PERFORMANCE OF THE MAGNETIC SYSTEM OF A 12 MEV UPC RACE-TRACK MICROTRON*

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Abstract

The design and characteristics of the end magnet of a 12 MeV electron race-track microtron (RTM) which is under construction at the Technical University of Catalonia is described. The RTM end magnet consists of four dipoles with the main field level about 0.8 T. As a source of the magnetic field a Sa-Co rare earth permanent magnet material (REPM) is used. This helps to get a quite compact design of the RTM and allows to place its magnets in a high vacuum environment of the accelerator vacuum chamber. We discuss results of numerical simulations of the tuning of the end magnets by means of special plungers and describe their engineering design which permits to assemble the magnets and fix the Sa-Co blocks without gluing. Also a method and results of the REPM blocks residual magnetization control are reported.

INTRODUCTION

The Technical University of Catalonia in collaboration with the Skobeltsyn Institute of Nuclear Physics (SINP) of the Moscow State University and CIEMAT (Madrid) is building a race-track microtron (RTM) whose main envisaged application is Intraoperative Radiation Therapy. The design of the accelerator is described in [1], the course of its development was reported in [2].

A schematic view of the RTM main unit is given in Fig. 1. It consists of electron gun (1), accelerating structure (linac) (2) with four accelerating and three coupling cavities, two end magnets (3, 4) and a horizontally focusing quadrupole (5). These elements are precisely fixed on a common rigid platform placed inside a steel box which plays the role of the vacuum chamber. The beam can be extracted from any of the four orbits with extraction magnets (6) and exits the microtron along the output trajectory (7). The main RTM parameters are listed in Table 1.
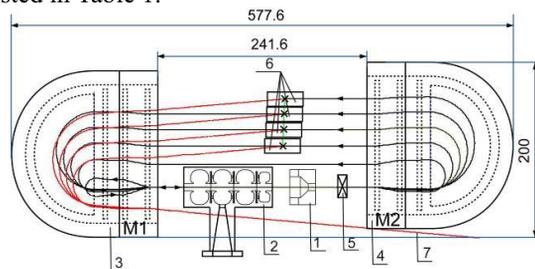
Figure 1: RTM scheme

Table 1: RTM parameters

Parameter	Value
Beam energies	6, 8, 10, 12 MeV
Operating frequency	5712 MHz
Synchronous energy gain	2 MeV
Pulsed beam current at the RTM exit	5 mA
End magnets field	0.8 T
Injection energy	25 keV
RTM head dimensions	670×250×210 mm

In all the RTM magnets as the source of the magnetic field a Rare-Earth Permanent Magnet (REPM) material is used. This allows to achieve rather compact magnetic systems which can be used inside the high-vacuum chamber.
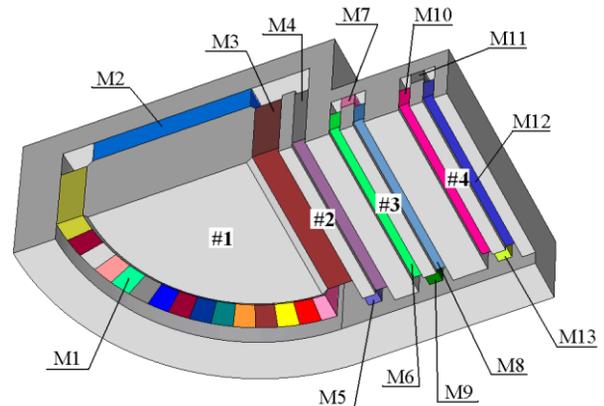
Figure 2: Geometry of the RTM end magnet used in ANSYS 3D simulations.

In the present machine with a low energy injection the end magnets, besides bending the particle trajectories by 180º, have other functions. Namely, end magnet M1 (see Fig. 1) also reflects the beam after the first acceleration back into the accelerating structure thus solving the problem of linac bypass. In addition, the beam vertical defocusing by the fringe field of the 180º bending dipole must be supressed and even converted in vertical beam focusing. All these requirements are implemented in a four-pole magnetic system described in Refs. [1], [3], its 3D geometry is shown in Fig. 2. The end magnets are symmetric with respect to the median plane and the vertical central plane, therefore from a one quarter of the magnet given in Fig. 2 the complete 3D geometry can be determined.

The system is composed by the main dipole (pole #1) responsible for the 180º bending of the beam, the inverse dipole (#2), whose field is adjusted so that an acceptable optics of the magnet is achieved, and two additional dipoles (#3 and #4) which displace the particle trajectories in such a way that the 2 MeV trajectory is reflected back into the linac. The poles are surrounded by REPM blocks (from M1 to M12) as shown in Fig. 2. In Fig. 3 the magnetic field profile in the median plane is plotted. The initial design parameters of the end magnet were calculated using the 2D POISSON code, the final optimized design was obtained from 3D simulations with the ANSYS code [4].
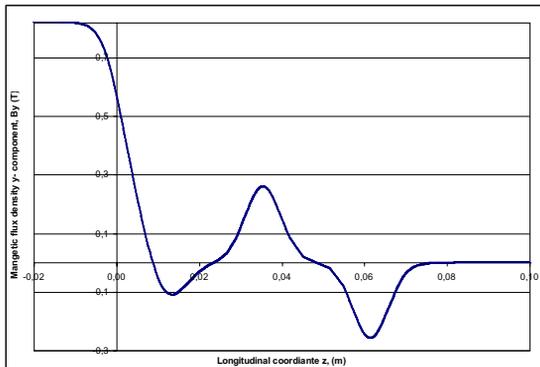
Figure 3: Vertical component of the magnetic field induction in the median plane of the 4-dipole end magnet as a function of longitudinal coordinate.

SIMULATIONS OF MAGNETIC FIELD TUNING

The main disadvantage of magnetic systems with permanent magnets is the difficulty in the adjustment of the magnetic field. A field tuning often becomes necessary in order to compensate imperfections of the magnet machining, assembling and REPM magnetization.

In the design of the 12 MeV RTM end magnets the field tuning is achieved by moving dedicated plungers through channels made in certain REPM blocks and corresponding parts of the yoke with respect to the poles. According to the design specifications the end magnets must provide the field uniformity in the good field region better than 0.075% in the main pole and 0.5% for the rest of the poles. To get a reasonable tuning range and to assure the required field uniformity it was decided to install four 10 mm diameter plungers at the main pole (#1), six 5 mm diameter plungers at the inverse pole (#2) and five 4 mm diameter plungers at the additional poles (#3, 4). The location of the plungers is shown in Fig. 4. Pole #1 plungers are moved in round channels made in the REPM blocks M2, pole #2 plungers above the M4 blocks and plungers of additional poles #3 and #4 in rectangular 5.4x5.0mm channels made in M7 and M11 blocks, respectively.

With the aim to reduce the effect of the magnetic saturation in the plungers the Vanadium-Permendur is used as the material. The design 3D simulations were performed with the ANSYS code. A detailed study of the field distribution in the median plane for different positions of the plungers was carried out. In particular, the field variation at each pole for the corresponding plungers being moved from one extreme position (plungers touch the pole) to the other one (the REPM part of the channel is free) was calculated. The obtained results are given in Table 2. The values and tolerances of the residual magnetizations of the REPM blocks were determined from the condition that for the position of the tuners corresponding to 20% of the total tuning range the nominal field profile shown in Fig. 3 must be reproduced. Also it was checked that for all the poles the field uniformity requirements are fulfilled.
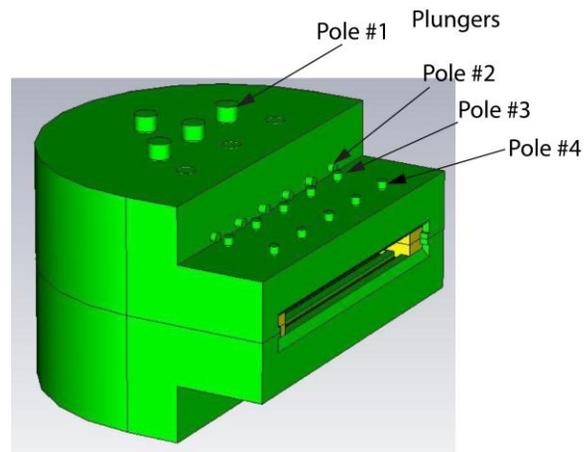
Figure 4: Position of plungers for different poles.

Table 2. Maximal variation of the magnetic field induction at each pole.

Pole number $\#i$	#1	#2	#3	#4
Relative field variation $\left|\Delta B_i / B_i\right|$	5.2%	7.9%	5.8%	5.9%

In the ANSYS simulations it was observed that the displacement of the main pole plungers affects the magnetic field in the inverse pole and vice versa. We obtained that for the maximal displacement of the main pole plungers the field in the centre of the inverse pole changes by 3.8%, whereas the maximal displacement of the inverse pole plungers leads to a 0.2% variation of the main pole field.

MAGNETS ENGENEERING DESIGN

We use Sm-Co as an REPM material. Though it is more fragile as compared with Nd-Fe-B, it is more appropriate for operation in a high vacuum environment, for example it can be used without special coating and can be heated up to 300-400 ^{0}C for outgassing. Characteristics of the specific Sa-Co blocks used for the RTM end magnet are B_r=1.1 T, H_{CB}=820 kA/m and the temperature factor equal to -0.033 %/^{0}C.

The magnet detailed design is shown in Fig. 5. In order to decrease the outgassing the REPM blocks are fixed inside the magnetic system mechanically by means of Al insertions and parts of yoke with special tips and without using glue. The poles and the yoke made of soft magnetic steel are coated by a thin, about 10 μm, Ni layer applying the sputtering method. All dead volumes inside the magnet body have pumping out hole.
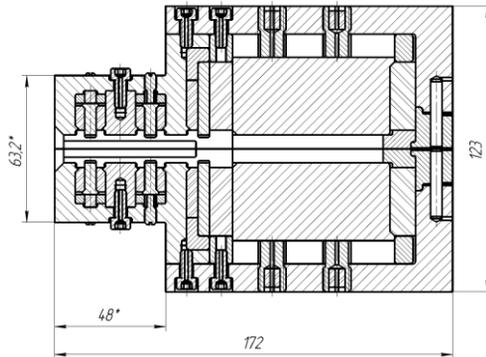
Figure 5: End magnet cross section.

The vertical component of the magnetic field in the gap between the poles must be symmetric, for this the upper and lower parts of each end magnet must be identical. This field symmetry will be controlled by measuring and adjusting to be equal the magnetic field distributions created by each of these parts separately at a plane close to the median plane in which a steel plate is placed.

REPM BLOCKS RESIDUAL MAGNETIZATION CONTROL

The value of the residual magnetization B_r induced in a specific REPM block during the production process at the factory does not necessarily coincide with the value of B_r providing the proper field in the 3D simulation. To establish the correspondence between the factory and design residual magnetizations the field distributions of two test Sa-Co blocks with dimensions 30x28x12 mm (PM1) and 72x40x11 mm (PM2) were measured and compared to results of their simulations.

The measurements were performed at an automated magnetic measurement table equipped with a precisely calibrated and temperature controlled Hall probe. The magnetic field induction component in the direction of the magnetization was measured at points of the plane situated at the distance 5 mm above the block surface at its both sides with the 3 mm step. The calculated field distributions were fitted to the measured ones by the least square method using B_r as a variable. The simulations were done assuming the uniform block magnetization.

In Figs. 6a and 6b the measured (red points) and calculated field distributions along the long block side at the central parts of PM1 and PM2, correspondingly, are shown. While for PM1 the shapes of the measured and calculated distributions are close, for PM2 a dip in the central part of the measured curve can be seen in contrast to the calculated one. This dip is explained by a non-

uniform block magnetization due to its large dimensions and imperfections of the magnetization method used at the factory.

As a result of the procedure described above the following estimates of Br were obtained:

- PM1, side1: 0.97±0.1 T, side 2: 0.96±0.1 T;
- PM2, side1: 0.740±0.005 T, side 2: 0.787±0.005 T.

Comparing them to the value B_r = 1.09 T reported by factory the correction factors are calculated.
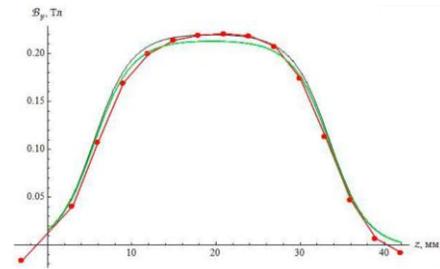
(a)
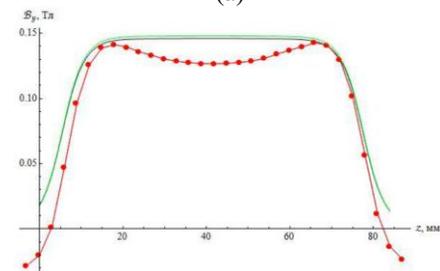
(b)

Figure 6: Field distributions along the long side of PM1 (a) and PM2 (b) obtained in the measurements (red points) and simulations for different B_r.

CONCLUSIONS

A mechanism of tuning of the field distribution in the RTM end magnets with Sa-Co permanent magnets has been suggested and simulated using the ANSYS code. The engineering design of these systems permitting their assembling without glue has been carried out. Measurements of the residual magnetization of test REPM blocks revealed a considerable difference between the value of B_r reported by factory and the ones found in the 3D simulation. This difference will be compensated by introducing a correcting factor in the magnetization procedure.

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