SELF-CONSISTENT ELECTRON-CLOUD SIMULATION FOR LONG PROTON BUNCHES*

A. Shishlo, Y. Sato, S. Cousineau, V. Danilov, S. Henderson, J. Holmes, Spallation Neutron Source, ORNL, Oak Ridge, Tennessee 37830, U.S.A.
R. Macek, LANL/LANSCE, Los Alamos, New Mexico 87544, U.S.A.
S.Y. Lee, IUCF, Bloomington, Indiana 47408, U.S.A.

Abstract

The results of numerical self-consistent electron-cloud simulations are presented and compared with data from the Proton Storage Ring at LANL. The ORBIT code with a recently developed electron-cloud module has been used. The model includes fully coupled "proton bunch – electron cloud" dynamics, a multipacting process model with a realistic secondary emission surface model, and a realistic lattice and injection scheme. The growth rates of proton-bunch transverse instabilities were studied as functions of the beam intensity, RF cavity voltage, external magnetic fields, and number of interaction points between protons and electrons in the model.

INTRODUCTION

The purpose of this work is to demonstrate that the ORBIT code with a newly developed electron-cloud (EC) module [1] can reproduce the main features of electron-cloud driven instabilities in long proton bunches, as in the Los Alamos Proton Storage Ring (PSR) and in the SNS Project's ring. Because PSR has accumulated a vast amount of experimental data on electron-cloud related instabilities [2], it is a natural choice for benchmarking the code that has been developed for the SNS Project. We focus the benchmark on a limited number of the PSR instability features because of the high computational cost of each simulation. In particular, we are trying to demonstrate the following:

- Existence of the instability.
- The coupling between proton instabilities and electron production. An intense electron flux coincides with high amplitude coherent proton bunch oscillations at the onset of substantial beam losses.
- Agreement with the observed frequency spectrum of the proton bunch oscillation.
- An asymmetry in directions where instabilities occur. The instabilities have been seen mostly in the vertical direction.
- The relationship between the maximum number of protons in the bunch and the threshold rf voltage.

What we mean by the term "self-consistent" as it relates to our model is that the electron-cloud buildup process and the proton and electrons dynamics all are tied together. Previously, the EC ORBIT module was successfully benchmarked against an exact analytic two-stream instability model [1]. In the next section the physical model for our simulations is discussed.

*Work conducted by the SNS Project. SNS is managed by UT-Battelle, LLC, under contract DE-AC05-00OR22725 for the U.S. Department of Energy.

PHYSICAL MODEL

The ORBIT code models the machine as a series of 'Nodes' that perform operations on a macro-particle beam. Initially, the PSR ring lattice is formed using linear 6D transport matrices calculated by MAD for drift, dipole, and quadrupole elements, an rf-buncher node, an injection node, and a longitudinal space charge node with inductive inserts. This last node is needed to provide a realistic longitudinal charge density distribution. This lattice was used to prepare a set of proton bunches for different rf-buncher voltages and beam intensities by simulating the PSR injection process for 3200 turns. Then, these proton bunches were used as starting distributions for calculations with a modified lattice in which one or several electron cloud nodes (ECN) were added. The simulations were carried out for several tens of turns including various diagnostics of the proton bunch and the electron cloud to detect instabilities. There was no injection as these were stored beam simulations. Our model lattice did not include collimation nodes, so we did not simulate proton beam losses.

During every turn each ECN models the electron cloud build up and its interaction with the proton bunch inside a short segment of the beam pipe. The electron cloud at the end of the turn is then used to provide the initial electrons for the next turn. The simulated electron cloud consists of macro-electrons whose trajectories are solutions of the equations of motion with time as the independent variable and with electromagnetic forces from the proton bunch, perfect conducting walls, the electron cloud itself, and external magnetic fields if they are present. To describe collisions of electrons with pipe walls a probabilistic model of secondary electron emission developed by M. Furman and M. Pivi was used with parameters for stainless steel [3]. Each EC Node was independent from the others and had its own electron cloud.

Actions from the electron cloud on the protons in the bunch were taken into account by applying a momentum kick to each proton

$$\Delta p = (L_{eff} \ / \ L_{ec}) \cdot e \cdot E_{ec} \cdot \Delta t \qquad (1)$$

where L_{ec} is a length of the EC Node, E_{ec} is an electric field created by EC, Δt is a time of motion of the proton through this EC region, and L_{eff} is an effective length for this EC node. The effective length was introduced to reduce computation time. The length of ECN should be short enough to assure the applicability of the formula (1) with a constant electric field. For the PSR ring this implies node lengths of several centimeters, and we would need tens of ECN to cover 1 m of a drift space. To avoid this we used ECNs with 5 cm length and the effective length parameters.

The parameters of simulations that are common for all variants are specified in Table 1.

Table 1: Simulation Parameters for PSR

Parameter	Symbol	Value
Total beam energy	E (GeV)	1.735
Ring Circumference	C(m)	90
Beam pipe radius	R(cm)	5
Total length of drifts	L_{DR}(m)	55
Total length of dipoles	L_{DP}(m)	30
Proton bunch potential grid	N_x x N_y x N_L	64x64x1500
Time steps per one passage	N_t	60000
Proton macro-particles	N_p	10,000,000

SIMULATION RESULTS

We considered different variants of the PSR ring lattice with respect to the number and positions of EC Nodes. The variants of the lattice are specified in Table 2. For all variants, the sum of all ECN effective lengths is equal to the total length of drifts and dipoles together. When ECNs were included inside the dipoles the sum of their effective lengths was set equal to the total length of dipoles from Table 1.

Table 2: Variants of the Lattice

#	Description
1	One EC Node located at a point with average value of vertical beta functions in drifts.
2	Five ECNs distributed over the lattice at points with different vertical beta functions.
3	Two ECNs inside dipoles and five ECNs as in the previous variant.

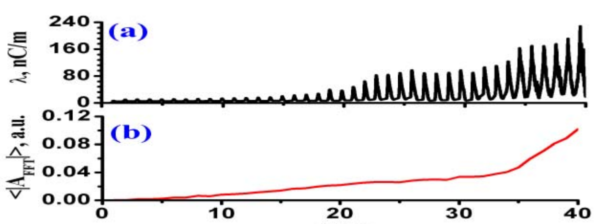

Figure 1: Instability development for variant 1 in Table 1. (a) – linear electron cloud density; (b) – average amplitude of the vertical beam oscillations.

One EC Node in the Lattice

Simulation results for variant 1 (Table 1), with a proton bunch population of $2 \cdot 10^{13}$, and zero rf buncher voltage are shown in Figures 1-3. The zero voltage means that we artificially eliminated longitudinal motion for all protons.

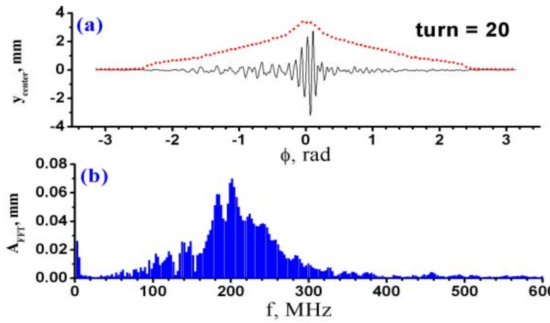

Figure 2: The proton bunch at turn 20. (a) – vertical oscillations as function of longitudinal phase with longitudinal profile. (b) – a frequency spectra.

The average amplitude of the proton bunch oscillations shown in Figure 1 was calculated as the average absolute value of FFT amplitudes with harmonic numbers in the

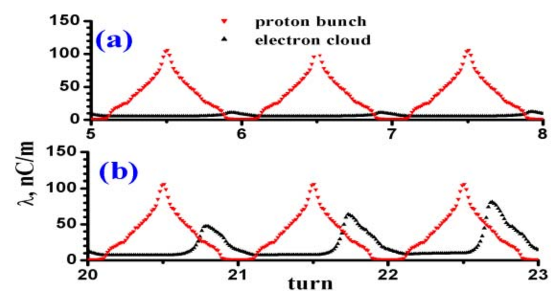

Figure 3: The electron cloud and proton bunch linear densities as functions of time (turn number). (a) - turns 5-8. (b) – turns 20-23.

range 25-100. We used this definition for all variants. Figure 1 demonstrates a very fast growth of vertical proton bunch oscillations that is accompanied by increasing electron cloud density multipacting peak. The dipole vertical oscillations of the proton bunch center are shown in Figure 2. At certain amplitudes they enhance the multipacting process by throwing electrons on pipe walls as is demonstrated in Figure 3. The position of the electron density peak changes, but it is still at the tail of the proton bunch when the peak value has grown by a factor of ten.

This calculation contains a number of discrepancies with the real PSR data. These include: the growth rate is too fast; the maximum of the frequency spectrum for this intensity should be around 150 MHz instead of 200 MHz; the instability is observed to start near the tail of the proton bunch instead of the center. Some of these are resolved by using a more realistic lattice with several ECNs and by applying a non-zero voltage to the rf-buncher.

 0-7803-8859-3/05/$20.00

Distributed EC Nodes

To provide a more realistic treatment of the EC effects we placed five ECNs in the lattice to give variant 2 in Table 2. These ECNs were distributed among the drift sections of the ring and represented the whole range of the vertical beta function. Thus, shapes and sizes of the transverse cross section of the beam along with the oscillation frequency of the electrons were different at different ECNs. The resulting frequency spectrum peaked around 150 MHz, in agreement with the experimental value for the 3.2 μC beam. All other characteristics were very similar to variant 1.

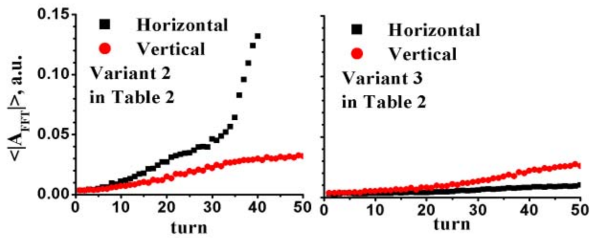

Figure 4: Effect on instabilities in both planes when the ECNs inserted into dipole magnets.

The last modification to the lattice was done by adding two additional EC Nodes, this time into dipole elements of the ring (variant 3 in Table 2). Before this modification, the simulations showed instabilities in vertical and horizontal planes. The growth rate of the horizontal oscillations sometimes was bigger than the rate in the vertical plane. After taking into account electron cloud in the dipole magnets we have reversed this situation, as shown in Figure 4. This effect can be explained by the fact that electrons inside the dipoles move primarily along the vertical magnetic field, so the horizontal oscillations of the electrons are suppressed.

The Threshold Value of the RF Voltage

In practice, the electron-cloud related instabilities in the PSR ring are controlled by applying a high voltage to the rf cavities. The higher rf buncher voltage leads to a larger

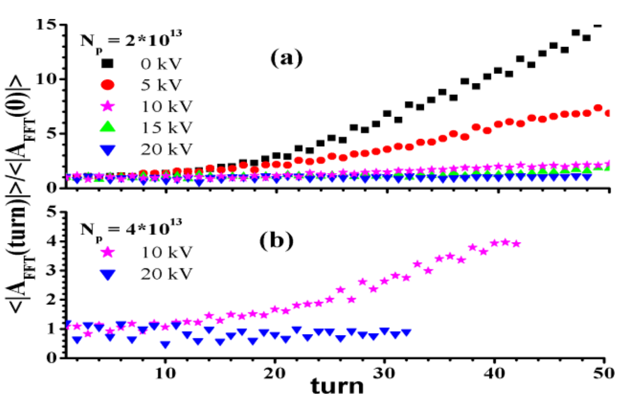

Figure 5: The time evolution of average amplitudes of the vertical proton beam oscillations. (a) – 3.2 μC and (b) - 6.4 μC cases.

energy spread in the proton bunch. The experimental data show that the maximum charge of the proton bunch scales linearly with the threshold value of the rf voltage. A set of simulations was carried out in an attempt to reproduce this dependence. We ran simulations for 3.2 and for 6.4 μC bunches at several values of the rf voltage. For all runs, lattice variant 3 in Table 2 was used.

The results of simulations with different rf voltage values are shown on Figure 5. They clearly demonstrate that instabilities can be suppressed by applying a sufficient rf voltage. Also, with increasing voltage the growth time of instabilities increases from tens to hundreds of turns. These numbers are in good agreement with experimental results.

Unfortunately, we have not the exact threshold values from our results. All we can say is that the threshold rf voltages for 3.2 and 6.4 μC beams are between 10 and 20 kV, and the threshold for 3.2 μC is lower than the threshold for 6.4 μC beam. To find the thresholds with a better accuracy we will have to simulate beam propagation for many turns and to consider more intermediate rf voltages. Because of the coarseness of our simulations, we overestimate the experimental threshold for the 3.2 μC bunch (the observed threshold is between 5 and 10 kV for various conditions) [2].

CONCLUSIONS

The overall simulation results for our simple model are very similar to the experimental data. They predict instability, a correlation between the electron flux on the beam pipe wall and proton bunch vertical oscillations, the prevailing oscillation in the vertical plane, frequency spectra, the instability growth times, and the stabilizing role of high rf voltage. The estimated threshold values of the rf voltage are somewhat above the experimental data. Summarizing, we have demonstrated that the ORBIT code can be successfully used for the self-consistent electron cloud simulations in proton accumulating rings with long bunches.

ACKNOWLEDGEMENT

This research used resources of the National Energy Research Scientific Computing Center (NERSC), which is supported by the Office of Science of the U.S. Department of Energy under Contract No. DE-AC03-76SF00098. The corresponding author acknowledges many helpful discussions with Sasha Alexandrov.

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