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PRINTED-CIRCUIT STEERING COILS*

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Summary

Beam steering coils utilizing "turns" etched on printed-circuit boards have been constructed and tested. This approach offers an economical method for achieving high-quality, compact steering coils. The circuit-boards are rolled into a cylinder and inserted inside a short steel tube. Boards for vertical and horizontal steering are located in separate layers. For our application, three coil sizes were constructed with inside diameters of 25 cm. 20.6 cm, and 17.3 cm respectively. Active length is 0.6 of the inside diameter in all cases. The coils produce an integrated deflection field in either the vertical or horizontal direction of ~ 316 Gauss-cm when excited with 5 A at ~ 30V. The conductor pattern on the circuit-board was designed to produce a nearly uniform angular deflection for all rays transmitted, in spite of the short length/diameter ratio. The magnetic field integrated over a length of 152 cm was measured at several radii and azimuths. Values at 0.4 and 0.8 of bore radius were within ~ 0.5% and ~ 1.5% respectively of the central value. Suggestions for further refinement of deflection uniformity are presented.

Conductor Pattern

For small-angle steering in absence of iron, only currents in the beam direction contribute to net angular steering. If the current distribution on a cylindrical shell (Fig. 1) satisfies

$$\int \frac{\partial i}{\partial \theta}\, dz \propto \cos\theta \qquad (1)$$

then steering is uniform for all rays at any x or y.

The conductor patterns for the ERA 4 MeV Injector[1] steering coils, shown in Figure 2, are applied to opposite sides of a printed-circuit board. The two sides are connected series-aiding by a soldered connection through the board at the center of each "spiral". The selected rectangular conductor array has uniform pitch p of the θ-going conductors, is an easy pattern to lay out, and is a satisfactory choice for short ℓ/a ratio. To satisfy (1), the z-θ conductor corner follows the curve

$$z = (\ell/2)\{1 \pm 2 \sin[(90^\circ - \theta)/2]\} \qquad (2)$$

The extra half-pitch length of some z-conductors is offset by a missing half-pitch on the reverse side of the board. "Spikes" were added at corners to try to discourage current from shortcutting the assumed rectangular path. The theoretical integrated steering field (G-cm) of this arrangement in free space is

$$\int_{-\infty}^{\infty} B_y\, dz = \pi\, I\, \ell^2/20\, ap \qquad (3)$$

If the conductors are placed inside a close-fitting iron shell of high permeability, image currents approximately double the steering strength given by (3).

Steering Coil Construction

A total of 16 steering coil assemblies of three different sizes have been built. The components of one assembly are shown in Figure 3. Circuit boards have .004" copper on both sides of .008" insulation laminate. Two boards are used for x-steering and two for y-steering. 0.016" insulation sheet is used between boards. Total radial thickness of boards and insulation is ~ .160". All boards and insulation were bonded with epoxy to provide mechanical integrity and thermal conduction to the water-cooled iron shell. The same pattern was used for all boards with photo-reduction, giving the correct circumference for each board. Principal parameters are:

Bore I.D.	17.3	20.6	25.0	cm
Effective length, ℓ,	10.5	12.5	15.1	cm
Iron length	11.4	13.3	15.9	cm
Resistance/circuit	6.0	6.0	6.0	Ω
Current I (Rated)	5.0	5.0	5.0	A.
$\int B_y dz$, calc.	330	330	330	G-cm

Current of 10 A. appears feasible, if desired. Use of the same pattern (reduced) results in equal resistance and equal integrated field for all sizes, which simplifies power supply requirements.

Magnet Measurements

Transverse magnetic fields, integrated over a length of 152 cm, were measured. The $\int Bdz$ on axis was 316 G-cm (96% of calculated). The field integral at 40% and 80% of bore radius deviated less than 0.5% and 1.5% respectively from the central value. The field integral was lower near the magnet poles ($\theta = \pm 90^\circ$, center of spiral) and higher 90° away. This field quality satisfies our needs. We suspect foregoing modest errors are attributable to the current pattern at the z-θ conductor corners. Improved uniformity should result from more refined study of these corner effects and/or revising the conductor spacing to compensate for the measured errors.

References

1. W. Chupp et al, "The ERA 4 MeV Injector", 1971 Particle Accelerator Conference Paper G-9.

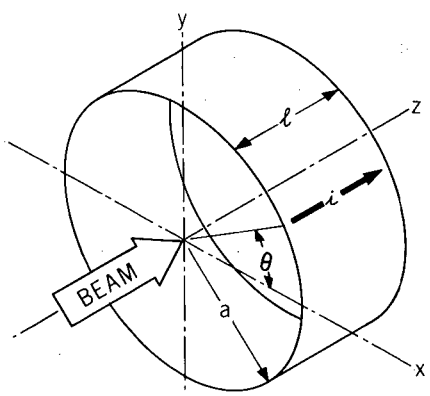

Figure 1. Steering current on cylindrical shell.

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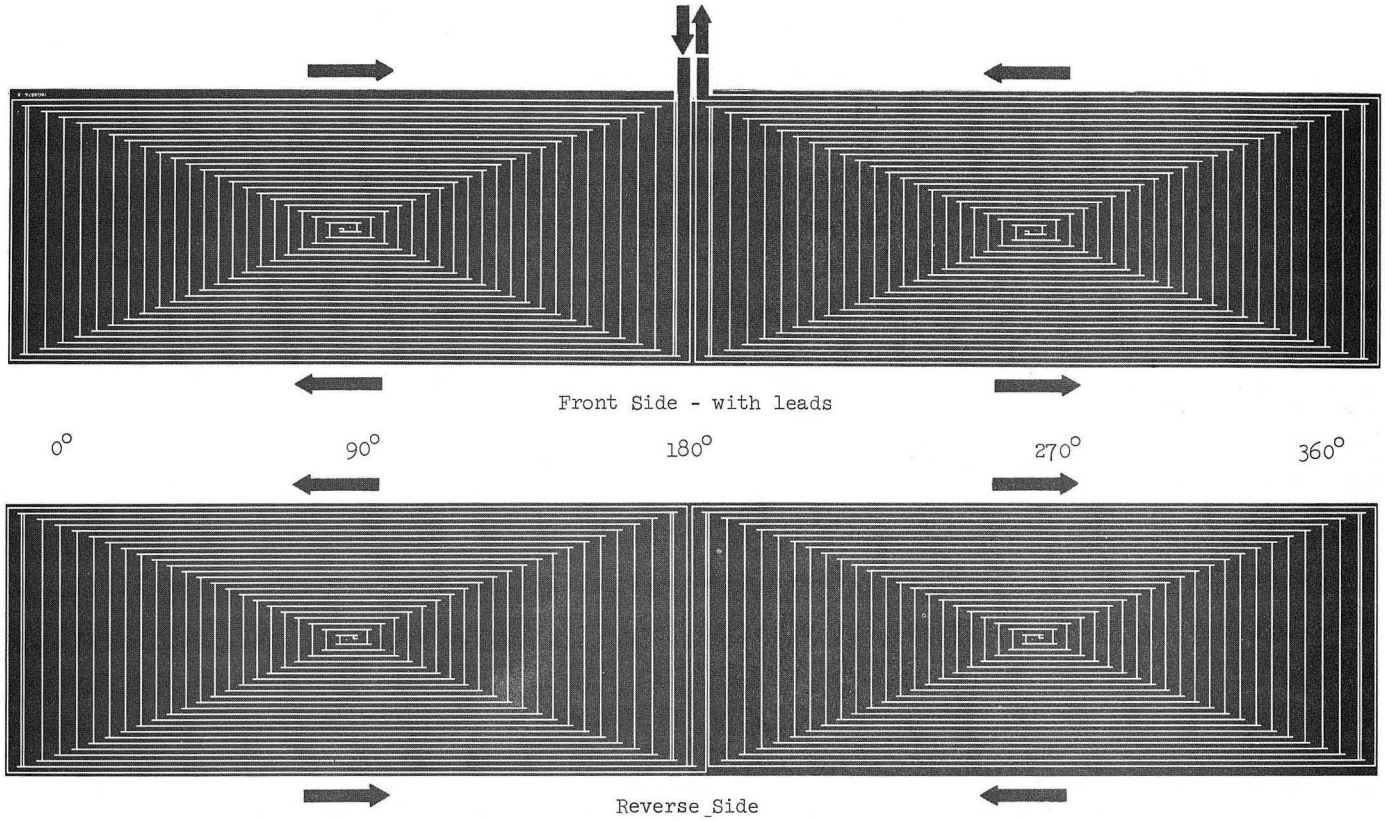

Figure 2. Conductor pattern for front and reverse sides of circuit board. Dark areas are copper. Light areas are insulation. Arrows show direction of current flow. Solder connection through board at center of each spiral.

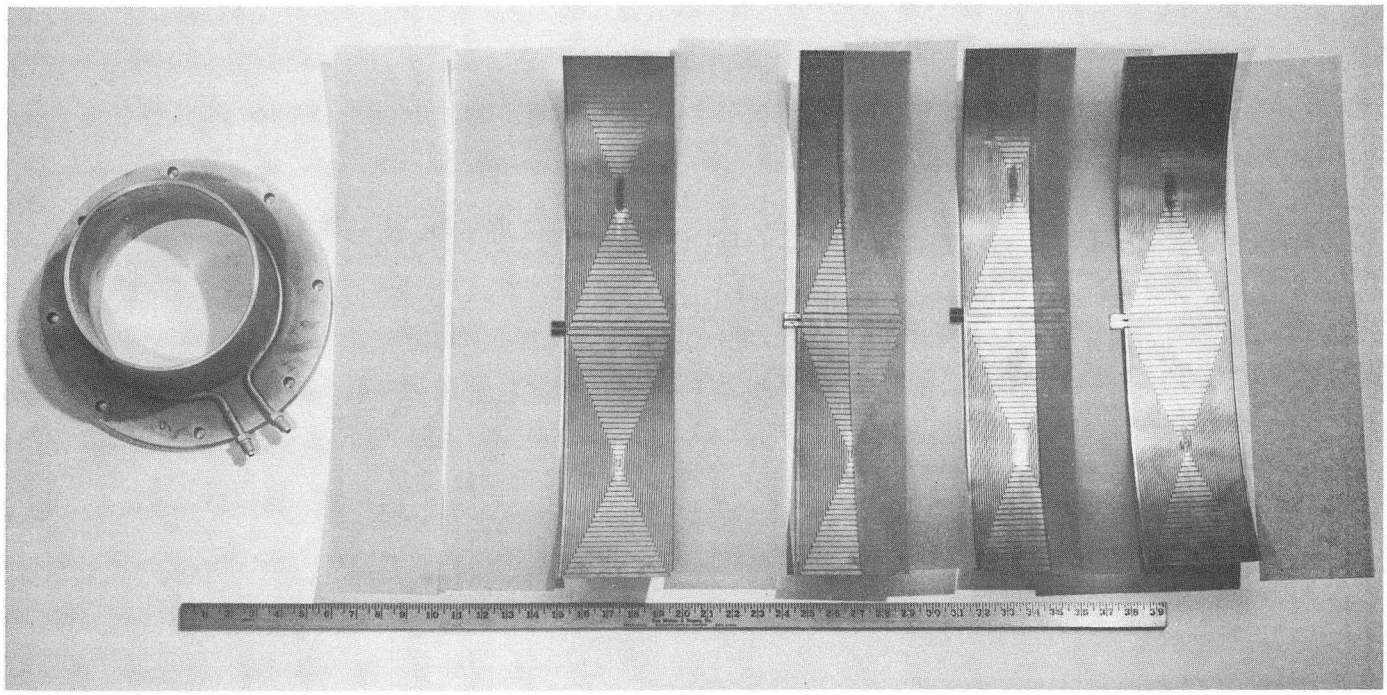

Figure 3. Component parts prior to assembly showing water-cooled iron shell, insulation sheets and printed-circuit "steering" boards.

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