0.0.1 Electron-Cloud Effect

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Background The electron-cloud (or photoelectron) effect (ECE) was first identified at the Photon Factory (PF) at KEK [1] as a fast transverse coupled-bunch instability that arises only when the machine was operated with a positron beam. Unlike the ion-induced instability, which was observed when the PF was operated with an electron beam, the positron beam instability persisted even with a substantial gap in the bunch train. In addition, the coupled-bunch mode spectrum was qualitatively different from that observed with an electron beam under otherwise similar conditions. The phenomenon disappeared when the bunch spacing s_B was sufficiently large, and it could not be attributed to known machine impedances. The amplitude of the unstable motion reached saturation and was accompanied by the excitation of vertical coupled-bunch oscillations, and possibly of vertical emittance growth.

Experimental analysis [1], simulations [2] and analytical work [3] led to the conclusion that the cause of the instability is an electron cloud that develops inside the vacuum chamber, coupling the transverse motion of the bunches. The ECE is related to beam-induced multipacting (BIM), first observed at the ISR [4] when operated with bunched proton beams. Being resonant in nature, BIM is perhaps the most dramatic manifestation of the ECE.

Following the observation at the PF, the ECE has also been observed at BEPC [5], APS [6–8], the positron rings of PEP-II [9] and KEKB [10], the SPS [11] and the PS [12]. An instability that has been observed at the PSR is now understood as an ECE [13]. A related instability has been observed at CESR [14], where electrons are trapped in the chamber by the combined magnetic field of the bending dipoles and the electric leak fields from the distributed ion pumps, leading to horizontal coupled-bunch motion.

Phenomenology In positron or electron rings, the electron cloud is formed when the synchrotron radiation (SR) emitted by the beam hits the walls of the vacuum chamber creating photoelectrons with typical energies of a few to tens of eV. As time goes by, these photoelectrons are transversely accelerated by the action of successive bunches, hitting the walls of the vacuum chamber with a much broader energy spectrum. They can then be absorbed or can emit secondary electrons which, in turn, are kicked by the beam. In proton rings, where the SR is typically negligible, the electron cloud starts from ionization of residual gas, or from electron generation at the walls of the chamber from stray beam particles. As these two sources of electrons are usually negligible, the electron cloud becomes significant only if BIM takes place. A notable exception will be the LHC [15], which will be the first proton storage ring in which the beam will emit substantial SR whose critical energy of ~ 45 eV will be larger than the work function of the vacuum chamber material, hence the mechanism for the formation of the electron cloud will be analogous to present-day positron rings. The compounding effect of the secondary electron emission process is particularly strong for positively-charged bunched beams. In the case of the PSR [13], which contains a single proton bunch, the ECE becomes significant owing to BIM during the passage of the trailing edge of the bunch.

The ECE combines many parameters of a storage ring such as beam energy, bunch current, bunch spacing, vacuum chamber geometry, vacuum pressure, and properties of the chamber surface material such as photoelectric quantum efficiency (photoelectric yield) Y, secondary electron yield (SEY) δ and photon reflectivity R [16]. The electron cloud develops quickly following injection of the beam into an empty chamber, with a typical rise-time of tens of bunch passages, and is sustained as long as there is beam in the machine. If there is a gap in the beam, or if the beam is extracted, the cloud dissipates with a falltime that is controlled by the low-energy characteristics of δ and the secondary emission energy spectrum of the chamber surface. For high enough δ, the electron cloud density may grow exponentially in time until the space-charge forces of the electrons suppress further electron production. In this case the average electron density reaches a saturation value comparable to the beam neutralization level. A sample simulation result is given in Fig. 1 [17].

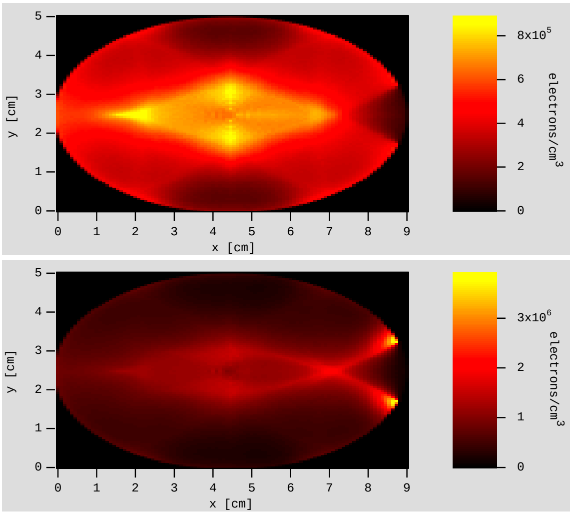

Figure 1: Simulated time-averaged electron density in a field-free region in the arcs of the PEP-II positron ring. Top: $R \simeq 1$. Bottom: $R \simeq 0$. The beam (not shown) goes through the center of the chamber. The low-density region to the right of the chamber is due to the electrons escaping through the antechamber slot.

Consequences The electron cloud couples the transverse motion of successive bunches, potentially leading to a coherent multibunch instability. The range of the effective wake function induced by the electron cloud is typically short (several to tens of bunch spacings), and the resultant coupled-bunch mode spectrum is broadband. For the case of PEP-II [17], the estimated instability growth time is $\tau \lesssim 1$ ms.

BIM has been observed in localized regions of PEP-II [9], KEKB [18], and the SPS [11], this latter when operated with LHC-style beams. The main observation is a strong, local, increase in the vacuum pressure as a function of bunch current. The pressure depends on the current in a nonlinear fashion, exhibits a threshold behavior, and is sensitive to the bunch fill pattern at fixed total current. The ECE can also lead to diagnostic problems owing to an effective shielding of the BPMs [12], and a tune shift along the bunch train that grows towards the tail bunch [19–21]. Single-bunch incoherent effects are also possible. For example, in the case of PEP-II [22], the electron cloud density can increase substantially (by a factor ~ 5) from the head to the tail within a given bunch, even if it is short (~ 1 cm). If the electron cloud density is sufficiently high, this electron density variation leads to performance-degrading effects such as a significant synchrotron tune spread, a head-tail/BBU instability that causes transverse beam blowup [9, 23–26], or particle losses [13].

In the case of the LHC, being a superconducting machine, the main practical effect from the electron cloud will be a substantial power deposition on the walls of the vacuum chamber by the electrons "rattling around" the chamber [15, 16, 27–31]. In the absence of mitigating mechanisms, this power is estimated to be larger than the SR power.

Dedicated electron detectors have been designed and used to measure the time structure, intensity, and energy spectrum of the electrons hitting the walls of the vacuum chamber [32–34]. Other methods to study the ECE include observations of the transverse beam size, frequency spectra, and vacuum pressure.

Mitigating mechanisms A low value of Y is clearly favorable, as the electron cloud density is a monotonically increasing function of Y. One way to reduce Y, that has been proposed for the LHC and tested at EPA [35,36], consists of adding small grooves perpendicular to the beam direction on the outboard side of the vacuum chamber wall, where the photons predominantly hit. The depth and pitch of the grooves are chosen to match the typical incident angle of the photons, effectively resulting in normal photon incidence. This technique effectively reduces electron photoemission by a factor of 2–4, and the photon reflectivity by a factor ~ 10, which is of added benefit.

If SR is significant, and if its critical energy is higher than ~ 4 eV, an antechamber on the outer-radius side of the vacuum chamber is valuable. Typical designs, as in the case of PEP-II [17], allow for most ($\sim 99\%$ of the photons) of the high-energy radiation to escape in order to extract most of the SR power from the chamber. Nevertheless, there is a fraction of low-energy photons that are radiated at wide angles hence cannot escape. These low-energy photons generate photoelectrons more efficiently [37] than high-energy photons (unless their energy is below the work function of the metal), hence the quantitative advantage of an antechamber *vis à vis* the ECE is not a simple linear function of the number of photons it allows to escape from the chamber.

If secondary emission is significant, a low value of δ helps. Although pure Al has a low δ peak value $\lesssim 1$, its surface is normally covered with a layer of Al_2O_3 whose peak $\delta \sim 2.5-3$ is among the highest of all practical metals. For this reason, the chambers in the arcs of the PEP-II positron ring have been coated with a layer of TiN of $\sim$ 1000 Å thick [38]. This coating, once conditioned, has a peak $\delta \sim 1.1$. Other practical metals, such as Cu and stainless steel, have peak $\delta \sim 1.3 - 1.5$ when adequately conditioned. Reducing the peak δ, however, is not enough: the low-energy ($\lesssim 10$ eV) value of δ, and certain details of the emission energy spectrum [39–41], have a significant effect on the survival of the electron cloud during a beam gap. It does not seem apparent how to control such details of the secondary emission process.

Active mechanisms have also been used such as raising the vertical chromaticity above its nominal value, or using octupolar fields [42, 43]. Solenoidal windings have been wrapped around the vacuum chamber of PEP-II and KEKB, covering as much of the field-free regions of the ring as possible [9, 25]. A relatively weak magnetic field (20–30 G) is sufficient to effectively trap the electrons near the vacuum chamber wall, thereby minimizing their effect on the beam. For the LHC, it has been proposed to add "satellite bunches" to the normal bunch fill pattern [44]. These bunches, whose intensity would be $\sim 15-20\%$ of nominal, would gently sweep the leftover electrons during a gap thus promoting their absorption at the walls, and thereby effectively clearing the electron cloud. Elaborate bunch fill patterns, with many gaps of various lengths, have been used at PEP-II [45]. These patterns have the effect of promoting the dissipation of the electron cloud during the passage of the bunch train. At the PSR, which has a single long bunch, it has been found that increasing the momentum spread of the beam increases the instability threshold [13].

Besides the usual accelerator conference proceedings, the following Internet sites contain a large number of ECE-related publications:

http://wwwslap.cern.ch/collective/ecloud02
http://conference.kek.jp/two-stream/
http://www.aps.anl.gov/conferences/icfa/two-stream.html
http://www.aps.anl.gov/asd/physics/ecloud/ecloud.html
http://wwwslap.cern.ch/collective/electron-cloud/electron-cloud.html

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