ELECTRON CLOUD SELF-CONSISTENT SIMULATIONS FOR THE SNS RING

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Abstract

This paper presents a computational investigation of the electron-proton instability in the Spallation Neutron Source (SNS) ring. The simulations have been performed using the ORBIT code, which includes a self-consistent electron-cloud model for long-bunched proton beams. The model features simultaneous calculations of the dynamics of the proton bunch, the electron cloud and a realistic secondary emission surface model. The frequency spectra and growth rates of the proton bunch transverse instability are studied as functions of the RF cavity voltage.

INTRODUCTION

The instabilities caused by coupled electron-proton oscillations may limit performance of intense proton storage rings. The electron-cloud effect (ECE) shows itself very clearly in the Proton Storage Ring (PSR) at Los Alamos National Laboratory [1]. Due to similarities between the PSR and SNS storage rings dedicated electron cloud studies and countermeasures have been considered from the early stages of the SNS project.

The first instability estimations (see, e.g., [2]) showed that electron cloud build-up might pose a risk for high current accumulation in the SNS ring. At the same time, experiments at the Proton Storage Ring (PSR) in Los Alamos demonstrated a promising reduction of the electron density in a chamber piece coated with titanium nitride (TiN) – a low secondary electron emission material (see [3] and references therein). This led to the decision to coat every piece of the SNS vacuum chamber with TiN. In addition, the SNS ring was equipped with an electron collector near the stripping foil and space was reserved for solenoidal magnets to reduce electron buildup near the places with high loss [4]. Compared with previous machines, these are all new e-p mitigating features.

Analytical and numerical analyses of ECE-driven instabilities for the SNS ring [5] predicted that for an SNS bunch with 2×10^{14} protons the first harmonic rf cavity voltage should be adequate to stabilize the beam for an electron density of 5 nC/m. The harmonic one design voltage for SNS is 40 kV. The analytic model used in [5] is fairly rough and it was supported by direct simulations with CSEC (Cylindrically Symmetric Electron Cloud). The electron cloud development for the TiN coated vacuum beam pipe of the SNS ring including the possible values of electron cloud linear density were calculated in a computer simulation with the code POSINST.

The present work uses the electron cloud module in the ORBIT code to verify early predictions about the stability of the beam in the SNS ring with respect to ECE. Previously, the ORBIT code and ECE module have been benchmarked against experimental results from PSR [6].

SIMULATION MODEL

The ORBIT code models an accelerator as a series of 'Nodes' that perform operations on a set of macro-particles that form a bunch. The SNS ring lattice used here is formed using TEAPOT-like elements for drift, dipole, and quadrupole elements, rf-buncher nodes, an injection foil node, and a longitudinal space charge node. This last node is needed to provide a realistic longitudinal charge distribution. This lattice has been used to prepare proton bunches by simulating the SNS injection process for 1060 turns. Then, proton bunches are tracked through a modified lattice with one or several inserted electron cloud nodes (ECN). The simulations with the new lattice have been carried out for several tens of turns including various diagnostics on the proton bunch and the electron cloud to detect instabilities. There was no injection of new protons for these stored beam simulations.

Each ECN contains an electron cloud consisting of macro-electrons. During passage of the proton bunch through this node, the macro-electrons move in the electro-magnetic field created by themselves, the proton bunch, the perfect conducting walls of the beam pipe, and any external magnetic field. New macro-electrons are produced as a result of proton beam loss on walls and by macro-electrons impacting the beam pipe. To describe collisions of electrons with pipe walls a probabilistic model of secondary electron emission developed by M. Furman and M. Pivi is used with parameters for stainless steel coated with TiN [7]. Each EC Node is independent of the others and has its own electron cloud.

Actions of the electron cloud on the protons in each longitudinal slice of the bunch are taken into account by applying a momentum kick to every proton in the slice

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

where L_{ec} is the length of the EC Node, E_{ec} is an electric field created by EC, Δt is the time of motion of the

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proton through this EC region, and L_{eff} is an effective length for the EC node. The effective length was introduced to reduce computation time. In principle, it is possible to cover the entire SNS lattice with ECNs, but the simulation time would be prohibitive because, at present, the ORBIT code has limited parallel scalability. Therefore the set of ECNs was replaced by one or a few nodes with effective lengths set to represent coherent action from electron clouds populating the entire ring. This is an unrealistic approach (it gives an overestimation of the electron cloud action on the proton bunch), but it provides a very conservative estimate of the stability limit. We will demonstrate this in the next section.

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

Table 1: Simulation Parameters for SNS

Parameter	Symbol	Value
Bunch population	N_p	1.5×10^{14}
Total beam energy	E (GeV)	1.0
Ring circumference	C(m)	248
Beam pipe radius	R(cm)	11
Total length of drifts	L_{DR}(m)	165
Total length of dipoles	L_{DP}(m)	50
Bunch potential grid	N_x N_y N_L	128x128x4000
Time steps per turn	N_t	80000
Proton macro-particles	N_m	30,000,000

BENCHMARK ORBIT WITH PSR DATA

Before using the ORBIT code for SNS electron cloud simulations, it was benchmarked against experimental PSR data [6]. The following conclusions resulted:

- ORBIT predicts the existence of the electron cloud driven instabilities.
- The instability threshold in proton beam intensity depends on the energy spread in the bunch, and therefore on the ring rf-cavity voltage. Applying higher rf-voltage to the ring cavities suppresses the instability and increases its threshold.
- Using only one electron cloud node in the simulation gives faster instability growth than is observed at PSR. When several ECNs are used, growth times and transverse oscillation frequency spectra are in close agreement with those observed experimentally.
- The domination of the vertical transverse instabilities over horizontal ones is explained by the presence of ECE inside dipole magnets of in the ring.
- Simulations are very time consuming, and can be carried out only on high performance parallel computers. The calculation time needed for the ECE simulations for SNS is about 3 times more than that for the PSR case.

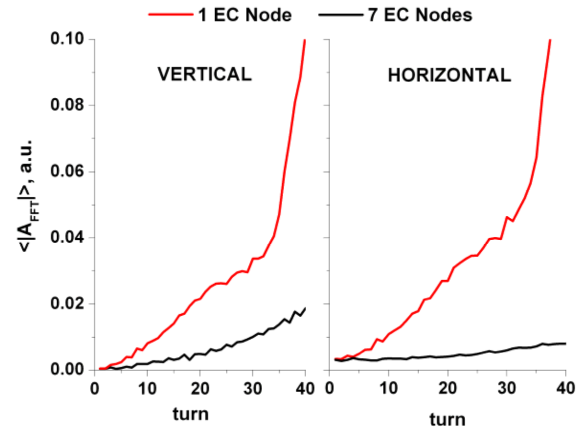

Figure 1: The average amplitude of the proton bunch oscillations for PSR electron cloud effect simulations.

The Fig 1 shows the instability growth in simulations where the number of ECNs was increased from one to seven, including two ECNs inside dipoles. From this we infer that the use of only one electron cloud node in the simulated SNS lattice will give an overestimated value of the ring rf-cavity voltage sufficient to suppress possible instabilities caused by ECE. This simplified simulation can be carried out with a reasonable and affordable computational time budget.

SIMULATION RESULTS

Our computations consist of two stages: electron cloud development simulations and proton bunch stability studies in the presence of ECE.

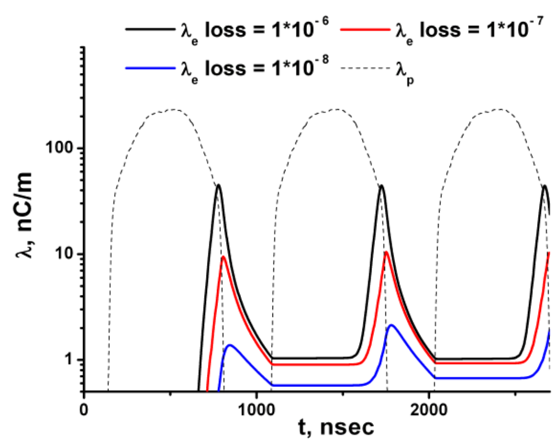

Figure 2: Simulated electron and proton bunch densities during the first SNS bunch passages for different proton loss rates per turn, assuming magnetic field-free region.

Formation of Electron Cloud

We begin by studying the formation of the electron cloud. One electron cloud node was placed in the ring lattice at a position with average values of transverse betafunctions. The longitudinal positions of the protons were frozen, and the bunch density was the same for each turn.

The electron densities are shown as functions of time in Fig. 2. The simulations were performed for different proton losses in the ring. The design value of proton loss for SNS is 0.1% of the beam intensity during the whole accumulation period of 1060 turns which gives about 10^{-6} probability of loss per turn per proton. These losses will occur mostly in the ring collimator, so the EC formation has been studied for a wide range of losses in other parts of the SNS ring. The variation of losses over two orders of magnitude results in only a factor of two difference in the electron densities (see Fig. 2).

Our results for this part are in good agreement with results of earlier studies of proton losses [7], where the physics of the electron cloud development is described in detail.

ECE Driven Instability Simulations

During the proton beam instability simulations two variants of tracking have been compared.

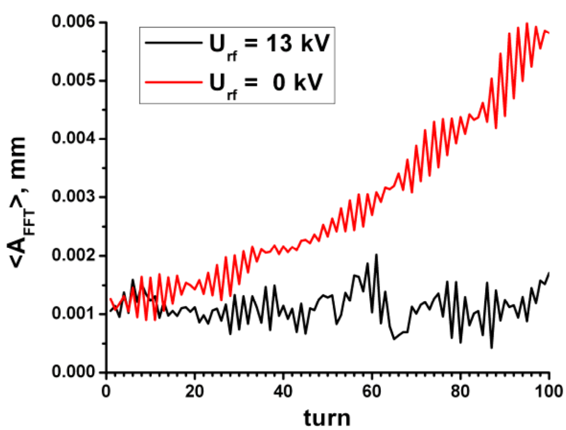

Figure 3: Average Fourier amplitudes of the horizontal oscillations of the center of the proton bunch in the SNS ring.

In the first, the macro-particles representing the bunch have been longitudinally frozen. In this case, there is no Landau damping and an instability of the horizontal motion of the proton beam has been found (Fig. 3). Figure 3 shows the average Fourier spectrum amplitudes of the horizontal motion of the beam center as a function of the turn number. The Fourier amplitudes were averaged over the 116-120 MHz frequency region. The results demonstrate a clear growth, but it is slower than that for PSR (see Fig. 1).

For the second case of simulations the actual energy spread (rms 2.1 MeV) of the macro-protons in the bunch has been used. The value of the spread corresponds to 30% of the nominal voltage in the rf-bunchers of the SNS ring. The damping caused by this spread completely suppresses any instability in the transverse beam motion (Fig. 3).

CONCLUSIONS

The simulations of the electron cloud driven instabilities for the SNS ring have been performed by using the ORBIT code. The SNS beam seems to be more stable than the beam in PSR. According to simulations for the SNS beam, applying only 30% of the design voltage to the rf-cavities will suppress the ECE instability. This result can be considered as a very conservative estimation, and it is in good agreement with previous analytical and numerical studies of the instabilities for SNS [5].

First experimental results show the ECE instability in the SNS ring [8] at intensity $2.5*10^{13}$ protons for coasting beam, no chopping. These results can not be compared with our simulations because of uncompleted longitudinal bunching in these experiments. They will be subject of further investigations.

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