Characterizing the Electron Cloud at the APS

Katherine Harkay
Advanced Photon Source

2007 Feb 1
CESR EC week, Cornell U.

APS EC study origins: circa 1997

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

LHC: Calculated predictions of a BIM resonance resulted in a crash program at CERN to study ECEs.

We were asked: why don't we observe ECEs in the APS with Al chambers (high δ) and positron beams? Started experimental program in 1997-8 first with e+ beam, then 1998-2004 with e- beam.

EC study goals

- Electron cloud effects (ECEs) have been very difficult to predict
  - Surface science is complex for technical materials and accelerator environment
  - Low-energy electrons notoriously difficult to characterize – experimental uncertainties
- Most advances have occurred when modeling is benchmarked against detailed measured data. Notable examples:
  - APS and PSR vs. POSINST
  - HCX (at LBNL) vs. WARP/POSINST
  - KEKB vs. PEHT/PEHTS
  - SPS (LHC) vs. ECLOUD/HEADTAIL
  - RHIC vs. CSEC, ECLOUD, maps
- Designed APS experiments in order to provide realistic limits on key input parameters for modeling efforts and analytical calculations to improve prediction capability and guide cures

Outline

- Brief review
  - Electron cloud generation
  - Amplification, multipacting
  - Diagnostics
- Experimental observations
- Modeling
- Summary

Electron cloud generation, effects

Electron cloud sources

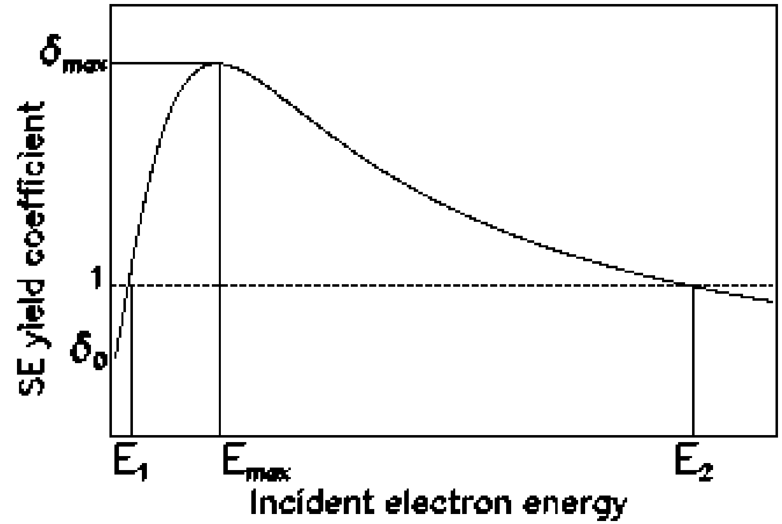
- Photoemission
- Secondary emission, δ
  - Electrons accelerated by beam
  - Beam losses, protons and ions (grazing incidence on walls, collimators)
- Ionization of residual gas

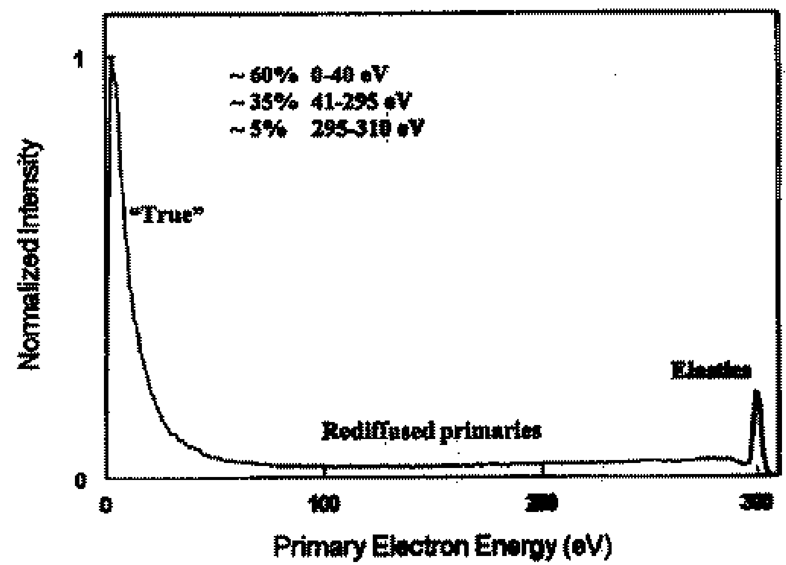
Secondary processes

- Electron-stimulated molecular desorption, vacuum pressure rise/runaway (PEP-II, APS, SPS, RHIC)
- Electron cloud trapping in magnetic fields (dipoles, quadrupoles, ion pump fringe field, etc) (HCX, PSR, CESR)
- Interference with standard beam diagnostics (SPS)

Secondary electron emission

- Universal δ curve, peak values surface dependent
  - δ_{max} ~1-3 metals, >10 non-metals
  - E_{max} 250-400 eV
  - E_1 ~20-50 eV
  - E_2 ~1 keV but much higher at grazing incidence
- EC lifetime depends strongly on δ_0 ~0.5 (CERN, PSR)
- Emission has 3 components*
  - True SE peaks at 1-3 eV, surface independent
  - Rediffused varies/sensitive to surface
  - Elastic depends on energy





* M. Furman, M. Pivi, PRSTAB 5, 124404 (2002)

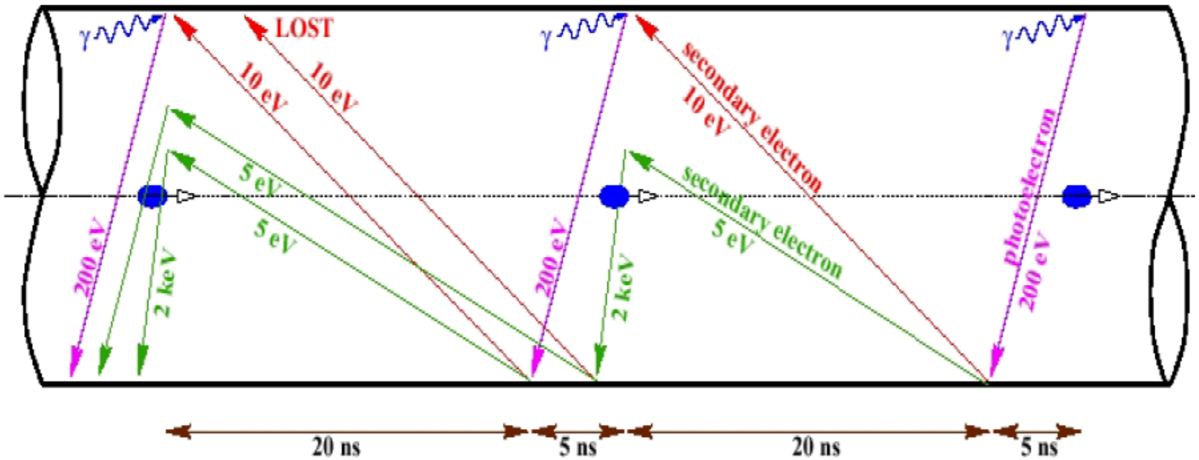
Fig. courtesy of R. Kirby

EC amplification processes

Dominant source of EC can vary

- Photoemission alone can be sufficient if no antechamber (KEKB, KEK PF, BEPC)
- Beam-induced multipacting can lead to large amplification if $\delta > 1$ (PEP-II, APS) [APS vs BEPC: K. Harkay et al., Proc. 2001 PAC, 671 (2001)]

Beam-induced multipacting (BIM)



LHC, SPS=25ns

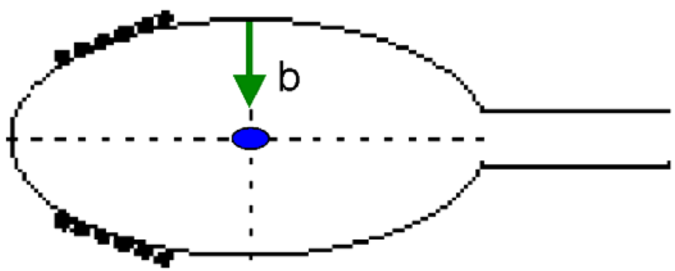
Fig. courtesy F. Ruggiero and G. Arduini

Multipacting condition vs. EC distribution, short bunches

- Cold-electron model [O. Gröbner, Proc. 10th HEAC, Protvino, 277, 1977]
- Multiple kicks, energy distribution (Zimmermann, Ruggiero)
- "General" condition: dependence on EC distribution (Furman, Heifets) [K. Harkay, R. Rosenberg, PRST-AB 6, 034402 (2003); L.F. Wang, A. Chao, H. Fukuma, Proc. ECLOUD04 (2004)]

Evidence of BIM at APS:

- Dramatic amplification of the cloud observed at 20-ns bunch spacing and threshold bunch current (~3×10^{10} positrons)
- Related pressure rise observed, indicative of SE-induced gas desorption.



Optimal BIM resonance condition:

- SE drifts ~b between bunches

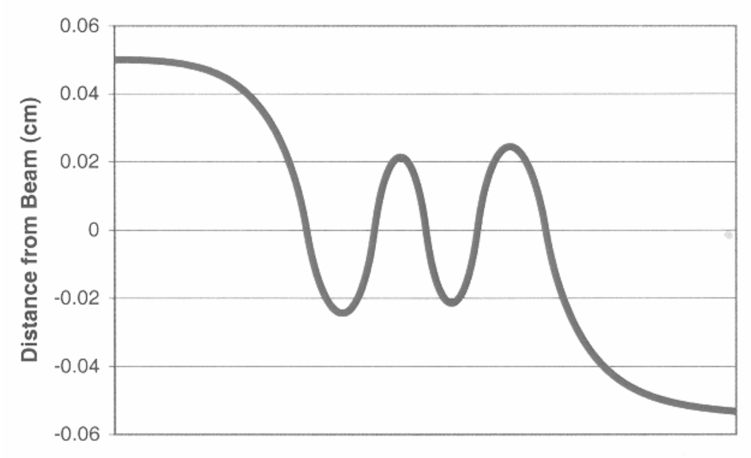
$$t = \frac{b}{v} = \frac{b}{c}\sqrt{\frac{mc^2}{2K_i}} \approx 19\ \text{ns}$$

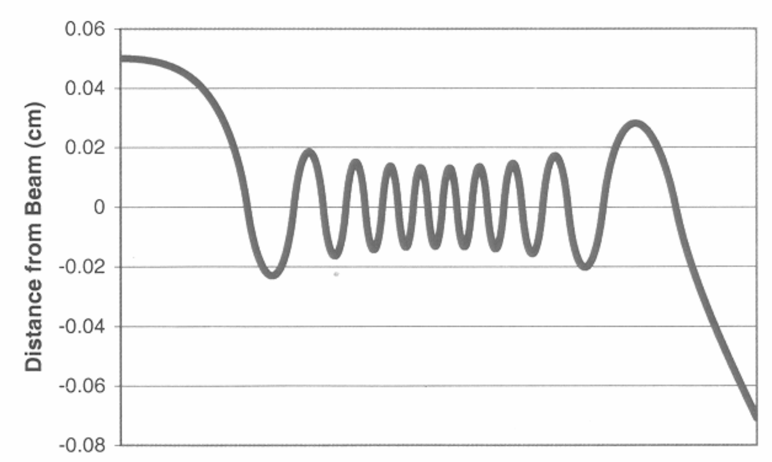
- gets kicked to wall with energy near peak of SEY(E_i)

$$K_f = \frac{\Delta p_e^{\ 2}}{2m_e} = \left(\frac{c r_e N_e}{r}\right)^2 \approx 400\ \text{eV}$$

Same argument for development of stripes in dipoles: stripe position is where energy gain is near E_{max}. Stripes move with beam current.

Impulse kick not valid near beam





bunch current 2 mA

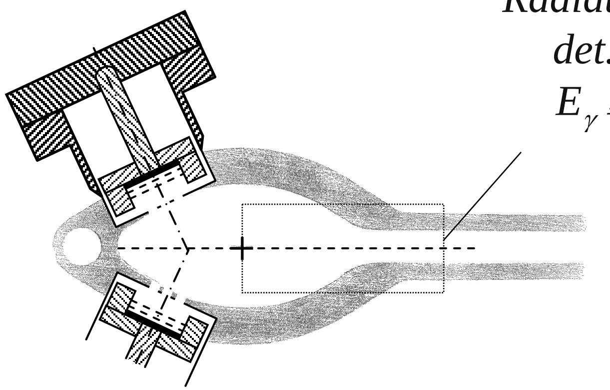
10 mA

For 40-ps-long (12-mm) positron APS bunches, cloud electrons that are within about 500 μm of the beam center oscillate several times in the bunch potential (calculations are for vertical plane). The transverse rms beam size is 350 μm (horizontal) and 50 μm (vertical).

[Courtesy L. Loiacono, from K. Harkay, R. Rosenberg, L. Loiacono, ICFA BD Newsletter 33, Apr 2004]

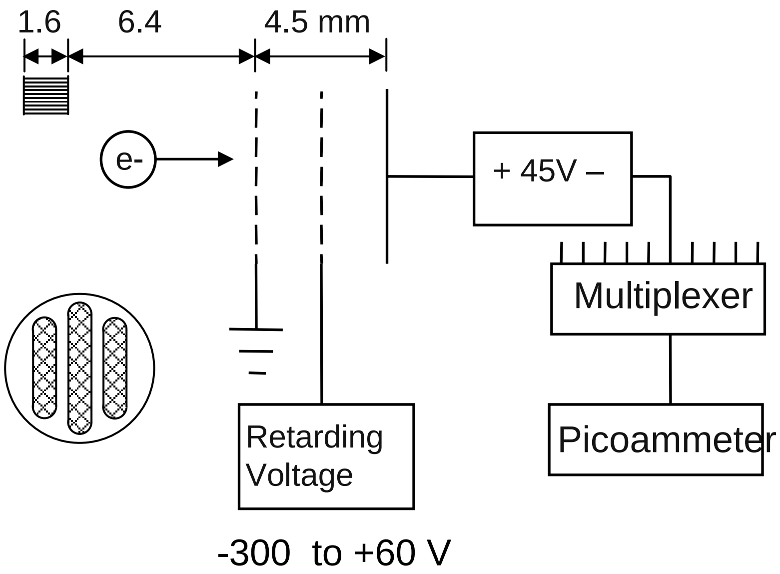
Retarding field analyzer (RFA)

RFA measures distribution of EC colliding with walls, trans. eff. 50%

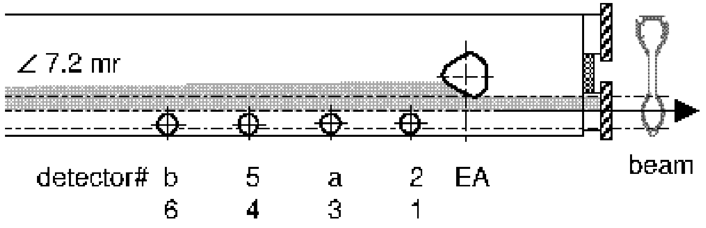


Radiation fan at det. #6 for $E_\gamma \geq 4$ eV

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

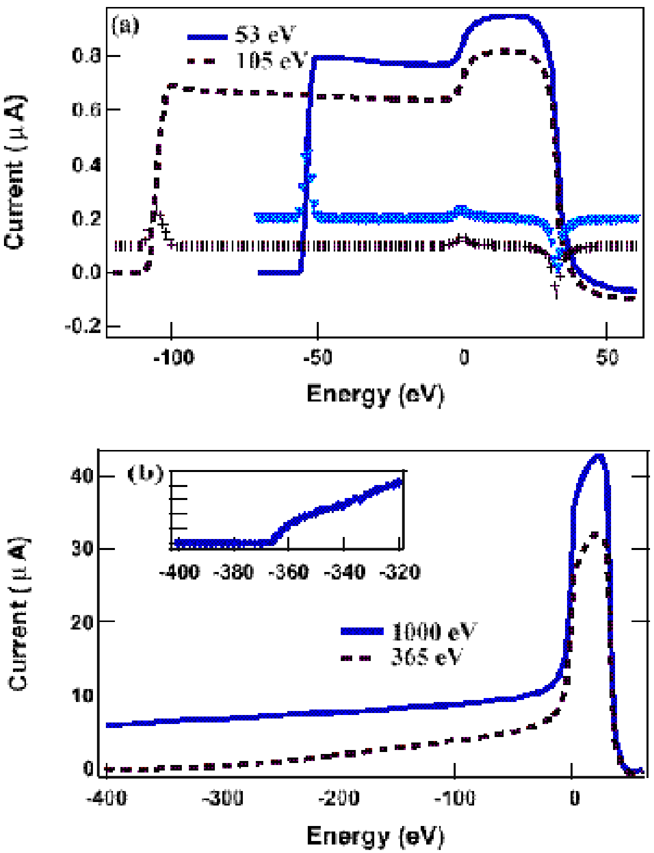


mounting on 5-m-long APS chamber, top view, showing radiation fan from downstream bending magnet. Pressure measured locally (3.5 m upstream of EA).

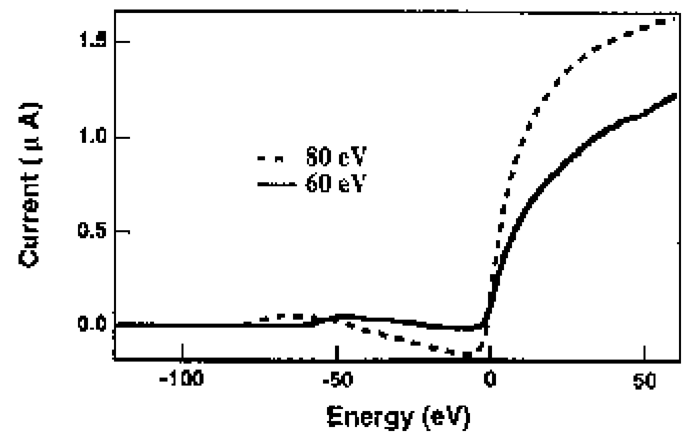


Advantage of RFA vs. biased electrode

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



Biased BPM, electron gun, normal incidence



EC in chamber is not shielded from biased grid or collector

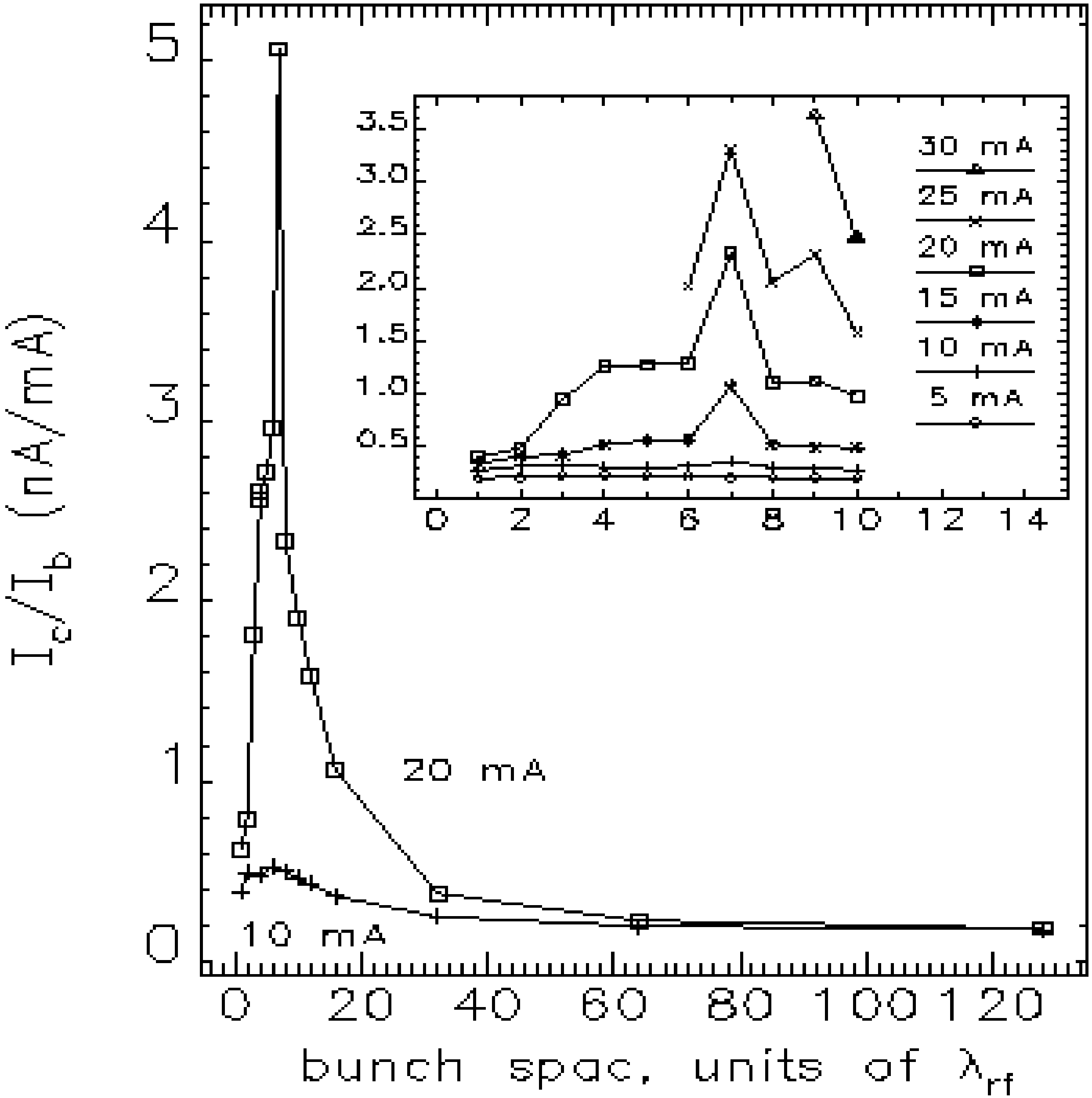
Varying electrode bias voltage

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

Difficult to deduce true wall flux

Outline

- Brief review
  - Electron cloud generation
  - Amplification, multipacting
  - Diagnostics
- Experimental observations
- Modeling
- Summary

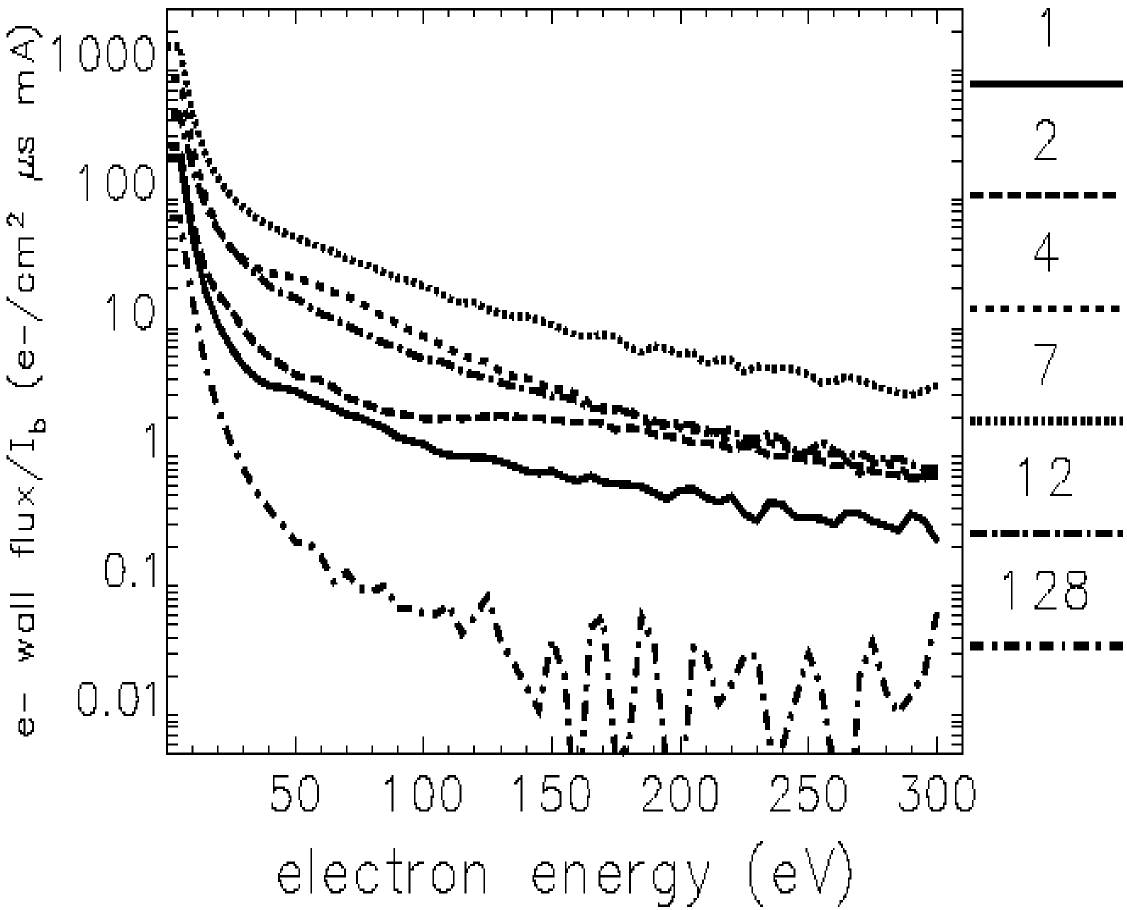


Dependence on bunch spacing

Measured (RFA 6) electron wall current (Ic) as a function of bunch spacing, normalized to the total beam current (Ib) (10 bunches; total current shown).

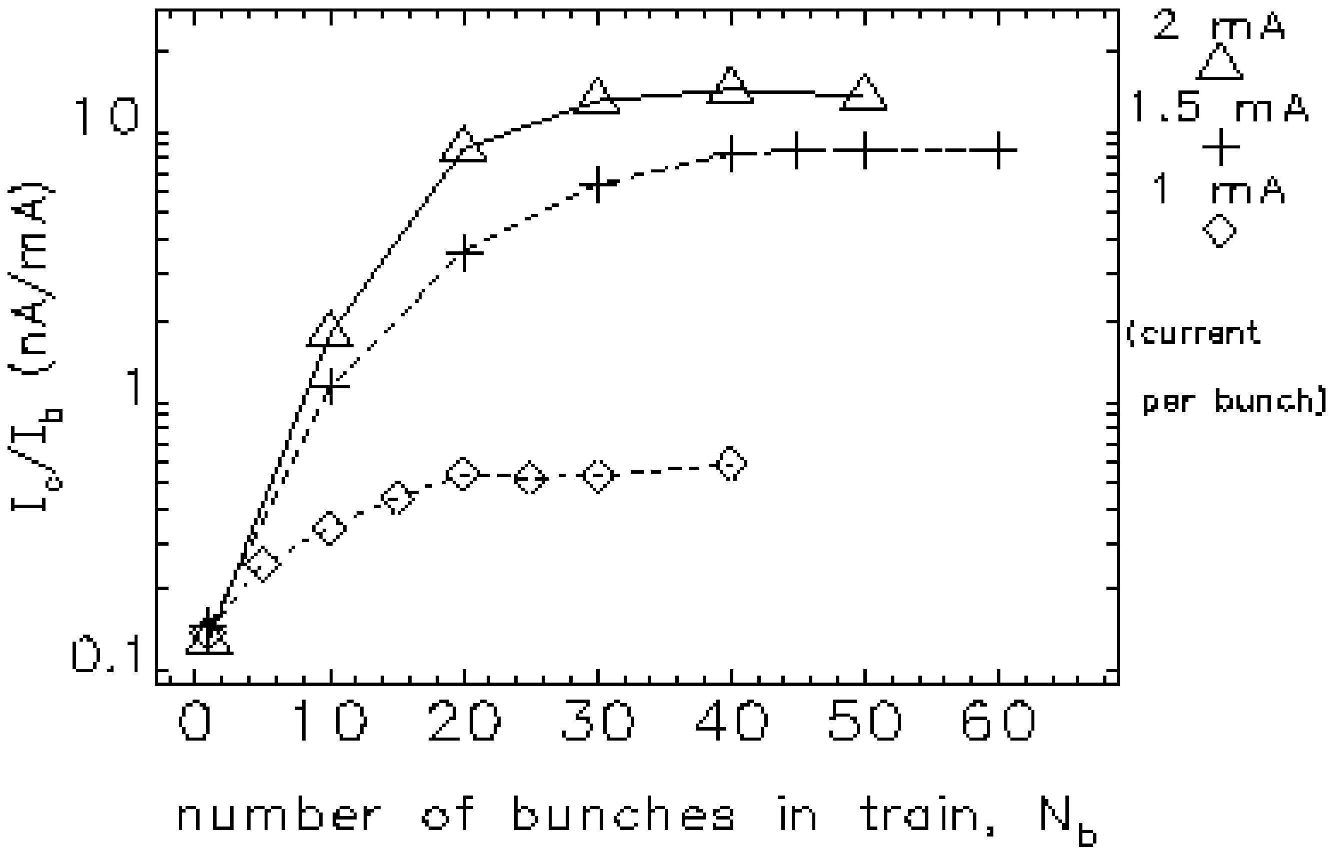
The inset shows a conditioning effect of more than a factor of two reduction after 60 Ah of beam operation.

Energy distribution



- Energy distributions from differentiated RFA signals as a function of bunch spacing (units of λ) (10 bunches, 2 mA/bunch)
- Low-energy part is well fit by a Lorentzian with <E> 2.5 eV and width 4 eV
- Long exponential tail on all but 128 λ
- Energy bumps observed for 2 λ and 4 λ, but not on longest tail for 7 λ
- Avg energy ~100 eV for e+ beam at 20 ns spacing; ~10 eV for e- beam at 30 ns spacing

Cloud build-up and saturation



EC saturates after 20-30 bunches (middle of straight)

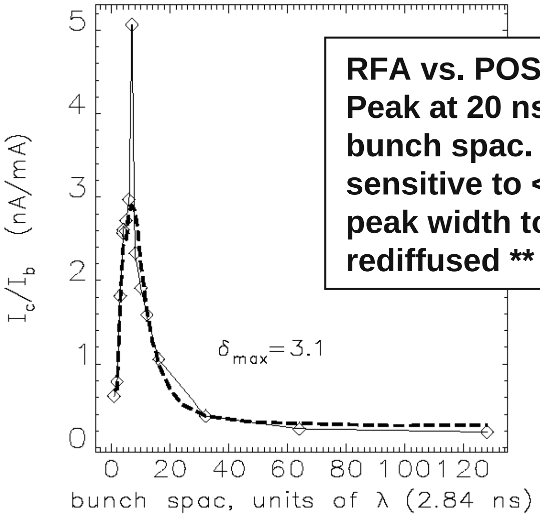
Level varies nonlinearly with bunch current ($7\lambda_{rf}$ bunch spacing)

Calculated EC density at saturation (e+ beam)

- **KEKB 6e11 m^{-3} (no solenoid) (H. Fukuma, ECLOUD02)**
- **APS 10e10 m^{-3} (")**
- **PEPII 10e10 m^{-3} (between solenoids) (A. Kulikov)**

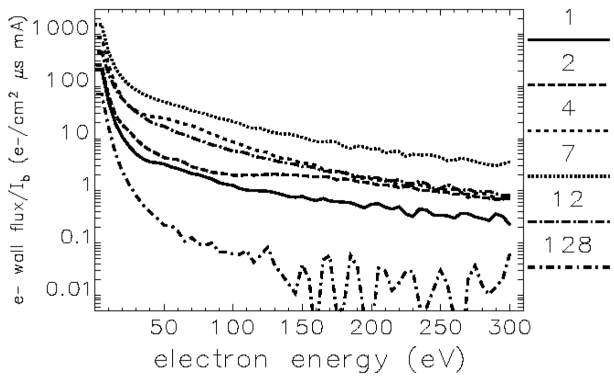
General multipacting condition vs. EC distribution

K. Harkay, et al., Proc. 2003 PAC, 3183; ICFA BD Newsletter 33 (2004)

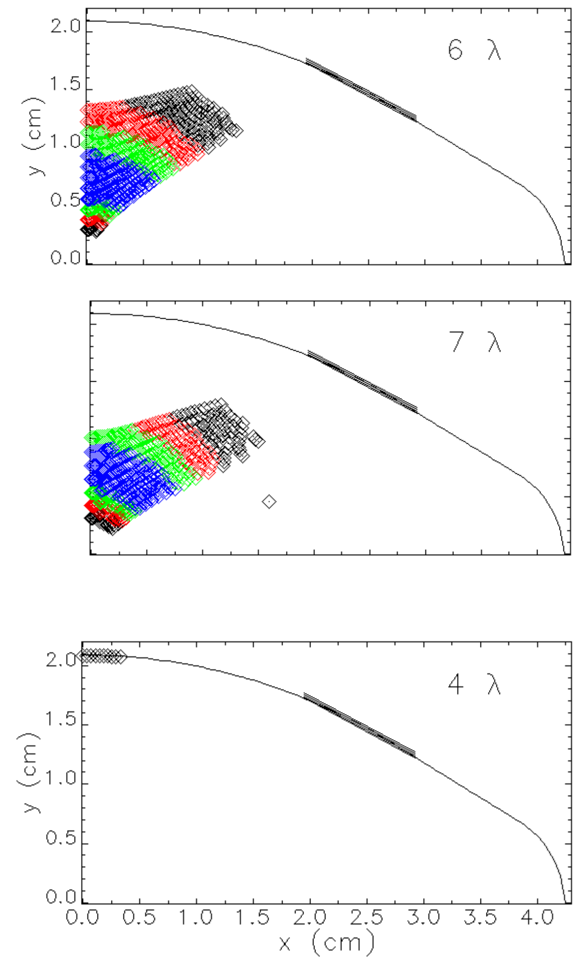


RFA vs. POSINST: Peak at 20 ns bunch spac. (7 bkt) sensitive to <SEE>, peak width to rediffused **

Most resonances for 6 – 7 bkt when 1.2 < <SEE> < 3.8 eV for 1.0 ≤ δ < 3.0



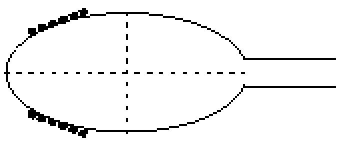
Cold SE predicts 4 bkt

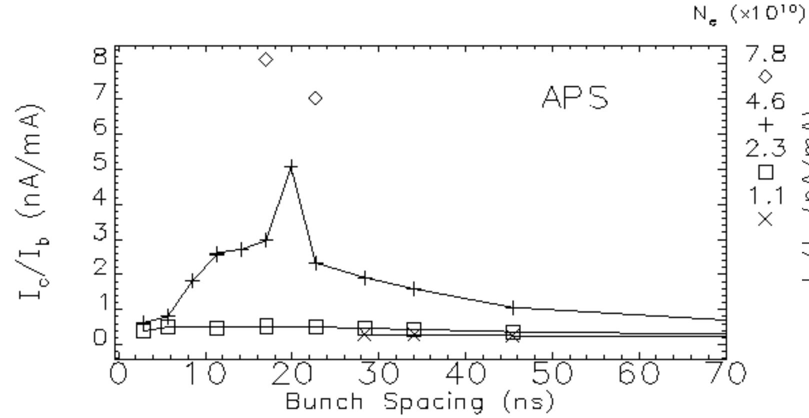


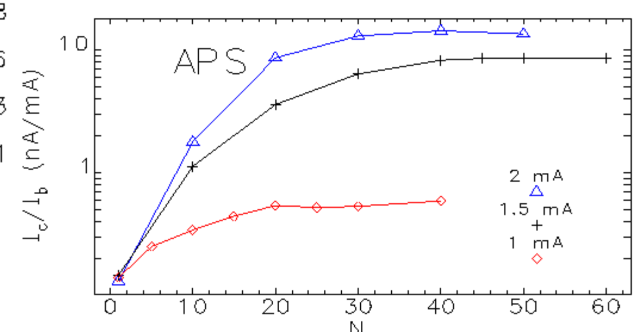
****U. Iriso, also for RHIC (CSEC and ECLOUD), EPAC06**

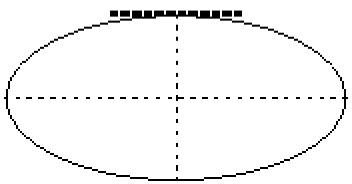
SE- vs. PE-dominated

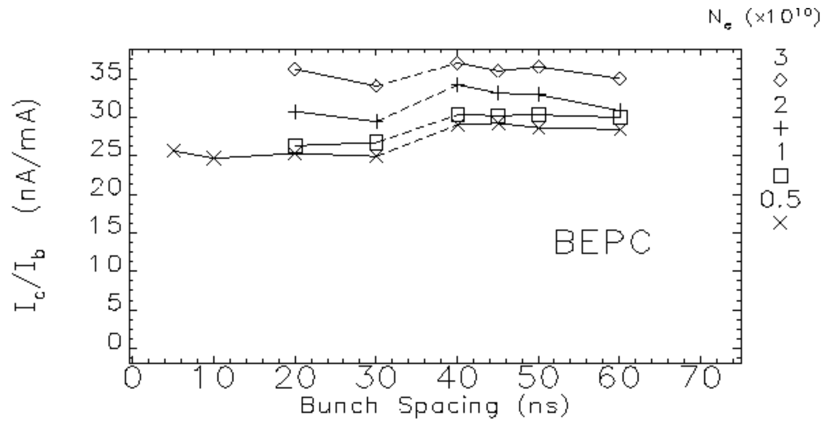
No BIM and nearly linear EC density observed in BEPC e+ ring

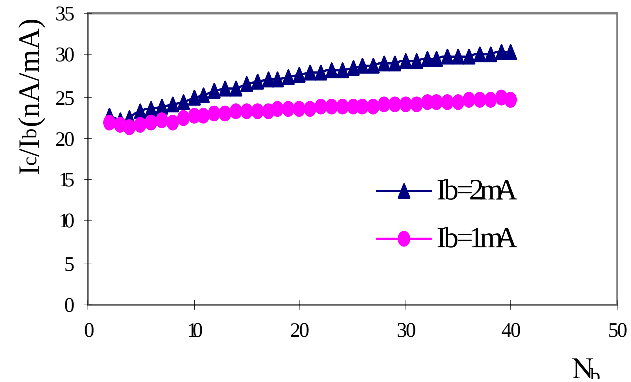








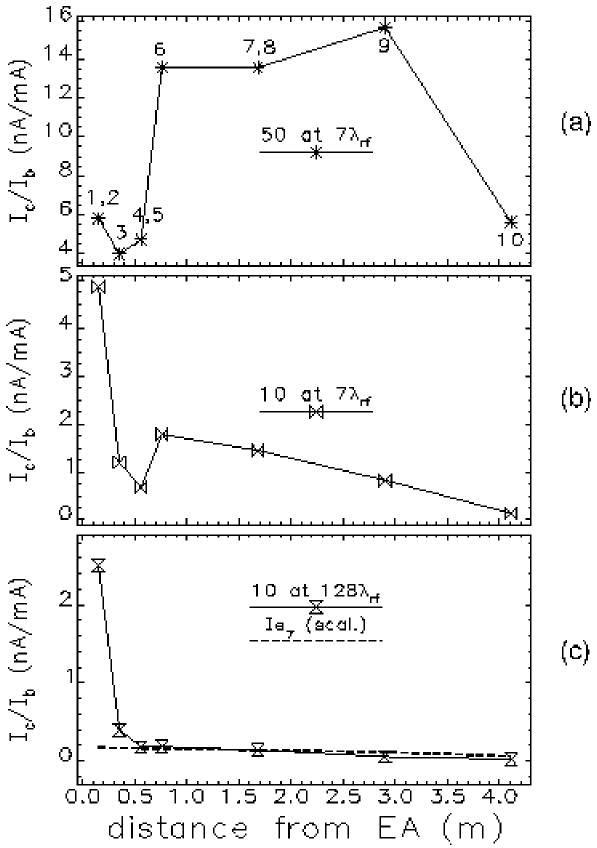




BEPC data courtesy of Z. Guo et al.

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

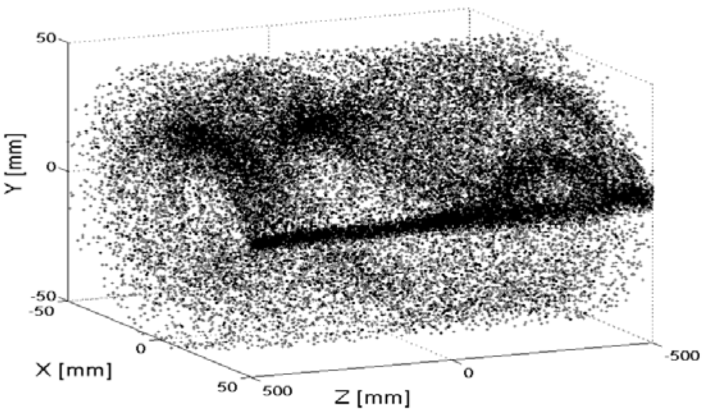
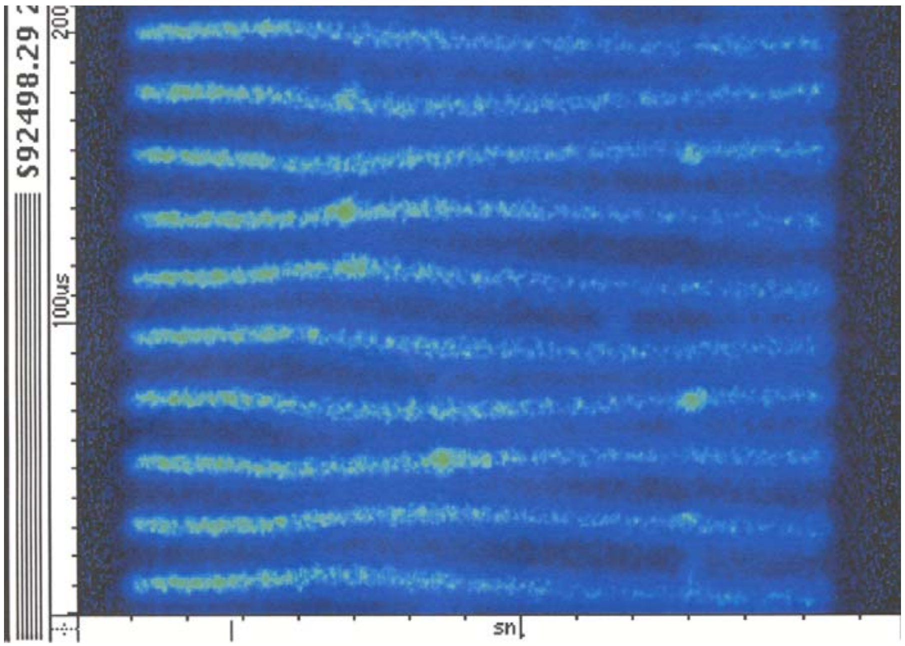


Fig. courtesy L. Wang, H. Fukuma, K. Ohmi, E. Perevedentsev, APAC01, 466 (2001)

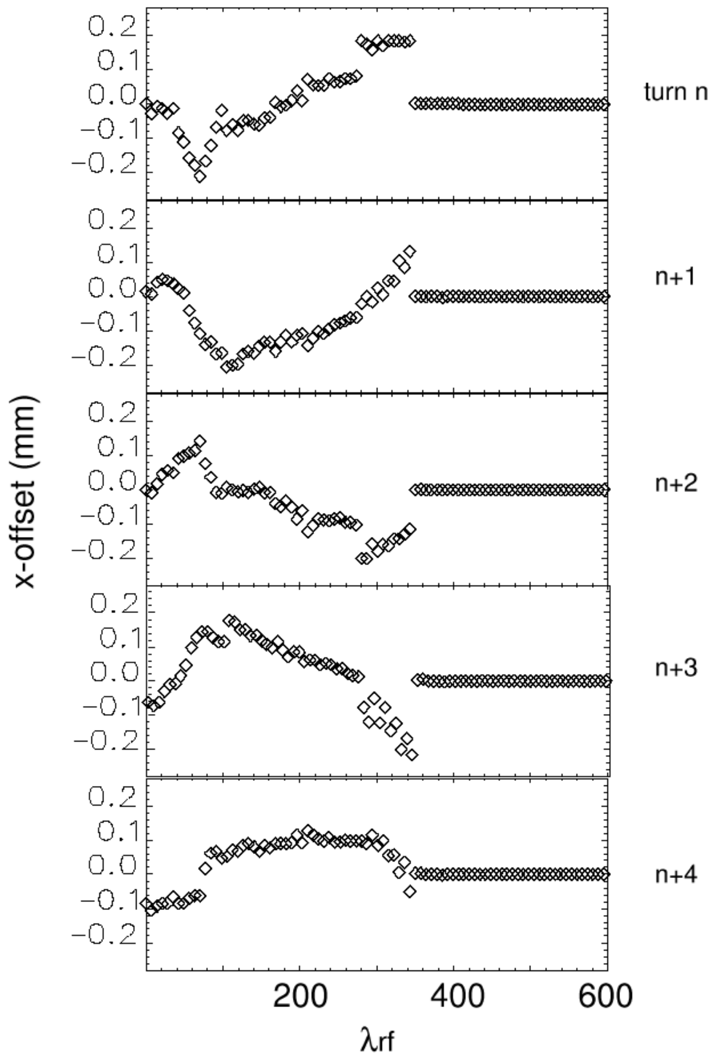
APS electron-cloud driven instability, e+

Acquired near end (9/28/1998) of positron beam operation: max e-cloud amplification with 7 λ_{rf} bunch spacing (head of bunch trains at left)



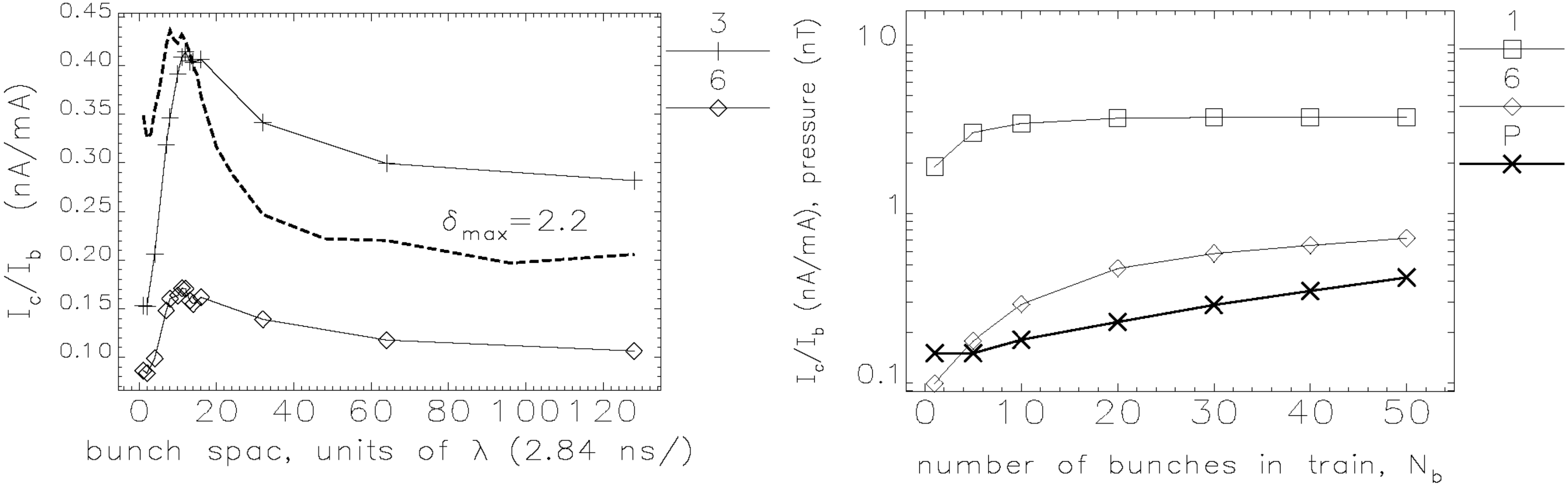
60 bunches, 96 mA, streak camera, x-t

50 bunches, 90 mA, stripline Δx



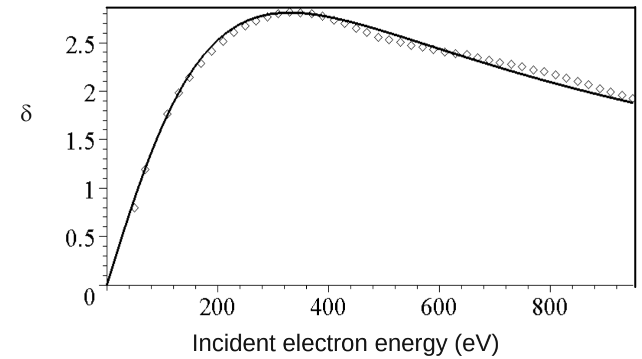
K.C. Harkay, R.A. Rosenberg, PRST-AB 6, 034402 (2003)

Electron beam



Right: Measured (RFA 3,6) and simulated (dashed line) wall current vs. bunch spacing. There is additional conditioning of 100 Ah for these data compared to positron data, main plot.
Left: Measured wall current as a function of bunch train length, 30 ns spacing. The signal near EA (RFA 1) is always higher than RFA 6. No anomalous pressure rise is observed.
Pressure rise was observed for certain fill patterns, but quickly conditioned away

Modeling with posinst



- APS parameters
- Posinst input params [Furman, Pivi]
- Photon number

$$N_\gamma = \frac{5\alpha}{2\sqrt{3}}\gamma\Delta\theta$$

Measured δ for APS chambers (courtesy R. Rosenberg), fitted to empirical formula in [Furman, Pivi]

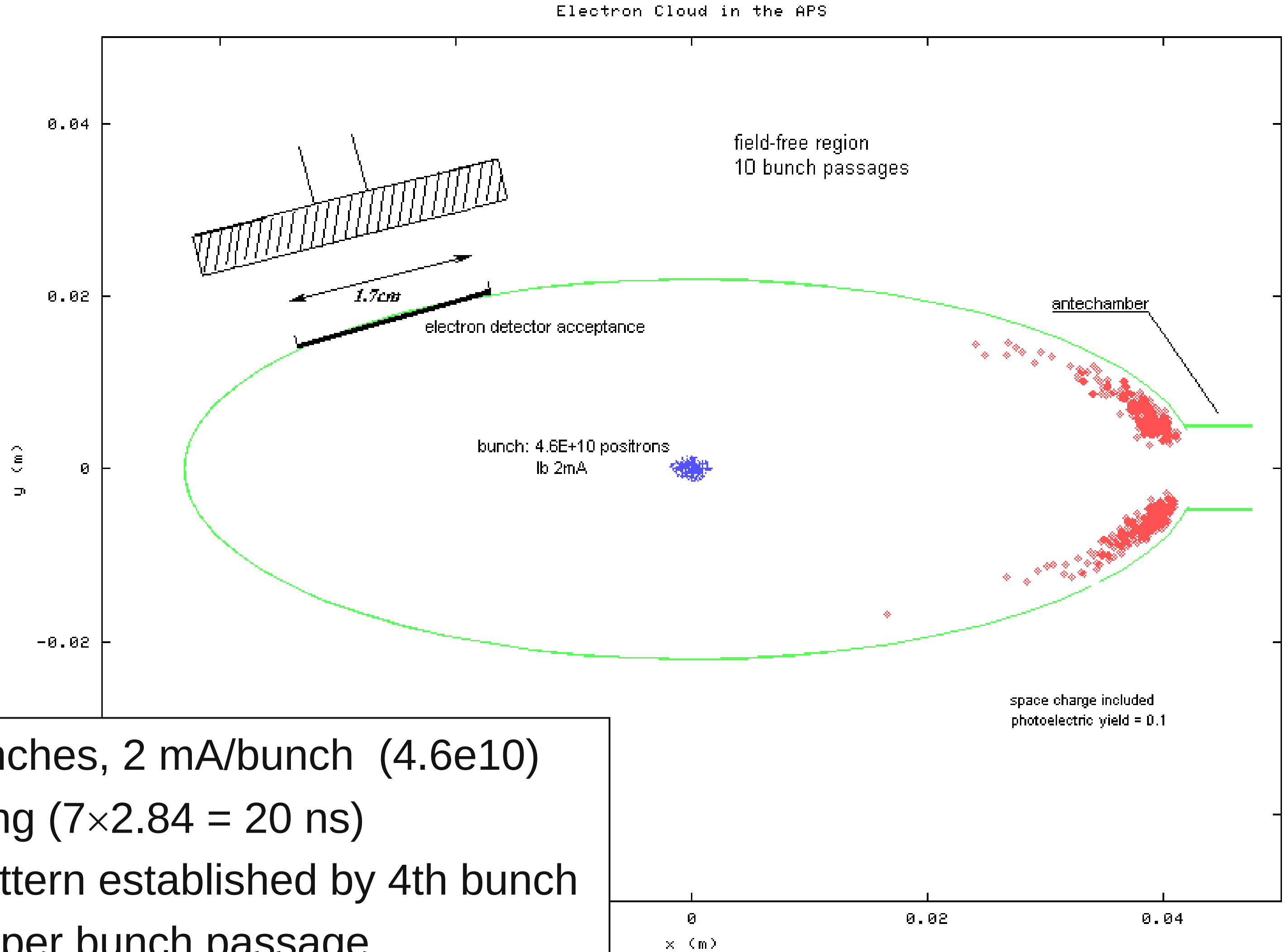
- Posinst output:
  - Avg bombardment rate (compare with RFA)
  - Avg density
  - Electron nex, ndant, ncoll, nsec
  - Electron Ekavg, Ekmax (chamber & wall collisions)

[Ref] M. Furman, M. Pivi, PRSTAB 5, 124404 (2002)

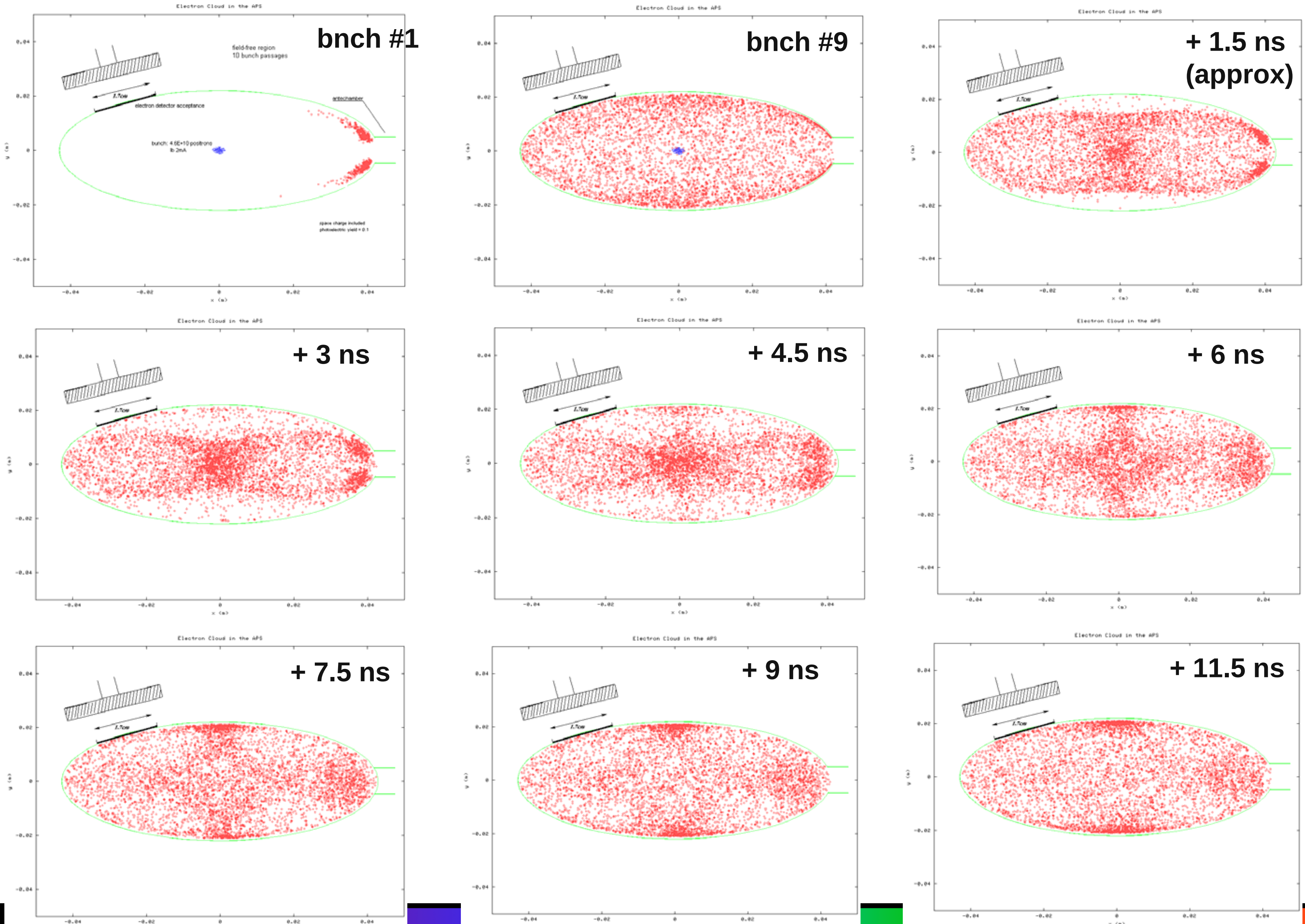
Machine parameters for APS

Beam energy	GeV	7
Circumference	m	1104
RF frequency	MHz	351.9
Minimum bunch spacing	ns	2.84
Harmonic number	–	1296
Chamber semi-axes (*a*, *b*)	mm	42.5, 21
Antechamber height	mm	10
Chamber material	–	Al
Distance from dipole magnet end to RFA (#6)	m	9.25 (e+/e-)
Dipole bend angle	rad	0.07854
Dipole length	m	3.06
Bunch length (rms)	cm	1

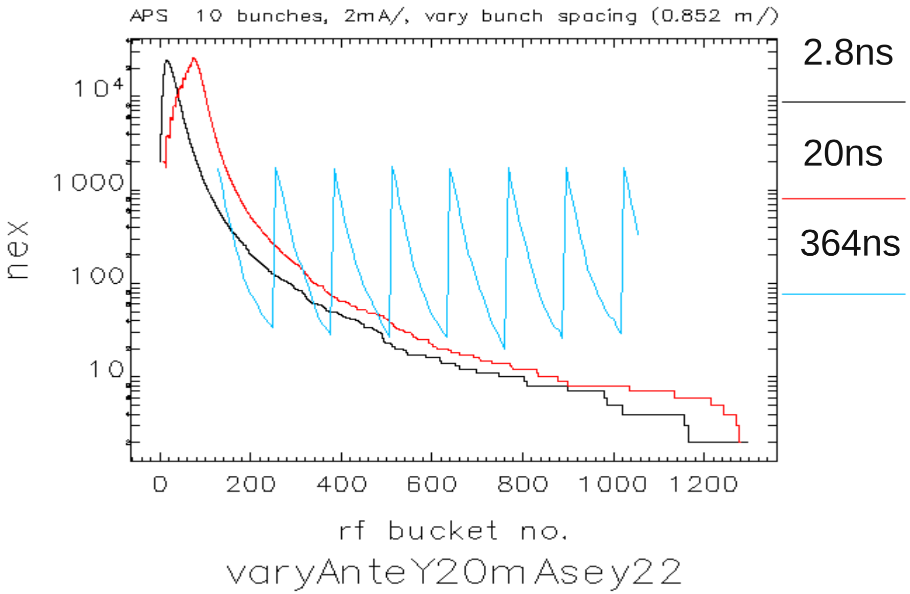
APS movie

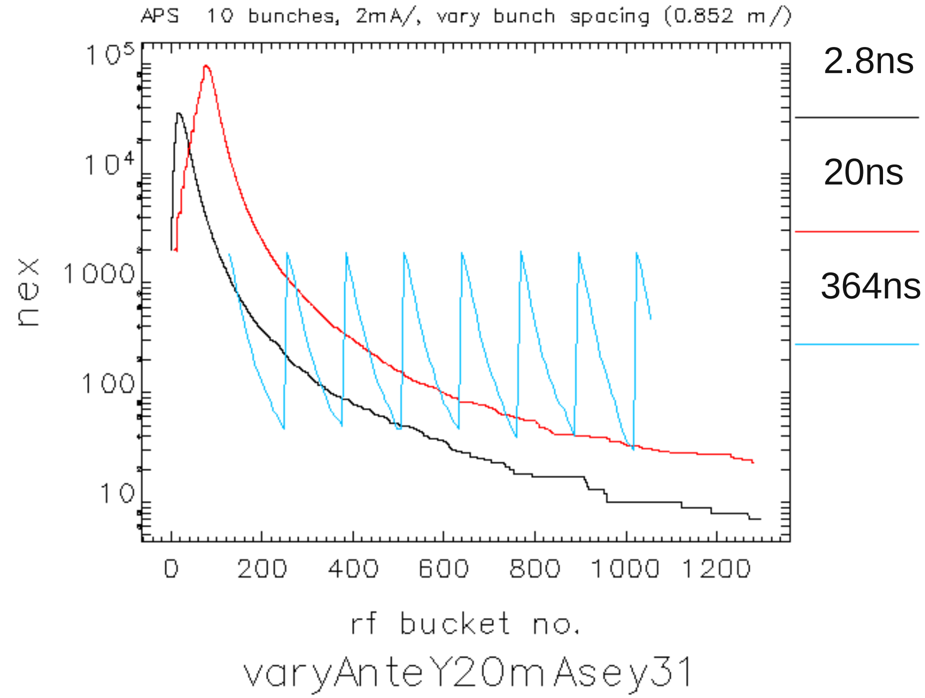


- 10 positron bunches, 2 mA/bunch (4.6e10)
- 7-bucket spacing (7×2.84 = 20 ns)
- Multipacting pattern established by 4th bunch
- ~12-13 frames per bunch passage
- ~1.5 ns/frame
- Computation and movie courtesy M. Pivi


bnch #1
bnch #9
+ 1.5 ns
(approx)
+ 3 ns
+ 4.5 ns
+ 6 ns
+ 7.5 ns
+ 9 ns
+ 11.5 ns
Electron Cloud in the APS
field-free region
10 bunch passages
antechamber
electron detector acceptance

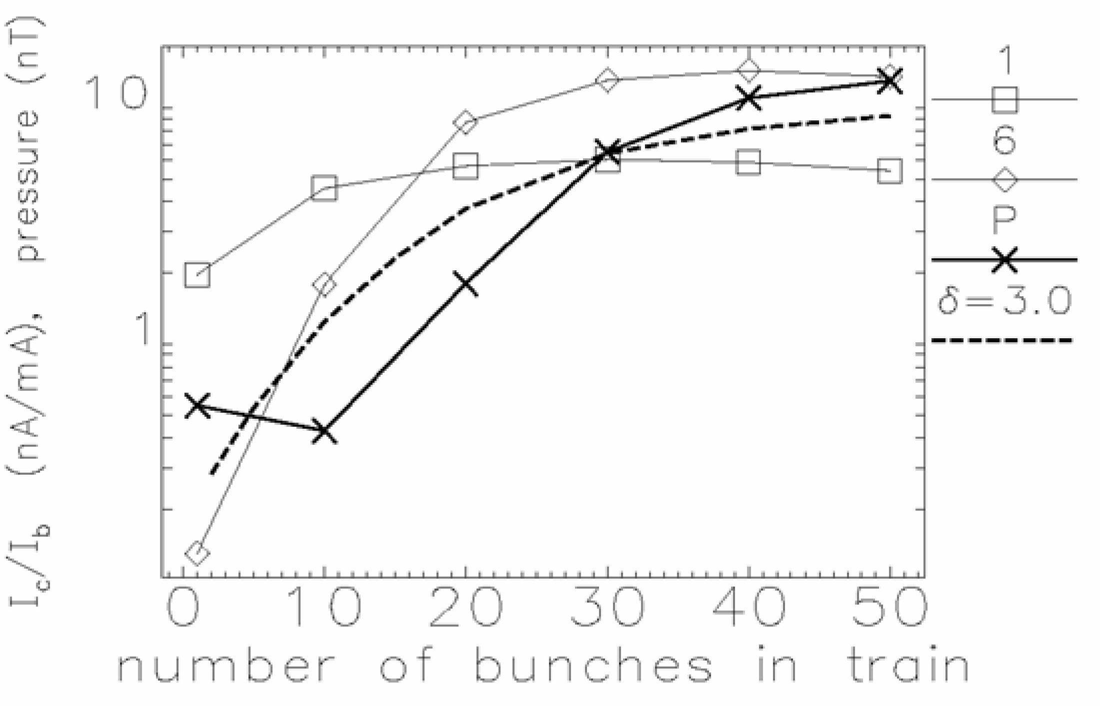
Modeled EC distribution, single turn (10-bunch train)

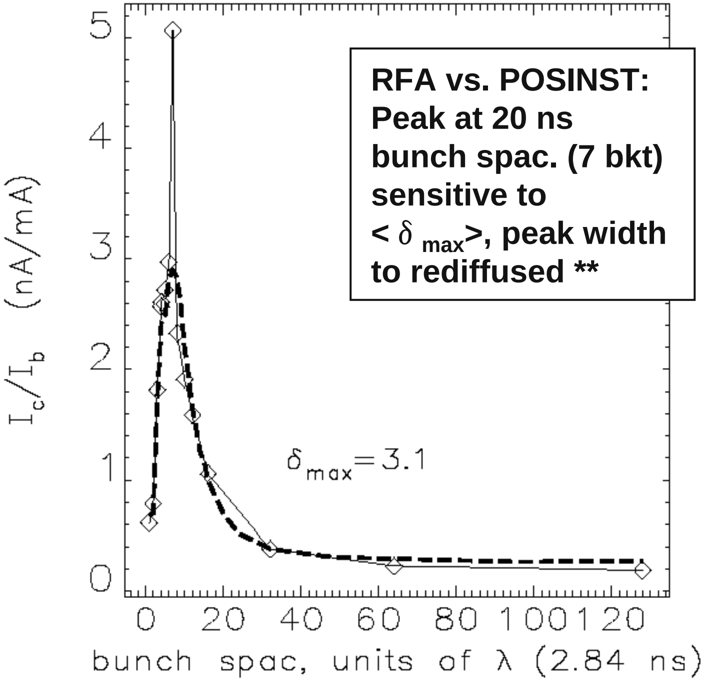




Comparison of δ_{max} 2.2 vs. 3.1; greatest effect at 20 ns spacing

Buildup over bunch train

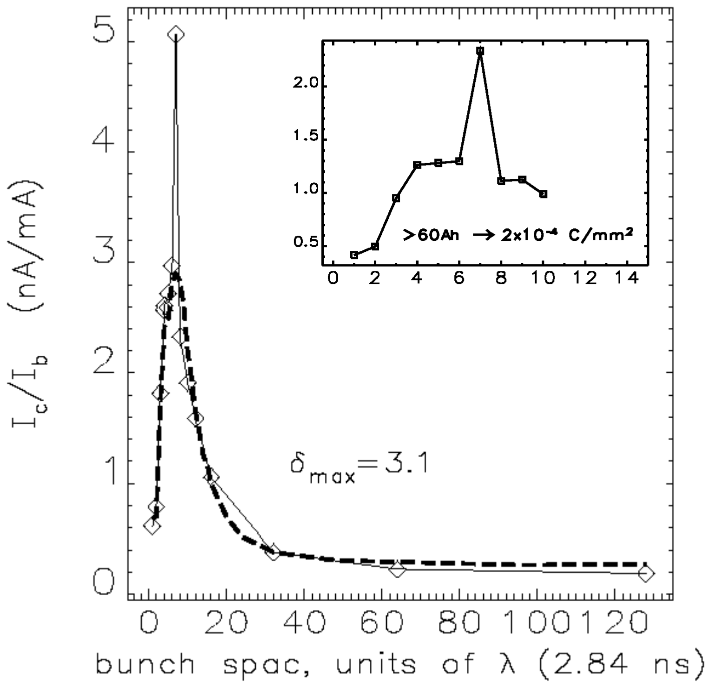


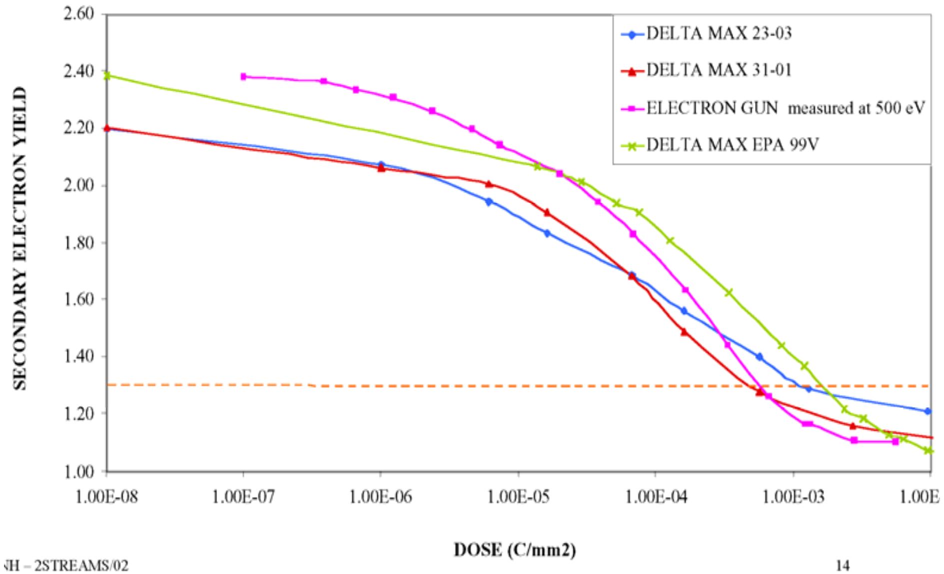


Right: Measured (RFA 1,6) and simulated (dashed line, δ_{max}=3.0) electron wall current as a function of bunch train length, 20 ns bunch spacing, comparing RFAs 65 cm apart. Anomalous pressure rise P is also shown.

Left: Comparison with simulated (dashed line, δ_{max}=3.1) electron wall current (Ic) as a function of bunch spacing (10 bunches; 2 mA/bunch).

Surface conditioning

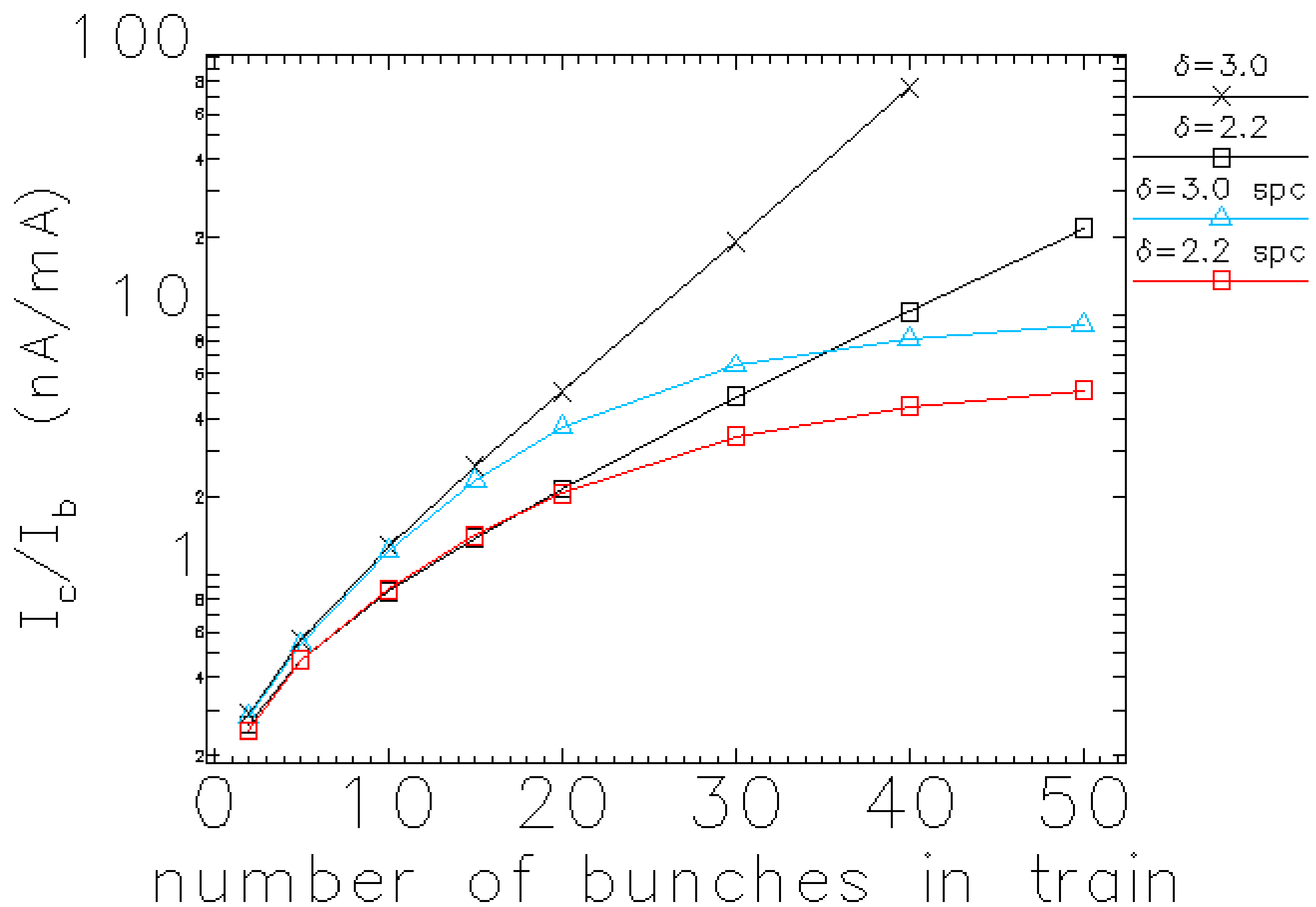




Courtesy N. Hilleret, Two-stream Instab. Workshop, KEK, Japan (2001)

Wall flux at APS reduced 2x after 60 Ah of surface conditioning (inset, left), equivalent to 10^{-3} C/mm^2 dose, consistent with CERN data (Cu). Conditioned Aluminum chamber RFA data consistent with δ_{max} 2.2.

Modeled effect of space charge, 20 ns bunch spacing



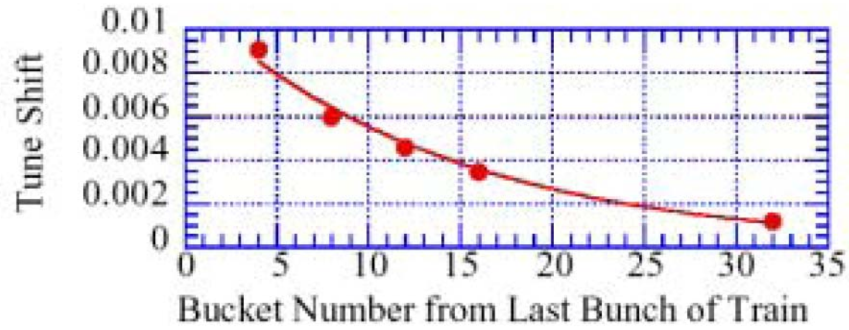
Summary

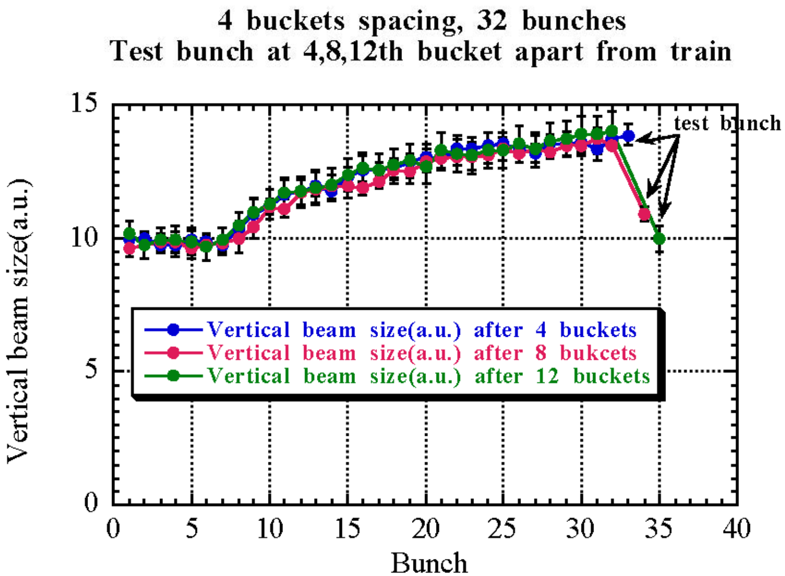
- Measured electron cloud distribution in APS for bunch trains vs current; positron and electron beam
- Strong beam-induced multipacting observed for 20 ns spacing positrons, threshold current; weak (but not zero) effect at 30 ns spacing for electron beams
- APS positron operation used much less or much greater than 20 ns spacing: never saw EC effects before dedicated investigation
- EC generation depends strongly on δ_{max} and rediffused components
- Energy distribution different for positrons vs electron beams, confirms expected beam-cloud dynamics
- Wall conditioning effect: δ_{max} started at 3.1, conditioned to 2.2

Extra slides

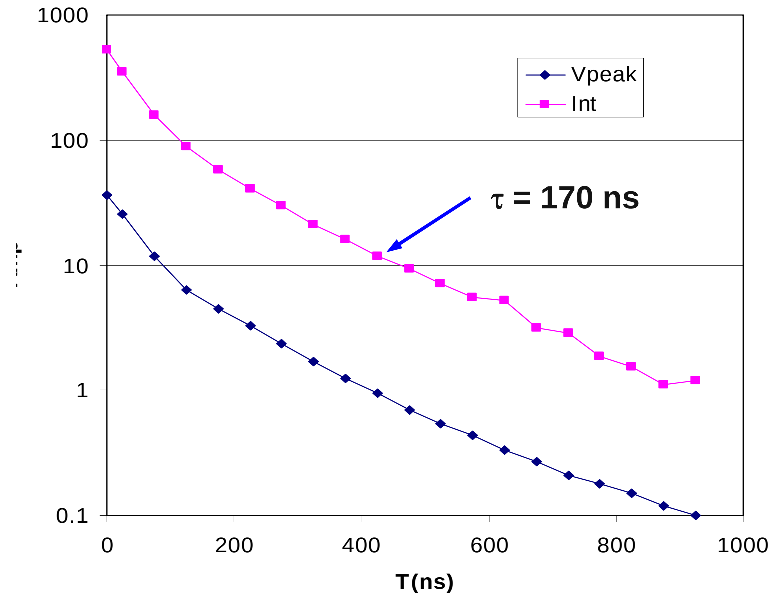
Decay time of electron cloud

KEKB





PSR



Courtesy of R. Macek

KEKB: 25-30 ns vs.

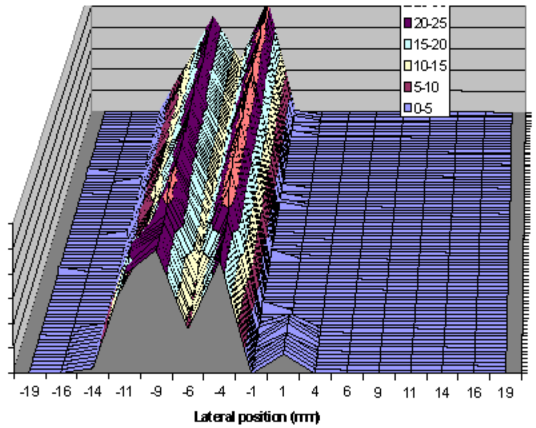
PSR: 170 ns decay time

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

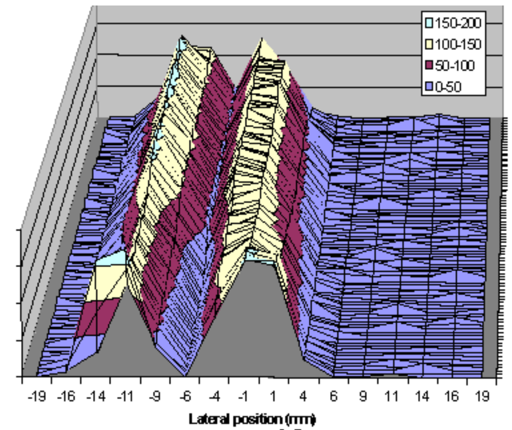
CERN SPS – LHC-type beams

Measured EC distribution in special dipole chamber fitted with strip detectors

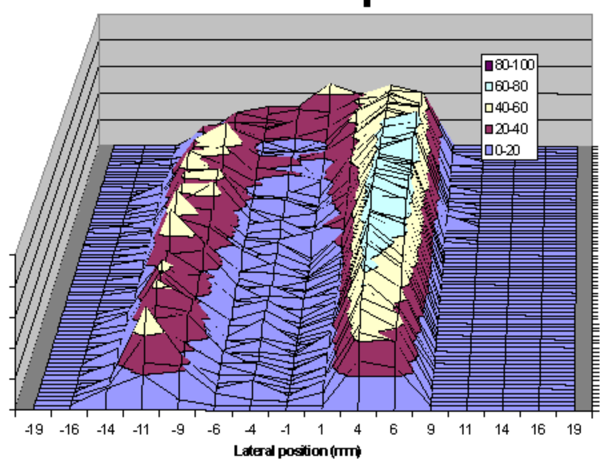
Qualitatively confirmed simulation showing two stripes



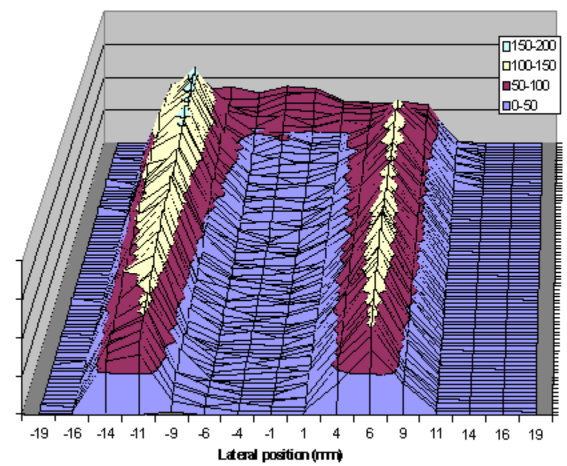
5.0×10^{10} p/b



6.0×10^{10} p/b



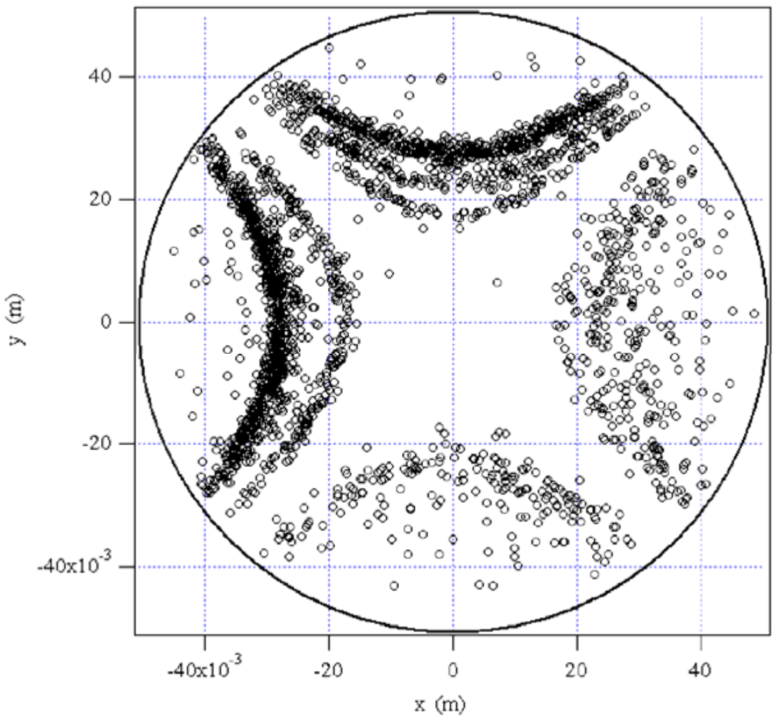
7.9×10^{10} p/b



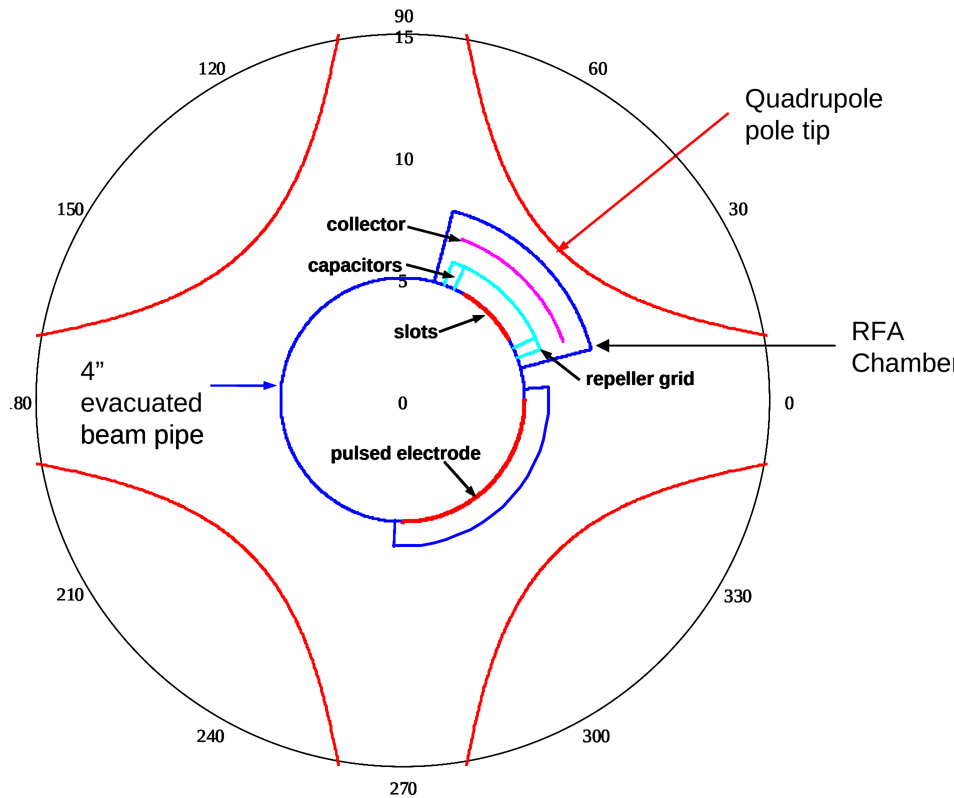
8.6×10^{10} p/b

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

Proposed electron sweeper for quadrupoles (PSR)



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

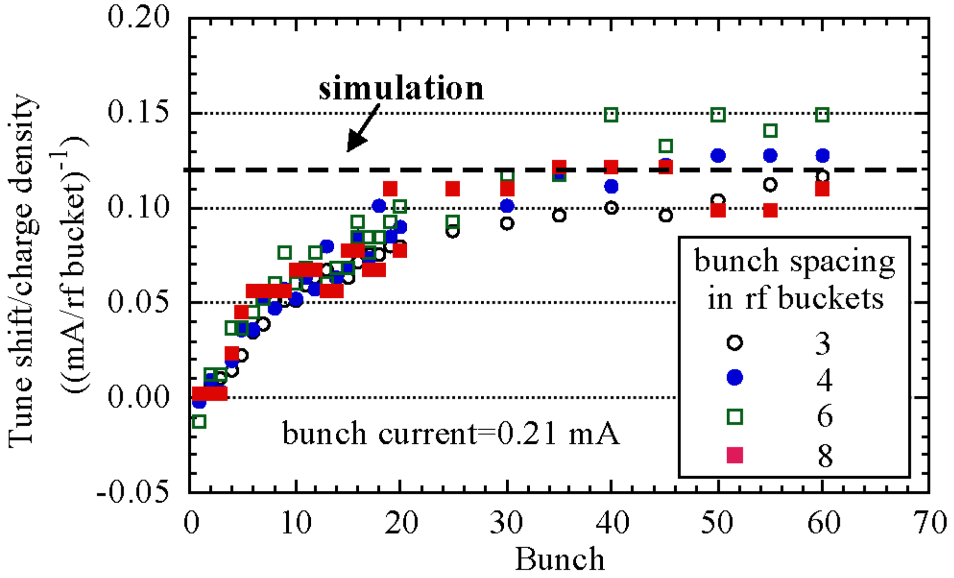


Schematic cross section of a proposed electron sweeping detector for a PSR quadrupole. (Courtesy R. Macek, M. Pivi)

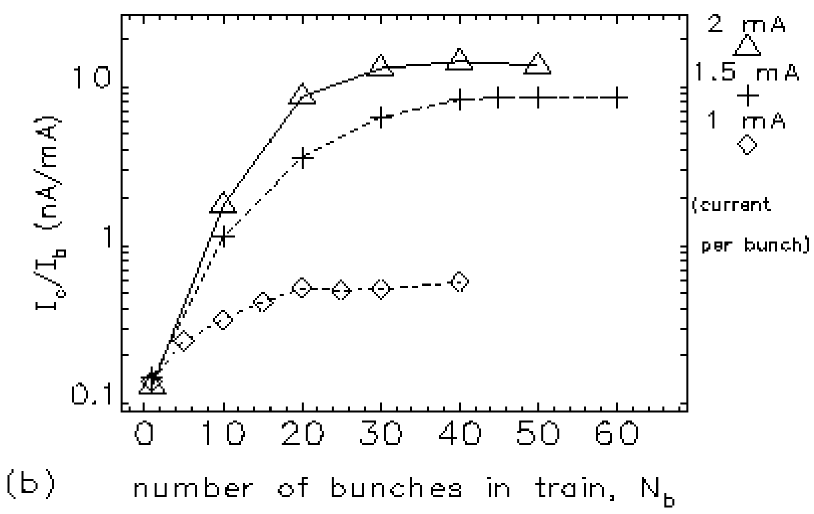
Cloud build-up and saturation

KEKB: EC saturates after 20-30 bunches per tune shift ($4\lambda_{rf}$ 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 ($7\lambda_{rf}$ bunch spacing)

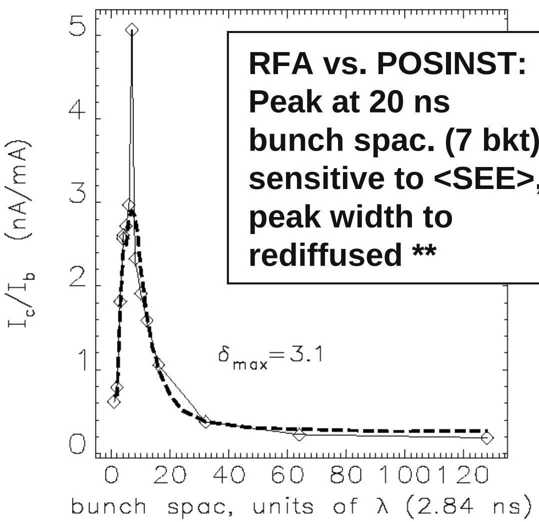


Calculated EC density at saturation (e+ beam)

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

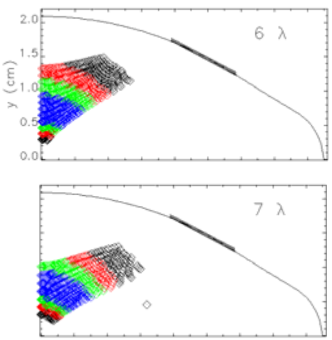
General multipacting condition vs. EC distribution

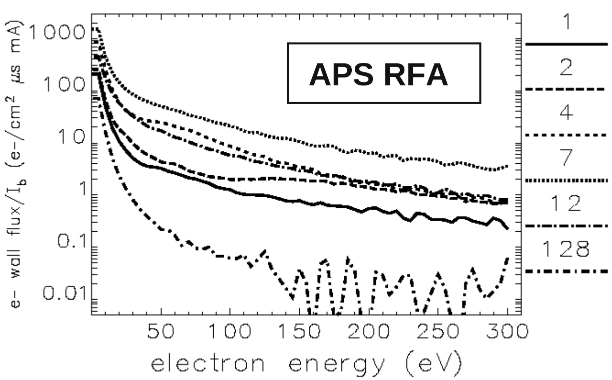
APS: K. Harkay, et al., Proc. 2003 PAC, 3183; ICFA BD Newsletter 33 (2004)



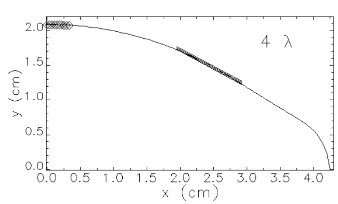
RFA vs. POSINST: Peak at 20 ns bunch spac. (7 bkt) sensitive to <SEE>, peak width to rediffused **

Most resonances for 6 – 7 bkt when 1.2 < SEE < 3.8 eV for 1.0 ≤ δ < 3.0



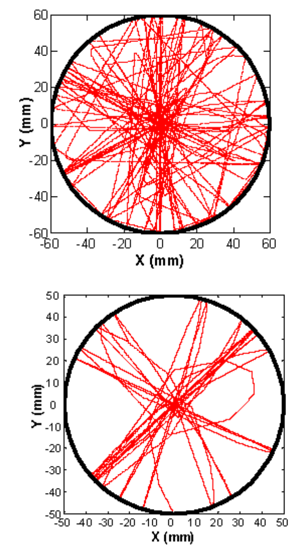


Cold SE predicts 4 bkt



****U. Iriso, also for RHIC (CSEC and ECLOUD), EPAC06**

L. Wang et al., ECLOUD04: RHIC. KEKB, SNS



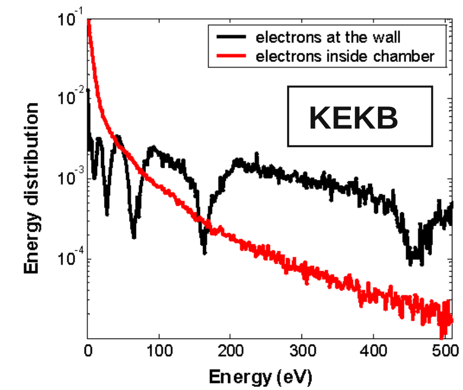


Figure 3: Energy distributions of the electrons at the wall and inside the beam chamber in the KEKB LER's beam. Bunch spacing is 2 ns.

Modeled EC distrib; RFA agrees

Figure 1: Electron's orbit (left column) and energy at the wall (right column). RHIC beam with bunch spacing 108 ns (top row); KEKB LER beam with bunch intensity 3.3×10^{10} and bunch spacing 8ns (bottom row).

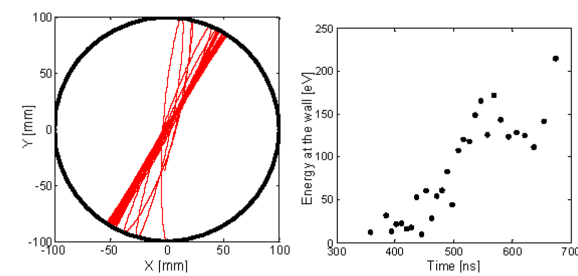
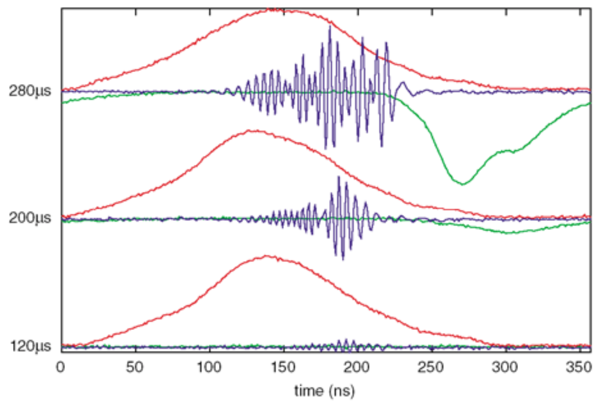
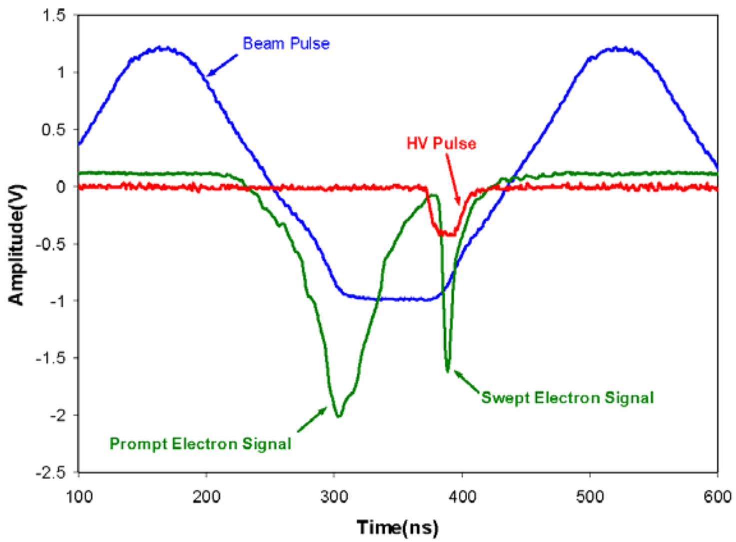


Figure 2: Electron's orbit (left column) and energy at the wall (right column) in the SNS accumulator ring. Bunch length is 700 ns.

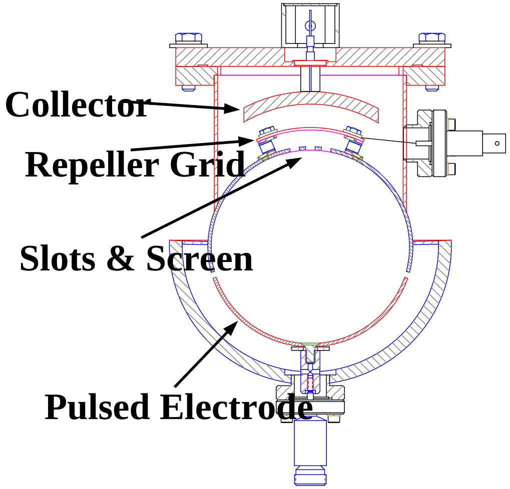
Trailing edge multipacting at Proton Storage Ring



Wideband coherent motion 50-300 MHz (4.4 μC/pulse)



7.7 μC/pulse



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

Prompt electron signal due to trailing-edge multipactor; swept electrons survive gap

bunch length = 280 ns

Figs. courtesy R. Macek A. Browman, T. Wang