Measurement and Modeling of Electron Cloud Trapping in the CESR Storage Ring

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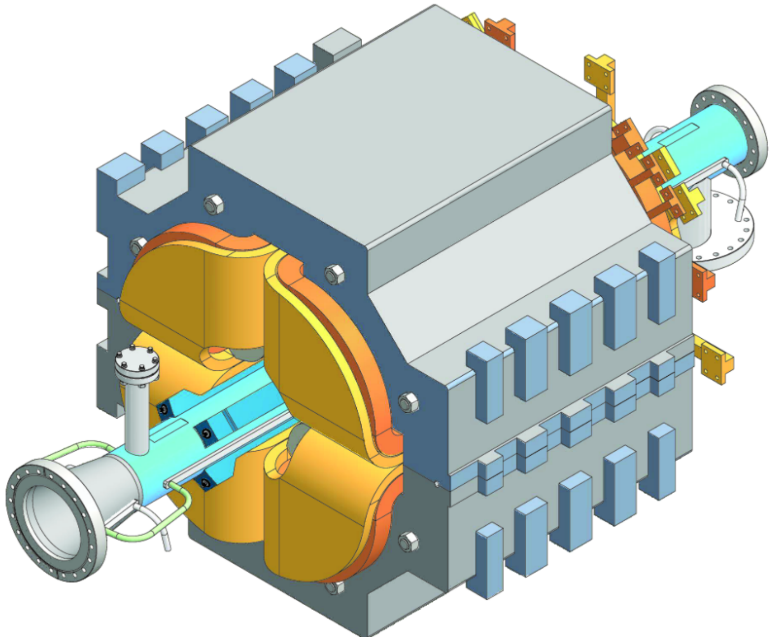
Cornell Laboratory for Accelerator-Based Sciences and Education

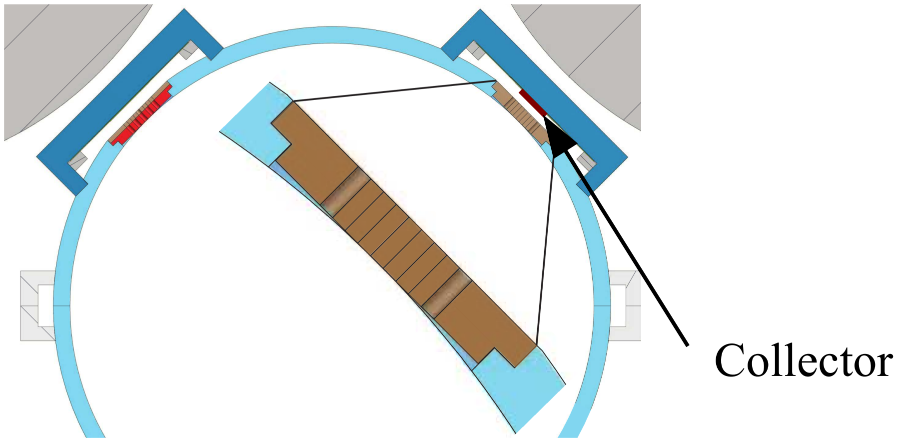
Low Emittance Rings 2014 Workshop

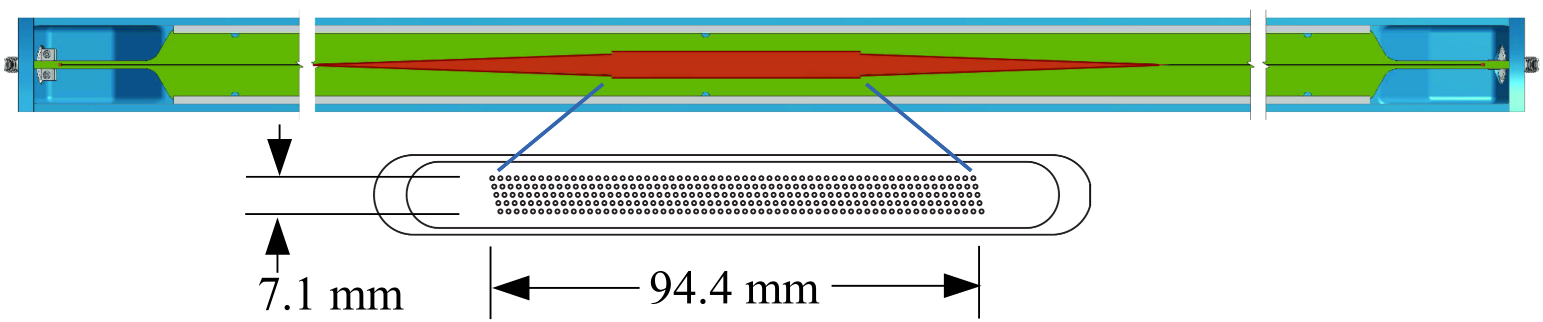
INFN-LNF, Frascati (RM), Italy

17 September 2014

Time-resolving shielded stripline electron cloud detector



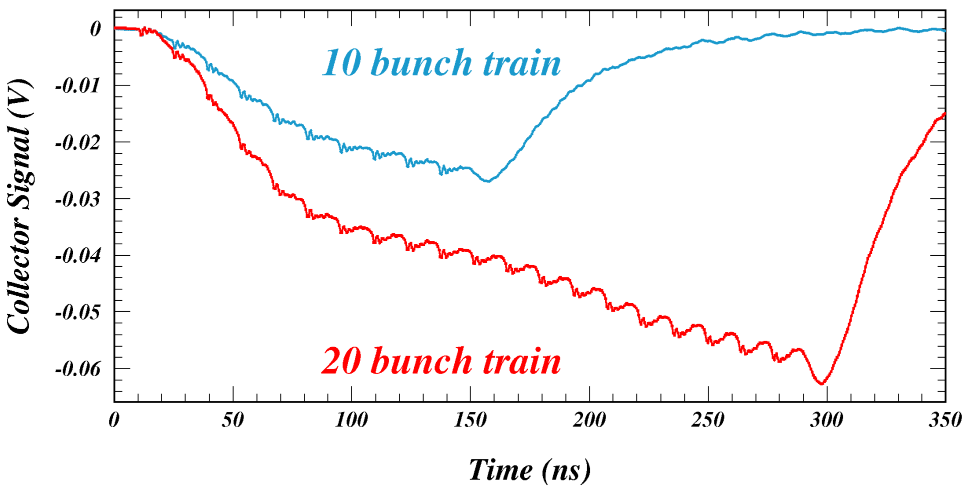




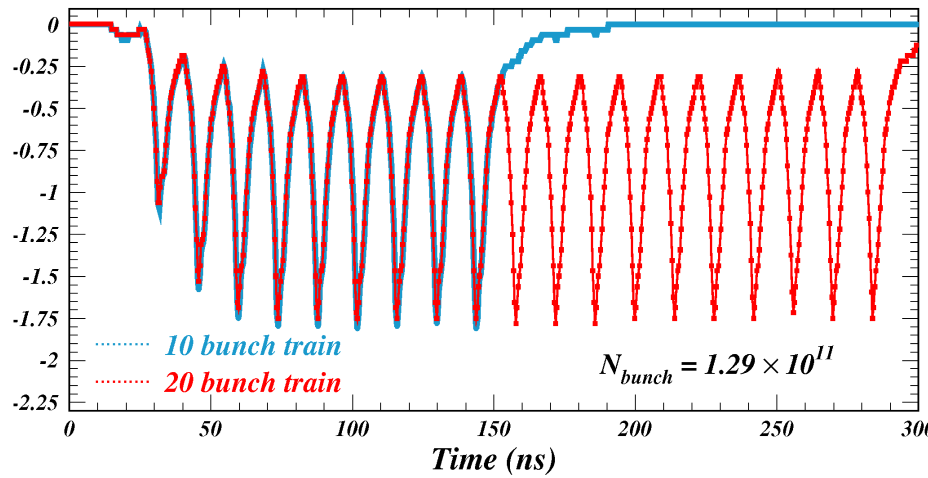
Discovery of electron trapping June 2013

Shielded stripline signals for 10- and 20-bunch trains of 5.3 GeV positrons in the 7 T/m quadrupole magnet

Shielded button electrode signals recorded simultaneously in a field-free region of the CESR ring



Observation of Electron Trapping in a Positron Storage Ring,
M.G. Billing et al, arXiv 1309.2625

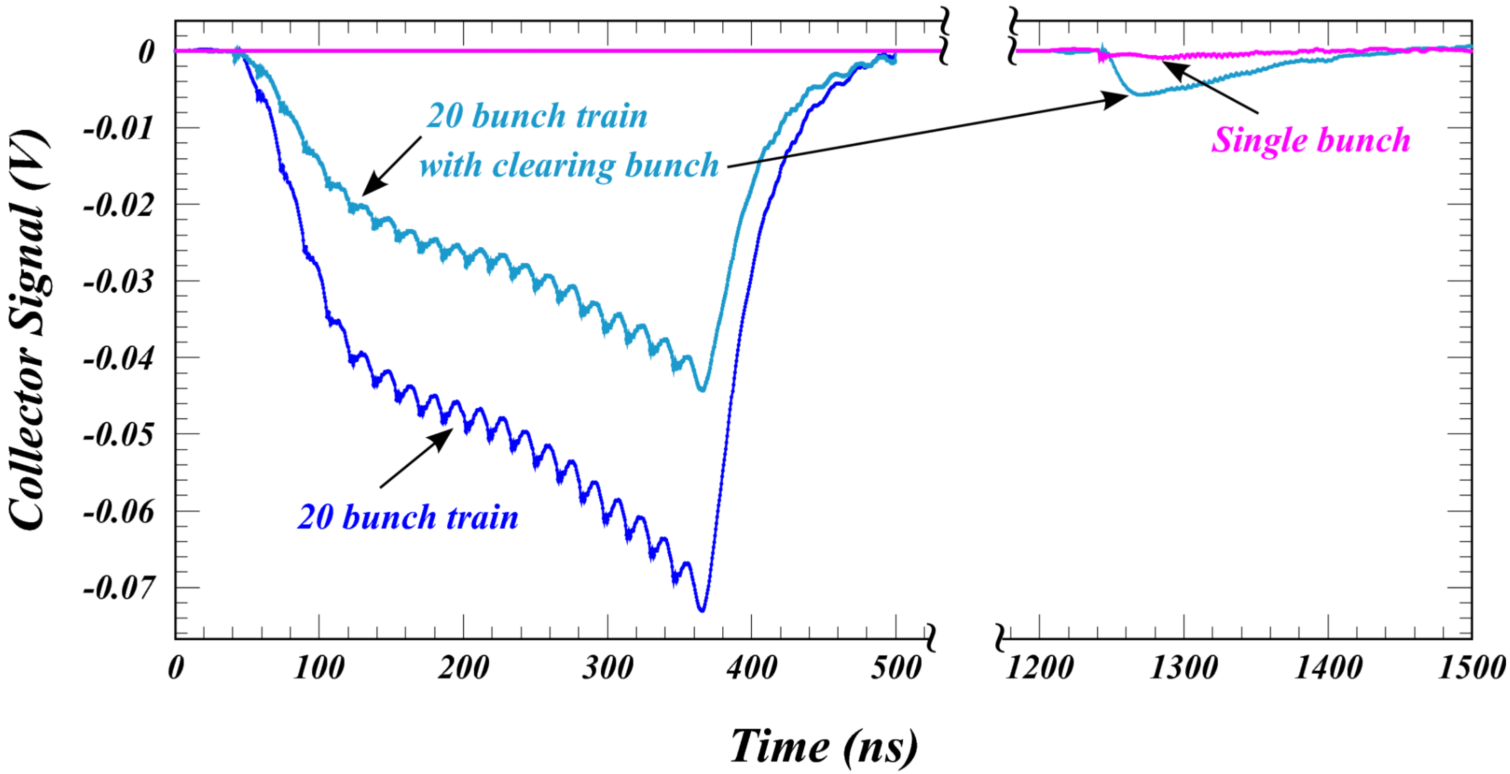


Shielded Button Electrodes for Time-resolved Measurements of Electron Cloud Buildup
JAC et al, Nucl. Instrum. Meth. **A749**, 42 (2014)

How do the first ten bunches know that ten more are coming?

Electron cloud which can contribute to the signal is trapped during the 2.3 μs interval between trains.
The change in slope indicates that six bunches suffice to clear this signal-producing trapped cloud.

Direct Measurement with Clearing Bunch April 2014



Blue: 20-bunch train signal
Cyan: 20-bunch train with clearing bunch following at 900 ns
Magenta: Signal from a single bunch plotted to coincide with the clearing bunch for comparison

Cloud is present 900 ns after train and is accelerated into the detector by the clearing bunch.
The clearing bunch reduces the cloud available to make signal during the following train passage.

Shielded stripline signal modeling with ECLOUD

*** Originated at CERN in the late 1990's**

*** Widespread application for LHC, KEK, RHIC, ILC …**

*** Under active development at Cornell since 2008**

*** Successful modeling of CESRTA tune shift measurements 2010**

*** Detailed photoelectron and SEY models developed 2010-2012**

*** Synrad3D photon absorption model included as input 2011**

*** Interactive modeling of time-resolved detector signals 2011 - 2013**

*** Quadrupole stripline detector model implemented in 2013**

I. Generation of photoelectrons
- **A) Production energy, angle**
- **B) Azimuthal distribution (v.c. reflectivity)**

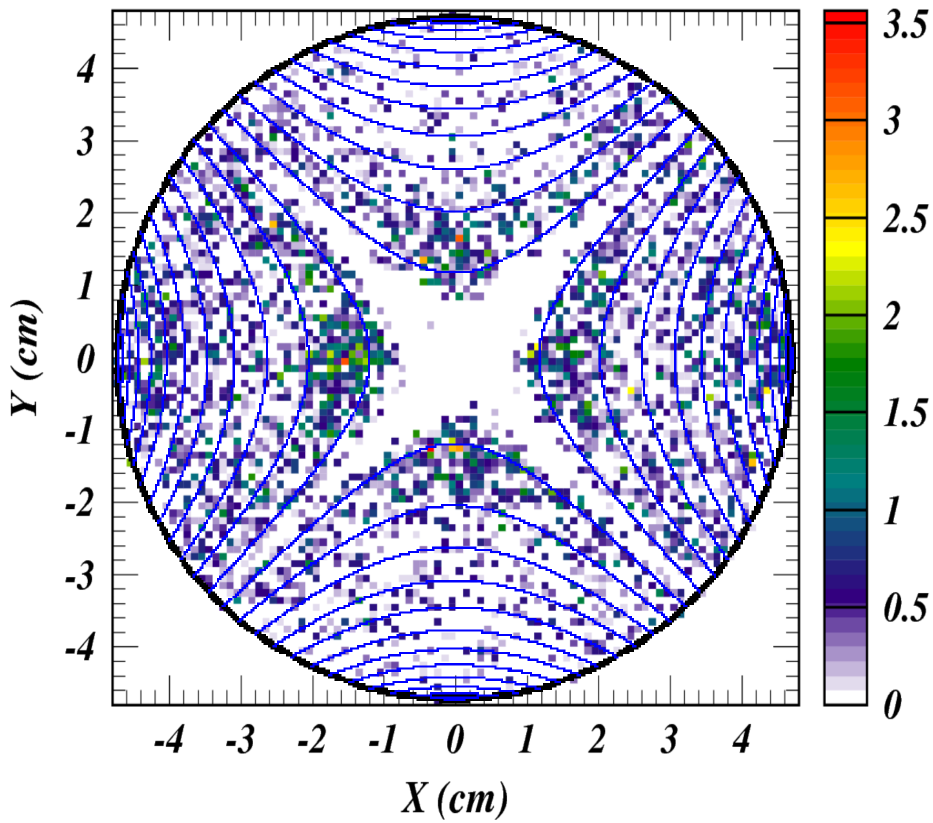
II. Time-sliced cloud dynamics
- **A) Cloud space charge force**
- **B) Beam kick**
- **C) Magnetic fields**

III. Secondary yield model
- **A) True secondaries (yields > 1!)**
- **B) Rediffused secondaries (high energy)**
- **C) Elastic reflection (dominates at low energy)**

IV. Model for a stripline detector in a quadrupole field
- **A) Acceptance vs incident angle, energy, B-field**
- **B) Charge entering holes removed from cloud**
- **C) Charge hitting wall creates secondaries**

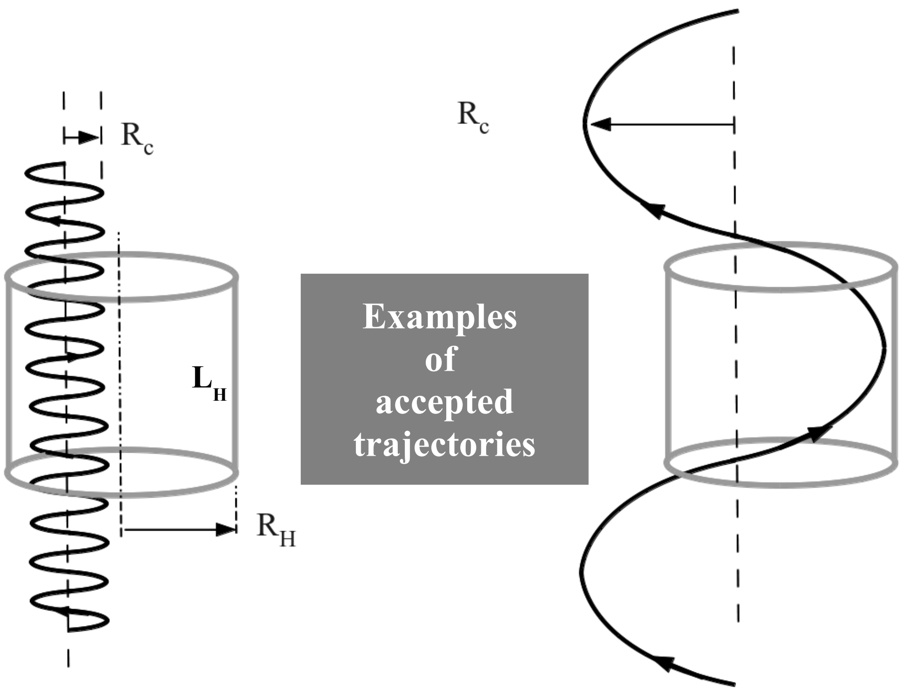
Electron Cloud Buildup Characterization Using Shielded Pickup Measurements and Custom Modeling Code at CESRTA, JAC and J.P. Sikora, ECLOUD12, CERN 2013-002, p. 241, arXiv 1307.4013

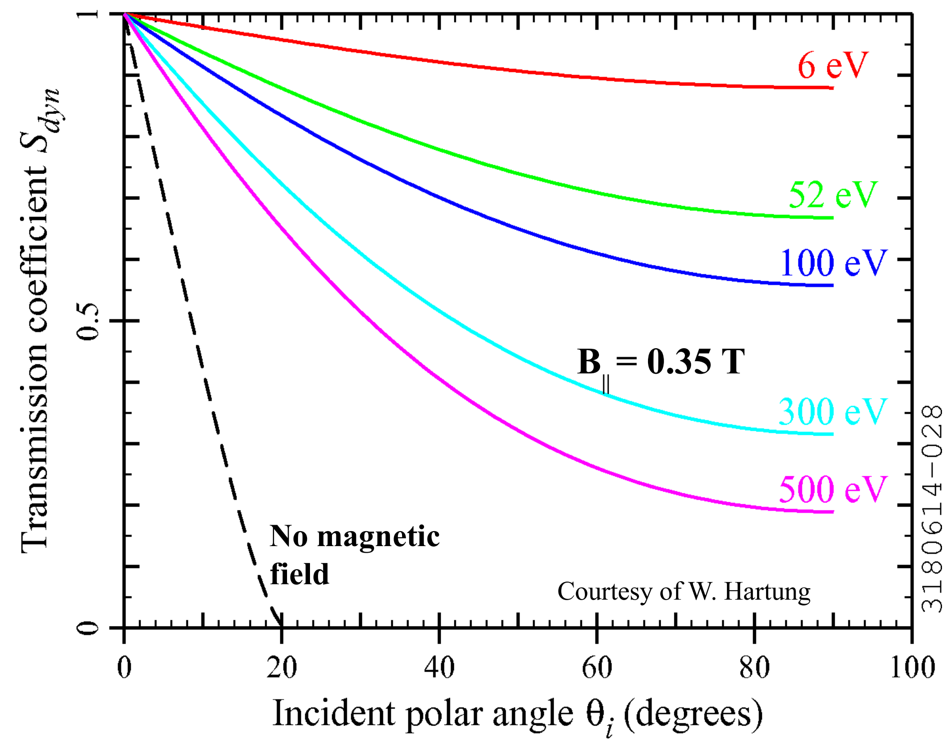
Snapshot of Modeled Trapped Cloud



Analytic form of the magnetic-field-dependent acceptance of the shielding holes

Numerical Modeling for CESRTA Measurements of Electron Cloud Buildup in a Quadrupole Magnet, JAC et al, TUPRI034, IPAC14





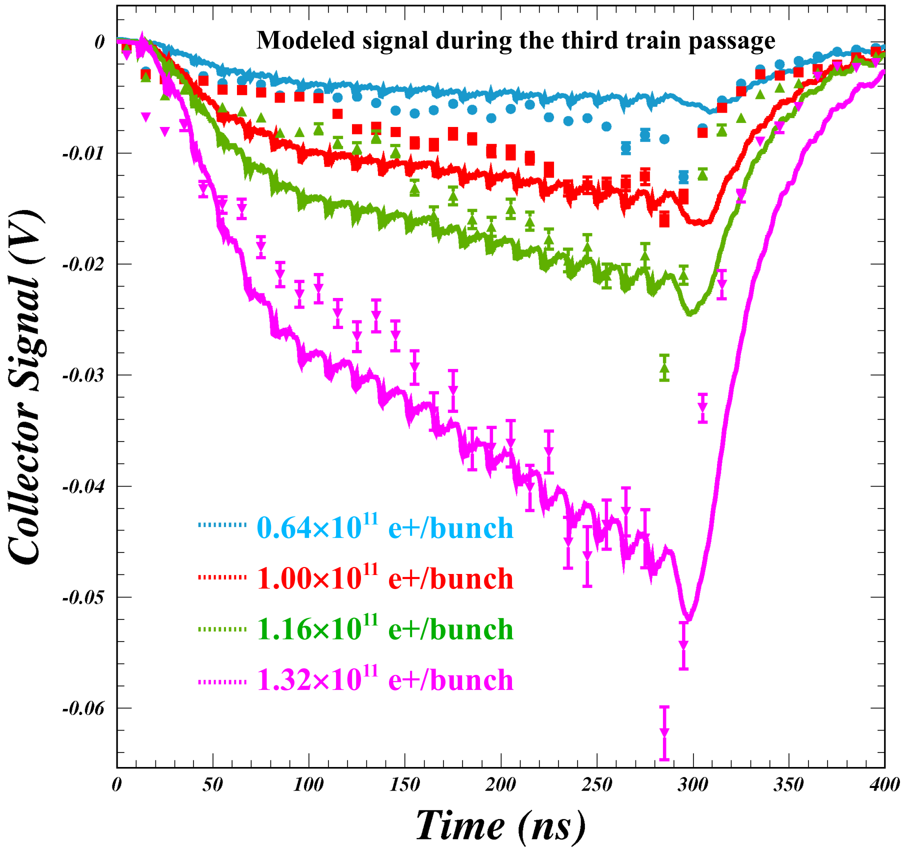
Direct relationship between incident energy, angle θ_i and cyclotron radius R_c, transit time

***Closed form* obtained for arbitrary hole aspect ratio L_H:R_H and magnetic field magnitude (!)**

Maximum accepted angle for zero field given by L_H:R_H = 3:1 (θ_i<20 degrees)

Acceptance for glancing incidence at high field and low energy

Shielded stripline signal modeling with ECLOUD



Signal charge is the incident charge weighted with the hole transmission factor

Voltage obtained from the amplifier input impedance of 50 Ω and +20 dB gain

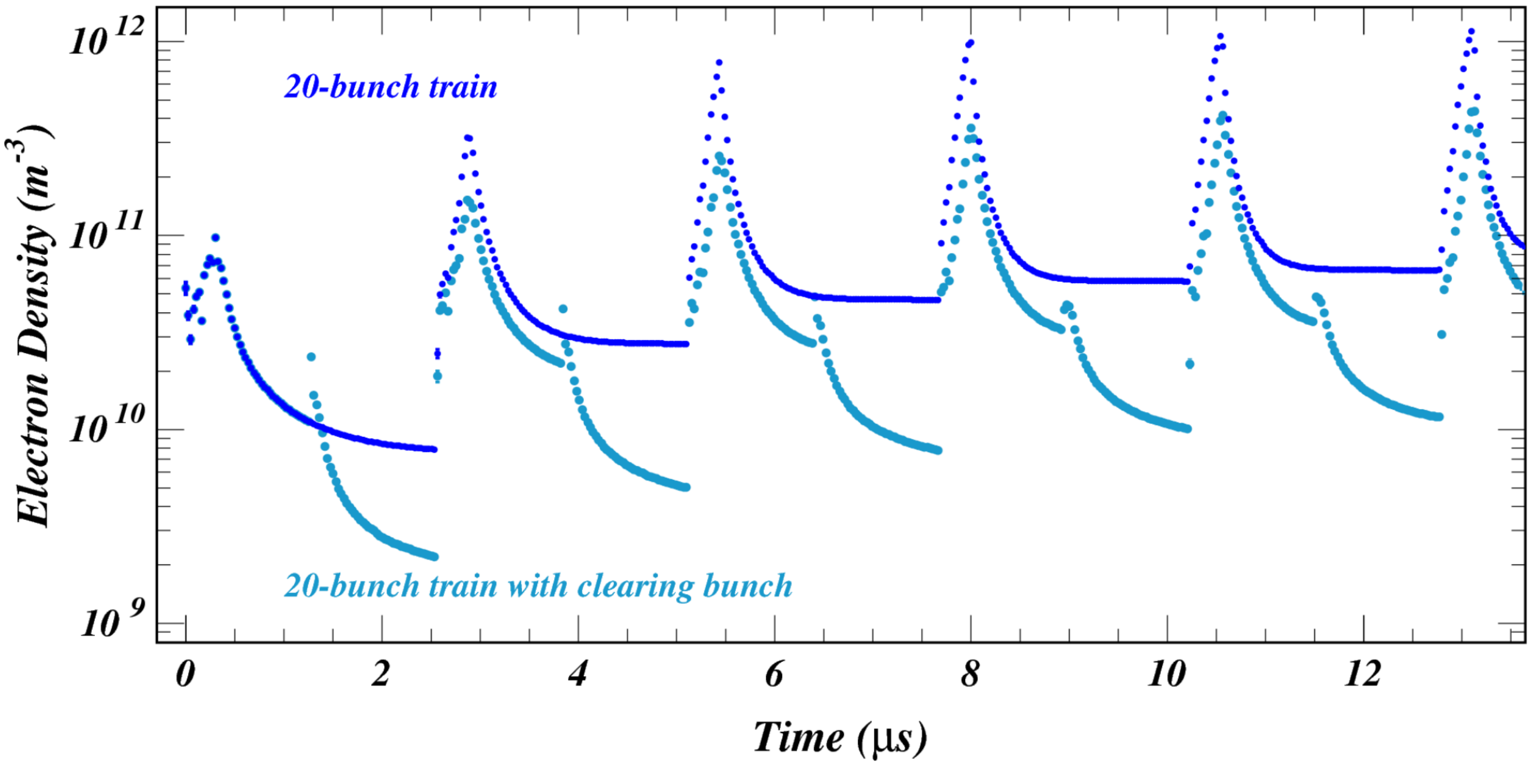
A noise-reducing 13-MHz low-pass filter is applied to model and measurement, resulting in correlated error bars

Charge which does not enter the holes produces secondaries

The modeled signal is very sensitive to the details of the SEY parameters, such as the relative contributions of the true, rediffused and elastic secondary production processes, the shape of the true secondary yield dependence on incident energy, the energy distribution of the produced secondaries, etc.

Modeling the effect of the clearing bunch

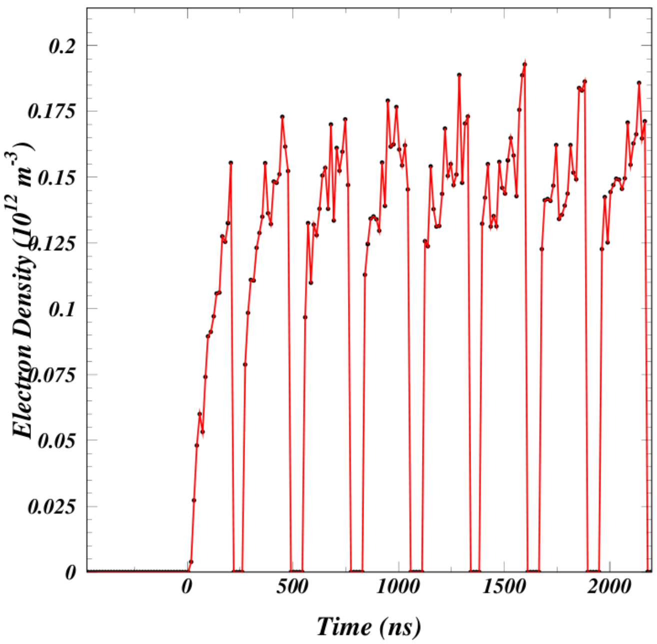
Observation of Electron Trapping in a Positron Storage Ring, M.G. Billing et al, arXiv 1309.2625



The model tuned to reproduce the measured signals is used to infer the general characteristics of the electron cloud.
Here we consider the effect of the clearing bunch on the total cloud density in the beampipe.

Without the clearing bunch about 7% of the cloud is trapped.
The clearing bunch reduces the trapped cloud density by about a factor of four.

Modeling for the Positron Damping Ring of the International Linear Collider

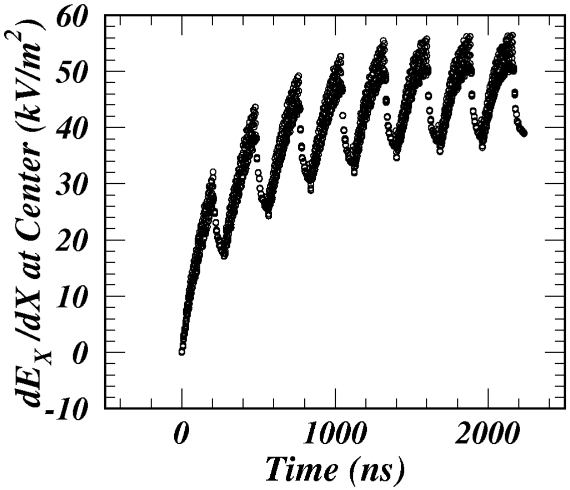


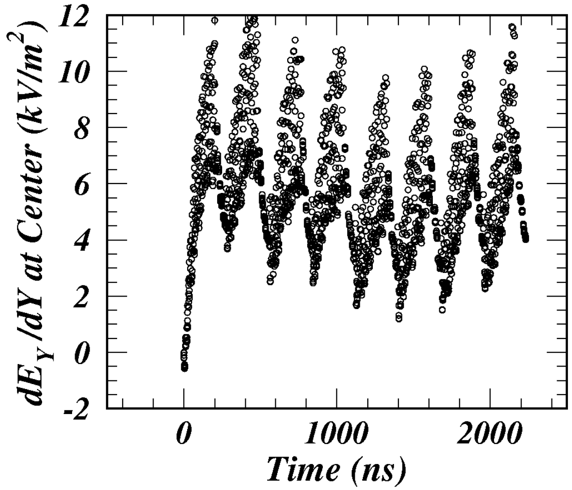
SYNRAD3D Photon Propagation and Scattering and Simulations, G.F. Dugan and D. Sagan, ECLOUD12, CERN 2013-002, p. 117

Investigation into Electron Cloud Effects in the International Linear Collider Positron Damping Ring, JAC et al, Phys Rev ST Accel Beams 17, 031002 (2014)

Observation of Electron Trapping in a Positron Storage Ring, M.G. Billing et al, arXiv 1309.2625

The cloud density within 20 σ_{beam} of the beam can reach 1.8×10^{12} e-/m^3 in the quadrupole magnets in the wiggler region of the ILC positron damping ring.





Optics-distorting electric field gradients arising as the beam attracts cloud can reach values as high as 50 kV/m^2.

Higher multipole fields should be taken into account as well.

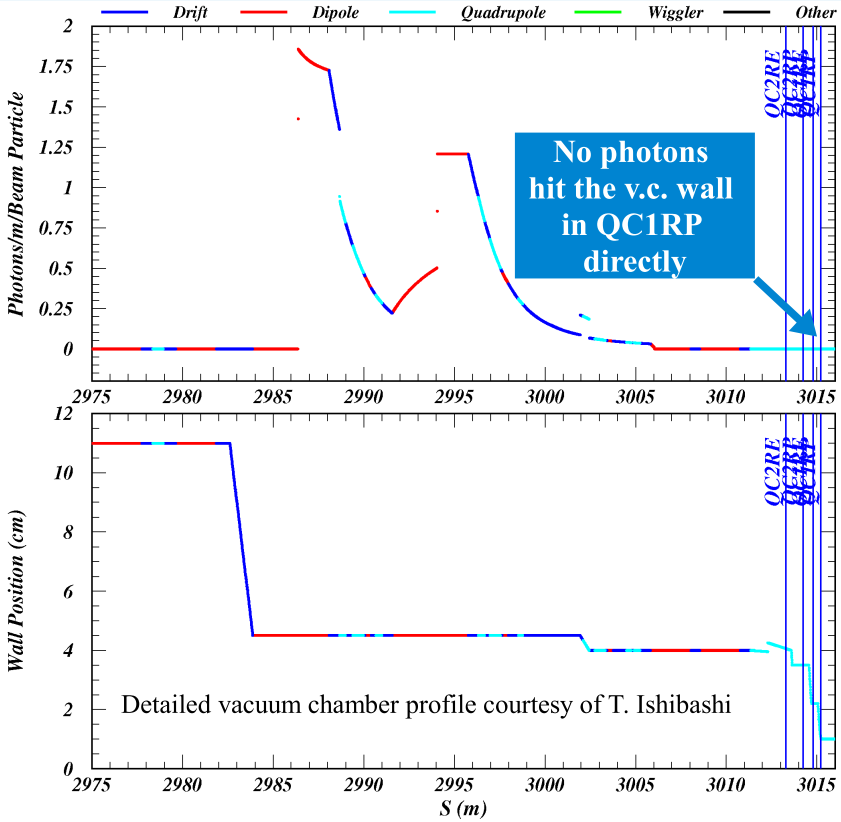
Modeling for SuperKEK-B (Preliminary)

Sync rad photon rate in final focus quadrupole QC1RP

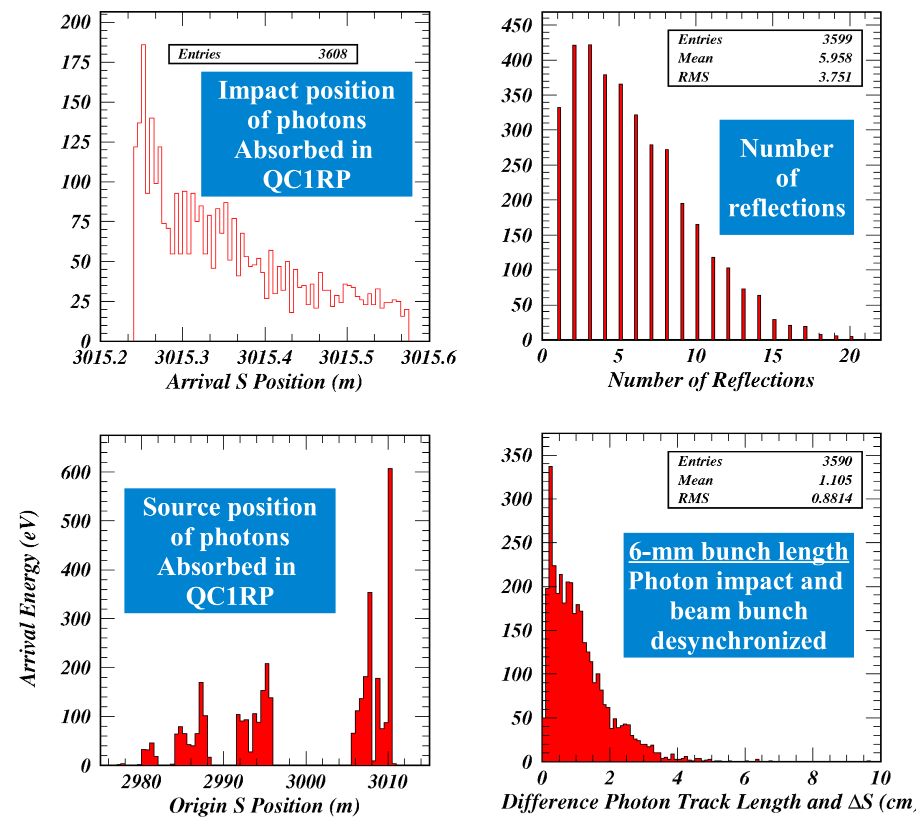
Design and Construction of the SuperKEKB Vacuum System, Y. Suetsugu et al, J. Vac. Sci. Technol. **A30**, 031602 (2012)

Study of Electron Cloud Effects in SuperKEKB, K. Ohmi and D. Zhou, proceedings of IPAC2014, Dresden, Germany, p. 1597

Assuming no photon scattering in vacuum chamber

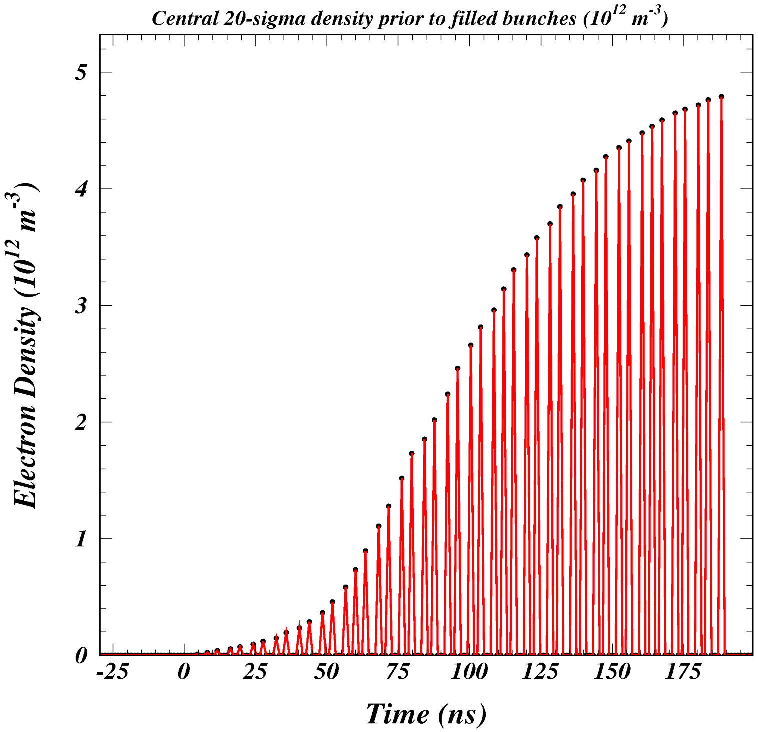


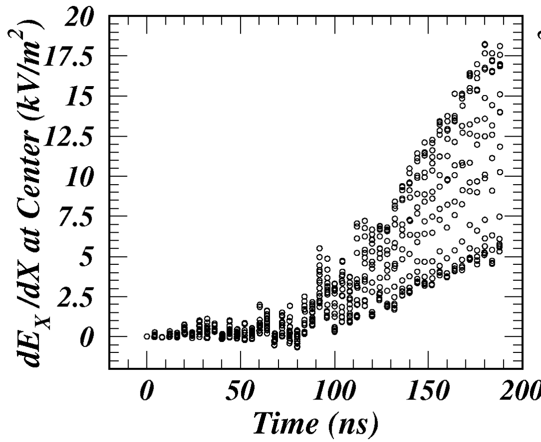
Including Synrad3D photon scattering simulation

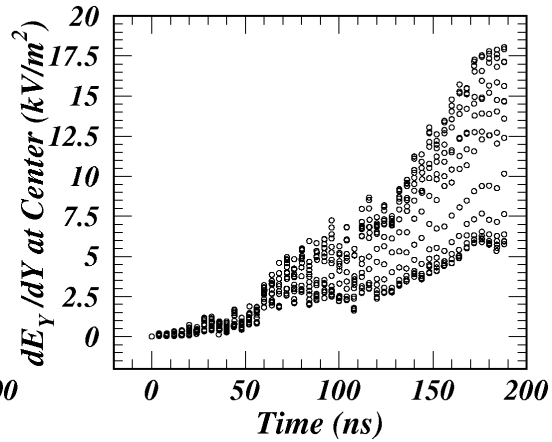


Calculations up to now have not taken into account photon scattering inside the beampipe.
Ohmi & Zhou (IPAC14) found the tune shift to be dominated by electron cloud near, but not in, the IR region.
Using the LER lattice and the detailed wall profile, we find the rate of photons absorbed in the QC1RP final focus quadrupole magnet (66 T/m !) to be rather high: 1 photon/m/e+.

Electron Cloud Buildup Modeling for SuperKEK-B (Preliminary)







ECLOUD simulation of electron cloud buildup in the QC1RP final focus quadrupole for 4-ns spaced bunches of population 9.6×10^{10} e+ shows the density within 20 σ_{beam} of the beam can reach 5×10^{12} e-/m^{3}.

Electron-cloud-induced field gradients on the beam axis in QC1RP reach values of 20 kV/m^2.

The corresponding vertical tune shift is

$$\Delta f_Y = c\,\beta_Y\,(dE_Y/dY)\;L_{QC1RP} / (\,4\,\pi\;E_{beam}\;L_{ring})$$

with β_Y =2500 m, L_{QC1RP}=0.334 m, E_{beam}=4e9 eV, and L_{ring}=3016 m

$$\Delta f_Y = 133\ \text{Hz}$$

This value can be compared to the 52.7 kHz fractional vertical tune in SuperKEKB.

QC1RP is one of four final focus quadrupole magnets.

Multi-turn analysis to investigate effect of electron trapping remains to be done.

Summary

Electron trapping due to the magnetic mirror mechanism has been observed for the first time in a storage ring.

The measurements are well reproduced by modeling based on synchrotron-radiation-induced electron cloud buildup.

Applications of the model to the ILC positron damping ring and the low-energy SuperKEKB positron storage ring are likely to provide useful information on electron-cloud-related performance limitations.

Background

I. Magnetic mirroring is a well-known phenomenon (plasma physics)
   i) Longitudinal and transverse momentum exchange as charges spiral along field lines
   ii) Adiabatic condition with conserved magnetic moment
   iii) Chaotic behavior in weak field regions
   iv) Escape zones and high-trapping zones (near, but not on, symmetry axis)

II. Coupled-bunch instability in KEK-B (L.Wang et al, Phys Rev E66, 036502 (2002))
   i) Observed even with cloud-mitigating solenoids on
   ii) Multi-turn electron cloud trapping in quadrupole and sextupole magnets considered as source
   iii) Modeled in detail, but link to instability inconclusive

III. CESRTA "lead-bunch blowup" phenomenon
   i) First bunch in 30-bunch train of positrons exhibits anomalous large vertical size
   ii) Reduced by adding a bunch near the end of the train or just before train
   iii) Motivated design and implementation of cloud detector in a quadrupole magnet

IV. First measurement of electron trapping in a positron storage ring (M.G. Billing et al, arXiv:1309.2625)
   i) Summer 2013 discovery by comparing signals from 10- and 20-bunch trains in a quadrupole magnet (7 T/m)
   ii) April 2014 studies of dependence on bunch population and spacing, and mitigation using clearing bunches
   iii) Extensive modeling to explain trapped cloud clearing during train passage, sensitivity to secondary electron emission model, mitigating effect of clearing bunch or bunches, time-dependence of cloud profile, nonlinear relationship of signal and cloud density

V. ILC positron damping ring study finds high cloud densities in wiggler-region quadrupoles (10 T/m) (JAC et al, Phys Rev ST Accel Beams 17, 031002 (2014))

VI. Heat load from trapped cloud in LHC final-focus quadrupoles identified as limit on future LHC operation (G. Iadarola, G. Rumolo and C. Zannini, 2014, in preparation)

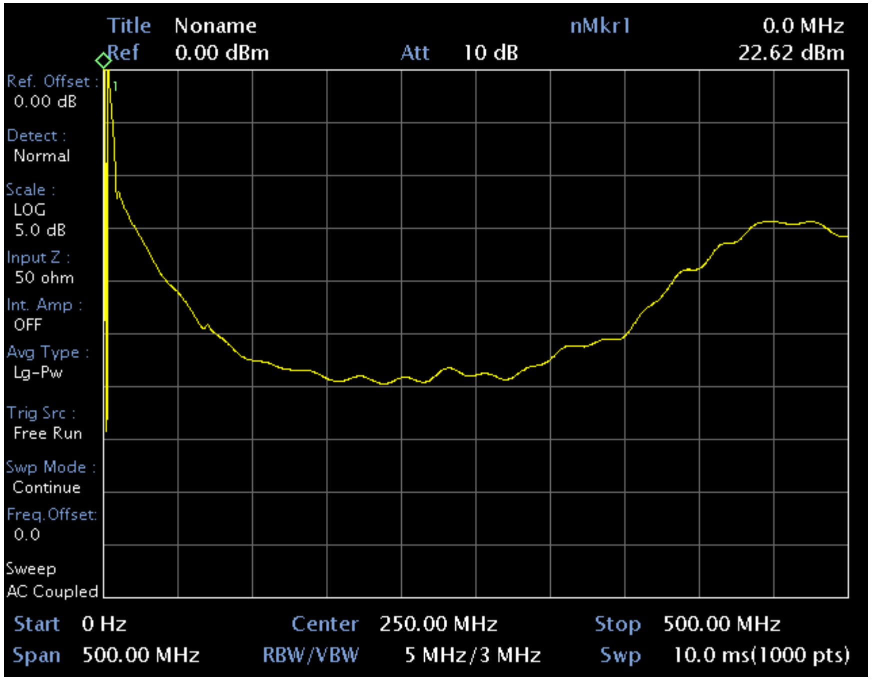
VII. Begin study of electron cloud in SuperKEK-B final focus quadrupole magnets (70 T/m !) (JAC, T. Ishibashi, in progress)

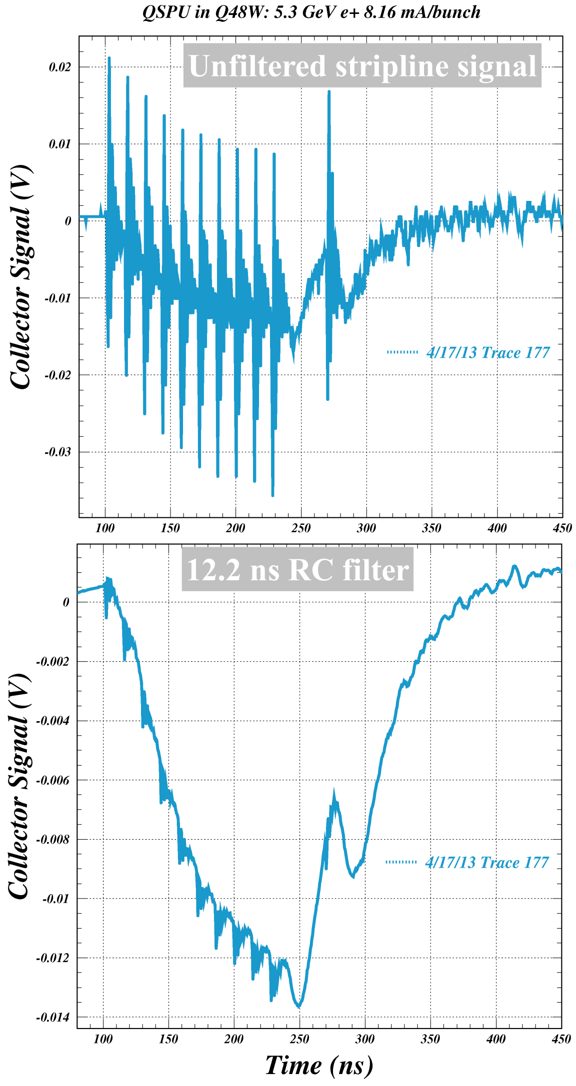
Time-resolving shielded stripline electron cloud detector

Stripline frequency response measured with a spectrum analyzer

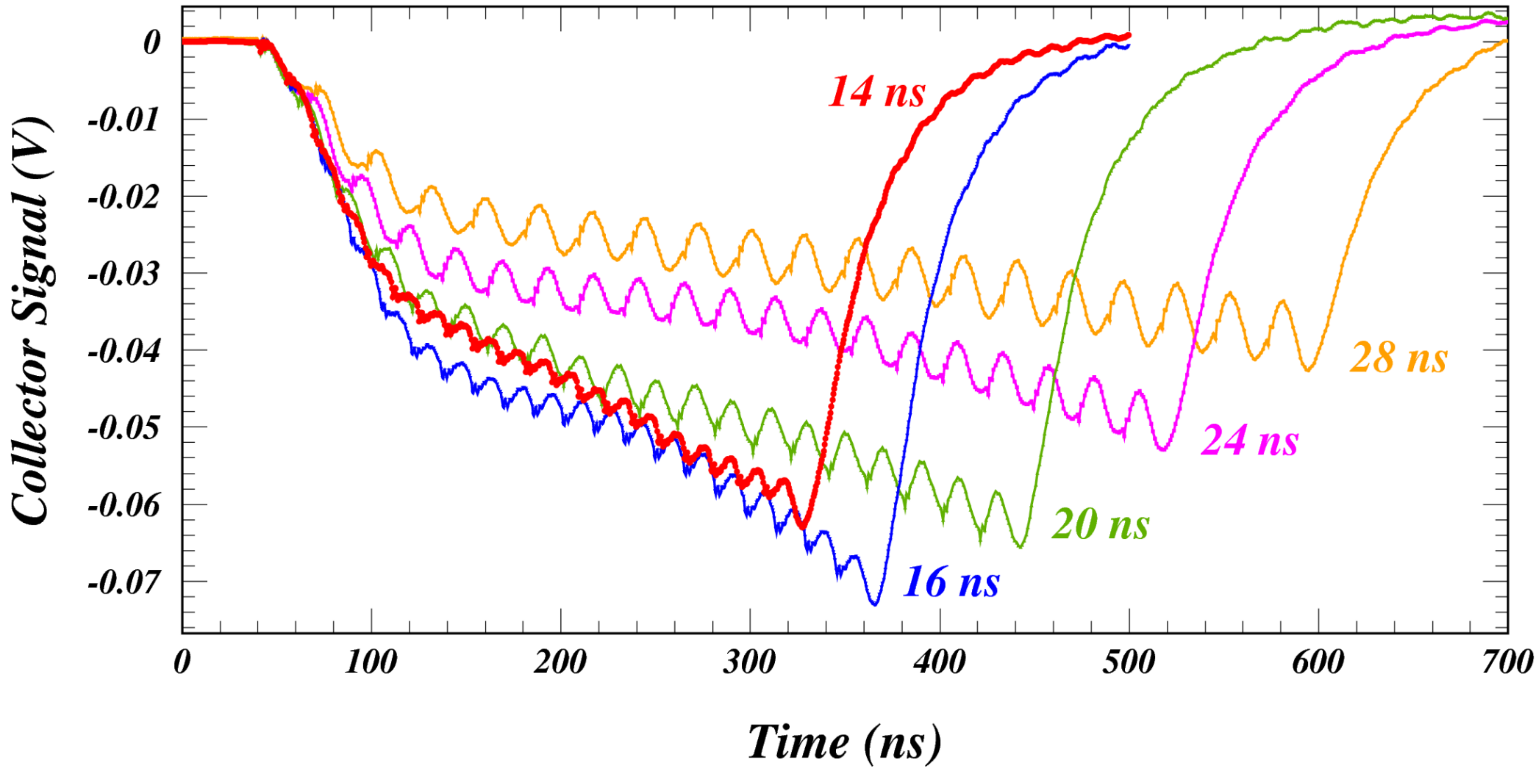
- Cutoff frequency is 13 MHz (RC=12.2 ns)

- High-pass feature results in sensitivity to beam-induced noise





Observation of Cloud Buildup Resonant with Bunch Spacing

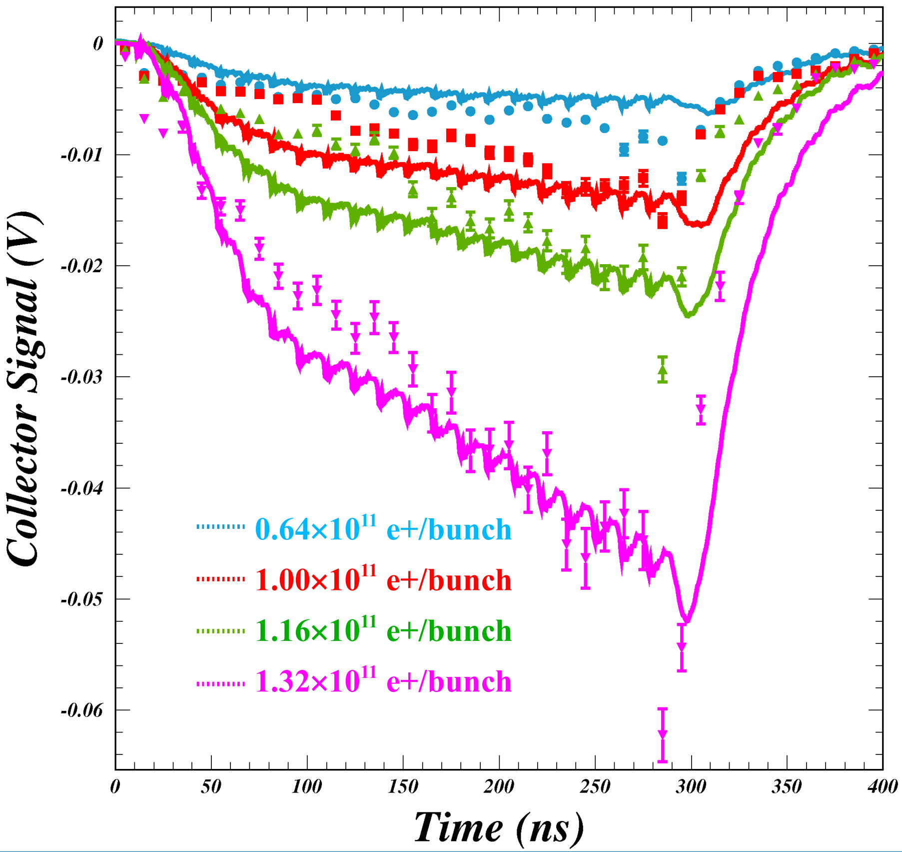


Signals from 20-bunch trains with spacings of 14, 16, 20, 24, and 28 ns are shown. The average bunch populations are 1.3x10^{11} positrons. The signal generally decreases as the bunch spacing is increased. However, the signal *increases* when the bunch spacing is increased from 14 ns to 16 ns, indicating a resonance in the production of cloud electrons.

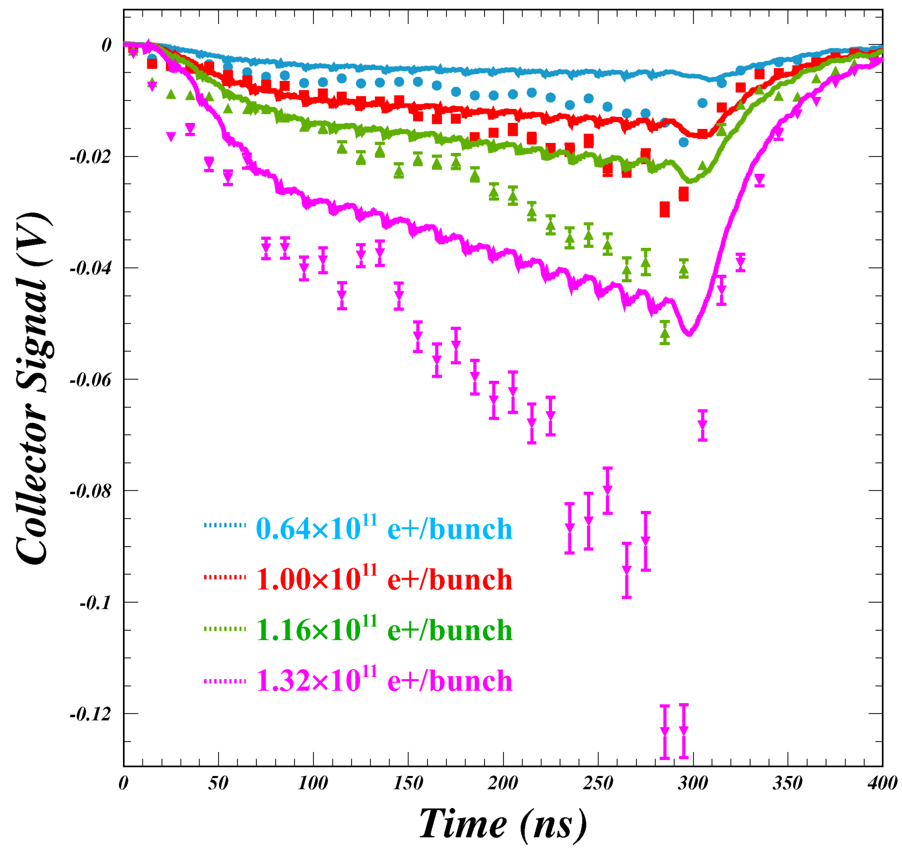
Be careful when choosing bunch spacing !

Shielded stripline signal modeling with ECLOUD

$\delta_{SEY}(E=E_{peak}) = 1.53$



$\delta_{SEY}(E=E_{peak}) = 1.63$



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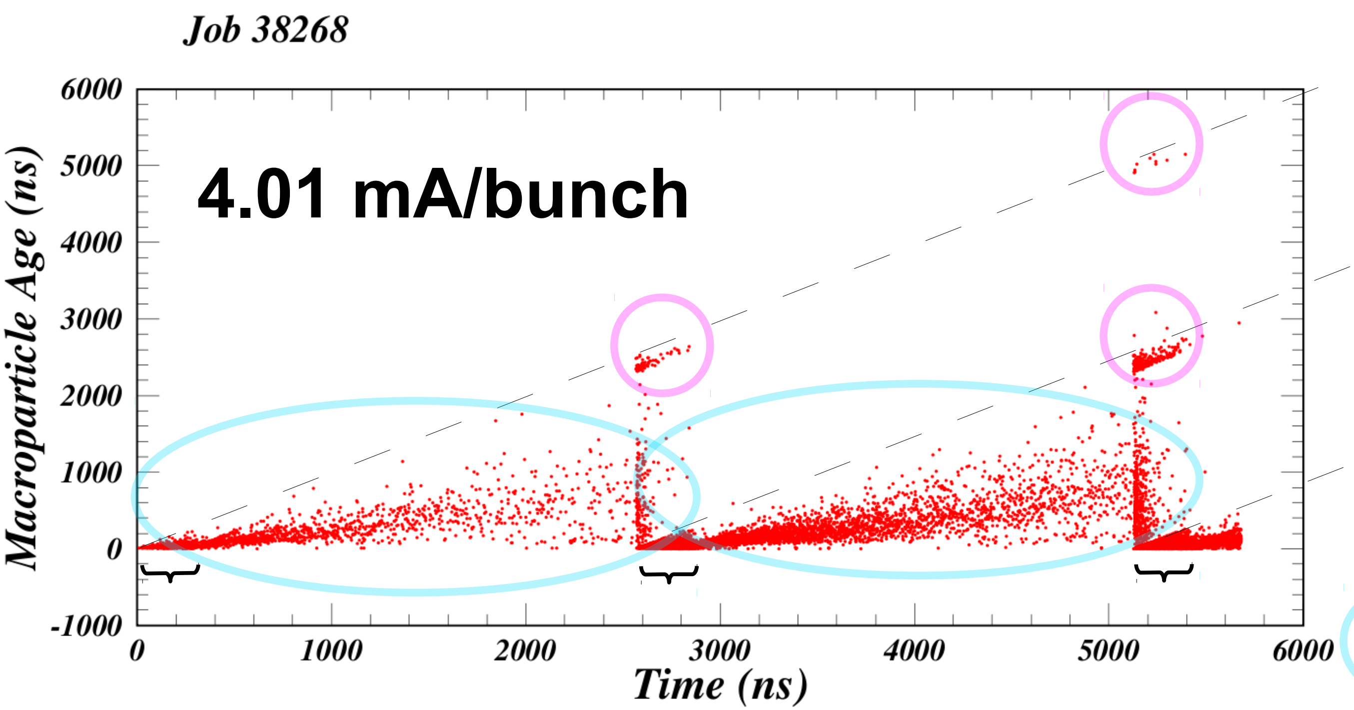
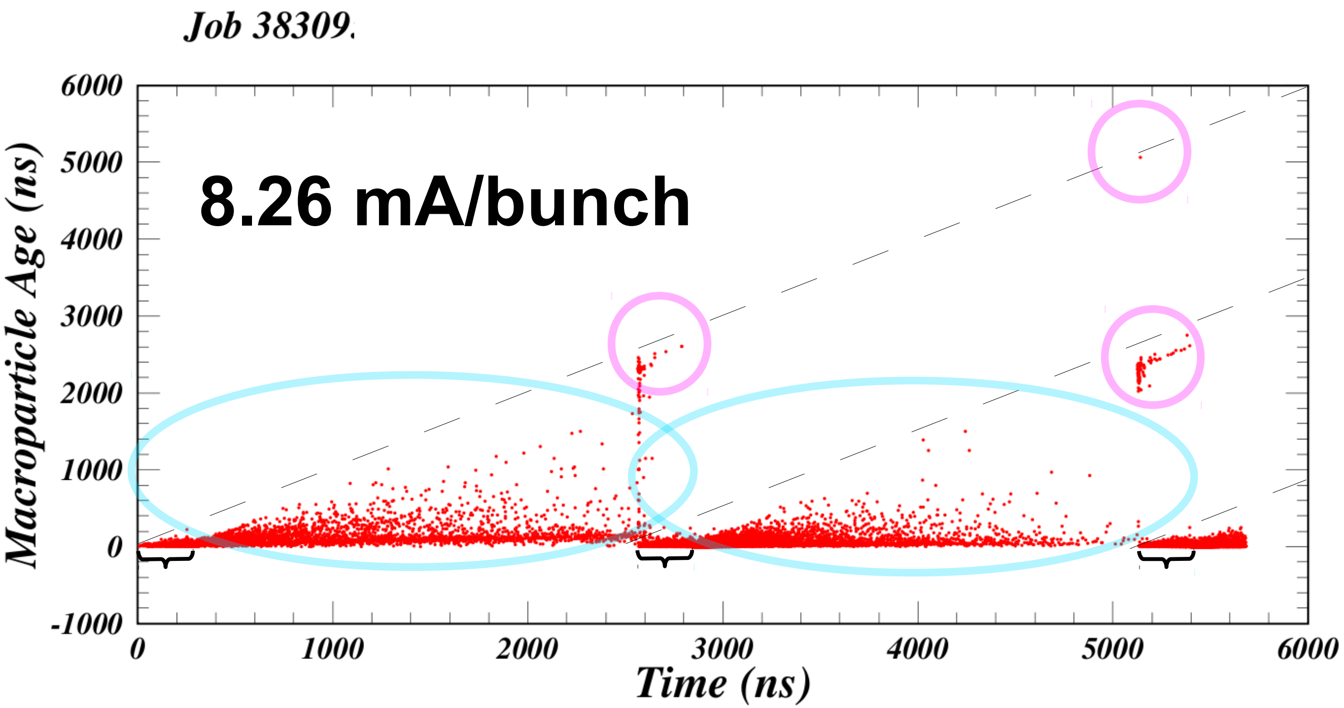


Trapped signal electrons produced near the end of a preceding train

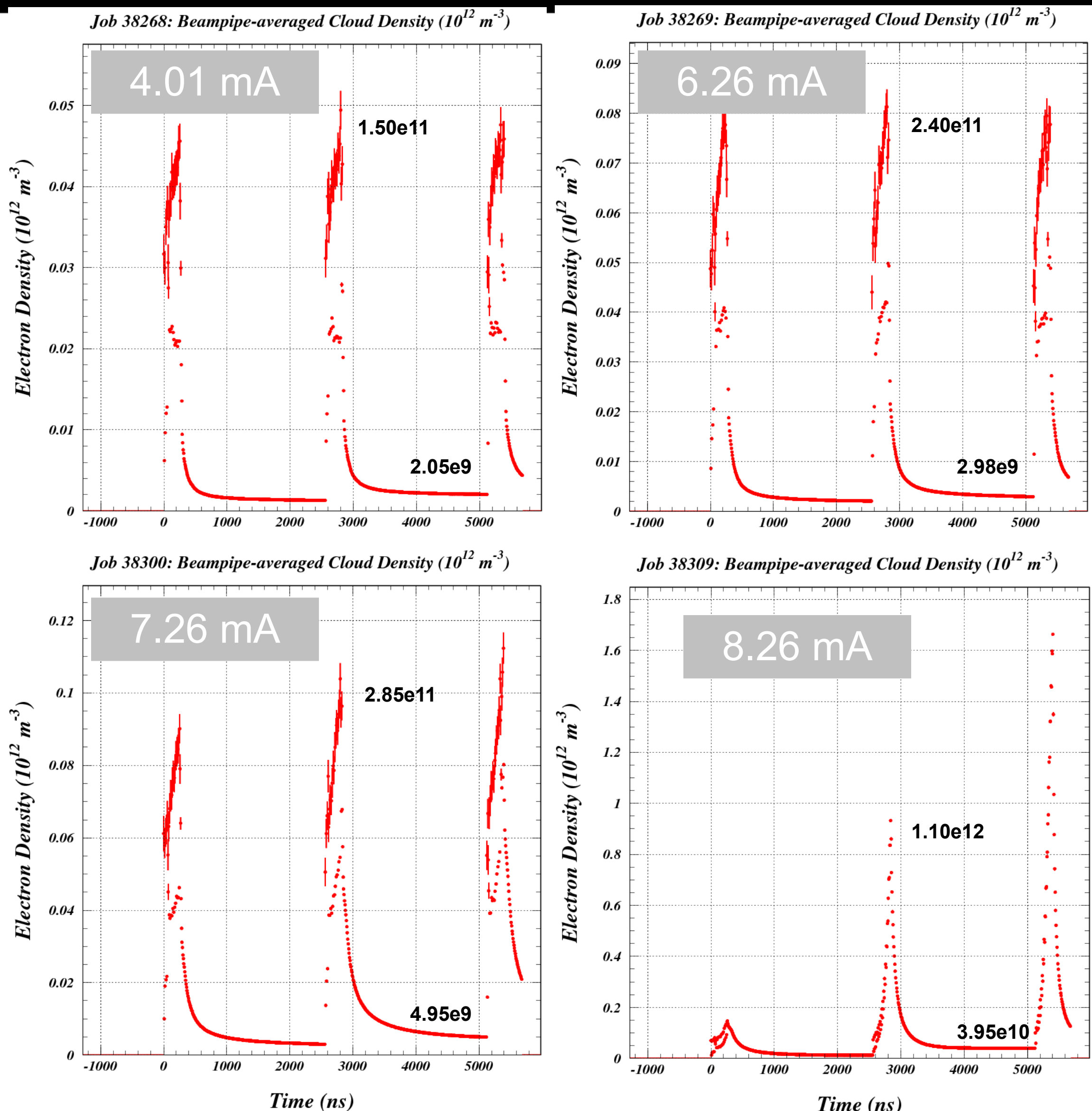
Since six bunches suffice to clear the trapped cloud which can produce signal, such electrons can only be produced during the trailing six bunches of a train

Trapped signal electrons produced between trains



Trapping for signal electrons occurs more effectively at lower bunch current

Striking divergence of the beam-pipe-averaged cloud density from 7.26 to 8.26 mA/bunch



The cloud density increases nearly linearly with bunch current from 4 to 7 mA, then shows an increase of a factor of five from the first train to the second, and an additional factor of two from the second to the third train passage.

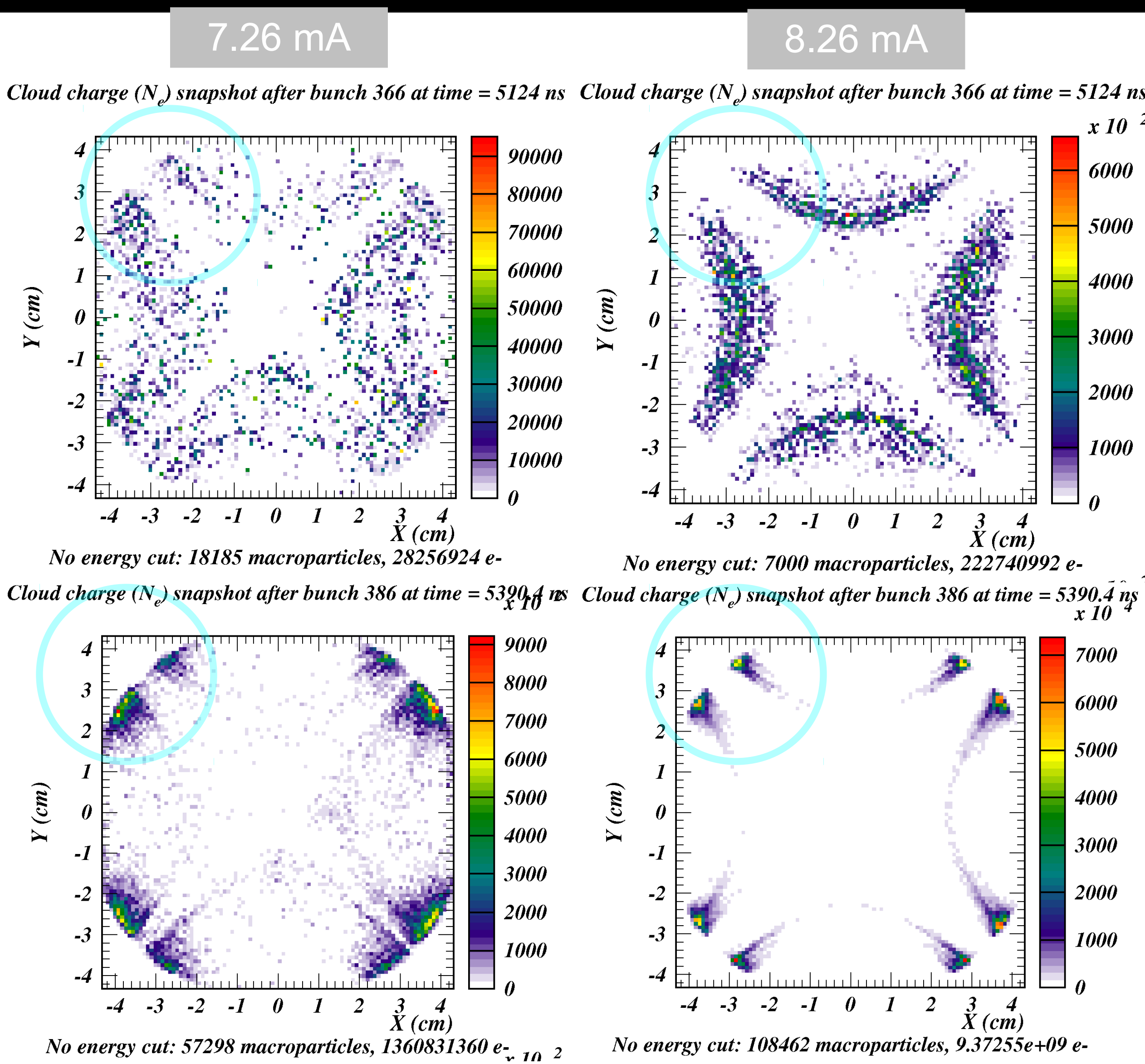
Ratios: 1 : 1.6 : 2.4 : > 36 (!)

1) The assumption of asymptotic behavior after only two turns is now questionable.

2) Why doesn't the modeled signal show this behavior?

NB: The peak densities differ from the axis values owing to bin averaging.

Where is the cloud hiding?



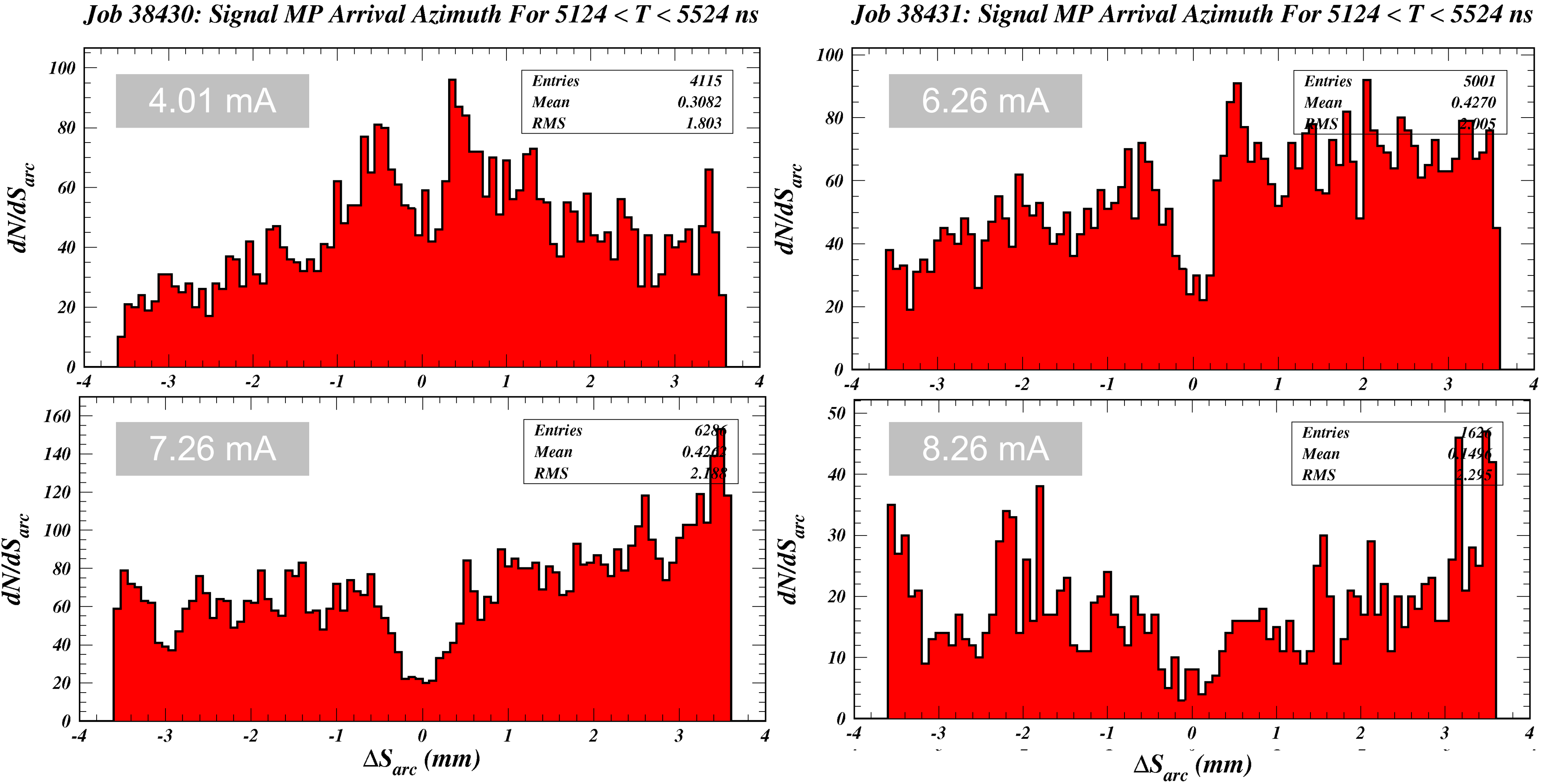
Trapped cloud at the end of the second turn

7.26 mA: 2.8e7 e
8.26 mA: 2.2e8 e

Cloud immediately following the 60th filled bunch

7.26 mA: 1.3e9 e
8.26 mA: 9.4e9 e

Where do the signal electrons enter the detector?

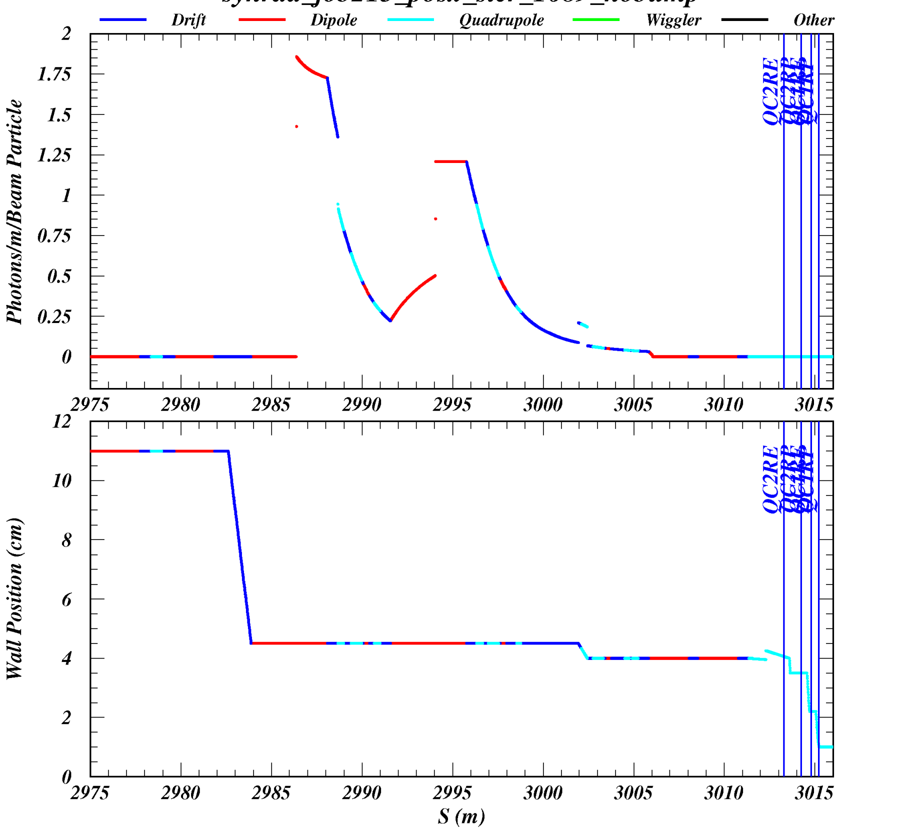


Potential signal electrons are missing the detector !
We should consider building a detector with more acceptance and transverse segmentation.

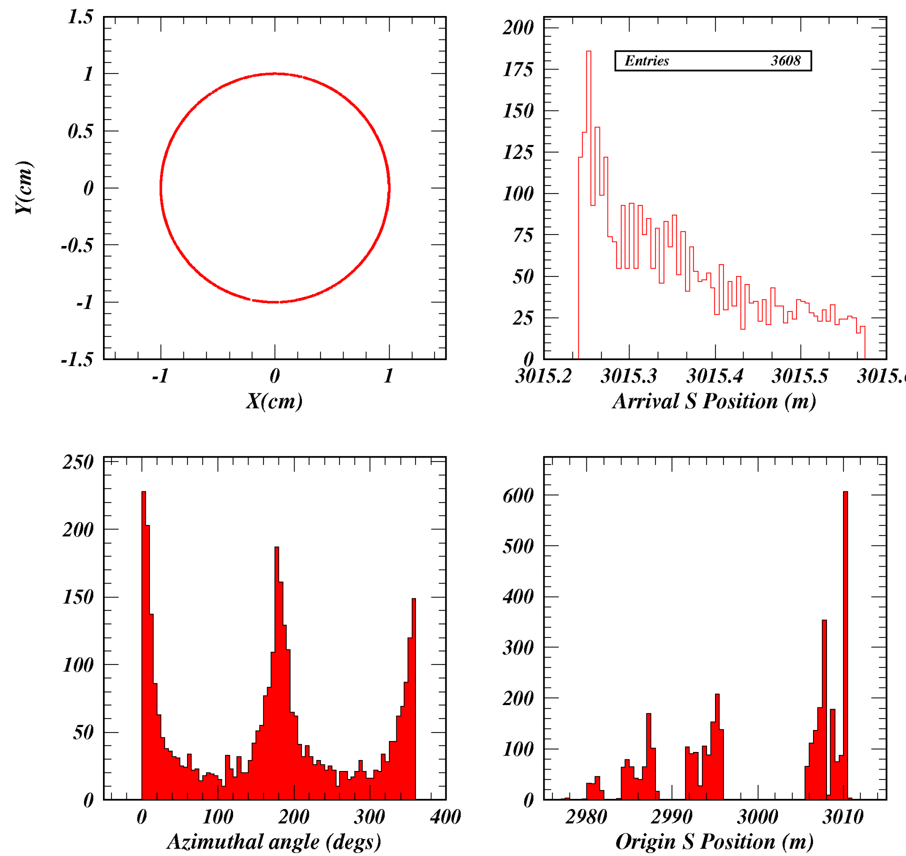
Modeling for SuperKEK-B (Preliminary)

Design and Construction of the SuperKEKB Vacuum System, Y. Suetsugu et al, J. Vac. Sci. Technol. **A30**, 031602 (2012)

No photon scattering in vacuum chamber



SYNRAD3D: SuperKEKB 4.0 GeV SLER_1689_nobump:QC1RP



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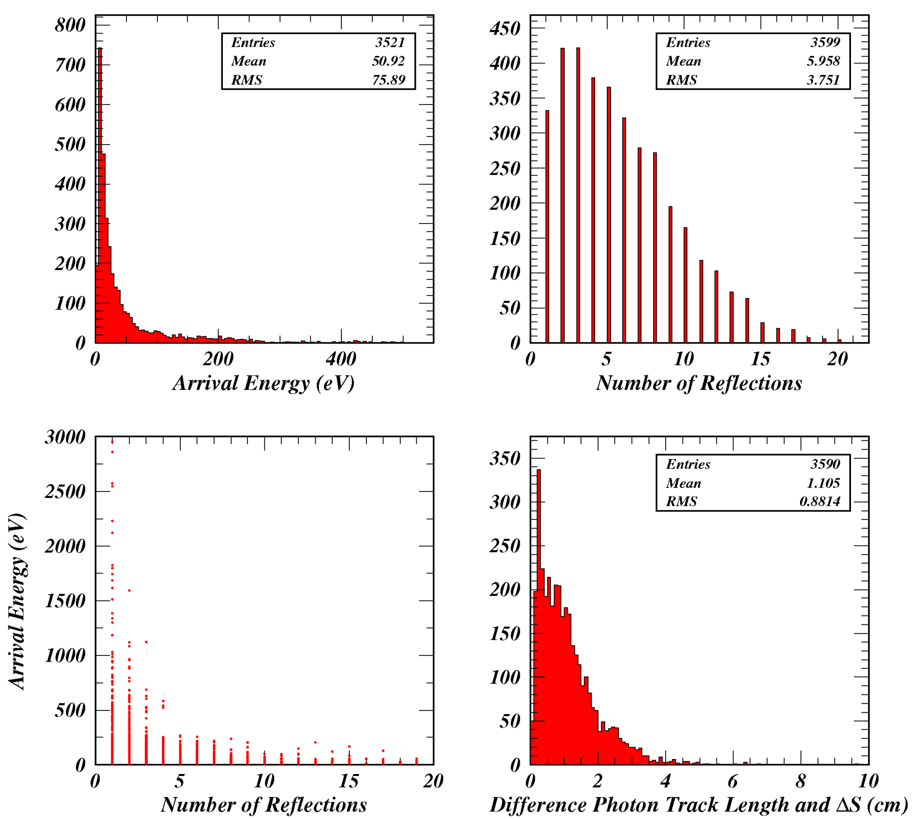
Using the LER lattice and the detailed wall profile provided by T. Ishibashi/KEK, we find the rate of photons absorbed in the QC1RP final focus quadrupole magnet (66 T/m) to be rather high: 1 photon/m/e+.

Cornell Laboratory for
Accelerator-based Sciences and Education (CLASSE)

SYNRAD3D Modeling for SuperKEK-B (Preliminary)

SYNRAD3D: SuperKEKB 4.0 GeV SLER_1689_nobump:QC1RP



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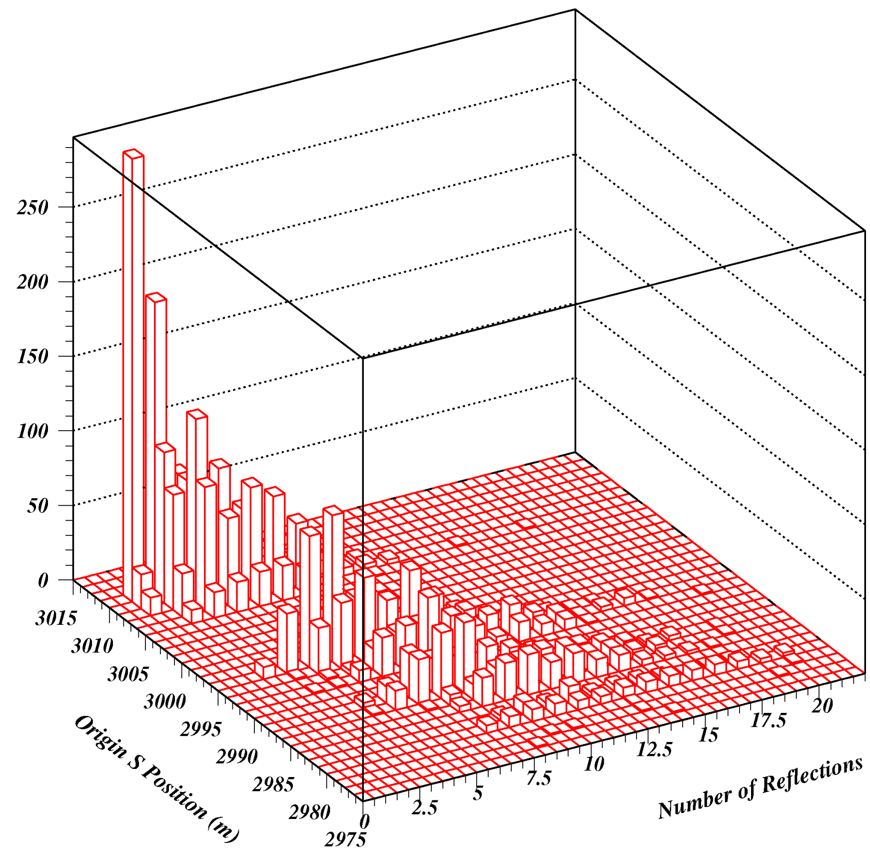

Synrad3D finds scattered photons absorbed in the QC1RP final focus quadrupole which originated in dipole magnets up to 36 m upstream and having undergone 1-20 scatters off the inner wall of the vacuum chamber.
Quite a few of the photon trajectories differ from the beam trajectory by more than the 6 mm bunch length.