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PHYSICAL DESIGN OF A 10 MeV ELECTRON LINAC FOR INDUSTRIAL APPLICATION AND MATERIAL IRRADIATION EFFECT RESEARCH*

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Abstract

A 35 MeV/2 mA S-band electron linear accelerator (Linac) used to interact with solid targets to generate neutrons, gamma rays, and X-rays has been proposed. Besides other industrial applications, it provides a scientific research platform for nuclear energy development, material development, biomedicine, and deep space exploration. The accelerator has a three-stage accelerating structure. After first-stage of the structure, the beam energy can reach 10 MeV, and then completes 270° vertical bend and 45° horizontal bend, respectively, for industrial applications and material irradiation effect research. This paper presents the first-stage acceleration of the Linac and its bend branch, including a pre-buncher, an acceleration structure (providing beam energy 10 MeV and average current 2 mA), 270° and 45° bending magnets, with beam loss rate less than 15%. A detailed physical design and dynamic simulation results are presented and discussed.

INTRODUCTION

A 20 kW/10 MeV electron linear accelerator is being developed, which is the first stage accelerating structure and the subsequent deflection beamline section of a 35 MeV electron accelerator. The main parameters of the accelerator are given in Table 1, and Fig. 1 shows the layout of the 10 MeV accelerator. The accelerator can achieve a high average current and a low beam loss rate with long duration of the pulse beam (the accelerator structure initially uses many low-β cavities to match the electron velocity, and the final beam loss rate is less than 10%). In this paper, detailed physical design and dynamic calculations from electron gun to the deflection beamlines are given [1].

Table 1: The Main Parameters of the 10 MeV Accelerator

Parameters	Values
Beam energy (MeV)	10
Pulse current (mA)	300
Beam pulse duration (μs)	16
Repetition frequency (Hz)	500
Beam energy spread (%)	<5
Beam loss rate (%)	<15

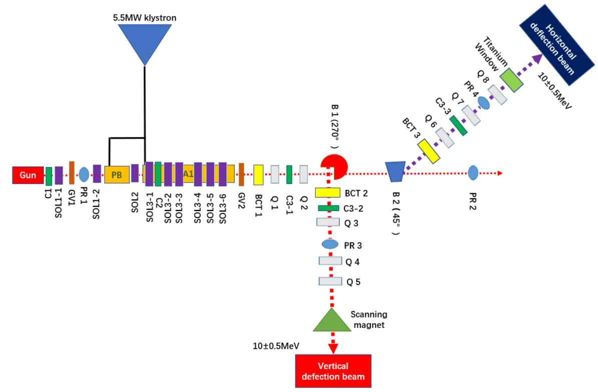

Figure 1: Layout of 10 MeV electron accelerator.

PHYSICAL DESIGN AND DYNAMIC SIMULATION

The 10 MeV electron accelerator is mainly composed of an electron gun, accelerating structure, 270° vertical deflection beamline and 45° horizontal deflection beamline. The structural design and simulation of each part is completed by EGUN, PARMELA and ELEGANT respectively, and the details are given below.

Electron Gun

We use the EGUN program to evaluate the dynamic performance of the beam emitted by the electron gun, design and optimize the shape and size of the focusing electrode as well as the anode. The result of 16 us/300 mA pulse beam at 60 kV high voltage is shown in Fig. 2, and Table 2 shows the parameters of the beam at electron gun exit with small beam envelope and emittance.

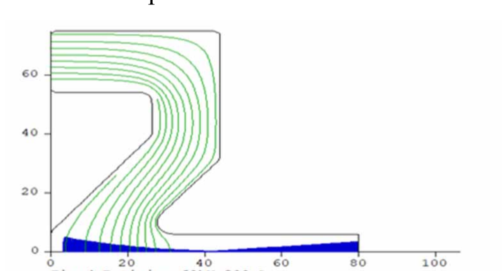

Figure 2: The result of 300 mA pulse beam in EGUN.

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Table 2: The Results of Beam Parameters

Parameters	300 mA
Average current density (A/cm²)	0.776
Beam diameter at exit (mm)	6.986
Perveance (μP)	0.0204
Emittance(4$\boldsymbol{\sigma}$) (mm • mrad)	17.81

Pre-buncher and Accelerating Structure

To improve the acceleration efficiency of long-pulse beam, a pre-buncher is introduced to bunch the beam. The pre-buncher adopts a single window-coupled standing wave cavity [2], and the accelerating structure adopts the variable-β traveling wave cavity, with 71 cells and a total length of about 2.43m. The RF power of the pre-buncher and accelerating structure is provided by a 5.5 MW klystron. It is calculated when the electric field gradient in the pre-buncher is about 0.35 MV/m, the bunching effect is better, and the corresponding input power is 13 kW; when the input power of the accelerating structure is 5 MW, the average electric field gradient is about 5MV/m (the beam loading effect at 300 mA has been considered) [3]. Therefore, the accelerating structure can actually be fed with more than 5 MW of RF power to ensure the energy gain requirement.

A total of 9 solenoids from SOL1-SOL3 are used to complete the transverse focusing of the beam and reduce the beam loss. The beam transverse envelope before and during the acceleration is given by Fig. 3. Mostly beam passes through the accelerating structure very well and only a few particles are being lost.

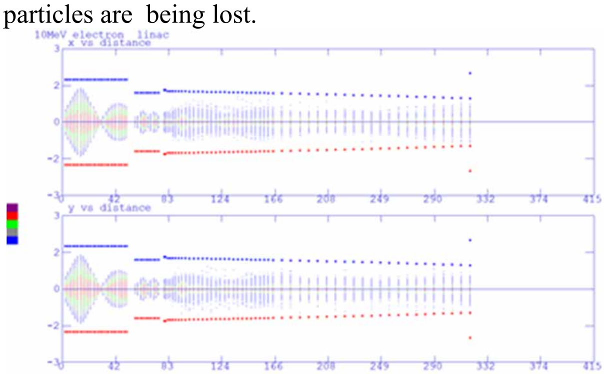

Figure 3: The beam transverse envelope.

The dynamics of beam accelerating (the number of initial particles are 50001) is calculated using the PARMELA program. The beam distribution before entering the accelerating structure after passing through the pre-buncher is given in Fig. 4. As can be seen from the figure, the pulse beam is bunched into bunchers, each at the same phase of the accelerating electric field.

The result of the beam at the exit of the accelerating structure is shown in Fig. 5, the central particle energy is 10.95 MeV, the average energy is 10.57 MeV, the transmission efficiency is 48843/50001≈97.7%, the average current is 300 mA ×500 Hz ×16 us × 97.5%≈ 2.34 mA, and the energy spread is 6.53%. While ensuring a low beam loss rate, the energy spread is also low.

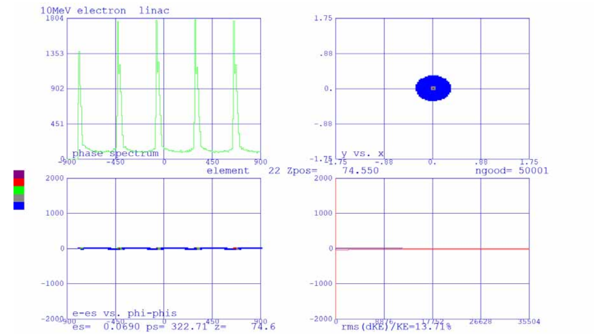

Figure 4: Beam distribution at accelerating structure entrance.

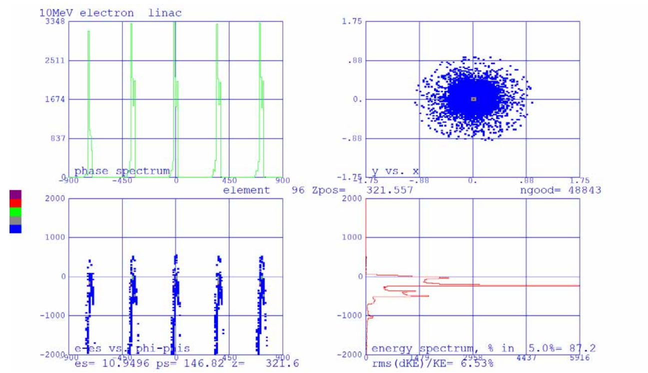

Figure 5: Beam distribution at accelerating structure exit.

Beamline

The 10 MeV accelerator has two deflection optical paths (Fig. 1). After the accelerating structure, a 270° magnet deflecting the beam vertically to the irradiation chamber. While a 45° magnet deflecting the beam horizontally to the materials effects laboratory after the 270° magnet. Two quadrupoles (Q1 and Q2) are placed between the exit of the accelerating structure and the 270° magnet to match the beamline, three quadrupoles (Q3-Q5) are placed on the 270° vertical beamline and three (Q6-Q8) on the 45° horizontal beamline to constrain the beam envelope and reduce beam loss.

Due to the energy spread of the beam, the deflection magnet causes a dispersion effect: particles of different energy are deflected to different positions by the magnetic field, resulting in an increase of the beam spot and emittance. However, the electron irradiation accelerator can allow the growth of beam spot and emittance with a certain range, and is more concerned about the irradiation power (reducing the beam loss rate) and uniformity (the suitability of the scanning system). So, considering the simplicity and convenience of the component, we choose a dipole magnet as the deflection magnet. The transmission matrix is given by Eqs. (1) and (2) (taking the deflection of the beam in the horizontal direction as an example), where r is the deflection radius, φ is the deflection angle, e1 is the incident edge angle, e2 is the exit edge angle (the edge angle plays a focusing role on the beam), δP/P is the momentum deviation, and L is the magnetic effective length [4].

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$$\begin{bmatrix} x \\ x' \\ \frac{\delta P}{P} \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 \\ \frac{tge2}{r} & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} cos\varphi & rsin\varphi & r(1-cos\varphi) \\ -\frac{sin\varphi}{r} & cos\varphi & sin\varphi \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} 1 & 0 & 0 \\ \frac{tge1}{r} & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} x_0 \\ x'_0 \\ \frac{\delta P}{P} \end{bmatrix} \quad (1)$$

$$\begin{bmatrix} y \\ y' \end{bmatrix} = \begin{bmatrix} 1 & 0 \\ \frac{tge2}{r} & 1 \end{bmatrix} \begin{bmatrix} 1 & L \\ 0 & 1 \end{bmatrix} \begin{bmatrix} 1 & 0 \\ -\frac{tge1}{r} & 1 \end{bmatrix} \begin{bmatrix} y_0 \\ y'_0 \end{bmatrix} \quad (2)$$

From the above equations, the deflected x, x', y, y' are obtained by Eqs. (3) and (4). According to different deflection angles, the appropriate deflection radius and edge angle are designed to ensure the normal transmission of the beam.

$$\begin{bmatrix} x \\ x' \\ \frac{\delta P}{P} \end{bmatrix} = \begin{bmatrix} x_0[cos\varphi\left(1-r*\frac{\delta P}{P}\right)+sin\varphi(tge1+r*x'_0)+r*\frac{\delta P}{P}] \\ \frac{\delta P}{P}[sin\varphi-tge2(cos\varphi-1)]+x_0\left[\frac{cos\varphi(tge1+tge2)+sin\varphi(tge1tge2-1)}{r}\right]+x'_0(cos\varphi+tge2*sin\varphi) \\ \frac{\delta P}{P} \end{bmatrix} \quad (3)$$

$$\begin{bmatrix} y \\ y' \end{bmatrix} = \begin{bmatrix} y'_0*L-y_0(\frac{L*tge1}{r}-1) \\ -y'_0\left(\frac{L*tge1}{r}-1\right)-\frac{y_0}{r}[tge2-tge1\left(\frac{L*tge2}{r}-1\right)] \end{bmatrix} \quad (4)$$

The requirement of this accelerator is the beam average current of the vertically irradiation at 10 MeV is not less than 1.8 mA. From Eqs. (3) and (4), the growth of the beam size is larger after the 270° dipole magnet. Therefore, it is necessary to focus on optimizing the edge angle of 270° magnet, as well as the layout and magnetic field strength of quadrupoles (Q3-Q5) to control the beam envelope and reduce beam loss. With an average energy of 10.57 MeV as the deflection center, the design parameters of the vertical deflection are: the deflection radius r ≈ 0.074 m, the magnetic field gradient B ≈ 0.5 T, e1 = e2 ≈ 25.21° . The optical path matching is performed using the ELEGANT program to complete the dynamic calculation, and the transmission efficiency and energy spread of the beam on the beamline are given in Fig. 6, respectively. From the figure, it is known that the final beam transmission efficiency is about 92.9%, and the energy spread is about 2.2%.

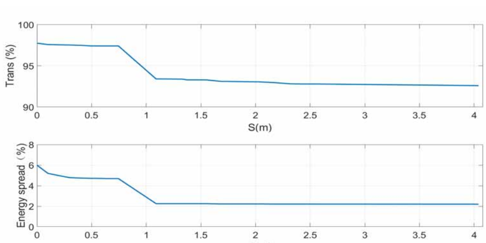

Figure 6: Transmission efficiency and energy spread in 270° beamline.

The beam average current of the horizontal deflection only needs to be not less than 0.2 mA. The requirement is not high, and the emission current of the electron gun can appropriately be reduced. The horizontal deflection magnet has a deflection radius r ≈ 0.148 m, a magnetic field gradient B ≈ 0.25 T, e1=0, e2 ≈ 17.19°. Figure 7 shows the transmission efficiency and energy spread (the simulation result is based on 300 mA pulse beam), where the transmission efficiency is about 90.6% and the energy spread is about 1.69%.

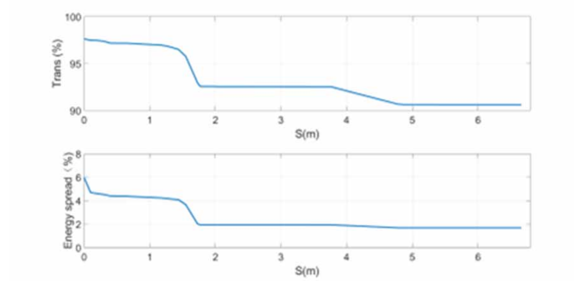

Figure 7: Transmission efficiency and energy spread in 45° beamline.

SUMMARY

We have completed the first half of the physical design of an S-band 35 MeV/2 mA electron Linac for targeting to produce various rays: electron gun to 10 MeV accelerating structure and deflected beamline, and verified it through beam dynamic calculations. The transmission efficiency of traditional irradiation accelerator is between 65% and 80%, and in order to achieve high-power irradiation beam, it is necessary to increase the repetition rate (generally greater than 550 Hz) [5] and pulse current (proportional to the beam loading effect) [6]. In this paper, it is proposed that when the repetition rate is 500 Hz and the pulse is 300 mA or less (it has shown that there is a certain surplus when the current is 300 mA), the capture efficiency during acceleration can be improved by increasing the number of low- β cavities. The final particle loss rate at the outlet of the accelerating structure is less than 3%, and at the irradiation site is less than 8%, which is a relatively good result. However, completing this type of accelerating structure is not easy and we will verify its feasibility from various aspects such as production and processing.

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