DESIGN AND ANALYSIS OF AN ELECTRON BEAM IN AN ELECTRON GUN FOR X-RAY RADIOTHERAPY

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Abstract

Electron linear accelerators are used as x-ray generators for diagnosing the human body. In this paper conceptual design of electron beam for compact electron gun was calculated by using EGN2w and CST-Particle Studio codes. The structure of the electron gun was used for Pierce and diode type and the specification of electron beam was selected as 500 cGy/min. Specifications of designed electron gun were focused on current, beam size and normalized emittance. Optimized beam current, diameter and normalized emittance are 226.88 mA, 0.689 mm (Full width) and 1.03π mm· mrad, respectively by using two simulation codes. Accuracy of simulation was verified by comparison of emitted beam current which has error of 0.74%.

INTRODUCTION

A compact electron linear accelerator (LINAC) that has some steps of an RF power supply has been researched. After 9.3 GHz RF modulator and magnetron are commercialized, researches studies of X-band RF cavities are expanded for miniaturization including the improvement of the injection beam at the electron gun [1]. Applications of a compact electron LINAC include radiotherapy machines, and the trend of current research is to increase maximum dose rate of X-rays for many degrees of freedom of treatment plans. In addition, they have been developed as a radiotherapy-assembled robot arms and as a gantry for radiotherapy [2,3].

Electron guns can be classified according to their purpose, such as controlled current, high power supply capacity, or high beam current. Medical electron LINACs are usually thermionic emission and pierce–type structure [4]. In particular, there is triode electron gun that uses a mesh grid to emit a pulse electron beam and to control the beam current [5]. However, the electron gun–controlled beam current should apply additional voltage to the grid and timing modulation for synchronization between the high voltage signal pulse in an electron gun and the RF power in the RF cavity. Therefore, a diode-type electron gun was chosen due to its simpler operating system and improved beam stability for DC operation over the triode electron gun. In this paper, an electron gun was suggested that has an appropriate beam current, 200 mA, and a low level of beam loss in the e-gun. Furthermore, the design of the electron gun was verified using beam dynamics code EGN2w and CST-Particle Studio [6,7]. The resulting electron gun are fabricating, and the gun's performance will be verified by measurement as soon as possible.

DESIGN AND ANALYSIS OF EGUN

Electron Beam Specification for Radiotherapy

For use in radiotherapy machines, X-rays should satisfy the condition of flatness in the emission area, and produce a dose rate of about 500–1000 cGy/min at a Source to Image-receptor Distance (SID) of 1 m. The specification of the electron beam should also be considered, in terms of not only its beam size and current, but also its dose rate and the flatness of the penumbra of the X-rays it produces. In the case of an electron gun, the permissible RF power of the power supply and the beam loss of the RF cavity should be considered for the design specifications [1]. The average current that emits X-rays that have dose rates of 500 cGy/min, with a flatted emission area of 15×15 cm^2 at the tungsten target surface is about 55 μA. When electrons are emitted as DC type from an electron gun, the beam current decreases by about half that of the previous one, due to the energy distribution of an RF electric field in a cavity. Nowadays, there have been research studies into minimizing beam current loss in a cavity without shielding material [3].

The peak current for producing electron energy at 6 MeV is determined by the specification of the magnetron, and it can calculate about 70 mA for duty cycle 0.0008, L-3 magnetrons (PM1110X) in this paper. The capture coefficient and iris radius of the cavity should be considered, because the electron beam can hit an internal wall, so the beam current required in an electron gun should be over 150 mA, with a margin of about 200 mA for beam loss and operating error. The beam diameter depends on the iris radius of the cavity and beam emittance, therefore the design of an electron gun was focused on an optimization of the structure for the emitting beam current and minimizing the emittance using simulation codes.

Design of Electron Gun

Diode-type electron guns can be divided into the emission and focusing parts. The emission part has the purpose of thermionic emission at the cathode surface, and the focusing part focuses and shapes the electron beam. Figure 1 shows the physical design used EGN2w code. Bottom line with dot, left upper line and right lines represent the conductors, cathode, and focus electrode and anode, respectively. A flat type cathode with a 1.5 mm radius was selected. The focus electrode was changed from a pierce electrode, and the anode was designed as a nose cone type [8].

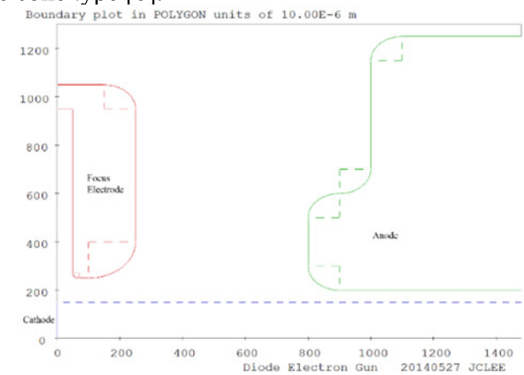

Figure 1: Physical Scheme of Electron Gun (EGN2W code).

Structures were optimized in a way that satisfied the position and phase space distribution of the electron beam at the end of an anode. The design goals are as follows: First, the designed beam current should be emitted in the space charge dominant region. Second, the cathode area was designed similar to the beam size as far as possible to minimize the beam emittance. It is important to adjust the balance between the electric field that focuses on the divergence of the electron beam and the low area of the cathode, because the compression ratio should satisfy near to one, to keep the laminar flow of the beam ray [9]. So specifications of the electron gun was shown in the table 1.

Table 1: Design Specification of Electron Gun

Cathode Dia.	3 mm
Cathode Type	Flat
Focus Electrode Aperture Dia.	2.5 mm
Anode Aperture Dia.	2 mm
Acceleration Gap	14.8 mm
Cathode Voltage	-20 kV
Focus Electrode Voltage	

Analysis of Electron Beam in Gun

Now, simulation of a DC type electron gun usually was used EGN2w code for the LINAC, klystron and, gyrotron, and this code calculates the Child-Langmuir equation considered space charge effect according to beam emission [9]. Therefore, it calculates the Child-Langmuir equations until the perveance factor of beam current density converges on a limited error by the space charge effect. In this paper, CST-PS can also be used to analyze the beam dynamics in three dimensions, and compare the results with EGN2w's in two dimensions. Beam current, size, and emittance were calculated considering the space charge effect in three dimensions through the Tracking solver in CST-PS.

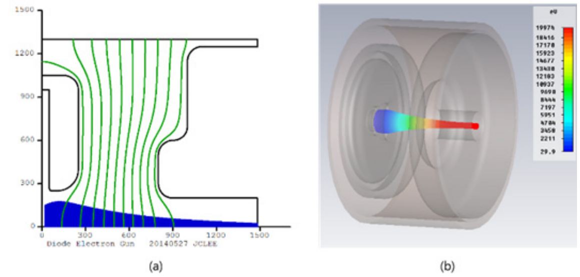

Figure 2: Beam trajectory for an electron gun using (a) EGN2w code, (b) CST-Particle Studio.

Figure 2 was shown the beam trajectory and equipotential line using EGN2w code. The initial point is f about 0.2 mm from the cathode surface, because of the virtual particle effect. The calculated mesh size is 0.01 mm, and the number of beam rays is 150 for analysis. In addition, the initial beam energy is 1 eV, the beam distribution was spread two rays built EGN2w commands.

CST-PS calculates the beam trajectory considering the Richardson equation for thermionic emission as well as Child-Langmuir equation [9]. Therefore, there are variations for thermal electrons, like the work function, operating temperature, and initial conditions. Lanthanum hexaboride was selected as a cathode, so simulation conditions were, the work function was 2.67 eV, the operating temperature was 2000 K, and the number of mesh was 3,666,352. Other initial parameters were same with the EGN2w code. Errors of iterations, CST-PS, and EGN2w were performed less than 1×10^{-2}.

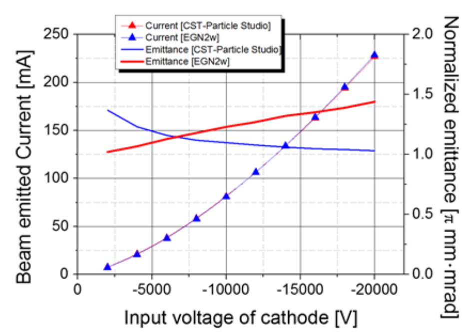

Figure 3: Comparison of beam currents and emittance from EGN2w and CST-Particle Studio.

Figure 3 indicated the trend of the emission current according to the negative high voltage of a cathode. When the magnitude of the negative high voltage increases, the emitted current shows a rapid increase at high voltages. In particular, an emitted current of over 226.88 mA (CST-PS), or 228.58 mA (EGN2w) can be achieved at -20 kV. At the same condition, the emittance distribution can also be calculated, and a high voltage makes a low emittance in Fig. 3. The current results of EGN2w and CST-PS were

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compared, two graphs are almost overlapped, and there were errors of about 0.74%, and the emittances of the two codes showed different trends according to the negative voltage, because of the consideration of the thermionic emission.

The optimization of the beam waist position was also calculated at the end of an anode when the beam current and emittance satisfied the design goals. The beam waist position and spot size depended on the diameter of the iris aperture in the RF cavity. The iris diameter was dependent on the resonant frequency, S, C, or X-band for radiotherapy, because a long wavelength requires a shorter iris diameter. The full width of the emitted beam is 0.689 mm, the RMS beam diameter is 0.242 mm when negative voltage is -20 kV, and the beam width was less than the general iris aperture in the X-band RF cavity. The designed electron gun has cylindrical symmetry on the beam axis, so the circular maximum and RMS beam size can be seen in Fig. 4. Finally, the current density distribution was analyzed; at the end of an anode, the distribution of current density was similar to a Gaussian distribution. There are two kinds of results, maximum position and RMS position. Emitted beam has transverse symmetry because X and Y-axis size almost be same. When the beam diameter was 0.5 mm (inside the red lines), the current density is 96.5%, except for a halo, as shown in Fig. 5. Simulation results were arranged in table 2.

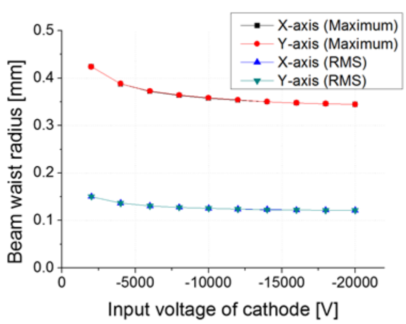

Figure 4: Beam size distribution (upper dot Maximum size, down dot RMS size).

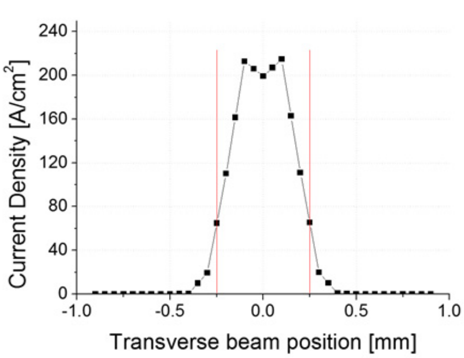

Figure 5: Transverse beam current density at the end of anode.

CONCLUSION

The design goal is to reduce beam losses in RF cavity for radiotherapy electron linear accelerators. So two simulation codes were used for verification of design. Final specification of an electron beam was found in the table 2. The diode-type electron gun was designed to optimize the beam spot diameter to 0.689 mm and normalized emittance to 1.03π mm· mrad at the end of an anode when the emitted beam current was satisfied at about 226.88 mA. These structures, the cathode, focus electrode and anode, were drawn compactly and considered for a radiotherapy machine different to an electron LINAC such as a nuclear experiment or ultrafast wavelength x-ray generator. The designed electron gun was verified through using and comparing simulation codes, EGN2w and CST-PS, so the reliability of the beam dynamics was checked.

Nowadays, the fabrication steps can be performed based on the physical beam design of the electron gun. In particular the distortion effect, which meant that the heating and B-field of the filament affected low energy electrons at the surface of a cathode, has been actively researched. Of course, the effect of the operating temperature to beam specification is also currently being studied. After the fabrication step, research into the electron beam according to the RF pulse signal will be performed.

Table 2: Simulation Results of the Electron Gun

Beam current (Max.)	226.88 mA
Normalized emittance	1.03π mm· mrad
Beam size (Full width)	0.689 mm
Beam size (RMS)	0.242 mm
Beam throw distance	14.8 mm
Accelerating gradient (beam axis)	1.351 kV/mm

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