SIMULATION STUDIES ON THE ELECTRON CLOUD INSTABILITY IN THE CSNS RING*

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Abstract

The electron proton (e-p) instability has been observed in many proton accelerators. It will induce transverse beam size blow up, cause beam loss and restrict the machine performance. A simulation code is developed to study the electron proton instability in the China Spallation Neutron Source (CSNS) ring. The results of numerical simulation of the electron cloud formation and the electron proton instability are presented.

INTRODUCTION

The electron proton instability has been considered as one of the potential threats in the proton rings [1, 2]. CSNS is a proton accelerator facility consists of a linac and a rapid cycling synchrotron (RCS) [3]. Two bunches with a population of 1.88×10^{13} will be accumulated and accelerated in the RCS ring, and the electron cloud might influence the machine performance in such high intensity ring. A code [4] investigating the electron cloud instability in the positron rings is upgraded to study the electron proton instability in the proton rings.

In this article, the electron cloud build up in the CSNS ring is discussed. Two variants of simulation of the electron cloud driven instability with and without energy spread are investigated.

SIMULATION MODEL

Three candidates of electron production are considered, which are lost protons hitting on the chamber wall, residual gas ionization, and secondary electron emission.

The electrons contributed by residual gas ionization are generated along the beam trajectory. The electrons due to lost protons hitting the vacuum chamber wall are generated on the wall surface. The simplified model proposed by Furman is used to describe this kind of electrons, which represents the number of electrons generated by one proton bunch per turn as $N_p \times Y \times p_{loss}$, where N_p is the bunch population, Y is the electron yield per lost proton, and p_{loss} is the proton loss rate per turn per beam particle [5]. The lost protons are supposed to be proportional to the longitudinal bunch intensity in the simulation. By using the assumption of $Y = 100$ e$^-$/p/loss, we obtain an electron production rate of 1.33×10^{-2} per turn, which is 3 orders higher than that of the gas ionization. The secondary electrons consist of elastically back-scattered electrons, re-diffused electrons and true-secondary electrons. The model proposed in [6] is used to describe the secondary electron emission process.

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The vacuum chamber is considered as a perfectly conducting pipe with circular cross section. Both the electrons and the protons are represented by macro particles. The macro electrons are tracked dynamically in the transverse plane. As the bunches are about several tens of meters in length, they are longitudinally sliced with equal length. The bunch gaps are divided into intermediate steps to calculate the electron dynamics and secondary electron emission. The particles in different slices are rearranged after each bunch passage according to their longitudinal position. The space charge force is calculated at each slice in the bunch and each step in the gap by using the PIC method.

In the simulation of the electron cloud driven instability, the electron cloud generation is considered simultaneously. The interaction of the proton bunch and the electron cloud is investigated in the transverse plane. The effect of the electron cloud act on the beam is represented by a transverse kick, and the electrons are treated fully dynamically otherwise.

Table 2: Simulation Parameters for CSNS

Parameters	Symbol, unit	Value
Inj./Ext. Energy	E_{in}/E_{ext}, GeV	0.08/1.6
Circumference	C, m	248
Bunch population	N_p, $\times10^{12}$	9.4
Number of bunches	n_b	2
Harmonic number	H	2
Repetition frequency	f_0, Hz	25
Betatron tune	ν_x/ν_y	5.86/5.78
Beam pipe radii	a/b, cm	10
Proton loss rate	P_{loss}, turn^{-1}	1.33×10^{-4}
Proton-electron yield	Y, e$^-$/p/loss	100
e$^-$ prod. rate due to ionization	Y_{ion}, e$^-$/p/turn	1.31×10^{-5}

SIMULATION RESULTS

In the following, we first give a description of electron cloud formation, and then present the simulation result of the electron proton instability.

Electron Cloud Build-up

One electron node is placed in the drift section with average beta functions. The proton bunch is longitudinally frozen, and the profile of the bunch is

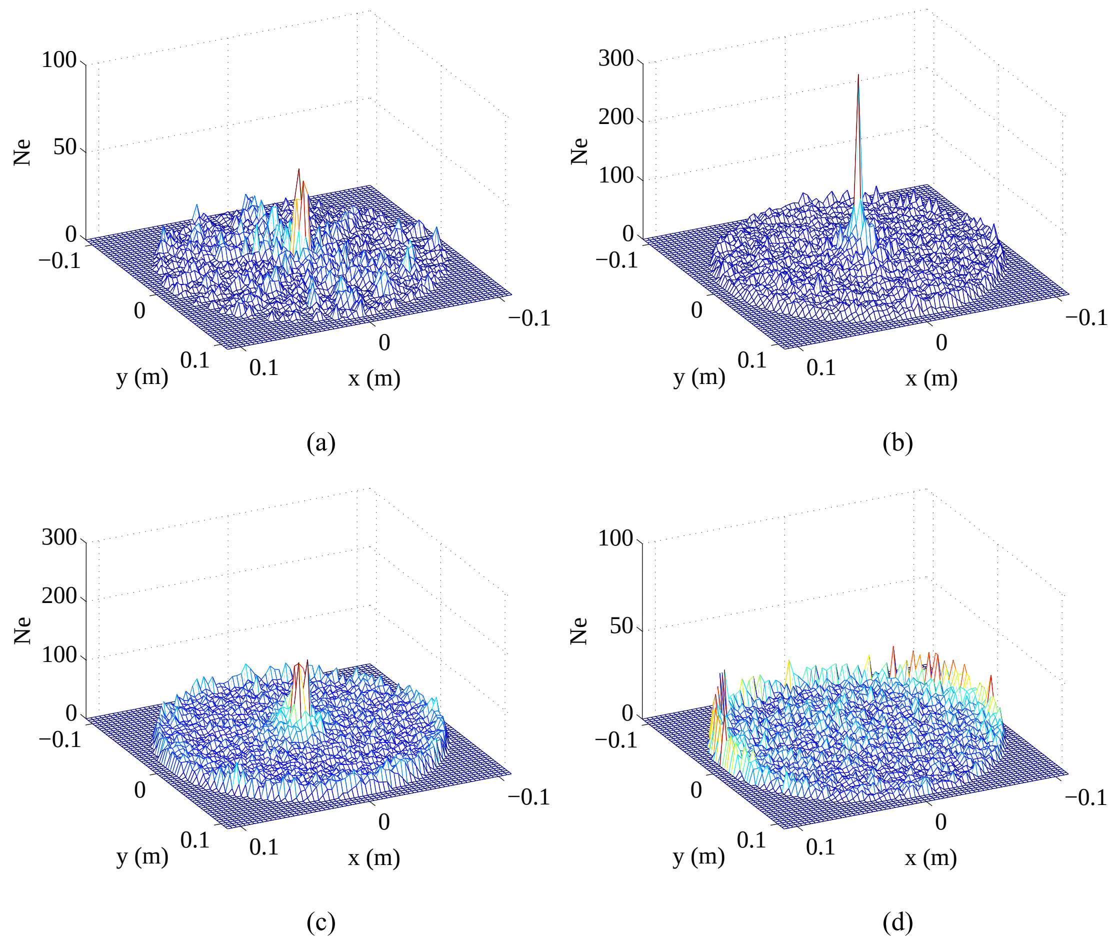

Figure 1: Electron distribution in the transverse section at the bunch head (a), bunch centre (b), peak of the electron density (c), and bunch tail (d).

shown in figure 4. The simulation study of the proton loss in the ring shows that about 6% of the beam intensity is lost during the first 1 ms [7], which gives a proton loss rate of 1.33×10^{-4} per turn. In the simulation, the bunch is represented by 200,000 macro particles and sliced into 500 slices. A transverse mesh size of 128×128 is used in the simulation. 100,000 primary macro electrons are generated during the bunch passage. Figure 1 shows the transverse distribution of the electron macro particles during one bunch passage.

The primary electrons generated by proton loss or ionization are mostly trapped at the bunch head. The number of trapped electrons reaches a maximum value at the bunch centre. Then some of the electrons escape from the potential well of the proton bunch, and strike on the beam pipe with high energies. The collision of the electrons with the wall excites secondary electrons and the total number of electrons is amplified. At the bunch tail, the electrons loss energy due to multipacting with the wall and the electron density decays.

Because the proton losses will occur mostly in the ring collimator, the simulation of the electron cloud formation is performed for different proton loss rates. The electron density developments for variant orders of proton loss rate are shown in Figure 2.

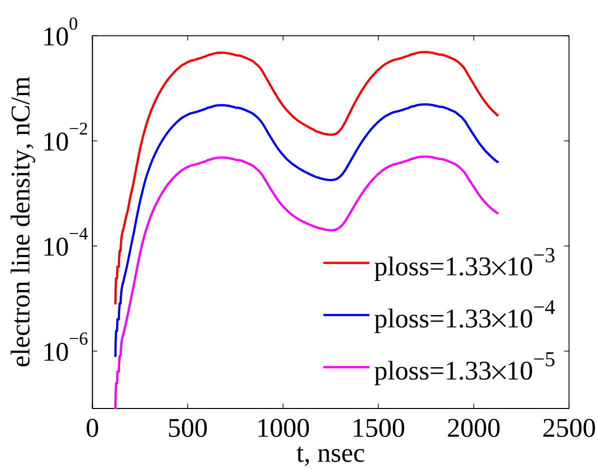

Figure 2: Electron line density for different proton loss.

Electron Cloud Driven Instability

During the electron proton instability simulation, two kinds of tracking have been compared.

In the first, the macro particles in the proton bunch are frozen longitudinally. The proton bunch is supposed to have uniform distribution in both transverse and longitudinal direction. Figure 3 shows the centroidal oscillation of the bunch as a function of the turn number. The result shows a growth in the vertical direction. By fitting the curve with an exponential function, we obtain a growth rate of about 980 turns. This is fast relative to the extraction time, but as the primary electrons are mainly contributed by the lost protons happened during the first 1 ms, this will not be a serious problem for the CSNS ring.

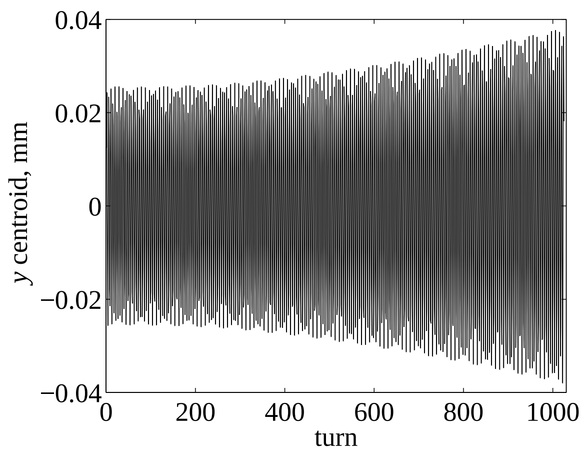

Figure 3: The vertical oscillation of the bunch centre.

For the second case, a real 3D distribution obtained via simulation of painting injection is used. In this case, a RF cavity node is added in the CSNS ring. The energy ramping of the bunches is considered at each turn. The longitudinal phase space distribution of the proton bunch is given in Figure 4.

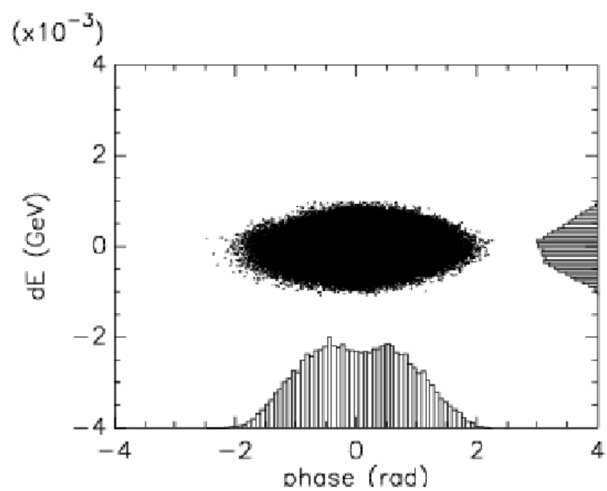

Figure 4: The longitudinal phase space distribution of the proton bunch.

The bunch centroidal oscillation is shown in Figure 5. The instability has been completely suppressed by the damping effect of the energy spread.

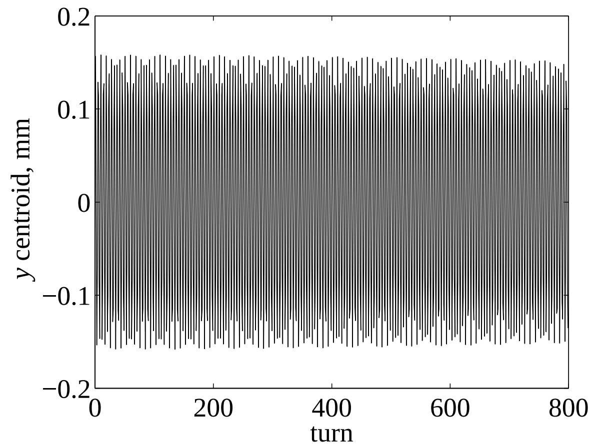

Figure 5: The vertical oscillation of the bunch centre.

SUMMARY

This paper present the primary simulation results of the electron cloud formation and the electron-proton instability in the CSNS ring. The results show that the primary electrons are mainly contributed by the loss protons hitting on the wall, which are then amplified by the secondary electron emission process. According to the simulation results, the multipacting effect is not very strong in the CSNS ring.

In the study of the electron cloud induced instability, two cases with and without energy spread is considered. When the bunch is longitudinally frozen, the simulation shows a clear growth with an exponential growth rate of 980 turns. But considering that the electrons are mostly generated in the first 1 ms when the proton loss occurs, this instability growth will not be a serious problem for the CSNS ring. When an energy spread of 1 MeV is considered, the instability is completely suppressed.

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