Summary of Session III[*]

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Abstract

This is a summary of the talks presented in Session III ("Simulations of Electron-Cloud Build Up") of the *Mini-Workshop on Electron-Cloud Simulations for Proton and Positron Beams ECLOUD-02*, held at CERN, 15–18 April 2002.

1 CONTRIBUTIONS

The talks presented in Session III, with speakers' names underlined, were:

1. *Adiabatic Theory of Electron Oscillations and its Application to SIS-100/200*, P. Zenkevich, N. Mustafin and O. Boine-Frankenheim.
2. *Electron-Cloud Simulations: Build Up and Related Effects*, G. Rumolo and F. Zimmermann.
3. *3D Simulation of Photoelectron Cloud in KEKB LER*, L. F. Wang, H. Fukuma, K. Ohmi, S. Kurokawa, K. Oide and F. Zimmermann.
4. *A Simulation Study of the Electron Cloud in the Experimental Regions of the LHC*, A. Rossi, G. Rumolo and F. Zimmermann.
5. *Qualitative Analysis of Electron Cloud Effects in the NLC Damping Ring*, S. Heifets.
6. *Electron Cloud Updated Simulation Results for the PSR, and Recent Results for the SNS*, M. Pivi and M. A. Furman.

2 SUMMARIES

Adiabatic Theory of Electron Oscillations and its Application to SIS-100/200. The SIS machines are synchrotrons being designed at GSI to store U_{238}^{+28} ions. SIS-100 will have an energy of 100 MeV/u with four bunches, while SIS-200 will have an energy of 1000 MeV/u. The subject of this paper is to study the motion of electrons trapped by the ion beam. The only source of electrons considered is ionization of residual gas. The electron line density, λ_e, is assumed to be uniform. The ion line density $\lambda_i(\tau)$, on the other hand, is a function of the normalized time $\tau = t/T$, where $t =$ time and $T =$ revolution period (or bunch period if more than one bunch). The normalized net line density function is

$$F(\tau) = \frac{Z_i \lambda_i(\tau) - \lambda_e}{Z_i \langle \lambda_i \rangle} \tag{1}$$

where Z_i is the ion charge. The scale of $F(\tau)$ is set by the neutralization factor $\eta = N_e/N_i Z_i$, where N_e and N_i are the total number of electrons and ions, respectively. The investigation was carried out for 4 assumed shapes of $F(\tau)$. In all cases, a gap is assumed between bunches. In the gap the ion density is assumed to be uniform and is characterized by a leak parameter $\chi =$ (ion density in gap)/(ion density at center of the beam). The transverse density of the ions and the electrons is assumed to be round-Gaussian, both of the same σ. For small amplitudes, the transverse equation of motion of an individual electron in the combined field of the ions and electron cloud can be linearized leading to Hill's equation in which $F(\tau)$ plays the role of the periodic focusing function. This equation is analyzed by standard transfer-matrix techniques, leading to linear instability for certain values of χ. If the electrons are stable, they form a core within the ion beam. Large-amplitude electron motion was also investigated. In this case, the heating of the electrons is assumed to be due to ion-electron Coulomb scattering. An electron is assumed to be lost if its energy exceeds the net beam potential (it is assumed to be absorbed at the vacuum-chamber walls with unit probability). This analysis leads to very small equilibrium values of η for both SIS-100 and SIS-200 under nominal conditions. Future plans call for code improvements, using the Monte Carlo method, and additional sources of electrons.

Electron-Cloud Simulations: Build Up and Related Effects. The CERN electron-cloud simulation code ECLOUD models the build up of an electron cloud in the vacuum chamber under the influence of a charged bunched beam. The primary sources of electrons are photoemission off the chamber walls, and residual gas ionization. The model also takes into account secondary emission by electrons striking the chamber walls, including elastic reflection. Direct and image (surface) forces on the electrons are considered, both from the beam and from the space charge of the electron cloud. These forces are applied to the electrons by an appropriate time discretization, both within a bunch and in the gaps between bunches. Longitudinal ($\mathbf{E} \times \mathbf{B}$) forces are also included. Besides field-free regions, the code can describe the electron cloud in several magnetic field configurations. Standard cases are dipole, quadrupole and solenoid fields, although any field can be considered if specified in analytic form. The secondary emission yield (SEY) has been modeled by fits to experimental data, including the reflected component. The code has been applied to describe various electron-cloud effects (ECEs) such as the electron density build-up and related phenomena such as electron energy spectra, heat load on the LHC beam screen, spatial patterns of the electron

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cloud, electron flux at pick-up buttons, multi-bunch instability growth rates, electron trapping by magnetic fields, and electron-cloud build up for electron beams. Results for the electron-cloud build up and heat load (for LHC) are sensitive to the parametrization of secondary emission and photoemission. Important are also the beam and electron image charges, the electron space charge, and magnetic fields, even if they are only a few Gauss. The simulated electron-cloud build up is in good agreement with observations for the CERN SPS, the CERN PS and the KEKB LER. An interesting disagreement between measurements and simulations pertains to the exact position of the two "vertical stripes" (locations of peak electron density) in an SPS dipole. The simulated separation between the stripes is about a factor ~ 2 larger than observed for a bunch population of 8×10^{10}. In recent developments, the code has been applied to study the electron cloud in KEKB LER quadrupole magnets, predicting the trapping of electrons for very long times. The code has also been applied to the case of electron (rather than positron) beams, in which case an electron cloud is seen to develop, although at lesser intensity than for positron beams.

3D Simulation of Photoelectron Cloud in KEKB LER. A 3-dimensional particle-in-cell (PIC) simulation code, PICEC3, has been developed to study the photoelectron cloud, including all space-charge effects. The code uses an irregular mesh in order to adequately represent the shape of the vacuum chamber. This irregular mesh requires a modification of the conventional algorithm to assign the charge of any given macroparticle to the nodes of the cell that contains it. Besides field-free regions, the code can be applied to any magnetic field configuration. The code includes models for photoemission and secondary emission, and has been applied to study the instabilities in the KEKB LER. Results show that a solenoidal field is very effective in confining the photoelectrons near the vacuum chamber wall, thereby creating a beneficial charge-free region in the vicinity of the beam. The more uniform the solenoid field, the more effective the confinement. A comparison with C-yoke magnets shows that solenoids are more effective at electron trapping. Multipacting can occur in a field-free region and in a dipole magnet. The code has been applied to quadrupole and sextupole magnets, for which a serious electron trapping phenomenon has been found during the train gap. The mechanism is analogous to the magnetic bottle confinement of plasmas. In order for the trapping to get started, the adiabatic condition of the electron motion in a magnetic field must be broken. This happens for sufficiently short bunches, in which case the electrons get a substantial impulse kick. The condition on the bunch length is $\sigma_z < 2\pi mc/eB$, where B is the field at the mirror point of the trapped electron trajectory. In practical units, this condition reads σ_z [mm] $< 10.7/B$ [T]. For KEKB conditions, the simulated trapping time in a quadrupole is $\sim 10^5$ ns. This long confinement time may cause multibunch instabilities. Simulation results on the trapping mechanisms agree well with theoretical analysis. The code has so far been applied to cylindrical vacuum chamber geometry and round gaussian beams, but the extension to more complicated cases is in progress.

A Simulation Study of the Electron Cloud in the Experimental Regions of the LHC. The vacuum chamber in the experimental regions of the LHC will be at room temperature and will have complicated geometry in order to accommodate the detectors (ATLAS, CMS-TOTEM, LHCb and ALICE) and the two coexisting beams. The baseline design calls for coating the chamber with TiZrV, a getter material that possesses the virtues of effective pumping after activation at 200 C, low SEY, and good stability *vis-à-vis* exposure to air. The primary motivation for these electron cloud studies is to determine the residual gas pressure and composition, of critical importance for the acceptable detector background level. Also important is the contribution of these warm sections to the electron-cloud effects on the beams. As opposed to the arcs, where the basic criterion on the SEY is the maximum tolerable heat deposition from the electron cloud, in the experimental regions the basic criterion on the SEY is the maximum tolerable gas pressure, particularly from electron-stimulated desorption (ESD). Depending on the exact location, the chamber radius varies in these regions from 22 to 200 mm. Since the electron-cloud simulation tool used does not at present allow for the modeling of two counter-circulating beams, the assumption was made that the ECEs could be bracketed by studying two extreme cases with the conventional (single-beam) simulation, namely: (a) bunch spacing has the nominal value ($s_b = 7.48$ m) but bunch intensity is twice the nominal value ($2N_b = 2.1 \times 10^{11}$), and (b) bunch spacing is $s_b/2$ but bunch intensity is N_b. In the real machine, these two cases obtain at discrete points along the chamber whenever the distance from the IP is an integer or half-integer multiple of s_b, respectively. Besides ESD, photon-stimulated desorption (PSD) was also taken into account (ion-stimulated desorption was considered and found to be negligible). Assuming peak SEY values of 1.1 or 1.4 and a calculated photon flux of 10^{16} γ/m/s, the simulation code yields the electron flux and energy spectrum at the chamber walls for a given radius. These results, combined with measured values of the PSD and ESD for TiZrV, yield the local pressure of H_2, CH_4, CO and CO_2. It was found that ESD is the main source of gas. In order to sharpen the quantitative predictive ability of the code, the simulations have been repeated for the SPS and compared with pickup electron signals and pressure rise measurements (in this case the main source of electrons is residual gas ionization). For a 72-bunch train at 26 GeV and $N_b = 8.3 \times 10^8$, the measured pickup signal in a field-free section matches the simulations for a pressure of 200 nT and a peak SEY=1.6. Similar tests have been carried out for other bunch-train patterns. Further benchmarks will be carried out, including tests in a special section of chamber coated with TiZrV.

Qualitative Analysis of Electron Cloud Effects in the NLC Damping Ring. The motivation of this work is to try to obtain analytic estimates of the electron-cloud density and magnitude of the resultant wake in order to interpret numerical results from simulations and allow parameter scaling without additional lengthy calculations. In this approach the beam is assumed to be non-dynamical hence unperturbable by the cloud. The analysis is developed for a quasi steady state equilibrium, defined by the condition $\kappa \ll 1$, where κ is given by

$$\kappa = \frac{N_b r_e s_b}{b^2} \tag{2}$$

Here N_b and s_b are the bunch population and spacing, respectively, r_e is the classical radius of the electron, and b is the vacuum chamber radius. The condition $\kappa = 1$ defines the beam-induced multipacting resonance condition [1], corresponding to the equality of the bunch spacing (in time units) and the traversal time of an electron across a chamber diameter under the impulse of a single bunch passage. The limit $\kappa = 0$ at fixed N_b and b corresponds effectively to a coasting beam, hence only a static electron cloud can develop in this limit. The condition $0 < \kappa \ll 1$ corresponds to a regime in which the beam and the electron cloud (or, at least, most of the electrons in the cloud) are weakly coupled hence an analytic approach may be fruitful. In the high-current limit of a bunched beam, $\kappa \gg 1$, the electrons cross the chamber so quickly under the action of a single bunch that an electron cloud in the usual sense is not well defined.

As a first approximation, the electron cloud distribution is computed in steady state for a coasting beam in a cylindrical chamber of radius large compared with the transverse beam dimensions. The electrons move in the combined potential of the beam and the space charge of the cloud. The requirement of zero radial electric field at the wall yields an average electron-cloud density

$$n_0 = \frac{N_b}{\pi b^2 s_b}\,, \tag{3}$$

corresponding to the average beam neutralization condition. The charge distribution is given by a Boltzmann form, $n(r) \propto \exp(-U(r)/T)$ where U is the self-consistent beam-cloud potential and T is a temperature. For a bunched beam with $\kappa \ll 1$, an electron takes, on average κ^{-1} bunch passages to cross the chamber. Since this is a large number, its motion can be taken to be sensibly random. Thermalization of the electrons takes place within some distance from the beam. Even if the linear bounce frequency of an electron within a bunch is $\gg$ bunch frequency, such electrons can still be described by the Boltzmann distribution due to randomness of the electron motion. Assuming that an electron that hits the chamber wall is absorbed, equating the average energy gain from a bunch-electron kick with the average energy lost by an electron hitting the wall defines the cloud temperature T in steady state. This calculation also yields the energy spectrum of the electrons hitting the wall. Photoelectrons and secondary electrons are attracted towards the beam. These newly-generated electrons produce jets that may have higher density than the average n_0. The calculation shows that these jets significantly increase the cloud density near the chamber center. Once saturation level is achieved, which takes a few bunch passages, the newly-generated photoelectrons and secondary electrons are repelled by the potential and are sent back to the chamber wall. This implies that the level of the density at saturation is fairly independent of the photoelectron and secondary yield. Multipacting does not change the temperature much but rather affects the distribution of electrons only in the vicinity of the wall. This explains why the average density of the cloud is close to that given by the beam neutrality condition. The analysis also yields the long-range wake and the corresponding linear growth rate of coupled-bunch instability.

This qualitative analysis for $\kappa \ll 1$ was applied to the NLC Main Damping Ring, for which $\kappa = 0.28$. Good general agreement is found with available simulations.

Electron Cloud Updated Simulation Results for the PSR, and Recent Results for the SNS. The LBNL electron-cloud code POSINST, which was initially developed to study the ECE in the PEP-II positron beam starting in 1995, has been recently applied to the electron-cloud instability seen at the Proton Storage Ring (PSR) ring at LANL, and to the storage ring of the Spallation Neutron Source (SNS), presently under construction at ORNL. The physical model embodied by this code is similar to that of the code ECLOUD, described above. However, the secondary emission process is somewhat different. An improved, complete, model for this process, including detailed descriptions of the three main components of the emission spectrum (true secondary, rediffused and backscattered electrons) has been recently included in the code. The code has been benchmarked against measurements at the PSR obtained by means of dedicated electron probes which measure the flux, time structure, and energy spectrum of the electrons striking the chamber walls. The PSR contains a single proton bunch of full length ~ 60 m and energy 1.735 GeV in a stainless steel chamber of 5 cm radius and 90 m ring circumference. The simulations show very clear trailing-edge beam-induced multipacting (BIM), in good agreement with measurements. This effect was clearly seen in a digital simulated movie of the electron cloud build up and dissipation during two bunch passages. The electrons that are present in the chamber during the beam gap typically have low energy; they are captured adiabatically by the beam during the passage of its leading edge, and released with equally low energy towards the end of the trailing edge. These electrons, therefore, do not contribute to trailing-edge BIM. However, the electrons that are generated from stray protons hitting the chamber *during* the bunch passage, especially those produced near the peak of the bunch current, are captured non-adiabatically and are released at high energy soon after the passage of the peak of the bunch, and contribute strongly to trailing-edge BIM. This phenomenon leads to a strong sensitivity of the electron-wall current (and hence the electron distribution) to the longitudinal profile of the bunch. The time-energy joint electron spectrum is in good qualitative agreement with measurements, although the quantitative agreement is within a factor ~ 2, assuming a peak SEY value of 2. Preliminary simulations for the SNS show that an average electron line density of ~ 150 nC/m may be reached in a field-free region, leading to a significant tune shift due to beam neutralization. Due to an unexpectedly large electron multiplication during the passage of the SNS beam, simulations have have so far used a low number of seed macroparticles per bunch passage, leading to poor statistics for peak SEY values above 1.3. The code will soon be improved to deal with this problem.

3 ACKNOWLEDGMENTS

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4 REFERENCES

[1] O. Gröbner, “Bunch-Induced Multipactoring,” Proc. 10th Intl. Accel. Conf., Serpukhov, 1977, p. 277.