Electron cloud effects in Cesr-TF and KEKB

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Contents

• History, electron cloud effect in KEK-PF
• Electron cloud build-up at KEKB
• Coupled bunch instability caused by electron cloud
• Single bunch instability caused by electron cloud
• Electron cloud effects in Cesr-TF
History

• Coupled-bunch instability had been observed at KEK-PF.
• Interpretation of the instability using photo-electron cloud model.
• Strange coupled bunch instability had been observed at CESR.
• The instability was observed at BEPC (China).
• Study of electron cloud effect for design of KEKB.
• Studies for PSR, LHC, SPS, SNS, JPARC, ILC ...many machines.
Multi-bunch instability observed at KEK-PF

- KEK-PF is a 2nd generation light source operated by both of positron and electron beams. $E=2.5 \text{ GeV} \ L=186 \text{ m}$, $Fr_f=500\text{MHz}$.
- Instability was observed at multi-bunch operation of positron beam. $N_{bunch}=200-300$ for $h=312$.
- Very low threshold. $I\sim 15-20\text{mA}$.
- The instability was not observed at electron beam operation.

- Had similar instability been observed at DORIS? Multi mode instability (197~ or 198~?)
- CESR, Electrons leak from Vacuum pump (J. Rogers et al.,).

BPM spectrum for V motion.

Electron 354 mA

Positron 324 mA & 240 mA

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

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.
Interpretation of instability due to photo-electron cloud

• Positron beam emits synchrotron radiation.
• Electrons are produced at the chamber wall by photoemission. Production efficiency \( \sim 0.1e^{-/\gamma} \).
• Electrons are attracted and interacts with the positron beam, then absorbed at the chamber wall after several 10 ns. Secondary electrons are emitted according the circumferences.
• Electrons are supplied continuously for multi-bunch operation with a narrow spacing, therefore electron cloud are formed.
• A wake force is induced by the electron cloud, with the result that coupled bunch instability is caused.

Recipes for electron cloud build-up are written in this paper.

PRL,75,1526 (1995)

FIG. 2. A stationary distribution of photoelectrons with $\epsilon_0 = 5$ eV.

direction, the practical density is given by multiplying $2 \times 10^4$ by the value from Fig. 2 in cm$^3$. Typically, if we use 100, as in the figure, the density is $2 \times 10^6$ cm$^{-3}$. We consider the space-charge effect of the electron distribution. The electric field due to the peak distribution, which is a few hundreds in the figures, can be estimated to be $\sim 100$ V/m. The field from the beam is $\sim 600$ V/m at a distance of 1 cm from the beam center. Thus, when the electron motion is near the beam, the field of the beam is dominant.
Number of produced electrons

Number of photon emitted by a positron par unit meter.
\[ Y_\gamma = \frac{5\pi \alpha \gamma}{\sqrt{3}} L \]
\[ \alpha : \text{fine structure const}=1/137 \]

- **KEKB-LER** \( \gamma=6850 \) \( \rightarrow \) \( Y_\gamma=0.15/m \)
- **KEK-PF** \( =4892 \) \( \rightarrow \) \( Y_\gamma=1.7/m \)

- **Bunch population**
  \( N_p=3.3\times10^{10} \) \( \) (KEKB-LER design 2.6A)
  \( N_p=5\times10^{9} \) \( \) (KEK-PF 400mA)
- **Quantum efficiency** \( (\eta=n_{p.e.}/n_\gamma) \) \( 0.1 \)
- **Energy distribution** \( 10\pm5 \) eV

- **KEKB-LER** \( Y_{p.e.}=0.015 \) e-/m.e+
- **KEK-PF** \( Y_{p.e.}=0.17 \) e-/m.e+
- **ionization** \( 10^{-8} \) e-/m.e+ , proton loss(PSR) \( 4\times10^{-6} \) e-/m.p
Electron cloud density given by simulation

60 bunches pass in every 8ns (KEKB).
This measurement gives electron cloud absorption rate (=production rate in equilibrium). To estimate the density, storing time should be multiplied.
Experiment and simulation results

$I_{pe} = 10 \, \mu\text{A} \text{ at } I_{+} = 600 \, \text{mA} \text{ at } 1.5 \, \text{m down stream of Bend.}$
Recent measurement of electron cloud
(not recent but 200*)

- Electron production rate increase as a function of the beam current. \( l_e = k l_b^{1.8} \).
- Photoemission, \( l_e = k l_b \).
- Index, 0.8, is due to multipactoring.

Y. Suetsugu, K. Kanazawa

ILC-DR 5GeV 400 mA
Coupled-bunch instability (CBI) caused by the electron cloud

- Wake field is induced by the electron cloud
- Coupled bunch instability due to the wake field causes beam loss.
Wake force and unstable mode for KEK-PF

Very fast growth of the coupled bunch instability was explained.
K. Ohmi, PRL, 75, 1526 (1995)
Measurement of the coupled bunch instability in KEKB

- Fast amplitude growth which causes beam loss has been observed.
- The mode spectrum of the instability depends on excitation of solenoid magnets.

Solenoid off

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

on (measurement)
Tracking

Solve both equations of beam and electrons simultaneously

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

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

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

(2)

K. Ohmi, PRE55, 7550 (1997)
K. Ohmi, PAC97, pp1667.

Take FFT for the bunch motion
CBI mode spectra in KEKB

**Experiment**

**Simulation**

Horizontal

Vertical

Bunches are filled every 4 bucket.

Su Su Win et al., (EC2002)
Effect of Solenoid magnet

- Solenoid magnets suppress the electron cloud effect partially.
- We can observe electron cloud effect characterized by solenoid magnet.

- Cloud distribution (K. Ohmi, APAC98)
Su Su Win et al., EC2002
Single bunch instability

Vertical Beam size blow up of positron beam at commissioning of KEKB

• A beam-size blow-up has been observed above a threshold current. The threshold is given for total current.

• The blow-up was observed in multi-bunch operation, but was perhaps single bunch effect. Beam size was measured by putting a bunch with an arbitrary current in a bunch train.

• Luminosity is limited by the beam size blow-up.

• Synchro-beta sideband induced by electron cloud head-tail instability was observed.
Measurements of the single bunch instability

- Beam size blow-up
- Synchro-beta sideband

Fukuma et al.

\[ \nu_y \sim \nu_y + \nu_s \]

J. Flanagan et al.
Head-tail instability model

- Simulation using Gaussian model, the same method as the study for CBI.
- Wake field approach, the same as CBI.
- PIC simulation (like beam-beam strong-strong)
Simulation using Gaussian micro-bunch model

\[
\frac{d^2 \mathbf{x}_{+,a}}{ds^2} + K(s) \mathbf{x}_{+,a} = \frac{2r_e}{\gamma} \sum_{j=1}^{N_e} F_G(\mathbf{x}_{+,a} - \mathbf{x}_{e,j}; \sigma(s)) \delta(s - s_j)
\]

\[
\frac{d^2 \mathbf{x}_{e,j}}{dt^2} = 2N_e r_e c^2 F_G(\mathbf{x}_{e,j} - \mathbf{x}_{+,a}; \sigma(s)) \delta(t - t(s_{+,a}))
\]
• Bunch head-tail motion w/wo synchrotron motion.

Vertical amplitude of the macro-particles in the longitudinal phase space are plotted. Multi-airbag model (z-δ) is used to visualize in these figures.

Head-tail and strong head-tail instability

\[ \rho_e = 2 \times 10^{11}, 4 \times 10^{11}, 10 \times 10^{11} \text{ m}^{-3} \]

- Unstable for Positive chromaticity --- head-tail
- Unstable for \( \rho_e = 10 \times 10^{11} \text{ m}^{-3} \) irrelevant to chromaticity --- strong head-tail
Wake field approach

• Linearized model.
• Numerical calculation including nonlinearity. (Similar way to the calculation of the multi-bunch wake field)

\[ W = K \frac{\lambda_e}{\lambda_p} \frac{L}{(\sigma_x + \sigma_y)\sigma_y} \frac{\omega_e}{c} \sin\left(\frac{\omega_e}{c} z\right) \]

K=1 for Linearized model. K~2-3 for the numerical calculation.
Vertical wake field given by the numerical method

- (1,1) is consistent with the analytical calculation.
- (10,10) is twice larger than (1,1).
- Instability threshold is calculated by the wake force.

K. Ohmi, F. Zimmermann, E. Perevedentsev, PRE65,016502 (2001)
Threshold of strong head-tail instability

- Mode coupling theory
  Threshold: $\rho_e = 1 \times 10^{12} \text{m}^{-3}$

- Coasting beam model

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

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

  Threshold: $\rho_e = 5 \times 10^{11} \text{m}^{-3}$

- Coasting beam model is better coincident with simulation.
Simulation with Particle In Cell method

- Electron clouds are put at several positions in a ring.
- Beam-cloud interaction is calculated by solving 2 dimensional Poisson equation on the transverse plane.
- A bunch is sliced into 20-30 pieces along the length.
PIC simulation

Snap shot of beam and cloud shape for $\nu_s = 0$ and $\nu_s > 0$

- Pink: size along bunch length
- Yellow: $<y>$ of cloud
- Dark blue: $<y>$ of bunch

BBU

Head-tail motion
Threshold behavior

- $\nu_s=0$ no threshold, $\nu_s>0$ clear threshold.
- $\rho_{e,th}=5\times10^{11}\text{m}^{-3}$
- The cloud density is consistent with that predicted by the measurement of electron current.
- This beam size blow-up can be understood as strong head-tail instability caused by electron cloud.
Solenoid winding in KEKB ring

(0) C-yoke permanent magnets are attached in the arc section of ~800m
(1) Solenoids are wound in the arc section of 800m (Sep. 2000).
(2) Solenoids are wound additionally in the arc section of 500m (Jan. 2001).
(3) Solenoids are wound in the straight section of *100m (Apr. 2001).
(4) Add solenoids even in short free space (August 2001).
(5) 95 % of drift space is covered (~2005).
(6) Solenoid in ¼ of quadrupole magnets (2005)
Solenoid magnets
Luminosity for Solenoids ON/OFF

- When solenoids turn off, stored current is limited to a lower value than usual operation due to beam loss (coupled bunch instability).
- Luminosity is quite low (~half).

Specific Luminosity for Solenoid ON/OFF (measurement at May.2001)
Effect of additional solenoid

Typical luminosity behavior at Dec. 2000 and March. 2001

- Adding solenoid, positron current with peak luminosity increases.
- Now peak luminosity is given at around 1600-1800 mA.

Beam-beam tuning also improves the luminosity.
Luminosity history of KEKB

Luminosity of KEKB
June 1999 - Dec. 2005

- Peak Luminosity 16.27 /nb/s
- 1183 /pb/day
- 7.36 /fb/7 days
- 29.02 /fb/30 days
- 528 /fb

Continuous Injection™
Measurement of synchro-beta sideband - evidence for head-tail instability

• If the beam size blow-up is due to head-tail instability, a synchro-betatron sideband should be observed above the instability threshold.

• The sideband spectra was observed with a bunch oscillation recorder.

• The threshold was consistent with simulations.

• The sideband appear near $\sim \nu_y + \nu_s$, while simulation gives $\sim \nu_y - \nu_s$, like ordinary strong head-tail instability.
Fourier power spectrum of BPM data

- LER single beam, 4 trains, 100 bunches per train, 4 rf bucket spacing
- Solenoids off: beam size increased from 60 µm -> 283 µm at 400 mA
- Vertical feedback gain lowered
  - This brings out the vertical tune without external excitation

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

Bunch Spacing vs Spec.
Lum. Luminosity-bunch current-sideband experiment

- Measure as a function of bunch current.
- Sideband is measured for noncolliding bunch.
Electron cloud induced head-tail instability

- E. Benedetto, K. Ohmi, J. Flanagan
- Measurement at KEKB

Simulation (PEHTS)
HEADTAIL gives similar results

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.
Feedback does not suppress the sideband

- Bunch by bunch feedback suppress only betatron amplitude.

Sideband signal is integrated over the train

Simulation (PEHTS)
Electron cloud effect in CESR, CesrTF and KEKB-low ε

• Tune shift measurement and electron build-up.
• Coupled bunch instability
• Single bunch instability

• Incoherent emittance growth
Number of produced electrons

Number of photon emitted by a positron par unit bending angle.

\[
\frac{dY_{pe}}{d\theta} = \frac{5}{2\sqrt{3}} \alpha \gamma \times 0.1(\text{rad}) \quad \text{Quantum eff.}=0.1
\]

• CESR 5GeV \( \gamma=10000 \) \( \rightarrow \) \( Y_{pe}=0.086/m, \) \( Ec=3\text{ keV} \)
• Cesr-TF 2GeV (arc) \( \gamma=4000 \) \( \rightarrow \) \( Y_{pe}=0.034/m, \) \( Ec=100\text{ eV} \)

• Bunch population
  \( N_p=2\times10^{10} \)
• electrons created by a bunch passage in a meter
  \( N_p \times Y_{pe}=1.7\times10^9 \text{ (5GeV)} \quad 6.8\times10^8 \text{ (2GeV)} \)

If electrons are accumulated 5 times,
• electron line density (m\(^{-1}\)) \( 8.5\times10^9 \text{ (5GeV)}, \ 3.4\times10^9 \text{ (2GeV)} \)
• volume density(m\(^{-3}\)) \( 1.7\times10^{12}, \quad 6.8\times10^{11} \)
• Corresponding Tune shift \( 0.0037, \quad 0.0037 \text{ (7.4e-4/bunch)} \)
• Beam line density \( N_p/4.2=4.8\times10^9 \)
Tune shift

- 2nd order moment ($<x_e^2>_c$, $<y_e^2>_c$) of electron cloud distribution gives tune shift, where $<x^2>_c = (x - <x>)^2$.

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

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

$$a = \frac{\langle y_e^2 \rangle_c}{\langle x_e^2 \rangle_c}$$

$$\Delta \nu_x + \Delta \nu_y = \frac{r_e}{\gamma} \oint \rho_e \beta ds \quad \text{if } \beta_x \sim \beta_y$$
Tune shift at KEKB

• Both showed similar density because of \( \nu_x + \nu_y = 0.015 \) and 0.012

Without solenoid

With solenoid
Tune shift at CESR

\[ \Delta \nu_x + \Delta \nu_y = \frac{r_e}{\gamma} \int \rho_e \beta ds \]

- Initial train of 10 bunches \( \Rightarrow \) 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

\[ \Delta \nu_y = 0.1 \text{ kHz/bunch} \]

N = 1.2 \times 10^{10}

\[ 1 \text{ kHz} \Leftrightarrow \Delta \nu = 0.0026 \]
\[ \rho_e \sim 1.5 \times 10^{11} \text{ m}^{-3} \]

\[ \beta = 30 \text{ m} \]

Error bars represent scatter observed during a sequence of measurements

*Preliminary*

Ohmi, et al., APAC01, p.445

July 16-17, 2007

Joint NSF/DOE Review of CesarTA Proposal
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 $\gamma$.
- Sign of photoelectron dominant

$\Delta \nu_y = 0.1$ kHz/bunch
Measured tune shift is 1/3 of the simple estimation

- Maybe reasonable considering magnetic field
- Electron distribution depends on magnetic filed

Straight section

\[ \nu_y > \nu_x \]

Magnetic field section

\[ \nu_y \sim -\nu_x > 0 \]
Wiggler section

- 1.3m (1m effective)x12, 2.1T, $\theta_{\text{tot}} = 3.78$ rad.
- $N_{\text{pe, tot}} = 15.9 \times 2 \times 10^{10} = 3.2 \times 10^{11}$ (5.2x10^{11} in arc).
- If the electrons localized in 20 m (for example), electrons are accumulated by $N_{\text{pe}} = 2.6 \times 10^{10}$ m^{-1}bunch^{-1}.
- Beam line density $N_p/4.2 = 4.8 \times 10^9$ m^{-1}.
- Electron production and buildup are suppressed by the space charge (neutralization) limit.
- Arc is dominant for the electron cloud tune shift and instabilities in CESR.
Coupled bunch instability

- $N_p = 1 \times 10^{10}$, 4 ns spacing.
- Growth time $\sim 25$ turn, 64 $\mu$sec.

- Since tune shift is 1/3 of the estimation, the growth may be also 1/3.
Threshold of the strong head-tail instability
(Balance of growth and Landau damping)

- Stability condition for $\omega_e \sigma_z/c > 1$
  \[
  U = \frac{\sqrt{3} \lambda_p r_0 \beta}{\nu_s \gamma (\omega_e \sigma_z/c)}\frac{|Z_\perp(\omega_e)|}{Z_0} = \frac{\sqrt{3} \lambda_p r_0 \beta}{\nu_s \gamma (\omega_e \sigma_z/c)} \frac{KQ \lambda_e}{4\pi \lambda_p \sigma_y (\sigma_x + \sigma_y)} L = 1
  \]

- 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
- $Q = \min(Q_{nl}, \omega_e \sigma_z/c) \quad Q_{nl} = 7$ is used.
- $K$ characterizes cloud size effect and pinching.
- $\omega_e \sigma_z/c \sim 12-15$ for damping rings.
- We use $K = \omega_e \sigma_z/c$ and $Q_{nl} = 7$ for analytical estimation.
## Threshold for various rings

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# Tune shift at the threshold

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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 at KEKB-lowe and OCS

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

- $\Delta \sigma_y / \sigma_y = 5.7 \times 10^{-6} \ll 1 / \tau_y = 2.5 \times 10^{-4}$
- Incoherent effect was negligible for KEKB in this condition.
Incoherent emittance growth at Cesr-TF

- For high \( \nu_s(\alpha) \) ring, coherent instability is strongly suppressed. Incoherent effect may be enhanced relatively.
- CESR (\( \nu_s = 0.098, \alpha = 6.4 \times 10^{-3} \))
- The incoherent growth is faster than radiation damping time at \( \rho_e = 1 \times 10^{12} \text{ m}^{-3} \).

By H. Jin
Bunch and e-cloud profiles at 500 turn

By H. Jin

No coherent motion

Coherent motion

Need to check tune dependence and lattice slice dependence
Summary for CESR and comment on experiments

• The cloud density is $\rho_e = 1.5-4.5 \times 10^{11}$ m$^{-3}$ for $N=1.2 \times 10^{10}$, 14 ns spacing at CESR.
• The density is reasonable for the photo-electron model, and arc section is dominant.
• The coherent instability is observed at 10 times higher cloud density. More bunches with short spacing or lower $\alpha$ may realize the unstable condition.
• The operation with $N=2 \times 10^{10}$, 6 ns spacing, may achieve the threshold $\rho_e \sim 1-2 \times 10^{12}$ m$^{-3}$.
• Incoherent emittance growth may be seen in CESR, though may not seen in damping ring nor KEKB low $\epsilon$.
• The coupled bunch instability should be seen, if bunches are stored uniformly, for example, 4-8 ns spacing, 100 mA depending on chromaticity (head-tail damping).