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| | *Date* 1999/02/25 | *File No.* TRI-DNA-99-2 |
| *Author* GM Stinson | | *Page* 1 *of* 11 |
| *Subject* A design for a 4-in. $x$-$y$ steerer for the MEBT beam line | | |

## 1. Introduction

The MEBT beam line of the ISAC facility requires (at least) six steering magnets. Three of these, located between the RFQ exit and the stripper, are $x$-$y$ magnets. For these some of the Chalk River steering magnets will be used. Of the remainder, two are to be located in the charge-selection section and need only to be capable of vertical steering. The final steering magnet is to be located downstream of the rebuncher where $x$-$y$ steering is required.

Because of space constraints it is necessary to design a new, more compact steering magnet for the last three locations. Rather than design a steering magnet expressly for the beam conditions expected in the MEBT it was felt that the design should be such as to be more generally useful. Consequently, a design based on that for the DRAGON facility[1)] was chosen. This note presents a design for such a magnet.

## 2. The design for a 4-in. $x$-$y$ steering magnet for the MEBT beam line

The design of ref[1)] was for a 6-in. steering magnet for the DRAGON facility. This design was modified as shown in figure 1 for use in the MEBT beam line. To keep the magnet compact an iron length of 2.500 in. was chosen. Although a maximum steering requirement of approximately 3,500 Gauss-cm is required for the MEBT, the design shown is capable of producing ≈7,000 Gauss-cm in each plane with the magnet is fully excited at its maximum design current of 100 Amperes. The design goal was to provide a uniform field over 75% of the aperture.

## 3. Results of POISSON runs for the design

POISSON[2)] runs were made for this design to verify that the results were similar to those reported in ref[1)]. A run was made with the $B_y$ coils *only* powered at 4,000 A-t each—a value corresponding to nominal full power. The command and AUTOMESH input files for this run are listed in table 1. Figure 2 shows the calculated results with only the $B_y$ coils powered. Figure 3-a shows the predicted variation of $B_y$ as a function of distance $y \leq \pm 0.75$ in. from the midplane. Figure 3-b shows similar data for values of $y = \pm 1.00$ in., $\pm 1.25$ in. and $\pm 1.50$ in. from the midplane and, for comparison, that on the midplane.

From these latter figures we read $B_{0,y}$, the field value (to the nearest 0.5 Gauss) at $x = 0$ and a particular value of $y$ and tabulate it and the deviation from it at values of $x$ corresponding to one-half and three-quarters of aperture.

Table 2 – Calculated fields as functions of $x$ and $y$

| $y$ (in.) | $B_{0,y}$ (Gauss) $x = \pm 1.50$ in. | $B_{0,y}$ (Gauss) $x = \pm 1.00$ in. |
|---|---|---|
| ±0.00 | $353.5^{+0.5}_{-1.5}$ | $353.5^{+0.5}_{-0.0}$ |
| ±0.25 | $353.5^{+0.5}_{-0.5}$ | $353.5^{+0.5}_{-0.0}$ |
| ±0.50 | $353.5^{+2.5}_{-0.0}$ | $353.5^{+1.0}_{-0.0}$ |
| ±0.75 | $353.0^{+4.0}_{-0.0}$ | $353.0^{+1.5}_{-0.0}$ |
| ±1.00 | $352.5^{+8.0}_{-0.0}$ | $352.5^{+2.0}_{-0.0}$ |
| ±1.25 | $352.0^{+8.0}_{-0.0}$ | $352.0^{+1.5}_{-0.0}$ |
| ±1.50 | $351.5^{+5.0}_{-0.5}$ | $351.5^{+0.0}_{-0.5}$ |

From these results we conclude that the uniformity of the field predicted by POISSON is ±1% over one-half of the magnet's aperture and ±2% over three-quarters of its aperture. This uniformity is deemed acceptable.

**4. Effective length estimation**

In ref[1] it was noted that an empirical effective length for steering magnets had been found to be given by the relation

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

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[3] $k$ 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. A value of $k = 0.70$ was used in ref[1]. In our case the pole-to-pole separation is $G + 2W = 5.6$ in. and the estimated effective length, assuming an iron length of $L_{iron} = 2.50$ in., becomes

$$L_{eff} = \begin{cases} 2.50\text{ in.} + 0.76(5.60\text{ in.}) = 6.76\text{ in. using the HERA data.} \\ \\ 2.50\text{ in.} + 0.70(5.60\text{ in.}) = 6.42\text{ in. using the data of ref}^{1)}. \end{cases}$$

An average of these values yields $L_{eff} = 6.59$ in. However, it is realized that the above formulation may not apply to the magnet in question because of its short longitudinal length. Consequently, B. Milton was asked to make a three-dimensional model of the magnet and use TOSCA[4] to compute a more realistic approximation for an effective length.

Figure 4 shows the results[5] of his calculations in a contour-map format in which the point $(x, y) = (0, 0)$ is the center of the magnet. Each curve corresponds to the specific effective length indicated in the legend. It is seen that over the range $|\,x\,| \leq 1.5$ in. and $|\,y\,| \leq 1.5$ in. the (calculated) effective length of the magnet varies from 9.6 in. to 9.9 in. or, stated differently, the effective length varies approximately 3% over three-quarters of the magnet aperture. We take the effective length of the magnet to be that along $x = y = 0$;

$$L_{eff\,TOSCA} = 9.60\text{ in.}$$

Figure 5 shows the predicted longitudinal extent of the field along the centerline. In this study the field at the magnet center $(x = y = 0)$ was computed to be

$$B_{x=y=0} = 284\text{ Gauss}$$

rather than 353 Gauss as computed by POISSON. Using these values we compute the $\int B\,dl$ as

$$\begin{aligned} \int B\,dl &= L_{eff}\,B_{x=y=0} \\ &= 2726\text{ Gauss-inches} = 6925\text{ Gauss-cm.} \end{aligned}$$

The estimated maximum steering requirement in this section of the MEBT beam line is 3350 Gauss-cm[6]. Consequently, this design for the steering magnet should provide more than adequate steering.

**5. Coil calculations**

This magnet has been detailed with a CAD system in the TRIUMF drawing office. The conductor that will be used is the same as that used in ref[1]. For completeness, a list of its properties is given at the top of the next page.

| | |
|---|---|
| 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 | $421.1\times10^{-6}$ Ω/ft |
| $k$ factor (British units) | 0.0622 |

We calculate the coil length using data computed during the production of the construction drawings[7]. We have, with lengths given in inches,

| Layer Number | Length per turn | Number of turns | Total length |
|---|---|---|---|
| 1 | 7.64 | 22 | 168.08 |
| 2 | 8.90 | 18 | 160.20 |
| 3 | 10.15 | 4 | 40.60 |
| | | | 368.88 |

Thus the estimated length of copper per coil is approximately 31 ft. To this we add an additional 5 ft. to allow for the 'tails' of the coil and 2 ft. to allow for cross-overs for layers 2 and 3. Further calculations are therefore based on a coil length of 38 ft.

$$\boxed{\text{Copper length per coil} = 38 \text{ ft.}}$$

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

$$\boxed{\text{Copper weight per coil} = 2.84 \text{ lb.}}$$

The resistance at 20°C is then

$$\begin{aligned} R_{20} &= (421.1\times10^{-6}\ \Omega/\text{ft})(38\text{ ft}) \\ &= 0.0160\ \Omega. \end{aligned}$$

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

$$\begin{aligned} R_{hot} &= R_{20C}\,[1 + (\text{Temp. coeff}/°\text{C})\Delta T\,(°C)] \\ &= 0.0160[1 + 0.00393(30)] \\ &= 0.01789\ \Omega \text{ per coil.} \end{aligned}$$

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

$$V_{minimum} = 1.1(100\text{ A})(2(0.01789\Omega)) = 3.94\text{ V.}$$

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

$$\boxed{\begin{aligned} \text{I} &= 100.0\text{ A} \\ \text{V} &= 5.0\text{ V minimum} \\ \text{P} &= 0.5\text{ kW minimum} \end{aligned}}$$

The power dissipation per coil is

$$\text{Power per coil} = P = I^2\, R_{hot} = \frac{100^2 \times 0.01789}{1000} = 0.179 \text{ kW}.$$

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

$$\begin{aligned} v \text{ (ft/sec)} &= \frac{2.19}{\Delta T(^\circ\text{F})}\, \frac{P \text{ (kW)}}{\text{Cooling area (in}^2)} \\ &= 3.04167 \times 10^{-2} \times \frac{P \text{ (kW)}}{\text{Cooling area (in}^2)} \end{aligned}$$

for $\Delta T = 72^\circ\text{F} = 40^\circ\text{C}$. With a cooling area of 0.006362 in.$^2$ and power dissipation of 0.179 kW. we have

$$v = \frac{2.19 \times 0.1789}{72 \times 0.006362} = 0.855 \text{ ft/sec}$$

The volume of flow required per circuit is

$$\begin{aligned} \text{Volume/circuit} &= 2.6\, v(\text{ft/min})\, [\text{Cooling area(in}^2)] \text{ IGPM} \\ &= 3.12250\, v(\text{ft/min})\, [\text{Cooling area(in}^2)] \text{ USGPM} \\ &= 3.12250(0.855)(0.006362) \\ &= 0.017 \text{ USGPM} \end{aligned}$$

The pressure drop per coil is given by

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

With $k = 0.0622$ we have

$$\Delta P = 0.0622 \times (0.855)^{1.79} = 0.0470 \text{ psi/ft}.$$

Thus the pressure drop per coil is

$$\boxed{\text{Pressure drop per coil} = (0.0470 \text{ psi/ft}) \times (38 \text{ ft}) = 1.79 \text{ psi}}$$

**6. Iron weight**

Figure 1 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. To estimate the weight of the magnet we begin by calculating the areas of the top and side yokes, taking dimensions from figure 1. Thus

| | Side yoke | | | Top yoke | | |
|---|---|---|---|---|---|---|
| | Width (in.) | Height (in.) | Area (in.$^2$) | Width (in.) | Height (in.) | Area (in.$^2$) |
| Flat section | 6.10 | 1.00 | 6.10 | 8.10 | 1.00 | 8.10 |
| Sloped section | 0.25 | 0.25 | 0.0313 | 0.25 | 0.25 | 0.0313 |
| Sloped section | 0.25 | 0.25 | 0.0313 | 0.25 | 0.25 | 0.0313 |
| Raised section | 2.40 | 0.25 | 0.60 | 2.40 | 0.25 | 0.60 |
| Total area | | | 6.763 | | | 8.763 |

The total area of the yokes is the 2(6.763 + 8.763) in.$^2$ = 31.050 in.$^2$. Taking the density of iron to be 0.2833 lb/in.$^3$ the estimated weight of the yoke is

$$
\begin{aligned}
W_{iron} &= \text{(Density)(Area)(Length)} \\
&= (0.2833\ \text{lb/in.}^3)(31.050\ \text{in.}^2)(2.50\ \text{in.}) \\
&= 21.99\ \text{lb.}
\end{aligned}
$$

We take

$$\boxed{\text{Weight of yoke} = 23\ \text{lb.}}$$

**7. Insertion length**

Table 1 lists the calculated parameters of the magnet. From data in this table we calculate the insertion length of the magnet to be

$$
\begin{aligned}
L_{insertion} &= \text{Iron length} + 2(\text{Coil-yoke clearance} + \text{Maximum coil width} + \text{Coil overwrap}) \\
&= 2.50\ \text{in.} + 2(0.050\ \text{in.} + 3(0.20\ \text{in.}) + 0.050\ \text{in.}) \\
&= 3.90\ \text{in.}
\end{aligned}
$$

**8. Discussion**

This report presents a design for a short, general use 4-in. bore $x-y$ steering magnet. The design is based on that for a similar 6-in. bore steerer for the DRAGON facility.

**References**

1. G. M. Stinson, *A final design for a 6-in. x-y steerer for the DRAGON facility*, TRIUMF Report TRI-DNA-99-1, January, 1999.

2. 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.

3. A. J. Otter, *HERA – Steering Dipole*, TRIUMF Report TRI-DN-85-19, July, 1985.

4. *The TOSCA Reference Manual*, Version 6.0, Vector Fields Limited, 24 Bankside, Kidlington, Oxford OX5 1JE, England, July, 1990.

5. B. F. Milton, *Private communication*, TRIUMF, February, 1999.

6. R. E. Laxdal, *Private communication*, TRIUMF, October, 1998.

Table 1 (Table 2 of ref[1])

Design parameters of the MEBT 4-inch $x - y$ steering magnet

| | | |
|---|---|---|
| Top yoke: | Thickness (max.) | 1.25 in. |
| | Width | 8.10 in. |
| | Length | 2.50 in. |
| | Weight | 6.21 lb. |
| Side yoke: | Thickness (max.) | 1.25 in. |
| | Width | 6.10 in. |
| | Length | 2.50 in. |
| | Weight | 4.79 lb. |
| Coil: | Conductor | 0.162 in. square |
| | Length per coil | 450.00 in. |
| | Weight per coil | 2.84 lb |
| | Resistance (hot) per coil | 0.0179 Ω |
| | Maximum current per coil | 100.0 A |
| | Voltage drop per coil | 1.80 V |
| | Power dissipation per coil | 0.179 kW |
| | Coolant flow rate per coil | 0.855 ft/sec |
| | Pressure drop per coil | 1.79 psi |
| Overall magnet: | Iron weight per magnet | 23.00 lb |
| | Copper weight per magnet (4 coils) | 11.50 lb |
| | Total weight per magnet (4 coils) | 34.50 lb |
| Power supply: | Maximum current | 100.0 A |
| | Minimum voltage (2 coils in series) | 5.0 V |
| | Minimum power (2 coils in series) | 0.5 kW |
| Magnetic: | Estimated effective length | 9.60 in. |
| | Estimated maximum $\int B\, dl$ | 7,000 Gauss-cm |

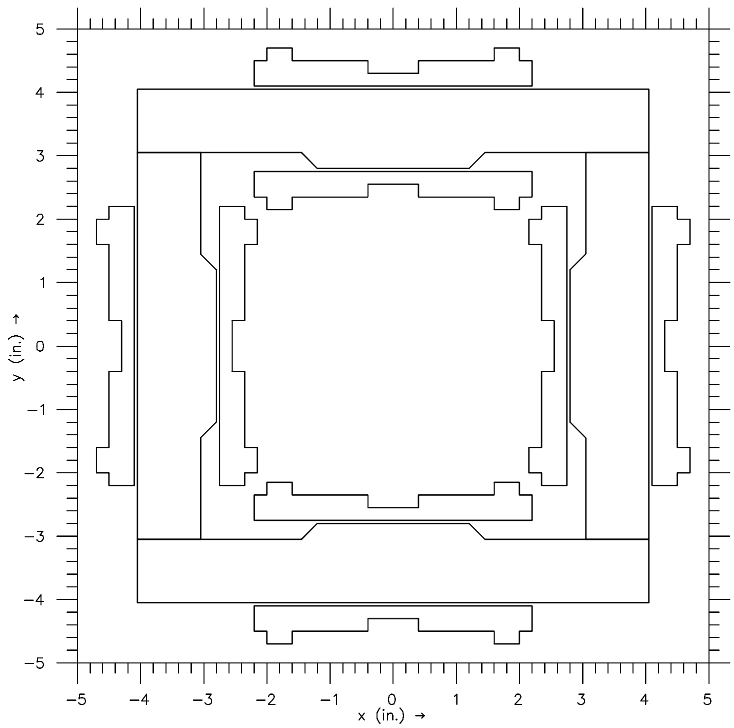


Fig. 1-a. Cross-section of the proposed 4-in. steering magnet.

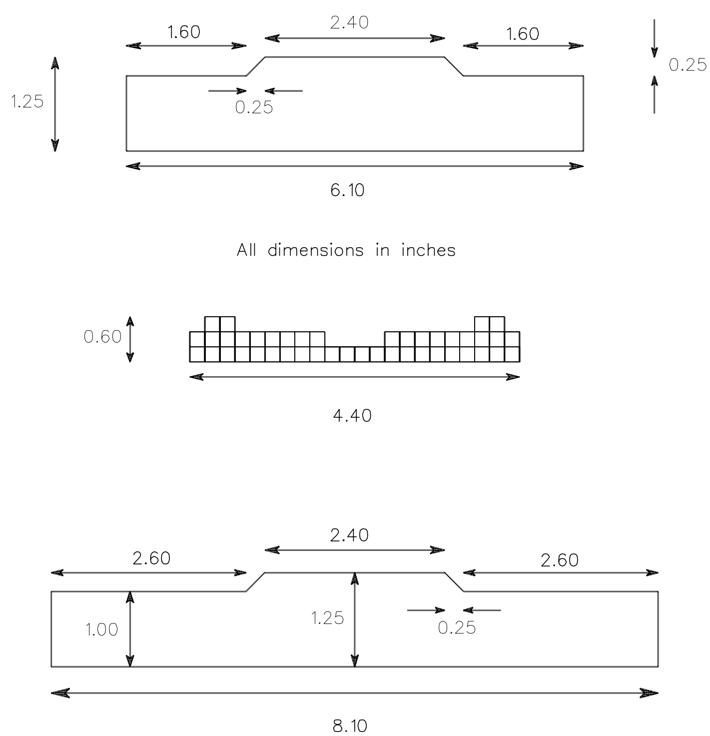


Fig. 1-b. Dimensions of the proposed 4-in. steering magnet components.

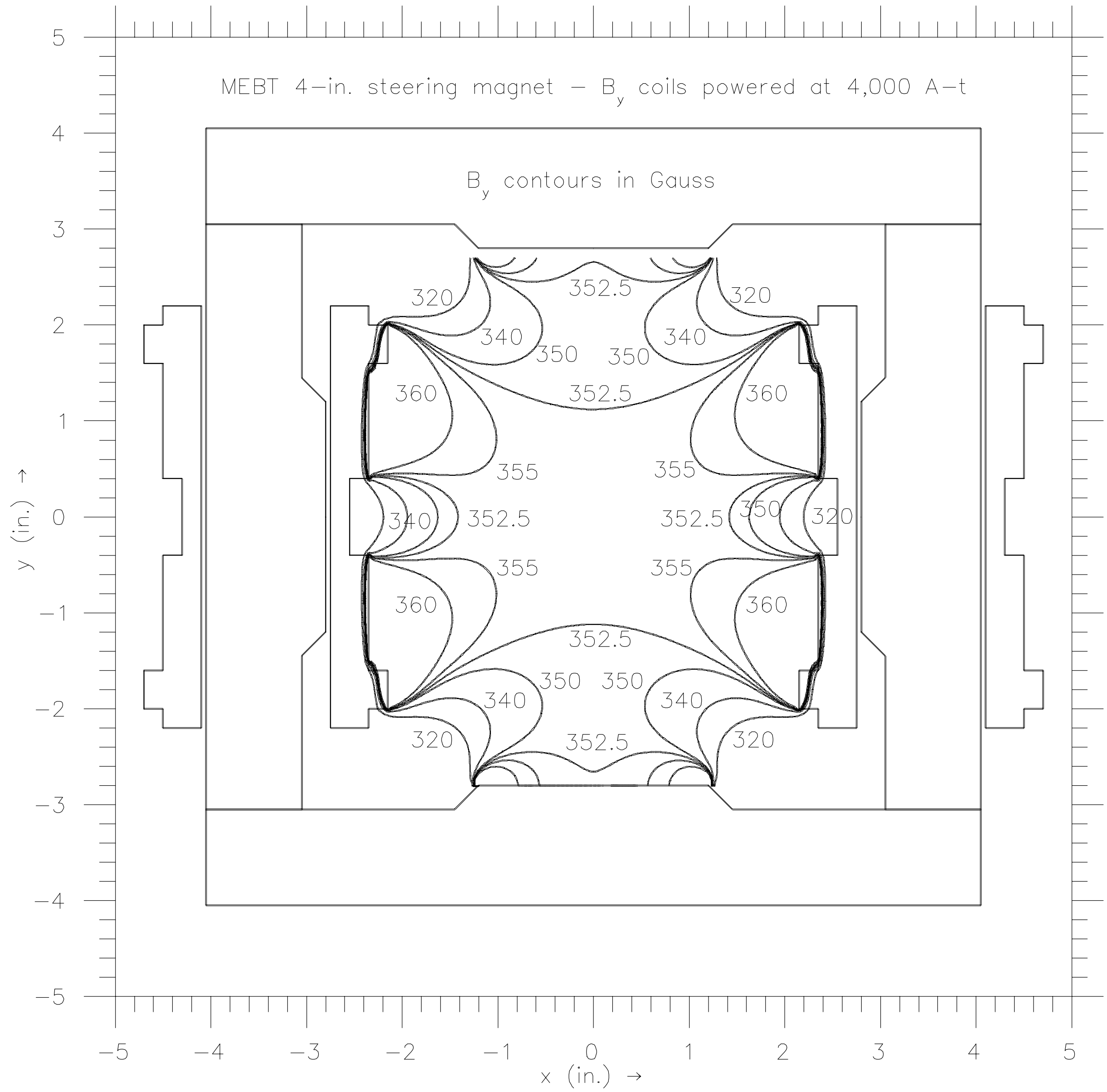


Fig. 2. Predicted field distribution in the gap with $B_y$ coils only powered.

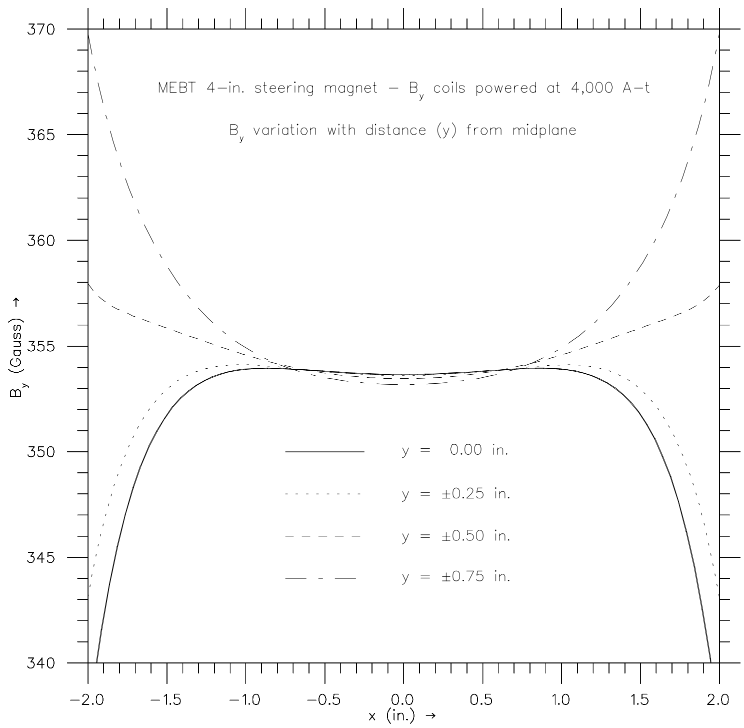


Fig. 3-a. Predicted variation of $B_y$ with distance from midplane ($y < 1$ in.).

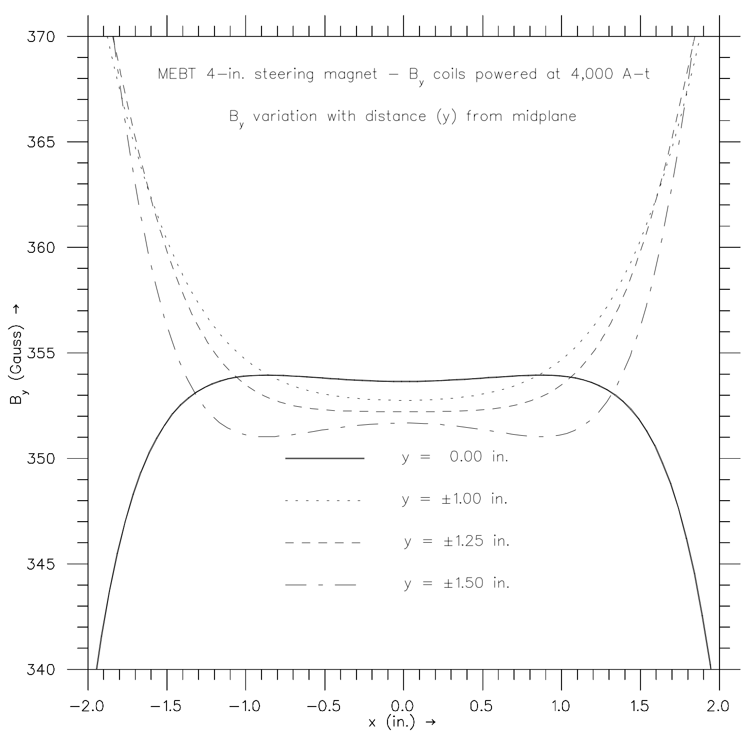


Fig. 3-b. Predicted variation of $B_y$ with distance from midplane ($y \geq 1$ in.).

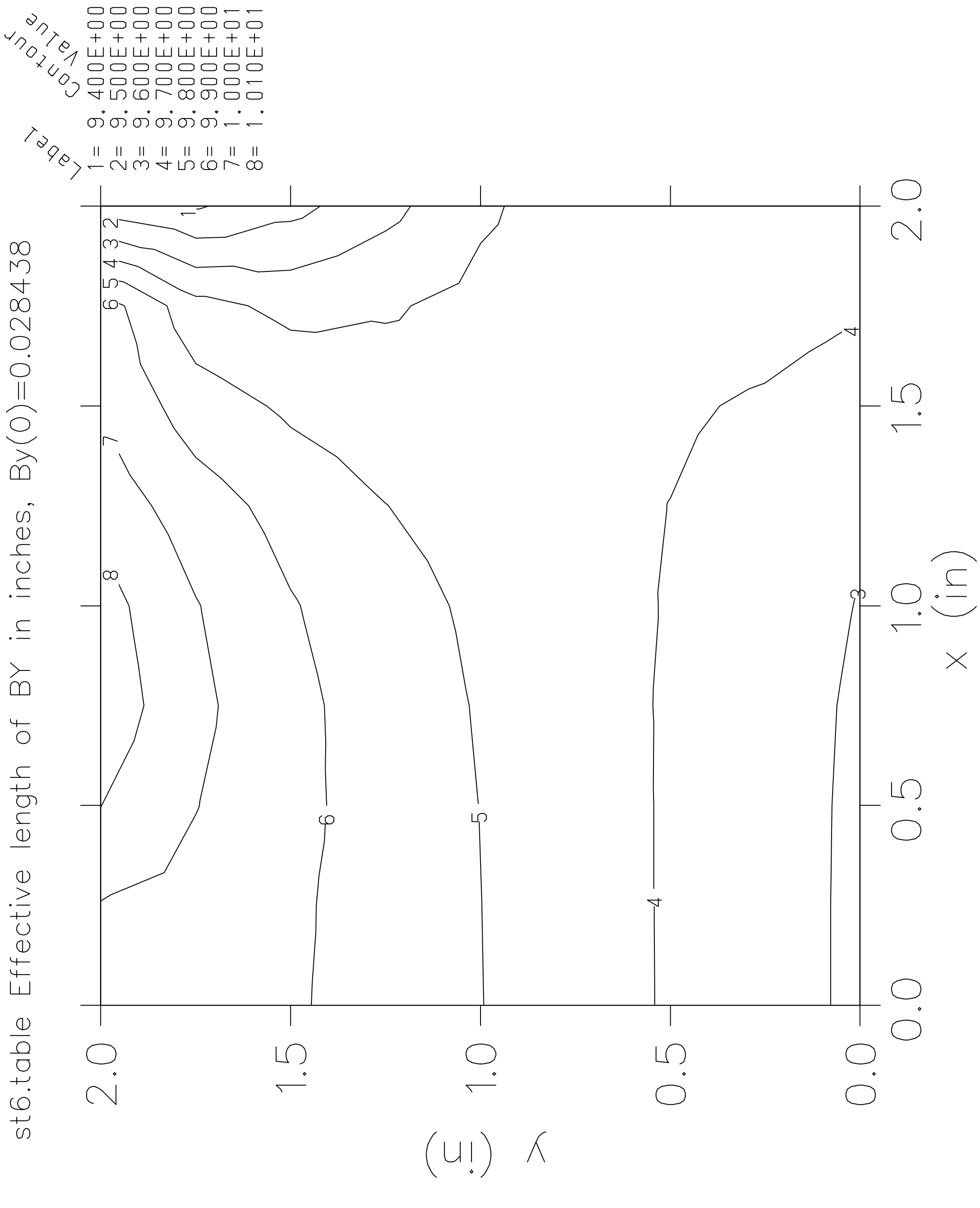


Fig. 4. Contour map of the predicted effective length of the steering magnet.

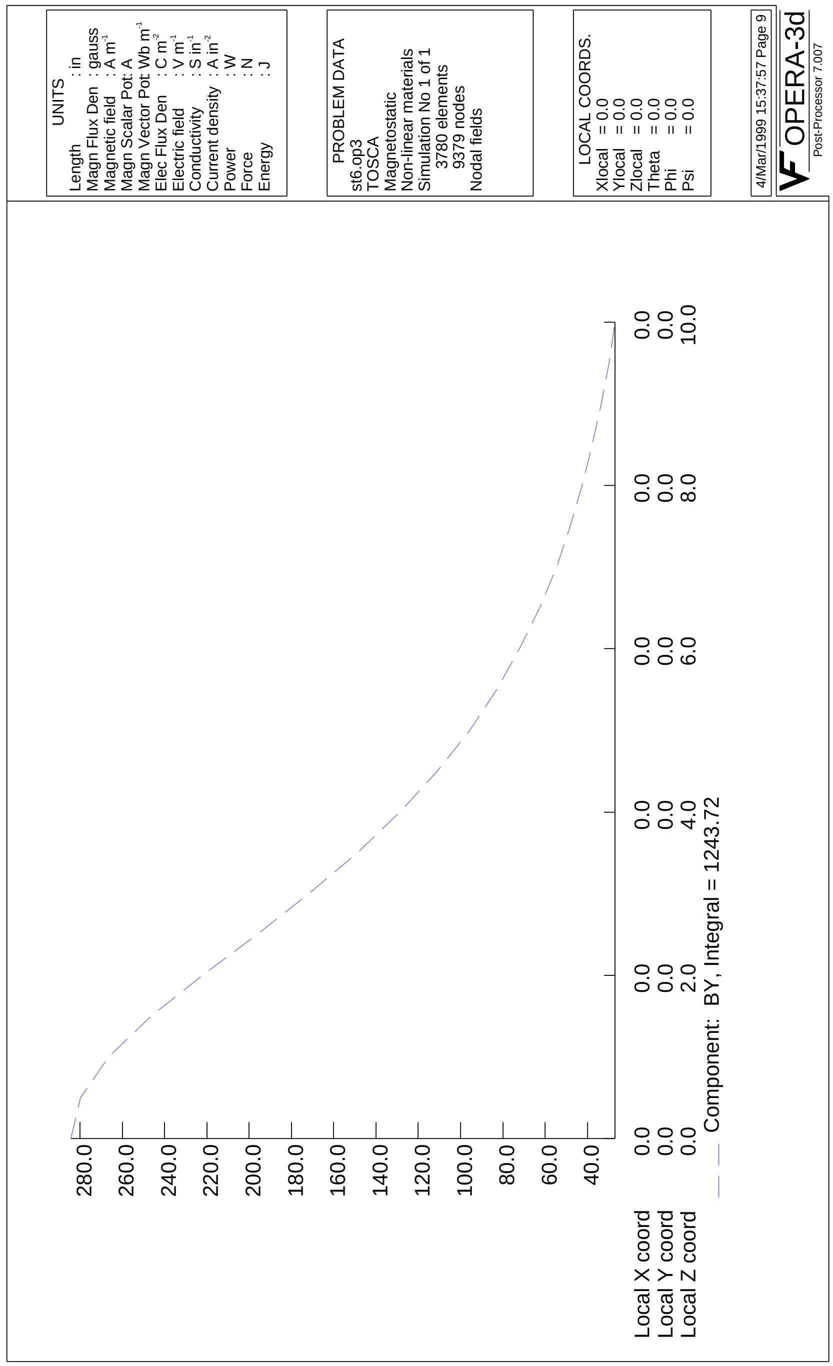


Fig. 5. Variation of the field along the longitudinal centerline of the magnet.