SUMMARY OF SESSION I, EXPERIMENTAL OBSERVATIONS AT EXISTING ACCELERATORS AND CONCERNS FOR FUTURE MACHINES

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Abstract

This report briefly summarizes the first session (I) at the mini-workshop, ECLOUD'02, held at CERN, 15-18 April 2002. As the title indicates, this session focused on experimental observations at existing accelerators and concerns for future machines. Observations were reported from KEKB, PEP-II, SPS, and PSR and design issues involving the electron cloud were presented for SNS, Linear Collider Damping Rings and the LHC. These represent a good sample of the broad spectrum of accelerator types impacted by electron cloud effects (ECE).

1 AGENDA

The list of presentations included:

0. F. Ruggiero (CERN) – *Welcome and Goals of the Workshop*.
1. H. Fukuma (KEK) – *Electron Cloud Effects at KEKB*.
2. F. J. Decker (SLAC) – *Electron Cloud Effects at PEP-II*.
3. K. Cornelis (CERN) – *Electron Cloud Instability at the SPS*.
4. M. Jimenez (CERN) – *Electron-Cloud Observations in the SPS*.
5. J. Wei (BNL) – *Electron Cloud Effects in High-Intensity Proton Machines*.
6. A. Wolsky (LBNL) – *Electron Cloud in Linear Collider Damping Ring*.
7. F. Zimmermann (CERN) – *Electron Cloud in the LHC*.

2 GENERAL COMMENTS

Ruggerio, in his opening remarks, set the tone for the workshop and listed the following guiding goals and expectations:

- Benchmark simulations against beam observations and against each other
- Determine which simulation approaches best represent reality
- Document the present understanding and determine the important open questions
- Develop a program for future research and development
- Strengthen and expand international collaborations for this work

This session contributed to these goals by discussing many of the beam observations and outlining the key concerns for major new or proposed machines. In addition, a number of comparisons to simulations were made.

In discussing experimental observations and their interpretation, a good starting point is a reasonably comprehensive itemization of the various observed or anticipated electron cloud effects (ECE). Such a listing or categorization of ECE and many of the machines where they have been observed (in parentheses) or, in the case of proposed machines [in square brackets], are at risk from the particular ECE includes:

- Beam induced multipacting
    - Resonant (APS, KEKB, PS, SPS), [LHC]
    - Trailing-edge multipactor (PSR), [SNS, JHF]
- Vacuum degradation i.e., electron-stimulated gas desorption, is perhaps the most common indication of beam induced multipactor or intense electron cloud formation
- Transverse coupled bunch instability from the electron cloud wake (APS, B factories, PS, SPS), [LHC]
- Transverse single bunch (head-tail) instability; emittance blowup (APS, B factories, PS, SPS)
- Transverse coasting beam or long bunch, two-stream instabilities (e-p) (ISR, PSR, AGSB), [SNS, JHF]
- Tune shifts (KEKB, AGS Booster) and tune spread are undoubtedly present at some level whenever an electron cloud is formed
- Heat load on vacuum chamber walls (SPS) is a major concern for the cold bore of [LHC]
- Cloud-induced noise or spurious signals in beam diagnostics (e.g., wire scanners, electrostatic pickups, ionization profile monitors) (PSR, PS, SPS, KEK-PS)
- Electrons trapped in distributed ion pump leakage field (CESR)
- Electrical breakdown or discharge in high voltage systems such as strip line kickers or unshielded rf gaps (possibly seen at PSR)

Longitudinal effects have not been specifically identified nor included in most theoretically treatments or analyses. They are undoubtedly present at some level, as noted by Ruggerio.

The sources of primary electrons are essential inputs to the simulations and vary across the spectrum of accelerators. Photoelectrons from synchrotron radiation are well understood and are undoubtedly the dominant source at positron rings and the anticipated source at LHC. For proton rings, the situation is less clear-cut and

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subject to greater uncertainty and ambiguity. At PSR significant primary electrons originate at the stripper foil (convoy electrons from the stripping process, secondary emission from foil hits by the stored beam, and even thermionic emission caused by beam heating of the foil) and from proton beam losses. Residual gas ionization is another source. When the electron cloud buildup can saturate before encountering a long gap, as seems to be the case for long bunch trains in a number of machines (e.g. the SPS), the exact source strength is less important than in smaller rings such as PSR or SNS.

3 REVIEW OF PRESENTATIONS

3.1 Electron Cloud Effects at KEKB

Fukuma reviewed experience with ECE at the KEKB low energy ring (LER), which included observations of emittance growth, instability mode spectra and growth times, tune shifts and luminosity degradation both with and without solenoids. In the absence of mitigation, emittance growth and luminosity degradation greatly limited facility performance. Solenoids, which now cover 95% of the straight sections (~70% of the ring circumference), were most beneficial in suppressing the electron cloud effects and have resulted in a good improvement in the KEKB luminosity.

Beam blowup in the LER at KEKB was eliminated after the last (5th) installment of solenoids. The tune shift along the train (from the electron cloud), which seems to be a good measure of the cloud density, was reduced by at least 40% after the 4th installment of solenoids. The growth rate of the coupled bunch instability was reduced by a factor of two after the 4th installment of solenoids. Mode spectra from simulations of the electron cloud induced coupled bunch instability (solenoids off) are in general agreement with observations for the vertical plane but not for the horizontal plane, if the photoelectrons are produced mainly at an illumination point of the synchrotron radiation. However, if the photoelectrons are produced uniformly over the surface of the vacuum chamber, then the simulated mode spectra are consistent with observations for both planes.

3.2 Electron Cloud Effects at PEP-II

Deckers reported that, despite an antechamber and TiN coatings in the LER arcs, significant ECE are observed at PEP-II. These include vacuum degradation, growth of beam size, and reduction of both luminosity and beam lifetime at high current. Solenoids, which now cover 95% of the drift spaces, have reduced multipacting as detected by vacuum pressure readings but have not eliminated the electron cloud and resulting performance degradation at the highest intensities.

Creative operational measures have been invoked to maximize luminosity in the presence of the electron cloud including:

- Minimizing emittance growth by optimizing the number of bunches and bunch spacing,
- Use of gaps between trains (mini-gaps) to clear the electron cloud, and
- Use of a ramp in bunch current after the ion gap to avoid losing HER bunches.

While good progress has been made to reduce the ECE with solenoids and creative operational measures, a number of puzzling or controversial issues remain. For example, the beam size blows up in the horizontal plane in experiments while simulations show it in the vertical. Also the variability in the instability thresholds from day to day is unexplained. The bottom line for PEP-II is that despite the lingering ECE effects, the solenoids and operational measures have permitted operation at up to 1750 mA in the LER without severe degradation of luminosity.

3.3 Electron Cloud Instability at the SPS

Cornelis presented persuasive evidence (beam position centroid measurements) for a fast (growth time ~ 50 turns) coupled bunch instability of low order in the horizontal plane and a single bunch (head-tail) instability in the vertical plane induced by the electron cloud. The later has a growth time that depends on intensity starting from ~ 500 turns just above threshold and going to ~ 100 turns at twice threshold intensity. The horizontal instability is amenable to control by the existing transverse feedback system. The cloud, as evidenced by observations detailed in the talk by Jimenez, develops first in the dipoles. This helps explain the difference in behavior of the instabilities in the two planes.

In the analysis by Cornelis, a bunch experiences a horizontal force from the horizontally constrained cloud in the dipoles proportional to its horizontal displacement. This system can be described as a set of coupled oscillators for the various bunches and can lead to the coupled bunch instability. In the vertical plane, the electrons are free to move toward the center of the bunch and can even be trapped inside the bunch producing the conditions that can produce a head-tail coupling and resulting instability. The equivalent impedance in the vertical has been measured by following the betatron phase evolution of head and tail over one synchrotron period after a vertical kick. Calculations (using a wake field approach) and measurements for the first bunch in the train and one residing in the cloud were in reasonable agreement after adjusting (shortening) the range of the wake for the bunching sitting in the cloud.

3.4 Electron Cloud Observations at the SPS

Jimenez reviewed an extensive program of systematic experimental observations pertaining to the electron cloud in the SPS for LHC-type beam (bunch spacing of 25 ns). This program was launched after large vacuum pressure increases, anomalous signals (baseline shift) on electrostatic pickups, and beam instabilities were observed the first time high-intensity bunches were injected under LHC conditions. Pressure rises indicated that the electron cloud appears in the dipoles at a significantly lower threshold than in the straight sections, which was confirmed in 2001 with new strip detectors placed in a special test dipole in the ring.

The novel strip detector was developed to detect the presence of the electron cloud impinging on the chamber walls in a dipole field and to measure the horizontal spatial distribution of the cloud. Simulations predicted there would be two peaks or strips in the cloud distribution (in a dipole) above the threshold for multipacting. These were subsequently observed in the strip detector and studied as a function of dipole field, bunch spacing and filling pattern.

A unique setup was deployed in the ring to provide in-situ measurements of the secondary emission yield (SEY) of Cu samples exposed to the beam induced electron cloud. These demonstrated the effect of beam scrubbing and showed a significant reduction in SEY as a function of integrated beam time under LHC conditions. The peak SEY went from 2.4 to 1.6 after 90 hours of integrated beam time. Beam scrubbing was also indicated by the decrease in pressure rise ($\Delta P/P$) from multipacting, which decreased linearly by a factor of ~40 over a period of ~60 hours of integrated LHC-type beam time.

Since the main concern for LHC is the heat load on the cold bore, a pick up calorimeter has been developed and calibrated. It will be used to measure the heat load in the SPS and extrapolate to LHC conditions. Future work will also include improved measurements of the spatial distribution of the cloud to firm up the location of the pumping slots in the LHC beam screens.

3.5 ECE in High Intensity Proton Machines

Jie Wei reviewed the current understanding of ECE in high intensity proton machines with emphasis on the effects most relevant to long-bunch accumulator rings, in particular, the existing PSR and implications for the SNS ring now under construction. He reported that another machine (RHIC) should be added to the growing list of accelerators where ECE is observed. There is now evidence for beam-induced multipactor from the newly commissioned RHIC where a strong vacuum pressure rise was observed when the bunch spacing was halved during high intensity gold beam injection. In addition, the fast instability observed for debunched coasting beams at the AGS Booster is thought to be the two-stream e-p instability.

In long-bunch accumulator rings the trailing edge multipactor mechanism, a nonresonant amplification process, prevails as contrasted with the resonant variety found in short bunch rings such as SPS or LHC or the positron rings. Trailing edge multipactor also differs in that the electron cloud buildup typically does not saturate as it does in a long train of bunches common in other rings where ECE is observed. The sources of primary electrons also differ. In PSR and SNS the stripper foil has several mechanisms for generating electrons including the several hundred keV electrons stripped from H^- (the so called “convoy” electrons), secondary emission and knock on electrons from foil hits by the stored beam and even thermionic emission from the foil. Continual proton losses from foil hits and other mechanisms or in collimators can generate many primary electrons per lost proton. The convoy electrons, if not properly collected, can also cause localized heat damage to the wall.

The most serious ECE for PSR and SNS is no doubt the two-stream e-p instability from coupled oscillations of the electron cloud and the proton beam. Enhanced Landau damping by higher rf voltage, multipoles, X,Y coupling and inductive inserts have been helpful in significantly raising the instability at PSR. Reduction of the primary electrons by lower vacuum, lower beam losses, clearing fields, collection of the convoy electrons and bias on the stripper foil reduce the prompt electron signal (largely due to trailing edge multipactor) at the end of each bunch passage but have little effect on the instability threshold because the electrons driving the instability are mainly those that survive the gap to be captured by the next pulse. Measurements of these with the electron sweeping detector at PSR show a saturation characteristic which can explain why variations of prompt electron have little effect on the instability. A larger reduction in the primary sources is probably needed to bring the electrons surviving the gap out of saturation. TiN coatings and weak solenoids have made large reductions in the prompt or multipactor electrons in a small test section in PSR. This is a potential cure but it has not been shown experimentally that this will be sufficient to greatly reduce the electrons surviving the gap. Combinations of methods may be needed to adequately suppress the electron cloud generation in SNS.

The SNS ring design has incorporated many measures to suppress electron production. Fractional beam losses will be kept low; the ring vacuum will be an order of magnitude better (~ 5 nTorr) than PSR, electrons at the stripper foil will be collected and backscatter suppressed, the vacuum chambers will be coated with TiN to suppress multipactor, and a beam-in-gap kicker will be deployed to keep the gap free of beam (10^{-4}level). Landau damping will be enhanced by a large momentum acceptance and sextupole families, use of momentum painting and high RF voltage. Space is also reserved for a possible wide band damper system.

3.6 Electron Cloud in Linear Collider Damping Ring

Wolsky discussed work to estimate the instabilities driven by the electron cloud in both the NLC and TESLA positron damping rings. He began with a comparison of parameters for the damping rings and currently operating positron storage rings of roughly comparable parameters. These comparisons alone raise the specter of ECE for future linear collider damping rings.

Simplified analytical models were used for rough estimates of thresholds and growth rates of the single bunch and coupled bunch modes. In these the cloud buildup was assumed to reach saturation with a density given by the neutralization condition. The wake field from the cloud was estimated from a broad-band resonator model with different parameters for short-range and long range wakes. Growth rates were estimated by standard theory. As a check the models were also applied to some existing positron rings with reasonable results. The analytical long range wake field for the NLC compared favorably to the results of POSINST simulations.

The main conclusion from this work was that the NLC and TESLA damping rings could, indeed, encounter performance-limiting ECE. More detailed studies with simulations are warranted and possible countermeasures such as TiN coatings need to be investigated.

3.7 Electron Cloud in the LHC

Zimmermann wrapped up the session with review of the latest estimates of ECE at LHC. For some time the main concerns have been the heat loads on the beam screen inside the superconducting magnets and through the pumping slots, although beam instability at injection could be a problem as well as vacuum pressure and gas desorption in the interaction regions.

For LHC the dominant source of primary electrons is the photo-electrons from synchrotron radiation from the 7 TeV proton beam. Parametric studies of the electron cloud buildup and resulting heat load in various ring components have been carried by computer simulation (ECLOUD). The cloud buildup and heat load are sensitive to a number of parameters including the maximum secondary emission yield (δ_{max}), photon reflectivity, bunch intensity, bunch spacing and inclusion of elastic electron reflection. It also depends on the type of magnetic field. Dipole fields had the lowest heat load while drifts were highest with quads in between.

In order to achieve the LHC design bunch intensity (1.1×10^{11} proton/bunch) at a bunch spacing of 25 ns within the planned cooling capacity, δ_{max} must be brought down to ~1.1. Measurements at CERN of δ_{max} (for Cu) as a function of electron bombardment dose indicate this can be achieved at a dose of 0.01 C/mm^2. The present strategy is to use beam scrubbing during commissioning to reduce δ_{max} to 1.1. Other features of the LHC recipe for dealing with ECE are to use a sawtooth chamber in the arc dipoles to reduce photon reflections and coat all warm section with non evaporable getter material (TiZrV), which has a low SEY and is quite stable. Finally, there are backup solutions of larger bunch spacing and the use of satellite bunches.

Estimates of the threshold cloud density for the single bunch transverse mode coupling instability (TMCI) are below the saturation electron cloud densities for LHC and SPS. The heat load in LHC could set a tighter tolerance, but, TMCI could still be a problem especially at injection.

4 CONCLUSIONS

Electron cloud effects, such as beam induced multipacting, vacuum degradation, instabilities and interference with diagnostics, are now observed at many high intensity machines and are a serious technical risk for new machines e.g. LHC, SNS and future linear colliders. Heat load on the cold bore of LHC is another important ECE. For the high intensity accumulator rings, the “convoy" electrons from the H$^-$ injection stripping process can cause local heat damage to the wall if not dealt with in a adequate fashion.

Significant progress has been made both to understand ECE at a fundamental level and to mitigate the adverse impact on accelerator design and operation. While there has been good progress, the problem is far from being resolved. The quantitative agreement between simulated results and measurements remains uneven, and the predictive power of the available tools does not appear to be sufficient to extrapolate with high confidence the present results to future machines with higher beam intensity. A significant part of the problem for proton machines is the level of uncertainty and ambiguity on the input parameters associated with the primary electrons and the SEY, which must be determined experimentally or by other analyses. More work is clearly needed.