RACE-TRACK MICROTRON WITH PULSE-TO-PULSE BEAM ENERGY SWITCH

Yu.A. Kubyshin#, Universitat Politècnica de Catalunya, Barcelona, Spain
I.Yu. Vladimirov, Laboratory of Electron Accelerators MSU Ltd., Moscow, Russia
V.I. Shvedunov, Skobeltsyn Institute of Nuclear Physics, Lomonosov Moscow State University, and Laboratory of Electron Accelerators MSU Ltd., Moscow, Russia

Abstract

A race-track microtron with a few beam orbits can be an alternative to a standard electron linear accelerator in a number of applications in which high beam power is not needed, like radiation therapy, industrial radiography or cargo inspection. In these cases the advantages of race-track microtrons are low RF power consumption, and consequently low cost of the RF system, and a possibility of beam energy switch in a wide range by extracting the beam from different orbits. In the present work we describe the concept of a race-track microtron with pulse-to-pulse beam energy switch in the range from 3.5 MeV to 9.5 MeV. Special attention is given to the optimization of the end magnets of a new type, which provide both the accelerating structure bypass and vertical beam focusing.

INTRODUCTION

Modern cargo inspection systems are based on pulsed X-ray sources with the end point energy in the range above 3 MeV and below 10 MeV which can be changed from pulse to pulse during the accelerator operation. The pulse-to-pulse energy switch is required for a procedure of identification of the material atomic number by a method proposed in Ref. [1]. Existing systems of this type have two output energies and are based on linear accelerators powered either by magnetrons or klystrons, in both cases the RF wave power is switched from pulse to pulse. We would like to note that linear accelerators with magnetrons are considerably cheaper than those with klystrons. In existing linac models the energy of the accelerated beam is changed by varying the output magnetron power from pulse to pulse. However, changing the high voltage of the cathode of a magnetron while its magnetic field remains constant leads only to a limited variation in the RF power, therefore the beam energy cannot be changed in a wide range. In addition, the voltage change leads to a variation of the frequency of the generated RF wave that complicates the work of the automatic frequency control system and makes the accelerated beam less stable in energy.

In the present paper we propose an alternative solution. Our X-ray source is based on a race-track microtron (RTM) with three output energies, 3.5, 6.5 and 9.5 MeV, and a magnetron as RF power source. The beam energy change in a wide range is achieved by a fast switch of beam extraction from one orbit to another. In this design the cathode voltage and the output power of the magnetron remain constant so that it operates in the optimal regime. Below we will give details of the machine design and discuss specific requirements that its end magnets must fulfil. This accelerator when operating at one of the three fixed energies can also be used for the industrial radiography and medical applications.

ACCELERATOR DESCRIPTION

The scheme of the RTM is shown in Fig. 1, its main parameters are given in Table 1. This design is a development of the ideas implemented in an accelerator proposed in [2] which is currently under construction at the Technical University of Catalonia [3].

The RTM consists of an electron gun (1), accelerating structure (linac) (2), bending end magnets M1 and M2 (3,4), three extraction magnets (5), quadrupole magnet (6) and a beam current monitor (7). The electron gun is similar to the one described in Ref. [4]. It is a thermionic source with an off-axis cathode and an on-axis channel for the passage of the higher orbit beams. The electron gun, quadrupole and beam current monitor are placed on the beam common axis which coincides with the linac axis. In addition there are a doublet of quadrupole lenses (8) situated on the axis of the extracted beam (9), a bremsstrahlung target (10) and a radiation shielding with a slit for the exit of the X-rays (11).

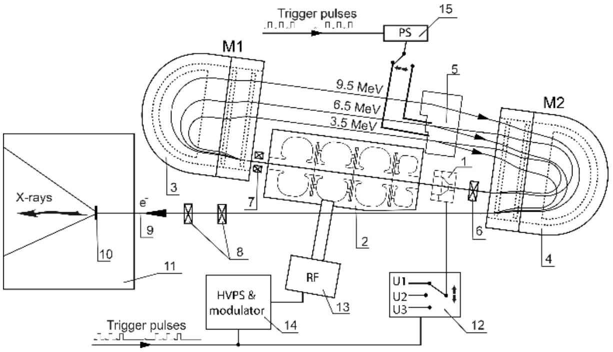

Figure 1: Scheme of the race-track microtron with the pulse-to-pulse energy switch.

The linac is a standing wave bi-periodic structure optimized for a capture efficiency that exceeds 50%. The linac provides the 3.5 MeV energy gain at the first beam passage through the linac and the synchronous energy gain of 3 MeV at the higher orbits. The RF wave is generated by a magnetron (13) of 2 MW maximal power at the frequency 2998 MHz. It is powered by a modulator (14) generating high voltage pulses of constant amplitude for all beam energies.

Table 1: Accelerator Main Parameters

Parameter	Value
Beam energy, MeV	3.5, 6.5, 9.5
Operating frequency, MHz	2998
Pulse train repetition rate, Hz	200
Pulse duration, µs	1.6
Generated dose rate, Gy/min	2

The value of the magnetic field B_0 in the end magnets is given by the condition of resonance acceleration

$$B_0 = \frac{2\pi\Delta E_s}{ec\lambda_{\mathrm{RF}}\nu}, \qquad (1)$$

where ΔE_s is the energy gain per turn, ν is harmonic number increment and λ_{RF} is the wavelength of the accelerating field. For $\Delta E_s = 3$ MeV, $\nu = 1$ and $\lambda_{\mathrm{RF}} = 0.1$ m one obtains $B_0 = 0.628$ T.

The beam is emitted in trains of three pulses with the energies 3.5 MeV, 6.5 MeV and 9.5 MeV, in sequence, with the interval between the pulses in the train equal to 150 µs approximately. The beam is extracted from the first and second orbits by the fast deflecting dipole magnets which are powered in turn during the corresponding pulses from a power supply (15). The extraction magnet placed at the third orbit is a permanent magnet. All three magnets deviate the beam to the same angle equal to 5º approximately. After passing through the end magnet M2 the deflected electrons follow a common trajectory along an output line towards the bremsstrahlung target situated at its end inside the radiation shielding.

An important requirement of accelerators used for cargo inspection is to provide approximately equal dose rates for each beam energy. In our design with a magnetron with the characteristics described above the average dose rate can be as high as 2 Gy/min for the pulse train repetition frequency 200 Hz, that is 0.67 Gy/min for each of the RTM energies.

The average dose rate D (Gy/min) at 1 m distance from the target and at 0º angle is related to the beam energy E_b(MeV), and average beam current $\bar{I}_b$ (mA), by the following approximate formula [5]:

$$D \approx 0.33 E_b^3 \bar{I}_b \qquad (2)$$

Thus for the pulse duration 1.6 µs and repetition rate 200 Hz the pulse current (pulse power) of the accelerated beam with the energy 3.5, 6.5 and 9.5 MeV is equal to 148 mA (520 kW), 23 mA (150 kW) and 7 mA (70 kW), respectively. Since the pulsed RF power dissipated in the walls of the linac is about 1 MW, the power transferred to the beam at the first orbit is quite high. The change of the beam current when the energy is switched could lead to a large variation of the accelerating field amplitude and, as a consequence, a change in the orbit distance from the common axis. Details of a solution to this problem will be published elsewhere, here we limit ourselves to a few remarks. Firstly, since the region of stable phase oscillations in RTMs is quite narrow the beam current considerably decreases with orbits. Therefore the beam current can be adjusted to the required value by a proper choice of the synchronous phase. Secondly, when extracting the beam from different orbits some additional correction of the beam current can be introduced by varying the voltage at the electron gun within a small range by means of a variable high voltage divider (12) (see Fig. 1). Combination of these two techniques can guarantee an approximately constant beam load of the linac for all three energies and, as a consequence, a constant amplitude of the accelerating field.

END MAGNETS

The magnetic field in the end magnets M1 and M2 (see Fig. 1) is created by blocks of Rare-Earth Permanent Magnet (REPM) material. The use of REPM allows to reduce the weight and size of these magnetic systems and simplify the accelerator operation. The two problems which exist in race-track microtrons, namely bypass of the accelerating structure by the beam after the first acceleration and beam vertical defocusing by the fringe field, in our case are solved due to a novel three-pole design of the end magnets. They consist of three pairs of poles with alternating directions of the magnetic induction vector in the gap (see Fig. 2). Such field distribution allows to achieve a larger distance of the first orbit from the beam common axis as compared with more traditional one-pole or two-pole designs (see Fig. 3) and also provides a beam vertical focusing at all orbits [6]. We would like to mention that in a previous work the abovementioned problems were solved by using a four-pole end magnet with beam reflection at the first orbit [7].

Hence, the end magnets must bend the electron trajectories by the 180º angle and meet the following main requirements: (1) assure the bypass of the accelerating structure at the first orbit, (2) provide a sufficient vertical focusing of the beam at all orbits, and (3) guarantee the distances between the orbits at their straight sections sufficient for placing the extraction magnets. Such magnet characteristics are achieved by a specific field distribution. In addition the end magnets should be compact and of relatively simple geometry.

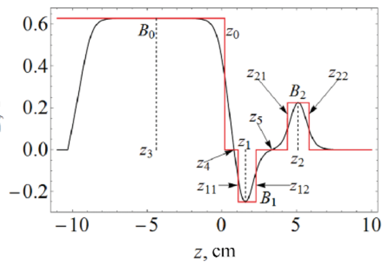

Figure 2: Distribution of the magnetic field in the three-pole end magnet. The black curve is a simulated distribution, red one is the equivalent rectangular distribution.

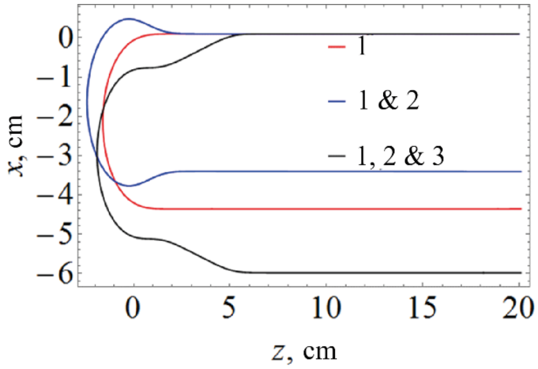

Figure 3: A comparison of electron trajectories in an end magnet with one (labelled with 1), two (1 and 2) and three (1, 2 and 3) pairs of poles.

With the aim to find a required magnetic field distribution, we first approximated the field by a piecewise constant (rectangular) profile and calculated the electron trajectories using the matrix formalism.

With the value of the magnetic field in the main pole region B_0=0.628T given by Eq. (1) we have fixed the sizes of the additional poles and distances between them and the REPM blocks. The plot of the resulting field distribution that fulfills the requirements listed above is given in Fig. 2, the obtained magnet geometry is shown in Fig. 4. According to our estimates the field in the region of poles 2 and 3 is approximately 0.23 T and 0.155 T, respectively.

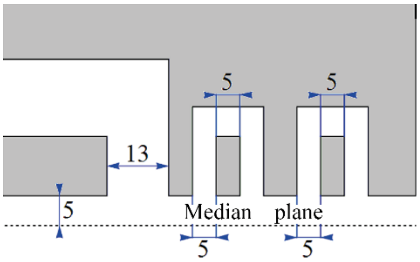

Figure 4: Dimensions of the poles and gaps for placing REPM blocs obtained within the rectangular approximation of the field distribution.

As the next step, we have performed 3D simulations of the end magnet using the CST STUDIO code [8] and obtained the rest of its parameters, namely the sizes and magnetization of the REPM blocks and the yoke dimensions. This optimized magnet geometry is shown in Fig. 5.

Finally, using the ASTRA code [9] we have calculated the distances d_i between the axis of the accelerating structure (common axis of beam trajectories) and the straight sections of the higher orbits and also the focusing powers f_i^{-1} for different beam energies (here $i = 1,2,3$ is the orbit number). The results of the simulations and the values of the same parameters calculated within the matrix formalism are given in Table 2.

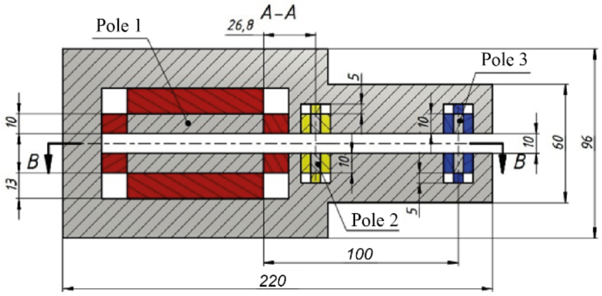

Figure 5: Optimized end magnet geometry.

Table 2: Focusing Powers and Orbit Distances from the Linac Axis for Different Energies

Parameter	Matrix formalism	ASTRA simulations
f_1^{-1}, m^{-1}	-0.572	-0.969
d_1, cm	6.05	6.0
f_2^{-1}, m^{-1}	-0.0629	-0.261
d_2, cm	8.62	8.59
f_3^{-1}, m^{-1}	-0.0016	-0.102
d_3, cm	11.73	11.66

CONCLUSIONS

In the present article we describe the concept of a race-track microtron (RTM) for cargo inspection complexes with a fast pulse-to-pulse beam extraction from the orbits with energies 3.5, 6.5 and 9.5 MeV. Also a novel design of the end magnets with REPM is described. We have carried out its optimization and found dimensions and magnetization of the REPM blocks, as well geometric parameters of the poles and the yoke. Details of the RTM design will be discussed in further publications.

REFERENCES

[1] Ogorodnikov S., Petrunin V., Phys. Rev. ST Accel. Beams, 5, 104701, 2002.
[2] Ishkhanov B.S., Pakhomov N.I., Shvedunov N.V., Shvedunov V.I., *et al.*, Proceedings of RuPAC XIX, 2004, P. 474-476.
[3] Kubyshin Yu.A., Berenguer J., Crisol A., Gonzalez X., *et al.*, Proceedings of PAC09, 2009, P. 2775-2777.
[4] Aloev A.V., Carrillo D., Kubyshin Yu.A., Pakhomov N.I., et al., Nucl. Instr. and Meth. A, 624, 2010, P. 39-46.
[5] W.P. Swanson, Radiological Safety Aspects of the Operation of Electron Linear Accelerators, Technical Reports Series No. 188.
[6] Babić H., Sedlaček M., Nucl. Instr. and Meth. 56, 170 (1967).
[7] Vladimirov I., Pakhomov N., Shvedunov V., Kubyshin Y., et al., Eur. Phys. J. Plus, 129, 271, 2014.
[8] CST STUDIO; http://www.cst.com
[9] K. Floettmann. ASTRA; http://www.desy.de/~mpyflo/