Summary of the ECLOUD'04 Workshop

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Abstract. The 31st ICFA Advanced Beam Dynamics Workshop on Electron-Cloud Effects "ECLOUD'04" was held April 19-23, 2004 at Napa, CA, USA. A broad range of current topics in this field were illuminated by 53 talks in 7 sessions plus 6 session summaries at the final summary session. These covered a variety of experimental methods and results, along with progress on understanding of the topic obtained from simulations and analytic theory, and evaluations of the effectiveness of various methods/mechanisms for mitigation of the adverse impact on accelerator performance. In addition, a panel discussion was held on "Future Needs and Future Directions". A summary of progress on the major themes covered at ECLOUD'04 is presented.

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INTRODUCTION

Important Electron Cloud Effects (ECE) include beam-induced multipacting, vacuum pressure rise, beam instabilities, emittance growth, heat-load on cryogenic beam chambers, tune shifts and interference with certain diagnostics. ECE have become an important and active research topic in accelerator physics because they have limited the performance of a number of existing accelerators such as the B-factories, the proton accumulator ring (PSR) at Los Alamos and RHIC, to name a few, and pose serious technical risks to the performance of a number of new high intensity accelerator projects including the LHC, SNS, J-PARC, Super B factories and NLC damping rings. Because of the interest in this topic, ECE have been the focus of a number of recent workshops including the Multi-Bunch Instability workshop at KEK, July 1997; Two-stream Instabilities, Santa Fe, February 2000; Two-stream Instabilities, KEK September 2001, and ECLOUD'02, CERN, April 2002. The 31st ICFA Advanced Beam Dynamics Workshop on Electron-Cloud Effects, "ECLOUD'04", held April 19-23, 2004 at Napa, CA, USA was the latest in this series and was co-sponsored by LBNL, CERN, ORNL and SNS, in addition to the ICFA Beam Dynamics Panel.

As in previous workshops the focus of ECLOUD'04 was broad covering all aspects of the phenomenon. Goals for the workshop included: 1) summarize our understanding, identify essential issues, and scope out future research avenues; 2) assess the state of theory and simulations; 3) identify and assess mitigation mechanisms; 4) compile a list of simulation codes and their features; 5) assess experimental methods and diagnostics plus; 6) strengthen and expand international collaborations.

There were 59 attendees from various institutions around the world and most attendees gave presentations. The workshop program consisted of 6 technical sessions, a panel discussion and a summary session. Two sessions (17 talks) were devoted to observations at existing accelerators and concerns for future machines. One session (7 talks) dealt with surface properties, measurements and treatments. Another two sessions covered simulations of e-cloud buildup and there was an all day session on theory and simulations of e-cloud instabilities. There was also a panel discussion on future needs and future directions. Workshop talks are posted at the workshop website http://icfa-ecloud04.web.cern.ch/icfa-ecloud04/. A link to the Workshop Proceedings is also posted at this website and a hard copy of the proceedings will soon be published as a CERN yellow report.

For this report, and following the ECLOUD'04 program, it is convenient to split the ECE problem into three parts in the traditional manner i.e.: e-cloud build-

up; interactions of the e-cloud with the beam to produce instabilities and/or emittance growth; and methods for mitigation of ECE. The split between buildup and the dynamics of electron cloud induced instabilities (ECI) is historical and was used to make computationally tractable these two aspects of the ECE. The combined approach, in which both the cloud build-up and electron-beam interactions are simultaneously modeled, is the goal of several code development efforts currently underway (NCSEC, ORBIT, PARSEC and a combining of POSINST + WARP) and were discussed at ECLOUD'04. Such a combined, self consistent treatment is needed for a more complete understanding of the problem e.g., the development of unstable beam motion influences the buildup of the electron cloud as has been observed experimentally at the LANL PSR. The code QUICKPIC represents an important step towards self consistency: in this case both the electrons and beam particles respond dynamically to each other, but the dynamics of wall collisions (especially secondary emission) remains to be included.

ELECTRON CLOUD BUILD-UP

Low energy background electrons are ubiquitous at accelerators and arise from a variety of sources including photo-electrons from synchrotron radiation, residual gas ionization, beam losses making grazing angle collisions with vacuum chamber walls and, in the case of H- injection schemes, from the stripper foil. Strong electron clouds arise when these electrons are trapped for relatively long periods of time (e.g. a DC coasting beam) or when the electrons undergo further amplification by beam-induced multipactor.

Much work on e-cloud build-up, both experimental and computational, was reported at this workshop. For a summary of this work, it is useful to break out three regimes of buildup that characterize different classes of accelerators. The first regime applies to machines with a long train of short beam bunches (cloud electrons undergo less than one or two oscillations during the bunch passage) as is the case for the positron rings at B factories, the CERN PS/SPS complex with LHC type beams, or the positron damping rings for NLC. The e-cloud buildup arises from amplification by beam-induced multipactor. The cloud density (above the multipactor threshold) typically saturates after some number of bunches from space charge forces or more generally when it reaches equilibrium between generation and losses. Simulation codes that have been used for this regime include ECLOUD, CLOUDLAND and POSINST.

Simulation results from these codes were reported in several talks at the workshop.

The second regime covers the so-called long-bunch beams (where the electrons undergo many oscillations during the bunch passage) in which case e-cloud amplification is by "trailing edge multipactor". This is the situation for the Spallation Neutron Drivers e.g., the Los Alamos PSR, SNS, ISIS and the J-PARC project. Simulation codes that have been used for this regime include ECLOUD, CLOUDLAND, POSINST and CSEC. Simulation results from POSINST and CSEC were reported that were in general agreement with PSR data, given the uncertainties on the secondary emission yield (SEY or δ) for the beam chambers and the source term for the seed electrons.

A third buildup scenario results from trapping of the primary electrons by the beam e.g. for long bunches or in DC coasting beam in a ring. This regime is particularly important for the linacs proposed for heavy ion fusion where significant beam scrapping by heavy ion beams can release many electrons per lost ion. In addition, ionization of residual and desorbed gas is expected to be an important source of electrons. The WARP code has been used to simulate e-cloud buildup for heavy ion accelerators. Trapping in the mirror-like fields of magnetic quadrupoles is another trapping mechanism that can also contribute to the buildup for all three buildup regimes.

The characteristics of SEY or δ are one of the most sensitive and therefore important pieces of physics input to simulations of e-cloud buildup in that the "gain" for the multipactor amplification depends strongly on δ_{max}. The SEY for low-energy electrons (≤ 10 eV) is particularly important for understanding the slow dissipation of electrons in relatively long (≥ 100 ns) beam-free gaps between bunches or bunch trains. Higher-than-expected values of δ, of order 0.5 in this region are needed to explain the measured exponential decay time of ~ 170 ns for electrons in the PSR after the beam is extracted. Recent measurements at CERN by R. Cimino et al., reported at this workshop, are plotted in Figure 1 and show high values of δ in this energy range. In fact, $\delta(0)$ is ~ 1 and the minimum value of δ is ~ 0.5 at an electron energy of 10-15 eV.

Numerous observations indicating e-cloud buildup were reported at this workshop. They were made using a variety of diagnostics including vacuum pressure rise, shielded collectors, the CERN strip detectors, the ANL-type retarding field analyzer (RFA) and variants thereof. In this section we will show some examples of the data presented at this

workshop. Vacuum pressure rises, presumably from electron stimulated desorption, are often one the first indications of beam induced multipacting and e-cloud buildup and have been reported at most machines where ECE impact accelerator performance. An example from RHIC is shown in Figure 2 along with the output of an RFA-style electron detector for a proton fill with 108 ns spacing. The electron cloud density implied by the electron detector signal can be reproduced in simulations (CSEC) if δ_{max} is adjusted.
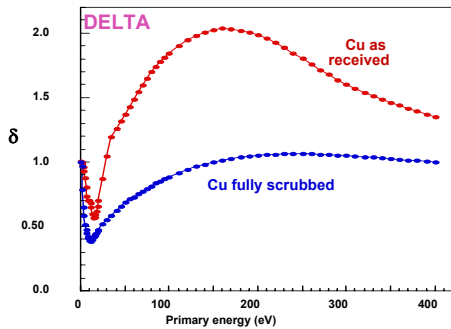

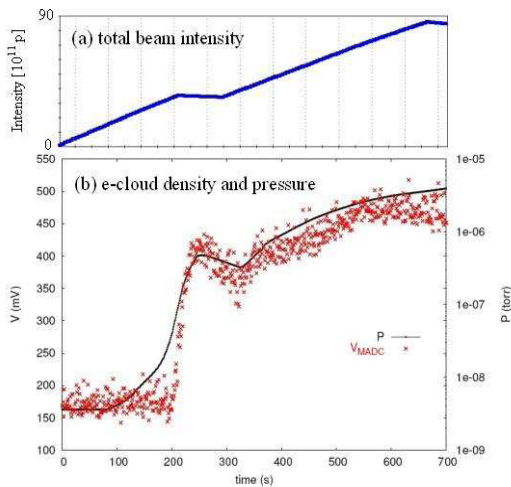**FIGURE 1.** Plots of SEY (δ) presented by R. Cimino at this workshop.

FIGURE 2. RHIC data on pressure rise and e-cloud signals. (From U. Iriso and W. Fischer at ECLOUD'04).

The CERN strip detector has been used extensively to study the electron flux hitting the wall in various locations in the SPS. The e-signal is collected on strips located behind holes in the chamber wall and provides information on the transverse distribution of the e-flux striking the wall. A sample of the data collected in a field-free region is shown in Figure 3.

Another type of diagnostic is the electron sweeping detector which is a variation of the RFA that has a sweeping electrode placed opposite of the RFA entrance. A several-hundred volt fast pulse applied to the electrode sweeps electrons into the RFA. It was designed to be able to measure the soft cloud remaining in the pipe during the passage of the gap between bunches for long bunch machines. It has been deployed at the LANL PSR and the KEK-PS MR. A sample of the data from KEK is shown in Figure 4. The sharp spike in the e-signal occurs when a short HV pulse is applied near the end of the gap between bunches. After sweeping, the subsequent "prompt" e-signal pulses that occur at the end of each bunch (from trailing edge multipactor) take a few turns to recover. This effect is not predicted in the simulations and was first seen at the LANL PSR.
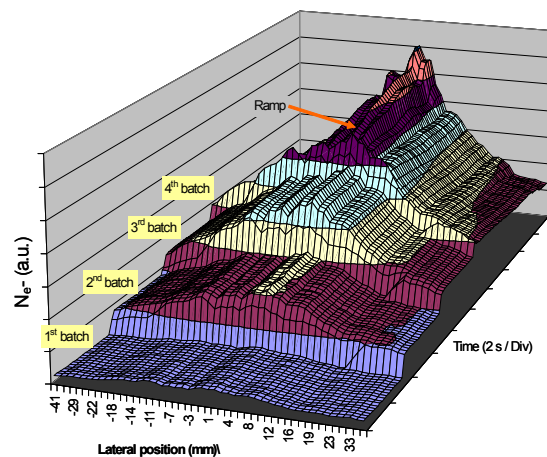

FIGURE 3. E-cloud buildup data from the CERN strip detector placed in a drift space in the SPS for LHC type beams with 25 ns bunch spacing (from M. Jiménez talk).
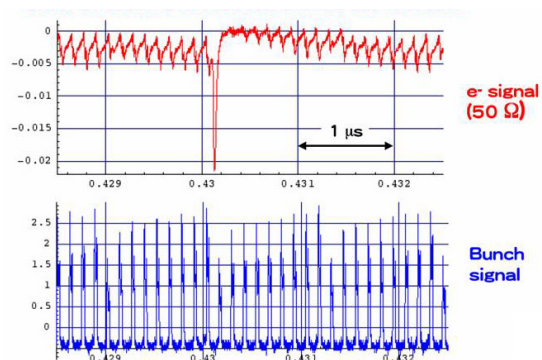

FIGURE 4. Data from electron sweeping detector in the KEK-PS MR (from talk by T. Toyama at ECLOUD'04).

RFA detectors with fast electronics on the collector are used at the LANL PSR to observe the flux of electrons hitting the wall during trailing edge multipactor. An example is shown in Figure 4 of the paper by C. Warsop, "A Review of Loss Mechanisms

and Key Design Choices for High Intensity Hadron Rings" in these (HB2004) proceedings. Simulations of the PSR e-cloud observations using POSINST and CSEC are in general agreement with the data.

ELECTRON CLOUD INSTABILITIES

Beam instabilities and/or emittance growth induced by strong electron clouds limit the performance of several accelerators. ECI observables include thresholds, mode spectra and growth rates. Some examples of the numerous observations reported at this workshop are shown in Figures 5-8 and discussed in this section.

Vertical beam blowup (LER)
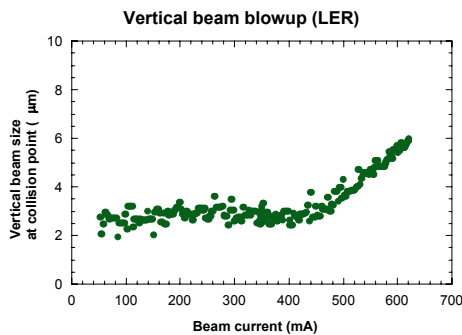
FIGURE 5. Vertical emittance data for KEKB showing the onset of emittance blowup from ECI (from talk by H. Fukuma at ECLOUD'04.)
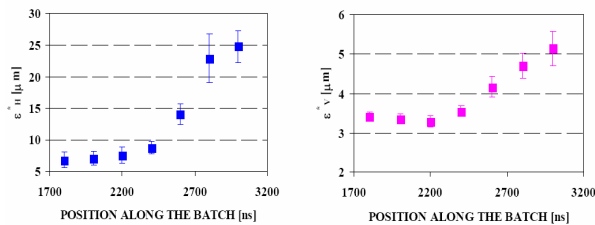
FIGURE 6. Horizontal emittance (left) and vertical emittance (right) growth along the batch for 1st 48 bunches in the CERN SPS with LHC beams.
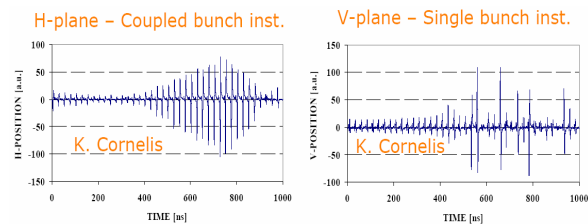
FIGURE 7. Snapshot of BPM signals (horizontal left, vertical right) for 1st 48 bunches in the CERN SPS with LHC beams (Fig. 6 & 7 from talk by G. Arduini at ECLOUD'04).
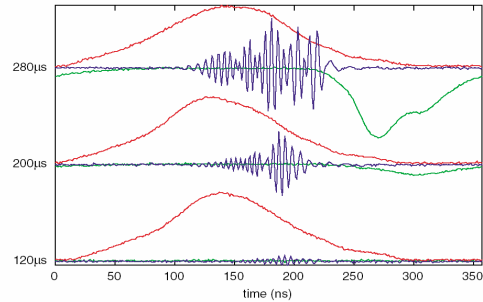
FIGURE 8. Time evolution of the e-p instability in the LANL PSR (from talk by M. Blaskiewicz at ECLOUD'04). The red curve is beam intensity, blue the vertical BPM signal showing high frequency centroid motion and green is an RFA signal of the electrons striking the wall. The RFA gain was lowered to keep the signal from saturating as the instability developed.

Both analytical models and simulation codes have been developed for ECI for both short and long bunch regimes. Analytical coasting beam centroid models have provided useful insight into ECI for the CERN ISR and the LANL PSR. Models using approximate analytical wake fields are more recent work that was reported at this workshop. A number of codes in use for ECI and discussed at the workshop include HEADTAIL, PEHTS, PEI, QUIKPIC, BEST, NCSEC, ORBIT and WARP. They cover a variety of approaches and some are tailored for particular regimes. Benchmarking of codes on some standard problems is underway.

Comparisons of simulations with experimental data show generally good agreement with thresholds, mode spectra and growth rates for KEKB and reasonable agreement on thresholds and modes at SPS/LHC. Analytical models and simulations agree with observations on mode spectra for PSR and are in rough agreement on thresholds. For a more complete summary of ECI at ECLOUD'04 see the session summary by Zimmermann and Wolski in the ECLOUD'04 workshop proceedings.

PROGRESS ON CURES

A very brief summary of the highlights on cures as presented at this workshop follows. Weak solenoids were very effective in reducing e-cloud activity and ECI at the B-factories, KEKB and PEP-II. Beam scrubbing/conditioning to reduce SEY has been shown to be effective for LHC beams at the CERN PS/SPS and has also proven effective at the LANL PSR. Tests at the SPS also suggest that beam scrubbing may be slower on a cold surface. Tests to date of non-

evaporable getter (NEG) coatings are very encouraging and such coatings are now planned for the warm sections of LHC and will also be tested at RHIC. Tests of grooved metal surfaces at SLAC showed a 30% reduction in effective SEY and more tests are planned. Damping of ECI by feedback was effective at the SPS for coupled-bunch ECI in the horizontal plane. Landau damping of ECI by increasing tune spread in various ways is effective at the LANL PSR as is coupled Landau damping.

PANEL DISCUSSION

Ten panelists, representing a large fraction of the current activity in this field, addressed the issues of future needs and future directions on ECE. A number of general themes emerged. There was general consensus that understanding the surface science underlying secondary emission and gas desorption is very important, needs more work and would benefit from greater inter-laboratory collaboration.

Systematic benchmarking of codes against one another, and against experimental data, is needed and would also benefit from international collaboration. Such an effort was started after the ECLOUD'02 workshop, and needs to be reinvigorated. A website for such an effort has been in place at CERN for over two years and anyone is welcome to contribute. The need for a self-consistent and combined treatment of e-cloud buildup and instability dynamics in the simulation codes was identified as priority item. Direct measurement of the e-cloud density at the beam location (rather than at the chamber surface) is of fundamental importance and requires new diagnostic methods. Careful evaluation of NEG coatings for long-term effectiveness in reducing SEY and its effectiveness in reducing gas desorption was recommended. Better understanding and characterization of gas desorption (and electron emission) by stray beam particles striking the vacuum chamber walls was identified as a high priority for the heavy ion machines such as RHIC, the heavy ion fusion linacs, and future machines at GSI.

be resolved in order to predict performance of new machines with high confidence. The B factories are running quite well now after controlling ECE largely by means of weak solenoid windings on a good fraction of the ring circumference. Extrapolation to higher intensity is not assured and additional mitigation of ECE may be needed for the proposed Super B Factory projects. The systematic program at the CERN SPS in preparation for LHC continues to provide a wealth of valuable information on many aspects of ECE especially on beam scrubbing which is a key element of the LHC strategy to control ECE. Vacuum pressure rise is a major limitation on RHIC performance and is not adequately understood. There is convincing evidence of ECE at RHIC but beam scraping losses appear to also contribute significantly to the pressure rise.

Various simulations of e-cloud buildup are in reasonable agreement with observations, given the uncertainties on input parameters, in particular the effective SEY of technical surfaces and certain source terms for the seed electrons. The effect of unstable coherent beam motion on multipacting is generally not included in the simulations. A novel approach to the e-cloud build-up, based on simple nonlinear maps that advance the e-cloud dynamics in time, yields results in striking agreement with traditional simulations at a tiny fraction of the CPU cost of the latter. Such results suggest an underlying simplicity of the dynamics. Understanding the physical reasons for such a success merits high priority.

Models and simulations of ECI give generally good agreement with experiments on mode spectra. Thresholds and growth rates are in good agreement for KEKB data but comparisons are less complete for other rings. Comparisons and benchmarking between codes and with experimental data are highly desirable and underway. This is an official goal of the US-LARP and the CARE program in Europe. Codes that self consistency combine e-cloud buildup and beam dynamics are very much needed but still present major challenges to present-day computing capabilities. Nevertheless several efforts towards this goal are underway.

CONCLUSIONS

This workshop demonstrated that good progress is being made towards a better understanding of ECE and means of controlling the adverse impact on accelerator performance. However, much remains to

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