Observation of Electron Trapping in a Positron Storage Ring

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The buildup of low-energy electrons limits performance in a wide variety of particle accelerators. Electron clouds can cause instabilities, emittance growth, and excess heat load, challenging cryogenic systems. Of particular concern is the persistence of the cloud between beam bunch passages, which can impose limitations on the stability of operation at high beam current. We have obtained measurements of long-lived electron clouds trapped in the field of a quadrupole magnet in a positron storage ring, with lifetimes much longer than the revolution period. Based on modeling, we estimate that about 7% of the electrons in the cloud generated by a 20-bunch train of 5.3 GeV positrons with 16-ns spacing and $1.3 \times 10^{11}$ population survive longer than $2.3 \mu s$ in a quadrupole field of gradient $7.4 \ T/m$. We have observed a non-monotonic dependence on the spacing of the bunches, indicating a beam-induced multipacting effect. A witness bunch provides a direct measurement of the trapped cloud density. The witness bunch is also observed to clear the cloud, demonstrating its effectiveness as a mitigation technique. Based on these observations, we derive an estimate of the effect of trapped electrons in the quadrupole magnets of the proposed International Linear Collider positron damping ring.

Electron cloud buildup has been observed in many types of accelerators since the 1960s [1], and was an important factor in the operation of the positron storage rings at KEK-B in Japan [2] and PEP-II in the U.S. [3]. Trapping of electrons oscillating around a 70-m-long proton bunch in the LANL PSR storage ring has been reported in Ref. [4]. Measurements of the time dependence of electron cloud buildup have been reported at LBNL [5], where the electrons were observed to be trapped in the fields of an ion beam and accelerator elements. Simulations have been used to study electron trapping in quadrupole and sextupole magnets for the parameters of the KEK-B positron ring [6], as well as for the Cornell Electron Storage Ring (CESR) and the positron damping ring of the International Linear Collider (ILC) [7]. The Large Hadron Collider (LHC) luminosity upgrade is contingent on reducing the bunch spacing to 25 ns [8], where electron cloud effects are so severe that they have been used for scrubbing runs [9]. Cloud mitigation efforts are underway, including application of carbon coatings to the dipole magnet vacuum chambers in the SPS [10]. Estimates of long-lived electron cloud buildup at the LHC and consequences for vacuum chamber heat load have been presented in Ref. [11]. More recently, the primary source of heat load in the final-focus quadrupoles of the LHC has been attributed to electron cloud buildup [12]. The design for the SuperKEK-B collider has been commissioned in two years has incorporated an extensive set of electron cloud mitigation techniques [13]. Since the solenoidal windings employed in the field-free regions of the ring cannot be used in the quadrupole magnets for reason of magnetic field quality, cloud mitigation methods are limited to titanium-nitride coatings and antechambers.

We report here on the measurement of electron trapping over an entire $2.5 \mu s$ CESR beam revolution period resulting from electron cloud buildup in a quadrupole magnet. Since the trapping mechanism is not contingent upon the beam potential, as in the case of the PSR, beam-free intervals in the ring are ineffective at clearing the electrons.

A principal goal of the Cornell Electron Storage Ring Test Accelerator program [14] is to investigate performance limitations in future high-energy low-emittance rings. These studies include measurements of electron cloud buildup caused by synchrotron-radiation-induced photoemission on the surface of the vacuum chamber. The CESR ring stores positron and electron beams of energy 1.8 GeV to 5.3 GeV arranged in bunches spaced in intervals of 4 or 14 ns with bunch populations ranging up to $1.6 \times 10^{11}$. A variety of detectors sensitive to cloud electrons incident on the vacuum chamber wall have been commissioned. Recently, we developed a novel method for time-resolved measurements of electron cloud buildup in a quadrupole magnet. Our interest in understanding electron buildup in CESR is to assess possible operational limitations on the damping rings required for a future high-energy linear $e^+e^-$ collider such as the ILC [15].

Time-resolving electron detectors have provided detailed information on local cloud formation, allowing the independent characterization of photoelectron and secondary electron production mechanisms [16, 17]. We have installed a shielded strip-line detector on a circular stainless steel vacuum chamber of inner diameter 95.5 mm inside a 60-cm-long quadrupole magnet. The detector is located in front of a magnet pole, as shown in Fig. [1a]. Electrons are collected on the 6-mm-wide copper trace (Fig. [1b]) which forms a transmission line with the grounded copper on the other side of the 0.12-mm-thick Kapton sheet. The pattern of $5 \times 60$ parallel holes 0.8 mm in diameter shown in Fig. [1b] allows passage of cloud elec-
trons through the beam-pipe to the strip-line. The hole diameter was chosen to achieve a depth-to-diameter ratio of 3:1, which effectively shields the detector from the directly induced signal from the beam bunch passages [18]. The hole pattern is 7.1 mm wide and 94.4 mm long. The collector was biased at +50 V relative to the vacuum chamber in order to prevent secondary electrons from leaving the collector surface. The front-end readout electronics consists of two Mini-Circuits ZFL-500 broadband amplifiers with 50 Ω input impedance and a total gain of 40 dB. Oscilloscope traces are digitized to 8-bit accuracy in 1000 time bins, typically 0.5 or 1.0 ns wide, averaging over 8000 triggers. The raw oscilloscope signals exhibit high-frequency beam-induced ringing following the passage of each bunch due to a high-pass characteristic of the strip-line. A 13 MHz low-pass digital filtering algorithm has been applied to the data presented here, suppressing this noise by an order of magnitude.

Figure 2 shows the oscilloscope traces recorded for 10- and 20-bunch trains of 5.3 GeV positrons for an average bunch population of $1.3 \times 10^{11}$. The enhanced signal during the first 10 bunches of a 20-bunch train relative to that for the 10-bunch train shows that electrons were trapped during the entire 2.3 µs interval prior to the return of the bunch train.

The increase in the signal for the 16-ns spacing relative to the 14-ns spacing shows that the beam-induced multipacting enhances long-term cloud electron trapping. At least as long as the 2.3 µs beam-free interval prior to the return of the bunch train. The decrease in cloud buildup rate following the first 6 bunches suggests that a subset of trapped electrons which can contribute signal has become depleted at that time. In spite of this clearing of the trapped reservoir of electrons, the signal does not return to the level of the 10-bunch signal, showing that the additional cloud seeded by the long-term trapping is self-sustaining. The signal depends strongly on the bunch population, decreasing by an order of magnitude as the bunch population decreases by a factor of two from $1.3 \times 10^{11}$.

The dependence of trapping on the bunch spacing is shown in Fig. 3. The increase in the trapped signal as the bunch spacing is raised from 14 ns to 16 ns is the signature of the beam-induced multipacting enhancement investigated by Harkay and Rosenberg at the Advanced Photon Source [19].

We have investigated the effectiveness of an intermediate bunch as a mechanism for clearing the trapped cloud. Figure 4 shows the three signals obtained from a 20-
bunch train, from a 20-bunch train with a clearing bunch of the same population following about 900 ns after the end of the train, and from a single bunch. The single-bunch signal is plotted to coincide with the signal from the clearing bunch for the purpose of comparison. The clearing bunch accelerates trapped cloud electrons into the detector, and thus provides direct evidence for the trapped cloud. In addition, the reduced signal from the 20-bunch train when the clearing bunch is present shows, however, that the cloud development proceeds at a lower density level following the clearing, since it does not return to the level of the signal for a 10-bunch train. The trapping results in a higher cloud density even though the higher density level following the clearing, since it does not return to the level of the signal for a 10-bunch train. The trapping results in a higher cloud density even after the trapped electrons have been removed.

The code has been supplemented with response functions for the ČeskTA time-resolving electron detectors. As a function of incident angle and energy, a fraction of the macroparticle charge hitting the wall in the region of the detector contributes to the modeled signal. The fraction is derived from an analytic calculation of the hole acceptance for the case of a magnetic field parallel to the hole axis. At zero field, the maximum angular acceptance corresponds to the depth-to-diameter ratio of 3:1. For an arbitrary magnetic field strength, the acceptance of the holes is derived by relating the incident kinetic energy and angle to the cyclotron radius and the wall traversal time, i.e. the fractional number of cyclotron revolutions performed. Thus the acceptance at high field extends to grazing angles of incidence when the cyclotron radius is smaller than the hole radius. The average macroparticle charge fraction which does not enter the holes generates secondary electrons per the secondary emission model. The amplitude of the modeled signal was found to be very sensitive to the assumed secondary emission yield, increasing by an order of magnitude as the peak secondary yield was increased from 1.4 to 1.9. The measured signal amplitude was reproduced with values for the peak secondary yield and elastic yield of 1.4 and 0.5, respectively. The model shows the signal to be generated predominantly by electrons originally produced on the field lines entering the detector, i.e. from a narrow surface region in front of the diametrically opposed pole and from 4-mm-wide regions on the vacuum chamber surface in front of the other two poles extending from the middle of the pole toward the detector. These signal macroparticles spiral around field lines which pass within a few millimeters of the beam. The electrons which remain trapped during the 2.3 μs prior to the train arrival are cleared out during the first 6 of the 20 bunch passages, reabsorbed either in the detector or the vacuum chamber wall. This clearing results in the abrupt reduction in the slope of the signal after 6 bunches. The signal also shows, however, that the cloud development proceeds at the higher density level following the clearing, since it does not return to the level of the signal for a 10-bunch train. The trapping results in a higher cloud density even after the trapped electrons have been removed.

Figure 5 shows the resulting modeled electron cloud density averaged over the test volume of the circular vacuum chamber for the case of 20-bunch trains of positrons with average bunch population $1.3 \times 10^{11}$, with and without an intermediate clearing bunch of the same population. The peak density in the absence of the clearing bunch reaches $1.1 \times 10^{12}$ m$^{-3}$ after three turns, about 7% of which is trapped until the train returns. The clearing bunch reduces the trapped cloud density by about a factor of four.
The modeled transverse distribution of the cloud trapped in the quadrupole magnets is shown at a time immediately preceding the return of the train in Fig. 6. The trapped electrons are concentrated in four quadrants near the beam outside of a central depletion zone of 2 cm radius and in the horizontal plane close to the vacuum chamber walls. The median energy of the trapped electrons is about 50 eV.

This characteristic of the quadrupole magnetic field to concentrate electrons near the beam raises concerns for storage rings with positively charged beams, since those electrons can be attracted into the beam. The investigation of Ref. 22 into electron cloud effects in the ILC positron damping ring design, including all proposed cloud mitigation measures, found that the highest electron cloud densities near the beam prior to the bunch arrival occur in the quadrupole magnets in the wiggler magnet section of the ring. We have employed the synchrotron radiation analysis of Ref. 22 in the 5 GeV, 3.2 km circumference ILC damping ring to estimate the cloud pinching effect in those quadrupole magnets, which are designed with a high gradient of 10 T/m. Figure 7 shows the electric field gradients calculated at the beam for the proposed 34-bunch trains. The bunches are spaced by 6.15 ns and each carry 2 × 10^10 positrons. The trains are separated by 11 empty bunches. The cloud pinch increases the horizontal gradient by 20% during passage of the 6-mm-long bunch, while the vertical gradient increases by nearly a factor of two. We find that the modeled cloud density averaged over the test volume of the beam-pipe reaches a value of about 10^13. The density within 5 rms beam-sizes of the beam axis increases by a factor of 5 during the bunch passage, reaching a value of 5 × 10^{12}. Unlike the dipole-dominated CESR ring, where dipole magnets occupy 62% of the ring and quadrupoles 6%, the fraction of the ILC damping ring occupied by dipoles is only 15%, while the quadrupoles occupy 10%. Our calculation of the field gradients arising from pinched electron cloud in the quadrupole magnets in the arcs of the ring show them to be four times those in the dipoles. Since the solenoid windings in the field-free regions effectively remove any electron cloud from the beam in the field-free regions, we expect cloud buildup and trapping in the quadrupoles to be the primary contribution to any eventual cloud-related performance limitations in the ILC damping ring.

In summary, our measurements with a time-resolving electron detector located in a quadrupole magnetic field have provided comparisons of signals from 10- and 20-bunch trains of positrons which show clear evidence for electron trapping during the entire 2.3 µs time interval prior to the return of the bunch train. Modeling tuned to the recorded signals indicates that approximately 7% of the cloud generated by a 5.3 GeV train of 20 bunches, each carrying 1.3 × 10^{11} positrons, remains trapped. The measurements show a non-monotonic dependence on bunch spacing indicative of beam-induced multipacting effects. The clearing effect of an intermediate bunch has been measured and successfully modeled, showing the trapped cloud can be reduced by a factor of four by such a clearing bunch. Application of our CesarTA-validated model to the case of the ILC positron damping ring shows that electron cloud buildup in the quadrupole magnets will likely dominate any cloud-related performance factors.

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FIG. 6. The modeled transverse distribution of the trapped cloud shown at the end of the first beam revolution. The color scale ranges up to a maximum of 3.5 × 10^9 electrons/bin.

FIG. 7. Modeled electric field gradients arising from electron cloud formation in the ILC positron damping ring quadrupole magnets. Electrons trapped near the beam are accelerated into the 6-mm-long bunch during passage.

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