ON MEASURING THE PROPERTIES OF THE ELECTRON CLOUD IN A HIGH-ENERGY ELECTRON-POSITRON MACHINE

K. HARKAY, ANL
R. ROSENBERG, ANL

International Workshop on Two-Stream Instabilities in Particle Accel. and Storage Rings
KEK, 2001 Sept 11-14

OUTLINE

- Introduction
- Retarding field analyzer (RFA)
- Electron cloud distributions: RFA (e+ and e- beams)
- Comparisons
  - Beam position monitors
  - Bessel Box analyzer (BBA)
- Calibration of RFA results
- Summary

ACKNOWLEDGEMENTS

M. Furman, M. Pivi, S. Heifets, R. Macek, J Galayda,
and L. Loiacono, Loyola U.

INTRODUCTION

BACKGROUND

- In response to concerns about electron cloud effects, especially at the B-factories, studies were undertaken at APS beginning in 1998 to directly measure the cloud electrons with positron and electron beams
- Specialized electron detectors based on those first designed and utilized at APS are now widely implemented: PSR (LANL), BEPC (IHEP, P.R. China), KEK-B, SPS (CERN), AGS Booster (BNL)

GOAL OF STUDIES at APS

- Characterize electron cloud (EC) distribution for better prediction of machine conditions leading to collective instabilities and other cloud-induced effects
- Identify and provide realistic limits on key ingredients in models:
  - surface effects (photoelectron and secondary electron yield coefficient (δ_{SEY}), secondary electron (SE) distribution)
  - chamber geometry (antechamber, end absorbers)
  - machine parameters (bunch current, bunch spacing)

PAPERS

K. Harkay, R. Rosenberg, Z. Guo, Q. Qin, *Proc. of 2001 PAC*.

R. Rosenberg and K. Harkay, *Proc. of 2001 PAC*.

R. Rosenberg and K. Harkay, *Nucl. Instrum. Meth. A* **453**, 507 (2000).

K. Harkay, *Proc. of 1999 PAC*, 123 (1999).

K. Harkay and R. Rosenberg, *Proc. of 1999 PAC*, 1641 (1999).

INTRODUCTION (CONT)

MAJOR RESULTS

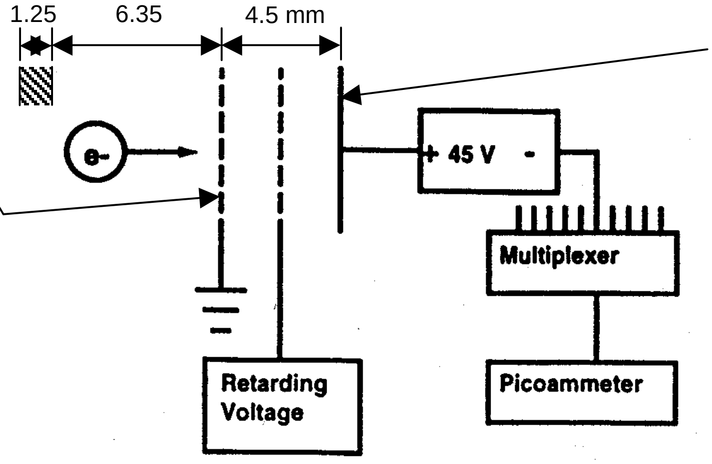
- Beam-induced multipacting (BIM) observed with **both** positron and electron beams
  - Cloud density rises exponentially over bunch train until saturation limit (thereafter rising linearly)
  - Amplification of cloud a strong function of bunch spacing (t_b);
    max at: e+ beam, t_b = 20 ns; e- beam, t_b = 30 ns
  - Amplification 20x less with electron beam
  - 20x rise in vacuum pressure with >1.5 mA/bunch (e+ beam, 100 mA)
  - Conditioning effect: cloud proportional to δ_{SEY}
- BIM condition observed at APS **not completely predicted** by simple formula of resonance condition
  - BIM (per ISR, 1977) involves bunch current and bunch spacing vs. electron time-of-flight across chamber
  - **“Optimal” BIM** condition proposed is also a function of **SE energy distribution**
- Comparison of APS data with LBNL model in good agreement, provided assumed values for δ_{SEY} and **SE energy distribution** carefully chosen (M. Furman and M. Pivi, *Proc. of 2001 PAC*)

From measurements of the electron cloud distribution at the wall (density and **energy**), we can draw assumptions of electron cloud production mechanisms and details of beam-cloud interaction.

FOCUS OF TALK: MEASURED ELECTRON CLOUD ENERGY DISTRIBUTION

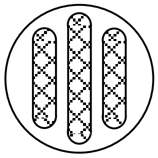
APS RETARDING-FIELD ELECTRON ENERGY ANALYZER (RFA)

Ground grid behind vacuum penetration shields cloud from bias

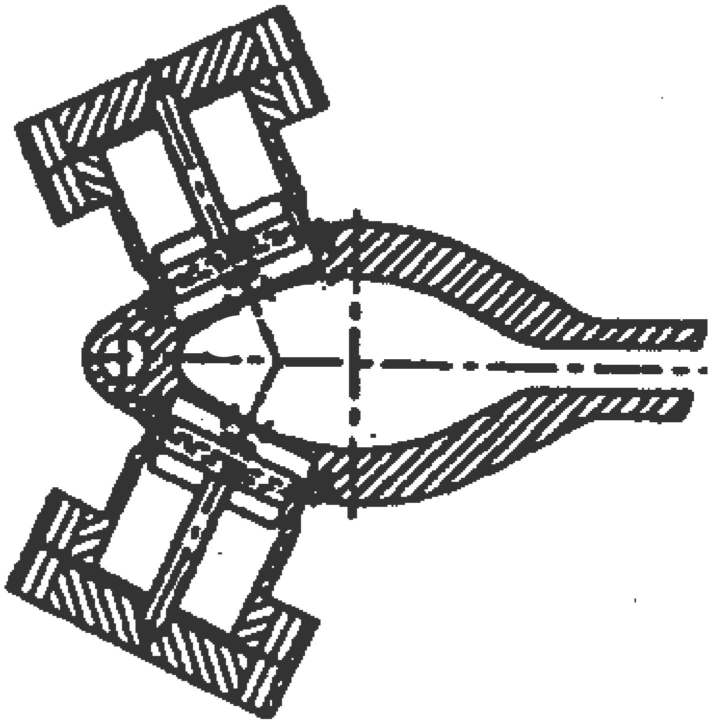


Collector graphite-coated (lower SEY); positive bias to enhance collection efficiency

-300 to +60 V



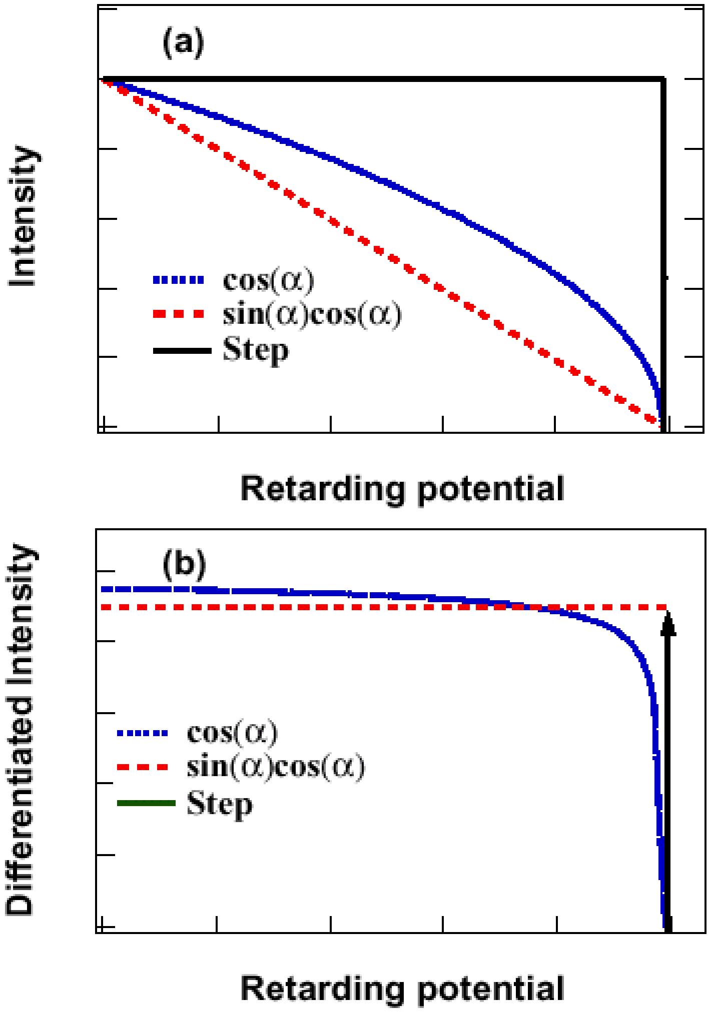
Penetration slot area ~1.25 cm^2



Cross-sectional view of vacuum chamber showing mounted detectors. Measured transmission through grids is ~80%.

R.A. Rosenberg and K.C. Harkay, *NIM A* **453**, 507 (2000)

Theoretical transmission of a planar RFA

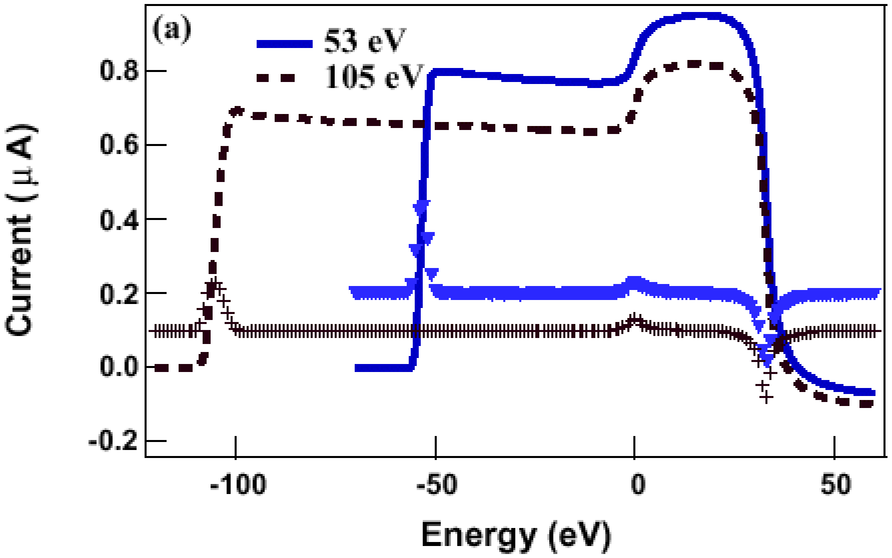


Solid line – ideal case for a parallel, nondivergent, mono-energetic beam of energy U_0.

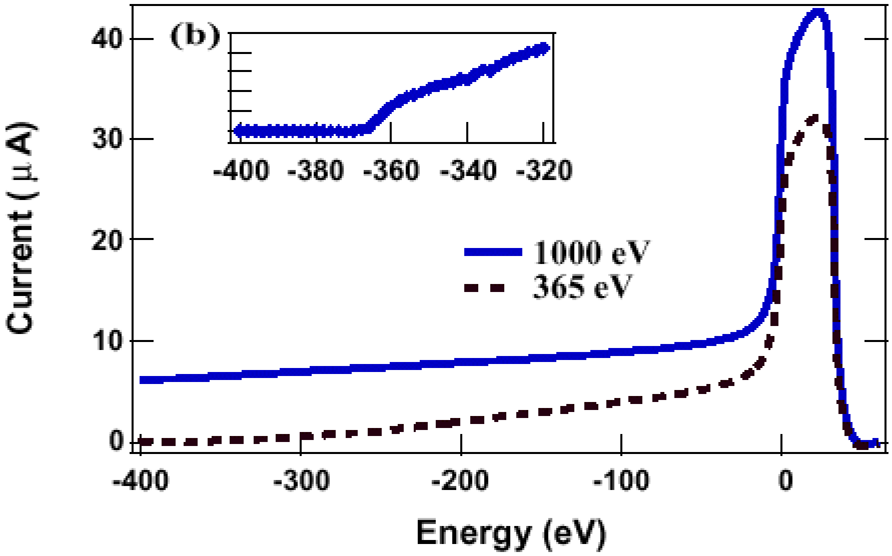
Dashed line – transmission assuming the electrons originate from a point source from a parallel surface with an angular distribution, $P(\alpha)d\alpha = 2\ \sin\alpha\ \cos\alpha\ d\alpha$, where α is the angle between the electrons and the surface normal.

Dotted line – transmission curve for a $\cos\alpha$ distribution.

Measured transmission of a planar RFA



Normal incidence



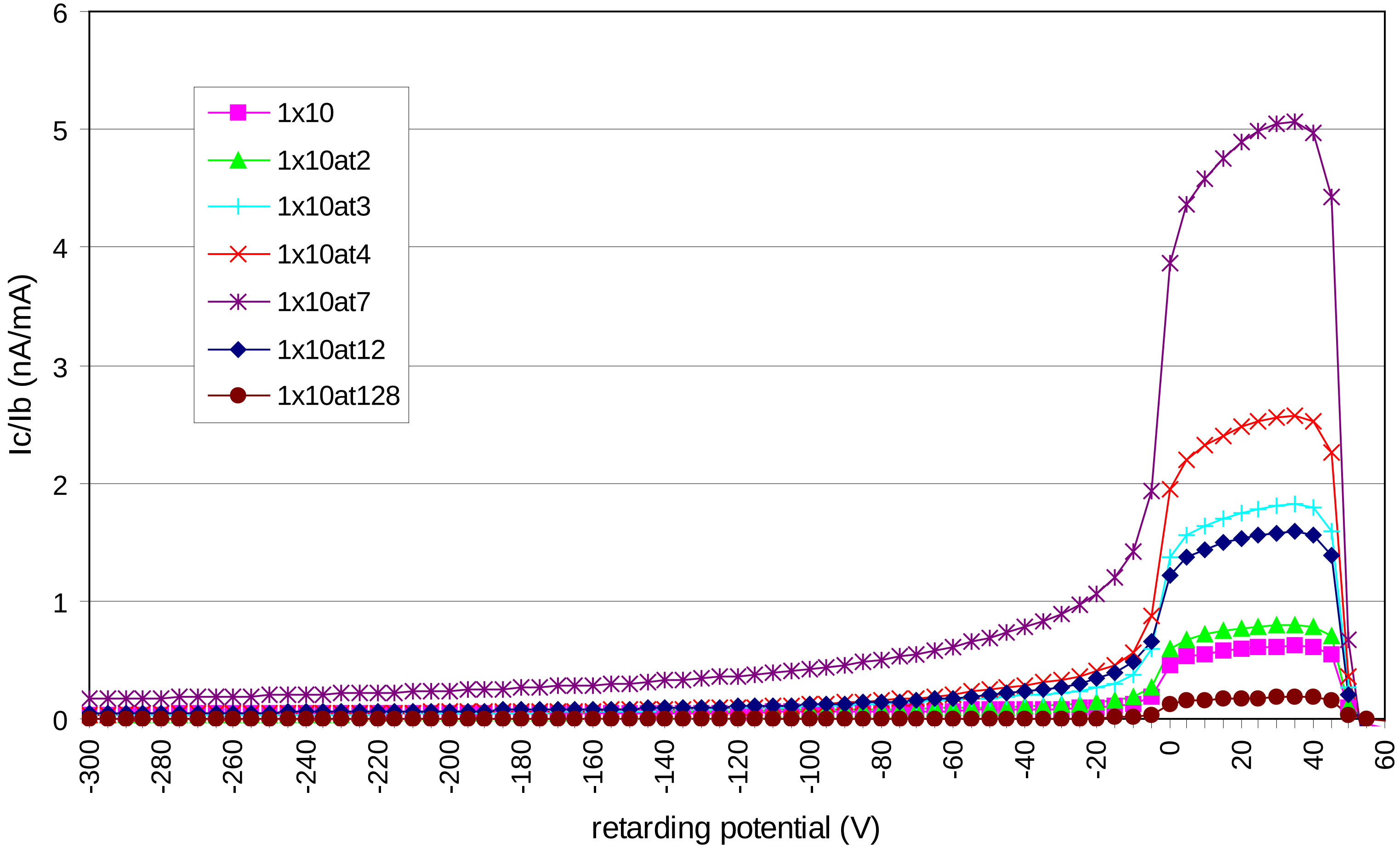
Scattered at 30° from normal

Top – Monoenergetic electron beams directed along the axis of the analyzer for energies of 53 and 105 eV.

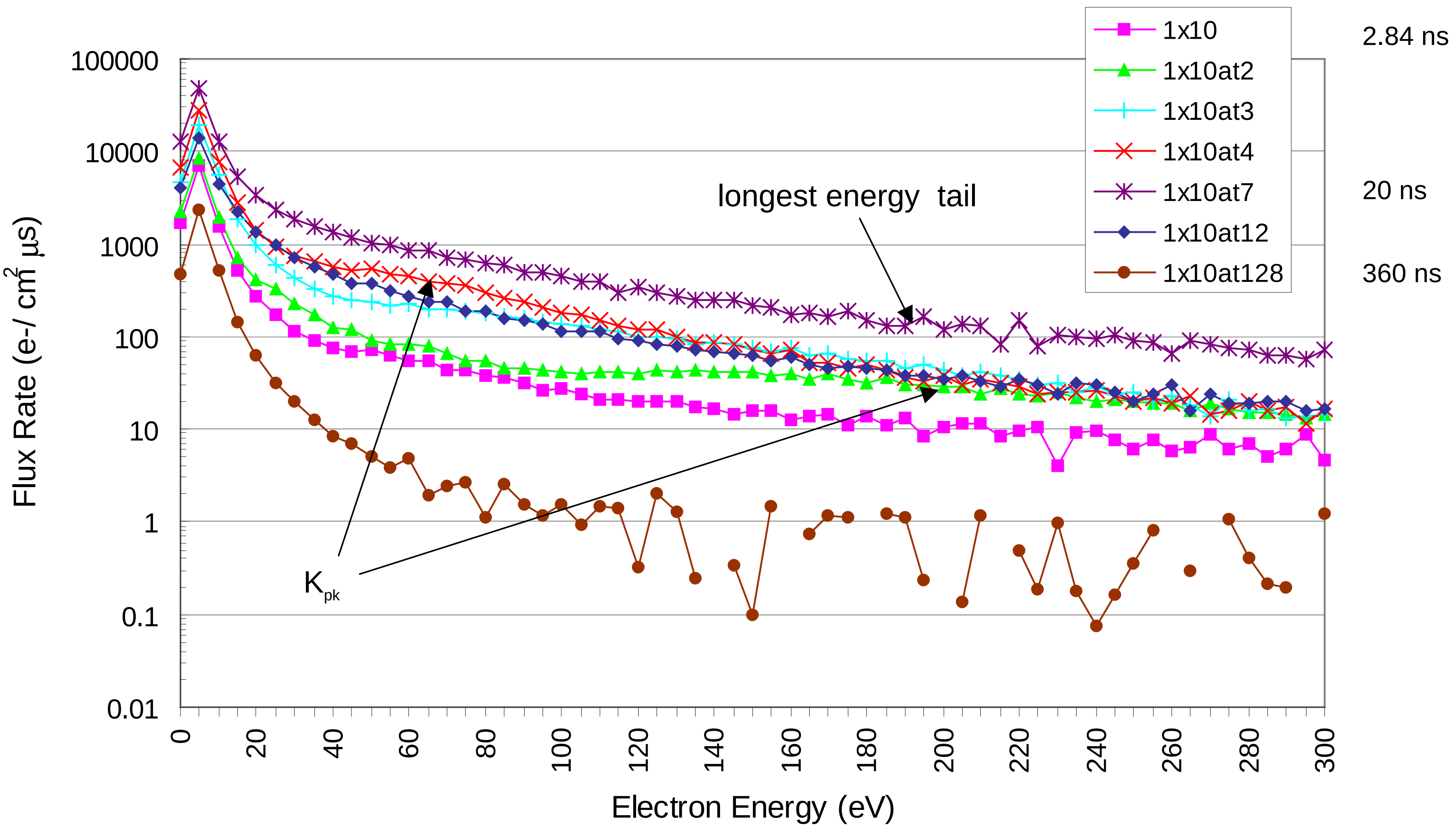
Bottom – Monoenergetic electrons (365, 1000 eV) scattered from an Al target. The inset shows the differentiated signal of the 365-eV beam near the transmission threshold.

ELECTRON CLOUD DISTRIBUTIONS: RFA

Collector current (norm) vs. retarding potential, e+ beam, 20 mA, 10 bunches, as a function of bunch spacing (units of λ_{rf} = 2.84 ns)

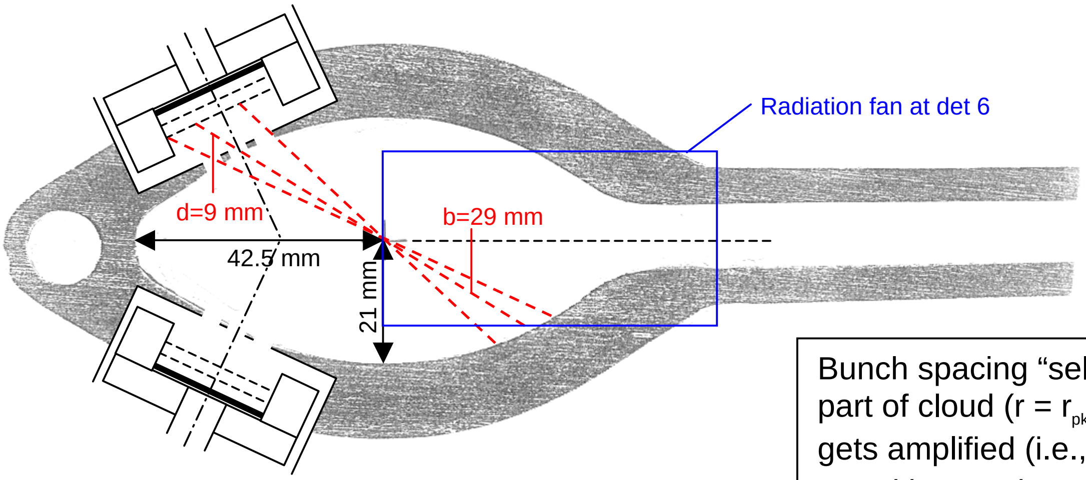


Electron energy distributions for e+ beam, 20 mA, 10 bunches, as a function of bunch spacing, t_b



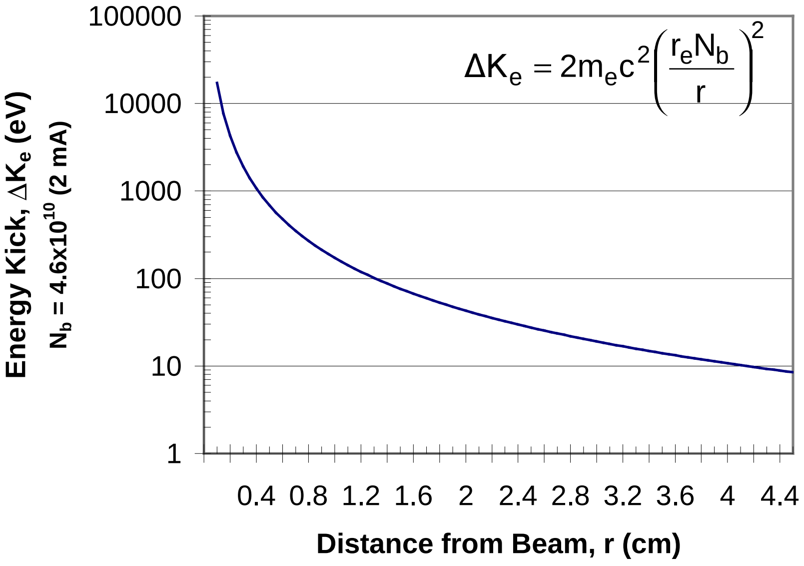
Amplification at K_{pk} of Detected Cloud Distribution

$n(\lambda_{rf})$	t_b (ns)	K_{pk} (eV)	r_{pk} (cm)	t_{pk} $\left(\frac{r_{pk}+b+d}{v_e(K_{pk})}\right)$ (ns)	t_{SE} $t_b-\left(\frac{r_{pk}+b}{v_e(K_{pk})}\right)$ (ns)	K_{SE} $\left(\frac{b-r_{pk}}{ct_{SE}}\right)^2\frac{E_0}{2}$ (eV)
2	5.68	200	0.9	5.6	1.2	35
3	8.52	100	1.3	8.6	1.5	10
4	11.36	65	1.6	11.3	2.0	4



Bunch spacing “selects” part of cloud ($r = r_{pk}$) that gets amplified (i.e., $t_b = t_{pk}$); SE with energies K_{SE} drift to position r_{pk} between bunch passages.

Optimal condition when K_{SE} = SE distrib. peak



$r_e = 2.82\text{x}10^{-13}$ cm, $m_ec^2 = 0.51$ MeV

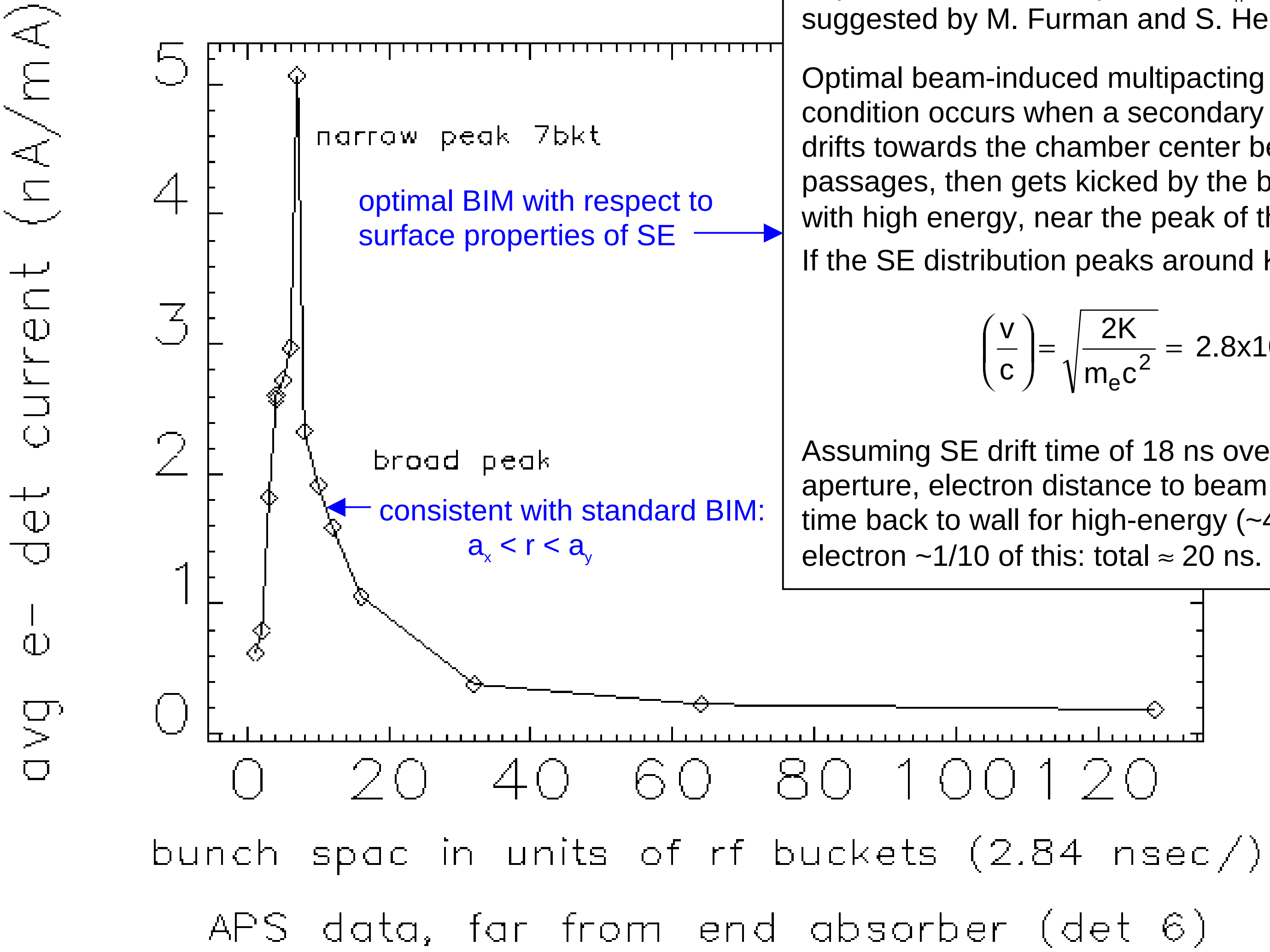
Beam-induced multipacting (BIM) resonance condition [Gröbner (1977)]:

$$t_b = \frac{b^2}{cr_eN_b};\quad \text{gives } t_b = 4\lambda_{rf},$$

but observed to be $7\lambda_{rf}$ at APS

⇨ formalism overly simplified; should include SE distrib.

Amplification of electron signal with bunch spacing



optimal BIM with respect to surface properties of SE →

← consistent with standard BIM: $a_x < r < a_y$

Explanation of narrow peak at $7\lambda_{rf}$ = 20 ns, as suggested by M. Furman and S. Heifets:

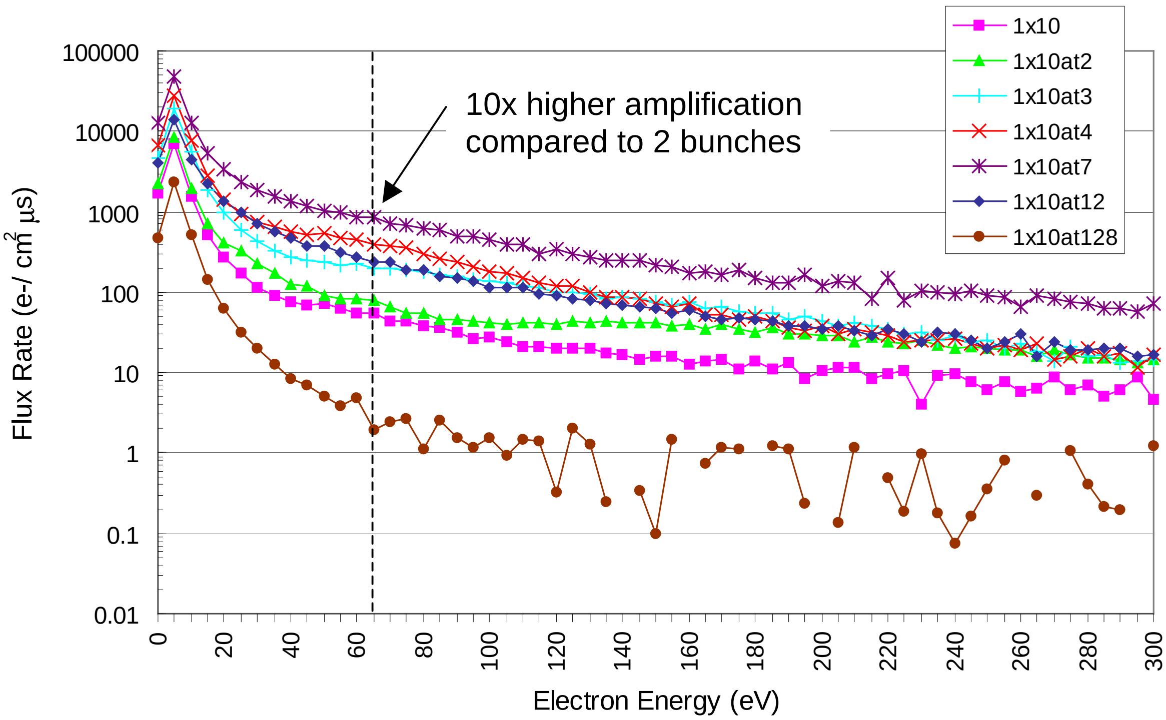
Optimal beam-induced multipacting resonance condition occurs when a secondary electron (SE) drifts towards the chamber center between bunch passages, then gets kicked by the beam to the wall with high energy, near the peak of the $\delta_{SEY}(E)$ curve.

If the SE distribution peaks around K=2 eV:

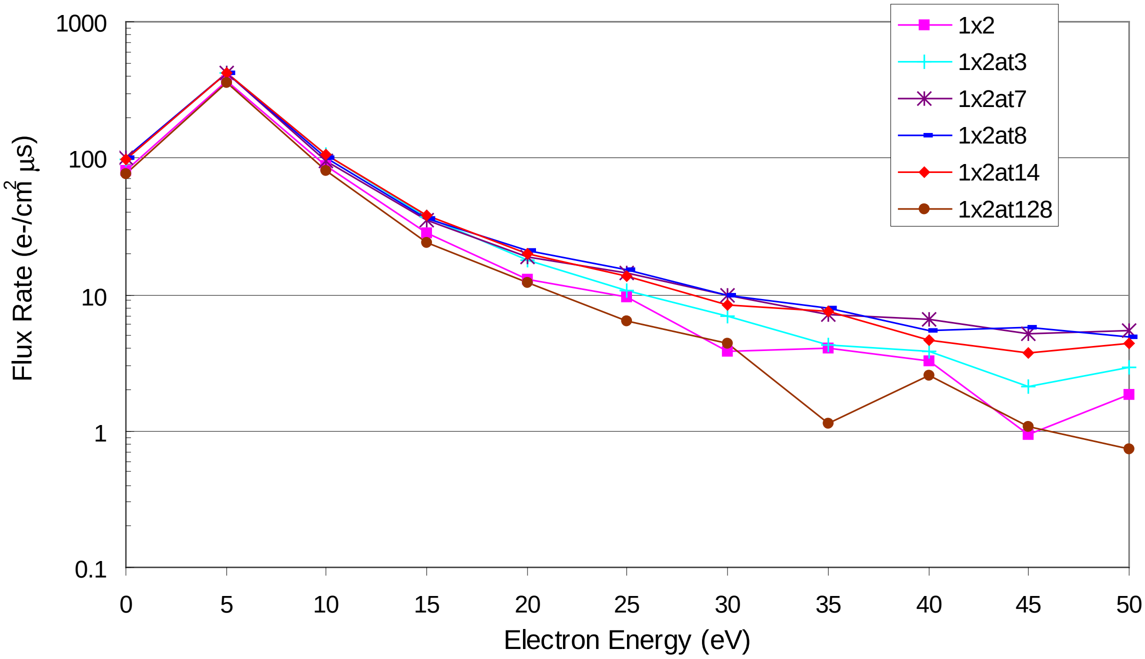
$$\left(\frac{v}{c}\right)=\sqrt{\frac{2K}{m_e c^2}} = 2.8\text{x}10^{-3}.$$

Assuming SE drift time of 18 ns over vertical aperture, electron distance to beam ~0.6 cm. Drift time back to wall for high-energy (~400 eV) kicked electron ~1/10 of this: total ≈ 20 ns.

Comparison of 10 vs 2 bunches
e+ beam, 2 mA/bunch

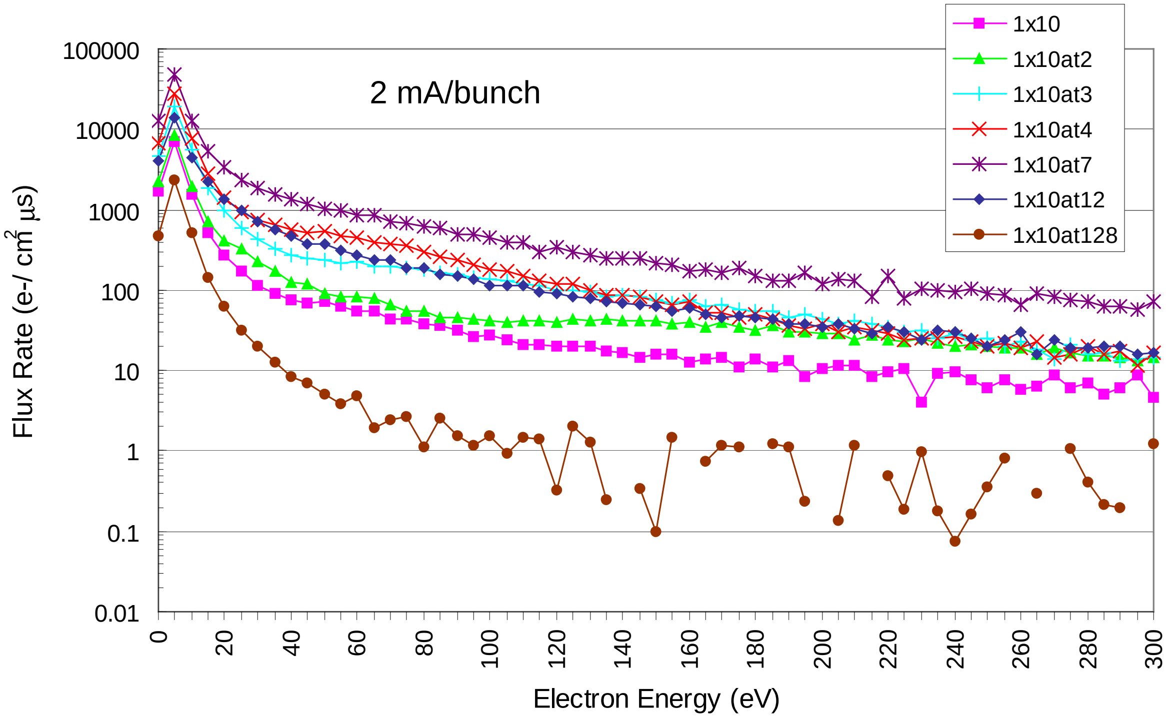


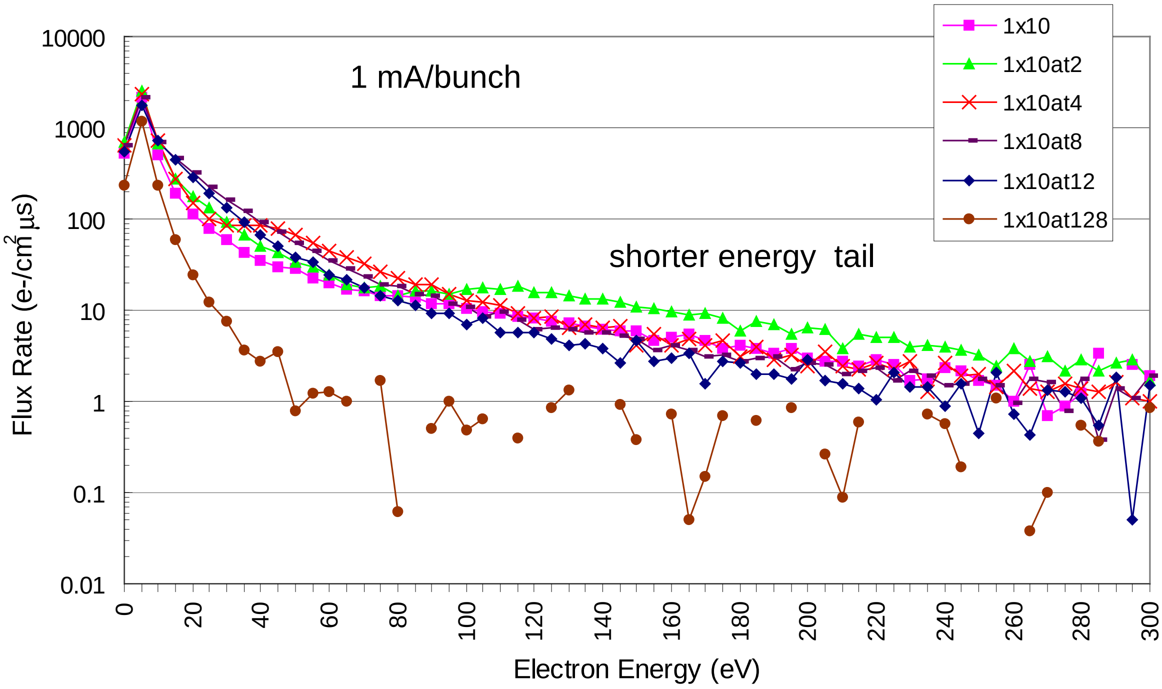
10x higher amplification compared to 2 bunches



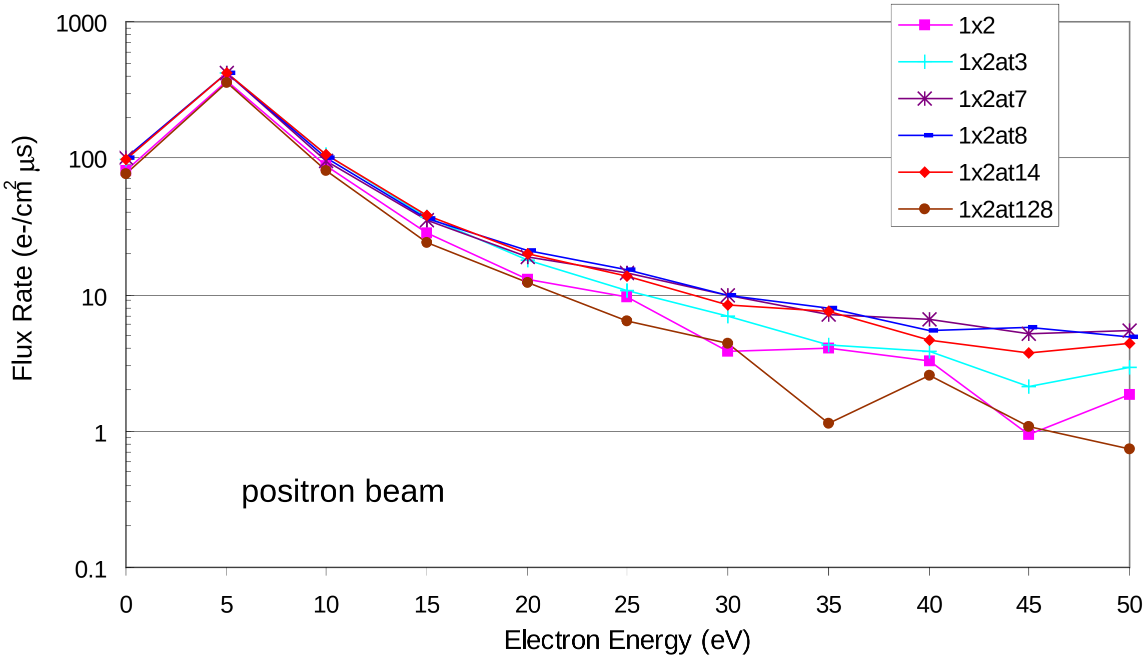
additional surface conditioning of 90 Ah, relative to above

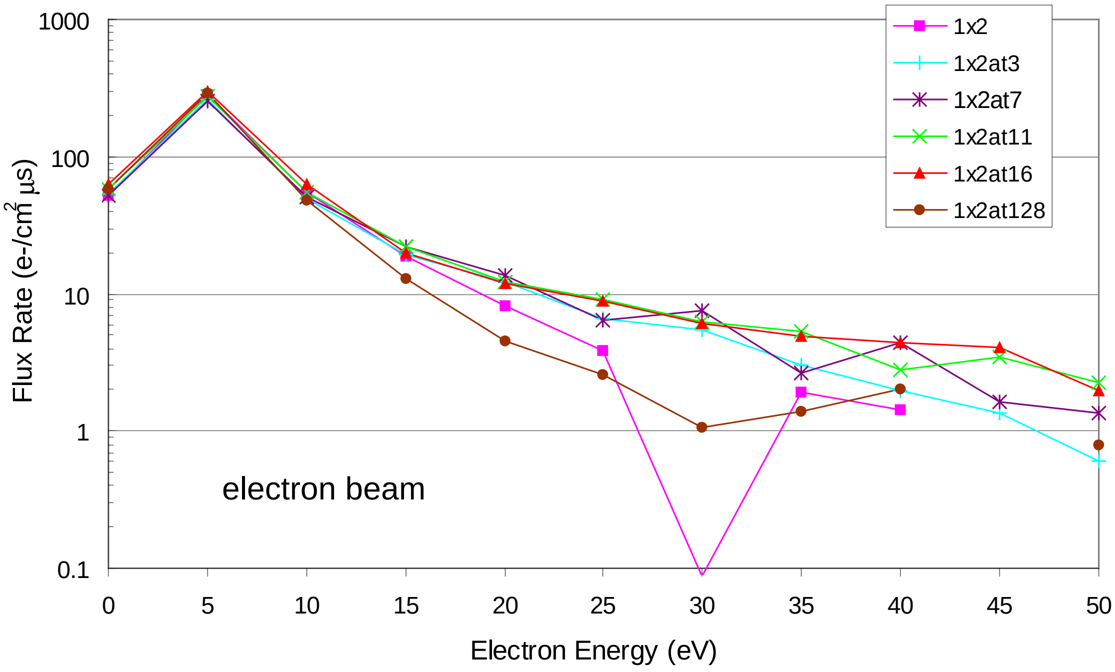
Comparison of 2 mA vs 1 mA/bunch
e+ beam, 10 bunches





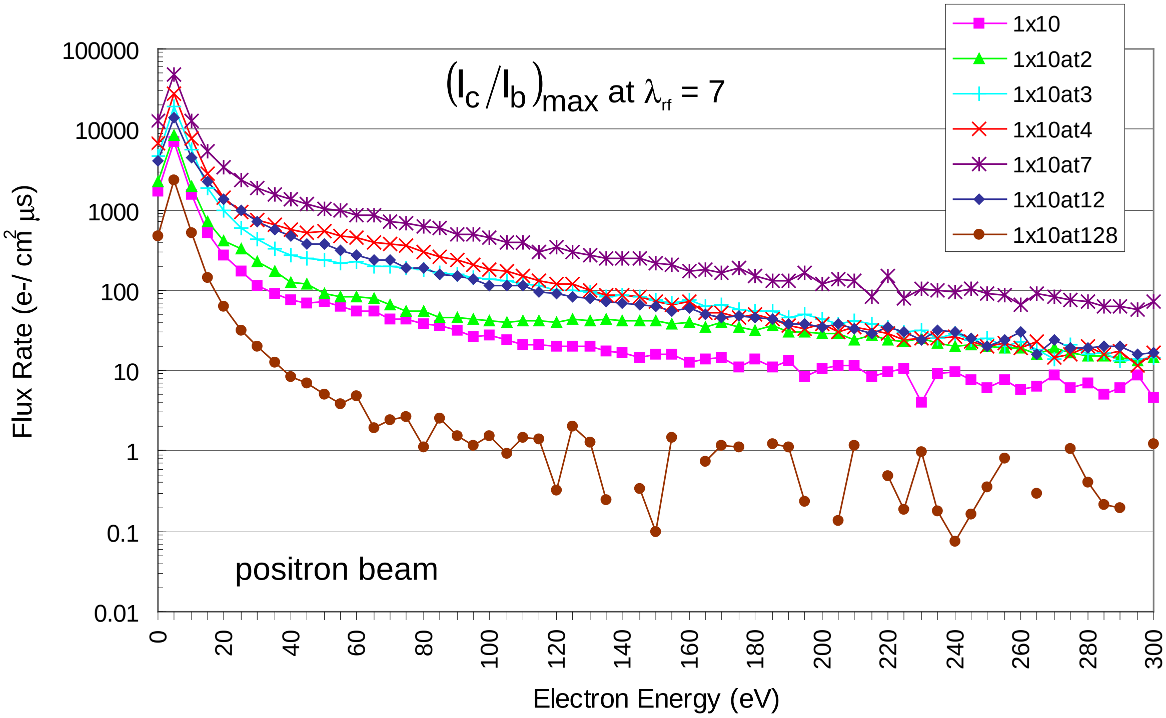
Comparison of positron vs electron beam, 2 mA/bunch, 2 bunches



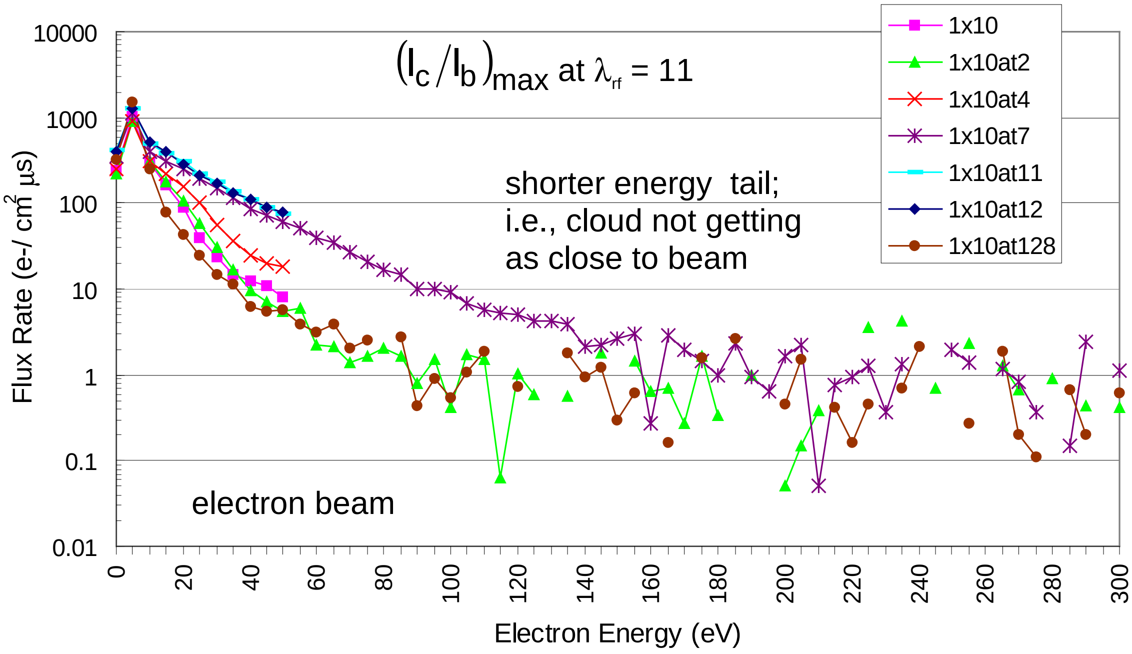


additional surface conditioning of 70 Ah, relative to above

Comparison of positron vs electron beam, 2 mA/bunch, 10 bunches


$(I_c/I_b)_{max}$ at λ_{rf} = 7

positron beam


$(I_c/I_b)_{max}$ at λ_{rf} = 11

shorter energy tail;
i.e., cloud not getting
as close to beam

electron beam

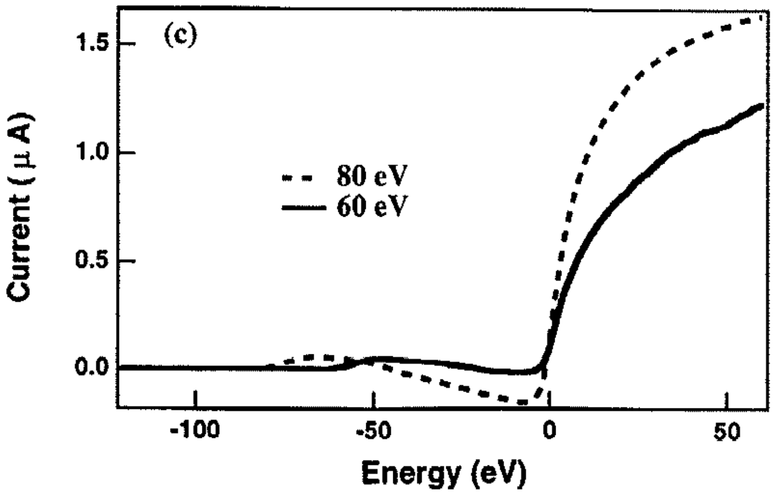
additional surface conditioning of 100 Ah, relative to above

COMPARISONS OF ALTERNATE ELECTRON DETECTORS

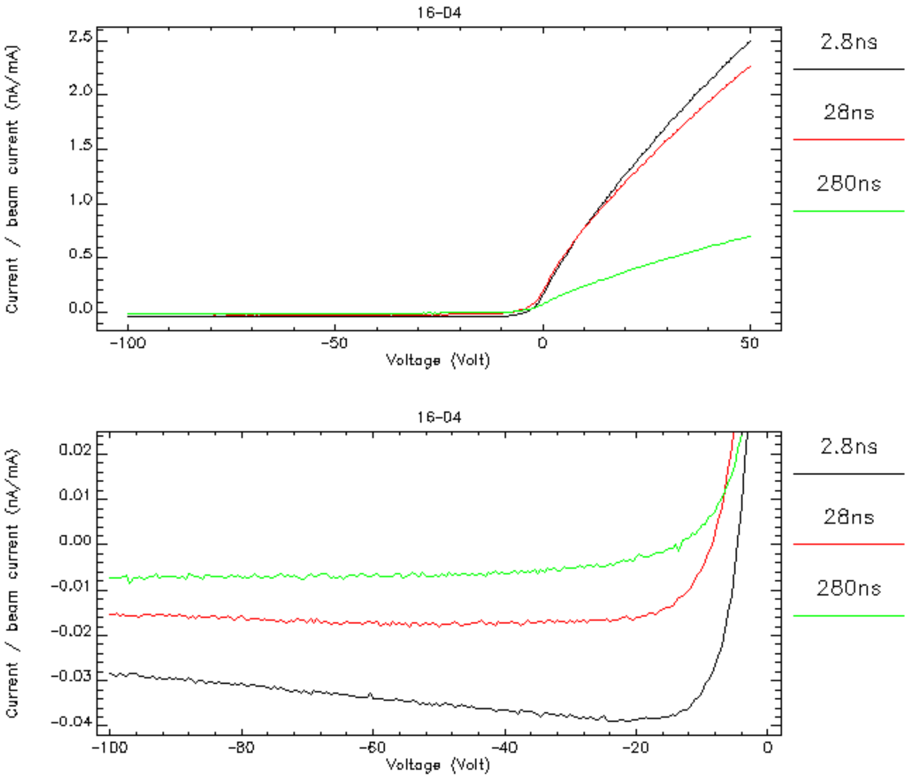
COMPARISON OF ALTERNATE DETECTORS, ELECTRONS COLLIDING WITH WALL

type	pros	cons
Retarding field analyzer (RFA)	• Simple to construct • Large transmission (80%)	• Analysis of energy spectra complicated
Plates; beam position monitors (BPMs)	• Readily available	• Biasing changes collection length • SE emission from surface affects measure of true flux
Bessel box analyzer (BBA)	• Direct analysis of energy spectrum possible	• Poor transmission; narrow angular acceptance

BPM measured signals: bench and in-situ



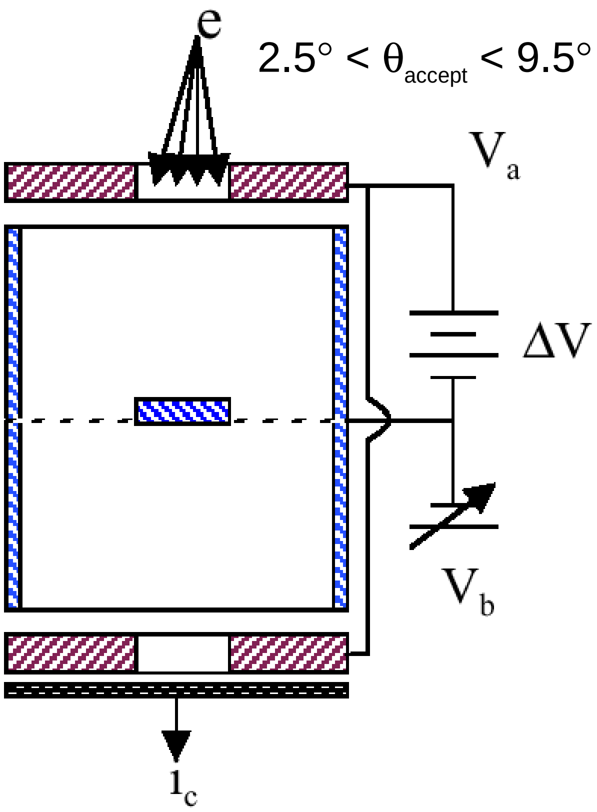
Signal produced from a BPM irradiated by 60 eV and 80 eV electrons as a function of bias voltage applied to the BPM.



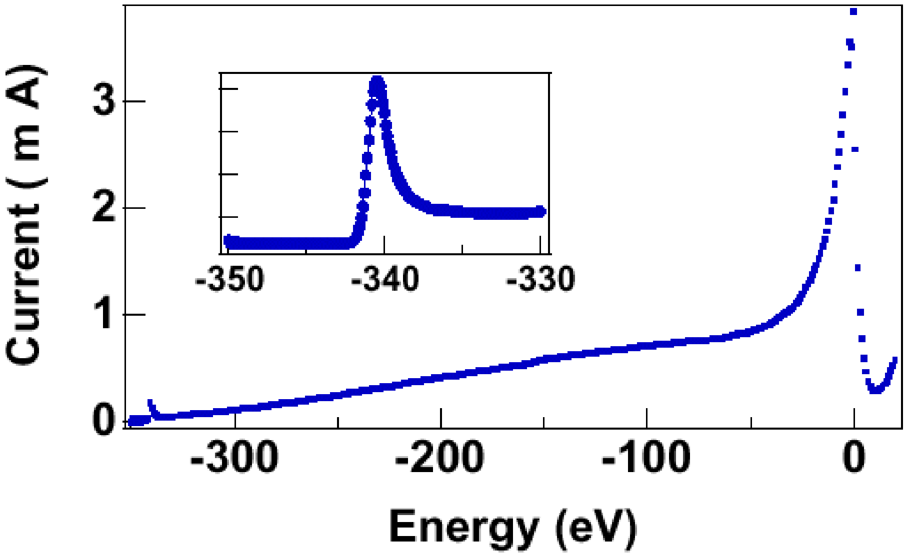
In-situ BPM signals for e+ beam, 2 mA/bunch, 10 bunches, vary spacing (λ_{rf} = 1, 10, 100), as a function of BPM bias voltage.

Bessel Box Analyzer (BBA) schematic and measured transmission:

$\Delta V = (V_b - V_a)$ determines the pass energy

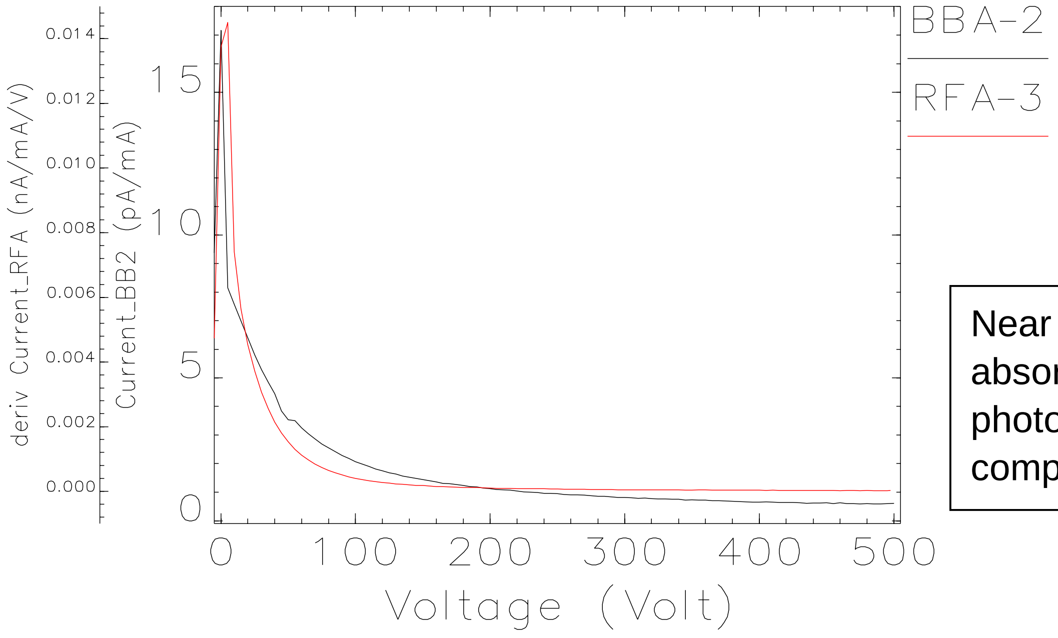


$2.5° < \theta_{accept} < 9.5°$

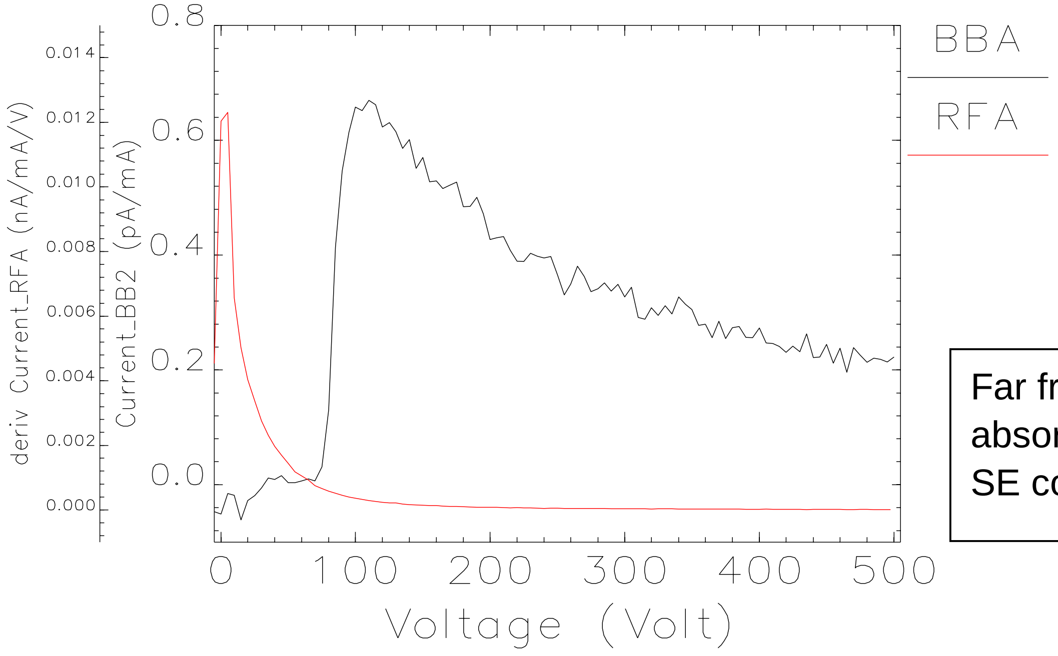


Spectrum of 340-eV electrons scattered from an Al surface using the BBA. The inset shows a detailed scan of the elastically scattered electrons.

BBA vs RFA (differentiated) at two different detector locations; electron beam, 20 bunches, 2 mA/bunch, λ_{rf} = 11

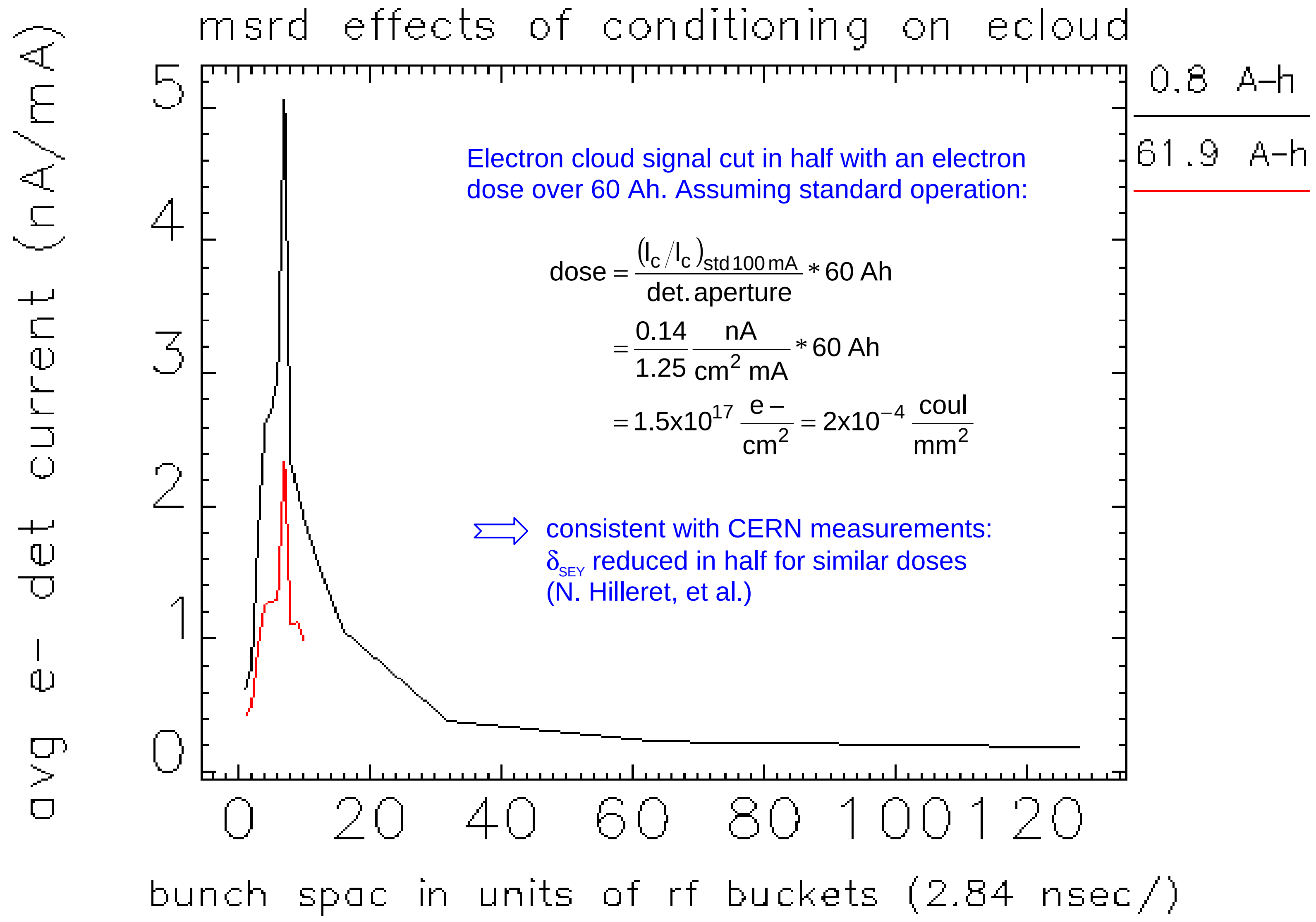


Near end absorber (larger photoelectron component)



Far from end absorber (larger SE component)

CALIBRATION OF RFA RESULTS



Electron cloud signal cut in half with an electron dose over 60 Ah. Assuming standard operation:

$$\text{dose} = \frac{(I_c/I_c)_{\text{std}\,100\,\text{mA}}}{\text{det. aperture}} * 60\ \text{Ah}$$

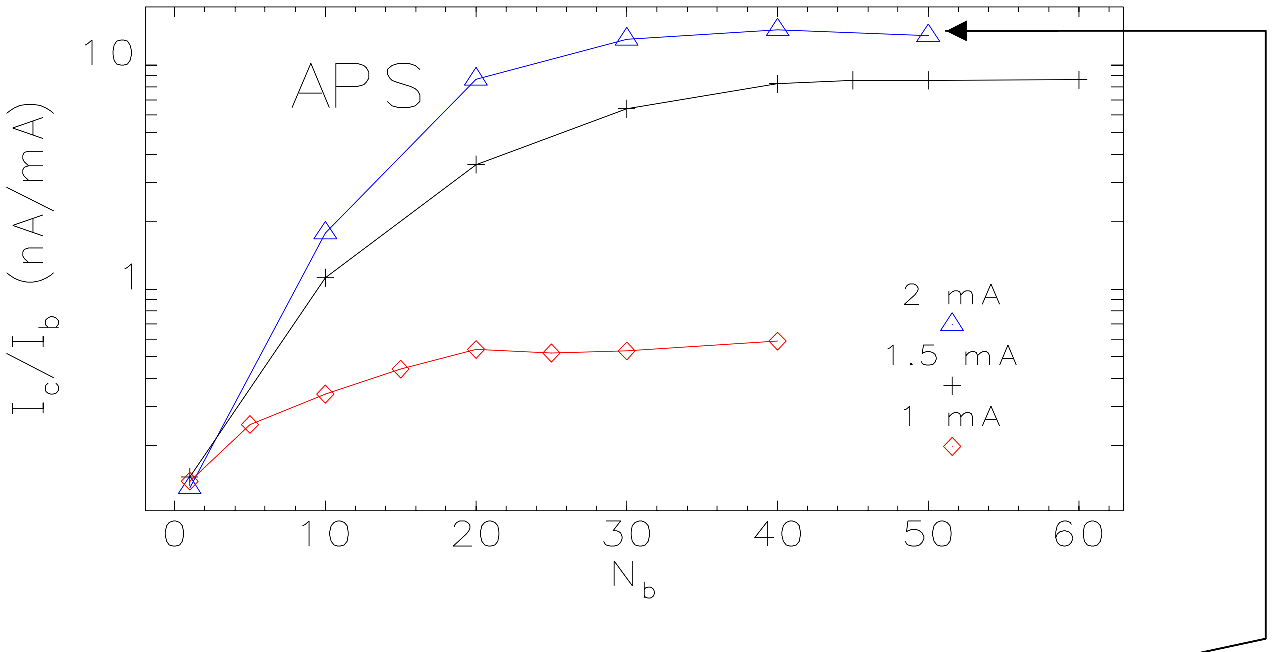
$$= \frac{0.14}{1.25}\,\frac{\text{nA}}{\text{cm}^2\ \text{mA}} * 60\ \text{Ah}$$

$$= 1.5\text{x}10^{17}\,\frac{e-}{\text{cm}^2} = 2\text{x}10^{-4}\,\frac{\text{coul}}{\text{mm}^2}$$

⇒ consistent with CERN measurements: δ_{SEY} reduced in half for similar doses (N. Hilleret, et al.)

APS data, far from end absorber (det 6)

ESTIMATE OF MAX CLOUD DENSITY
e+ beam, cloud in saturation
(> 30 bunches @ BIM spacing λ_{rf} = 7)

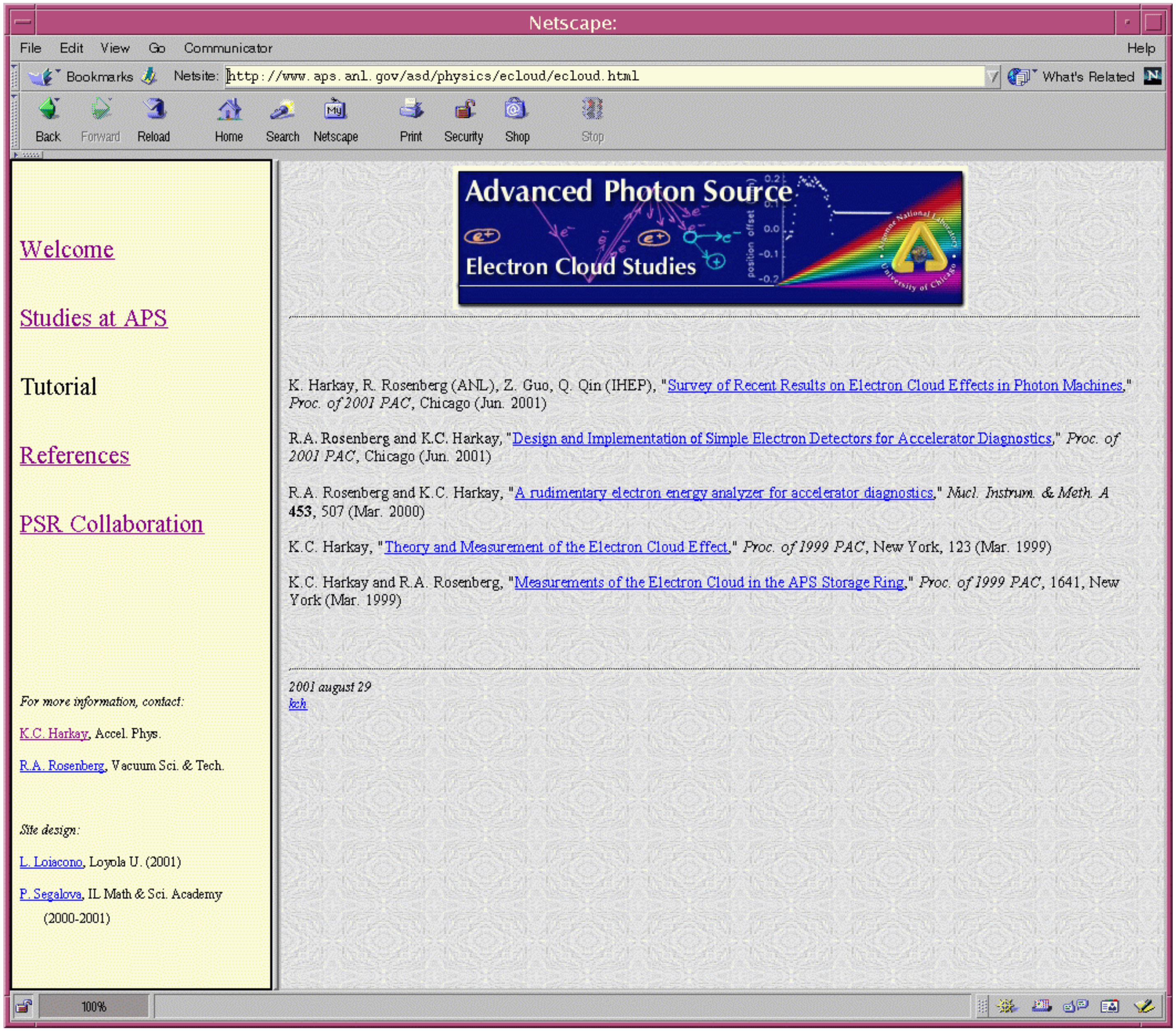


- Vacuum pressure 20x higher than standard 100-mA operation (23 bunches, 4 mA/bunch, 153-ns spacing)
- Electron cloud density at saturation:

$$\langle v_e \rangle_{200eV} = 8.4\text{x}10^8 \text{ cm/s}$$

$$n_e = \frac{I_c \text{ flux rate}}{\langle v_e \rangle} = \frac{15\text{x}10^{-9}}{1.25}\left[\frac{\text{C}}{\text{s cm}^2\text{ mA}}\right]\frac{100}{1.6\text{x}10^{-19}}\left[\frac{\text{mA e}-}{\text{C}}\right]\frac{1}{8.4\text{x}10^8}\left[\frac{\text{s}}{\text{cm}}\right]$$

$$= 10^4\left[\frac{\text{e}-}{\text{cm}^3}\right]$$



http://www.aps.anl.gov/asd/physics/ecloud/ecloud.html

Welcome

Studies at APS

Tutorial

References

PSR Collaboration

For more information, contact:

K.C. Harkay, Accel. Phys.

R.A. Rosenberg, Vacuum Sci. & Tech.

Site design:

L. Loiacono, Loyola U. (2001)

P. Segalova, IL Math & Sci. Academy (2000-2001)

K. Harkay, R. Rosenberg (ANL), Z. Guo, Q. Qin (IHEP), "Survey of Recent Results on Electron Cloud Effects in Photon Machines," *Proc. of 2001 PAC*, Chicago (Jun. 2001)

R.A. Rosenberg and K.C. Harkay, "Design and Implementation of Simple Electron Detectors for Accelerator Diagnostics," *Proc. of 2001 PAC*, Chicago (Jun. 2001)

R.A. Rosenberg and K.C. Harkay, "A rudimentary electron energy analyzer for accelerator diagnostics," *Nucl. Instrum. & Meth. A* **453**, 507 (Mar. 2000)

K.C. Harkay, "Theory and Measurement of the Electron Cloud Effect," *Proc. of 1999 PAC*, New York, 123 (Mar. 1999)

K.C. Harkay and R.A. Rosenberg, "Measurements of the Electron Cloud in the APS Storage Ring," *Proc. of 1999 PAC*, 1641, New York (Mar. 1999)

2001 august 29
kch

SUMMARY

- Energy spectrum of electron cloud (EC) obtained from differentiated RFA signal
  - Detector energy response a function of incident angle; not included in analysis
  - Features in spectra reveal details of beam-cloud interaction
  - Energy tail indicative of how close cloud electrons drift to beam center
- Amplification of cloud electrons at specific energies observed
  - Bunch current and spacing “selects” cloud energy detected
  - Observed spectrum may depend on detector location
- Optimal beam-induced multipacting (BIM) condition for multiple bunches includes SE energy distribution peak (EC established)
  - SEs produced between bunch passages drift near beam
  - SEs kicked by beam to energy, K_i, near peak of $\delta_{SEY}(K_i)$
  - BIM resonance condition when drift times for low-energy SE plus high-energy kicked electron equal the bunch spacing
  - Optimal when EC fills chamber, resonance condition satisfied for $0<r<b$ for energies near peak of SE distrib.
- Positron beam

  10 bunches, 1 vs. 2 mA/bunch
  - Energy tail longest with 2 mA/bunch; vacuum pressure rise
  - Shorter tail (1 mA/bunch) = EC doesn’t drift as close to beam

  2 mA/bunch, 2 bunches vs. 10 bunches
  - Nonlinear EC growth: 10x higher amplification with 10 bunches compared to 2 bunches (BIM, < 50 eV)

- Positron vs. electron beam

  10 bunches

  - 10x higher EC amplification for e+ beam compared to e- beam at optimal bunch spacing
  - Few high-energy (> 150 eV) cloud electrons with e- beam (cloud doesn't drift as close to beam)

  2 bunches

  - Cloud nearly identical for e+ and e- beams (accounting for surface conditioning)
- RFA vs. other detectors (electrons measured at wall)
  - RFA: drop in signal levels measured over time consistent with surface conditioning
  - BPM: difficult to interpret EC density and energy dependence for biased pickup
  - BBA: good theoretical energy resolution, but relatively small angular acceptance
- Alternate techniques

  At wall

  - Electron sweeper (per Macek, et al., at PSR)
  - Time-resolved, fast, amplified RFAs (per Macek, et al.)
  - Screened strip detectors in dipoles (per Cornelis, et al., SPS)

  In chamber volume

  - Pair of striplines: separate proton beam- (v_z) and electron cloud- ($v_{x,y}$) induced signals (per G. Lambertson)
  - Measure attenuation at cyclotron resonance of rf wave transmitted through cloud in dipole (per S. Heifets)
  - Measure cloud-induced tune shift (per F. Mills)