# MECHANISM OF ELECTRON MULTIPACTING WITH A LONG BUNCH PROTON BEAM*

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*Abstract*

The mechanism of electron multipacting in long bunched proton machine has been quantitatively described by the electron energy gain and electron motion. Some important parameters related to electron multipacting are investigated in detail. It is proved that multipacting is sensitive to beam intensity, longitudinal beam profile shape and transverse beam size. Agreement is achieved among our analysis, simulation and experiment.

## INTRODUCTION

Most operators of high-beam intensity machines have encountered electron cloud instability since it was first reported at INP PSR in 1965 [1]. For a coasting beam, electrons accumulate at the chamber's center due to trapping by the beam's potential rather than the beam inducing multipacting. Multipacting, induced by bunched beams apparently causes electrons to accumulate inside the vacuum chamber and then interact with the proton- or positron-beam, causing its instability. Experimental observations of electron-cloud instabilities are distinctively different for "short bunches", where multi-bunch multipacting is expected to be important (PS, SPS, and B factories) and for "long bunches", where it is dominated by single-bunch, trailing-edge multipacting [2]. The mechanism of beam-induced multipacting is quite different for the two. The SNS's beam is a bunched beam wherein the electron cloud is mainly produced by multipacting. Many studies of electron-cloud buildup in long-bunch proton machines have been done based on numerical methods [3–8]. This report briefly discusses the mechanism and main parameters related to the electron multipacting with a long bunched-beam.

## MECHANISM OF MULTIPACTING

The so-called "trailing edge multipactor" was used to qualitatively explain the mechanism of electron multipacting with a bunched long proton beam [2]. Analysis shows that electrons generated before the center of the bunch can be trapped by the beam's potential. The oscillation amplitude of trapped electrons can be described by the adiabatic invariant [7]. Fig. 1 shows the typical orbit of electron by beam loss in the SNS accumulator ring.

The many surviving electrons from the last bunch gap modulate the beam's dynamics; they may destabilize the beam because they can be deeply trapped inside it. They have weak effect on multipacting due to their long-term trapping and low energy at the chamber's surface. On the other hand, electrons born at the wall after the peak of the pulse passes will be accelerated towards the beam's center and decelerated after passing through it. They will drift straight to the opposite wall of the chamber, gaining certain energy as they reach it. If the gain is high enough, then the secondary emission yield (SEY) can exceed unity, and be further amplified on each successive traversal of the beam's pipe. Electrons born at the wall between the bunches' center and tail are the only source of multipacting due to their having a short transit time and sufficient energy when they hit the chamber's surface.

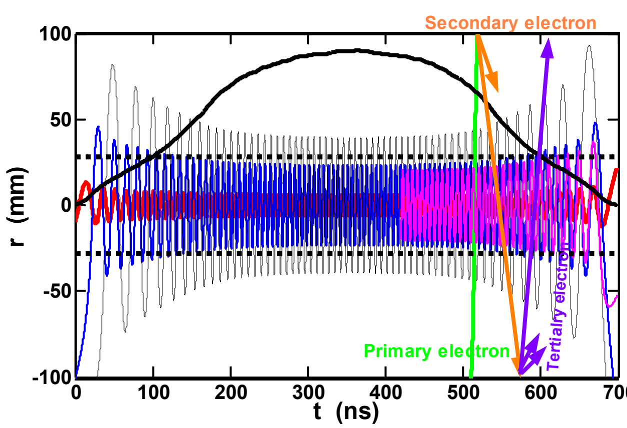


FIG. 1: (Colour) Typical orbits of various electrons with the SNS beam; the bold solid line shows the shape of the longitudinal beam profile and the dashed black lines show its transverse size. The blue and red lines show the orbits of surviving electrons from the last bunch gap. They are trapped inside beam during its passage and can cause beam instabilities. The solid back line shows the orbit of an electron that is emitted at the chamber surface between bunch's head and center. It oscillates with large amplitude and lost between bunch's center and tail. The green line shows an electron that is emitted at the chamber's surface between bunch center and tail. It is important for multipacting, as it generates secondary and tertiary electrons. The pink line shows the orbit of an electron generated by ionization.

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A more detailed analysis shows that the electrons' energy at the wall's surface is proportional to the derivative of the beam-line density and inversely proportional to its square root [7]

$$\Delta E = -\frac{1}{2}\beta c\sqrt{\frac{me}{2\pi\varepsilon_0}}\frac{\partial\lambda}{\partial z}\frac{1}{\sqrt{\lambda}}\left(a(2\zeta-1)\arcsin\frac{1}{\sqrt{\zeta}}+a\sqrt{2\ln\frac{b}{a}}+\sqrt{2\zeta}\int_a^b\frac{dr}{\sqrt{\ln(b/r)}}-\frac{1}{\sqrt{2}}\int_a^b\frac{1+2\ln(r/a)}{\sqrt{\ln(b/r)}}dr\right). \quad (1)$$

Where $a$ is the transverse beam size, $b$ is the pipe radius and λ is the beam line density. Therefore, the electrons' energy at the wall is usually bigger around the bunch's tail due to the small beam-line density there, and hence, multipacting is stronger as shown in Fig. 2. That can explain why cutting the bunch's tail can effectively reduce multipacting [4]. An experiment carried out at the LANL's PSR shows that variation of the RF buncher phase can change the beam's longitudinal profile and electron signal [9]. Thus, we can optimize the design of a real machine to lower the electrons' energy gain. The energy spreader and corrector in the SNS ring can significantly suppress the beam's tail [10] and hence, reduce multipacting. Simulation also verified the effect of the beam's longitudinal profile on multipacting [7]. The longitudinal profile factor can be used to explain the mechanism involved. Simulation demonstrated that a beam with a Gaussian profile exhibits stronger multipacting than do beams with sinuousoidal and elliptical ones. The electron density in SNS ring is close to that with the sinuousoidal profile. For the SNS beam, the electron's peak energy at the wall is about 300eV and multipacting starts at 500ns with 700ns bunch length. Therefore, multipacting time is about 200 ns. Electrons can across the chamber more 15 times on average during this period. Assuming the same secondary-emission parameters and electron yield per turn for the SNS and PSR, the simulated electron density is close for these two rings.

Table 1 shows the important parameters related to electron multipacting with long bunch. For a beam with a fixed longitudinal profile shape, both the energy gain and multipacting frequency are proportional to the square root of the beam's intensity. Accordingly, the electron cloud is very sensitive to the beam's intensity. The electrons generated by the residual gas is not important for multipacting due to their long term trapping by beam field.

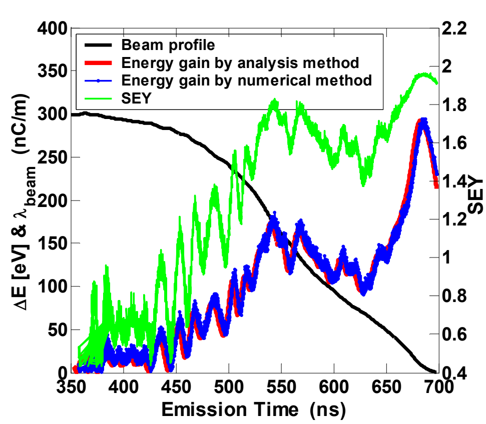


FIG. 2: Energy gain and SEY of multipacting electrons

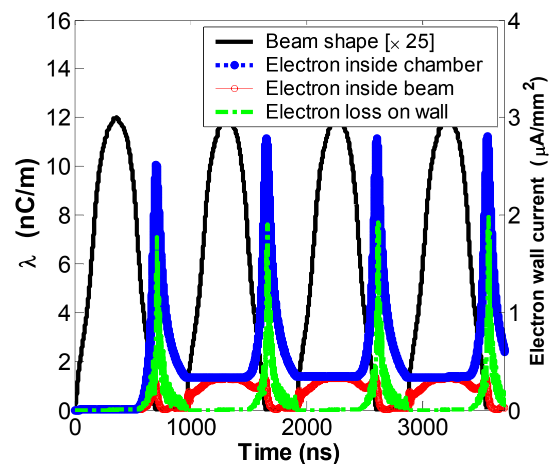


FIG. 3: (Color) Electron cloud buildup in the SNS drift region. The black line shows the beam's longitudinal profile. The blue line is the electron cloud's line density inside chamber, representing the total number of electrons and hence, multipacting. The red line shows the electron line density inside beam; it drives beam instabilities. The green line gives the current density of electrons striking the wall, which can be used to compare with experiment results.

Table 1: Important parameters related to multipacting

| Parameters | $\rho_{chamber}$ (Multipacting) | $\rho_{beam}$ (stabilities) | mechanism |
|---|---|---|---|
| Longitudinal beam profile | sensitive | sensitive | profile factor |
| Beam intensity | very sensitive (no saturation) | very sensitive (saturates) | multipacting frequency & energy gain |
| Beam transverse profile | insensitive | insensitive | space charge doesn't sensitive to transverse profile |
| Flat beam | effective | effective | Electron orbit polarization |
| Peak SEY | Effective (~linearly) | Effective (~saturates) | SEY |
| Energy at peak SEY | Effective (~linearly) | Effective (~linearly) | energy gain is below 300eV |
| Electrons by ionization | insensitive | insensitive | adiabatic motion (trapping) |

## MULTIPACTING IN DIPOLE MAGNET

In a strong dipole magnet, an electron can only effectively move along the vertical magnetic field lines. Its vertical motion is similar to the radial motion of an electron in the drift region. For example, the beam's vertical space-charge field can vertically trap electrons emitted before the bunch's center; electrons emitted from the chamber's surface around the bunch's tail can excite multipacting. Figure 4 shows the relationship of the electron's energy gain at the wall surface with the X-coordinate. It peaks at the chamber's center, which equals the energy gain in the drift region given by Eq. (1), and decreases at both sides. Thus, multipacting in a dipole magnet depends on the horizontal coordinate. It is the strongest at the chamber's center and weakens with the increment of |X|. The simulated distribution of the electron cloud in a dipole magnet (Fig. 5), is consistent with the gain in electron energy (Figure 8). Similar to the drift region, there is a strong multipacting at the tail. In the present proton machine, multipacting can occur only at the chamber's horizontal center because the electron energy peaks there below a few hundreds eV. It is less than 300 eV in the SNS dipole magnet.

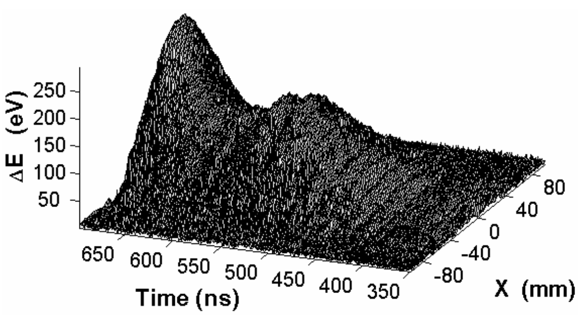


FIG. 4: Energy gain of multipacting electrons in the SNS's dipole magnets with $B_y$=7935 Gauss.

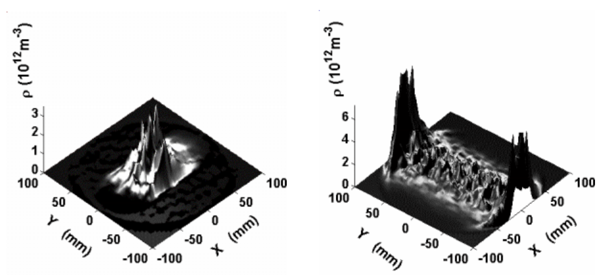


FIG. 5: Electrons' transverse distribution in the SNS dipole magnet at bunch's center (left) and tail (right)

## ELECTRON CLOUD IN QUADRUPOLE

Figure 6 shows results of simulations for the electron cloud's transverse distributions in a normal quadrupole magnet of the SNS ring. In quadrupole magnets, very weak multipacting occurs around the middle of each magnetic pole at the bunch tail because only those electrons moving along these field lines receive enough energy by a mechanism similar to that inside a dipole magnet. The simulated electron cloud is more than two orders-of-magnitude smaller than in the drift region due to the electron's low energy at the wall's surface. Quadrupole and sextuple magnet fields are mirror fields that may trap electrons via the mirror-field trap mechanism. However, mirror-field trapping requires that the bunch length is shorter than the period of gyration [12]. Therefore, electrons emitted from the chamber's surface cannot be trapped due to the long bunch length. The distribution of the electron cloud shown in Figure 6 implies that there is no mirror-field trap; the electron cloud would stay closer to the mirror points of the field lines if mirror-field trapping happens. Compared with the electron cloud in the drifting region, the simulated decay time of the electron cloud at the bunch gap in quadrupole and sextupole magnets is much longer due to the weak space-charge effect, and the confinement of the electron's orbit by the magnetic fields. Similar to drift region and dipole magnet, electron cloud is trapped by the beam's space charge force at chamber's center during the passage of beam center.

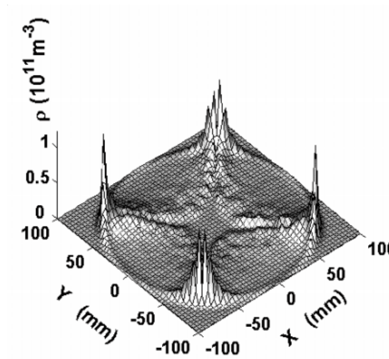


FIG. 6: Electrons' transverse distributions in the SNS's quadrupole with a field gradient 4.7T/m

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