Title

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Summary: Electron-Cloud Effects and Fast-Ion Instability*

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Abstract

This is my summary of the talks on the electron-cloud effect and the fast-ion instability that were presented at the *8th ICFA Beam Dynamics Mini-Workshop on Two-Stream Instabilities in Particle Accelerators and Storage Rings*, Santa Fe, NM, February 16–18, 2000.

1 Talks.

For the purposes of this summary, I have divided the talks into three groups, listed below along with speaker names and titles:

- § Electron-cloud effects and two-stream instabilities at electron, positron rings and photon sources:
  - K. Harkay: "Perspective on electron-cloud effects"
  - H. Fukuma: "Experiment on photoelectron instability at BEPC and KEKB"
  - S. Heifets: "Observation of the beam-induced multipacting at PEP-II"
  - R. Rosenberg: "Electron detectors for diagnostics of electron-cloud effects"
  - K. Harkay: "Electron-cloud effects at APS"
- § Electron-cloud effects and two-stream instabilities at high-energy proton rings:
  - G. Arduini: "Observations of the electron-cloud effects at the CERN SPS"
  - F. Zimmermann: "Simulations for LHC and SPS"
  - O. Gröbner: "Implications of the electron-cloud effect on the design of the LHC vacuum system"
  - M. Pivi: "Laboratory system to simulate bunch-induced multipacting"
  - F. Zimmermann: "Short summary of the electron-cloud session at the recent Chamonix workshop"
- § Fast beam-ion instability:
  - T. Raubenheimer: "Fast beam-ion instability: simulations and results from the ALS"
  - G. Stupakov: "Effects of tune spread on fast ion instability"
  - J. Y. Huang: "Observations of the fast ion instability at PAL and KEKB"
  - C. Tschalaer: "Beam-ion oscillations at MIT-Bates"
  - S. Heifets: "Smooth theory of ion trapping"

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2 Electron-cloud effect.

The electron-cloud effect (ECE) pertains primarily to positively-charged beams, typically positrons and protons. The effects are, in general, a function of a combination of beam and vacuum chamber parameters, chiefly bunch length, charge, and spacing, and vacuum chamber geometry and electronic surface properties. For electron and positron rings of current interest (PEP-II, KEKB, PF, BEPC, DAFNE, APS), where this effect has been (or is expected to be) observed, the bunch length is $\sigma_z \sim 1$ cm, bunch spacing is $s_B \sim 0.5-2$ m and the bunch population is $N \sim 10^9 - 10^{11}$. For proton machines (SPS and LHC), these parameters are $\sigma_z \sim 8$ cm, $s_B \sim 7.5$ m and $N \sim 10^{11}$. The vacuum chamber transverse radius for either type of machine is in the range $\sim 1-5$ cm and the average transverse rms beam size is in the range $\sigma_t \sim 0.1-1$ mm. The beam energy is also relevant, and is typically large, with $\gamma \sim$ (a few) $\times 10^3$, the low end being $\gamma \sim 30$ for the SPS. The PSR is in a different parameter regime, with long bunch length ($\sigma_z \sim 60$ m), high bunch population ($N \sim 4 \times 10^{13}$) and low beam energy ($\gamma = 1.85$).

For the above-mentioned lepton machines, and for the LHC, the beam is accompanied by photons generated by synchrotron radiation from the bending magnets. These electrons strike the walls of the vacuum chamber, generating photoelectrons with a yield Y. These electrons are kicked by the beam and may strike the vacuum chamber, generating, in turn, secondary electrons with a secondary emission yield δ. For lower-energy proton machines (SPS, ISR) there is no synchrotron radiation, but electrons can be generated by beam-ionization of the residual gas. In any case, the beam is thus accompanied by an electron cloud in the vacuum chamber. The secondary emission process can have a "multiplier effect" that may lead to runaway growth in the electron cloud density. The quantity that controls this growth is the effective yield, δ_{eff}, which is the convolution of the energy spectrum of the electrons hitting the wall with the energy dependence of δ. If $\delta_{\text{eff}} < 1$, the wall acts as a net electron absorber, moderating the electron cloud. If, on the other hand, $\delta_{\text{eff}} > 1$, there is a runaway condition which terminates only when the space-charge forces from the electron cloud are so intense that further electron emission is suppressed. This equilibrium is reached when the electron-cloud density is comparable to the beam neutralization level.

The intensity as well as the energy spectrum of the electrons hitting the walls can now be measured with the electron detectors developed at the ANL (Rosenberg, Harkay). Recent measurements at the PSR show an exponentially decreasing spectrum up to 250 eV (Browman). It would be interesting to extend the energy-spectrum measurements to higher energies and to compute δ_{eff} from these measurements. These new electron detectors are an important instrumentation advance in the field and hold the promise for a more detailed understanding of the PSR instability and the ECE in general.

Perhaps the most obvious ECE is beam-induced multipacting (BIM). It was first observed in a special-purpose section of aluminum vacuum chamber installed at the ISR when this machine was operated in bunched-beam mode in 1977 (Gröbner, Zotter). BIM requires two conditions: (1) $\delta_{\text{eff}} > 1$, and (2) a resonance condition involving the bunch current, bunch spacing and chamber radius. This condition defines a current threshold. Recently BIM has been observed at the SPS at 28 GeV when testing LHC-style beams (Arduini). The BIM threshold condition is in good agreement with the observations, as it was in the past for the ISR. The main consequence of BIM is a nonlinear pressure rise as a function of current, and this effect is sensitive to the bunch structure of the beam at fixed total current. The BIM resonance condition admits higher-order resonances that lead to weaker forms of BIM. As an example of this, PEP-II shows evidence of BIM in certain localized regions in the straight sections that manifests itself in a nonlinear pressure rise as the beam current is increased beyond a certain value (Heifets). Although at present this BIM does not imply operational difficulties at PEP-II, a weak solenoidal magnet has been wrapped around one of the straight sections in order to suppress it. Simulation programs (Zimmermann) for the ECE do include the energy dependence of δ as well as the electron-cloud dynamics and kinematics, hence all these resonance effects are imbedded in the codes. For the case of PEP-II, early simulations of the ECE showed that BIM would be a serious effect if the vacuum chamber, which is made of aluminum, were left uncoated. The simulations also showed that a TiN coating would significantly ameliorate the effect owing to the reduced value of δ.

Measurements of the intensity of the electrons hitting the walls of the chamber have been carried out at the APS for some time now, both with electron and positron beams, using the electron detectors developed at ANL (Harkay, Rosenberg). The electron current has been measured at various places in the ring for various bunch fill patterns and beam currents. A present challenge for the simulations is to explain these results, particularly an enhancement seen at a bunch spacing of 7 RF wavelengths.

Besides BIM, the ECE can also lead to beam instabilities. A dipole instability first observed at the PF at KEK five years ago has been qualitatively reproduced at BEPC (Fukuma). Simulations are in qualitative agreement with observations. Recently, the KEKB positron beam has exhibited beam blowup as a function of current in the absence of beam-beam collisions. Presumably, this effect is due to trapped electrons (a possible dipole instability was controlled with chromaticity and feedback). The bunches show vertical beam blowup along the train, together with a tune shift along the train. The beam blowup is a decreasing function of bunch spacing. A large number of weak permanent magnets have been installed on the outboard side of the vacuum chamber downstream of the dipole bending magnets in order to suppress the photoelectrons. Two types of magnets have been tried, but the results, although qualitatively beneficial, have been quantitatively minor (Fukuma). Two explanations have been advanced for the weakness of this effect: (1) the surface reflectivity of the chamber might be high, leading to a redistribution of the photons downstream of the point of first strike. This would lead to a distributed, rather than localized, photoelectron emission; and (2) the photoelectrons may be sufficiently energetic that they escape the confinement provided by the magnets. This beam blowup appears at present to be an important limitation on the luminosity performance of KEKB. Calculations of the beam blowup, which are similar to those for the single-bunch FII effect, are consistent with observations (Zimmermann).

A third cause for concern from the ECE is the power deposition on the vacuum chamber walls by the electrons "rattling around" the chamber. This effect is only important for superconducting machines owing to the load it imposes on the cryogenic system, and is presently a significant issue for the design of the LHC vacuum chamber (Gröbner). A "crash program" was launched at CERN some three years ago to investigate theoretically and experimentally the ECE at the LHC. In this case, the bunch spacing (25 ns) is larger by a factor of 5-6 than the typical traversal time of the electrons across the chamber. Most photoelectrons cross the chamber at relatively low energy and are absorbed at the opposite wall before the next bunch comes by. However, a few very low energy electrons remain in the chamber and receive a large kick from successive bunches, hitting the wall at relative high energy and contributing substantially to the power deposition. In addition, these high-energy electrons can lead to significant secondary production. There is a critical value of the peak value of δ ($\hat{\delta}$) beyond which the power deposition rises steeply. This value has been estimated to be $\delta_{\rm crit} \sim 1.3$ (Zimmermann). It is therefore desirable to have $\hat{\delta} < 1.3$. In addition, the power deposition is proportional to the photoelectric yield Y, hence one wants to have Y as low as possible. Furthermore, the photon reflectivity R enters the power deposition in a more indirect way, and it is also desirable to have $R \sim 0$. One way to reduce Y and R is to change the geometrical properties of the copper surface of the beam screen by creating grooves on the horizontal "edges" of the pipe perpendicular to the beam direction. These grooves are more efficient at intercepting photons than a smooth surface. Experiments at the EPA electron ring have shown that this "ribbed surface" reduces R by a factor ~ 10 and Y by a factor $2-4$ relative to the smooth-surface values. As part of the crash program, standing wave tubes have been used to mock the effects of BIM on the vacuum chamber. Results are in good agreement with simulations for this apparatus, and various surface conditioning effects on the secondary electron yield have been investigated. One promising surface material is TiVZr (Pivi, Hilleret). Overall, the CERN crash program has made excellent progress in identifying and measuring the essential parameters relevant to the ECE at the LHC, and in evaluating possible cures.

Simulation studies over the past few years suggest that the three machines LHC, PEP-II and KEKB have somewhat different parameter sensitivities *vis-à-vis* the ECE. In the case of the LHC, all three parameters Y, R and δ are important, and it is of interest to reduce all three. For the PEP-II positron ring, R turns out to be not very important, while Y has been, in effect, reduced substantially in the arcs by the existence of an antechamber slot that allows $\sim 99\%$ of the photons to escape. On the other hand, δ is important as the natural value of δ is quite large for aluminum. Early simulations showed that coating the chamber with TiN would substantially improve the situation, and such a decision was consequently adopted. For KEKB, the chamber is made of copper with cylindrical cross-section without antechamber. Photoelectric production is significant, and simulations show that the photoelectrons typically take a relatively long time (tens of bunch passages) to traverse the chamber. Secondary electron production is not important owing to the low average energy of the electrons hitting the walls. Thus most of the electrons are photoelectrons, and tend to accumulate near the center of the chamber, leading to an enhanced sensitivity of the beam dynamics to the electron cloud. It appears that an approach similar to the LHC ribbed surface would be beneficial to KEKB, owing to the reduction of both R and Y. In addition, if R could be made small, then presumably the above-mentioned permanent magnet scheme (Fukuma) would be of additional benefit.

3 Fast-ion instability.

The fast-ion instability (FII) pertains to negatively-charged beams, typically electrons. T. Raubenheimer reviewed the theory and the linear model, presented simulation results and estimates for the growth rate for various machines. The theory has been tested at the ALS with a bunch train followed by a large gap, so that the possibility of conventional ion trapping was excluded. The vacuum pressure was deliberately increased by injecting helium. There was strong evidence for the FII, but the growth rate was too short to be measured. It was suggested that the beta-function variation along the machine be included in the calculation in order to obtain a firm value for the growth rate at the ESRF, where the FII has apparently not been seen. G. Stupakov talked about tune spread effects. A computation of the tune shift along a bunch train shows that it is 1/2 of the naïve estimate. In response to a recent claim that tune spread provides sufficient BNS damping to suppress the FII, Stupakov pointed out that, while this is mathematically true in the linear model, in practical cases the damping occurs at such large amplitudes that the linear model is not applicable. J. Y. Huang presented observations of the FII at PAL and KEKB. As in the case of the ALS, these observations required a deliberate vacuum pressure increase by injecting helium. CCD and streak cameras were used, allowing the observation of each bunch independently. Snapshots show clear tail oscillations and vertical beam size growth. At low helium pressure, the spectrum shows peaks at the linear-theory ion frequencies. At 3.34 nT helium pressure there is a large peak due to large oscillation amplitudes. C. Tschalaer talked about an analytic approach to beam-ion oscillations at the MIT-Bates electron ring. Single-mode calculations agree with beam width measurements. The effect of tune on the amplitude of oscillations has been confirmed, and the oscillations can be prevented by choosing the tune above the integer. The effect on emittance is small, while effects from gas pressure, current and energy remain to be tested. Slow clearing of ions by a beam gap does not appear to be every effective. S. Heifets gave a brief presentation on a smooth theory of ion trapping: when a bunch traps ions its size grows and hence becomes less efficient at trapping further ions. The process reaches equilibrium, and its dynamics is described by a Fokker-Planck equation, whose steady state can be extracted and analyzed.