# A PERMANENT RACE-TRACK MICROTRON END MAGNET

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We present a design for a Rare-Earth Permanent Magnet end dipole magnet for our 70 MeV mobile Race-Track Microtron. We review the properties of these magnetic materials, describe the optimal magnetic circuit configuration and our choice of magnet parameters, and propose a method to form and tune the magnetic fringe field.

## I. INTRODUCTION

A new class of rare-earth magnetic materials have opened a new chapter in permanent magnet technology. To date **R**are-**E**arth **P**ermanent **M**agnet accelerator applications have been confined to small aperture quadrupoles, ring dipoles, and undulators [1,2]. Encouraged, we have designed an electron recirculator dipole magnet for our 70 MeV mobile **R**ace-**T**rack **M**icrotron [1].

Three rare-earth transition metal magnets are produced commercially, all of which have extremely large coercitivity and maximum energy product $(BH)^{max}$ as seen in Table I. The **B** vs. **H** hysteresis diagram of these materials shows that B-H coordinates are nearly linear in the second quadrant, $(BH)^{max}$ lying at the center and the return path following the hysteresis profile. Thus, a REPM is demagnetized neither by external fields nor by disassembly/assembly, a useful practical property. REPM anisotropy is described by

$$\mathbf{B}_{\parallel} = \mathbf{B}_r + \mu_0\, \mu_{\parallel}\, \mathbf{H}_{\parallel}$$

and

$$\mathbf{B}_{\perp} = \mu_0\, \mu_{\perp}\, \mathbf{H}_{\perp}\ ,$$

where the directional indices are with respect to the preferred field orientation, the so-called ease axis. Since $\mu_{\parallel}$ and $\mu_{\perp}$ are unity a REPM does not concentrate external magnetic flux in its body.

Table I.
Some REPM material parameters.

| | $\mathbf{H_c}$ (kOe) | $(BH)^{max}$ (MGOe) |
|---|---|---|
| $SmCo_5$ | 7.8 - 9.0 | 20 - 22 |
| $Sm_2Co_{17}$ | 8.2 - 10.0 | 25 - 27 |
| $Nd_2Fe_{14}B$ | 9.2 - 11.4 | 35 - 40 |

## II. MAGNETIC CIRCUIT CONFIGURATION

The three principal bending magnet magnetic circuits depend on the REPM placement as seen in Fig. 1. In the first, the REPM flux is transported to the gap by a steel yoke and pole ferrules. In the second, the REPMs are placed in center of the yoke, while in the third case the REPMs are placed adjacent to the gap. The magnetic flux in the gap, $\Phi_g$, depends on the REPM location, no isolators being in the magnetic circuit, and the accompanying parasitic fringe flux. Therefore, the total REPM flux, $\Phi_t$, is the sum of the useful flux, $\Phi_g$, and the parasitic flux which is approximately the sum of the flux between the *a* magnetic circuit elements, $\Phi_a$, between the *b* elements, $\Phi_b$, and between the ends of element *c*, $\Phi_c$. A REPM usage quality is defined by its disperse coefficient,

$$\sigma = \Phi_t/\Phi_g = 1 + (\Phi_a + \Phi_b + \Phi_c)/\Phi_g\ .$$

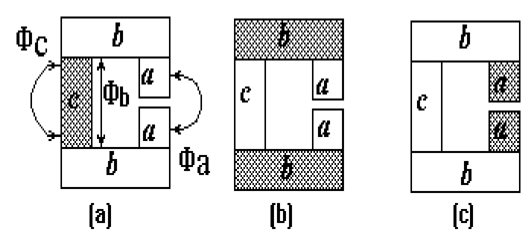


Fig. 1. Bending magnet configurations.

The flux coupling the magnetic circuit elements is proportional to the magnetic potential difference between these elements. For configuration [a] these differences are largest for elements *a-a* and *b-b*, so $\Phi_a$ and $\Phi_b$ are large. For configuration [c] the magnetic potential difference between elements *a-a* and *b-b* is zero, and so the REPM is better used here than in configuration [a] as only one the parasitic flux, $\Phi_a$, is present in contrast to three - $\Phi_a$, $\Phi_b$, and $\Phi_c$ in [c]. Intermediate is configuration [b]. The calculated relative gap induction ratio, [a]/[b]/[c], is 0.45/0.75/1.0. Thus, the optimum circuit configuration for our RTM end bending magnets is approximated by configuration [c].

## III. OPTIMAL MAGNET PARAMETERS

The magnet working point is usually near $(BH)^{max}$ so the total REPM thickness, h, of C-type magnet pole pieces is approximately equal to the gap height, g, which produces a gap magnetic field, $\mathbf{B}_g$, of $\mu_0\mathbf{H}_c/2$ ~0.5 T, obtainable with minimal REPMs quantity. However, for our RTM bending magnets this result may be not optimal since $\mathbf{B}_g$ may require that the magnet dimensions and weight be as small as possible.

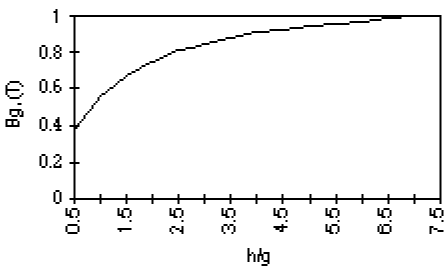


Fig. 2. $\mathbf{B}_g$ dependence on the REPM thickness-gap height ratio, h/g for $\mathbf{H}_c$ = 10.8 kOe and $(BH)^{max}$ = 31.3 MGOe.

Our simulated [3] RTM magnet gap field dependence on the total REPM thickness is shown in Fig. 2. The REPM volume is $hA_p$, where $A_p$ is pole face area is defined by the radius of last microtron orbit, ~$1/B_g$. Thus, the $V(B_g)/V_0$ dependence on h/g, where $V_0$ is the REPM volume with h = g can be calculated. Fixing the RTM output energy, the magnetic induction in the steel magnet parts, and $\mathbf{B}_g = \mathbf{B}_0$, if $\mathbf{B}_g$ is decreased then pole dimensions and the magnetic flux are increased by $1/B_g$ and end magnet weight also increases.

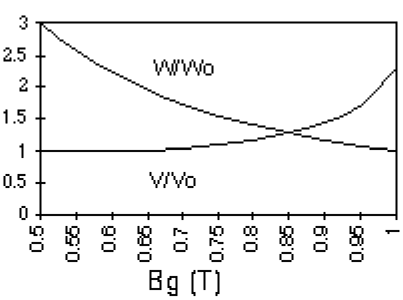


Fig. 3. Magnet weight and REPM volume dependence on $B_g$.

The REPM volume and end magnet weight dependence on $B_g$ are shown in Fig. 3, where $W_0$ is weight of a magnet with $B_g$ = 1 T. The choice of $\mathbf{B}_g$ is a compromise which defines the total magnet cost. A small RTM, energy 10-20 MeV, will be relatively light and cheap with an optimal $B_g$ of 0.6-0.8 T. A 50-100 MeV RTM acceptable gap field requires larger and heavier magnets. If $\mathbf{B}_g$ is increased the energy gain per turn will increase proportionally, while if $\mathbf{B}_g$ is decreased more RTM orbits will be required for the same output energy, thus complicating beam focusing and increasing the linac current load. So for our mobile 70 MeV RTM [4] we chose $B_g$ = 0.9 T requiring a REPM volume of ~0.0145 $m^3$ , gap height of 20 mm, and pole face area of 60 x 32 $cm^2$.

## IV. MAGNET FRINGE FIELD SHAPE

The RTM bending magnet fringe field is strongly defocusing requiring a special reverse direction fringe magnetic field to obtain stable vertical oscillations [5]. This in turn reduces the orbit diameter requiring a complicated reverse direction acceleration system to allow the beam to clear the linac. After the first linac passage the end magnet fringe field focuses the beam. Thus, the beam optics and trajectory geometry must be solved simultaneously requiring an appropriate fringe field configuration in the design stage and a careful accelerator tuning procedure in the operational stage. The effective orbit diameter depends on the distance between the main bending field region and the reverse direction field which in conventional RTM bending magnets is formed by adding steel poles and coils located a considerable distance from the main poles to avoid unacceptably distorting total fringe field.

We use the anisotropic REPM properties to construct a fringe field with reversed magnetization direction. Since each REPM element is magnetically independent an additional REPM element may be placed close to the main REPM segment thus reducing the reverse-main field distance while increasing the first orbit diameter. By using a narrow axially asymmetry linac [6] we obviate our original complicated first orbit loop geometry. Moreover, using REPMs decouples the problem of stable transverse motion from that of trajectory geometry allowing an optically better fringe field configuration to be found. Thus, our REPMs simplify accelerator tuning while improving the beam parameters.

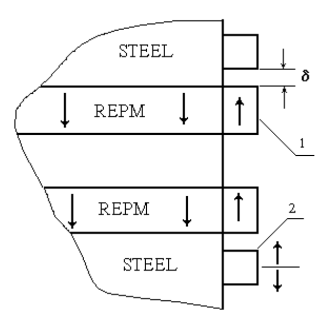


Fig. 4. Magnetic circuit end configuration: 1 - added REPM units and 2 - movable steel elements.

The additional reverse magnetization REPM elements, shown in Fig. 4, define the fringe magnetic field distribution. By varying the geometry of these elements we found a fringe field shape which allows the first orbit diameter in our mobile 70 MeV RTM to increase to 40 mm and still have sufficient focusing power. To shape the fringe field we place simple movable steel elements near the magnet end. These elements change the air gap dimensions, δ, and, thus, magnetic circuit parameters and the reverse field amplitude. An increase in δ from zero to 5 mm decreases the reverse field amplitude by 15%.

## V. CONCLUSIONS

The large REPM magnetization energy and anisotropic properties allow us to obtain magnetic gap induction with which to shape better fringe fields than we achieved with conventional electromagnets. Furthermore, a RTM with REPM bending end magnets no longer requires magnet coils, (other than small correcting coils), their power supplies and cooling equipment. This results in reduced total accelerator power consumption, simplified construction and servicing, a streamlined control system, enhanced overall operational reliability, and reduced space requirements. Important additional advantages accrue to mobile RTMs, for example, serving as a light source to detect explosives in buried military munitions and land mines [7].

We express our appreciation to Klaus Halbach for pioneering REPM accelerator applications and for his generous help in initiating us to this field, and to V.S. Skachkov for general disscussion of REPM implimentation.

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