Report of the Working Group on Electron Cloud Effects

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The Working Group (3) on Electron Cloud Effects (ECE) was organized for the 13th ICFA Beam Dynamics Mini-Workshop on Beam Induced Pressure Rise at BNL. Participants are listed in the Appendix. During this group's meeting on Thursday afternoon, Dec 11, 2004, several topics were discussed including:

- Definition of electron cloud or electron cloud effect and related terms
- Clarification of points raised at the BNL workshop
- Status of our present understanding
- Unresolved issues
- Future plans and work that needs to be done
    - Needed experiments
    - Comparison of codes and comparison of simulations to experiments
- Recommendations for RHIC

A summary of the discussions follows.

Definitions

K. Harkay requested a definition of the electron cloud or electron cloud effect since the term is used by various speakers to cover a number of different situations. In the ensuing discussion it became clear that the terms had different meanings for various groups. While individual research groups or localized communities can share a common understanding of the terms, the meanings are not universal and it behooves speakers to define their meaning for wider audiences. For many machines, the term implies creation of a significant electron density in the beam chamber through amplification of the initial or primary electrons by some form of beam-induced multipactor process. However, there are machines where a large number of photo-electrons create a troublesome electron density without the need for further amplification by beam induced multipactor. Similarly, heavy ions scraping the chamber can also release copious numbers of electrons without further amplification by multipactor processes. At the end of the discussion it was generally accepted that an electron cloud is a collection of sufficient low energy electrons in the beam chamber to cause a noticeable effect on the beam or the accelerator performance.

There is no single electron cloud effect to associate with the term. An electron cloud of sufficient density can produce a variety of effects, whose importance varies with the particular situation. A list of electron cloud effects observed to date at one or more accelerators includes:

- Gas desorption (pressure rise), the subject of this workshop
- Betatron tune shifts along a bunch train
- Coupled-bunch instabilities
- Space charge neutralization
- Single-bunch instabilities, often referred to as two-stream instabilities in plasma physics
- Emittance growth along a bunch train
- Heat load on cryogenic walls
- Interference with diagnostics

In the course of the discussion other terms came up that needed a context dependent definition including “saturation”, “neutralization” or “equilibrium” value of the electron cloud spatial or line density. In multi-bunch machines the electron cloud builds up along the bunch train until it reaches a constant value, which is loosely and variously referred to by any one of these terms, but is perhaps best described by the equilibrium value where the electron loss rate equals the electron generation rate. In the Los Alamos PSR, the electron density surviving the gap between bunch passages “saturates” i.e., reaches a maximum value nearly independent of beam intensity, beam losses and other parameters that influence the line density of electrons generated during trailing edge multipactor. Even the term “beam scraping” admitted to more than one meaning. The lesson here is that speakers and authors should be careful to define their use of these terms, especially for wider audiences.

Clarification of certain points raised at this workshop

This working group discussed a number of issues that came up during the workshop. One of the ongoing puzzles has been the absence of any observed electron cloud effects at ISIS. The working group leader asked Giulia Bellodi (RAL) to give an impromptu summary of the work on this subject carried out at RAL. She reported on her comparison of POSINST and ECLOUD simulations of PSR, ISIS and ESS. The difficulties of putting in the geometry of the ISIS vacuum chamber whose aperture varies continuously to keep a more or less constant ratio of aperture to beam size were noted. In addition, the RF shields (array small rods parallel to the beam) in the ceramic chambers are difficult to model. She reported that it took 4000-5000 slices of the PSR beam pulse to get convergence in the answers, especially for a Gaussian longitudinal beam profile.

Dr. Bellodi also discussed preliminary results of an experimental search for an electron cloud at ISIS. They used channel plates to amplify the electron signal. This set up did have some time resolution but was not fast enough for turn-by-turn resolution. In general, they saw a weak signal early in the ramp (~ 0.1 nA/cm^2) and at the end of acceleration saw a number of electrons more or less consistent with residual gas ionization by the beam.

J. M. Jimenez (CERN) noted that the saturation (equilibrium) density cloud density at SPS does not differ between Cu and Stainless Steel but the POSINST simulations showed a factor of 5-10 difference. M. Furman suggested that it may be due to conditioning (beam scrubbing) in the experiments whereas the simulations use secondary emission yields (SEY) for unconditioned materials.

J. M. Jimenez and F. Ruggiero pointed out that the evidence for or against electron cloud effects in the arcs at RHIC has very important implications for the LHC project. D. Trbojevic (BNL) noted that they can not, at the present, directly measure pressure rise in the RHIC arcs. An upper bound from the increase in heat load can be estimated but it has large uncertainties. It was agreed that an electron detector in the RHIC arcs would be most informative and the Working Group recommends that such a detector be installed.

The potential of non-evaporable getter coatings (NEG) to reduce the SEY of beam chambers is a relatively new development attracting considerable attention as a possible cure for ECE. Needless to say, accelerator personnel are very interested in any observations and operating experience with these materials. In this regard, we should mention the positive operating experience at ESRF, reported by Roberto Kersevan at this workshop where NEG coatings were used to avoid a pressure bump in the middle of a straight section and the radiation safety problem (bremstrahlung) such a bump can cause. A cautionary note was reported by Yulin Li in studies at Cornell where a powdery substance developed on a NEG coated surface after extensive pumping tests. It was suggested this may be due to excessive H_2 sorption. There was some discussion and considerable confusion during this meeting over second and third hand reports that the SEY curve for a NEG sample went from ~1.3 to ~ 1.6 in 22 days of exposure to vacuum of ~$3x10^{-10}$ Torr during offline tests at SLAC, which were ultimately clarified and confirmed by reference to the published results[1].

The present understanding of electron cloud effects

R. Macek led a discussion of the present understanding of electron cloud effects which is summarized below. For more information, see the informative recent review of theoretical investigations on the electron cloud by Frank Zimmermann in the August 2003 issue (No. 31) of the ICFA Beam Dynamics Newsletter.

It was noted that the important basic features are understood at varying levels of detail and sophistication. For example, the SEY and emission spectrum curves in the POSINST code are quite detailed and validated against a significant body of data. In another example, according to Francesco Ruggiero, the existence and positions of two electron stripes (high-density spots) in the electron cloud density in a dipole magnet was predicted by Frank Zimmermann's simulations before it was observed experimentally at the CERN SPS, as was the dependence of stripe position on bunch spacing.

While there have been some notable successes as mentioned above, the overall understanding of electron cloud effects is not complete. Some simplification of the physics models is generally needed to produce a tractable code. However, depending on the accelerator and the beam being modeled, the missing physics may or may not have a significant impact on the results. This is not always easy to judge beforehand. For a variety of reasons, it is useful to identify and be aware of the missing physics. For example, the electrons stripped at the injection foil and those from secondary emission of the stored beam striking the foil, and even thermionic emission from the foil, are not in the models for PSR, SNS, ESS and ISIS. Typically, the electrons born at the wall (which are important for trailing edge multipactor) from residual gas ions created by beam ionization and driven to the wall are not included. The extra residual gas ionization from the electron cloud is also not included in some codes. In a related subject, the issue of whether the gas ions liberated by residual gas ionization can affect the electron dynamics was studied by F. Zimmermann and G. Rumolo[2] and found to be negligible for SPS/LHC conditions.

Clearing fields are being considered for mitigation in certain applications, e.g. at the stripper foil for SNS, but have not yet been included in the SNS simulations. At this time, L. Wang (BNL) is incorporating clearing fields in the CLOUDLAND code for electron buildup. Simulations with clearing fields included have been done earlier for LHC and KEKB[3],[4].

Perhaps the most important and difficult code development task remaining is the coupling of a good model for electron build-up with the complete dynamics of the beam motion in a fully dynamical simulation. The problem is being addressed but is very computer intensive. As a result considerable approximation has been invoked by various authors to obtain results with present day computing capabilities.

Another problem with the simulations is the number of poorly determined input parameters. For example, the SEY for technical surfaces in particular machines can vary greatly depending upon the history of beam scrubbing, venting, etc. The peak SEY can have a large effect on the gain from beam induced multipactor especially in situations such as the long bunch beam at the LANL PSR, where the trailing edge multipactor gain has not yet reached "saturation". The absolute value of the source term for seed electrons from beam losses is very uncertain because the details of the beam losses - their location, angle of incidence and distribution of scattered and secondary hadrons are very difficult to determine with the required accuracy. When the build up reaches an equilibrium level, as is the case for certain machines with a long train of short bunches, the source term has little influence on the equilibrium value but can affect the time to reach equilibrium. However, for a machine such as the LANL PSR, where equilibrium is not reached, the electrons from trailing edge multipactor are observed to depend linearly on the losses.

At this time, the confidence in the predictions of electron cloud effects for the new machines is not high enough for the risks involved. To a considerable extent this is because the consequences of being wrong can be very costly. More benchmarking and successful comparisons with experiments are needed. Successful predictions made before the experimental results are obtained are especially valuable in building confidence. When experimental results are known in advance the natural tendency is stop the code development when agreement is reached or adjust parameters within uncertainties to get agreement with the data.

Some unresolved issues

A number of unresolved issues were touched on by the working group.

As noted in the last section, detailed estimates of seed electrons from beam losses for long bunch machines such as the LANL PSR, SNS ring and the ISIS ring are poorly determined and almost impossible to measure. One approach that was mentioned by R. Macek, is to use one set of experimental data on electron signals to fix the source term by varying the input parameters until the simulations agree with the data set. Then, with the source term fixed, one can vary other beam parameters e.g. beam intensity, to obtain tests of the simulations. Another approach, not yet undertaken, is to do detailed simulations of losses using particle tracking codes such as ORBIT along with simulations of the scattered beam using a code such as MCNPX or LAHET to see where the scattered beam goes. This would be followed by estimates of the secondary electrons from the grazing angle encounters with beam chambers using the semi-empirical models described in the Thieberger et al paper[5].

The measurements of microwave transmission at CERN made by F. Caspers et al and reported at this workshop by F. Ruggiero are rather surprising and not well understood but could be compatible with the effect of dust particle stirred by the beam. A new test involving mechanical shaking of the beam pipe will be performed at the SPS in a few months.

There are still significant discrepancies between experiments and simulations that ought to be resolved regarding the flux and spectrum of electrons hitting the wall for SPS. At the LANL PSR, the observed electron bursts are not understood and the same is true of the so called "1st pulse instability."

Worked needed or planned for the future

There was general agreement that more detailed benchmarking of codes was a high priority need. This includes code-to-code comparisons, and more definitive comparisons with experiments, which explore a number of parameter variations. Macek noted that there is a large amount of experimental data at PSR that has not been compared with simulations.

Franceso Ruggiero outlined a number of needs and plans for the LHC/SPS facilities. These included:

- Efforts to further simulate heat load on cryogenic walls and compare with warm/cold measurements
- Explore the dependence of the energy spectrum on bunch dimensions
- Simulate spectrum of multi-bunch instabilities including the conventional impedance
- Calculate growth rates and scaling of single bunch instability and emittance growth with damper and $Q' \neq 0$
- Simulate LHC scrubbing scenarios, heat load, collimator regions, and emittance preservation
- Compare simulations for field-free region, dipoles and quadrupoles at $\delta_{max} = 1.5$ (value achieved by beam scrubbing) and bunch intensity, $N_b \cong 1.2x10^{11}$. This task is motivated by SPS observations which indicate that, for typical LHC bunch intensities up to $Nb \sim 1.2x10^{11}$, multipacting (and beam scrubbing) stops in the field-free regions when δ_{max} is reduced below ~1.5 (by beam scrubbing), while there is still multipacting in the arcs.

To date there has been little experimental work on the electron cloud in quadrupoles. However, a number of simulations show that significant numbers of electrons can be trapped for a long time in the mirror-like magnet field of quadrupoles[6,7]. J. M. Jimenez mentioned that studies using a strip detector in a quadrupole are planned at CERN. R. Macek described some simulations of the electron cloud by M. Pivi for a PSR quadrupole and a proposal for a detector to observe the cloud, especially that due to the trapped electrons. See Figures 1-3 below.

Pivi's simulations used the POSINST code and a constant source term independent of location for seed electrons from beam losses. The simulations show a maximum electron density (averaged over the chamber cross-section) in quadrupoles that was about a factor of 6 below those for a drift space. If one takes account of the fact that beam losses at grazing angle are expected to be significantly larger in quadrupoles than in drift spaces, then the electron density in quadrupoles could make the largest contribution to the ring average of the electron line density. The other noteworthy feature of Pivi's simulations is the significant fraction (~10% of the peak) of electrons trapped in the quadrupole fields.

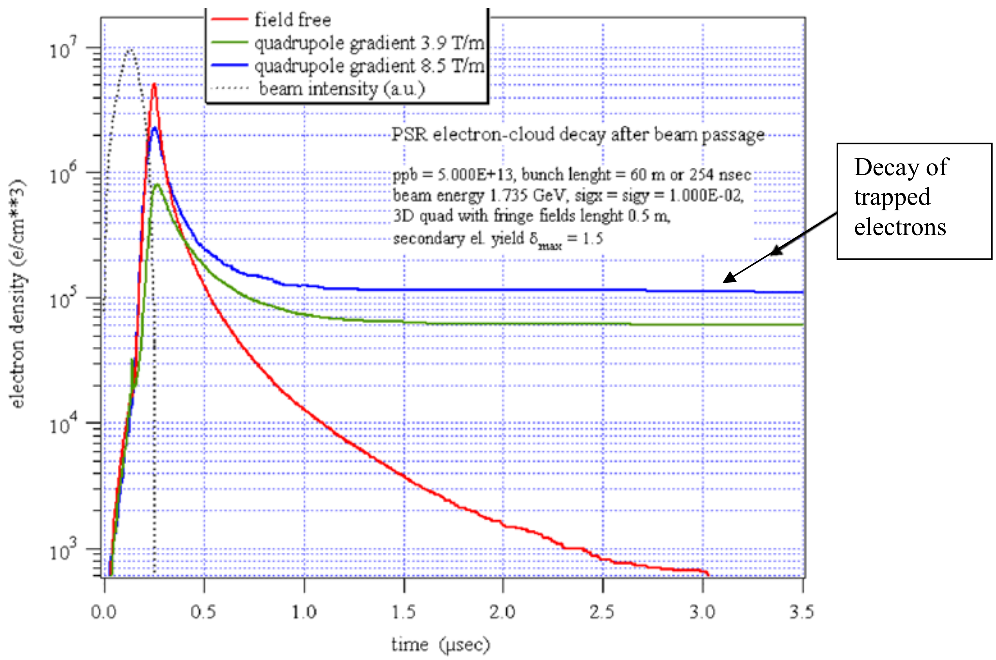

Figure 1. Simulations of electrons in a PSR quadrupole. (Courtesy M. Pivi). The red curve is the simulated electron density in a field free region, the green curve is the electron density for the standard-gradient quadrupole (3.9 T/m) in the PSR and the blue curve for a gradient of 8.5 T/m. Note the very slow decay of electrons trapped in the quadrupole long after the beam pulse has passed.

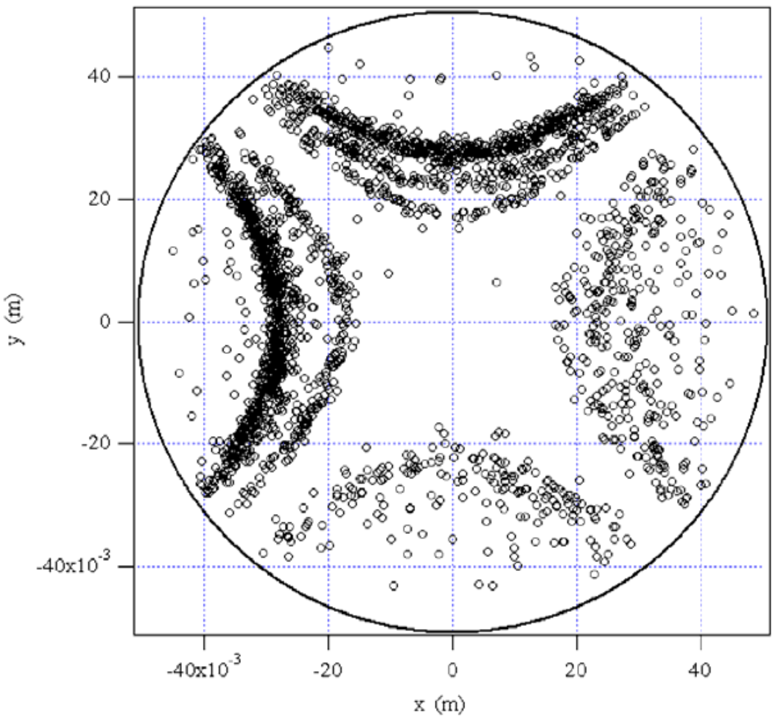

Figure 2. Snapshot of trapped electrons in a PSR quadrupole 5 μs after passage of the beam pulse. (Courtesy M. Pivi). As it might be expected, the trapped electrons follow the magnetic field lines.

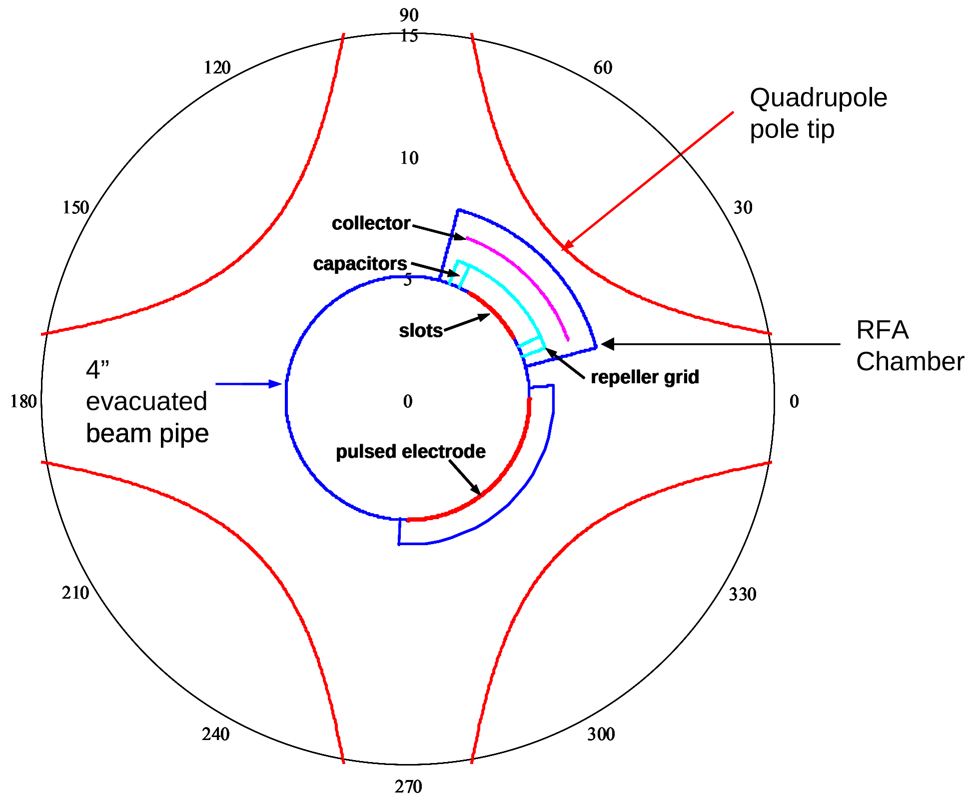

Figure 3. Schematic cross section of a proposed electron sweeping detector for a PSR quadrupole.

The proposed detector (Figure 3) is an adaptation of the electron sweeping detector developed at PSR for use in a drift space. A pulsed electrode would be used to sweep trapped electrons into the chamber of the retarding field analyzer (RFA). The proposed detector makes use of the fact that the aperture of the PSR quadrupoles is significantly larger (7 inch diameter) than the aperture of other beam chambers (4 inch) in PSR. Thus, the 4 inch aperture of the beam chamber in the quad is not a limiting aperture.

Recommendation from the Working Group

The question of possible electron clouds in the cold arcs of RHIC was discussed in the working group meeting and afterwards by email. Francesco Ruggiero noted that the existence or absence of electron clouds in the RHIC arcs has important implications for LHC. Thomas Roser and S.Y. Zhang mentioned that the absence of cryogenic heat load (within significant errors) and electron cloud induced instability or emittance growth support the case that they do not have electron clouds in RHIC arcs. The evidence on the change in total heat load (when operating at conditions that might lead to multipacting) was briefly discussed but level of uncertainty on the measurements was reported to be large. The issue of electron clouds in the RHIC arcs does not seem to be resolved at this juncture.

It was the consensus of the working group during the meeting to recommend that the RHIC operation try to find a way to detect any electron cloud in the RHIC arcs. This would help clarify the situation at RHIC and the information would be of great value to the community, especially for LHC. That said, it should be noted that installations in the cold parts of the machine are very expensive and any single detector could only sample a very limited part of the RHIC circumference. The working group made no attempt to do a careful cost-benefit analysis of such a program.

The working group meeting ended with mention of the ECLOUD'04 workshop scheduled for April 19-23, 2004 at Napa, CA.

Acknowledgements

I would like to thank all of the participants for a most interesting meeting. I would especially thank those (including Frank Zimmerman, who was not present) who read over this report and supplied invaluable comments and corrections.

References

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Appendix

List of Working Group Participants

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