ELECTRON CLOUD SIMULATIONS TO COLD PSR PROTON BUNCHES*

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Abstract

We present ORBIT code simulations to examine the sensitivity of electron cloud properties to different proton beam profiles and to reproduce experimental results measured at the proton storage ring (PSR) at the Los Alamos National Laboratory. Using cold proton bunch model, we study the dependence of the prompt and swept electron intensities vs the bunch charge and the recovery of electron clouds after sweeping on the beam loss rate and the secondary electron yield (SEY). Our simulations indicate that the fractional proton loss rate in the field-free straight section may be an exponential function of proton beam charge and may also be lower than the averaged fractional proton loss rate in a whole ring.

INTRODUCTION

The electron cloud effect (ECE) has been considered as one of main sources of beam instability and emittance growth, which leads uncontrolled beam loss, in high intensity proton storage rings [1]. Using the Furman-Pivi algorithm [2], the ECE has been studied for the PSR and RHIC [3, 4]. In order to provide a more self-consistent treatment of particle beam dynamics, we develop an electron cloud simulation module [5, 6] in the popular accelerator code ORBIT [7, 8].

This paper describes its application to understand the ECE in PSR. We concentrate on to study the features of electron clouds themselves but not the proton beam. Thus, we simulate the e-p problems with no feedback kicks on the proton beam and keeping the same passage of proton bunch in every turn, namely *cold* proton bunch. To compare our simulations with experimental data in PSR, the simulated electron cloud region has no applied magnetic field and is straight section in a ring as the position of the electron detector in PSR. All experimental data [9] used in this paper are taken at PSR. All physics parameters in this paper are inspired by PSR (see Table 1).

In our model, we also assume a constant electron yield per lost proton as that of Ref. [4]. Thus, the fractional proton loss rate is proportional to the amount of primary electrons produced in every proton bunch passage.

When every proton bunch passes the electron cloud region, the number of newborn primary electrons produced on the surface of the vacuum chamber at rest is

$$n_{e,p} = Y \times p_{\text{loss}} \times N_p,$$

where Y is the electron yield per lost proton, p_{loss} is the fractional proton loss rate, and N_p is the line density of proton bunch. We adopt the physics model of the stainless steel vacuum chamber surface used by Furman and Pivi's [2, 6]. To change δ_{max} away from a value of 2, we modified the ORBIT secondary emission model [6], the SEY $\delta(E_0)$ as a function of the incident electron energy E_0 can be set to a given δ_{max} while keeping the same zero energy value at $\delta(E_0 = 0) = 0.5$ [4]. In our model, we change the maximum of the SEY curve without changing the peak position.

THE PROTON BUNCH SLOPE DEPENDENCE OF ELECTRON-CLOUD GROWTH AND ENERGY DISTRIBUTION OF ELECTRON HITTING SURFACE

In this section, we see the behavior of electron cloud due to shapes of cold proton bunches. We consider triangular shapes for proton bunches in longitudinal proton coordi-

Table 1: Physics and numerical parameters.

PARAMETER	Symbol(unit)	PSR
RING PARAMETERS		
Proton beam energy	E (GeV)	0.793
Bunch population	N_p (10^{13})	~ 5
Ring circumference	C (m)	90
Revolution period	T (ns)	358
Bunch length	τ_b (ns)	254
Gaussian beam size	σ_x, σ_y (mm)	10, 10
Beam pipe semiaxes	a, b (cm)	5, 5
SIMULATION PHYSICS PARAMETERS		
Fractional proton loss	p_{loss} (10^{-6}/turn)	4
Proton-electron yield	Y	100
Maximum SEY	δ_{max}	≤ 2.0
NUMERICAL PARAMETERS		
number of beam slices		128
EM time steps /turn		1500
Tracker steps /timeStep		20

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nate. We arrange two types of triangles: the same head triangles and the same tail triangles.

The same head distribution accumulate the same number of primary electrons in an electron cloud region by the time when its peak pass the region, but has different tail slope each other after the peak. The same tail proton bunches show the effect of the amount of primary electrons before the peak on the electron cloud growth. Through the simulations of these bunches [11], we find that a longer proton bunch tail gives a larger electron cloud, a later peak and a larger growth rate. The steeper tail of proton bunch gives a higher energy of electrons hitting surface, which corresponds less SEY if the energy is over 300 eV. A larger primary electrons during increasing process of a proton bunch has little effect on electron cloud growth rate and amount of electron cloud. The energy of electrons hitting surface, namely the secondary electron emission process, is mostly determined by the proton bunch tail slope. We can say a beam profile of longer head is a possible way to accumulate more protons without making electron cloud larger.

PROMPT AND SWEPT ELECTRON SIMULATION AND DISCUSSION OF PHYSICS PARAMETERS WITH COMPARING PSR DATA

In this section we try to reproduce the experimental data measured at the PSR [9] of the *prompt* electron signal and the *swept* electron signal vs proton bunch charge through ORBIT simulations. Both signals are taken at the same *electron sweeper* located in a straight section in PSR. The electron sweeper can sweep most of electrons inside vacuum chamber when a high voltage (HV) pulse is applied on it after the proton bunch passed through the detector area. Without the application of HV pulse, it is an electron detector that counts surface electron current from chamber to its collector. The *prompt* electron signal is defined as the peak height of electron signal without HV pulse in the steady state. The *swept* electron signal is the spike height after the application of a HV pulse sweep.

In our simulation, the peak of the surface current, which is the absorbed electron current through the vacuum chamber surface, can be treated as the *prompt* electron signal. Also, the electron cloud line density at the head of the succeeding proton bunch pulse can be treated as the *swept* electron signal.

We assume that $p_{\rm loss}$ is a function of bunch charge, and the rate of seed electron production depends on bunch charge. We perform simultaneous fitting of both the experimental *prompt and swept* slopes using a single fitting parameter $p_{\rm loss}$. Our assumption is reasonable because higher bunch charge will have higher beam loss rate due to many beam dynamics problems. We however assume a constant δ_{max}, which depends on beam pipe condition such as scrubbing, vacuum condition etc.

The fitting procedure is as follows: (1) We assume $\delta_{max} = 1.7$. (2) The simulated *prompt and swept* values

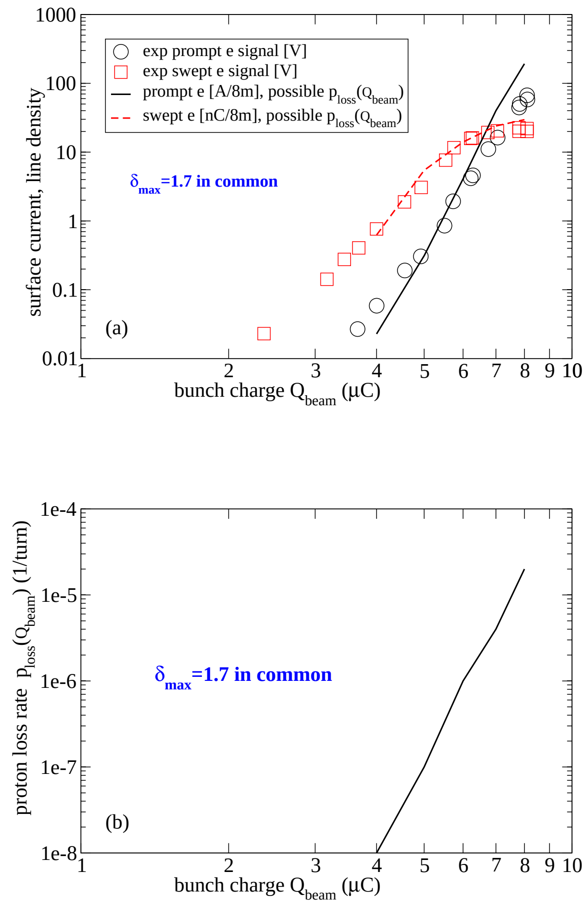

Figure 1: Using a constant SEY of $\delta_{max} = 1.7$, we fit the prompt and swept data with varying fractional proton loss rate $p_{\rm loss}(Q_{\rm beam})$ as a function of bunch charge $Q_{\rm beam}$ in (a). The resulting fractional proton loss rate is shown in (b).

of $p_{\rm loss} = 4.0 \times 10^{-6}/{\rm turn}$ for bunch charge $7\mu{\rm C/pulse}$ are set as the reference point. (3) For a given bunch charge $Q_{\rm beam}$, we find the parameter $p_{\rm loss}$ such that the prompt and swept signals fit both experimental *prompt and swept* slopes. (4) The fractional proton loss rate function $p_{\rm loss}(Q_{\rm beam})$ is determined by repeating the step (3).

Figure 1 shows the slope fitting of both simulated *prompt and swept* data. We note that resulting the proton loss function $p_{\rm loss}(Q_{\rm beam})$ is nearly exponential. There are some remaining questions about the assumption of fractional proton loss rate as a function of bunch charge. The simulated beam of $4\mu{\rm C/pulse}$ in Fig. 1 has maximum proton beam line density 160 nC/m and electron cloud peak line density 0.092 nC/m. This amount of electron cloud may be too small to cause proton beam instability, though the instability is measured even for a beam of less $4\mu{\rm C/pulse}$ at PSR. In the future, we need to study a proper origin of fractional proton loss rate function, simulation to check centroid oscillation of proton beam with the parameter of small fractional proton loss rate.

We need to remind ourselves that there are different sources of primary electrons. Therefore, the functional dependence of $p_{\rm loss}(Q_{\rm beam})$ may reflect the unknown electron sources at high bunch charge.

ELECTRON CLOUD RECOVERY SIMULATION AFTER SWEPT

In PSR, it has been experimentally observed that the peak signal of electron cloud is reduced substantially after the clearing of electrons cloud in the gap by an electron sweeper device. The electron cloud takes several turns to recover [9]. To reproduce this feature, in our simulation, there are no electron clouds before the first turn, and the surviving electrons from previous gap follow turn-by-turn. In general, lower bunch charge, lower fractional proton loss rate and lower maximum SEY are the factors to increase the number of recovery turns.

We calculate the electron cloud recovery time and compare with the PSR experimental result that electron cloud in the case of 7.5μC bunch current needs 5 turns to recover [9]. Through the comparison, we estimate that the fractional proton loss rate of 7.5μC beam in drift space is around $p_{\rm loss} = 1.0 \times 10^{-8}$ at $\delta_{max} = 2.0$, or $p_{\rm loss} = 1.0 \times 10^{-7}$ for $\delta_{max} = 1.7$.

From the prompt and swept electrons vs bunch charge study, we find that we need $p_{\rm loss} = 4.0 \times 10^{-6}$ with $\delta_{\rm max} = 1.7$ for 7.0 μC bunch charge. Varying other parameters, we need $p_{\rm loss} > 1.0 \times 10^{-6}$ to fit the prompt and swept data. The prompt and swept electron data indicated that there were a lot of seed electrons observed in the electron detector area.

On the other hand, from the recovery time study, we find that $p_{\rm loss} \approx 1.0 \times 10^{-7} \sim 1.0 \times 10^{-8}$ for the 7.5 μC beam. The recovery time experiments indicate that once the seed electrons are swept away, it takes a few turns to recover these electrons. The seed electrons are not generated by proton loss at the detector area. Generally, electrons does not move in the longitudinal coordinate, and thus electrons outside the simulated region are not considered in our model. However, recent experimental results at PSR [10] indicate that electrons can eject from quadrupole magnets into the drift space. If this is the case, the recovery turns essentially depend on the traveling time of these electrons. To include this scheme may be a possible way to achieve the self-consistency between the recovery estimation and the assumption of fractional proton loss rate function.

We have also found that the energy distributions of electrons hitting the surface of vacuum chamber in 5 recovery turns are nearly identical even though the peak height of electron cloud increases turn by turn. Therefore, the energy distribution is mainly determined not by the amount of carry-over electrons but by longitudinal proton bunch profile discussed earlier. This is consistent with the result of triangular proton bunches that the same kick from proton bunch potential gives similar energy range of surface hitting electrons among different amount of primary electrons originally trapped inside proton bunch.

CONCLUSIONS

We have examined electron cloud properties using ORBIT code simulations of *cold* proton beam bunch. We use the PSR parameters for our physics study and the simulated electron cloud region is located in a straight section, where there is no magnetic field.

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