SINGLE BUNCH BEAM LOADING EXPERIMENT ON THE OSAKA UNIVERSITY ELECTRON LINAC

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Abstract

Experimental study on single bunch beam loading in an accelerating waveguide has been performed. The energy loss of a single bunch passing through an L-band cavity is estimated to be 1.225 keV / nC from the experimental results.

Introduction

When charged particles are accelerated in a linear accelerator, there is necessarily a transfer of energy from the accelerating field to the particle beam. This results in a reduction of the total accelerating field in the waveguide. Consequently subsequent bunch of particles travelling down the waveguide will experience less energy gain than the previous bunch of particles accelerated. This effect, the resultant reduction in the energy gain of later beam bunches, is known as beam loading.

For the travelling wave linear accelerator, the beam loading problem should be considered from the standpoint of superposition theorem, in which the fields in the accelerating waveguide can be composed of the following two parts; the field from the external rf power source, and the field excited by the beam itself. These two fields and their phases can be treated quite independently. Therefore the energy gain of the beam from the rf power source and the energy loss due to beam loading can also be treated independently. When a bunch of charge Q travels along an accelerating waveguide, total energy gain of the bunch per one cavity takes the form

$$U = EgQ - BQ^2 , \tag{1}$$

where E is the average applied field along the bunch trajectory, g is the effective accelerating length, and BQ^2 is the radiation loss by the interaction of beam with waveguide. B is a proportionality factor, the dependence of which is on the geometrical parameters of the accelerating waveguide and the bunch.

Because of the quadratic increase of the radiation loss with the charge Q, the interest in an accurate evaluation of the loss factor B suddenly rises with the advent of "the high current single bunch electron linear accelerators" for radiation physics and chemistry. The energy loss to the higher modes of the accelerating waveguides and of any other structure such as vacuum vellows, vacuum valves, beam monitor devices, should be taken into consideration. The average gain of energy of electrons in a single bunch would reduce linearly with increasing charge. If the charge of the single bunch is so intense that the radiation loss excesses the energy gain from the accelerating field, it is impossible to accelerate the single bunch to high energies.

Osaka University Electron Linac

The Osaka University L-band Electron Linac has been constructed for studies on picosecond phenomena in radiation physics and chemistry. The choice of L-band was mainly determined by the requirement for high current, which makes it possible to measure even the weak interaction of beam with material. A pulsed beam generated by an electron gun is modulated at the sixth subharmonic frequencies of 216.7 MHz by a single gap cavity (SHPB) and the beam electrons are bunched at the end of their drift distance. About half the amount of the injected charge of that cyclic period would be bunched into one cycle of the basic machine frequencies of 1300 MHz. In order to produce a single bunch, the gun pulse should be less than half cyclic period of the SHPB. A linac injector can generate a pulsed beam of 6 A for 3 nS pulse duration. As a result, a single bunch, the charge of which is up to 14 nC without satellite, or up to 16.5 nC with a satellite (7.8 %), can be accelerated to 30 MeV.

Sigle Bunch Waveform

In order to determine the single bunch waveform, a Cerenkov light radiated from a cell filled with Xe gas is measured by an ultrafast streak camera (Hamamatsu C979 and C1098). Figure 1 shows a typical bunch waveform obtained at the pulse repetition rate of 1.111 pps to avoid the effect of time jitter. The length of the single bunch is estimated to be 38 ps at FWHM.

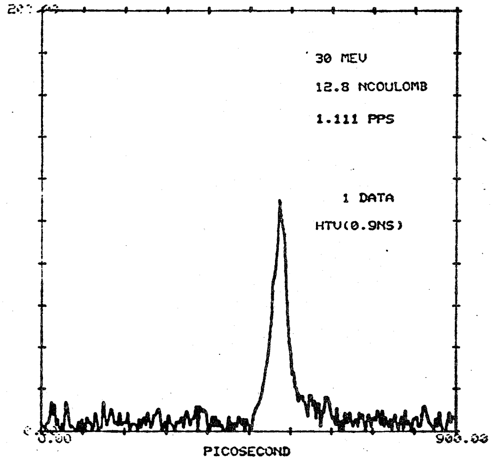

Fig. 1. Single bunch waveform.

Energy Spectrum of Bunch

The energy spectrum of the electrons in a bunch is measured by a 90° analyzer magnet, the momentum resolution of which is better than 10^{-3}. The magnetic strength of the analyzer magnet is detected with a fluxmeter, and the current transmitted through the exit slit is collected with a Faraday cup. Figure 2 shows three energy spectra: the first is for a single bunch of 12 nC; the second is for two bunches of 12 nC (each bunch is 6 nC); the third is for a single bunch of 6 nC. The spectra show that the average energies of the first and the second bunch are estimated to be 28.6 MeV and 28.3 MeV respectively. The second bunch gains energy at a reduction of 1 %. The reduction in the energy gain of second bunch is considered to be due to beam loading. In fact, the total energy stored in the accelerating waveguide is 18 J, and the total energy gain of the first bunch is evaluated to be 0.17 J. The spectra of the single bunch also show the difference between the two cases. When a single bunch has higher charge, the spectrum shifts to lower side of energy. It seems that the single bunch loses its energy by the radiation loss in proportion to quadratic increase of the charge in a bunch.

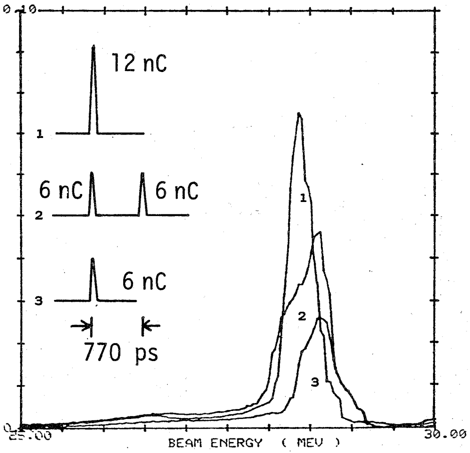

Fig. 2. Energy specra of a single bunch and two bunches.

Single Bunch Beam Loading

If a bunch of electrons excites the waveguide, the average energy of the electrons in a bunch should be linearly reduced with increasing charge. The radiation loss was investigated by varying charges. The charge of a single bunch can be easily controlled by adjusting the voltage of grid-cathode pulse and it is measured by means of current integration. Figure 3 and 4 show energy spectra of the single bunch for various charges in a bunch. In these figures, it is shown that the energy spectrum shifts to the lower side of the energy with increasing charge.

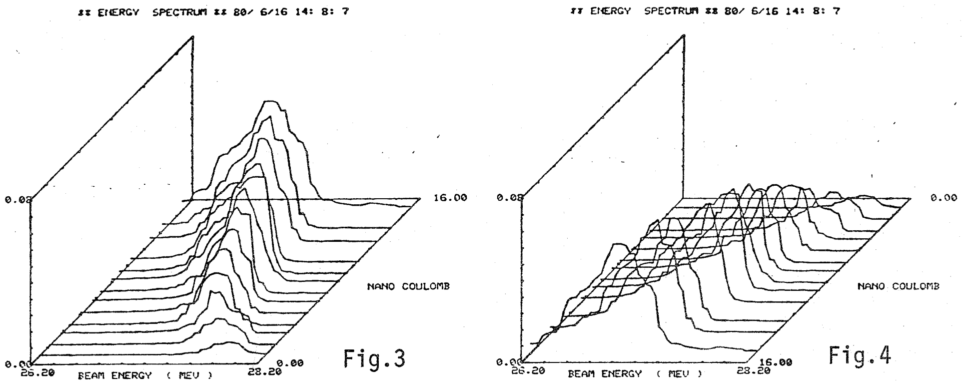

Fig. 3 and 4. The energy spectra of single bunches for various charges.

In order to investigate the dependence of radiation loss on the accelerating field, the rf power and the rf phase into the accelerating waveguide are varied respectively. The average energies of electrons in single bunches are plotted with charges (see Fig. 5 and Fig. 6).

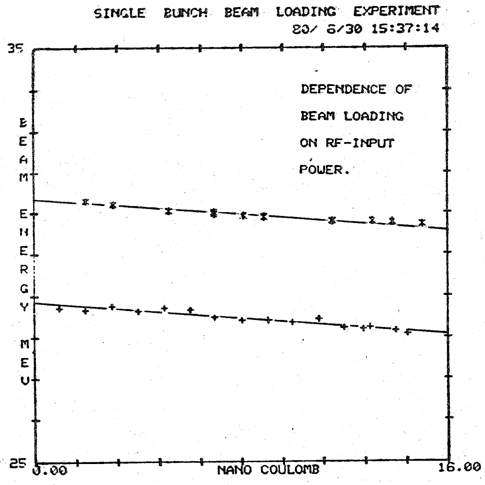

Fig. 5. Dependence of single bunch beam loading on rf-input power.

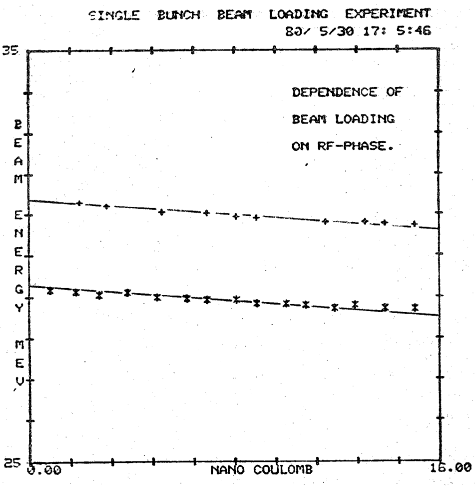

Fig. 6. Dependence of single bunch beam loading on rf-phase.

The timing of a beam injection is also varied in order that in the accelerating waveguide the single bunch may travel through the part where the rf power is empty. Figure 7 shows the dependence of the average energy of electrons in a bunch on the charge.

Experimental Results and Discussion

From the data described above, it is evident that the single bunch beam loading never depends on the rf power, rf phase, or injection timing of the bunch. In other words, it is not to depend on the energy stored in the accelerating waveguide, but only on the charge of the single bunch itself. Accordingly, it is reasonable to consider that the beam loading of single bunch is the radiation loss expressed in Eq. (1).

It might be possible to neglect the radiation loss in the waveguides of buncher sections, and then loss factor B per one cavity, total radiation loss in a cavity, is evaluated to be 1.225 keV/nC. It has also been reported that the single bunch of 0.16 nC (0.9 - 19 GeV) loses energies of 33 - 45 MeV in 81416 cavities of SLAC[1]. The loss factors in these cases are estimated to be 2.5 - 3.5 keV/nC.

From the modal analyses for radiation loss of a point charge, it is reported that the radiation loss BQ^2 depends on the geometrical parameters of a cavity and on the value of γ as follows;

$$BQ^2 = \frac{0.6\,Q^2 g^{\frac{1}{2}} \gamma^{\frac{1}{2}}}{4\pi\epsilon_0 \; a^{\frac{3}{2}}} \quad \text{(Lawson)} \qquad (2)$$

$$BQ^2 = \frac{g^2\,Q^2}{4\pi\epsilon_0 \cdot 2a^2 d} \quad \text{(Kolpakov)} \qquad (3)$$

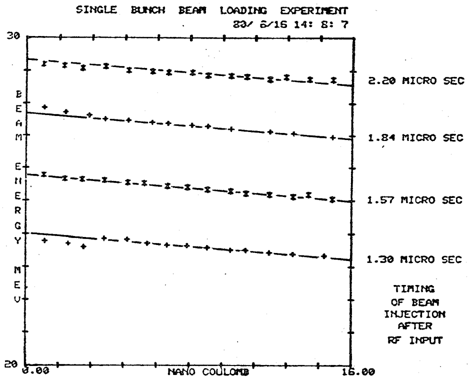

Fig. 7. Dependence of a single bunch beam loading on the timing of beam injection after rf-input.

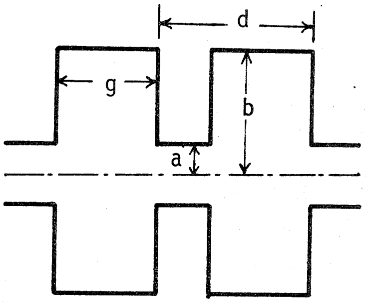

Fig. 8. Geometrical parameters of cavities.

where a,g and d are geometrical parameters as shown in Fig. 8. Assuming that the radiation loss is inversely in proportion to the size of a cavity, it is possible to compare the radiation loss between L-band and S-band cavity. When the single bunch of 30 MeV passes through a S-band cavity, the radiation loss factor B is evaluated to be 2.7 keV / nC. Accordingly it is concluded that the beam loading of single bunch, that is the radiation loss, is not to depend on the energy between 30 MeV and 19 GeV.

All the data obtained during the experiment were acquired and proceeded by the Linac Real Time Data Processing System linked with MELCOM 70/35(160kB) and MELCOM 70/25(128kB).

References

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