OBSERVATION AND MODELING OF ELECTRON CLOUD INSTABILITY*

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Abstract

This paper will review experimental results and the state of the art in the analysis and simulation of the electron cloud instability in hadron and positron storage rings.

INTRODUCTION

After more than a decade of intensive study, electron cloud effects and instabilities continues to be an active topic, and the development and implementation of cures remain very important for modern, high-performance accelerators. Over the past three years, over 20 papers have been published in Phys. Rev. ST – Accel. Beams and Phys. Rev. Letters. If we include recent accelerator conferences and workshops, there have been well over a hundred papers presented. In this conference alone, 23 abstracts explicitly mention electron cloud. There are now many experts in the field in the areas of experimental measurements, modeling, surface science, and theory.

First Observations

The early history of the first observations of electron cloud (EC) effects in coasting and bunched proton beams extends back 30-40 years and has been discussed elsewhere [1,2]. At that time, however, the focus was on quickly stabilizing the beams and not on extensive academic study. A systematic program of experimental study began when similar observations were made at the Proton Storage Ring (PSR) at LANL around 1988. The first observations in positron rings were made ~1989 when transverse multibunch collective instabilities were observed in the KEK Photon Factory (PF), IHEP Beijing e+e– collider (BEPC), and later, ~1997, in the Cornell CESR collider. Transverse single-bunch instabilities attributed to electron clouds were first observed in positron rings at the KEKB and SLAC PEP-II B factories in the 1999-2000 timeframe. A review of these single-bunch instabilities can be found in [2]. Finally, the first *in situ* measurements of the EC distribution under beam-induced multipacting conditions using dedicated electron detectors based on the retarding field analyzer (RFA) [3] were made at the Advanced Photon Source (APS) at ANL in 1997-99 [4] and at the PSR in 2000 [5].

The story of the PSR instability is illustrative of the inherent complexities in characterizing electron cloud effects. Experimental observations of a vertical instability accompanied by beam loss were reported first (~1988). These data were consistent with the electron-proton (e-p) two-stream instability. However, the sources of the high numbers of electrons required to cause the instability could not be accounted for. The instability was correlated with a vacuum pressure rise, which implied that ionization electrons were important, but deliberately increasing the pressure did not change the instability threshold. It was postulated that in order to accumulate, electrons must be trapped by beam leakage into the gap between bunch passages; however, careful measurements failed to show clear evidence of this. Many remained unconvinced of the nature of this instability until the electron cloud was measured in 2000 with an RFA and RFA sweeper. These data led to a new understanding of electron cloud amplification in a long proton bunch, a mechanism that was coined "trailing edge multipactor" by R. Macek. All the electrons in the chamber are trapped when the head of the bunch passes. At the peak of the bunch, beam losses on the walls produce secondary electrons that are accelerated by the beam. Because the line charge density decreases towards the tail of the bunch, these secondaries experience a net energy gain as they oscillate in the beam potential. Collisions with the walls produce tertiary electrons, and so on. Very low-energy electrons have a very long survival time due to reflections at the walls. The secondary electron yield coefficient δ for low-energy electrons turned out to be finite: $\delta_0 \approx 0.5$-1, and was measured at CERN [6] and SLAC [7]. New observations continue at PSR, raising more questions; for example, the "first turn" instability that has a lower instability threshold compared to following pulses. This is thought to be related to the increased electron emission from the H^- injection stripper foil [8].

Modeling Development

Returning to 1995, both KEKB and PEP-II B factories were under development and became concerned about EC effects. Calculated predictions of a multipacting resonance in LHC, also under development, resulted in a crash experimental program at CERN to study EC effects. As a result, computer models were developed. The first-generation codes were 2D analytical or PIC codes that modeled the EC generation and instabilities (Furman, Ohmi, Zimmermann). A detailed semi-empirical secondary electron emission model was developed by Furman and Pivi that has since become a standard in many newer codes [9]. Later, second-generation 2D/3D codes were developed for more realistic modeling of positron, proton, and heavy ion beams. A comprehensive compilation and comparison of the features of the many EC codes was made by A. Adelmann [10]. An extensive benchmarking study was launched after ECLOUD02, led by F. Zimmermann. A standard set of beam parameters similar to the LHC parameters was used to model EC buildup and single-bunch instabilities. The results from the various codes vary by 3 – 100, and the reasons for these variations are under detailed review. A summary of the benchmarking studies can be found in [11].

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Modern Study

Electron cloud effects have been very difficult to predict. Surface science is complex for technical materials (as compared to single crystals) and the accelerator environment where secondary emission properties change under photon and electron bombardment. Low-energy electrons are notoriously difficult to characterize, and precise characterization of the EC distribution is limited by experimental uncertainties. Most advances have occurred when modeling is benchmarked against detailed measured data, especially when the experiments are designed to provide realistic limits on code input parameters. Notable examples include:

- APS and PSR vs. POSINST
- High Current Experiment (HCX) at LBNL vs. WARP/POSINST
- SPS (LHC) vs. ECLOUD/HEADTAIL
- KEKB vs. PEHT/PEHTS
- RHIC vs. CSEC, ECLOUD, maps

EC studies and cures resulting from these efforts have benefited many existing machines and those under commissioning or design: e.g., LHC, SNS at ORNL, JPARC at KEK, and International Linear Collider (ILC).

In the following sections, we highlight recent experimental results and the state of the art in the analysis and simulation of the electron cloud instability in hadron and positron storage rings. Space limitations prevent a discussion of all the excellent results. The reader is invited to read the many excellent reviews and papers presented at conferences and topical workshops [12].

EC GENERATION, AMPLIFICATION

The various contributions to the electron cloud production and distribution are detailed in [9]. The dominant source of EC can vary depending on the details of the vacuum chamber. Photoemission alone can be dominant if there is no antechamber (e.g., KEKB, PF, BEPC). Beam-induced multipacting can lead to large amplification if $\delta > 1$ (e.g., PEP-II, APS). A comparison of EC buildup at APS and BEPC can be found in [13]. Secondary emission under electron collisions has been characterized to a large degree [9]. For high-intensity proton and ion beams, secondary emission due to beam losses that collide with the walls at grazing incidence is an important EC source and is not well characterized. Electron or beam-stimulated molecular desorption plays an important role in the vacuum pressure rise observed (e.g., PEP-II, APS, SPS), in some cases leading to a runaway effect (e.g., RHIC). These surface effects are discussed in more detail in the next section. Electron cloud trapping in magnetic fields (dipoles, quadrupoles, ion pump fringe field, etc) can produce dense, localized EC distributions that can cause instabilities; new results are discussed in a later section.

Generalized Multipacting Condition

A more detailed picture of multipacting, the most important EC amplification process, has emerged recently. We already outlined trailing edge multipacting in long proton bunches. In short bunches, the first description was a cold electron model: a resonance can occur if a cold electron generated at the wall and accelerated by the beam (approximated by an impulse kick) traversed the chamber and struck the opposite wall at the time of the next bunch passage [14]. If the energy of the electron is near the peak of the δ curve, amplification can occur. The multipacting condition is now understood to be modified in several ways. First, when the bunches are more closely spaced, the secondaries can receive several kicks before reaching the wall (Zimmermann, Ruggiero). Second, the secondaries in fact drift from the wall because they are created with a characteristic distribution; this modifies the resonance condition (Furman, Heifets). The true secondary electron distribution peaks between 1-3 eV, independent of the material. There are also elastically scattered and inelastically scattered ("rediffused") components that are highly variable and material-dependent. In benchmarking the POSINST code with APS data, assumptions about the secondary electron distribution was essential in reproducing the observed multipacting resonance at 7 rf bucket spacing (20 ns). The cold electron model predicted 4-bucket spacing. Furthermore, the width of the resonance peak was very sensitive to assumptions of the rediffused component [4,15]. A similar sensitivity study was carried out for RHIC with a very similar conclusion [16]. If one considers a range of secondary energies 1-3 eV and a range of δ values near the peak, a set of resonances can be determined, and the density of solutions can determine the bunch spacing for the highest amplification (e.g., APS [15]). Similar calculations were carried out by Wang for RHIC, KEKB, SNS, and the "random" multipacting resonance predicted by the model and resulting energy distribution at the chamber wall compares well with RFA data [17].

SURFACE SCIENCE

Beam losses on the walls, including designed losses at collimators, occur at grazing incidence (mrad or less). Molecules liberated due to proton or ion-stimulated desorption can become ionized by the beam and significantly increase the EC lifetime and amplification, a process believed important at RHIC. Ion-stimulated molecular desorption rates vary between 10 – 1e7, averaging around 1e5, for grazing incidence. There is large systematic variation in such data (orders of magnitude), and better understanding of the underlying surface chemistry/physics is needed. A program of systematic measurements is underway at a number of institutions to improve the results: CERN, GSI, BNL, HCX [18,19]. Despite the large ion desorption coefficient, the vacuum runaway at RHIC is dominated by electron-impact gas desorption. This was measured to be 0.05 (0.01 after scrubbing) [20]. The secondary electron yield coefficient of proton impact can be larger than 100 at grazing incidence [18]; this may contribute to significant electron cloud trapping in quadrupoles at PSR.

CURES

The importance of developing cures against EC cannot be over emphasized. There has been much advance beyond the early cures of TiN coating and use of solenoids to confine the EC near the chamber walls. There is an international R&D effort among several institutions, (SLAC, KEK, CERN, LANL, and Frascati) to study the use of coatings, grooves, and antigrazing surfaces. A summary of this effort can be found in [21].

Grooves, Antigrazing Surfaces

Perhaps the most exciting development is the success of rectangular grooved surfaces proposed by Stupakov [22] in significantly reducing δ. Measurements at SLAC show that the peak δ can be reduced from 1.65 (ungrooved) to <0.9 (grooved) for Cu. More importantly, according to simulations, the grooves are potentially effective in a dipole B-field where solenoids are ineffective [21]. Such a grooved chamber is to be installed in PEP-II for tests. Antigrazing surfaces have been designed for LHC to reduce the photoemission rate from grazing incident photons. Antigrazing surfaces have also been tested in RHIC to reduce the beam-stimulated molecular desorption (discussed above). The data show that the vacuum pressure rise is reduced by over an order of magnitude at the location of the newly designed collimator [23].

Coatings

Advances have also been made in improved coatings and understanding why they are effective. TiN coatings produced under high pressure have ridges and are more effective in reducing δ [18]. Non-evaporative getter (NEG) coatings have also been extensively studied; in addition to adsorbing gas, the surface roughness helps reduce δ by 30-50% [18]. The electron emission for 1-MeV K+ ions was measured for smooth surfaces vs. those treated by dust or bead blasting. At small incidence angles, the emission reduction is several orders of magnitude. The ion range must be much smaller than the roughness, otherwise the emission can increase [24]. The effectiveness of surface roughness can be understood as follows, analyzing a micrograph of the RHIC chamber (roughness ~10 μm): the ion collision with mrad incidence makes many material/vacuum transitions [25].

E-p Feedback

In addition to passive measures, active feedback (FB) is a possible cure for EC-induced instabilities. The e-p instability signature is sufficiently different from the usual case that tests were undertaken at PSR in a multi-institution collaboration: SNS, LBNL, Indiana U., and SLAC. The instability threshold was observed to increase by 20-25% with the prototype feedback system. The feedback system was turned off during accumulation and store, then turned back on to characterize the growth rates. The first phase e-p growth rate was 1.03×104 s^{-1}. The FB damping rate was computed to be 1.75×104 s^{-1}. A second phase, faster e-p growth rate occurred during this test with a growth rate of 3.35×104 s^{-1}. Beam in the gap may be responsible for the second-phase instability in initial analysis [26].

ACTIVE STUDY

Trapping in Quadrupoles

At the PSR and HCX, large beta functions in quads results in high beam loss (halo) at the quads, and the electrons produced can become trapped in the mirror field. An RFA electron sweeper has been designed for the quadrupoles [27], and tests are planned at PSR later this year. Self-consistent 3D modeling was carried out for electron trapping in the quads in HCX using WARP/POSINST, and the results compare well with measurements [28].

At KEKB, a single-bunch blowup is observed when the average bunch spacing is reduced to 3.27 buckets. It is postulated that the responsible electrons are trapped in the quads. They are studying the effect of installing solenoids at the quads to test this theory [29].

Strategically placed clearing electrodes have been proposed as a cure for electrons trapped in the quads [30].

LHC Heat Deposition

New calculations have been carried out for the EC power deposition on the LHC cold dipole sections. The predicted power deposition could be 2× larger than earlier predictions, and again demonstrates the strong sensitivity of the computations to assumptions about the EC distribution [31].

Maps

3D modeling is computationally expensive. Such codes can predict second-order transitions (smooth EC and vacuum growth), but cannot model first-order transitions, e.g., vacuum pressure runaway in RHIC – physics is missing. Iriso and Peggs proposed a simple analysis based on maps. Maps can predict first-order transitions and identify good bunch patterns in RHIC in a fraction of computation time [32]. The premise is as follows: For a given surface, for the EC buildup the only thing changing between the bunch m and bunch $m+1$ is the density, ρ_m and ρ_{m+1}. A plot of the data shows that ρ can be represented by a polynomial function whose coefficients incorporate all the surface and bunch-charge details. The map results compare well with RHIC data and with CSEC and ECLOUD. Maps have also been applied to LHC [33].

NEW OBSERVATIONS

Single-Bunch Effects

- *KEKB:* A coherent EC-driven single-bunch instability has been observed that is similar to the fast head-tail instability. Recently, $\nu_\beta + a\nu_s$ sidebands have been observed due to EC, where ν_β and ν_s are the betatron and synchrotron tunes, respectively, and $1 < a < 2$. Modeling reproduces the measured sidebands qualitatively, and the quantitative differences are under study [34,35].

- *LHC:* Modeling predicts an incoherent single-bunch instability that results in the beam size blowing up. This blowup is potentially a more serious concern than the EC-induced heat load in so far as the blowup reduces the specific luminosity. The slow blowup is believed to be due to periodic resonance crossing or periodic linear instability threshold crossing, and in the simulations can be affected by the working point. Measurements carried out in the SPS show some confirmation with the modeling predictions: changing the working point changed the rate of emittance growth and beam losses [36].

Others

- *SNS:* Extensive modeling of the SNS based on the PSR experience led to incorporating a number of EC control measures. These include TiN coating, electron catcher and clearing electrode near the H^- stripper foil, solenoids near high-loss regions, and electron detectors. These efforts to control the EC have paid off. Early commissioning results show no e-p instabilities in bunched beam up to almost 6e13 ppp. EC instabilities were observed in coasting beam and low chromaticity at 1e14 ppp. From these data, the estimated EC impedance is very large: 2 MΩ/m. [37].
- *FNAL:* There is some evidence that EC effects have been observed in a number of rings. A dynamic pressure rise was observed in the Main Injector, and simulations show an instability threshold just above the operating intensity. In the Booster, the real impedance based on beam measurements is 5-10× higher than expected, and accumulation of an EC could possibly explain the discrepancy. An ion-electron two-stream instability has been observed in other electron coolers. In the Recycler, the emittance is sensitive to the working point and coupling, which may be consistent with this instability [38].
- *Intense Pulsed Neutron Source (IPNS) at ANL:* Recent measurements carried out on the 450-MeV rapid cycling synchrotron show an instability whose signature is very similar to the e-p instability in the PSR – a broad spectrum that shifts and transverse oscillations that move from tail to head. An RFA is installed and analyses of these data are ongoing [39].
- *CESRc:* The collider is to be converted into a test bed for the ILC damping ring [40], and EC study is a priority for the positron ring. There may be some indication that EC effects have been observed in the present ring, which has strong damping wigglers, and there are plans to experimentally study the EC.

SUMMARY

Electron cloud effects remain very important in high-performance rings, and new observations continue to surprise us. There has been much progress on cures for positron rings. Recently, there has been increased focus on developing improved cures for proton and ion beams. Surface science is highly complex, particularly relating to secondary emission and molecular desorption. Benchmarking of models against measured data is absolutely critical to advance our understanding. Diagnostics in use include RFA and variations (APS, PSR, SPS, KEKB, etc.), the GESD and gridded electron collector (HCX), and other beam diagnostics: beam size, spectra, centroid motion, tune shift, etc. The modeling effort is driving towards massively parallel 3D calculations with as much physics included as possible, and comparisons between the modeling and measurements is improving. However, simplified models also hold promise in lending insight and predictive capability: e.g., maps, multipacting, and impedance. Much work has been done in studying EC effects over the past several years in particular, and this review only touches the surface. The next workshop, ECLOUD07, is planned in early 2007 in Asia, and is being organized by K. Ohmi and H. Fukuma (KEK), and E-S. Kim (PAL).

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REFERENCES

[1] V. Dudnikov, Proc. 2001 PAC, 1892 (2001).
[2] F. Zimmermann, PRST-AB 7, 124801 (2004).
[3] R.A. Rosenberg and K.C. Harkay, NIM A 453, 507 (2000).
[4] K.C. Harkay and R.A. Rosenberg, PRST-AB 6, 034402 (2003).
[5] R. J. Macek et al., Proc. 2001 PAC, 671 (2001).
[6] V. Baglin et al., CERN-LHC-Project-Report-472 (2001).
[7] R. Kirby and F. King, NIM A 469, 1 (2001).
[8] R. Macek, Proc. ICFA High Brightness Hadron Beams Workshop, KEK/JAEA (2006).
[9] M.A. Furman and M.T.F. Pivi, PRST-AB 5, 124404 (2002).
[10] A. Adelmann et al., Proc. ECLOUD04 (see talk).
[11] E. Benedetto et al., Proc. 2004 EPAC, 2502; see also F. Zimmermann, Ref. [8], code benchmark session.
[12] **Review talks at Accelerator Conferences:** J.T. Rogers (PAC97), F. Ruggiero (EPAC98), K. Harkay (PAC99), F. Zimmermann, K. Harkay (PAC01), G.

Arduini, F. Zimmermann (EPAC02), M. Furman, M. Blaskiewicz (PAC03), M. Pivi, L. Wang (PAC05)**;** **(**http://www.jacow.org); **ICFA BD Newsletter No. 33, Apr. 2004:** special edition on Electron Cloud Effects in Accelerators **(**http://www-bd.fnal.gov/icfabd); **Workshops, past:** ***Multibunch Instabilities Workshop***, KEK, 1997 KEK Proc. 97-17; ***Two-Stream ICFA Mini Workshop***, Santa Fe, 2000 (http://www.aps.anl.gov/conferences/icfa/two-stream.html); ***Two-Stream Workshop***, KEK, 2001 (http://conference.kek.jp/two-stream/); ***ECLOUD02***, CERN, 2002 (http://slap.cern.ch/collective/ecloud02); ***Pressure Rise Workshop***, RHIC/BNL, Dec. 2003 (http://www.agsrhichome.bnl.gov/AP/PressureRise/Page1.htm); ***ICFA ECLOUD04***, Napa, CA, Apr. 2004 (http://www.cern.ch/icfa-ecloud04/); ***ICFA High Brightness Hadron Beams***, KEK/JAEA, May 2006 (ftp://ftp.kek.jp/kek/abci/ICFA-HB2006).

[13] K. Harkay et al., Proc. 2001 PAC, 671 (2001).

[14] O. Gröbner, Proc. 10th HEAC, Protvino, 277 (1977).

[15] K. Harkay, et al., Proc. 2003 PAC, 3183 (2003); ICFA BD Newsletter 33 (2004).

[16] U. Iriso, MOPCH135, these proceedings.

[17] F. Wang, A. Chao, H. Fukuma, Proc. ECLOUD04 (2004).

[18] S.Y. Zhang, T. Roser, Pressure-Rise Workshop Summary (Ref. [12]).

[19] M. Kireeff Covo et al., PRST-AB 9, 063201 (2006); U. Iriso and W. Fischer, PRST-AB 8, 113201 (2005); E. Mahner et al., PRST-AB 8, 053201 (2005) and PRST-AB 6, 013201 (2003); P. Thieberger et al., PRST-AB 7, 093201 (2004) and PRA 61, 042901 (2000).

[20] U. Iriso, W. Fischer, MOPCH134, these proceedings.

[21] M. Pivi et al., Proc. 2005 PAC, 24 (2005).

[22] G. Stupakov, Proc. ECLOUD04, Ref. [12].

[23] S.Y. Zhang et al., PRST-AB 8, 123201 (2005).

[24] A.W. Molvik et al., PRST-AB 7 093202 (2004).

[25] P. Thieberger et al., PRST-AB 7, 093201 (2004).

[26] R. Macek, Proc. HB2006; C. Deibele, THPCH13, these proceedings.

[27] R. Macek et al., Proc. ECLOUD04 (Ref [12]).

[28] J-L Vay et al., Proc. HB2006; Proc. 2005 PAC, 525 and 1479 (2005).

[29] H. Fukuma et al., THPCH051, these proceedings.

[30] L. Wang, H. Fukuma, et al., MOPLS143, these proceedings.

[31] M. Furman and V. Chaplin, PRST-AB 9, 034403 (2006).

[32] U. Iriso, S. Peggs, PRST-AB 8, 024403 (2005); Proc ECLOU04; MOPCH132, MOPCH133, these proceedings.

[33] T. Demma et al., THPCH047, these proceedings.

[34] J. Flanagan et al., PRL 94, 054801 (2005).

[35] K. Ohmi et al., Proc. HB2006 (Ref. [12]); and THPCH050, these proceedings.

[36] E. Benedetto et al., PRST-AB 8, 124402 (2005); Proc. 2005 PAC, 387 and 1344; and THPCH018, these proceedings.

[37] V. Danilov, S. Cousineau, Proc. HB2006 (Ref. [12]).

[38] See separate contributions by R. Zwaska V. Lebedev, and A. Burov, in Proc. HB2006 (Ref. [12]).

[39] G.E. McMichael et al., MOPCH126, these proceedings.

[40] M. Palmer, MOPLS141, these proceedings.