LARGE PERMANENT MAGNET DIPOLE PERFORMANCE*

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Abstract

We designed, built, tuned, and installed in our Race-Track Microtron (RTM) a pair of Sm_2Co_{17} Rare-Earth Permanent Magnet (REPM) dipoles that provide a ~0.96T field uniform to 0.3% in the 500×250×20 mm^3 working region. By accelerating electrons through all 14 orbits to 67.5 MeV, we have negotiated the difficult 1st orbit beam passage with its critical focusing and orbit displacement requirements, thus proving our magnet system design.

1 INTRODUCTION

Figure 1: 70 MeV RTM end magnet.

Our compact mobile 70 MeV RTM [1] requires large volume, high precision, highly reliable REPM bending magnets [2,3] without power supplies and cooling coils and a simple control system. Figure 1 shows our 'box' bending magnet with field clamp. The yoke shields the working region from external parasitic magnetic fields and prevents contamination by stray magnet fields. The magnet consists of a main 180° bending field and a reverse polarity entrance/exit field required by the 1st orbit RTM beam optics. The reverse field minimum is narrow and located close to main field so that the 5 MeV 1st orbit beam can clear the accelerating structure, as seen in Fig. 2. Realizing the required reverse field shape was an essential difficulty for our RTM that could only be solved with REPM magnets, not with electromagnets.

2 MAGNET DESIGN

We designed our RTM end magnets to have a 1 T main field uniform to 0.3%. The fringe field vertically focuses the 5 MeV beam with a 1 m focal length to provide the required 1st orbit displacement, *d*, of more than 32 mm and to be uniform to 1% along the entrance/exit slit. The main field is tunable in level and skew to ±2%, the reverse field to ±5%. Finally, the main fields in the two magnets need to be within 0.1% of each other.

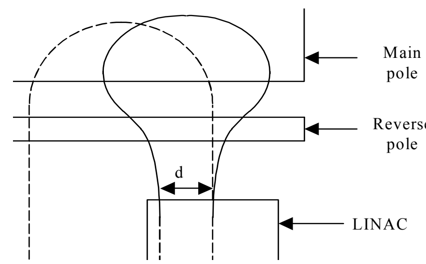

Figure 2: Reverse pole modified trajectory (—).

We first analytically calculated our magnetic system and then made extensive simulations with various geometries and materials. We represented the magnetic properties of the uniformly magnetized REPM blocks either by equivalent surface charges or by current sheets. We found that our box design could provide main fields of up to 1.8 T.

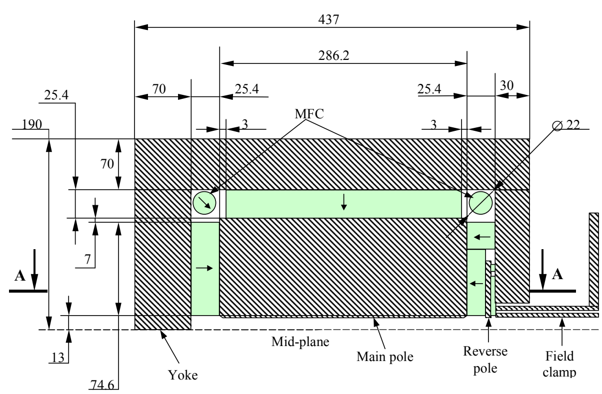

Figure 3: Half bending magnet section.

We numerically calculated our magnets with both two- (2D) and three-dimensional (3D) magnetostatic codes. We estimated the parameters that gave us an appropriate reverse field form in 2D and then calculated the entire magnet geometry with 3D codes. Our simulations resulted in a magnet model seen in Figs. 3-4 where all dimensions are in mm and arrows in the REPM materials indicate the magnetization.

Our magnet system consists of four iron poles with REPM materials attached to all surfaces except those facing the electrons. An iron shielding yoke

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surrounds the entire structure and conducts the flux back through the magnet mid-plane. Electrons enter/exit the magnet volume through a slit in the yoke. Two large poles form the main field while two smaller poles create the reverse field. All REPM material is recessed from the pole surfaces and the main gap-facing pole edges are chamfered.

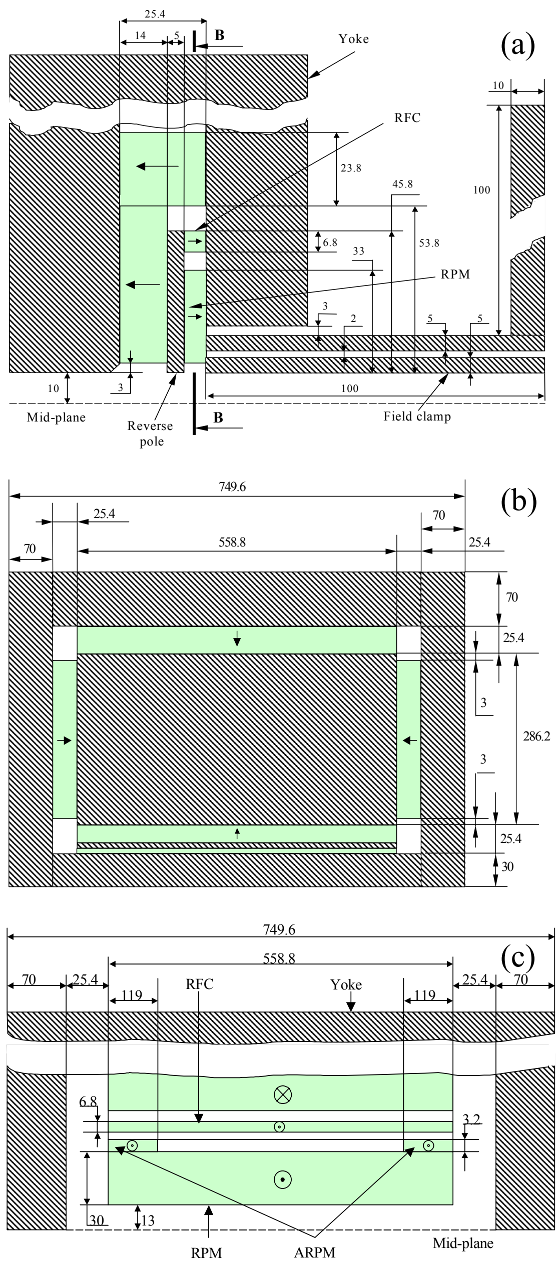

Figure 4: (a) Half reverse pole section, (b) Section **A-A,** and (c) Section **B-B**.

Main Field Correctors, seen in Fig. 3, and Reverse Field Correctors, seen in Fig. 4, adjust the respective field distributions. By rotating the MFC, which are cylindrical REPM blocks with magnetization vectors perpendicular to the block axes, we adjusted the main field level and canceled its skew components. The RFC are sliding rectangular REPM blocks. Additional tuning blocks between the reverse pole and the yoke provide reverse field uniformity along the entrance/exit slit.

The finite permeability of steel produces a non-zero yoke scalar potential creating a long field tail near the slit entrance/exit that destroys the 1st orbit beam optics. To realize the required fringe field distribution, we attach a field clamp directly to the reverse pole REPM material, with sides parallel to the yoke face, which shields the region inside the clamp from the stray fields.

3 TUNED FIELDS

We had built two 790×460×420 mm^3 magnets, SN01 and SN02, that each weigh 1,200 kg. We mapped the fields using a Hall probe, accurate to 0.05%, with the MFC providing the maximum magnetic flux, and found 0.963 (SN01) and 0.958 T (SN02), or ~4% less than the required 1.0 T design value. The difference between levels is greater than the design 0.1%. These deviations from the design values, which were solely the result of deficiencies introduced by the magnet manufacturer, have caused problems in the commissioning of the RTM. The main field was uniform in each magnet to ~0.3%.

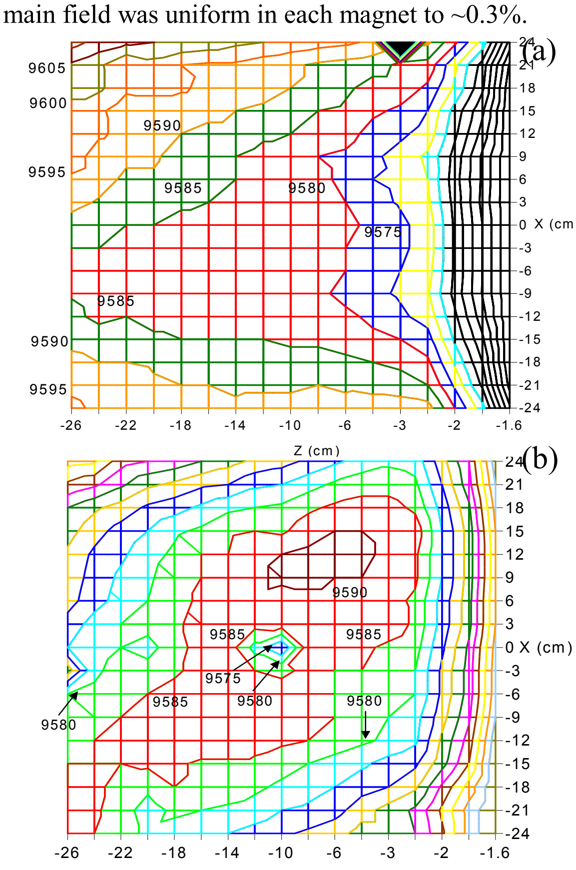

Figure 5: Mid-fields: (a) SN01 and (b) SN02.

To tune the field levels, we decreased the SN01 field by slightly rotating its MFC so that both magnet fields were equal to within 0.1%. We mapped the mid-plane fields of each tuned magnet, which are seen in the contour maps of Fig. 5.

We leveled the reverse fields by sliding the 30×8×3 mm^3 magnetized RFC blocks in their channels. We also inserted steel shims to decrease the field levels.

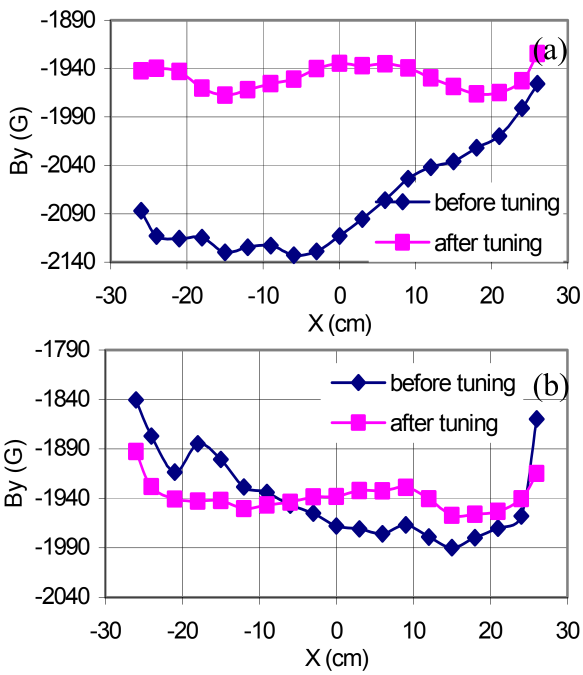

Figure 6: Reverse fields: (a) SN01 and (b) SN02.

To tune the reverse field distributions, we measured the minimum fields parallel to the entrance/exit slits, which are seen in Fig. 6 before and after tuning. The tuned distributions gave the acceptable calculated 1^{st} orbit beam displacements and focal lengths.

Tests with an electron beam have shown the RTM to function at the full 67.5 MeV energy after traversing all 14 orbits. We obtained a stable 1^{st} orbit beam passage where the beam optics parameters are the most critical. As the 1^{st} orbit beam passes through the 1 mm long, 8 mm diameter aperture only 30% of it survives compared to the the 40% predicted. Since we are just beginning to optimize the RTM operations, we are optimistic that we will achieve the design value.

4 CONCLUSION

We have designed, built, and tuned two novel end magnets for our RTM using REPM materials to provide ~0.96T main fields uniform to 0.3% in the 500×250×20 mm^3 working region which give the required 1^{st} orbit displacement and focusing.

5 ACKNOWLEGMENTS

A.D. Ryabov and A.G. Abramov provided essential assistance in evaluating the 3D magnet models. Our now operational magnets represent the realization of a design developed by the late Klaus Halbach while instructing one of us (GN) in the art that he pioneered.

6 REFERENCES

[1] V.I. Shvedunov, A.I. Karev, V.N. Melekhin, N.P. Sobenin, and W.P. Trower, "Improved Mobile 70 MeV Race-Track Microtron Design," in Proc. 1995 Particle Accelerator Conf., L. Gennari, ed. (IEEE, Piscataway, 1995) v.2, p.807.

[2] K. Halbach, O.V. Chubarov, A.I. Karev, G.A. Novikov, V.I. Shvedunov, and W.P. Trower, "Hybrid Race-Track Microtron End Magnets," IEEE Nucl. Symp. Conf. Rec. 15 (1997) 637.

[3] G.A. Novikov, O.V. Chubarov, K. Halbach, A.I. Karev, V.I. Shvedunov, and W.P. Trower, "Novel Race-Track Microtron End Magnets," Nucl. Instrum. Meth. B139 (1998) 527.