TRANSIENT BEAM LOADING COMPENSATION IN L-BAND TRAVELING-WAVE ACCELERATING STRUCTURE WITH INTENSE ELECTRON BEAM *

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Abstract

An intense L-band electron linac is now being commissioned at ACEP (Advanced Center for Electron-beam Processing in Cheorwon, Korea) for irradiation applications. It is capable of producing 10-MeV electron beams with the 30-kW average beam power. The constant-impedance accelerating structure is operated under fully-beam-loaded condition with the RF power of peak 25 MW and the beam current of 1.45 A. The total attenuation coefficient of the structure is 0.17 and the RF filling time is 0.9 μs along the 2.3-m accelerating structure. To suppress the energy spread due to the transient beam loading effect, we consider three methods: modulating the beam current amplitude, modulating the RF amplitude, and adjusting the beam injection time. In this paper, we calculate the transient beam energy numerically for the above cases. We also propose the actual compensation method.

INTRODUCTION

PAL/POSTECH developed a 10-MeV, 30-kW RF linac in collaboration with KAPRA. In order to treat high power, the L-band RF system and accelerating structure are adopted due to thermal stability compared with an S-band. A travelling-wave accelerating structure is adopted for industrial purposes due to the following reasons. It needs no circulator necessary for the standing-wave structure. Also the RF power coupling is independent of the beam current. To achieve higher power efficiency, the accelerator is operated with almost a fully beam-loaded condition [1].

A 1.3-GHz klystron provides peak 25-MW, average 60-kW RF power to the accelerating column with 8-μs pulse length and 300-Hz repetition rates. Eight inverter power supplies and a matched pulse modulator supply 275-kV and 260-A pulsed power to the klystron. Each inverter generates the charging voltage of 45 kV and average 30 kW. A pulse forming network in the pulsed modulator consists of 15 stages of a 50-nF capacitor and a 2.2-μH inductor. A thyratron tube switches on the modulator circuit and a 1:13-transformer steps up the voltage before the klystron [1, 2].

The accelerating structure consists of 31 cells, five bunching cells and the rest normal cells. It is resonated with 2π/3 mode at 1.3 GHz. The RF filling time is 0.8 μsec. When the input RF power is 25 MW, it is a fully beam loaded condition with the beam current of 1.45 A [1, 2]. The temperature of RF cavities in the accelerating structure is maintained within 40 ± 1 °C. Detailed accelerator parameters are listed in Table 1.

Table 1: Accelerator parameters

Accelerator Parameters	
Operating Frequency	1.3 GHz
Pulsed RF Power	25 MW
RF Pulse Length	8 μs
Repetition Rate	300 Hz
Averaged RF Power	60 kW
E-gun High Voltage	- 80 kV
Pulsed E-gun Current	1.6 A
Beam Pulse Length	7 μs
Beam Energy	10 MeV
Output Beam Current	1.45 A
Beam Transmission Rate	90%
Averaged Beam Power	30 kW
Shape of Accelerating Cell	Disk-loaded
Operating Mode of Accelerator	2π/3 mode
RF Filling Time	0.8 μs
Operating Temperature	40°C ± 1°C
Averaged Accelerating Gradients	4.2 MV/m
Beam Loading Factor	- 4.7 MeV/A
Temperature Shift Factor	- 2.3 MeV/1°C

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BEAM LOADING EFFECT

Electric fields attenuated through a traveling-wave accelerating structure is defined by [3].

$$\frac{dE(z,t)}{dz} = -\alpha E(z,t) - \alpha r_L i_b(t)\,, \tag{1}$$

where α is the attenuation coefficient, r_L is the shunt impedance per length, and i_b is the beam current. The L-band accelerating structure are shown in Figure 1. Left five cells are used for bunching. The phase velocities are increased gradually from 0.65c to c (speed of light). The shunt impedances and the attenuation coefficients are listed in Table 2. When the input RF power is 25 MW, the voltage gain through the accelerating structure is 17 MV without the beam loading. The beam power becomes maximum with the beam energy of 10 MeV and the beam current of 1.5 A, according to the steady state solution of Equation (1).

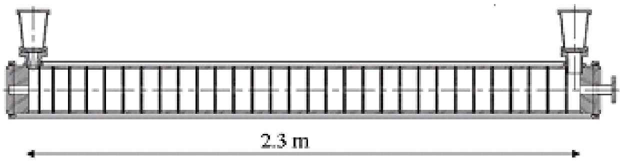

Figure 1: L-band accelerating structure (left end: RF input coupler, right end: RF output coupler).

Table 2: Parameters of cells in the accelerating structure. (v_{ph}/c : phase velocity over 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

With partial derivative of the left-hand side in equation (1),

$$\frac{\partial E(z,t)}{\partial z} + \frac{1}{v_g}\frac{\partial E(z,t)}{\partial t} = -\alpha E(z,t) - \alpha r_L i_b(t)\,, \tag{2}$$

where v_g is group velocity of the accelerating structure [3]. The first term of the right-hand side represents the attenuation of the RF power. The second term represents reduction of the RF power filled in the structure by the beam, called the beam loading effect.

This partial differential equation can be solved with a numerical method. The electric field $E(z,t)$ can be assumed to be defined with discrete time and space as $E(z_j, t_n)$, called E_j^n. The beam current $i_b(t)$ is also defined as $i_b(t_n)$, called i^n. Now, equation (2) is represented as a difference equation by

$$\frac{E_j^{n+1} - E_j^n}{\Delta z} + \frac{1}{v_g}\frac{E_j^{n+1} - E_j^n}{\Delta z} = -\alpha E_j^n - \alpha r_L i^n\,, \tag{3}$$

where $\Delta z, \Delta t$ are increments in the longitudinal distance and time. Therefore, the electric fields is propagated by

$$E_{j+1}^n = (1 - \alpha\Delta z E_j^n) - \frac{\Delta z}{v_g \Delta t}(E_j^n - E_j^{n-1}) - \alpha\Delta z r_L i^n\,, \tag{4}$$

with the given initial conditions of the beam current and the electric fields at the first cell defined by ,

$$E(z=0,\, t) = \sqrt{2\alpha r_L P_0(t)}\,, \tag{5}$$

where $P_0(t)$ is the input RF power into the structure [3].

If the RF power and beam current are square pulse with 25 MW and 1.5 A, the accelerating voltage is obtained by integrating the on-axis electric fields, as shown in Figure 2. The RF is injected from 1 μs and the beam is injected from 2 μs. The unloaded voltage is calculated without the beam loading term in equation (2). The beam induced voltage is calculated with beam loading term only in equation (2). Since the beam loaded voltage, defined by a summation of the unloaded and beam induced voltage, is gradually decreased initially, the beam energy is spread.

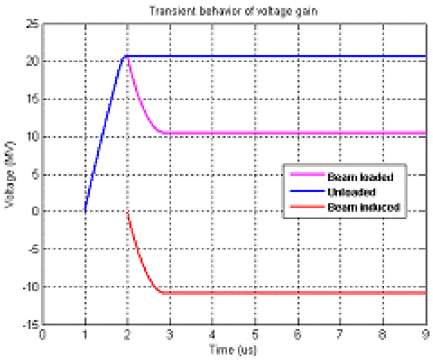

Figure 2: Temporal evolution of the unloaded, beam-loaded, and loaded voltages.

COMPENSATION OF TRANSIENT BEAM LOADING EFFECT

The transient beam loading effect can be compensated by the following methods. If the beam is injected before the RF power is filled up so that falling of the beam induced voltage crosses over rising of the unloaded voltage in Figure 2, the initial increase of the accelerating voltage is suppressed. It is implemented by adjusting the beam injection time relative to the RF injection time [4]. On the other hand, if the unloaded voltage rises slowly or the beam induced voltage rises rapidly, the transient region of the accelerating voltage is suppressed. It is implemented by modulation of the RF amplitude and the beam current [5].

Figure 3 shows a set of the measured waveform for the RF power and the electron beam current. The input power into the accelerating structure is 10 MW and the output current from the structure is 1.1 A. With these pulse shapes, we numerically calculated the accelerating voltage gain and their variation under the compensation of the transient beam loading.

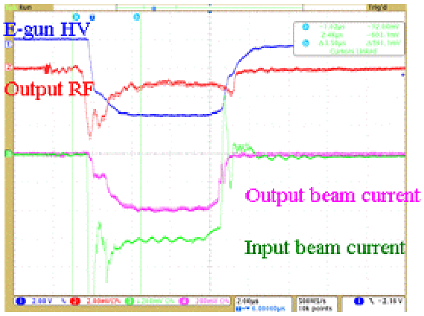

Figure 3: Pulse waveform for the electron beam and RF. From top, high-voltage applied to the electron gun, output RF power from the accelerating structure, the output beam current accelerated through the structure, and the input beam current injected into the structure.

The RF power and beam current can be assumed as the blue lines in Figure 4 (b) according to the measured pulse shapes. The corresponding accelerating voltage is the blue line in Figure 4 (a). The initial accelerating voltage is twice than the steady-state value and decays for 2 μs. If the beam is injected after half of the RF filling time from the RF injection as like the red line in (b), the initial voltage is reduced to almost the steady-state one even though there is still a broad peak in (a) - red line. If the beam current is changed as like the green line in (b), the transient region of the voltage in (a) is suppressed in the amplitude and time. In addition, if the RF power is increased with a finite rising time as like the magenta line in (b), the peak voltage is more reduced as in (a). As the result, the distribution of the accelerating voltages is the red column in Figure 5 and the spread is reduced with compensation as like the blue column.

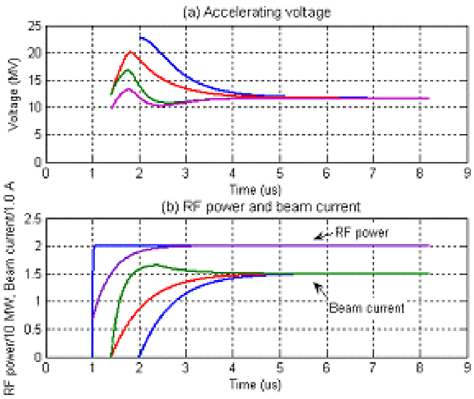

Figure 4: Accelerating voltages (a) with the RF power and beam current (b) (blue: no compensation, red: adjusting the beam injection time, green: modulating the beam current, magenta: modulating the RF amplitude).

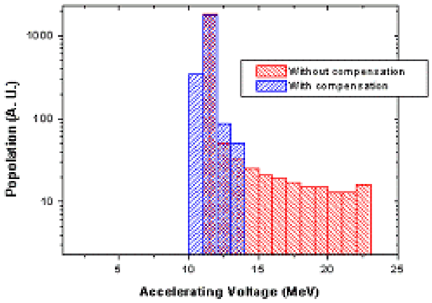

Figure 5: Distribution of accelerating voltages distribution with (blue) and without (red) compensation.

DISCUSSION

The accelerating voltage spread due to the transient beam loading effect are calculated numerically for the L-band intense accelerating structure. To suppress the energy spread, we adopt compensation method and calculated the beam voltage numerically: adjusting the beam injection time and modulating the RF amplitude and the beam current. With proper procedures, the beam energy spread can be reduced significantly.

The beam injection time can be adjusted by changing the delay time between the beam and RF trigger. The beam current can be modulated with the pulsed high-voltage applied to the E-gun cathode. For the modulation of the RF amplitude, the pulsed high-voltage applied to the klystron is to be modulated simultaneously with the phase of the drive RF.

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