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

Jim Crittenden

Cornell Laboratory for Accelerator-Based Sciences and Education
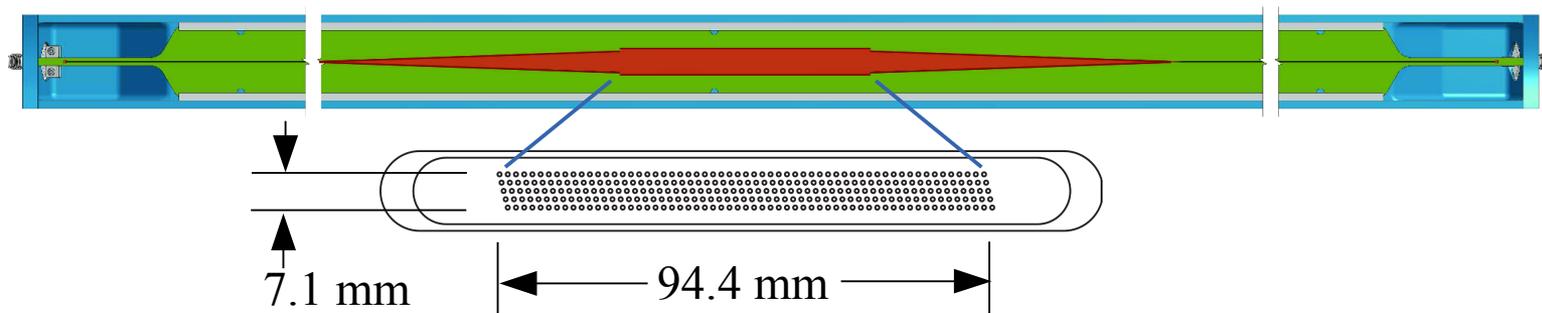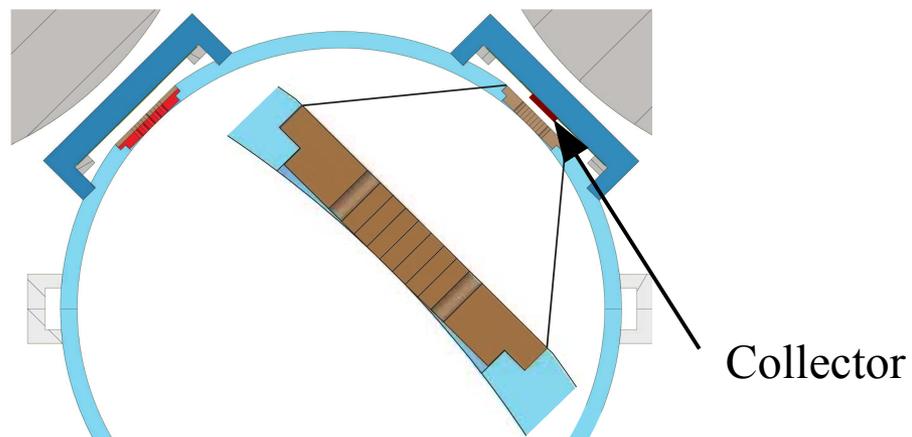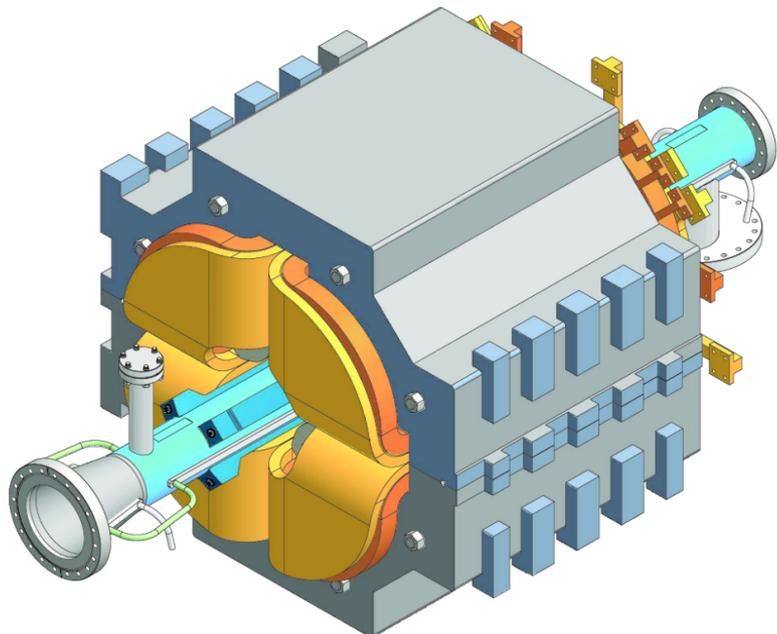
Low Emittance Rings 2014 Workshop
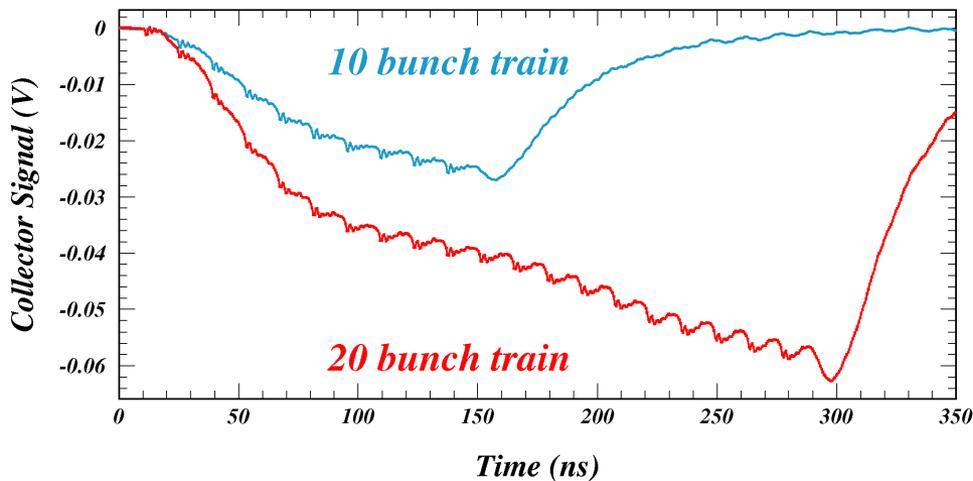
INFN-LNF, Frascati (RM), Italy

17 September 2014

Time-resolving shielded stripline electron cloud detector

Collector

7.1 mm

94.4 mm

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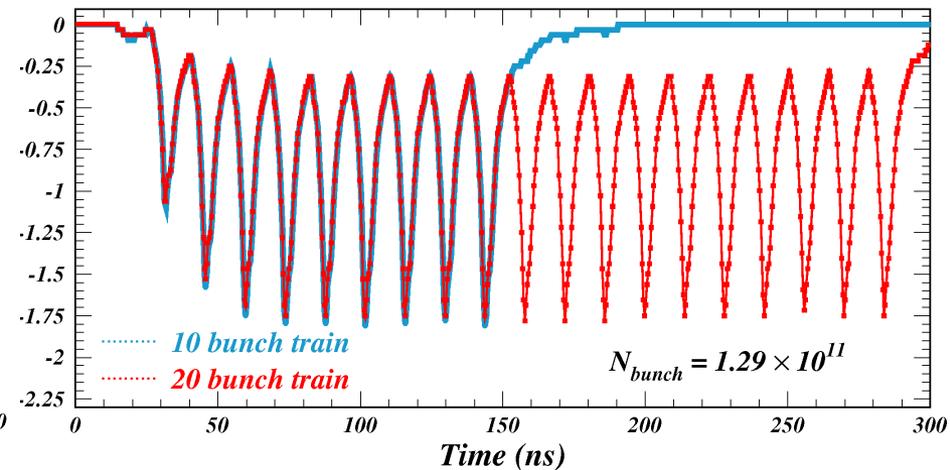
Observation of Electron Trapping in a Positron Storage Ring,
M.G. Billing et al, arXiv 1309.2625

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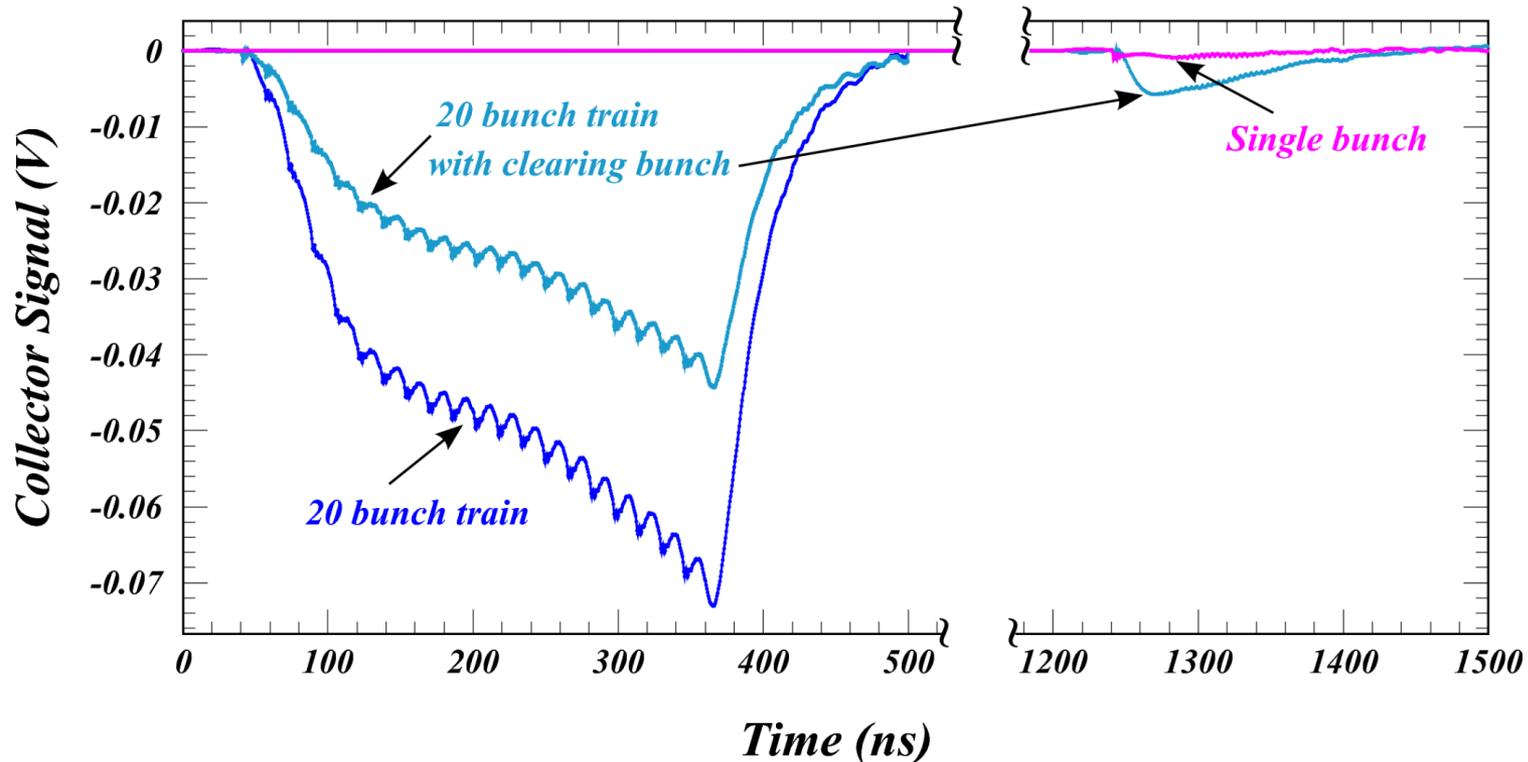JAC et al, Nucl. Instrum. Meth. **A749**, 42 (2014)

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.

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.

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

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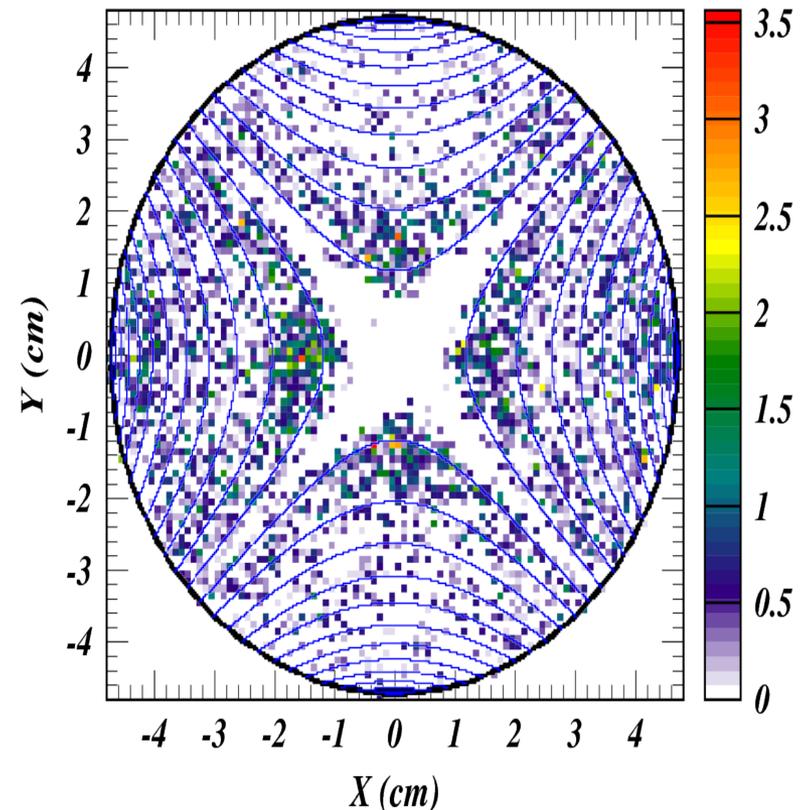
IV. Model for a stripline detector in a quadrupole field
- A) Acceptance vs incident angle, energy, B-field
- B) Charge entering holes removed from cloud
- C) Charge hitting wall creates secondaries

Snapshot of Modeled Trapped Cloud

Numerical Modeling for CESRTA Measurements of Electron Cloud Buildup in a Quadrupole Magnet, JAC et al, TUPRI034, IPAC14
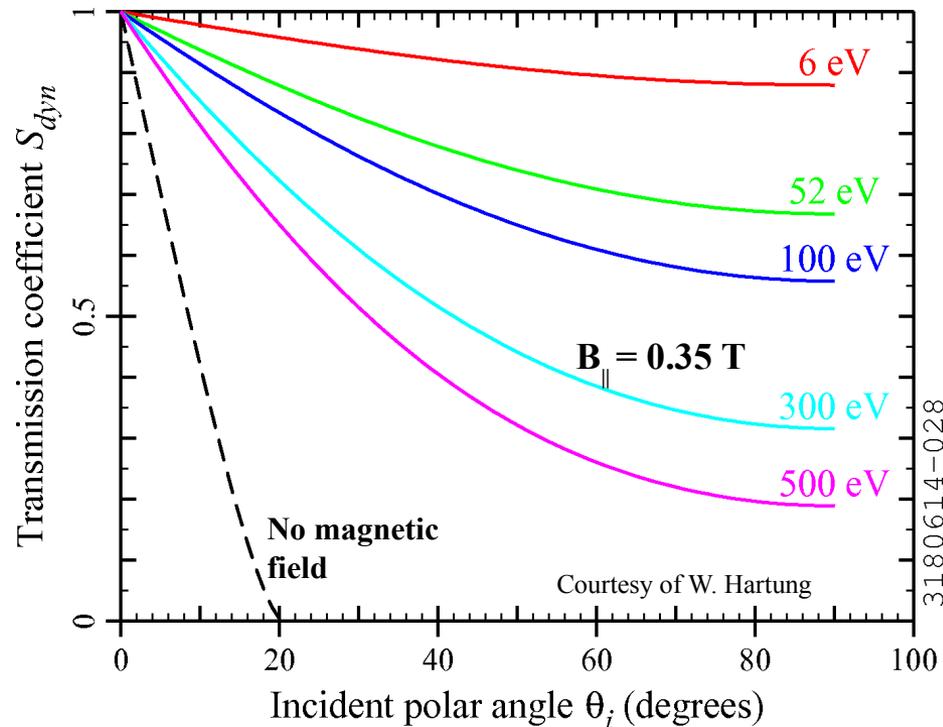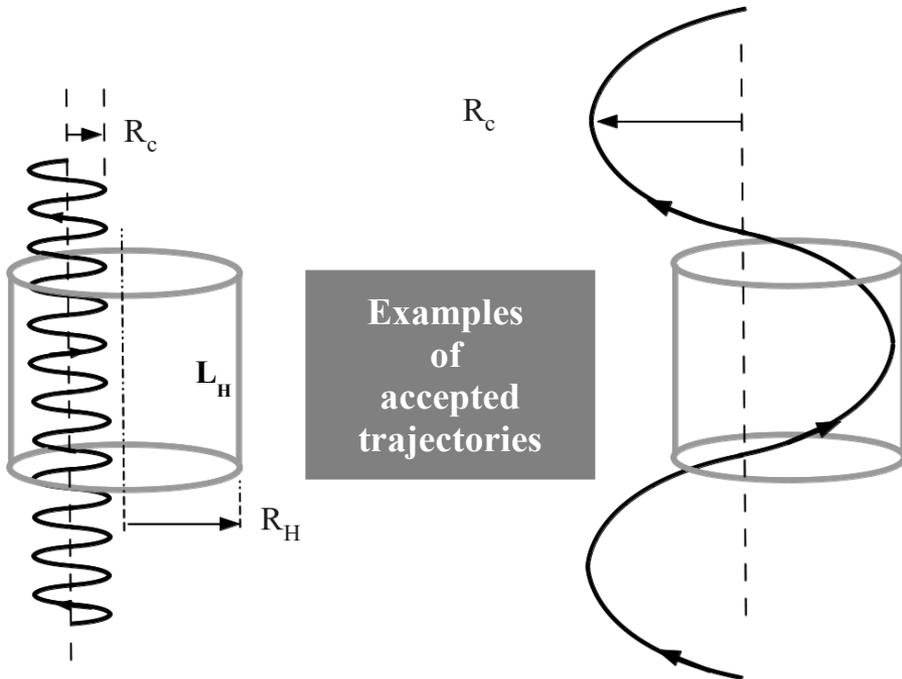
Direct relationship between incident energy, angle θ_i and cyclotron radius R_c, transit time
Closed form **obtained for arbitrary hole aspect ratio L_H:R_H and magnetic field magnitude (!)**

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

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Modeled signal during the third train passage

Plot legend:
- 0.64×10^{11} e+/bunch
- 1.00×10^{11} e+/bunch
- 1.16×10^{11} e+/bunch
- 1.32×10^{11} e+/bunch

Y-axis: *Collector Signal (V)*
X-axis: *Time (ns)*
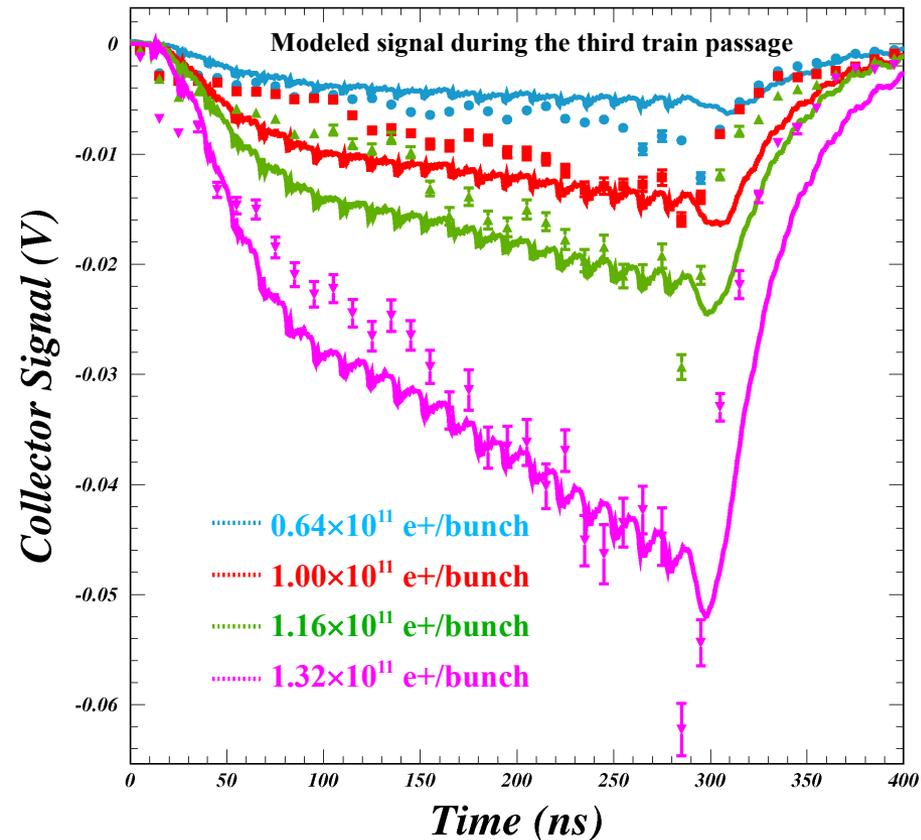
Signal charge is the incident charge weighted with the hole transmission factor

**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.

Observation of Electron Trapping in a Positron Storage Ring, M.G. Billing et al, arXiv 1309.2625
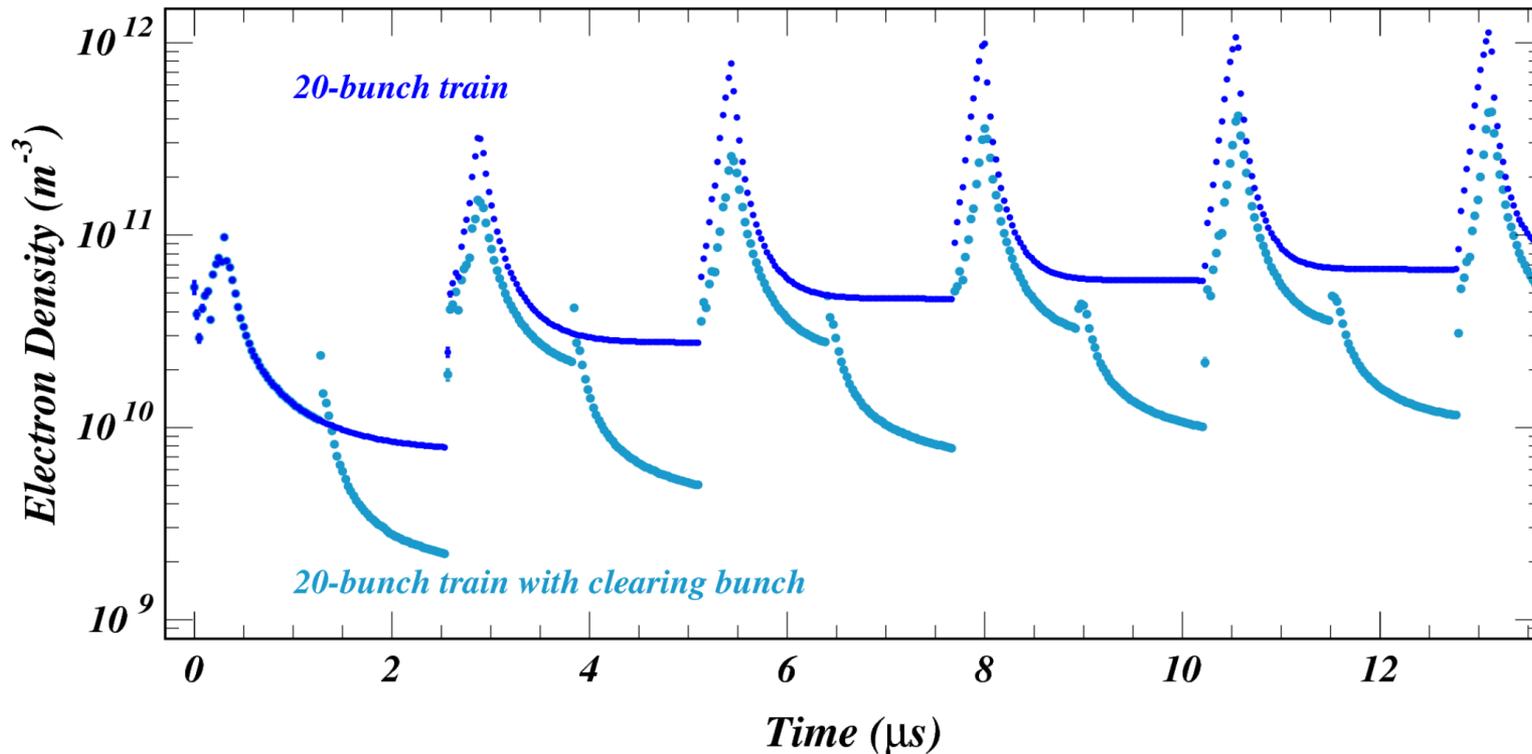
The model tuned to reproduce the measured signals is used to infer the general characteristics of the electron cloud.
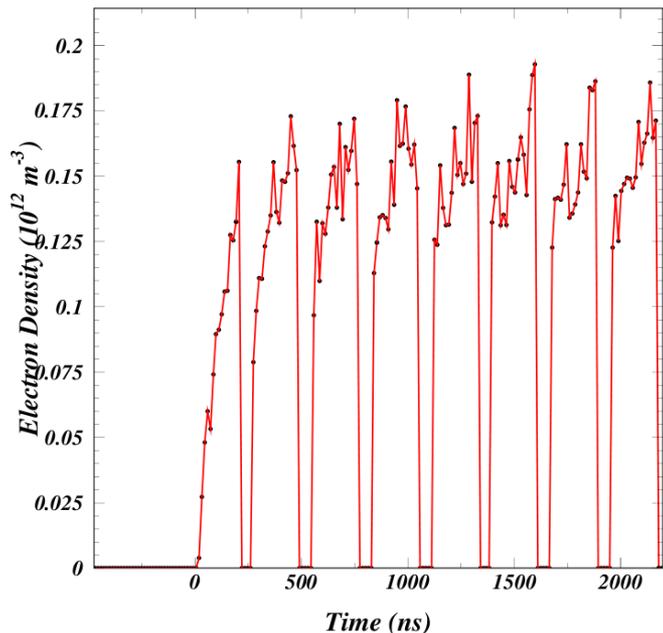**Here we consider the effect of the clearing bunch on the total cloud density in the beampipe.**

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.

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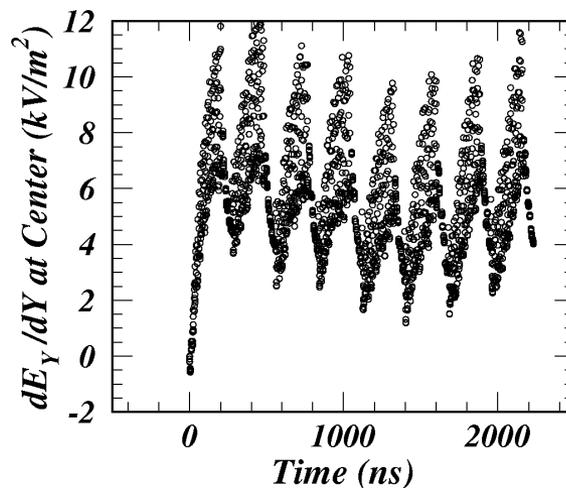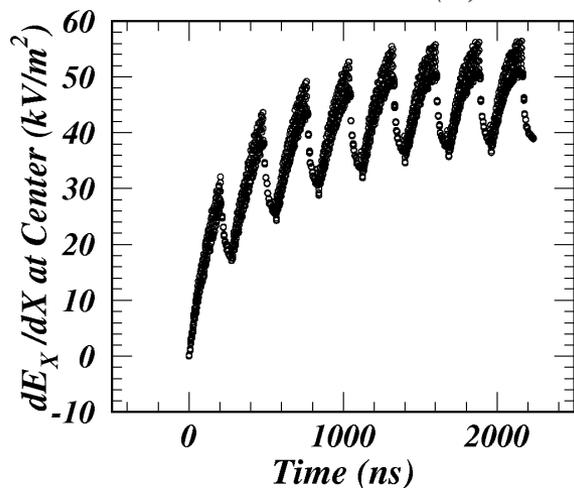
Optics-distorting electric field gradients arising as the beam attracts cloud can reach values as high as 50 kV/m^2.

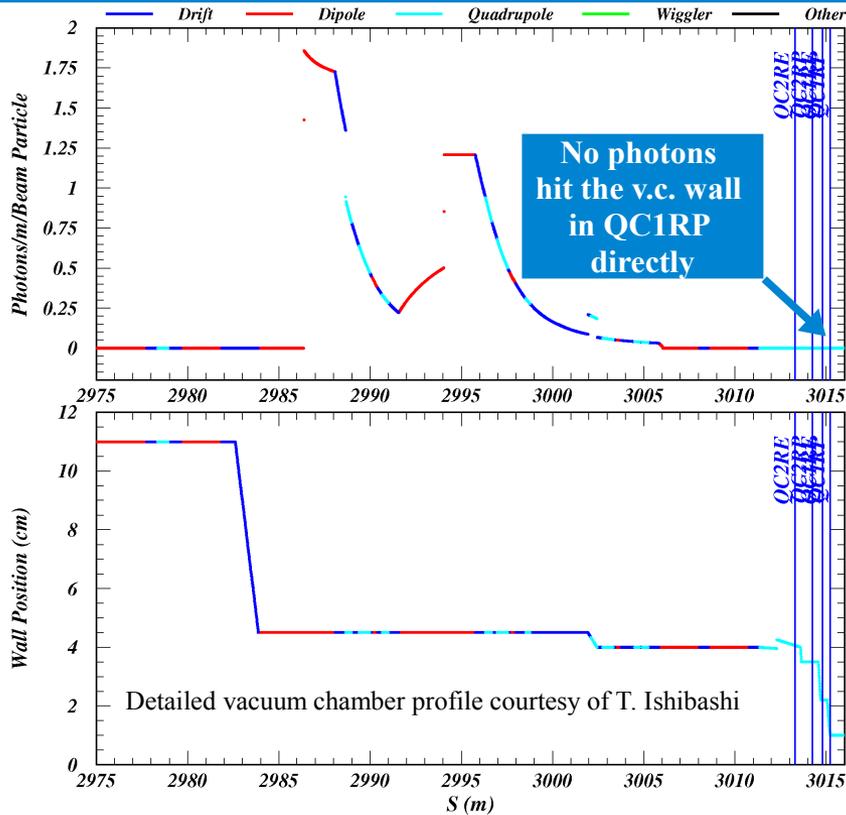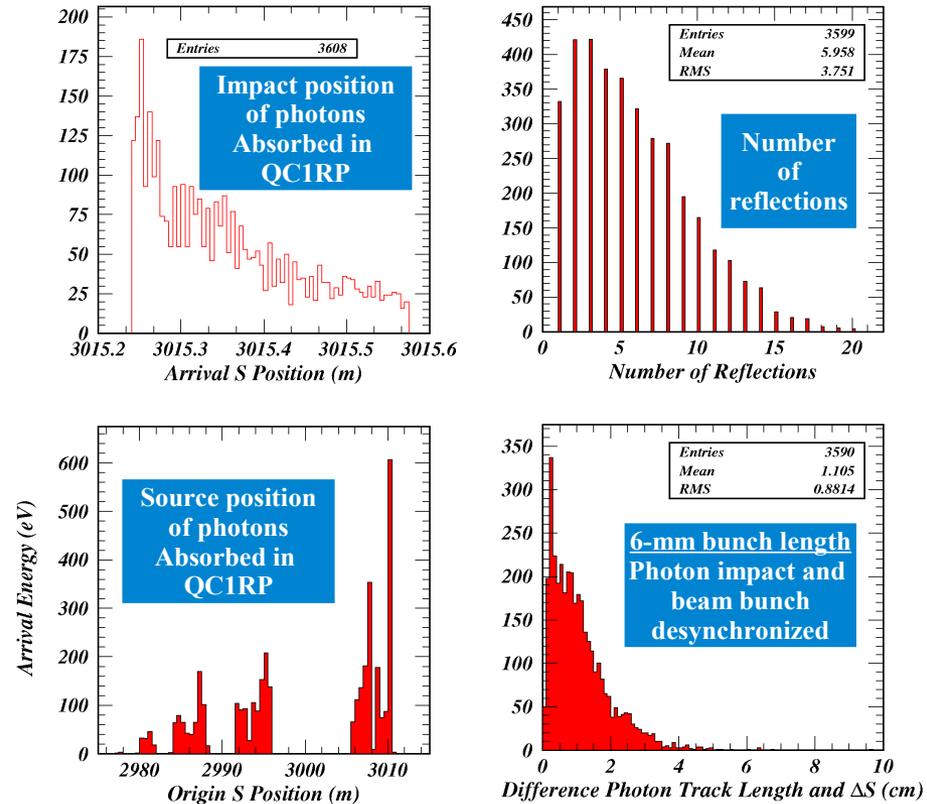**Higher multipole fields should be taken into account as well.**

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

No photons hit the v.c. wall in QC1RP directly

Detailed vacuum chamber profile courtesy of T. Ishibashi

Impact position of photons Absorbed in QC1RP

Number of reflections

Source position of photons Absorbed in QC1RP

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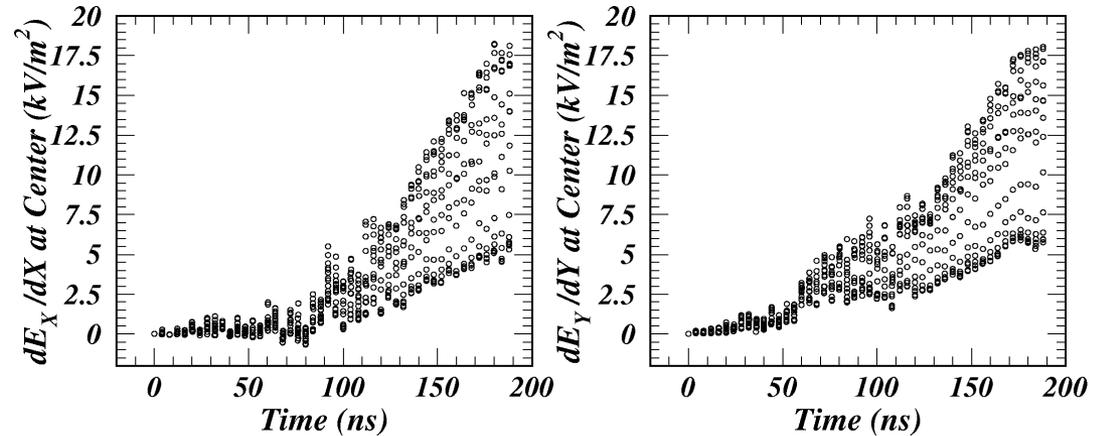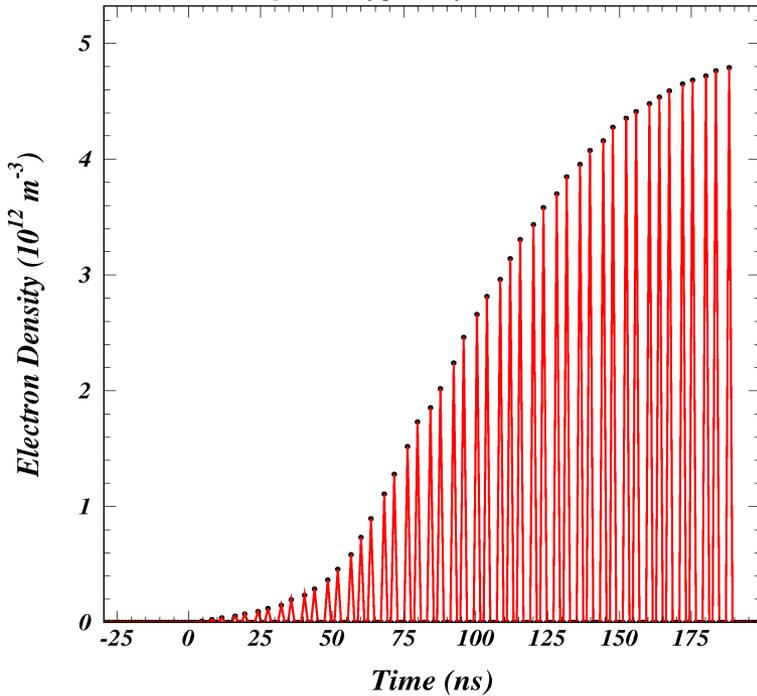
Calculations up to now have not taken into account photon scattering inside the beampipe.
Ohmi & Zhou (IPAC14) found the tune shift to be dominated by electron cloud near, but not in, the IR region.
Using the LER lattice and the detailed wall profile, we find the rate of photons absorbed in the QC1RP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

Electron Cloud Buildup Modeling for SuperKEK-B (Preliminary)

Central 20-sigma density prior to filled bunches (10^{12} m^{-3})

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
$$\Delta f_Y = 133\ Hz$$
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.

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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 !)
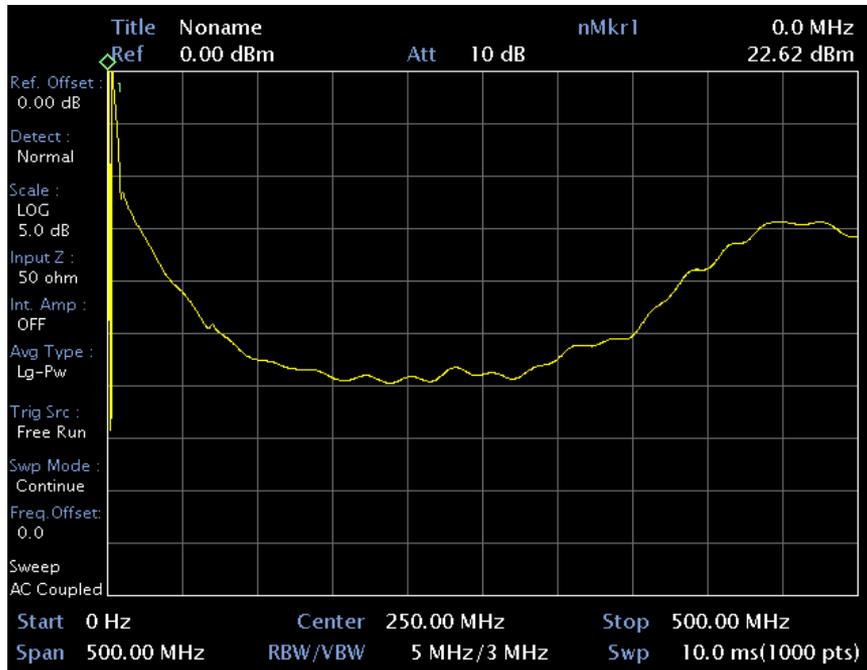   **(JAC, T. Ishibashi, in progress)**

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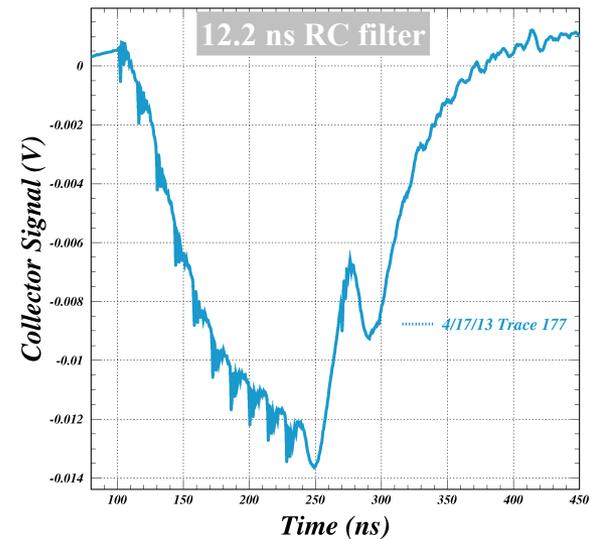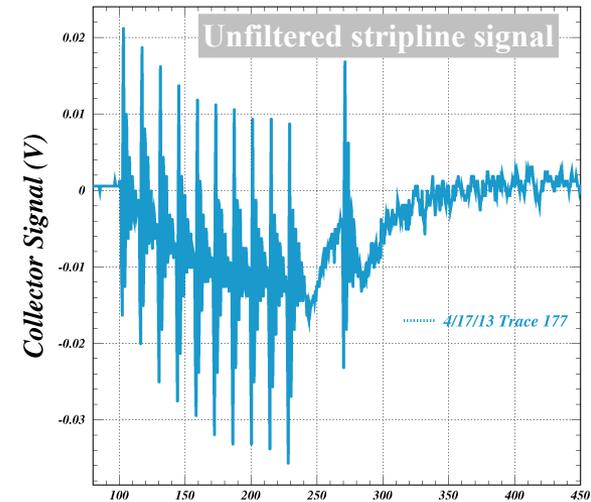Accelerator-based Sciences and Education (CLASSE)

Stripline frequency response measured with a spectrum analyzer

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

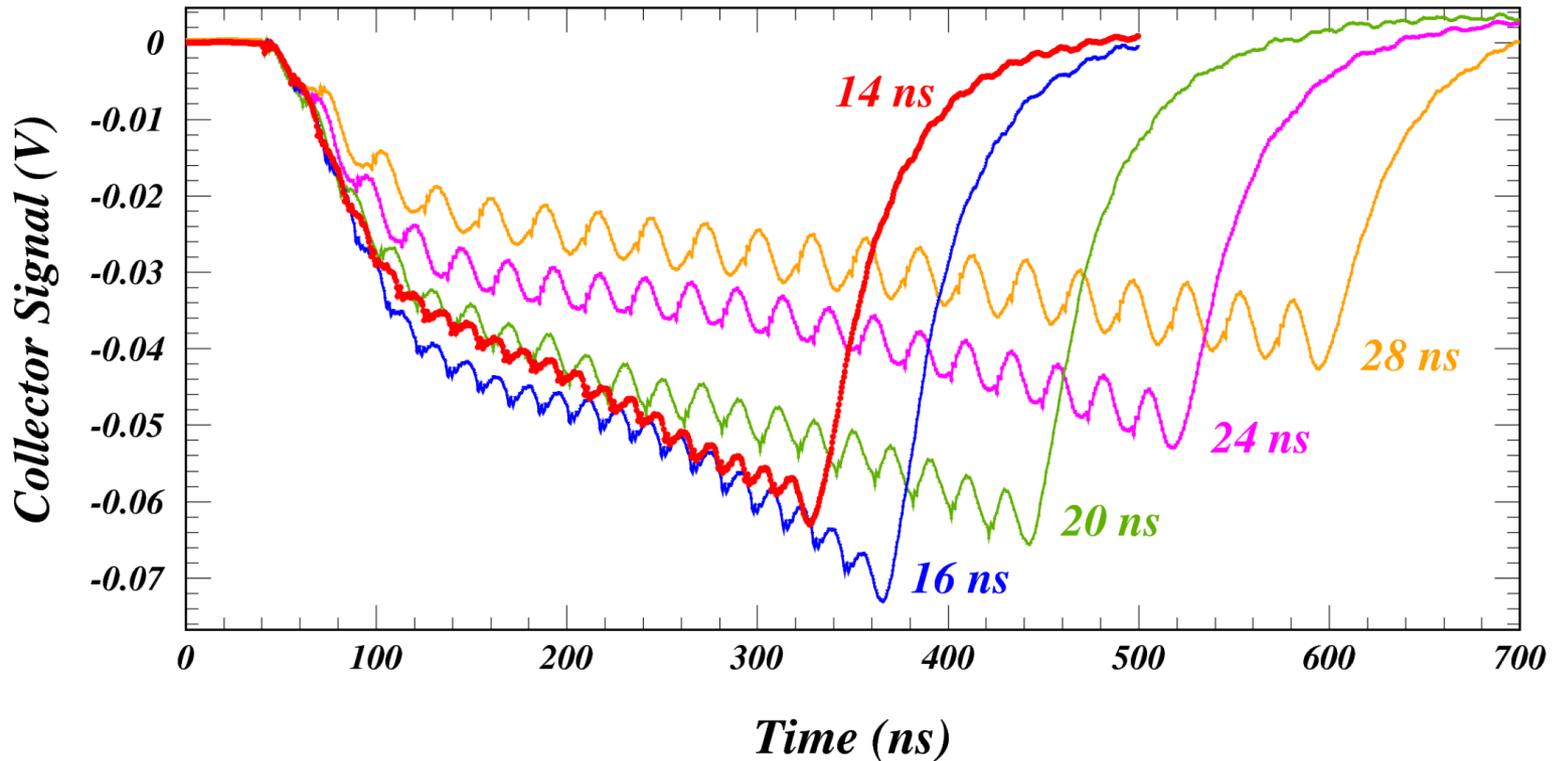- **High-pass feature results in sensitivity to beam-induced noise**

QSPU in Q48W: 5.3 GeV e+ 8.16 mA/bunch

Unfiltered stripline signal

4/17/13 Trace 177

12.2 ns RC filter

4/17/13 Trace 177

Signals from 20-bunch trains with spacings of 14, 16, 20, 24, and 28 ns are shown. The average bunch populations are 1.3×10^{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
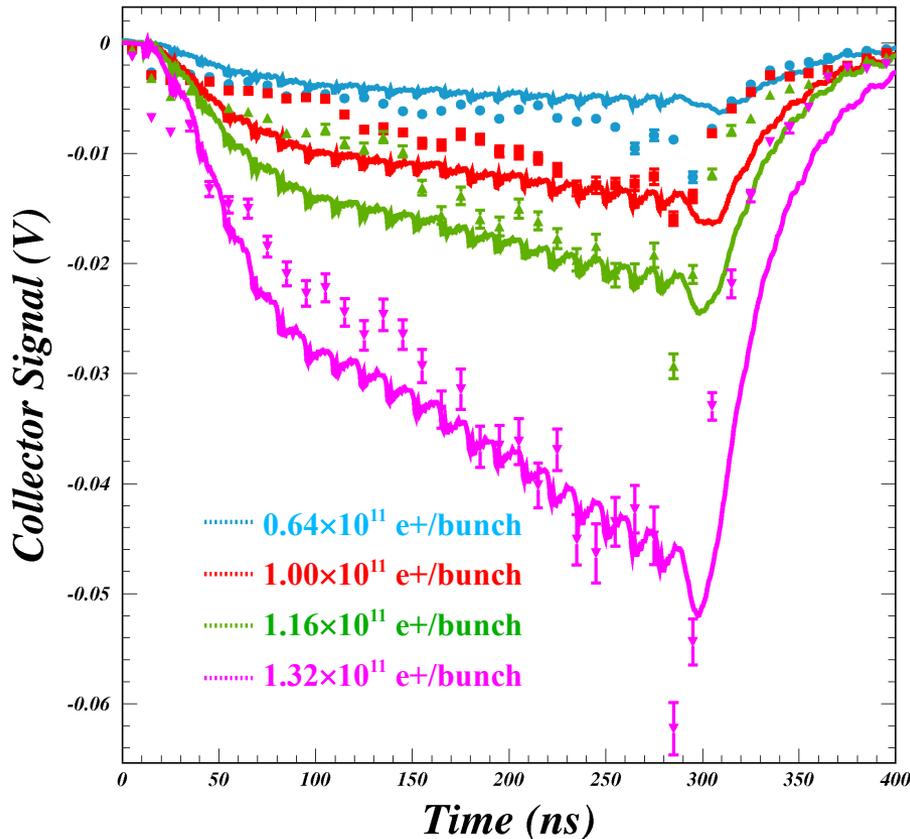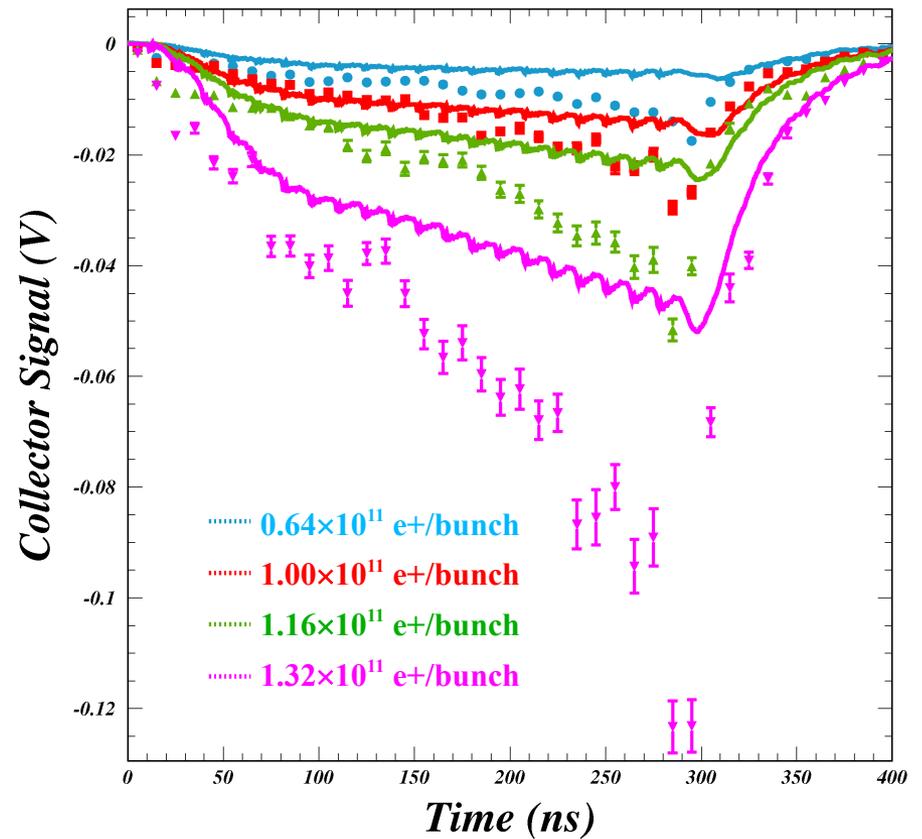
The modeled signal is very sensitive to the details of the SEY parameters, such as the relative contributions of the true, rediffused and elastic secondaries, the shape of the true secondary dependence on incident energy, the energy distribution of the produced secondaries, etc.
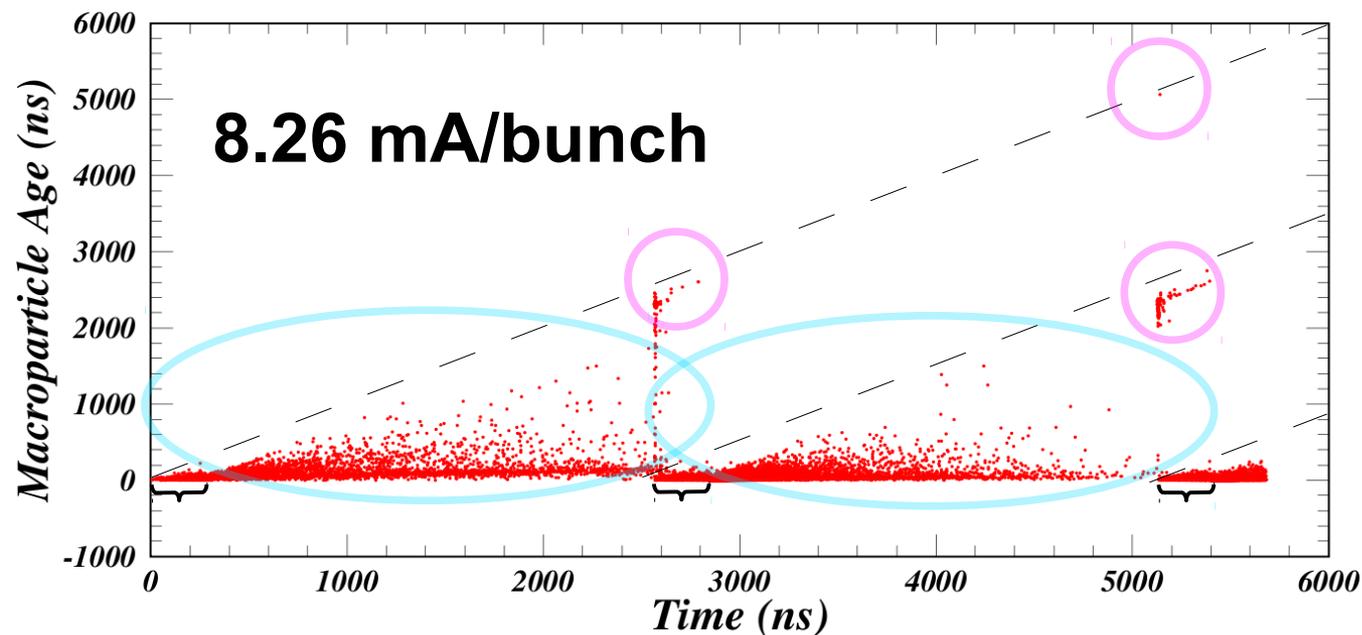
Job 38268

4.01 mA/bunch

Job 38309.

8.26 mA/bunch
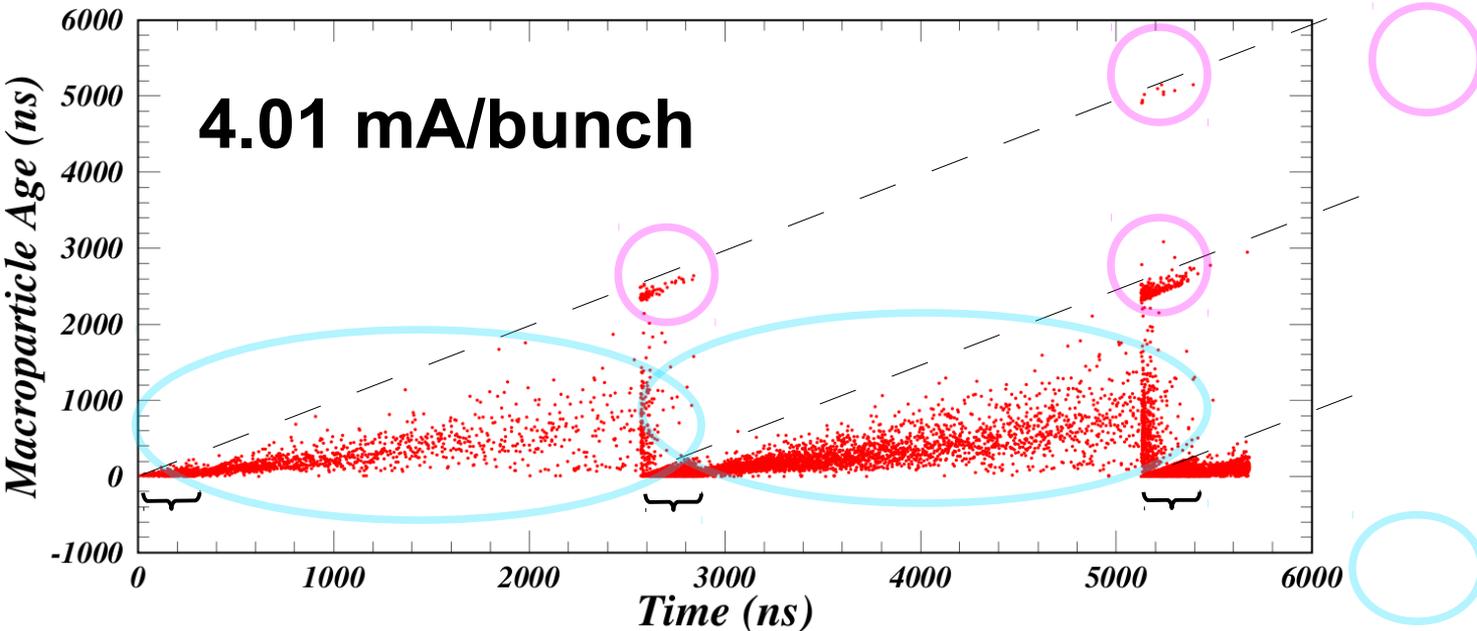
Trapped signal electrons produced near the end of a preceding train

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

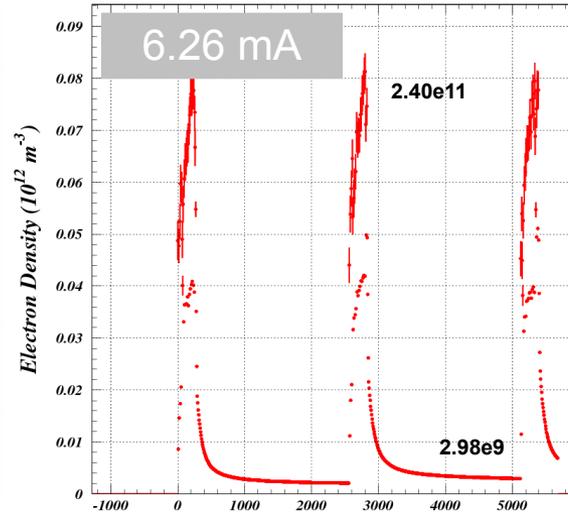Trapping for signal electrons occurs more effectively at lower bunch current

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LOW ε RING

Job 38268: Beampipe-averaged Cloud Density (10^{12} m^{-3})

4.01 mA

1.50e11

2.05e9

Electron Density (10^{12} m^{-3})
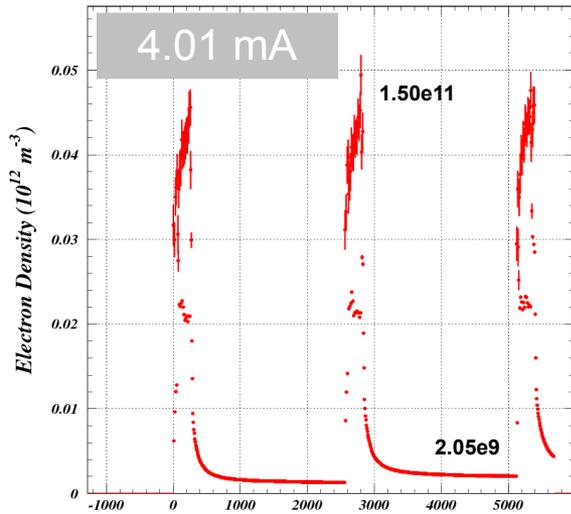
Job 38269: Beampipe-averaged Cloud Density (10^{12} m^{-3})

6.26 mA

2.40e11

2.98e9

Electron Density (10^{12} m^{-3})

Job 38300: Beampipe-averaged Cloud Density (10^{12} m^{-3})

7.26 mA

2.85e11

4.95e9

Electron Density (10^{12} m^{-3})

Time (ns)
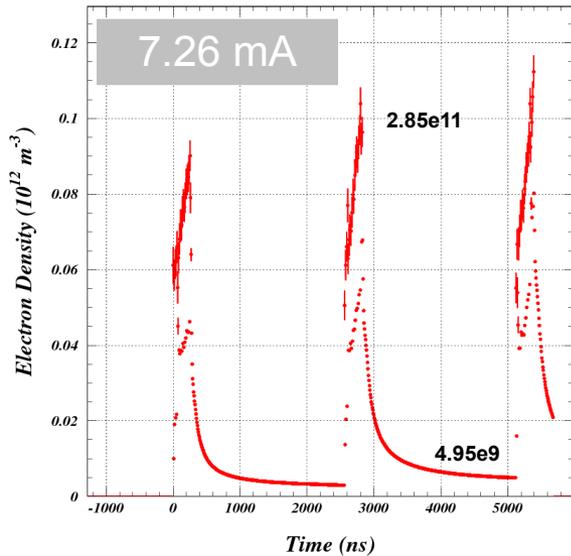
Job 38309: Beampipe-averaged Cloud Density (10^{12} m^{-3})

8.26 mA

1.10e12

3.95e10

Electron Density (10^{12} m^{-3})

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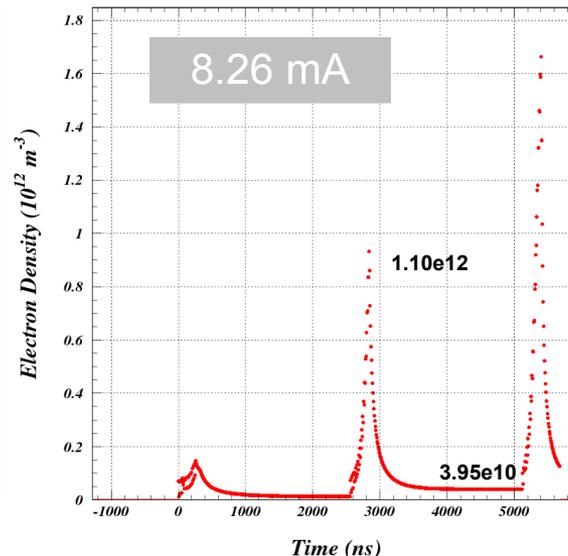
The cloud density increases nearly linearly with bunch current from 4 to 7 mA, then shows an increase of a factor of five from the first train to the second, and an additional factor of two from the second to the third train passage.

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.
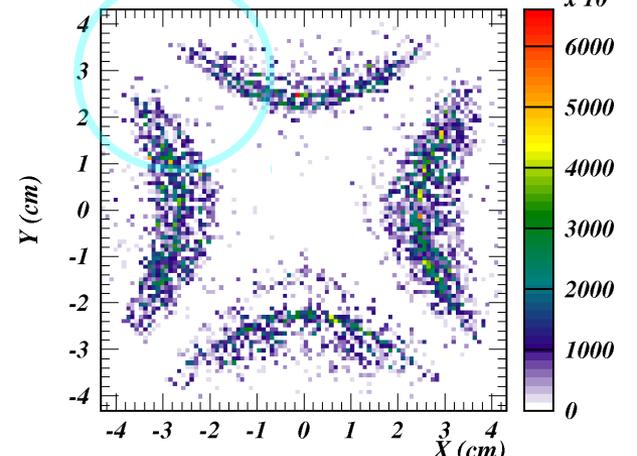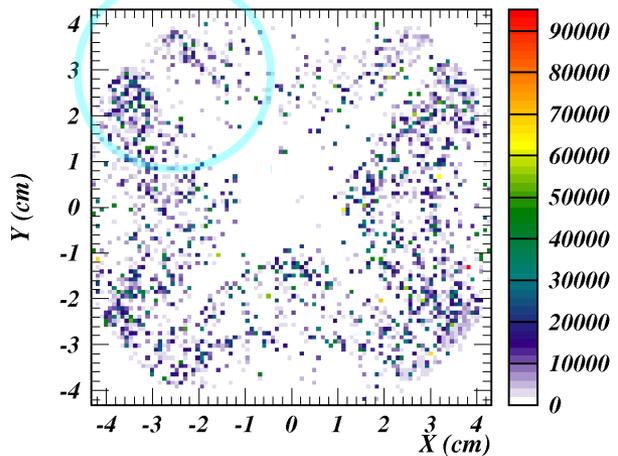
7.26 mA

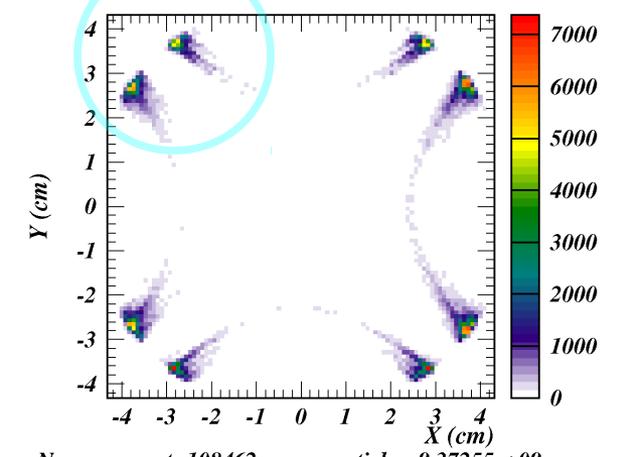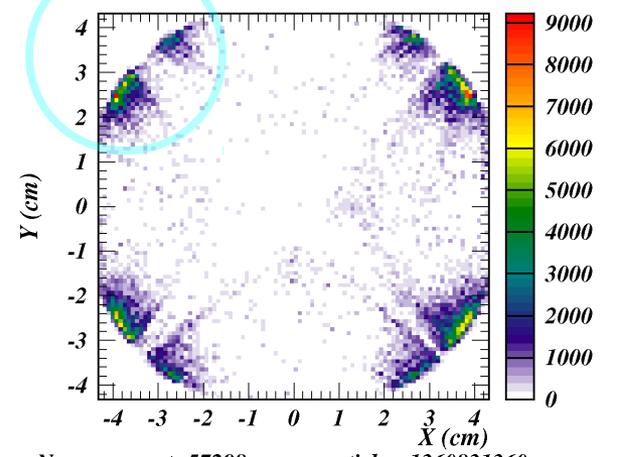**8.26 mA**

Q48W Detector Position

Cloud charge (N_e) snapshot after bunch 366 at time = 5124 ns

Cloud charge (N_e) snapshot after bunch 366 at time = 5124 ns

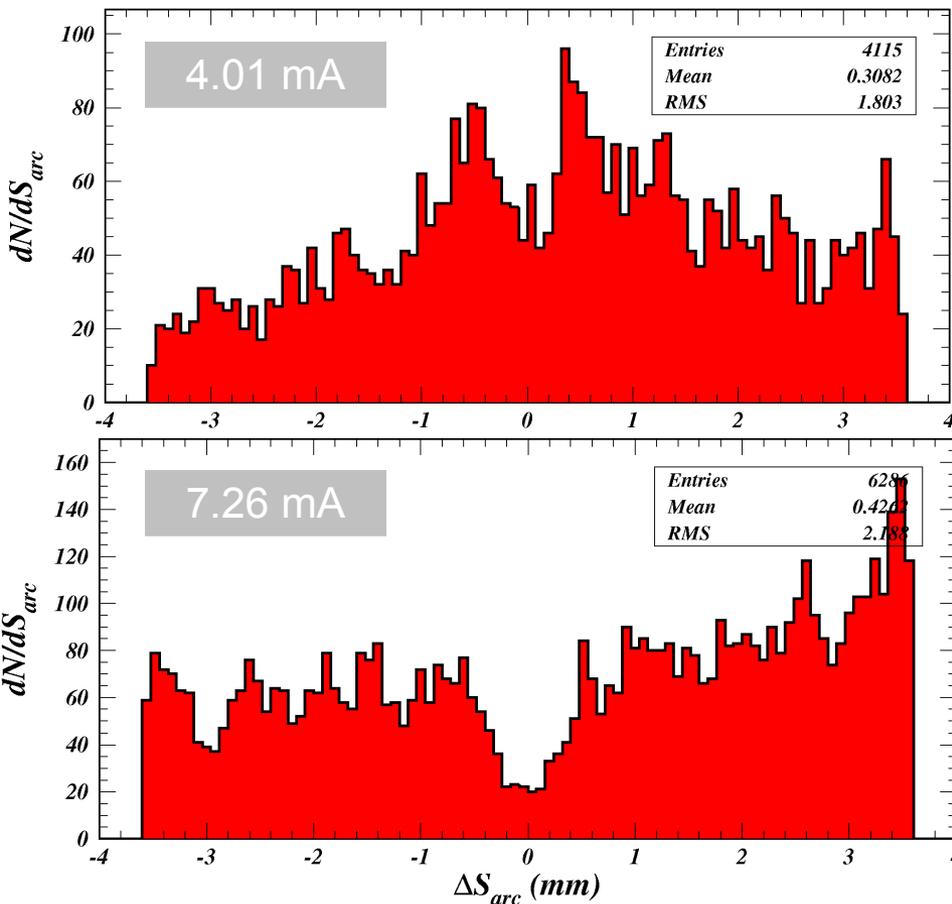*No energy cut: 18185 macroparticles, 28256924 e-*

No energy cut: 7000 macroparticles, 222740992 e-

Trapped cloud at the end of the second turn

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

Cloud charge (N_e) snapshot after bunch 386 at time = 5390.4 ns

Cloud charge (N_e) snapshot after bunch 386 at time = 5390.4 ns
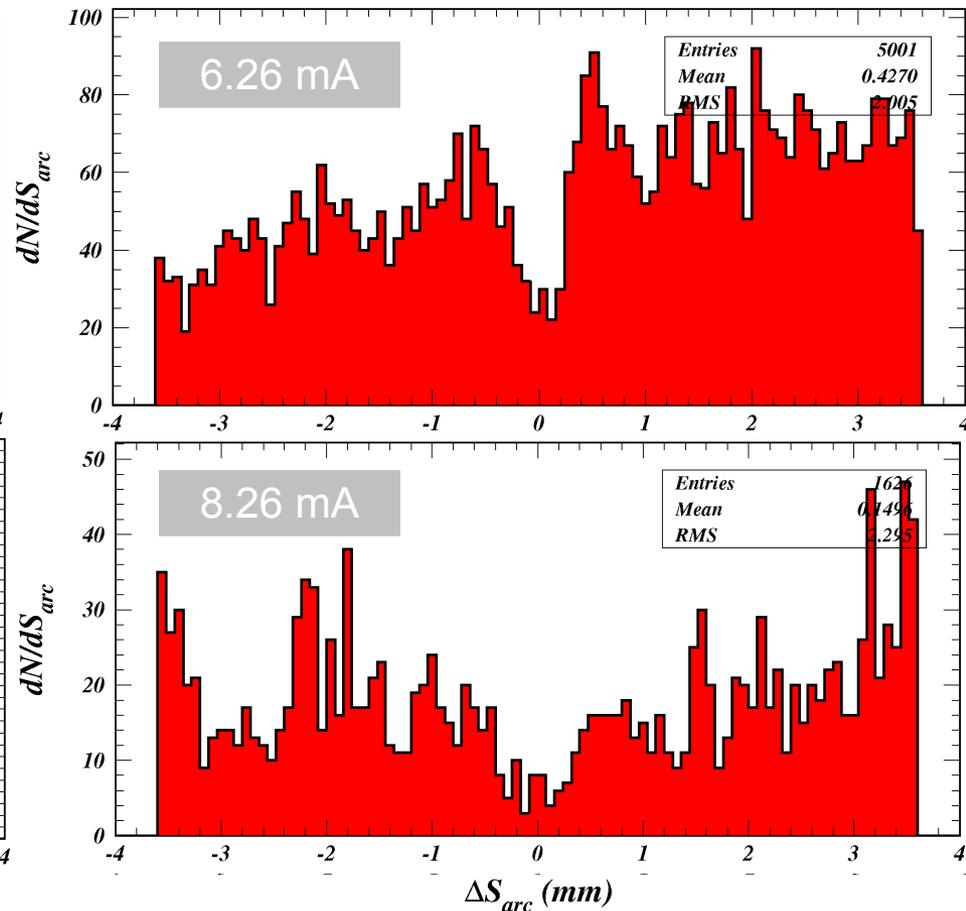

No energy cut: 57298 macroparticles, 1360831360 e-

No energy cut: 108462 macroparticles, 9.37255e+09 e-

Cloud immediately following the 60th filled bunch

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

Job 38430: Signal MP Arrival Azimuth For 5124 < T < 5524 ns   *Job 38431: Signal MP Arrival Azimuth For 5124 < T < 5524 ns*

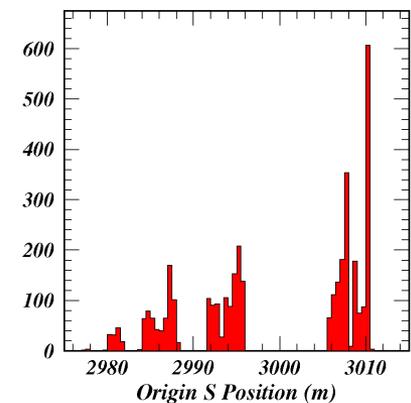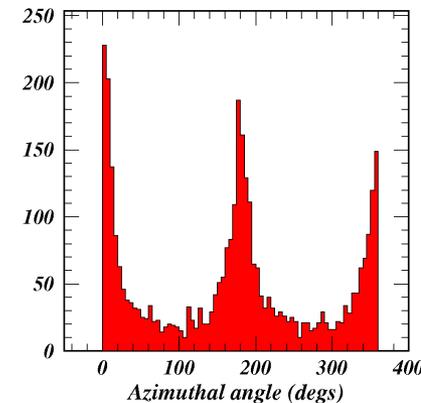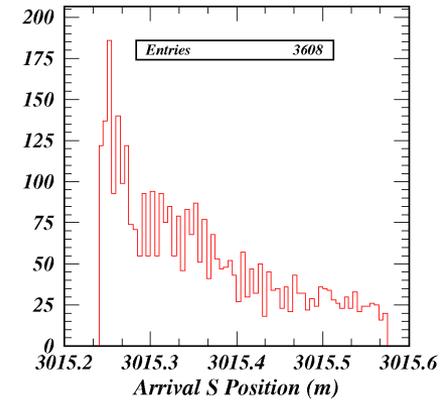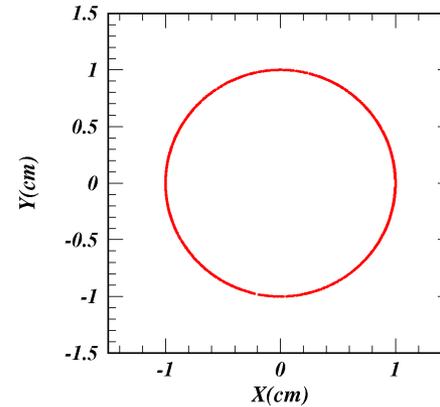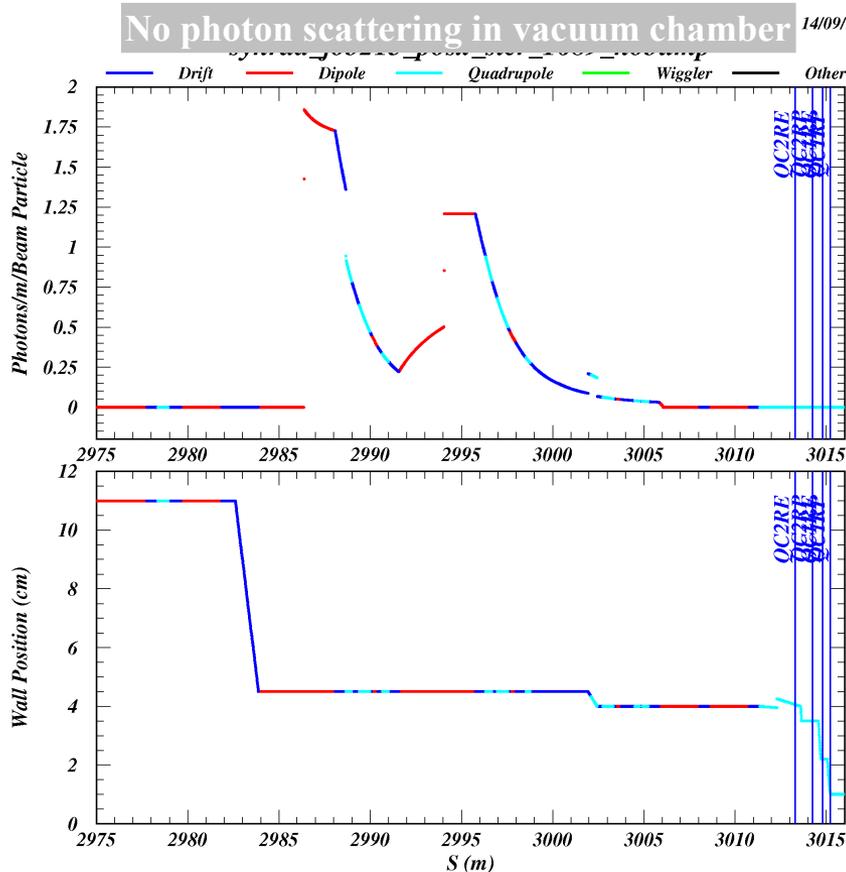**Potential signal electrons are missing the detector !**
We should consider building a detector with more acceptance and transverse segmentation.

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

SYNRAD3D: SuperKEKB 4.0 GeV SLER_1689_nobump:QC1RP

No photon scattering in vacuum chamber   14/09/10   11.21

Calculations up to now have not taken into account photon scattering inside the beampipe.
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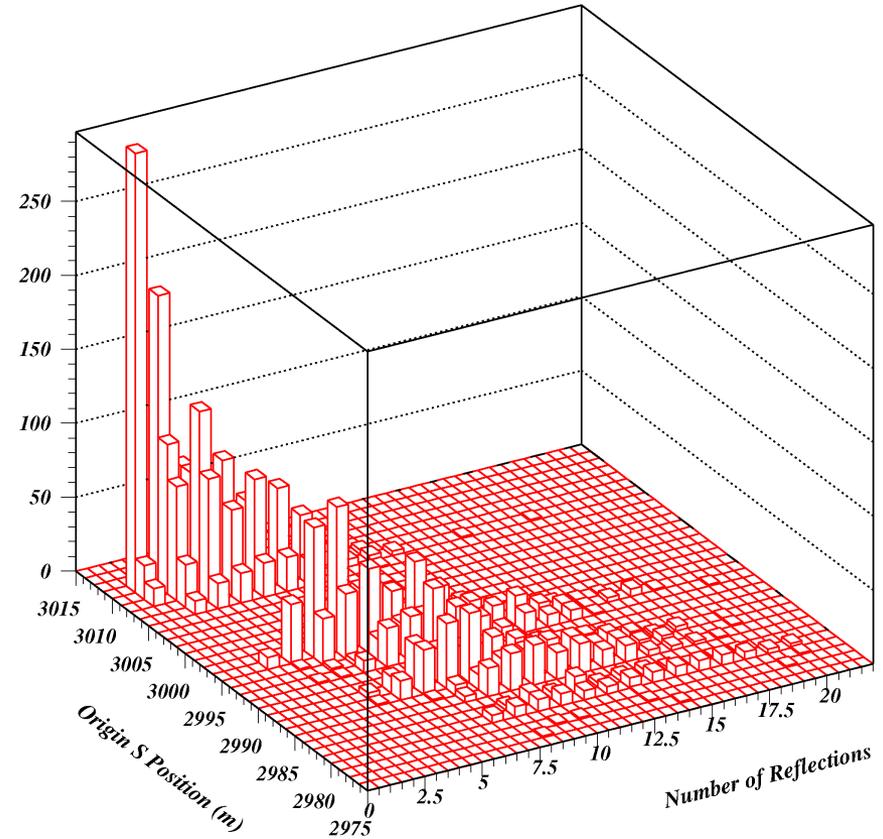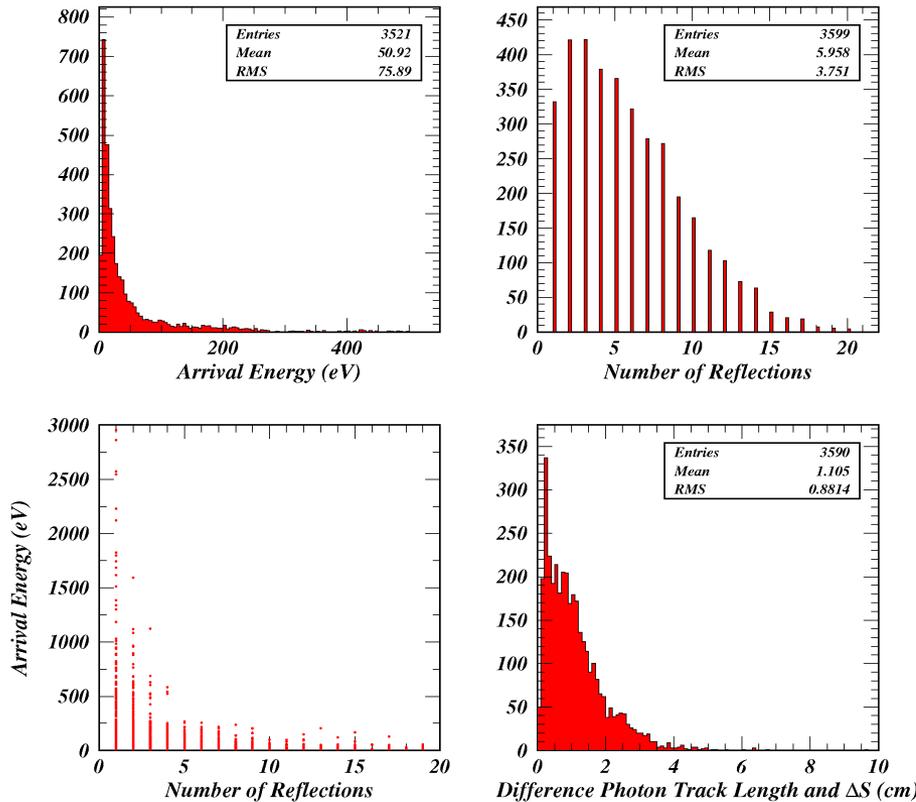
Synrad3D finds scattered photons absorbed in the QC1RP final focus quadrupole which originated in dipole magnets up to 36 m upstream and having undergone 1-20 scatters off the inner wall of the vacuum chamber.
Quite a few of the photon trajectories differ from the beam trajectory by more than the 6 mm bunch length.