JP0150515

JAERI-Conf 2001-002

ICANS-XV
15th Meeting of the International Collaboration on Advanced Neutron Sources
November 6-9, 2000
Tsukuba, Japan

6.1 New Developments on the e-p Instability at the Los Alamos Proton Storage Ring*

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Abstract

New results are reported from an R&D program aimed at greater understanding and control of the e-p instability observed at the Los Alamos Proton Storage Ring (PSR). Numerous characteristics of the electron cloud for both stable and unstable beams in PSR were measured with ANL electron analyzers and various collection plates. Strong suppression of the electron flux density by TiN coating of the vacuum chamber in a straight section was also observed, thereby confirming an essential role for secondary emission at the walls. Landau Damping by a variety of techniques including higher rf voltage, transverse coupling, multipole fields in the lattice, and the use of inductive inserts has been effective in controlling the e-p instability. By these methods, the instability threshold has been raised significantly to 9.7 micro Coulombs per stored pulse.

* Work conducted by the Los Alamos National Laboratory, which is operated by the University of California for the United States Department of Energy under contract W-7405-ENG-36.

1. Introduction

The strong, fast, transverse instability observed at PSR exhibits many of the characteristics expected of the two-stream (e-p) instability observed years ago at the Bevatron and the ISR [1]. For much of the history of PSR, the instability was controlled by applying sufficient rf buncher voltage to raise the instability threshold beyond the desired operational peak intensity. However, the advent of the present PSR upgrade project, with its goal to increase the intensity to 200 μA @30Hz, required improved control of the instability [2]. In addition, this instability poses a technical risk for the SNS project. Together these factors provided strong motivation for a renewed R&D program aimed at developing both a better understanding and improved control of this instability.

For quite some time, the working model of e-p at PSR has been Neuffer's picture [1], which combined the analytical features of a coasting beam model with trapping of electrons by a small amount of beam in the gap. This picture was qualitatively consistent with the available evidence, which primarily came from observations of the unstable proton beam motion. Some of the most compelling evidence for e-p concerns the frequency spectra of the unstable beam motion at threshold. The mean frequency occurs at the calculated electron "bounce" frequency (in the space charge field of the proton beam) and varies with intensity and beam size as predicted.

Major issues and unknowns concern the dominant sources of the electrons and the degree of neutralization of the beam. Significant variations in several known sources of electrons have had little effect on the instability. For example, increasing the vacuum pressure by factors of 10 to 100 produced insignificant changes in the instability threshold intensity. Likewise, increases in the beam losses by factors of 2-3 had no effect. Suppression of electrons in the injection section by various clearing fields also had little effect on the instability. However, some evidence for an avalanche of electrons associated with unstable beams had been observed with biased collection plates.

To resolve these issues and meet the intensity upgrade goals, a two-pronged approach was adopted in 1999, which consisted of:

a) Tests and demonstrations of potential cures and
b) R&D studies aimed at greater fundamental understanding of the instability, in particular a better understanding of the electron cloud in PSR.

Key results are summarized below. For more information access the website for the 8th ICFA Mini Workshop on Two-Stream Instabilities in Particle Accelerators and Storage Rings, Santa Fe, NM Feb 16-18, 2000 at:
http://www.aps.anl.gov/conferences/icfa/two-stream.html.
Recent work on the PSR instability work was presented in several talks in Session I, which are in the electronic workshop proceedings linked to the website.

2. Tests and Demonstrations of Potential Remedies

In the Neuffer picture of the PSR e-p instability, higher buncher voltage would increase the Landau damping caused by the higher tune spread resulting from the increased momentum spread. Another feature of the prevailing picture was trapping of electrons by a small amount of beam in the gap. Higher rf voltage was expected to reduce beam leaking into the gap from longitudinal space charge forces and thus, should provide additional suppression of the instability by this mechanism.

The twin themes of Landau damping and beam in the gap, which motivated many experiments and were used to interpret much of the available data, also inspired several potential cures that were studied, tested and found effective at PSR. These included:

- Higher rf buncher voltage made possible by improvements to the rf buncher system,
- Landau damping with sextupole and octupole fields
- Coupled Landau damping using a skew quadrupole, and
- The use of inductive inserts to passively compensate longitudinal space charge forces.

A third theme, control by suppression of electron production, has proven very difficult to implement everywhere in the ring. The partial suppression attempted to date has produced, at best, only modest improvement in the instability threshold intensity.

The rf buncher in PSR was refurbished in 1998 and the maximum sustainable voltage raised from 12 kV to 18 kV. The increase in the instability threshold intensity was significant and agreed with a linear extrapolation of previous results. Following a suggestion from J. Griffin, and in collaboration with Fermilab, inductive inserts constructed from ferrite rings [3] were tried and found to be effective in raising the instability threshold. The idea was to passively compensate longitudinal space charge in an effort to keep beam from leaking into the gap. Inductive inserts are equivalent to adding additional rf voltage (with appropriate harmonics). This would also increase the momentum spread and therefore should provide additional Landau damping.

A quite useful measure of the effect of various controls is the instability threshold intensity curve, where the stored beam intensity at the threshold for instability is plotted as a function of rf buncher voltage as shown in Figure 1. The lowest curve in Figure 1 was obtained for the ring with no inductors installed and with the sextupoles set to zero current. After installation of sufficient inductance to fully compensate longitudinal space charge, the instability threshold curve was raised significantly (middle curve in Figure 1). Further improvement was obtained when the sextupoles were turned on and optimized (highest curve in Figure 1).

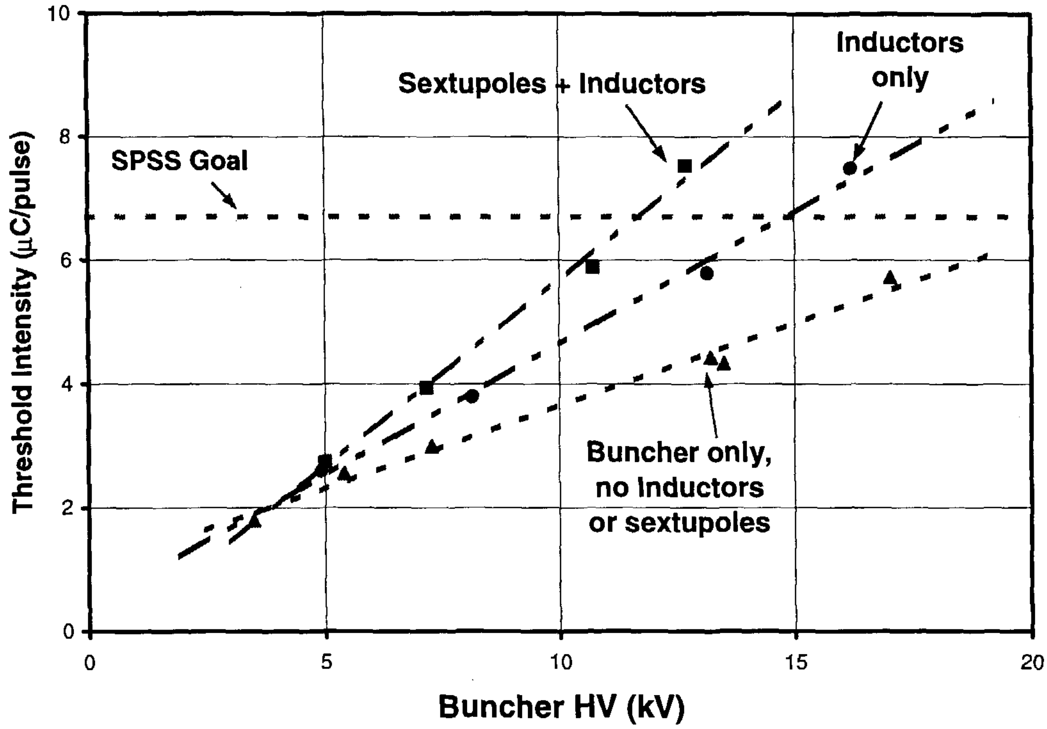

Figure 1. Effect of inductive inserts and sextupoles on the instability threshold-intensity curves.

It should be noted that inductive inserts, when operated at room temperature, produced a potentially troublesome longitudinal modulation or instability that was most noticeable for coasting beams and short-pulse bunched beams. At the suggestion of M. Popovic (FNAL), heating the inductors was tried and proved effective in controlling the longitudinal instability. An engineered version of the heated inductive inserts was recently installed and is now used routinely. It has the added benefit of permitting stable operation with a significant increase in the bunch length thereby shortening the accumulation time for a given stored beam intensity.

Transverse (X,Y) coupling via a skew quadrupole was found to be surprisingly effective. According to Metral's theory of coupled Landau damping [4], transverse coupling shares the stabilizing tune spreads and growth rates in both planes thereby providing extra damping. The effect of coupling at PSR is shown in Figure 2 where the rf buncher voltage at the instability threshold is plotted as a function of the skew quadrupole current for a fixed beam intensity of 5 μC/pulse. The horizontal and vertical fractional betatron tunes were within ~0.025 to ensure adequate coupling. The effect of the skew quadrupole was to lower the buncher voltage required to keep the fixed intensity beam stable. On the downside, the emittance exchange from coupling increased beam losses in a non-linear fashion.

The effect of sextupoles and octupoles (not shown) is very similar to the effect of the skew quadrupole. All decrease the threshold buncher voltage and increase beam losses. The strategy for PSR is to use each of these devices at low excitation where the losses haven't increased appreciably but where the effect on the instability is sizeable. It is hoped that the suppression of the instability from all these devices is additive. To date, the pair-wise effect of sextupoles and inductors or a skew quadrupole and inductors has been demonstrated to combine favorably.

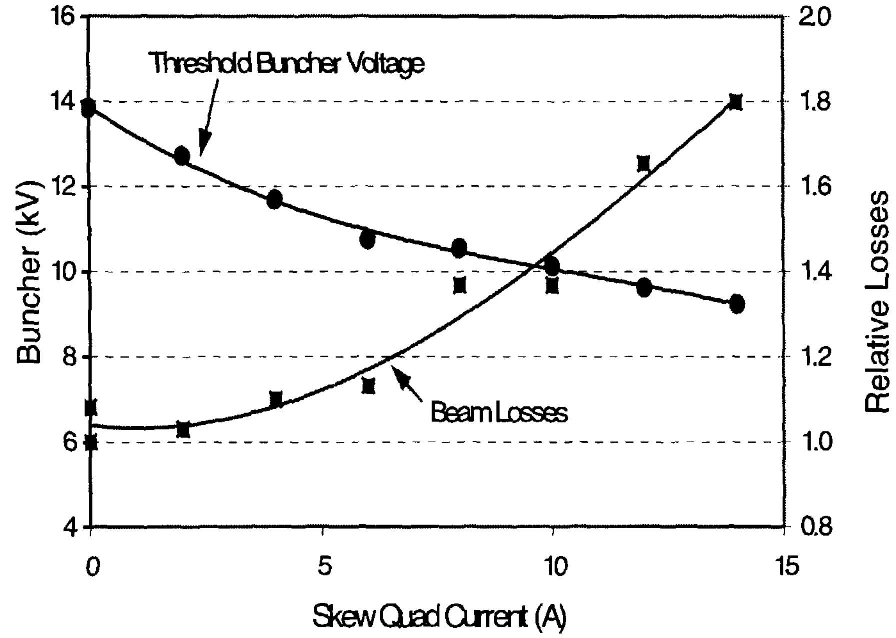

Figure 2. Instability threshold voltage and relative beam losses as a function of skew quad current for fixed beam intensity (stored charge of 5 μC/pulse).

The program of tests culminated in demonstration of a record, stable beam store of **9.7 μC/pulse**, which is 45% higher than needed to meet the SPSS enhancement project peak intensity specification of 6.7 μC/pulse. The demonstration at low repetition rate was made using the combined effect of the maximum available rf voltage (18 kV), of heated inductors (~190° C), and the use of a skew quadrupole. To accumulate this intensity with the existing H^- ion-source, it was necessary to operate with a number of non-standard linac parameters. For example, the beam gate was stretched out to 1225 μs (50-60 % higher than normal), a feature which is possible at low repetition rates. The heated inductors provided an inductance 50% higher than needed for full compensation of longitudinal space charge. This permitted increasing the injected bunch width to 305 ns (20 % higher than normal). The record accumulation produced a peak circulating current of 82 A that was still stable after an additional 400 μs store at the end of accumulation. While the demonstration showed adequate control of the instability at high peak intensities, the beam losses were too high for routine operation. In addition, some emittance growth, presumably from space charge effects, was observed at the higher peak intensities. Reduction of the slow beam losses at the higher peak intensities will be a major goal for future PSR development work.

3. Studies of the Electron Cloud in PSR

One of the longstanding unknowns for the e-p instability at PSR has been the origin and characteristics of the electron cloud. In the past, some indications of the electron cloud were obtained using various biased collection plates. However, biased plates perturb the electron and beam environment and may significantly change the electron cloud characteristics. An improved electron measurement system was needed. Fortunately, improved detection and characterization of the electrons striking the wall was made possible by use of several special electron analyzers developed at ANL. These detectors were designed to introduce minimal perturbations to the beam and electron cloud [5]. When augmented by high-speed electronics developed at LANL, these devices enable one to measure the flux density, time structure and energy spectra of electrons striking the wall [6].

Over time a number of these devices were placed in different locations in the ring including:

- a straight section in a low beam-loss region,
- a straight section in a high loss region,
- downstream of the injection stripping foil, and
- in a straight section which contained small ceramic breaks in the beam pipe.

These were augmented with small collection plates for use in dipole and quadrupole magnets.

A representative set of signals from an ANL analyzing detector for stable beam (~ 8 μC/pulse) is shown in Figure 3 for several values of the repeller voltage from -300 V to

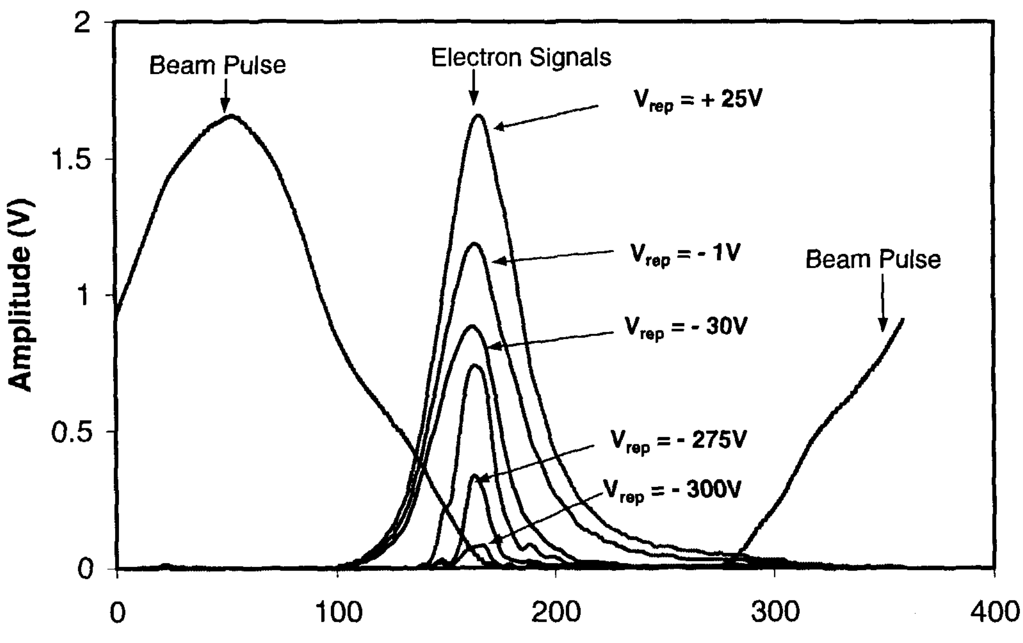

Figure 3. Electron signals during a single revolution in the ring shown in proper time relation to the beam signal (wall current monitor).

+ 25 V. These detectors collect electrons with energies higher than the value set by the negative repeller voltage, thus providing data on the cumulative energy spectrum, which in this case extends out just beyond 300 eV. From these signals, it is apparent that most of the electrons strike the wall in a relatively short pulse at the end of the beam pulse. In general, the higher energy electrons are in a shorter pulse. The long tail on the signal for the +25 V repeller setting undoubtedly includes secondary and tertiary electrons produced by the impact of higher energy electrons. Note that the tails of the low energy signals extend into the start of the next passage of the beam pulse.

The observed electron flux density is surprisingly high, e.g. in comparison with that expected from residual gas ionization. The peak of signal for a repeller voltage of + 25 V corresponds to ~ 400 $\mu A/cm^2$ striking the wall at this detector. This is orders of magnitude higher than the ~ 2 nA/cm^2 expected from residual gas ionization (assuming that the electrons generated in one beam pulse passage emerge in a pulse ~ 40 ns wide at the end of each beam pulse).

Numerous studies were made of the dependence of electron signals (for stable beams) on a variety of beam and environmental factors including location, beam intensity, pulse shape, local beam losses and vacuum pressure. It was found that the electron flux increases strongly with beam intensity as well as with local beam losses and vacuum pressure. In addition, the flux density varies markedly with beam shape. The very strong dependence on beam intensity is illustrated in Figure 4 where the filtered electron signal (averaged over a few turns) is plotted as a function of the circulating beam intensity measured during accumulation in the ring. Note the suppressed zero for the beam intensity. A power law fit to this data showed the electron flux density striking the wall varied as the 5.6 power of the beam intensity. For stable beams of intensities greater than ~ 5 μC/pulse, high electron flux densities were observed wherever diagnostics were placed including inside dipoles and quadrupole magnets.

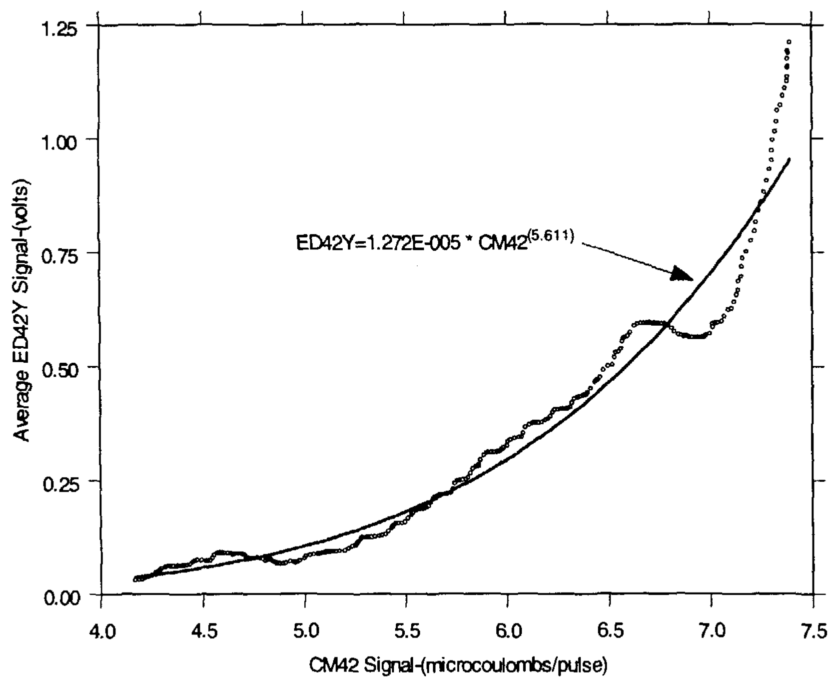

Figure 4. Variation of the filtered electron signal (labeled ED42Y) with beam intensity (labeled CM42 Signal) during accumulation.

Even higher numbers of electrons (factors of 2 to 10 more) are observed with unstable beams. The other characteristics are similar to those for stable beams; in particular most electrons still emerge at the end of the pulse. Interestingly, the excess of electrons (over that for a stable beam of the same intensity) is observed during the unstable beam motion but not before the motion becomes unstable.

It has been suspected for some time that a type of beam induced multipactor or secondary emission avalanche at the vacuum walls plays a role in generating the electron cloud at PSR. If so, suppression of the secondary emission yield by TiN coatings could reduce the electron cloud generation. In an important test at PSR, TiN coating of a 2.7 m straight section gave a factor of 100 or more suppression of the observed electron signal and strongly suggests the crucial role of secondary emission in electron generation.

Increases in vacuum pressure have been taken as evidence for beam induced multipactor at certain other machines. In an experiment at PSR using high intensity pulses (~ 8.2 μC/pulse) at low repetition rate (~0.2 Hz), the pressure changed from 4×10^{-9} Torr before the beam pulse to a peak of 3.5×10^{-8} Torr. The pressure excursion had a rise time ~ 8 ms and a decay time of ~ 0.5 s. At 6.7 μC/pulse the pressure pulse was down a factor of ~5. This observation is roughly consistent with the change in electron flux striking the wall assuming that the electron flux causes a release of adsorbed gas from the walls roughly proportional to the electron flux striking the walls.

A conditioning effect on the threshold for the e-p instability has been observed on several occasions since 1997. In the past year, a more systematic effort was made to quantify the effect beginning with the startup in April 2000 after a several month shutdown during which parts of the ring were up to air. The data are shown in Figure 5 where a sequence of instability threshold curves is plotted beginning with 4/8/00, 2 days after startup. The curves

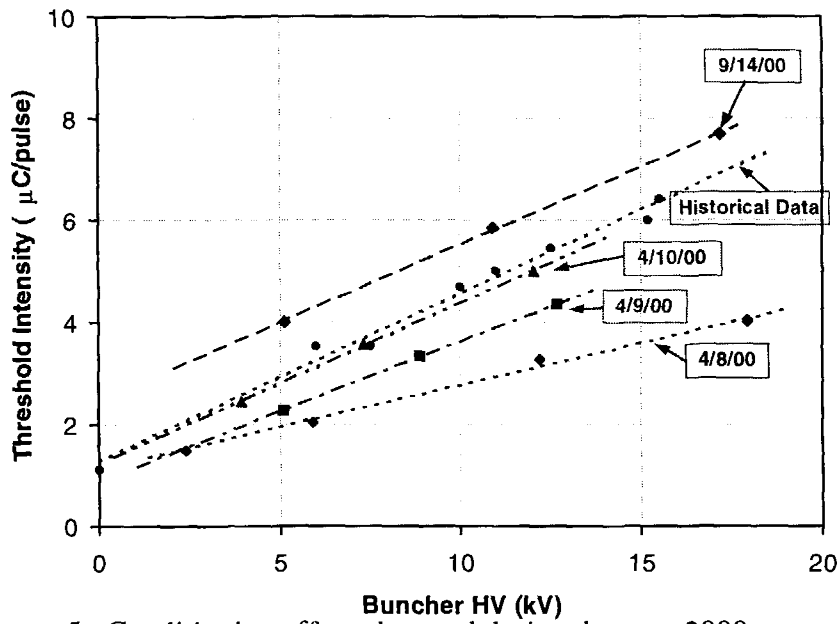

Figure 5. Conditioning effect observed during the year 2000 run cycle.

quickly improved over the next two days and approached the historical data (obtained from production beams well into the respective run cycles). The last curve on 9/14/00 was obtained after several weeks of routine operation at ~100 μA @ 20 Hz (5 μC/pulse). These data clearly show a sizeable improvement over time suggesting that the electron flux striking the wall scrubs the surface and lowers the secondary emission yield (SEY). Direct measurements of the SEY (from accelerator materials) have quantified the effect of electron bombardment of surfaces [7].

Two candidate mechanisms for explaining the observed production of the PSR electron cloud have been considered. In the first, which is shown schematically in Figure 6, electrons captured by the beam (e.g. from residual gas ionization or electrons that survive the gap)

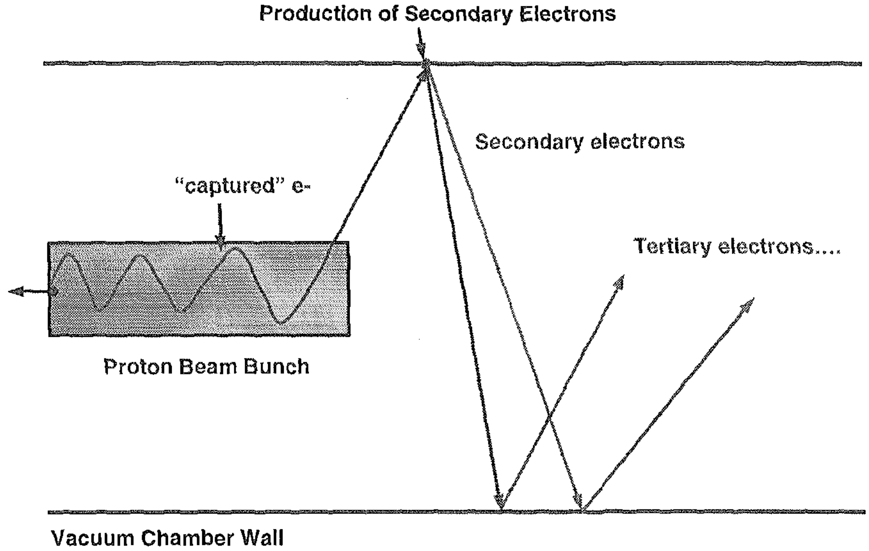

Figure 6. Production and accumulation of electrons by electrons captured in the beam.

oscillate in the potential well of the proton beam. They emerge at the end of the pulse with energies that depend on initial conditions and beam intensity but can range up to ~ 200 eV for 8 μC/pulse beams. When these strike the wall, secondaries are produced with yields that can be greater than unity. The secondaries have a lower energy spectrum but can travel to the opposite wall and reflect or make tertiary electrons. These interactions with the wall will degrade the electron energies to a few eV in which case it can take many nanoseconds for them to reach the wall and be absorbed. If a large enough fraction survive the gap, there will be an accumulation or buildup until the production and loss rates are in equilibrium.

A second candidate mechanism is based on what is aptly described as "trailing edge multipactor" and is shown schematically in Figure 7. Electrons born at the wall near or after

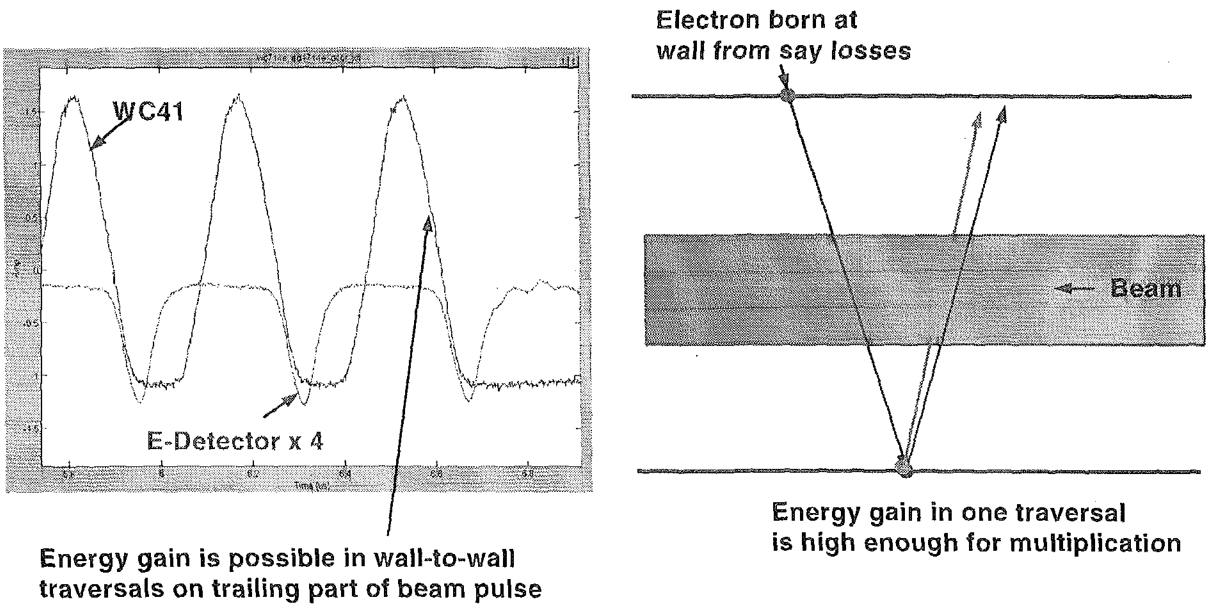

Figure 7. Schematic description of the "trailing edge multipactor" mechanism.

the peak of the pulse will be accelerated towards the center of the beam and be decelerated after passing through the beam center. On the trailing edge of the beam pulse, such electrons will reach the opposite wall with some energy gain. If the energy gain is high enough, then the secondary emission yield can exceed unity and result in amplification on each successive traversal of the beam pipe. For an 8 μC/pulse triangular beam, a calculation indicates gains of ~1000 are possible for an electron born at the wall and at the peak of the beam pulse [8]. In this mechanism, large fluxes of electrons can be produced during each passage of the beam without the need for some to survive the gap.

One way to separate the relative contributions of the two mechanisms is to measure electrons from the passage of a single beam pulse in the extraction line. No accumulation from previous pulses is possible. This experiment was recently performed for a beam of 6.8 μC/pulse with the results shown in Figure 8. There was a strong electron signal (for a

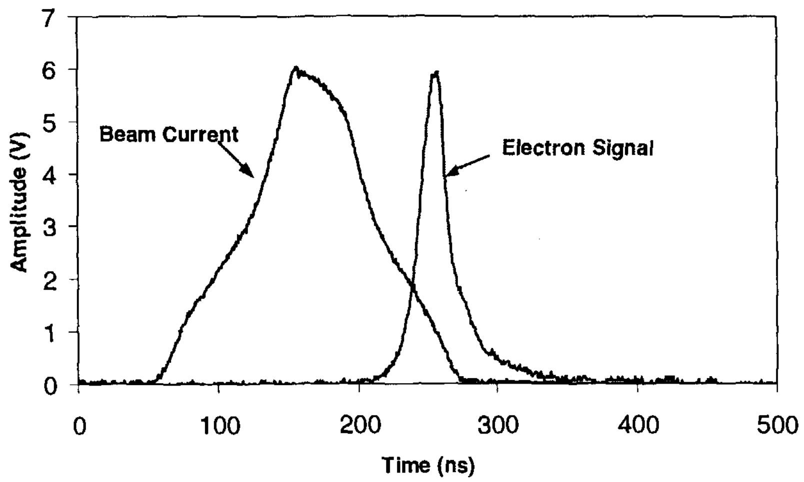

Figure 8. Electron signal in relation to a 6.8 μC beam pulse in a single pass experiment.

repeller voltage of +25 V) with a pulse shape and time relationship to the beam pulse that is essentially identical to those observed in the multipass situation in the ring. In fact, the electron flux density at the wall is somewhat higher than for the comparable situation in the ring. Varying the repeller voltage produces smaller and narrower electron signals, which disappear around -300 volts or so on the repeller. This characteristic is also similar to that observed in the ring. In addition, the electron signal is a very strong function of beam intensity. A power law fit to the data on intensity dependence (not shown) required an exponent of 7, which is also similar to that observed in a straight section in the ring. These results strongly support the hypothesis that trailing edge multipactor is the dominant source of electrons striking the vacuum chamber wall.

A large amount of data has been collected on the electron cloud in PSR of which only a small sample has been presented here. Interpretation in terms of the electron density in the beam is critical for comparison with e-p theory but is not straightforward or unique. The electron analyzer only measures the electrons striking the wall, not the electron density in the beam. To infer electron cloud properties in the beam, a model is needed that can be fit to these data for the unknown parameters.

What model or combination of models should be used and what are the important factors? Electrons from trailing edge multipactor may cause large signals at the wall but contribute with a low weight to the electron density in the beam because they pass only once through the beam with a short dwell time (~5 ns) compared to captured electrons (~250 ns). Cold electrons, captured from the gap, contribute with a high weight since they oscillate against the protons throughout the passage of the beam pulse. As such, they are also likely to be more important to the instability dynamics. Hence, an important unknown is the number of electrons that survive the gap to be captured by the next pulse. The electron signals in Figure 3 do show that a few percent of the low-energy electron signal is present at the beginning of the next beam pulse. Undoubtedly more cold electrons are still in the pipe at smaller radii. A simulation now being developed by M. Furman and M. Pivi at LBNL may provide an answer.

A numerical example of a neutralization estimate using the data shown in Figure 3 for Vrep = +25 V is informative. Integration over time yields an electron flux of 23 picoCoulombs/cm^2/turn. As has already been noted, estimates of the neutralization are model dependent. On the one hand, if all of the electrons are from captured electrons and their secondaries in equal amounts, then the estimated electron line density in the pipe is ~340 pC/cm/turn implying an average neutralization of 27%. On the other hand, if all observed electrons are from trailing edge multipactor, then the estimated average electron line density is ~7 pC/cm/turn implying ~0.6% neutralization. The true value probably lies somewhere in between, perhaps 2-3%. Further improvements in the estimates would be aided by detailed simulations of electron generation where all of the relevant physics is included.

4. Summary and Conclusions

Recent progress on control of the instability at PSR can be summarized in one word, Landau damping. Increased rf voltage, X,Y coupling, multipoles and inductive inserts have significantly raised the instability threshold. These are more than sufficient to meet the peak intensity specification for the ongoing intensity upgrade project. However, these measures have their downside, increased losses. Thus, the main remaining challenge for the PSR intensity upgrade and beyond is to find ways to reduce the uncontrolled beam losses at higher intensities.

A wealth of data on the electron cloud has been collected but, to date, there is no unique interpretation in terms of electron density in the beam. The latest evidence suggests that the "trailing edge multipactor" mechanism is the source of most of the observed electron signal striking the vacuum chamber walls. However, electrons from this source may or may not make the dominant contribution to the electron density in the beam or to the electrons that drive the instability. There is indication that a few percent of the electrons survive the passage of the gap and without the need for significant beam-in-the-gap. It is important to obtain more information on this point, as these electrons would be captured by the next beam pulse.

TiN coatings have greatly reduced the observed electron signal in the straight section where they were tested. As such, these coatings offer the prospect of a cure with no increase in losses. However, this possibility has not yet been demonstrated. The experience to date (copious numbers of electrons in all locations) suggests that it may be necessary to coat the entire ring in order to cure the instability. This would be a major undertaking and is not likely in the near future.

There is a need for better theory to guide the choice of experiments and to interpret the data. In addition, better theory is needed for a reliable extrapolation of the PSR experience to new higher intensity machines. It is a complicated problem and before the instability is fully resolved, information on electron generation will need to be combined with the dynamics of the instability.

5. Acknowledgements

Progress on the instability at PSR has been aided by contributions from several individuals at other institutions. The corresponding author gratefully acknowledges the contributions from the following individuals:

- Katherine Harkay and Richard Rosenberg (ANL) for providing the ANL electron analyzing detectors,
- Dave Wildman (FNAL) for providing the prototype inductive inserts also Bill Ng and Jim Griffin for calculations and advice on inductive inserts,
- David Olsen, Slava Danilov (ORNL) and Justin Jones (ANL) for their efforts in providing vacuum chambers for the TiN tests,
- Dan Wright (SLAC) for TiN coating of the test chambers for PSR.

The corresponding author also acknowledges many helpful discussions with members of the PSR e-p Theory collaboration including Miguel Furman, Mauro Pivi and Glen Lambertson (LBNL), Katherine Harkay (ANL), Mike Blaskiewicz (BNL), Ron Davidson and Hong Qin (PPPL), Tai-Sen Wang and Paul Channell (LANL).

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