

TUZH103

Electron Cloud Experiments, Simulation and Cure*

H. Fukuma, KEK

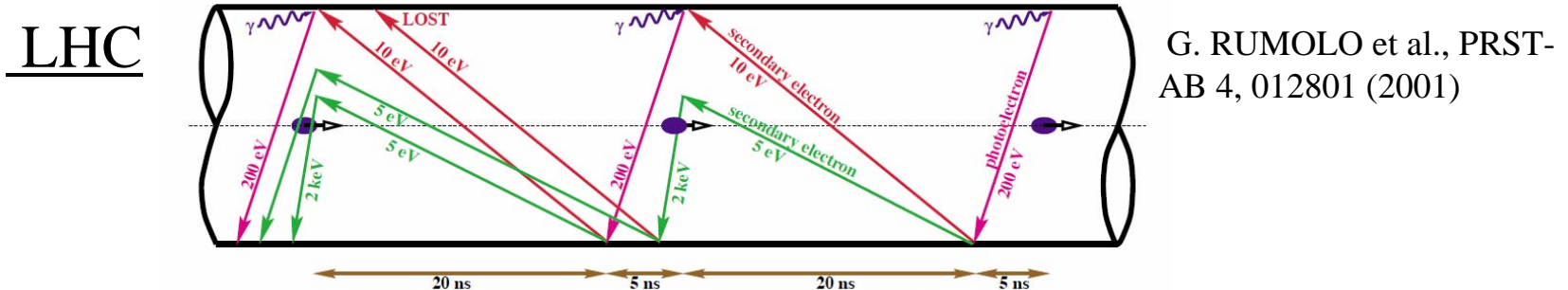
APAC2007, Indore, 30th Jan., 2007

1. Introduction
2. Electron cloud observations and experiments
3. Modeling and simulations
4. Cures
5. Impact on under-construction and planned accelerators
6. Summary
7. Acknowledgments

*This work was supported by JSPS Core University Program.

1. Introduction

1) What is an electron cloud ?



- Many electrons stay in accelerators.
- Primary electrons can be produced by synchrotron radiation, lost particles hitting a chamber wall, or by ionization of the residual gas.
- If the charge of a beam is **positive**, the primary electrons receive a kick from the beam toward the center of beam pipe and hit the opposite wall, then **secondary electrons** are produced.

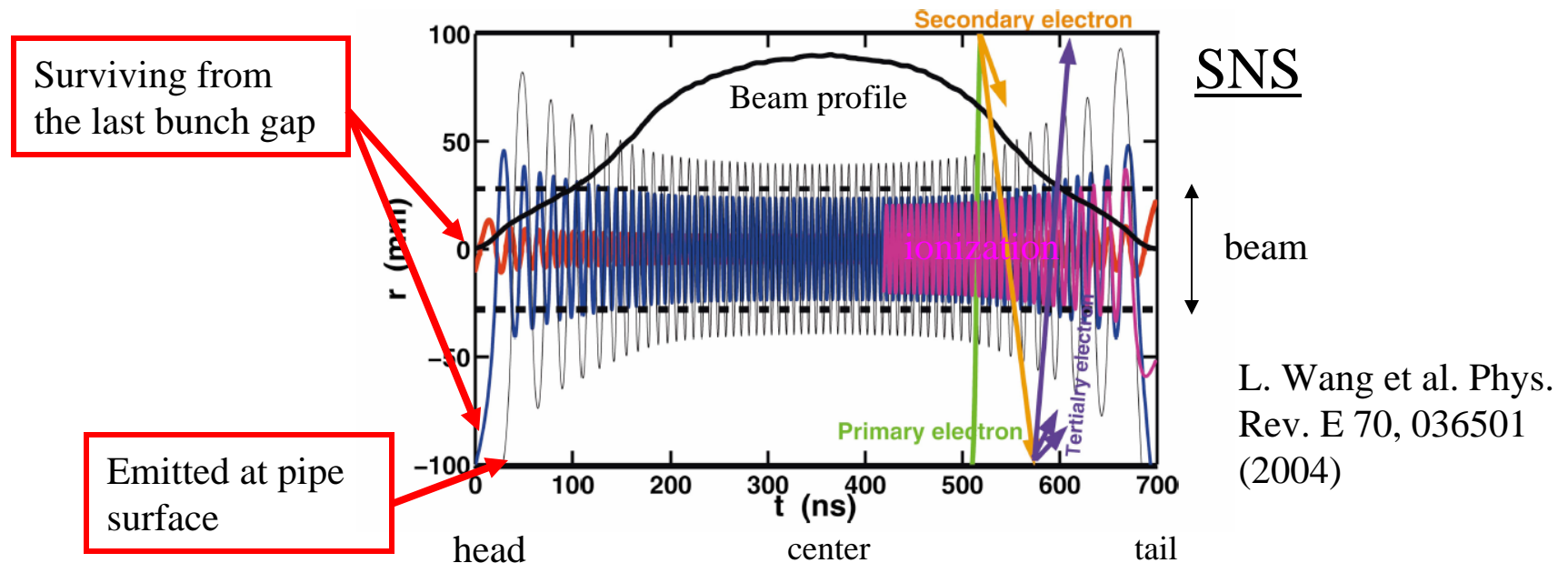
Maximum secondary electron yield(SEY) is ~ 1.4 for Cu, 2 for SUS.

- Under some operational conditions, an amplification of electrons occurs.

➡ **Beam Induced Multipacting (BIM)**

- The primary and secondary electrons form a group of electrons called **an electron cloud (abbreviated to EC)**.

Long bunch of proton beam (Trailing edge multipacting, R. Macek)



- All electrons are trapped or captured before the center of the bunch passes through the EC.

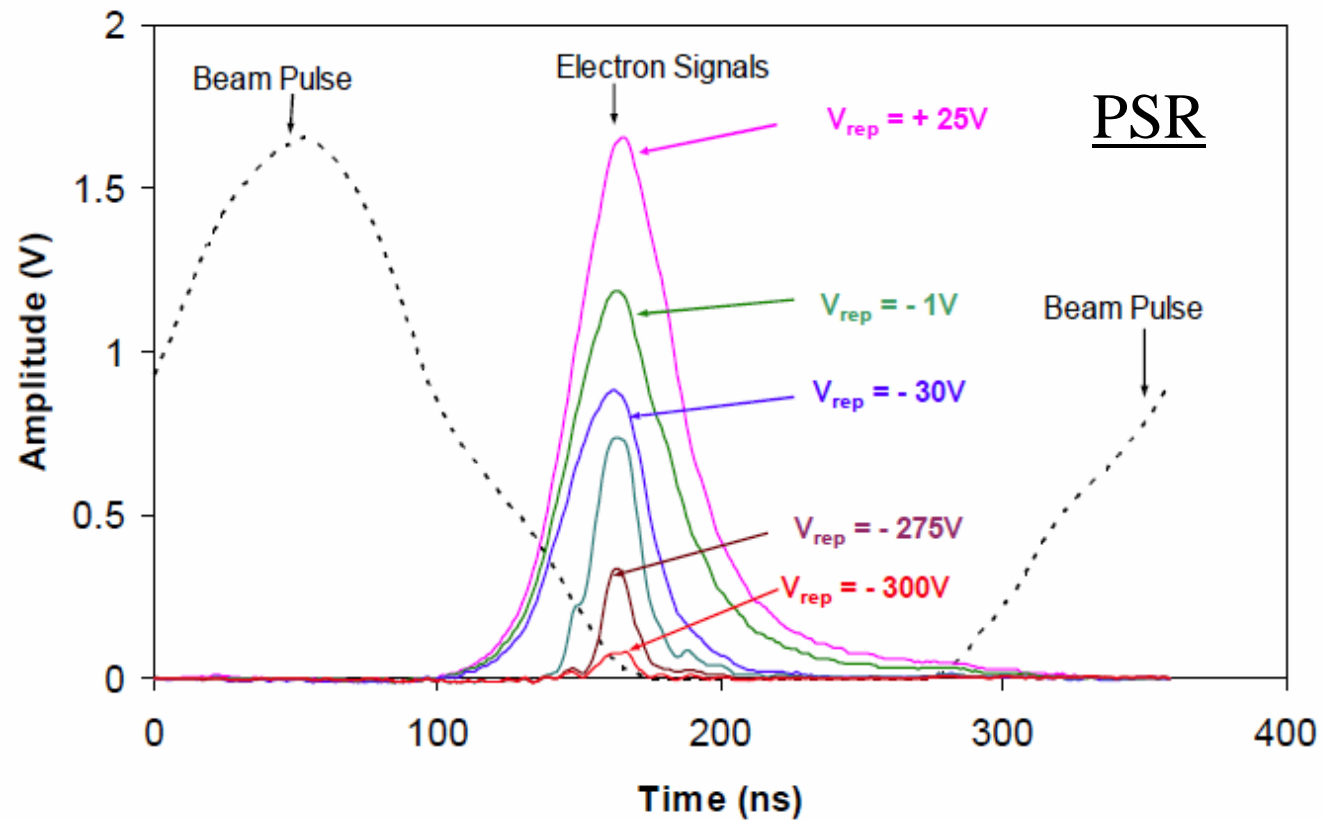
Trapped electrons are released at the tail.

- Electrons emitted at the pipe surface between the bunch's center and the tail hit the opposite surface **due to the negative slope of the longitudinal beam density**.

The amplification of the electrons (i.e. BIM) occurs towards the tail.

➡ Many electrons are produced **at the tail of the bunch**.

Trailing edge multipacting



R.J. Macek et al., at PAC2003

2) Electron cloud effects

a) Pressure rise

Gas desorption by electron bombardment

b) Electrical noise to instrumentations

c) Beam induced multipacting (BIM)

d) Heat load on a cold chamber wall (e.g. LHC)

Electron bombardment on the cold wall

e) Tune shifts

Coulomb force of the EC

f) Coupled bunch instability

Long/medium range wake force of the EC

g) Single bunch (strong head-tail) instability

Short range wake force of the EC \Rightarrow Beam size blowup

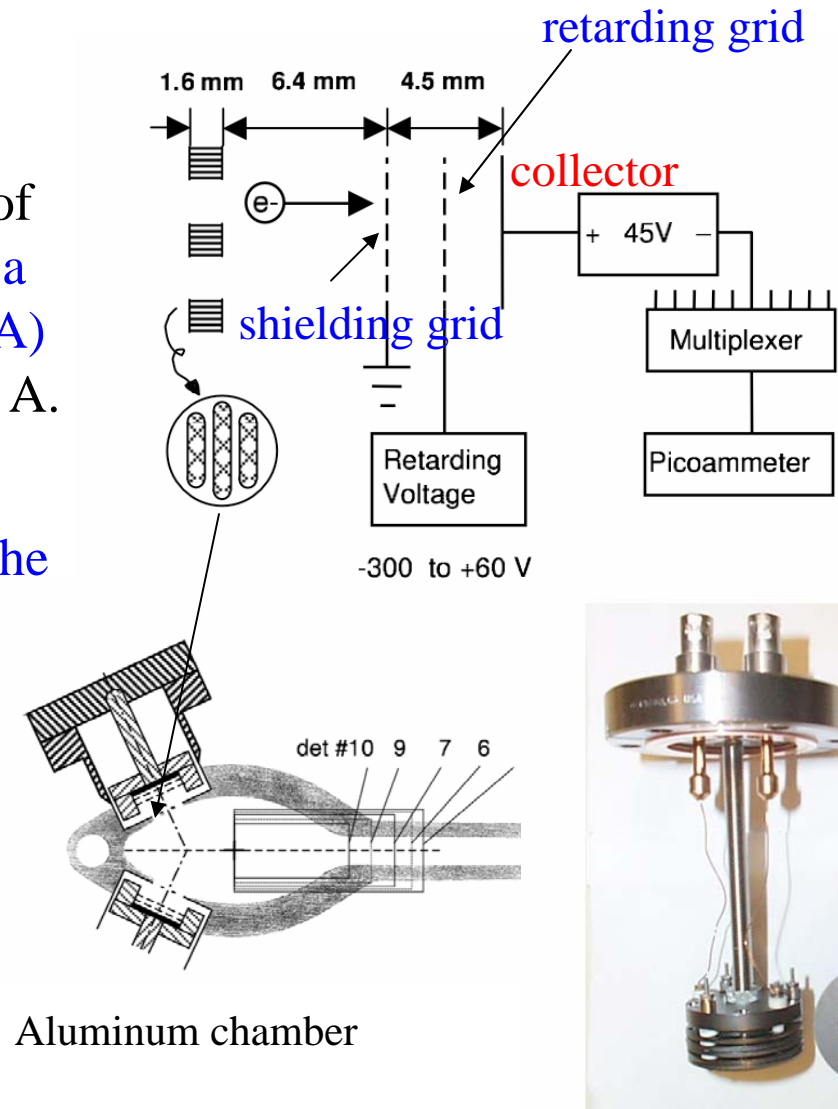
h) Emittance growth below the threshold of the instability

Pinched EC and synchrotron oscillation

2. Electron cloud observations and experiments

1) Electron measurements

- The flux and energy distributions of electrons are measured usually by a **planar retarded field analyzer (RFA)** pioneered by K. C. Harkey and R. A. Rosenberg at APS(ANL).
- A **retarding grid** enables to select the electron energy.

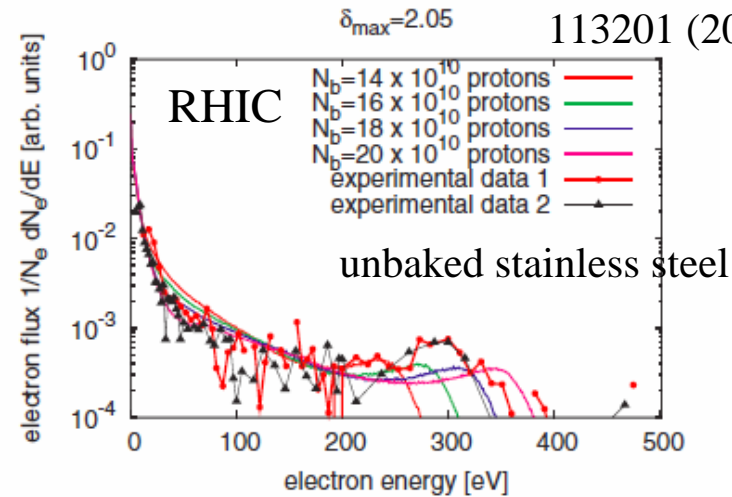
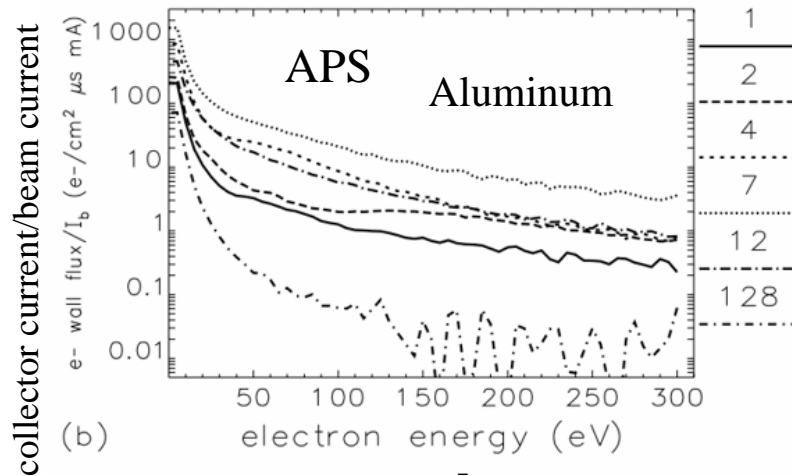


R. A. Rosenberg, at Two-Stream00. R. A. Rosenberg, K. C. Harkey, N.I.M., A453(2000)

K. C. Harkay, R. A. Rosenberg, PRST-AB, 6, 034402 (2003)

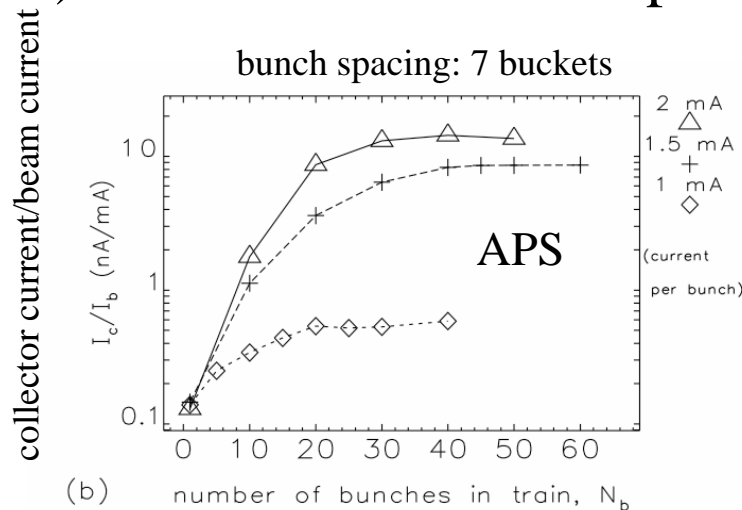
U. Iriso and W.
Fischer, PR ST-AB 8,
113201 (2005)

A) Electron energy distribution by the RFA



- The data shows the electron energy hitting the wall is very low, typically less than 10 eV.

B) Electron cloud buildup and saturation measured by the RFA



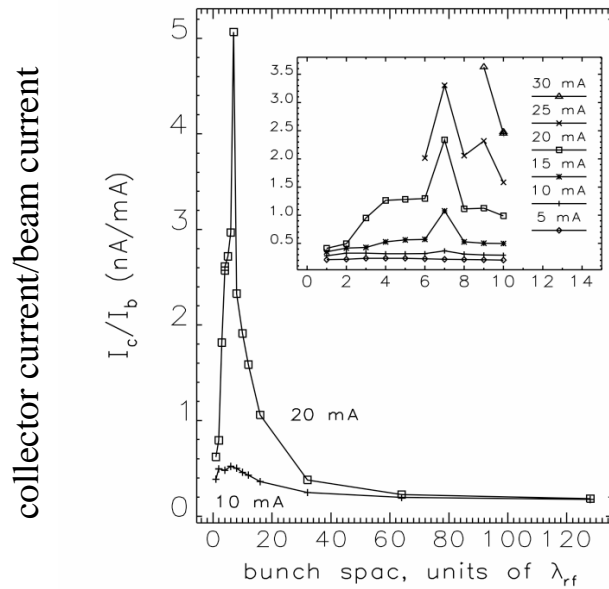
- The EC increases along the bunch train then reaches the saturation.

➡ Electron cloud buildup

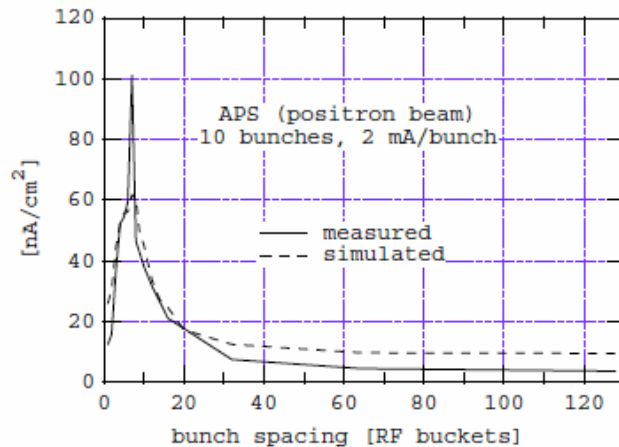
K. C. Harkay, R. A. Rosenberg, PRST-AB, 6, 034402 (2003)

C) Beam induced multipacting (BIM)

Measurement at APS



K. C. Harkay, R. A. Rosenberg, PRST-AB, 6, 034402 (2003)



M. A. Furman et al., Proc. PAC2001, 679 (2001)

- There is a peak at 7 buckets spacing.

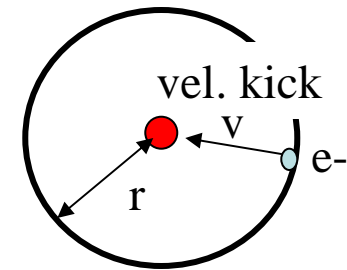
BIM condition

$$2r/v = s_B/c$$

s_B : bunch spacing

$$s_B = \frac{r^2}{r_e N_b}$$

← bunch population



"r" varies if a chamber is not round.

$$\Rightarrow s_B = 4 \text{ to } 7 \text{ buckets spacing}$$

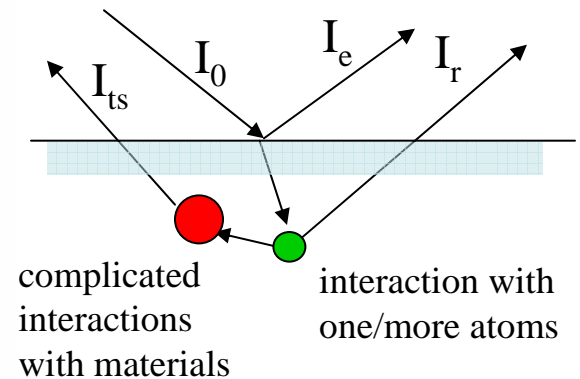
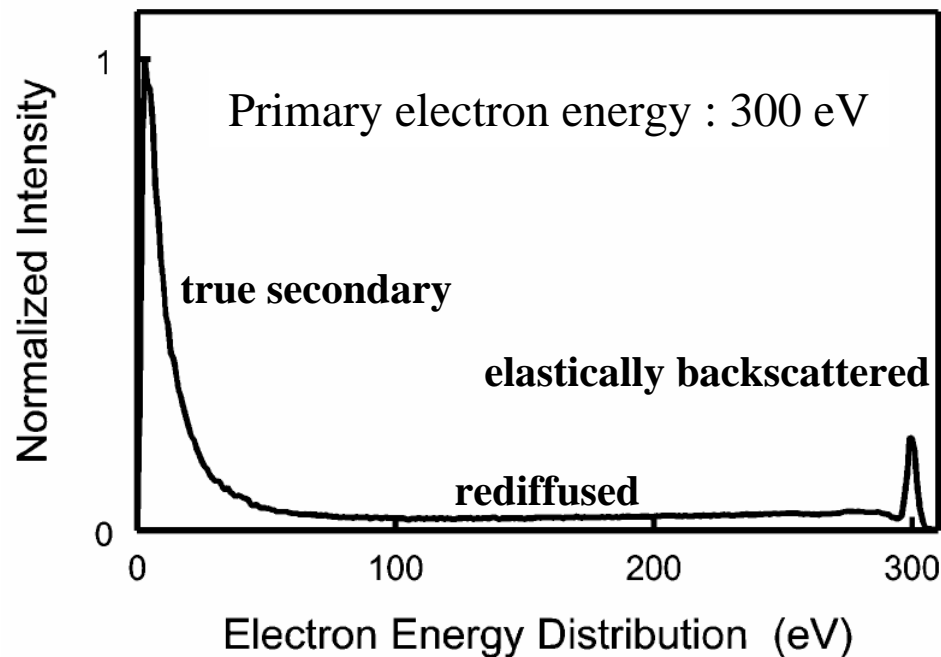
- The result is qualitatively explained by a simulation by POSINST.

3) Emission of secondary electrons

- One of the most important parameters in EC formation is a **secondary emission yield (SEY), δ** , defined as the electron current emitted from a surface / the incident electron current.

A) Energy spectrum of secondary electrons

- The secondary electrons are classified into three categories, true secondary, elastically backscattered and rediffused electrons.



M. Furman, M. Pivi, PRST-AB 5, (2002) 124404

B) Incident energy dependence

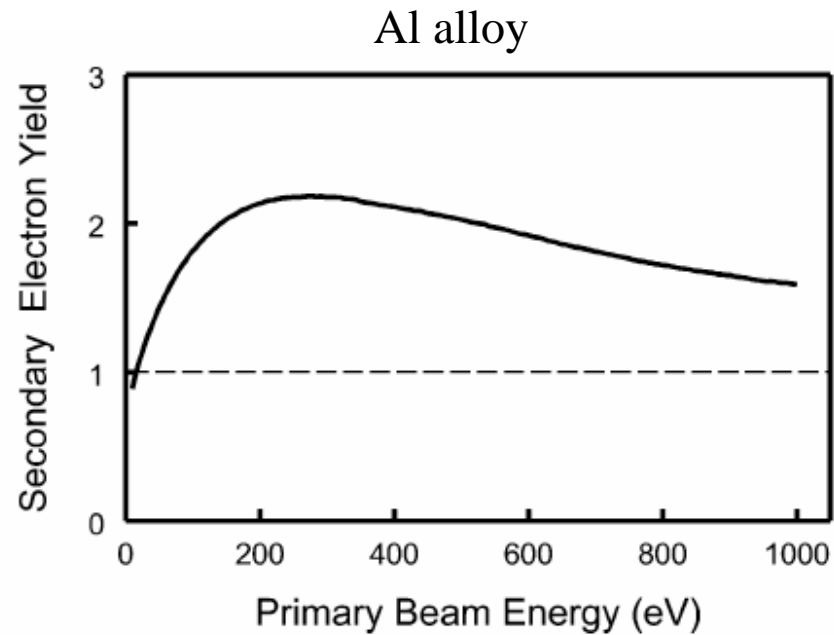


Fig. 4. SEY of alkali-etched Al alloy in Fig. 1.

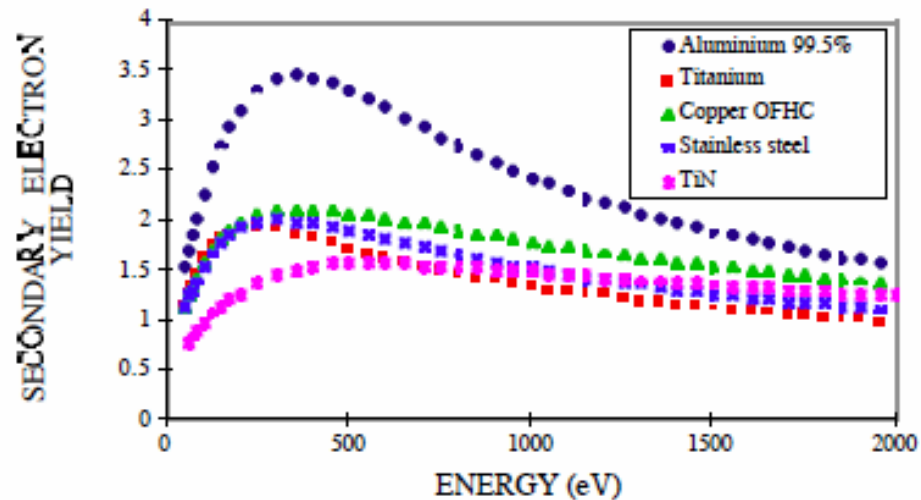
R. E. Kirby, F. K. King, N. I. M. A 469 (2001) 1

The SEY has a peak δ_{\max} around 200 - 300 eV.

C) Materials and surface dependence

- The secondary emission is a surface dependent phenomenon.
- The SEY depends on the material and influenced by the surface preparation such as a baking and an argon glow discharge.

Material dependence



N. Hilleret et al., EPAC2000

D) Coating

- Coating of the chamber surface by low SEY materials, e.g. [titanium nitride \(TiN\)](#), is effective to decrease the electron buildup.
- NEG material such as [titanium-zirconium-vanadium \(TiZrV\)](#) is an alternative low SEY material.

It has another advantages.

- ◇Low electron impact molecular desorption rate.
- ◇Additional pumping after activation.

- SLAC laboratory measurement

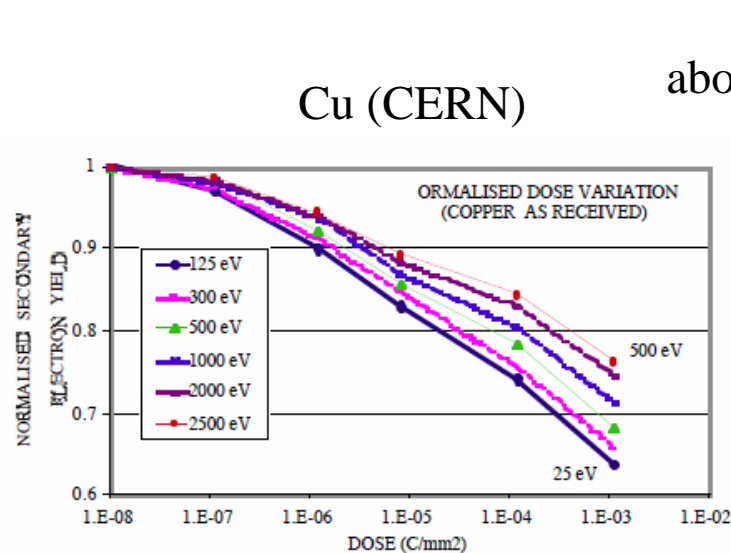
	TiN	TiZrV
δ_{\max}	1.5	<1.4

- [The large scale application of NEG coating has been effective in reducing the electron cloud in RHIC.](#)

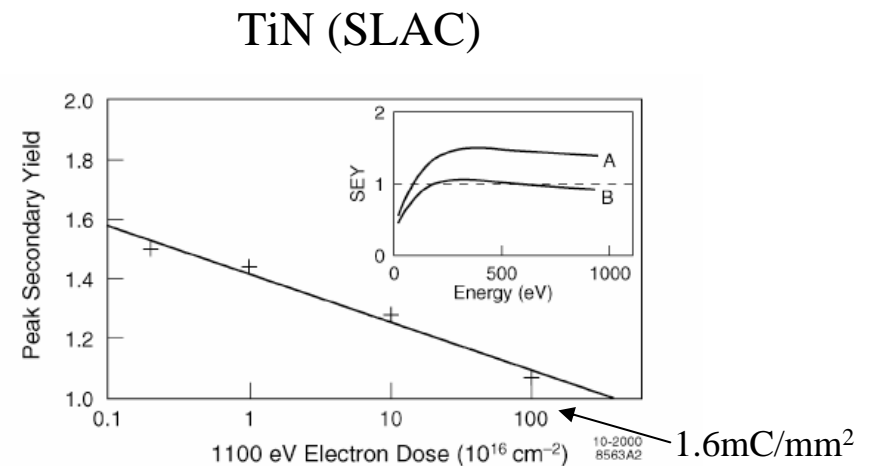
E) Scrubbing

- A decrease in the SEY by electron bombardment is called **scrubbing or conditioning**.
- Typically a dose close to 1mC/mm^2 is necessary for SEY to reach saturation level.

Ex. KEKB : 10 mC/mm^2 @ 40 A hours (at 5.6m away from a bend) (Y. Suetsugu)



N. Hilleret et al., EPAC2000

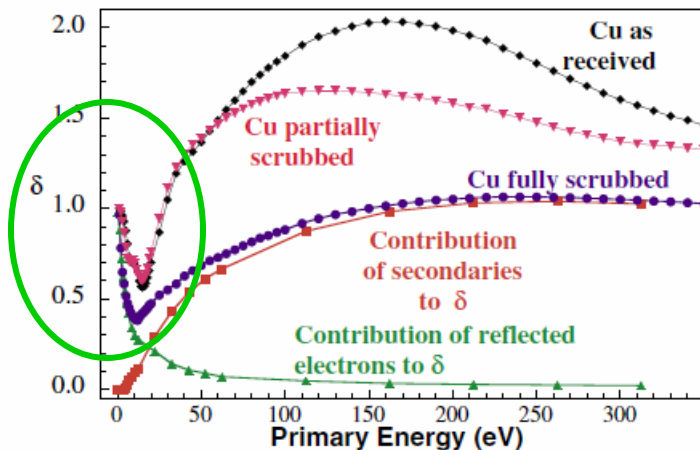


R. E. Kirby, F. K. King, N. I. M. A 469 (2001) 1

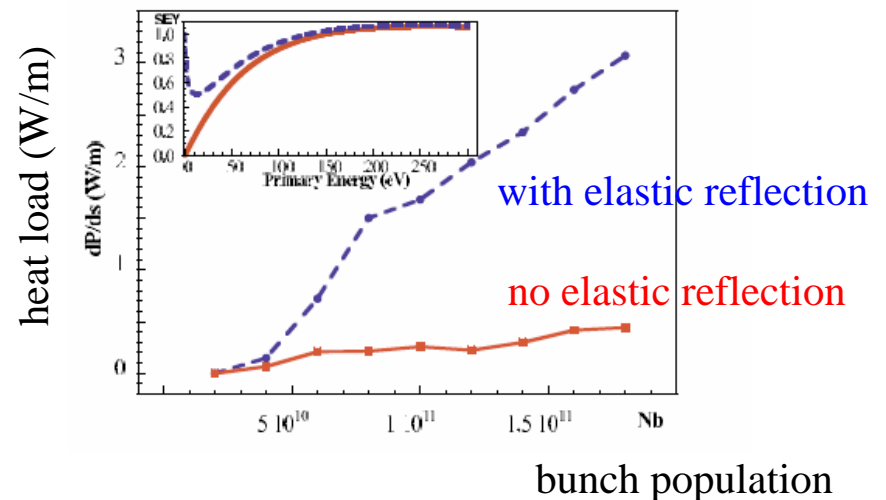
- A KEK measurement shows that the decrease of δ_{max} is caused by **graphitization** where a contaminated layer of carbon is changed to graphite which has low δ_{max} .

F) SEY at very low energy

- The SEY at very low energy is important because the energy distribution of the electrons on the wall peaks at very low energy (< 20 eV for the LHC).
- A measurement shows that the SEY approaches unity in the limit of zero primary electron energy.
- The data indicate **long lived low energy electrons** in a beam pipe.
- A simulation shows that the surface heat load in the LHC is greatly affected by the SEY at low energy.



R. Cimino et al., P.R.L. 93, (2004)

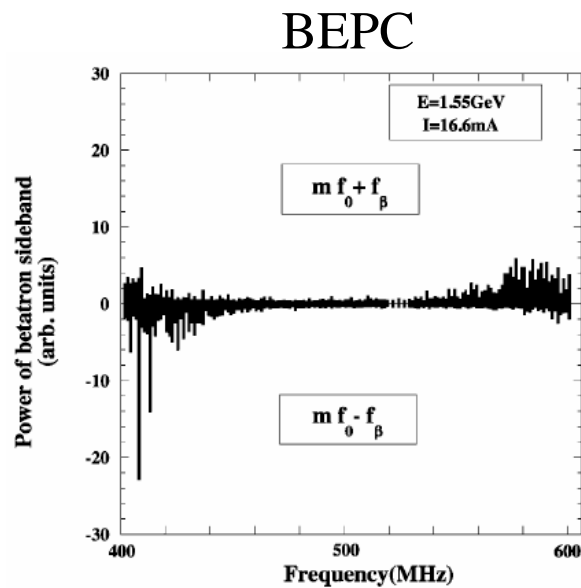


Simulated average heat load in the LHC dipole magnet.

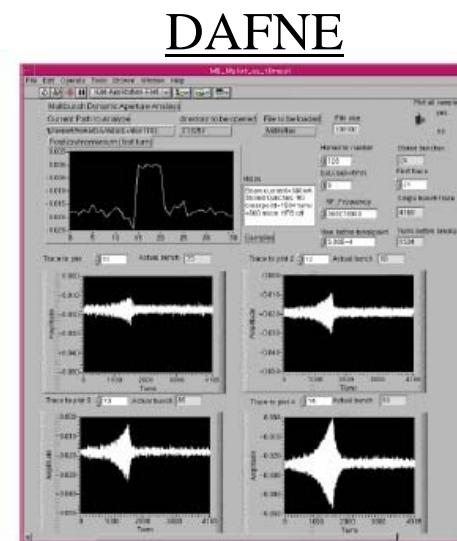
2) Instabilities

A) Transverse coupled bunch instability

- The transverse coupled bunch instability (CBI) observed at KEK PF in 1995 triggered extensive study of the electron cloud instability. Now the CBI is observed in many accelerators.
- The oscillation spectrum is broad reflecting short/medium range nature of the beam-EC interaction.
- A horizontal CBI is found at DAFNE. The instability is believed to be caused by the EC in the wigglers and the resistive wall.



Y.Z.Guo et al., PR ST - AB, 5, 124403 (2002)

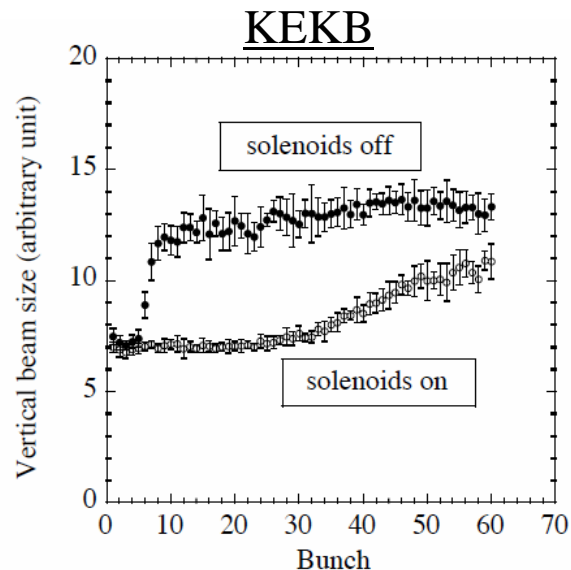


A. Drago et al., at EPAC04

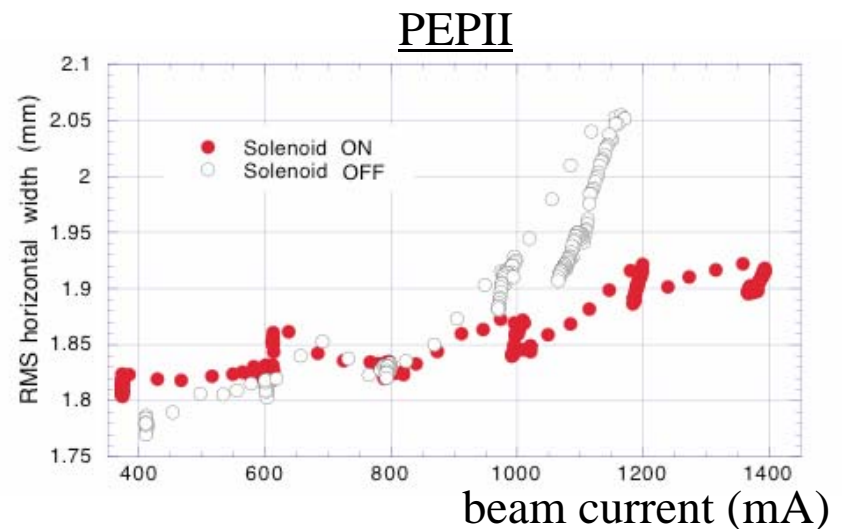
B) Single bunch instability

a) Beam size blowup

- A beam size blowup which affects the luminosity was observed in B factories since very beginning of the operation.
- K. Ohmi and F. Zimmermann proposed that the blowup is caused by the strong head-tail instability by the EC.
- The solenoid is very effective to suppress the single bunch instability in B factories.



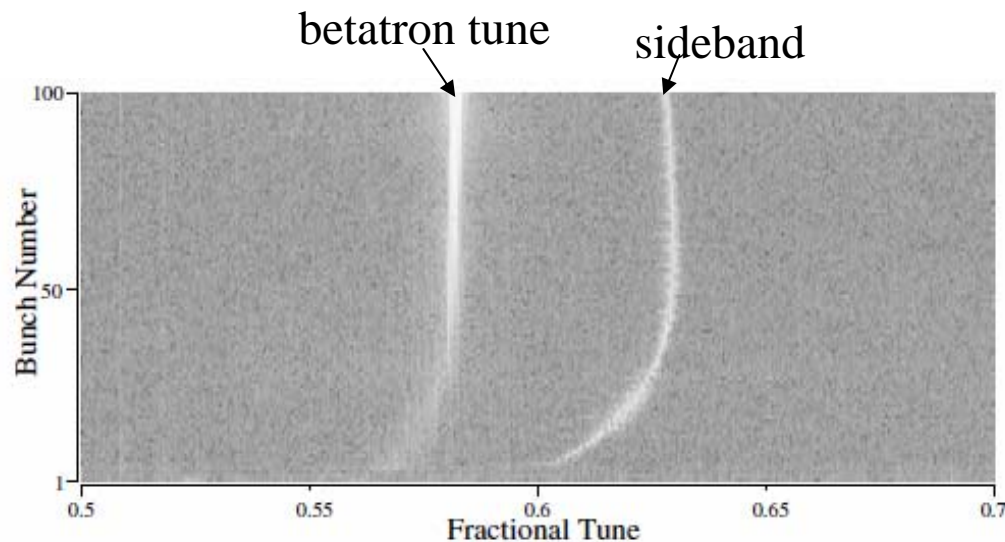
H. Fukuma et al., HEAC2001



R. L. Holtzapple, SLAC-PUB-9222 (2002)

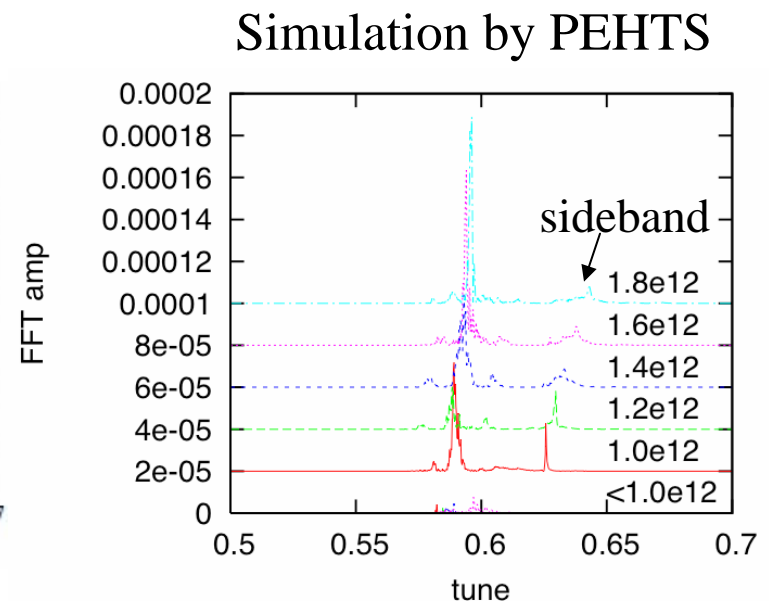
b) Sideband

- A vertical betatron sideband was found at KEKB.
- The threshold where the sideband appears coincides with that of the beam size blowup.
- Appearance of the sidebands also associated with loss of luminosity.
- The sideband appears to be a signature of the strong head-tail instability due to EC.



Vertical tune along a train

J. W. Flanagan et al., PRL 94, 054801 (2005)



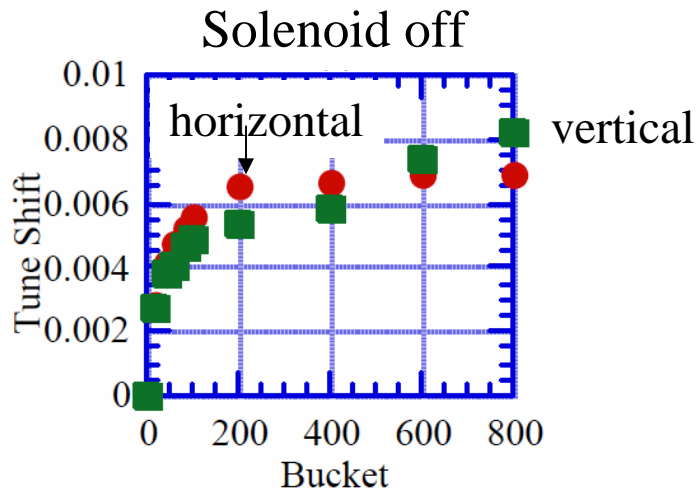
K. Ohmi, talk at ILCDR06 (2006)

3) Tune shift

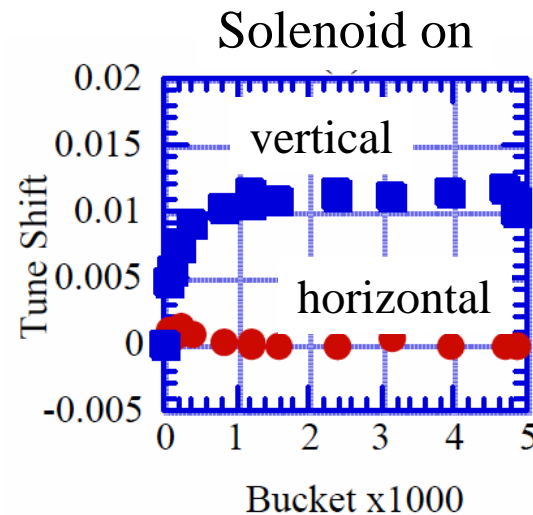
- The EC can cause a betatron tune shift due to electro-static force between the EC and the beam. (K. Ohmi et al. (APAC01)).
- By measuring the tune shift we can get the information of the density and the lifetime of the EC.
- Effect of solenoid on the tune shift at KEKB

Vertical tune shift is not fully suppressed with solenoids.

The reason for the asymmetric contribution of the solenoids is not understood yet.



4 RF bucket spacing, 0.5mA/bunch



3.5 RF bucket spacing, 1.0mA/bunch

T. Ieiri et al., Proc.
EPAC2006, 2101 (2006)

4) Electron cloud in magnets

A) Spatial distribution of electrons

- Spatial distribution of the EC in a dipole was measured by a **strip detector** originally developed at CERN.
- The measurement showed two stripes of the electrons which had been **predicted** by the simulation by F. Zimmermann.

Strip detectors

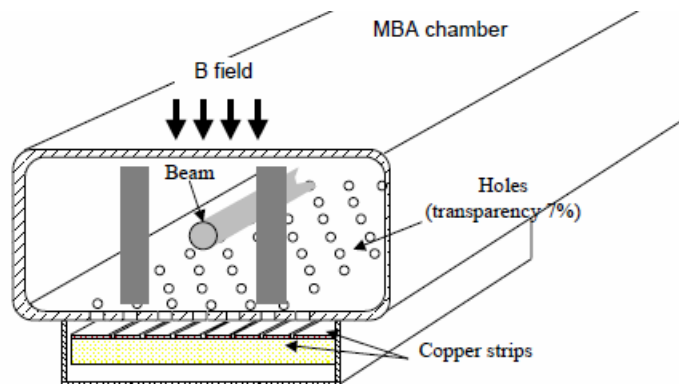
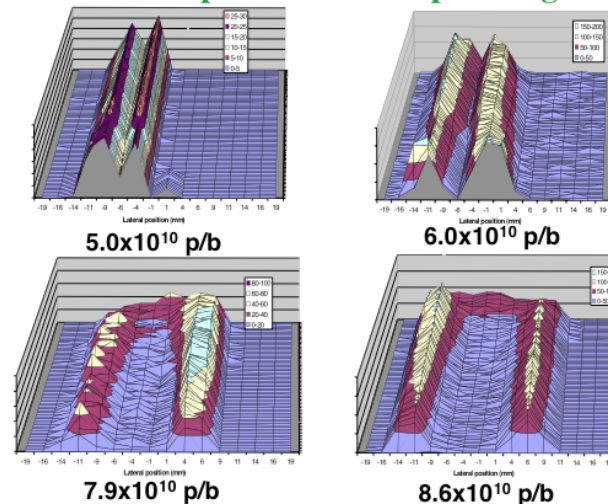


Fig.1: Schematic view of a strip-detector showing the position of the collecting strips with respect to the beam.

J. M. Jimenez et al., LHC Project Report 634



SPS(CERN) Beam Effects: Bunch Intensity Effect of a dipole field: 2 strips @ high intensities



G. Arduini, P. Collier, G. Ferelli, B. Henrich, N. Hilleret, L. Jansen, J.M. Jimenez, J.M. Laurent, U. Iriso, K. Weiss, F. Zimmermann

15/04/2002

ECLOUD02 CERN GENEVA
J.M. Jimenez, LHC Division - Vacuum Group

J.M. Jimenez, at ECLOUD02.

B) Trapping in a quadrupole

- Trapping of the electrons in a quadrupole was found by simulation.
- The trapping is similar to the plasma trapping in a mirror magnetic field.
- The trapped electrons could have a long life time in train gaps, then may give an influence to the bunch coming after the bunch gap.

Trapped electrons

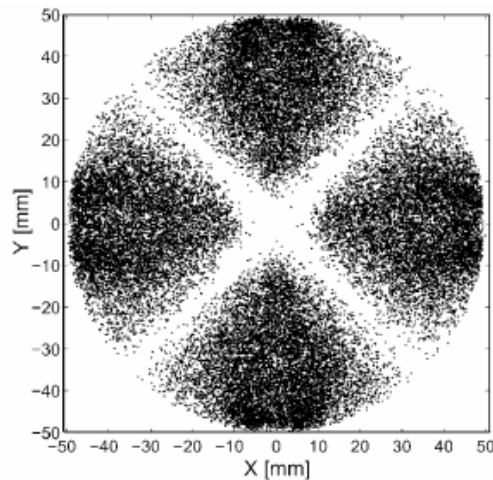


FIG. 15. Photoelectron distribution during the bunch train passage before a positron bunch arrives.

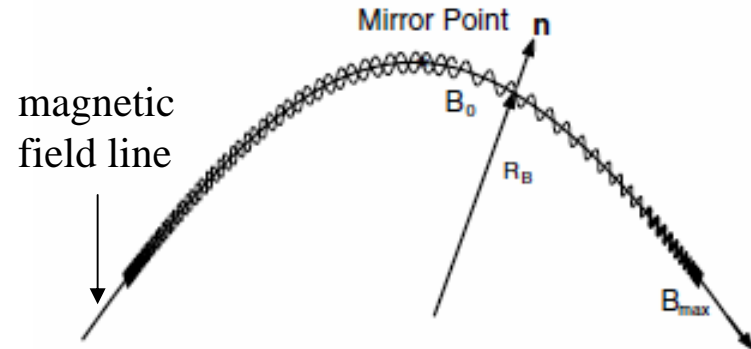


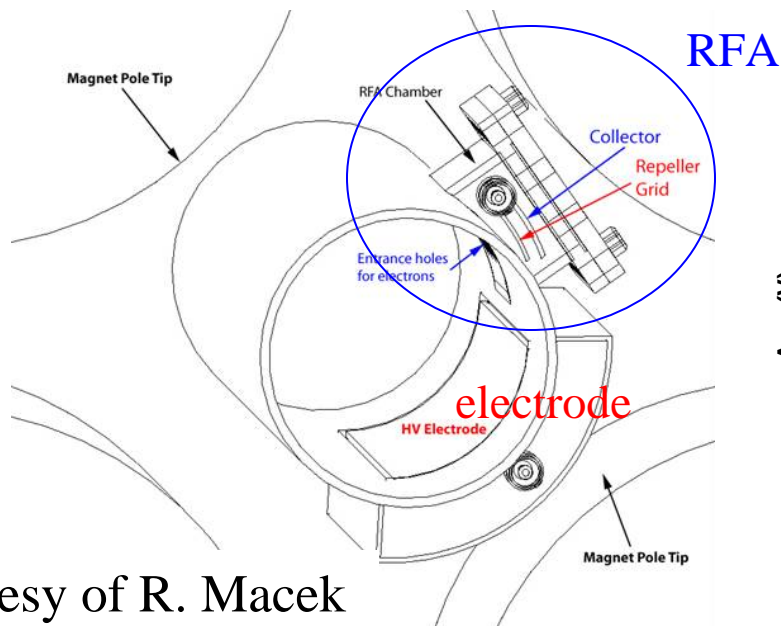
FIG. 14. Motion of electron in a mirror magnetic field.

L. F. Wang et al., PR E 66, 36502 (2002)

Measurement at PSR

- An electron sweeper was installed in a quadrupole at PSR.
- The sweeping electrode pulsed (-500V) for 100ns ~16 μ s after last beam bunch.
- According to the first measurement, long decay times (50-100 μ s decay constant) were observed for electrons trapped after beam extraction.
- Simulation study is in progress.

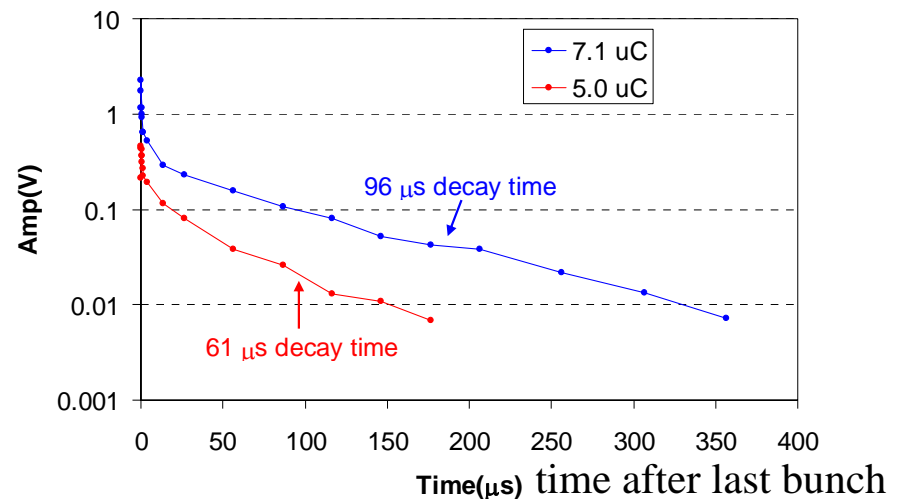
Schematic Layout in PSR Quadrupole



Courtesy of R. Macek

R. Macek et al., talk at ILCDR06 (2006)

ES43Q "swept" electron Dissipation Curve



- The trapping of the electrons in a quadrupole is being studied also at HCX with 1MeV K^+ beam (A. Molvik, Proc. HB2006 (2006)).

3. Modeling and Simulation

- Simulation of the EC effects is usually classified into two categories, the EC buildup and the instability calculations.
- Many programs have been developed in accelerator laboratories and institutes.

1) Cloud buildup simulation

CSEC, CLOUDLAND, Y. Liu's code, S. Novokhatski and J. Seeman's code(Vlasov eq.), PEI, POSINST etc.

2) Instability simulation

HEADTAIL, Y. Liu's code, PEI, PEHT, PEHTS,QUICKPIC etc.

Here as examples, three codes, **CLOUDLAND, PEI and PEHTS** are briefly described.

1) Cloud buildup (CLOUDLAND)

- Typical flow of the program

- a) Generate electrons.

- b) Calculate kick to electrons by the beam.

- c) Calculate kick to electrons by the space charge force of the EC.

- d) Move electrons in the chamber including magnetic field.

- e) Generate secondary electrons on the surface of the chamber.

a) Generate primary electrons

i) Photoelectrons by synchrotron radiation

- Number of photoelectron

$$N_{pe} = \eta_e \cdot \frac{5\pi}{\sqrt{3}} \cdot \gamma \cdot \alpha \cdot N_{bunch} / C \quad \Rightarrow \quad 1 \times 10^9 \text{ /m/bunch for KEKB}$$

- Energy, typically 5eV.

ii) Electron produced by ionization

$$N_{ie} = n_g \sigma_i N_{bunch} \quad \Rightarrow \quad 4.3 \times 10^2 \text{ /m/bunch for KEKB}$$

Electrons are produced near the beam.

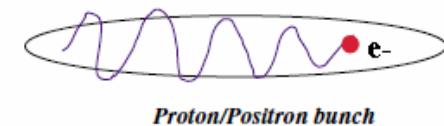
iii) Electron produced by a lost proton

Stripping foil, halo collimator, chamber wall etc.

$6.7 \times 10^7 \text{ /m/bunch}$: for uncontrolled loss in J-PARC RCS at injection.

b) Calculate kick to electrons by the beam

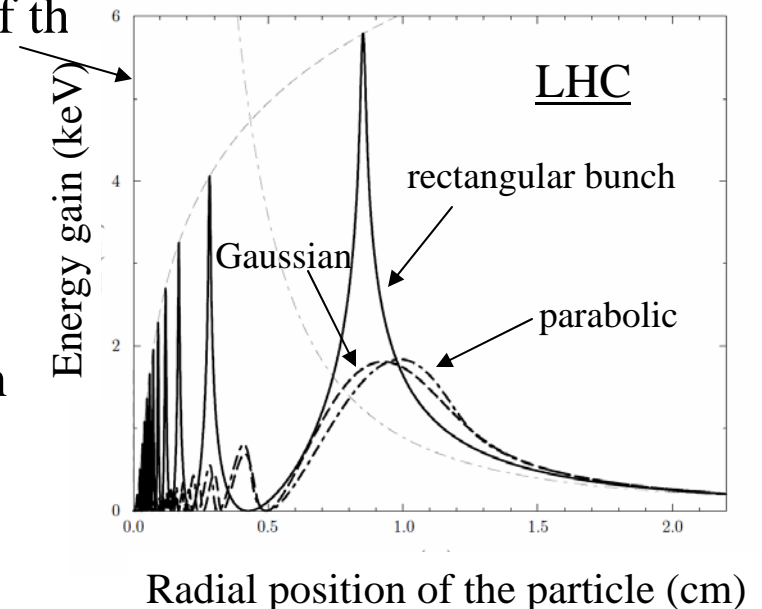
- The kick is given by the Bassetti-Erkin formula.
- Bunch is divided into several pieces, typically 40, to kick the electron in order to take account the electron movement during kicks.
- Electrons near the bunch oscillate in the bunch.
- Energy gain of the electron depends on its initial position and longitudinal profile of the beam.



c) Space charge force of the EC

Particle-In-Cell method

- Assign the charge of a macro electron to nearby mesh points.
- Solve Poisson equation by the finite element method.

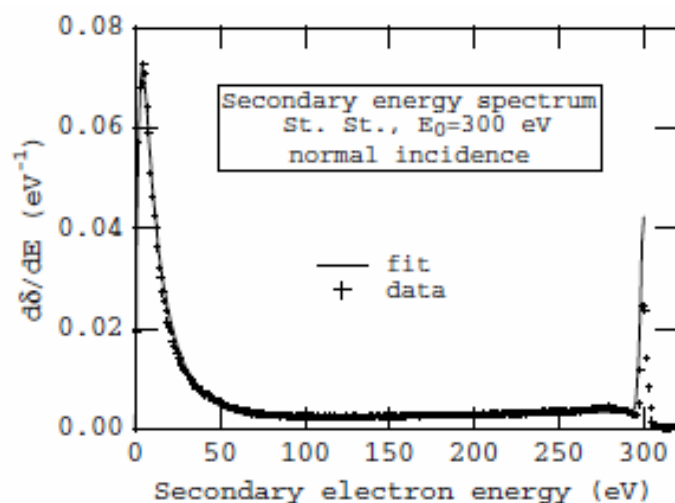


J. S. Berg, LHC Project Note 97 (1997)

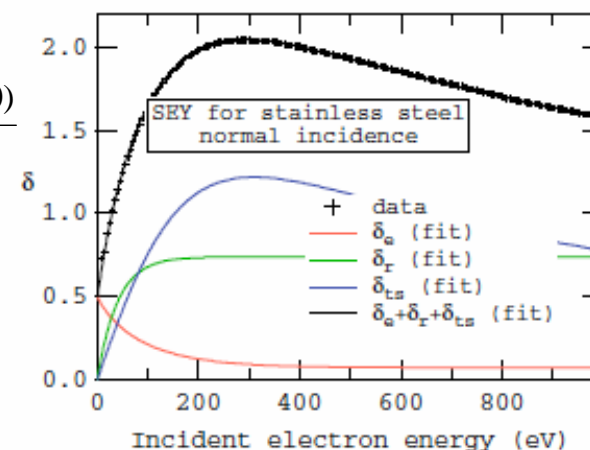
e) Generate secondary electrons on the surface of the chamber

Furman and Pivi model

a) Incident energy dependence (normal incidence)



$$\int_0^\infty dE \frac{d\delta(E_p, 0)}{dE}$$



Secondary electron

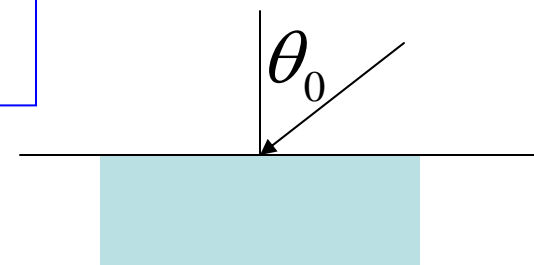
true secondary, elastically reflected, rediffused

b) Incident angle dependence

$$\delta(E_p, \theta_0) = \delta(E_p, 0) \cdot [1 + u(1 - \cos^v \theta_0)]$$

c) Angular distribution of the emitted electrons

Polar angle : $\cos \theta$, Azimuthal angle : uniform



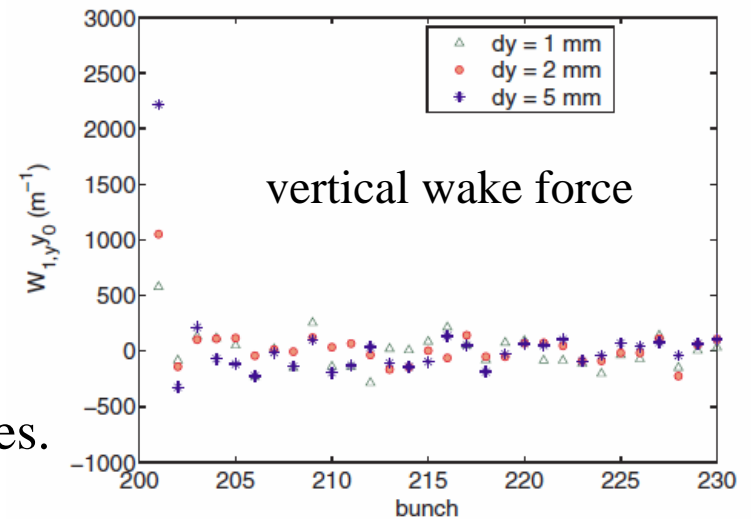
M. A. Furman and M.
T. F. Pivi, PRST-AB 5,
124404 (2002)

2) Transverse coupled bunch instability (PEI)

- The electron cloud build-up is estimated in a similar way as described before assuming that the motion of the bunch is not affected by the EC.
- The growth rate of the CBI is calculated by two ways.

A) Wake force method

- A bunch is slightly displaced in the EC.
- The trailing bunches experience forces from the perturbed cloud.
- The wake field is calculated from these forces.
- The method assumes a linearity and superposition of the beam-EC force.



S. S. Win et al., PRST-AB 8, 94401 (2005)

B) Tracking method

- The equations of motion are directly solved numerically.
- This method is time consuming, but the linearity and the superposition of the beam-EC interaction are not assumed any longer.

3) Single bunch instability (PEHTS)

- The bunch and the EC are modeled as a group of macro particles like in the strong-strong model of the beam-beam force.
- A simple kick and drift integrator is used to integrate the motion of particles.
- Beam-EC kick is calculated from the electric potential by [Particle-In-Cell method](#).

Fourier transform is applied to use an FFT which speeds up the calculation.

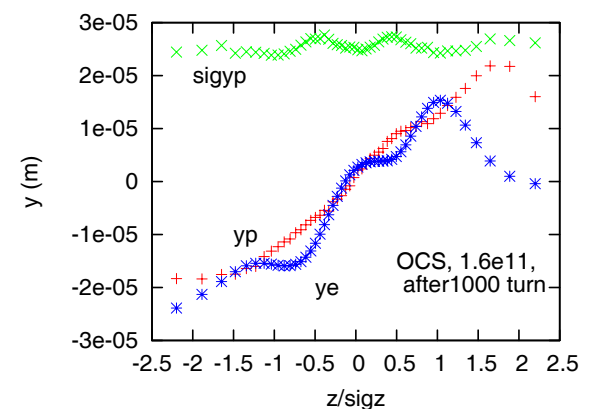
$$\phi(r) = \int dr' G(r-r') \rho(r'), \quad G(r) = \ln |r|$$

$$\hat{\rho}(k) = \int \rho(r) \exp(ik \cdot r) dr, \quad \hat{G}(k) = \int G(r) \exp(ik \cdot r) dr$$

$$\Rightarrow \phi(r) = \frac{1}{(2\pi)^2} \int \hat{G}(k) \hat{\rho}(k) dk$$

The beam-EC kick is evaluated from the interpolated potential.

Head-tail oscillation



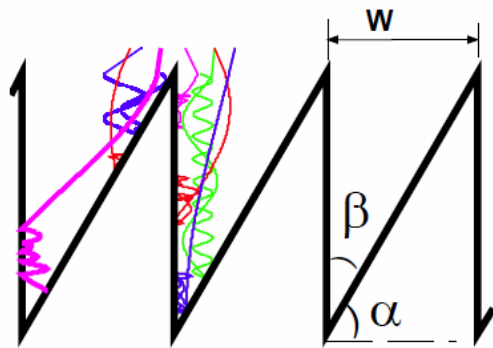
4. Cures

A) Coating and scrubbing

- Coating of the chamber surface by low SEY materials, e.g. TiN and TiZrV, is effective to decrease the electron buildup.
- The scrubbing helps to decrease the SEY further as described before.

B) Grooved surface

- A grooved surface effectively lowers the SEY both in field free and the magnetic field regions.
- In the magnetic field,
 - ◇ If the electron hits the edge, the secondary electrons execute gyration, then hit the wall with low SEY due to their low energy.
 - ◇ If the bunch spacing is longer than gyration period, the number of electrons decreases due to successive secondary emission.



L. Wang et al., SLAC-PUB-12001 (2006)

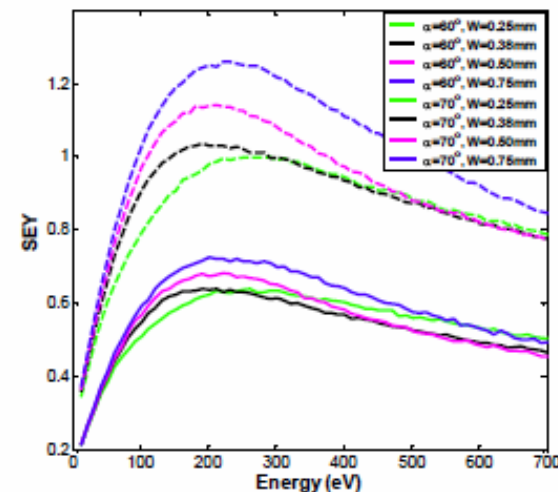
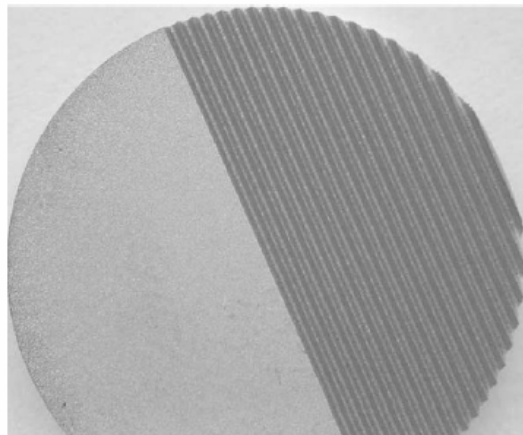


Fig. 7. Effective SEY from sawtooth surface in a dipole magnetic field. $\delta_{\text{max}}=1.74$, $E_{\text{max}}=330\text{eV}$, $B_0=0.3\text{Tesla}$.

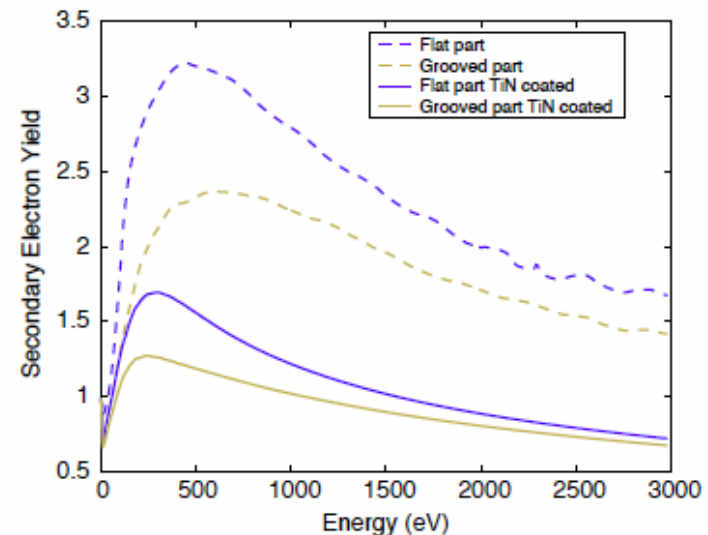
- A grooved surface contributes to the resistive wall impedance.

A calculation shows that the impedance is enhanced by a factor of 1.5 for a rectangular groove with a round fin tip.

- A laboratory test of a triangular grooved surface was done at SLAC. The result shows that the effective SEY decreases to 1.1 with TiN coating.



Aluminum triangular grooves are 1mm deep and full opening angle, α , is 40 deg..



F. Le Pimpec et al., NIM A 551 (2005) 187

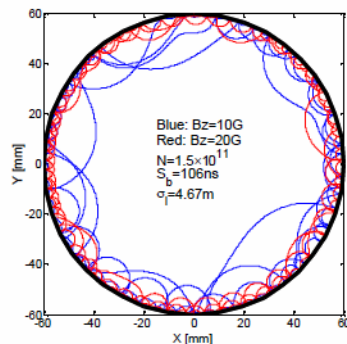
C) Solenoid

- A weak solenoid confines electrons near the chamber wall.
- The solenoid is effective to decrease the electron density especially near the beam.
- A typical solenoid field is several 10s Gauss because the energy of the electrons is low.
- A resonate growth of the electrons, which should be avoided, was predicted.

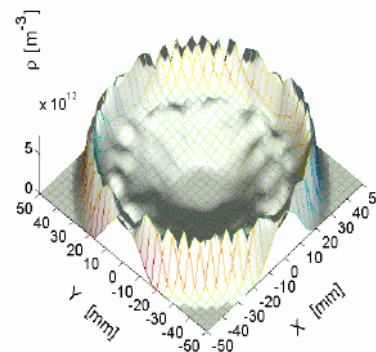
Cyclotron period/2 = Time interval between two consecutive bunches

The magnetic field at resonance is 40 G, if the bunch spacing is 4ns.

- Solenoids can not be applied in a strong magnetic field.



KEKB LER, 8ns spacing, 8×10^{10} positrons



L. F. Wang et al., ELOUD04

D) Clearing electrode

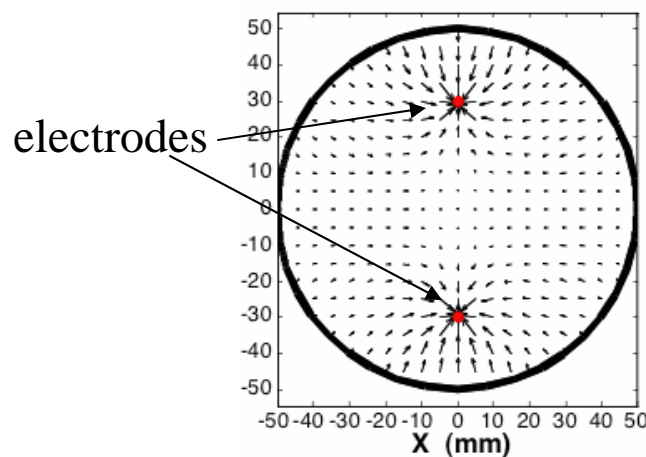
- An electrode is a candidate for clearing the electrons.
- Unlike the solenoid, the electrode works in a strong magnetic field.

i) Multi-wire electrode

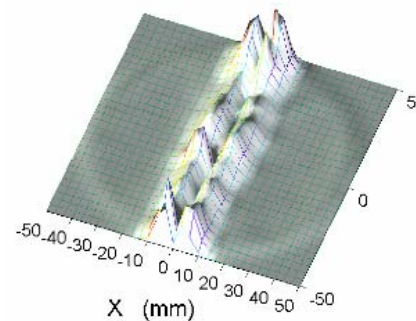
- Electrodes are negatively biased. They push electrons to the wall immediately after the electrons are created on the wall.
- Required voltage is an order of hundred volt because the electron energy is low, typically 5 eV.
- As the electrodes are located apart from the wall they reduces the physical aperture of the machine.

The impedance by the electrodes may be an issue.

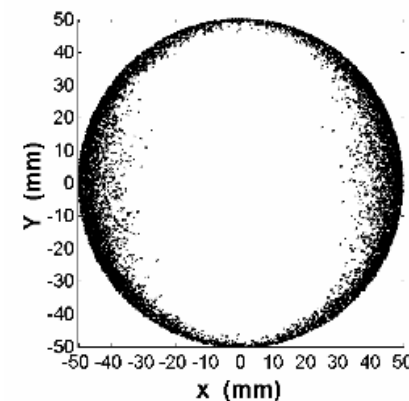
L. F. Wang et al., Proc.
EPAC2006, 1489 (2006)



EC in a dipole of KEKB



Voltage of electrodes : 0V



-400 V

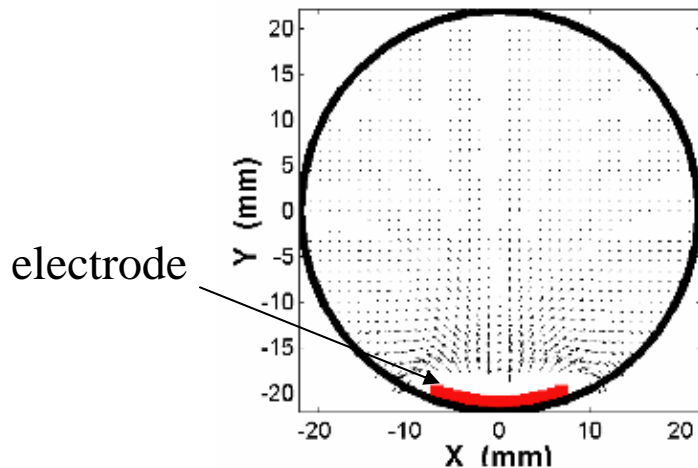
ii) Traditional strip line electrode

- Positive voltage is applied to attract the electrons to the electrodes.
- Gaps between electrodes and the chamber can be narrow.

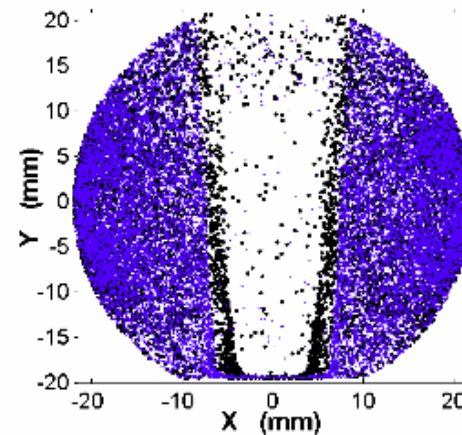
The electrodes may be better on reducing the impedance than the multi-wire electrodes.

Dipole of ILC damping rings

Electrodes configuration



Electron distribution



L. F. Wang et al., Proc. EPAC2006, 1489 (2006)

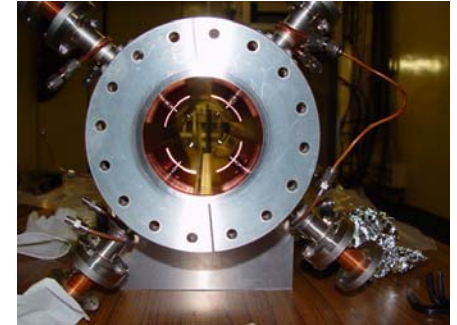
E) Feedback system

- A bunch by bunch feedback system is effective to suppress the CBI.

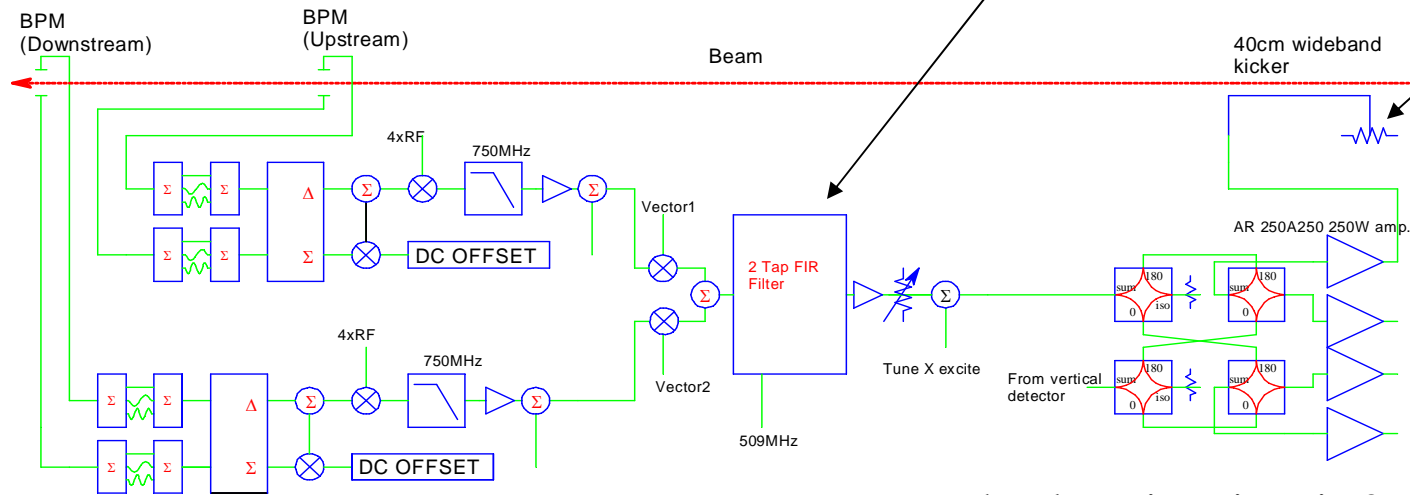
Filter board with custom
multiplex/demultiplex IC



Strip line kicker



KEKB



The damping time is 0.5ms (50 turns).

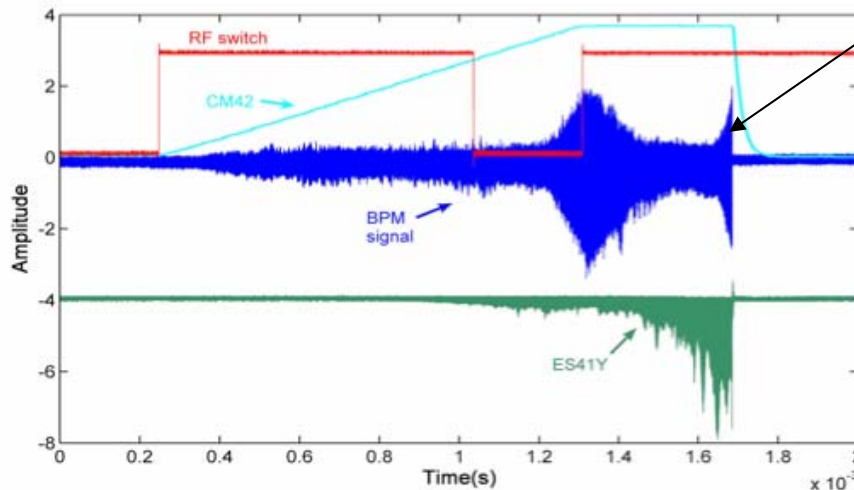
KEKB Transverse Bunch Feedback System

M. Tobiyama, LLRF05

- The e-p instability for **long proton bunch** machines differs from other instabilities that have been treated by the feedback systems.
- A proof of principle experiment is in progress at PSR.

PSR (Bunch length : 70 m, Circumference : 90 m, energy : 800 MeV)

- The system consists of a strip line BPM, a comb filter and two 100 W power amps for a strip line kicker.
- Band width of the feed back after BPM is 50 - 250MHz.
- Result of "damp-grow-damp" experiment



Second growth (feed back on).
Likely caused by beam-in-the-gap.

- Damping rate of the feedback
 $1.75 \times 10^4 \text{ sec}^{-1}$

- The highest amplitude growth rate ($10^5/\text{s}$) to be damped at PSR is a challenge for feed back systems.

Courtesy of R. Macek

R. Macek et al., Proc. HB2006 (2006)

5. Impact on under-construction and planned accelerators

A) ILC damping ring

- Simulations show that the EC density near the beam is suppressed below instability threshold if the SEY is less than 1.2 and the solenoids are installed in drift regions.
- Following mitigation methods are considered.

1) Conditioning

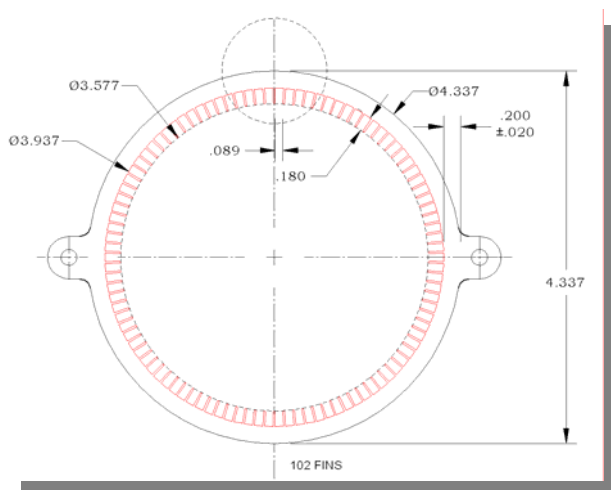
- ◇ In-situ measurement of SEY is planned at PEP-II.
- ◇ The SEY of a sample conditioned by synchrotron radiation is measured in a laboratory.

2) Fin or grooved chamber

- Rectangular Grooves in field free region have been installed in PEPII.

The beam test will start soon.

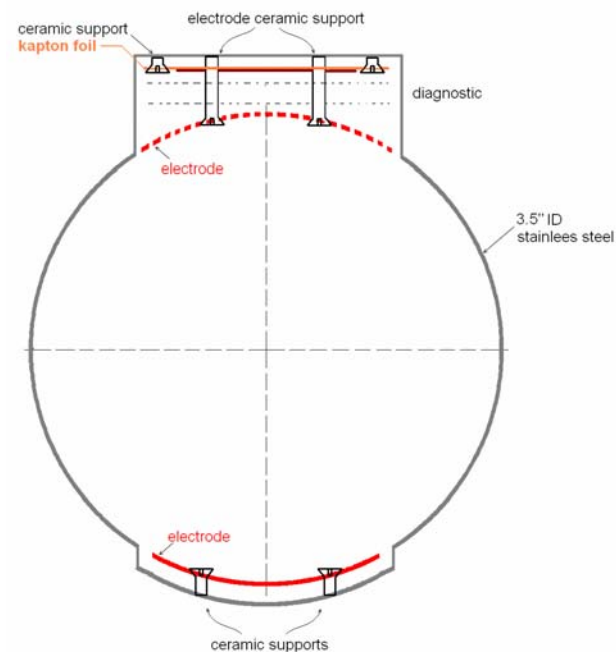
- Triangular Grooves in a dipole magnet will be fabricated and tested in PEPII.



TiN coated Aluminum.

3) Clearing electrodes

- Strip line electrodes in a dipole magnet will be fabricated and tested in PEPII.



Courtesy of M. Pivi

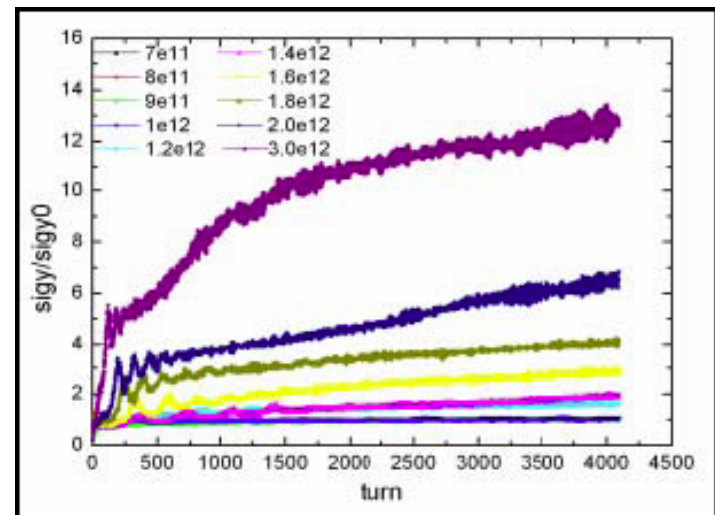
B) BEPCII

- The antechamber with TiN coating is adopted in the arc to reduce the primary and secondary electron yields.
- According to a simulation the EC density can be reduced to $1.3 \times 10^{11} \text{m}^{-3}$.
- A simulation of the instability shows that

1) the threshold electron density of the strong head-tail instability is $9.2 \times 10^{11} \text{m}^{-3}$ which is higher than the expected electron density,

2) the growth time of the CBI is about 4.3 ms which should be damped by the feedback system.

Simulation of beam size blowup



C) LHC

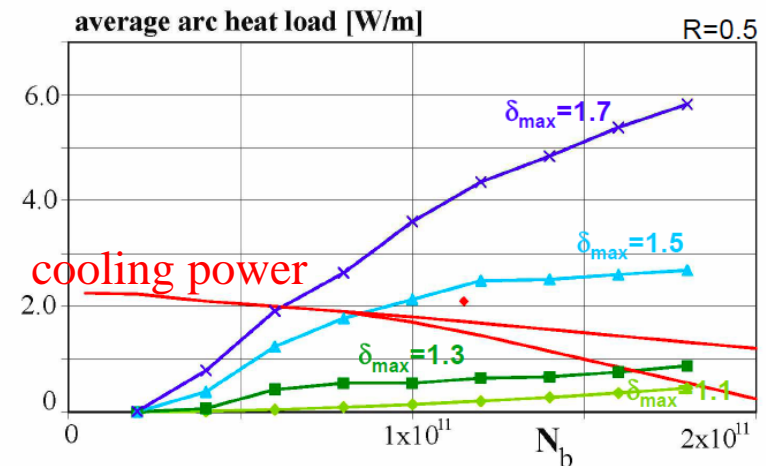
- The impact of secondary electrons due to the EC is i) a heat load on the beam screen and ii) a potential emittance growth.

Heat load

- The electrons hitting the wall deposit the energy to the wall, which gives heat load to the cryogenic system.

- If $\delta_{\max} > 1.3$, the resulting heat load exceeds the cooling capacities of the beam screen.
- To achieve $\delta_{\max} < 1.3$, the beam screen surfaces need to be conditioned during the machine commissioning.

arc heat load vs. intensity, 25 ns spacing, 'best' model



F. Zimmermann, Electron Cloud, LHC MAC, June 2005

- A simulation by POSINST including rediffused electrons shows that δ_{\max} must be less than 1.2 for the available cooling capacity of 1.7 W/m.

6. Summary

- The EC effects have been studied for 40 years. The results contributed to performance improvements of the existing accelerators and to the design of the new accelerators as shown in the recent success of SNS where many EC countermeasures were taken based on design studies.
- In author's view the following might be interesting subjects for further study.
 - 1) the slow emittance growth below the threshold of the coherent instability,
 - 2) the density and the distribution of the EC in magnets,
 - 3) the effect of the grooved surface and electrodes in the beam,
 - 4) in-situ measurement of the secondary electron yield of technical materials which includes the scrubbing effect,
 - 5) the active feedback system for a long proton bunch,
 - 6) the understanding of the tune shift caused by the EC,
 - 7) the study of the sideband to obtain the information of the beam-EC interaction at short range.

7. Acknowledgments

- I would like to thank all authors of the papers where I referred in this talk.
- I also would like to thank J. W. Flanagan, S. Kato, B. Macek, K. Ohmi, M. Pivi, Y. Suetsugu and L. F. Wang for useful comments and information.
- I especially thank F. Zimmermann for his valuable comments in preparation of this talk.
- I apologize to those who contributed to the study of the electron cloud but are not mentioned in this talk due to a lack of his knowledge.