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DESIGN OF C-BAND ELECTRON LINEAR ACCELERATOR FOR A COMPLEX OF RADIATION THERAPY*

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Abstract

The report presents the design of the linear electron accelerator for a complex of radiation therapy. The three-electrode electron gun and C-band accelerating structure are optimised to produce a therapeutic electron beam with an energy of 6 MeV and a dose rate of 10 Gy/min and a beam with an energy of 2.5 MeV to obtain a portal image. The beam size at the bremsstrahlung target in both modes does not exceed 2 mm. The total length of the accelerating system with the electron gun does not exceed 330 mm. The accelerating structure is fed by RF power from a multibeam klystron at a frequency of 5,712 MHz with a maximum pulsed power of 3.5 MW.

INTRODUCTION

This work describes the results of beam dynamics calculation in the linear accelerator with the maximum energy of 6 MeV, intended for the complex of radiation therapy KLT6 [1].

The following requirements are specified for the linear accelerator KLT6:

- Accelerator length, i.e. distance from the bremsstrahlung target to the radiation shielding exterior part: maximum 350 mm.
- Minimum lateral dimensions of the accelerating structure to reduce the radiation shielding weight.
- Sequential operation at two values of the accelerated electron beam energy: 6 MeV in the therapeutic dose delivery mode and 2.5 MeV in the portal image acquisition mode.
- Maximum dose rate at the axis at the distance of 1 m from the bremsstrahlung target without a flattening filter with the energy of 6 MeV in the therapeutic dose delivery mode: at least 10 Gy/min.
- Electron beam diameter at the bremsstrahlung target: maximum 2 mm at half height of charge distribution.

The accelerator, we are developing, differs from those used in similar complexes by a possibility to switch energy of the accelerated electron beam within a broad band, as well as by small longitudinal and lateral dimensions of the accelerating structure.

In order to achieve the declared characteristics of KLT6, we have selected a 5-cm wavelength band of the accelerating field (C-band). As for a combination of a number of characteristic of the accelerating structures (in particular, value of the effective shunt impedance, maximum accelerating field strength, diameter of the beam hole, overall dimensions), the C-band is the most appropriate for the compact electron accelerators with a relatively low average accelerated beam power (no more than several kilowatts).

We plan to use as an RF source the multi-beam klystron KIU-273 with reversed permanent magnet focusing, operating at 5,712 MHz with maximum pulsed power 3.5 MW [2].

PARAMETERS OF THE ACCELERATING STRUCTURE

The basis of the accelerator is a bi-periodic accelerating structure with on-axis coupled cells, operating at the frequency of 5,712 MHz in the standing-wave mode, optimised for operation in a broad band of energies of the accelerating beam. The structure was developed earlier by Laboratory of Electron Accelerators MSU Ltd (LEA MSU) for the accelerator of the mobile cargo inspection system [3]. The distributions of the electric field of operating mode within the structure volume and along its axis are shown in Fig. 1(a) and 1(b), respectively.

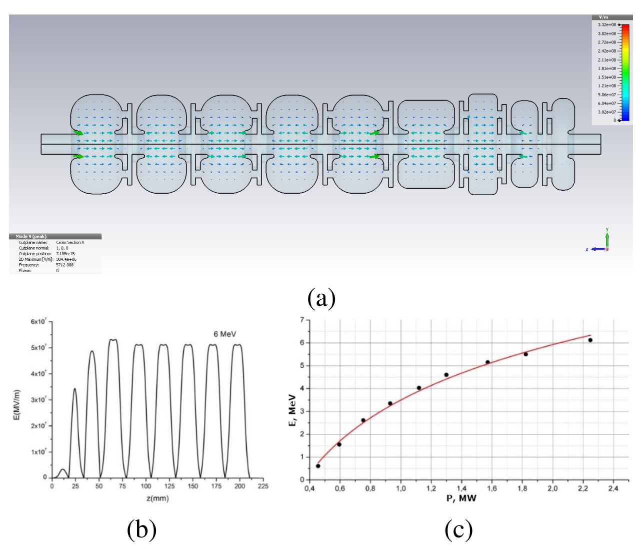

Figure 1: (a) Geometry of the accelerating structure with operating mode electric field distribution. (b) Distribution of the electric field along the axis. (c) Relationship between the output beam energy and the pulsed RF power loss in cavities walls.

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The initial part of the accelerating structure was optimised in order to ensure a longitudinal and transverse beam focusing. The accelerated beam energy is regulated by changing the level of RF power delivered to the accelerating structure. With at least a double change in the accelerated beam power, the value of the current capture efficiency of the electron gun is at least 50% and the focal spot size at the bremsstrahlung target does not exceed 2 mm at half height of current distribution. The length of the accelerating structure, including the initial part, is 210 mm. The maximum electric field strength along the axis for the energy of 6 MeV exceeds 50 MV/m and the maximum field strength at the inner surface reaches 170 MV/m. Figure 1(c) shows calculated relationship between the accelerated beam energy and the pulsed RF power loss in the walls. To obtain the energy of 6 MeV, the RF power losses shall be about 2.3 MW; the energy of 2.5 MeV is reached with the RF losses of about 0.8 MW.

The prototype of this accelerator [3] is designed for generation of the maximum dose rate of bremsstrahlung radiation at the axis at the distance of 1 m from the target $D = 0.6$ Gy/min with the duty-off factor $Q = 840$. For the KLT6 project, the dose rate should be increased almost by 20 times with the same duty-off factor.

The pulse current of the accelerated beam required for generation of the specified dose rate may be evaluated based on the empirical formula for the dose rate of bremsstrahlung radiation at an angle of 0° at a distance of 1 m from the bremsstrahlung target [4]:

$$D \approx 0.33 E^3 I_{pulse}/Q \text{ (Gy/min)},$$

where E is an energy of the electron beam at the bremsstrahlung target, MeV; I_{pulse} is a pulse current of the beam, mA. For the values $E = 6$ MeV, $Q = 840$, $D = 10$ Gy/min, we obtain $I_{pulse} \approx 120$ mA. This value of the accelerated beam current can be obtained at the injection current from the electron gun $I_{gun} \approx 250 - 300$ mA.

ELECTRON GUN

To generate the designed dose rate of 10 Gy/min with the energy of 6 MeV and the beam spot size at the bremsstrahlung target of maximum 2 mm, the geometry of the three-electrode electron gun has been optimised. The calculations have been made using the CST code [5].

The design of the electron gun optimised for KLT6 is shown in Fig. 2(a). A cathode having the diameter of 4 mm and the sphere radius of 5 mm and a flat control electrode are used in the gun. Figure 2(b, c) show, respectively, the beam current and the RMS radius at the enterence to the accelerating structure as function of the control electrode voltage. The current value, needed to generate the dose rate of 10 Gy/min, is reached at the control electrode voltage relative to the cathode of less than 3 kV. At the enterence to the accelerating structure, the beam has the RMS radius of no more than 0.6 mm and the moderate divergence, which should ensure its acceleration with low loss in the beam channel of 8 mm in diameter.

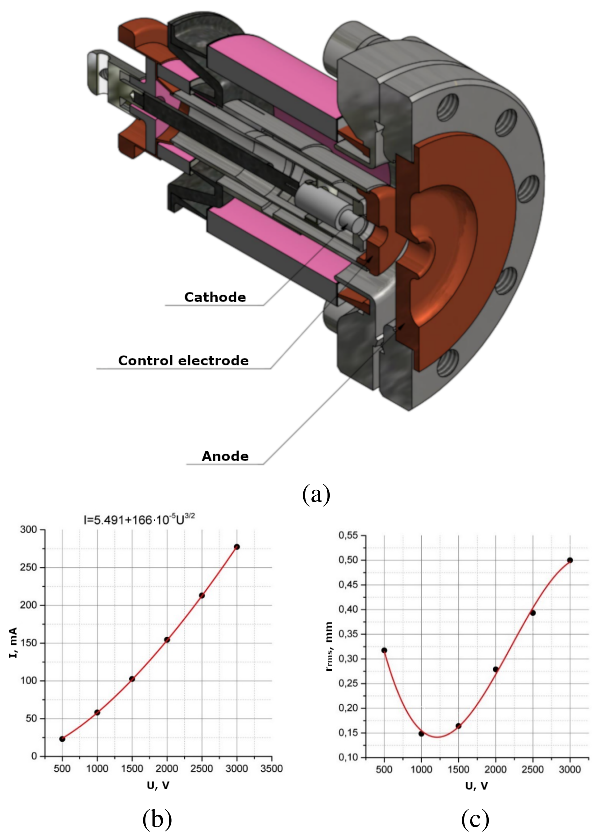

Figure 2: (a) Design of the electron gun of the accelerator for KLT6. (b) Beam current. (c) RMS radius at the enterence to the accelerating structure as function of the control electrode voltage.

BEAM DYNAMICS IN THE ACCELERATING STRUCTURE

The beam dynamics in the accelerating structure with the electron gun described in the previous section has been also calculated using the CST code [5]. Figure 3 shows calculated beam spots, histograms of current transverse distribution, and energy spectra at the bremsstrahlung target for the accelerated beam energies of 6 MeV and 2.5 MeV. The main results of calculations are summarised in Table 1.

Table 1: Main Results of Beam Dynamics Calculation for the Energies of 6 MeV and 2.5 MeV.

Parameter	6 MeV	2.5 MeV
Dose rate, Gy/min	10.5	0.37
Current of the gun, mA	245	245
Accelerated current, mA	150	124
Capture efficiency, %	60	50
RMS radius of the beam, mm	0.7	0.84
RMS divergence, mrad	8.2	29
Energy spectrum width, keV	100	500
RF loss in walls, MW	2.3	0.8
Beam power, MW	0.9	0.25

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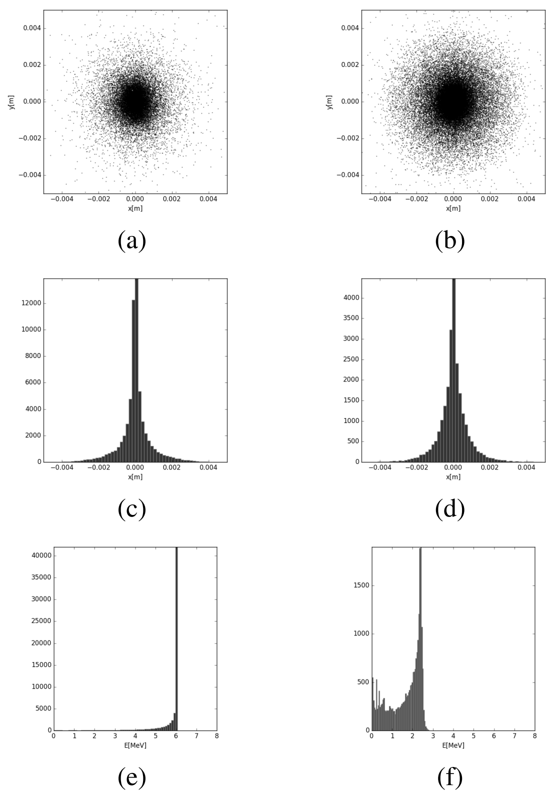

Figure 3: Beam spots (a, b), histograms of current transverse distribution (c, d), energy spectra of the beam (e, f) at the bremsstrahlung target for the energies of 6 MeV (left column) and 2.5 MeV (right column).

As it follows from the calculations, the necessary dose rate for both energies, calculated taking into consideration the energy spectrum of accelerated beam, may be generated with the same voltage at the control electrode of about 3 kV, which ensures the gun current of 245 mA. If necessary, the dose rate may be regulated by changing the duty-off factor by means of regulation of beam current pulse duration or pulse repetition rate.

CONCLUSION

The calculations of beam dynamics in the C-band electron accelerator for the complex of radiation therapy KLT6, intended for the generation of bremsstrahlung radiation with the beam energy switched over between the values of 2.5 MeV and 6 MeV for procedures of stereotactic and 3D conformal radiation therapy, have been made. The calculation data have been used for development of the accelerator design.

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