CONCEPTUAL DESIGN OF THE MINIATURE ELECTRON ACCELERATOR DEDICATED TO IORT

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Abstract

We describe conceptual design of a compact and lightweight electron accelerator dedicated to intraoperative radiation therapy (IORT). Maximum energy 12 MeV electron beam is obtained with six recirculations through 2 MeV C-band linac. Beams with energy from 4 to 10 MeV also can be extracted from accelerator. Accelerator dimensions are 500x200x110 mm$^3$, its weight is less than 40 kg and consumed pulsed RF power is below 600 kW. We present results of accelerator optimization including choice of operating wavelength and beam dynamics simulation.

INTRODUCTION

IORT as a method for cancer treatment by tumour rest or tumour bed irradiation during operation is known for many years, but only in last ten years first compact electron accelerators dedicated to IORT were developed. The main requirements to such accelerator are: beam energy variable in the range 6-12 MeV, maximum dose rate delivered to the tumour by electron beam 10-20 Gy/min with minimal uncontrollable dark current contribution, accelerator head with radiation shielding must have minimal weight and dimensions to be easy and precisely positioned against tumour with a robotic arm, the overall installation weight and dimensions must be also minimized to use it in ordinary operating room. If in addition cost of such machine will be lower as compared with present medical accelerators, then it also could be used for external radiation therapy in small hospitals.

Modern IORT electron accelerators are built as X-band [1] or S-band [2] linacs. We present conceptual design of a compact race-track microtron (RTM) - machine which combines advantages of the linear and cyclic accelerators and permits to get electron beam with high intensity, narrow spectrum and precisely fixed energies using less power and in more compact and less weight installation.

RTM PARAMETERS AND SCHEME

Our RTM parameters are summarized in the Table 1, its schematic view is given in Fig. 1, where (1) is electron gun, (2) – injection magnet, (3) – linac, (4), (5) – end magnets, (6) – correcting dipoles, (7) – quadrupole, (8) – extraction magnet, (9) – extracted beam.

We chose RTM parameters compromising accelerator weight, dimensions and effectiveness. The relation between main RTM parameters - synchronous energy gain, $\Delta E_s$, magnet field, $B$, operating wavelength in free space, $\lambda$, and increment index, $\nu$, is defined by the condition of synchronous acceleration:

$$B = \frac{2\pi\Delta E_s}{\nu\lambda} \quad (1)$$

The higher is magnet field the less is trajectory diameter for beam maximal energy $E_{\text{max}}$, i.e. the less are transverse RTM dimensions. To simplify RTM design and operation and to increase its efficiency we, following to [3,4], use rare earth permanent magnet (REPM) material as a field source in our end magnets. In a so called “box” design [5] such magnet can be built with field level up to 1.8 T. However from practical considerations (amount of REPM material, use of cheap magnetic steel, ratio of useful field volume to overall magnet volume) field level should not exceed 1 – 1.2 T.

Table 1: RTM Parameters

<table>
<thead>
<tr>
<th>Beam energies</th>
<th>6, 8, 10, 12 MeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>Operating wavelength</td>
<td>5.24 cm</td>
</tr>
<tr>
<td>Synchronous energy gain</td>
<td>2 MeV</td>
</tr>
<tr>
<td>End magnets field</td>
<td>0.8 T</td>
</tr>
<tr>
<td>Injection energy</td>
<td>25 keV</td>
</tr>
<tr>
<td>Pulsed RF power</td>
<td>600 kW</td>
</tr>
<tr>
<td>RTM dimensions</td>
<td>500x200x110 mm</td>
</tr>
<tr>
<td>RTM weight</td>
<td>&lt;40 kg</td>
</tr>
</tbody>
</table>

Choice of $\nu=1$ is natural to provide maximum RTM longitudinal acceptance. Operating wavelength can be taken from S-, C- or X-band keeping in mind availability of relatively cheap radar magnetrons. Decrease of the wavelength for given magnet field decreases the energy gain per turn, which would mean decrease of linac
dimensions, weight and consumed RF power. However, number of orbits is increased and linac beam hole becomes smaller – both factors can lead to excessive beam losses. The other reason which prevents from the choice of a too short wavelength is the following. RTM linac must provide effective capture in acceleration of non-relativistic beam after injection and effectively accelerate relativistic beam at subsequent orbits. For fixed accelerating gradient the shorter is wavelength, the less is particle energy gain per cell, the more cells with $\beta < 1$ are required to capture and accelerate non-relativistic particles - such structure non-effectively accelerates relativistic beam. After extensive simulation of the RTM beam dynamics, of the linac and the end magnets we found that C-band is optimal for building small size and efficient 12 MeV RTM for IORT. Specifically, we chose first harmonic of the 2856 MHz frequency. i.e. $\lambda = 5.24$ cm, synchronous energy gain $\Delta E_s \approx 2$ MeV to provide standard set of fixed beam energies, so $B \approx 0.8$ T.

RTM design essentially depends on the linac bypass method after first acceleration. Axially-symmetric structure accelerating cell (AC) radius is $\sim 0.37 \lambda$, while first orbit distance from the linac axis for the end magnets with reversed fringe field [6] and non-relativistic injected beam can not be made more than $\sim 0.31 \lambda$, so beam would hit linac at the first orbit. To resolve problem we reflect beam after first acceleration by the end magnet field back to the standing wave linac, accelerate beam in the reverse direction [7] and so double its first orbit energy. Thus maximum number of linac passages by the beam in our accelerator is six, while the number of orbits is five.

Simple optics is sufficient with only five orbits to hold beam transversally. We focus beam horizontally by short REPM quadrupole singlet placed at a common RTM axis which is first met by the beam at energy 4 MeV. Vertically beam is focused by the end magnets fringe field and field gradient.

We extract beam starting from the second orbit with REPM extraction magnet inserted at the return path.

**SIMULATION RESULTS**

*Linac*

Our linac is on-axis coupled standing wave bi-periodic accelerating structure. It must effectively accelerate both non-relativistic and relativistic electrons. In beam dynamics simulation to find optimal linac parameters we varied number of ACs with $\beta < 1$ and $\beta = 1$ and their relative on-axis field strength. Our optimal variant has first $\beta = 0.55$ AC and four $\beta = 1$ ACs. Field distribution on the structure axis is shown at Fig. 2.

To provide synchronous energy gain 2 MeV by relativistic electron at synchronous phase $\varphi_s = 16^0$ with effective shunt impedance of $\beta = 1$ AC $Z_e \approx 115$ M$\Omega$/m total RF power required to produce accelerating field is $P_{RF} \approx 550$ kW. In Fig. 3 the energy gain dependence on phase is shown for 25 keV and 6 MeV injected electrons.

**End Magnets**

End magnets provide beam reflection back to accelerating structure after first acceleration, synchronous beam recirculation through accelerating structure and vertical plane beam focusing. We chose Nd-Fe-B as a REPM material for our end magnets and optimized their parameters with 3D code iteratively calculating field distribution and beam dynamics. To provide 2 MeV beam reflection with reasonable optics we optimized reverse field position, width and amplitude. For providing vertical focusing at second and subsequent orbits we introduced linear field decrease inside magnet for $\sim 2\%$ at the position of last, 12 MeV, orbit. Final magnet field distribution is shown in Fig. 3(a), while focal power dependence on energy is given in Fig. 3(b).
material. Magnet design permits to adjust reverse field position.

Capture Efficiency

![Figure 5: Longitudinal RTM acceptance (white region) and emittance (black dots) at 2 MeV](image)

In Fig. 4 we show RTM longitudinal acceptance (white region) calculated for 2 MeV beam entering linac after bending magnet and corresponding 2 MeV beam emittance. About 40% of gun electrons fit to RTM acceptance, the rest are lost mostly during first acceleration. Use of pre-buncher to increase capture efficiency and hence to decrease parasitic radiation produced by the lost electrons is impractical for this compact machine. A special design gun with RF grid can be considered to generate beam density modulated at operating frequency.

RTM SYSTEMS

RTM operation is provided by RF, power supply, vacuum, thermo-stabilization, positioning, radiation shielding and control systems. Radar magnetron with typical parameters: pulsed voltage 25 – 30 kV, current 60 - 70 A, efficiency ~30% and output power ~600 kW at operating frequency ~5.7 GHz is planned for use. To provide necessary dose with pulse repetition rate 10-100 Hz and pulse length ~1 µs, output pulsed current 1 - 1.5 mA is sufficient. Thus, with beam losses taken into account, RF power transferred to the beam will not exceed 20-25 kW and beam loading will not influence essentially on accelerator operation.

To simplify accelerator engineering design, decrease its weight and dimensions we place race-track microtron elements at hard but light precisely machined platform and put whole accelerator in vacuum box with internal dimensions ~500x200x120 mm³ pumped by distant ion pump.

The total weight of the main RTM elements – end magnets, linac and platform will not exceed 40 kg. To provide accelerator radiation shielding vacuum box walls can be made thick enough, in this case accelerating head weight will essentially depend on vacuum box weight.

For stable accelerator operation its linac and end magnets temperature must be stabilized by water flow with accuracy about 0.1°C

RF system details depend essentially on the magnetron placement. The magnetron connected with accelerating structure via circulator and vacuum window and its pulse transformer can be placed directly at accelerating head, simplifying RF system, but increasing head dimensions and weight. The magnetron can be also placed in separate module and connected with accelerating structure via flexible waveguide and rotary joint.

REFERENCES


