B - 12 Electromagnetic Fields excited by a High-current Single Bunch travelling through the Accelerating Waveguide

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Abstract

The single bunch with the charge up to 14 nC is accelerated by the 35 MeV Osaka University Single Bunch Electron Linear Accelerator. The average energy of electrons in a single bunch decreases proportional to the charge. The radiation loss of a single bunch is evaluated to be 0.77 - 0.87 MeV / 16 nC in 39 cavities of the accelerating waveguide. A theoretical estimation performed with a diffraction model is compared with the experimental results. Electromagnetic fields excited by a high-current single bunch are simulated for the cavity of accelerating waveguide.

I. Introduction

Recently there has been a great interest in the radiation loss from a bunched beam of a high-current electron storage ring due to the transient excitation of both the rf accelerating cavities and the components of the transport system [1-4]. Theoretical estimations of radiation loss indicate the following facts: first, the beam-cavity interaction may make significant demands for increased rf power in the accelerating cavity; second, it may cause the maximum currents of a bunch in a steady state of acceleration in the storage ring; third, it may bring other deleterious effects such as a bunch instability or a distortion of bunch shape. Unfortunately, theoretical estimations can be made only for the idealized case, and different theories seem to give different results [1-7]. In view of the theoretical uncertainties, it is highly desirable to have an experimental determination of the radiation loss that will be generated in the cavity.

An experiment on the radiation loss of a single bunch with 10^9 electrons have been performed in the 81416 cavities of the linear accelerator as SLAC [8]. From the experimental result in this highly relativistic case the following conclusion can be derived: the radiation loss is independent of enrgy in the range between 0.9 GeV and 19 GeV. On the other hand, it is very difficult to estimate the radiation loss of a single bunch of lower energy experimentally, since the total radiation loss in the accelerating waveguide should be decreased for a low energy linear accelerator of short length. The possibility of an accurate evaluation of the radiation loss suddenly rises with the advent of the high-current single bunch electron linear accelerators [9-12]. A high-current single bunch containing of the order of 10^{11} electrons (16 nC) can be accelerated by the 35 MeV Osaka University Single Bunch Electron Linear Accelerator. The experimental observation of radiation loss of a single bunch has been carried out in the waveguide of the Osaka University machine [13-14].

II. Energy Spectrum of the Single Bunch

The energy spectrum of the accelerated single bunch is measured by a 90° analyser magnet, the momentum resolution of which is better than 10^{-3}. The magnetic strength of the analyser is slowly scanned by an automatic scanning circuit, and it is monitored by a fluxmeter. The current transmitted through the exit slit is collected with a Faraday cup and it is measured by an electrometer (Keithley 610CR). Analog outputs of both the fluxmeter and electrometer are transffered to a realtime data processing system, and then the energy spectrum is plotted on the graphic display.

The bunch electrons extracted from the beam window of the 270° bending magnet are collected with a Faraday cup. The total charge in a single bunch is determined by the following method: the charges collected with the Faraday cup are recharged into a CR circuit with a coaxial line extended to the control desk, and then the current discharged through the resistor is measured by an oscilloscope.

Figure 1 shows the dependence of the energy spectrum of the single bunch on the charge. It shows the fact that both the maximum and the minimum energy of the single bunch decreases with increasing charge. In other words, the energy of electron in a single bunch decreases with increasing charge. It is reasonable to consider that the single bunch losses its energy by the radiation loss in the cavity of the accelerating waveguide of the linear accelerator.

III. Radiation Loss Factor

The energy spectrum shown in fig. 1 indicate that the average energy of a single bunch is linearly decreases with increasing charge. Therefore the beam loading of the single bunch can be obtained by plotting the average energy of electrons in a single bunch against charge. From the experimental results, the radiation loss factor, the total radiation loss factor through the accelerating waveguide, is evaluated to be 0.77 MeV / 16 nC at 24 MeV and 0.87 MeV / 16 nC at 31 MeV. Using the diffraction model [6], the total radiation loss has been estimated to be 1.11 MeV / 16 nC at 24 MeV and 1.24 MeV / 16 nC at 31 MeV [14]. The total radiation loss of a highly relativistic single bunch in the L-band accelerating waveguide of the Osaka University machine has been also estimated to be 1.91 MeV / 16 nC [14]. The radiation loss in each cavity of L-band accelerating waveguide has been estimated to be 40.2 - 55.6 keV per 16 nC.

It has been reported that the highly relativistic single bunch of 0.16 nC (0.9 - 19 GeV) loses energies of 33 - 44 MeV in the S-band cavity of SLAC [8]. The radiation loss factor for an S-band cavity for these cases is estimated to be 40 - 56 keV / 16 nC. It seems that the radiation loss factors in L-band and S-band cavities are comparable with each other. These two experimental results show that in order to design a high-current single bunch electron linear accelerator, the following points should be taken into consideration: the radiation loss should be considered when a single bunch containing more than 10^{11} electrons is to be accelerated in the rf cavity. If the advent of the high-current electron injector with a new method of charge enhancement is realized by powerful technical developments, there might be a practical upper limit of current for rf acceleration of a single bunch in a linear accelerator. If a single bunch of higher charge is accelerated by a linear accelerator, the radiation loss will be comparable to the total energy gain of the accelerated single bunch.

IV. Transient Electromagnetic Fields excited by a Single Bunch travelling through the Cavity

The radiation loss factor evaluated by using the diffraction model is described in the previous chapter. In order to evaluate the radiation loss, the single bunch is assumed to be a point charge. There have been the data of energy spectum differ from those shown in fig. 1. These data indicate that the maximum energy is independent of the charge in a single bunch and at the same time it is constant (see fig. 2). In this case, only if the bunch length is taken into consideration, these data can be explained as follows: the bunch width is estimated to be 10.8 mm, which cannot be neglected in comparison with the length ($g = 51.2$ mm) of each cavity in the L-band accelerating waveguide. Therefore, it is reasonable to consider that the radiation loss of an electron depends on the place of the electron in the single bunch. The electron in the front part of the bunch does not lose any energy but the radiation loss of the electron increases with its position.

If the front part of the bunch is accelerated on the crest of the accelerating field, the electrons having maximum energy should exist in the front part of the bunch. The radiation loss increases with charge, but the maximum energy ought to be independent of the charge. In other cases, the maximum energy should be decreased with increasing charge. As a result, in order to evaluate the accurate radiation loss of the single bunch, the theory obtained considering the bunch length is required.

The direct calculation of the transient electromagnetic fields in an rf cavity is the decisive method to evaluate the radiation loss of the single bunch [4]. The energy gain of electrons inside a bunch can be calculated by using the resonant modes of the cavities. These modes are usually computed with the widely known computer program SUPERFISH [15]. On the contrary, electromagnetic fields excited by a single bunch can be computed without any assumptions or restrictions required for the idealized cases. A single bunch of electrons travelling along the z-axis through an accelerating cavity can be described by the current density $\vec{J}$. The electric and the magnetic fields excited by the single bunch in the infinitely conducting cavity can be obtained by the following Maxwell equations with boundary condition.

$$\text{rot}\ \vec{H} = \vec{J} + \epsilon_0 \frac{\partial \vec{E}}{\partial t} + \sigma \vec{E}\ , \tag{1}$$

$$\text{rot}\ \vec{E} = -\mu_0 \frac{\partial \vec{H}}{\partial t}\ , \tag{2}$$

$$\text{div}\ \vec{H} = 0\ , \tag{3}$$

$$\text{div}\ \epsilon_0 \vec{E} = q\ . \tag{4}$$

Figure 3 shows the typical electric field lines excited by the single bunch (39.5 ps in fwhm, 14 nC) in an L-band cavity. The radiation loss of the electrons in a single bunch can be evaluated by an integration of the field energy inside the cavity over all the time while the bunch has travelled trough and left the cavity.

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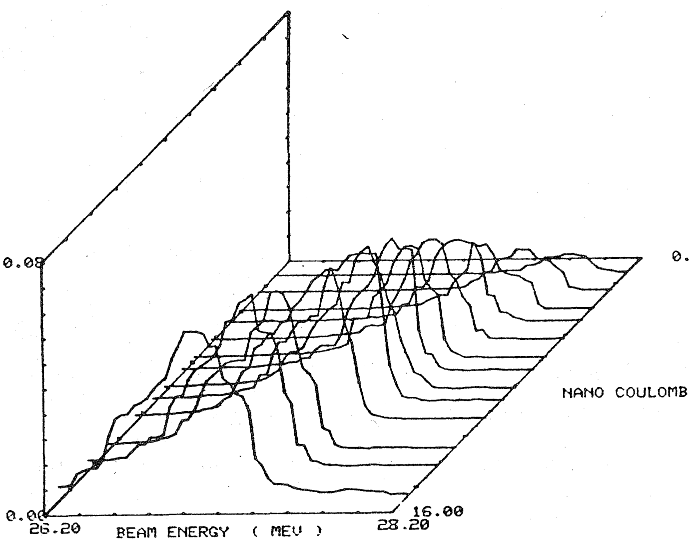

Fig. 1. Energy spectrum of the single bunch. The maximum and the minimum energy decreases with increasing charge.

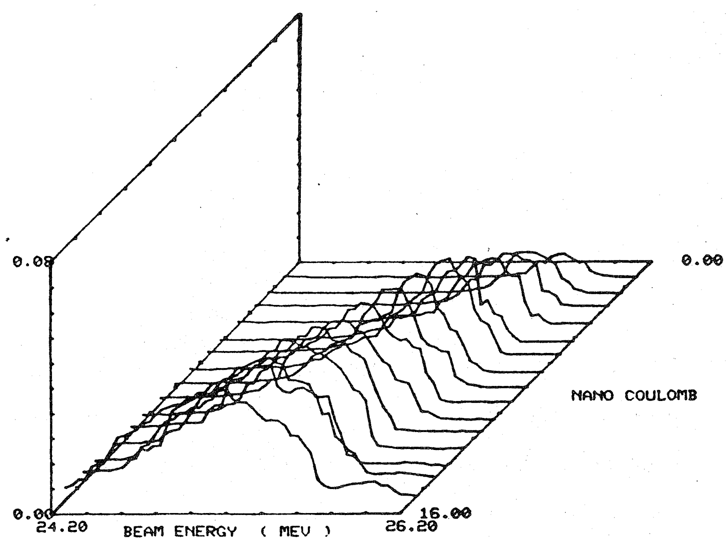

Fig. 2. Energy spectrum of the single bunch. The maximum energy is independent of the charge.

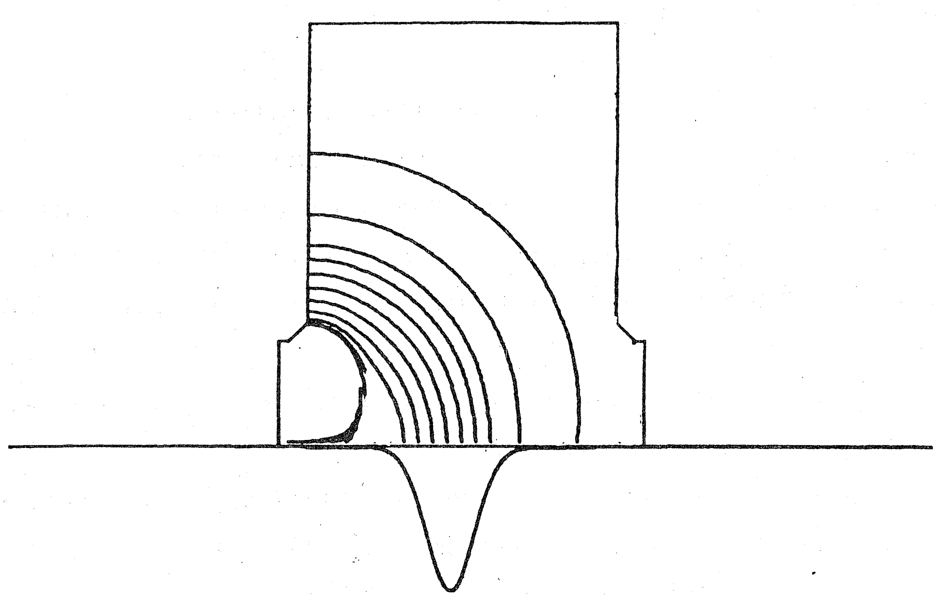

Fig. 3. The electric field lines excited by the single bunch (39.5 ps, 14 nC) in an L-band cavity of the Osaka University Linear Accelerator.