Summary of Session IV: Simulations of Electron-Cloud Instabilities

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Abstract

I summarize the session IV of the ECLOUD'02 worskhop, which was devoted to the simulation of electron-cloud instabilities.

1 INTRODUCTION

In Session IV, 10 presentations were given:

- *Simulation of Emittance Growth due to Electron Cloud in the PEP-II Positron Ring* by Y. Cai (SLAC),
- *Electron Cloud Simulations: Beam Instabilities and Wake Fields* by G. Rumolo (CERN),
- *Study for ep Instability in JAERI-KEK Joint Project* by T. Toyama (KEK),
- *Study for ep Instability in High Intensity Proton Rings* by K. Ohmi (KEK),
- *Head-Tail Instability Caused by Electron Cloud* by E. Perevedentsev (INP),
- *Wake Field of the e-Cloud and its Effect on the Upgrade of PEP-II* by S. Heifets (SLAC),
- *Electron Cloud in the PSR and SNS* by M. Blaskiewicz (BNL),
- *Effect of Electron Cloud on the Bunch Oscillations in KEKB LER* by S. S. Win (KEK),
- *Study of Electron Cloud Effect in JLC Damping Ring* by K. Ohmi (KEK), and
- *Effect of Bunch Length, Chromaticity, and Linear Coupling on the Transverse Mode-Coupling Instability due to Electron Cloud* by E. Metral (CERN).

In the following, I discuss the session highlights and some unresolved questions.

2 TALKS

2.1 Electron Cloud Simulations for PEP-II (Y. Cai)

Y. Cai presented the results of a micro-bunch simulation, which uses a model first described in Ref. [1]. He also included radiation damping for the centroid motion of each bunch slice (or micro-bunch). The deflection of the electrons is computed by assuming a constant transverse size of each bunch particle. The inverse force is obtained from the action-reaction principle. Using PEP-II LER parameters, he observed a clear threshold in the electron cloud density beyond which the vertical beam size rapidly increases. Above threshold the beam-size growth time is of the order of the synchrotron period (40 turns). The threshold coincides with the threshold of the transverse mode-coupling instability. This is evidenced by computing the Fourier spectrum of the beam dipole motion: the threshold of beam-size growth corresponds to the merger of the $l = -1$ and $l = 0$ head-tail modes. An experimental measurement at PEP-II showed a similar signature of mode coupling as obtained in the simulation. The simulated threshold for the horizontal blow up is about two times higher.

The measured spectrum resembles the spectrum simulated for a density of $\rho_e = 10^{11}$ m^{-3}, which is about half the saturated density found in electron build-up simulations and only 20% of the estimated threshold density. Indeed, this value corresponds to only 1% of the average neutralization density, which is attributed to the effectiveness of the solenoid windings.

Using the independently simulated electron density $\rho_e = 2 \times 10^{11}$ m^{-3} and a build-up time constant of 50 ns, Y. Cai studied the beam size increase along a bunch train and found a 30% blow up, roughly consistent with observations at PEP-II and KEKB.

The effect of chromaticity was explored for a density of $\rho_e = 8 \times 10^{11}$ m^{-3}, *i.e.*, well above the TMCI threshold of 5×10^{11} m^{-3}. A positive chromaticity had no significant effect, while for negative chromaticity both horizontal and vertical beam sizes increased strongly. This may be consistent with observations. However, the actual electron density in PEP-II seems to be below the threshold.

In this context it is interesting that the simulation shows a significant growth of the beam size also at lower currents (below the threshold). The reason for this beam-size increase is not yet explained. So far the effect of chromaticity in this regime, *i.e.*, below the TMCI threshold, has not been investigated. Such a study would help in unravelling the origin of the blow up, and in contriving a cure.

A second unresolved mystery is that in the simulation the vertical blow up is much stronger than the horizontal, whereas in reality the horizontal emittance blow up is larger.

2.2 Beam Instabilities and Wake Fields (G. Rumolo)

G. Rumolo described the HEADTAIL code developed at CERN for the simulation of single-bunch instabilities driven by the electron cloud. The code includes fully 3-

dimensional beam motion, a PIC module for computing the electric fields of the beam and the electrons, the option of nonzero chromaticity, external magnetic fields, detuning with amplitude, arbitrary initial electron distributions (*e.g.*, two vertical stripes), conventional a wake field, proton space charge, beam-beam collision, and synchrotron oscillations. For the computation of space charge, the interaction with the electron cloud, and the conventional wake field, the macroparticles constituting the bunch are temporarily assigned to a number of longitudinal slices, for each of which the interaction is calculated successively. The linear space-charge force is modelled by an additional rotation in transverse phase space around the center of the associated local beam slice. The instability simulation is performed over many turns (several synchrotron periods). The code can also compute the transverse wake field, by displacing a single slice transversely, and calculating the force on later parts of the bunch. The longitudinal wake field is obtained by identifying the longitudinal slice position with time.

The simulation reveals the electron phase space, and in particular the pronounced pinching of electrons at the center of the bunch during its passage. An additional broadband impedance and a space-charge tune spread have a strong impact on the dynamics of the single-bunch instability simulated for the LHC beam in the SPS. The vertical emittance growth can be suppressed by a large chromaticity $Q'_y \geq 10$ (or $\xi_y \geq 0.4$). The inclusion of the proton space-charge force qualitatively changes the character of the instability, converting an otherwise smooth blow up into violent oscillations along the bunch.

The simulated transverse wake fields depend on the position of the displaced source slice. This is easily understood from the electron pinch and from the variation of the electron oscillation frequency along a Gaussian bunch. The wake fields also differ strongly whether one computes the field on axis or the field averaged over the transverse beam distribution. A dipole field suppresses the horizontal wake and also lowers the vertical. The longitudinal wake field was shown to be insignificant for the SPS.

Simulations were also performed for KEKB. A strong dipole motion inside the bunch is visible for the vertical plane only. This is due to the flatness of the bunch, and it is consistent with observations. A chromatcity of $\xi_y = 0.35$ cures this instability.

A detailed comparison of KEKB simulation results using the HEADTAIL code and the PIC module of K. Ohmi's PEI code has shown a good agreement in the emittance growth for several different chromaticities. The results also appear to be consistent with experimental observations [4], both exhibiting a similarly beneficial effect of positive chromaticity.

The KEKB solenoids with a field of 30 G do not much affect the single-bunch instability, because the cyclotron period is much longer than the bunch length. However, simulations have shown that for the longer bunches in the SPS a 100-G solenoid suppresses the electron pinch and also couples the wakes excited in the two transverse planes.

2.3 *Electron-Cloud Build-Up and Instability for High-Intensity Proton Rings and in particular for the JAERI-KEK Joint Project (T. Toyama, K. Ohmi)*

The JKJ project comprises two high-intensity proton rings accelerating to 3 GeV and to 50 GeV, respectively. The electron-cloud effects observed at the LANL PSR and BNL AGS have motivated a study of e-p instability for JKJ.

Simulations of electron-cloud build up were performed for various machines and the saturated electron densities were compared with instability thresholds predicted by a dispersion relation. This dispersion relation was obtained by approximating the single-bunch wake field by a resonator (derived from a simulation), and then evoking a coasting beam approximation, which included Landau damping due to the slippage factor and the beam energy spread. As an independent cross check, the instability growth rates were directly simulated by micro-bunch tracking.

The results suggest that the JKJ rings should operate below the instability threshold. The PSR is found to be unstable, while the ISIS ring (UK) is predicted to be stable, both in good agreement with observations.

The secondary emission yield of various materials was measured in the laboratory before and after sputtering the surface with Argon ions. The sputtering reduces the yield of all materials. The isotropic graphite had the lowest yield in either case. The TiN film presumably contained carbon and oxygen impurities.

In a dedicated experiment at the KEK PS electron-cloud signals were detected on pick ups with a high-impedance termination. The signal showed a clear baseline drift during the passage of a bunch train, which depended strongly on the number of bunches. A bias voltage or a weak solenoid field strongly affected the signal, which indicates that electrons are at the origin of the shift.

Simulations of the electron-cloud build up are roughly consistent with the measurement and also show that the simulation result critically changes when elastically reflected electrons are taken into account.

More studies are planned, for example, the simulations for JKJ will be repeated using a more realistic model, which includes the elastically scattered electrons, the measured secondary emission yields, and also the electron space charge.

2.4 *Head-Tail Instability caused by Electron Cloud (E. Perevedentsev)*

E. Perevedentsev presented a comprehensive treatment of the combined head-tail and TMCI instability driven by the electron cloud. The wake field due to the electron cloud may be parametrized either by a broadband resonator or by a Struve function. The latter can further be approximated by a J_1 Bessel function.

He then applied a standard mode coupling analysis to the electron cloud instability in KEKB and in the CERN SPS. The coupling matrix was limited to 3 radial moides and truncated at azimutahl modes $-5 \leq l \leq 4$. The convergence was checked by extending the order of truncation. Next, the tune variation along the bunch due to the electron pinch was included in the TMCI calculation. It was found that this pinch is stabilizing, in accordinace with earlier studies by V. Danilov for conventional wake fields [3].

Most importantly, in the write-up for these proceedings, E. Perevedentsev generalized the mode coupling theory to the case of a wake field $W(z, z')$, depending on the longitudinal coordinates z and z' of the source and test particle, respectively. This describes the electron cloud more appropriately than a conventional wake $W(z - z')$, since the electron distribution changes during the bunch passage. The generalized wake field can be computed by simulations.

Also a simple feedback with resistive and reactive components was introduced. An analysis for the conventional wake field shows that a large chromaticity can suppress the instability. For a chromatic phase shift of $\chi \sim 2$ all lower-order modes are stable in KEKB and in the SPS, which both correspond to the case of a 'long bunch', defined by a number of oscillations along the bunch which is equal to 1 or larger.

An optimum stabilization may be reached by a judicious combination of moderate chromaticity and choice of feedback phase.

E. Perevedentsev finally considered the coasting beam limit. Treating the cases of low-order modes and modes near the resonant frequency he derived somewhat different stability conditions. In positron rings, high-order instability modes are rapidly damped by a diffusion process arising from the synchrotron-radiation quantum fluctuation.

Assuming saturation, the threshold current scales in proportion to the bunch spacing. On the other hand, in the short bunch limit, the threshold current scales as the square root of the bunch spacing.

The generalized wake concept provides us with an extremely powerful tool for more accurately analysing the electron-cloud head-tail instability.

2.5 *Electron Cloud at High Beam Current: PEP-II Upgrade (S. Heifets)*

The presentation by S. Heifets discussed the prospect of obtaining even higher beam currents at PEP-II, without aggravating the electron-cloud effects. This is motivated by a proposed upgrade which should increase the PEP-II luminosity by more than an order of magnitude, with a stored beam current up to 18 A. S. Heifets introduced two paramaters characterizing the electron-cloud build up: κ and ζ, defined by

$$\kappa = \frac{2N_b r_e s_b}{b^2} \tag{1}$$

and

$$\zeta = \frac{s_b}{b}\sqrt{\frac{2E_0}{mc^2}}\ . \tag{2}$$

The former describes the distance traversed by an electron which is near the wall when a bunch passes by until the arrival of the next bunch in units of the beam-pipe radius. It is 2 times the multipacting parameter considered by O. Grobner [2]. The second parameter describes the distance travelled by a secondary electron emitted with energy E_0 over a time corresponding to the bunch spacing s_b, again in units of the beam-pipe radius. The expectation is that for high values of κ and low ζ the center of the beam pipe is almost free of electrons, and there will be no electron-cloud instability. S. Heifets confirmed this by a simplified simulation study. This parameter regime exactly corresponds to that of an upgraded PEP-II, envsioning closely spaced bunches (small s_b) and high bunch charges (large N_b).

In these conditions, the cloud density is no longer set by the condition of neutrality, but by an equality of the electron space-charge potential and the initial energy E_0. This means that the electron density will be much lower than naively expected. However, inside dipole fields the electron density might grow to larger values.

For certain intermediate beam currents, the simulation showed an increase of the electron-cloud density for every other bunch, which may explain why the PEP-II luminosity was observed to alternate periodically from bunch to bunch.

At low current, the wake field is determined by electrons in the vicinity of the beam. An additional effect is the asymmetry introduced by the jet of primary photoelectrons or by an ante-chamber. The estimated change in equilibrium beam energy due to the static dipolar force is small. At high current the bunch-to-bunch wake field arises from the asymmetry of the secondary electrons caused by a transverse bunch offset. An explicit formula for $\zeta \ll 1$ was given. The azimuthal harmonic $m = 2$ of the electron cloud generates a contribution to the tune shift which is equal and of opposite sign in the two transverse planes. The primary jets of photoelectrons cause a variation of tune shift and orbit distortion along the bunch. The head-tail instability can be treated using the Satoh-Chin formalism, by a proper choice of the rang of the coupling matrix. The instability may be stabilized if the number of head-tail oscillations along the bunch is large.

2.6 *Electron Clouds in the PSR and SNS (M. Blaskiewicz)*

M. Blaskiewicz discussed electron-cloud effects in the PSR and SNS, first considering the electron cloud generation and then the beam stabiilty. A remarkable plot from the PSR (Fig. 1 in the talk) shows the threshold rf voltage as a function of beam charge. Two curves for 30% different bunch lengths were almost identical. It appears difficult to explain this independence of bunch length by common instability models.

Primary electrons are assumed to be generated by losses and gas ionization. Secondary electrons are parametrized in the usual way, *i.e.*, using the Seiler formula. A rough estimate is a generation rate of 200 electrons per lost proton and 0.1% loss, resulting in 2×10^8 primary electrons per meter and turn.

In a simple coasting beam model, where space charge is assumed to be the dominant contribution to the tune shift, the threshold bunch current should scale as the third power of the bunch length (note the striking difference to the observed independence!). The focus of the simulations has thus been the scaling with the bunch length and the modelling of a realistic electron cloud.

The simulation model used is essentially 1-dimensional, describing only the vertical motion of protons and electrons. The forces between proton beam and electrons are approximated, so that they are correct in the limits of small and large amplitudes. The electron cloud is represented by a small number (20–200) of macroparticles, the beam by 2×10^6 macroparticles, and space-charge kicks are applied about 10 times per betatron oscillation. Many parameters were varied in the simulations. Electron densities of 1 nC/m led to a rapid instability with beam loss. Smaller densities could give rise to persistent oscillations at a finite amplitude. The simulated threshold densities and threshold rf voltages differ from the observation in the PSR by factors of about 0.2 and 1.5. The origin of the additional damping is unclear.

Complementary to the simulation, an eigenmode analysis was performed, where the rf voltage was approximated by a square potential. Again the threshold rf voltage varies strongly with bunch length. The eigenmode analysis was benchmarked against a coasting beam calculation. The results are sensitive to tails in the momentum distribution.

The same eigenmode analysis was applied to the 2-MW SNS and an electron density of 2 nC/m, corresponding to fairly large values of secondary emission yield and electron reflectivity. The threshold predicted for the SNS looks acceptable.

A convergence test of the eigenmode analysis required many modes in order to reproduce the known beam breakup limit, and showed that the coasting beam dispersion relation gives a good estimate for the threshold.

2.7 Coupled Bunch Instability in KEKB LER (S.S. Win)

S.S. Win presented measurements and simulation results for the spectrum and growth rates of multi-bunch instabilities driven by the electron cloud in KEKB.

Multibunch mode spectra and instability growth rates were measured with solenoids on and off. At beam currents approaching 1 A, the instability growth rates, measured after deactivating the transverse feedback, are of the order of 500 μs. With solenoids off the spectra show a strong peak near mode number 800 (out of about 1300) and two smaller peaks around 1100 and 150 (and a fourth peak at 350 in the horizontal plane). On the other hand, when the solenoids are turned on, only low-order modes near 0 are excited.

Good agreement between simulated mode spectra and measurements was achieved, by assuming — in the case without solenoids — that the photoelectrons are generated uniformly around the chamber wall and not concentrated at the primary illumination point. The case with solenoids also shows a good agreement, but is insensitive to details of the initial electron distribution. If one assumes a solenoid field of about 10 G, the simulated horizontal growth rate agrees with the measurement, and the simulated vertical growth rate is about 50% higher.

2.8 Electron Cloud in the JLC Damping Ring (K. Ohmi)

K. Ohmi studied the electron cloud phenomenon in two versions of the JLC damping ring, which differ by the bunch spacing (1.4 ns and 2.8 ns, respectively).

He first studied the electron cloud build up. The photon absorption efficiency of the antechamber was estimated at 80% based on an experiment at KEKB. The simulated cloud densities in saturation at the center of the chamber then are 8×10^{12} m^{-3} and 3×10^{12} m^{-3}.

The simulated growth rate of the coupled bunch instability was found to be 26 μs (20 turns) or 130 μs (100 turns), for the two bunch spacings.

The single-bunch wake field was computed analytically and by a macroparticle simulation. The coasting beam instability threshold was then used to estimate the threshold electron density. For a synchrotron tune of $\nu_s = 0.01$, it is about half the density simulated for the 1.4-ns spacing. Some ambiguity remains in the choice of the wake quality factor, Q, and the enhancement factor due to the electron pinch, K.

K. Ohmi concluded that a further reduction in the electron density by a factor 5–10 will be needed. Clearly, the electron cloud would favor the larger bunch spacing, where the conditions appear considerably more relaxed.

Finally, results were also presented for DAFNE. The average electron density for present beam conditions is estimated at 6×10^{11} m^{-3}, which is 3 times less than the predicted single-bunch instability threshold. Since the design current of DAFNE is 5 times higher than the present value, the instability might be observed in the future.

2.9 Effect of Bunch Length, Chromaticity and Linear Coupling (E. Metral)

E. Metral analysed the electron cloud instability by adapting the transverse mode-coupling theory. He approximated the wake field by a resonator. The strong dependence of the electron-cloud wake-field parameters on bunch length, transverse beam size, and bunch current were taken into account.

The model was applied to the CERN SPS, and it was shown that for the 2001 beam parameters, a strong sensitivity to chromaticity and bunch length is expected in agreement with the observations. For short bunches ($\sigma \leq 15$ cm) or high chromaticities ($\xi_y > 0.8$) the LHC beam in the SPS is expected to be stable up to nominal intensity.

In the SPS, most of the electrons reside in dipole fields, where the horizontal single-bunch wake vanishes, since the electrons here only move vertically. Therefore, linear coupling can share the growth rate between the two planes, and increase the instability rise time by a factor of two. It is foreseen to test this stabilization scheme in 2002.

3 OPEN QUESTIONS AND FUTURE STUDIES

One burning question concerns the missing physics input that could explain why the blow up in PEP-II preferentially occurs in the horizontal plane and not in the vertical as simulated. Another question is the character of the PEP-II instability below the simulated TMCI threshold.

It is not enirely clear if the observed electron cloud effects in PEP-II are consistent with simulations or not, given the installation of antechambers and extensive TiN surface coating. A comprehensive comparison would be most valuable for the accelerator-physics community.

Experimental and simulation studies should further be advanced, in order to explore the high-intensity ‘blow-out’ regime contemplated for the PEP-II upgrade.

The striking fact that the measured threshold rf voltage in the PSR is nearly independent of the bunch length still calls for an explanation.

A highlight of this session is the generalized TMCI theory including pinch effect and time-dependent wake field. The new theory should be applied and benchmarked against simulations and experiments.

A small mystery is why the (photo?)-electrons in KEKB seem to be generated so uniformly around the chamber wall.

Additional refined studies may be necessary for a reliable prediction of electron cloud effects in future high-intensity proton rings and in future linear colliders, though a promising start has been made and the preliminary results are encouraging.

The stabilization of the electron-cloud instability by linear coupling should be tested experimentally.

4 ACKNOWLEDGEMENT

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5 REFERENCES

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