ENERGY SPECTRUM OF AN ELECTRON CLOUD WITH SHORT BUNCH

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Abstract

The transverse instability in a beam and the blow-up in its size caused by an electron cloud become increasingly important in high-intensity accelerators. The electron cloud builds up through beam-induced multipacting. We investigated the energy spectrum of an electron cloud with short bunch using particle simulation. A "stop-band" structure is found and a model is suggested to explain and to describe this phenomenon. The number of stop-bands depends only upon the beam (bunch spacing and intensity) and the radius of the vacuum pipe. The electron- energy spectrum provides useful information for understanding multipacting and measuring the electron's energy.

INTRODUCTION

The secondary emission yield (SEY) strongly depends on the energy of the incident electrons. The energy of preliminary electron, only a few eVs, is not enough for multipacting. However, electrons can receive energy from the beam's potential. The beam induces electron multipacting [1, 2] and it strongly depends on the interaction between the beam and the –electrons. Accordingly, electron energy at the wall, and hence, multipacting, is contingent upon many parameters, such as the beam's pattern, the bunch's intensity, profile, and length, and the chamber's size.

In a long bunch machine, the electron's energy at the wall can be calculated and multipacting can be clearly described by the electron's energy gain and drifting time [3]. In a short bunch machine, an electron usually receives multiple kicks before it hits the wall. Its energy at the beam wall is significantly sensitive to the electron's initial condition, such as emission time, and beam. Analyses have estimated the energy gain [4, 5] based on some assumptions. We investigated the electron's energy gain in a short bunch machine using a numerical method [6] that includes secondary emissions and space charge.

RANDOM ELECTRON MULTIPACTING IN A SHORT BUNCH MACHINE

In a static model, the energy received from the bunch by an electron near the beam chamber surface is

$$\Delta E \approx 2m_e c^2 r_e^2 \frac{N_b^2}{r_b^2} \qquad (1)$$

where r_e is the classic radius of the electron, N_b is the bunch intensity, and r_b is the radius of beam chamber.

When the wall-to-wall transition time is equal to the bunch spacing, it is called the multipacting condition [7, 8]. The bunch intensity at this condition is

$$N_{th} = \frac{r_b^2}{r_e c t_{sp}} . \qquad (2)$$

where t_{sp} is the bunch spacing in time. Table I shows the bunch intensity at the multipacting condition in different machines. Most electron machines run with a bunch intensity below the multipacting intensity wherein electrons take more than one bunch-spacing time to transit the chamber. On the other hand, the bunch intensity is above this threshold in proton machines, such as the LHC and RHIC, where an electron hits the wall before the next bunch arrives. The SPS has a very flat chamber where the bunch density is above the multipacting density vertically but below it horizontally.

Table 1: Multipacting bunch density at different storage rings.

Machine	r_b(cm)	t_{sp} (ns)	N_b (10^{10})	N_{th} (10^{10})
KEKB	5	8/2	5	36/150
PEPII	4.5/2.5	8	5	29/9
NLC DR	1.6/3.6	1.4	0.75	22/110
TESLA	5	20	2	15
DAΦNE	3.5	5	5.4	27
HERA-e	4/2	100		2/0.5
LHC	2.2/1.8	25	10	2.3/1.5
SPS	7/2.2	25	10	23/2.3
RHIC	6	108/216	10	4

Is Eq. (2) really required for assessing electron multipacting? Actually, Eq. (2) is neither sufficient nor necessary for multipacting [9]. In the most electron-storage rings, an electron receives multiple bunch kicks from the beam before it hit the wall. Its energy at the wall could be much larger than the value given by Eq. (1) because it receives stronger beam kicks around the chamber's center during its transit. For example, the electron's energy at the wall can be up to 1keV in the KEKB LER. The same conclusion applies in storage rings where the bunch intensity is above the multipacting density. Fig. 1 shows the electron's orbit and energy at the chamber wall. The latter clearly displays irregularity that depends on the electron's initial condition (emission time, position, and velocity). The simulated energy at wall usually is larger than that derived from Eq. (1), which gives an energy about 20 eV for both the KEKB LER beam and RHIC's beam.

Multipacting with a short bunch differs from regular multipacting. The orbit and energy of the electron vary randomly according to its initial condition (it has a spread), the beam, and the chamber's geometry. In general, it is a random multipacting.

However, the electron's energy with long bunch at the wall can be calculated. It is expressed as a function of chamber size, transverse beam size and beam line density [3]. It is strongly depends on the beam profile:

$$\Delta E \propto -\frac{\partial \lambda}{\partial z} \frac{1}{\sqrt{\lambda}} \qquad (3)$$

where λ is the beam line density. The peak energy at the wall for the LANL PSR and SNS ring is about 300 eV. Strong multipacting always happens around the bunch tail due to the high energy gain there. FIG. 2 shows an electron's orbit and energy at the wall in SNS case. The electron continuously hits the wall for more than 20 times around the bunch tail with the energy above the multipacting threshold, which agrees well with the analytic one.
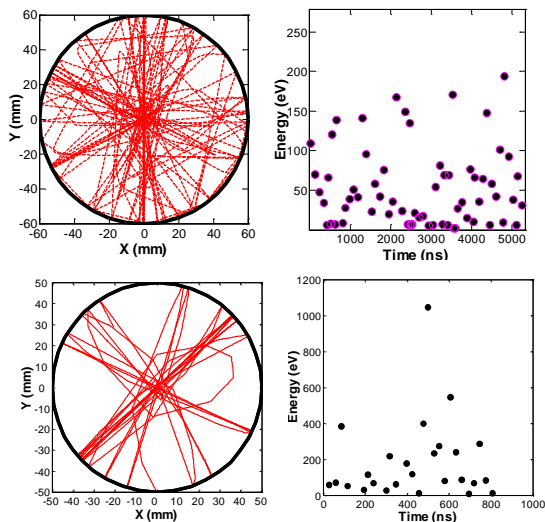

Figure 1 Electron's orbit (left column) and energy at the wall (right column). RHIC beam with bunch spacing 108 ns (top row); KEKB LER beam with bunch intensity 3.3×10^{10} and bunch spacing 8ns (bottom row).
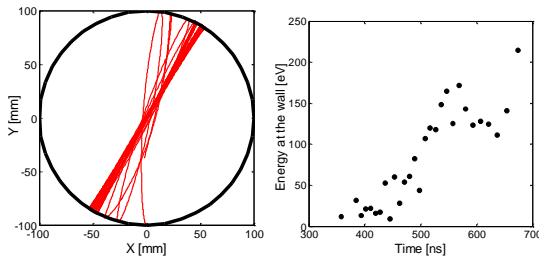

Figure 2 Electron's orbit (left column) and energy at the wall (right column) in the SNS accumulator ring. Bunch length is 700 ns.

DISCRETENESS IN THE ELECTRON'S ENERGY SPECTRUM

There are two types of electrons. First is those electrons that hit the chamber wall. The SEY, and hence, multipacting, depends on their energy. Another type of electrons is those that stay within the chamber. They interact with beam and cause the blow-up of the beam size and instabilities. Fig. 3 shows the energy spectrum of these two types for the KEKB LER beam. The energy spectrum of electrons inside the chamber is continuously and monotonously distributed. However, there are many structures in that of the electrons hitting the wall. The spectrum at some energy range is very low, similar to the "stop-band" in wave transmission. We also call this kind of structure in the energy spectrum a "stop-band". ECLOUD revealed a similar phenomenon [9].

The structure in the energy spectrum of electrons that hit the wall comes from multi-bunch effect. Fig. 4 shows the energy distribution of electrons inside chamber plotted as a function of energy and radial coordinate. It clearly demonstrates the dependence of energy distribution on radial position. The spectrum has some structures at certain radial coordinates, although the integrated one over the whole radial coordinate is monotonic function of energy (Fig. 3). Comparison of the spectrum of these two types of electrons suggests they are correlated. Thus, the energy spectrum of electrons at the wall is similar to that of those electrons inside the chamber whose radial coordinate is equal to the pipe's radius. This feature is more clearly shown by the snapshot of the electrons' distribution in Fig. 5. Therefore, the "stop-band' in the spectrum of electron at the wall is derived from the spectrum of electrons inside chamber.
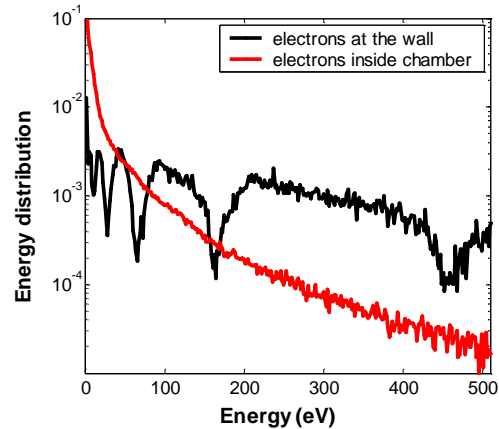

FIGURE 3 Energy distributions of the electrons at the wall and inside the beam chamber in the KEKB LER's beam. Bunch spacing is 2 ns.
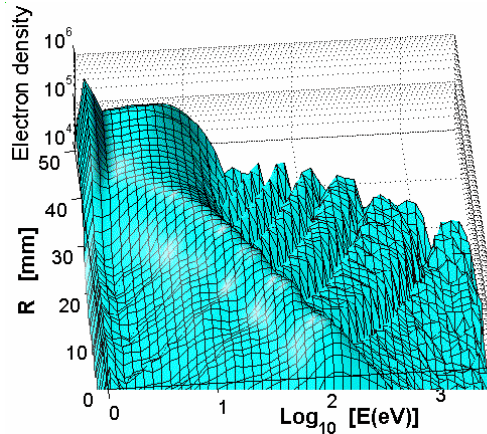
FIGURE 4 Energy distributions of the electrons inside the beam chamber with 2 ns bunch spacing
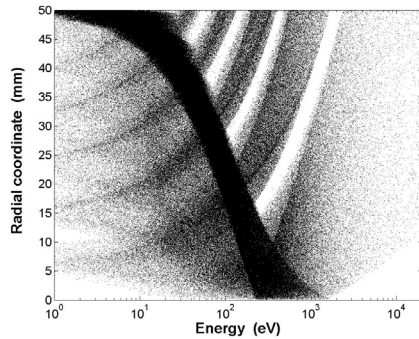

FIGURE 5, Snapshot of the electrons' distribution as a function of energy and radial coordinate.

The discreteness in the energy spectrum is a major characteristic of the electron cloud in a short bunch machine. It reflects the effect of multiple passages of the positron/proton bunches. The number of "stop-bands" depends only on the beam (bunch spacing and bunch intensity) and the radius of the beam's chamber. It corresponds to the time in bunch spacing for the electrons to transit the chamber. The n-th stopband occurs when the electron of that particular energy is swept out by the (2M-n)-th bunch following that electron's birth (where M is the number of the stop-band). The first stop-band is on the side with low energy. For the example, as shown in Figures [3-4], it takes at least 5~6 bunch spacing for electrons to transit the chamber.

The structure of energy spectrum is sensitive to the bunch's spacing and current, and the chamber's size. It is insensitive to the secondary emission parameters.

Bunch Spacing

FIG. 6 shows the effect of bunch spacing on the energy spectrum of electrons at the wall. There are more "stop-bands" when the bunch spacing is small because more bunches will kick the electrons during their movement from the wall to the opposite surface. FIG. 7 shows our experiment results at KEKB LER with 8ns bunch spacing; they roughly agree with the simulation depicted in Fig. 6. We note that the energy spectrum is sensitive to

the chamber's radius or the electrons' radial coordinate. In experiments, the electron collector receives electrons with a certain radial coordinate range due to its size. It is not surprising that there is no "stop band" for long bunch spacing where the bunch's intensity is above the threshold given by Eq. (2).
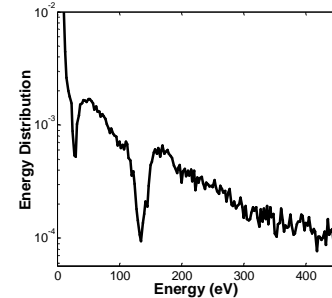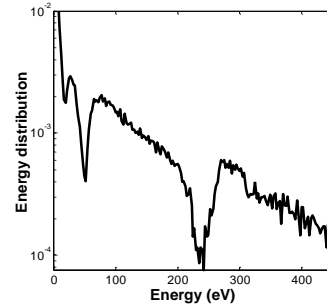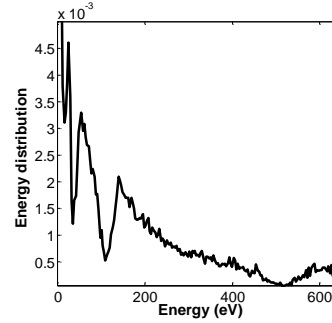

FIGURE 6 Energy distributions of the electrons at the wall with different bunch spacing: 4ns (top); 6ns (middle); and 8ns (bottom). Bunch intensity 3.3×10^{10}
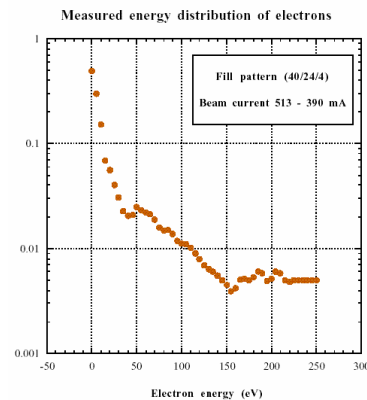

FIGURE 7 Measured energy spectrum of electrons at the wall in the KEKB LER with 8 ns bunch spacing.

Chamber Size

For chambers with a large radius, more positron bunches pass the electron cloud before they hit the wall. Therefore, there are more stop-bands, as shown in Figure 8. It is interesting that more electrons have high energy with large-sized chamber. However, electron density is low because it takes longer for an electron to transit the chamber for once multipacting. The simulated electron volume density at the chamber's center is, respectively, 4×10^{13} m^{-3} and 3×10^{12} m^{-3} for a 30-mm and 100-mm chamber radius. The multipacting is significantly sensitive to this parameter.
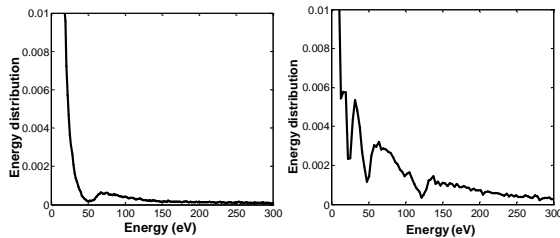

FIGURE 8 Energy spectra of the electrons at the wall in the KEKB LER with an assumed chamber of (left) 30mm, and, (right) 100 mm radius. Bunch intensity 3.3×10^{10} and spacing 8ns.

Bunch Intensity

For lower beam intensity, more positron bunches pass the electron cloud before they hit the wall. Therefore, there are more stop-bands. Figure 9 shows the energy spectrum with half the bunch intensity of that in Fig. 6 (8ns bunch spacing). The energy spectrum differs for different bunch intensities, and hence, multipacting differs.
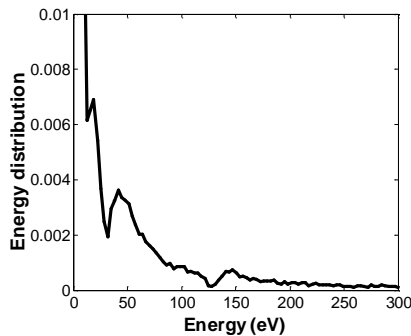

FIGURE 9 Energy spectrum of electrons at the wall in the KEKB LER with 8 ns bunch spacing and 1.65×10^{10} bunch intensity.

Dipole magnet

Inside the dipole magnet, multipacting occurs near the horizontal center of the chamber. The position of the multipacting strips depends on the beam (bunch intensity, and spacing), the chamber's radius, and the magnetic field. Consequently, both multipacting and energy are angular and B-field dependent. FIG. 10 shows the distribution of the electron cloud in the transverse plane of the chamber and the energy distribution.
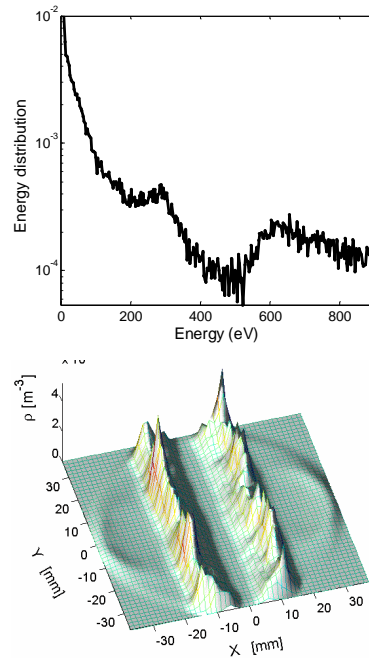

FIGURE 10 Energy spectrum of the electrons at the wall in the dipole magnet of SUPER-KEKB with 2 ns bunch spacing and 1.2×10^{11} bunch intensity.

SUMMARY

The electron multipacting with a short bunch is of a random type, wherein it is sensitive to the electron's initial condition. A "stop-band" structure was found in the energy spectrum. The discreteness in the energy spectrum is the main characteristic of an electron cloud in a short bunch machine. It results from the effect of multiple passages of the positron/proton bunches and it is sensitive to the bunch's spacing and intensity, and the chamber's radius. Therefore, multipacting is sensitive to these parameters.

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