ELECTRON CLOUD EXPERIMENTS, SIMULATION AND CURE*

H. Fukuma#, KEK, Tsukuba, Japan

Abstract

This paper reviews experiments, simulations and mitigation methods of electron cloud effects. A concise review of electron cloud effects was recently given by K. C. Harkay at EPAC06 [1]. Inevitably, several topics in this report overlap with Ref. 1.

INTRODUCTION

Many electrons stay in accelerators. Primary electrons can be produced by synchrotron radiation, lost particles hitting a chamber wall, or by ionization of the residual gas. If the charge of a beam is positive, the primary electrons receive kicks from the beam toward the center of beam chamber and hit the opposite wall, then secondary electrons are produced. Under some operational conditions of machines rapid growth of the electrons known as beam induced multipacting (BIM) [2] can occur. The primary and secondary electrons form a group of the electrons called the electron cloud (EC) which is built up along a bunch train.

In proton rings with long bunches, a large number of electrons are observed at the tail of the bunch due to a mechanism called "trailing edge multipacting" [3, 4]. Before the center of the bunch passes through the EC, all the electrons, i.e. electrons surviving electrons from the last bunch, electrons emitted at the chamber surface by the beam loss and electrons produced by ionization, are trapped in the bunch, and then released at its tail of the bunch. Electrons emitted at the chamber surface between the bunch centre and the tail are not trapped but hit the opposite surface due to the negative slope of the longitudinal beam density. Then amplification of the electrons can occur towards the tail. Trapped electrons and multipacting electrons together result in the large number electrons at the tail.

The EC causes harmful effects on the accelerator performance as discussed below.

OBSERVATIONS AND EXPERIMENTS

Measurements of Electron Yield

A planar retarded field analyzer (RFA) pioneered at APS is widely used to measure the flux and energy distribution of electrons on the chamber wall [5]. Measurements showed that the energy of electrons hitting the wall is very low, typically less than 10 eV. BIM was observed at APS, where the electron yield abnormally increased at the bunch spacing of seven. The result is consistent with a simulation by POSINST [6].

Time resolved measurement by an RFA at PSR showed numerous electrons generated at the tail of the bunch. The measurement led to the discovery of the trailing edge multipacting [3]. The full number of electrons in the beam chamber was measured by an electron sweeper originally designed at PSR. It consists of an RFA and a pulsed electrode which sweeps electrons into the RFA. A large number of electrons, which is approximately equal to that needed to cause the e-p instability, were found in the bunch gap. The long exponential tail of the decay of the electron yield in the gap implies a relatively high secondary emission yield from low energy electrons of 2-5 eV.

Pressure Rise

Electrons hitting the chamber wall desorb molecules on the wall, thereby causing a pressure rise. The pressure increases non-linearly with the beam current if the BIM occurs. In RHIC the number of bunches of the ion beam is limited to about half of the possible number by dynamic pressure rises caused by the EC [7]. The molecular desorption coefficients (MDC) were studied at RHIC [8]. For unbaked stainless steel and assuming CO, the MDC was 0.05. A conditioning effect on the MDC by the beam was observed.

Emission of Secondary Electrons

One of the most important parameters in EC formation is the secondary emission yield (SEY). The secondary electrons are classified into three categories according to their energy spectrum: true secondary electrons, elastically backscattered electrons and rediffused electrons [9]. The SEY as a function of the primary electron energy has a peak δ_{max}, typically 1.5 - 2, around 200-300 eV. As the secondary emission is a surface dependent phenomenon, the SEY depends on the material and is influenced by the surface preparation [10, 11].

A decrease in δ_{max} by electron bombardment is called scrubbing. Scrubbing has been observed in several laboratory measurements [11, 12] and also in-situ at the CERN SPS [13]. After an electron bombardment of 1mC/mm^2, δ_{max} decreased from 1.5 to 1.1 for TiN and from 1.4 to 1.2 for TiZrV [12]. An electron dose of 1mC/mm^2 seems necessary for δ_{max} to decrease below 1.2. A possible mechanism of the scrubbing called graphitization was found by a laboratory measurement at KEK [14]. As-received copper was irradiated by an electron beam of 5 keV. After the irradiation of electrons (total dose of 1 x 10^{20} e-/cm^2), δ_{max} was reduced from 1.85 to 1.02. It was found that a contaminated layer of carbon was changed to graphite which has a low δ_{max}. A further in-situ measurement of the SEY is underway in the KEKB.

---

*Work supported by JSPS Core University Program.

#hitoshi.fukuma@kek.jp

The SEY at very low energy is important because the energy distribution of the electrons on the wall peaks at very low energy, e.g. below 20 eV for the LHC. At CERN it was found that the SEY approached unity in the limit of zero primary electron energy [15]. A simulation shows that the surface heat load in the LHC is greatly affected by the SEY at low energy [15].

Electron current for a Cu chamber or coated chambers by TiN and NEG material was measured under intense photon irradiation at KEKB [16]. A simulation showed that intense photoelectrons reduce the effect of low SEY on the electron yield. The suppression of the photoelectrons with an antechamber and/or a solenoid is indispensable to make effective use of a low SEY surface.

Instabilities

The transverse coupled bunch instability (CBI) observed at KEK PF in 1995 triggered extensive study of the EC instability [17, 18]. Now instability due to EC is observed in many accelerators.

In BEPC a vertical CBI that can be explained by EC was found in the positron beam after the observation at the PF [19]. The instability was suppressed by increasing the chromaticity. Landau damping is considered to be the main factor of the effect.

In a measurement at KEKB, the mode spectrum of the CBI changed with or without solenoid field, which is a clear evidence of the EC instability [20]. The comparison between the measurement and a simulation shows that 1) with solenoids on, there were no modes which came from the field free region and the dipole region, 2) the lower SEY of 1.0 is favored and 3) the effective solenoid field seems weaker than the nominal field strength, 45 G.

A strong horizontal dipole instability was observed at the positron ring in DAFNE after the long shut down in 2003 [21]. Signatures of the EC effects such as a large positive tune shift and a non-linear pressure rise were observed in the positron ring. The growth time was about 10 μsec which is shorter than the synchrotron period. The unstable mode was -1. Winding solenoids in straight sections did not change the threshold of the instability. The instability is believed to be caused by the EC in the wigglers and the resistive wall impedance.

In RHIC significant EC effects were observed when the bunch spacing was 108 ns [22]. The effects were the fast transverse instability, emittance growth, and beam loss when the beam was accelerated across the transition. The EC effects occurred both in the warm (~30% length) and cold (~70% length) regions.

A beam size blow-up was observed in the positron rings of two B-factories [23, 24]. The blow-up is explained by a single bunch head-tail instability caused by the EC [25]. Multi-bunch operation is necessary to produce the EC. The blow-up was one of the big issues limiting the luminosity at PEPII and still limits the luminosity at KEKB. The blow-up in both rings is greatly suppressed by applying a weak solenoid field in vacuum chambers.

A vertical betatron sideband was found at KEKB [26]. Appearance of the sideband depends on the strength of solenoids and is also associated with loss of luminosity during collision. The threshold where the sideband appears coincides with that of the beam blow-up. The sideband appears to be a signature of the strong head-tail instability due to the EC. The sideband is seen on the upper side of the betatron peak, which suggests that the effective wake function is a focusing wake generated by the pinched EC. Recently simulations by HEADTAIL and PEHTS succeeded in reproducing the sideband when the size of the EC was ten times larger than that of the beam [27].

Betatron Tune Shift

The EC causes a betatron tune shift [28]. The tune shift caused by the EC was observed at several accelerators such as RHIC, DAFNE and KEKB. By measuring the tune shift we can get the information on the density and the lifetime of the EC.

In a recent measurement at KEKB the tune shift of a test bunch which was placed after the end of a bunch train was measured by changing the distance between the train and the test bunch, b_s [29]. The current dependent tune shift (CDTF), defined as the tune shift divided by the bunch current, was positive if b_s was shorter than 10 rf buckets, then changed to the negative if b_s exceeded 10 rf buckets. The change of the sign of the CDTF is not understood yet.

In KEKB when the solenoids were turned on the tune shift by the EC almost disappeared in the horizontal plane but remained in the vertical plane. The reason for the asymmetric contribution of the solenoids is not understood yet [29].

Electron Clouds in Magnets

Spatial and energy distributions of the EC in a dipole were measured by a strip detector originally developed at CERN [30]. The SPS measurement by the strip detector showed two stripes of electrons which had been predicted by the simulation by ECLOUD. The spatial distribution of the EC in a quadrupole measured by the strip detector showed a large electron flux close to the pole tips where the magnetic flux is concentrated [31]. The simulation by CLOUDLAND supports the measurement.

Trapping of the electrons in a quadrupole was found by simulation [32]. It is similar to the plasma trapping in a mirror magnetic field. The trapped electrons could have a long lifetime in train gaps and may affect the bunch coming after the bunch gap.

The electron sweeper was installed in a quadrupole magnet at the PSR. First result showed the long decay time (50-100 μs decay constant) of the EC after beam extraction [33].

At KEK a solenoid of 17 Gauss made of a thin flat cable was installed in 88 quadrupole magnets [34]. If the electrons are generated inside a quadrupole, for example by ionization, the electrons would be trapped and accumulate near the beam. The solenoid may affect the electrons near the beam where the quadrupole field is very weak. In the measurement no clear effect of the solenoids was found on the sideband, the vertical beam size and the luminosity. The strength of the solenoids might be too weak to remove the electrons near the beam if the electrons are there.

The trapping of the electrons in a quadrupole is being studied also at HCX with 1MeV K^+ beam [35].

MODELING AND SIMULATION

Simulation of the EC effects is usually classified into two categories, the EC buildup and the instability calculation. Programs developed [36] are CLOUDLAND, CSEC, ECLOUD, PEI, POSINST etc. for the EC buildup simulation and ECI, HEADTAIL, PEHT, PEHTS, QUICKPIC etc. for the instability simulation. Here as examples, three codes, CLOUDLAND, PEI and PEHTS are briefly described because the author is somewhat familiar with them.

Electron Cloud Buildup

CLOUDLAND [37] consists of 1) generation of electrons, 2) calculation of kick to electrons by the beam, 3) calculation of kicks to electrons by the space charge force of the EC, 4) movement of electrons in the chamber including magnetic field and 5) generation of secondary electrons on the surface of the chamber.

The kick to the electrons by the beam is given by the Bassetti-Erkine formula. A bunch is divided into several pieces, typically 40, to kick the electron, taking into account the electron movement during kicks [38]. While electrons far from the bunch simply receive a kick, electrons near the bunch oscillate in the bunch field. The space charge force of the EC is obtained from the potential which is a solution of Poisson equation solved by the Particle-In-Cell (PIC) method. The secondary electrons are generated by the Furman and Pivi model [9].

Coupled Bunch Instability

In PEI [18, 39] the EC buildup is calculated in a similar way as described in the previous subsection assuming that the motion of the bunch is not affected by the EC. Then the growth rate of the CBI is calculated in two ways: 1) the wake force method and 2) the tracking method. The wake field is calculated by slightly displacing a bunch in the EC then calculating forces from the perturbed EC. The growth rate is obtained from the usual dispersion relation. The method assumes linearity and superposition of the beam-EC force. In the tracking method, the equations of motion are directly solved numerically. This method is time consuming, but the linearity and the superposition of the wake are not assumed any longer. Fourier transform of the amplitudes of all bunches gives a spectrum of unstable modes.

Single Bunch Instability

In PEHTS [40] the bunch and the EC are modeled as a group of macro particles like in the strong-strong model of the beam-beam force. The bunch is divided into slices. A simple kick and drift integrator is used to integrate the motion of particles. The beam-EC kick is calculated from the electric potential with PIC method. An FFT is applied to solve the potential in order to speed up the calculation. The beam-EC kick is evaluated from the potential on the mesh by interpolation.

Code-to-code Benchmarking

Code-to-code benchmarking is done by international collaboration [41]. For the EC buildup at LHC, the simulated saturation densities differ by a factor 3–4 between codes, the buildup time by even more. The differences are largely explained by the modeling of secondary emission. Sufficient knowledge of the in-situ surface properties is important to obtain reliable results in simulation.

Others

Incoherent emittance growth by the EC below the threshold of coherent instability is found at CERN by simulation [42]. Two mechanisms are identified, 1) a beam particle periodically crossing a resonance and 2) a beam particle periodically crossing a region of the bunch where its motion is linearly unstable. While the former leads to formation of halo, the latter leads to beam-core blow-up. Essentials for both processes are synchrotron motion and incoherent tune shift caused by the pinched EC. For 1), protons at large synchrotron amplitude can cross a resonance back and forward by the synchrotron oscillation, which statistically leads to a beam size growth like diffusion. For 2), the tune shift on the beam axis can be so large that the motion becomes linearly unstable.

Combined phenomenon of beam-beam and beam-EC interactions is proposed [43]. The short-range wake forces due to the EC and the beam-beam interaction may couple and cause a combined phenomenon of complex nature. The effect may lower the threshold current of the blow-up by the EC as shown by the simulation.

The EC can be treated as a bunch to bunch evolution using simple maps, $\rho_{m+1}=a\ \rho_m+b\ \rho_m^2+c\ \rho_m^3$, where ρ_m is electron density before bunch m passes and ρ_{m+1} the electron density after bunch m passed by [44]. Coefficients a, b and c are functions of beam parameters, the chamber geometry and the secondary emission characteristics. They are determined by the EC buildup simulation. "a" is also estimated by an analytic method [45]. As the calculation time of the map is very fast, the map can be a useful tool for the survey of the EC evolution in parameter space, which is time consuming in computer simulations.

CURES

Coatings and Scrubbing

Coating of the chamber surface by materials with low SEY is effective to decrease the electron buildup [10, 11, 12, 14]. Typical coating materials are TiN and NEG materials such as TiZrV. Application of NEG coating on a large scale has been effective in reducing the EC in RHIC [46]. The scrubbing helps to decrease the SEY further as described before.

Grooved Surface

A grooved surface effectively lowers the SEY both in field free and the magnetic field regions [47, 48]. In the magnetic field, if the electron hits the edge of the groove the secondary electrons execute gyration then hit the wall with low SEY due to their low energy. If the bunch spacing is longer than gyration period, the number of electrons decreases due to successive secondary emission. A grooved surface is not so effective for beams with long bunch length. A calculation shows that the resistive wall impedance is enhanced by a factor of 1.5 for a rectangular groove with a round fin tip [49]. If the region of the BIM is limited such as two stripe regions in a dipole, the area of the grooved surface can be reduced, which decrease the impedance. According to a laboratory test of a triangular grooved surface at SLAC the effective SEY decreased to 1.1 in a TiN coated chamber [12]. A triangular grooved surface in a dipole will be tested in this year at SLAC.

Solenoid

A weak solenoid confines the electrons near the chamber wall. The solenoid is effective in decreasing the electron density especially near the beam. A typical solenoid field is several 10s Gauss because the energy of the electrons is low. A resonant growth of the electrons, which should be avoided, was predicted [50, 51]. The resonance occurs if half of the cyclotron period is equal to the time interval between two consecutive bunches. For example the magnetic field at resonance is 40 G if the bunch spacing is 4 ns. Solenoids cannot be applied in a strong magnetic field.

Clearing Electrode

An electrode is a candidate for clearing the electrons [52]. Unlike the solenoid, the electrode can work in a strong magnetic field. Two types of electrodes are proposed, the multi-wire electrode and the strip line electrode. The multi-wire electrodes are negatively biased. They push electrons to the wall immediately after the electrons are created on the wall. Required voltage is an order of hundred volt because the electron energy is low, typically 5 eV. As the electrodes are located apart from the wall they reduces the physical aperture of the machine and the impedance by the electrodes may be an issue. The design of this type of electrode is in progress at KEK.

The traditional strip line electrode is positively biased to attract the electrons to it. As the gap between the electrode and the chamber can be narrow the strip line electrode may be better in reducing the impedance than the multi-wire electrode. The size of the electrode can be minimized inside magnets because the high density region of the electrons is limited in space. The installation of the prototype of the strip line electrode in PEPII is being discussed. A strip line electrode was proposed for the LHC dipole magnet [53], where the copper electrode coated with TiZrV would also provide distributed high-throughput pumping. Presently strip line electrodes based on a double-layer enamel coating is considered for the new LHC injectors and the CLIC damping ring [64].

Anti-grazing Ridge

Anti-grazing ridges were tested at RHIC. They can largely prevent the shallow angle incidence of the ions. As a result the desorption and production of positive ions due to beam halos can be reduced [54]. Measurements with a proton beam showed that the anti-grazing ridges significantly improved the vacuum performance.

Active Feedback System

A bunch-by-bunch feedback system is effective in suppressing the CBI [55]. The typical damping time is 0.5ms at KEKB.

The e-p instability for long proton bunch machines differs from other instabilities that have been treated by the feedback systems. A proof-of-principle experiment on the long bunch e-p feedback system is in progress at PSR [56]. The bandwidth of the feedback system is 50 - 250 MHz after the BPM. The damp-grow-damp experiment showed a damping rate of the feedback system of 1.75 x 10^4 sec^{-1}.

IMPACT ON UNDER-CONSTRUCTION AND PLANNED ACCELERATORS

In BEPCII the antechamber with TiN coating is adopted in the arc to reduce the primary and secondary electron yields [57]. According to a simulation, the EC density can be reduced to $1.3\mathrm{x}10^{11}\mathrm{m}^{-3}$ if an antechamber with TiN coating and the photon absorbers at the chamber wall are used. A simulation shows that 1) the threshold electron density of the strong head-tail instability is $9.2\times10^{11}\mathrm{m}^{-3}$ which is higher than the expected electron density and 2) the growth time of the CBI is about 4.3 ms which should be damped by the feedback system.

In J-PARC, a TiN film is coated on the inner surface of the duct in order to reduce secondary electron emission in the 3 GeV RCS, while the SUS chambers of the 50 GeV MR are not coated. Simulation shows that Landau damping due to energy spread will cure the instability here [58]. The EC in quadrupole magnets will be studied in the future [58].

In LHC a concern is the heat load to the cryogenic system by the electrons hitting the wall. If $\delta_{\max}$ exceeds 1.3 the heat load exceeds the available cooling capacity of the beam screen [59, 60]. Beam scrubbing is necessary in order to decrease $\delta_{\max}$ below 1.3. A simulation including rediffused electrons shows that $\delta_{\max}$ must be less than 1.2 [61]. The slow emittance growth described earlier is another potential issue [59].

For the ILC damping ring, simulations show that the EC density near the beam is suppressed below instability threshold if the SEY is less than 1.2 and the solenoids are installed in the drift regions [62]. Several mitigation methods are considered and extensive R&D is planned. In order to study the scrubbing, in-situ measurement of the SEY is planned at PEPII. A rectangular grooved surface in field free region will be tested in PEPII in 2007. A triangular grooved surface and clearing electrodes in a dipole magnet will be fabricated and tested in PEPII in 2007.

SUMMARY

The EC effects have been studied for 40 years. The results contributed to performance improvements of the existing accelerators and to the design of the new accelerators as shown in the recent success of SNS where many EC countermeasures were taken based on design studies [63]. In the author's view the following might be interesting subjects for further study: 1) the slow emittance growth below the threshold of the coherent instability, 2) the density and the distribution of the EC in magnets, 3) the effect of the grooved surface and electrodes on the beam, 4) in-situ measurement of the SEY of technical materials including the scrubbing effect, 5) the active feedback system for a long proton bunch, 6) the understanding of the tune shift caused by the EC and 7) the study of the sideband to obtained the information on the short-range beam-EC interaction.

The author apologizes to those who contributed to the study of the EC but are not mentioned in this report due to a lack of his knowledge.

ACKNOWLEDGMENTS

The author would like to thank J. W. Flanagan, S. Kato, R. Macek, K. Ohmi, M. Pivi, Y. Suetsugu, L. F. Wang and F. Zimmermann for useful comments and information.

REFERENCES

[1] K. C. Harkay, Proc. EPAC2006, 1887 (2006).
[2] O. Gröbner, Proc. PAC1997, 3589 (1998).
[3] R. J. Macek et al., Proc. PAC2001, 688 (2001).
[4] L. Wang et al., PR E 70, 036501 (2004).
[5] K. C. Harkay and R. A. Rosenberg, PRST-AB 6, 34402 (2003).
[6] M. A. Furman et al., Proc. PAC2001, 679 (2001).
[7] W. Fischer, Proc. EPAC2006, 905 (2006).
[8] U. Iriso and W. Fischer, PRST-AB 8, 113201 (2003).
[9] M. A. Furman and M. T. F. Pivi, PRST-AB 5, 124404 (2002).
[10] R. E. Kirby and F. K. King, NIM A 469 (2001) 1.
[11] V. Baglin et al., Proc. EPAC2000, 217 (2000).
[12] F. Le Pimpec et al., NIM A 551 (2005) 187.
[13] J. M. Jimenez et al., Proc. ECLOUD02 17 (2003).
[14] M. Nishiwaki, Thesis, the Graduate Univ. for Advanced Studies, in Japanese (2006).
[15] R. Cimino et al., PRL 93, 14801(2004).
[16] Y. Suetsugu et al., NIM A 554 (2005) 92.
[17] M. Izawa et al., PRL 74, 5044(1995).
[18] K. Ohmi, PRL 75, 1526 (1995).
[19] Z. Y. Guo et al., PRST-AB 5, 124403 (2003).
[20] M. Tobiyama et al., PRST-AB 9, 012801 (2006).
[21] A. Drago et al., DAFNE Technical Note G-67 (2006).
[22] J. Wei et al., Proc. PAC2005, 4087 (2005).
[23] H. Fukuma et al., Proc. EPAC2000, 1122 (2000).
[24] R. L. Holtzapple, SLAC-PUB-9222 (2002).
[25] K. Ohmi and F. Zimmermann, PRL 85, 3821 (2000).
[26] J. W. Flanagan et al., PRL 94, 054801 (2005)
[27] K. Ohmi, talk at ILCDR06 (2006).
[28] K. Ohmi et al., Proc. APAC2001, 445 (2001).
[29] T. Ieiri et al., Proc. EPAC2006, 2101 (2006).
[30] J. M. Jimenez et al., LHC Project Report 634 (2003).
[31] J. M. Jimenez, private communications.
[32] L. F. Wang et al., PR E 66, 36502 (2002).
[33] R. Macek et al., talk at ILCDR06 (2006).
[34] H. Fukuma et al., Proc. EPAC2006, 2901 (2006).
[35] A. Molvik, Proc. HB2006, THAW02 (2006).
[36] See, for example, Proc. ECLOUD02 and ECLOUD04.
[37] L. F. Wang et al., PRST-AB 5, 124402 (2002).
[38] J. S. Berg, LHC Project Note 97 (1997).
[39] S. S. Win et al., PRST-AB 8, 94401 (2005).
[40] K. Ohmi, Proc. PAC2001, 1895 (2001).
[41] E. Benedetto et al., Proc. EPAC2004, 2502 (2004).
[42] E. Benedetto et al., PRL 97, 034801 (2006).
[43] K. Ohmi and A. W. Chao, PRST-AB 5, 101001 (2002).
[44] U. Iriso and S. Peggs, PRST-AB 9, 71002 (2006).
[45] U. Iriso and S. Peggs, Proc. EPAC2006, 357 (2006).
[46] S. Y. Zhang et al., Proc. EPAC06 595 (2006).
[47] G. Stupakov and M. Pivi, Proc. ECLOUD'04, 139 (2004).
[48] L. Wang et al., SLAC-PUB-12001 (2006).
[49] K. Bane and G. Stupakov et al., Proc. EPAC2006, 2961 (2006).
[50] S. Novokhatski and J. Seeman, Proc. PAC2003, 315 (2003).
[51] Y. Cai et al., PRST-AB 7, 24402 (2004).
[52] L. F. Wang et al., Proc. EPAC2006, 1489 (2006).
[53] P. McIntyre and A. Sattarov, Proc. PAC2005, 2971 (2005).
[54] S. Y. Zhang et al., PRST-AB 8, 123201 (2005).
[55] M. Tobiyama and E. Kikutani, PRST-AB 3, 012801 (2000).
[56] R. Macek et al., Proc. HB2006, TUAX04 (2006).
[57] J. Q. Wang et al., Proc. EPAC2004, 2131 (2004).
[58] K. Ohmi and T. Toyama, Proc. HB2006, THAW06 (2006).
[59] F. Zimmermann, "LHC electron-cloud update", LHC MAC, June, 2005.
[60] O. Brüning, Proc. EPAC06, 14 (2006).
[61] M. A. Furman and V. H. Chaplin, PRST-AB 9, 034403 (2006).
[62] M. Pivi, talk at Proc. ILCDR06 (2006).
[63] N. Holtkamp, Proc. EPAC06, 29 (2006).
[64] http://care-hhh.web.cern.ch/CARE-HHH/ECL2/