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The first experimental observation of magnetic resonances in electron clouds is reported. The resonance was observed as a modulation in cloud intensity for uncoated as well as TiN-coated aluminum surfaces in the positron storage ring of the PEP-II collider at SLAC. Electron clouds frequently arise in accelerators of positively charged particles, and severely impact the machines' performance. The TiN coating was found to be an effective remedy, reducing the cloud intensity by three orders of magnitude.

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The first experimental observation of magnetic resonances in electron clouds is reported. The resonance was observed as a modulation in cloud intensity for uncoated as well as TiN-coated aluminum surfaces in the positron storage ring of the PEP-II collider at SLAC. Electron clouds frequently arise in accelerators of positively charged particles, and severely impact the machines' performance. The TiN coating was found to be an effective remedy, reducing the cloud intensity by three orders of magnitude.

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In the vacuum chamber of particle storage rings or accelerators, the formation of electron clouds may be initiated by photoelectrons released from surfaces and ionized residual gas molecules. The cloud density increases when electrons accelerated by the beam field impinge on the chamber wall and cause surface secondary emissions. Electron clouds, at sufficiently high density, can cause single- and coupled-bunch beam instabilities, emittance increase, pressure rise, and heat deposition at the wall, ultimately compromising a machine's performance. It is an important issue for many currently operating facilities with high-intensity positively charged particle beams, as well as in the design of the positron damping ring of the proposed International Linear Collider (ILC). Experimental and simulation results, as well as possible remedies, have been discussed and reviewed in a series of international workshops [1, 2].

The electron cloud effect is expected to be particularly severe in magnetic field regions. It has been studied in a dipole in the proton storage ring SPS [3], and in a wiggler in the KEK B-Factory [4]. In this Letter, we report detailed investigations of electron clouds and the observation of magnetic resonances in chicane dipole magnets in the positron storage ring of PEP-II. The experiment was designed to measure the total intensity, the horizontal distribution, and the vertical kinetic energy of the cloud electrons reaching the chamber wall for a variety of beam currents and magnetic field strengths, and to test possible mitigation methods.

The chicane was located in a dedicated 4.2 m long beamline in a PEP-II straight section. The magnets' 15 cm aperture accommodated both the beam pipe (10 cm outer diameter) and the detector assembly. The maximum field was 1.46 kG, matching the design strength of the ILC damping ring arc dipoles [5]. Each magnet was calibrated on a test bench to an accuracy of 0.03% in integrated field using a stretched-wire system. The magnet's power supply was stable at the 0.05% level over an 8 hour period. The field-free sections were covered with current carrying windings producing a 20 Gauss solenoidal field to suppress electron cloud formation. The positron beam first passed through an uncoated aluminum chamber section along the center-line, encountering the first dipole after approximately 1.5 m. When it reached the center of the second dipole, the trajectory had been offset by approximately 3.5 mm. Here, the inner surface of the aluminum chamber was coated with an 100 nm thin-film of TiN deposited by reactive sputtering from an axial Ti cathode in an Ar/10%N_2 atmosphere.

Each of the first three dipoles, separated center-to-center by 73 cm, was instrumented with a retarding field analyzer (RFA) housed in an aluminum box welded on top of the beam pipe. Each RFA consisted of 3 layers of thin copper wire grids and one layer of stainless steel collectors located furthest from the beam. The grids generated a highly uniform electric field that allowed measurement of the vertical kinetic energy (K_y) of cloud electrons entering the detector region. The 17 stripe collectors, each independently biased at +45 V, were placed on an horizontal plane length-wise along the beam direction. An array of 2 mm diameter holes in the chamber wall, covering 15% of the local surface area, allowed shielding of the beam fields and detection of the electron cloud with minimal disturbance.

A photograph of the apparatus in the first chicane dipole is shown in Figure 1. The chamber wall exposed to direct synchrotron radiation beam was located on the $x > 0$ side; y is vertical. For the data presented here, PEP-II operated with 1722 bunches, with 6.65×10^{10} positrons per bunch at an average beam current of 2500 mA. The beam energy was 3.1 GeV. The beam bunches were 11.5 mm long (rms), spaced 4.2 ns apart.

The number of electrons emitted from the surface is determined by the secondary electron yield (SEY). The SEY scales approximately as $1/cos(\theta)$, where θ is the incident angle with respect to the surface normal. For a fixed θ, SEY increases rapidly as a function of incident energy until it reaches a maximum, and then decreases slowly at higher energies. The SEY parameters were measured in the laboratory using test samples, before and after

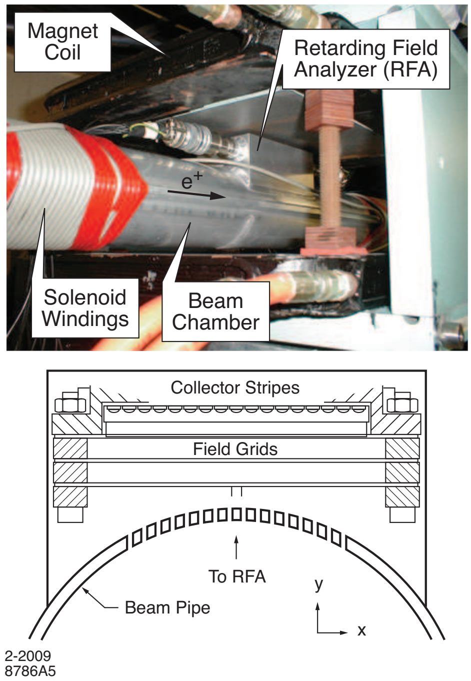

FIG. 1: Photograph of the apparatus in the first chicane dipole of the electron cloud experiment at PEP-II. A cross section schematic of the electron detector is also shown.

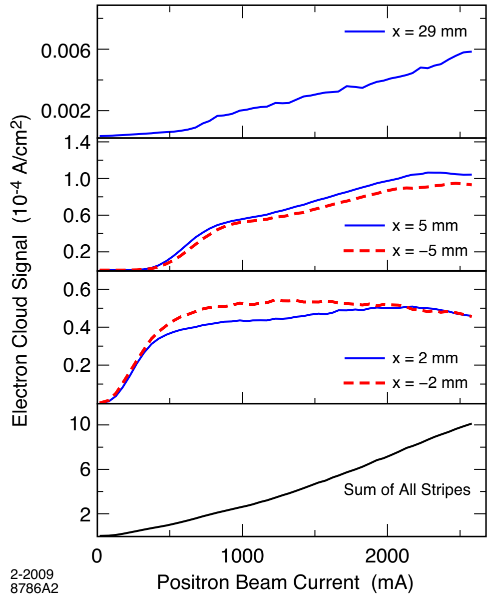

FIG. 2: Electron cloud signal as a function of beam current for uncoated aluminum surface at B_y = 861 G. Data from 5 selected RFA collector stripes as well as the total signal summed over all 17 collectors are shown.

exposure to positron beams in a setup installed at an upstream beamline location. The SEY maximum for uncoated aluminum surface was determined to be 3.2 at an incident energy of 300 eV, decreasing to 2.4 after beam exposure. While for a TiN-coated aluminum substrate, the maximum was 1.8 at 500 eV, reducing to 0.95 after beam exposure [6–8].

During electron cloud build-up, low energy secondary electrons emitted from the surface are accelerated by the passing positron bunch. In the magnetic field-free case, the electrons oscillate about the beam axis for 4 to 5 bunch crossings on average before impinging on the chamber wall. In the dipole field, the electrons become transversely localized. They are constrained to move predominantly vertically along helical tracks. The cloud density stabilizes within approximately 100 bunch crossings when the rate of electron production reaches an equilibrium with the rate of loss due to re-absorption. The cloud electron flux at the chamber wall was measured by sampling the collector current at 1 second intervals, long after the build-up had reached equilibrium. The collector current returned to ground via a load resistor, causing the bias voltage to "droop", by up to 1 volt at the highest observed signal. Its effect on the RFA's collection efficiency was negligible.

The secondary electron's energy gain was strongly position-dependent, as the beam's electric field increased rapidly within the bunch's radius and decreased inversely with distance outside the bunch. The transversely segmented RFA was well-suited to study the local cloud dynamics in a dipole magnet. The observed K_y spectrum was consistent with expectation based on the chamber geometry and beam parameters. For uncoated aluminum surface and at nominal beam current, the largest vertical kinetic energy gain was several keV, which was beyond the SEY peak. It occurred for electrons in the central region at $x \sim 0$, the transverse position of the beam axis inferred from the symmetric cloud density lateral distribution. Electrons with large K_y also had small θ. The combined effect was a reduced secondary electron yield and a depleted electron cloud density at the center. A lateral distribution with a double-peak structure was observed. This is consistent with earlier work [3, 9].

The electron cloud signals detected in selected collector stripes are shown as a function of beam current in Figures 2 and 3, at $B_y = 861$ G. For uncoated aluminum surface, the cloud density growth in the center region (-2 mm $< x <$ 2 mm) stalled after an initial rise, and the ensuing increase was nearly absent. The large energy gain at this position, beyond the SEY peak, apparently caused a reduction in secondary electron production even at relatively low beam current. Further away from the center, at $x = 29$ mm for example, the energy gain was small and the build-up was almost linear with beam current. At $|x| = 5$ mm, where the highest electron cloud signal was observed, the beam current dependence appeared to change at approximately 750 mA and 2200 mA. Data for TiN-coated surface are qualitatively similar, al-

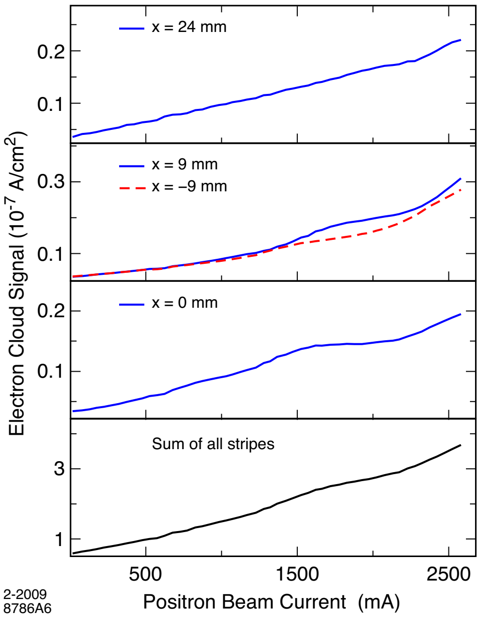

FIG. 3: Same as Figure 2 for TiN-coated surface for 4 selected collector stripes, and note the factor of 1000 change in scale.

though the strong suppression in the center region was not observed. This could be due to the higher peak SEY energy for TiN coating.

The observed beam current dependencies as a function of x indicate complex electron dynamics that depend on beam parameters and surface properties. This requires further study, and detailed simulations are being performed. Comparing the total signal for both surfaces, the TiN-coating had reduced the electron cloud intensity by at least 3 orders of magnitude at the nominal beam current of 2500 mA.

Recent simulation studies revealed interesting cloud dynamics as the dipole field strength varied [10]. The phase of the electron's gyration motion with respect to the arrival time of the positron bunch varies with B_y through the electron's cyclotron period, $\tau_c = 2\pi m_e\gamma/eB_y$, where m_e is the electron's mass, e its charge, and γ its Lorentz factor. At resonance, the ratio $n = \tau_b/\tau_c$ takes on integer values, where τ_b is the bunch spacing, and the electron motion is in phase with the external force (momentum kick by the beam field). According to simulations using ILC parameters [10], the in-phase electrons, on average, gain more transverse momentum than the out-of-phase ones. And because most of the cloud electrons initially have energies below the SEY peak, the energy gain and the associated increase in θ result in an increase in secondary electron production. Thus, an enhancement in the electron cloud signal is expected at resonance.

We sought to observe this resonance effect at PEP-II by scanning B_y in steps of 1 Gauss over a range of 0 to

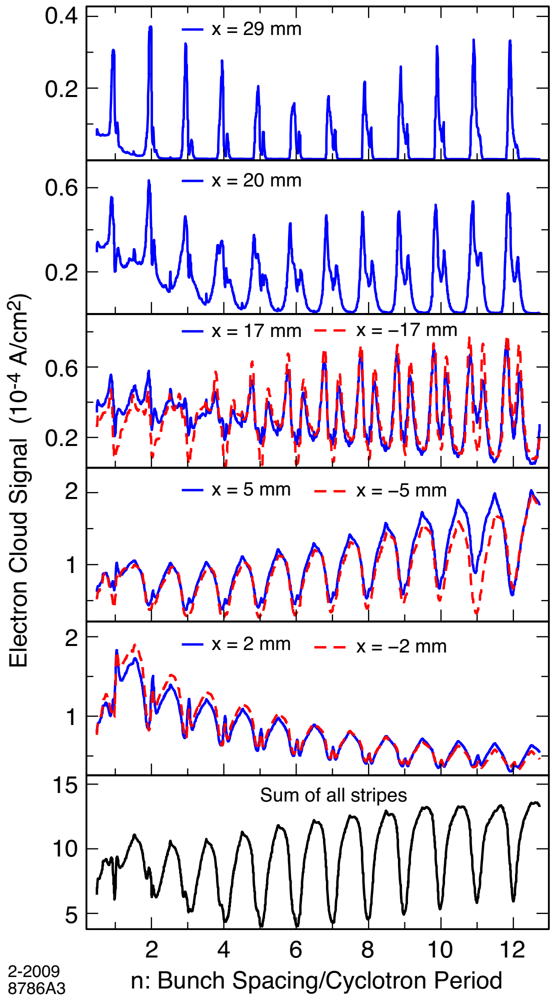

FIG. 4: Electron cloud signal from uncoated aluminum surface as a function of the ratio n at 2500 mA beam current. Data from 8 selected collector stripes as well as the total signal summed over all 17 collectors are shown

1.1 kG. The measured electron cloud signals are shown as a function of the ratio n in Figures 4 and 5 for uncoated and TiN-coated aluminum surfaces, respectively. For uncoated aluminum surface, data from the collector stripe furthest away from the beam ($x = 29$ mm) showed clear resonance peaks at the expected integer n values. At collector stripes closer to the beam axis ($x = 0$), the peaks showed a double-spike structure. This effect was so severe that at $x = \pm 5$ mm, the signal enhancement had shifted to half-integer values of n. This was not observed for TiN-coated surface, where resonances occurred for integer n (at large n) for all collector stripes.

The double-spike feature was observed in simulations for uncoated aluminum surfaces when space charge forces become important [10]. From Figures 2 and 4, it can be seen that the effect was most significant at $|x| = 5$ mm, where the observed electron cloud signal, and thus the in-

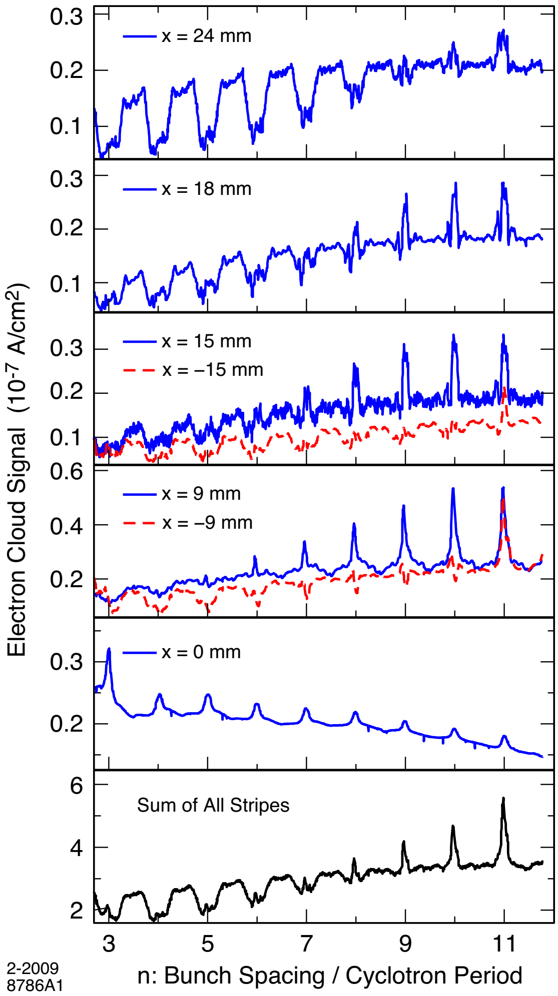

FIG. 5: Same as Figure 4 for TiN-coated surface for 7 selected collector stripes, and note the factor of 1000 change in scale.

ferred cloud density, was the highest. On the other hand, single resonance peaks were preserved where the observed cloud signal was small, for TiN-coated aluminum surface, and for uncoated aluminum at transverse locations away from the center (at $x = 29$ mm for example.) This qualitative agreement shows that the on-going detailed simulation study is expected to yield insights into the complex dynamics caused by a strong space charge force in highly non-uniform electron clouds.

Also shown in the two figures are comparisons of collector signals at equal but opposite transverse distances from the beam axis. For uncoated aluminum, the cloud signals appeared symmetric. For TiN-coated surface, the signal on the side exposed to the direct synchrotron radiation typically showed an enhancement of 10% to 20%. The signal was weak and it was susceptible to systematic effects, especially at very small and very large dipole fields. For clarity, only data within the $2.5 < n < 11.5$ range are shown in Figure 5.

For future work, the long term stability of the TiN coating will be studied. Complementary mitigation techniques will also be tested. Two more beam chambers, one with a triangular groove profile on the inner surface to trap low energy electrons, and one with TiZrV Non-Evaporable Getter (NEG) coating which has a lower initial maximum SEY, have been designed. The grooved chamber is being fabricated and it will be tested using the apparatus described here at the new CesrTA experimental facility [11].

In summary, electron cloud dynamics in a dipole magnetic field were investigated in detail using a transversely segmented RFA. Magnetic resonances were observed. These could be exploited to mitigate the impact of electron clouds in future colliders. Also, TiN coating was found to reduce the cloud density by more than three orders of magnitude.

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