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DESIGN OF 3 MeV S-BAND ELECTRON LINAC STRUCTURE WITH 2.5 BUNCHING CELLS

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Abstract

The Korea Atomic Energy Research Institute (KAERI) has been designing several 3 MeV S-band RF electron linear accelerators (linacs) for non-destructive testing. Until now, the bunching cell of the linac has a full-cell geometry. However, to maximize the acceleration of electrons after emission from the electron gun, the geometry of the first bunching cell is modified from a full-cell to a half-cell. To accelerate electron beams more gently, recently, we increased the total number of bunching cells from 1.5 to 2.5. In this paper, we describe design concepts and detailed optimization processes of a 3 MeV linac with the 2.5 bunching cells to optimize RF parameters such as the quality factor, resonance frequency, and uniformity of electric -field distribution along the linac. Finally, we will discuss the application of 3 MeV linac.

INTRODUCTION

Electron accelerators have been widely used in industrial and medical applications such as non-destructive testing (NDT) and radiation treatment. Non-destructive inspection technology is used in the automobile, oil/gas, and aerospace fields. This technology inspects whether an object has defects without damaging it. Non-destructi-ve technology is used to find defects in a wide variety of manufactured products including shipbuilding equipment, steel, and shipyards. Thus, we have increased our sales in this area, and the annual global market size and market growth tendency are increasing every year. This technology consists of an inspection system, an electron linear accelerator, an object, and detector for generating Bremsstrahlung X-Rays (braking radiation X-rays). X-rays can be used to obtain a clear image of hidden objects (defects) in a vessel that has a higher penetration of X-rays when the energy gain is higher.

The aim of this study was to develop an accelerator structure with a 3 MeV S-band (= 2856 MHz) and an electron beam to generate 3 MeV X-rays. Figure 1 below is a graph showing the X-ray absorptivity in the substance (Pb, Fe, Al, C and B) [1]. The X-ray in the 200 keV region has a good resolution, but the penetration is low. The higher X-rays in the 9 MeV region have a penetration capability can go through over 40 cm thick iron plates [2] thick iron plate. Therefore, the iron plates are more transparent, but the resolution is poor at 9 MeV.

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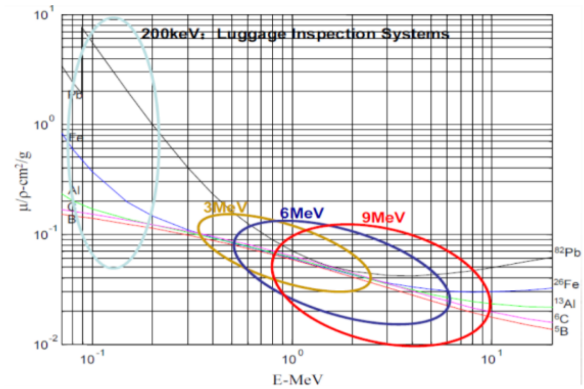

Figure 1: Absorption Rate and Electron Energy Graph.

Between 200 keV and 9 MeV energy region, 3 MeV X-rays have an excellent energy range in terms of material resolution, and its penetration is relatively higher than those in the low-energy range (1 to 2 MeV). 3 MeV X-ray can penetrate over 20 cm iron plate. The non-destructive inspection technology for engine and equipment defects can also be used effectively in various fields to find other defects. As a result, 3 MeV X-ray is an energy region with good transmission and good resolution. It is advantageous to use an energy of 3 MeV to find defects in engines and equipment. The satisfactory dose rate for a 3 MeV case is 3 Gy/min at 1m of X-ray detector.

To construct an electron linear accelerator for a non-destructive inspection system, we designed the structure of the S-band linear accelerator by executing a number of simulations. Originally, the KAERI had successfully fabricated an electron linac structure with a full-cell geometry for the first bunching cell. However, in the entire cell shape, the accelerating electric field is not the maximum at the inlet of the cell [3]. Therefore, the space charge is strong due to the high energy at the incidence area and not the beam accelerating effect. Recently also to accelerate the electron beams more gently, we increased the total number of bunching cells from 1.5 to 2.5. This paper describes the design concept and optimization of a new 3 MeV linac. The 2.5 bunching cells of 3 MeV linac is higher current and its capture coefficient more than 1.5 bunching cells.

DESIGN CONCEPT OF 3 MEV LINAC

To achieve a 3 MeV linac design, it should be able to obtain a 3 Gy/min dose rate [4].

$$J_X = \eta \cdot \tau \cdot F \cdot I \cdot E^n, \quad (1)$$

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J_x(cGy/min at 1 m) proportional to the duty factor τF (τ is the pulse width, F is repetition rate), n is a factor related to the electron energy, n = 3 (3 MeV), η is a photon conversion coefficient that is related to the crystal to be used and the electron energy E in MeV and current I in μA (η = 0.0271, 3 MeV). From this equation [5], to obtain a 3 Gy/min dose rate, 510 mA of electron beam current is required. From the following equation,

$$V_s = \frac{2\sqrt{\beta}}{1+\beta}\sqrt{Z \cdot L \cdot P_0}cos\varphi - \frac{1}{1+\beta} I \cdot Z \cdot L, \quad (2)$$

we can estimate the RF power requirement. If 510 mA of electron beam current is required, then 3.4 MW of RF beam power must be applied. β is the beta coupling, Z is the shunt impedance, L is the length of the linac, P_0 is the RF power, I is the electron beam current, and V_s is the electron beam energy. Differentiating the second equation yields β_{opt}:

$$\beta_{opt} = \left[\frac{I}{2}\sqrt{\frac{ZL}{P}} + \sqrt{1 + \frac{I^2 ZL}{4P}}\right]^2, \quad (3)$$

this formula can be derived from reflection equation . We input some of equation to obtain the P_r/P_0 (reflection) equation. The minimum optimum β_c factor can be obtained as well.

$$\frac{P_r}{P_0} = |\Gamma|^2 = \left\{\frac{\beta_c - (1+\frac{p_b}{p_c})}{\beta_c + (1+\frac{p_b}{p_c})}\right\}^2, \quad (4)$$

(P_b = beam power, P_c = without beam loading, P_0 = input power to the structure, P_r = reflected power from the coupler, P_r/P_0= reflection, P_T = the transmitted power, P_L = Ohm dissipation of the cavity wall). From equation 4, for a 3 MeV case, the best β_c factor is 5.4, as shown Fig. 2. Our requirement electron beam current is 510 mA and RF power is 3 MW, respectively. At this situation, the electron beam can generate high-energy X-ray dose rate 3 Gy/min. Effective power coupling coefficient is 5.4 then RF power reflection loss will be reduced to minimum.

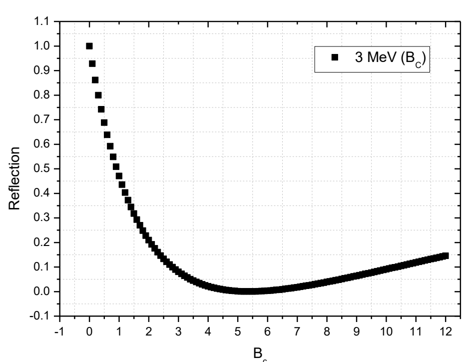


Figure 2: Reflection and Power Coupling Coefficient.

DESIGN OF 2.5 BUNCHING CELLS AND POWER COUPLING CELL

The accelerating structure consists of 2.5 bunching cells and a power coupler cell. The buncher cell accelerates the electron beam from the DC electron gun. The quality of the electron beam depends on the structure. The structure of the buncher cell consists of BAC cells, BSC cells, and AC cells. The value in the first half BAC is 0.6 and the value in the AC cell is 1. The BAC cell is asymmetric and has different coupling slits on both sides. It is determined that the intensity ratio of the accelerating electric field in the BAC cell and the AC cell is approximately 0.6:0.8:0.9 as shown in Fig. 3 (a).

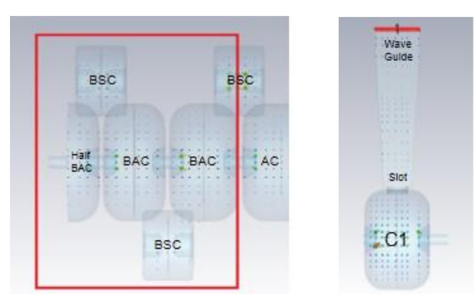
Table 1: Bunching Cell Parameters

Buncher	β_C	Energy Gain (keV)	Length (mm)
Buncher 1	0.6	260	31.5
Buncher 2	0.8	390	42
Buncher 3	0.9	437	47.25

The cell length D is determined by the velocity of the electron to be accelerated and the phase velocity of the RF wave that is synchronized with the accelerated electron. For the side-coupled standing wave cell, the transit time of an electron passing through a distance D should satisfy the following as summarized in Table 1 :

$$D = \frac{\frac{v_c \cdot \lambda}{c}}{2} = \frac{\beta_c \lambda}{2} \ (\beta_c = \text{the velocity of electron}). \quad (5)$$

According to operating frequency of 2856 MHz, the type of R32 (153IEC) rectangular waveguide could be selected. Its frequency range from 2.6 to 3.95 MHz, cut off frequency is 2078 MHz, with inner section 7.2 cm length, 3.4 cm width and 0.2 cm wall thickness. This waveguide is a standard waveguide, made up of copper. The power coupler exhibits a slightly different field distribution compared with a normal accelerating cell. However, in this preliminary simulation step, we found that it exhibits the same field distribution as that of the AC cells. The AC cells designed β value is 1 as shown in Fig.3 (b).



(a) (b)

Figure 3: 2.5 Bunching Cells and Power Coupler Cell.

OPTIMIZATION OF ELECTRIC FIELD DISTRIBUTION

From the geometry optimizations of 2.5 bunching cells, two accelerating cells, and a power coupling cell, we can

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obtain the CST simulations of individual components. By tuning the resonance frequencies of 2.5 bunching cells and three accelerating cells including a coupling cell, we combine the whole linac structure to obtain a reasonably uniform electric field distribution along the structure [6]. The best result of the *Q*-factor and uniform electric field distribution can be obtained when the 2.5 bunching cells is higher than that of 1.5 bunching cells, as shown in Fig. 4. Because the acceleration efficiency of the electron beams is directly related to the uniformity and magnitude of the electric field, they are the most important factors and must be emphasized during structure tuning.

After performing numerous CST simulations (CST MICROWAVE STUDIO) using the eigen-mode solver and frequency domain solver, the geometries of the normal accelerating cells, bunching cells, and power coupler cell were optimized. As shown in Fig. 5, the electric field distribution of the structure was optimized at 2858 MHz for the π/2 operation mode. Its best optimized RF parameters are summarized in Table 2. To obtain a larger shunt impedance, the geometry of the nose-cone was optimized. The optimized RF parameters are close to our target values, as summarized in Table 2. Figure 6 shows the PIC (Particle In Cell) simulation result when bunching cell is 2.5. It consists of electron gun, linac structure, and X-ray target. It was found that 2.5 bunching can achieve a higher 5% of electron current than 1.5 bunching.

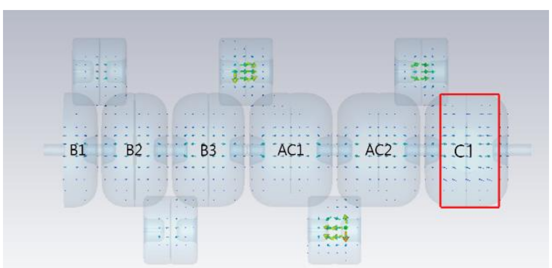

Figure 4: E-field Distribution for 1.5, 2.5 Bunching Cells.

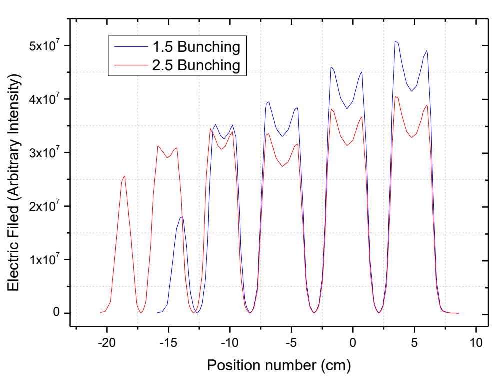

Figure 5: Electric Field Distribution in the Linac.

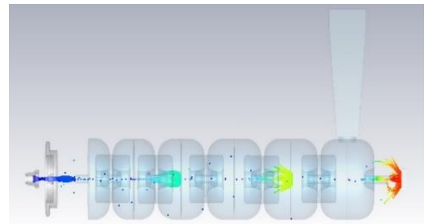
Figure 6: Beam Dynamics Simulation.

Table 2: RF Parameters of Optimized Linac Structure

RF Property	Value	Unit
Frequency	2858	MHz
Length of linac	0.28	m
Quality factor Q_0	7947	·
Shunt impedance, R_{sh}	70	MΩ/m
Optimal coupling coefficient	5.4	·
Operation mode	π/2	·
Beam current	510	mA
Input power for 3 MeV	3.4	MW

SUMMARY

A shunt impedance of 70 MΩ/m and a quality factor of 7947 at the π/2 mode frequency of 2858 MHz were obtained with an average optimal coefficient of 5.4. The RF parameters and the drawing of the S-band linac structure were devised through a CST simulation. Subsequently, the linac structure was designed. The best results for the *Q*-factor and electric field flatness were obtained using the 2.5 bunching cells as summarized in Table 2. The ratio of electric field between the bunching cells and normal accelerating cells could be adjusted by tuning the gap between the side-coupling cells [7]. Finally, we can get the high electron beam current, high capture coefficient, and the uniformity of the electric field along the structure when designed the 2.5 bunching cells.

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