THE RESONANT EXTRACTION MAGNET AT THE ZERO GRADIENT SYNCHROTRON*

L. G. Ratner, R. J. Lari, J. A. Bywater, E. C. Berrill
Argonne National Laboratory
Argonne, Illinois

Abstract

A sextupole field over ±5 in. was required for resonant extraction at the Zero Gradient Synchrotron (ZGS). The desired maximum product of effective length times d^2B/dx^2 was 1.0 kG-ft/in.^{2}. In addition, this parabolic shaped field was made adjustable with the addition of a dipole coil, so as to translate the whole parabola up or down. The magnet was designed as a "C" frame magnet of clear aperture 5.5 in. high by 32 in. wide to match the vacuum chamber dimensions of the ZGS.

This paper describes the utilization of the computer program TRIM to determine the steel and copper configuration. In addition, the mechanical/electrical design and actual magnetic measurements of the completed magnet are presented.

Conceptual Design of the Steel and Copper Geometry

A "C" frame magnet with pole face coils was chosen for this design over the conventional six-pole sextupole magnet because of the clear aperture dimensions of 5.5 in. high by 32 in. wide. The sextupole field can be produced by a linear current distribution as shown in Fig. 1. The "stair-step" coil approximates the relation

$$NI = kx \qquad (1)$$

and is formed by keeping I fixed and increasing N with x. Since this coil produces a parabolic shaped field, it is called the "parabolic" coil. The "main" coil current distribution produces a uniform field as shown in Fig. 2. This field was calculated using the computer program TRIM. From Fig. 2, it is seen that the useful width of the parabolic field is about ±3 in. for a parabolic coil ±6 in. wide. Hence, the coil should extend to ±10 in. if the useful parabolic field is to be ±5 in. Also from Fig. 2, it is seen that the main coil field is uniform over ±11 in. or about ±0.75 of the distance to the main coil. Hence, the main coil should start at a distance greater than 6.7 in. from the center to produce a uniform field over ±5 in. A coil configuration satisfying these conditions is shown in Fig. 3. It is to be noted that the main and parabolic coils overlap from 7.5 to 10.5 in. in order to minimize the ampere turns of each coil and maximize the useful flux produced by the coils. The calculated field and gradient for a gap height of 6.0 in., length of 20 in., and $\ell_0 \ddot{B}$ of 1.0 kG-ft/in.^{2} are given in Figs. 4 and 5. About 21% of the total flux is now in the useful region of ±5 in. Figure 6 shows the flux lines for this magnet. The average flux density in the yoke is 12 kG and is as large as 24 kG on the pole face.

Mechanical and Electrical Design

The final design of the magnet was changed from the computer design in that the gap was made 6.5 in. and the length increased to 30 in. to reduce the current and field values. The magnet cross section dimensions and coil placement are shown in Fig. 7.

The core was fabricated from Armco M-22 cold rolled 24-gage (0.025 in.) electrical steel with core plate C-4 insulation. Three different lengths of 10-in. wide sheet were used for each layer during stacking. The joint between sheets of the three lengths was alternated in every other layer to form an interlocking "C" core as shown in Fig. 7. Machined end plates of 5/8-in. AISI-1020 steel were used to aid in compressing the laminations uniformly. After stacking sufficient layers of laminations to provide a 30-in. overall core length, 18 tie rods 5/8-in. diam were inserted through the core. The tie rods were tightened to provide a 60-psi clamping pressure on the lamination surfaces.

The stacked core was vacuum impregnated with epoxy resin for mechanical stability and also to reduce outgassing, as this magnet is placed within a ZGS straight section vacuum box. After impregnation, 0.010-in. thick stainless steel sheets were bonded to the outside laminated surfaces to further aid in reducing the outgassing rate.

The coil assembly consists of two coils, a top and bottom, the bottom coil being a mirror image of the top coil. Figure 3 shows the cross section through one-half of the top coil. Table I summarizes the operating characteristics of the coil assembly.

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TABLE I. Coil Operating Characteristics

	Main Coil	Parabolic Coil
Current	1800 A	1500 A (Per Coil)
Voltage	105 V	111 V
Resistance	0.05808 Ω (Series Aiding)	0.037 Ω (Parallel Connection)
Inductance	1997.9 μH	532.3 μH
No. Turns	24	74
Conductor Size	0.230 in.^{2}	0.230 in.^{2}
Cooling Hole Diam	0.128 in.	0.128 in.
Copper Area	0.03838 in.^{2}	0.03838 in.^{2}
Current Density	46,900 A/in.^{2}	39,100 A/in.^{2}
Temperature Rise	8°F*	12°F**
Water Pressure Drop	140 psi	140 psi

*100-msec rise, 100-msec flattop, 3-sec repetition rate
**150-msec rise, 100-msec flattop, 3-sec repetition rate

Each coil consists of two independent windings: the 12-turn main coil winding and the 37-turn parabolic coil winding, each with its own power leads. The turn-to-turn insulation consists of 0.004-in. by 0.50-in. wide Kapton[1] H film tape applied half lapped. After taping, the turns were wound on a metal form. The required turn spacing was maintained by inserting NEMA Grade G-10 fiberglass blocks as required. In order to keep the water temperature rise to acceptable limits; i.e., 60°F maximum for a 25% duty cycle, multiple water circuits were provided by center taps built into the coil at the terminal end. Thirty water circuits were provided, 6 for the main coil winding and 24 for the parabolic coil winding.

After forming a coil, the windings were saturated with epoxy resin and then wrapped with two servings of the 0.004-in. Kapton H film tape, each serving applied half lapped. The resin formulation used was

Shell Epon 828	100 parts
Jones Dabney Epi-Cure 841	30 parts
Shell PGE	15 parts

The straight sections of the coil (through the gap) were clamped between flat plates and the upturn ends wrapped with Mylar shrink tape before oven curing the epoxy resin for 6 h at 150°C. The coils were assembled with the core and clamped against the pole faces of the magnet. Power terminals provided for various series or parallel connecting arrangements of the main and parabolic coils. The top and bottom main coils were connected in series and the parabolic coils in parallel, each energized from separate pulsed power supplies.

Water headers were made from NEMA Grade G-10 fiberglass blocks. The coil water circuits were run from the coil to the headers using copper tubing. The connection to the header was made with standard "O" ring type vacuum fittings. The headers provided the necessary electrical break between the coil and the water supply system.

Magnetic Field Measurements

The magnet was measured using a long search coil (105.5 in. long by 0.25 in. wide) connected to an electronic integrator, A-to-D converter, and read on-line into a small scale computer. The measurements system has been described in the past proceedings of this conference.[2,3,4] Measurements were made of the total $\int Bdl$ (using the long coil) for three cases, parabolic coil only, main coil only, and both coils simultaneously. The family of field shapes for the parabolic coil is shown in Fig. 8 and those for the main coil in Fig. 10. As previously mentioned, the parabolic field shape can be translated up and down. For a given current on the parabolic coil, a main coil current can be found which will cause the field along the center of the magnet to be zero. One typical operating case is shown in Fig. 9 where both coils are energized. The parabolic field shape in the region $-4 < x < +4$ is given by the expression:

$$\int Bdl = 3599.8\,(x+0.193)^2 \qquad \text{(G-in.)} \qquad (2)$$

where x is in inches. This expression was obtained by a least squares polynomial fit to the measured values.

The second derivative of this expression is

$$\frac{d^2 \int B dl}{dx^2} = 7200 \frac{\text{G-in.}}{\text{in.}^2} = 0.6 \frac{\text{kG-ft}}{\text{in.}^2} \qquad (3)$$

which is the actual operating conditions used during extraction.

Summary and Conclusions

It has been shown that an adjustable sextupole field over ±5 in. can be achieved with the use of pole face coils. The parabolic coil has a linear current distribution, and the dipole coil approximates a current sheet. Magnetic field measurements agree with the scaled computer calculations. The resonant extraction magnet described in this paper was installed in the ZGS in June, 1970 and has been successfully used to obtain up to 70% efficiency in extracting the proton beam.[5]

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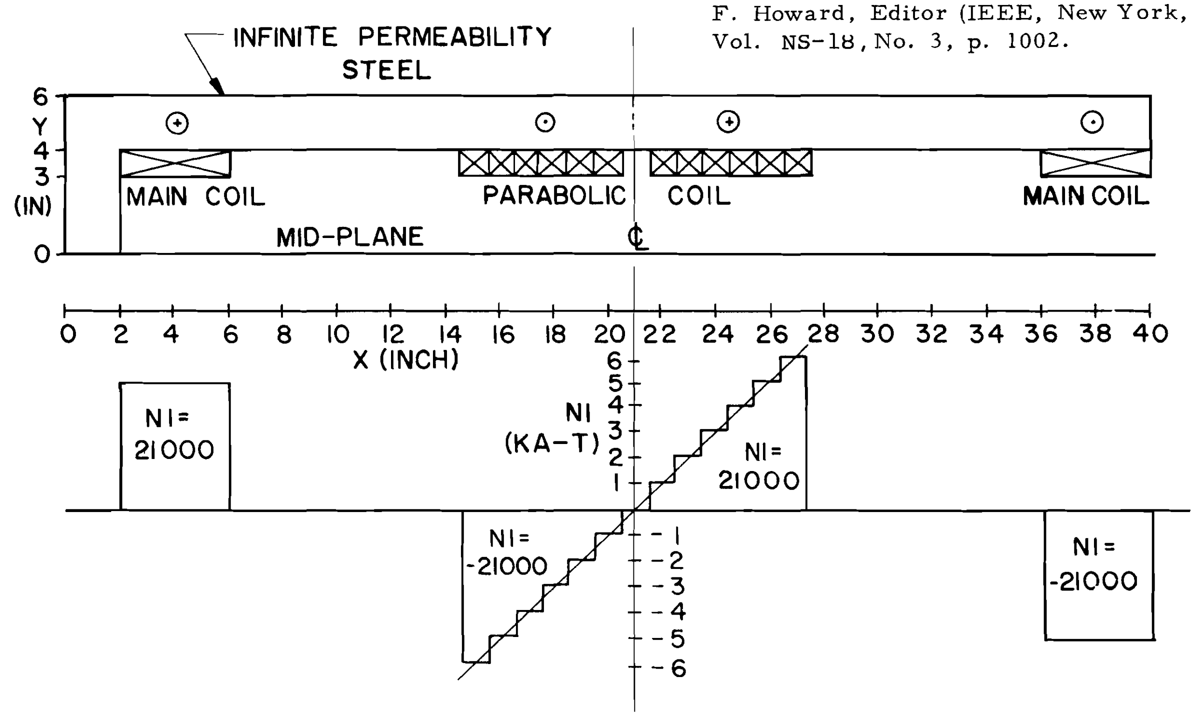


FIGURE I. PRELIMINARY MAGNET DESIGN

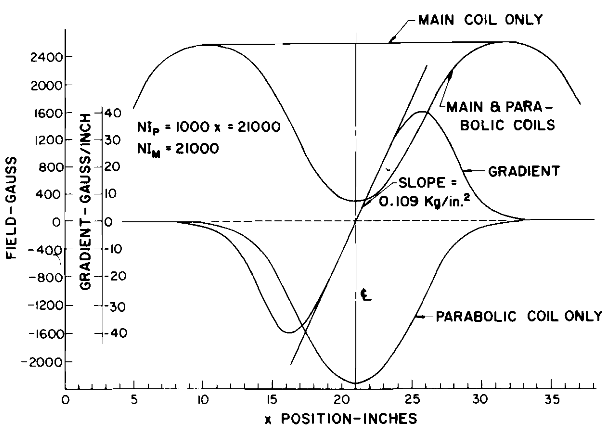


FIGURE 2. FIELD AND GRADIENT vs. POSITION

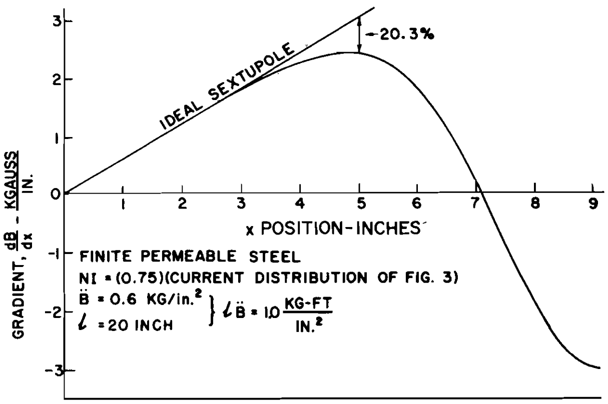


FIGURE 5.
GRADIENT vs. POSITION

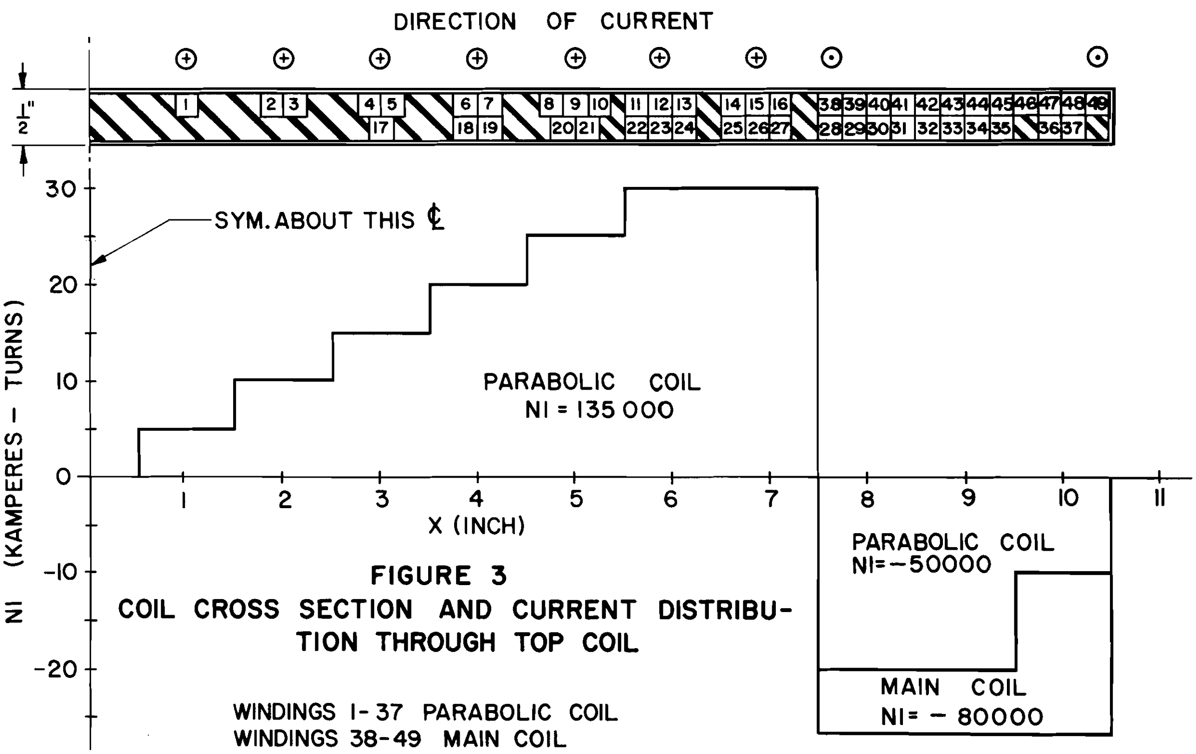


FIGURE 3
COIL CROSS SECTION AND CURRENT DISTRIBUTION THROUGH TOP COIL

WINDINGS 1-37 PARABOLIC COIL
WINDINGS 38-49 MAIN COIL

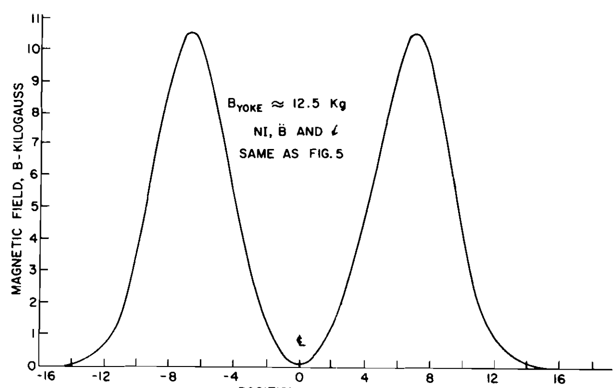


FIGURE 4. MIDPLANE FIELD vs. POSITION

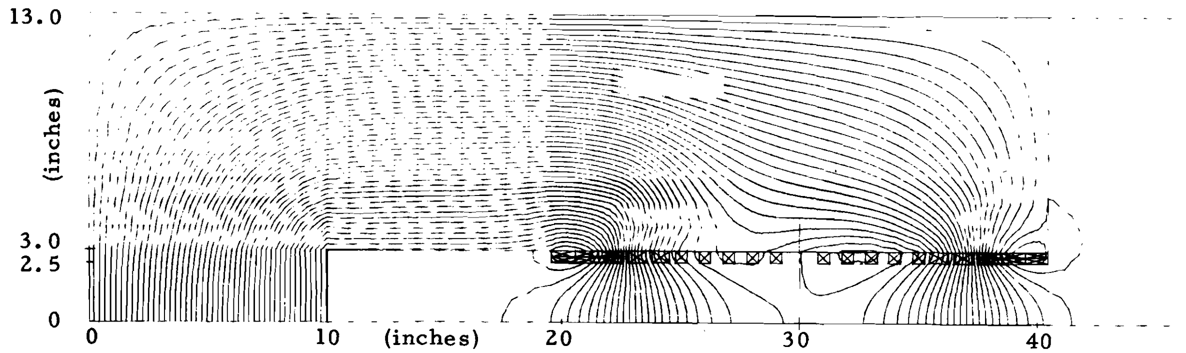


FIGURE 6. FLUX LINES

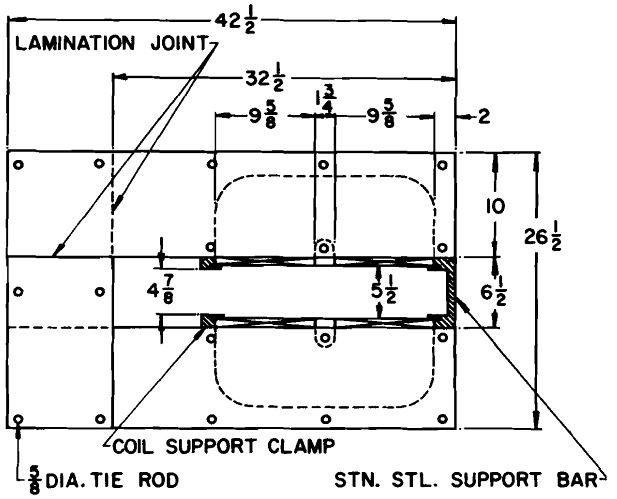
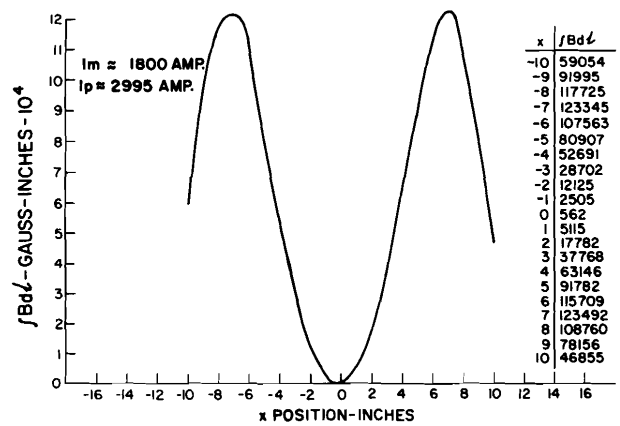


FIGURE 7. CROSS SECTION THROUGH MAGNET



x	∫Bdℓ
-10	59054
-9	91995
-8	117725
-7	123345
-6	107563
-5	80907
-4	52691
-3	28702
-2	12125
-1	2505
0	562
1	5115
2	17782
3	37768
4	63146
5	91782
6	115709
7	123492
8	108760
9	78156
10	46855

FIGURE 9

MAIN AND PARABOLIC COIL FIELD, ∫Bdℓ vs. POSITION

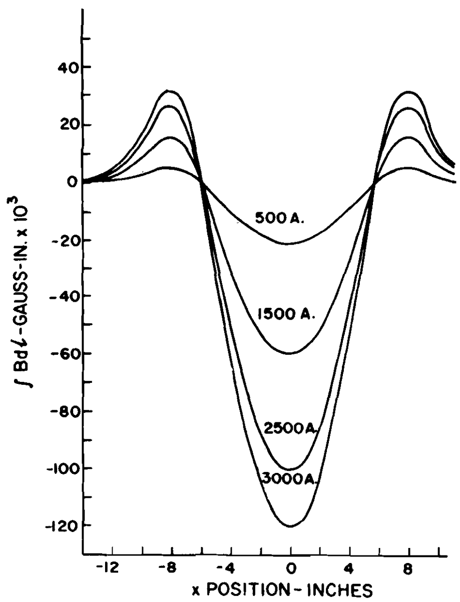


FIGURE 8. PARABOLIC COIL ONLY FIELD, ∫Bdℓ vs. POSITION

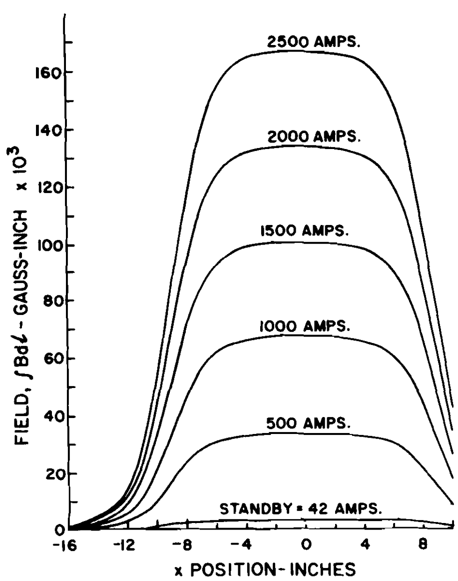


FIGURE 10. MAIN COIL ONLY - FIELD, ∫Bdℓ vs. POSITION