ENERGY SPREADS BY TRANSIENT BEAM LOADING EFFECT IN PULSED RF LINAC

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Abstract

In an L-band electron linac for industrial applications, initial energy spreads are generated by the transient beam-loading effect, since it is operated under the fully beam-loaded condition for power efficiency. In order to maximize the beam power and maintain the beam energy less than 10 MeV for radiation safety, we suppress the initial energy spreads by beam current modulation with RF power modulation. In this study, we calculate the temporal profile of beam energy by a numerical method and verify it by measurement. As a result, the average beam energy and the corresponding beam power are improved by nearly 60% compared with the case without any modulations. The effect of beam current modulation on bunching and acceleration is also discussed in this paper.

INTRODUCTION

In RF linacs for high-power beams, a high power-conversion-efficiency is required from the RF to the beam. According to the theory of the beam-loading effect, there exists an optimum beam current at which the beam power is maximized, called the fully beam-loaded condition [1]. Under this condition, the beam current is so high that temporal energy spreads are induced in the transient region of the beam-loading effect.

The transient beam loading effect is compensated by the following methods. One is the adjustment of the beam injection time with respect to the RF, called the ΔT-method [2]. It is implemented by controlling the trigger delay between the RF and the beam. Since this method cannot suppress the energy spreads perfectly, additional methods are required [1]. Modulation of the RF power can suppress the rest of the energy spreads not compensated by the previous method [3,4]. For this method, the phase and amplitude of low-level RF are controlled, in general. Another method is the use of special accelerating sections operated with a slightly different resonant frequency from the main sections, called the ΔF-method [5,6]. This method is applicable only in multi-section linacs.

For irradiation sources with a beam energy of almost 10 MeV, compensation for the transient beam-loading effect is also required for radiation safety, since electrons with an energy higher than 10 MeV produce undesirable neutrons and make structures in the irradiation zone radioactive [7]. If the energy spreads of initial bunches in a bunch train are not suppressed, the average beam energy should be decreased, and the beam power is degraded consequently. In the L-band traveling-wave linac developed by PAL/ POSTECH for electron-beam processing [8,9], the initial energy spreads are suppressed by beam current modulation as well as RF power modulation and the ΔT-method. In this paper, we calculated the temporal energy gain in the accelerating structure. This calculation is verified by beam energy measurement. We obtained the modulated beam current that suppresses the initial energy spreads by partial modulation of the RF power and the ΔT-method. Since the beam current is modulated by high voltages applied to the E-gun cathode, we discuss the effect of velocity and intensity modulations on the bunching and transmission in the accelerating structure.

ACCELERATING STRUCTURE

The accelerating structure consists of 5 bunching cells and 26 normal cells, which is operated with the 2π/3-mode traveling waves at 1.3 GHz. The phase velocities of the bunching cells increase gradually from 0.65 c to c (the speed of light), although those of the normal cells are identical [8]. The shunt impedances, attenuation coefficients, and group velocities are described in Table I. With these attenuation coefficients, the RF filling time of the accelerating structure is 0.9 μs while the RF pulse length is 7 μs.

Table 1: Parameters of cells in the accelerating structure (v_{ph}/c: the phase velocity over the speed of light, v_g/c: group velocity over speed of light)

Cavity	v_{ph}/c	r_L ($M\Omega/m$)	α (Neper/m)	v_g/c
1st buncher	0.65	19	0.0538	0.0170
2nd buncher	0.75	25	0.0489	0.0167
3rd buncher	0.88	33	0.0442	0.0165
4th buncher	0.92	35	0.0431	0.0164
5th buncher	0.98	39	0.0415	0.0163
Normal	1.00	42	0.0756	0.0089

MEASUREMENT OF BEAM ENERGY

The numerical solution of the beam energy is compared with the experimental results. Fig. 1 shows a schematic diagram of the experimental setup for measuring the RF power, beam current, and beam energy. The input RF power injected into the accelerating structure is measured at directional coupler 1 (DC1) as shown in Fig. 1. The transmitted RF power is measured at DC2. The accelerated beam current is measured at the beam current monitor (BCM) consisting of a toroidal current transformer. The beam energy analyzer (BEA) measures deposited currents into a stack of aluminum plates. The beam energy is obtained by a comparison of that measurement with the MCNP simulation [10].

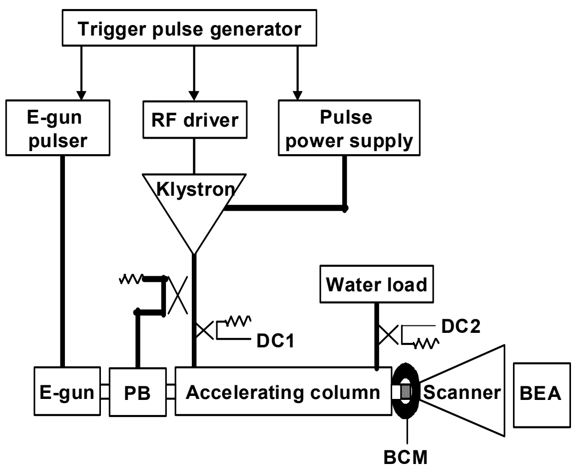

Figure 1: Schematic diagram of the L-band accelerator (left end: RF input coupler, right end: RF output coupler).

The temporal distribution of the calculated beam energy is compared with that of the measured beam energy for two cases of the beam current shape in Fig. 2. We calculate the beam energies numerically solving the power diffusion equation in the accelerating column [11]. The beam currents are modulated by adjusting the beam injection time, since the emission current from the E-gun has a finite rising time. For both cases in Fig. 2, the theoretical beam energy is also in agreement with the experimental one.

SUPPRESSION OF ENERGY SPREADS

The actual initial beam pulse is shown in Fig. 3 (a). It is designed to provide a flat waveform on top as much as possible. The pulse rising time is adjusted to limit the excess current of the switching device in the pulse circuit due to the E-gun arcing. When the nominal RF power is given by Case I in Fig. 3 (b), the beam energy is distributed as in Case I in Fig. 3 (c). Case II represents the modulated beam current. By reducing the charging capacitance of the pulse circuit, the rising time is shortened while the rate of decrease is increased. As the rising time is shortened, initial high-energy beams are suppressed more, as shown by Case II in Fig. 3 (c).

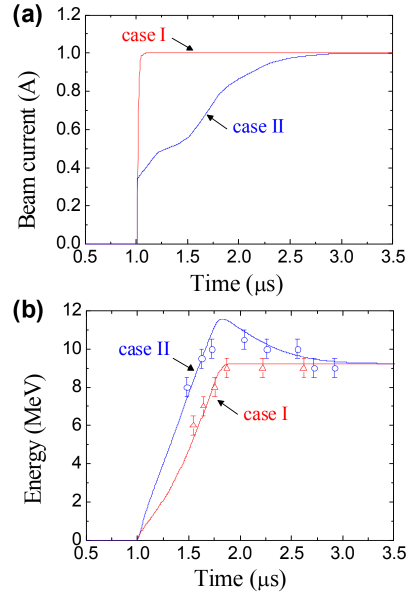

Figure 2: Temporal profile of the beam energy for different beam current shapes: Case I, the square beam pulse; Case II, the modulated beam current. The RF is injected at 1 μs with a square pulse. The beam currents shown in (a) are measured values, which are used to obtain the beam energies, shown in (b). For the beam energies in (b), the lines are theoretical values and the dots are experimental values.

In this case, the RF power is not changed as in Cases I and II in Fig. 3 (b). The energy variation in the steady state is acceptable since the purpose of the energy modulation is to limit the peak energy rather than to achieve temporally stable beam energy. The remaining beams with energies higher than 10 MeV can be suppressed with an additional modulation of the RF power as in Case III in Fig. 3 (b). The modulated profile of the RF power can be achieved by adjusting the electric circuit of the pulse-forming network applied to the klystron, instead of controlling the low-level RF. With this modulation, the peak energy is finally reduced to 10 MeV, preserving the average energy as in Case III in Fig. 3 (c). If we don't adopt any modulation, the average energy should be reduced to 5.5 MeV for radiation safety. Therefore, the average beam energy of Case III in Fig. 3 is improved by nearly 60% compared with the case without any modulation.

Since the beam current is modulated by the voltages applied to the E-gun cathode, the velocities of electron beams emitted from the E-gun are also modulated. For the beam current in Case II in Fig. 3 (a), the highest and lowest E-gun voltages are 75 and 66 kV, respectively. The phase difference induced by the velocity modulation is 37° in 1.3 GHz RF from the pre-buncher to the accelerating structure. This phase difference is safe for the beams to be transmitted since the phase acceptance is 180° for the beam transmission [12]. The effect of beam current modulation on the bunching and transmission was also investigated in a previous simulation study using the PARMELA code [13]. The electron beam with currents of 0.8 – 1.6 A can be accelerated in this accelerating structure within 3% variation of the transmission rate. Also, the beam energy is proportional to the square root of the input RF power in this range of beam currents. Therefore, according to this simulation, the beam should be well bunched and accelerated with the modulated current of Case II in Fig. 3 (a).

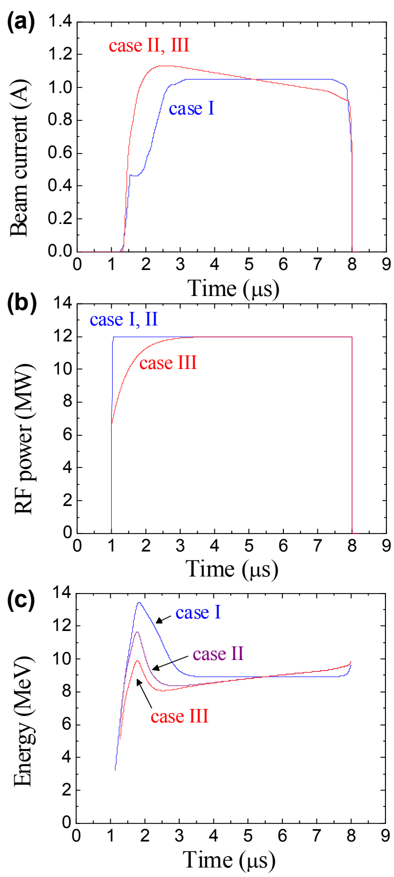

Figure 3: Compensation effect on the beam energies induced by modulation of the beam current and RF power: Case I, before compensation; Case II, beam current modulation; Case III, Case II + RF power modulation. The beam energies in (c) are theoretical values.

CONCLUSION

In this study, methods to suppress the initial beam energy spreads are examined in the intense electron linac used for irradiation applications. The beam energy values calculated by the numerical method are in good agreement with the experimental values, which are measured on the basis of the penetration characteristics of electrons through aluminum. Using the calculation method, we obtained the modulated beam current profile that suppresses the initial energies to less than 10 MeV while maintaining the average energy. As a result, the average beam energy and the corresponding beam power are nearly 60% larger than those in the case without any modulation. The beam current modulation reduces the pulse rising time while increasing the rate of decrease. The final energy profile is not uniform even in the steady-state region. However, it is acceptable for irradiation applications. Since the beam current is modulated by the voltages applied to the E-gun cathode, one can implement this modulation by adjusting the charging capacitance of the E-gun pulser. Although the velocity and intensity are modulated in the emission current, it is confirmed by experiment and simulation that the electron beams are well bunched and accelerated.

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