PERSPECTIVE ON ELECTRON CLOUD EFFECTS

KATHERINE C. HARKAY

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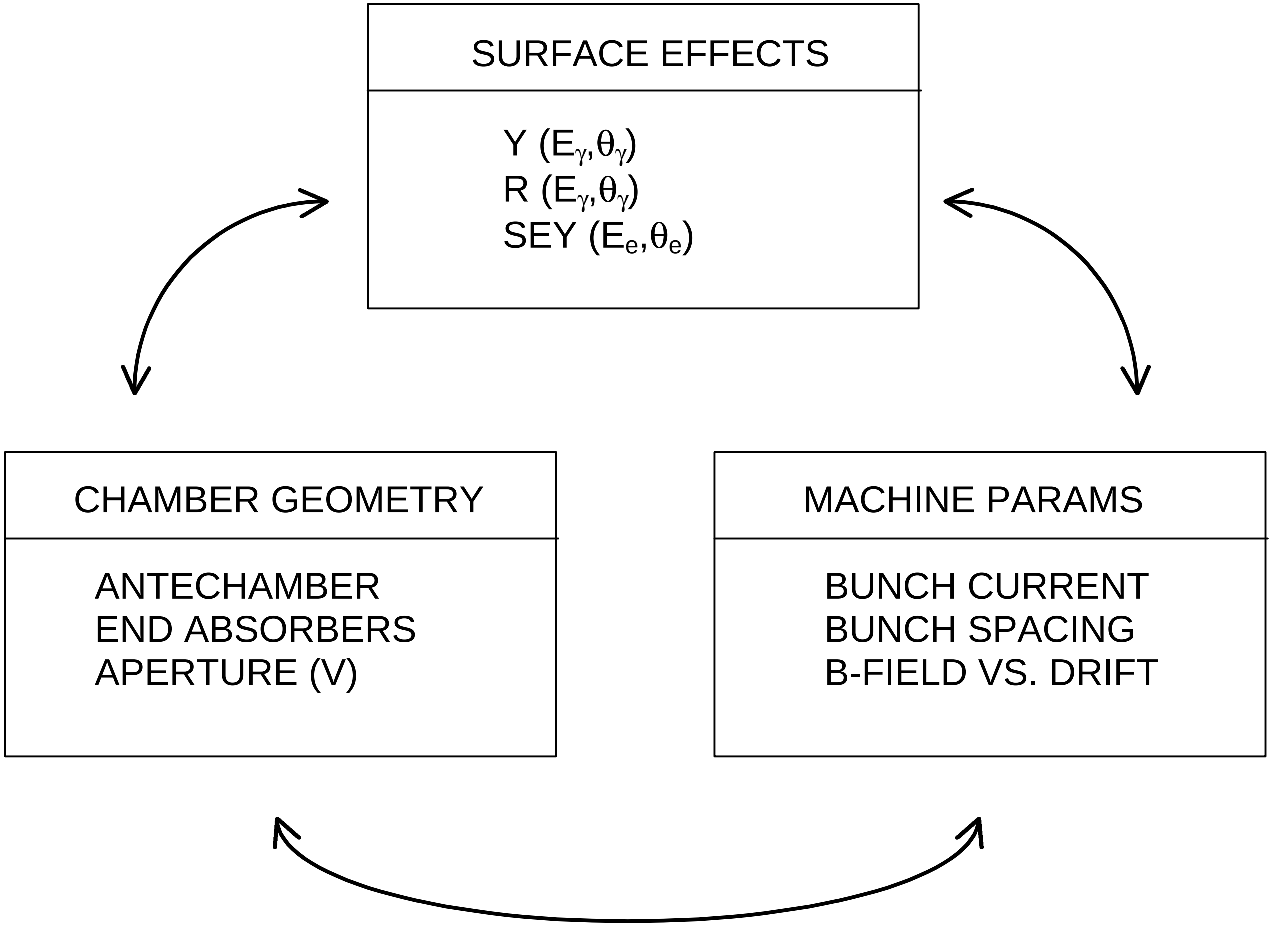
R. Rosenberg, ANL
J. Galayda, ANL
M. Furman, LBNL
S. Heifets, SLAC
R. Macek, LANL

OUTLINE

- Critical parameters
- Recent measurements
- Theory/simulation
- Cures/Challenges
- Summary

CRITICAL PARAMETERS FOR ELECTRON CLOUD



SURFACE EFFECTS

Y (E_γ,θ_γ)
R (E_γ,θ_γ)
SEY (E_e,θ_e)

CHAMBER GEOMETRY

ANTECHAMBER
END ABSORBERS
APERTURE (V)

MACHINE PARAMS

BUNCH CURRENT
BUNCH SPACING
B-FIELD VS. DRIFT

— Not obvious that simple scaling rules can be found —

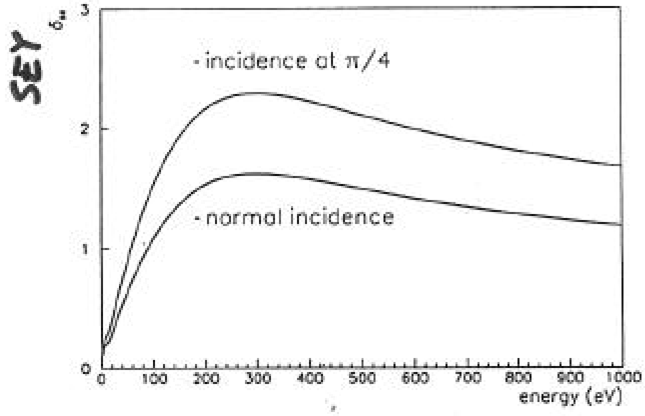


Figure 1: **Secondary electron yield $\delta_{\rm SEY}(W,\theta) = \frac{\delta_{\rm max}}{\cos\theta}\, h\left(\frac{W}{W_o}\right)$, as a function of the primary electron energy W** for normal incidence $\theta = 0$ (lower curve) and incidence at $\theta = \pi/4$ (upper curve). The maximum yield $\delta_{\rm max}$, corresponding to a primary electron energy W_o typically around 300 eV, is a characteristic of the metal, while h is a universal function having the phenomenological expression $h(\xi) = 1.11\,\xi^{-0.35}\left(1 - e^{-2.3\,\xi^{1.35}}\right)$.

F. Ruggiero

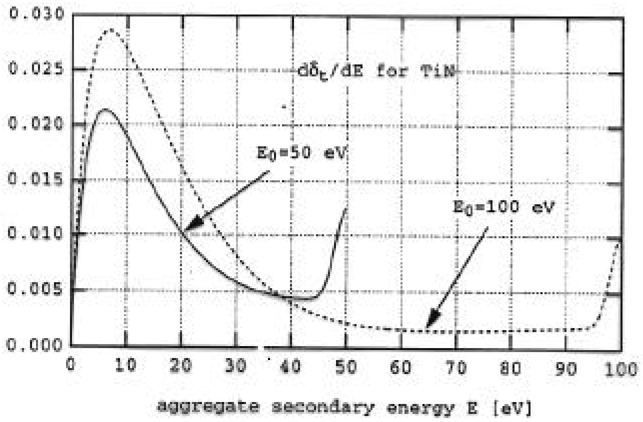
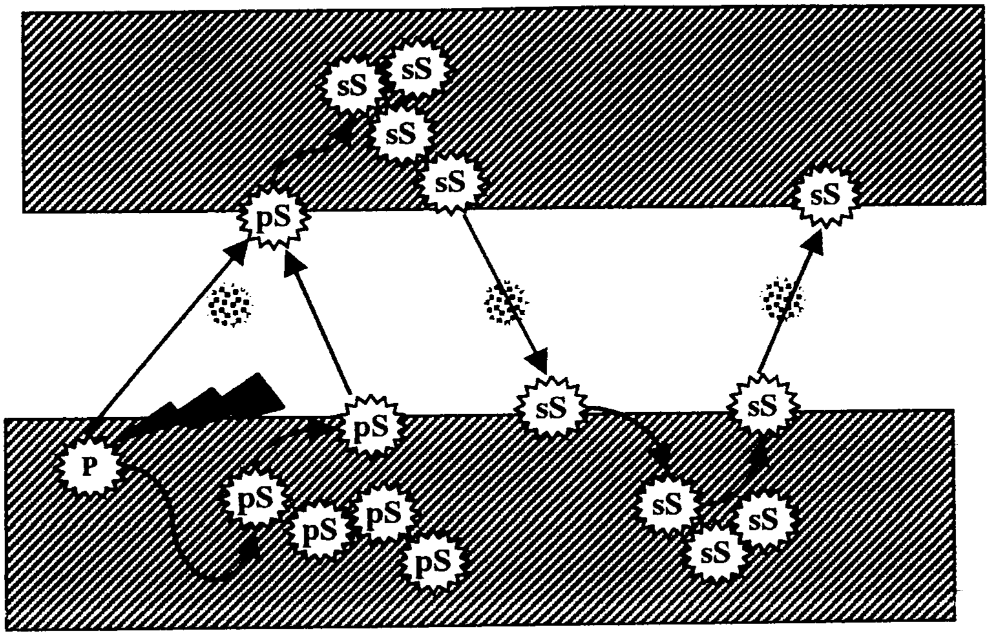


Figure 9: The energy dependence of the SEY, $d\delta_t/dE$, at normal incidence for incident electron energies $E_0 = 50$ and 100 eV. This function is computed for the parameters stated in the text, keeping up to the $n = 10$ term in Eq. (4.22).

M. Furman

MECHANISMS FOR

BEAM-INDUCED ELECTRON CLOUD

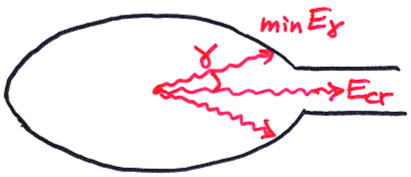


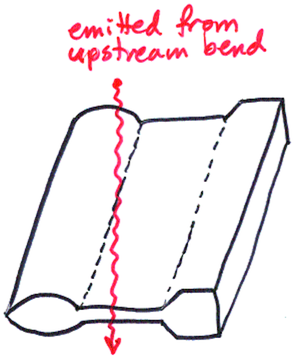
R. Rosenberg

⁘	beam bunch	
⚡	synchrotron photons	
P	photoelectrons	PE: primary component
pS	primary secondary electrons	
sS	secondary secondary electrons	SE: secondary component

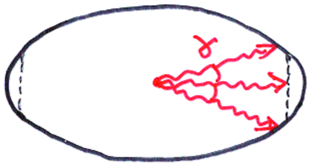
VACUUM CHAMBER GEOMETRY

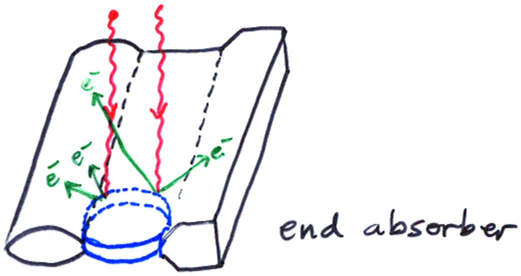
Typical antechamber

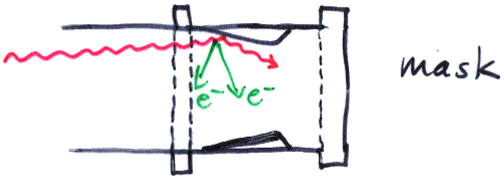




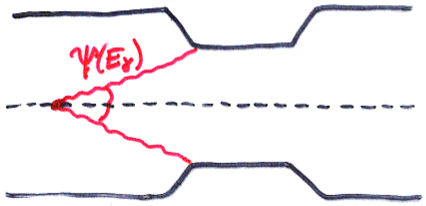
No antechamber / radiation absorber or mask







small-gap restriction



ELECTRON CLOUD EFFECTS INCLUDE

- Beam-induced multipacting -> vacuum and beam lifetime degredation
- Collective effects produced by
    - effective wakefield of the cloud; “non-resonant” interaction with beam: electron cloud instability (ECI)
    - cloud electron trapped in magnetic fields, eg. DIPs (CESR), or beam (e-p)
- Heat load on cryogenic systems by electron bombardment of walls (LHC)

EFFECTS CAN BE IMPORTANT IN e+, e- and p RINGS

WHO IS INTERESTED IN ELECTRON CLOUD EFFECTS?

HIGH-ENERGY, MULTIBUNCH e- e+ RINGS

- KEK Photon Factory (1995, K. Ohmi)
- Beijing e- e+ collider (BEPC)
- CESR (Cornell) (electrons trapped in DIP fields)
- B-Factories (PEP-II, KEKB)
- Phi-Factories (DAPHNE)

HIGH-INTENSITY and/or HIGH-ENERGY HADRON RINGS

- LHC
- Proton Storage Ring (PSR), LANL
- Boosters (BNL, KEK, etc)
- Proton Drivers (Spallation Neutron Source, Muon Collider)

MACHINE PARAMETERS

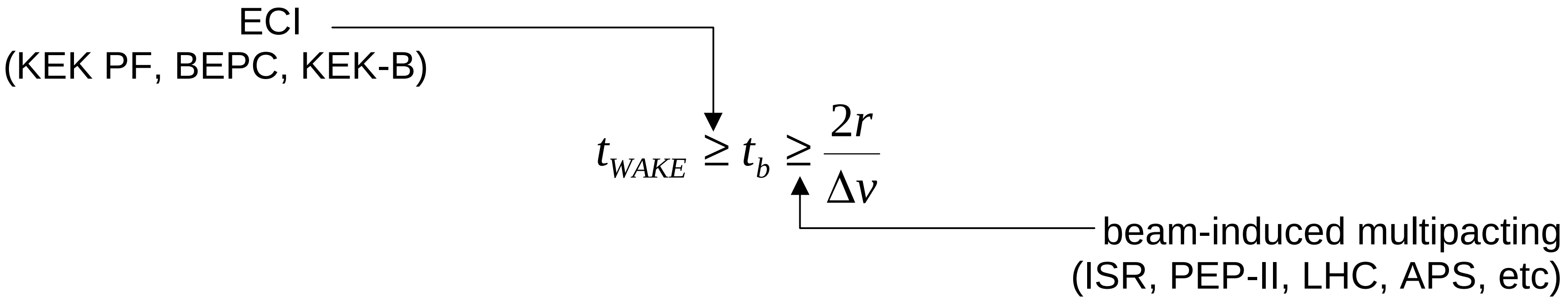
	PF	BEPC	CESR	APS	KEKB	PEP-II	LHC
E (GeV)	2.5	2.2	5.3	7	3.5 / 8*	3.1 / 9*	7000
max. # bunches, N	312	160	1281	1296	5120	1658	2835
min. bunch spac. (m)	0.6	1.5	0.6	0.85	0.59	1.26	7.5
I (max.) (mA)	300	20 - 30	300	100	2600/1100	2140/980	540
photon critical E (keV)	4	2.3	3.7	19.5	6[&]	4.8[&]	0.044
chamber radius or semi-axes (h, w) (mm)	–	29 60	25 45	21 42	48[&]	25 45[&]	22
chamber surface material	Al	Al	Al	Al	Cu	TiN,Cu,SS	Cu

* LER (e+) / HER (e-)

[&] LER only

– not available

APPROX. REGIMES FOR VARIOUS EFFECTS



ECI
(KEK PF, BEPC, KEK-B)

$$t_{WAKE} \geq t_b \geq \frac{2r}{\Delta v}$$

beam-induced multipacting
(ISR, PEP-II, LHC, APS, etc)

where

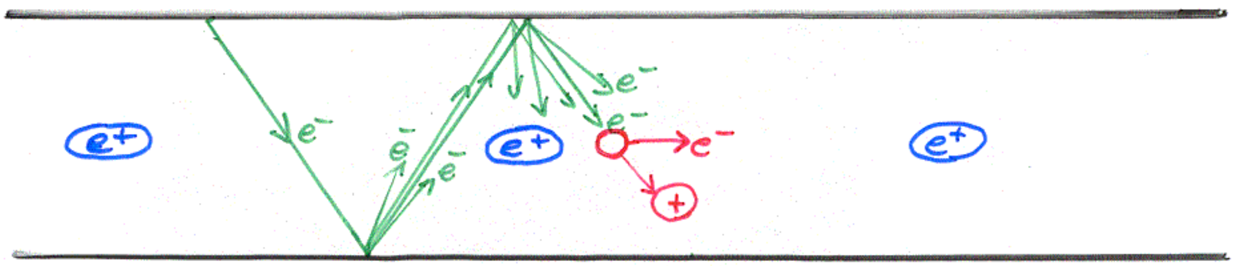
t_{WAKE} is the range of the effective EC wakefield,
t_b is the bunch spacing,
r is chamber half-height and
Δv is velocity change of electron due to kick by beam bunch

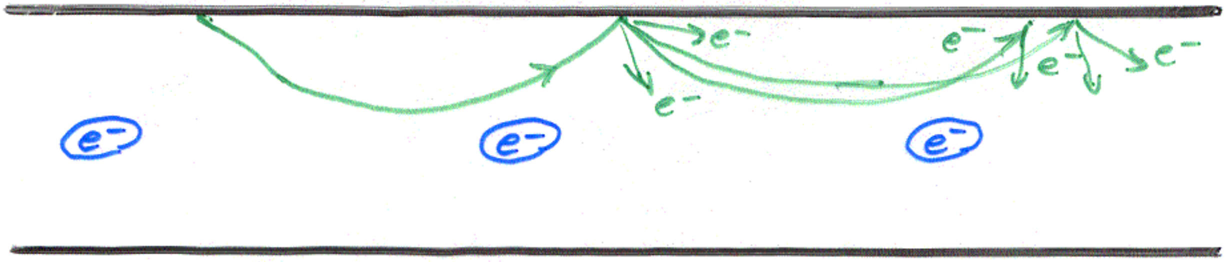
PRIMARY ELECTRON DOMINATED:

SEY unimportant
Very large or very small t_b
$t_{WAKE} \longrightarrow \langle E_{e-} \rangle$

SECONDARY ELECTRON DOMINATED: BEAM-INDUCED MULTIPACTING

BEAM-INDUCED MULTIPACTING





Large SEY + resonant $t_b \longrightarrow$ PE unimportant

- Run-away buildup of electrons
- Electron induced gas desporption
- Secondary electron (SE) dominated
- $t_{WAKE} \longrightarrow \langle E_{e-} \rangle, \langle n_{e-} \rangle$

RECENT MEASUREMENTS

Goal: realistic limits on critical input parameters in the models to improve predictive power

APS

- Measure the properties of the electron cloud directly: a special 5-m vacuum chamber installed, equipped with rudimentary electron energy analyzers, BPMs and targets

PEP-II

- No evidence of ECI, but clear evidence for beam-induced multipacting, with a large pressure rise above 1 mA/bunch in 500-1000 bunches

BEPC (ECI)

- Time-domain measurements using a single-pass BPM system; measured ECI rise times of ~6 ms compare well with the predicted value of 3 ms.

KEK-B (ECI?)

- Vertical blowup (σ_y) as a function of (bunch current / bunch spacing)

CERN (main issue: beam-induced multipacting heat load for LHC)

- Photon irradiation tests using an existing EPA beam line (CERN) to study the Y and R
- Multipacting tests using a resonant coaxial cavity

BEAM-INDUCED MULTIPACTING

Independent experimental results at APS, PEP-II, and CERN are beginning to converge

- APS: long trains of bunches spaced at 20 ns and 2 mA/bunch accompanied by a significant local pressure rise (pressure rise with 1 mA/bunch not significant)
- PEP-II: very similar bunch current-dependent pressure rise effect, with a threshold above 1 mA/bunch.
- Vertical aperture and 20-ns bunch spacing at APS are nearly the same as the LHC aperture and bunch spacing, for which calculations predict that multipacting conditions are satisfied
  - maximum energy of primary electrons incident on the walls differ (using the impulse approx.): 200 eV at LHC vs. 10 eV at APS, BUT
  - peak of the SE energy distribution (~5 eV) nearly independent of material and incident electron energy*

* W. H. Kohl, Handbook of Materials and Techniques for Vacuum Devices, AIP Press (1995);
Seiler, Phys. 54 (11) (1983)

SURFACE CONDITIONING and SEY

Electron bombardment of the chamber surface lowers the SEY *in-situ* or in bench tests

APS (Al): SE-dominated signal reduced to 45% after 60 A-h of stored beam
(est. 5 x 10^{18} e/cm^2 dose at 100 mA)

SLAC: a 25% reduction after a dose of ~10^{18} e/cm^2 (15 A-h equivalent in PEP-II)

CERN: a dose of ~10^{18} C/cm^2 reduced the SEY for Cu to below 1.3, the critical value for multipacting in LHC (~200 h)

THEORY/SIMULATION

- The three major numerical models for electron cloud effects were developed by:

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

M. Furman and G. Lambertson, LBNL [Proc. of MBI97, KEK Proc. 97-17]

F. Zimmermann, SLAC [SLAC-PUB-7425 (1997)], further developed by

O. Brüning, CERN [Proc. of 1998 EPAC, 332 (1998)]

- Simulation studies are complemented by analytical work by (list incomplete):

S. Heifets, SLAC [Proc. of CEIBA95, KEK Proc. 96-6 (1996)]

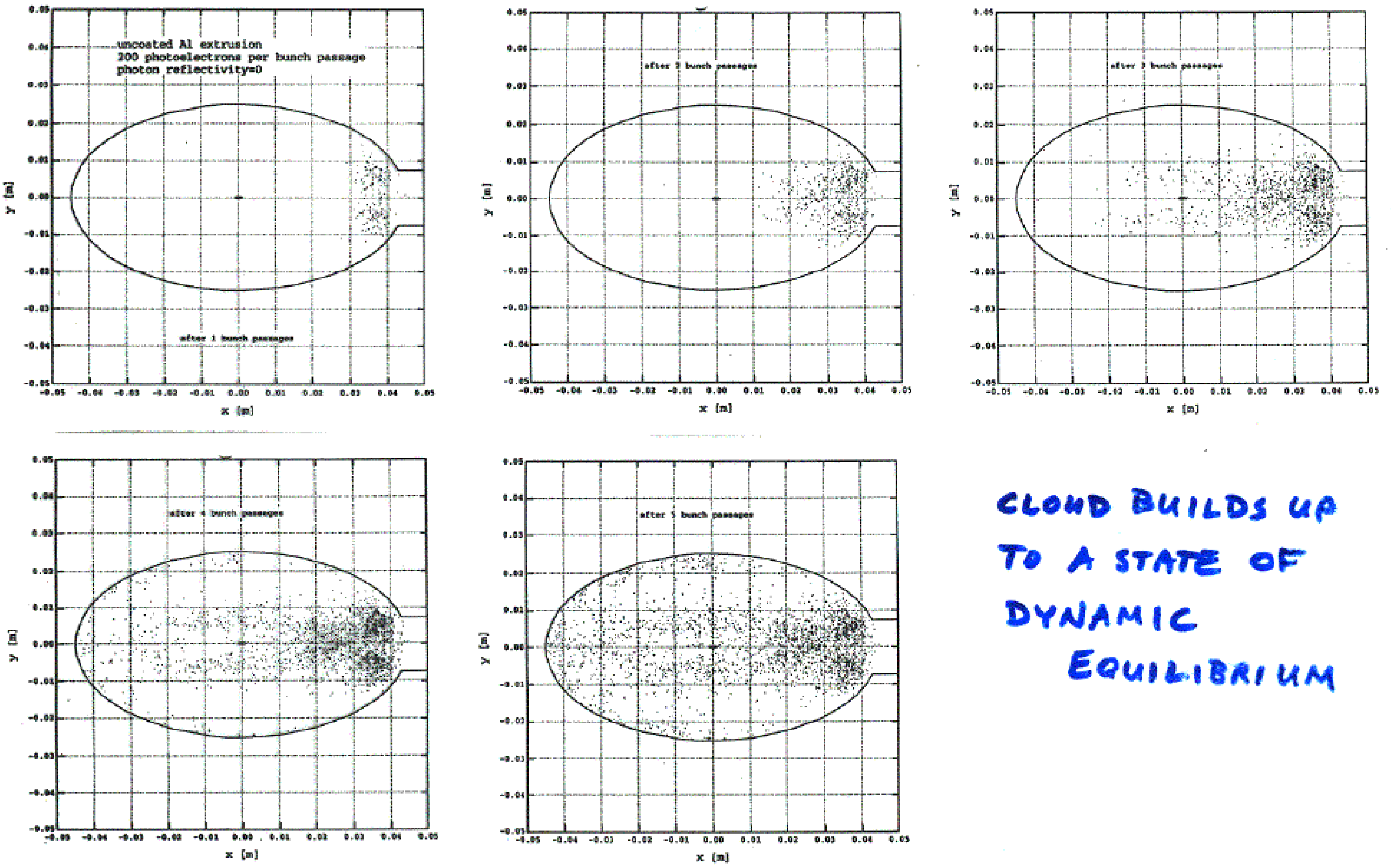
N. Dikansky and A. Burov, BINP [KEK Proc. 97-17, 200 (1997)]

G. Stupakov, SLAC [LHC Project Note 141 (1997)]

L. Vos, CERN [LHC Project Note 150 (1998)]

- Quantitative comparisons of codes are improving

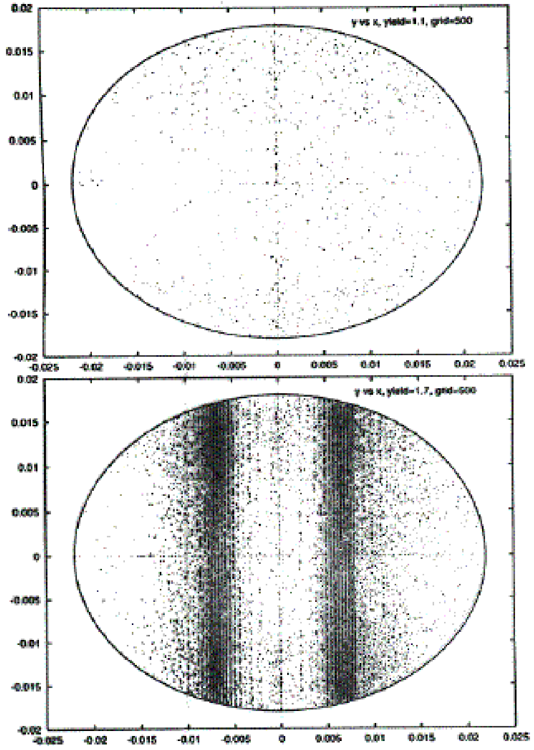
CLOUD BUILD-UP (R=0): SAMPLE SIMULATION RESULTS FOR PEP-II (M. Furman, MBI97)



CLOUD BUILDS UP
TO A STATE OF
DYNAMIC
EQUILIBRIUM

EC WITH DIPOLE FIELD

- confined to tight vertical helices
- p_x suppressed



SEY=1.1

SEY=1.7

Figure 5: Transverse distribution of macroelectrons after 40 bunches for a maximum secondary emission yield δ_{max} of 1.1 (top) and 1.7 (bottom). Horizontal and vertical dimensions are given in units of m.

R=0.9

F. Zimmermann, SLAC-PUB-7425

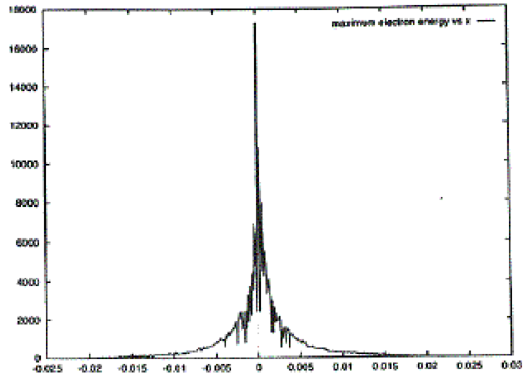
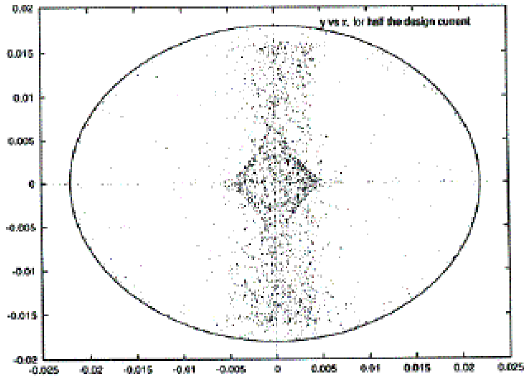


Figure 6: Maximum electron energy (in eV) after the passage of the 41st bunch as a function of the horizontal electron position (in m). Energies with maximum secondary-emission yield (~400 eV) are found about 5-8 mm from the beam-pipe center. This could explain the strong nonuniformity of the horizontal distribution seen in the bottom part of Fig. 5.

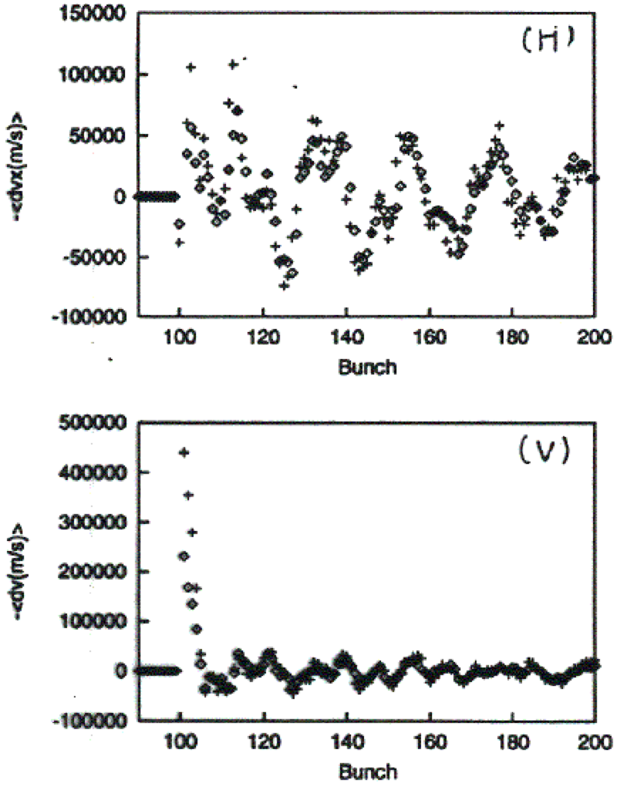


$\frac{N_b}{2}$

Figure 7: Transverse distribution of macroelectrons for half the design current per bunch after 40 bunches for a maximum secondary emission yield δ_{max} of 1.7. Horizontal and vertical dimensions are given in units of m.

K. Ohmi, MBI97

KEKB-LER



Growth of nth bunch [M. Furman]

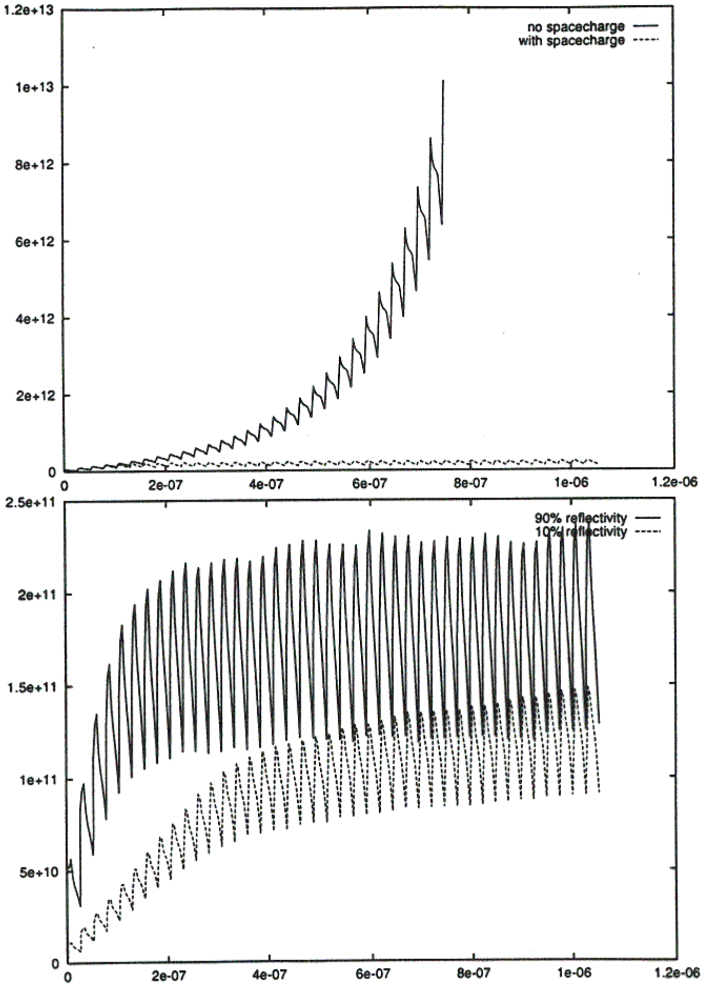
$$y_n = \frac{1}{n!}\left(\frac{t}{\tau}\right)^n y_0$$

Figure 4: Horizontal and Vertical wake force. The wakes by 0.5mm and 1mm displacements are marked by tilt boxes and crosses, respectively

R = 0

F. Zimmermann
SLAC-PUB-7425
(1997)

SATURATION DUE TO SPACE CHARGE



NO s.c.

W/s.c.

Figure 3: Charge of the electron cloud (in units of e) accumulated in a bending magnet as a function of time (in s); top: with and without space charge; bottom: with an emission probability η_{pe}^{eff} of 1 photoelectron/photon (corresponding to 90% photon reflectivity at the beam screen) and with an effective emission probability of only 0.2 photoelectrons per photon (for a reduced photon reflectivity). A maximum secondary-emission yield δ_{max} of 1.5 was assumed.

CURES

ACTIVE

- feedback realistic: electron cloud instability growth rate ~ 6 ms measured at BEPC

PASSIVE

- Weak solenoidal field (50 G) effective in field-free region, but not with strong dipole (KEK-B, CERN)
- Clearing electrodes have not shown promise as being effective (PF, PSR, etc)
- Avoid beam-induced multipacting through choice of bunch spacing
- Chamber surface preparation
  - coating with low SEY material, e.g. TiN (PEP-II, CERN)
  - standard *in situ* bakeout
  - *ex situ* bakeout in air of thechnical Cu surface: thick oxide layer lowers SEY (I. Bojko et al., CERN)
  - ribbed structures (shadow upper/lower chamber wall from reflected photons) (CERN)
  - electron bombardment

CHALLENGES

SURFACE EFFECTS UNDERSTOOD?

MEASUREMENTS REQ'D: SEPARATE SPATIAL & ENERGY DISTRIB'S OF CLOUD?

Greatest variations in predicted cloud saturation levels and instab growth rates involve

- electron production processes
- influence of external magnetic field

EITHER/OR?

- separate effects due to chamber impedance from electron cloud wake
- are "non-resonant" ECI and beam-induced multipactor independent?

UNIVERSAL SCALING RULES?

- beam-induced multipactor: maybe!
- ECI less clear: dependence on s_L, t_b, I_b, s_y, etc

MODELING

- chamber geometry z-dependence

MORE QUANTITATIVE THEORY NEEDED

- many experimental results explained after the fact: need predictive capabilities

SUMMARY

- Electrons are ubiquitous in accelerators/storage rings
- Experimental and theoretical/modeling work ongoing
- Independent experimental results at APS, PEP-II, CERN on beam-induced multipacting are beginning to converge (-> universal scaling rules?)
- How far can active damping and passive control raise the instability or beam-induced multipacting thresholds?
- Need a more comprehensive, quantitative theory to address challenges