Electron cloud study for ILC damping ring at KEKB and CESR

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ILC damping ring workshop

KEK, Dec. 18-20, 2007

Contents

- Electron cloud study for ILC-damping ring at KEKB and CESR.
- Threshold of single bunch instability
- Experiences of KEKB and PEP-II
- Tune shift and cloud density.
- Incoherent emittance growth.

Activities in KEKB for the ILC damping ring study

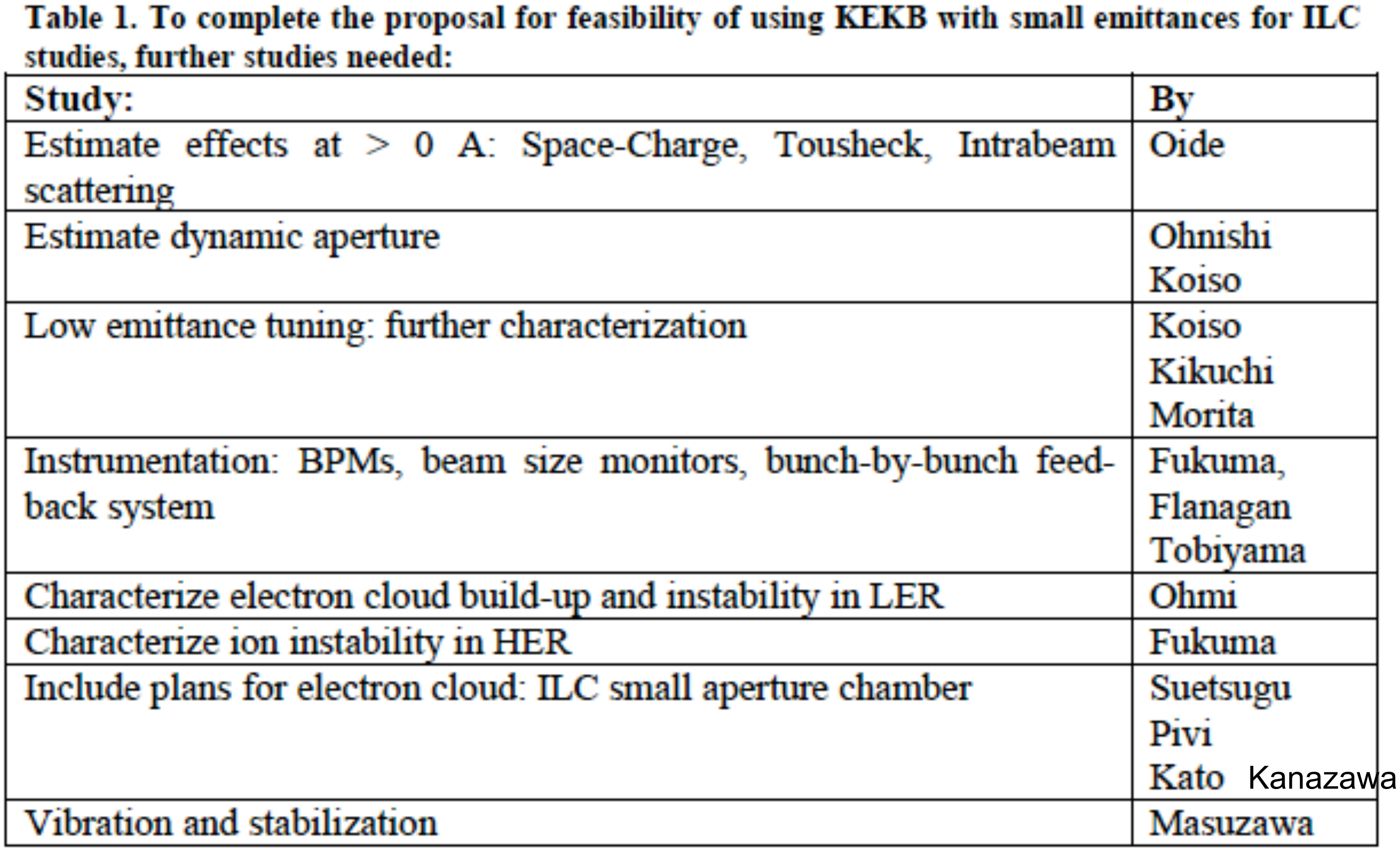


Table 1. To complete the proposal for feasibility of using KEKB with small emittances for ILC studies, further studies needed:

Study:	**By**
Estimate effects at > 0 A: Space-Charge, Tousheck, Intrabeam scattering	Oide
Estimate dynamic aperture	Ohnishi Koiso
Low emittance tuning: further characterization	Koiso Kikuchi Morita
Instrumentation: BPMs, beam size monitors, bunch-by-bunch feed-back system	Fukuma, Flanagan Tobiyama
Characterize electron cloud build-up and instability in LER	Ohmi
Characterize ion instability in HER	Fukuma
Include plans for electron cloud: ILC small aperture chamber	Suetsugu Pivi Kato Kanazawa
Vibration and stabilization	Masuzawa

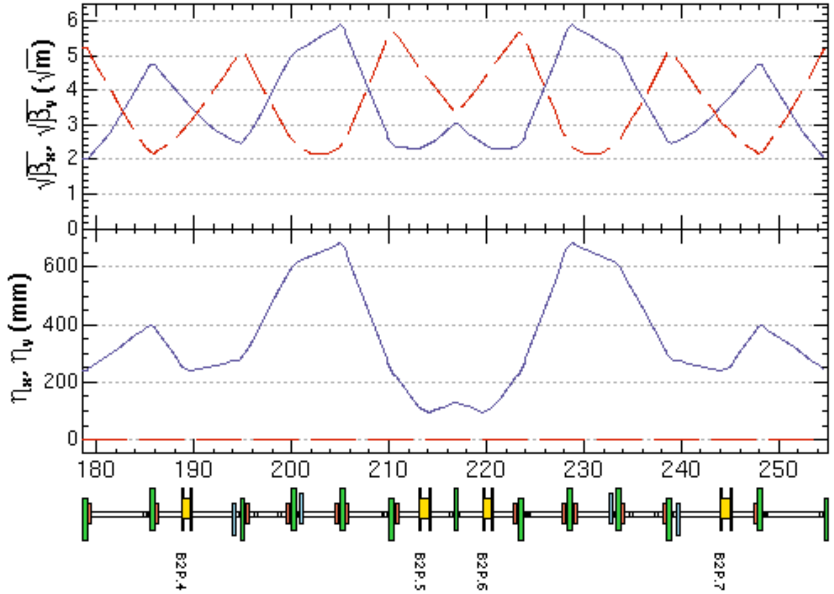
Optics parameters

	Physics run	**Low emittance**	CesrTF	OCS	PEP-II
Circumf. (m)	3016	3016	768	6	2200
E (GeV)	3.5	2.3	2.0	5.0	3.1
ε_x (nm)	18	1.5	2.3	0.5	48
α (10^{-4})	3.4	2.4	64	4.2	13
σ_z (mm)	6	4.2 (6.1)	6.8	6	12
Rf voltage	8.0	2.0 (1.0)	15	24	
σ_δ (%)	0.073	0.048	0.086	0.128	0.081
$\tau_{x,y}$ (ms)	40	150	56.4	26	40
Bucket height		1.86 (1.13)		1.5	

Emittance increases due to IBS. (ε_x(nm), ε_y(pm))
KEKB-DRT (1.5,1,5)->(5, 5) or (1.5, 6)->(4, 16)
CesrTF (1.8,4.5)->(6,16)

Optics (ring & cell)

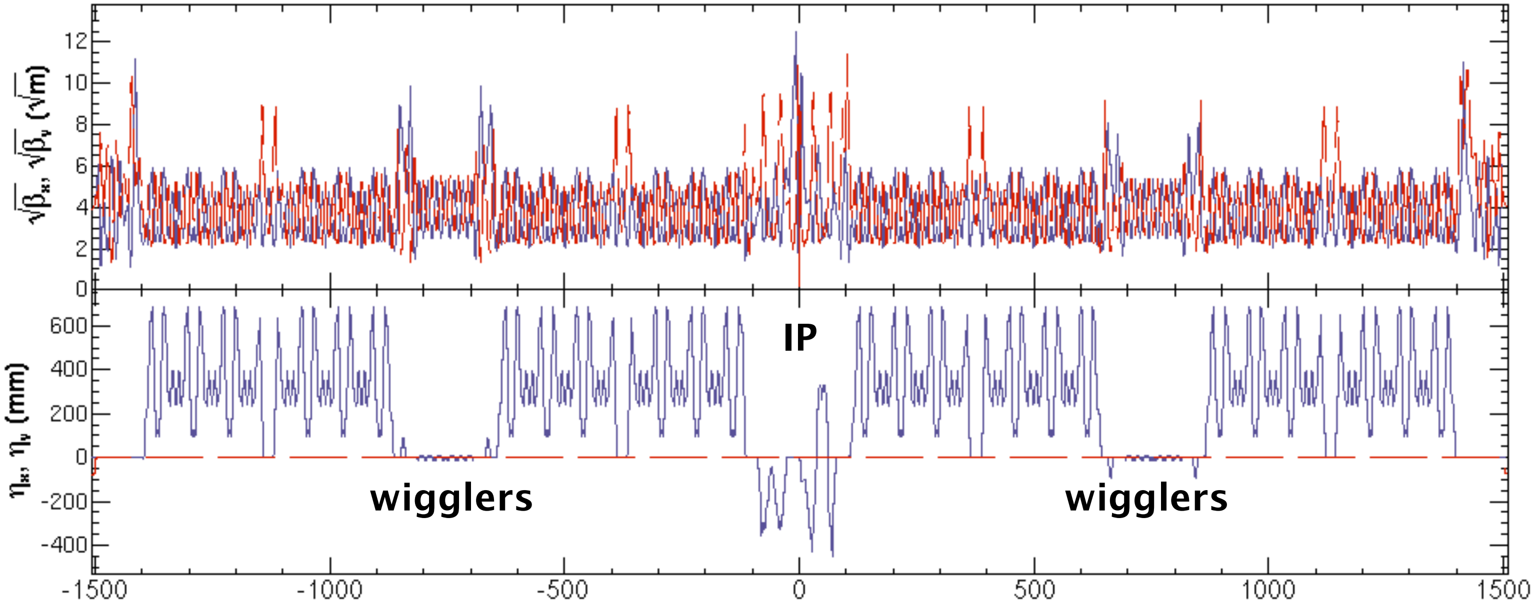
(H. Koiso)



◆**All magnetic fields are scaled from 3.5 to 2.3 GeV.**

◆**Wiggler field: 0.77 → 0.51 T**

◆**Detuned β*x/y: 90/3 cm**



Electron cloud instabilities

- Coupled bunch instability

  Ante-chamber, coating and sophisticated bunch by bunch feedback system is expected to suppress this instability. Measuring the mode spectrum helps to be understood the electron collective motion.

- Single bunch instability

  This instability depends on the local density near the beam and various beam parameters, energy, emittance …. The threshold is somewhat affected by radiation damping.

- Incoherent emittance growth

  The diffusion rate depends on the local density near the beam and various beam parameters, energy, emittance …. Which is dominant the diffusion and the radiation damping?

Focus what we should do

- The electron cloud build up does not depend on the emittance strongly.
- The cloud density depends on energy and current for photoemission dominant, and depend only on current for multipactoring or space charge dominant.

- The instability depends on the emittance, energy and damping time.
- We can not realize the damping ring condition anyway.
- For the coherent instability, it is important to understand how the threshold depends on the parameters.
- For an incoherent effect, beam size measurement without current dependence is necessary.

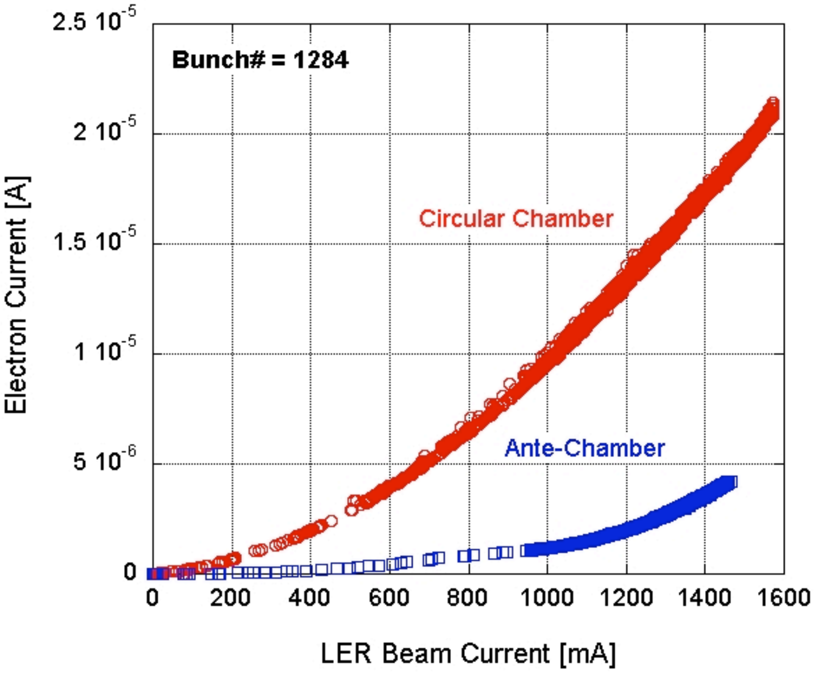
Electron cloud density

- We realize the low emittance with low energy operation.
- Measurement of electron current depending on the beam energy and current in drift space and magnets. Check the emittance dependence.
- Cloud density is estimated by the electron current times its travel time.
- The travel time is obtained by analyzing the electron motion. $T \sim 1/v \sim I_b^{1/2}$ for low density limit.
- Relation between chamber diameter, electron current and density.
- How do ante-chambers reduce electron cloud?

- These works have been done and is continued in KEK, SLAC and many Labs.

Example of electron current measurement

- $I_e = k\, I_b^{1.8}$, $\rho_e = k\, I_b^{1.3}$ in drift.
- Space charge dominant, $\rho_e = k\, I_b$.
- Ante-chamber reduces electron cloud 1/10 at I=1A with 8 ns spacing in a 10 cm diameter chamber.
- How is the density in magnets?
- How is the energy dependence?



Y.Suetsugu, K. Kanazawa

ILC-DR 5GeV 400 mA

Single bunch instability

- Electrons oscillate in a bunch with a frequency, ω_e.

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

- $\omega_e \sigma_z / c > 1$ for vertical.
- Vertical wake force with ω_e was induced by the electron cloud causes strong head-tail instability, with the result that emittance growth occurs.

- Linear theory
- Simulation based on the strong-strong model.

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

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

$$U=\frac{\sqrt{3}\lambda_p r_0\beta}{\nu_s\quad\gamma\quad\omega_e\sigma_z/c}\frac{\left|Z_\perp(\omega_e)\right|}{Z_0}=\frac{\sqrt{3}\lambda_p r_0\beta}{\nu_s\quad\gamma\quad\omega_e\sigma_z/c}\frac{KQ}{4\pi}\frac{\lambda_e}{\lambda_p}\frac{L}{\sigma_y(\sigma_x+\sigma_y)}=1$$

- 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

- $Q=\min(Q_{nl},\ \omega_e\sigma_z/c)$
  Q_{nl}=5-10?, depending on the nonlinear interaction.
- K characterizes cloud size effect and pinching.
- $\omega_e\sigma_z/c$~12-15 for damping rings.
- We use $K=\omega_e\sigma_z/c$ and $Q_{nl}=7$ for analytical estimation.

Threshold for various rings

	KEKB	KEKB	KEKB-DRt	CesrTF	ILC-OCS	PEPII
L	3016	3016	3016	768.44	6695	2200
gamma	6849	6849	4501	3914	9785	6067
Np	3.30E+10	7.60E+10	2.00E+10	2.00E+10	2.00E+10	8.00E+10
ex	1.80E-08	1.80E-08	1.50E-09	2.30E-09	5.60E-10	4.80E-08
bx	10	10	10	10	30	10
ey	2.16E-10	2.16E-10	6.00E-12	5.00E-12	2.00E-12	1.50E-09
by	10	10	10	10	30	10
sigx	4.24E-04	4.24E-04	1.22E-04	1.52E-04	1.30E-04	6.93E-04
sigy	4.65E-05	4.65E-05	7.75E-06	7.07E-06	7.75E-06	1.22E-04
sigz	0.006	0.007	0.009	0.009	0.006	0.012
nus	0.024	0.024	0.011	0.098	0.067	0.025
Q	3.6	5.9	7	7	7	3.7
omegae	1.79E+11	2.51E+11	5.29E+11	5.01E+11	6.31E+11	9.20E+10
phasee	3.6	5.9	15.9	15.0	12.6	3.7
K	3.6	5.9	15.9	15.0	12.6	3.7
rhoeth	6.25E+11	3.81E+11	9.60E+10	2.92E+12	1.91E+11	7.67E+11

From the present status of KEKB and PEP-II

- Without solenoid, the strong head-tail instability occurs at 1000 bunch and 500 mA.
- Simulations (PEHTS) and analytic formula give threshold density 0.7×10^{12} m^{-3} and 0.63×10^{12} m^{-3} at the beam parameters, 0.5 A.
- The electron density is 0.7×10^{12} m^{-3} at 1000 bunch and 500 mA.
- With solenoid, the strong head-tail instability occurs at 1300 bunch and 1700 mA. Simulations gives threshold density 0.4×10^{12} m^{-3} and 0.38×10^{12} m^{-3} at the beam parameters.
- In PEP-II (3 A and 4 ns spacing), the cloud density is less than 0.77×10^{12} m^{-3}. The density is less than 0.5A/3A=1/6 of KEKB, effect of ante-chamber and coating.

Scaling to ILC-DR current (400mA)

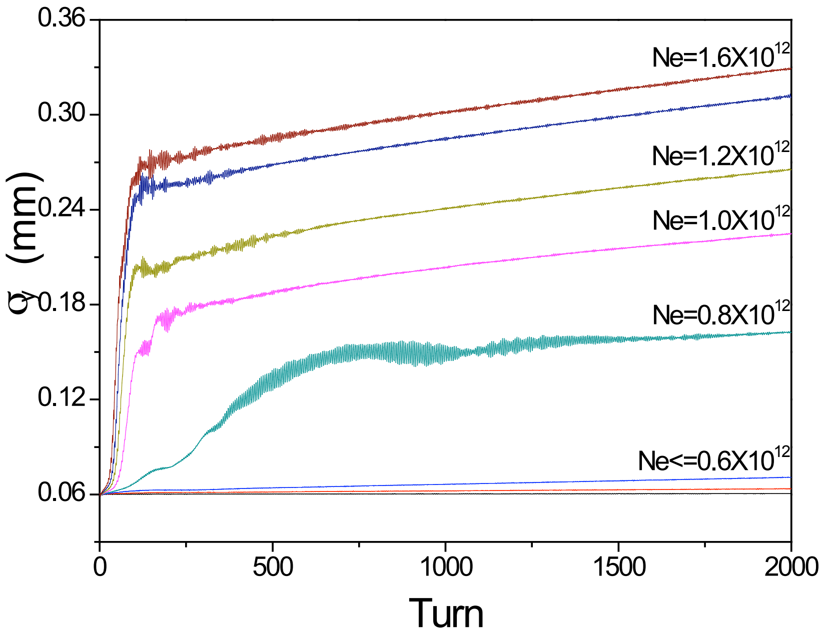
- KEKB 3.5 GeV 1700 mA, 0.4×10^{12} m^{-3} corresponds to 2.3 GeV, 400mA, 0.06×10^{12} m^{-3} .
- PEP-II 3000mA, $<7.7\times10^{12}$ m^{-3} corresponds to 400mA, 0.1×10^{12} m^{-3} .
- This density is lower than the threshold of the damping ring model with KEKB.

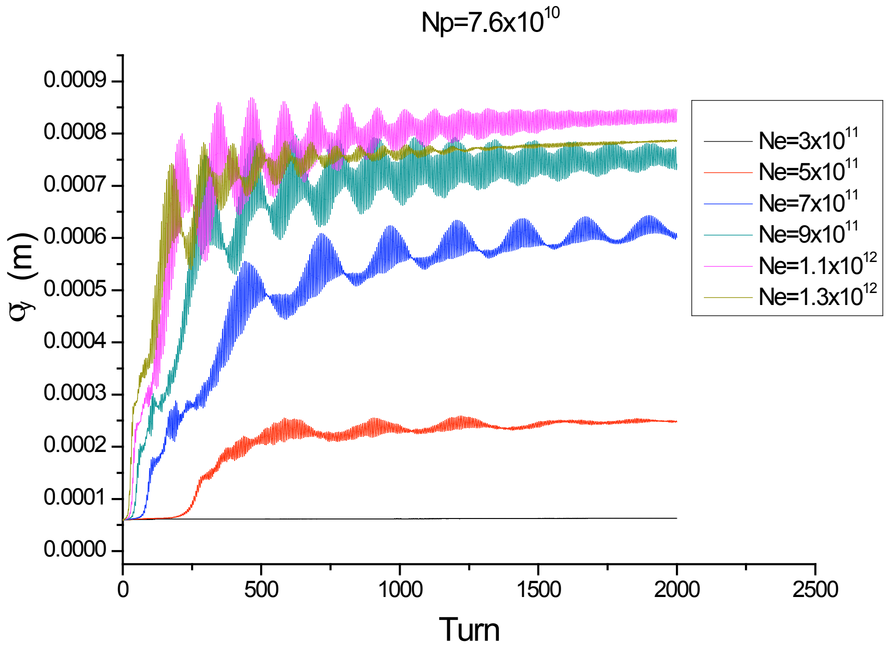
- The chamber diameter and magnet configuration are different from those of the KEKB.
- Extrapolation with simulations.

Scaling for Energy

- Actual damping ring is operated 5 GeV.
- Instability threshold increase as ~γ.
- Cloud density linearly depends on γ for photoelectron dominant, which is pessimistic case. It does not depend for multipactoring and space charge dominant, which is optimistic case.
- Shorter damping time ($\tau \sim \gamma^3$) helps to suppress the instability.

$N_+ = 3.3\text{x}10^{10},\ \ 7.6\text{x}10^{10}$





By H. Jin

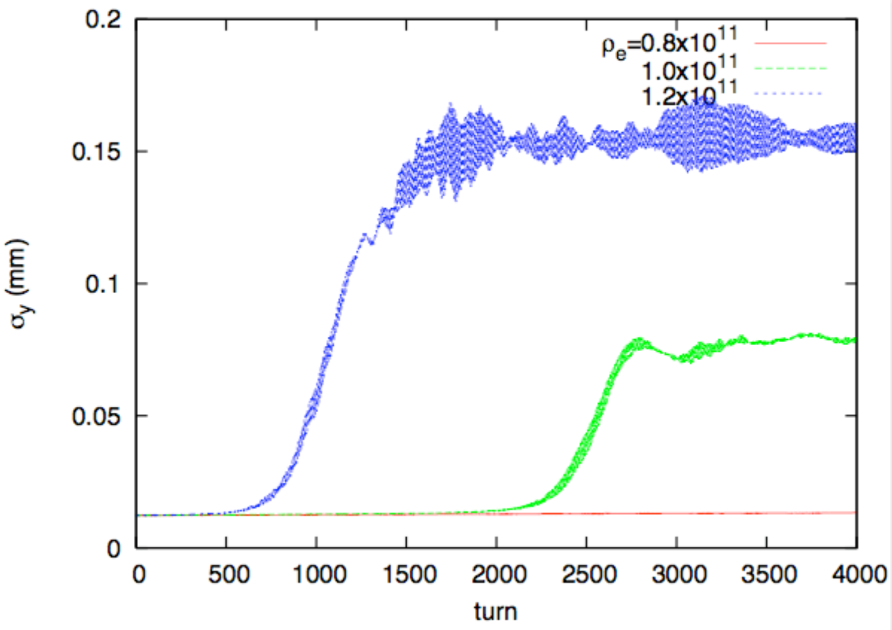
Low emittance operation in KEKB for ILC

	Nor ε	Nor ε	Low ε–I	Low ε–II
E (GeV)	3.5	3.5	2.3	5.0
N_+ (10^{10})	3.3	7.6	2.0	2.0
N_b	1000	1338	1250	2500
I (mA)	500	1700	400	800
ε_x (nm)	18	18	1.5	1.0
σ_z (mm)	6	7	9	9
ν_s	0.024	0.024	0.011	0.011
$\omega_e \sigma_z/c$	3.1	5.1	12.5	12.5
$\rho_{e,th}(m^{-3})$	$7x10^{11}$	$4x10^{11}$	$1x10^{11}$	$2.2x10^{11}$
$\rho_e(m^{-3})$	$7x10^{11}$	$4x10^{11}$	$0.6x10^{11}$	$2.7x10^{11}$

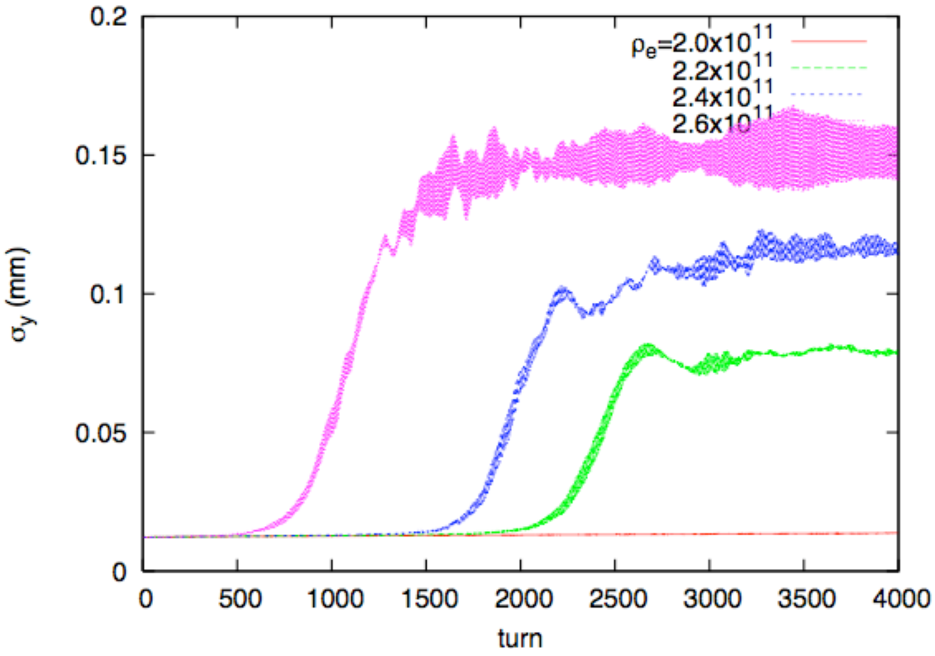
- $\rho_{e,th}$: threshold density,
- ρ_e: estimated or predicted electron density for cylindrical chamber

Threshold cloud density given by PEHTS at the Low emittance

2.3 GeV, 5 GeV



$\rho_{e,th}$=1.0x10^{11} cm^{-3}



$\rho_{e,th}$=2.2x10^{11} cm^{-3}

Tune shift

- 2nd order moment ($\langle x_e^2\rangle_c$, $\langle y_e^2\rangle_c$) of electron cloud distribution gives tune shift., where $\langle x^2\rangle_c = \langle x-\langle x\rangle\rangle^2$.

$$\mathbf{E} = \frac{\rho e}{\varepsilon_0}\left(\frac{ax}{1+a}\hat{\mathbf{x}} + \frac{y}{1+a}\hat{\mathbf{y}}\right)$$

$$(\Delta\nu_x, \Delta\nu_y) = \frac{r_e}{\gamma}\left(\oint \frac{\rho a}{1+a}\beta_x ds, \oint \frac{\rho}{1+a}\beta_y ds\right)$$

$$a \equiv \left\langle y_e^2 \right\rangle_c \Big/ \left\langle x_e^2 \right\rangle_c$$

$$\Delta\nu_x + \Delta\nu_y = \frac{r_e}{\gamma}\oint \rho_e \beta ds$$ if $\beta_x \sim \beta_y$

Tune shift at the threshold

	KEKB	KEKB	KEKB-DRt	CesrTF	ILC-OCS	PEPII
L	3016	3016	3016	768.44	6695	2200
gamma	6849	6849	4501	3914	9785	6067
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rhoeth	6.25E+11	3.81E+11	1.22E+11	4.76E+12	1.91E+11	7.67E+11
dnx+y@th	0.0078	0.0047	0.0023	0.0263	0.0111	0.0078
DampT-xy	40	40	75	56.4	26	40
DampR-xy	2.51E-04	2.51E-04	1.34E-04	4.54E-05	8.58E-04	1.83E-04

Tune shift at KEKB

(T. Ieiri, Proceedings of Ecloud07)

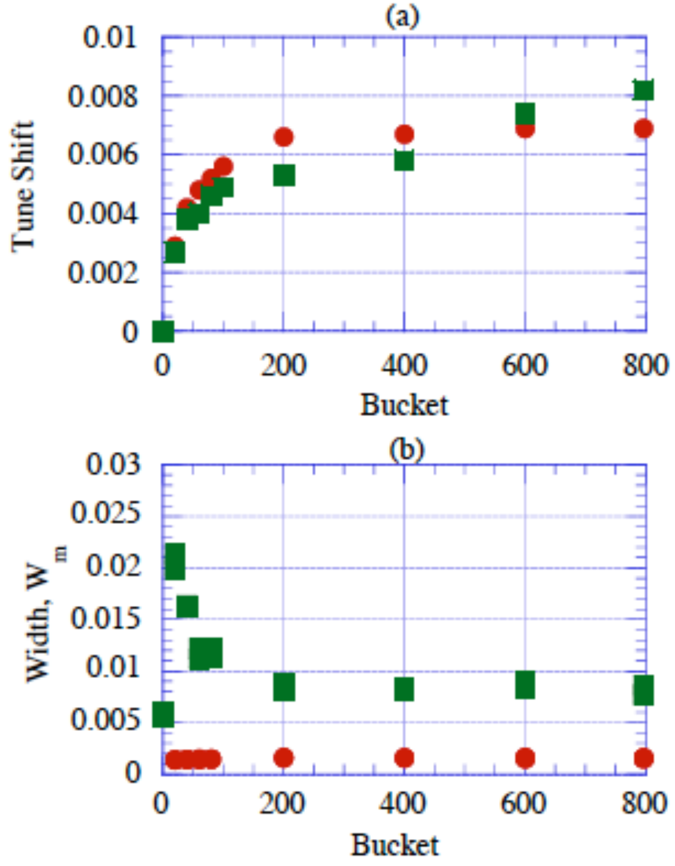


Figure 4: Tune shift (a) and spectrum width (b) along a train. The red dots (horizontal) and green squares (vertical) are measured at a bunch current of 0.5 mA. The tune of the head bunch of the train is used as the reference.

Without solenoid

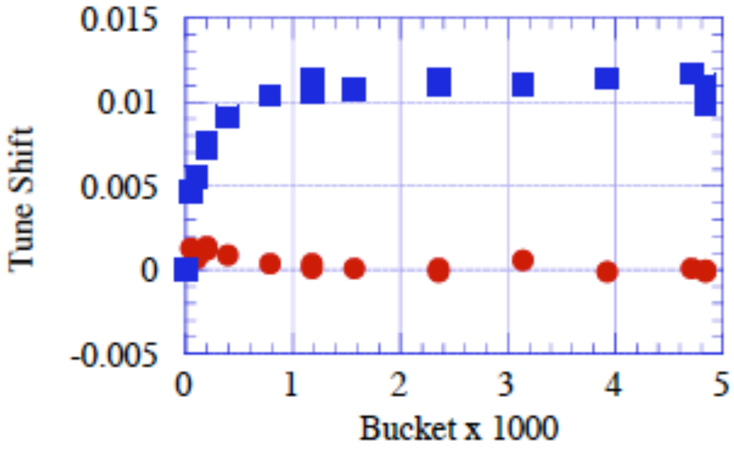


Figure 11: Horizontal (red dots) and vertical (blue squares) tune-shifts along the bunch-train. The bunch current is 1.0 mA with an average spacing of 7 ns.

With solenoid

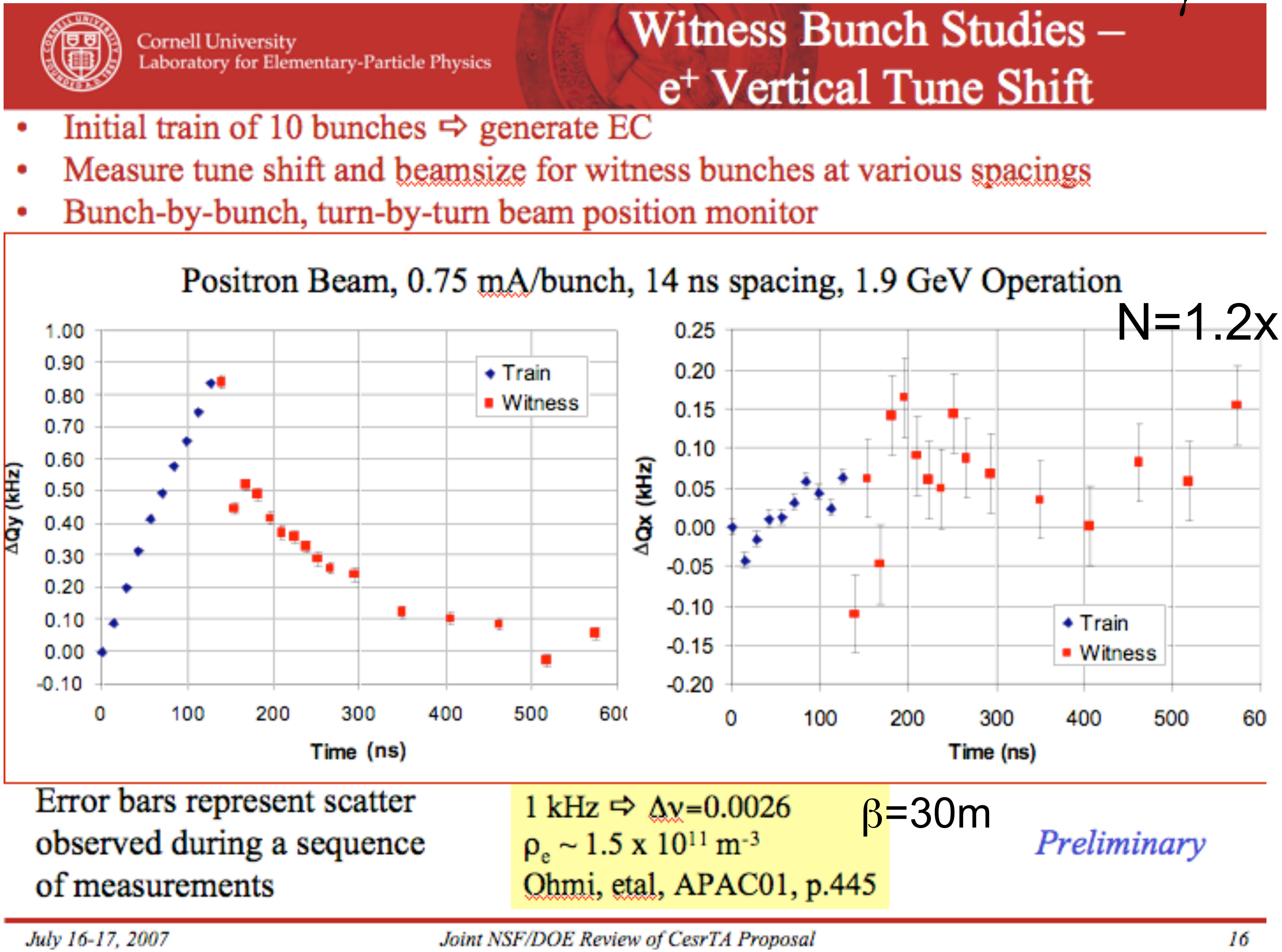
- Both showed similar density because of $\nu_x+\nu_y=0.015$ and 0.012

Notice for the tune measurement at KEKB

- The observed tune shift is larger than that at the instability threshold.
- A coherent tune shift is merged in the observation.
- The beta function is somewhat ambiguous
- The radiation damping suppress the instability. Damping wiggler contributed suppression of the instability in an early experiment. The instability is saw-tooth type with the period depending on the damping time, maybe.

Tune shift at CESR

$$\Delta\nu_x + \Delta\nu_y = \frac{r_e}{\gamma}\oint \rho_e \beta ds$$



Cornell University
Laboratory for Elementary-Particle Physics

Witness Bunch Studies – e^+ Vertical Tune Shift

- Initial train of 10 bunches ⇨ generate EC
- Measure tune shift and beamsize for witness bunches at various spacings
- Bunch-by-bunch, turn-by-turn beam position monitor

Positron Beam, 0.75 mA/bunch, 14 ns spacing, 1.9 GeV Operation

N=1.2x10^{10}

Error bars represent scatter observed during a sequence of measurements

1 kHz ⇨ Δν=0.0026
ρ_e ~ 1.5 x 10^{11} m^{-3}
Ohmi, etal, APAC01, p.445

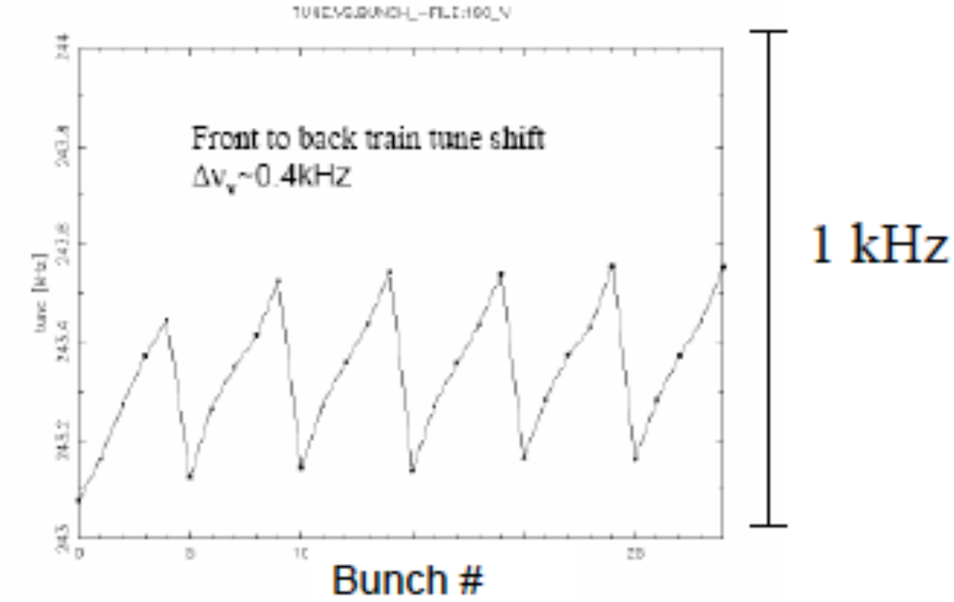
β=30m

Preliminary

July 16-17, 2007 *Joint NSF/DOE Review of CesrTA Proposal* *16*

Tune shift for 5.3 GeV in CESR

- 5.3 GeV 5 bunch (D. Rice, Sep 06)
- Tune shift is similar as that for 1.9 GeV.
- Cloud density is linear for γ.
- Sign of photoelectron dominant?


vertical tune vs. bunch, I = 1 mA

Comment for CESR measurement

- The coherent instability is observed at 10 times higher cloud density. More bunches with short spacing may realize the unstable condition.
- The cloud density is ρ_e=1.5-4.5x10^{11} m^{-3} for N=1.2x10^{10}, 14 ns spacing at CESR.
- KEKB without solenoid gave ρ_e=7x10^{11} m^{-3} for N=3.3x10^{10} , 8 ns spacing. Since the photon density is 1/Circumf., the electro density is reasonable for no solenoid nor ante-chamber.
- The operation with N=2x10^{10}, 6 ns spacing, which induces ρ_e~1x10^{12} m^{-3}, is stable due to the high $\nu_s(\alpha)$.

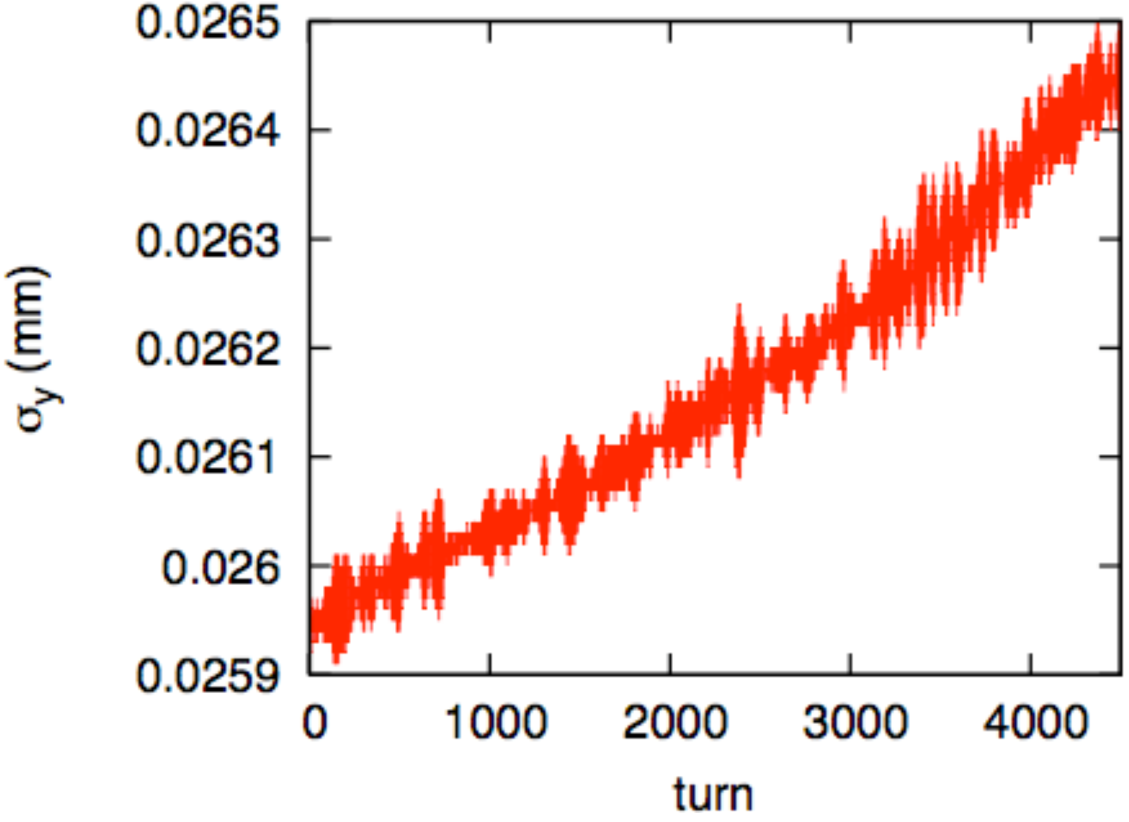
Incoherent emittance growth

- Mechanism: Nonlinear diffusion related to resonances and chaos
- The diffusion rate and the radiation damping time

- For an incoherent effect, beam size measurement without current dependence is necessary.
- It seems to be difficult in present KEKB tool.

Incoherent emittance growth below the threshold of the fast head-tail

- OCS arc lattice is used for KEKB.
- $\rho_e = 3\times10^{10}\ \mathrm{m}^{-3}$ ($\rho_{e,th} = 1\times10^{11}\ \mathrm{m}^{-3}$)



Growth rate is slower than radiation damping rate

- $\Delta\sigma_y/\sigma_y=5.7\times10^{-6} << 1/\tau_y=2.5\times10^{-4}$
- Incoherent effect was negligible for KEKB in this condition.

- For high $\nu_s(\alpha)$ ring, coherent instability is strongly suppressed. Incoherent effect may be enhanced relatively.
- ->CESR ($\nu_s=0.098$, $\alpha=6.4\times10^{-3}$)

Summary

- How the measured electron density is understood.
- Effect of solenoid (KEKB) and ante-chamber (PEP-II).
- Threshold for the low emittance operation with KEKB should be safe. It is important to check the fact.
- Measurement of the threshold for various emittance and energy characterizes the instability.
- Extrapolation of the cloud density for realistic chamber diameter and magnet configuration.
- Characteristic of CESR: the high momentum compaction suppresses instability due to a high cloud density, which is much higher than that of ILC-DR.