

# ELECTRON-CLOUD BENCHMARKING AND CARE-HHH CODES

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## Abstract

The state-of-the-art in code benchmarking for various types of electron-cloud simulations is reviewed. In particular, we recall possible meanings of benchmarking, summarize past and more recent code comparisons, present examples of code verification against machine experiments, mention some remaining uncertainties, and formulate a few goals for the future. The code-benchmarking effort is supported by the CARE-HHH initiative on accelerator physics simulation codes, whose further objectives include a web repository and code expansion.

## INTRODUCTION

At HHH-2004 M. Furman pointedly remarked [1] that the term ‘code benchmarking’ may carry a variety of meanings, for example *debugging*, i.e., the code should calculate what it is supposed to calculate; *validation*, i.e., results should agree with established analytic result for specific cases; *comparison*, i.e., two codes should agree if the model is the same; or *verification*, i.e., the code should agree with measurements. The need for debugging is obvious, but validation is often difficult for complex simulations of nonlinear processes. The HHH benchmarking concentrates on the two remaining areas of code comparison and experimental verification. Prominent examples for the latter include the experimental benchmarking of ECLLOUD at the CERN SPS [2], the verification of POSINST and CSEC with beam observations at the APS and PSR [3, 4], and the benchmarking of WARP/POSINST simulations against the HCX experiment [5, 6].

Five different types of electron-cloud codes exist, namely *build-up codes* (POSINST, PEI, ECLLOUD, CLOUDLAND, EPI, CSEC, and, possibly, MEC); *multi-bunch instability codes* (PEI-M); *single-bunch instability codes* (PEHT, PEHTS, HEADTAIL, and QUICKPIC); *codes for incoherent electron-cloud effect* (HEADTAIL-WS, MICROMAP, and CLOUD\_MAD); and *self-consistent codes* (ORBIT, WARP/POSINST, PARSEC, and, with certain restrictions, BEST).

## ELECTRON-CLOUD BUILD UP

In 2002 a comparison was performed for the 5 codes ECLLOUD, CLOUDLAND, CSEC, PEI, and POSINST [7]. In 2004, an improved version of ECLLOUD was benchmarked with PEI and EPI. In addition a detailed comparison of ECLLOUD and POSINST was conducted by G. Bellodi for EPAC’04 [7] and, later, expanded for HHH-2004 [8]. These studies highlighted the importance of the secondary-electron energy spectrum, of the secondary yield at low incident energies, as well as of the so-called elastically reflected and re-diffused secondary-electron components. Some results from 2002/04 are displayed in Fig. 1.

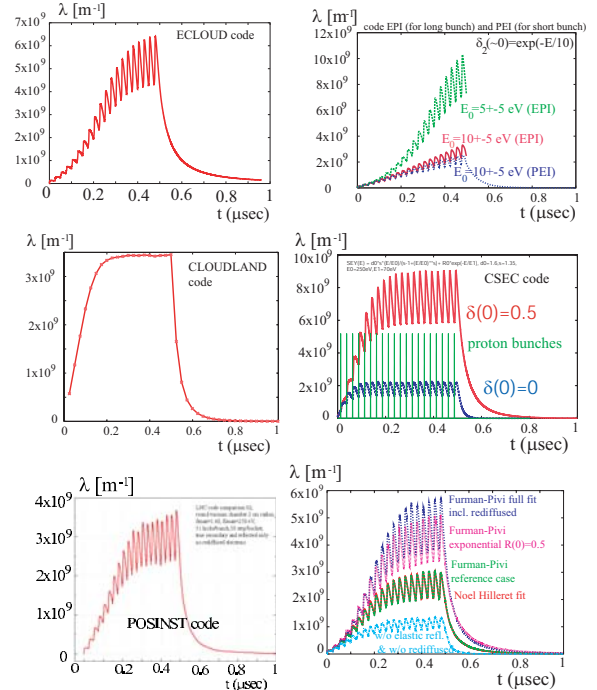


Figure 1: Results of build-up simulations for the same example case by various codes: ECLLOUD using the parametrization of [9] (top left), EPI and PEI (top right), CLOUDLAND (centre left), CSEC (centre right), POSINST (bottom left), and once again ECLLOUD, but now with five different parametrizations of elastic reflection (bottom right); for details see [7].

Consistent with the earlier findings, a recent comparison of POSINST and ECLLOUD simulations for an LHC arc dipole exhibits a satisfactory agreement without re-diffused electrons [10]. In addition, the electron-cloud evolution in the ILC 6-km Damping Ring (DR) ‘‘OCS’’ was simulated by the 3 codes ECLLOUD, POSINST and CLOUDLAND [11] (see Fig. 2). Results typically agree within a factor of two.

A problem of the build-up simulations is the strong sensitivity of the results to partly unknown and time-dependent surface properties, e.g., the maximum secondary emission yield as a function of the angle of incidence,  $\delta_{\max}(\theta)$ , the energy at which the secondary yield is maximum,  $\epsilon_{\max}(\theta)$ , the reflectivity of low-energetic electrons,  $R$ , the fraction of re-diffused electrons, the energy spectrum of the secondary electrons, etc. Due to these uncertainties it is not yet possible to make as precise a prediction for electron-cloud effects as for conventional impedance. The main approaches to overcoming this problem are extensive laboratory and in-situ measurements of surface properties, as well as code benchmarking against beam measurements.

As an example, the dependence of the secondary emis-

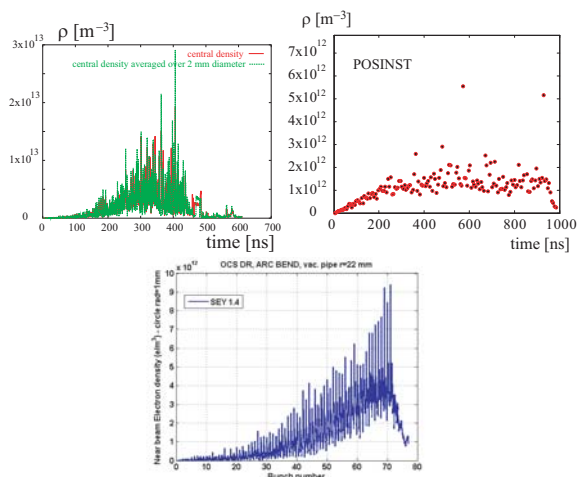


Figure 2: Central electron cloud density in the ILC DR OCS, simulated by ECLLOUD (top left — with  $R = 50\%$  elastic reflection at 0 energy), CLOUDLAND (top right — courtesy L. Wang, with  $R = 10\%$ ) and POSINST (bottom — courtesy M. Pivi, with  $R \approx 40\%$ ), as a function of time, for  $\delta_{\max} = 1.4$   $\epsilon_{\max} = 200$  eV, a bunch spacing of 6.154 ns[11], and using the Hilleret parametrization [12].

sion yield  $\delta(\epsilon, \theta)$  on the impact angle  $\theta$  was measured by Kirby and King for copper samples with different surface finish and surface chemistry [13]. The measurements revealed an enormous variation in behavior. The dependence of the yield  $\delta$  on the angle of incidence appears to become more monotonic after treatment with argon ion sputtering.

In view of the aforementioned uncertainties, an experimental benchmarking appears indispensable. The underlying idea is that the uncertain surface parameters can be constrained by performing multiple beam measurements and comparing the relative changes. Successful experimental verifications include the fitting of ECLLOUD simulations against SPS measurements [2]. Here, the average electron flux at the wall was measured and simulated for two different bunch spacings and for two different numbers of trains; see the left picture of Fig. 3. Comparing the ratio in the electron fluxes for the different cases, and also the absolute value of the flux, three curves are obtained which intersect in a single point, as shown in the right picture. Some of the remaining uncertainties pertain to the vacuum pressure, which affects the rate of primary electrons from gas ionization, and to details of the chamber geometry. The SPS benchmarking has demonstrated that the elastic reflection of low-energy electrons is less than 100%, and that a final maximum secondary yield of about 1.2 has been achieved after a few days of “scrubbing” with beam.

## MULTI-BUNCH INSTABILITY

PEI-M is the only code simulating multi-bunch electron-cloud instabilities. Its benchmarking could, therefore, be done only against experiments. Without magnetic field, the simulated richly structured multibunch mode spectra

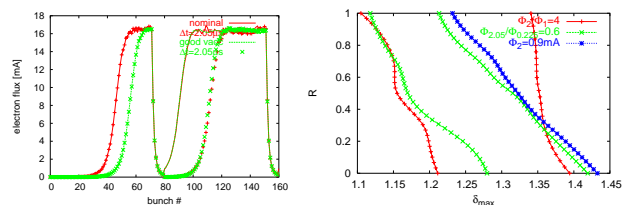


Figure 3: Left: simulated development of the electron cloud for two consecutive batches in the SPS, with a distance between of 225 ns (lines) or 2050 ns (points); the two sets of curves correspond to two different vacuum levels; right: combined representation of the simulation parameters which fit the different measurements. The best overall agreement is found for  $\delta_{\max} \approx 1.35$  and  $R \approx 0.3$  [2].

for KEKB equal the measured ones, as shown in Fig. 4, if the simulation assumes an initially uniform distribution of photoelectrons [14]. Simulations also reproduce the very different spectra measured in the presence of a solenoid field, but only if for the latter a strength of 10 G is chosen [14], which is 4–5 times lower than the actual field in the solenoids [15]. Measured and simulated growth rates agree within 50% both with solenoids on and off [14]. In the simulation, solenoid fields of 20 G or higher introduce additional peaks in the spectrum which are not observed experimentally. Though the benchmarking was successful, we lack an understanding of the effective solenoid field.

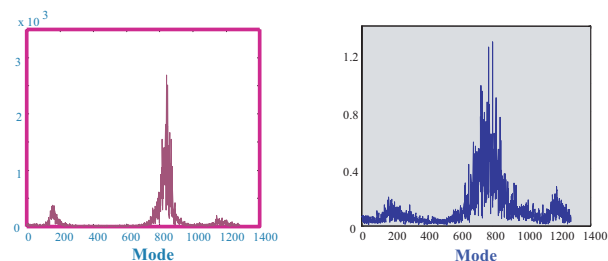


Figure 4: Measured (left) and simulated vertical multi-bunch mode spectrum (right) for the KEKB Low Energy Ring without solenoid field [14].

## SINGLE-BUNCH INSTABILITY

For single-bunch electron-cloud instabilities and incoherent effects a few codes are available. In 2002, a benchmark of HEADTAIL, PEHTS, and QUICKPIC was attempted [7]. Figure 5 presents some example results, which highlighted the importance of correctly distributing the beam-electron interactions around the ring [7]. In 2006, HEADTAIL was again benchmarked with PEHTS [16]. Noteworthy, the single upper synchrotron sideband observed at KEKB above threshold has recently been reproduced in both codes [16]. In PEHTS, the appearance of the sideband depends on the size of the cloud chosen. At various occasions, HEADTAIL simulations were also verified with SPS observations [17, 18, 19].

In addition, HEADTAIL-WS was benchmarked against MICROMAP. Here, the incoherent emittance growth due to an electron cloud was simulated by either code [19]. For an

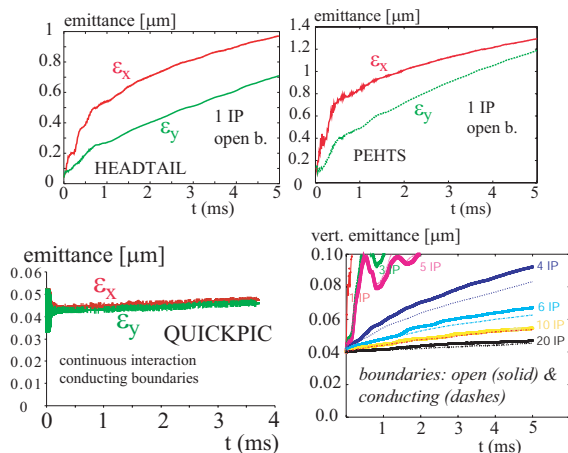


Figure 5: Results of instability simulations for an example case by various codes: HEADTAIL with 1 IP (top left), PEHTS (top right), QUICKPIC (bottom left), and HEADTAIL with various numbers of IPs for both open and conducting boundaries ; for details see [7].

identical frozen electron distribution the results are nearly indistinguishable. If an attempt is made to roughly approximate the real pinched electron distribution in MICROMAP with the simplifying, but incorrect, assumption of charge conservation (i.e., by ignoring that electrons stream in from larger amplitudes), the results remain qualitatively similar, but the growth rates differ by about a factor of two [19]. This comparison has proven that the emittance growth seen in HEADTAIL is not a numerical artifact due to particle-in-cell (PIC) noise, and it suggests that we can use the much faster programme MICROMAP for accessing the qualitative behavior on longer time scales [19].

## OUTLOOK

A panel discussion at HHH-2004 focused on the goals of electron-cloud code benchmarking and code development [20]. The outcome was that the codes should help to address the performance limiting issues, such as vacuum pressure rise (RHIC), instabilities (PSR), and emittance growth, and that reliable predictions are the ultimate goal. In particular, the simulations should predict the conditions before an accelerator is built. Benchmarking profits from the ever increasing computing power, which by 2060 will exceed the brain power of the entire mankind. One of the key directions to pursue is self-consistency. M. Furman, J.-L. Vay, R. Cohen, and others have combined WARP and POSINST, so as to integrate, in a single code, ions, residual gas, space charge, electron build up, electron-driven instabilities, and beam loss. The WARP/POSINST roadmap outlined at ECLLOUD'02 and ECLLOUD'04 has by now been largely implemented. A future 'complete' simulation code, grown around a self-consistent electron-cloud core, may also encompass beam optics, conventional impedances, including the beam-induced electric and magnetic fields, and beam-beam effects [20, 21].

The CARE-HHH goals for accelerator-physics codes comprise [23] (1) a common code repository for linear

and nonlinear optics programs, impedance estimates, and simulation codes for collective effects, such as conventional instabilities, beam-beam, space charge and electron-cloud effects; (2) the code validation by mutual comparisons and benchmarking against machine experiments and a centralised documentation, fostering code reliability; (3) the extension of simulation codes to cover relevant beam physics and implementation of effective procedures for beam measurements, machine protection, background control, and performance optimization. A web site for the CARE-HHH code repository has been established [22, 23]. About 35 codes are presently included. Pertinent information was collected via a standard questionnaire. As a first spin-off, several code home pages have been created or updated, e.g., [24] and [25]. Presently, benchmarking information is being added to each code category.

## ACKNOWLEDGEMENT

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