MODELING INCOHERENT ELECTRON CLOUD EFFECTS[*]

E. Benedetto, G. Rumolo, D. Schulte, R. Tomas, F. Zimmermann, CERN; G. Franchetti, GSI;
K. Ohmi, KEK; M. Pivi, T. Raubenheimer, SLAC; W. Fischer, BNL; K. Sonnad, J.-L. Vay, LBNL

Abstract

Incoherent electron effects could seriously limit the beam lifetime in proton or ion storage rings, such as LHC, SPS, or RHIC, or blow up the vertical emittance of positron beams, e.g., at the B factories or in linear-collider damping rings. Different approaches to modeling these effects each have their own merits and drawbacks. We describe several simulation codes which simplify the descriptions of the beam-electron interaction and of the accelerator structure in various different ways, and present results for a toy model of the SPS. In addition, we present evidence that for positron beams the interplay of incoherent electron-cloud effects and synchrotron radiation can lead to a significant increase in vertical equilibrium emittance. The magnitude of a few incoherent e^+e^- scattering processes is also estimated. Options for future code development are reviewed.

INTRODUCTION

Incoherent electron-cloud effects (IECE) can potentially degrade the beam quality of the Large Hadron Collider (LHC), soon to be commissioned at CERN [1, 2]. They could also explain the poor beam lifetime and bunch shortening, varying along the bunch train, which are observed with LHC-type beam in the CERN SPS [3].

RHIC beam losses at transition have as well been attributed to incoherent electron-cloud effects, e.g. [4]. During the most recent polarized proton run at RHIC, bunches shortened through rf quadrupole pumping in the AGS were injected in order to increase the luminosity through the reduction of the hour-glass effect at store. However, the luminosity of the stores with bunches of reduced length was lower than the luminosity of stores with longer bunches of comparable intensity [5]. At the same time, a higher dynamic pressure was observed at injection. This could be an indication that electron clouds at injection have increased the proton beam emittance.

Also positron storage rings can be affected by the nonlinear field of the pinched electron cloud forming towards the tail of a bunch. The ensuing chaotic diffusion together with synchrotron radiation may yield a new equilibrium emittance. Evidence for such effect is observed at the KEKB Low Energy Ring, where the average positron beam size gradually increases as a function of beam current [6], well below the threshold of the electron-cloud induced fast head-tail instability [10].

SIMULATION CODES

A number of simulation codes are available to model the interaction of the beam and the electron cloud. CMAD, EPI, HEADTAIL (HT), PEHTS, QUICKPIC, TAILHEAD (TH), and WARP/POSINST are particle-in-cell (PIC) codes. Other programmes include MICROMAP and IECP. Information on most of these codes plus references can be found in the CARE-HHH accelerator-physics code web repository [8]. TH, CMAD, and IECP are new.

TAILHEAD from CERN is a recent derivate of HEADTAIL, which between successive interaction points (IPs) transports beam particles using the optical transport matrices computed by MAD. HEADTAIL uses either simplified rotation matrices or lattices constructed from thin-lens quadrupoles and drifts [2]. The computing time of TH is indistinguishable from HT, since the time needed for tracking the beam particles through the magnetic elements is negligible compared with the calculation of the beam-electron interaction.

HEADTAIL and TAILHEAD correctly model a single bunch-ecloud interaction, but the finite grid size in the transverse directions introduces numerical noise, which is partly controlled by distributing the beam over at least 10×10 cells. Additional methods are available to minimize the numerical noise arising from the discretization, e.g., symmetrizing the electron distribution. The bunch-electron interaction can either be calculated once per turn to speed up the computation, in which case the lumped nonlinear "kick" artifically excites all resonances, or it can be distributed over many interaction points (IPs) per turn. Both HT and TH can read an independently computed electron distribution from the ECLOUD build-up code at the start of the programme execution. Also both codes offer a frozen-field option where the electron potential along the bunch is calculated only once, during the first bunch passage through the cloud at a specific optical location, and then the same potential is again applied whenever the beam returns to an optically equivalent location in the ring, and on successive turns. Freezing the potential in this way speeds up the computation by a factor 6–8, and it also suppresses PIC random noise. However, self-consistency is lost, i.e., the effect of beam loss or emittance growth on the subsequent electron motion is not taken into account, and coherent instabilities are prevented.

Much faster simulations are realized by abandoning the exact calculation of the electron potential and instead using an approximative, and noiseless, analytical model, whose parameters are fitted to the (frozen) potential computed by HEADTAIL. This latter scheme has been implemented in the code MICROMAP [1], which uses a refined lattice

model, thereby reproducing the correct excitation pattern of resonance lines permitted by the lattice symmetry, at the expense of the approximated bunch-electron interaction. A benchmarking of MICROMAP against HEAD-TAIL showed that for the same number of nonlinear kicks per turn the emittance growth agreed within a factor of two, or even better, using an electron-pinch model corresponding to a free-field region [1]. The pinch model in MICROMAP still requires improvements for electron distributions which are not axis-symmetric, e.g., in a dipole field. By its very construction, this code always uses a frozen field approximation.

The opposite approach is adopted by CMAD, which is a self-consistent code newly developed at SLAC. CMAD is intended for simulating both the electron cloud build-up and related beam instabilities. By means of parallel (Message Passing Interface - MPI) computation, the CMAD code tracks the beam in an existing (MAD-type) lattice and continuously resolves the interaction between the beam and the cloud within each element of the lattice, using different cloud distributions at each magnet location. CMAD is in the preliminary code-benchmarking phase.

IECP is similar to MICROMAP, in that the effect of the pinched electron cloud enters as an additional analytical kick which depends on the longitudinal and transverse position inside the bunch. The beam motion in all three degrees of freedom is described only in terms of rotation maps. As a new feature, IECP contains both damping and excitation terms from synchrotron radiation, which are modelled following the prescription of Siemann [11].

SPS TOY MODEL

For code benchmarking we choose a simplified SPS model, consisting of 108 FODO cells with 2 dipoles per cell. The phase advance per cell is $\pi/2*0.968$ which reproduces the SPS tunes (26.1815, 26.136). The model dipoles can be split into pieces to allow for electron-cloud "kicks" to be applied at various locations along a FODO cell. Table 1 lists the main model parameters. The rms bunch length was computed assuming "linear" synchrotron motion.

Simulations were run with TAILHEAD for different electron densities, one or two interaction points per half cell, and either dynamic or frozen cloud. The single beam-cloud interaction was located halfway between two successive quadrupoles. The two interaction per half cell were arranged at the dipole ends next the QF and QD quadrupoles, so that in this second case the beta functions vary between successive IPs. This arrangement was chosen in order to drive lattice resonances.

Some results from TAILHEAD are presented in Fig. 1. The fast instability threshold corresponds to an average electron density of about 2.75×10^{11} m^{-3} for one IP, and to an even lower threshold density, between 1 and 2×10^{11} m^{-3}, for two IPs per half cell. At a density of 2×10^{11} m^{-3} and two interaction points, the dynamic cloud leads to rapid emittance growth, while the frozen

Table 1: Parameters of the SPS toy model.

variable	symbol	value
species		proton
total energy	E	26 GeV
Lorentz γ	γ	27.71
circumference	C	6912 m
momentum compaction	α_C	0.00164
horizontal tune	Q_x	26.1815
vertical tune	Q_y	26.136
transition energy	γ_{tr}	24.728
synchrotron tune	Q_s	0.0025
rms momentum spread	$(\Delta p/p)_{\mathrm{rms}}$	2×10^{-3}
rms bunch length	σ_z	0.293 m

cloud shows a much smaller emittance increase. In case of a purely incoherent effect, the dynamic and the frozen cloud should give the same growth. At densities where the dynamic and frozen simulations appear to give consistent results, there is hardly any incoherent emittance growth visible over the time scale considered. For example, with two IPs and at a reduced density of 10^{11} m^{-3} the emittance growth simulated in the dynamic model would be consistent with no growth, and, over the small number of turns considered, it appears to be dominated by statistical noise. The same statements apply to the corresponding simulation with frozen potential. The frequency that is present in the emittance evolution for the dynamic cloud at all three electron densities appears to be twice the synchrotron frequency, while the beating frequency visible for the frozen cloud is about two times smaller and may equal the synchrotron frequency.
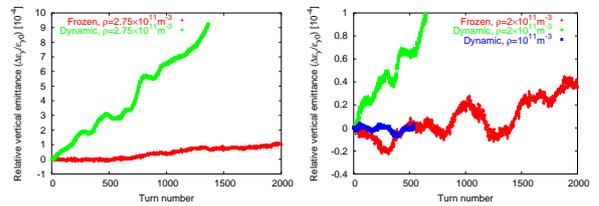

Figure 1: Emittance growth simulated with TAILHEAD considering a single electron-beam interaction point at the center of each half cell (left) and with two interaction points, close to the QD and QF quadrupoles (right). The electron cloud responds either dynamically, or it is frozen. The electron density is 2.75×10^{11} m^{-3} for the left picture and either 1×10^{11} m^{-3} or 2×10^{11} m^{-3} on the right.

POSITRON BEAMS

To assess the importance of incoherent electron-cloud phenomena in positrons storage rings the effect of syn-

chrotron radiation must be included. The IECP code was written for a first exploratory study. We consider parameters of the ILC OCS damping ring, and assume an initial density of 2×10^{11} m^{-3}, corresponding to a vertical tune shift at the bunch head of 0.01. Due to the electron pinch, this vertical tune shift increases, roughly linearly, by a factor of about 140 along the length of the bunch. Taking into account the spiky nature of the pinched electron distribution, which is revealed in HT simulations, the electron cloud is modelled as a transversely Gaussian charge distribution of rms size equal to one tenth of the rms beam size, whose density linearly increases over the length of the bunch. Simulations which include both synchrotron radiation and electron cloud show that after roughly one radiation damping time of about 1000 turns, a new equilibrium emittance is established (Fig. 2). For the parameters considered, the vertical rms emittance is enhanced by 50% above the low-current radiation equilibrium without electron cloud.
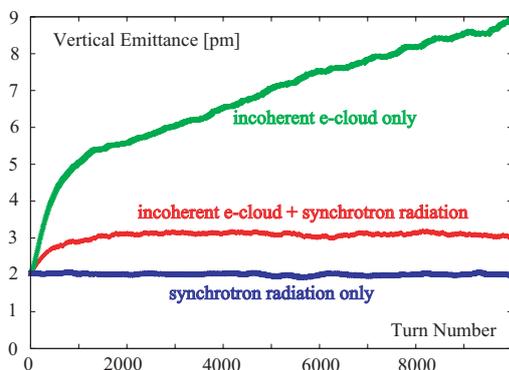

Figure 2: Vertical emittance in the ILC 6-km damping ring (OCS) as a function of turn number, with synchrotron radiation only, with a frozen electron-cloud pinch only, and with the combined effect, simulated by IECP using a single beam-electron IP per turn and an initial tune shift, at the head of the bunch, of $\Delta Q \approx 0.01$, corresponding to an electron density of 2×10^{11} m^{-3}. The incoherent tune shift is taken to increase 140 times during the bunch passage.

Positrons can also undergo incoherent scattering off the pinched electrons or annihilate with them. Both of these processes would reduce the beam lifetime. The elastic Bhabha scattering cross section corresponding to a relative energy loss of δ_{cut}, or more, is [12] $\sigma_{\text{el}} \approx 2\pi r_e^2/(\gamma \delta_{\text{cut}}) \approx$ 5 mbarn, where the numerical value applies to the ILC 6-km damping ring for $\delta_{\text{cut}} \approx 1\%$. The annihilation cross section is [12] $\sigma_{\text{an}} \approx \pi r_e^2/(\gamma + 1)(\ln(2\gamma) - 1) \approx 0.2$ mbarn. The annihilation processes are rare compared with elastic scattering. The beam lifetime due to the latter follows from $\tau_{\text{beam}} \approx 1/(\sigma_{\text{el}} \rho_e c)$. Assuming a pinched electron density at the center of the bunch of $\rho_e \approx 10^{13}$ m^{-3}, the beam lifetime is still a magnificent 7×10^8 s.

STRATEGY

For an accurate modeling, many electron-cloud kicks are needed over one betatron wavelength. To speed up the simulation time, we look for methods to combine the effects of successive kicks into "generalized" kicks, e.g., ones affecting both position and slope and which are applied at the end of one betatron period, after one arc, or once per turn. An approximation of a similar sort has been proposed for lattices with 90-degrees phase advance per cell, namely computing the nonlinear kicks only over a single lattice unit with π phase advance (2 cells) and multiplying them with the number of such units constituting the ring [9]. An underlying assumption is always that the effect of the electron cloud on the beam is sufficiently small, so that second order effects can be neglected over a turn or fraction of a turn.

An ultimate goal of the incoherent electron-cloud modeling remains the reliable prediction of the emittance growth and beam lifetime in the LHC. However, so far the emittance growth for hadron beams has eluded quantitative predictions even in those cases where the source is perfectly known both in intensity and location, such as the beam-beam interaction. Therefore, a more realistic intermediate aim may be parameter studies to explain observations and to suggest means of improving the accelerator performance, e.g., choice of working point and chromaticity.

SUMMARY

Numerous codes are available for simulating incoherent electron-cloud effects. Their assumptions and approximations are quite different. Comparing the results from these codes appears therefore essential in order to decide the route forward, and worldwide benchmarking efforts need to continue. Incoherent electron cloud effects were shown to be important also for positron beams in the presence of synchrotron radiation, where they can lead to a significant emittance blow up. In particular, they could set tighter electron-cloud tolerances for the ILC and CLIC designs than previously assumed.

REFERENCES

[1] E. Benedetto, G. Franchetti, et al, PRL 97, 034801 (2006).

[2] E. Benedetto, PhD thesis, Politecnico di Torino, 2006.

[3] G. Franchetti et al, Proc. LUMI'06 Valencia.

[4] S.Y. Zhang et al, MOPLS025, EPAC'06 Edinburgh.

[5] S.Y. Zhang and V. Ptitsyn, BNL C-A/AP/257 (2006); S.Y. Zhang and V. Ptitsyn, ECLOUD'07 (2007).

[6] H. Fukuma et al, HEACC'01 Tsukuba.

[7] F. Zimmermann, PRST-AB 7, 123801 (2004).

[8] *http://oraweb.cern.ch:9000/pls/hhh/code_website.startup*

[9] K. Ohmi, K. Oide, PRST-AB 10, 014401 (2007).

[10] K. Ohmi, F. Zimmermann, PRL 85, 3821 (2000).

[11] R.H. Siemann, PAC 1983, Santa Fe, 2373.

[12] W. Heitler, The Quantum Theory of Radiation, Clarendon Press, Oxford (1954).