Design and Fabrication of a Multi-Purpose Panofsky Magnet

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Abstract

A fast, flexible magnet system, consisting of a Panofsky-style ferrite picture-frame magnet and pulsed power supply, has been developed. Magnet specifications are: 8 cm × 8 cm aperture, 23 cm length, 500 A pulsed/160 A DC, and 1 μs risetime. Designed for general accelerator physics studies, the magnet may be quickly converted from dipole to quadrupole or sextupole and higher multipole configurations by easily changing winding end terminations. In the quadrupole configuration a field gradient of 0.5 T/m is achieved at 500 A. This magnet has become an important tool for nonlinear beam dynamics experiments at the IUCF Cooler Ring.

I. INTRODUCTION

It is well known that beam loss occurs at sum resonances, when the betatron tunes ν_x, ν_z satisfy

$$m_x\nu_x + m_z\nu_z = \text{integer},$$

with integer m_x, m_z. Thus, beam dynamics experiments at sum resonances is important in accelerator physics; correction of these sum resonances can improve accelerator performance. A typical beam dynamics experiment is usually performed by measuring the Poincaré map at a resonance condition. However, the beam current within a sum resonance is too small to obtain any useful information; e.g., the stopband width of $\nu_x + 2\nu_z = 13$ resonance at the IUCF Cooler Ring is typically 0.01. A fast quadrupole capable of producing a tune shift of the order of 0.03 at a rise time of 1 μs would serve the purpose for accelerator physics experiments. The method is to jump onto the sum resonance by using the fast quadrupole and observe the beam response as a function of initial betatron amplitudes. Such a process can be achieved by firing a fast quadrupole and then allowing the magnet current (and tune) to die away from the resonance band, back to the original DC tune. One useful operational outcome of such a technique is the ability to jump over intrinsic depolarizing spin resonances and thereby accelerate beam with little polarization loss [1].

To investigate these behaviors and related nonlinear dynamics at the IUCF Cooler Ring we developed a fast ferrite magnet and pulsed power supply. The magnet uses Panofsky-style picture frame construction [2], with solid copper windings embedded along the ferrite inner walls. By designing the windings as separate from the winding end terminations we have achieved a magnet of considerable flexibility. Changing end terminations allows use as both dipole and quadrupole; modeling also suggests sextupole configurations.

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II. MAGNET DESIGN

We had on hand a large number of 2.54 cm × 5.02 cm cross-section, 22.9 cm long ferrite slabs. These were cleaned and glued together with a commercial cyanoacrylate ester instant adhesive [3]. The ferrite frame was strengthened by bonding 0.32 cm thick G-10 fiberglass sheets to the ferrite outer walls using silicone RTV. The assembled ferrite frame measured 15.2 cm × 15.2 cm outside dimensions, 23 cm long, with a 10.2cm × 10.2 cm inner aperture (effectively reduced to 8 cm × 8 cm by the later addition of the copper conductors and fiberglass carrier plates). The top ferrite slabs are free to slide in and out of the lower "U" shaped ferrite frame. This allows insertion around a beampipe by temporarily disconnecting the end termination cables, raising the magnet from below the beampipe, reinstalling the top ferrite/conductor assembly, and reconnecting the end termination cables.

The winding conductors were fabricated from 1.9 cm wide, 0.64 cm thick copper bars. Because the turn-to-turn voltage during the 1 μs current ramp-up exceeds several kV, conductor edges were radiused to minimize E-field strength, which otherwise leads to flashover during turn-on. Winding ends were drilled and tapped for #8 screws to form end connections. Carrier plates, constructed of 0.64 cm thick G-10 fiberglass, were milled out to accept the copper bars. These bars were bedded into the G-10 with a thin RTV layer; the G-10 carrier plates similarly attached to the ferrite inner walls (Figure 1.).

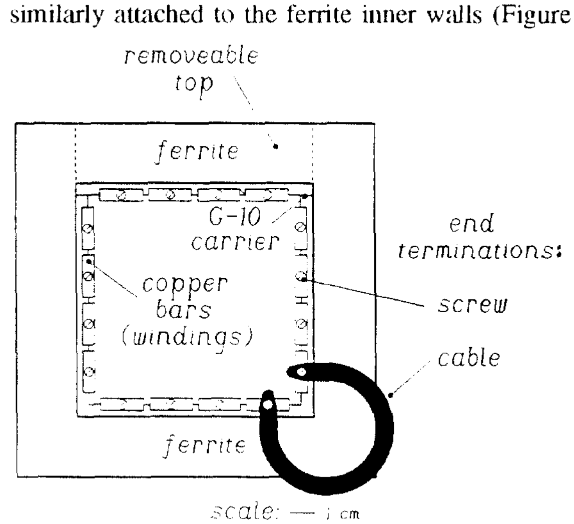

Fig. 1 Magnet construction

The completed magnet was mounted on a support base with leveling & centering screws.

For low frequency modulation field monitoring, a demountable, compact field pick-up coil can be attached inside the magnet aperture. This connects to integrator/amplifier electronics mounted on the base plate, providing a high-level field monitor signal over 30 Hz to 300 kHz.

III. POWER SUPPLIES

For pulsed current work, a supply using capacitor energy storage and ignitron switch tube was designed and built (Fig. 2). Both high- and low-voltage capacitor banks in the supply

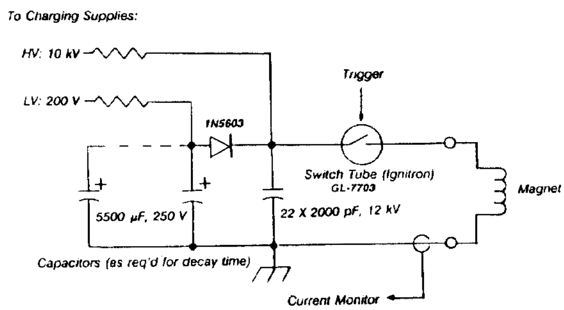

Fig. 2 Pulsed supply topology

are precharged from 10 kV and 200 V charging supplies. A trigger pulse fires the GL-7703 ignitron tube; magnet current resonantly rings up when the charged, 44,000 pF, 12 kV capacitor bank is placed across the magnet. As the magnet approaches peak current at 1/4 cycle (1 µs) into the sinusoidal ring, magnet voltage approaches zero crossing. At this point the 1N5603 diode stack forward biases, placing the 22,000 µF low-voltage sustaining current capacitors across the magnet. The magnet and capacitors then discharge as a simple RC combination with $\tau = 3$ ms time constant. Circuit construction utilizes 22 paralleled 2000 pF, 12 kV plastic capacitors for the high-voltage capacitors and four 5500 µF, 250 V capacitors for the low voltage bank, allowing considerable flexibility in adjusting rise/decay times for different magnet loads. High- and low-voltage capacitors must be charged in a certain ratio, with a low-voltage offset added for diode forward drop. Tracking is handled by an analog charge programming circuit, adjusted for optimum high-to-low-voltage transition (Fig. 3).

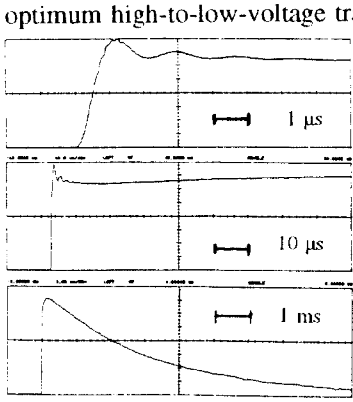

Fig. 3 Pulsed supply current (into quadrupole)

The ignitron approach gives timing jitter of the order of 200 ns over several dozen pulses (and total system delay of about 2 µs). Jitter is not as good as with thyratrons but (with Cooler ring single-bunch orbit time of 1 µs at 45 MeV) acceptable. Peak ratings for the GL-7703, at 100 kA and 25 kV, far exceed figures for thyratrons of comparable price. Tube robustness and simplicity is another advantage of the ignitron approach, improving reliability by eliminating costly precision filament supplies and reservoir heaters.

Present limitations on higher current performance for the supply/magnet system come from the 1N5603 high-voltage diodes. Extensive testing with $\tau = 3$ ms has set a peak pulse current rating of 500 A as an upper limit.

For low-current, low-frequency work a bipolar 20 A power supply is used. Measurements on stainless steel beampipe of 0.23 cm wall thickness gives an upper -3 dB rolloff at 1.2 kHz [4], allowing modulation studies [5] at these low frequencies.

IV. MAGNET MODELING AND MAPPING

The Panofsky design makes use of conductor images appearing in the ferrite such that, with proper geometry, a symmetrical, infinitely repeating arrangement of current carrying conductors effectively exists. As conductor symmetry is critical in establishing imaging and desired field uniformity,

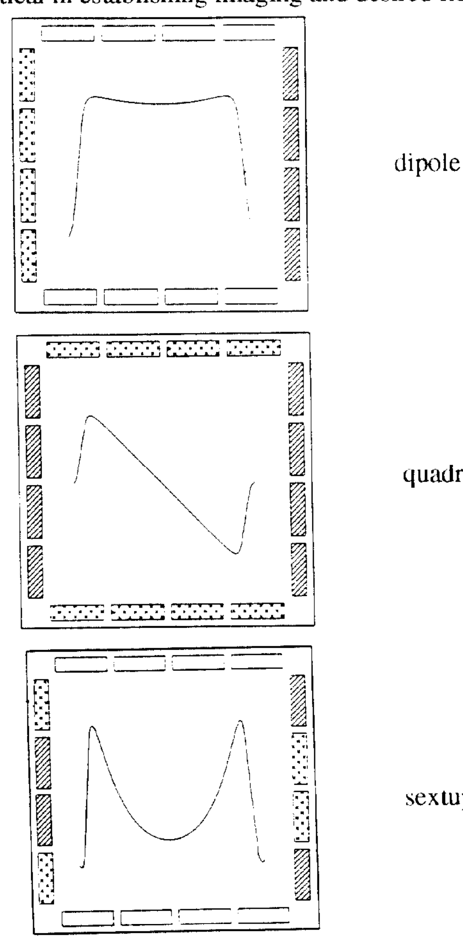

Fig. 4 Magnet multipole configurations ($B_y(x)$)

minor misalignments create error multipoles. Although, in principle, single sheet conductors along the ferrite walls could be used to establish field, in practice this has the disadvantages of requiring high currents and causing non-uniform current distribution during short current risetimes. After evaluating supply requirements and mechanical complexity, the compromise of 4 conductors/side was chosen. As seen in Fig. 1, mechanical details prevent the 8 corner conductors from being placed symmetrically with respect to the ferrite (the conductor-ferrite edge gap should be half the conductor-conductor edge gap). This creates, in the dipole example of Fig. 4, about a 6% sextupole component on top of the dipole field. To correct this effect we evaluated the addition of small corrector windings in the corners; optimum results were obtained by making corrector winding current 1/4 of main conductor current, shown in Fig. 5.

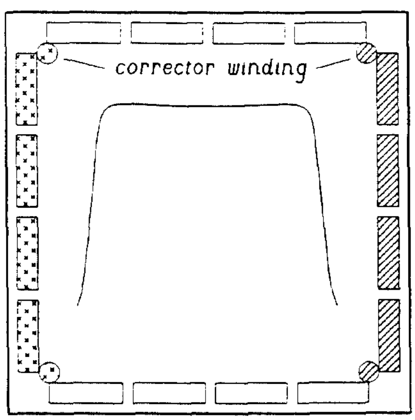

Fig. 5 Dipole with symmetry corrector windings

We used the POISSON modeling code to evaluate DC performance; figure 4 shows dipole, quadrupole, and sextupole results. To establish DC field maps we ran the magnet at its temperature-rise-limited rating of 175 A, with figure 6 showing

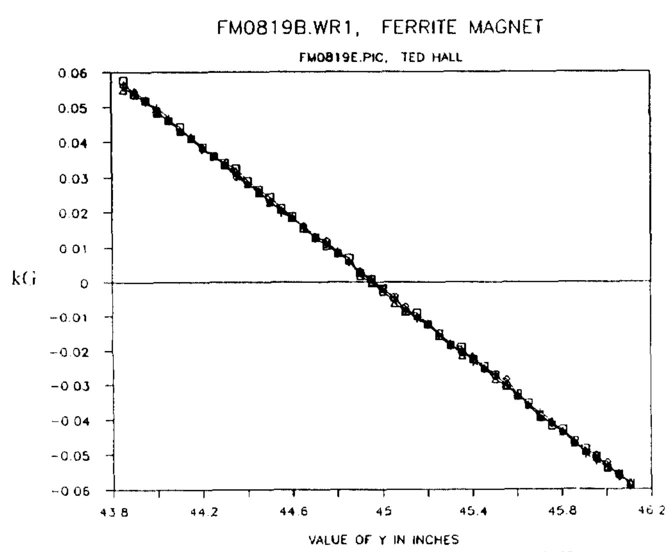

Fig. 6 Quadrupole DC map data (horizontal scan)

good quadrupole field linearity. Four passes smoothed out the mapper data, which is running at about the hardware noise floor here. The 0.19 T/m gradient matched the POISSON result; at a 500 A supply limit this gives 0.5 T/m.

To evaluate pulsed performance, a pickup loop and passive RC integrator was employed to observe the B field pulse leading edge. Figure 7 shows quadrupole results, indicating excellent linearity across the aperture.

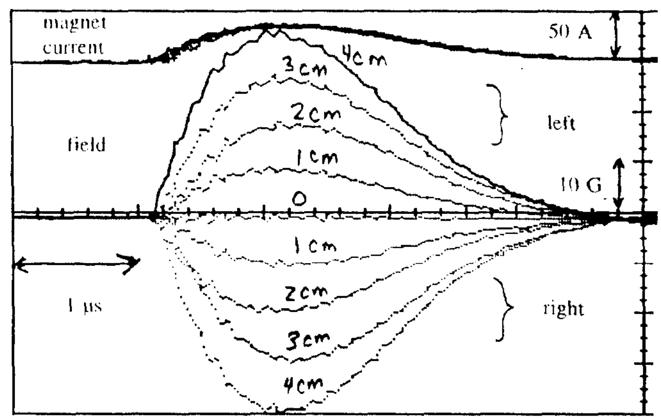

Fig. 7 Quadrupole pulsed field map (horizontal scan)

V. Results and Further Plans

The magnet has been successfully used as both dipole and quadrupole. For low-frequency work the magnet is inserted around normal 0.23 cm wall thickness stainless steel beampipe. High speed pulsed runs require insertion around a 7.6 cm diameter ceramic beampipe. Future work may employ the magnet in quadrupole mode which, in conjunction with a fast kicker, would allow beam echo studies.

VI. Acknowledgements

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VII. References

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