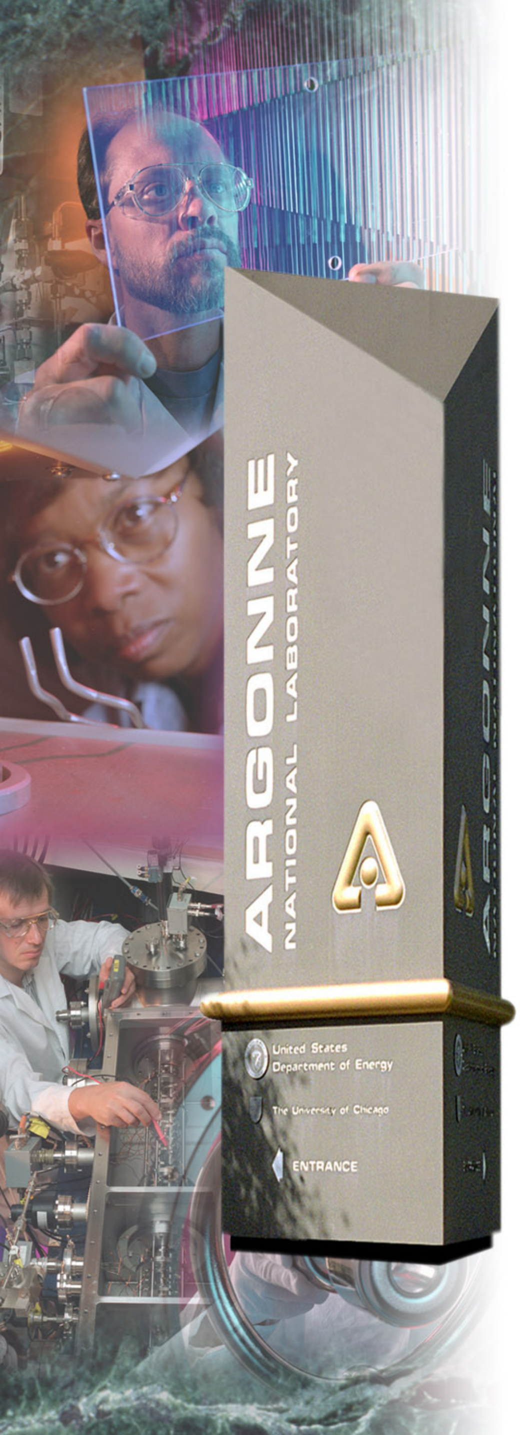

Electron Cloud Observations: A Retrospective

K.C. Harkay
Advanced Photon Source, ANL

31th Advanced ICFA Beam Dynamics Workshop
on Electron Cloud Effects

Napa, CA, Apr. 19-23, 2004

Office of Science
U.S. Department of Energy

A U.S. Department of Energy
Office of Science Laboratory
Operated by The University of Chicago

Retrospective: 1. Looking backward; contemplating things past; 2. an exhibition of a representative selection of an artist's life work

Sometimes it is useful to contemplate an entire body of work: EC observations and analysis – selected examples shown

Acknowledgements – an incomplete list…

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A. Kulikov
R. Kirby
F. Zimmermann

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A. Novokhatski
J. Seeman
Y. Cai
A. Browman
T-S. Wang
J.M. Jiminez
L. Wang

K. Ohmi
E. Perevedentsev
Z. Guo
BEPC team
PEPII team
LHC/SPS team
PSR team
APS team

Outline

- **Brief history**
- **Electron cloud**
  - Effects
  - Production
  - Diagnostics
- **Experimental observations**
- **Cures**
- **Summary**

Introduction

- A growing number of observations of electron cloud effects (ECEs) have been reported in positron and proton rings
- Low-energy, background electrons ubiquitous in high-intensity particle accelerators
- Amplification of electron cloud (EC) can occur under certain operating conditions, potentially giving rise to numerous effects that can seriously degrade accelerator performance
- EC observations and diagnostics have contributed to a better understanding of ECEs, in particular, details of beam-induced multipacting and cloud saturation effects
- Such experimental results can be used to provide realistic limits on key input parameters for modeling efforts and analytical calculations to improve prediction capability

References & Workshops

Review talks at Accelerator Conferences: J.T. Rogers (PAC97), F. Ruggiero (EPAC98), K. Harkay (PAC99), F. Zimmermann (PAC01), G. Arduini (EPAC02), M. Furman, M. Blaskiewicz (PAC03) http://www.aps.anl.gov/asd/physics/ecloud/papers_top.html

ICFA Beam Dynamics Newsletter No. 31, Aug. 2003: special edition on High Luminosity e+e- Colliders http://wwwslap.cern.ch/icfa/

Workshops, past:

- ***Multibunch Instabilities Workshop*, ** KEK, 1997 KEK Proc. 97-17
- ***Two-Stream ICFA Mini Workshop*, ** Santa Fe, 2000 http://www.aps.anl.gov/conferences/icfa/two-stream.html
- ***Two-Stream Workshop*, ** KEK, 2001 http://conference.kek.jp/two-stream/
- ***ECLOUD02*, ** CERN, 2002 http://slap.cern.ch/collective/ecloud02/
- ***Beam-Induced Pressure Rise***, BNL, Dec. 2003 http://www.c-ad.bnl.gov/icfa/
- ***ECLOUD04*, ** Napa, CA, Apr. 2004 http://www.cern.ch/icfa-ecloud04/

Origins

Electron cloud effects (ECEs) were first observed ~30 yrs ago in small, medium-energy proton storage rings; described as: Vacuum pressure bump instability, e-p instability, or beam-induced multipacting:

- **BINP Proton Storage Ring** [G. Budker, G. Dimov, and V. Dudnikov, Sov. Atom. E. 22, 5 (1967); see also review by V. Dudnikov, PAC2001, 1892 (2001)]
- **CERN Intersecting Storage Ring (ISR)** [Hereward, Keil, Zotter (1971)]
- **Proton Storage Ring (PSR)** [D. Neuffer et al. (1988, 1992)]

First observation in a positron ring ca. 1995: Transverse coupled-bunch instability in e+ ring only and not in e- ring:

- **KEK Photon Factory (PF)** [M. Izawa, Y. Sato, T. Toyomasu, PRL 74, 5044 (1995) and K. Ohmi, PRL 75, 1526 (1995)]
- **IHEP Beijing e+/e- collider (BEPC)**: experiments repeated and PF results verified [Z.Y. Guo et al., PAC1997, 1566 (1997)]

See articles by H. Fukuma, F. Zimmermann, *ICFA BD Newsletter* No. 31, Aug. 2003

Origins (cont.)

Transverse multibunch instabilities at CESR discovered to be due to trapped electrons in DIP leakage field [T. Holmquist, J.T. Rogers, PRL 79, 3186 (1997)]

SLAC PEP-II and KEKB B-factories both under development; became concerned about ECEs:

Separate codes developed to model EC generation and instabilities (M. Furman, K. Ohmi, F. Zimmermann, and colleagues)

- PEP-II: coat chambers with low-δ TiN
- KEKB: add solenoidal windings around entire chamber

Calculated predictions of a BIM resonance in LHC, also under development, resulted in a crash program at CERN to study ECEs.

We were asked why we don't observe ECEs in the APS with Al chambers (high δ) and positron beams? Started experimental program in 1997-8 first with e+ beam, then since 1998 with e- beam.

Outline

- Brief history
- **Electron cloud**
  - Effects
  - Production
  - Diagnostics
- Experimental observations
- Cures
- Summary

Electron cloud effects

- Vacuum and beam lifetime degradation through electron-stimulated gas desorption
- Collective instabilities
  - e-p instability (coupled oscillations)
  - Transverse coupled-bunch instability (electron cloud “wake”)
  - Single-bunch instability; emittance blow-up (“head-tail” instability; luminosity degradation)
- Electrons trapped in spurious magnetic fields, e.g., distributed ion pump leakage field (CESR)
- Cloud-induced noise in beam diagnostics (e.g., wire scanners, ion profile monitors, etc.)
- Enhancement of other effects, i.e., beam-beam (?)

Electron cloud production

- **Primary**
  - Photoelectrons
  - Ionization of residual gas
  - Beam loss on chamber walls
- **Secondary**
  - Secondary emission (δ is secondary electron yield coefficient)
  - $\delta_0 \sim 0.5$

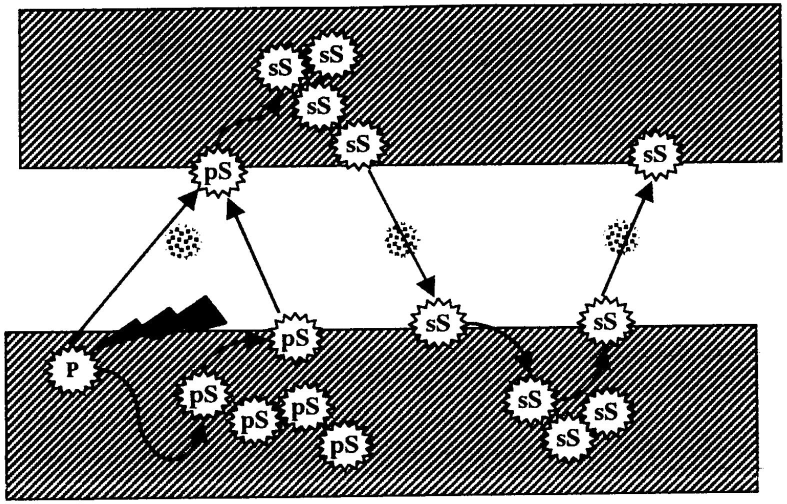
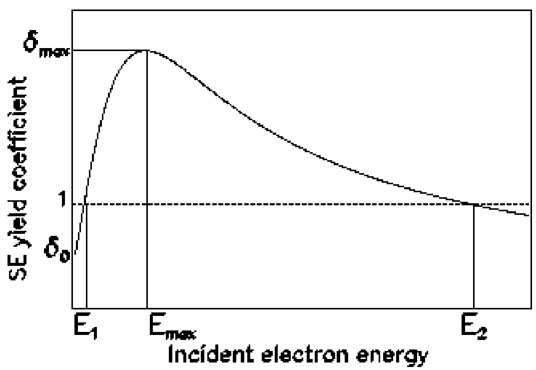


Figure courtesy of R. Rosenberg



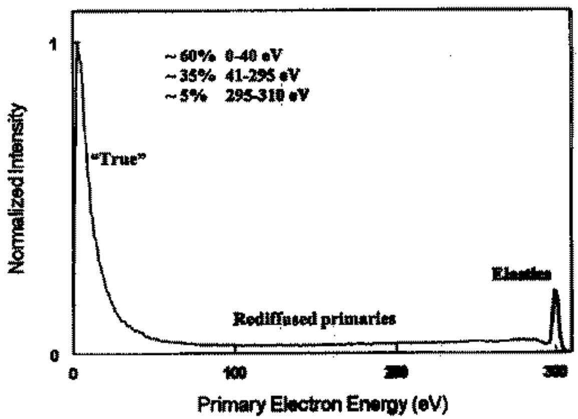
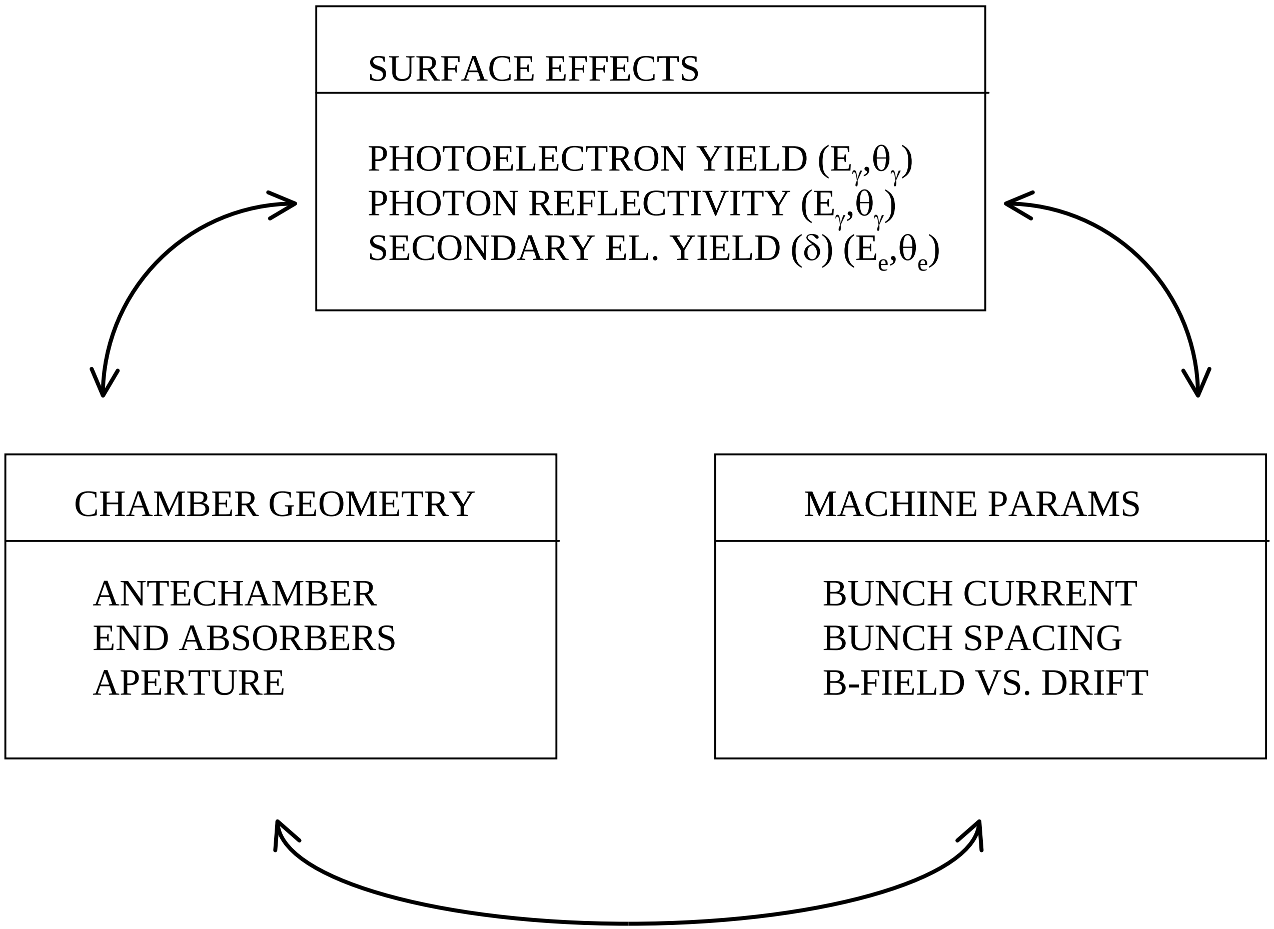


Figure courtesy of R. Kirby

Electron cloud production (cont.)

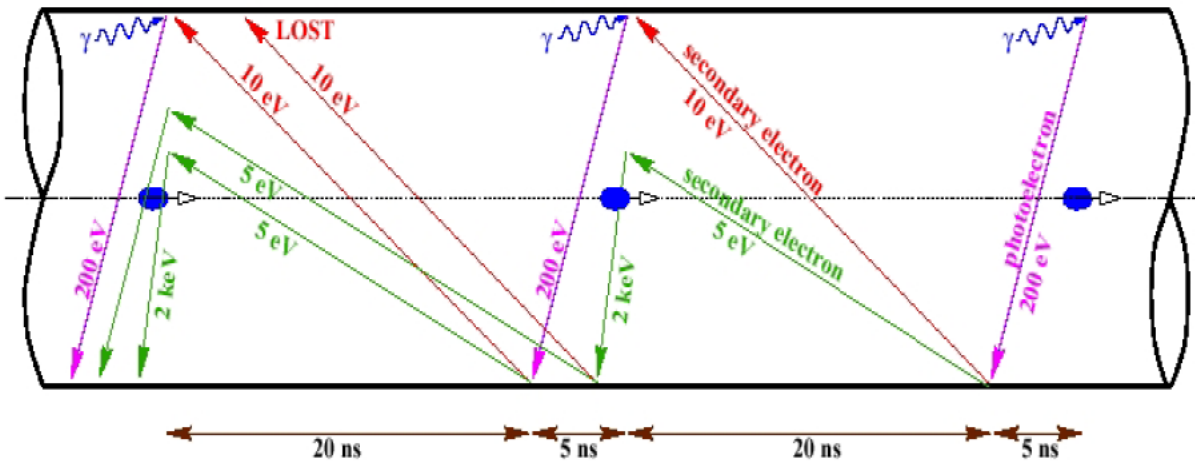


Photoelectrons can dominate the cloud if there is no antechamber

Beam-induced multipacting

$\tau_{bunch} < 1/f_e < s_{bunch}$

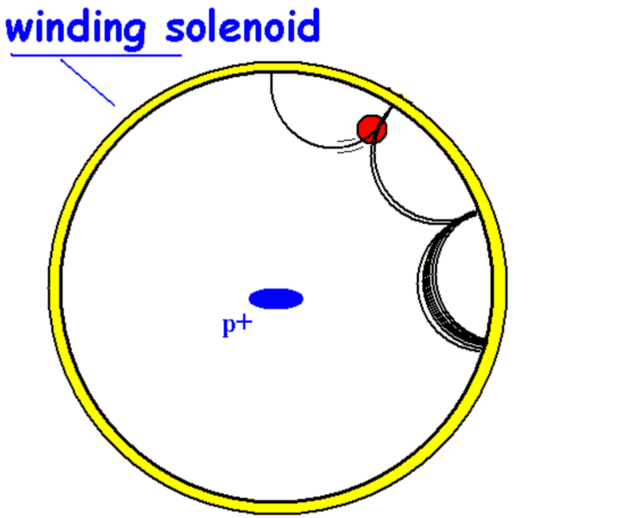
(LHC, SPS-25 ns)



Schematic courtesy of G. Arduini

- **δ > 1 required for amplification**
- **Energy distribution of SE leads to more general BIM condition (first suggested by S. Heifets and M. Furman)**
  [see also K. Harkay, R. Rosenberg, PRST-AB **6**, 034402 (2003) and K. Harkay, L. Loiacono, R. Rosenberg, PAC2003 (2003)]

Another potential resonance



if e⁻ tof=t_{bb} → resonce effect

Resonance multipacting in solenoid field when the electron time of flight is equal to the bunch spacing

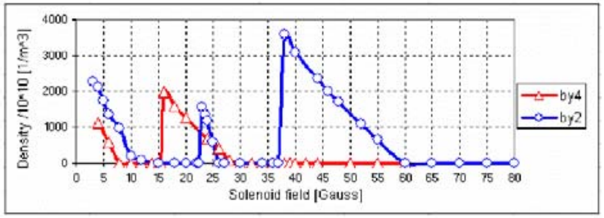


Figure 5: Electron cloud saturated density (N= 2, 4).

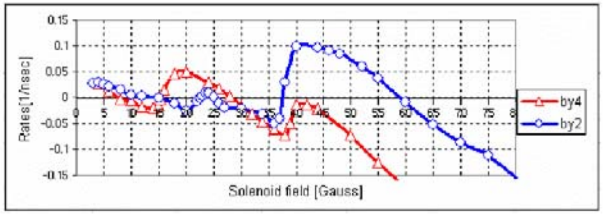
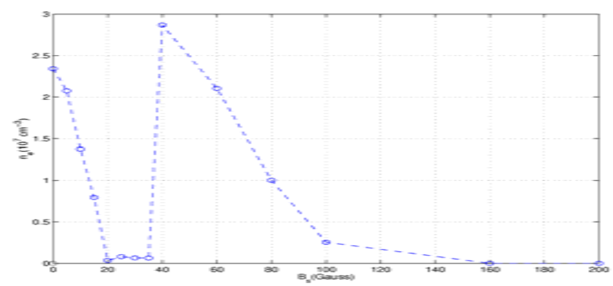


Figure 6: Growth/damping rates for (N=2, 4).

e⁻ density at by-2 and 4 RF buckets spacing,
A. Novokhatski and J. Seeman (PAC03 paper)



e⁻ density at by-2 RF buckets spacing,
Y. Cai and M. Pivi (PAC03 paper)

Standard beam diagnostics and EC

BPMs, strip electrodes, profile monitors

Vacuum pressure

Types of data:

- noise, interference
- pressure rise due to electron-stimulated gas desorption
- instability mode spectrum
- bunch-to-bunch tune shift, beam size

Pros:

- Readily available
- Quantify EC distribution at beam

Cons:

- Indirect evidence for EC
- Biasing BPMs or clearing electrodes disturbs EC
- Difficult to extract properties of EC for accurate modeling

Dedicated EC diagnostics

Retarding field energy analyzer (RFA)

Variations on RFA: time-resolved signals

Solenoid magnet (a cure for EC effects)

In-situ measurements of surface conditioning (lower δ)

Types of data:

- EC flux on chamber walls (field-free and in dipoles)
- EC energy distribution
- EC in gap between bunch passages

Pros:

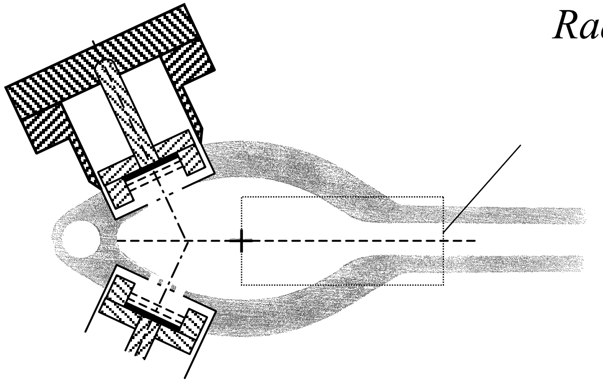
- Direct measure of EC properties and indirect measure of beam-cloud interaction, without disturbing EC distribution

Cons:

- Only EC flux at wall; availability of space; limited energy resolution

Retarding field analyzer (RFA)

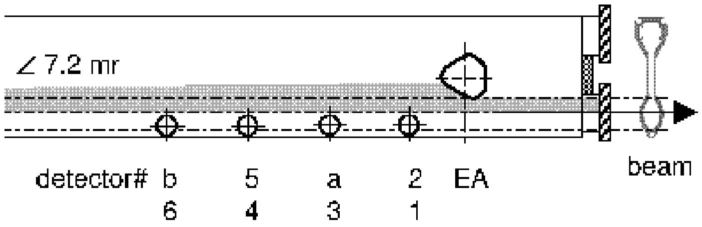
RFA measures distribution of EC colliding with walls



Radiation fan at det. #6 for $E_\gamma \geq 4$ eV

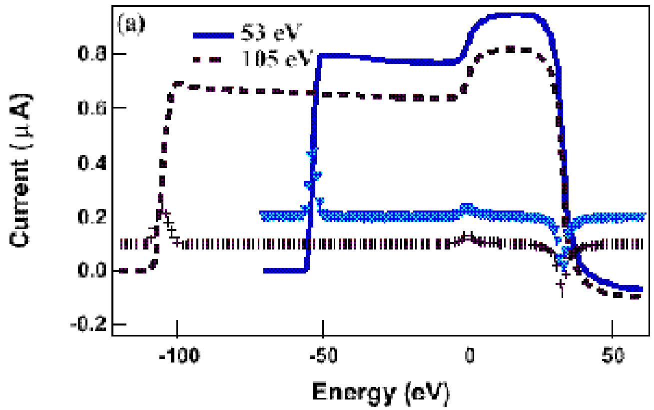
mounting on APS Al chamber ***behind vacuum penetration*** *(42* x *21 mm half-dim.)*

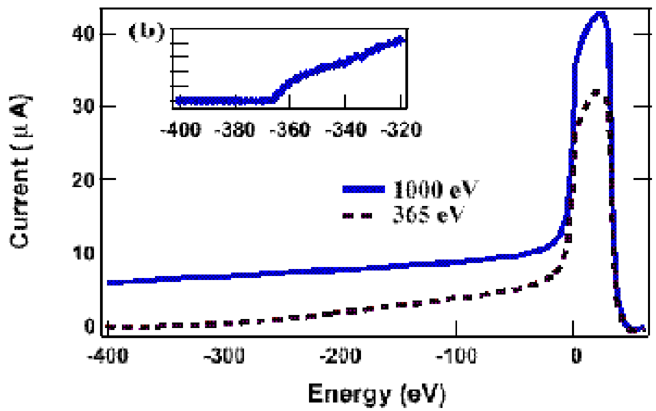
mounting on 5-m-long APS chamber, top view, showing radiation fan from downstream bending magnet



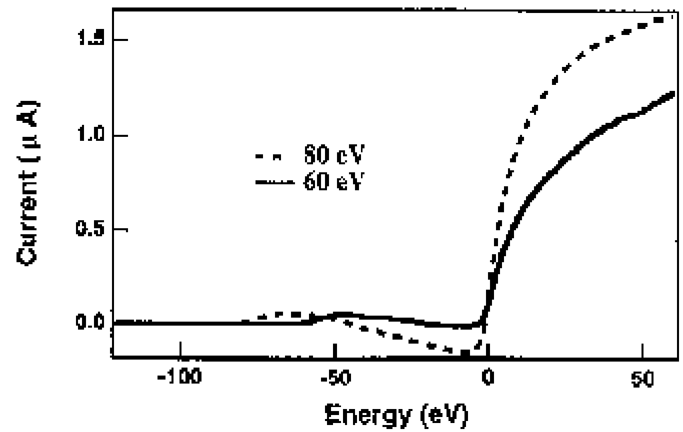
Advantage of RFA to biased electrode

RFA, normal (top) vs. angular (bottom) incidence (collector biased +45 V)





Biased BPM, normal incidence



EC in chamber is not shielded from biased grid or collector

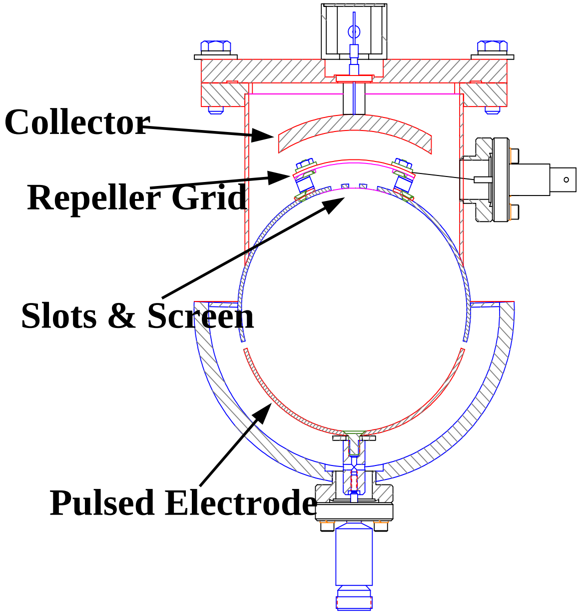
Varying electrode bias voltage

- **Changes incident electron energy**
- **Changes collection length**

Difficult to deduce true wall flux

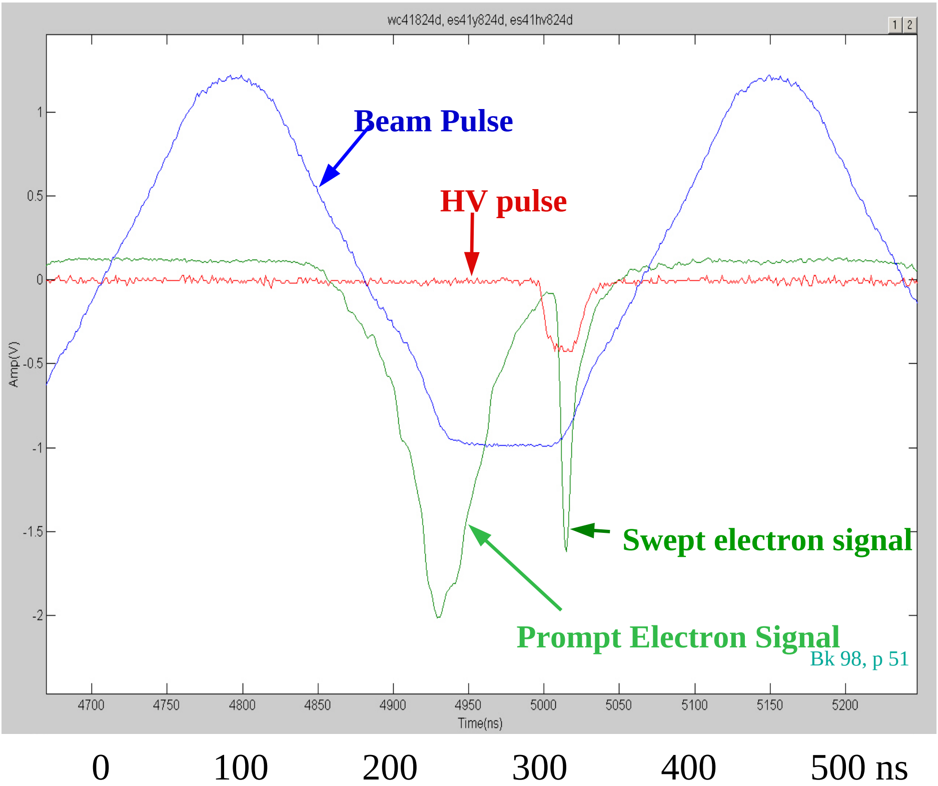
Electron sweeper at Proton Storage Ring (PSR)

LANL Electron Sweeper (~500 V pulse)
80MHz fast electronics added

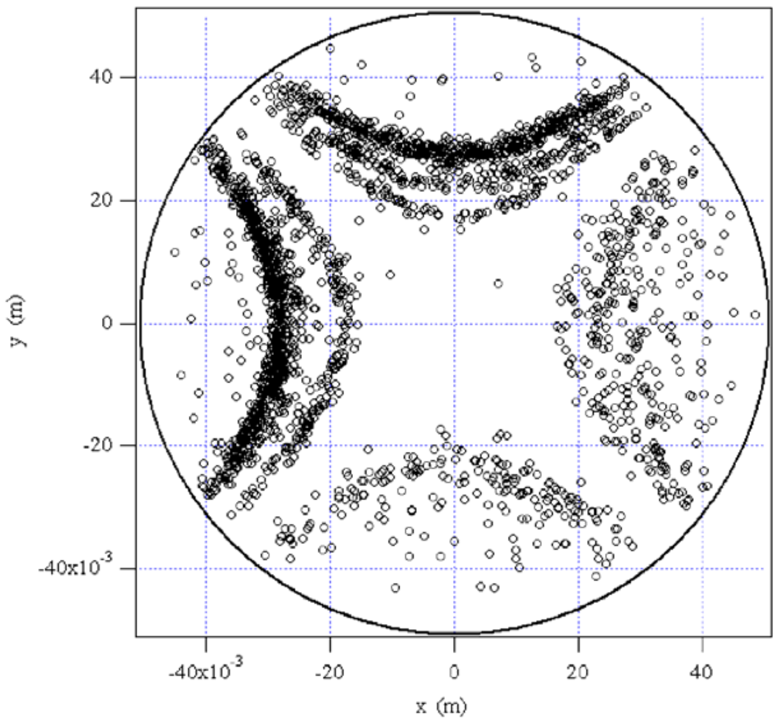


Courtesy R. Macek A. Browman, T. Wang

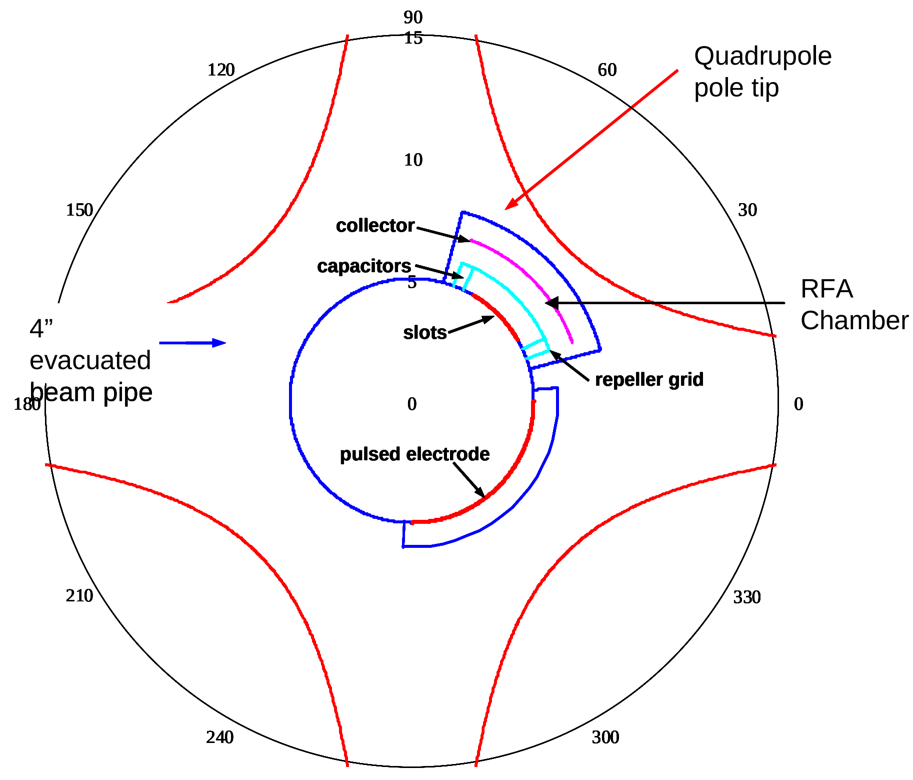
Prompt electron signal due to trailing-edge multipactor; swept electrons survive gap
(7.7 μC/pulse, bunch length = 280 ns; repeller –25 V)



Proposed electron sweeper for quadrupoles



Snapshot of trapped electrons in a PSR quadrupole 5 μs after passage of the beam pulse. (Courtesy M. Pivi)



Schematic cross section of a proposed electron sweeping detector for a PSR quadrupole. (Courtesy R. Macek, M. Pivi)

Outline

- Brief history
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  - Effects
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- **Experimental observations**
- Cures
- Summary

Experimental observations

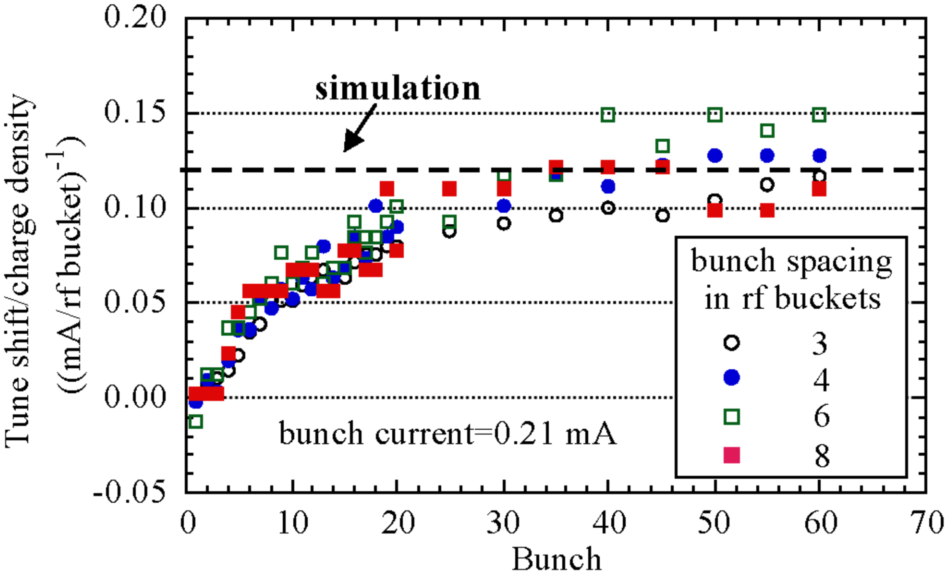
- Cloud build-up and saturation
- Vacuum pressure rise
- Surface conditioning
- Z-dependence
- Secondary electron (SE)- vs. photoelectron (PE)-dependence
- Proton rings
  - CERN SPS with LHC-type beams
  - Proton Storage Ring (PSR)
- Electron decay time
- EC-induced collective effects

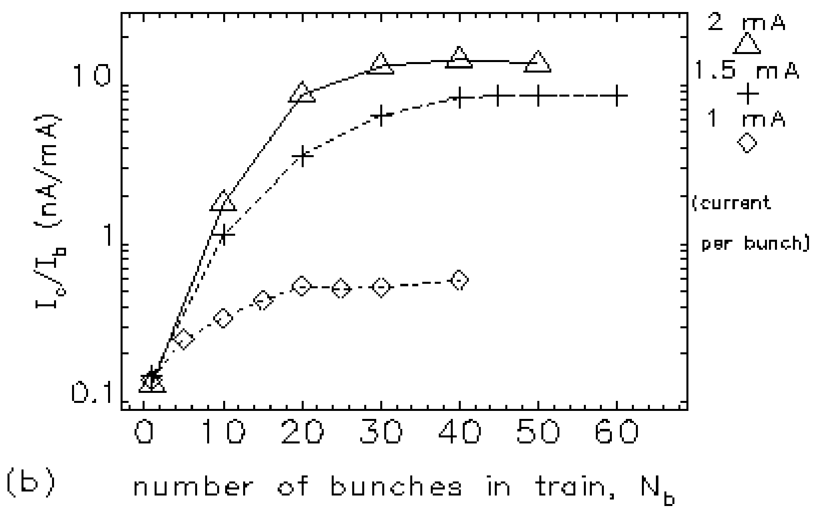
Cloud build-up and saturation

KEKB: EC saturates after 20-30 bunches per tune shift (4λ_{rf} bunch spacing)

Figure courtesy of H. Fukuma, Proc. ECLOUD'02, CERN Report No. CERN-2002-001(2002)

APS: EC saturates after 20-30 bunches (middle of straight); level varies nonlinearly with bunch current (7λ_{rf} bunch spacing)



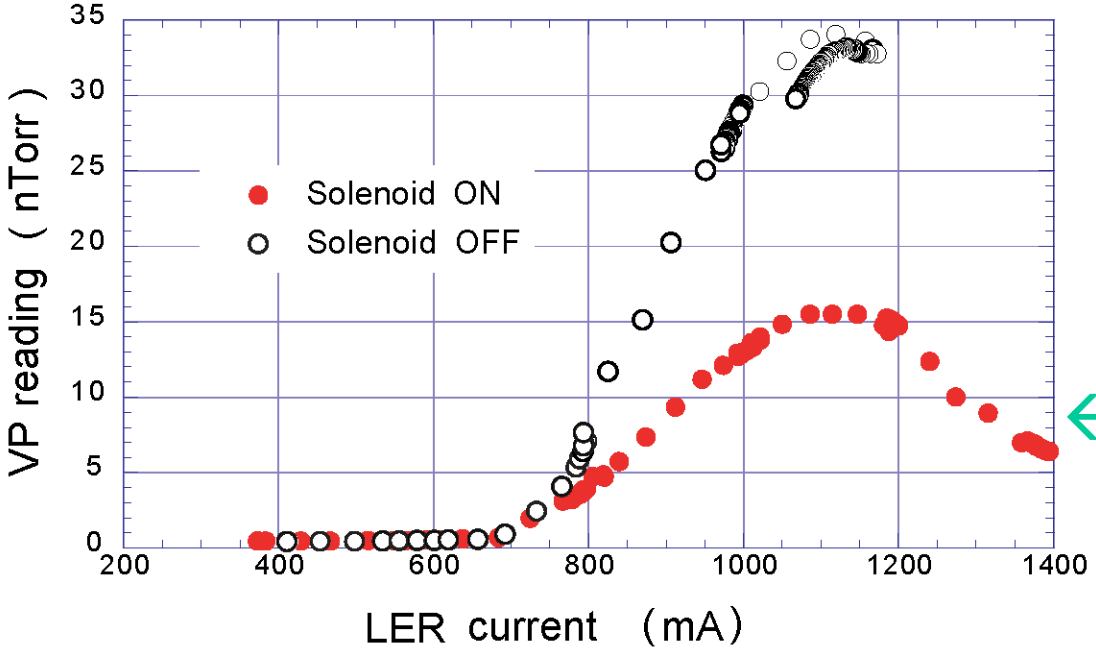


Calculated EC density at saturation (e+ beam)

- **KEKB 6e11 m-3 (no solenoid)**
- **APS 10e10 m-3 (")**
- **PEPII 10e10 m-3 (between solenoids) (Kulikov's talk)**

Vacuum pressure rise

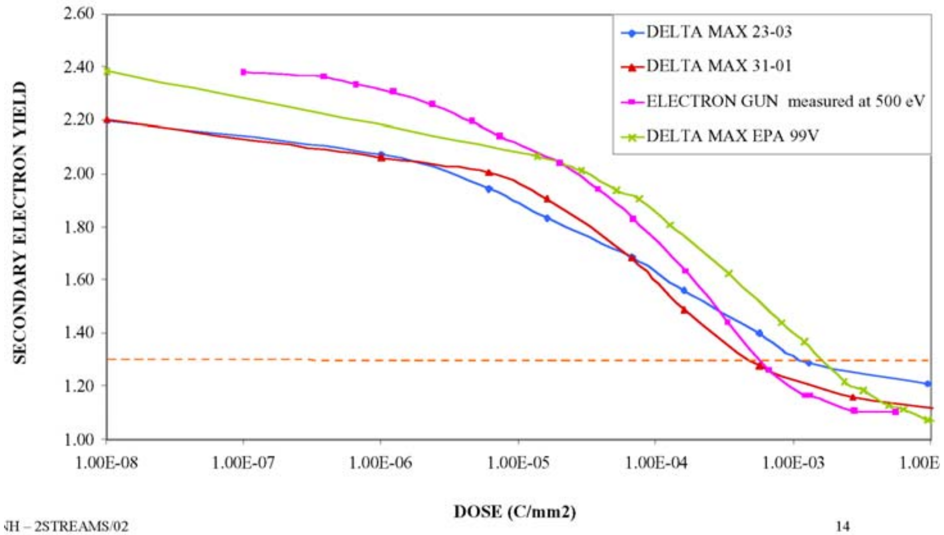
PEP-II: courtesy of A. Kulikov et al., PAC 2001, 1903 (2001)



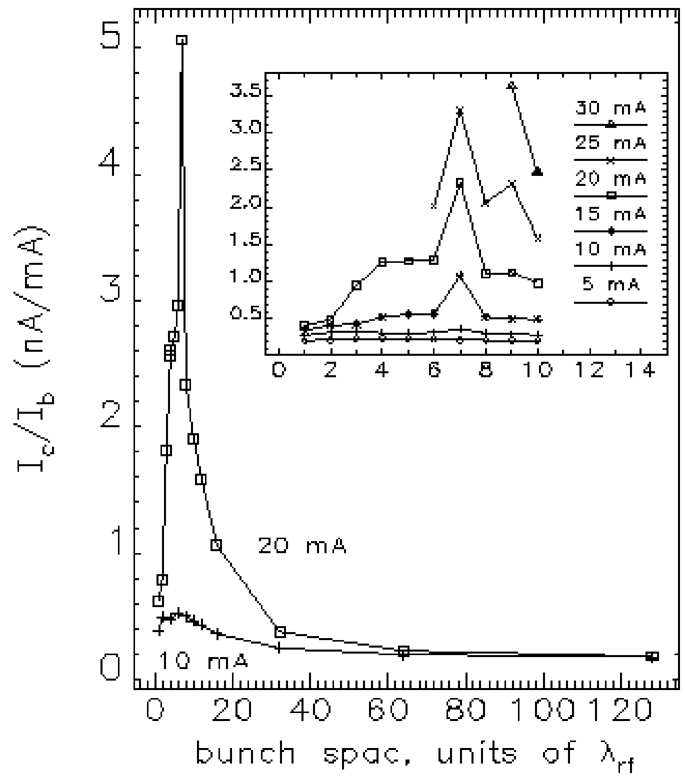
Resonant-like behavior

Pressure rise also observed in KEKB, SPS, APS, RHIC (EC in latter?)

Surface conditioning



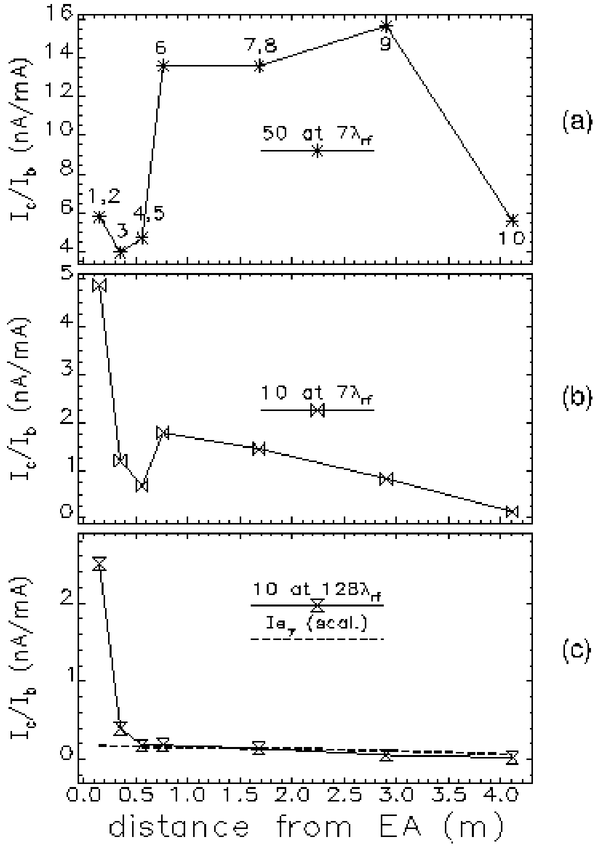
Courtesy of N. Hilleret, Proc. Two-stream Instability Workshop, KEK, Japan (2001)



Wall flux at **APS reduced 2x** after 60 Ah of surface conditioning, equivalent to **10^{-3} C/mm^2 dose, consistent with CERN data** (Cu) (APS chamber Al)

Z-dependence

APS: Measured RFAs as function of bunch number, spacing, and distance from photon absorber (2 mA/bunch).



KEKB: EC with space charge in solenoid modeled with 3D PIC code

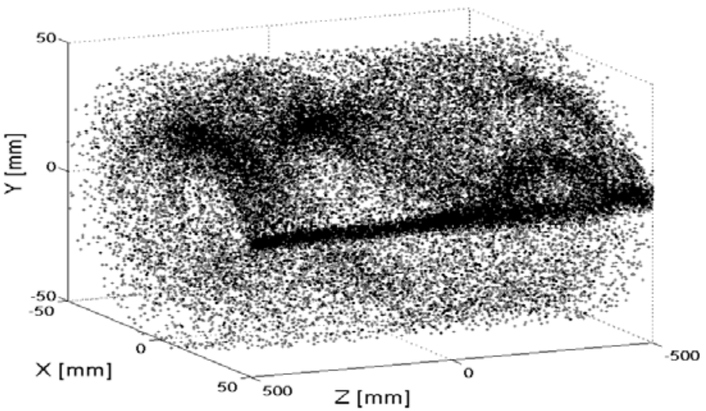
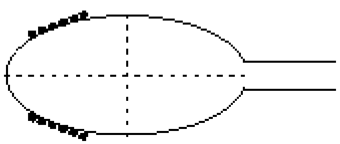
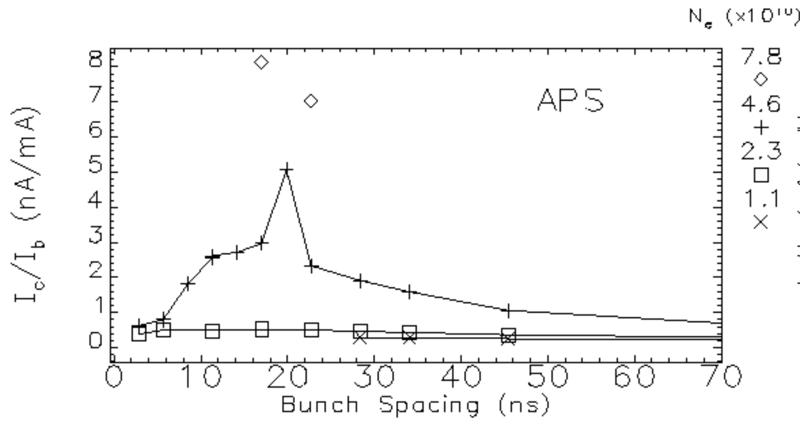


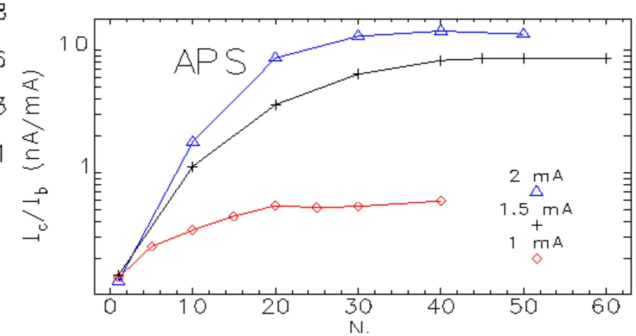
Figure courtesy of L. Wang, H. Fukuma, K. Ohmi, E. Perevedentsev, APAC 2001, 466 (2001)

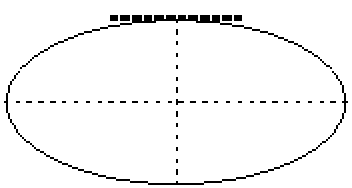
SE- vs. PE-dominated

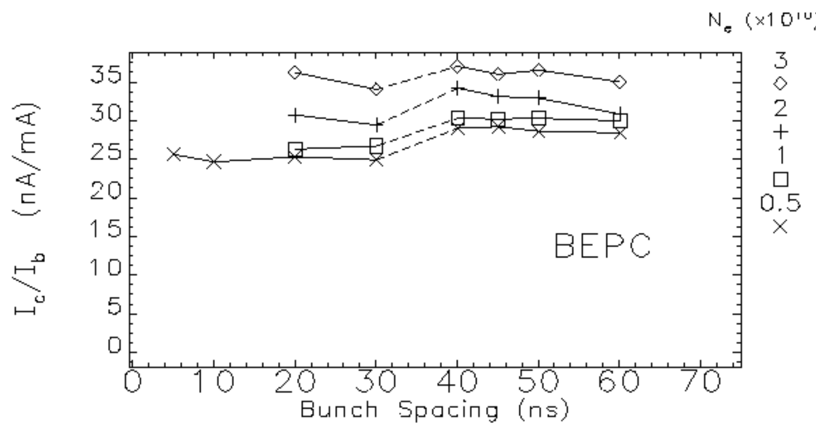
No BIM and nearly linear EC density observed in BEPC e+ ring

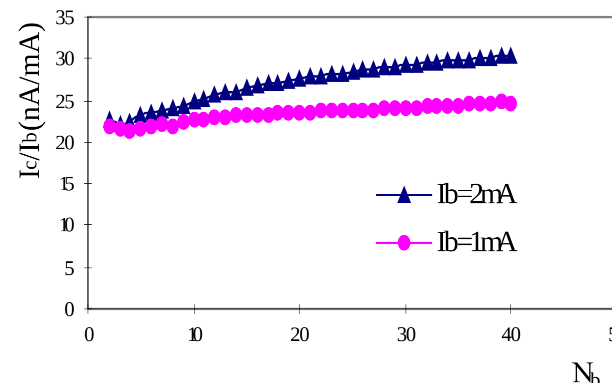










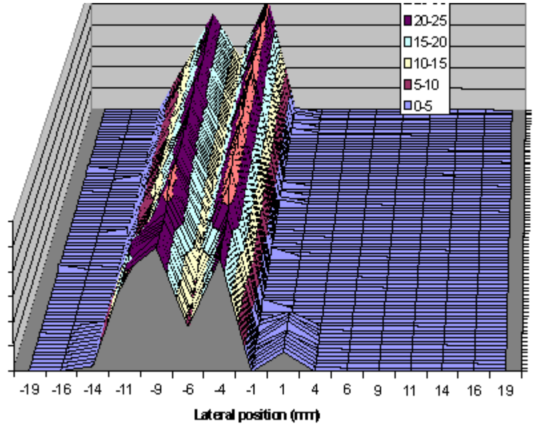


BEPC data courtesy of Z. Guo et al.

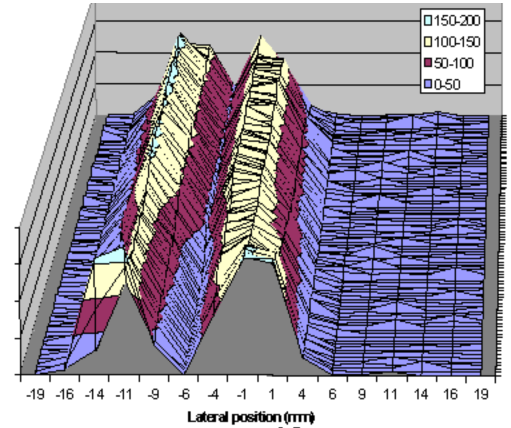
CERN SPS – LHC-type beams

Measured EC distribution in special dipole chamber fitted with strip detectors

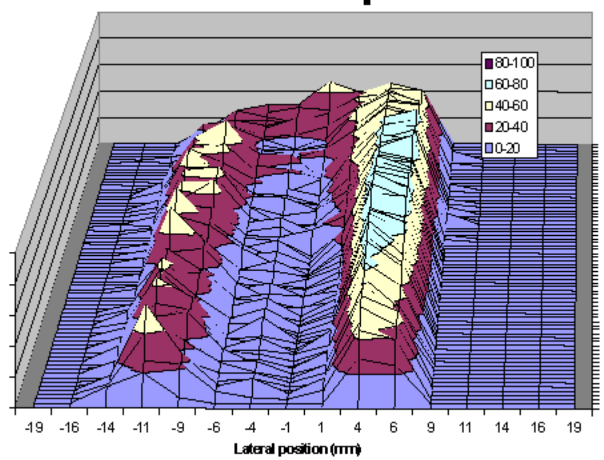
Qualitatively confirmed simulation showing two stripes



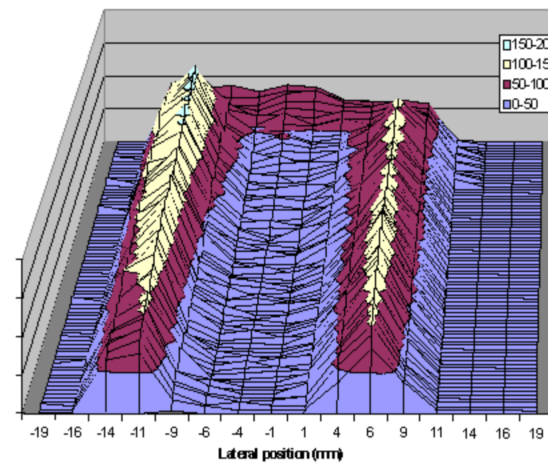
5.0×10^{10} p/b



6.0×10^{10} p/b



7.9×10^{10} p/b

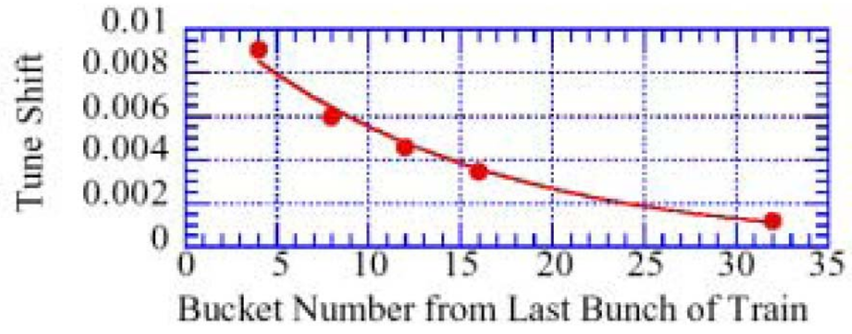


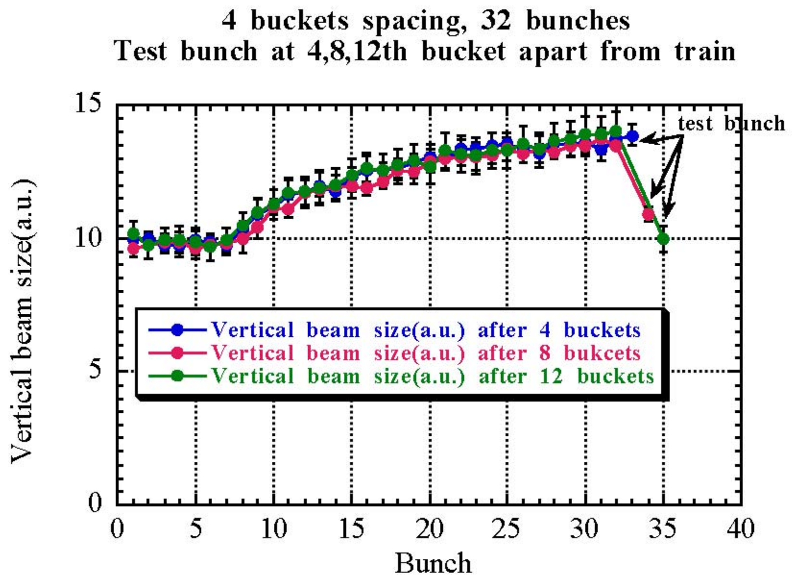
8.6×10^{10} p/b

Figures courtesy of J.M. Jiminez, G. Arduini, et al., Proc. ECLOUD'02, CERN Report No. CERN-2002-001 (2002)

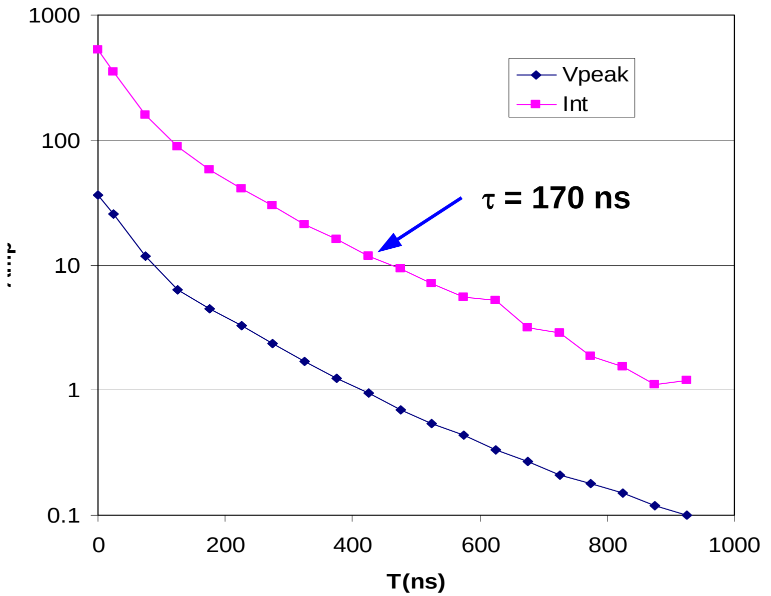
Decay time of electron cloud

KEKB





PSR



Courtesy of R. Macek

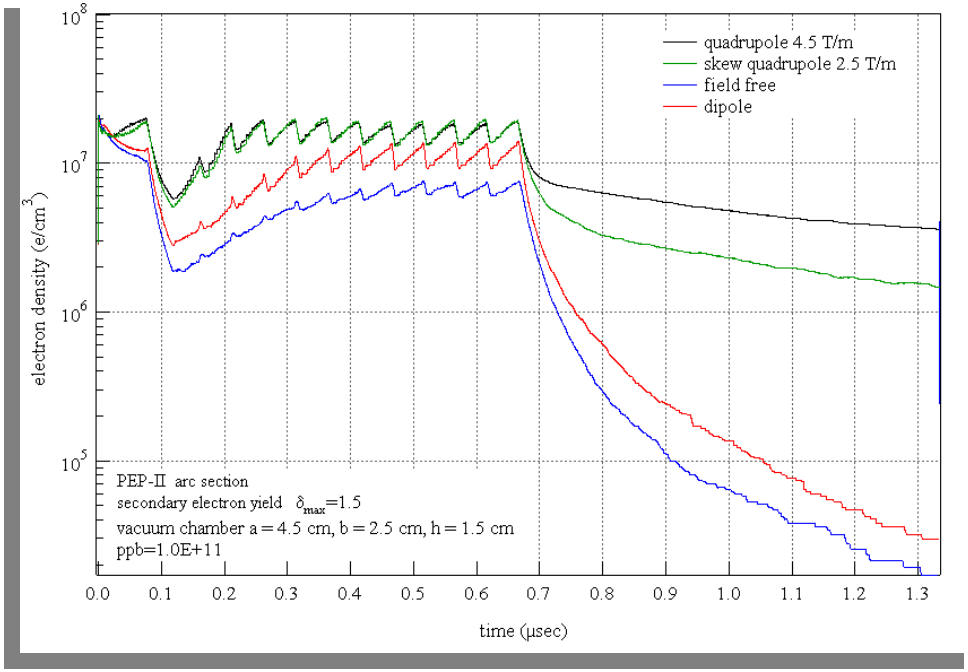
KEKB: 25-30 ns vs.

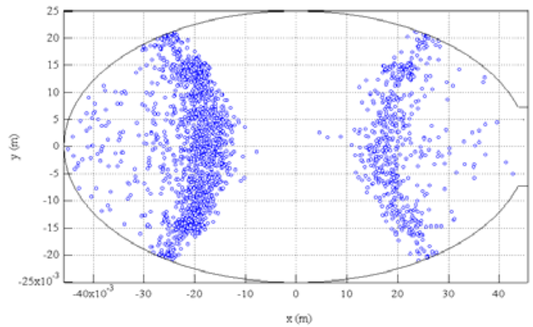
PSR: 170 ns decay time

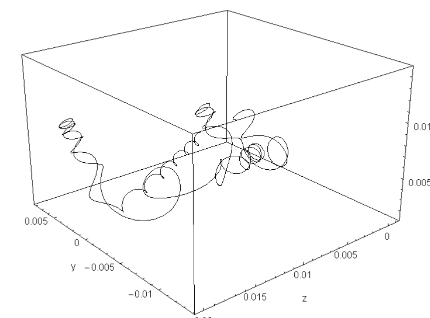
Courtesy of H. Fukuma, Proc. ECLOUD'02, CERN Report No. CERN-2002-001 (2002)

Electron trapping mechanism in quadrupole

Particular attention at quadrupoles where electron trapping mechanism is possible (magnetic mirror, see also Jackson .. !)







(ex: NLC MDR quad)

PEP-II arc simulations + skew quadrupole. Decay time after long gap. By-2 bucket spacing, 10 out of 12 bunches with mini-gaps, 10^{11} ppb. Arc quadrupole gradient 4.5 T/m and skew quarupole 2.5 T/m. Elliptic vacuum chamber 4.5 x 2.5 cm with antechamber.

$$\left|\frac{v_{\parallel,0}}{v_{\perp,0}}\right| = \left(\frac{B_{pipe}}{B_0} - 1\right)^{1/2}$$

Stanford Linear Accelerator Center

PEP-II - electron cloud studies – Oct 2003

Slide courtesy of M. Pivi

EC-driven collective effects

	Horizontal plane	Vertical plane
KEK PF	--	coupled bunch (CB)
BEPC	--	CB
KEKB LER	CB	CB; single bunch
CESR	CB (DIPs)	CB (?)
PEP II LER	single	--
APS (e+)	CB	--
PSR	--	single
SPS-LHC	CB	single
PS-LHC	Single	--
DAΦNE	(below	threshold ?)

See also article by H. Fukuma, *ICFA BD Newsletter* No. 31, Aug. 2003

Contributions to understanding ECEs come from a growing community

Modeling efforts and benchmarking continue to be refined as more physics added:

- **Accelerator physics**
- **Vacuum, surface chemistry**
- **Plasma wakefield accelerators**
- **Heavy ion fusion**
- **Photocathode materials science, electron guns**
  - Modeling electron dynamics in MV fields requires accurate EC distribution

Electron cloud and other effects

- Combined phenomena (enhancement) of beam-beam and electron cloud (E. Perevedentsev, K. Ohmi, A. Chao, PRSTAB 5, 101001 (2002))
- Combined effect of EC and intensity-dependent geometric wakes
- Microwaves as diagnostic or suppressor of cloud (S. Heifets, A. Chao, F. Caspers, F.-J. Decker) (new data: T. Kroyer's talk)
- Effects in electron beams: heat deposition

  Calculations (*POSINST*) of power deposition on walls for super-conducting ID give up to 1 W/m *with electron beam* (Al, 4x less with TiN). Code benchmarked for both e+ and e- APS beams.

Outline

- Brief history
- Electron cloud
  - Effects
  - Production
  - Diagnostics
- Experimental observations
- **Cures**
- Summary

Cures

- Avoid BIM resonance through choice of bunch spacing, bunch current, and chamber height; include SE emission energy in analysis
- Minimize photoelectron yield through chamber geometry (antechamber, normal incidence)
- Consider passive cures implemented in existing machines:
  - Surface conditioning or surface coatings to minimize δ; e.g. TiN, TiZrV NEG, sawtooth (new: G. Stupakov's talk)
  - Solenoids: azimuthal B-field keep SEs generated at wall away from beam; effective in machines dominated by ECs in the straights (i.e., *not* in the dipoles)
- Implement fast beam feedback
- Continue to refine models and continue to develop and implement electron cloud diagnostics, especially in B-fields

Summary

- **Electron cloud effects are increasingly important phenomena in high luminosity, high brightness, or high intensity machines**
    - Colliders, Storage rings, Damping rings, Heavy ion beams
- **EC generation and instability modeling increasingly complex and benchmarked against *in situ* data: δ, δ_0, photon reflectivity, and SE energy distributions important**
- **Surface conditioning and use of solenoidal windings *in field-free regions* are successful cures: will they be enough?**
- **What are new observations and how do they contribute to body of work and understanding physics of EC?**