Numerical Modeling for CESRTA Measurements of Electron Cloud Buildup in a Quadrupole Magnet†

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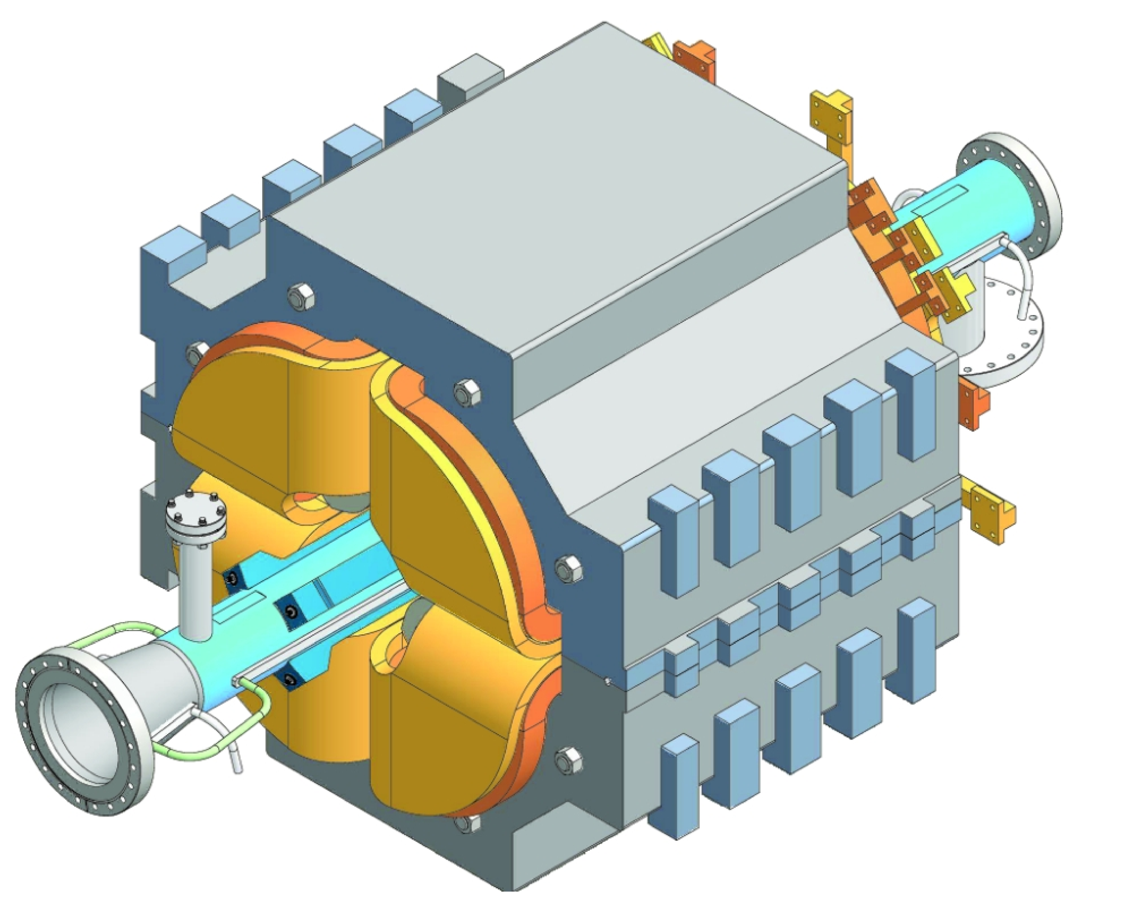
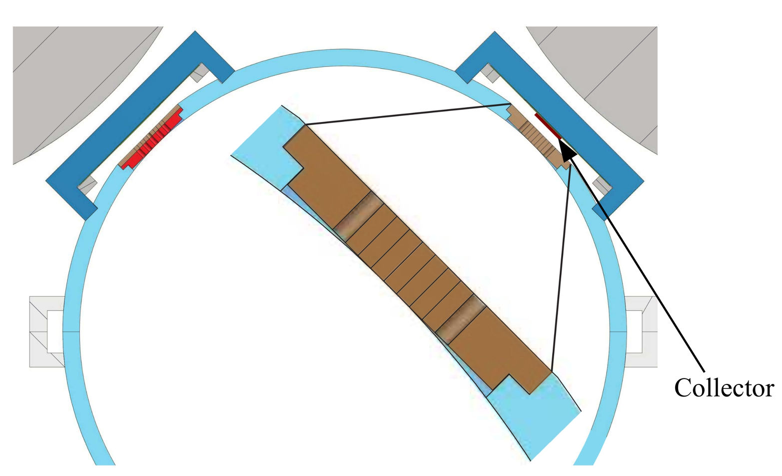
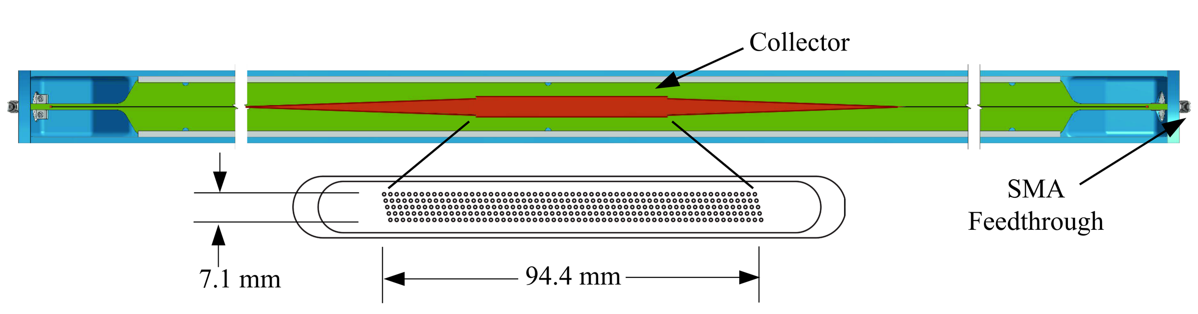


The beam-pipe with detector assembly is shown installed in the quadrupole magnet.

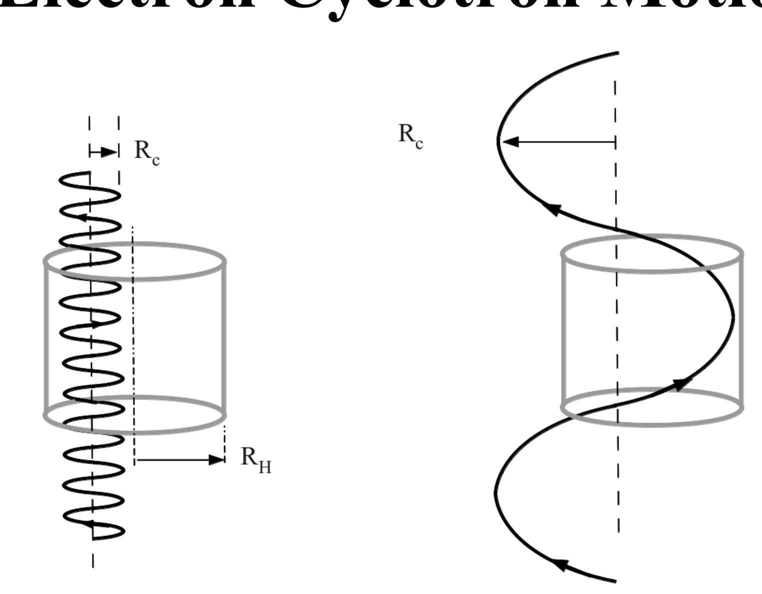


This detail cross section shows the array of holes and their placement in front of the collector stripline. The collector is centered on one of the pole faces of the quadrupole and is biased at +50 V to prevent the escape of secondary electrons from its surface.



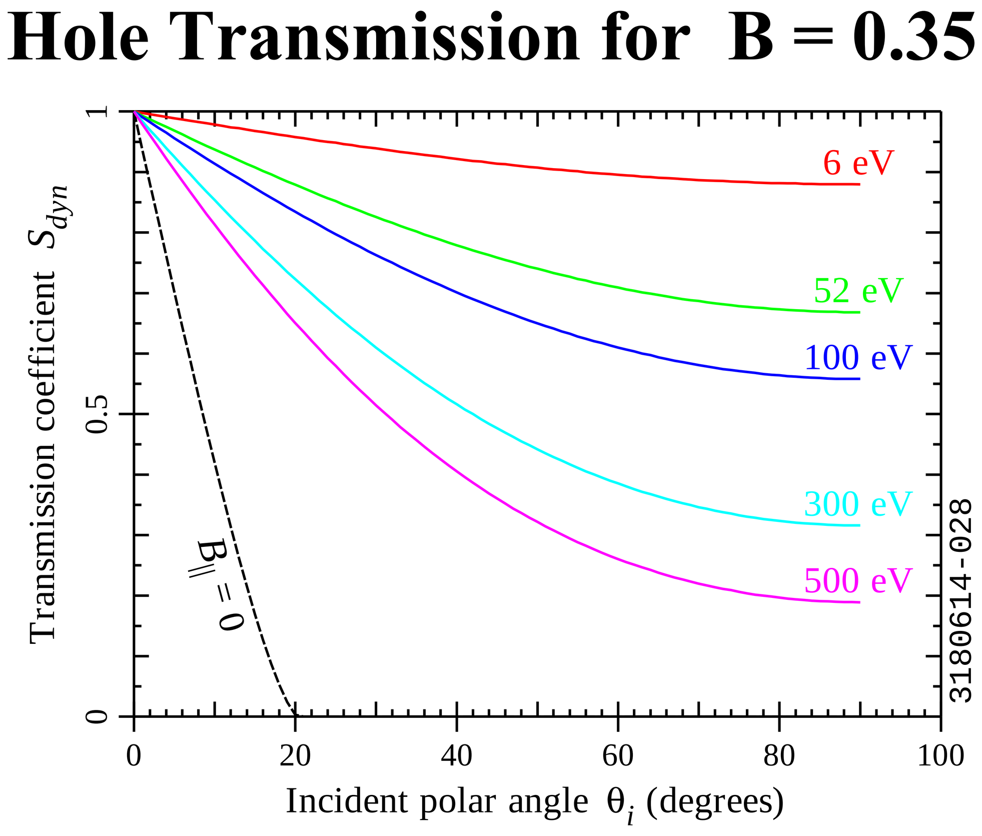
This is an enlarged front view of the 7x94 mm array of holes. The hole diameter is 0.79 mm. The hole depth:diameter ratio of 3:1 prevents most of the direct beam-induced signal from entering the detector. Electrons pass through the holes and strike the collector, which is etched on 0.12 mm kapton. The signal is coupled out of the detector with a tapered stripline and SMA feedthroughs at either end of the quadrupole.

Electron Cyclotron Motion



This sketch shows two examples for the transmission of cloud electrons through the holes in the presence of a vertical magnetic field. The electrons spiral around field lines with cyclotron radius R_c through holes of radius R_H. The left figure shows the case of $R_c < R_H$, with the electron effectively occupying a column of radius R_c within the hole. The figure on the right shows a case with $R_c > R_H$ where the electron executes less than half a cycle while it is in the hole.

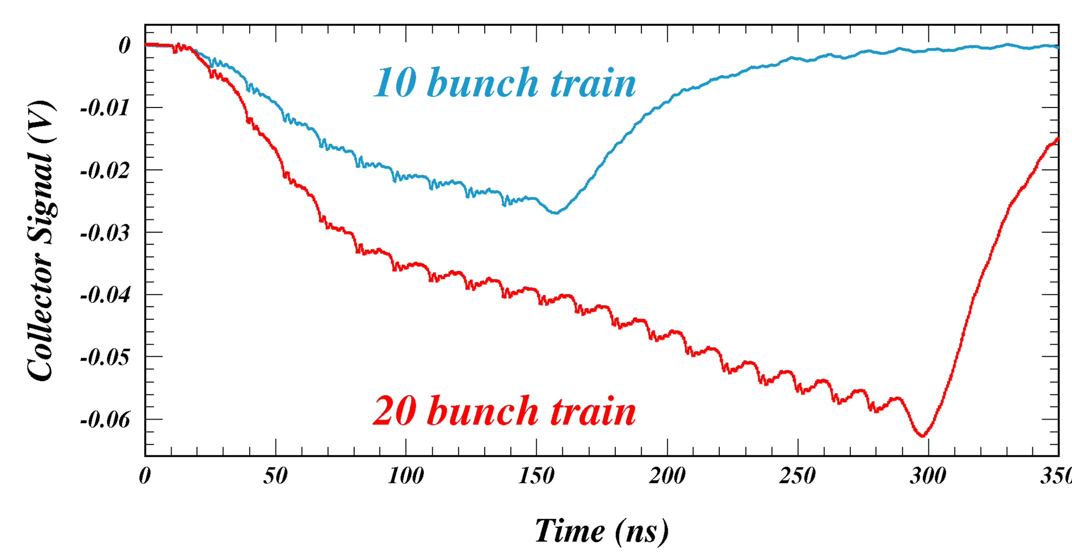
Hole Transmission for B = 0.35 T



The analytical calculation of the hole transmission coefficient S_{dyn} versus incident angle θ_i for the case of no magnetic field (dashed curve) and for electron kinetic energies ranging from 6 to 500 eV in a 0.35 T magnetic field aligned with the hole axis. For high magnetic field and low electron energy, transmission extends to grazing angles of incidence.

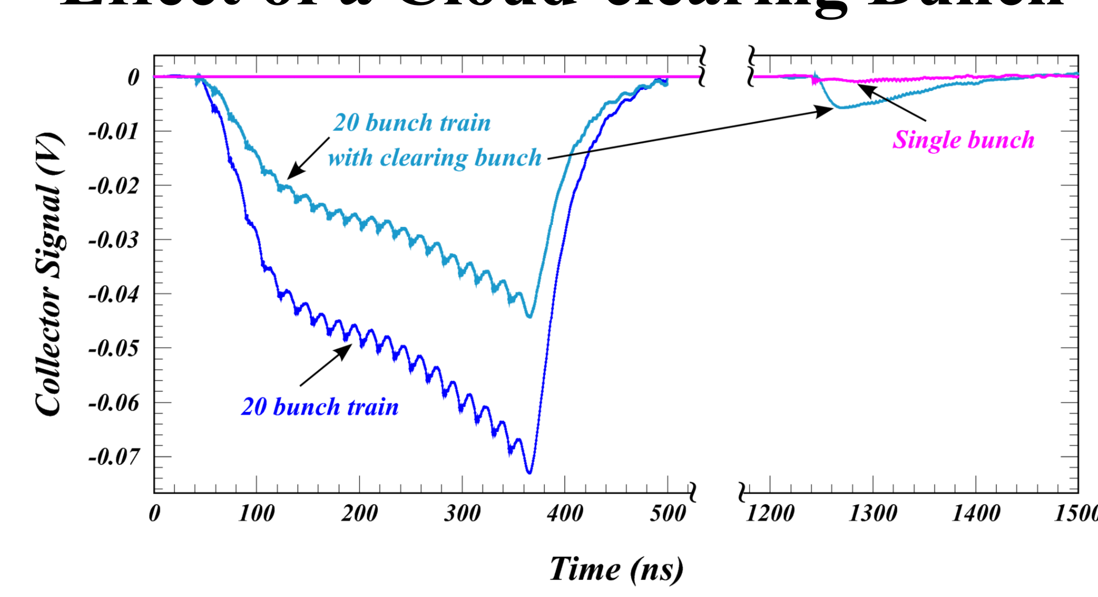
Abstract
We describe a numerical model for measurements of the formation of long-lived electron clouds in a quadrupole magnet in the CESR storage ring. The shielded stripline detector measures the electron flux incident on the vacuum chamber wall directly in front of one of the poles of the magnet. The model includes photo-electron production by synchrotron radiation, electrostatic forces from the bunched positron beam and the cloud, macroparticle tracking in the field of the quadrupole, secondary electron emission from the 9.5-cm-diameter cylindrical stainless steel beam-pipe and an analytic calculation of the transmission function of the holes in the vacuum chamber which allow cloud electrons to reach the stripline collector. These modeling studies provide a quantitative understanding of the trapping mechanism which results in cloud electrons surviving the 2.3-µs time interval prior to the return of a train of positron bunches. These studies have been performed in the context of the CESR Test Accelerator program, which aims to quantify and mitigate performance limitations on future low-emittance storage and damping rings.

Observation of Electron Trapping



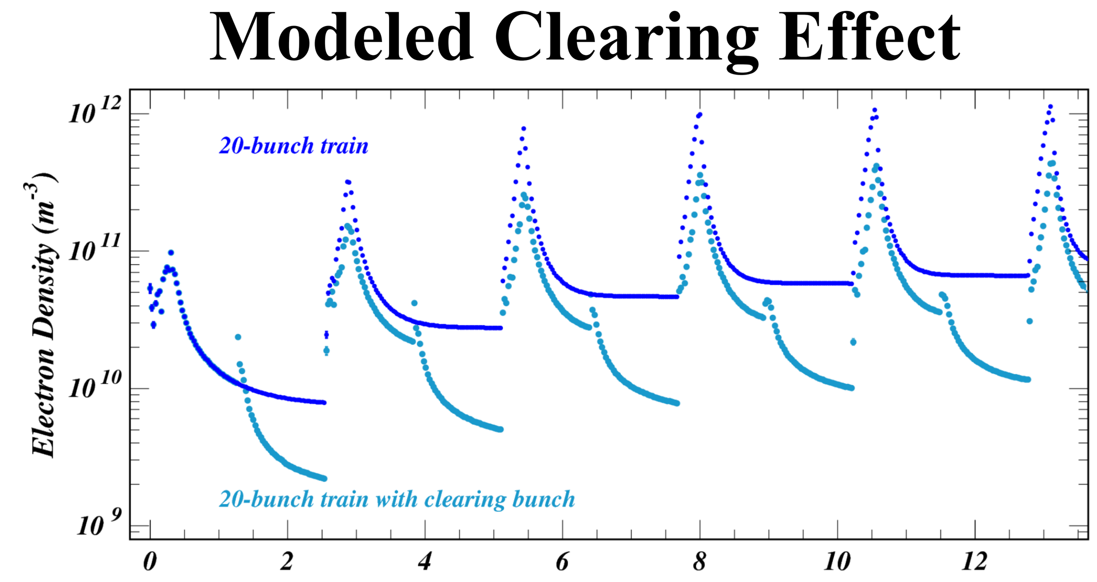
Electron detector signals recorded for 10- and 20-bunch trains of 5.3 GeV positrons for an average bunch population of 1.3×10^{11}. The signal from the first 10 bunches of a 20-bunch train are larger than the one from a 10-bunch train. This was the first evidence for long-term trapping of the electron cloud in a quadrupole. How do the first 10 bunches "know" the next 10 bunches are coming?

Effect of a Cloud-clearing Bunch



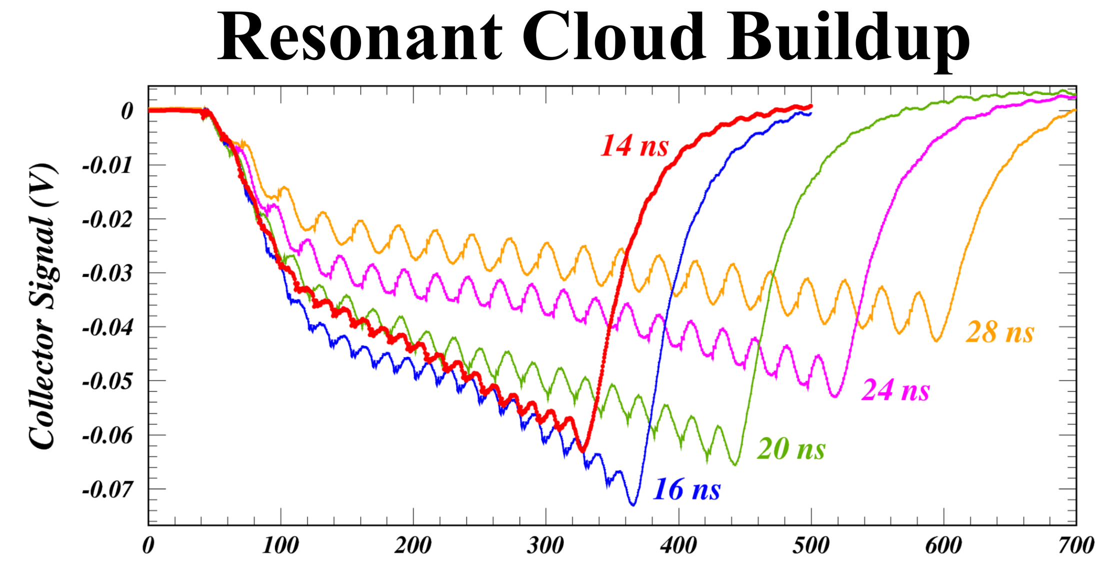
The three signals from a 20-bunch train, a 20-bunch train followed by a witness bunch ~900 ns after the train and a single bunch are shown in the figure above. All bunches have the same population of 1.3×10^{11} positrons. The spacing of the 20 bunches is 16 ns. The single bunch signal is plotted to coincide with the witness bunch for purposes of comparison. The much larger signal from the witness bunch shows that trapped cloud is accelerated into the detector. The decrease in the 20-bunch signal when the witness bunch is added shows the clearing effect of the witness bunch.

Modeled Clearing Effect



The modeled average electron cloud density for several turns of a stored 20-bunch train with and without a witness/clearing bunch. The simulation shows a reduction in the peak density when the witness/clearing bunch is added. The peak density in the absence of the clearing bunch reaches 1.1×10^{12} m^{-3} after three turns, about 7% of which remains trapped during the 2.3µs inter-train interval. The clearing bunch reduces the trapped cloud density by about a factor of 4.

Resonant Cloud Buildup



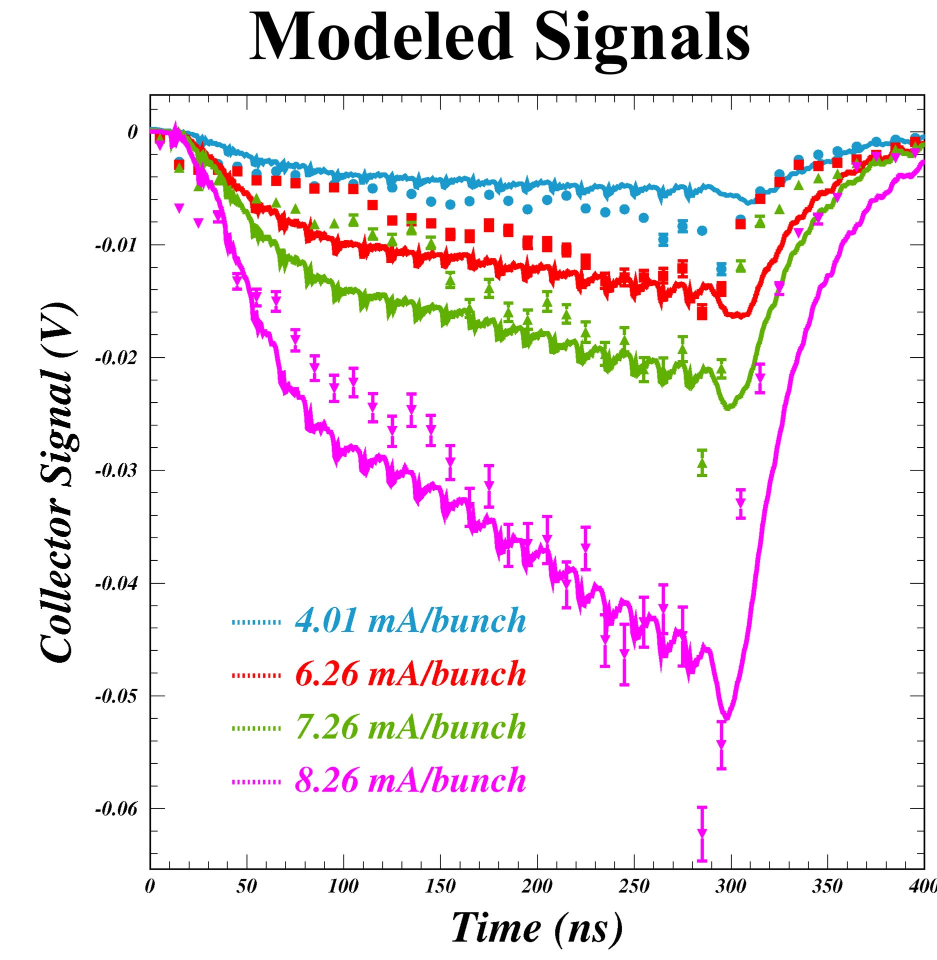
Signals from 20-bunch trains with spacings of 14, 16, 20, 24, and 28 ns are shown. The average bunch populations are 1.3×10^{11} positrons. The signal generally decreases as the bunch spacing is increased. However, the signal *increases* when the bunch spacing is increased from 14 ns to 16 ns, indicating a resonance in the production of cloud electrons.

Electron cloud simulation package 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
* Interactive quadrupole stripline model implemented in 2013

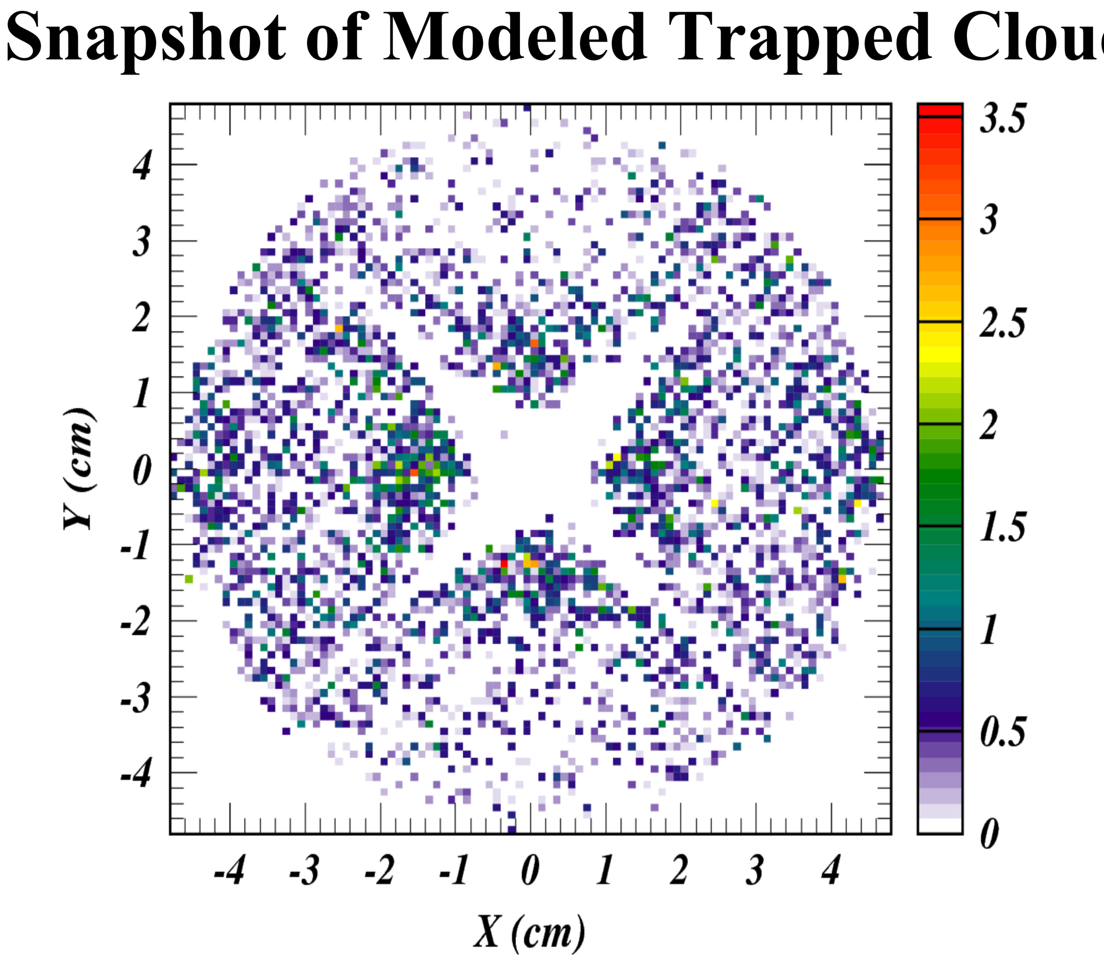
I. Generation of photoelectrons
   A) Production energy, angle
   B) Azimuthal distribution (v.c. reflectivity)
II. Time-sliced cloud dynamics
   A) Cloud space charge force
   B) Beam kick
   C) Magnetic fields
III. Secondary yield model
   A) True secondaries (yields > 1!)
   B) Rediffused secondaries (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

Modeled Signals



Recorded and modeled shielded stripline detector signals for trains of 20 bunches with average bunch population ranging between 6.4×10^{10} and 1.3×10^{11} positrons.
The simulated signal charge is calculated as the incident macroparticle charge multiplied by the hole transmission factor. The charge fraction which does not enter the holes is used to calculate the charge of secondaries produced on the wall in the detector region. The signal charge is summed during a time step to calculate the current, which is then converted to the simulated measured voltage using the amplifier impedance of 50Ω and gain of 100.
A noise-reducing 13-MHz low-pass filter has been applied to the modeled signal as well as to the oscilloscope trace, with the consequence that the statistical error bars in the model are highly correlated.

Snapshot of Modeled Trapped Cloud



A cross section of model output is shown at a time just before the return of the bunch train. Regions of higher electron cloud density are established by the quadrupole field lines at locations that are near the beam axis. The color scale ranges up to 3.5×10^6 electrons/bin.

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