RARE-EARTH END MAGNETS OF A MINIATURE RACE-TRACK MICROTRON AND THEIR TUNING*

I.Yu. Vladimirov#, N.I. Pakhomov, V.I. Shvedunov, MSU, Moscow, Russia
V.V. Zakharov, Tehnomag ltd., Kaluga, Russia
Yu.A. Kubyshin, UPC, Barcelona, Spain
J.P. Rigla, I3M, Valencia, Spain

Abstract

We report basic results on the tuning of permanent end magnets of a compact 12 MeV race-track microtron (RTM) which is under construction at the Technical University of Catalonia. They are magnetic systems composed of four dipoles with the rare-earth permanent magnet (REPM) material used as a source of the magnetic field. The steel poles of the magnets are equipped with tuning plungers which allow to adjust the magnetic field level. In the article we shortly describe the tuning procedure and different techniques that were used in order to fulfill strict requirements of the field characteristics of the end magnets. It is shown that the obtained magnetic systems provide correct beam trajectories in the 12 MeV RTM. More detailed information about tuning procedure and results of tuning will be published elsewhere.

INTRODUCTION

The Technical University of Catalonia (UPC) in collaboration with the Skobeltsyn Institute of Nuclear Physics of the Moscow State University (SINP MSU) and CIEMAT (Madrid) is building a race-track microtron whose main envisaged application is intraoperative radiation therapy. Modification of this compact low power consumption accelerator can be used also for cargo inspection and radiography. The design of the accelerator is described in [1], the course of its development was reported in [2].

A four-poles scheme of permanent end magnet shown in Fig. 1 was chosen for our RTM with a C-band linac to provide the first orbit closure and beam focusing in the vertical plane [3].

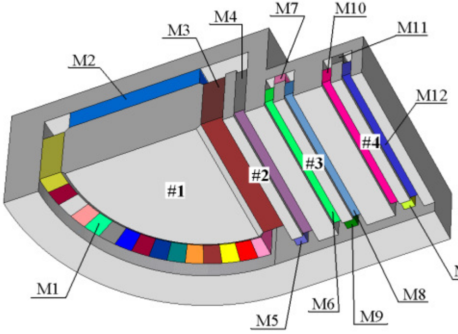

Figure 1: Geometry of the RTM end magnet. ¼ of magnet is shown.

To provide a high field uniformity at the poles a box type [4] design was chosen with steel poles (#1-#4) surrounded by REPM blocks M1–M13 and with the poles-REPM blocks system enclosed in a steel yoke.

A magnet engineering design was described in [5], one of the two manufactured magnets is shown in Fig. 2. The magnet dimensions are W×L×H=190×172×123 mm, the weight is approximately 21 kg, the poles field level in the median plane must be tuned to the values $B_1 : B_2 : B_3 : B_4 = -0.797\ \mathrm{T} : +0.115\ \mathrm{T} : -0.239\ \mathrm{T} : +0.239\ \mathrm{T}$.

As compared to the original design two elements shown in Fig. 2, namely active screen (1) at the magnet entrance and semicircle steel jacket (2) at the rear part of yoke, were added to the magnet in order to remove effects of yoke saturation which were not predicted in simulations.

To produce a fine field adjustment a set of tuners for each pole was introduced which permitted to change the field level within 5-8% [5]. Holes for tuners made in the REPM blocks M2 of pole #1 (Fig. 1) decreased the field level at this pole so that the maximum SmCo blocks magnetization appeared to be insufficient for achieving the project field level for pole #1, therefore the SmCo M2 blocks were replaced by NdFeB blocks.

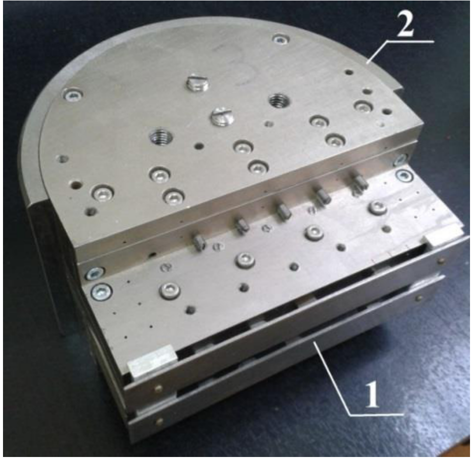

Figure 2: Assembled magnet.

TUNING PROCEDURE

Tuning of a permanent RTM end magnet is very different from that of an electromagnet. A properly designed and constructed RTM electromagnet requires a special tuning only if a very high field uniformity at a level of 0.01% or better is required [6].

Basic problems of a permanent magnet design is an uncertainty, up to 5–10%, in the REPM blocks magnetization and a non-uniformity of magnetization over the block volume. Additional problems arise from

---

*Work supported by grants 2009 SGR 1516 of AGAUR (Generalitat of Catalonia) and FIS2012-38480 of MINECO (Spain).

timerke@mail.ru

ISBN 978-3-95450-132-8

strong magnetic forces acting between magnet parts and the fragility of a REPM material, especially of SmCo.

If, due to magnetization uncertainty, the total energy stored in REPM blocks of a one half of the magnet is different from the stored energy of the other half then the magnetic median plane will be displaced with respect to the geometrical median plane and the beam will get a transverse kick due to a lens created by a field variation at the magnet entrance.

To minimize such magnetic median plane displacement our magnet was built from two identical halves (Fig. 3) differing only by the direction of the REPM block magnetization. Both halves were tuned separately to the same field level. For this each half was placed on a thick soft magnetic steel plate with good surface quality, imitating symmetry boundary conditions, and its field was measured with a probe at the distance 3 mm above the plate. The measured field level at the poles centre was compared with previously calculated values: $B_1 \colon B_2 \colon B_3 \colon B_4 = -0.797\ \mathrm{T} \colon +0.153\ \mathrm{T} \colon -0.297\ \mathrm{T} \colon +0.297\ \mathrm{T}$, and adjusted to them.

A rough field adjustment was done by using the following two REPM magnetization techniques: (1) the magnetization of large blocks was adjusted by heating and placing them in a constant magnetic field; (2) for small blocks a pulsed magnetic field at the room temperature was used. The final field adjustment was done by using the tuners. After that the two halves were assembled together using special jigs and the field distribution in the median plane was measured with a Hall probe.

Figure 3: Two halves of the end magnet.

Figure 4: End magnet at an automated measurement stand.

The automated stand used for the field distribution measurements is shown in Fig. 4. The Hall probe with a low temperature sensitivity and a thermo resistor are fixed together at a stem. The stem is moved by step motors in two directions in the horizontal plane with an accuracy about 0.01 mm. In the vertical plane the stem position is adjusted manually with the accuracy 0.05 mm.

The Hall probe was calibrated at different temperatures using an NMR magnetometer, the temperature sensitivity coefficients were defined and used for the correction of measured data.

The requirement of compactness of our RTM and the necessity to place the magnets inside a vacuum chamber exclude the possibility of installation of steering coils at the orbits. This imposes tough requirements on the field uniformity and accuracy of magnets positioning in the RTM: if a quadrupole lens installed at the common RTM axis is disabled, then for the beam passage through all the orbits the random deviations of the bending angle from 180^0 for any orbit must be less than 0.06^0 whereas the accuracy of the magnet installation angle must be better than 0.01^0.

However, during the magnets tuning it was found that the criteria ordinary used for estimations of the field quality of RTM electromagnets, such as the field uniformity at the poles or deviation of the measured field from the calculated one, are difficult to fulfill in our case. The reason is that the non-uniformity of magnetization and mechanical defects of the REPM blocks facing the median plane affect essentially the median plane field distribution. Besides this local effects of steel saturation at poles #2-#4 contribute additionally to the field non-uniformity and its deviation from the calculated value.

To resolve the problem of the beam passage through RTM without steering coils we used the following approach: (1) By means of the tuners we adjusted the field in the median plane at the pole centres to the project value. (2) By adjusting the parallelism of the poles to median plane with fixing screws and thin insertions we achieved the maximum field uniformity over the main pole #1 and along poles #2-#4 in the transverse direction, limited by mentioned above effects. (3) We elaborated a simplified RTM model, shown in Fig. 5, and calculated specific orbits positions and beam passage through the RTM in its real geometry and with the measured median plane fields. (4) For orbits with a relative bending angle error exceeding $\sim 3\times 10^{-4}$ we applied a local shimming thus decreasing the error.

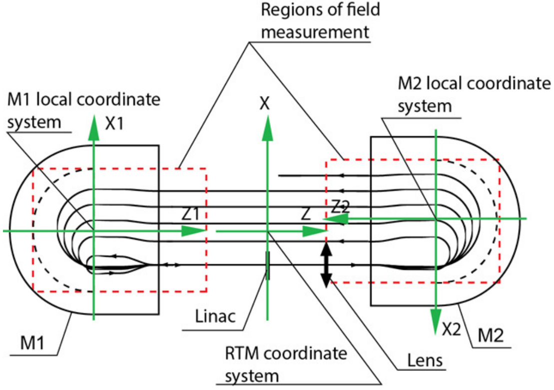

Figure 5: Simplified RTM model.

RESULTS OF MAGNETS TUNING

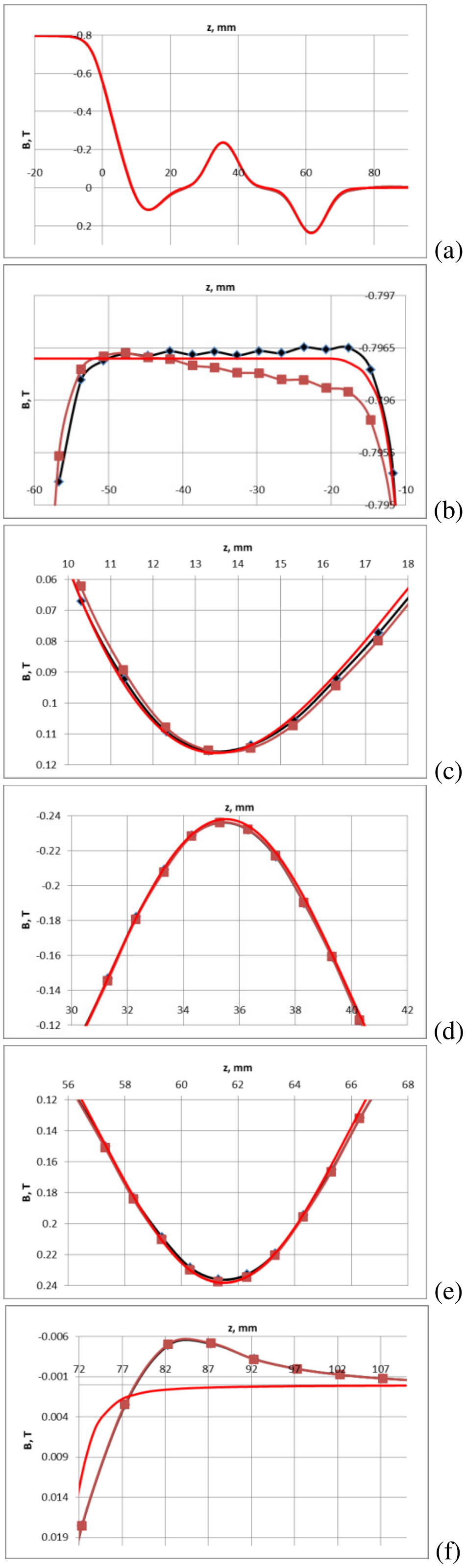

Figure 6: Field distributions in the median plane at the magnet centre: (a) in the whole region, (b) – (e) poles #1 - #4, respectively, (f) field at the magnet entrance. The red curve is the project field, blue and brown lines are the M1 and M2, respectively.

Some results of field tuning are shown in Fig. 6 and 7. In Fig. 6 field distributions in the median plane at the magnet centre are shown for the project field and for the measured fields at M1 and M2 magnets. At pole #1 the field deviation from the project value is within 0.04%, for the rest of the poles is less than 1%.

Due to the yoke saturation effect the field at the magnet entrance was essentially higher than the calculated one. To suppress this field an active screen ((1) at Fig. 2) was placed at the front part of the magnet and its strength was adjusted so that the field integral of the corrected field over the fringe zone was equal to the project field integral. The resulting fields are shown in Fig. 6 (f).

In Fig. 7 the field distributions in the region of pole #1 are shown, in this case the field uniformity is within 0.05%. Orbits simulations with the measured fields showed that for the quadrupole focal length -0.4 m the beam passes through all orbits with a maximum deviation from linac axis at 8 MeV equal to 1.35 mm.

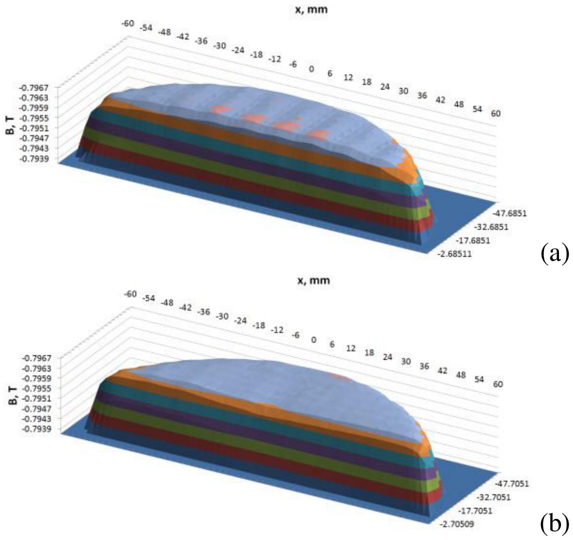

Figure 7: Field distribution in the region of pole #1 for M1 (a) and M2 (b) magnets.

CONCLUSIONS

The end magnets for the miniature RTM have been designed, constructed and tuned with the accuracy sufficient for beam acceleration without steering coils.

REFERENCES

[1] A.P. Poseryaev et al., EPAC'06, Edinburgh, June 2006, WEPCH175, p. 2340 (2006).
[2] Yu.A. Kubyshin et al., PAC'09, Vancouver, May 2009, WE6PFP112, p. 2775 (2009).
[3] J.P. Rigla et al., EPAC`08, Genoa, June 2008, WEPC159, p. 2380 (2008).
[4] G.A. Novikov et al., NIM B, 1998, Vol. 139, p. 527.
[5] I.Yu. Vladimirov et al., RuPAC`12, Saint-Petersburg, September 2012, WEPPC014, p. 472 (2012).
[6] H. Herminghaus et al., PAC’83, IEEE NS-30, p. 3284 (1983).