Coherent and incoherent effects of e-cloud

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MCBI2019,

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Contents

Electron cloud effects

- Coherent instability
  - Coupled bunch instability
  - Single bunch instability

- Incoherent effect
  - Tune shift
  - Emittance growth

Coupled bunch instability observed in KEK-PF (1989-)

- KEK-PF、E=2.5 GeV L=186 m, Frf=500MHz, 2nd generation light source. Positron storage was done to avoid ion trapping instability.
- The instability is observed in positron multi-bunch operation, N_{bunch}=200-300 (backet num.=312).
- Low threshold current for the instability, I_{th}~15-20mA, while operation 300 mA
- The instability was not observed in electron storage.

Izawa et.al., Phys. Rev. Lett. 74, 5044 (1995).

Frequency spectra of Beam Position Monitor.

Electron storage 354 mA

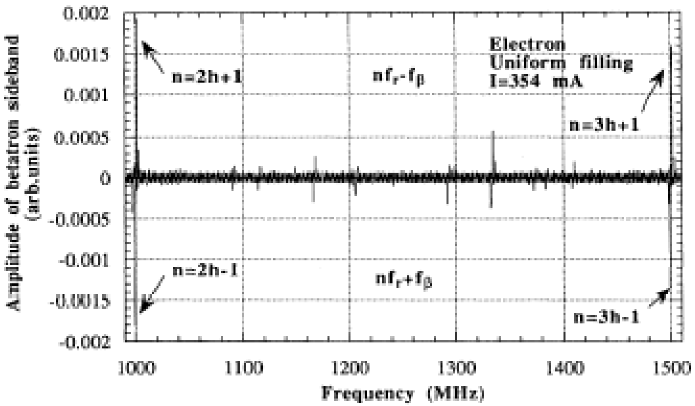


FIG. 1. Distribution of the betatron sidebands observed during electron multibunch operation with uniform filling.

Positron 324 mA & 240 mA

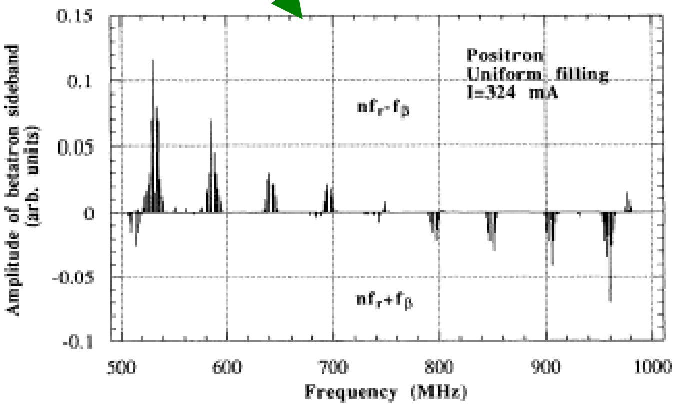


FIG. 2. Distribution of the betatron sidebands observed during positron multibunch operation with uniform filling.

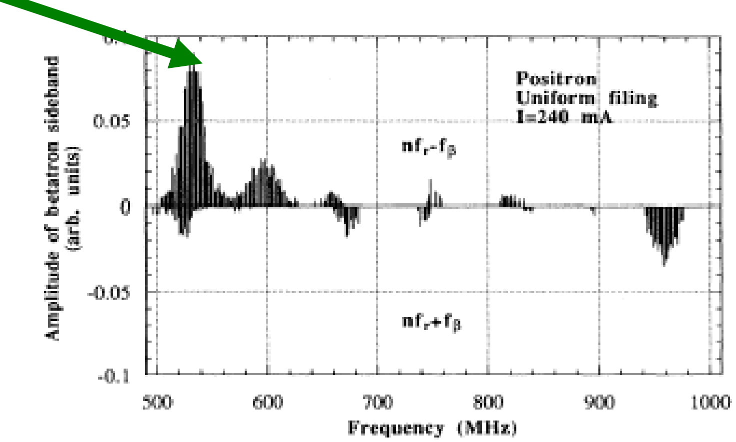


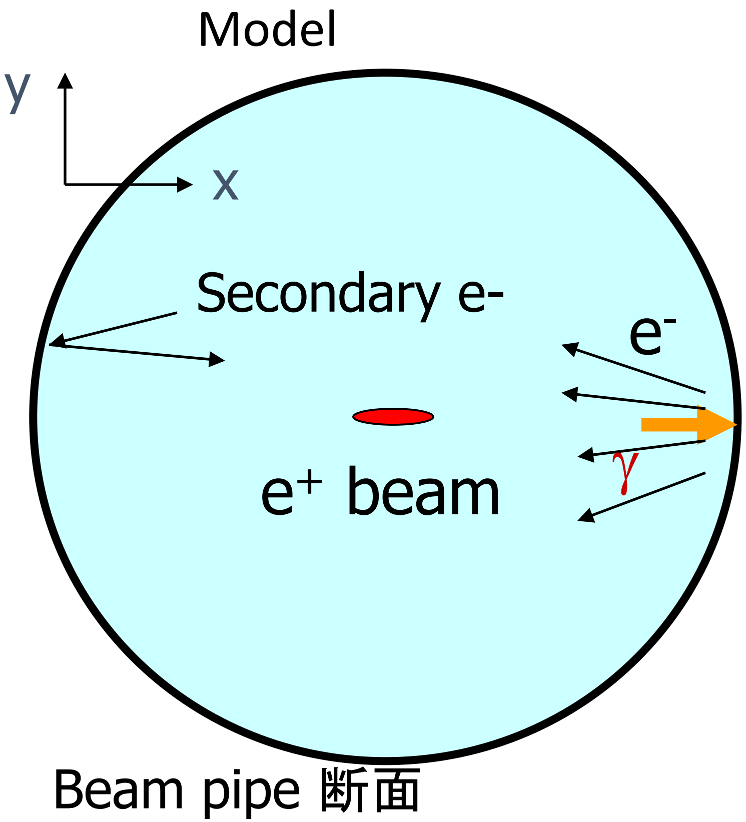
FIG. 3. Distribution of the betatron sidebands observed during positron multibunch operation with uniform filling. Only the stored current is different from Fig. 2.

Understanding of the instability caused by photoeoelectron cloud

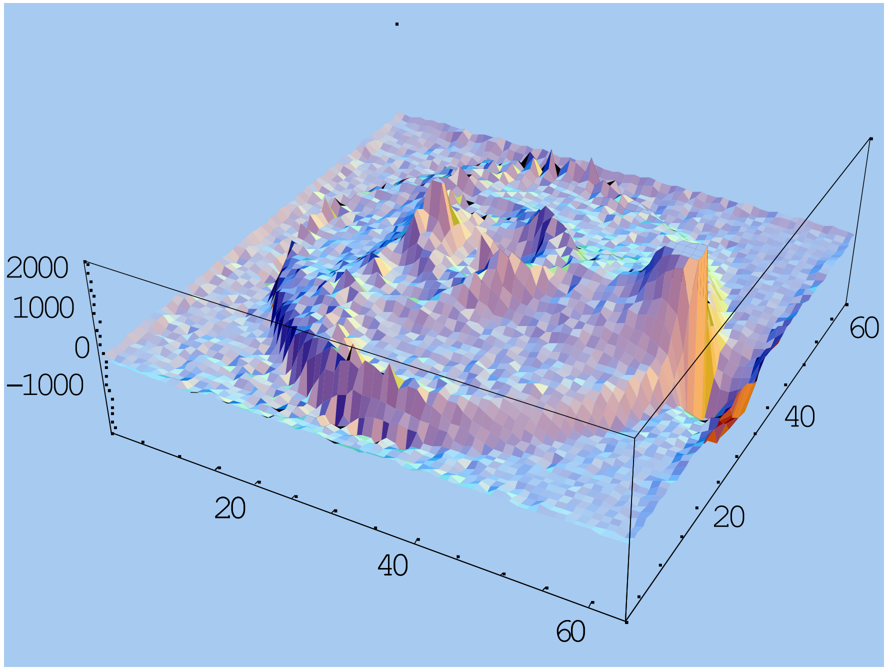
- Positron beam emits photons due to synchrotron radiation.
- Electrons are produced at the beam pipe wall due to photo-emission, where electron production efficiency is ~ $0.1e^{-}/\gamma$.
- Electrons are attracted by positron beam and interact them. Electrons travel in the beam pipe 20-50 ns and absorbed into the wall. Secondary electrons are produced at the electron absorption.
- In multibunch operation (~5ns spacing), electrons are supplied continuously, then electron cloud is formed.
- The electron cloud induces bunch-by-bunch correlation and results coupled bunch instability.

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

Photo electron production model and electron cloud formation in computer simulation

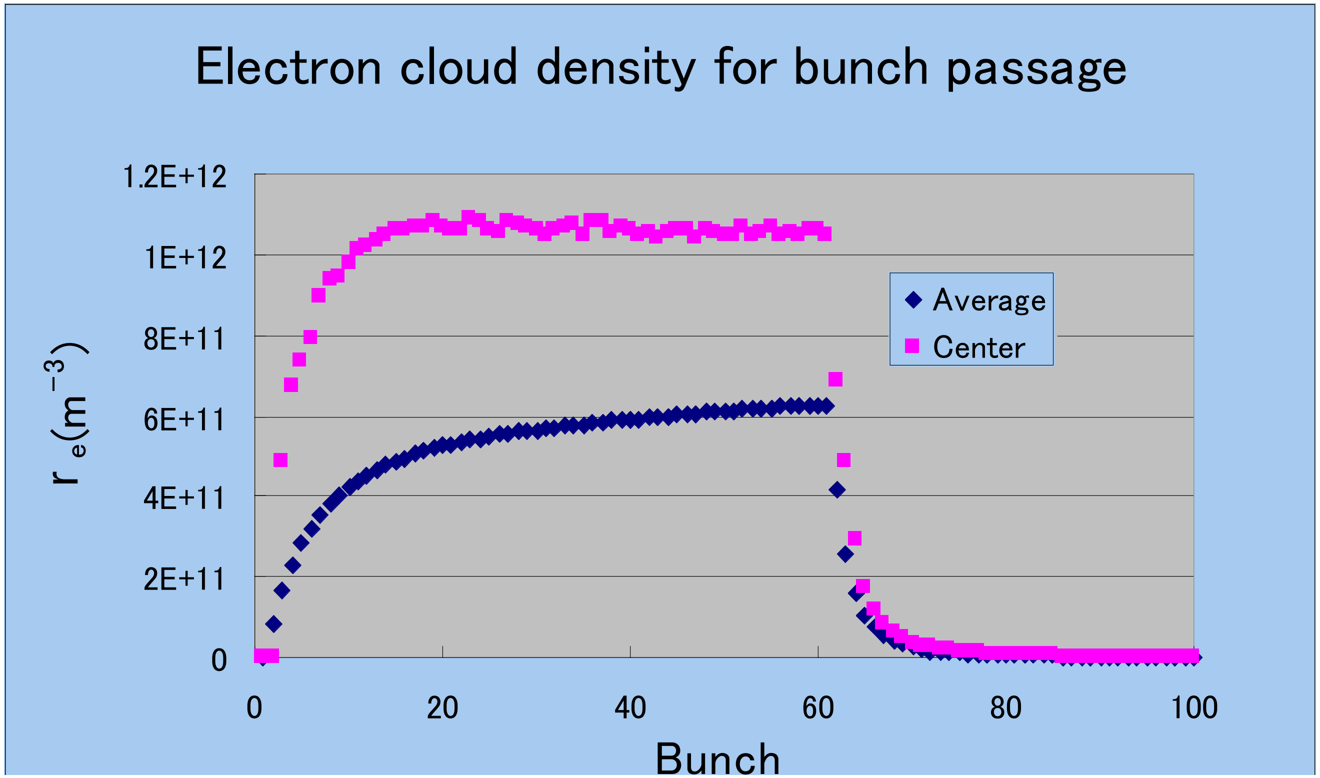


Electron density



Electron density by simulation

Molecular density of 1atm　10^{25} m^{-3}



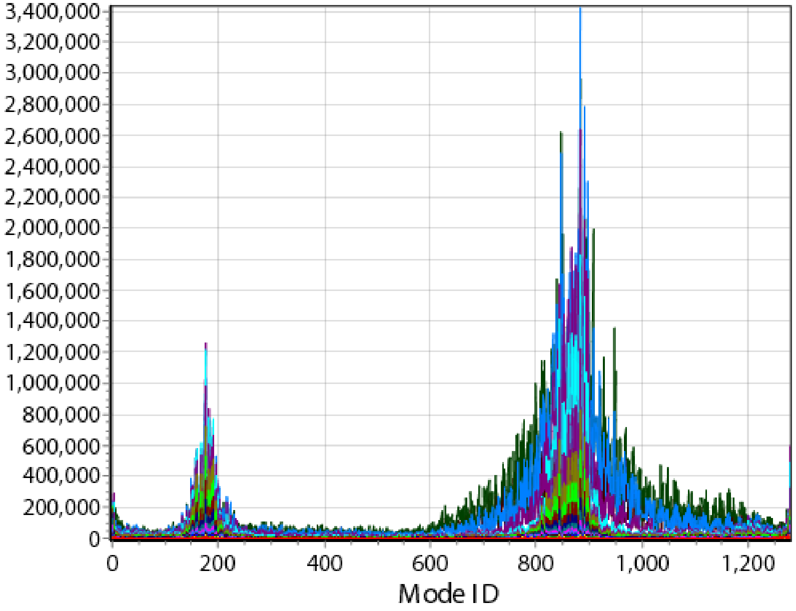
60 bunches pass in every 8ns (KEKB).

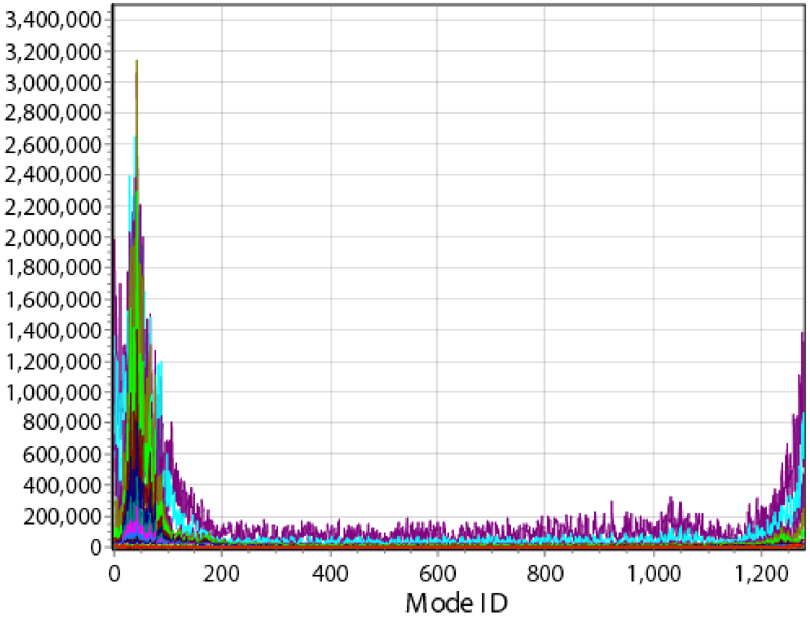
Coupled bunch instability observed in KEKB

- Strong instability which causes beam loss was observed.
- Unstable mode depends on Solenoid ON/OFF.

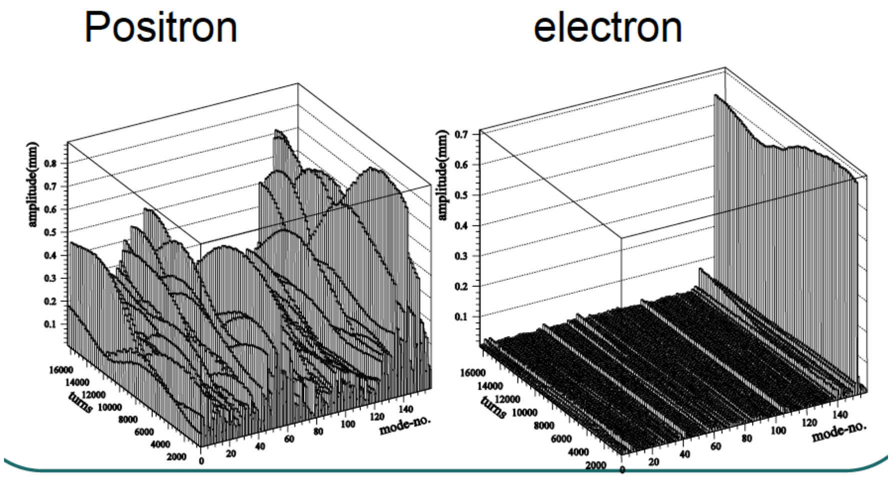
M. Tobiyama et al., PRST-AB (2005)

Solenoid off on (measurement)





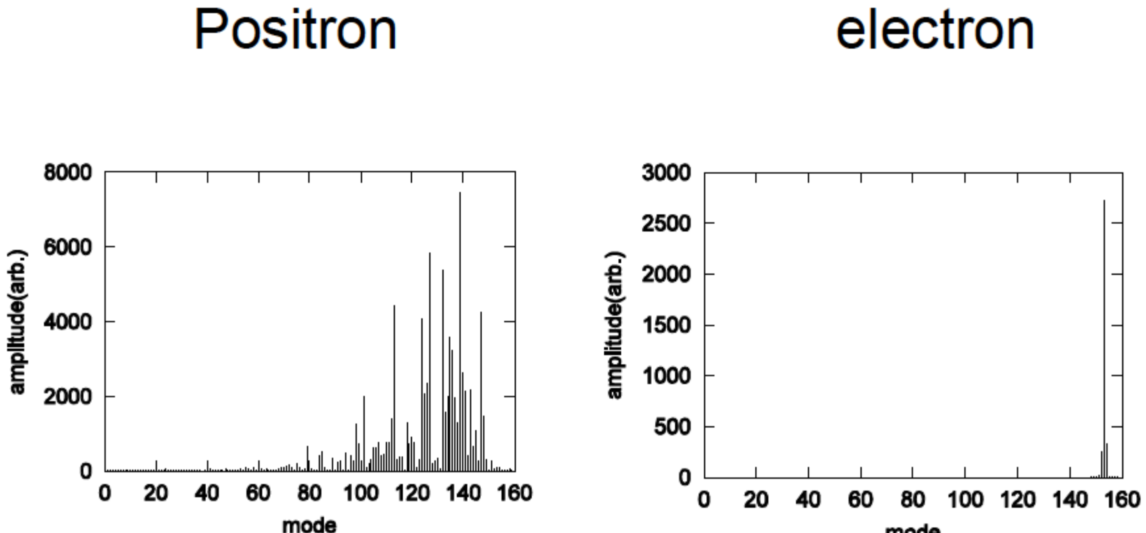
Measurement and simulation in BEPC



Guo, et al, PRST (2002).

Vertical instability was observed.

- Mode spectra for electron cloud and ion instabilities



FFT of y_p

Simulation of CBI

K.Ohmi, PRE55,7550 (1997)

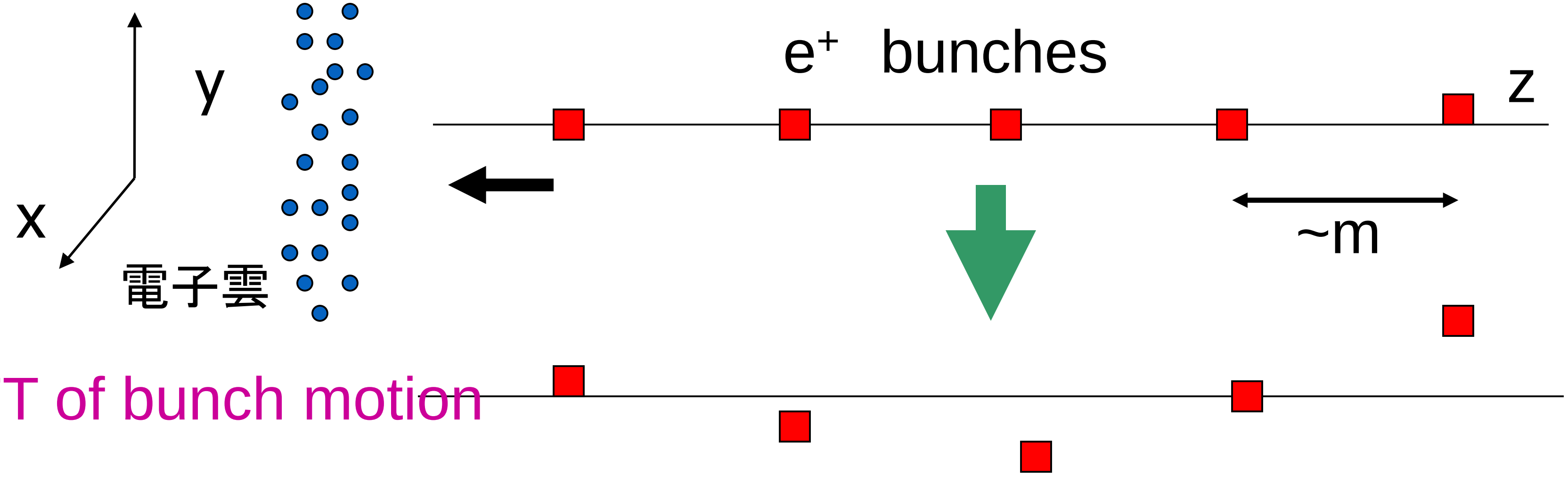
K.Ohmi, PAC97, pp1667.

Solve beam and electron motion simulteneously

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

$$\frac{d^2\mathbf{x}_{e,a}}{dt^2} = \frac{e}{m}\frac{d\mathbf{x}_{e,a}}{dt}\times\mathbf{B} - 2N_p r_e c\sum_n\sum_{i=1}^{N_b}\mathbf{F}(\mathbf{x}_{e,a} - \mathbf{x}_{p,i})\delta(t - t_i(s_e + nL))$$

$$- r_e c^2\frac{\partial\phi(\mathbf{x}_{e,a})}{\partial\mathbf{x}_{e,a}} \qquad (2)$$



FFT of bunch motion

Coupled bunch instability

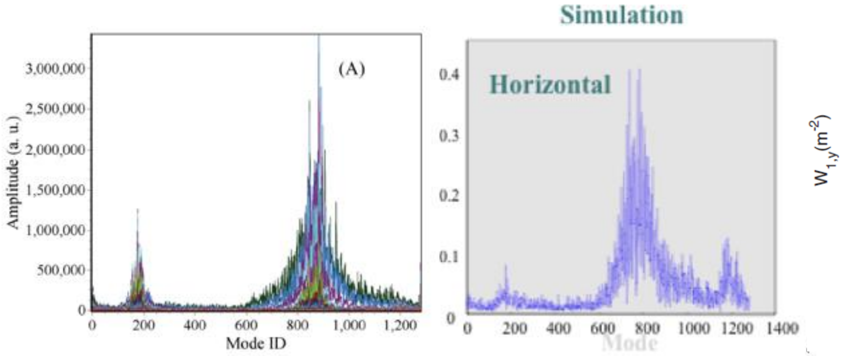


Figure 7: Horizontal mode spectrum in KEKB. Left picture is given by measurement with solenoid OFF [4,5]. Right picture is simulated by electron cloud in drift space.↵

↵

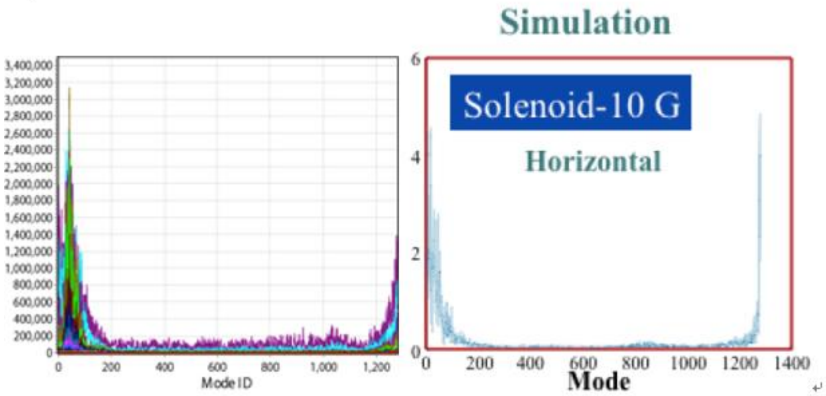
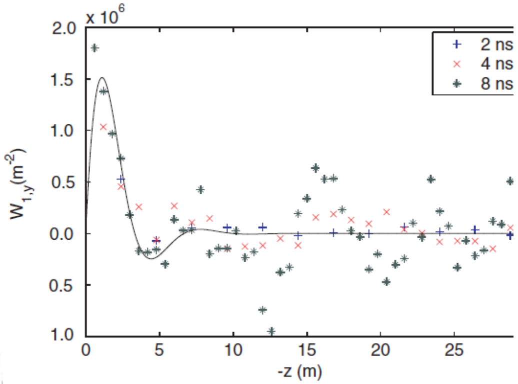
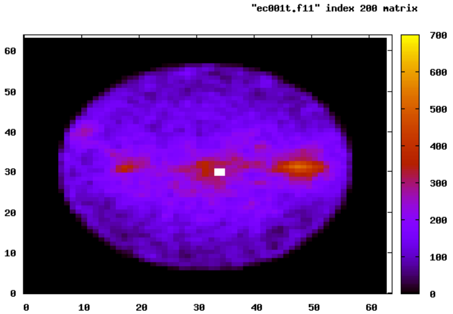
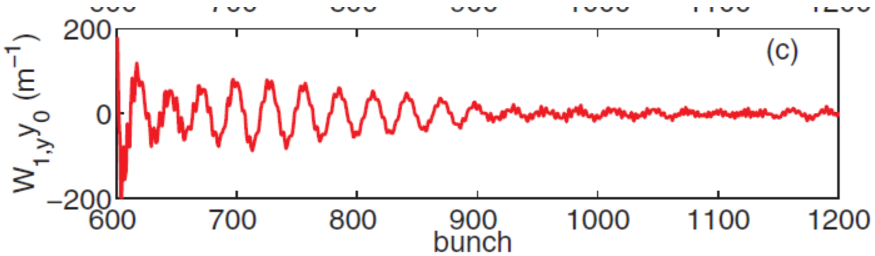


Figure 8: Horizontal mode spectrum in KEKB. Left picture is given by measurement with solenoid ON [4,5]. Right picture is simulated by electron cloud in solenoid field 10G.↵

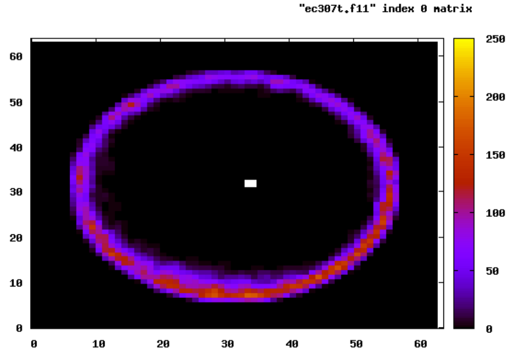




High R/Q and Low Q=1



Lower R/Q and higher Q=10 Growth of CBI is similar as drift electron.

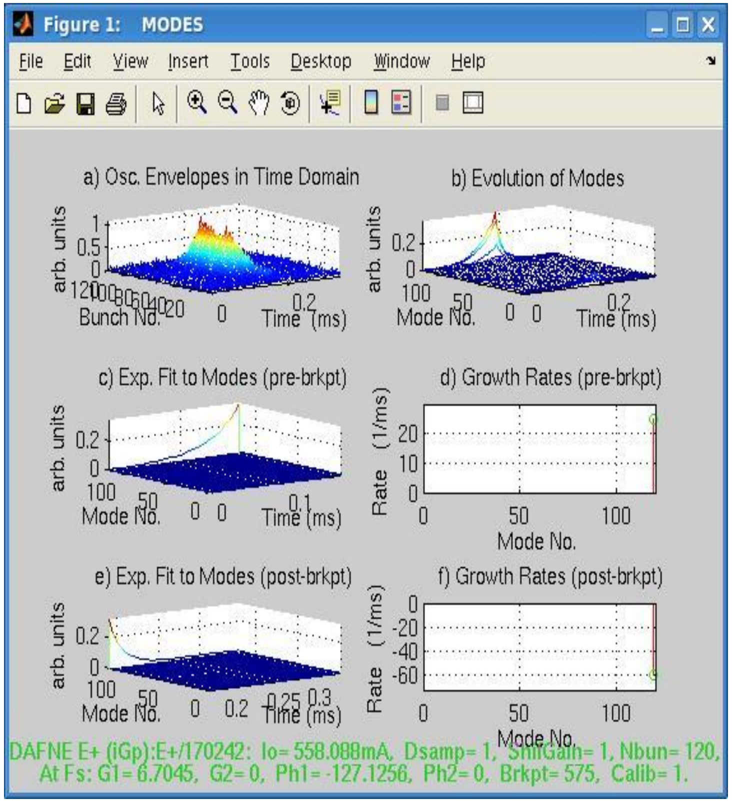


$$\omega_R=\lambda_p r_e c^2/r^2\omega_c$$

Coupled bunch instability due to electron cloud in bending field

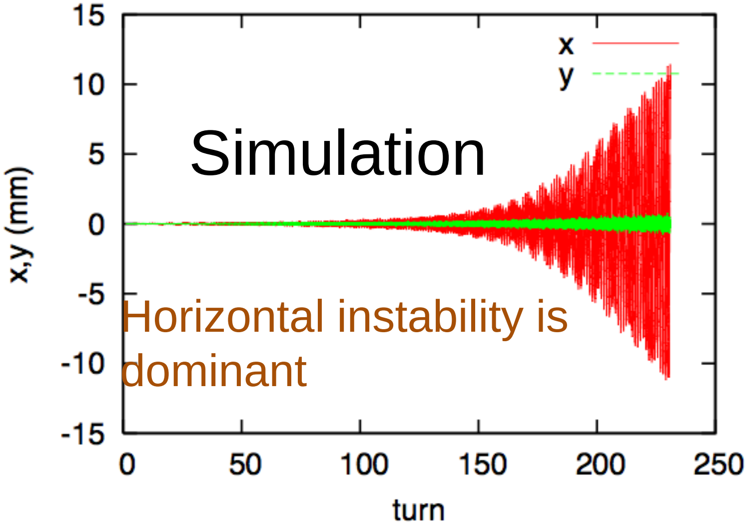
Measurement in DAFNE

M. Zobov, ECLOUD12



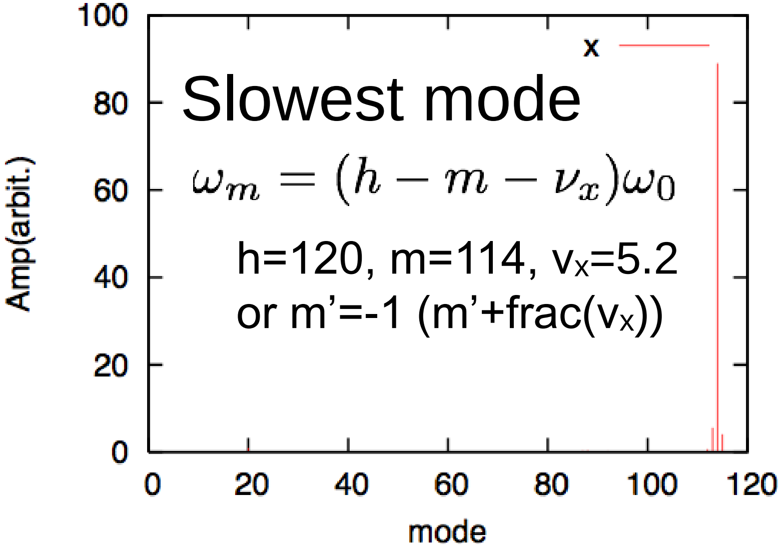
DAFNE E+ (iGp):E+/170242: Io= 558.088mA, Dsamp= 1, ShifGain= 1, Nbun= 120,
At Fs: G1= 6.7045, G2= 0, Ph1= -127.1256, Ph2= 0, Brkpt= 575, Calib= 1.

Horizontal coupled bunch instability



Simulation

Horizontal instability is dominant



Slowest mode

$$\omega_m = (h - m - \nu_x)\omega_0$$

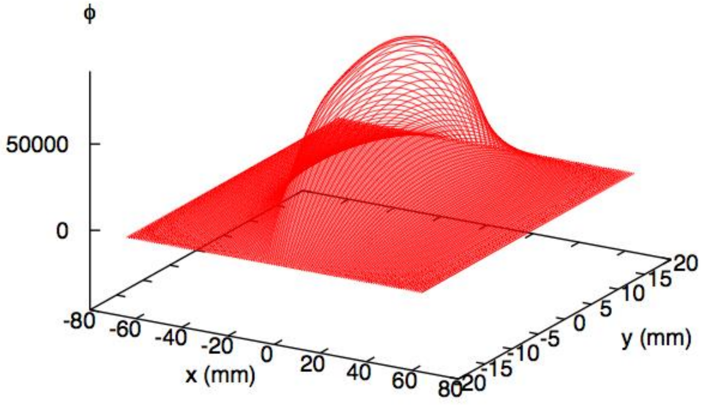
h=120, m=114, v_x=5.2

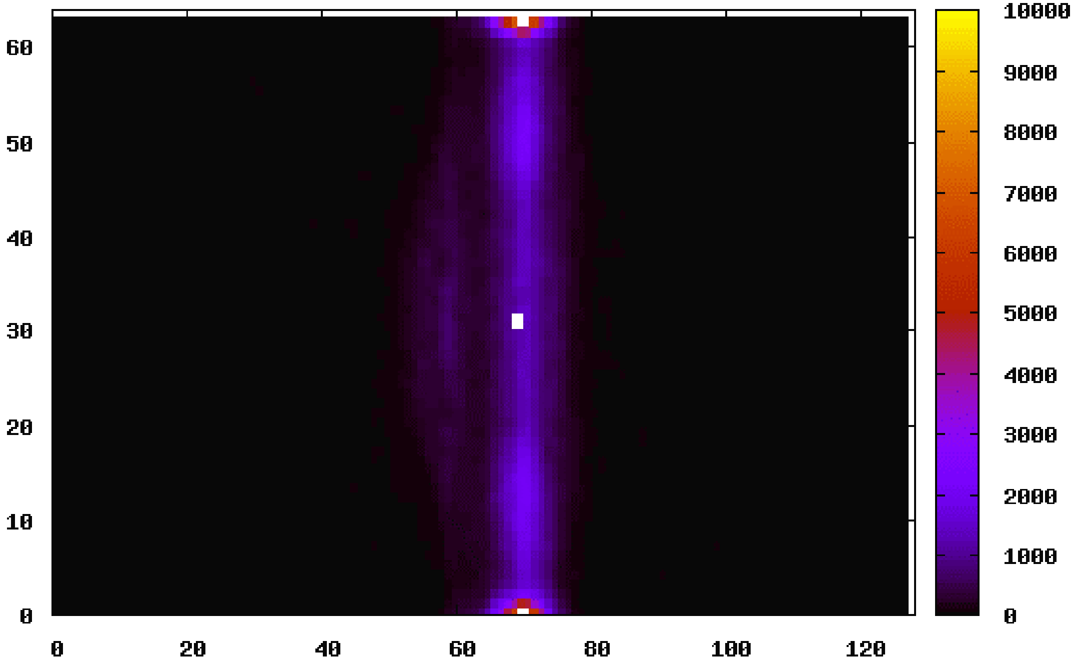
or m'=-1 (m'+frac(v_x))

Coherent motion of beam and electron stripe in DAFNE

- Electron stripe is formed in bending magnet.
- The beam and stripe move coherently, then horizontal coupled bunch instability is induced.

Electron potential





Single bunch instability

Beam size blowup in KEKB

- Beam size blowup was observed above a threshold current.
- The blowup is observed in multi-bunch operation, but no bunch-by-bunch correlation in the bunch motion.
- Coherent or incoherent?
- It was concluded as coherent single bunch instability.
- Luminosity was limited by the beam-size blow-up.

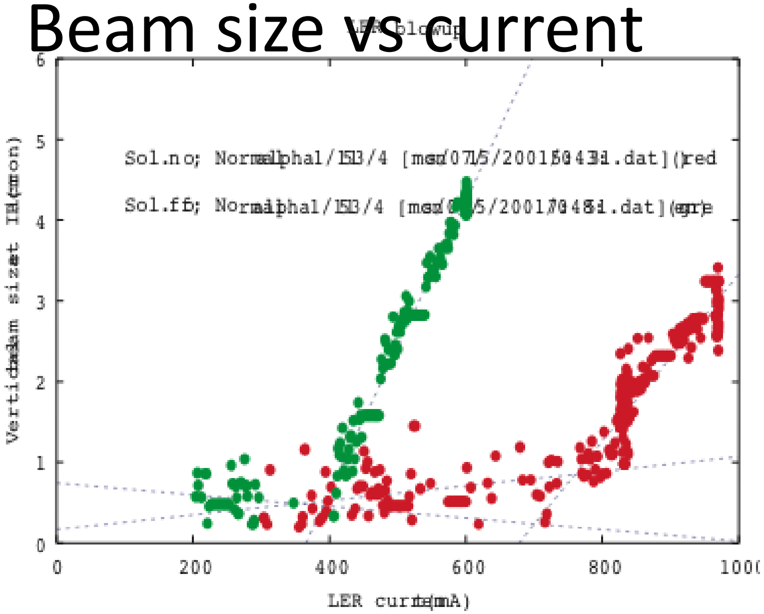
- Instability signal proper to electron cloud induced single bunch instability.

Observation of single bunch instability

- The beam size blowup in KEKB is caused by coherent instability.

Beam size blowup

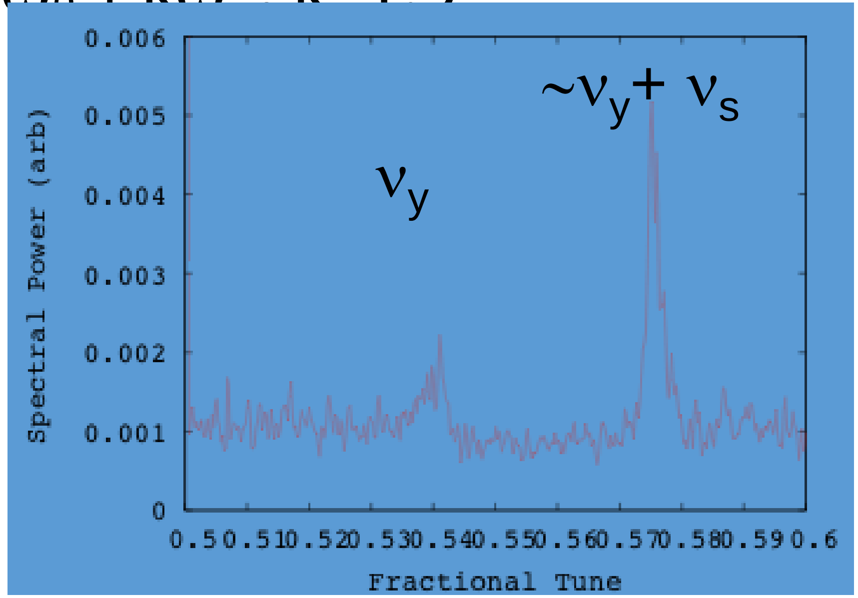
Beam size vs current



Fukuma et al.

Instability signal

$\omega_\beta + k\omega_s$, k~1.5



J. Flanagan et al.

KEKB: measurement and simulation of fast head-tail instability

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

J. Flanagan et al., PRL94, 054801 (2005)

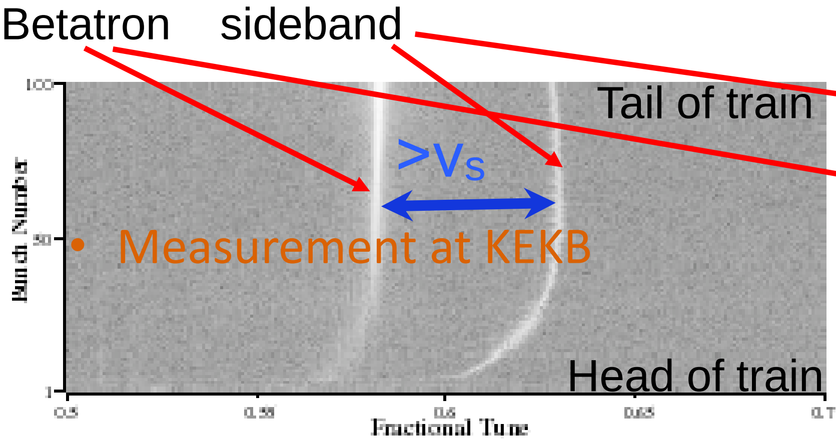
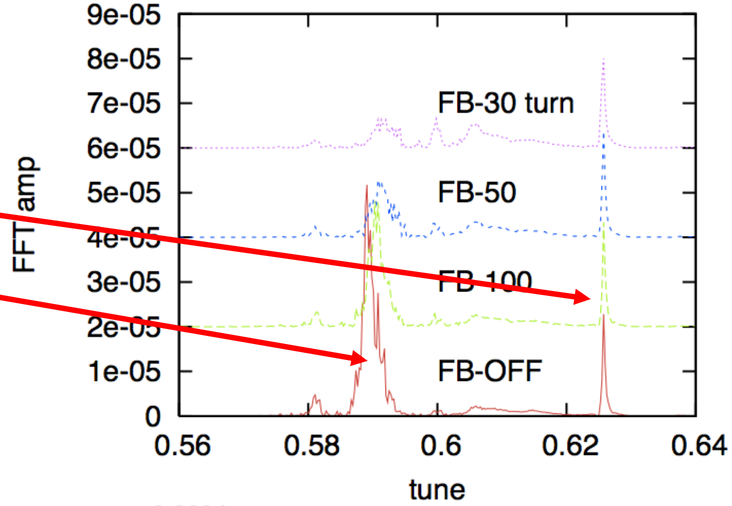
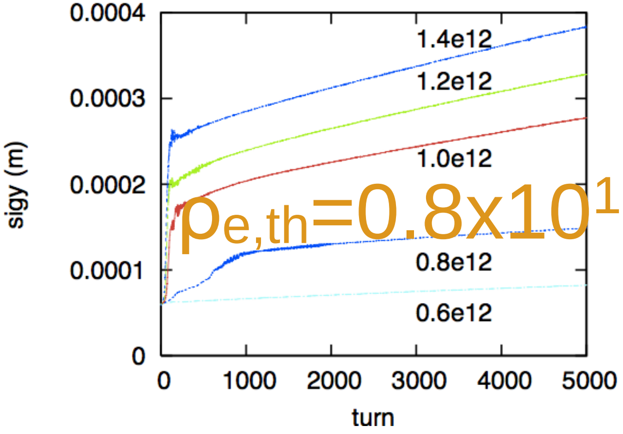


FIG. 1. Two-dimensional plot of vertical bunch spectrum versus bunch number. The horizontal axis is the fractional tune, from 0.5 on the left edge to 0.7 on the right edge. The vertical axis is the bunch number in the train, from 1 on the bottom edge to 100 on the top edge. The bunches in the train are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

Simulation (PEHTS)

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





$\rho_{e,th}=0.8\mathrm{x}10^{12}\mathrm{m}^{-3}$

Solenoid winding in KEKB-LER

(0) A lot of permanent magnets were puts along the arc section in the ring ~800m.

(1) The magnets (800m) are replaced by solenoid magnets (Summer 2000).

(2) Additionally 500m magnets are wounded (Jan. 2001).

(3) Magnets were added in straight section (Apr. 2001).

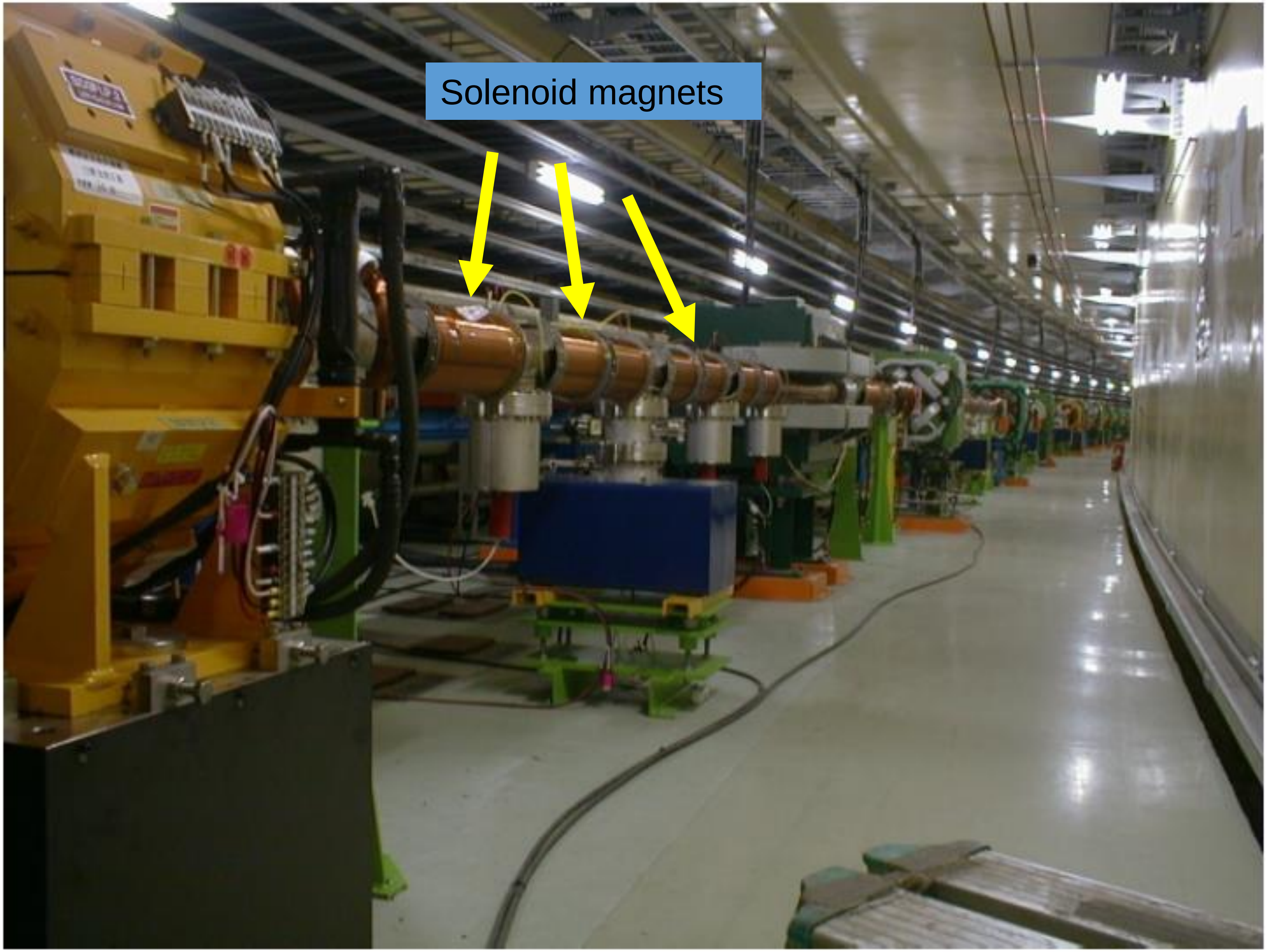
(4) Add solenoids even in short free space (Summer 2001).

(5) Solenoid magnets cover 95 % of free space (~2005).

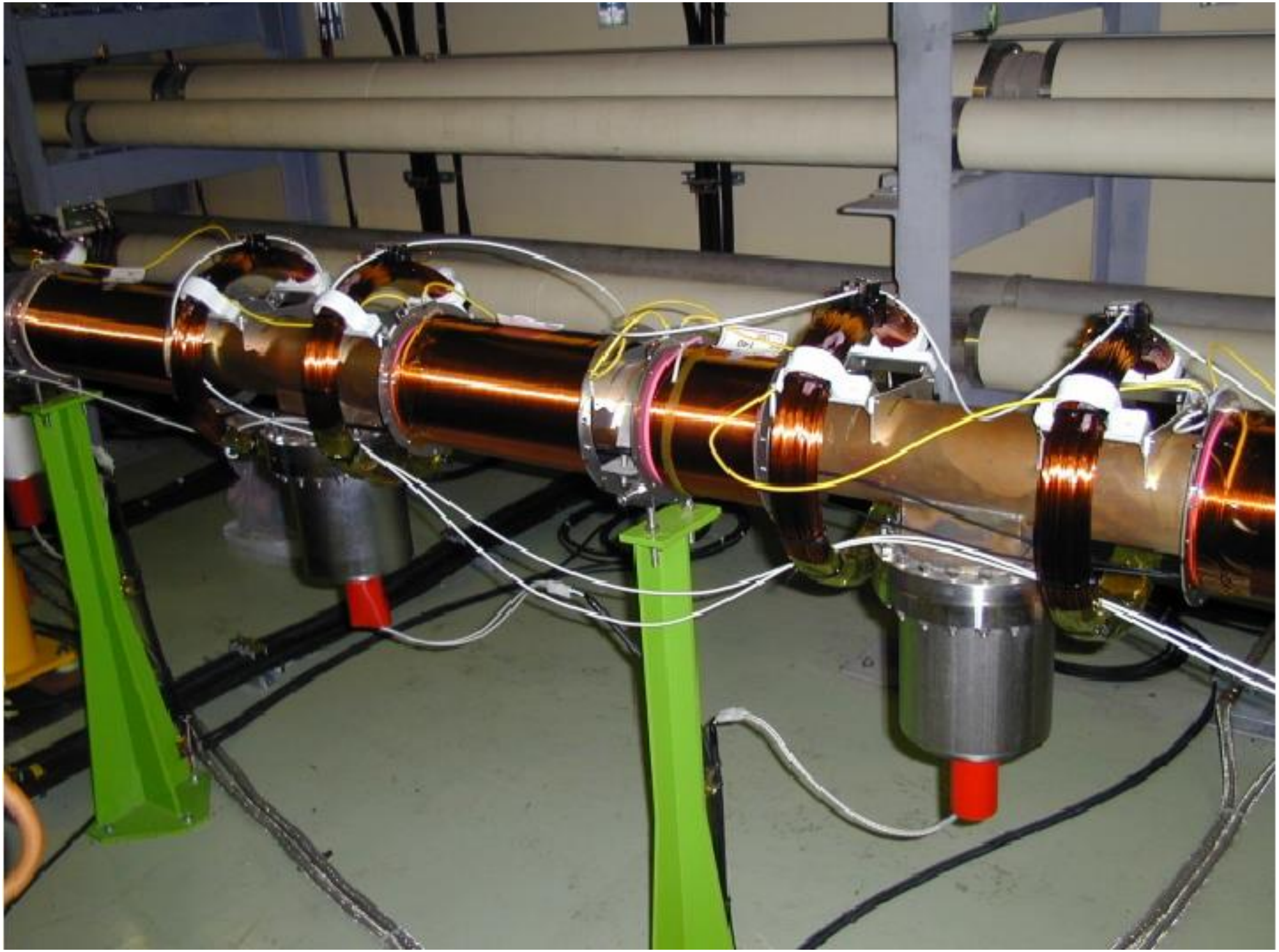
(6) Inside of ¼ of Quadrupoles (2005年)

Managed by H. Fukuma et al.

Winding solenoid in PEP-II is earlier than KEKB.



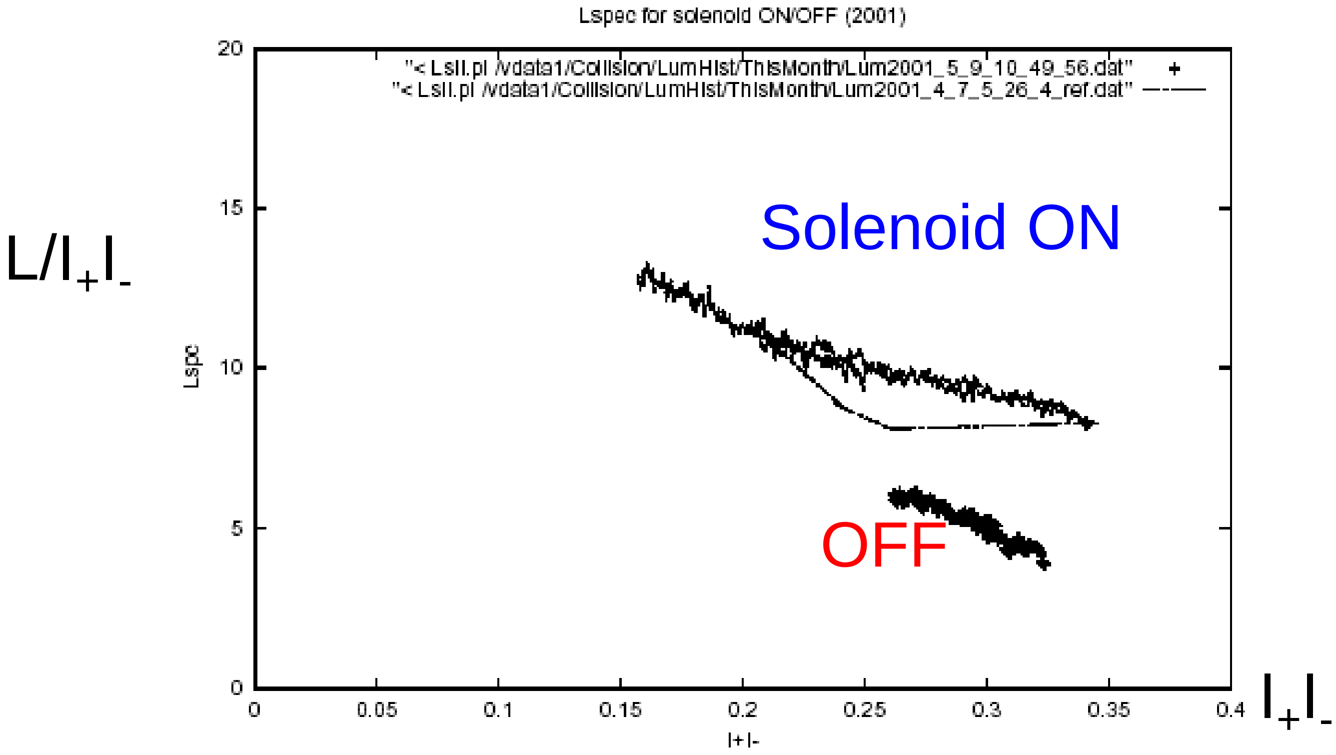
Solenoid magnets



Luminosity for Solenoid ON/OFF

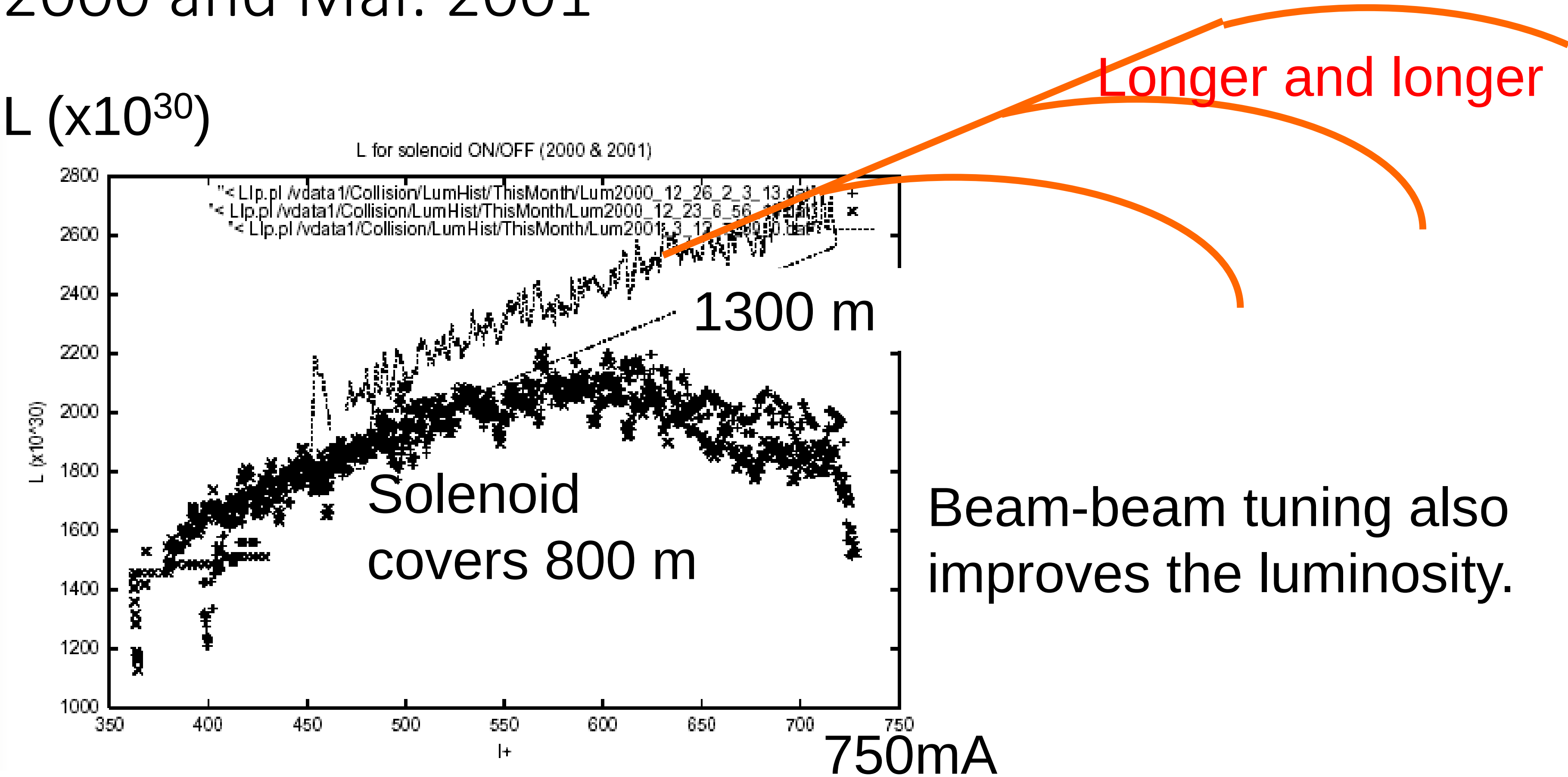
- Luminosity was very low (~half) for Solenoid OFF.
- Maximum stored current is limited due to coupled bunch instability for solenoid OFF
- Effect of added solenoid in 2000 end (+500m).

Specific luminosity for solenoid ON/OFF (measurement at May.2001)



Add solenoids and luminosity increase Dec. 2000 and Mar. 2001

L $(x10^{30})$



Longer and longer

1300 m

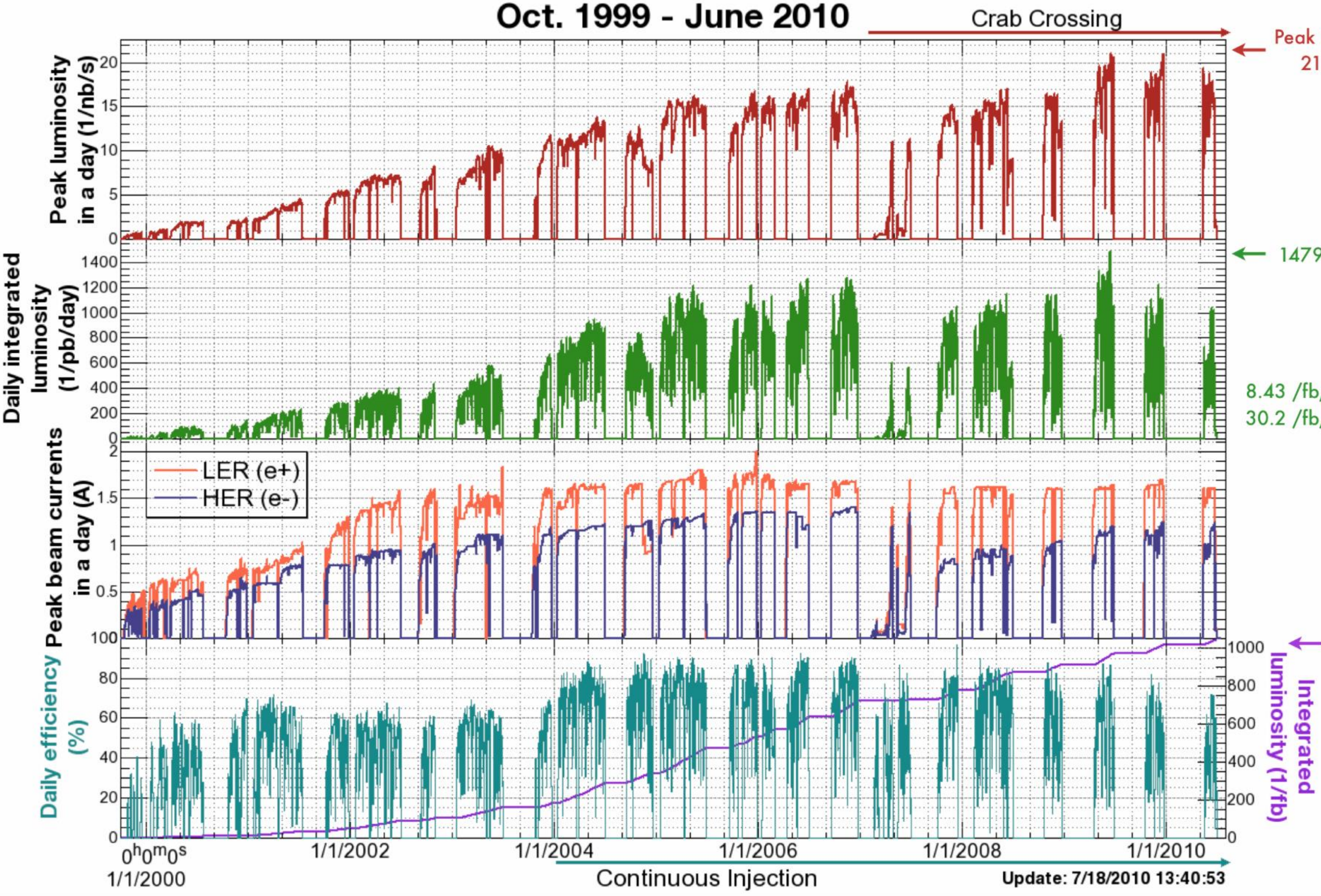
Solenoid covers 800 m

750mA

Beam-beam tuning also improves the luminosity.

- Peak luminosity increased for adding solenoid magnets.

Luminosity of KEKB
Oct. 1999 - June 2010



Peak Luminosity 21.1 /nb/s

1479 /pb/day

8.43 /fb/7 days
30.2 /fb/30 days

1039 /fb

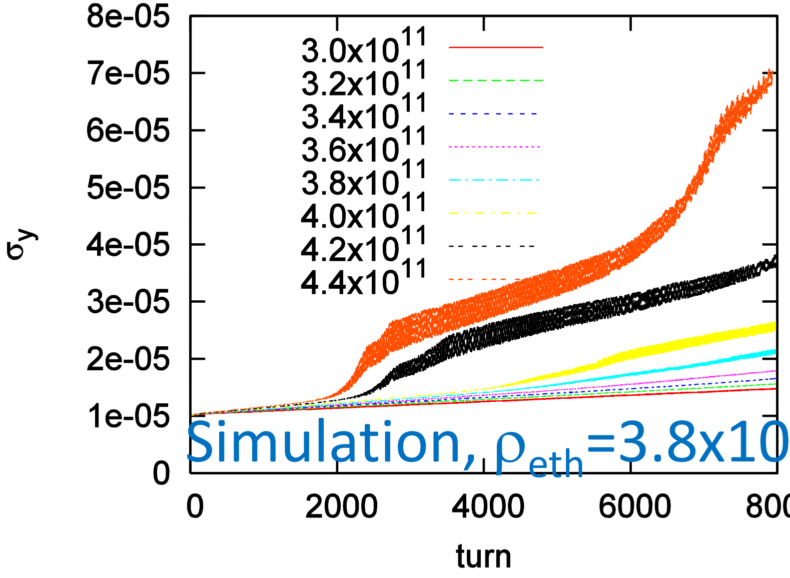
SuperKEKB

- C=3016.3m, e^+(4GeV)-e^-(7GeV) circular collider
- Half crossing angle, ϕ_c=41.5mrad, σ_z=6/5mm.

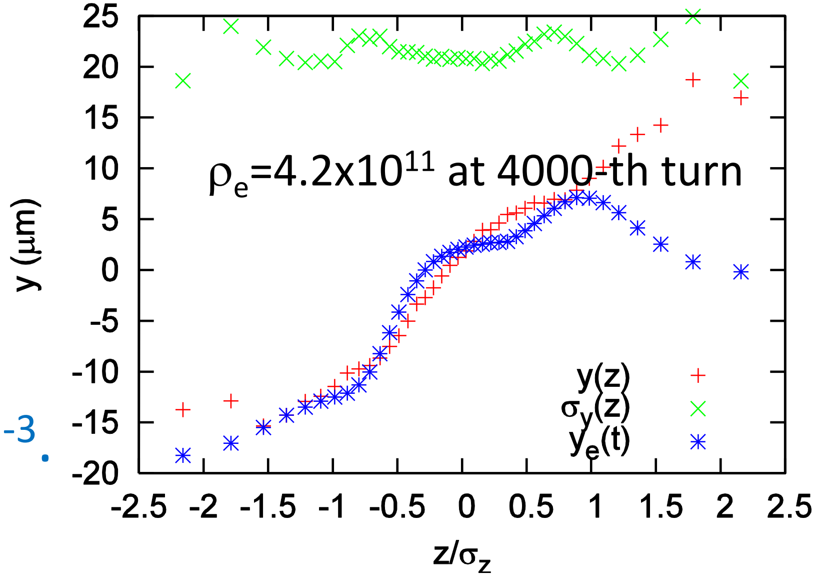
	Phase 2 (May 2018)		**Phase 2.3 (β*, 4x8x)**		**Design**	
	LER	HER	LER	HER	LER	HER
β_x*[mm]	200	200	128	100	32	25
β_y*[mm]	4	4	2.16	2.40	0.27	0.30
ε_x [nm]	2.1	4.6	2.1	4.6	3.2	4.6
$\varepsilon_y/\varepsilon_x$ [%]	5		1.4		0.27	0.28
I_b [mA]	340	285	0.64	0.51	1.44	1.04
ξ_x			0.0053	0.0021	0.0028	0.0012
ξ_y	0.019	0.013	0.0484	0.05	0.088	0.081
N_{bunch}	788		1576		2500	
L [$cm^{-2}s^{-1}$]	1.3×10^{33}		2×10^{34}		8×10^{35}	
PA Φ_c	10	8	15.2	9.7	24.7	19.4

Instability simulation at SuperKEKB design stage

- Using code PEHTS



Simulation, ρ_{eth}=3.8x10^{11} m^{-3}.



$$\rho_{e,th} = \frac{2\gamma\nu_s\omega_e\sigma_z/c}{\sqrt{3}KQr_e\beta_y L} = 2.2 \times 10^{11}\ \mathrm{m}^{-3},$$

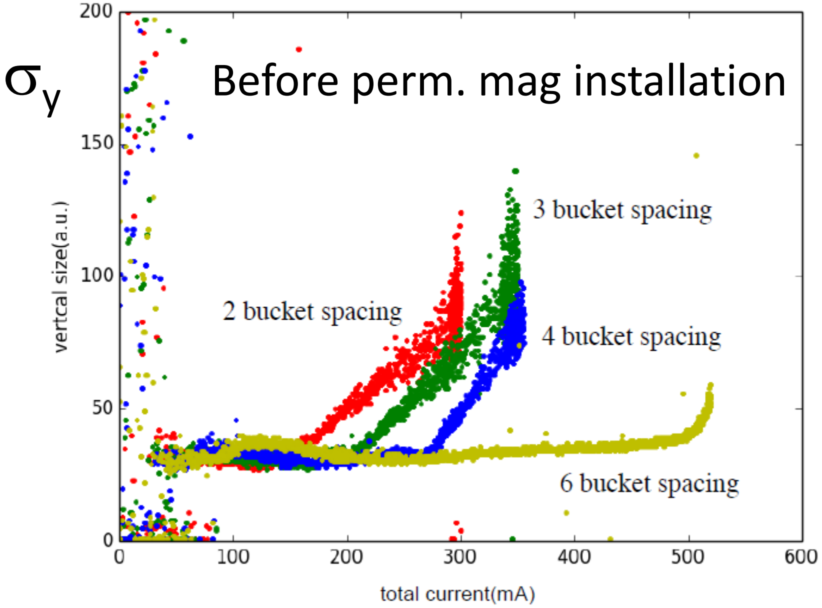
where $K = \omega_e\sigma_z/c = 17$ and $Q = min(\omega_e\sigma_z/c, 10)$

Design target for vacuum system: $\rho_e<10^{11}$ m^{-3} in average of whole ring

Beam size blow-up in LER

- Beam-size blowup observed in KEKB has been seen in early stage of SuperKEKB commissioning

1. Threshold I~300mA in Apr 19 (Y. Funakoshi)
2. Electron cloud has been monitored at AL chamber w and w/o TiN coating (Y. Suetsugu).
3. Beast study threshold I~600mA, N_{bunch}=1576 in May 17 (Nakayama et al)
4. Aluminum bellows, which were not coated by TiN, were suspected as an electron source.
5. Permanent magnets were installed at the aluminum bellows.(Y. Suetsugu et al.)
6. The blow up was suppressed. Systematic studies in 8 July (H. Fukuma et al.)



June 1, 2016
4 train x150 bunches, N_{bunch}=600

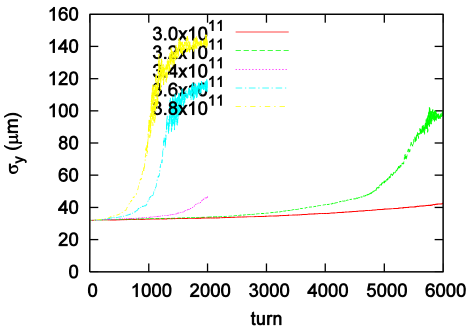
Threshold beam current
160, 200, 260,500 mA for 2, 3, 4, 6
bucket spacing

H. Fukuma et al.,

Simulation studies using beam study condition

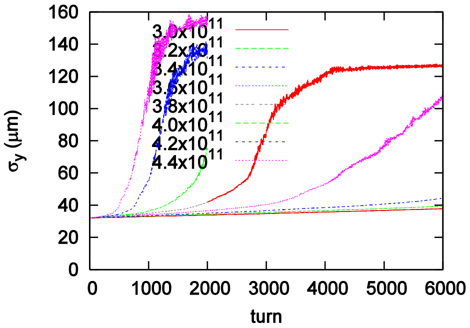
Threshold of the electron density

ε_x=2nm, ε_y=15pm, σ_z =6mm, ν_s=0.019



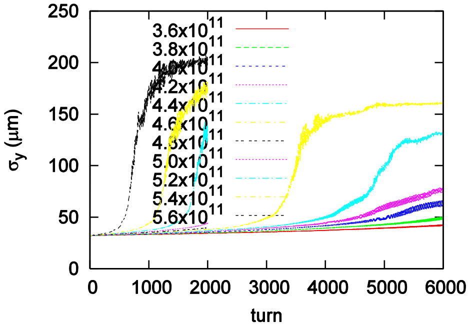
Np=1.6x10^{10}

$\mathrm{I_{th}}$=160mA, 4ns spacing



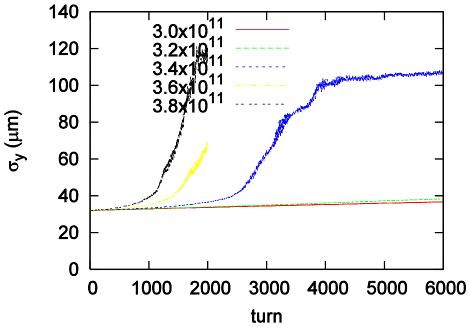
Np=2.7x10^{10}

$\mathrm{I_{th}}$=260mA, 8ns spacing



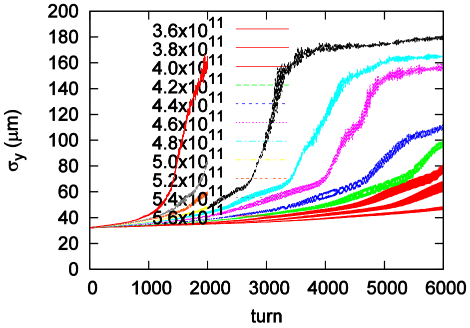
Np=3.65x10^{10},

$\mathrm{I_{th}}$=350mA, 6ns



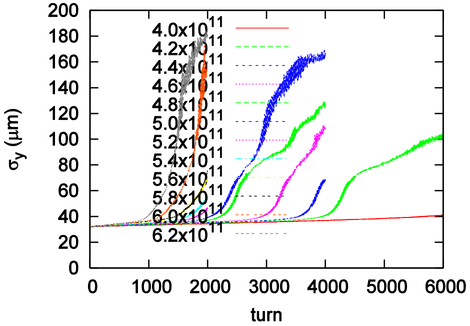
Np=2.1x10^{10}

$\mathrm{I_{th}}$=200mA, 6ns spacing



Np=5.2x10^{10}

$\mathrm{I_{th}}$=500mA, 8ns spacing



Np=6.25x10^{10},

I=600mA, 8ns

Electron density at the blow-up threshold

Only Al part

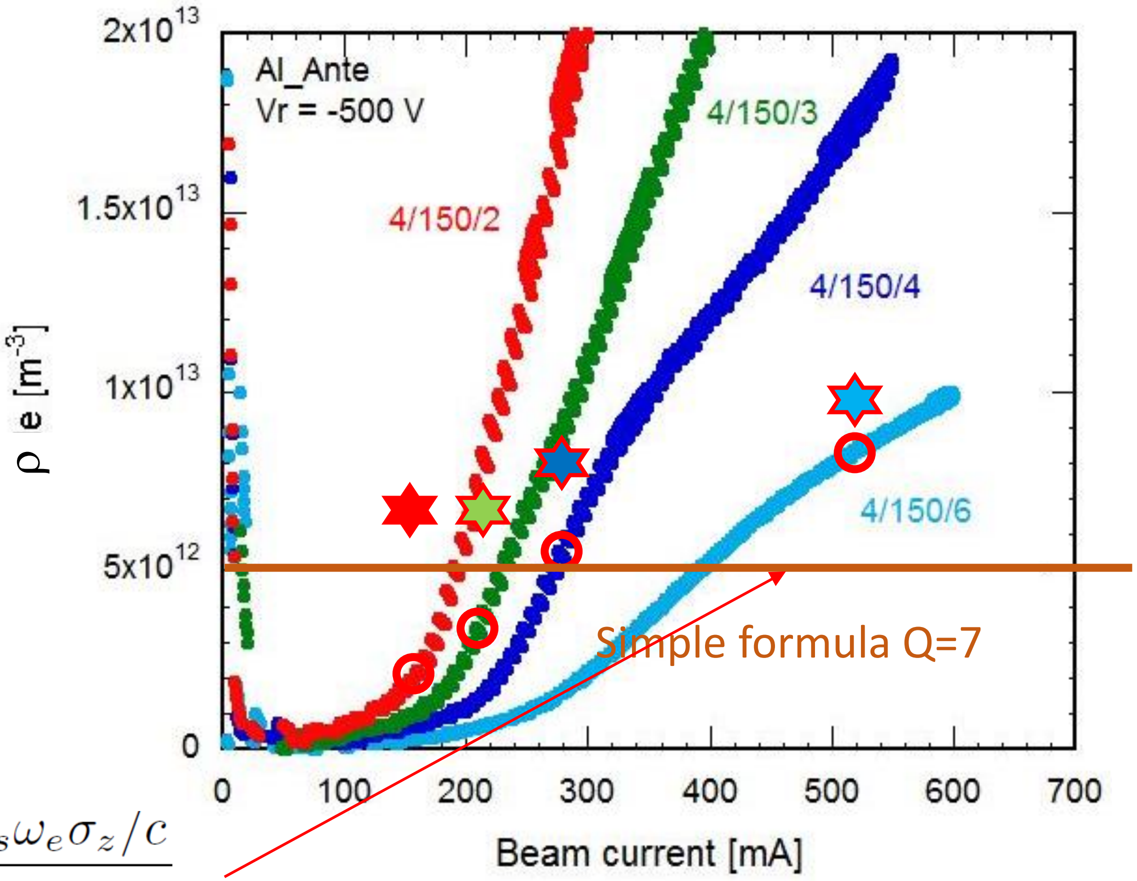
5% of whole ring

If electrons only exist the bellow section, 1/20 number is averaged density.

- We can compare simulation and measurement, if Al part is dominant.
- The discrepancy of sim. and meas. may be due to electrons in whole ring.
- In narrower bunch spacing, electrons are accumulated in whole ring.

✡ Simulated electron density at the threshold current

○ Measured threshold current and density

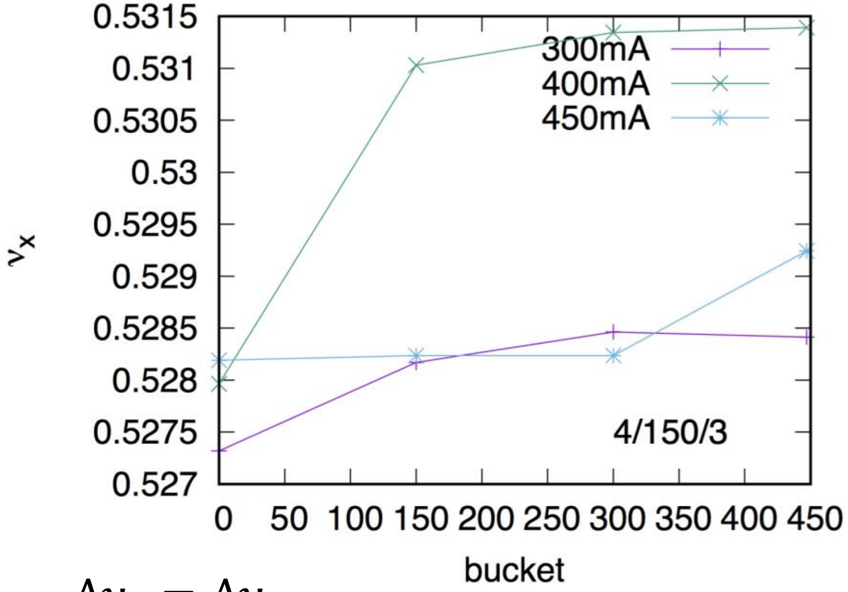


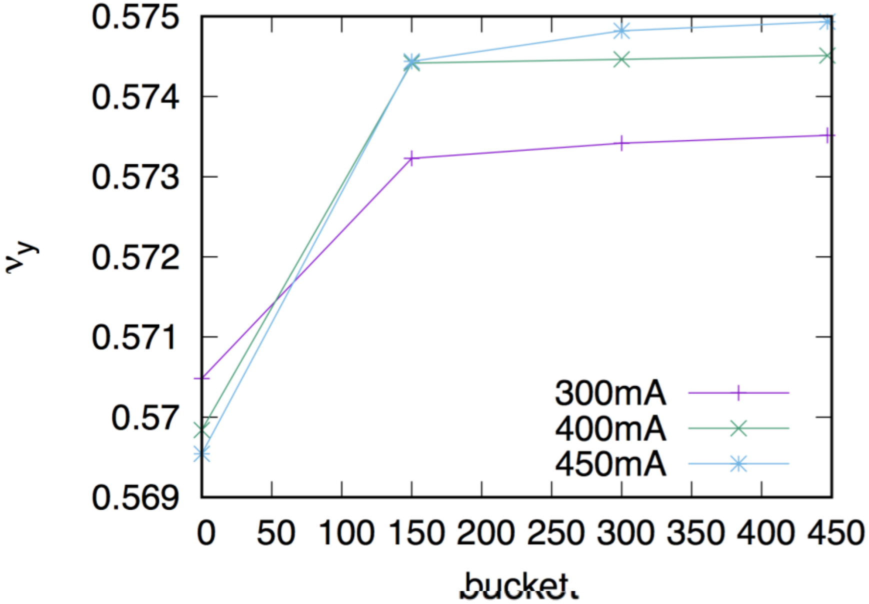
Simple formula Q=7

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

Tune shift measurement along bunch train

Tune shift along bunch train in LER





$\Delta\nu_x = \Delta\nu_y$

$$\Delta\nu_y = \frac{\rho_e r_e \beta_y}{2\gamma} C$$

$\Delta\nu_y$ =0.005 より ρ_e = 8×10^{11} m^{-3}

$\Delta\nu_x = 0$

$$\Delta\nu_y = \frac{\rho_e r_e \beta_y}{\gamma} C$$

$\Delta\nu_y = 0.005$

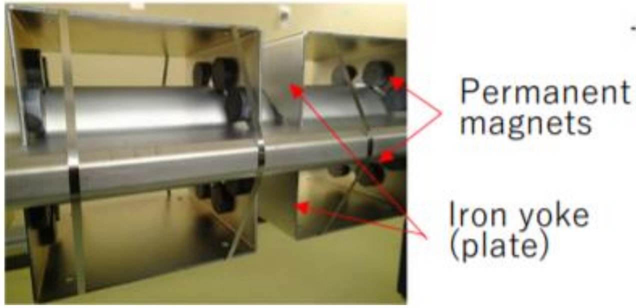
$\rho_e = 4 \times 10^{11}\, m^{-3}$

Agree with density measurement

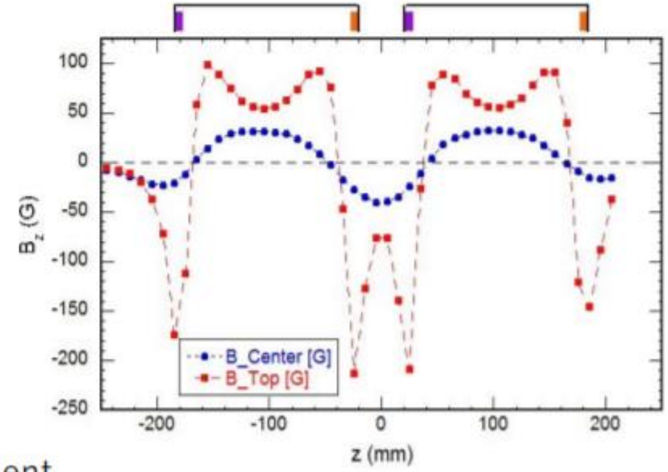
Mitigation using permanent magnets

- Permanent magnets were installed on ~86% of the drift spaces before Phase-2.
- Approximately 91% of the drift spaces were covered with them before Phase-3.

Type-1 unit



Magnetic field of Type-1 unit
Typical strength ~ 60 G

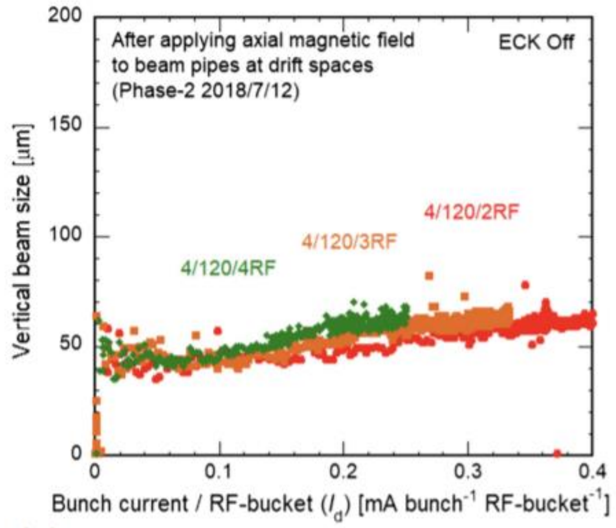


23rd KEKB Review

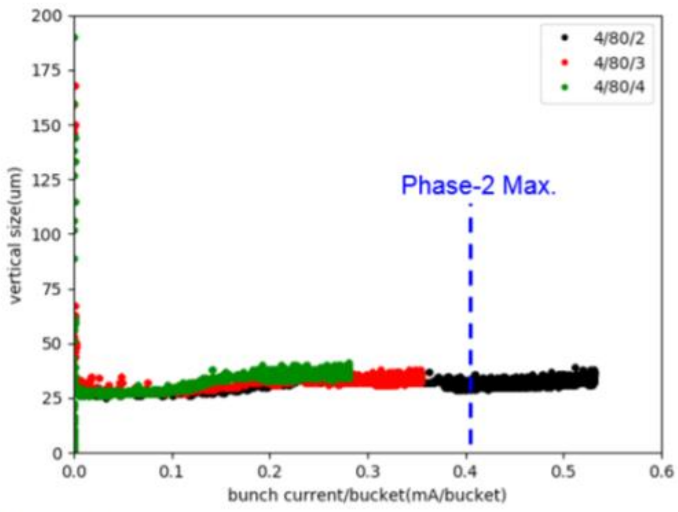
Vertical beam size measurement

- No beam size blowup up to 1.1mA by 4ns, while design is 1.5mA.
- Small increase of beam size is seen, but luminosity does not decreases in collision. Perhaps calibration of beam size monitor is not perfect.

ECE study in Phase-2

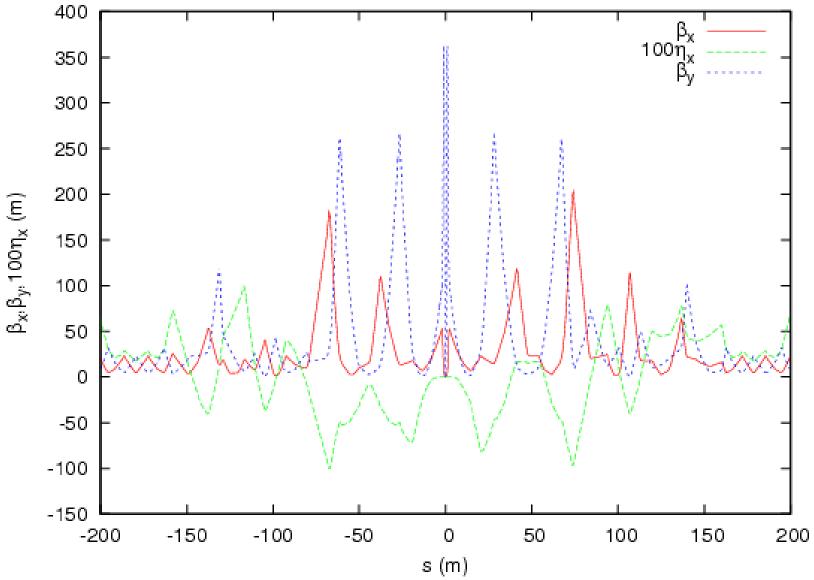


ECE study in Phase-3 (preliminary).

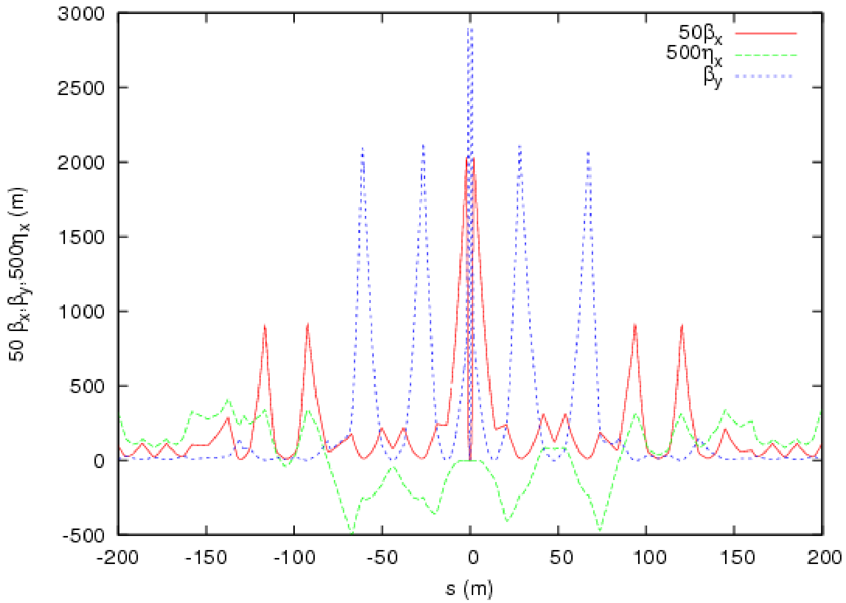


IR optics

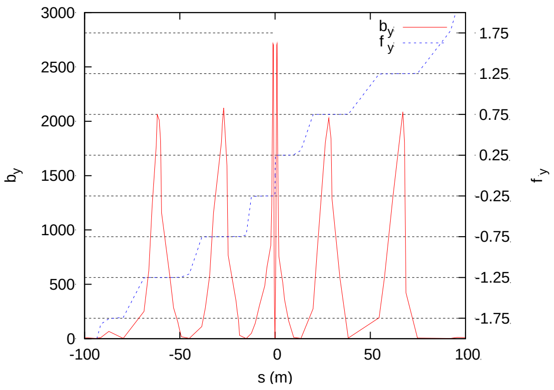
- 8x8x



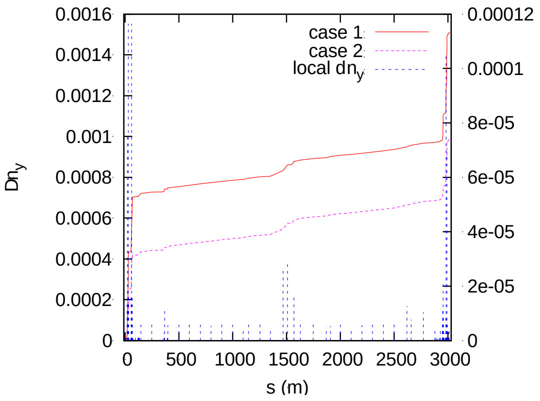
design

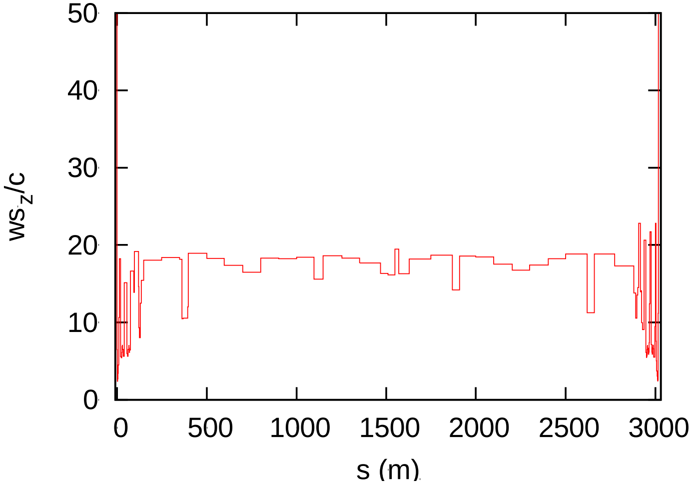


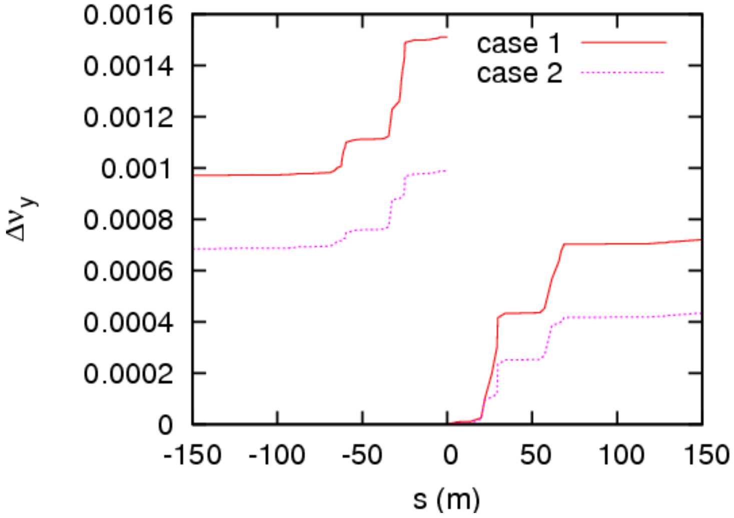
- Extremely high beta ~2000 m. Even the length is short, contribution may be dominant.
- Betatron phase is separated π each high beta area. Resonances with high harmonics are excited.
- Consider two cases in which electrons are accumulated at Q in LCC (1:pessimistic) or not (2:optimistic).

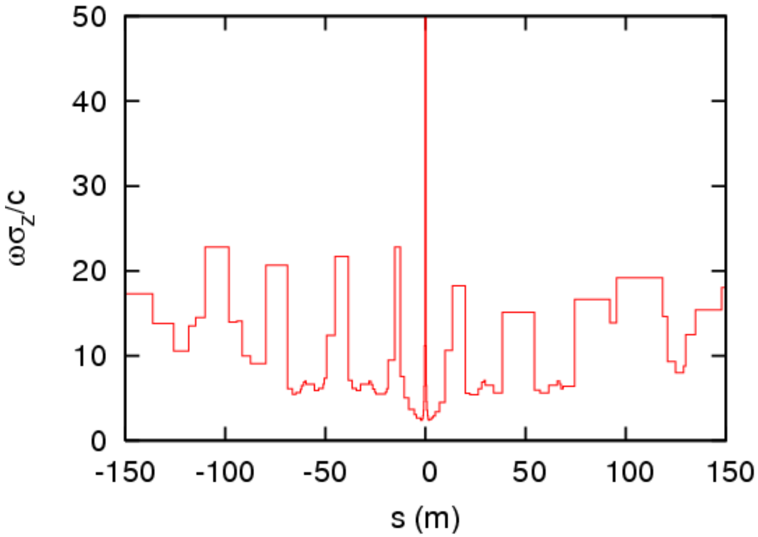


Tune shift and electron frequency of electron cloud at IR





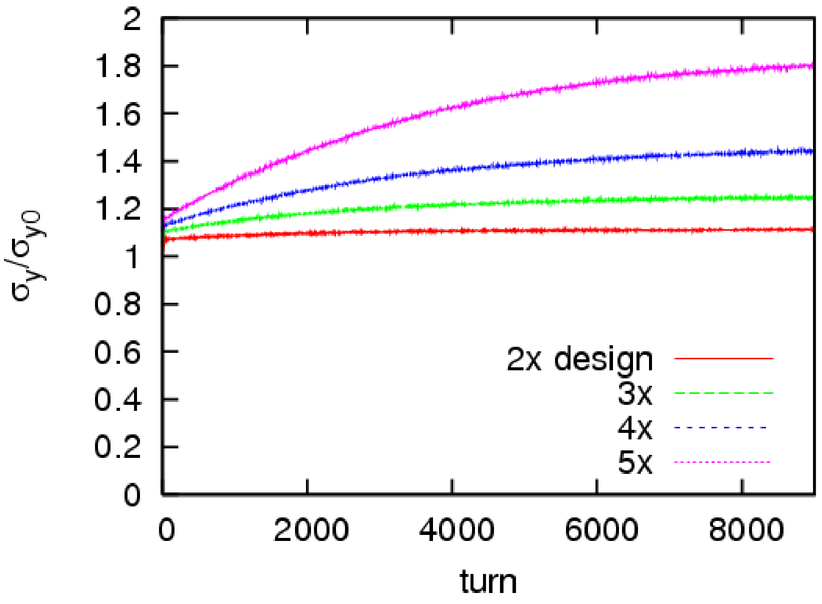


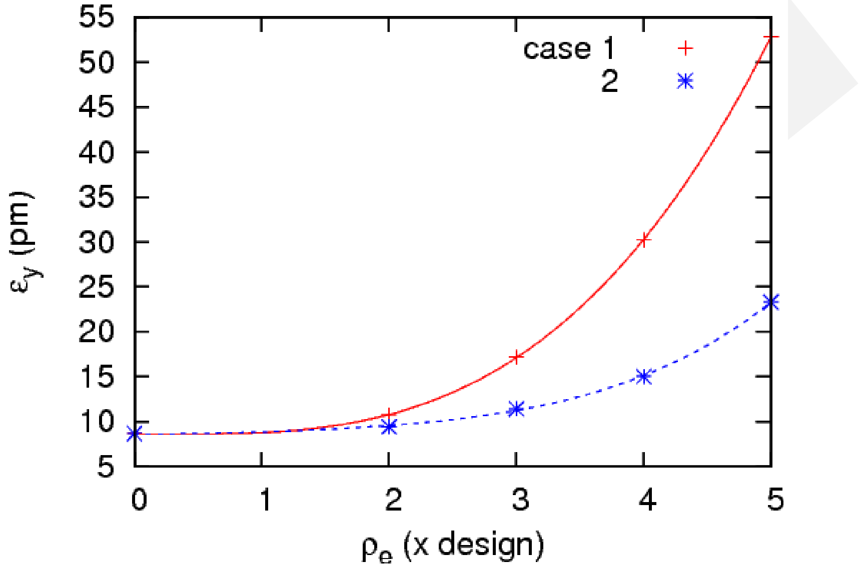


70% of the tune shift comes from QC's. (focus case 2)

Radiation damping and equilibrium vertical emittance

- Radiation damping ~5000 turns is taken into account.
- If electron density is in our assumption, no emittance growth. 3x of assumption gives emittance increase.
- No sign of incoherent emittance growth experimentally in 2019.





Phase II and III commissioning status for electron cloud

- Start from March 2018
- Squeezing β^*. (80mmx2mm in Jul 2019)
- Measurement of electron cloud instabilities, coupled bunch and single bunch instabilities were continued.
- Solenoid type of modes were observed in coupled bunch modes (growth>~4ms, slower, Tobiyama).
- No single bunch instability (beam size blow-up) 1.1mA/bunch, Lsp=4ns (Design 1.4mA/b, 4ns).
- Electron cloud is well controlled.
- Incoherent emittance growth has not seen.

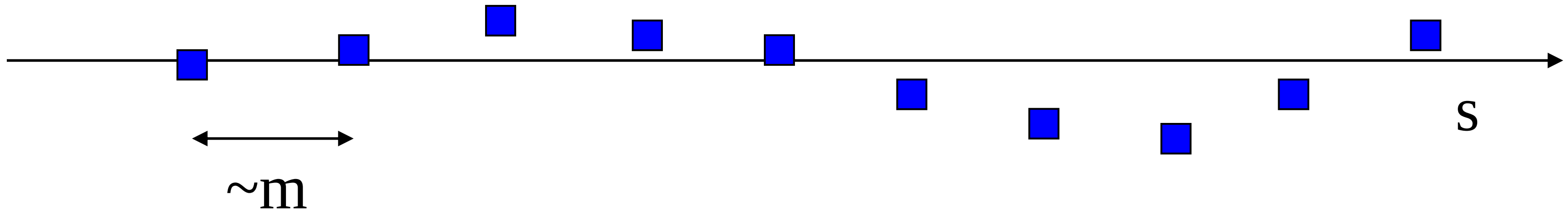
Summary for electron cloud effects, coherent and incoherent

- Coherent coupled bunch instability has been observed since electron cloud .
- Unstable mode is determined by electron motion in cloud.
- Coherent single bunch instability has been observed at KEK and SuperKEKB. Freq. signal corresponding head-tail motion has been observed.
- Luminosity performance has been remarkably improved by suppression of the electron cloud.
- Incoherent emittance growth has not been observed in KEKB/SuperKEKB.
- Electron cloud instability and its mitigation are one of the most prominent success of beam dynamics.

Thank you for your attention

Coupled bunch instability

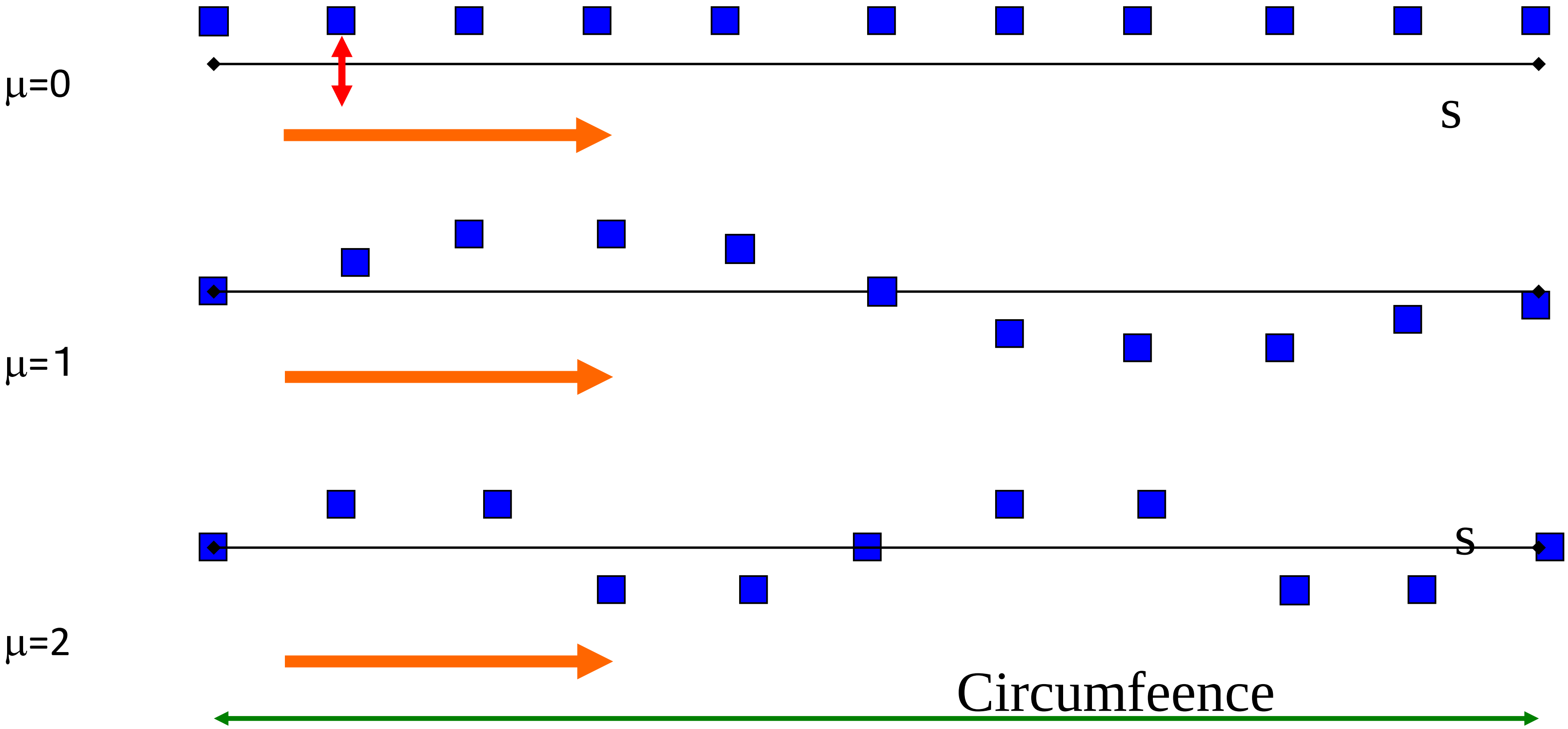
- Center of mass of each bunch oscillates around a closed orbit, betatron oscilation.
- Correlation between bunches is chracterized by mode number (μ).



- The mode number (μ) is the periodicity in a snap shot of bunch positions.

Oscillation mode (snap shot)

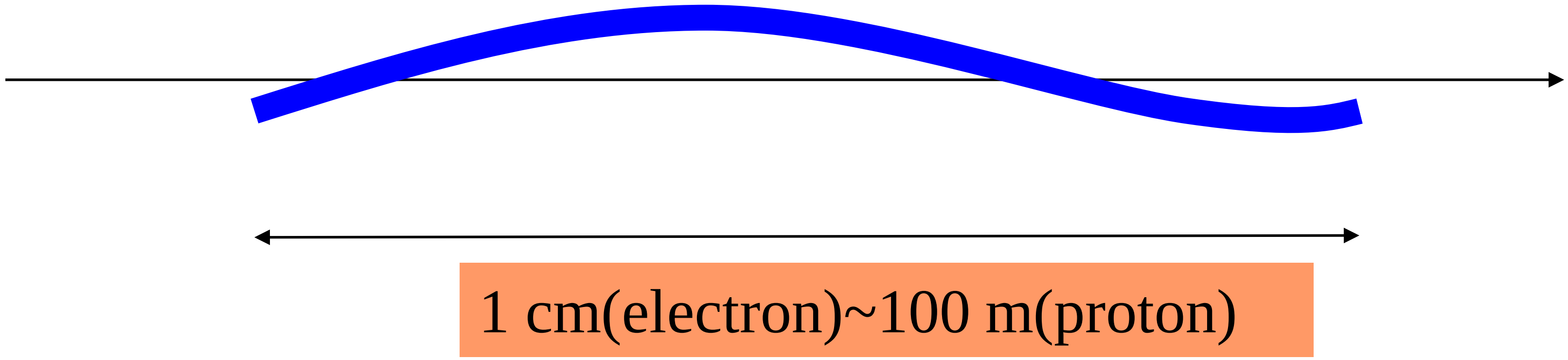
- Bunches travel with the light speed oscillating with betatron frequency (ω_β).



BPM detects signal with $|(h+\mu)\omega_0+\omega_\beta|$ for the beam with betatron oscillation.

Single bunch instability

- Inner bunch oscillation.
- Particles in a bunch oscillate transversely with betatron frequency, simultaneously they oscillate along traveling direction relatively; synchrotron oscillation ($\omega_s << \omega_\beta$).



1 cm(electron)~100 m(proton)

- Combined oscillation of betatron with ω_β and synchrotron with ω_s ; synchro-betatron oscillation.
- Frequency observed at BPM is $\omega_\beta + n\omega_s$, where n is mode number characterizes synchrotron sideband.
- No bunch-by-bunch correlation. Measurement a bunch with timing gate is required.