta_i Q}$$

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

$\omega_e\sigma_z/c$		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}

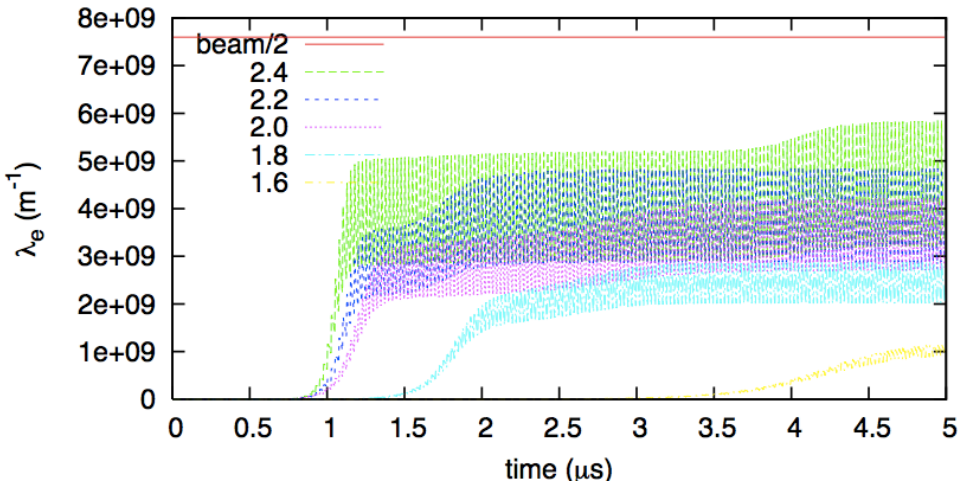
Simulations are showed latter

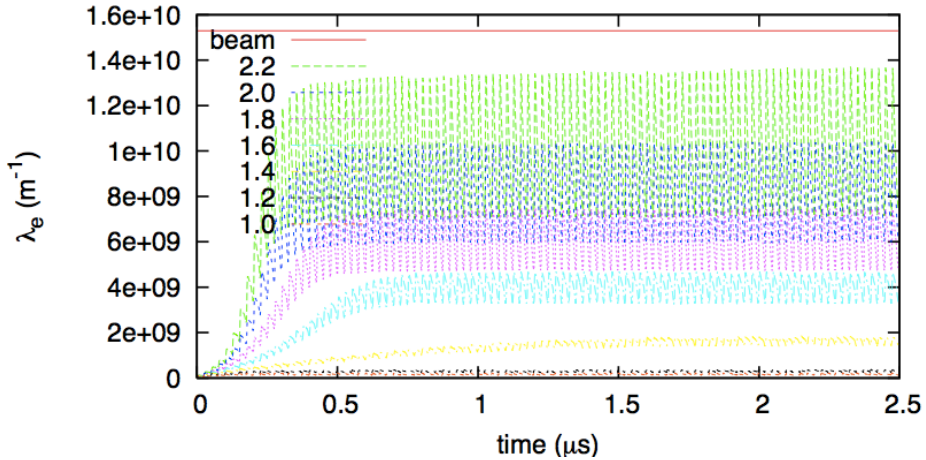
Electron source

- 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

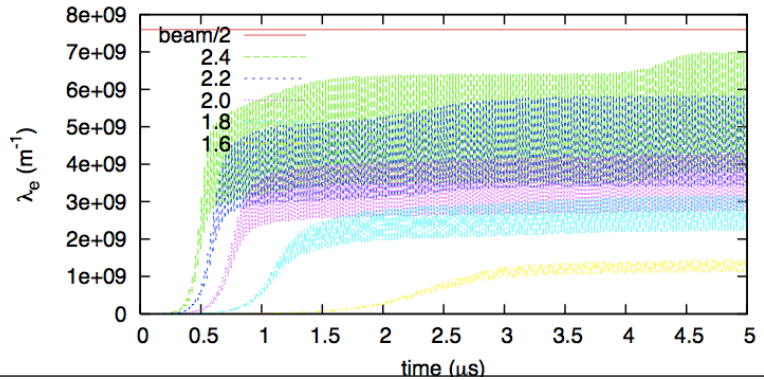
- injection top energy





Used cylindrical pipe r=2cm

- 100 time worse vacuum

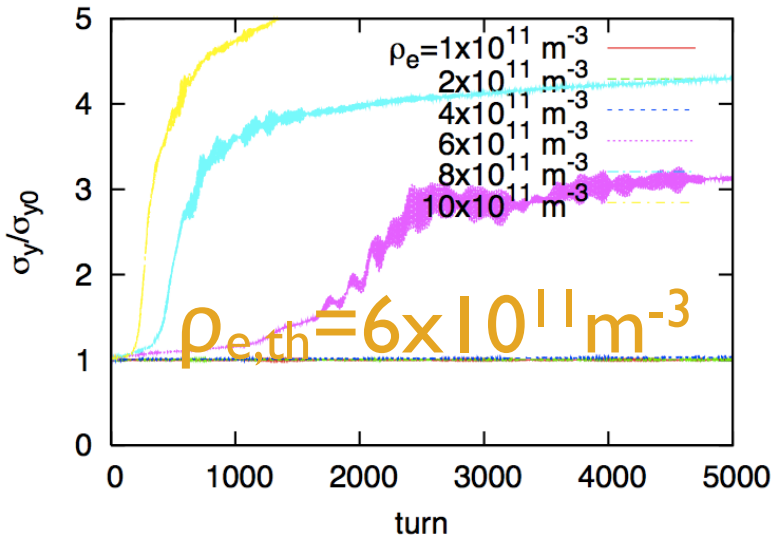


Since multipacting is dominant in injection, the density is almost independent of initial yield

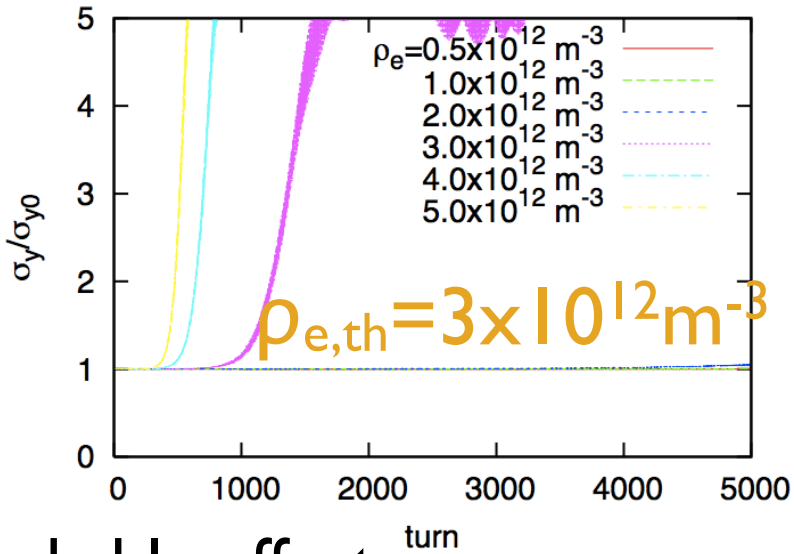
Simulation results (PEHTS)

in Bend

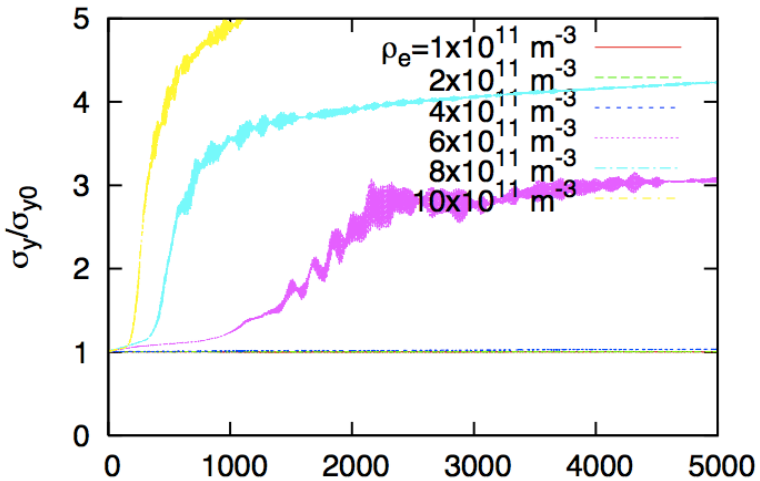
- injection

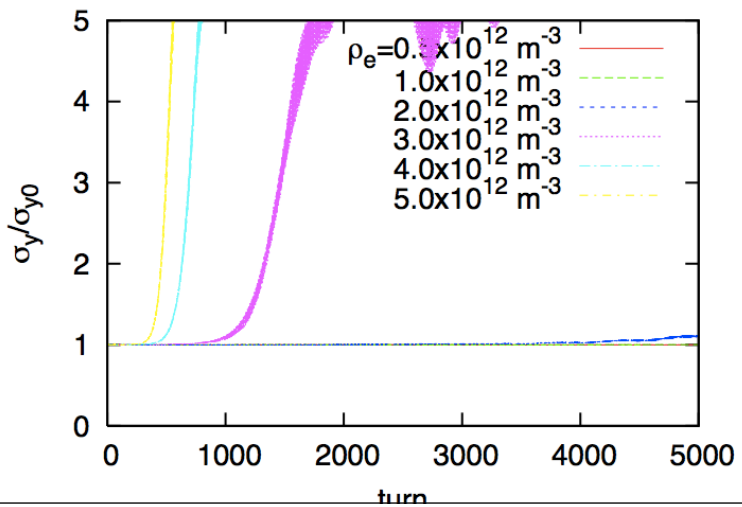


top energy



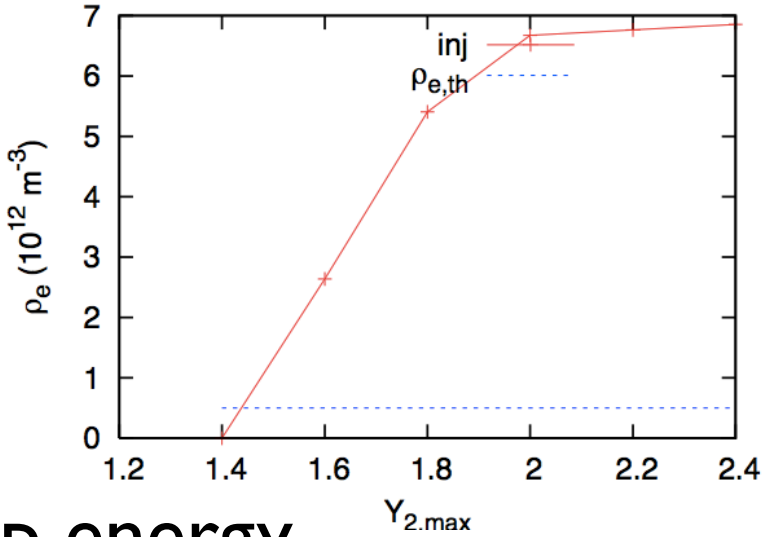
- dispersion 1.5m, no remarkable effects



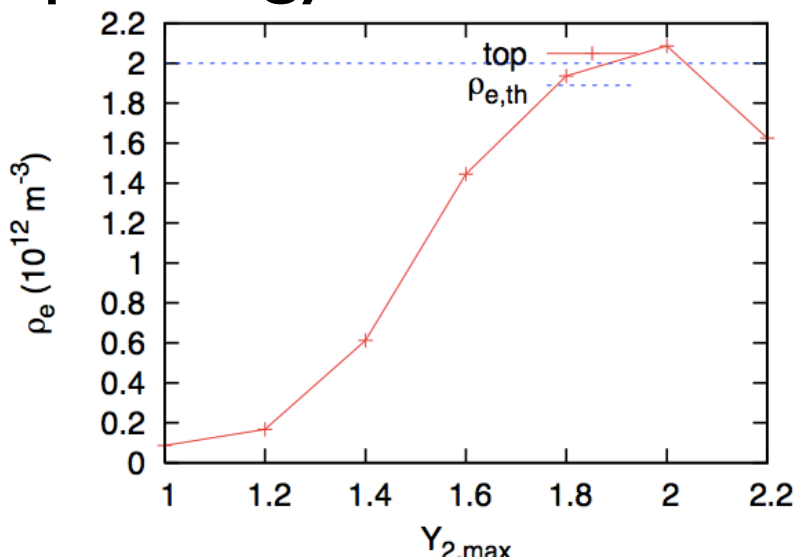


Electron density and the threshold in Bend

- Injection



- Top energy

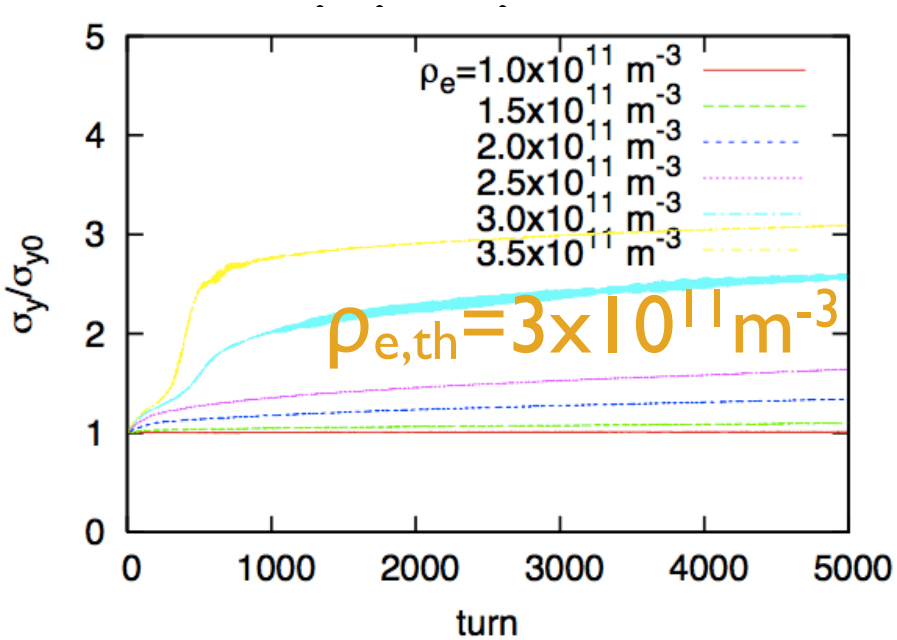


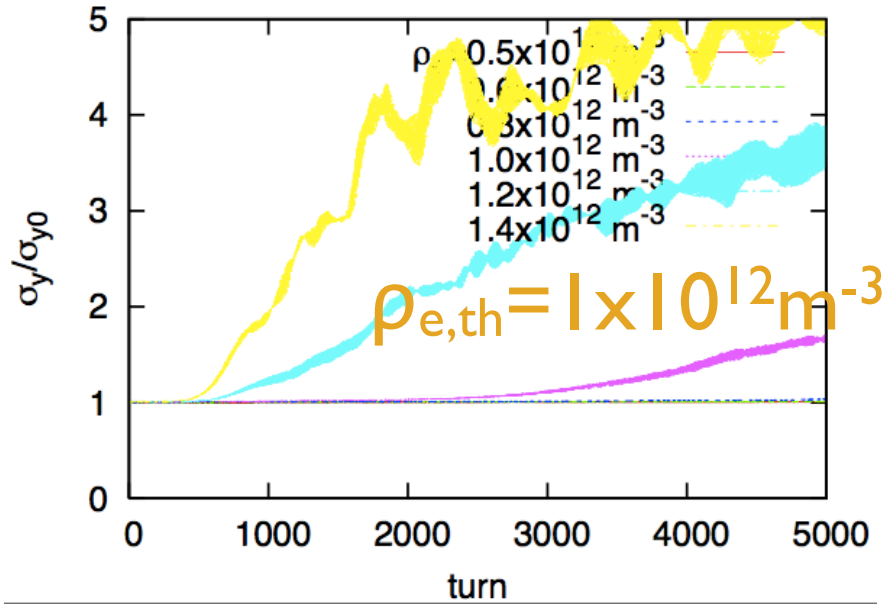
ρ_e: electron density just interacting with beam

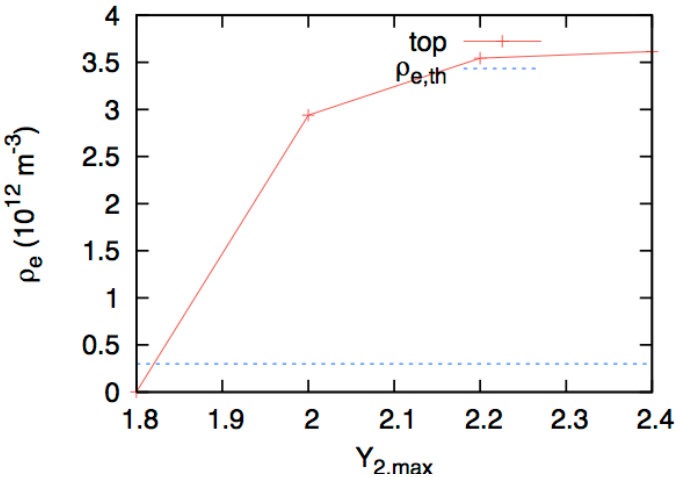
$\rho_{e,th}=2\times10^{12}m^{-3}$ is determined by simulation in previous slide

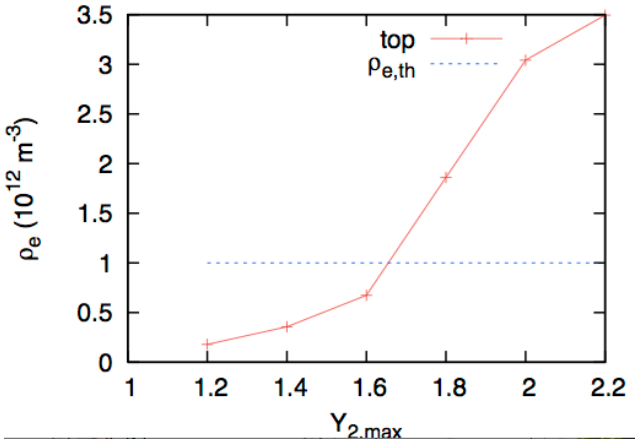
Electron density and the threshold

in Drift space









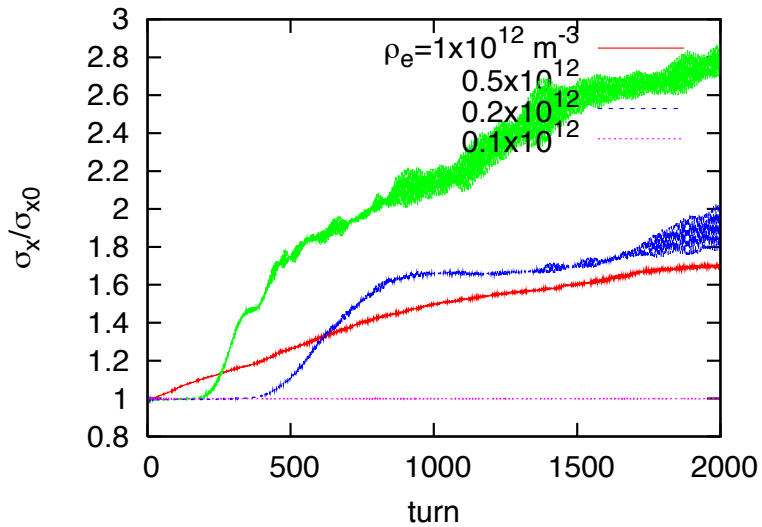
SPS

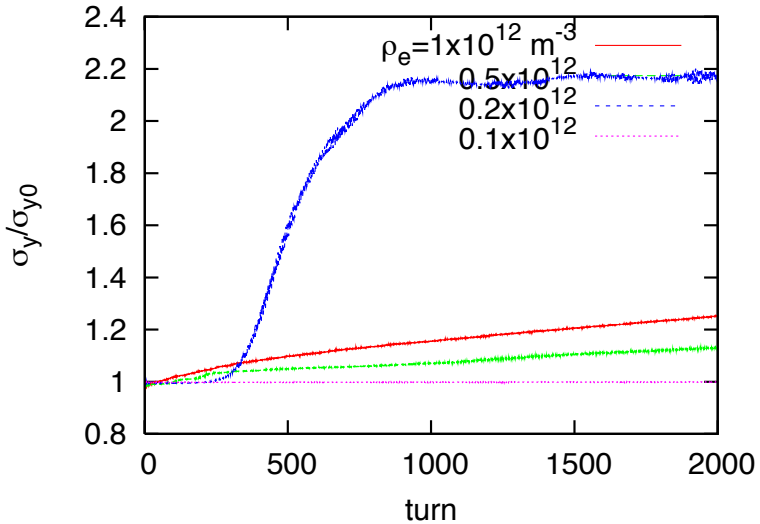
- $E=26$ GeV, $\varepsilon=1.01\times10^{-7}$, $\beta_x=33.85$m, $\beta_y=71.87$m
- $\sigma_z=0.229$m, $\sigma_E=0.19\%$, $\alpha=1.92\times10^{-3}$, $\nu_s=0.00564$
- $\omega_e/2\pi=355$ MHz, $\omega_e\sigma_z/c=1.7$
- $\rho_{e,th}=1.4\times10^{11}$ m^{-3}.(use the formula)

$$\rho_{th} = \frac{2\gamma\nu_s\omega_e\sigma_z/c}{\sqrt{3}\,KQr_e\beta_y L};$$

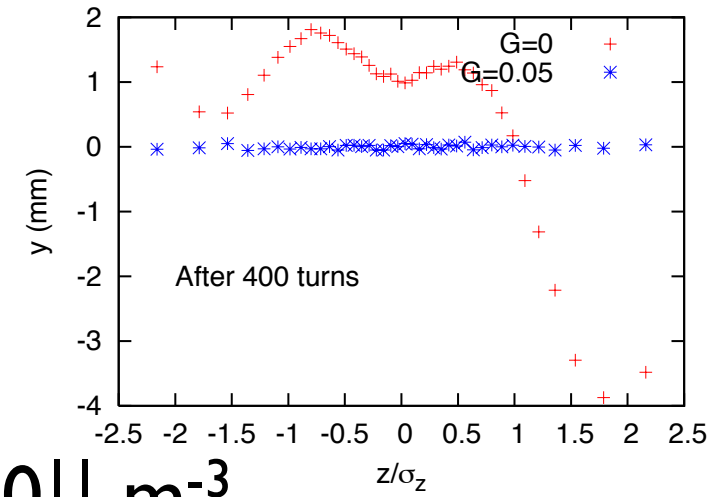
Electron cloud instability in drift

- Note $\sigma_x < \sigma_y$





- Instability signal is clear near the threshold



- Incoherent (artifact) effect is strong in high density.

ρ_{th}=1~2x10^{11} m^{-3}.

J-PARC and neutron sources

- J-PARC
- LINAC 181MeV ->400MeV
- Rappid Cycle Synchrotron (RCS)
  400(181)MeV->3 GeV 25 Hz 1MW
- Main Ring (MR)
- 3GeV->30GeV 0.3-0.2 Hz 0.75MW

Old work

K. Ohmi et al., PRST(2002)

TABLE I. Basic parameters of the proton rings.

		J-PARC							
		3 GeV		50 GeV					
Variable	Symbol	Inj.	Ext.	Inj.	Ext.	PSR	ISIS	SNS	AGS
Circumference	L (m)	348.3	348.3	1567.5	1567.5	90	163	248	800
Relativistic factor	γ	1.4	4.2	4.2	54	1.85	1.07	2.02	3.0
Bunch population	$N_p(\times 10^{13})$	4.15	4.15	4.15	4.15	3	1.25	20.5	1.2
Number of bunches	n_b	2	2	8	8	1	2	1	6
Harmonic number	H	2	2	9	9	1	2	1	6
rms beam sizes	σ_r (cm)	1.9	1.2	1.1	0.5	1.0	3.8	2.8	0.7
Bunch length	ℓ_p (m)	110	82	82	16	65	60	200	68
rms energy spread	$\sigma_{\delta E/E}$ (%)	0.6	0.7	0.7	0.25	0.4	0.5	0.5	0.28
Slippage factor	η	−0.48	−0.047	−0.058	−0.0013	−0.187	−0.83	−0.204	−0.146
Synchrotron tune	ν_s	0.0058	0.0005	0.0026	0.0001	0.0003	0.0036	0.0004	0.0017
Beam pipe radius	R (cm)	12.5	12.5	6.5	6.5	5	8	10	5

Trailing edge Multipacting

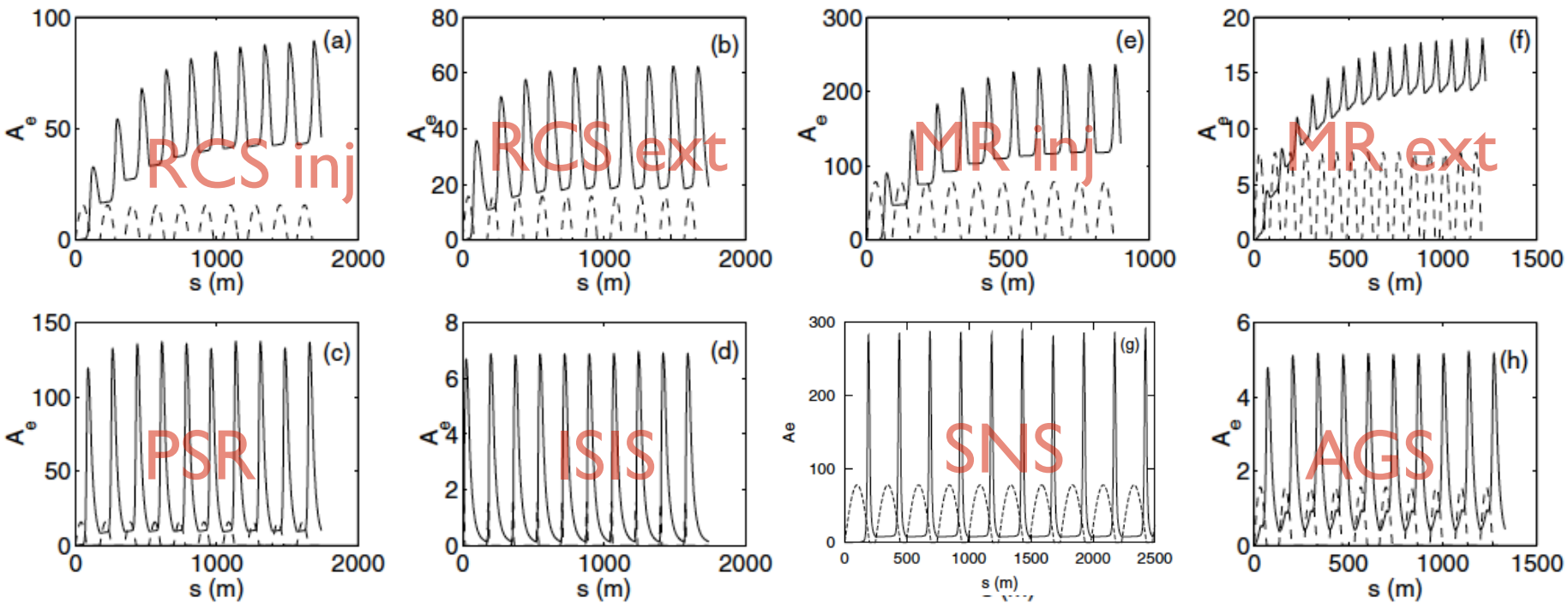


FIG. 2. Electron amplification factor. The proton beam profiles are plotted by the dashed lines in the pictures with arbitrary units. Electrons are produced at the chamber surface. (a) 3 GeV injection; (b) 3 GeV extraction; (c) 50 GeV injection; (d) 50 GeV extraction; (e) PSR; (f) ISIS; (g) SNS; (h) AGS.

$Ae = N_e / N_{e,0}$: Amplification of electron

Summary for simulation results

- Neutralization factor

K. Ohmi et al., PRST(2002)

TABLE II. Electron cloud buildup of the proton rings.

	J-PARC							
	3 GeV		50 GeV					
Variable	Inj.	Ext.	Inj.	Ext.	PSR	ISIS	SNS	AGS
A_e (bottom)	42.0	18.0	9.4	0.13	118	12.9	7.8	0.42
A_e (peak)	87.6	62	136	6.9	236	17.5	286	5.18
f (bottom)	0.020	0.0067	0.0035	0.000 01	0.034	0.003	0.007	0.0001
f (peak)	0.042	0.023	0.05	0.0005	0.067	0.005	0.25	0.0015

- Stability,

TABLE III. Wake field and stability for electron cloud instability.

	J-PARC							
	3 GeV		50 GeV					
Variable	Inj.	Ext.	Inj.	Ext.	PSR	ISIS	SNS	AGS
$Z(\omega_e)_{1,L}/Q$ (MΩ/m)	0.29	0.24	0.68	0.019	0.46	0.0051	0.03	0.024
$Z(\omega_e)_{1,H}/Q$ (MΩ/m)	0.61	0.83	9.7	0.96	0.90	0.0085	1.23	0.37
$\omega_e \ell_p / c$	133	182	199	276	166	27	272	153
U_L	0.07	0.23	0.11	0.02	1.6	0.007	0.10	0.004
U_H	0.15	0.78	1.6	1.2	3.2	0.012	4.0	0.06

SNS is serious only tail part shown in previous slide.

Latest works (2006)

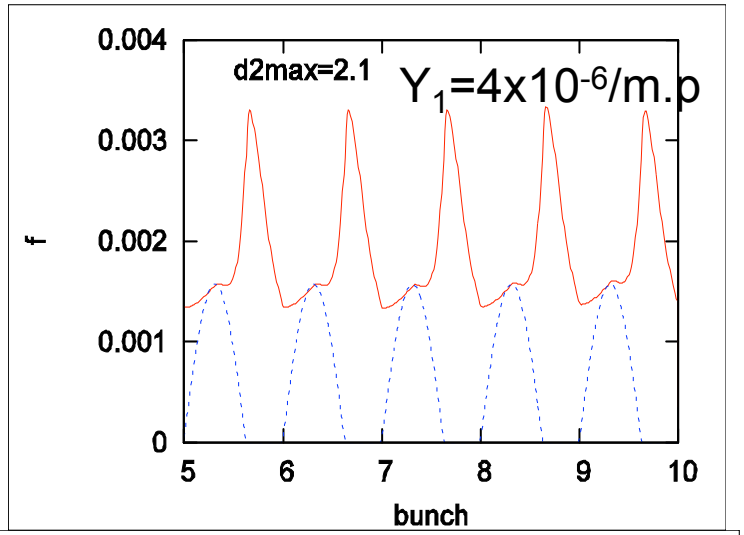
Estimation of electron yield (Toyama et.al.)

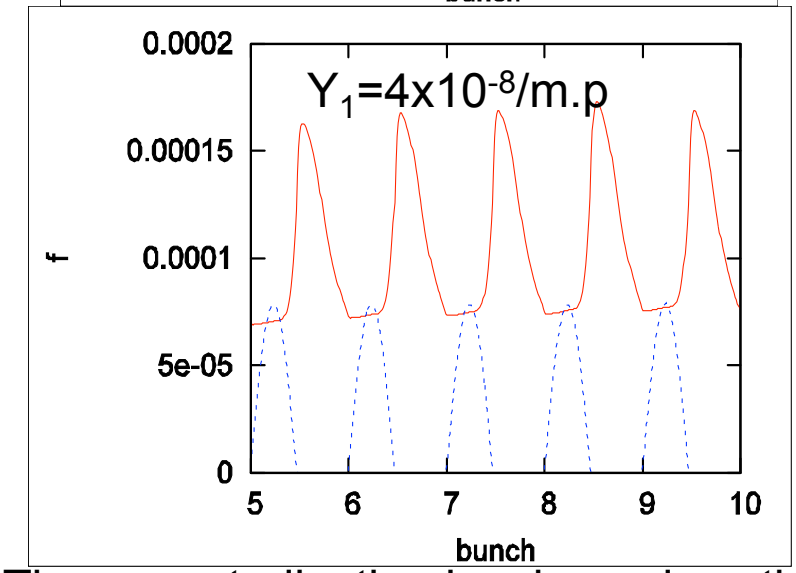
		Proton loss	electron yield	Y1 (/m.p)	Cure
RCS	Charge exchange carbon foil (140 W)	-	1.7×10^{14}/500 μs	1.1×10^{-5}	electron catcher
	Second stripping foils H^0 < 400 W H^-	- -	5×10^{11}/500 μs -		- -
	Halo collimator 181 MeV < 4 kW 400 MeV	< 5.5×10^{12} < 2.5×10^{12}	5.5×10^{14}/500 μs 2.5×10^{14}/500 μs	8.2×10^{-5} 2.8×10^{-5}	solenoid solenoid
	Uncontrolled loss 181 MeV 400 MeV	< 1.1×10^{11} < 5×10^{10}	1.1×10^{13} 5×10^{12}	1.6×10^{-6} 5.6×10^{-7}	- -
MR	Hallo collimator controlled loss (450 W)	< $6.6 \times 10^{11} \times 5$	$6.6 \times 10^{13} \times 5$		solenoid
	Uncontrolled loss for fast extraction (1.37 kW)	1.65×10^{13}/0.6 s	1.65×10^{15}/0.6 s	2.8×10^{-8}	
	Uncontrolled loss for slow extraction (7.5 kW)	5.2×10^{12}/s	5.2×10^{14}/s	5.4×10^{-9}	

Y_1: Normalized electron yield, electron created by a proton per meter.

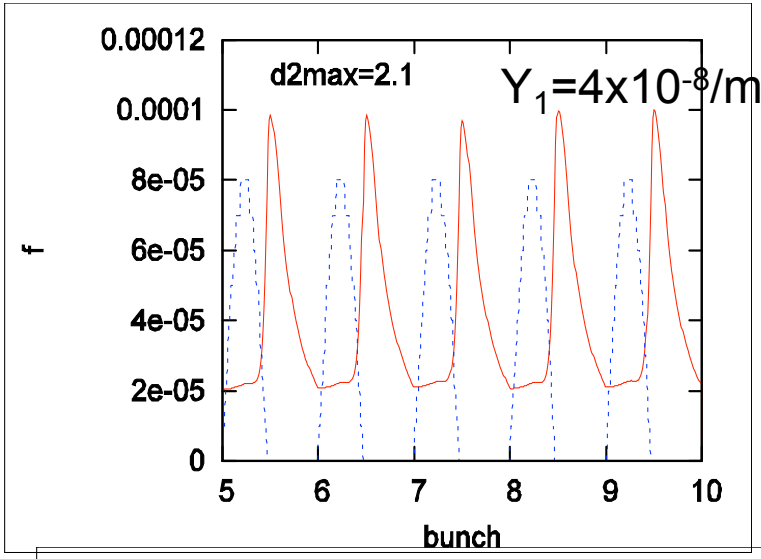
Drift space

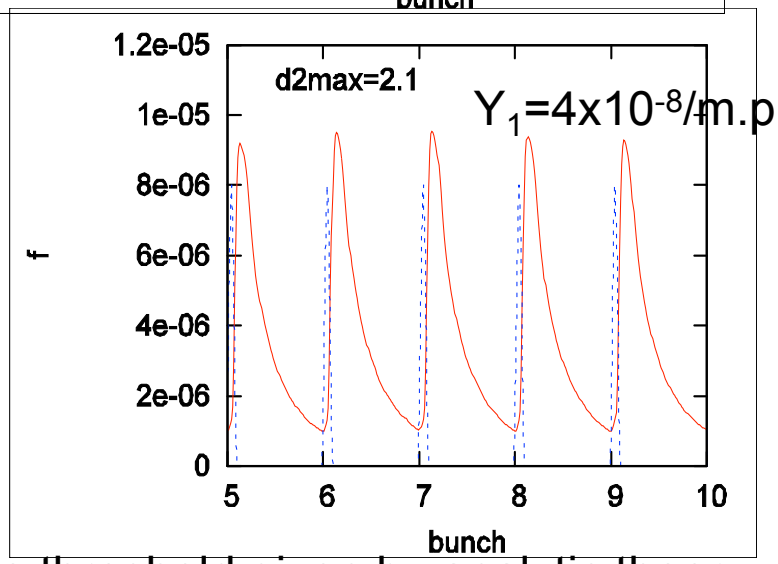
RCS





MR





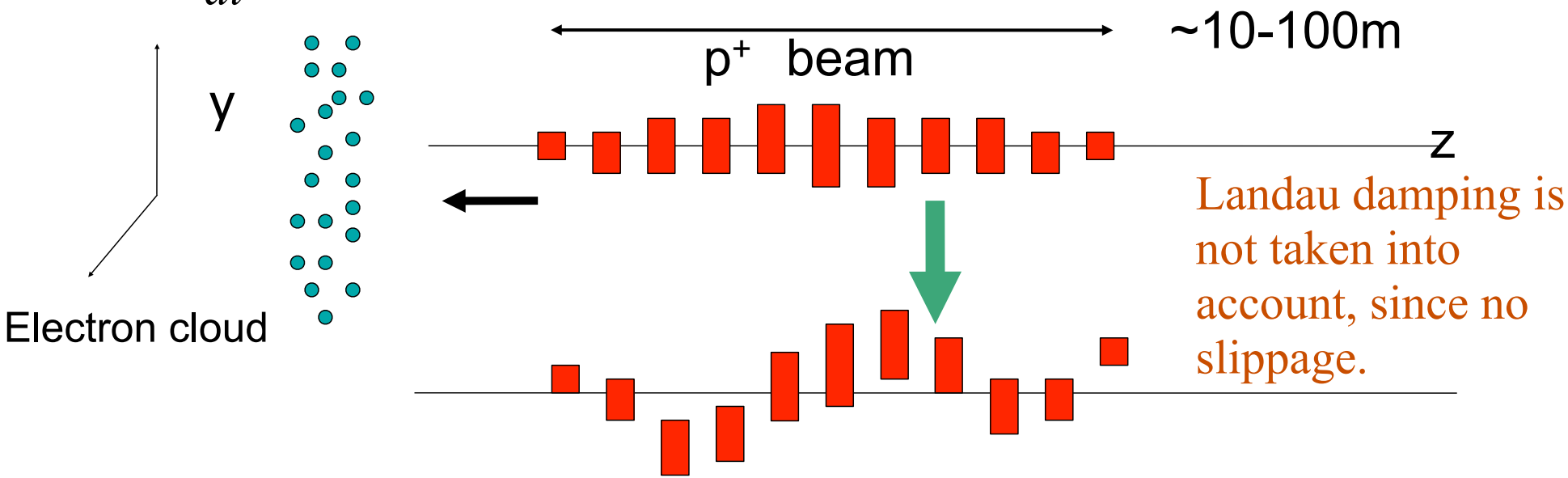
These neutralization levels are less than the threshold given by analytic theory.

Tracking simulation for long proton beam

- Solve both equations of beam and electrons simultaneously and self consistently.
- Electrons are produced and tracked with the exact initial condition.

$$\frac{d^2\mathbf{x}_{p,a}}{ds^2} + K(s)\mathbf{x}_{p,a} = \frac{2r_p}{\gamma}\sum_{j=1}^{N_i}\mathbf{F}_G(\mathbf{x}_{p,a} - \mathbf{x}_{e,j};\sigma(s))\delta(s - s_j)$$

$$\frac{d^2\mathbf{x}_{e,j}}{dt^2} = 2N_p r_e c^2 \mathbf{F}_G(\mathbf{x}_{e,j} - \mathbf{x}_{p,a};\sigma(s))\delta(t - t(s_{e,j}))$$



Stability for the instability

- Landau damping is well-known phenomenon.
- The stability is estimated by considering Landau damping.
- Criteria, U>1 unstable U<1 stable

$$U = \frac{\sqrt{3}\, T_0 / \tau_G}{\nu_s \omega_e \sigma_z / c} = 1$$

T_0 / τ_G : Growth rate

$\frac{\nu_s \omega_e \sigma_z / c}{\sqrt{3}}$: Landau damping rate

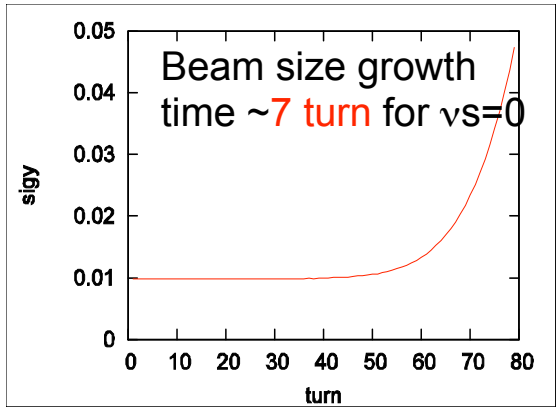
- Analytic formula for resonator model

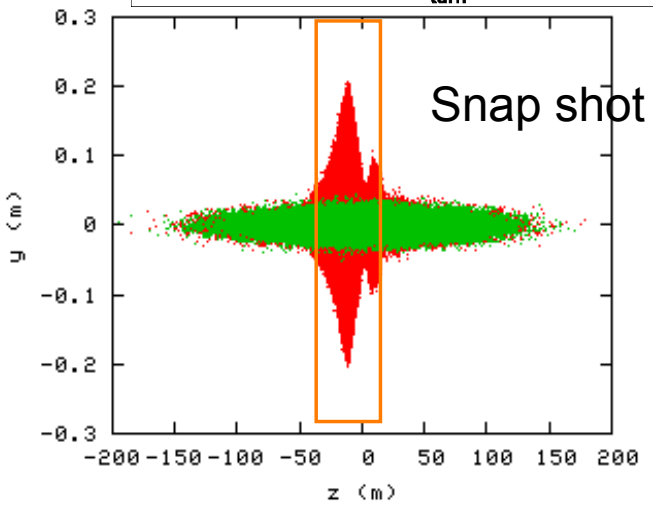
$$\frac{T_0}{\tau_G} = \frac{\lambda_p r_0 \beta}{\gamma} \frac{|Z_\perp(\omega_e)|}{Z_0}$$

$$\frac{Z(\omega_e)}{Z_0} = \frac{1}{4\pi} \frac{\lambda_e}{\lambda_p} L \frac{Q}{\sigma_y (\sigma_x + \sigma_y)}$$

Landau damping in a simulation

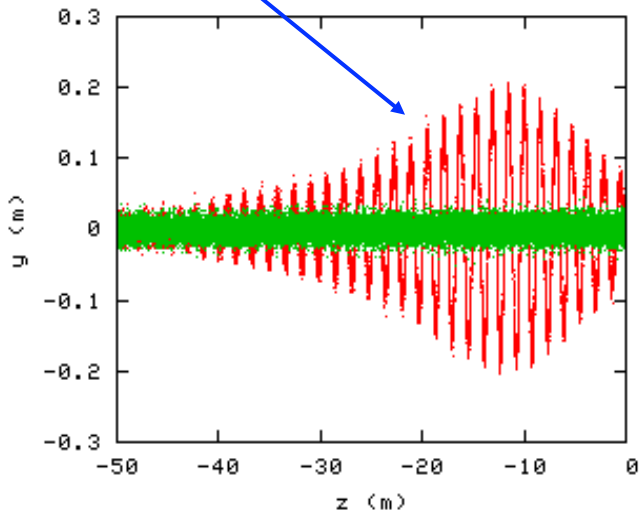
- Landau damping due to energy spread (slippage).
- Landau damping works very well as is expected!

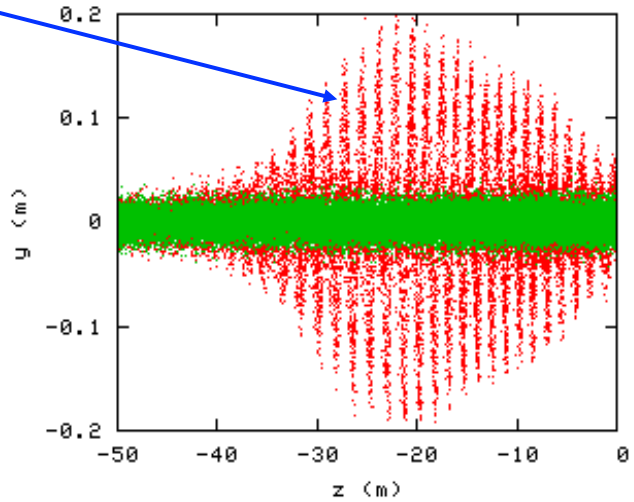




Green ν_s=0.0002(U=1.07)

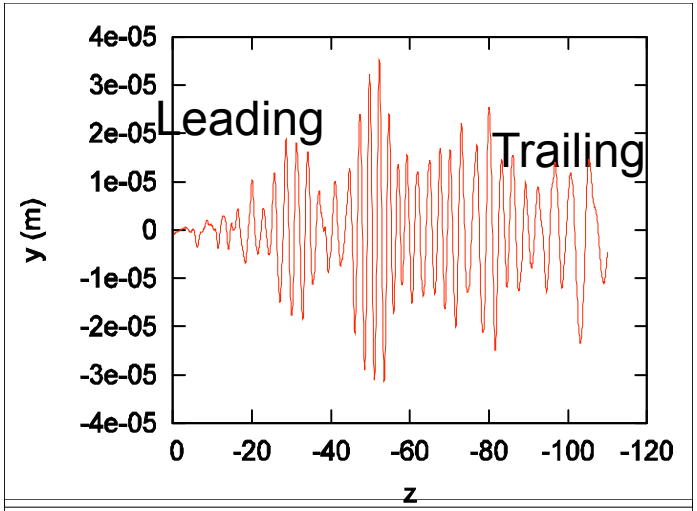
Red ν_s=0 or 0.0001(U=2.14)

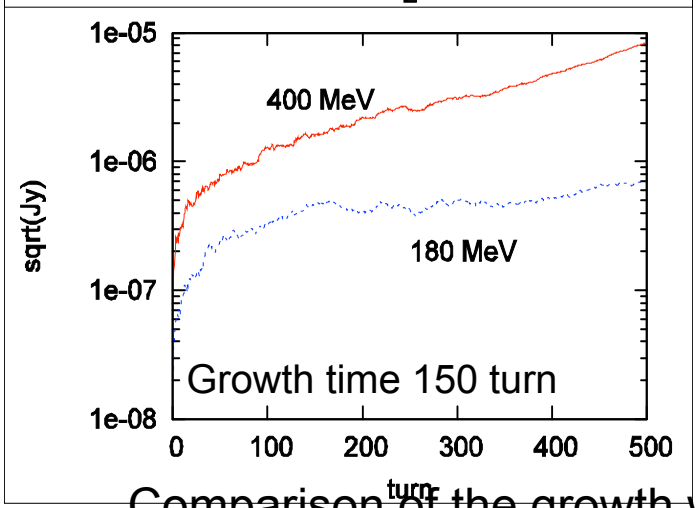




Results of the tracking simulation (RCS)

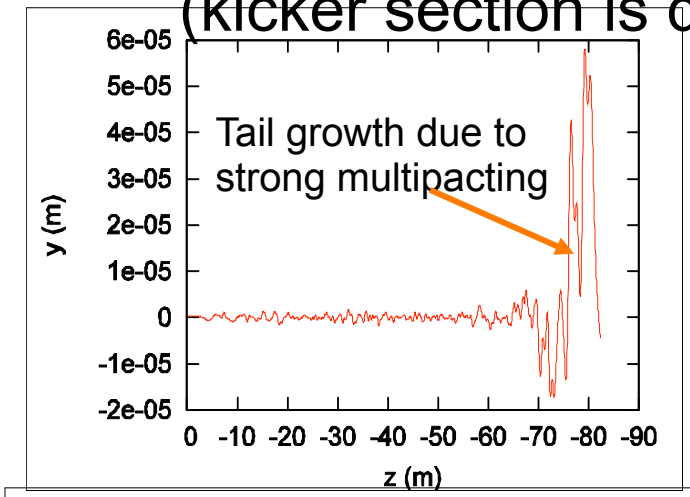
3GeV RCS inj.



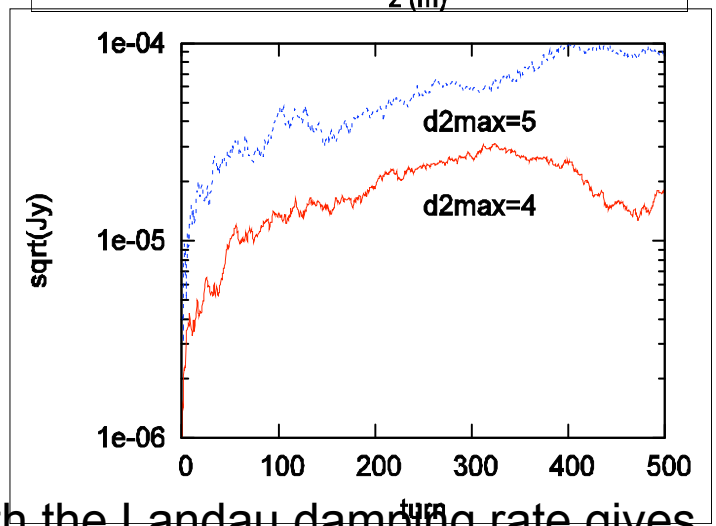


Extraction

(kicker section is dominant)



Transverse bunch profile



Growth

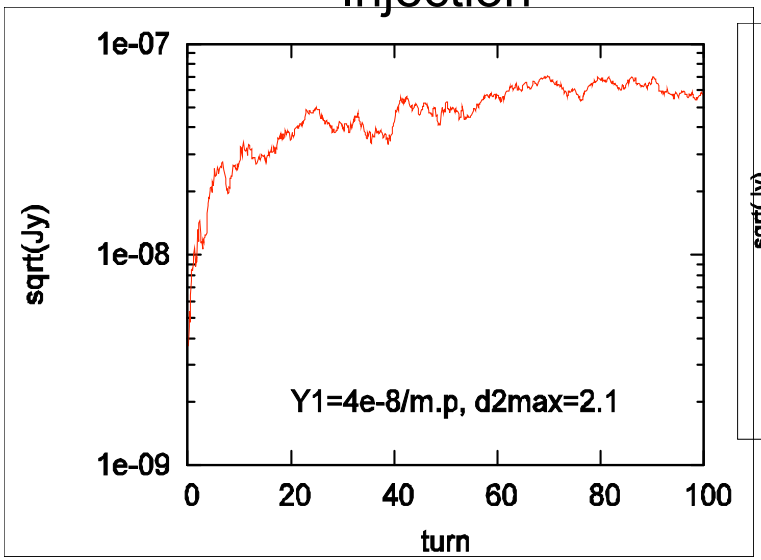
Comparison of the growth with the Landau damping rate gives information whether stable or not.

These growths do not arise due to Landau damping.

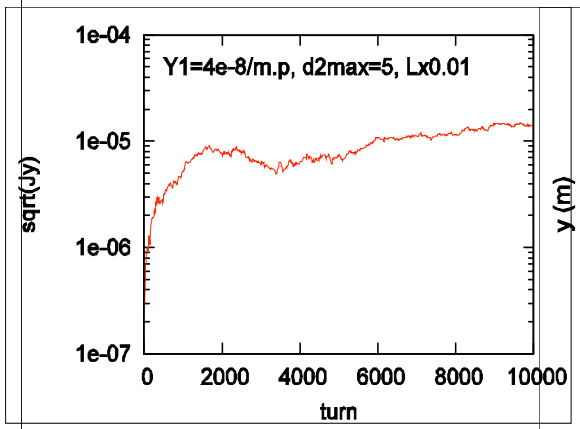
Results of the tracking simulation (MR)

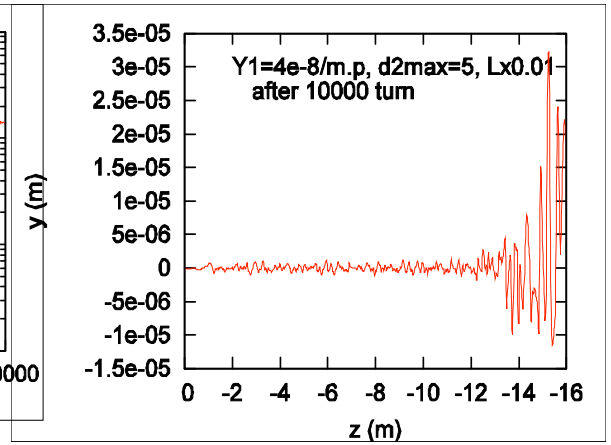
- Length of Ferrite section is ~20 m, 1.3 % of the circumference.
- Neutralization factor at δ_{2max}=4-5 is 100 times that at δ_{2max}=2.1.
- Contributions to instability of high and low multipactoring sections are similar.
- The density (neutralization factor) is less than the threshold given by analytic formula.

Injection



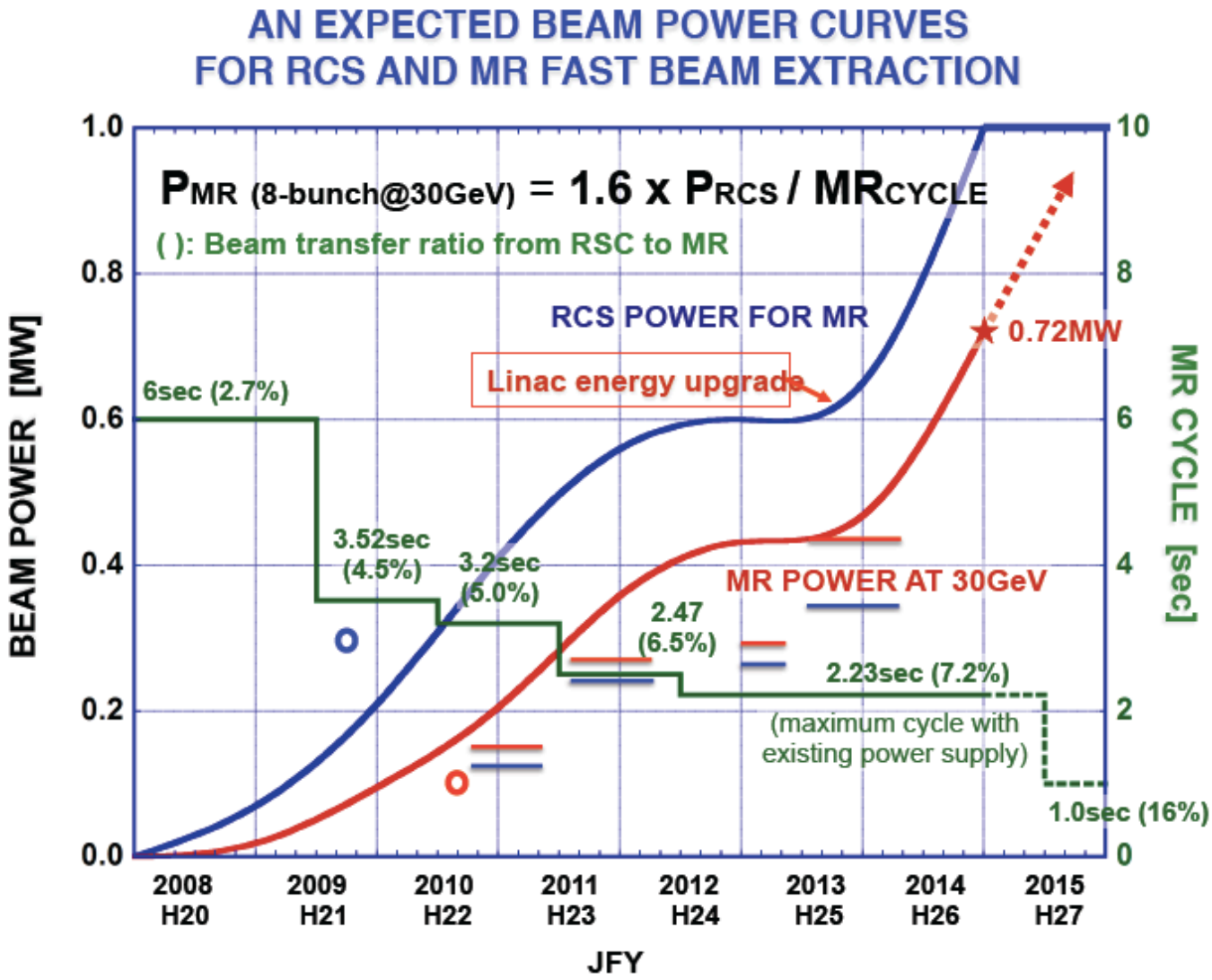
extraction





Simulation shows slower growth than Landau damping. Instability does not arise.

J-PARC operation start from 2008



Instability observed in J-PARC MR

T.Toyama, ATAC2011

- Transverse instabilities
  - Physics runs are operated with

    $\xi_x, \xi_y \sim -7 - -5$,

    BxB feedback ON,

    $N_B \sim 8\times10^{13}$ ppp / 8 bunches, P ~ 120 kW.

    → No fatal instability
  - studied:

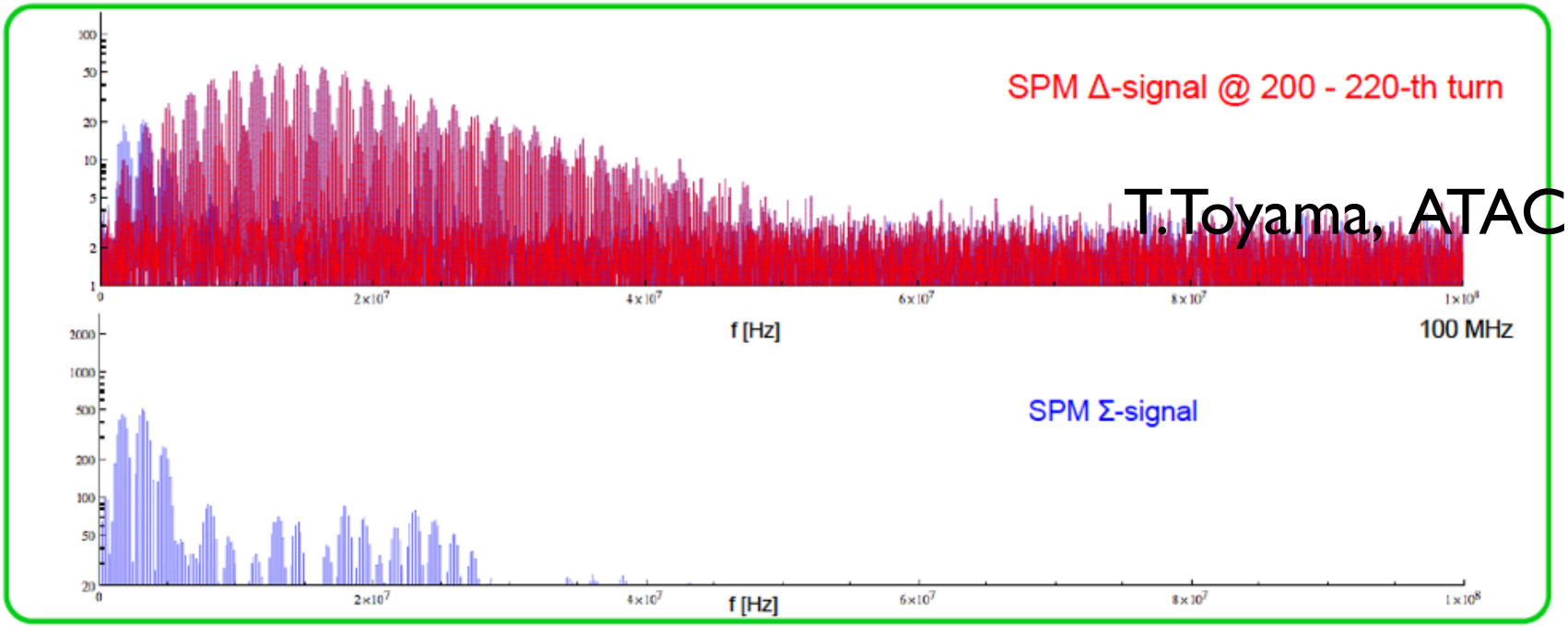
$\xi_x, \xi_y \sim -3, -1.5, -0.75, 0, 0.75, 1.5, 3$

$\xi_x \sim -6, \xi_y \sim +6$ Instability is observed.

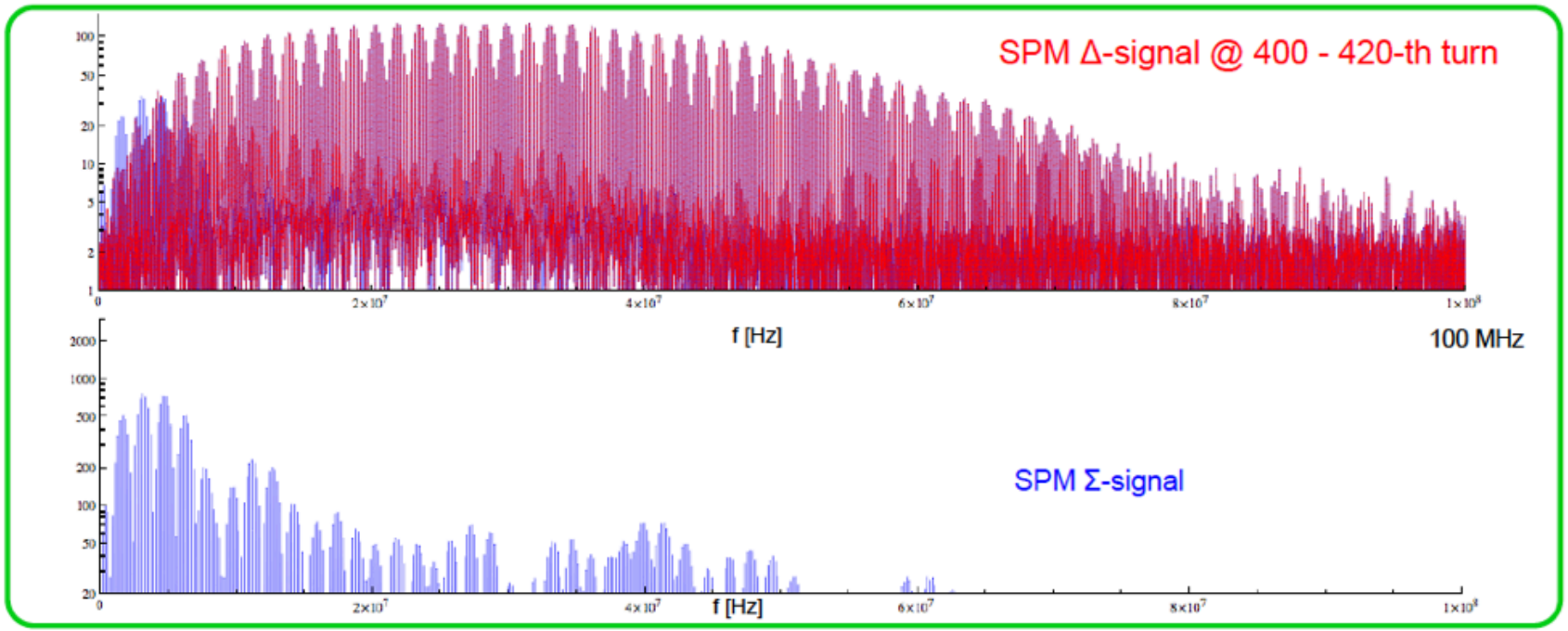
Parameters of proton rings

	RCS-inj1	RCS-inj2	RCS-ext	MR-inj	MR-ext	MR-inj 2011Feb	MR-ext	SNS
L (m)	348	348	348	1567	1567	1567	1567	248
γ	1.19	1.4	4	4	50.9	4	30.9	2.02
$N_p(10^{13})$	2.5	4.15	4.15	4.15/2.5	4.15/2.5	1	1	20
n_{bunch}	2	2	2	8/17	8/17	8	8	1
H	2	2	2	9/18	9/18	9	9	1
σ_r(cm)	1.9	1.9	1.2	1.1	0.35	1.4	0.5	0.7
l_p(m)	110	110	82	82/40	16/8	30		200
η	-0.48	-0.48	-0.047	-0.058	-0.0013	-0.058	-0.002	-0.204
ν_s	0.0058	0.0058	0.0005	0.0026	0.00007	0.0026	0.0001	0.0004
$\omega_e/2\pi$ (MHz)						80		
$\omega_e l_p/c$		133	182	199/99	276/138	50.4		153
$\nu_s\ \omega l_p/3^{1/2}c$	0.45	0.45	0.053	0.30	0.011	0.065		0.035
F_{th}(%)	28.0	28.0	3.0	3.1	0.04	2.7		6.5

ω: electron freq. in beam, $\nu_s\ \omega lp/3^{1/2}c$: Landau damping rate/turn, f_{th}: threshold electron neutralization factor given by analytic formula.



T.Toyama, ATAC2011

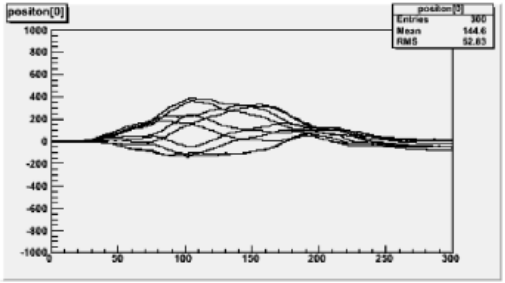


Δ-signal turn-by-turn plot, after injected

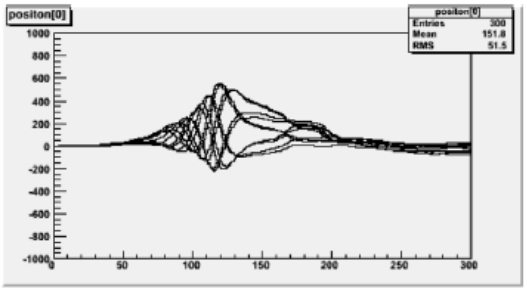
T. Toyama, ATAC2011

Sextupole ~ –4.5 (–15%)
N_B = 115 kW
1st bunch

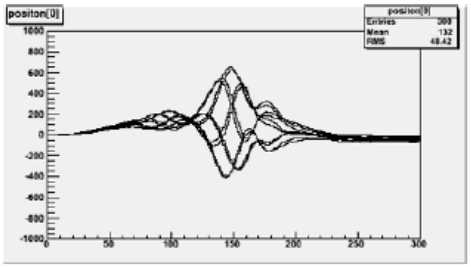
100 - 110 turns

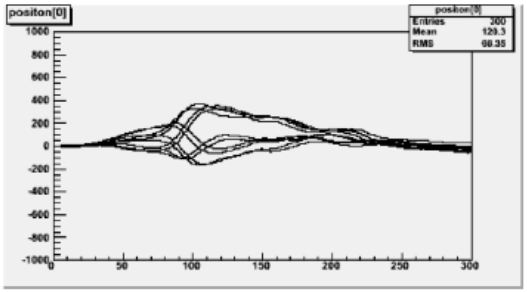


300 - 310 turns

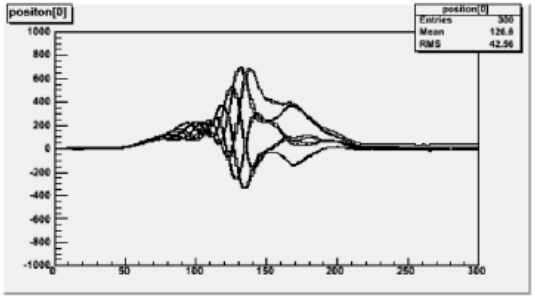


500 - 510 turns

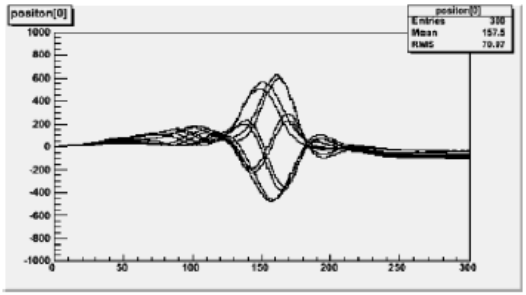




200 - 210 turns



400 - 410 turns



600 - 610 turns

Summary for J-PARC

- If beam loss (electron yield) is well controlled, electron cloud instability should be weak in simulations. (chicken or egg)
- Horizontal instability has been observed in J-PARC MR. Frequency ~60MHz or lower.
- Electron frequency is ~80MHz, somewhat different.
- Single bunch effect, independent of total current.
- This instability seems to limit the intensity.
- Beam studies just start now.

Fermilab Main Injector

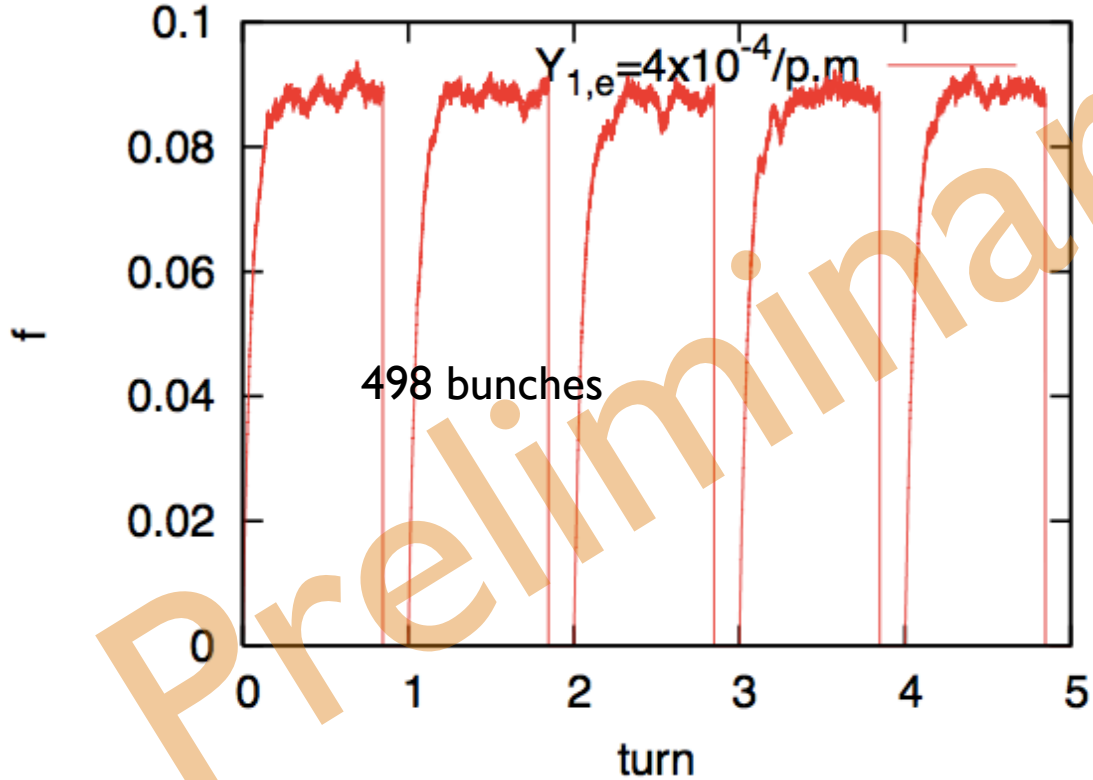
Table 1-1: Main Injector Parameter List Thanks R. Zwaska

Circumference	3319.419	m
Injection Momentum	8.9	GeV/c
Peak Momentum	150	GeV/c
Minimum Cycle Time (@120 GeV)	< 1.5	s
Minimum Cycle Time (@150 GeV)	2.4	s
Number of Protons	3×10^{13}	
Number of Bunches	498	
Protons/Bunch	6×10^{10}	
Max. Courant-Snyder Amplitude Function (β_{max})	57	m
Maximum Dispersion Function	1.9	m
Phase Advance per Cell	90	degrees
Nominal Horizontal Tune	26.425	
Nominal Vertical Tune	25.415	
Natural Chromaticity (H)	-33.6	
Natural Chromaticity (V)	-33.9	
Transverse Admittance (@ 8.9 GeV)	> 40p	mm-mr
Longitudinal Admittance	> 0.5	eVs
Transverse Emittance (Normalized)	12p	mm-mr
Longitudinal Emittance	0.2	eVs
Harmonic Number (@53 MHz)	588	
RF Frequency (Injection)	52.8	MHz
RF Frequency (Extraction)	53.1	MHz
RF Voltage	4	MV
Transition Gamma	21.8	

Threshold density for single bunch instability in Main Injector

- $\omega_e/2\pi$=73 MHz, $\omega_e\sigma_z/c$=4.6
- $\rho_{e,th}$=2.2x10^{11} m^{-3}.(use the formula)
- $\lambda_{e,th}$=10^8 m^{-1}, f_{th}=0.005, if all electrons are located near the beam.
- Landau damping rate, $\nu_s\omega_e\sigma_z/3^{1/2}c$=0.012
- The growth slower than 0.012^{-1}=80 turn is stabilized.

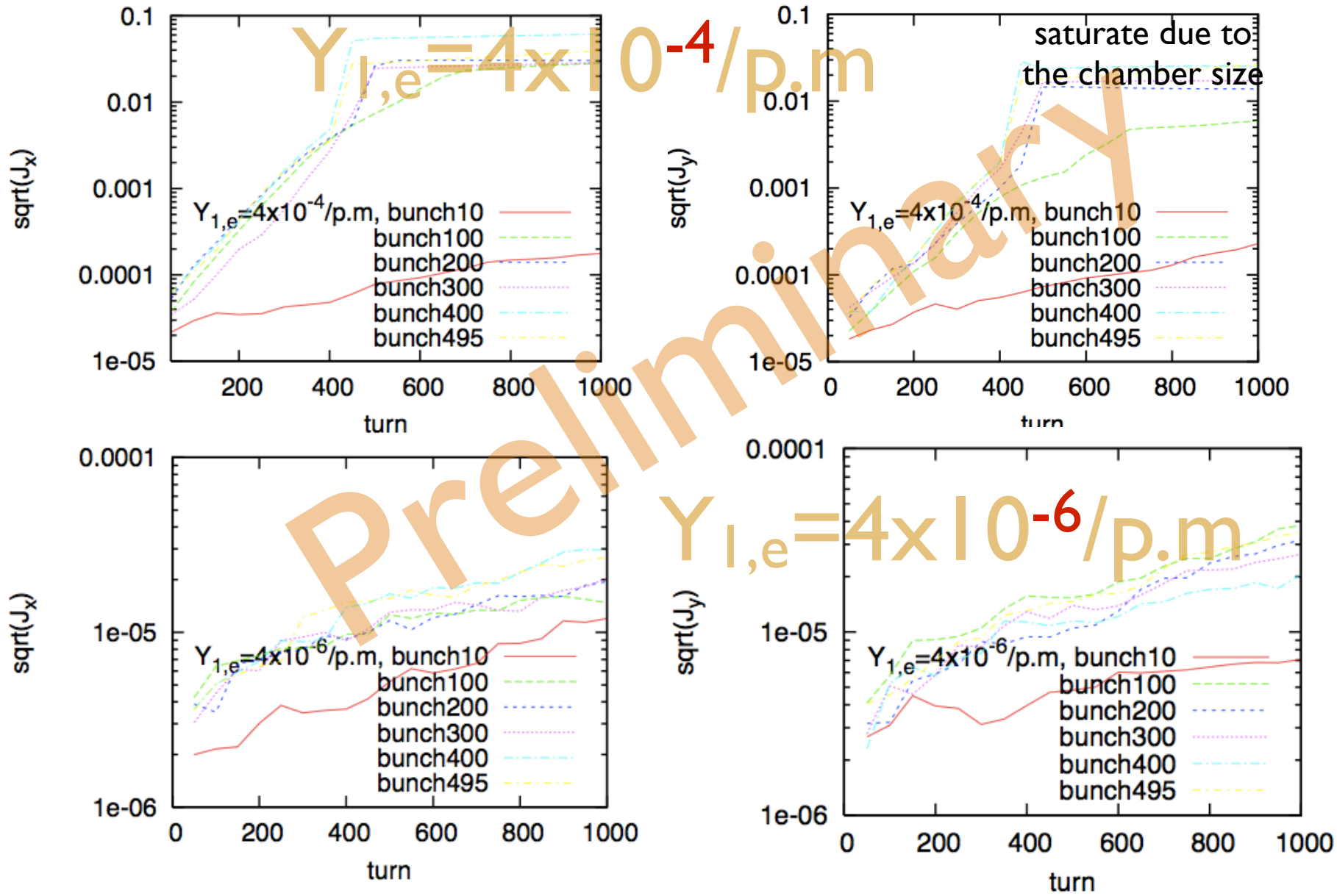
Neutralization factor



- An example. $Y_{1,e}$=4x10^{-4}/p.m , 4 order higher than ionization. The neutralization factor f linearly depends on the initial yield.

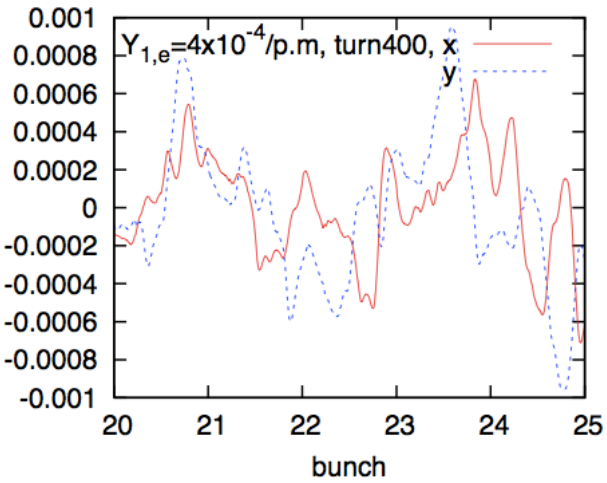
Growth of the transverse amplitude

$\varepsilon^{1/2}=10^{-3}$

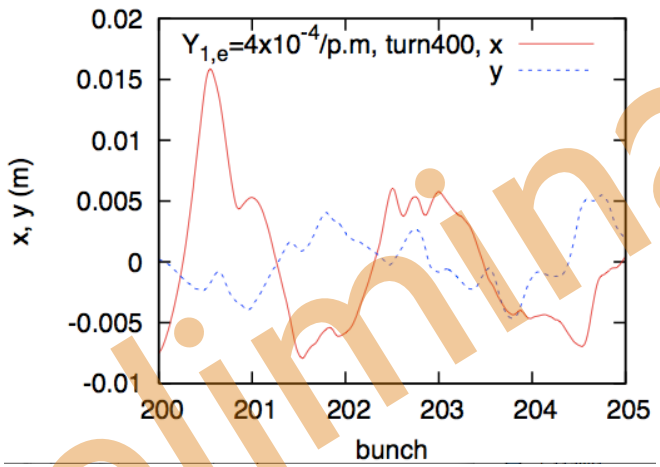


Bunch transverse motion

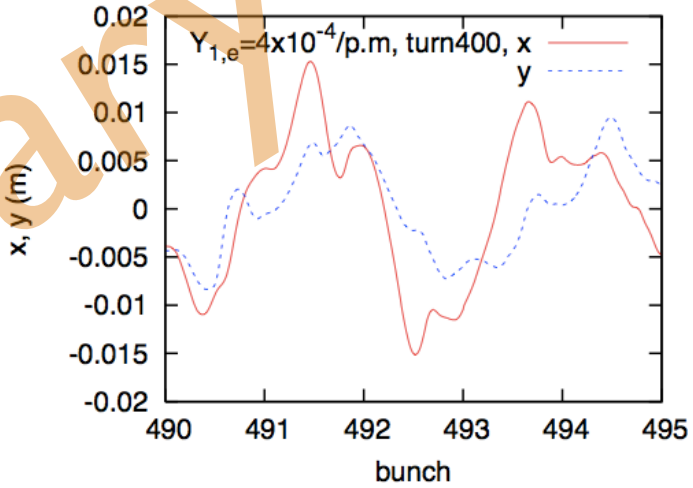
$\sigma_{x,y}$~3mm



head

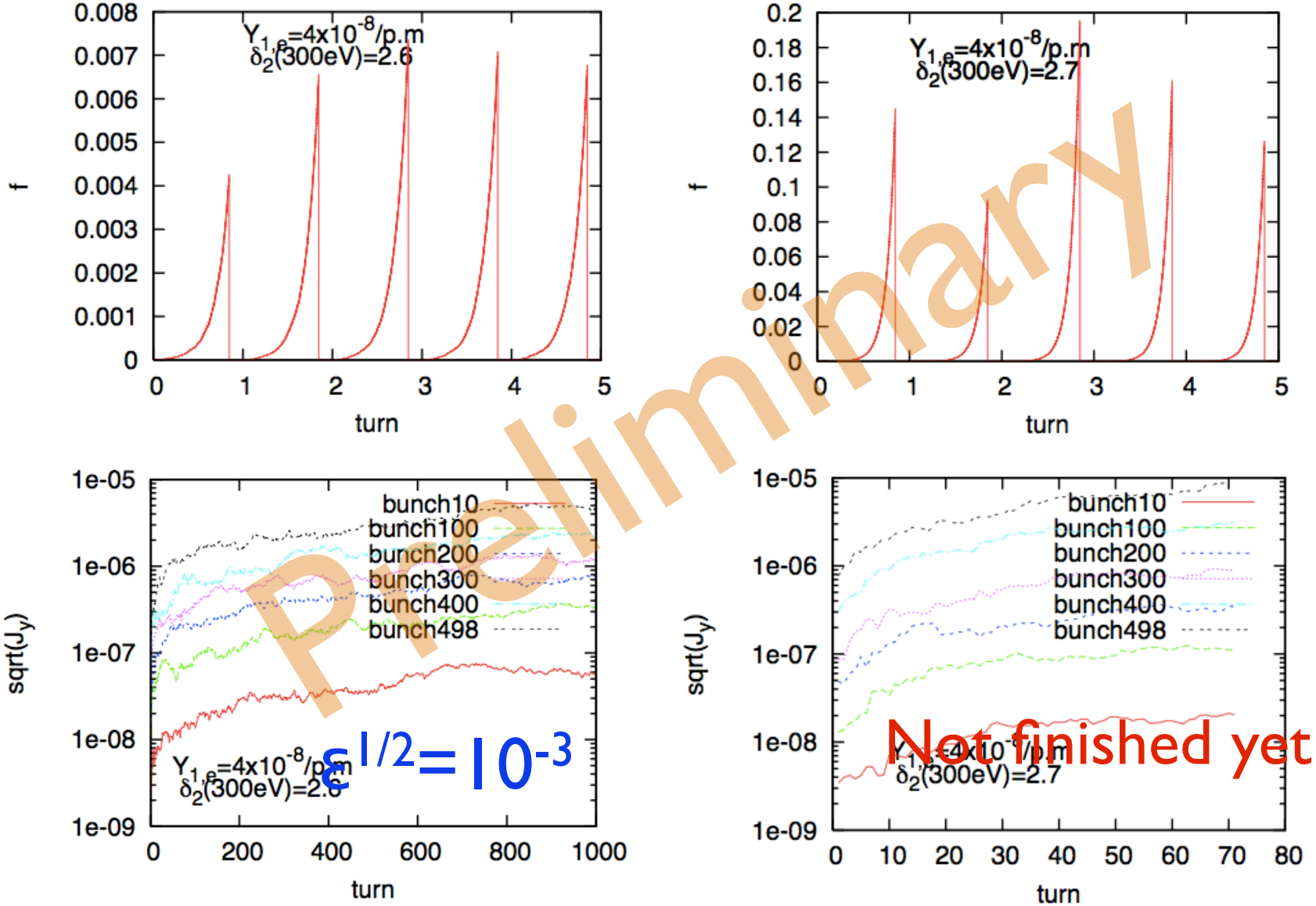


center



tail

Higher secondary efficiency



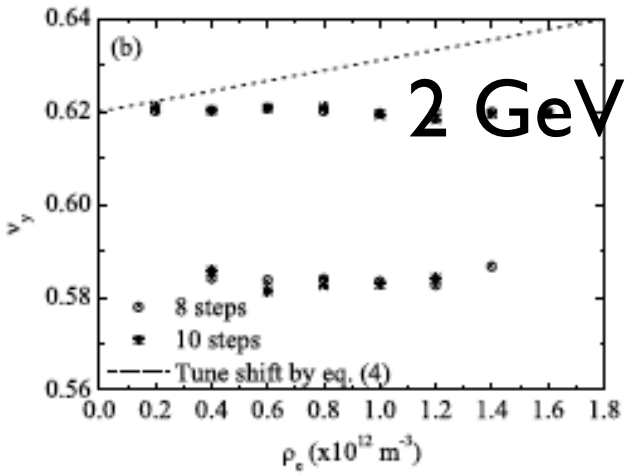
δ_2=2.6-2.7 is critical value.

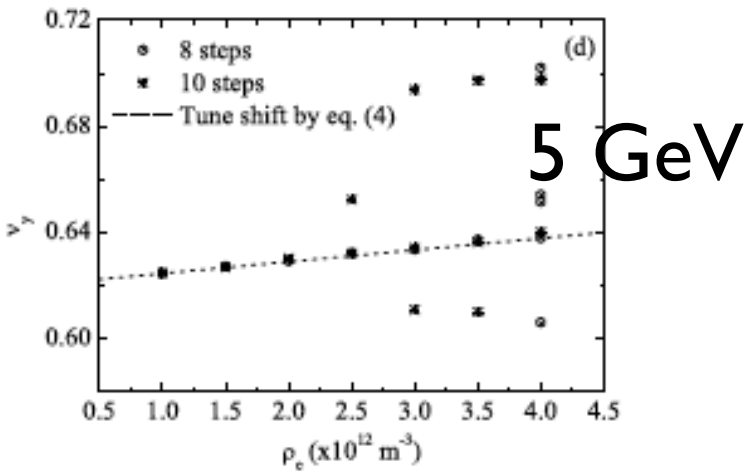
Summary for proton rings

- Electron source is secondary emission, while it was photo-emission in present positron rings.
- The cloud build-up is very sensitive for secondary rate, bunch profile initial yield and ....
- Electron cloud instability for proton rings has not well understood yet in my impression.
- Ecloud effects should be understood toward high intensity in J-PARC and Fermi MI.

Thank you for your attention

Simulated beam spectra

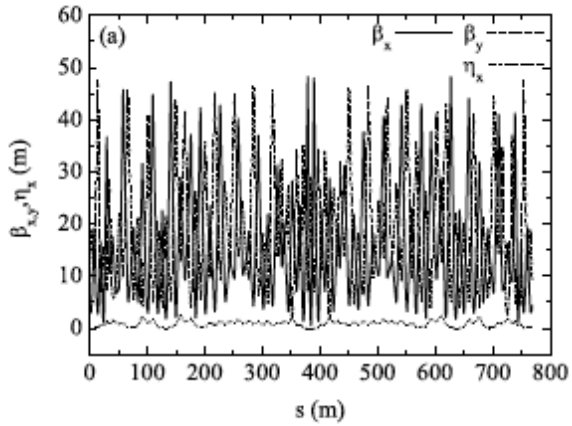


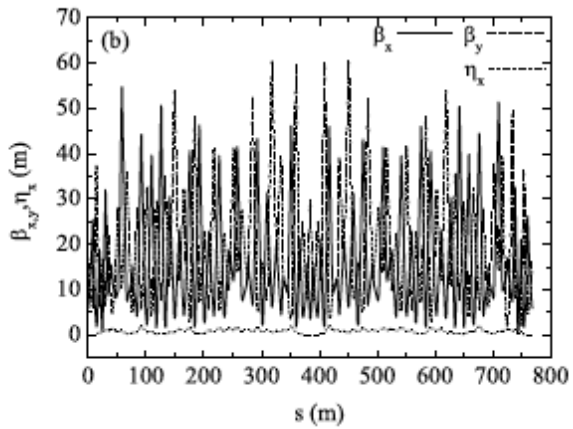


- Lower sideband is seen for high $\omega_e\sigma_z/c$, 2GeV.
- Upper sideband is seen for low $\omega_e\sigma_z/c$, 5 GeV.

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

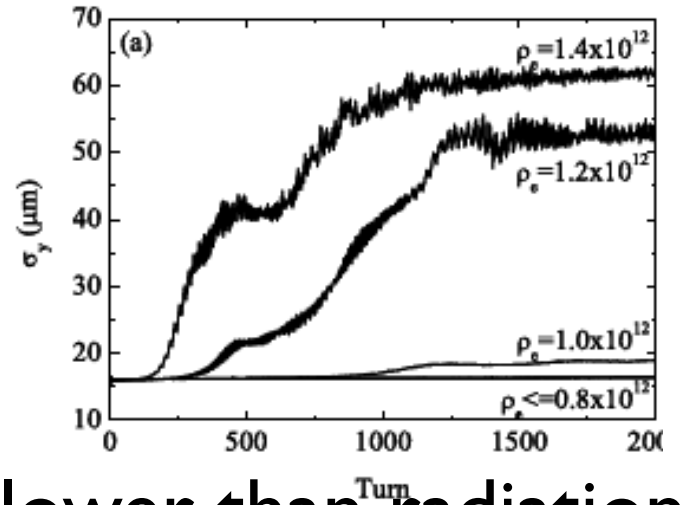
ϕ: cloud interaction

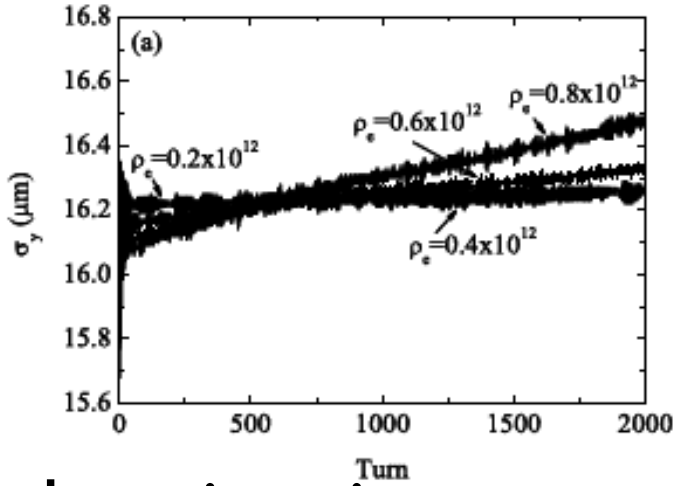
$$kx^m \Rightarrow k\beta_i^{m/2} J^{m/2} \cos(m\Delta\psi_{1i})$$

Slow growth lower than the threshold

2GeV

$\rho_{th}=1.2\times10^{12}$

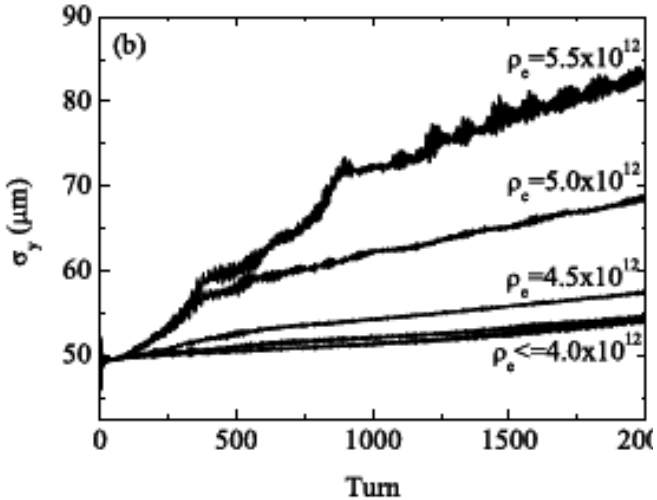


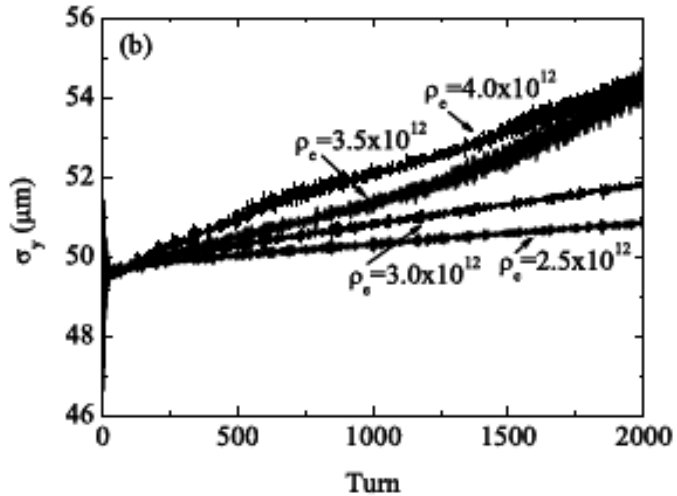


Slower than radiation damping time

5GeV

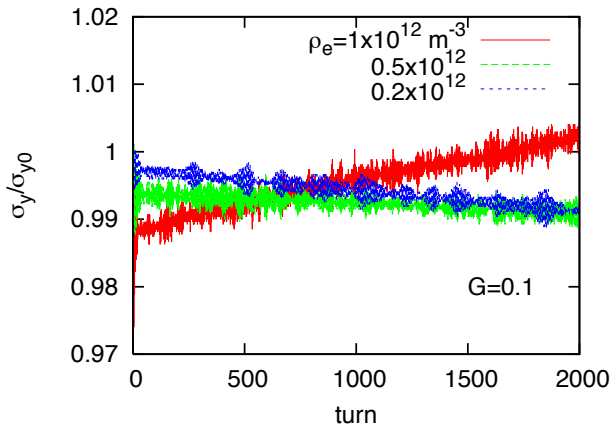
$\rho_{th}=5\times10^{12}$

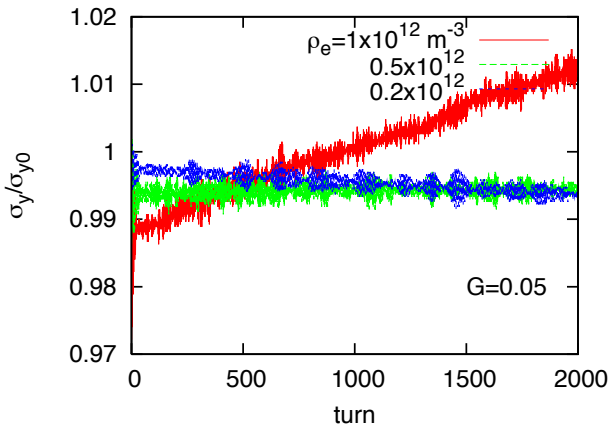


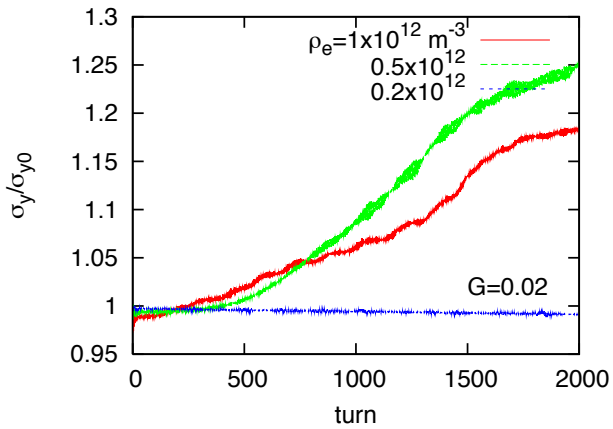


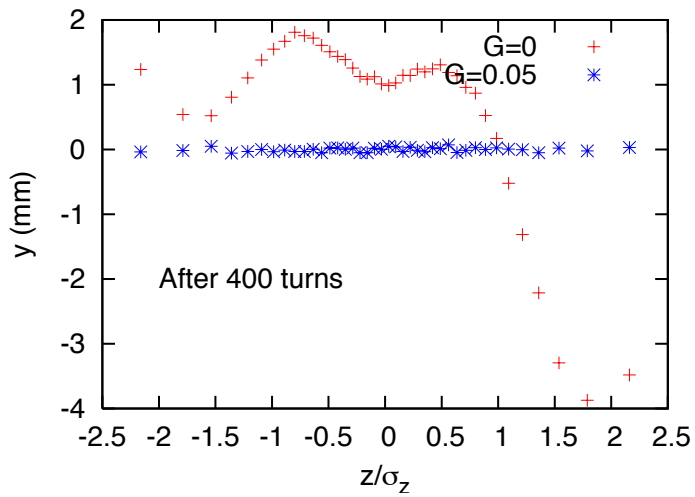
High frequency Feed back

- Feedback slice by slice, nonuniform 40 slices.









The feedback with <10GHz should give the same result, since high frequency component is not contained.