Electron Cloud Effects at SuperKEKB

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d’Elba, Italy

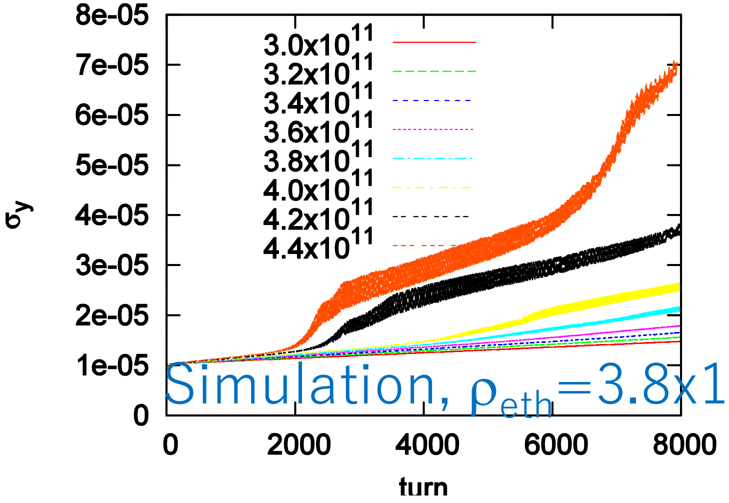
SuperKEKB

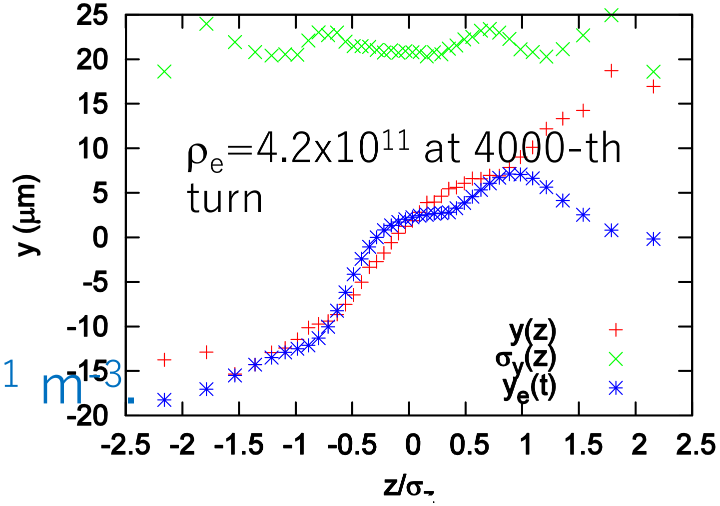
- C=3016.3m, e^+(4GeV)-e^-(7GeV) circular collider
- Half crossing angle, ϕ_c=41.5mrad, σ_z=6/5mm.

	Phase 2 (May 2018)		Phase 3 2021-2022		Design	
	LER	HER	LER	HER	LER	HER
β_x*[mm]	200	200	80	60	32	25
β_y*[mm]	4	4	1	1	0.27	0.30
ε_x [nm]	2.1	4.6	4.0	4.6	3.2	4.6
ε_y [pm]	5		25		0.27	0.28
I_b [mA]	340	285	1	0.8	1.44	1.04
ξ_x			0.0**	0.0*	0.0028	0.0012
ξ_y	0.019	0.013	0.0**	0.03	0.088	0.081
N_{bunch}	788		1576		2500	
L [$cm^{-2}s^{-1}$]	1.3×10^{33}		4.6×10^{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, $\rho_{eth}=3.8\mathrm{x}10^{11}\ \mathrm{m}^{-3}$.

$$\rho_{e,th} = \frac{2\gamma\nu_s\omega_e\sigma_z/c}{\sqrt{3}KQr_e\beta_y L} = 2.2\times10^{11}\ \mathrm{m}^{-3},$$

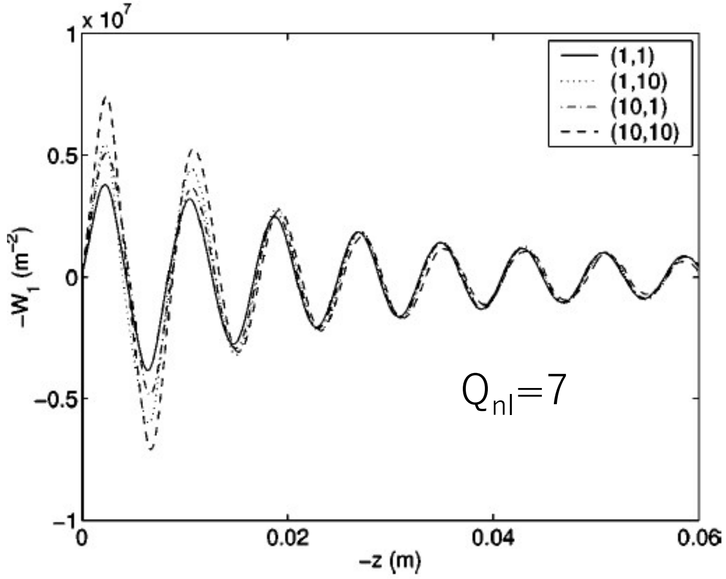
$$\omega_e = \sqrt{\frac{\lambda_p r_e c^2}{\sigma_y(\sigma_x+\sigma_y)}}$$

where $K=\omega_e\sigma_z/c=17$ and $Q=\min(\omega_e\sigma_z/c, Q_{nl})$

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

Wake force induced by electron cloud

- Discuss later in detail.



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)

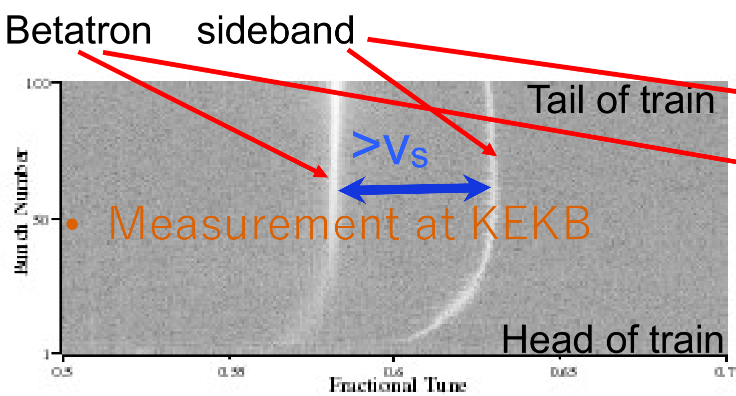
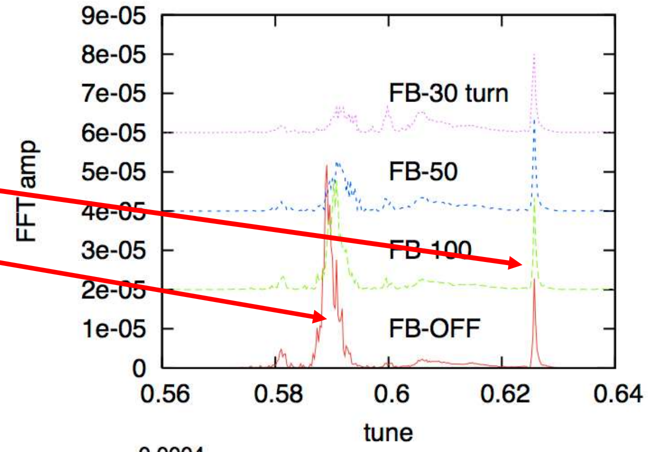
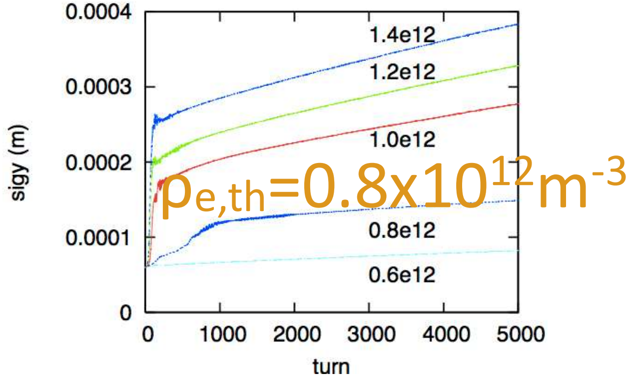


FIG. 1. Two-dimensional plot of vertical bunch spectrum versus bunch number. The horizontal axis is the fractional tune, from 0.5 on the left edge to 0.7 on the right edge. The vertical axis is the bunch number in the train, from 1 on the bottom edge to 100 on the top edge. The bunches in the train are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





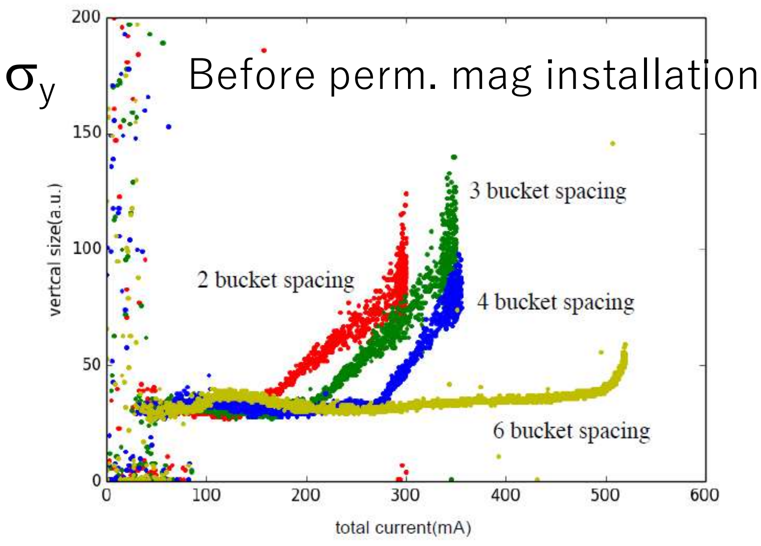
Phase I commissioning

- 2017 Feb.-June
- No collision. Test as two storage rings, e+(LER) and e-(HER).
- I=1A(e+) and 0.8A(e-) were stored.
- Electron cloud studies were performed.
  - Beam size blow-up caused by electron cloud was seen, but was recovered by permanent solenoid magnets.

Beam size blow-up in LER

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

1. Threshold I~300mA in Apr 19
2. Electron cloud has been monitored at AL chamber w and w/o TiN coating
3. Aluminum bellows, which were not coated by TiN, were suspected as an electron source.
4. Permanent magnets were installed at the aluminum bellows.(Y. Suetsugu et al.)
5. The blow up was suppressed.
6. Systematic studies were done in 1 June before PM and in 8 July after PM installation.

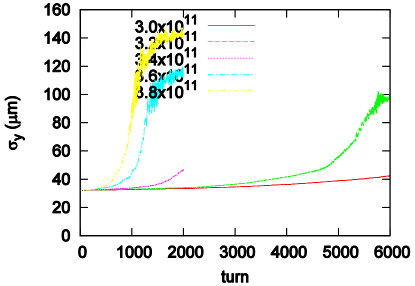


June 1, 2016
4 train x150 bunches,
N_{bunch}=600
Threshold beam current
160, 200, 260,500 mA for 2, 3, 4, 6 bucket spacing

Simulation studies using beam study condition

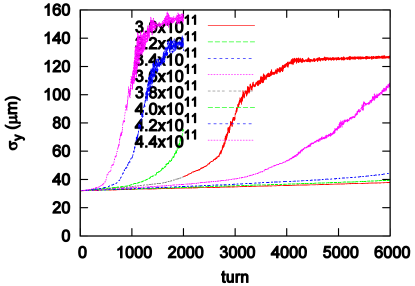
Threshold of the electron density

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



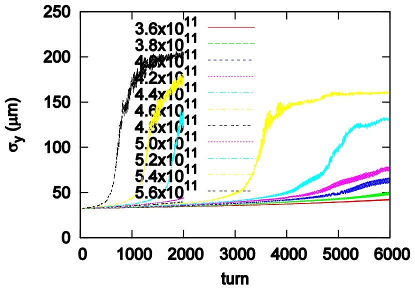
Np=1.6x10^{10}

I_{th}=160mA, 4ns spacing



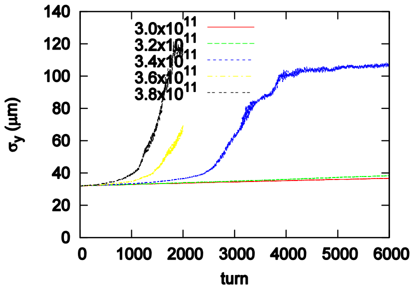
Np=2.7x10^{10}

I_{th}=260mA, 8ns spacing



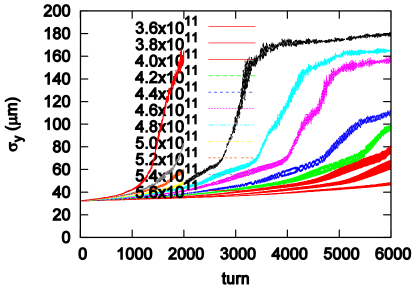
Np=3.65x10^{10},

I_{th}=350mA, 6ns



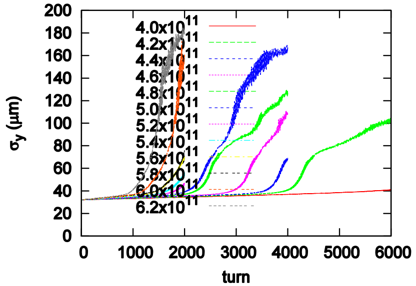
Np=2.1x10^{10}

I_{th}=200mA, 6ns spacing



Np=5.2x10^{10}

I_{th}=500mA, 8ns spacing



Np=6.25x10^{10},

I=600mA, 8ns

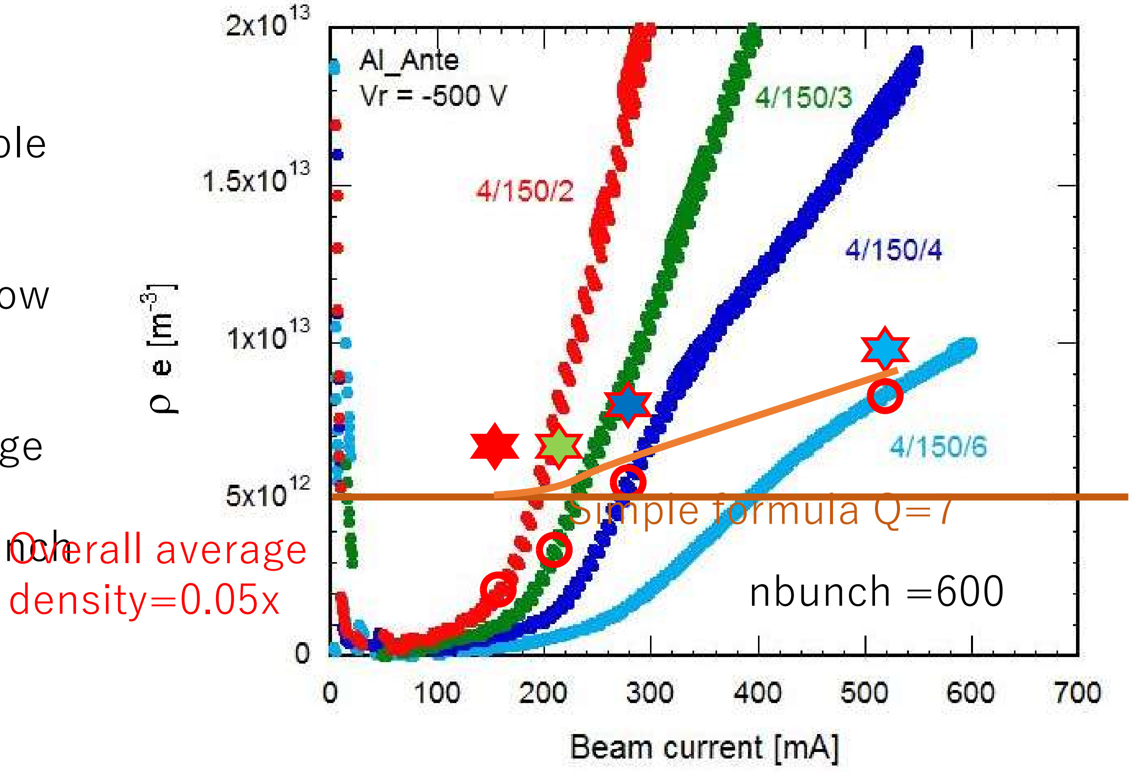
Electron density at the blow-up threshold

✡ Simulated electron density at the threshold current

○ Measured threshold current and density

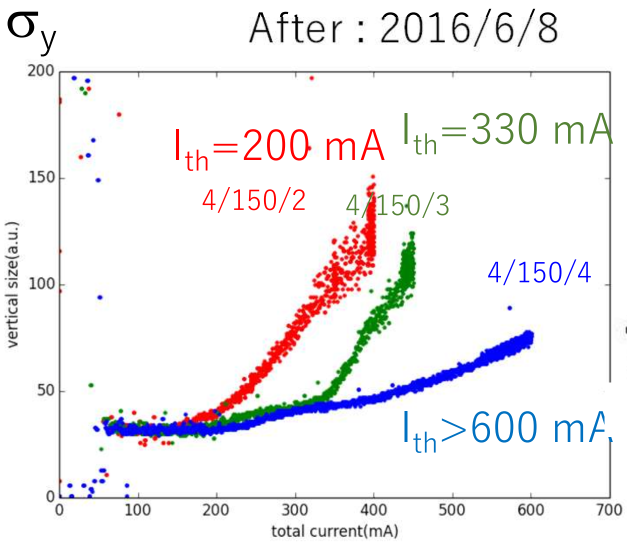
Local density at Al chamber
Al part (bellow) occupies only 5% of whole ring, but dominant for ecloud instability.

Discrepancy in ★ and ○ is seen at narrow bunch spacing.
Electrons in antechamber part (95%) contributes the instability, especially large bunch spacing.
Overall density contributes at narrow bunch spacing.



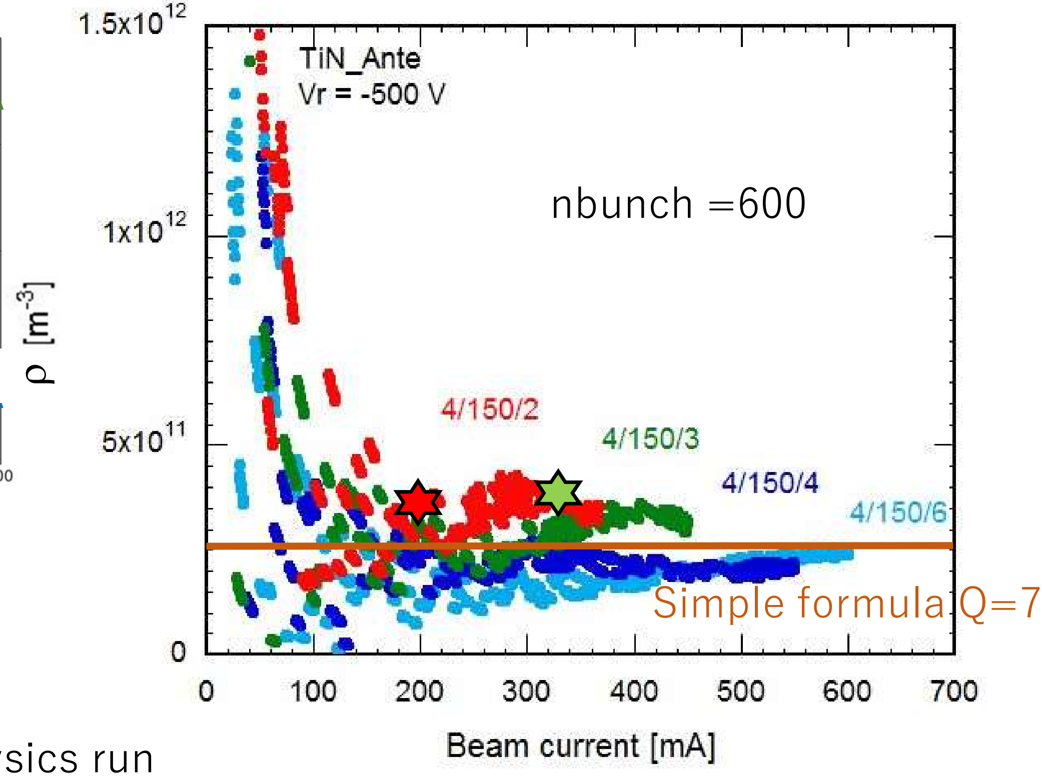
After installation of permanent solenoid at Al bellows

- The density at Al bellows is not dominant for the instability.
- Threshold is determined by the overall averaged density.



Beam study nbunch =600
160mA to 200mA by 2 bucket
200mA to 330mA by 3
260mA to >600mA by 4
SuperKEKB nbunch=1500-2500 in physics run

Simulated electron density at the threshold current



Summary of measurement and simulation

Before PM installation

Assume simulation is correct

- ρ_{th}(by 2)=$2x10^{12}x0.05+\rho_2(160mA)$, $\rho_2(160mA)=2.25x10^{11}$
- ρ_{th}(by3)=$3x10^{12}x0.05+\rho_3(200mA)$, $\rho_3(200mA)=1.75x10^{11}$
- ρ_{th}(by4)=$6x10^{12}x0.05+\rho_4(260mA)$, $\rho_4(260mA)=1.25x10^{11}$
- ρ_{th}(by6)=$8x10^{12}x0.05+\rho_6(500mA)$, $\rho_6(500mA)=0.75x10^{11}$

After PM installation

Assume linear increase for I

- ρ_{th}(by2)= $\rho_2(200mA)$ $\rho_2(200mA)=2.8x10^{11}$ 3,4
- ρ_{th}(by3)= $\rho_3(330mA)$ $\rho_3(330mA)=2.9x10^{11}$ 3,8
- ρ_{th}(by4)= $\rho_4(>600mA)$ $\rho_4(600mA)=2.9x10^{11}$ 4.2
- $\rho_6(600mA)=0.9x10^{11}$

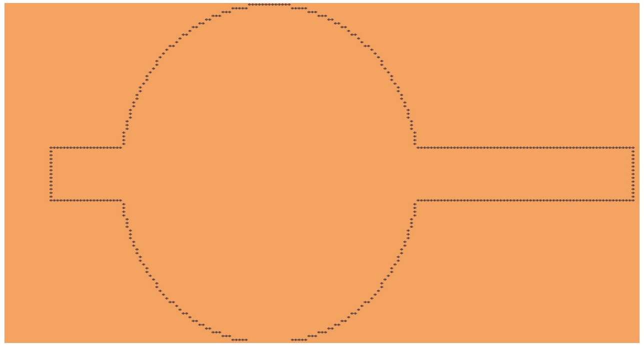
Operation with 600 bunches

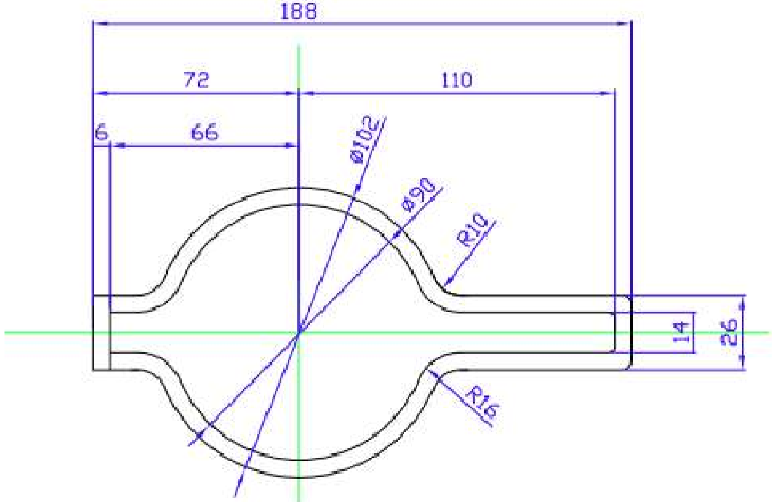
Finding

- ρ_{th} given by simulation can explain measurement.
- In the formula, $\rho_{e,th} = \dfrac{2\gamma\nu_s\omega_e\sigma_z/c}{\sqrt{3}KQr_e\beta_y L}$
  - $Q=\min(\omega_e\sigma_z/c, Q_{nl})$, Q_{nl} is around ~6.
- Q is lower for higher bunch current, I>0.5mA.
- The formula works well as a first step evaluation.

Electron buildup simulation in ante-chamber

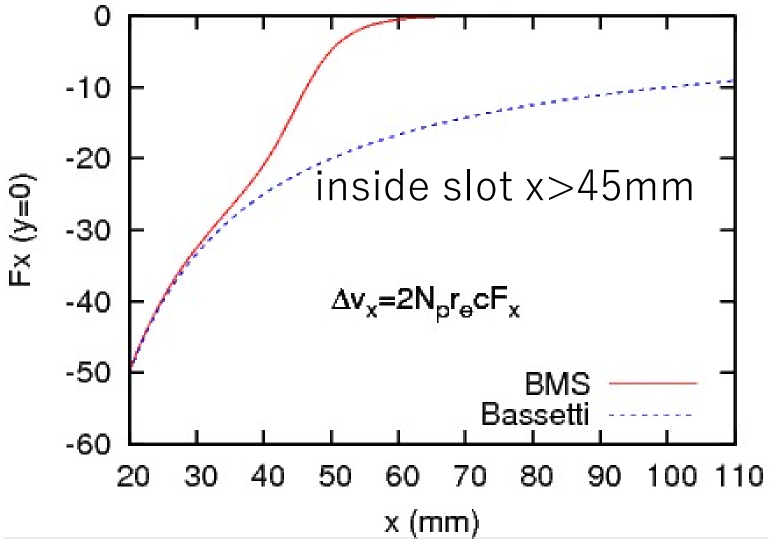
- Band matrix solver for electric field induced by electron cloud.

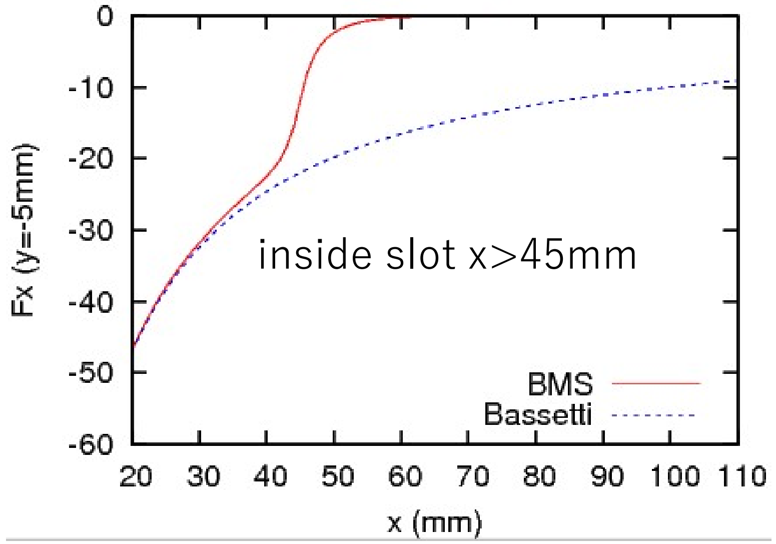


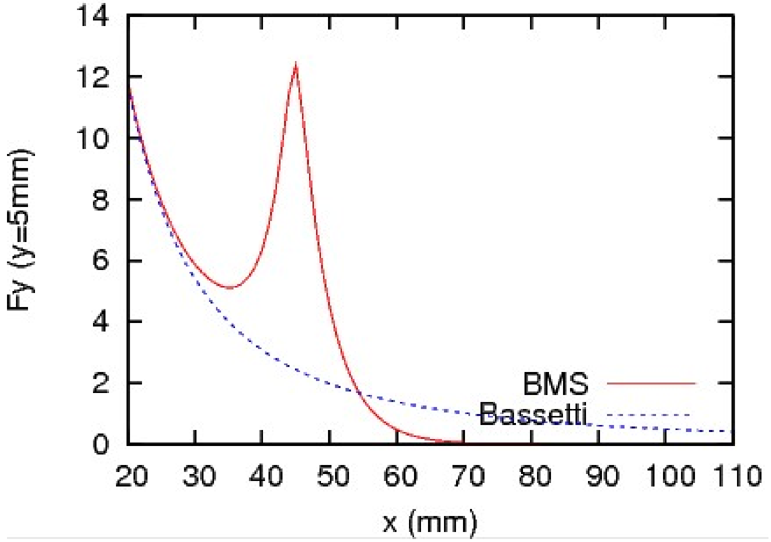


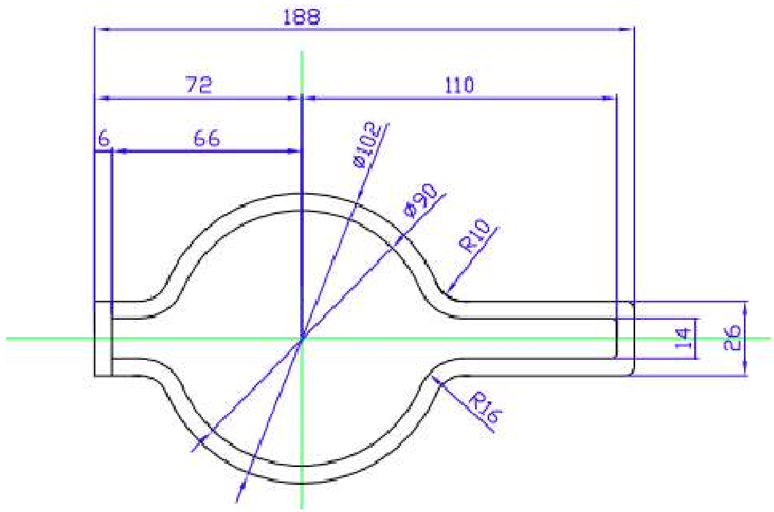
- Beam force, combination of Basetti-Erskine formula ($r<10\sigma_x$) and potential solver ($r>10\sigma_x$).
- Synchrotron light is assumed to illuminate innermost of the ante-slot.
- Electron production, $\cos(\theta)$ distribution for normal direction.

Beam force near ante-slot



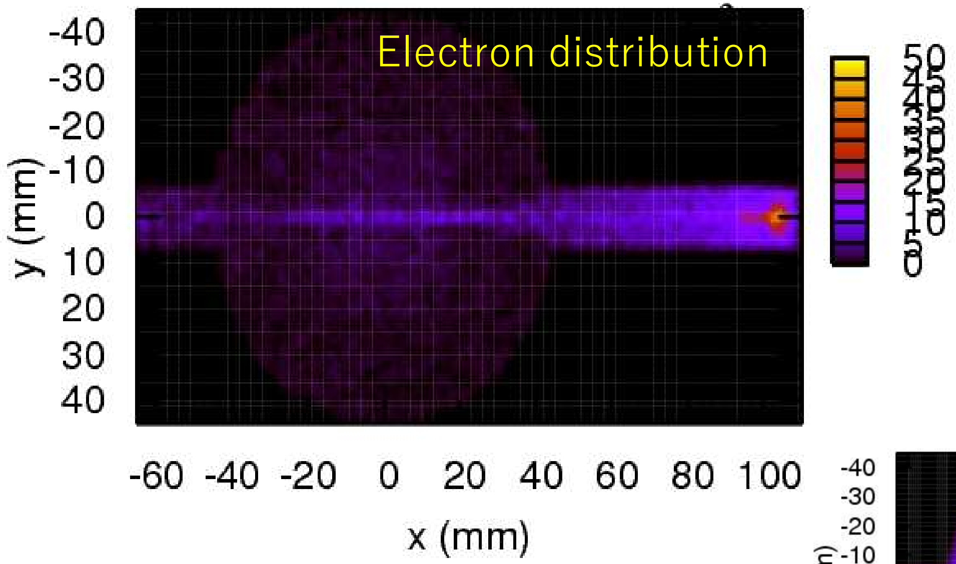


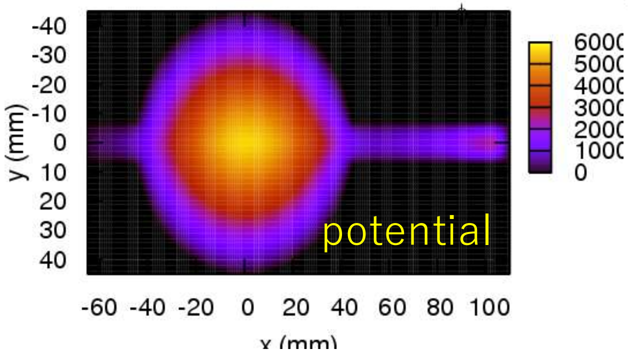


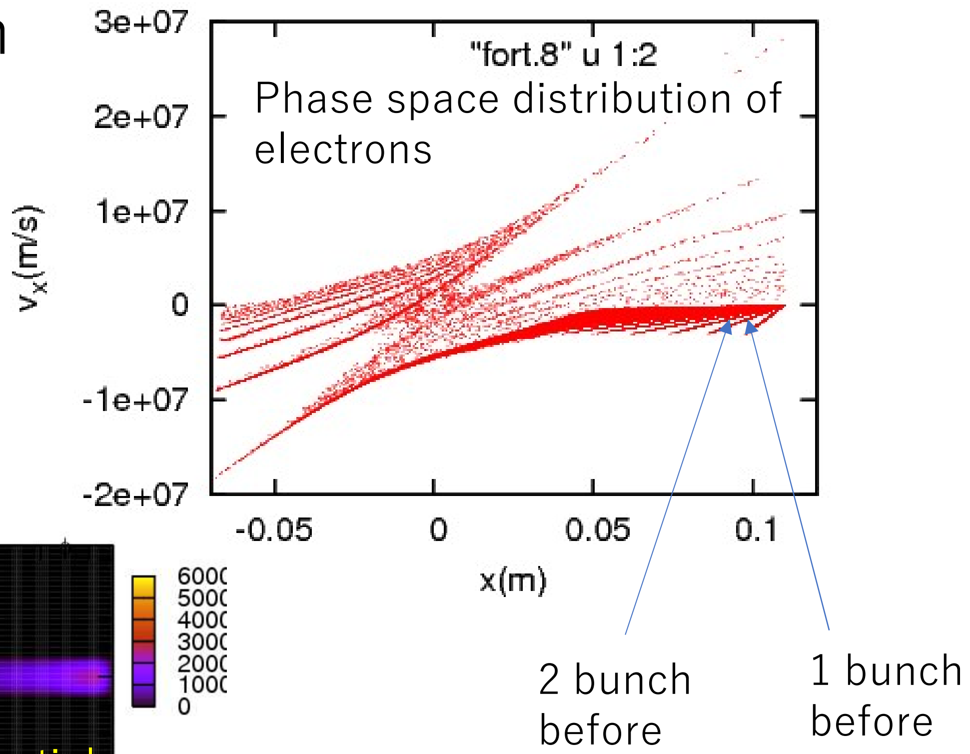


Electron distribution, potential and motion

- Weak space charge limit. Production rate $0.8 \times 10^{5} m^{-1}$/bunch, beam line density 2×10^{10} m^{-1}.
- No secondary no reflected electron



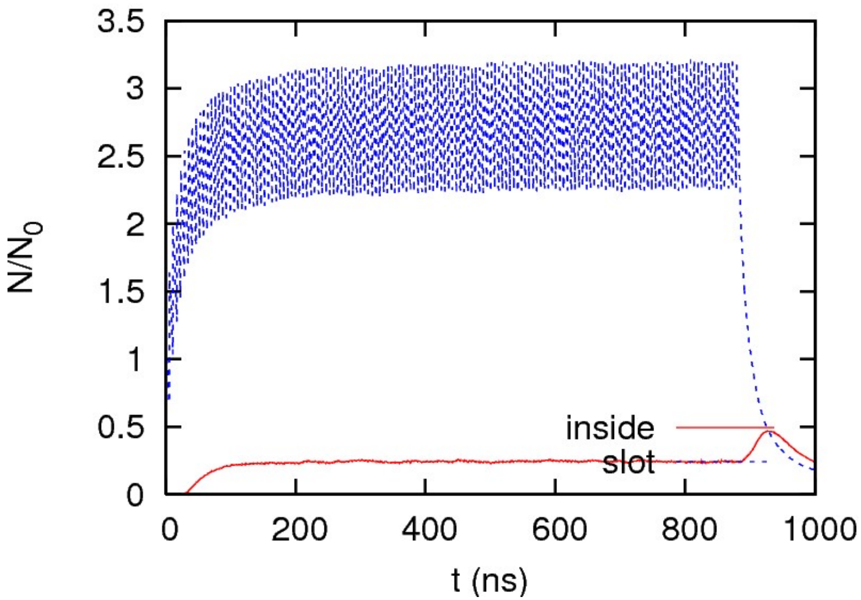


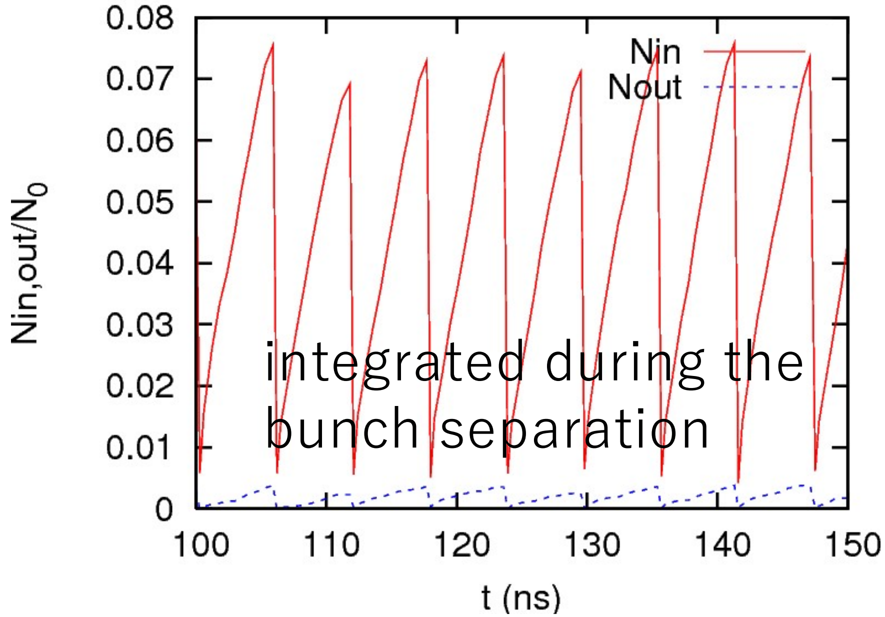


Ecloud Simulation in antechamber

- N_0: Number of electron created at illuminated point (slot end), N_{in}: #electron go inside the beam area, N_{out}: go out to the slot area.
- N_p=6.26x10^{10} (1mA/bunch), 6ns spacing, λ_p=3.48x10^{10} m^{-1}.
- Weak space charge limit, production rate 5x$10^5$$m^{-1}$/bunch
- No secondary, no reflected electrons.

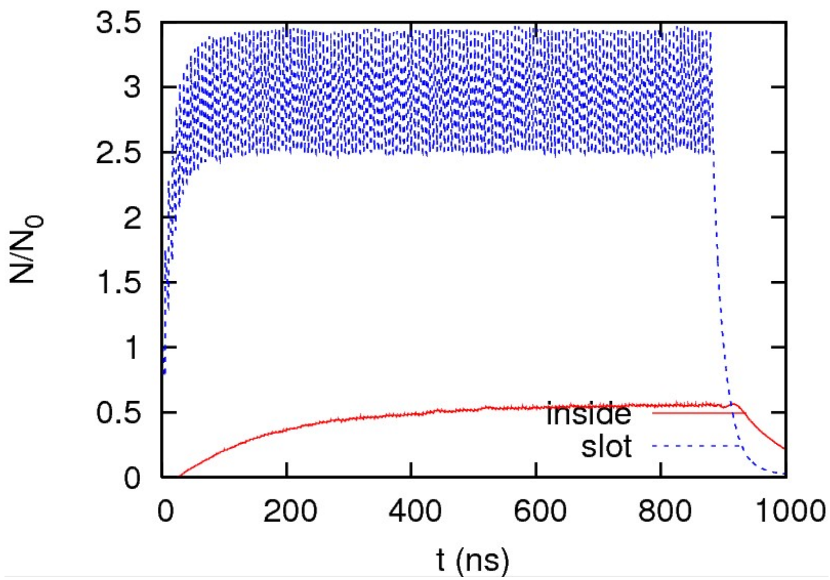
Far downsream, straight section

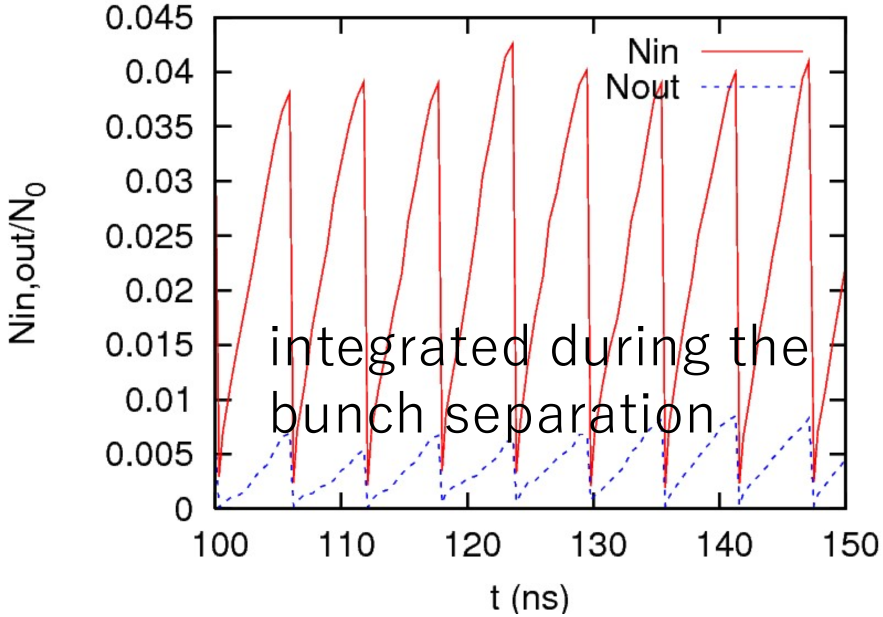




Ecloud Simulation in antechamber

- N_0: Number of electron created at illuminated point (slot end), N_{in}: #electron go inside the beam area, N_{out}: go out to the slot area.
- $N_p=6.26\times10^{10}$ (1mA/bunch), 6ns spacing, $\lambda_p=3.48\times10^{10}$ m^{-1}.
- Production rate, 0.016 e-/m/e+, 10x10^{8}m^{-1}/bunch.
- Secondary SEY=1.2, reflected electrons 0.7.

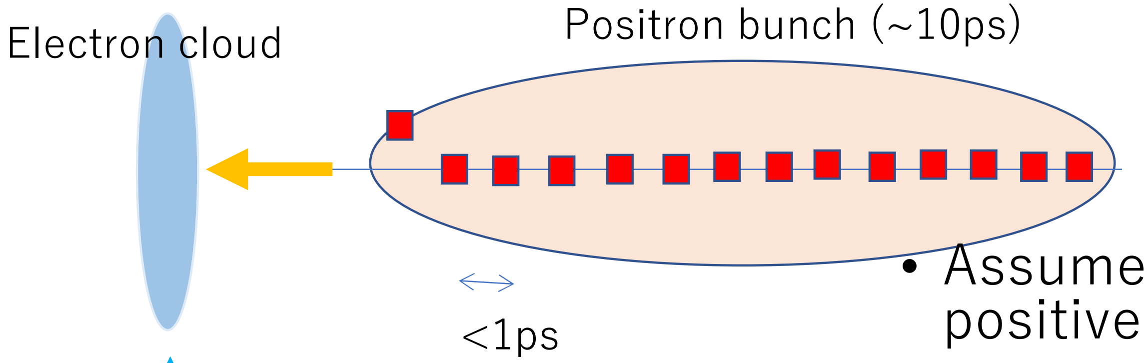




Finding in ecloud simulation in the antechamber

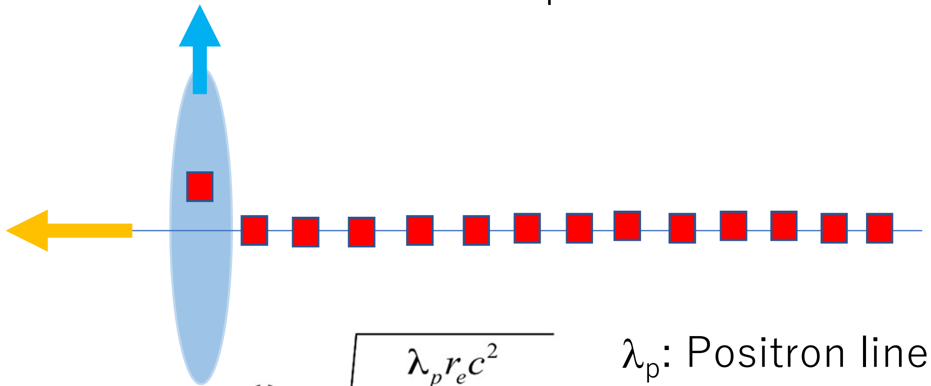
- Beam force arrives only 5mm inside of slot.
- Number of electrons coming from the slot is 7% of created electron at slot end for weak electron density. The number is reduced to 3-4% for average electron production.
- The number change a little for the bunch current 0.5 or 1mA.

Electron cloud Wake model (single bunch)



Uniform distribution for z.

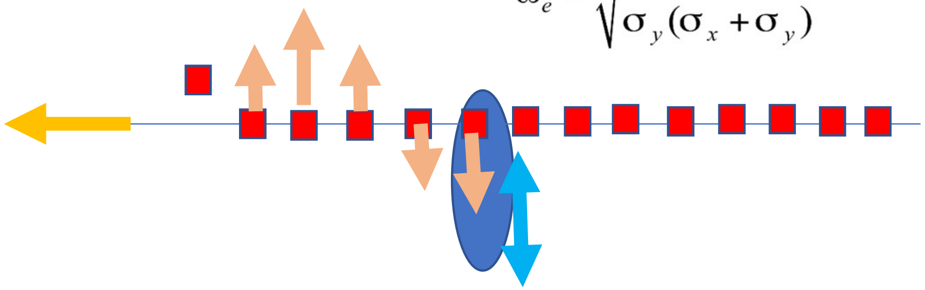
- Assume a part of bunch shifts positive direction.



- Electron cloud is kicked positive direction

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

λ_p: Positron line density in a bunch



- Electron cloud oscillates with ω_e.
  - Positron bunch is kicked by the deviation of the electron cloud.
  - Electron cloud is pinched, then the density increases.

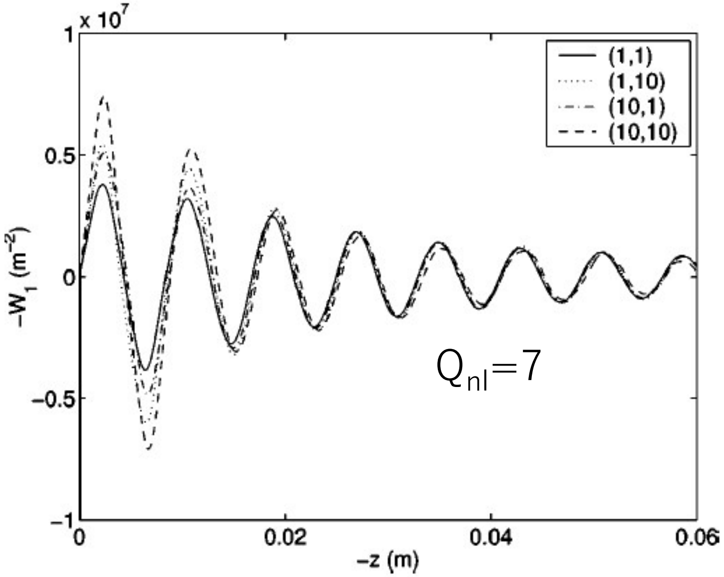
Example of wake force

K.Ohmi, F. Zimmermann, E. Perevedentsev, PRE65, 016502 (2001)

- For small x-y size of electron cloud,

$$W(z) = c\frac{R_S}{Q}\frac{\omega_R}{\overline{\omega}}\exp\left(\frac{\alpha}{c}z\right)\sin\left(\frac{\overline{\omega}}{c}z\right)$$

$$cR_S/Q = \frac{\gamma\omega_b^2\omega_c}{\lambda_b r_c c^3}L \qquad \omega_{b,y}^2 = \frac{2\lambda_c r_e c^2}{\gamma k_y(\sigma_x+\sigma_y)\sigma_y}, \qquad \omega_{c,y}^2 = \frac{2\lambda_b r_e c^2}{k_y(\sigma_x+\sigma_y)\sigma_y}$$



Instability threshold for coasting beam model

- Instability threshold in coasting model (A. Chao's textbook Chap 5)
  - Coherent growth due to the wake force
  - Decoherence due to the longitudinal slippage

Stability condition

$$\frac{cR_S}{\omega_e} = \frac{\gamma L \eta_p \omega_e \sigma_\delta}{\sqrt{3} N_b r_e \beta \omega_0} \longrightarrow \rho_{e,th} = \frac{2\gamma\nu_s\omega_e\sigma_z/c}{\sqrt{3}KQr_0\beta L}$$

- Wake is terminated by the bunch length, $Q=\mathrm{Min}(\omega_e\sigma_z/c, Q_{nl}=7)$.
- Number of electrons, which contributes to the instability, depends on $\omega_e\sigma_z/c$. The enhancement K is chosen $K=\omega_e\sigma_z/c$.

$$cR_S/Q = \frac{\gamma\omega_b^2\omega_e L}{\lambda_b r_e c^3} \qquad \omega_b^2 = \frac{\lambda_e r_e c^2}{\gamma\sigma_x\sigma_y} \qquad \omega_e^2 = \frac{\lambda_b r_e c^2}{\sigma_x\sigma_y}$$

$$\lambda_e = K \times 2\pi\sigma_x\sigma_y \qquad \lambda_b = \frac{N_b}{2\pi\sigma_z}$$

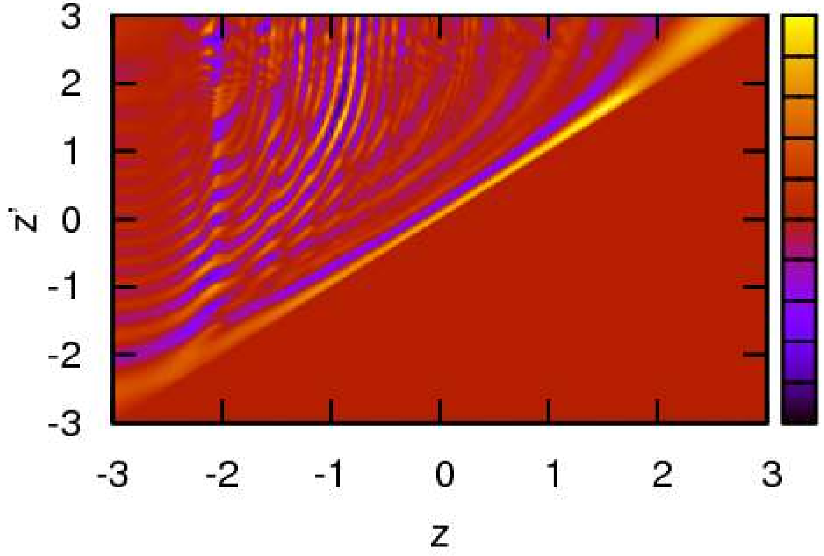
Realistic model: Gaussian distribution for z

- Conventional wake is a function of z-z', where z is a variable of motion and z' is the position with displacement in a bunch.
- Longitudinal distribution is Gaussian, $e^{-z^2/2\sigma_z^2}$.
  - Frequency of electron ω_e in bunch potential depends on z.
  - Electrons are pinched, thus the transverse profile of electrons depends on z.
- Wake force is a function of z and z', Wy(z,z').
- The wake force are calculated by a simulation, in which momentum kick at z is calculated for giving a deviation in a part of bunch (z').

Wake force induced by electron cloud

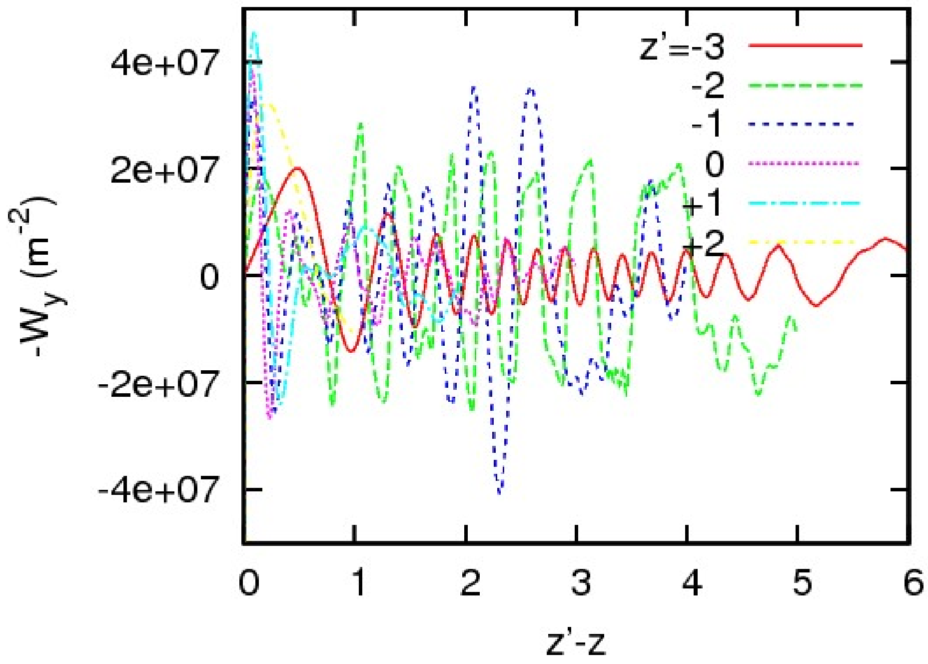
- Wy(z,z') depends on z and z'.

2D plot for $W_y(z,z')$



$W_{Q,y}(z)$: diagonal component of Wy(z,z)

$W_y(z\text{-}z';z')$ (σ_z unit)



$W_y(z,z') \neq 0$ for z'>z.

How to treat this wake force in Vlasov solver

- Momentum kick induced by electron cloud

$$\Delta p_y = -\frac{\lambda_e L r_e}{\gamma}\left[W_{Q,y}(z)\rho_y(z) + \int_z^\infty W_y(z,z')\rho_y(z')dz'\right]$$

$$\rho_y(z) = \rho(z)y(z) \qquad \rho(z) = \int \psi(z,\delta)d\delta$$

$$\rho_y(z) = \int y(z,\delta)\psi(z,\delta)d\delta$$

- Expression by longitudinal phase space variables

$$\Delta p_y(z,\delta) = -\frac{\lambda_e L r_e}{\gamma}\int_{-\infty}^{\infty}[W_{Q,y}(z,z)\delta(z-z') + W_y(z,z')]\psi(z',\delta')y(z',\delta')dz'd\delta'$$

$$\Delta p_y(J,\phi) = -\frac{\lambda_e L r_e}{\gamma}\int_{-\infty}^{\infty}[W_{Q,y}(z)\delta(z-z') + W_y(z,z')]\psi(J')y(J',\phi')dJ'd\phi'$$

- Azimuthal mode expansion

$$\frac{y(J,\phi)}{\sqrt{\beta_y}} = \sum_{l=-\infty}^{\infty} y_l(J)e^{il\phi} \qquad \sqrt{\beta_y}p_y(J,\phi) + \frac{\alpha_y}{\sqrt{\beta_y}}y(J,\phi) = \sum_{l=-\infty}^{\infty} p_l(J)e^{il\phi}$$

Reduce to the Eigenvalue problem

- Momentum kick for azimuthal mode

$$\Delta p_l(J) = -\frac{N r_e \beta_y}{\gamma} \int dJ' \sum_{l'=-\infty}^{\infty} [V_{l,l'}(J,J')\psi(J')y_{l'}(J) + W_{l,l'}(J,J')\psi(J')y_{l'}(J')]$$

$$V_{l,l'}(J,J') = \frac{1}{2\pi} \iint_0^{2\pi} d\phi d\phi' W_{y,Q}(z-z')e^{-i(l-l')\phi}$$

$$W_{l,l'}(J,J') = \frac{1}{2\pi} \iint_0^{2\pi} d\phi d\phi' W_y(z-z')e^{-il\phi+il'\phi'}$$

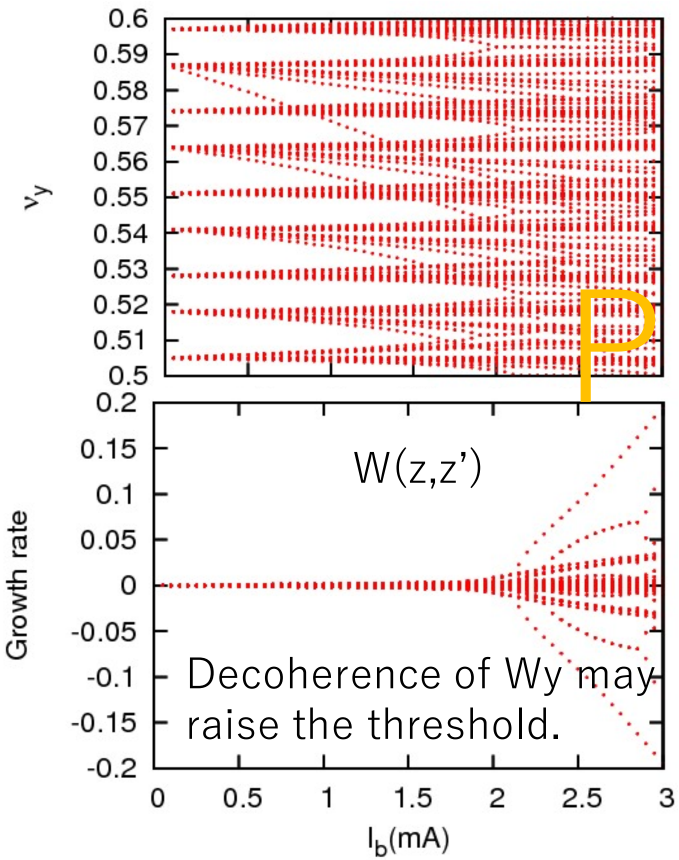
- Discretizing for J, the transformation is expressed by matrix.

$$\Delta p_l(J) = \sum_{j'=0}^{N_J} \sum_{l'=-l_{max}}^{l_{max}} M_{jl,j'l'} y_{l'}(J')$$

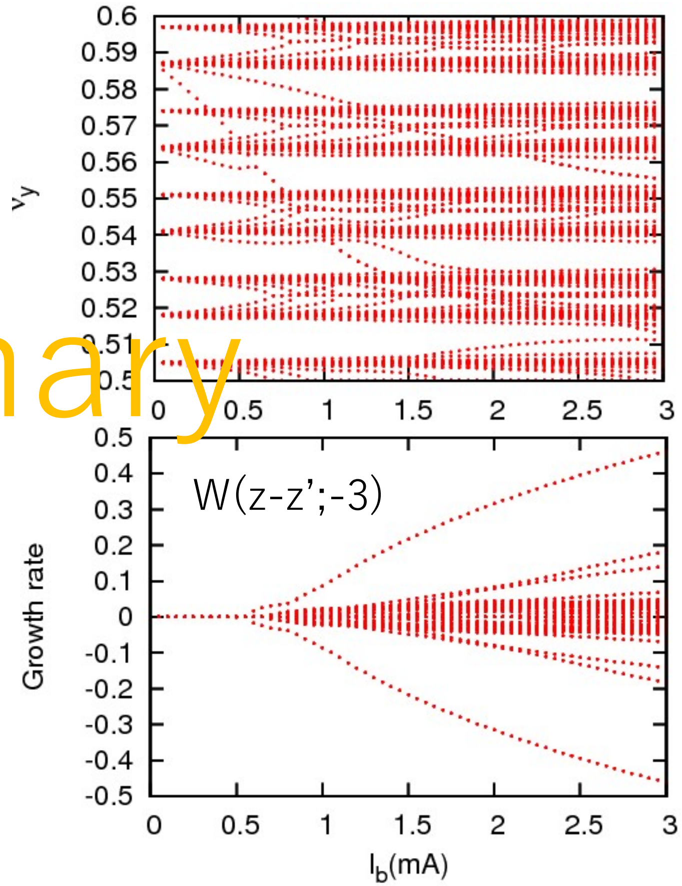
$$M_{jl,j'l'} = -\frac{N r_e \beta_y}{\gamma} \left[\sum_{j''} V_{l,l'}(J,J'')\psi(J'')\Delta J \delta_{jj'} + W_{l,l'}(J,J')\psi(J')\Delta J \right]$$

Eigen mode analysis for W(z,z')

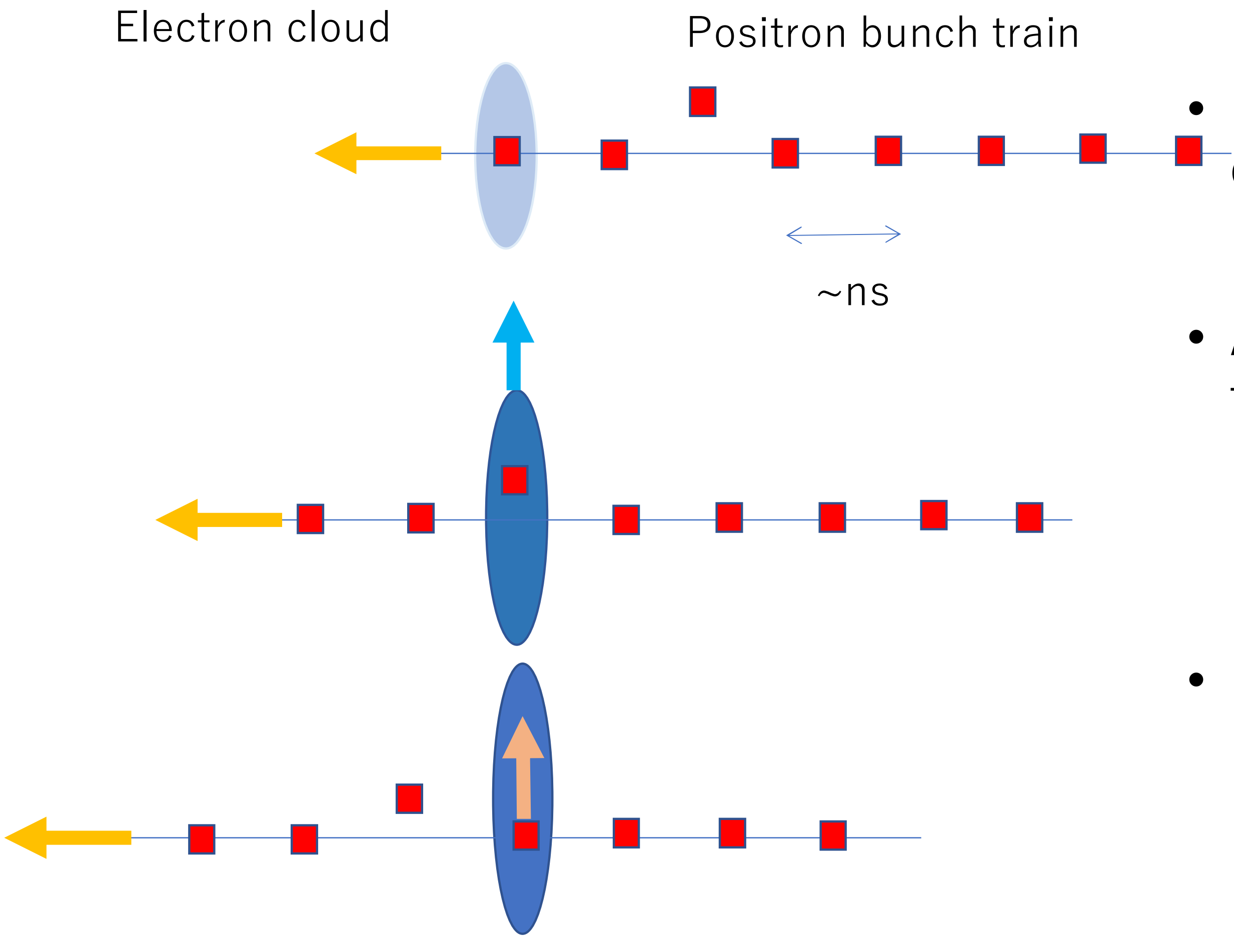
- One turn Matrix with the size $(2xn_J x(2l_{max}+1))^2$ is constructed by multiplication of syncho-beta and the wake transformations.



Preliminary



Electron cloud Wake model (multi-bunch)



- Positron bunch starts to create electron cloud.
- A bunch shift positive in stationary formed electron cloud.
  - Electron cloud start to move positive.
  - The bunch is kicked positive.
- Electrons in cloud

Coupled bunch instability

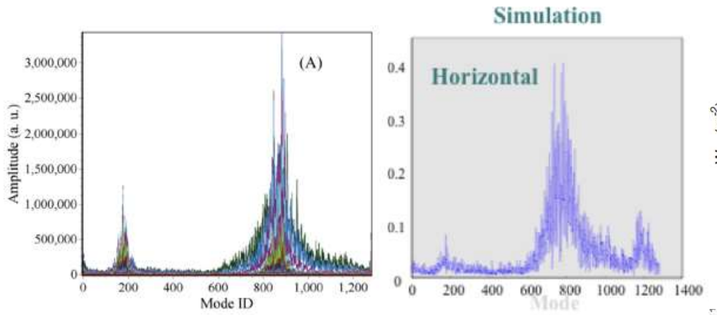
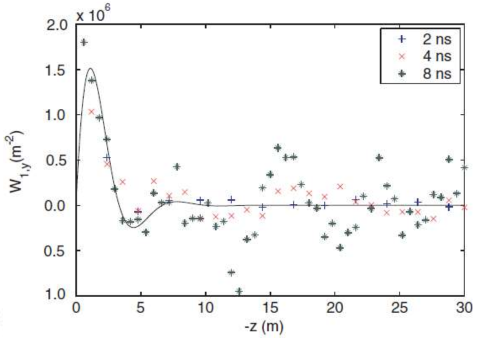
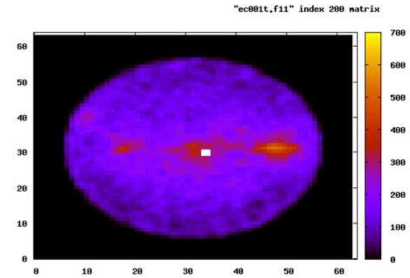
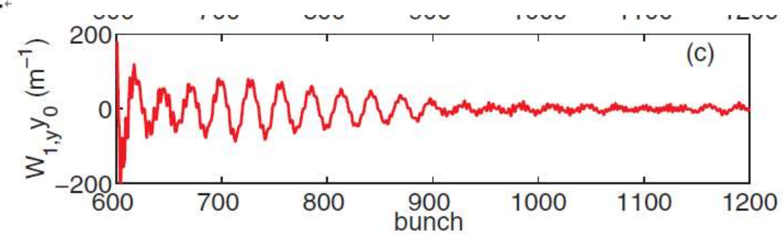


Figure 7: Horizontal mode spectrum in KEKB. Left picture is given by measurement with solenoid OFF [4,5]. Right picture is simulated by electron cloud in drift space.





High R/Q and Low Q=1



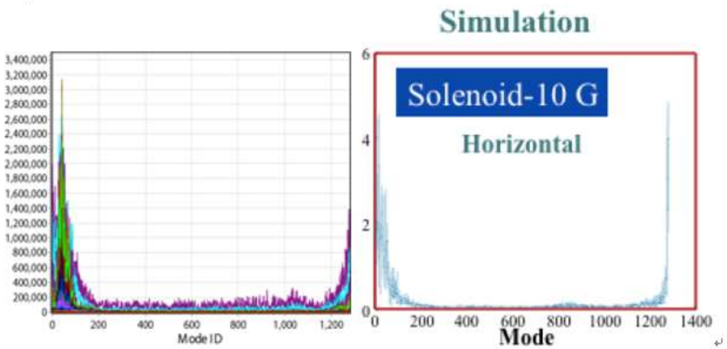
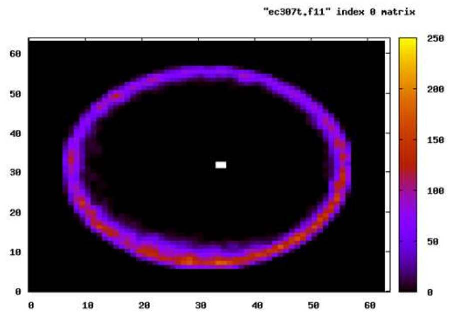


Figure 8: Horizontal mode spectrum in KEKB. Left picture is given by measurement with solenoid ON [4,5]. Right picture is simulated by electron cloud in solenoid field 10G.

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



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

Summary

- Electron cloud instability had been seen in early stage of SuperKEKB commissioning (Phase I, 2016).
- The instability was cured by installation of weak solenoids at aluminum bellow section.
- The density of instability threshold is almost consistent with simulation and theory.
- In recent measurement (June, 2022), any beam size blow up was not observed.
- Specific luminosity did not depend on the number of bunches in physics and machine experiments. No electron effects in luminosity.
- Electron leakage from antechamber slot was estimated as several, 3-7 %.
- TMCI analysis for W(z,z') is available.

Thank you for your attention

Simulated threshold electron density (before/after permanent magnet installation)

- N_b=600, ε_x=2nm, ε_y=15pm, σ_z =6mm,

$N_{p,th}$ (10^{10})	$\omega_e/2\pi$ (GHz)	$\omega_e\sigma_z/c$	ρ_{eth} (Q=10) ($10^{11}m^{-3}$)	ρ_{eth} (Q=6) ($10^{11}m^{-3}$)	ρ_{eth} (Simu) ($10^{11}m^{-3}$)	spacing	$I_{p,th}$ (mA)
1.6	61	7.7	1.91	2.45	3.2	2 (4ns)	160
2.1	71	8.9	1.65	2.45	3.4	3 (6ns)	200
2.7	80	10.1	1.47	2.45	3.6	4 (8ns)	260
5.2	111	14.0	1.47	2.45	4.0	6 (12ns)	500
2.1	71	8.9	1.65	2.45	3.4	2 (4ns)	200
3.65	91	11.5	1.47	2.45	3.8	3 (6ns)	350
6.25	122	15.3	1.47	2.45	4.2	4 (8ns)	>600

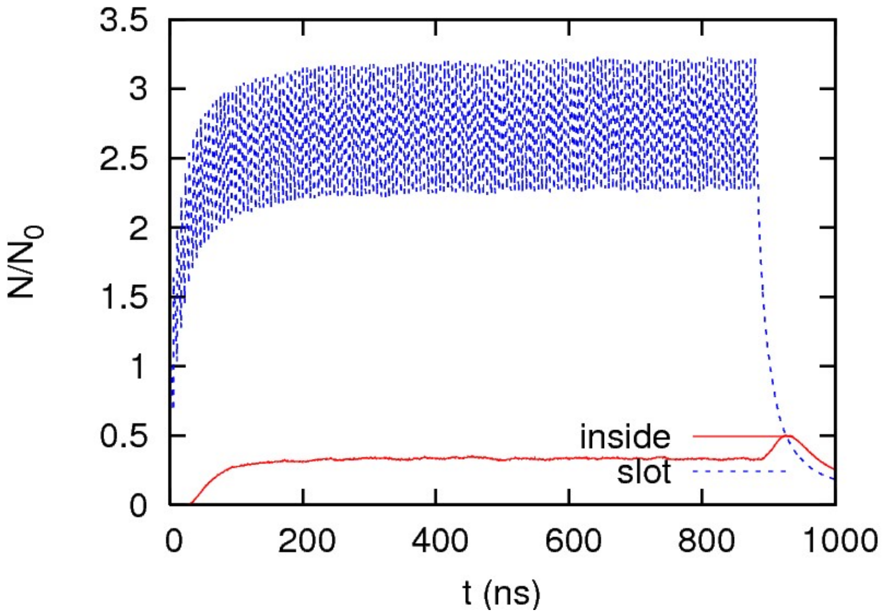
$$\rho_{e,th} = \frac{2\gamma\nu_s\omega_e\sigma_z/c}{\sqrt{3}KQr_0\beta L}$$

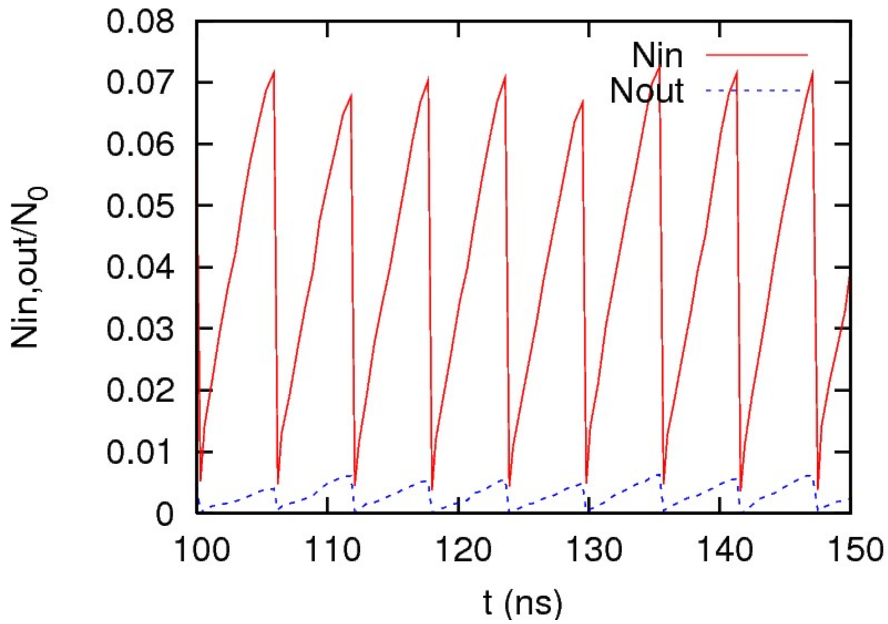
$$K = \omega_e\sigma_z/c$$

$$Q = \min(\omega_e\sigma_z/c, 6)$$

チェンバー内の電子数シミュレーション

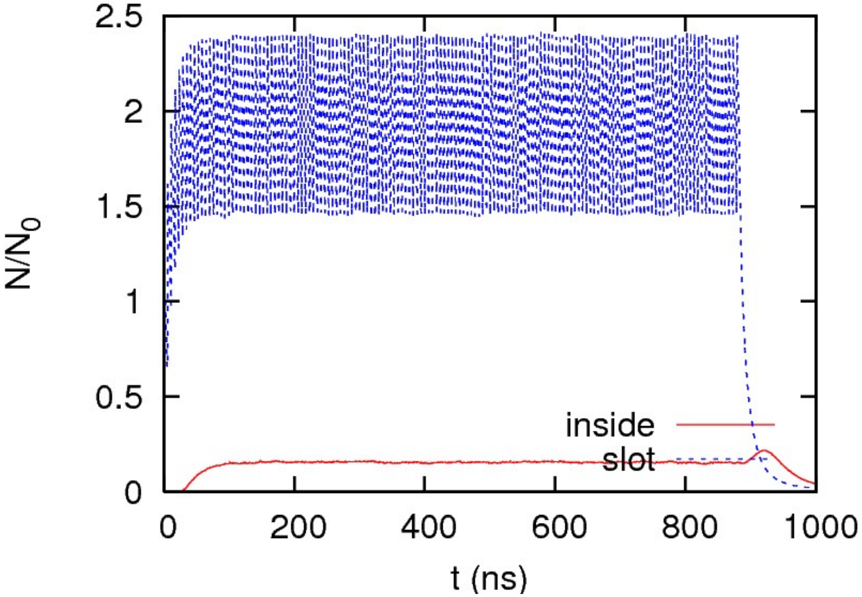
- 放射光が当たっている場所（アンテチェンバースロット最奥部）から電子が放出される。数を1単位とする。
- N_p=3.13x10^{10} (0.5mA/bunch), 6ns spacing, λ_p=1.74x10^{10} m^{-1}.
- Weak space charge limit, production rate 5x$10^5$$m^{-1}$/bunch
- No secondary, no reflected electrons.

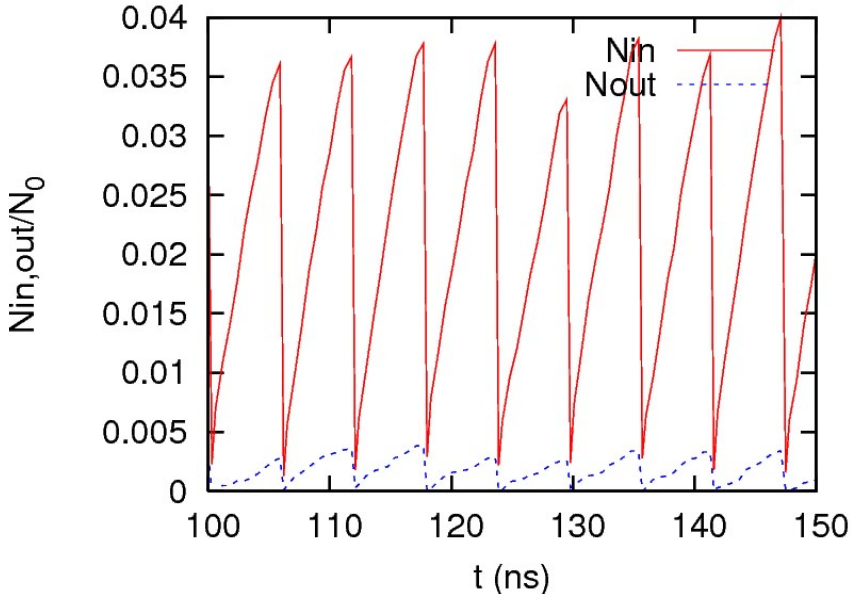




チェンバー内の電子数シミュレーション

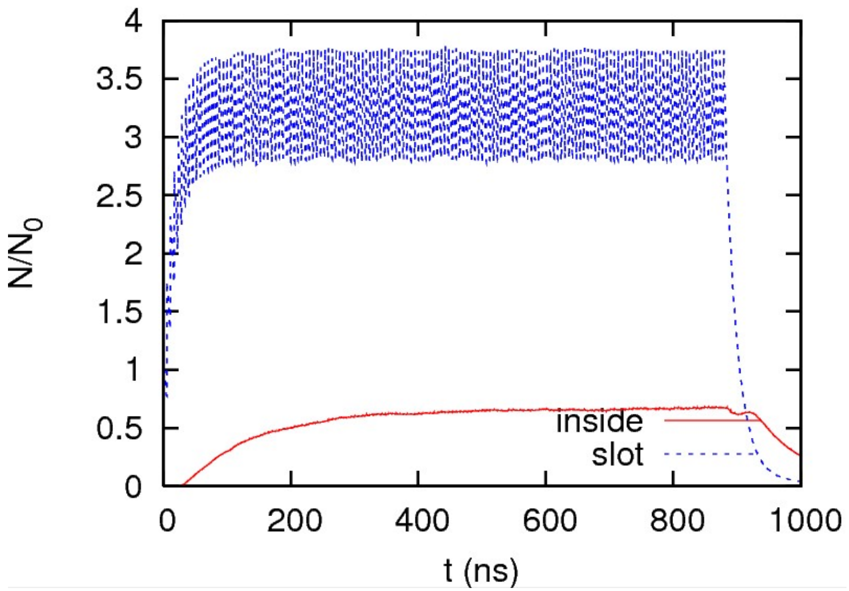
- 放射光が当たっている場所（アンテチェンバースロット最奥部）から電子が放出される。数を1単位とする。
- $N_p=3.13\times10^{10}$ (0.5mA/bunch), 6ns spacing, $\lambda_p=1.74\times10^{10}$ m^{-1}.
- Production rate, 0.016 e-/m/e+, $5\times10^{8} m^{-1}$/bunch.
- No secondary, no reflected electrons.

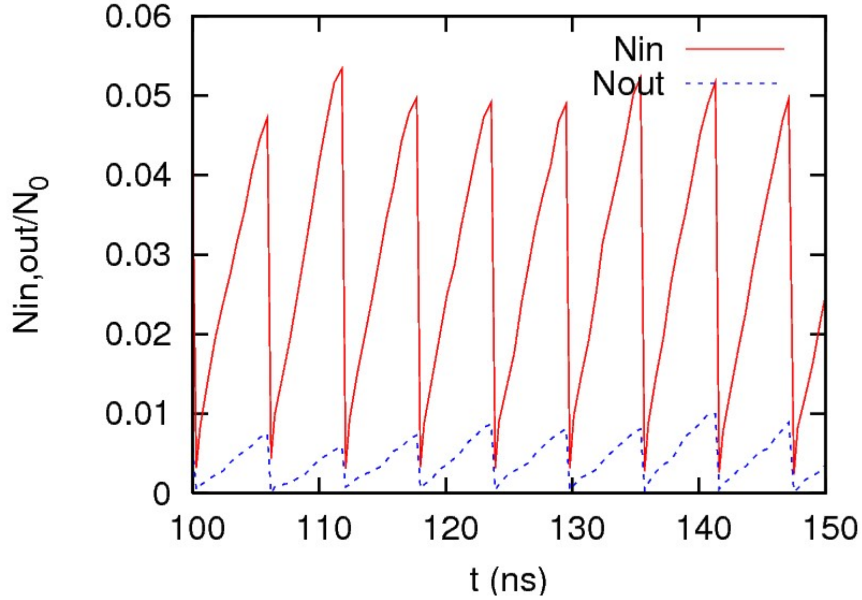




チェンバー内の電子数シミュレーション

- 放射光が当たっている場所（アンテチェンバースロット最奥部）から電子が放出される。数を1単位とする。
- N_p=3.13x10^{10} (0.5mA/bunch), 6ns spacing, λ_p=1.74x10^{10} m^{-1}.
- Production rate, 0.016 e-/m/e+, 5x$10^8$$m^{-1}$/bunch.
- Secondary SEY=1.2, reflected electrons 0.7.





チェンバー内の電子数シミュレーション

- 放射光が当たっている場所（アンテチェンバースロット最奥部）から電子が放出される。数を1単位とする。
- N_p=6.26x10^{10} (1mA/bunch), 6ns spacing, λ_p=3.48x10^{10} m^{-1}.
- Production rate, 0.016 e-/m/e+, 10x10^{8}m^{-1}/bunch.
- No secondary, no reflected electrons.