THE BASE PARAMETERS OF THE COMPACT 27 GHZ ELECTRON LINAC FOR MEDICAL APPLICATION

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Abstract

A compact and light-weight electron linac is attractive for a number of medical applications including intra-operational and cyber-knife systems. Nowadays the design of such accelerator can be based on using of a powerful high-voltage high-frequency gyrotron which can provide now in pulse regime a peak power up to 15 MW at the frequency about of 30 GHz. Taking into account this new possibility the results of design and numerical simulations for the electron beam dynamics in a linac with the operating frequency of 27 GHz are presented in the paper. Designed linac consists of two parts: gentle buncher and main accelerating section. The beam bunching is complicated at 1 cm wavelength because high energy about 2 MeV is necessary for beam injection into the main stage with *v*/*c*=1. Beam dynamics simulations are held using BEAMDULAC-BL code [1]. The electrodynamics study of the accelerating structure based on biperiodical structure is presented. The electron gun simulation is also discussed. The RF feeding is planned to be realized using a gyrotron to be designed in IAP RAS. The gyrotron is capable of producing 2 MW peak RF power in pulses with pulse duration 400 µs and a repetition rate of 10 Hz.

INTRODUCTION

Many medical applications need to designs of a compact electron accelerator. Conventional C-band travelling and standing wave accelerating structures are widely used by leading manufacturers for 2D, 3D, conformal radiotherapy or IMRT. However two applications namely intro-operational radiotherapy and cyber-knifes require using of the more compact accelerators and technical systems. The beam energy about 6 MeV is necessary in both applications.

Compaction of an accelerating structure can be reached by increasing frequency of the accelerating field (6, 10 GHz, also 17 and 30 GHz frequency ranges are possible). Also these accelerating structures require less RF power supply. Efficient medical accelerators in S- and X-band's are well-known [2-4] and 17 GHz band linac design was also discussed [5].

Let we discuss the possibility of 30 GHz band medical linac design. Such frequency band is not novel and was proposed to use as an example for CLIC project [6]. We propose to use the conventional disk-loaded-waveguide (DLW) structure operation on standing wave and π/2 mode (biperiodical accelerating structure, BAS). Operating frequency is 27 GHz.

Due to low wave length (≈1.1 cm) structure has low aperture and especial electron gun design is necessary to provide pencil beam injection. The averaged beam current which is necessary to intro-operational radiotherapy or cyber-knife is about 20-40 µA. Thus pulse current should be equal to 8-10 mA due to duty factor about 0.4 % which is typical now for power sources operating in 30 GHz band.

One of possible power source types in 30 GHz band is high power pulse gyrotron. Such generators can produce the long pulses (hundreds of µs) with low repetition rate, thus the power system of proposed linac will differs from conventional C-band medical linac due to.

ELECTRON GUN

The requirements to the beam injection parameters are the following: energy 50 keV, pulse current 8 mA in pulse duration about 0.5 ms, beam diameter on accelerating structure front-end about 1 mm. We decide to use well-known electron source with «INDOR» optic from COREX [7]. Cathode voltage is 50 kV, cathode-grid voltage is 1 kV. Computer simulation results from PIC code SUMA [8-9] are shown in Fig. 1.

On the distance 4.3 cm from cathode electron beam has diameter 0.95 mm, current 8.1 mA and phase space equal to 2.47 cm·mrad.

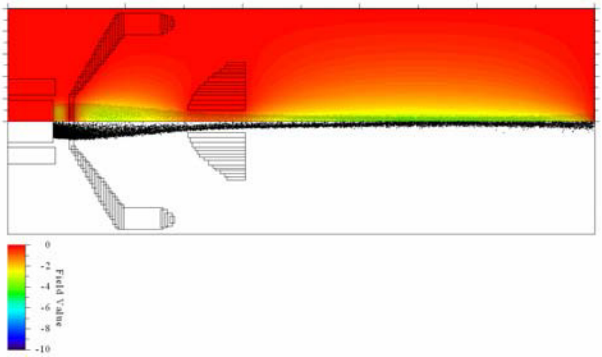

Figure 1: Electrons distribution (lower) and their self-field equipotential lines (upper) in electron gun.

BEAM DYNAMICS IN ACCELERATOR

The beam dynamics analysis in the designed accelerator was done with using of BEAMDULAC-BL code [1]. It was suggested to divide the accelerating channel to two parts (the buncher and main accelerating section).

The beam dynamics in the buncher was studied first. The phase velocity and RF field amplitude are monotonic increasing functions of the longitudinal coordinate. Such bunching scheme ("gentle buncher") provide high capturing efficiency and low bunch phase size. The main bunching part parameters and beam dynamics simulation results are specified in Table 1.

Further the analysis of beam dynamics in main accelerating section was done. The phase velocity and RF field amplitude are constant in the second linac part. Main accelerating stage characteristics and beam dynamics simulation results are also presented in Table 1. The beam cross-section and longitudinal emittance are shown in Fig. 2 (red and blue points correspond to initial and output values, respectively).

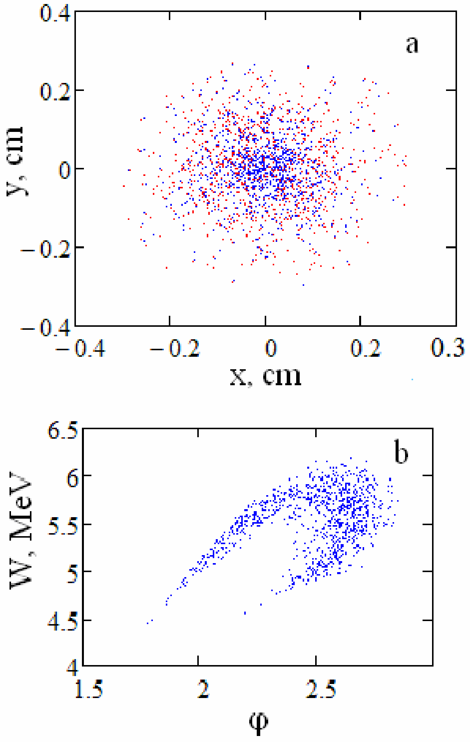

Figure 2: Output beam cross-section (a) and longitudinal emittance (b). Red and blue points correspond to initial and output values, respectively.

It should be noted than the longitudinal magnetic field is necessary to provide beam transverse focusing. The solenoid with 30 cm length and 0.01 T on axis is necessary effective beam focusing (see Fig. 2a).

We can summarize the beam dynamics simulation results. It was shown that the electron beam can be effectively bunched and accelerated to the energy 6 MeV in BAS with operating frequency 27 GHz. The total current transmission coefficient for full structure reaches to 72 %. The beam envelope can be effectively controlled.

BIPERIODICAL STRUCTURE AT 27 GHZ

The standard biperiodical accelerating structure (BAS) based on the disk–loaded structure operating on the standing wave is proposed to use for the accelerator as it was noted above. The operating frequency of 27 GHz allows to significant reduction in the accelerating structure size comparatively the presently used 5 and 10 cm structures. The general view of the BAS cell is illustrated in Fig. 3.

Table 1: Optimal characteristics of the buncher and the main accelerating part and beam dynamics simulation results.

Parameter	Value buncher	Main part
Maximal RF field amplitude, kV/cm	300	410
Length, cm	25	50
Injection energy, MeV	0.05	2
Injection beam current, mA	10	8
Output energy, MeV	1.94	6.03
Current transmission coefficient, %	83.2	86.5
Transverse particles losses, %	0	0
Longitudinal particles losses, %	16.8	13.5

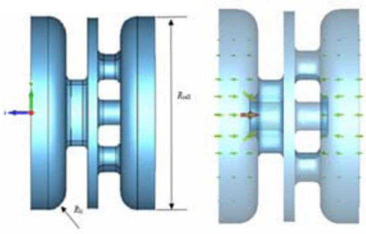

Figure 3: General view of the BAS cell and electric field in cell.

Optimal sizes of the biperiodical structure were defined by means of parameter tuning of accelerating and coupling cells for the π/2 mode at frequency 27 GHz and alignment of field's amplitude distribution. As result of simulations the cell geometry with optimal parameters was designed and electrodynamics parameters of structure are specified in Table 2. The biperiodical accelerating structure model consisting of 9 accelerating and 8 coupling cells with magnetic coupling windows (Figs. 3, 4) was used for simulation after tuning of the one-period model. All accelerating and coupling cells were tuned to the operating frequency. The 27 GHz coupler was also designed and tuned. The general view of structure with coupler and power feeding waveguide is shown in Fig. 4.

Accelerating electric field amplitude distribution along the longitudinal axis of the structure is shown in Fig. 5.

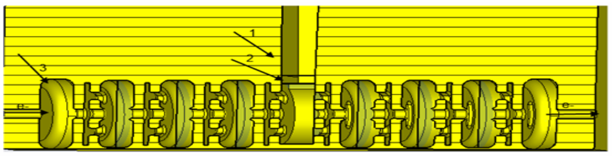

Figure 4: General view of the accelerating structure, 1 – coupler, 2 – power feeding waveguide, 3 – regular accelerating cell.

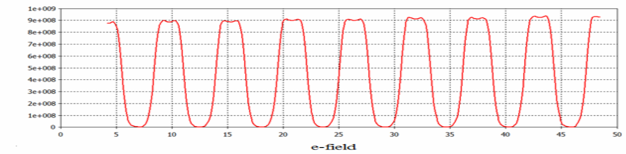

Figure 5: Accelerating electric field amplitude distribution along the longitudinal axis.

Table 2: Electrodynamics Characteristics of the BAS

Parameter	Value
Operating mode	π/2
Radius of the accelerating cell, R_{cell}, mm	8,8
Radius of blending sidewall, R_{lc}, mm	1
Frequency, GHz	27
Shunt impedance, MΩ	170
Field amplitude, MV/m	382
Coupling coefficient	0.09
Q – factor	4684

GYROTRON BASED MW FEEDING SYSTEM

High-efficiency pulse and CW gyrotrons of frequency range 27-30 GHz have been developed at the Institute of Applied Physics of Russian Academy of Sciences. Pulse power reaches 15 MW at the efficiency of 50% in gyrotrons with the high operating voltage 500 kV (Fig. 6) [10]. Accordingly to preliminary estimations based on the gyrotron theory and experimental results pulse and average power of the order of 2 MW and 8 kW, respectively, which are required for the designed accelerator can be provided in a gyrotron with the operating voltage 100 kV and current 50 A that may be supplied by a conventional modulator.

CONCLUSION

The conceptual design of the compact 27 GHz and 6 MeV accelerating structure was discussed. The electron gun was designed to produce pencil beam. The beam dynamics was studied by means of the numerical simulation and it was shown that the current transmission coefficient for full structure is reaches to 72% and the beam envelope can be effectively controlled by means of the short solenoid. The biperiodical accelerating structure was designed and tuned. It was shown that such structure has higher shunt impedance but lower Q-factor comparatively C- or S-band structures. The high power gyrotron was discussed as a perspective power source.

Figure 6: High-power gyrotron designed at IAP RAS.

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