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Author GM Stinson		*Page* 1 *of* 22
Subject A simple 6-in. x-y steerer for the DRAGON facility		

1. Introduction

Steering magnets that are capable of steering in each of the horizontal (x) and vertical (y) directions are required for both the ISAC DRAGON facility and the MEBT line that transports beam from the RFQ and matches it into the DTL of the accelerator system. In both cases space is at a premium; however, the space problem is much more acute in the MEBT.

In 1985 A. Otter designed an x-y steering magnet for HERA[1]. More recently, TRIUMF has received x-y steering magnets from AECL. The problem with both of these designs lies in their overall lengths—that is, the iron length plus two coil thicknesses—together with the $\int B\,dl$ (≈10,000 G-cm) that is required. These make either design unsuitable even with a reduced iron length.

This note presents conceptual designs—all variations on a theme—for a 6-in. x-y steering magnet that might be suitable for the DRAGON facility. Should one of these designs prove feasible, a similar design for the MEBT line will be made.

2. A review of the previous designs for x-y steering magnets

Figure 1 shows cross-sections of the HERA design of Otter and that of the AECL magnets.

Note: The dimensions shown in figure 1 were taken by the author from drawings in the case of the HERA magnet and from measurement in the case of the AECL magnets. Consequently, any dimensions and profiles should be regarded as approximations only. The author is solely responsible for any incorrect parameters shown in this figure.

The HERA steering magnet is compact and is designed to fit closely around the beam pipe. In measurements of the completed magnets it was found that the effective length of a magnet could be expressed as

$$L_{eff} \;=\; L_{iron} \;+\; k\,(G \;+\; 2\,W)$$

where L_{eff} is the effective length of the magnet, L_{iron} is its (longitudinal) length, G is its air gap, W is the thickness of its coil and k is a multiplying constant. For the HERA magnets k was found to have a value of $k \;=\; 0.76$ for $L_{eff} = 37.5$ cm, $L_{iron} = 25$ cm, $G = 11$ cm and $W = 2.75$ cm.

Because data for the AECL steering magnets was not available, D. Evans and B. Keeley were asked to do a quick, hand-measured $B\,I$ curve and longitudinal and transverse scans along the respective centerlines of one of the magnets. Their data[2] for the $B\,I$ curve and the transverse scan is shown in figure 2; that for the longitudinal scan and the resulting $\int B\,dl$ curve, obtained by the author using PLOTDATA[3], is shown in figure 3. From the latter we find for a maximum measured field of 428 Gauss at a current of 5 Amperes

$$L_{eff}(\text{AECL}) \;=\; \frac{\int B\,dl}{B_{max}} \;=\; \frac{10{,}705\ \text{G-cm}}{428\ \text{G}} \;=\; 25.01\ \text{cm} \;=\; 9.847\ \text{in.}$$

On the assumption that the prescription of Otter is equally valid for these magnets and using the values $L_{iron}(\text{AECL}) = 5.00$ in. and $(G + 2\,W)_{AECL} = 7.00$ in., we find that

$$k_{AECL} \;=\; \frac{L_{eff}(\text{AECL}) \;-\; L_{iron}(\text{AECL})}{(G \;+\; 2\,W)_{AECL}} \;=\; \frac{9.847\ \text{in.} \;-\; 5.00\ \text{in.}}{7.00\ \text{in.}} \;=\; 0.69.$$

It is seen that these two values of k are in reasonable agreement. Because the basic design presented here

is closer to the AECL design than the HERA design, in what follows we shall use a value of $k = 0.70$.

3. Proposed design parameters for the basic steering magnet

As previously noted the major draw-back of the HERA and AECL steering magnets is their insertion length. In each case the coil thickness contributes considerably to the overall length of the magnet.

Each of the above magnets uses air-cooled, solid conductor. Otter notes that if the HERA magnets are on fully, the magnet gets very hot. Similarly, in the mapping of the AECL magnet at its maximum rated current of 5 A the magnet became uncomfortable to touch because of the heat generated. Consequently, it is proposed to use hollow, water-cooled conductor in the design presented here. It is realized that this complicates somewhat the magnet design but the use of a small conductor with a curren t-carrying capacity will make a magnet of shorter overall dimensions.

It is proposed to use 0.1620 in-square, hollow conductor for the coil. The properties of this conductor are listed in Anaconda data sheets as follows.

Outer dimension	0.1620 in. (square)
Inner diameter	0.0900 in. (circular)
Copper area	0.01934 in.^{2}
Cooling area	0.006362 in.^{2}
Weight	0.07473 lb/ft
Resistance at 20°C	421.1×10^{-6} Ω/ft
k factor (British units)	0.0622

For the purposes of this report we allow an overwrap of two layers of 0.007 in.-thick insulation and an additional 0.010 in. for keystoning and interturn spacing. Thus we consider the overall dimension of a wrapped conductor to be 0.200 in.

Having chosen a conductor we take the minimum bending radius to be at least four times the conductor dimension. Thus we take

$$R_{min} = 4(0.162 \text{ in.}) \approx 0.70 \text{ in.}$$

We allow 0.125 in. for insulation between the yoke and the coil so that the ends of the yoke have a radius of

$$R_{yoke} = (0.70 \text{ in.} - 0.125 \text{ in.}) = 0.575 \text{ in.}$$

Thus the thickness of the yoke becomes

$$t_{yoke} = 2\,R_{yoke} = 1.150 \text{ in.}$$

and, defining L_{str} as the length of the straight portion of the yoke, the overall yoke length becomes

$$L_{yoke} = 2\,R_{yoke} + L_{str} = (L_{str} + 1.150) \text{ in.}$$

Figure 4 shows a cross-section of the proposed basic design for the steerer. Thus, given a coil length of 5.20 in. the coil is shown to have (5.20 in./0.200 in. per coil) = 26 turns per layer or 52 turns per coil. Thus the current density in the coil is approximately 5,170 A/in.^{2} at an operating current of 100 A.

The distance between the yokes is 7.40 in. so that allowing for 0.050 in. for insulation between the coil and the yoke and a similar amount over the exterior of the coil, the clear gap of the steering magnet is

$$\text{Clear gap} = (7.400 - 4(0.050 + 0.200)) = 6.40 \text{ in.},$$

an amount sufficient to fit over a 6-in. diameter beam tube. The length L_{str} is to be determined; it will be chosen once given the allowed insertion length and a calculated effective length.

4. POISSON studies of the simple steering magnet

POISSON[4] studies of the simple steering magnet were undertaken with *only* the horizontal coils powered at 5,000 A-t. Shown in the upper portion of figure 5 is the predicted field distribution in the gap of this magnet. The lower portion of the figure shows the predicted variation of the field as a function of y, the distance from the midplane. (Although y values are shown as plus-or-minus values about the midplane, only positive values were plotted on the grounds that because of symmetry field deviations above and below the midplane should be identical.) For comparison, figure 6 shows similar predictions from POISSON runs for the HERA magnet at an excitation of 4,400 A-t. .

Although the upper portions of figures 5 and 6 appear to indicate that the HERA magnet is more uniform in the center region than is the simple DRAGON design considered here, examination of the lower portions of the figures indicates that such is not true. Indeed, at half-aperture [$y = \pm 1.50$ in. (± 38 mm for the HERA design)] the overall field variation from the field at the magnet center $B_{0,0}$ is $B_{DRAGON} = 354^{+18}_{-14}$ G and that for the HERA magnet is $B_{HERA} = 376^{+15}_{-9}$ G, values that are not significantly different. At two-thirds of the aperture these values increase to $B_{DRAGON} = 354^{+18}_{-23}$ G and $B_{HERA} = 376^{+15}_{-29}$ G.

Because of the possibility that a field variation of the order of 10% is unacceptable, several variations of the design of the simple magnet were studied. All use the same conductor at an excitation of 5,000 A-t. The configurations studied are listed below.

1. An extra layer of 4 turns was added at each end of the coil so as to form a bump on each end. In addition, the pole profile was altered to provide a 2 inch wide central flat with a sloped portion that dropped 0.25 in. over a 1.0 in. distance on either side of the central flat. POISSON predictions for the field in the gap are shown in the upper portion of figure 7. The lower portion shows the predicted variation of field as a function of distance from the midplane. For this configuration the predicted variation from the central field is $B_{DRAGON} = 342^{+10}_{-9}$ G for $y = \pm 1.5$ in. and $B_{DRAGON} = 342^{+10}_{-16}$ G for $y = \pm 2.0$ in.
2. The original coil configuration was retained except for the removal of four turns at the center, thus producing a hole in the coil. The modified pole profile was kept. POISSON predictions for this modification are shown in figure 8. Here the predicted variation from the central field is $B_{DRAGON} = 344^{+11}_{-10}$ G for $y = \pm 1.5$ in. and $B_{DRAGON} = 344^{+11}_{-20}$ G for $y = \pm 2.0$ in.
3. A design incorporating a coil with both a bump and a hole as well as a modified pole geometry was investigated. The results of the POISSON study of this variation are shown in figure 9. In this case variation from the central field is found to be $B_{DRAGON} = 338^{+7}_{-7}$ G for $y = \pm 1.5$ in. and $B_{DRAGON} = 338^{+7}_{-12}$ G for $y = \pm 2.0$ in.
4. Another design that was studied consisted of variation 3 above with the addition of an extra 2-layer winding at the coil ends. Further, the bump was shifted one turn toward the end of the coil. POISSON results for this variation are shown in figure 10. Variation from the central field for this design is found to be $B_{DRAGON} = 331^{+2}_{-5}$ G for both $y = \pm 1.5$ in. and $y = \pm 2.0$ in.
5. This is identical to variation 4 *except* that the inner coils were flat rather than contoured to the yoke as in variation 4. This simplifies fabrication of the coils and, if viable, could reduce their costs. Figure 11 shows the POISSON results for this case. Variation from the central field for this design is found to be $B_{DRAGON} = 331^{+1}_{-4}$ G for $y = \pm 1.5$ in. and $B_{DRAGON} = 331^{+4}_{-4}$ G for $y = \pm 2.0$ in.

Table 1 summarizes data taken from figures 5 through 11. Listed are the predictions of POISSON for the variation of the fields from the value at the magnet center at a given distance from the midplane. Data for all of the models listed above are given.

From the data presented here it is clear that the fourth and fifth variations provides the most uniform field in the magnet gap. The uniformity of the former extends over a slightly larger region than does that of the latter. However, the fifth variation allows a simpler coil construction than does the fourth and, consequently, should be somewhat less costly to construct.

However, it must be recognized that POISSON is a two-dimensional program and thus assumes that the magnet is of infinite length. Because a short magnet is visualized it may be that none of the above predictions would be realized in practice unless a three-dimensional study were undertaken.

5. Estimation of the effective length of the steering magnet

In what follows we assume that the steering magnet is constructed as per variation 5 above. Comments made below would equally apply to a magnet fabricated according to prescription 4.

In section 2, above, it was noted that the effective length of a magnet of this design was empirically given by

$$L_{eff} \;=\; L_{iron} \;+\; k\,(G \;+\; 2\,W)$$

and a value of $k = 0.7$ was suggested. For the designs considered here, the value of $(G \;+\; 2\,W)$ was given in section 3 as 7.40 in. Consequently, we assume that the effective length of the magnet may be expressed as

$$L_{eff} \;=\; L_{iron} \;+\; 0.7(7.40) \;=\; L_{iron} \;+\; 5.18 \text{ in.}$$

We now note that the coils of either of variations 4 or 5 have 64 turns each rather than the 52 turns stated in section 3 and we recall that the POISSON runs predicted that 5,000 A-t would produce a central field of approximately 330 G. Being conservative and taking a central field value of 300 G, then it is to be expected that a 64-turn coil should produce a central field of approximately (64/52)300 G $\approx$ 370 G when run at the same current as the 52-turn coil. Consequently, to achieve the required value of

$$\int B\,dl \;=\; 10{,}000 \text{ G-cm} \;=\; 3{,}937 \text{ G-in.},$$

we require

$$\int B\,dl \;=\; 3{,}937 \text{ G-in.} \;=\; (370 \text{ G})(L_{iron} \;+\; 5.18 \text{ in.})$$

or

$$L_{iron} \;=\; \frac{3{,}937 \text{ G-in.}}{370 \text{ G}} \;-\; 5.18 \text{ in.} \;=\; 10.641 \text{ in.} \;-\; 5.18 \text{ in.} \;=\; 5.461 \text{ in.}$$

Consequently, we take the iron length of the steering magnet to be

$$\boxed{L_{iron} = 5.00 \text{ in.}}$$

and the effective length of the magnet is then estimated to be

$$\boxed{L_{eff} = L_{iron} + 5.18 \text{ in.} = 10.18 \text{ in.}}$$

6. Final design of the steering magnet

Figure 12 shows a cross-section of the final design of the steering magnet together with dimensions of the side and top yokes and of the coil. Table 2 lists the calculated parameters of the magnet. From data in this table we calculate the insertion length of the magnet to be

$$\begin{aligned} L_{insertion} &= \text{Iron length} + 2(\text{Coil-yoke clearance} + \text{Maximum coil width} + \text{Coil overwrap}) \\ &= 5.00 \text{ in.} + 2(0.050 \text{ in.} + 3(0.20 \text{ in.}) + 0.050 \text{ in.}) \\ &= 6.40 \text{ in.} \end{aligned}$$

To estimate the weight of the magnet we begin by calculating the areas of the top and side yokes. Thus

	Side yoke			Top yoke		
	Width (in.)	Height (in.)	Area (in.^{2})	Width (in.)	Height (in.)	Area (in.^{2})
Flat section	7.90	1.00	7.90	9.90	1.00	9.90
Sloped section	1.00	0.25	0.125	1.00	0.25	0.125
Sloped section	1.00	0.25	0.125	1.00	0.25	0.125
Raised section	1.60	0.25	0.40	1.60	0.25	0.40
Total area			8.55			10.55

The total area of the yokes is the $2(8.55 + 10.55)$ in.$^2 = 38.2$ in.^{2}. Using a density of iron of 0.2833 lb/in.^{3} the estimated weight of the yoke is

$$\begin{aligned} W_{iron} &= (\text{Density})(\text{Area})(\text{Length}) \\ &= (0.2833 \text{ lb/in.}^3)(38.2 \text{ in.}^2)(5.00 \text{ in.}) \\ &= 54.11 \text{ lb.} \end{aligned}$$

We take

Weight of yoke = 55 lb.

For the amount of copper needed for a coil we now assume that the radius of curvature of the yoke ends is the maximum yoke thickness plus twice the coil-yoke clearance. Thus

$$R_{coil,minimum} = 1.25 \text{ in.} + 2(0.050 \text{ in.}) = 1.35 \text{ in.}$$

Then the length per turn of the innermost winding is

$$\begin{aligned} L_{turn,inner} &= 2(L_{iron} - R_{coil,minimum}) + 2\pi R_{coil,minimum} \\ &= 2[5.00 \text{ in.} - 1.35 \text{ in.} + \pi(1.35 \text{ in.})] = 15.78 \text{ in.} \end{aligned}$$

Similarly, the length per turn of the center winding is

$$\begin{aligned} L_{turn,center} &= 2(L_{iron} - R_{coil,minimum}) + 2\pi(R_{coil,minimum} + \text{one conductor width}) \\ &= 2[5.00 \text{ in.} - 1.35 \text{ in.} + \pi(1.55 \text{ in.})] = 17.04 \text{ in.} \end{aligned}$$

and that of the outer winding is

$$\begin{aligned} L_{turn,outer} &= 2(L_{iron} - R_{coil,minimum}) + 2\pi(R_{coil,minimum} + \text{two conductor widths}) \\ &= 2[5.00 \text{ in.} - 1.35 \text{ in.} + \pi(1.75 \text{ in.})] = 18.30 \text{ in.} \end{aligned}$$

Consequently, with 30 turns in the inner coil, 26 turns in the center coil and 8 turns in the outer coil, the overall length of the coil is

$$\begin{aligned} L_{coil} &= 30(L_{turn,inner}) + 26(L_{turn,center}) + 8(L_{turn,outer}) \\ &= 30(15.78 \text{ in.}) + 26(17.04 \text{ in.}) + 8(18.30 \text{ in.}) \\ &= 1{,}062.84 \text{ in.} \end{aligned}$$

We further allow a length of $4\,L_{iron} = 20$ in. for crossovers for each of the center and outer coils and a further 10% for winding losses. Thus the amount of copper per coil is estimated to be

$$\boxed{\text{Copper length per coil} = 1{,}225 \text{ in.}}$$

At a linear density of 0.07473 lb/ft, the weight per coil is estimated to be

$$\boxed{\text{Copper weight per coil} = 7.63 \text{ lb.}}$$

and we take the weight of copper per magnet to be

$$\boxed{\text{Copper weight per magnet} = 35 \text{ lb.}}$$

The resistance at 20°C is then

$$\begin{aligned} R_{20} &= (421.1\times10^{-6}\ \Omega/\text{ft})\left[\frac{1{,}225}{12}\,\text{ft}\right] \\ &= 0.0430\ \Omega. \end{aligned}$$

Allowing a 30°C rise above ambient of the coil we have

$$\begin{aligned} R_{hot} &= R_{20C}\,[1 + (\text{Temp. coeff}/^\circ\text{C})\Delta T(^\circ C)] \\ &= 0.0430[1 + 0.00393(30)] \\ &= 0.0481\ \Omega \text{ per coil.} \end{aligned}$$

Assuming an excitation current of 100 A and a 10% lead loss, each power supply must be capable of supplying two coils in series. Thus its minimum voltage must be

$$V_{minimum} = 1.1(100\text{ A})(2(0.0481\Omega)) = 10.58\text{ V.}$$

Thus, for each of the horizontal and vertical steering magnets the minimum rating of the power supply is

$$\boxed{\begin{array}{lcl} \text{I} & = & 100.0\text{ A} \\ \text{V} & = & 11.0\text{ V minimum} \\ \text{P} & = & 1.1\text{ kW minimum} \end{array}}$$

The power dissipation per coil is

$$\text{Power per coil} = P = I^2\,R_{hot} = \frac{100^2\times0.0481}{1000} = 0.481\text{ kW.}$$

Using British units, the required flow rate of the coolant is

$$\begin{aligned} v\ (\text{ft/sec}) &= \frac{2.19}{\Delta T(^\circ\text{F})}\,\frac{P\ (\text{kW})}{\text{Cooling area (in}^2\text{)}} \\ &= 3.04167\times10^{-2}\times\frac{P\ (\text{kW})}{\text{Cooling area (in}^2\text{)}} \end{aligned}$$

for $\Delta T = 72^\circ\text{F} = 40^\circ\text{C}$. With a cooling area of 0.006362 in.^{2} and power dissipation of 0.481 kW. we have

$$v = \frac{2.19\times0.481}{72\times0.006362} = 2.30\text{ ft/sec}$$

The volume of flow required per circuit is

$$\begin{aligned} \text{Volume/circuit} &= 2.6\, v(\text{ft/min})\,[\text{Cooling area}(\text{in}^2)]\ \text{IGPM} \\ &= 3.12250\, v(\text{ft/min})\,[\text{Cooling area}(\text{in}^2)]\ \text{USGPM} \\ &= 3.12250(2.30)(0.006362) \\ &= 0.046\ \text{USGPM} \end{aligned}$$

The pressure drop per coil is given by

$$\Delta P = k\, v^{1.79}\ \text{psi/ft.}$$

With $k = 0.0622$ we have

$$\Delta P = 0.0622\times(2.30)^{1.79} = 0.276\ \text{psi/ft.}$$

Thus the pressure drop per coil is

Pressure drop per coil = (0.276 psi/ft)×(1,225 in./12 in./ft) = 28.20 psi

7. Discussion

This report has presented a study of various designs for a 6-in. x-y steering magnet for the DRAGON facility. A final design has been suggested. The design to be chosen will, of course, depend on the amount of steering that is required.

For completeness, figure 13 shows the results of a POISSON study of the proposed design with all four coils powered at 5,000 A-t per coil. Comparison of figures 11-a and 13-a shows that the predictions for the field contours are identical for each of the horizontal and vertical planes. Figure 13-b shows the fields in the yoke predicted by POISSON at the point of maximum flux concentration, in the case studied at the intersection of the right side yoke and the top yoke. For reference purposes, the center of the magnet is located at $K = L = 115$; each increment in K and L corresponds to a distance of 0.05 in. Except for a small region around the inner corner, it is seen that the predicted fields inthe y oke are less than 5 kG. Even allowing a factor of two for flux concentration because of the finite length of the magnet, a value of less than 10 kG is obtained. Consequently, a yoke constructed from mild steel could be contmplated.

References

1. A. J. Otter, *HERA – Steering Dipole*, TRIUMF Report TRI-DN-85-19, July, 1985.
2. D. Evans and B. Keeley, *Private communication*, TRIUMF, October, 1998.
3. J. L. Chuma, *PLOTDATA Command and Reference Manual*, TRIUMF Report TRI-CD-87-03b, June, 1991.
4. M. T. Menzel and H. K. Stokes, *User's Guide for the POISSON/SUPERFISH Group of Codes*, Los Alamos National Laboratory Report LA-UR-87-115, January, 1987.

Table 1

Variation of fields from values at the magnet center as a function of distance from the midplane‡

Numerical values are the fields in Gauss at the horizontal and vertical center of the magnets. The plus and minus values are the deviations from those values at $x = \pm 1.5$ inches for a given value of y.

Model	Distance (y) from midplane in inches				
	0.0	0.5	1.0	1.5	2.0
HERA	376^{+2}_{-1}	374^{+7}_{-0}	372^{+19}_{-0}	367^{+21}_{-0}	362^{+0}_{-15}
Simple DRAGON	354^{+18}_{-0}	352^{+18}_{-0}	347^{+15}_{-0}	340^{+8}_{-0}	331^{+0}_{-0}
Variation 1	342^{+10}_{-0}	341^{+10}_{-0}	338^{+7}_{-0}	333^{+4}_{-0}	329^{+0}_{-3}
Variation 2	344^{+11}_{-1}	343^{+11}_{-1}	339^{+8}_{-0}	334^{+4}_{-0}	329^{+0}_{-5}
Variation 3	338^{+7}_{-0}	337^{+4}_{-0}	335^{+7}_{-0}	333^{+3}_{-0}	330^{+0}_{-4}
Variation 4	331^{+1}_{-0}	331^{+1}_{-0}	330^{+2}_{-0}	330^{+1}_{-0}	330^{+0}_{-4}
Variation 5	331^{+0}_{-1}	331^{+0}_{-0}	330^{+2}_{-0}	330^{+2}_{-0}	330^{+0}_{-3}

‡ Excitation of the HERA magnet was 4,400 A-t; that of all others was 5,000‘A-t.

Table 2

Design parameters of the DRAGON $x - y$ steering magnet

Top yoke:	Thickness (max.)	1.25 in.
	Width	9.90 in.
	Length	5.00 in.
	Weight	14.94 lb.
Side yoke:	Thickness (max.)	1.25 in.
	Width	7.90 in.
	Length	5.00 in.
	Weight	12.11 lb.
Coil:	Conductor	0.162 in. square
	Length per coil	1,225.00 in.
	Weight per coil	7.63 lb
	Resistance (hot) per coil	0.0481 Ω
	Maximum current per coil	100.0 A
	Voltage drop per coil	4.81 V
	Power dissipation per coil	0.481 kW
	Coolant flow rate per coil	2.30 ft/sec
	Pressure drop per coil	28.20 psi
Overall magnet:	Iron weight per magnet	55.00 lb
	Copper weight per magnet (4 coils)	35.00 lb
	Total weight per magnet (4 coils)	90.00 lb
Power supply:	Maximum current	100.0 A
	Minimum voltage (2 coils in series)	11.0 V
	Minimum power (s coils in series)	1.1 kW

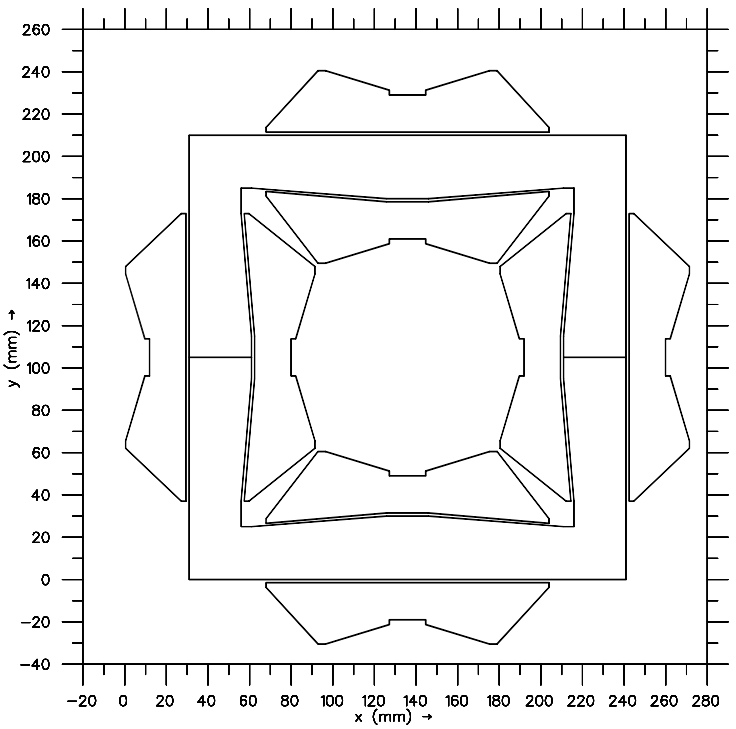

Fig. 1-a. Cross section of the HERA steering magnet of Otter.

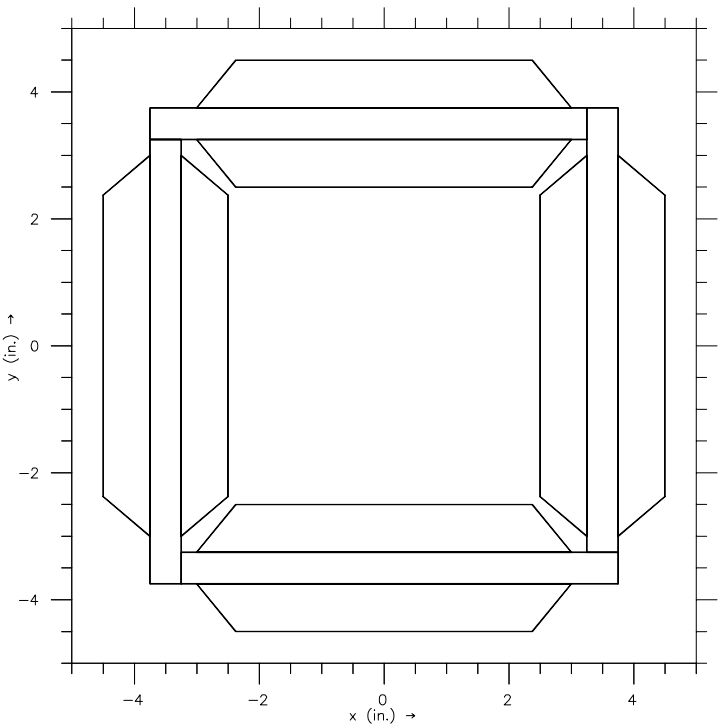

Fig. 1-b. Cross section of the AECL steering magnet.

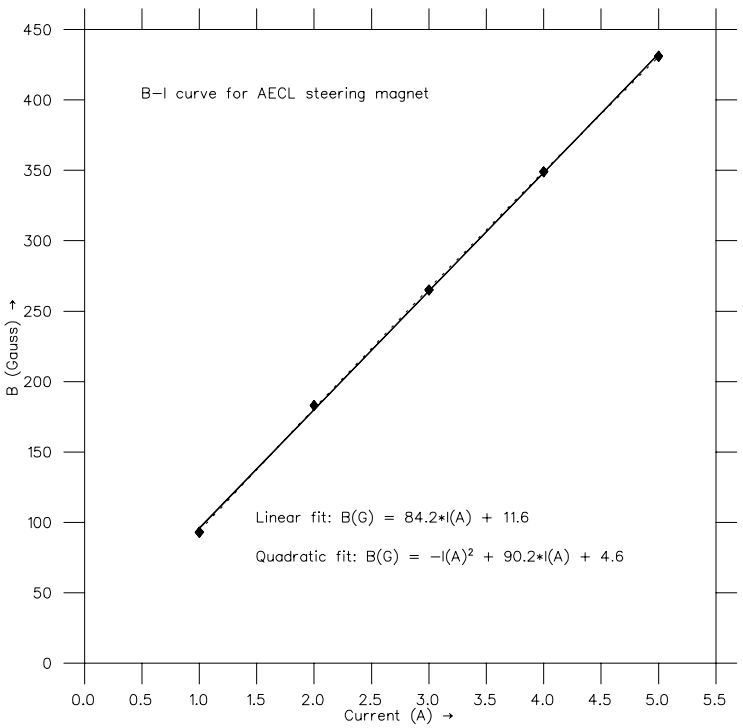

Fig. 2-a. Measured $B\,I$ curve of an AECL steering magnet.

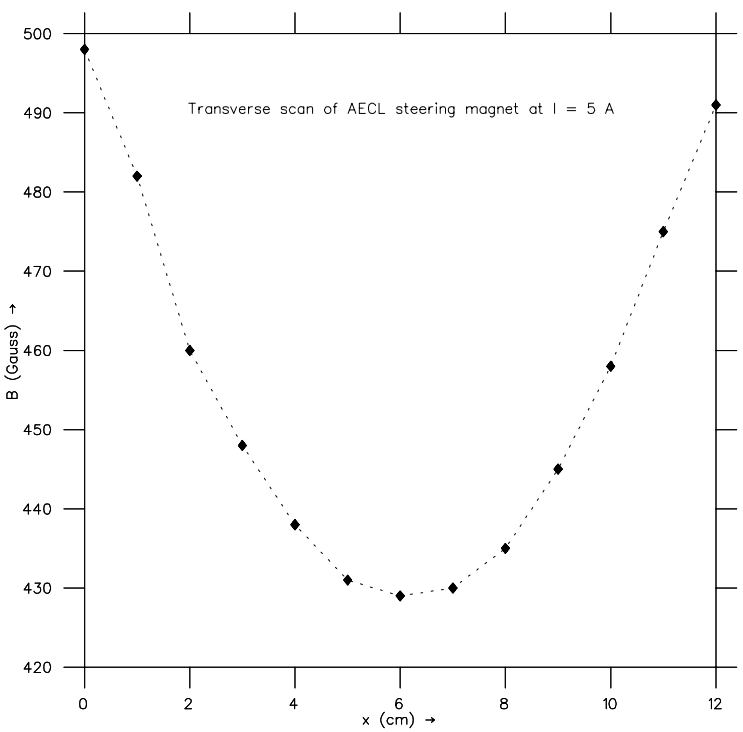

Fig. 2-b. Measured field along the transverse midplane of the AECL steering magnet.

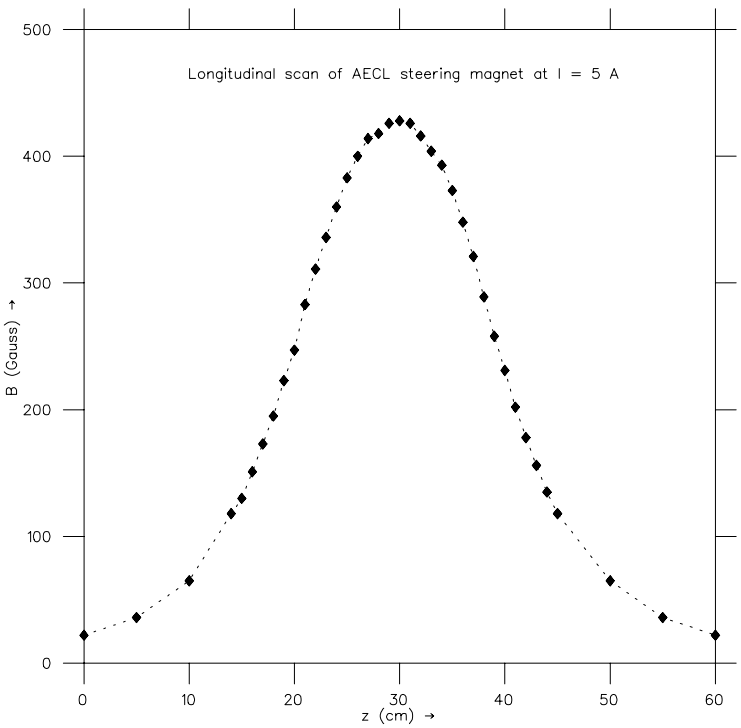

Fig. 3-a. Measured field along the longitudinal midplane of the AECL steering magnet.

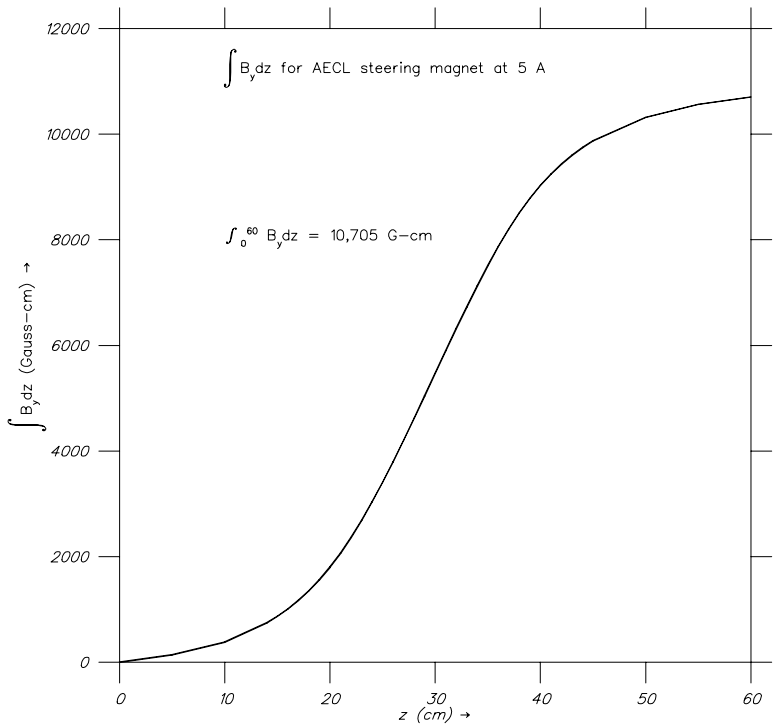

Fig. 3-b. Computed $\int B\,dl$ the transverse midplane of the AECL steering magnet.

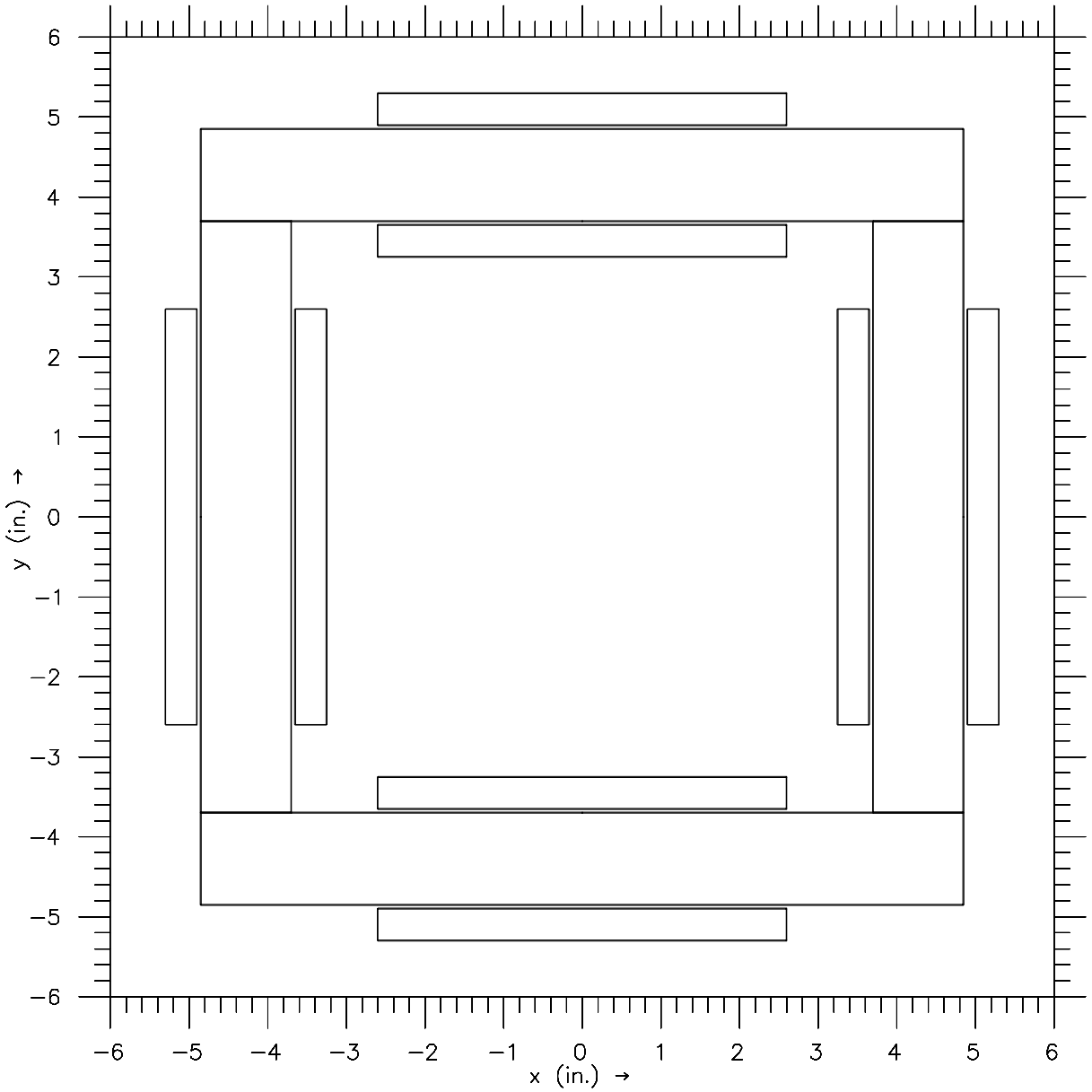

Fig. 4. The proposed design for a simple 6-in. steering magnet for the DRAGON facility.

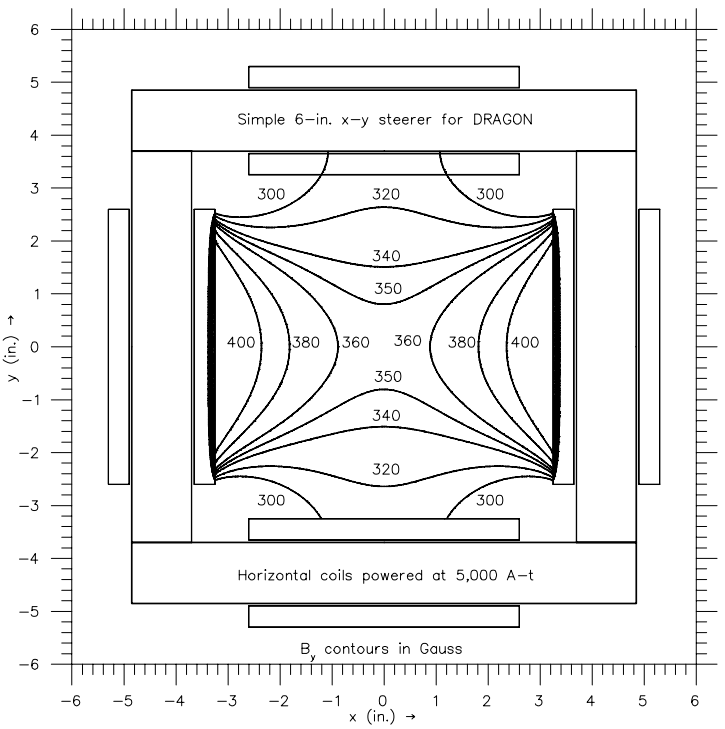

Fig. 5-a. Predicted field distribution in the gap of the simple steering magnet.

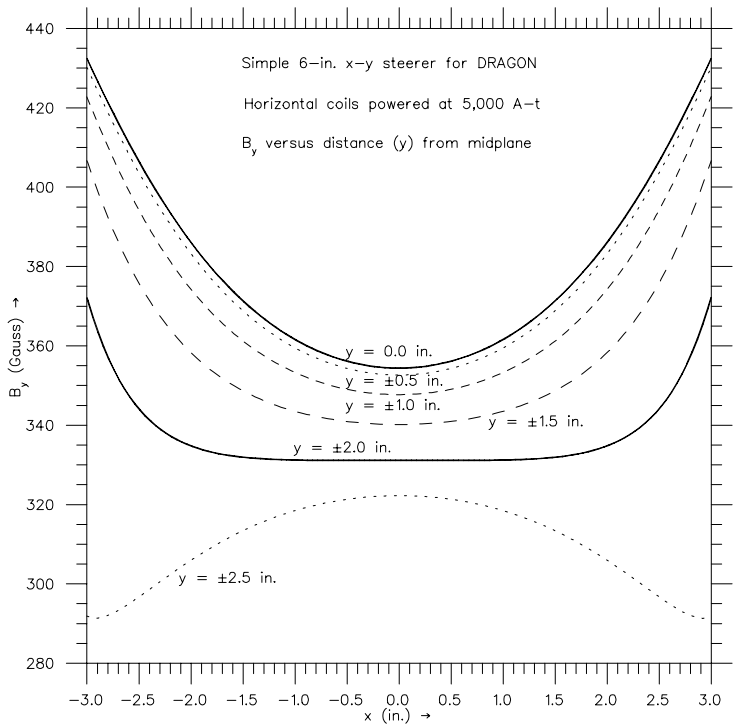

Fig. 5-b. Predicted variation of B_y as a function of distance from the mid-plane for the simple magnet.

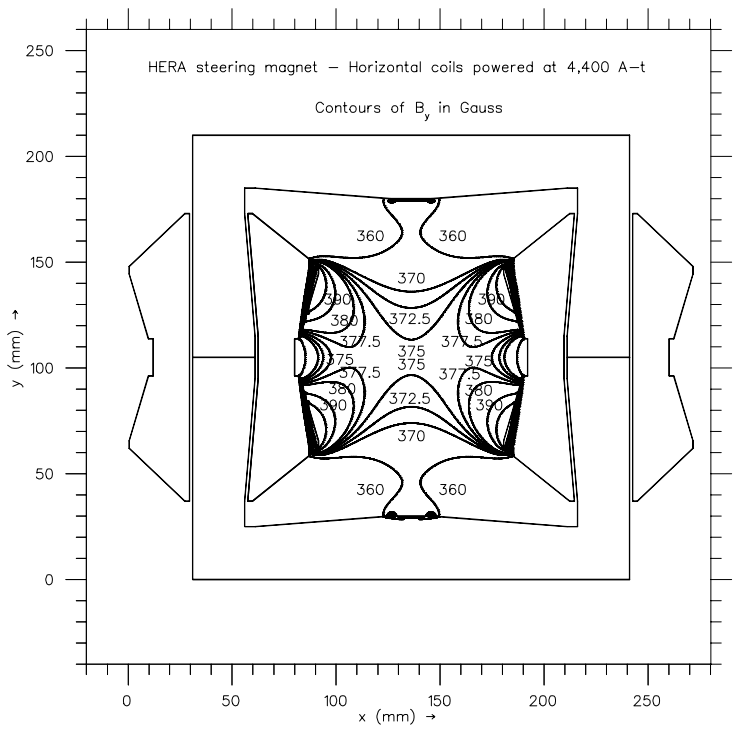

Fig. 6-a. Predicted field distribution in the gap of the HERA steering magnet.

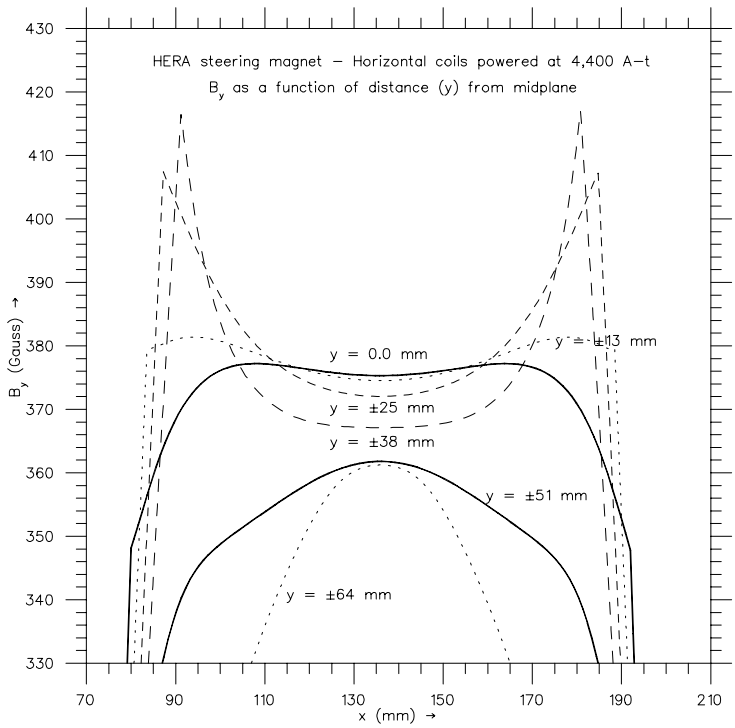

Fig. 6-b. Predicted variation of B_y as a function of distance from the mid-plane for the HERA magnet.

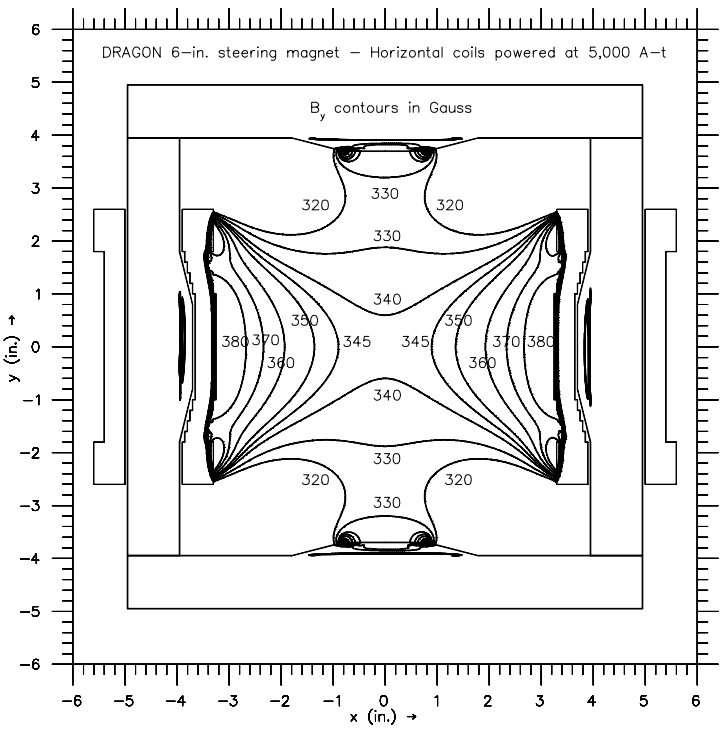

Fig. 7-a. Predicted field distribution in the gap of variation 1 of the steering magnet.

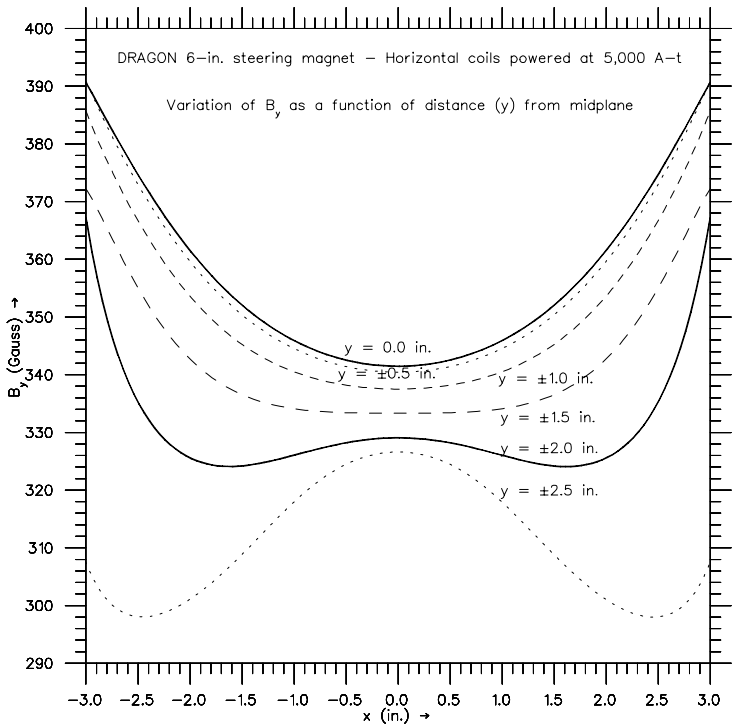

Fig. 7-b. Predicted variation of B_y as a function of distance from the mid-plane for magnet variation 1.

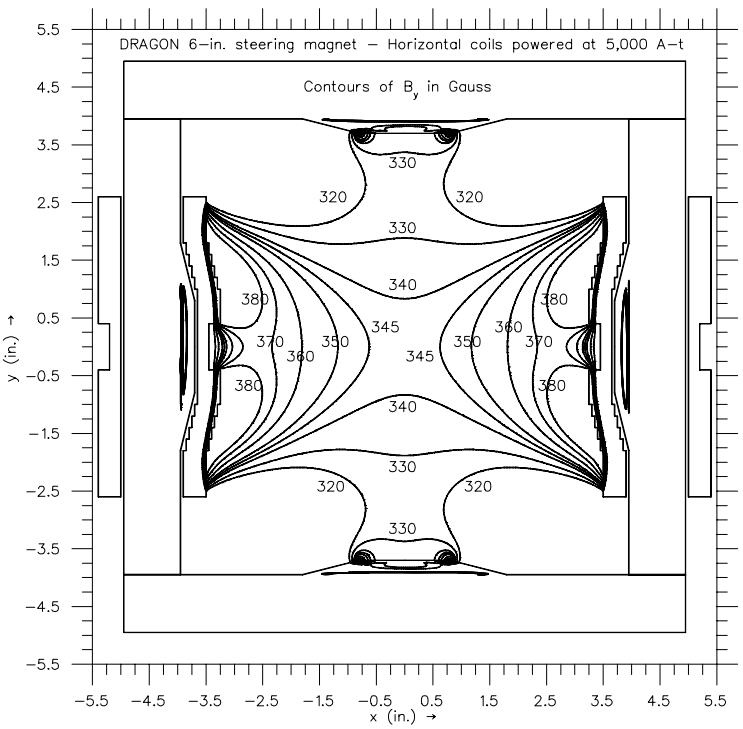

Fig. 8-a. Predicted field distribution in the gap of variation 2 of the steering magnet.

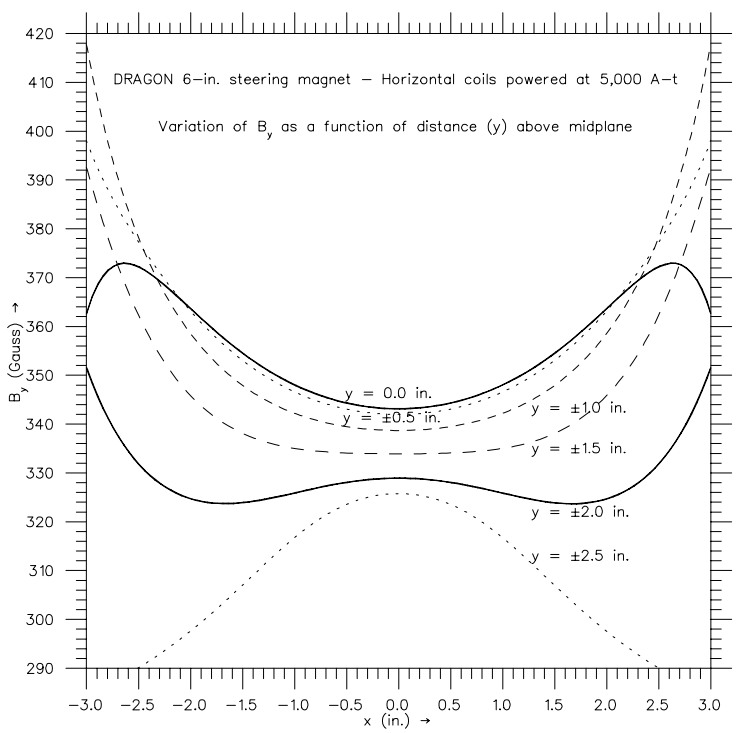

Fig. 8-b. Predicted variation of B_y as a function of distance from the mid-plane for magnet variation 2.

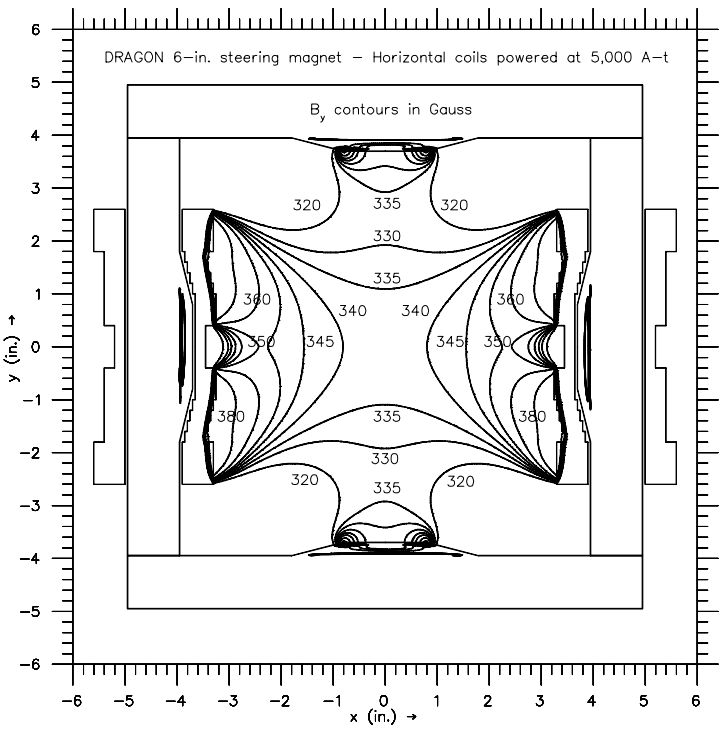

Fig. 9-a. Predicted field distribution in the gap of variation 3 of the steering magnet.

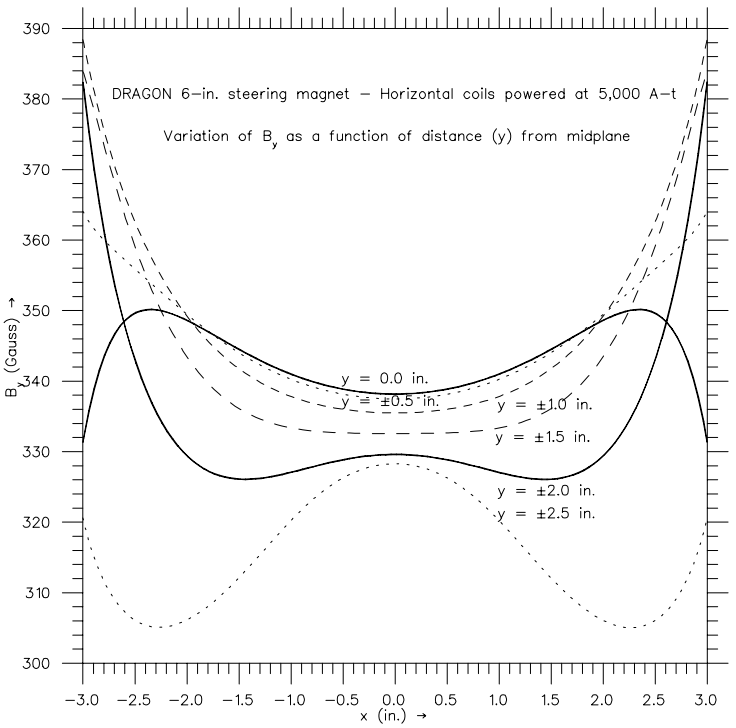

Fig. 9-b. Predicted variation of B_y as a function of distance from the mid-plane for magnet variation 3.

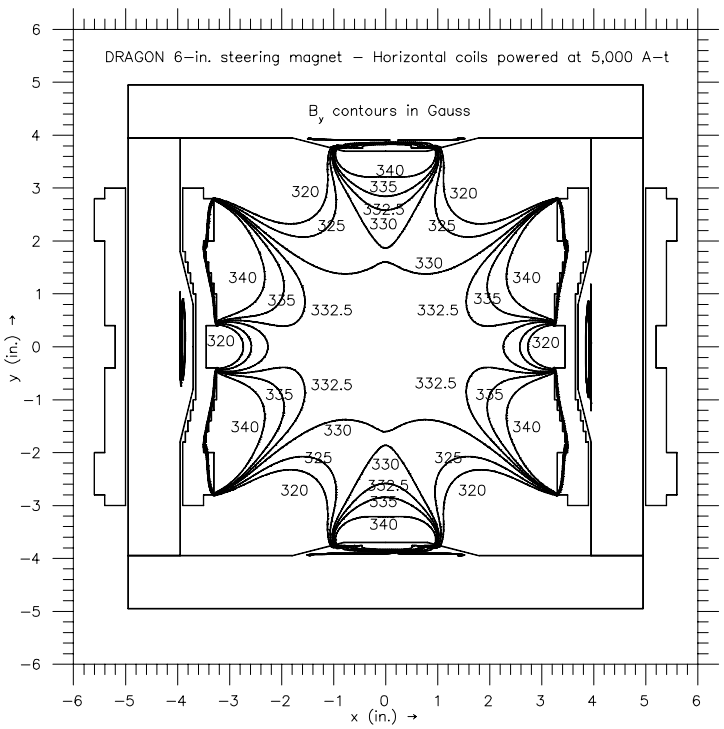

Fig. 10-a. Predicted field distribution in the gap of variation 4 of the steering magnet.

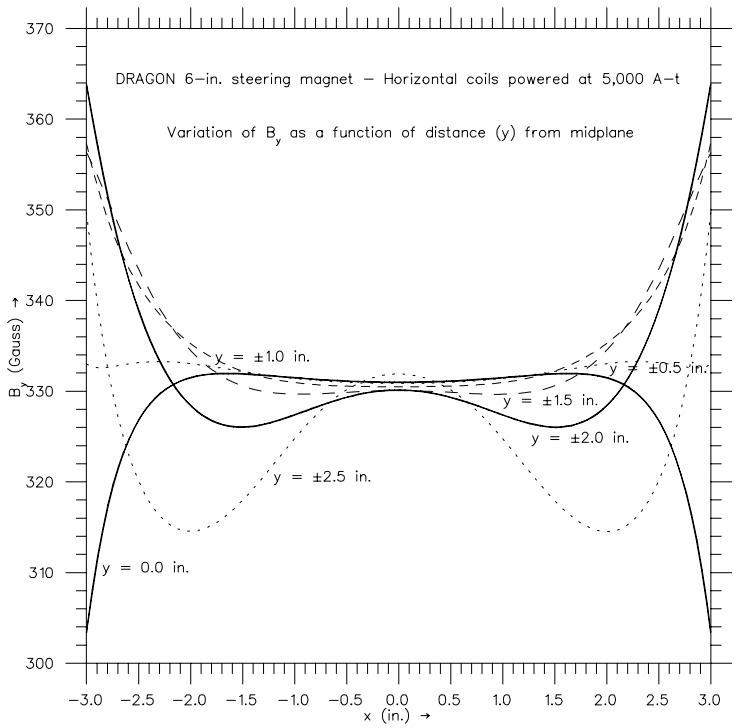

Fig. 10-b. Predicted variation of B_y as a function of distance from the mid-plane for magnet variation 4.

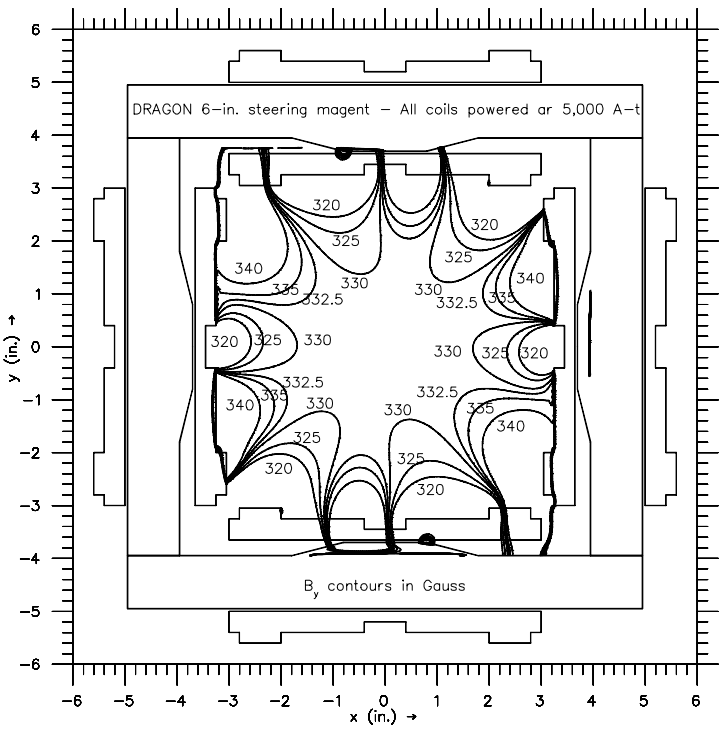

Fig. 11-a. Predicted field distribution in the gap of variation 5 of the steering magnet.

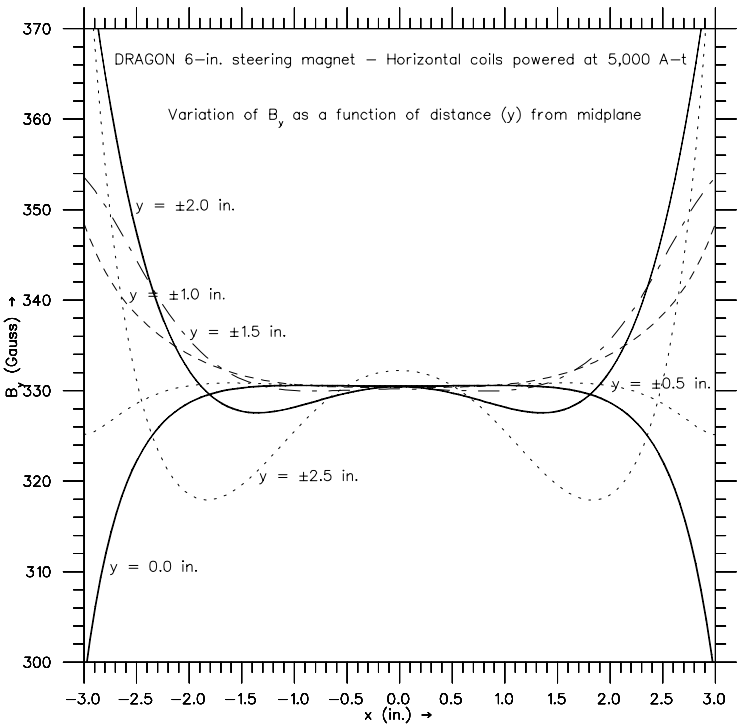

Fig. 11-b. Predicted variation of B_y as a function of distance from the mid-plane for magnet variation 5.

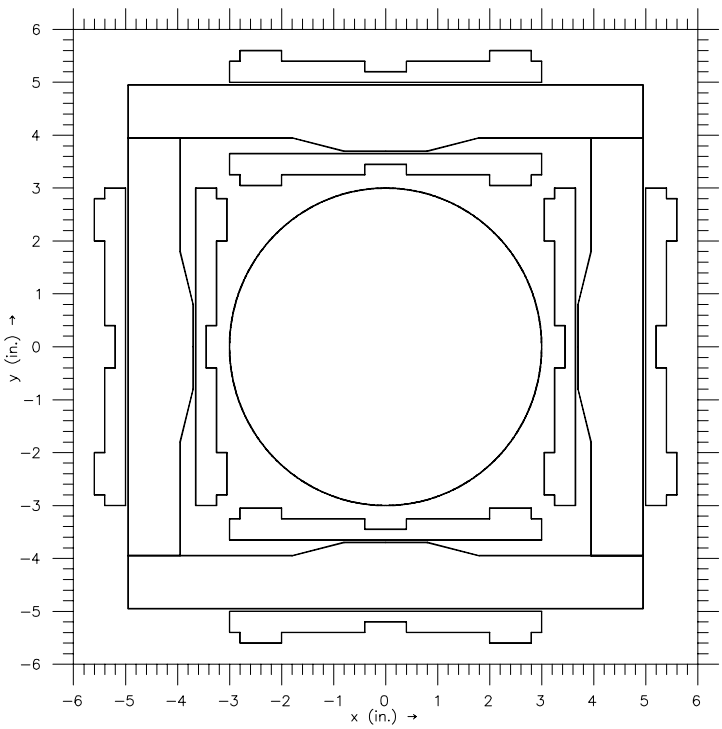

Fig. 12-a. Cross-section of the proposed steering magnet.

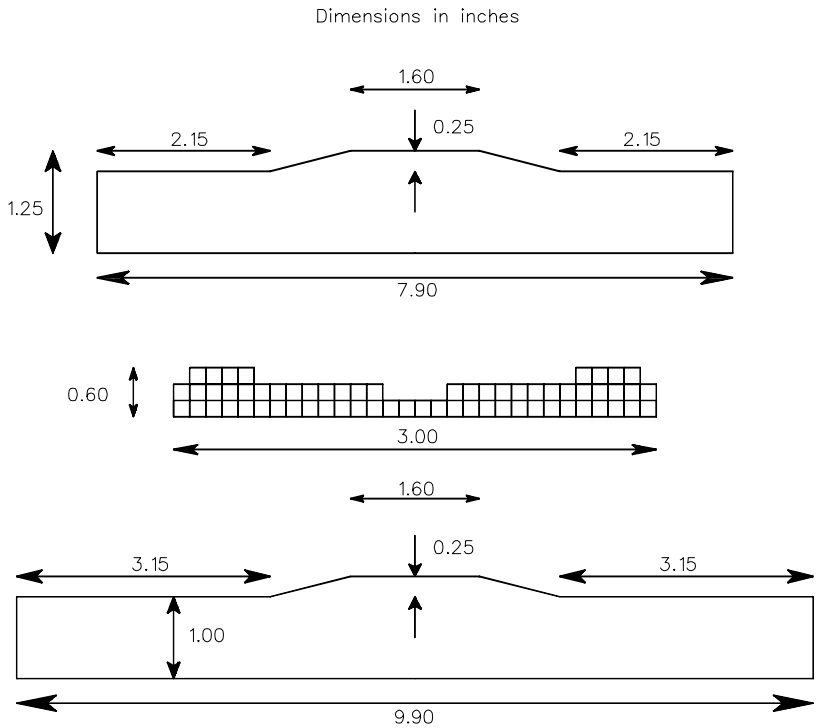

Fig. 12-b. Dimensions of the proposed steering magnet components.

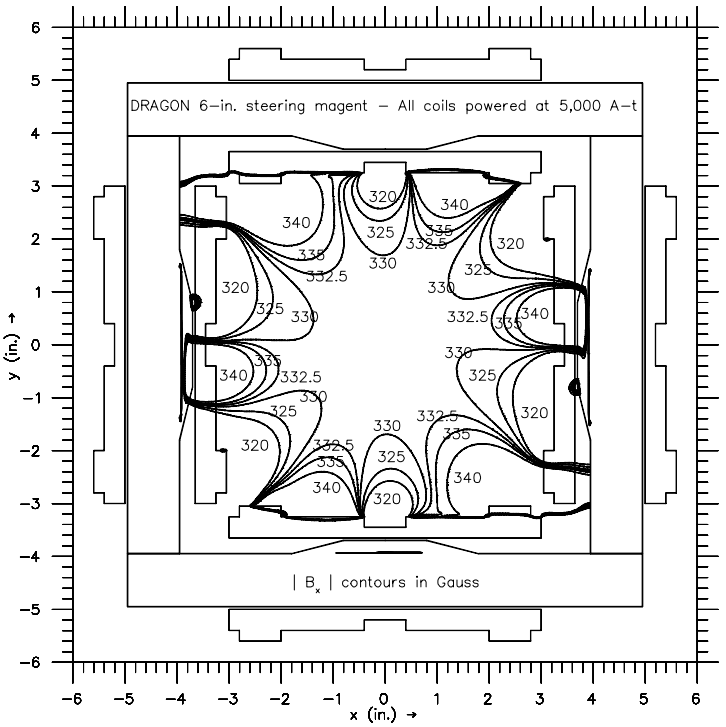

Fig. 13-a. Predicted field distribution of $|B_x|$ with B_x and B_y coils each powered at 5,000 A-t.

THE FOLLOWING IS A MAP OF /B/(KG) UPPER --- CYCLE 17730
/B/(KG) LOWER

L
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. K .....
... .
.

		185	186	187	188	189	190	191	192	193	194	195	196	197	198	199	200				
199	U	2.15	2.16	2.17	2.18	2.19	2.19	2.17	2.14	2.08	1.99	1.89	1.80	1.72	1.63	1.55	1.47				
	L	2.25	2.28	2.32	2.36	2.39	2.42	2.42	2.38	2.28	2.14				1.98	1.84	1.73	1.63	1.54	1.46	
198	U	2.22	2.25	2.28	2.31	2.35	2.38	2.40	2.41	2.38	2.30	2.17	2.02	1.89	1.78	1.68	1.59				
	L	2.31	2.36	2.42	2.49	2.57	2.66	2.74	2.79	2.75	2.59				2.35	2.10	1.91	1.78	1.67	1.57	
197	U	2.32	2.37	2.42	2.49	2.57	2.65	2.73	2.77	2.76	2.64	2.42	2.17	1.97	1.83	1.72	1.62				
	L	2.41	2.48	2.57	2.68	2.81	2.95	3.11	3.23	3.20	2.92				2.57	2.21	1.97	1.81	1.70	1.60	
196	U	2.36	2.42	2.50	2.59	2.70	2.82	2.95	3.09	3.22	3.25	3.03	2.69	2.30	2.05	1.87	1.75				
	L	2.42	2.50	2.59	2.71	2.86	3.06	3.32	3.69	4.10	3.90				3.19	2.70	2.28	2.01	1.84	1.72	
195	U	2.45	2.53	2.63	2.75	2.91	3.11	3.37	3.70	4.10	4.13	3.39	2.84	2.37	2.08	1.89	1.77				
	L	2.48	2.58	2.69	2.83	3.03	3.32	3.76	4.55	6.37	4.13				3.23	2.73	2.29	2.03	1.85	1.74	
194	U	2.44	2.52	2.62	2.75	2.91	3.14	3.47	3.98	4.92	7.10	4.50	3.36	2.80	2.35	2.07	1.89				
	L										6.38	4.22	3.26	2.74	2.32	2.06	1.88				
193	U										4.52	3.70	3.08	2.66	2.29	2.05	1.89				
	L										4.59	3.72	3.10	2.66	2.30	2.06	1.90				
192	U										3.70	3.60	3.21	2.84	2.49	2.21	2.02				
	L										3.70	3.59	3.20	2.84	2.49	2.22	2.02				
191	U										3.28	3.13	2.89	2.63	2.35	2.14	1.98				
	L										3.28	3.12	2.88	2.61	2.35	2.14	1.98				
190	U										3.02	2.97	2.84	2.66	2.44	2.25	2.08				
	L										3.02	2.96	2.84	2.66	2.44	2.24	2.08				
189	U										2.82	2.76	2.64	2.48	2.31	2.16	2.03				
	L										2.82	2.75	2.64	2.48	2.31	2.16	2.03				

Fig. 13-b. Predicted field distribution at the maximum values of flux in the yoke with B_x and B_y coils each powered at 5,000 A-t.