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BEAM DYNAMICS STUDIES ON THE 50 MeV ELECTRON LINEAR ACCELERATOR FOR ULTRA-HIGH DOSE RATES

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Abstract

Electron beams with ultra-high dose rates (> 40 Gy/s), which enable effective radiotherapy to act on deep-seated tumors in less than a second, can be generated by linear accelerators. To successfully achieve FLASH radiotherapy, we have performed the 50 MeV linear accelerator design studies. The designed electron accelerator consists of a thermionic electron gun, sub-harmonic buncher, buncher and 2.856 GHz traveling wave structure. In this report the design layout and particle tracking simulation results of the 50 MeV electron linac with high beam current are presented in detail.

INTRODUCTION

Electron beams with low dose rates and energy are mainly used in conventional radiotherapy. Therefore, the number of treatments received increases, and there is a limit to treatment for deep-seated tumors. In contrast to conventional radiotherapy, FLASH radiotherapy uses ultra-high dose rates and high energy of electron beams, so the number of treatments received can be reduced and even deep-seated tumors can be treated by FLASH radiotherapy. The side effects can also be reduced because damage to healthy tissues decreases. To accomplish FLASH radiotherapy, it is necessary to design a linear accelerator for the electron beams suitable for FLASH radiotherapy.

Design Goals

The dose rate and penetration depth of the electron beams are related to the beam current and energy, respectively. FLASH radiotherapy requires the electron beam current of > 15 A and beam energy of 50 MeV for ultra-high dose rates (> 40 Gy/s) and deep penetration depth [1]. The design goals of the electron linear accelerator are as follows. The electron linac must :

- be capable of accelerating the electron beams with high current (~15 A).
- be able to accelerate the electron beam energy up to ~50 MeV.
- have a high transmission rate.

DESIGN LAYOUT

The linear accelerator is made up of a 200 keV thermionic electron gun, a 476 MHz sub-harmonic buncher (SHB), a 2856 MHz buncher and a 2856 MHz acceleration structure for effective bunching and accelerating of the electron beams. Three solenoids (SOL01, SOL02, SOL03) and four coils (CO01, CO02, CO03, CO04) are used as the focusing elements of the linear accelerator. Figure 1 shows the schematic layout of electron linear accelerator.

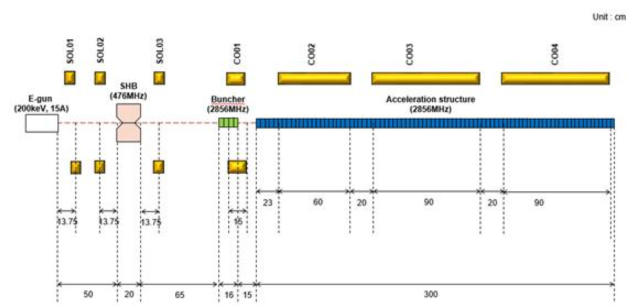

Figure 1: Schematic layout of electron linear accelerator.

MAIN COMPONENTS

The main features of the sub-harmonic buncher, buncher and acceleration structure are described in this section.

Electron Gun

The electron gun is a thermionic cathode gun, and the voltage between the cathode and the anode is 200 kV. Figure 2 shows the electrons flow in the gun with the cathode with a radius of 10 mm and the beam parameters emitted from the electron gun are listed in Table 1.

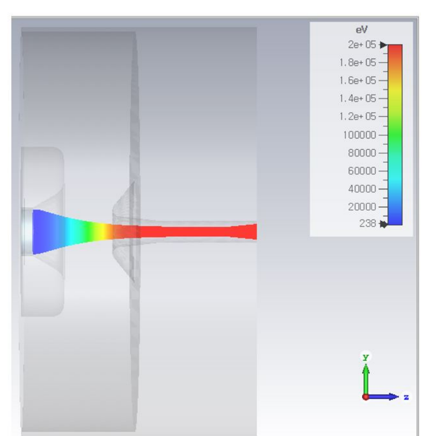

Figure 2: Electrons flow in the gun.

Sub-harmonic Buncher

A sub-harmonic buncher with a standing wave structure with a resonance frequency of 476 MHz is used to send a

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Table 1: Input Beam Parameters

Parameters	Values
Energy	0.200 MeV
α_x / α_y	0.3610 / 0.3388
β_x / β_x	4.5685 / 4.4428 cm/π · rad
$\epsilon_{n,rms}$	2.1802 πcm · mrad
Bunch length	1.05 ns
Beam current	15 A

high amount of charge within a single bunch. This frequency corresponds to 1/6 of the main buncher frequency.

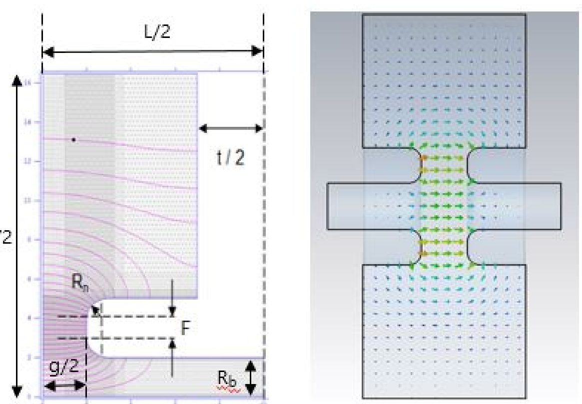

Figure 3: Design parameters (left) and field distributions (right) of the sub-harmonic buncher.

The design of the sub-harmonic buncher focuses on minimizing the power dissipation inside the cavity. Figure 3 shows the design parameters (left) of an one cell sub-harmonic buncher and the field distributions (right) of the designed sub-harmonic buncher. The main RF parameters of the designed sub-harmonic buncher are summarized in Table 2. The simulated RF parameters in Table 2 are the results when the cavity material is set to steel use stainless(SUS).

Table 2: Main RF Parameters of the Sub-harmonic Buncher

parameters	Values
Frequency	476 MHz
Q	3114.7
Shunt impedance	3.336 MΩ/m
Gap voltage	60 kV
Power dissipation	5.395 MW

For maximum bunching performance, it is necessary to optimize the distance between the sub-harmonic buncher and the buncher. Its distance is calculated using equation (1) :

$$L_{bunching} = \frac{\lambda_{RF} m_e c^2 \beta^3 \gamma^3}{2\pi e V} \quad (1)$$

where λ_{RF} is the cavity RF wave length, $m_e c^2$ is the rest energy of electrons, β is the ratio of v to c, γ is the particle Lorentz factor, e is the electron charge and V is the cavity gap voltage.

Buncher

The 2856 MHz buncher is a 4-cell traveling wave structure with copper disks. Its RF phase change per cavity is $2\pi/3$, and the phase velocity is $0.75c$. One cell length is ~26.242 mm, and the parameters of the designed buncher are given in Table 3.

Table 3: Main RF Parameters of Buncher

parameters	Values
Frequency	2856 MHz
Q	11 247.6
Attenuation per unit length (α_0)	0.3636 m^{-1}
Shunt impedance	39.606 MΩ/m
Field gradient	6 MV/m
Input power	~ 2 MW

Acceleration Structure

The 2856 MHz acceleration structure is a disk-loaded traveling wave cavity of constant gradient accelerating structure. One cell length of the acceleration structure is ~34.989 783 mm because of the phase velocity $\beta = 1$. The acceleration structure has 86 cells (84 normal cells + 2 coupler cells) and has overall length of ~3 m. To achieve a constant field slope, the diameter of the disc hole is reduced from 25.323 mm to 18.361 mm. The main RF parameters of the acceleration structure is listed in detail in Table 4.

Table 4: Main RF Parameters of Acceleration Structure

parameters	Values
Frequency	2856 MHz
Q	13 706 ~ 13 771
Total power attenuation (τ_0)	0.57 neper
Shunt impedance	52 MΩ/m ~ 65 MΩ/m
Field gradient	16.7 MV/m
Input power	21 MW

BEAM DYNAMICS

To study the beam dynamics of a 50 MeV electron linear accelerator, we use the PARMELA code to track electron multi-particles. Beam profiles simulated by EGUN and CST code are used as input of PARMELA code [2, 3]. Figures 4 and 5 show the input and output beam distributions, respectively. The maximum beam envelopes in x and y direction are indicated in Figure 6.

When the electron beam with the characteristics of 200 keV/ 15 A/ 1.05 ns from the initial electron gun passes through the accelerator, the energy of the electron beam increases to ~50 MeV and the energy spread (RMS) becomes 1.15 MeV. Its beam bunch length (RMS) and transmission

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rate are 0.024 ns and 78.83 %, respectively. The detail parameter values for the electron beams at the end of the accelerator structure are listed in Table 5. Figure 7 shows the magnetic field distribution in the 50 MeV electron linear accelerator. The high magnetic field is demanded in the outside of the acceleration structure because of the space charge effect due to the high current.

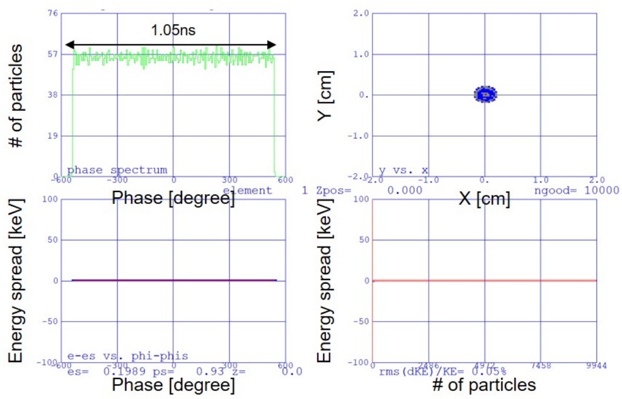

Figure 4: Input beam distributions.

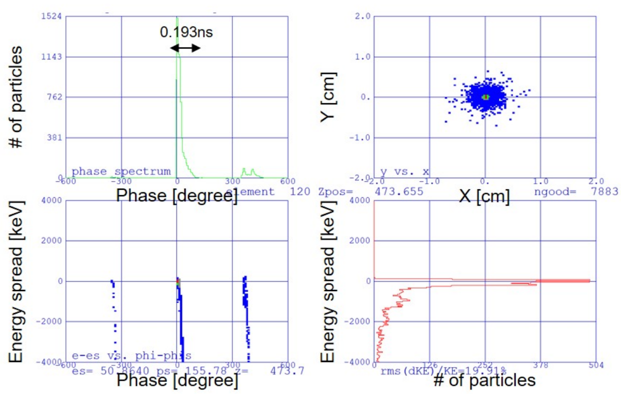

Figure 5: Output beam distributions.

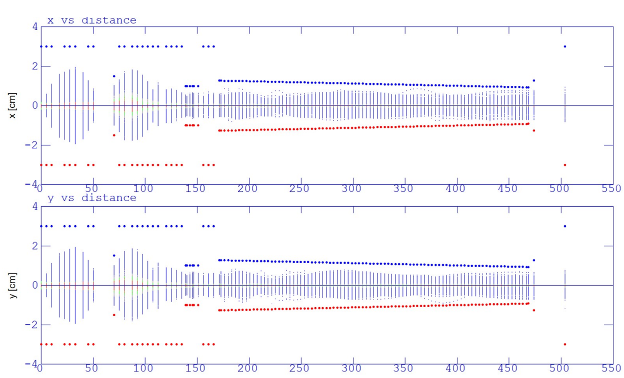

Figure 6: Maximum beam envelopes.

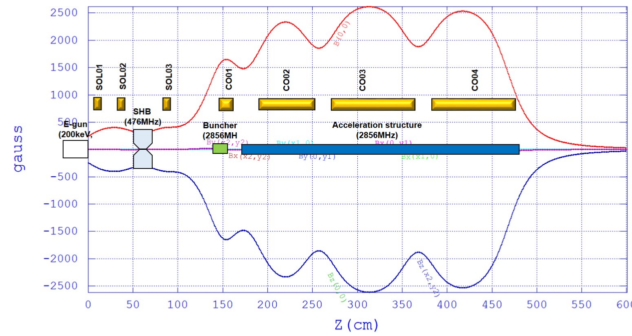

Figure 7: Magnetic field distributions.

Table 5: Beam Parameters at Acceleration Structure Exit

parameters	Values
Transmission rate	78.83 %
Bunch length (RMS)	0.193 ns (0.024 ns)
Beam RMS radius	~1.25 mm
$\epsilon_{n,rms}$	~7.4 πcm · mrad
Beam current	~13.6 A
Energy RMS spread	~1.15 MeV

CONCLUSION

The design study on the 50 MeV/ 15 A electron linear accelerator is demanded in order to provide ultra-high dose rates for FLASH radiotherapy. The linear accelerator composes a thermionic electron gun, a sub-harmonic buncher, a buncher, an acceleration structure and focusing elements. Multi-particle tracking simulations are performed with PARMELA code. The output beam has 50 MeV/ 13.6 A/ 0.024 ns values.

ACKNOWLEDGEMENTS

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