

A FIXED GRADIENT RARE EARTH PERMANENT ALPHA-MAGNET¹

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Abstract

We have developed a rare earth permanent magnet (REPM) α -magnet to deflect a 50 keV bunched electron gun beam onto our 70 MeV race-track microtron (RTM) accelerating structure axis. Here we describe the epoxy incorporated REPM granule magnet elements, the magnet design and adjustments, and the measured entrance/exit gap fields. Finally, we report on the magnet performance with an electron beam.

1 INTRODUCTION

We will use a dispersion free α -magnet [1] to inject our 50 keV pre-buncher modulated electron gun beam into our pulsed 70 MeV RTM [2]. To not interfere with the RTM electron orbits, we mount the electron gun and pre-buncher vertically off-axis, injecting the beam on-axis through our 1 T/m gradient α -magnet.

We cannot use a conventional half-quadrupole electromagnet design because our 1st orbit is only 33.5 mm from the RTM axis. Although a Panofsky quadrupole [3] made of thin current sheets would be sufficiently narrow, our large gradient would require a high current with its attendant large heat load and expensive current source.

REPM material has long been used to build compact focusing devices for particle accelerators [4] and so taking advantage of the close analogy between REPM and current sheets [5], we have built an α -magnet with the required field which we report now.

2 MAGNET DESIGN

It was initially suggested [5] that we use a special Panofsky lens made with simple cross-section REPM elements. However, with our restricted magnet height, these elements would be extremely close to the working region requiring an element magnetisation accuracy that would be difficult to achieve in practice. Further, Nd-Fe-B elements with $B_r \sim 1.1$ T would have to be very thin.

We instead have chosen to use REPM elements with varying magnetic moments, allowing us to tune the field by changing the element geometry, position, and magnetisation, as well as the removable iron yoke shape. In each magnet quadrant, we have 11 horizontal and 3

vertical 5×5 mm² elements as seen in Fig. 1. We chose the 100 mm α -magnet length to minimize the longitudinally decreasing fringe field effects.

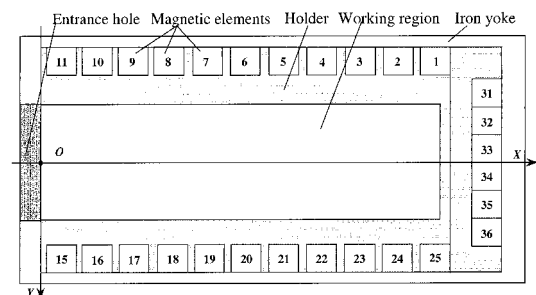


Figure 1: α -magnet elevation view.

To provide our required 1 T/m gradient, we used epoxy embedded Nd-Fe-B granular elements with magnetisations, $\mu_0 I$, of 0.4-0.5 T. We tuned the element moments by demagnetising each individually, the magnetisation being normal to the yoke surface. Our α -magnet is geometrically symmetric with respect to the xz median plane but its field is antisymmetric.

We ground each element to ~ 5.35 mm ± 50 μ m across its magnetisation dimension, while the heights ranged from 3 to 5.2 mm in the magnetisation direction. The 100-103 mm element longitudinal dimension variability and edge shape little influenced the working volume field distribution. The α -magnet yoke, a soft iron box, was mounted in a brass frame.

Using a pulsed field coil, we first magnetised the elements to saturation with a ~ 1 ms, 3 kA pulse current having good hysteresis loop symmetry. Then we demagnetised each to its design magnetic moment using a ballast resistor to limit our demagnetisation attenuation to $\sim 1\%$ and the capacitor discharge voltage determined the demagnetisation.

We flipped each symmetric element before mounting it to compensate for small systematic element magnetisation directional variations. However, at small magnetisation, unacceptable field variations persisted near elements 10, 11, 15, and 16 (Fig. 1), which we reduced to acceptable levels by grinding each to a 3 mm height.

We measured the field distribution using a stable high-temperature Hall magnetometer mounted on a precision microscope stage which we positioned to better than ± 10

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μm in x and y and ± 0.5 mm in z . We calibrated the probe to better than 0.1% in a uniform NMR field.

We used a constant surface current density model to calculate the initial element magnetic moments and then iteratively fit the field distribution measured along several trajectories. Finally, we calculated the difference between the initial magnetic moments and those of the required gradient field.

Table 1: Field parameters.

y (mm)	z (mm)	a (T/m)	b (mT)	Δ_{rms} (%)
0	-20	1.02	-0.199	1.12
0	-10	1.02	-0.122	0.77
-10	0	1.02	-0.075	2.99
0	0	1.01	-0.028	0.36
+10	0	1.10	-0.335	2.18
0	+10	0.99	0.011	0.35
0	+20	0.97	-0.013	0.87

We tuned the α -magnet with no entrance aperture by controlling B_y , the field gradient, G , and the difference, D , between the measured B field and the ideal linear field. Measuring in x at various y and z , we then described the measured field as $B_y = ax + b$, the results of which are seen in Table 1. The rms deviation of the measured field from the ideal, Δ_{rms} , was less than 3% over the working volume.

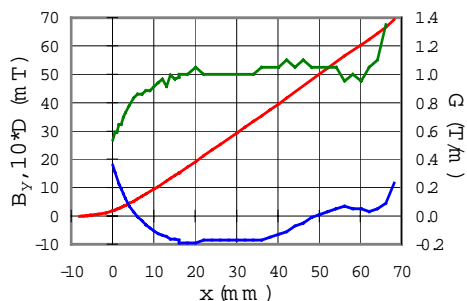


Figure 2: Measured B (middle), calculated G (top) and D (bottom)

To insert the vacuum chamber into the α -magnet gap, we made an oval entrance hole in the front wall, which slightly perturbed the field distribution. In Fig. 2 we show B , G , and D in the median plane at $y = z = 0$. The substantial deviations of G from 1 T/m and D from zero at the magnet entrance little influenced the beam dynamics because of the small field in that region.

3 BEAM TESTS

An ideal α -magnet has no dispersion at its “magic” $\sim 40.7^\circ$ incident beam angle, however its vertical and horizontal plane beam optics are complicated, requiring a 3rd order matrix to describe them.

Before installing our α -magnet in its test stand, we made beam dynamics simulations [6] to compare its

properties with those of an ideal magnet. In Fig. 3(a) we contrast the calculated real and ideal linear field dispersion at the magnet exit with incident beam angles, while in Fig. 3(b) we see the exit trajectory divergence of a 1 mm off-axis test particle. In practice the difference between our real and an ideal magnet is negligible.

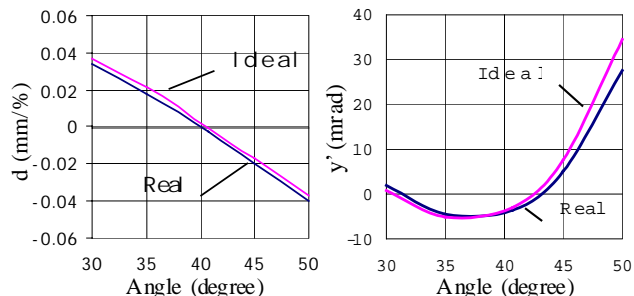


Figure 3: Calculated real and ideal α -magnet (a) dispersion and (b) exit trajectory divergence

We then installed our α -magnet, a photograph of which with its vacuum chamber and support is seen in Fig. 4, in our RTM accelerating structure test stand [7].

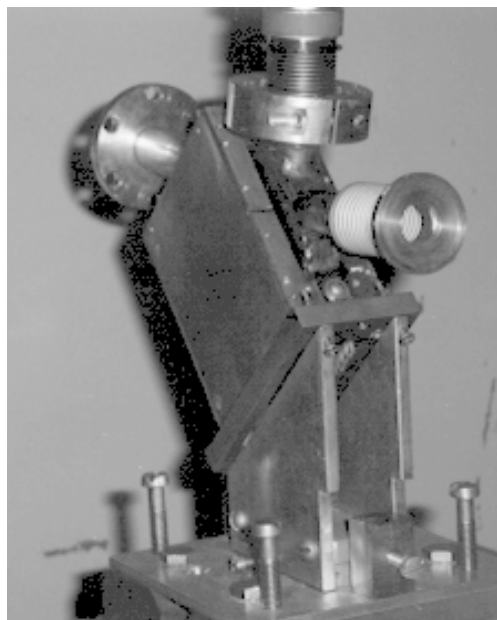


Figure 4: α -magnet with vacuum chamber and support

We successfully injected a pre-buncher modulated 50 keV electron beam with currents up to 200 mA on to the accelerating structure axis. To focus the beam, we installed REPM rings at the pre-buncher exit and the accelerating structure entrance. We measured the beam current at the gun exit with a transformer beam current monitor (BCM) and at the accelerating structure entrance with a Faraday cup (FC). We steered the beam with coils and adjusted the α -magnet position using BCM and FC pulses. Figure 5 shows unnormalized current pulses measured at the gun exit and structure entrance.

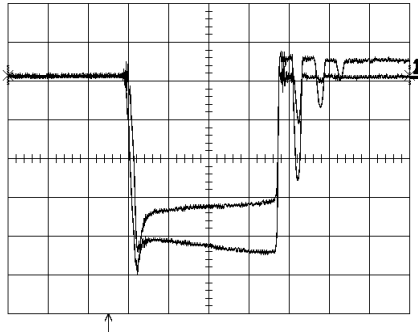


Figure 5: Gun exit BCM (upper) and structure entrance FC (lower) current pulse traces

Once tuned we obtained 100% current transmission through our α -magnet with more than 60% of the gun current captured in our accelerating structure [7].

4 CONCLUSION

We have demonstrated a compact REPM α -magnet whose highly linear field can be realized for gradients up to 10 T/m, suggesting its use for injecting and compressing electron beams.

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