DESIGN OF 12 MEV RTM FOR MULTIPLE APPLICATIONS*

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Abstract

Design of a compact 12 MeV race-track microtron (RTM) is described. The results of operating wavelength choice, accelerating structure and end magnets optimization and beam dynamics simulation are represented. The use of a C-band linac and rare earth permanent magnet based end magnets permit to design RTM which is more compact and more effective as compared with the same energy circular microtron or linac. Electron beam with energy 6–12 MeV in 2 MeV step can be extracted from RTM. The estimated pulsed RF power required for feeding the linac is about 700 kW, total mass of accelerator is less than 40 kg and its dimensions are about 500x200x110 mm^3.

INTRODUCTION

Potential applications of a Race Track Microtron (RTM) in the energy range 2-70 MeV include (see table 1): internal and external radiation therapy; cargo inspection and defectoscopy; production of medical isotopes via photonuclear reactions; elemental analysis of substances; nuclear physics study and generation of electromagnetic radiation via different mechanisms in a small university laboratory; injection to synchrotron and storage ring.

Table 1: RTM Applications.

Application	Energy range, MeV	Average beam current, μA
Medicine, Intraoperative RT	6–12	~1
Medicine, External RT	4–50	~100
Elemental analysis	15–40	~10
Explosive detection	30–70	~10–100
Cargo inspection, defectoscopy	2.5–10	~10–100
Isotopes production (PET, I^{123}, etc)	15–30	~100

Modern industrial and medical electron accelerators in the energy range 10-30 MeV are built as X-band [1] or S-band [2] linacs. We present conceptual design of a 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

Parameters of RTM we propose are summarized in table 2, its schematic view is given in Fig. 1, where (1) – electron gun, (2) – linac, (3), (4) – end magnets, (5) – quadrupole lens, (6) – extraction magnets, (7) – extracted beam, (8) – quadrupoles.

We chose RTM parameters compromising accelerator weight, dimensions and effectiveness. The relation between main RTM parameters – synchronous energy gain, ΔE_s, magnet field, B_0, operating wavelength in free space, λ, and increment index, ν, is defined by the condition of synchronous acceleration:

$$B_0 = \frac{2\pi\Delta E_s}{\nu c\lambda} \qquad (1)$$

The higher is magnet field the less is trajectory diameter for beam maximal energy E_{max}, i.e. the less are transverse RTM dimensions. To simplify the RTM design and operation and to increase its efficiency we, following [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 a field level of up to 1.8T. 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 2: RTM parameters.

Beam energies	6, 8, 10, 12 MeV
Operating wavelength	5.24 cm
Synchronous energy gain	2 MeV
End magnets field	0.8 T
Injection energy	25 keV
Pulsed RF power	<750 kW
RTM dimensions	500x200x110 mm^3
RTM weight	<40 kg

The choice ν = 1 is natural since it provides the maximal 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 a given magnet field decreases the energy gain per turn, which would mean a decrease of the 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. Another disadvantage of the choice of a too short wavelength is the following. The RTM linac must provide an effective capture in acceleration of non-relativistic beam after injection and effectively accelerate relativistic beam at the subsequent orbits. For a 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 the non-relativistic particles. Then the structure becomes less effective in accelerating the relativistic

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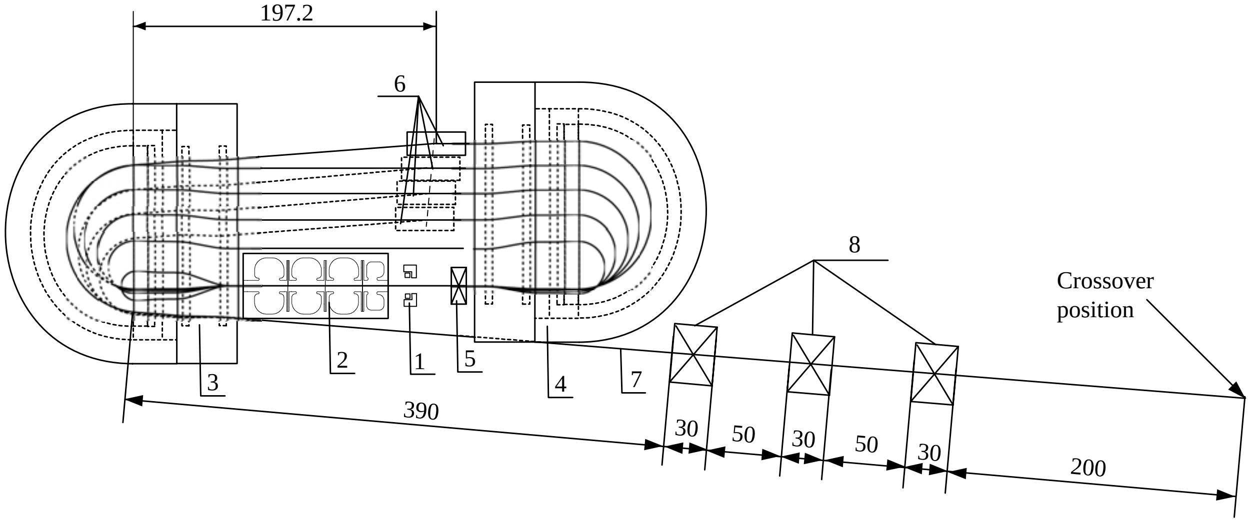

Figure 1: RTM Schematic (dimensions in mm).

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 RTM with final energy ~10–20 MeV. Specifically, we chose the first harmonic of the 2856 MHz frequency. i.e. λ = 5.24 cm, synchronous energy gain $\Delta E_s \approx 2$ MeV to provide standard set of fixed beam energies, hence $B \approx$ 0.8 T.

The RTM design essentially depends on the linac bypass method after first acceleration. Axially-symmetric structure accelerating cell (AC) radius is ~0.37λ, while the 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 ~0.31λ, so that the beam would hit linac at the first orbit. To resolve the problem we reflect the beam after first acceleration by the end magnet field back to the standing wave linac, accelerate the beam in the reverse direction and in this way double its first orbit energy. Thus the maximal number of linac passages of the beam in our accelerator is six, while the number of orbits is five.

With only five orbits a simple optics is sufficient to confine the beam transversally. We focus the beam horizontally by a short REPM quadrupole singlet placed at a common RTM axis which is first met by the beam at energy 4 MeV. The beam is vertically focused by the end magnet fringe field.

A set of REPM dipoles inserted at the return path provides the beam extraction at the second and higher orbits.

SIMULATION RESULTS

Linac

Our linac is an on-axis coupled standing wave bi-periodic accelerating structure. It must effectively accelerate both non-relativistic and relativistic electrons. To find the optimal linac parameters in beam dynamics simulation we varied the number of ACs with β < 1 and β = 1 and their relative on-axis field strength. Our optimal design consists of one β = 0.5 AC and three β = 1 ACs. The field distribution on the structure axis is shown in Fig. 2.

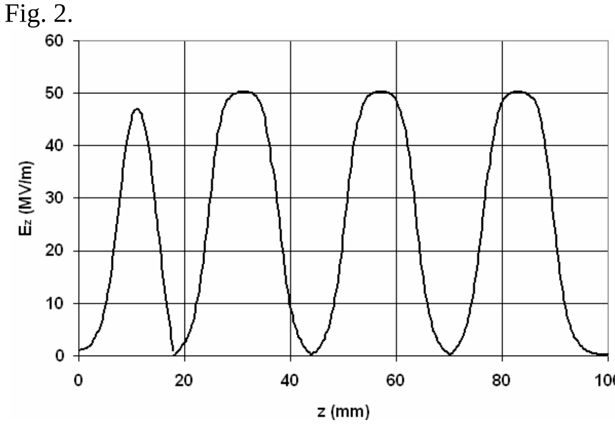

Figure 2: Linac on-axis field.

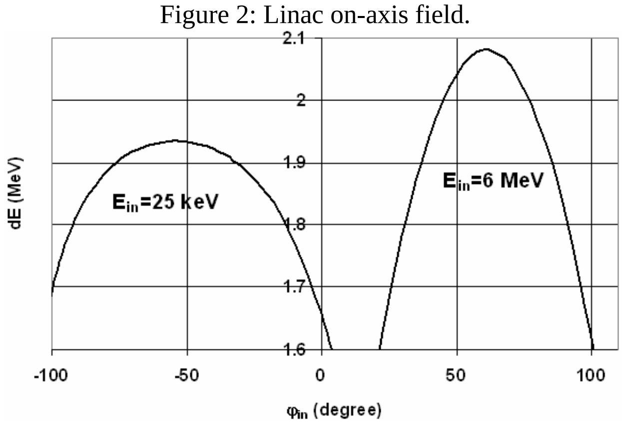

Figure 3: Linac energy gain.

The total RF power required for providing the synchronous energy gain ΔE_s = 2 MeV of a relativistic electron with the synchronous phase φ_s = 16° with optimized effective shunt impedance of β = 1 AC $Z_E \approx 95$ MΩ/m equals $P_{RF} \approx$ 700 kW. The dependence of the energy gain on phase is shown in Fig. 3 for 25 keV and 6 MeV injected electrons.

End Magnets

The 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 codes iteratively calculating the field distribution and beam dynamics. To obtain the reflection of the 2 MeV beam with reasonable optical properties we optimized the fringe field position, its shape (number of poles) and amplitude. The final magnet field distribution is shown in Fig. 4, where B_0 = 0.8 T.

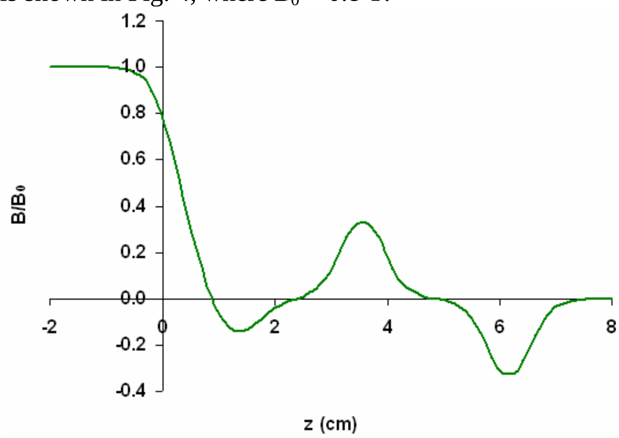

Figure 4: Fringe field of end magnets.

The optimized weight of one end magnet is ~15 kg, including ~13 kg of steel parts and ~2 kg of REPM material. Such magnet design permits to adjust reverse field position.

Capture Efficiency

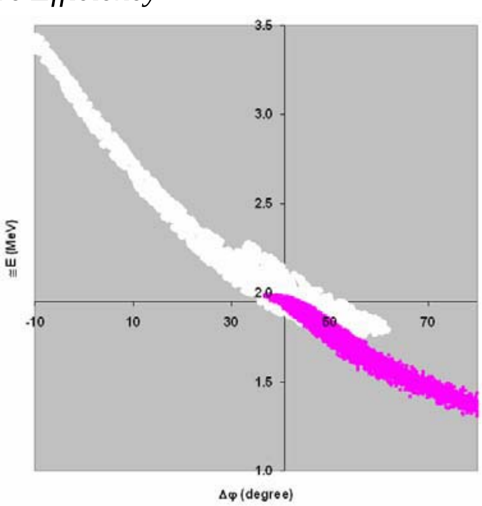

Figure 5: Longitudinal RTM acceptance (white region) and beam emittance (pink region)at 2 MeV.

In Fig. 5 one can see the RTM longitudinal acceptance (white region) calculated for the 2 MeV beam entering the linac after the end magnet and corresponding 2 MeV beam emittance. Zero energy and phase deviation point is placed at the point corresponding to the asymptotically synchronous particle. About 25% of gun electrons fit to the RTM acceptance, the rest are lost mostly during first acceleration. Use of a pre-buncher to increase the capture efficiency and hence to decrease the parasitic radiation produced by the lost electrons is impractical for such compact machine. To meet the requirements of compactness and simplicity we decided to use an electron gun with annular cathode placed on the symmetry axis of accelerating structure.

RTM SYSTEMS

RTM operation is provided by the RF, power supply, vacuum, thermo-stabilization, positioning, radiation shielding and control systems. A radar magnetron with typical parameters: pulsed voltage 25 – 30 kV, current 60 - 70 A, efficiency ~30% and output power ~800 kW at operating frequency ~5.7 GHz is planned to be used. The beam loading will not influence essentially the accelerator operation at the average beam current ~10μA.

To simplify the accelerator engineering design, decrease its weight and dimensions we place race-track microtron elements on a hard, but light, precisely machined platform and put the assembled accelerator in a vacuum box with internal dimensions ~500x200x120 mm^3 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 an accelerator radiation shielding the vacuum box walls should be made thick enough, in this case the accelerating head weight will essentially depend on the vacuum box weight.

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