Summary of the Session on Electron-Cloud Theory and Simulation

F. Zimmermann, CERN, Geneva, Switzerland

Abstract

This paper summarizes the presentations and discussions in the session on theory and simulation at the international workshop on Two-Stream Instabilities, held at KEK September 11–14, 2001.

1 INTRODUCTION

In the session covering electron-cloud theory and simulation the following 10 talks were given:

- Simulations of Electron-Cloud Effects, F. Zimmermann
- Longitudinal Wake Field due to Electron Cloud, F. Zimmermann
- A 3D Model for the ep Instability in Proton Accumulator, V. Danilov
- Fast Single Bunch Instabilities in Storage Rings, D. Pestrikov
- Head-Tail Instability Caused by Photoelectron Cloud, E. Perevedentsev
- Study for Tune Shift Caused by Electron Cloud, K. Ohmi
- Simulation Studies of the Two-Stream Instability in Intense Particle Beams Based on the Vlasov-Maxwell Equations, H. Qin
- Updated Simulation Results of the Electron Cloud for the PSR and Secondary-Electron Energy Spectrum Model, M. Pivi
- 3D Simulation of Electron Cloud Effects, L. Wang
- Simulation of Multipactoring Effects, Y. Suetsugu

I will briefly describe the contents and highlights of each talk, then address the present level of understanding, and finally discuss the open questions.

2 PRESENTATIONS

2.1 Electron-Cloud Simulations

F. Zimmermann discussed the electron-cloud simulation studies performed at CERN [1]. Two simulation programs are being used. The first programme models the build-up of the cloud; the second programme the single-bunch instability that arises from the interaction on successive turns of a single bunch with the cloud generated by the previous bunches. He described the ingredients of the first program, and emphasized the importance of elastically reflected electrons on addition to the true secondaries. Simulation results for the SPS, KEKB, and two linear-collider damping rings (CLIC and NLC) indicates that for all these accelerators the electron cloud is a potential problem. F. Zimmermann then discussed the single-bunch instability modelled by the second programme. The simulation results suggest a strong synergy between space charge (or beam-beam interaction) and the electron cloud. The space charge qualitatively changes the instability characteristics. A simplified 4-particle model may explain the large impact of space charge, which is seen in the simulation. A concern for the LHC is the additional heat load deposited by the electron cloud on the beam screen inside the cold magnets which is held at a temperature of 4–20 K. Simulation results illustrated this point. Also the predicted LHC heat load sensitively depends on details in the assumed parametrization of the secondary emission yield. The simulations for an LHC dipole magnet show the existence of two vertical stripes of enhanced electron density. These stripes correspond to regions where the beam-induced multipacting primarily occurs and where thus the maximum heat load is expected. The horizontal position of these stripes depends on the bunch intensity and several other parameters. The exact position and size of the stripes are critical, since the stripes should not lie on top of the beam-screen pumping slots, which would provide for a direct passage of electrons onto the 1.9 K cold bore of the magnet.

2.2 Longitudinal Wake Field due to Electron Cloud

F. Zimmermann showed how the single-bunch longitudinal wake field can be extracted from 2-dimensional simulations of a single bunch passing through an electron cloud, by identifying the time of passage with the longitudinal position along the bunch [2]. The longitudinal wake field was shown to be of the order of 1–10 V/m and therefore insignificant for both SPS and KEKB.

2.3 A 3D Model for the ep Instability in Proton Accumulator

V. Danilov discussed two mechanisms of electron accumulation [3]. The single-pass accumulation occurs due to trailing-edge multipacting where electrons are accelerated and lost when the bunch intensity decreases. An effective trailing-edge multiplication factor was computed as a function of the maximum secondary emission yield of the vacuum chamber, considering various longitudinal bunch profiles. The amplification factor for the SNS accumulator by far exceeds that for the PSR. The multi-pass effect assumes the survival of electrons in the gap. V. Danilov then showed that single-pass accumulation would saturate when the electron density reaches the density of the proton beam, while multi-pass accumulation saturates at about 1% of the proton density. The latter value is quite close to the observed value at the LANL PSR, which may indicate that multi-pass accumulation is important. Coating of the SNS vacuum chamber with TiN is highly recommended. To more accurately predict the occurrence of ep instability in the SNS, a complete 3D simulation code is under development including the 3D space charge force of the proton beam, a 2D space charge field of the electrons, and a detailed model of secondary emission.

2.4 *Fast Single Bunch Instabilities in Storage Rings*

D. Pestrikov discussed fast single-bunch instabilities, whose rise time is short compared with a synchrotron oscillation period [4]. Considering an example wake field with exponential decay and solving the equations of motions for this model, he showed that these instabilities are characterized by two time scales. During a first transient period the instability resembles the beam break up. The oscillations in this period exhibit neither eigenvalue spectra nor threshold currents, and can be suppressed by Landau damping, *e.g.*, by the ring chromaticity. The second phase corresponds to the self-consistent period, with well separated eigenmodes. This period will correspond to reality only if the transient oscillation amplitudes remain so small that the perturbation theory still applies. D. Pestrikov found that very high values of chromaticity would be required to damp the two fastest-growing modes of the self-consistent oscillations.

2.5 *Head-Tail Instability Caused by Photoelectron Cloud*

E. Perevedentsev presented several analytical estimates for the single-bunch instability driven by the electron cloud [5]. He discussed the two-stream equations of motion, the electron decoherence and parametrization of the wake force, the strong head-tail instability with a fast oscillation wake field, the effect of diffusion on the higher-order head-tail modes, and a simple model of the transverse feedback. Instability thresholds were computed as a function of the wake-field and beam parameters. For a 'magical' chromatic phase shift of $\chi = 1/\sqrt{2}$ all the principal beam modes are damped. E. Perevedentsev recommended to optimize feedback settings and chromaticity together so as to minimize the vertical beam blow up at KEKB. In particular, he stressed that a partially reactive feedback may be better than a purely resistive one. The presently favored TMCI model of the electron-cloud instability predicts the correct threshold, but at KEKB direct evidence of the head-tail instability ('banana' oscillations, or merging of synchrotron sidebands) is still missing.

2.6 *Study for Tune Shift Caused by Electron Cloud*

K. Ohmi studied the characteristics of the beam-cloud interaction, in particular the coherent tune shift and the transverse wake field induced by the cloud [6]. For a small size of the electron cloud, the tune shift should vary with the bunch length. However, for a large cloud this is no longer the case, and the tune shift agrees with the 'naive' estimate, computed for a frozen electron distribution. This implies that electrons which are several rms beam sizes away from the beam contribute to the tune shift. Electrons responsible for the head-tail wake field are confined to smaller amplitudes. The simulated horizontal wake field is of similar magnitude as the vertical wake. The wake fields can be parametrized by a damped resonator. Simulations using a rigid Gaussian model of the beam show a chromatic $l = 1$ head-tail instability for positive chromaticity, even for low electron densities. This regular higher-order head-tail instability is not observed in PIC simulations. The latter show a clear instability threshold at a cloud density of $\rho_e \approx 5 \times 10^{11}$ m^{-3} for KEKB, corresponding to the onset of the strong head-tail instability. The difference may be due to additional frequency spread present in the PIC simulation.

2.7 *Simulation Studies of the Two-Stream Instability in Intense Particle Beams Based on the Vlasov-Maxwell Equations*

H. Qin discussed computer simulations of two-stream instabilities applied to the PSR parameters [7]. These simulation are based on a solution of the Vlasov-Maxwell equations using the code BEST. In order to reduce the statistical noise, a δf method is employed, studying the evolution of a perturbation around the stationary equilibrium solution. For the coasting beam model considered, such a stationary solution is known. The simulation results illustrate the Landau damping due to momentum spread and space-charge induced tune spread, and reveal the energy exchange mediated by collective eigenmodes. The PSR problem requires 'large scale' computing, which means that the growth rate is much smaller than the oscillating frequencies. Perhaps most noteworthy among the results presented are the sharp resonance (in longitudinal wave number) at the onset of instability, which is consistent with observations, the prediction of a well-defined instability threshold varying with the degree of neutralization and with the beam momentum spread, and the existence of a late-time nonlinear phase of the instability, where the growth rate is even faster than in the linear phase.

2.8 Updated Simulation Results of the Electron Cloud for the PSR and Secondary-Electron Energy Spectrum Model

M. Pivi described the ingredients of the program POSINST developed at LBNL, and showed simulation results for the PSR [8]. The electron kinematics is treated in 3D, but at the moment only 2D forces are calculated. Primary electrons are generated at the chamber wall, representing beam loss. The simulated number and time structure of the electrons hitting the wall is consistent with PSR observations. The simulated electron energy spectrum extends to 200 eV, a factor two smaller than the measured maximum of 400 eV. A possible explanation is that electrons from gas ionization are not yet included, and might reach higher energies. Assuming the secondary emission yield of TiN the simulated electron density is reduced by 3 orders of magnitude. The simulation indicates a strong effect of the re-diffused and elastically reflected electrons. It also shows 'microbursts' lasting for a couple of turns, similar to those seen with Rosenberg-type electron-cloud monitors at the PSR. In the future, M. Pivi plans to include the effect of gas ionization, to check the dependence of the simulated incident electron flux on the beam intensity, and to study the beam dipole motion.

2.9 3D Simulation of Photo-Electron Cloud in KEKB LER

L. Wang described a newly developed 3D simulation program for the electron cloud build up [9]. The code feature include a 3D space-charge solver, the treatment of various (arbitrary) magnetic field configurations, and a charge allocation either by finite elements or via a Green's function. Cloud patterns, electron build up and electron decay can be simulated. L. Wang's simulations show that of all magnetic fields studied the longitudinal solenoid gives the maximum suppression of the cloud build up. He finds that electron space charge is not important if secondary emission is not included. Most intriguingly, the simulation shows the existence of magnetic bottles, which can trap electrons for arbitrarily long times after the passage of a bunch train. The highest number of trapped electrons, almost 50% of the total, is simulated for quadrupole magnets. The simulation also suggests that short trains reduce the average cloud density. The simulated electron energy spectrum is smooth, and shows little sructure.

2.10 Simulation of Multipactoring Effects

At KEKB a nonlinear pressure rise with beam current is observed, which varies with the bunch spacing. One explanation is beam-induced multipacting. Y. Suetsugu [10] presented a simulation model of the beam-induced multipacting process combined with electron-induced gas desorption, by which he can predict the nonlinear pressure rise as a function of beam current for various filling patterns. The agreement between prediction and measurement is excellent. The simulation model reproduces the dependence of the measured pressure rise on the bunch filling pattern, on the bunch current, and on the strength of a solenoid field. Y. Suetsugu also showed tantalizing evidence that the onset of the nonlinear pressure rise is strongly correlated with the threshold for the vertical beam-size blow up. His observations and simulation results indicate that the blow up at KEKB may be dominated by multipacting.

3 ACHIEVEMENTS AND OPEN QUESTIONS

Simulations and analytical estimates can quantitatively reproduce and 'explain' many of the observations at KEKB LER, the LANL PSR, and the CERN SPS, such as the value of the electron cloud density, the coherent tune shift, the total number of electrons incident on the wall and their time structure, the decay and build-up times of the electron cloud, the existence of two electron stripes inside an SPS dipole and the distance between these stripes, the mode spectrum of the electron-cloud driven coupled-bunch instability at the KEK photon factory and BEPC, the single-bunch instability threshold at KEKB, and the possible synergy between space charge forces or beam-beam interaction and the electron-cloud driven single-bunch instability.

Despite of these successes, a large number of open questions remain. These include the following:

- PEP-II observes a large horizontal blow up, but at KEKB the beam blows up only in the vertical plane.
- At PEP-II the number of bunches in a train after which the beam blows up does not change with the solenoid field, at KEKB there is a strong dependence (for short trains).
- Multipacting is measured in the PEP-II arcs, although simulations had predicted there should be no problem after TiN coating.
- After the installation of the KEKB solenoids, there is still a persistent slow blow up, starting after about 30 bunches. Perhaps the new simulation results by L. Wang here give a first hint to a possible explanation.
- Also observed at KEKB is a significant hysteresis of the blow up, with a time constant of 100 s. It is hard to conceive any physical process with this time constant, except for gas ionization — which, however, in simulations was shown to be unimportant — or some thermal effect.
- Why do DAFNE and BEPC not observe multipacting, despite of an aluminium vacuum chamber?
- At KEKB the solenoid field strongly alters the frequencies of unstable multibunch modes, in a way which appears to be opposite to the expected (with

solenoids active the unstable modes concentrate at low freqencies).

- Why do the solenoids reduce the coherent tune shift only by 30% and not more?
- How can we extend the wake concept so as to better model the electron-cloud response, for which time invariance and superposition principle are not strictly fulfilled?
- Different simulations and theories give different and even contrary predictions for the effect of chromaticity.
- Can the electron cloud support collective plasma waves, and, *e.g.*, give rise to a 'magnetron effect' [11] (thus quenching the LHC magnets)?
- At the SPS, the multipacting threshold measured in a dipole field is lower than that in a field-free region, which seems to be in contrast to the simulation.
- The LHC heat loads simulated at CERN and LBNL differ strongly, when elastically reflected electrons are taken into account.
- What determines the equilibrium beam size [12]? At KEKB it is indepedent of the radiation damping time.
- Can a reactive feedback reduce the blow up [5]?

4 ACKNOWLEDGEMENTS

I would like to thank S.-I. Kurokawa and H. Fukuma for their support and the excellent workshop, and everybody at KEK for the great hospitality.

5 REFERENCES

[1] G. Rumolo, F. Zimmermann, "Electron-Cloud Simulations," and "Electron Cloud Instability with Space Charge or Beam Beam," these proceedings.

[2] G. Rumolo, F. Zimmermann, "Longitudinal Wake due to Electron Cloud," these proceedings.

[3] V. Danilov, S. Cousineau, J. Holmes, "A 3D Model for the ep Instability in Proton Accumulator," these proceedings.

[4] D. Pestrikov, "Fast Single-Bunch Instabilities in Storage Rings," these proceedings.

[5] E. Perevedentsev, "Head-Tail Instability Caused by Photo-electron Cloud," these proceedings.

[6] K. Ohmi, "Characteristics of Beam-Electron Cloud Interaction: Tune Shift and Instability," these proceedings.

[7] H. Qin, "Simulation Studies of the Two-Stream Instability in Intense Particle Beams Based on the Vlasov-Maxwell Equations," these proceedings.

[8] M. Pivi, "Simulation Results of the Electron-Cloud Effect at the LANL Proton Storage Ring," these proceedings.

[9] L. Wang, H. Fukuma, K. Ohmi, "3D Simulation of Photo-electron Cloud in KEKB LER," these proceedings.

[10] Y. Suetsugu, "Simulation of Multipactoring Effects," these proceedings.

[11] F. Caspers, private communcation (1999), and comment at Chamonix X (2000).

[12] K. Oide, private communication (2001)