A VARIABLE GRADIENT RARE EARTH PERMANENT ALPHA-MAGNET[1]

V.S. Skachkov[2]
World Physics Technologies, Inc. Blacksburg VA 24060 USA

Abstract

We have developed a Rare Earth Permanent Magnet (REPM) α-magnet that is installed at the exit of a 1.6 MeV Radio-Frequency (RF) electron gun, which, together with the injector accelerating structure, matches the longitudinal phase space to our 35 MeV RaceTrack Microtron (RTM) acceptance. The magnet, two movable layers of Nd-Fe-B elements, can achieve gradients of 3.5 to 4.5 T/m with good field linearity. We have installed a cooled diaphragm in the α-magnet vacuum chamber so it can be placed at the maximally dispersed beam to obtain short gun beam bunches with small energy spread. Here we describe the magnet design and adjustment, and present the measured gap fields.

1 INTRODUCTION

We are constructing a RTM with high brightness beams of 5-35 MeV with bunch charge of ~150 pC [1]. Our α-magnet in the RTM injection system must provide dispersion-free longitudinally compressed bunches from the 2,856 MHz RF gun with a central energy of 1.6 MeV. This requires a 4 T/m field gradient adjustable to ±10% to permit a match to the RTM acceptance and a 80 mm penetration depth. A half-quadrupole electromagnetic α-magnet is too large for our trajectory and field and a Panofsky half-quadrupole [2], while more compact, consumes too much energy.

2 THEORY

A magnetic quadrupole lens with its two-dimensional (x,y) z-independent field can be realized with REPM elements surrounded by a soft iron yoke. Our α-magnet design provides a linear field in a rectangular working region with a depth in x several times greater than its height y.

REPM elements, with their uniform magnetisation

$$\boldsymbol{I}(r_M,\varphi_M)=I\,[\boldsymbol{n}\cdot cos(\varphi_M-\psi)-\tau\cdot sin(\varphi_M-\psi)], \quad (1)$$

where I and ψ are the magnetisation modulus and x-axis angle respectively, excite surface currents on the inner yoke surface. A yoke profile, $r(\varphi)$, produces a magnetic field gradient, G,

$$\frac{G}{2\mu_0 I}r^2\, sin\, 2\varphi = r\, cos\,(\varphi-\psi)+C\,, \quad (2)$$

which is family of hyperbolae. We use this equation to calculate a variety of quadrupoles with various REPM element shapes and yoke configurations. For some Cs these hyperbolae degenerate into pairs of straight lines. Figure 1 shows the simplest lens cross-section with a single pair of these lines, S_1Q and S_2Q. To eliminate the field sources at S_1P and S_2P, the magnetisations, $\boldsymbol{I}_1$ and $\boldsymbol{I}_2$, need to be oriented normal their respective faces.

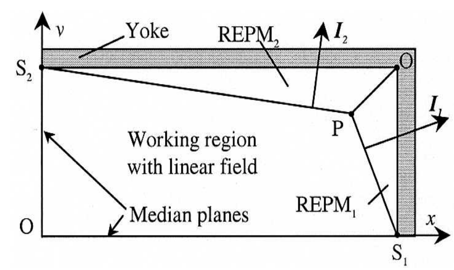

Figure 1: A quadrant of an ideal REPM quadrupole lens

To obtain the required linear field in the OS_1PS_2O working region, angles ψ_1 and ψ_2 as well as I_1 and I_2 must satisfy

$$G=\frac{\mu_0 I_1}{x_0}sin\psi_1=\frac{\mu_0 I_2}{y_0}cos\psi_2\,, \quad (3)$$

where $x_0 = OS_1$ and $y_0 = OS_2$. With $|\boldsymbol{I}_1| = |\boldsymbol{I}_2|$, no sources are on the PQ face, the REPM analogue of the Panofsky lens [2].

As x_0 grows, the $REPM_1$ contribution to the field near the origin is reduced until some x_0 to α-trajectory depth, x_α, ratio when this element can be removed. Thus we control the gradient by varying y_0 since $G \sim 1/y_0$. For small gradient adjustments, x_0/x_α becomes smaller and the non-linear influences from removing $REPM_1$ become negligible.

3 MAGNET DESIGN

Real REPMs restrict the minimal distance between the elements and the space adjacent to the working region. For very compact magnets such as the one described in ref. [3], the ideal system REPM elements can be subdivided so that each individual element magnetization can be locally tuned to diminish field distortions.

Our α-magnet, shown in Fig. 2, has two layers of 18 to 20 8×20 mm^2 Nd-Fe-B elements (1) that excite the gap field in the vacuum chamber (2) which the electron beam

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[2] Permanent address: Institute for Theoretical and Experimental Physics, 117218 Moscow, Russia

enters/exits through a 30×100 mm^2 hole in the yoke front wall (3). G can be adjusted from 3.5 to 4.5 T/m so that electron trajectories can penetrate up to 100 mm and their width, $2z_\alpha$, is 80 mm when the layers are moved over a range, D, of 24 mm. Both layers move simultaneously in opposite directions changing the magnet aperture, h_a, without changing the xz median plane.

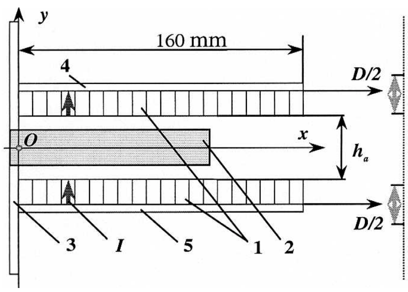

Figure 2: α-magnet magnetic system.

Our REPM element magnetisation, ***I***, is chosen normal to the moveable iron yoke plates (4) and (5). At 80 mm into the gap and between the chamber and upper REPM layer, we install a small Hall probe that allows the field to be remotely and automatically adjusted. On the right of the chamber, we provide a cooled moveable beam diaphragm.

To produce the required linear field in $0< x< x_\alpha$, we vary the element magnetisation up to x = 110 mm. The resulting field distribution is far from linear, not identical to that of the ideal lens of Fig. 1. From the x = 110 mm to the layer end, the magnetisation is constant and is the largest that the Nd-Fe-B can produce. Our demagnetisation technique is described elsewhere [3].

In the longitudinal direction, all elements have the same magnetisation. To reduce the fringe field fall off, which begins at z_α ~40 mm, to 1 % for the largest magnet aperture, h_a = 66 mm, we make the magnet 200 mm long and divide it into five 40 mm sections.

4 MAGNET FIELDS

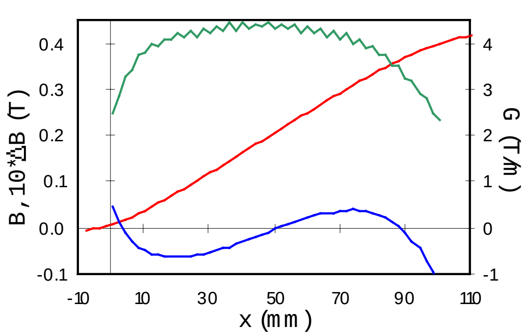

Figure 3: Median plane G (top), B (middle), and B (btm)

We measure the median xz plane field distribution with a Hall probe magnetometer calibrated in a uniform field. The gradient and its deviation from linear at the nominal 4 T/m gradient are shown in Fig. 3. The field deviates slightly from linear near the origin due to the beam port and at the opposite side where the magnetisation saturates. These excursions are less than 2.5 % of the maximum field at $x = x_\alpha$ = 100 mm.

Table 1: rms fitted field parameters.

a (T/m)	b (mT)	ΔB_{rms} (mT)	B_{norm} (mT)	$\%_{rms}$
3.59	12.4	4.8	350	1.4
4.15	10.3	4.3	410	1.1
4.83	7.7	3.7	480	0.8

The fitted element magnetizations near the origin increase the region in front of the wall as does fitting in the x = 70-90 mm region, both of which decrease the average G. Although deviations in both regions are undesirable, the ΔB behavior is almost constant over the entire gradient adjustment range as seen from the fitted rms $B_l = ax + b$ parameters, presented in Table 1 for the nominal and limiting Gs, shown in Fig. 4. Thus the tuning is acceptable, since the field distribution is similar over the entire adjustment range.

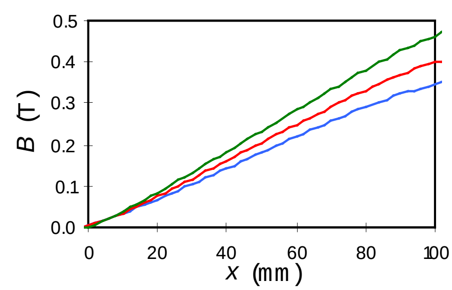

Figure 4: Nominal adjusted G (middle) and limit fields

The rms field deviation grows with the magnet aperture but, because of the chosen ratio of the layer length along the x-axis to x_α, this rms deviation is reduced to ~1 % of B_{norm} at x = 100 mm. The slope a overlaps the gradient adjustment range and the small b says that the field grows almost linearly from the origin.

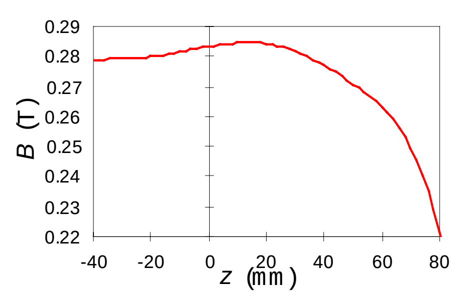

Figure 5: Measured longitudinal field for h_a = 66 mm

Figure 5 shows that our 200 mm length elements provide a field flat and linear to better than 1 % of all electron α-magnet trajectories and for the entire range of magnet aperture heights.

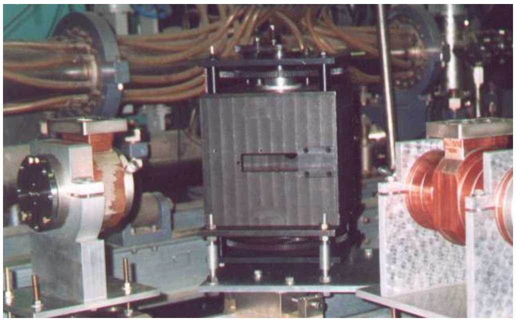

Figure 6: 35 MeV RTM REPM α-magnet.

Our 35 MeV RTM REPM α-magnet is shown in Fig. 6 (center) installed at the exit of a 1.6 MeV RF electron gun (right) without the vacuum chamber.

5 CONCLUSIONS

We have demonstrated that a variable gradient REPM α-magnet with a linear field can be used to inject, bunch, and compress electron beams.

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