TRIUMF	UNIVERSITY OF ALBERTA EDMONTON, ALBERTA	
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Author GM Stinson		*Page* 1 *of* 15
Subject Conceptual design for a 'Stinson' Mark 2 x–y steering magnet for the ISAC–II HEBT beamline		

1. Introduction

Compact steering magnets were required for the HEBT beamline of the ISAC–I project. The design for such a magnet, given in ref[1], was accepted and is detailed in TRIUMF drawing IMC0010D. This magnet was designed to operate at a maximum excitation current of 100 A. Magnetic measurements at that current indicated a $B \cdot L$ product of approximately 6,400 G-cm and an effective length of approximately 20 cm.

Calculations of the steering requirements for the HEBT beamline of ISAC–II indicate that a minimum requirement for the $B \cdot L$ product is 13,000 G-cm[2]. A further requirement of these steering magnets is that they too are also to be compact.

The concept of this design was first presented to R. laxdal in a memo from the author[3]. Later on April 12, 2005 the author, R. Laxdal, A. Hurst, and G. Clark met for a design review of this proposal. G. Clark had some comments concerning the details presented in the memo. About these he spoke with the author prior to the meeting, presented them at the meeting, and e-mailed them to the author the next day[4]. The consensus of those at this review meeting was that the concept was valid and that a more detailed design note should be issued.

This report presents a more detailed version of the design concept. Included where appropriate are discussions of the points raised by G. Clark.

Because the steering magnets of the design presented in ref[1] have (apparently) have become known among aficionados at TRIUMF as 'Stinson' steerers, we call this 'beefed-up' version of the magnet a 'Stinson' steerer Mark 2.

2. Coil choice and parameters

Given that the steerers for ISAC–II require roughly twice the $B \cdot L$ product of those of ref[1] and that they are to be of a similar design, there would appear to be two choices: either use the existing design and increase the current by the appropriate factor or use a larger conductor that would tolerate a higher current and attempt to design a compact yoke around it.

The main problem that we see with the first option is that of the current density in the conductor. If the maximum $B \cdot L$ product of the magnet of ref[1] is taken as 6,500 G-cm and it is assumed that the effective length is unchanged with excitation, then a current of 200 A is necessary to meet the $B \cdot L = 13,000$ G-cm requirement of the new steering magnets. The conductor used for them was 0.162 inch square with a circular cooling channel of diameter 0.09 inch. The copper area of the conductor is given as 0.01934 inch^2. Consequently, the current density in the copper would be $J = (200\,\mathrm{A})/(0.01934\,\mathrm{inch}^2 = 10,341\,\mathrm{A/inch}^2$. This value is 2.5 times that normally used at TRIUMF for room-temperature magnets. In addition, as noted by G. Clark in the review meeting the iron of the magnet would probably become saturated under these conditions.

TRIUMF has on hand four unopened and two partially used reels of a conductor that should be suitable for use in a new design. This material was ordered in a metric size although markings on the unopened reels seem to indicate an outer dimension of 0.235 inch square for the *bare* conductor. The size ordered was 6 mm square conductor equivalent to that listed in the Outokumpu catalog as size number 6860; its parameters are listed in the table at the top of the next page.

Table 1. Parameters of Outokumpu #6860 6 mm square conductor

Outer dimension	0.23622 inch-square
Inner dimension	0.13780 inch diameter
Copper area	0.04004 inch^2
Cooling area	0.01491 inch^2
Copper weight	0.15500 lb/ft
Copper resistance	$203.451859 \times 10^{-6}\ \Omega$/ft
k factor	0.03700

This existing conductor is coated with a layer of double Dacron glass (DDG insulation. Measurements of the outer dimension of the conductor yielded an average dimension of 0.246 inch, implying a total DDG thickness of 0.011 inch if the markings on the unopened reels are to be believed or of 0.010 inch if the bare conductor is 6 mm (0.236 inch) square. Thus the thickness of DDG insulation is either 0.055 inch or 0.006 inch, depending on which outer dimension of the bare conductor one takes.

3. Coil design

Because the basic design of this new steerer was known, most of the design detail of the coil was done using the program POISSON[6)]. Various coil configurations were considered assuming that the maximum value of the excitation current would be limited to 200 A. From the data given in Table 1 above it is seen that at an excitation current of 200 A the current density in the conductor is $J = (200\,\mathrm{A})/(0.04004\,\mathrm{inch}^2) = 4,995\,\mathrm{A/inch}^2$. This value is higher than the usual design value used at TRIUMF (3,000 to 4,000 A/inch^2) but is acceptable.

The major criterion of the design was to produce a magnet that would have a field uniformity of better than 1% over a central circular diameter of 2 inches, which is the diameter of the bore of the quadrupoles to be used in the transport line. The configuration chosen is shown in figure 1.

The coil configuration shown in figure 1 has a 16-turn first layer, a 12-turn second layer, an 8-turn third layer, and a 4-turn fourth layer. Coil dimensions are shown in figure 2.

3.1 Coil dimensions

In ref[3)] the measured size of the conductor (0.246 inch) was used to calculate the expected size of the coil. A spiral wrapping of fiberglass, 0.007 inch thick and spaced 0.25 inch apart, was assumed to be applied over the DDG-wrapped conductor. Thus the width of a wrapped conductor assumed was 0.260 inch. In addition, an inter-turn spacing of 0.010 inch and a (vertical) keystoning of 0.010 inch was assumed. Thus the following table was given in ref[3)]. The unparenthesized numbers in the first column are values for the horizontal plane; the parenthesized numbers are values for the vertical plane. It was assumed that a ground wrap of thickness 0.050 inch was applied directly to the magnet poles.

Table 2. Nominal coil dimensions from ref[3)].

	Horizontal	Vertical
Conductor + DDG 16(4)×0.246 in.	3.936 in.	0.984 in.
Fiberglass insulation 32(8)×0.007 in.	0.224 in.	0.056 in.
Inter-turn spacing 15(3)×0.010 in.	0.150 in.	0.030 in.
Keystoning 0(4)×0.010 in.	0.000 in.	0.040 in.
Ground wrap 1(1)×0.028 in.	0.028 in.	0.028 in.
Total	4.338 in.	1.138 in.

The maximum width of the coil was taken to be 4.40 inches and its maximum height to be 1.16 inches. Thus the average width per turn was taken as 0.275 inch and the average height per turn was taken as

0.290 inch. These are nominal values and do not take into account any variation in the size of the the bare conductor or that of the thickness of the DDG insulation.

G. Clark in ref[4] makes the following comments on this calculation.

> Essex Magnet Wire Engineering Data book (page 44) gives the *minimum increase* (over [bare] copper OD) for Bare Double-Dacron Glass is 0.012 inch. This implies the minimum thickness is 0.006 inch.
>
> [On] Page 2 in your calculation of the coil size would it not be appropriate to use the max. conductor size (0.236 + 0.004) inch plus the *minimum increase* for the DDG (0.012 inch)?

These comments are quite valid for the determination of the maximum dimensions of the coil. In Table 3 below the above calculation is repeated to determine the maximum dimensions of the coil.

Table 3. Calculation of the maximum coil dimensions.

	Horizontal	Vertical
Conductor + DDG 16(4)×0.252 in.	4.032 in.	1.008 in.
Fiberglass insulation 32(8)×0.007 in.	0.224 in.	0.056 in.
Inter-turn spacing 15(3)×0.010 in.	0.150 in.	0.030 in.
Keystoning 0(4)×0.010 in.	0.000 in.	0.040 in.
Ground wrap 1(1)×0.028 in.	0.028 in.	0.028 in.
Total	4.434 in.	1.162 in.

This revised calculation is consistent with taking the maximum horizontal dimension of the coil to be 4.40 inches and a maximum height of the coil to be 1.16 inches. Thus we retain the average width and height per turn values that were used in ref[3]—0.275 inch horizontally and 0.290 inch vertically. We also note that neither of the calculations of Tables 2 or 3 take into account any variation in thickness of the fiberglass overwrap, although we have used a total thickness of 0.015 inch in the calculations.

3.2 Length per coil

In ref[3] the length of copper conductor per coil was estimated as follows. So as not to reduce the cooling area of the conductor as it is wound over the poles of the magnet it was assumed that the upstream and downstream faces of the yoke were machined with a radius of 0.75 inch. This radius is approximately three times the conductor dimension, although ideally we would prefer to use a radius of four times the conductor dimension or 1 inch. However, the radius of 0.75 inch was felt sufficient that the area of the cooling channel was not significantly impaired and that the use of this radius would keep the insertion length of the magnet to a reasonable size.

Then the radius of the curved portion of one turn of the inner layer is

$$\begin{aligned} R_1 &= \text{Pole radius} + \text{pole ground wrap} + (\text{vertical height/per turn}/2) \\ &= 0.75\,\text{in.} + 0.05\,\text{in.} + (0.290/2)\,\text{in.} \\ &= 0.945\,\text{in.}\ , \end{aligned}$$

and those of the outer layers are related by

$$\begin{aligned} R_n &= R_{n-1} + \text{inter-turn spacing} + \text{vertical height/per turn} \\ &= R_{n-1} + 0.30\,\text{in.} \end{aligned}$$

where $n > 1$. We design the pole with a one-inch straight section in addition to the two radii such that its longitudinal length is 2.5 inches. Then the length per turn of one winding of the nth layer is

$$\ell_n = 2[\pi\, R_n + 1]\,\text{in.}$$

Writing N_n for the number of turns per layer and L_n for the total length per layer we have the following.

Table 4. Calculation of the length per coil.

Layer	R_n (in.)	ℓ_n (in.)	N_n	L_n (in.)
1	0.945	7.938	16	127.002
2	1.245	9.823	12	117.871
3	1.545	11.708	8	93.660
4	1.845	13.593	4	54.370
Total				392.903

We take the total length of copper per coil as 400 inches or 33.3 ft. To this we add 3 ft for lead length and obtain an estimated length per coil of 36.3 ft.

$$\boxed{\text{Estimated length per coil} = 36.3\,\text{ft.}}$$

3.3 Electrical requirements

Using a length per coil of 36.3 ft and the parameters of the conductor listed in Table 1 we calculate the following.

Table 5. Weight and resistance per coil.

Length per coil	=	36.300 ft
Weight per coil	=	5.627 lb
R_{20C} per coil	=	7.385 mΩ
R_{hot} per coil	=	8.256 mΩ

At an excitation current of 200 A the current density in the conductor is 4,995 A/in.^{2} = 7.742 A/mm^2. The two coils are powered in series for steering in a given direction. Consequently, the resistance of two coils in series is twice that listed in Table 5 or 16.512 Ω. In Table 6 we give the power requirements for this situation.

Table 6. Calculation of the power requirements for two coils in series.

I	=	200.0 A
R	=	16.512 mΩ
V	=	3.302 V
P	=	0.660 kW

To allow for lead loss we suggest the following minimum specifications for the power supply.

$$\boxed{\begin{array}{lcr} I & = & 200.0\,\text{A} \\ V & = & 6.0\,\text{V} \\ P & = & 1.2\,\text{kW} \end{array}}$$

3.4 Cooling requirements

The coils of this magnet could be cooled either in series or in parallel. For parallel cooling we calculate as follows. The power dissipated in a single coil at a current of 200 A is

$$\text{Power per coil} = P = I^2 R_{hot} = \frac{(200\,\text{A})^2 \times 0.008256\,\Omega}{1000} = 0.330\,\text{kW}.$$

In British units the required flow rate of the coolant is for $\Delta T = 72°\text{F} = 40°\text{C}$

$$v\,(\text{ft/sec}) = \frac{2.19}{\Delta T(°\text{F})} \cdot \frac{P\,(\text{kW})}{\text{Cooling area (in.}^2)} = 3.04167 \times 10^{-2} \times \frac{P\,(\text{kW})}{\text{Cooling area (in.}^2)}$$

With a cooling area of 0.01491 in.^{2} and a power dissipation of 0.330 kW we have

$$v = \frac{2.19 \times 0.330}{72 \times 0.01491} = 0.673\,\text{ft/sec.}$$

The volume of flow required per coil is

$$\begin{aligned}\text{Volume/coil} &= 2.6\,v\,(\text{ft/min})[\text{Cooling area (in.}^2)]\,\text{IGPM}\\ &= 3.1225\,v\,(\text{ft/min})[\text{Cooling area (in.}^2)]\,\text{USGPM}\\ &= 3.1225(0.673)(0.01491)\\ &= 0.03133\,\text{USGPM}\ .\end{aligned}$$

The pressure drop per coil is found from

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

With $k = 0.037$ we have

$$\Delta P = 0.037 \times (0.673)^{1.79} = 0.0182\,\text{psi/ft.}$$

Thus the pressure drop per coil is

$$\text{Pressure drop per coil} = (0.0182\,\text{psi/ft.})(36.3\,\text{ft}) = 0.661\,\text{psi.}$$

These results together with those obtained in a similar manner for series-cooled coils are summarized in Table 7.

Table 7. Cooling parameters for parallel-cooled and series-cooled coils.

	Series power Parallel cooling	Series power Series cooling
Power dissipated in coil(s) (kW)	0.330	0.660
Speed of coolant (ft/sec)	0.673	1.346
Flow volume (USGPM)	0.031	0.063
Pressure drop per foot (psi)	0.018	0.063
Total pressure drop (psi)	0.661	4.572

In ref[4)] G. Clark makes the following comment about these results.

> The velocities indicated are not turbulent, so you cannot use the Anaconda k-flow formula. You can reduce ΔT, increasing the flow and velocity to get a Reynolds number greater than 2,320. Then you can use the Anaconda k-flow formula.

This too is a valid point. If the allowable temperature increase is reduced from $\Delta T = 72°\text{F} = 40°\text{C}$ as used above to $\Delta T = 54°\text{F} = 30°\text{C}$ and the calculations repeated we obtain the results shown below.

Table 8. Cooling parameters for an allowed temperature increase of $\Delta T = 54°\text{F} = 30°\text{C}$.

	Series power Parallel cooling	Series power Series cooling
Total power dissipated (kW)	0.330	0.660
Speed of coolant (ft/s)	0.898	1.795
Volume of flow (USGPM)	0.042	0.084
Pressure drop per foot (psi)	0.031	0.106
Total pressure drop (psi)	1.107	7.656

For completeness we list in Table 9 similar parameters for an allowable temperature increase of $\Delta T = 36°$F $= 20°$C.

Table 9. Cooling parameters for an allowed temperature increase of $\Delta T = 36°\text{F} = 20°\text{C}$.

	Series power Parallel cooling	Series power Series cooling
Total power dissipated (kW)	0.330	0.660
Speed of coolant (ft/s)	1.346	2.693
Volume of flow (USGPM)	0.063	0.125
Pressure drop per foot (psi)	0.063	0.218
Total pressure drop (psi)	2.306	15.953

As a check on the values in Tables 7, 8, and 9 a cooling calculation for these cases was made following the recipe given in ref[5]. The results for an excitation current of 200 A and an inlet water temperature of 20°C are tabulated in Table 10 for the case of parallel cooling and in Table 11 for the case of series cooling.

Table 10. Calculations for parallel cooling based on the method of G. S. Clark[5].

	$\Delta T = 20°$C	$\Delta T = 30°$C	$\Delta T = 40°$C
Average water temperature (°C)	30.0	35.0	40.0
Coil resistance at T_{av} (mΩ)	7.675	7.820	7.965
Minimum voltage (V)	1.535	1.564	1.593
Minimum power (kW)	0.307	0.313	0.319
Required flow speed (ft/sec)	1.259	0.856	0.655
Required flow (USGPM/min)	0.0584	0.0398	0.0304
Reynolds number	1,676.	1,262.	1, 062.1
Pressure drop (psi)	3.231	1.982	1.376

Table 11. Calculations for series cooling based on the method of G. S. Clark[5].

	$\Delta T = 20°$C	$\Delta T = 30°$C	$\Delta T = 40°$C
Average water temperature (°C)	30.0	35.0	40.0
Coil resistance at T_{av} (mΩ)	15.350	15.640	15.930
Minimum voltage (V)	3.070	3.128	3.186
Minimum power (kW)	0.614	0.626	0.637
Required flow speed (ft/sec)	2.517	1.712	1.310
Required flow (USGPM/min)	0.117	0.080	0.061
Reynolds number	3,351.8	2,524.3	2,124.3
Pressure drop (psi)	19.836	9.988	6.158

The first thing to notice about the results given in Tables 10 and 11 is that the minimum voltage and power requirements are *lower* than those given in §3.3. The reason for this is that the Clark method calculates the coil resistance at the temperature $T_{av} = T_{inlet} + \Delta T/2$—the *average* coolant temperature—whereas that of §3.3 is calculated at the temperature $T_{max} = T_{inlet} + \Delta T$—the maximum coolant temperature. Consequently, the resistance increase is smaller using the Clark approach and this leads to lower voltage and power requirements for a given excitation current. Similarly, because of the reduced power requirements a lower flow rate is required for a given temperature rise when using the Clark approach.

Because off-the-shelf power supplies tend to come in quantized units of current and voltage we shall continue to use the power supply suggested in §3.3.

From the data of Table 10 it is seen that none of the parallel-cooled cases studied meet Clark's criterion of a Reynolds number greater than 2,320. Of the series-cooled cases only that for an allowed $\Delta T = 40°$C fails this criterion and then only by ≈10%. Consequently, it is suggested that a coolant temperature increase of 30°C be allowed and that the two coils be cooled in series.

4. Yoke dimensions

As may be seen from figure 1, the yoke of the magnet consists of four identical sections that are bolted together. A 0.050 inch-thick layer of insulation is wound directly on the poles and acts as the ground insulation between the coils and the yoke. After this insulation has been applied a coil is wound over the insulation on each coil.

Figure 3figure 3 details the geometry of one section of the yoke. The upper portion of this figure indicates that the (maximum) yoke thickness is 1.50 inches—a value 0.25 inch larger than the design of ref[1)]. The reason for this is to not impair coolant flow through the conductor. Ideally this radius should be the four conductor dimensions but we feel that the use of the smaller radius will not significantly impair cooling. The pole thickness is increased by machining a 'pole' on each side of the yoke; a yoke of the original magnet has a 'pole' machined on one side only.

The length of each section is 7.60 inches. 0.50 inch longer than that of a yoke piece of the magnet design of ref[1)].

The middle portion of figure 2 shows that the width of the yoke is 2.50 inches, the same as that of the original magnet. The locations of bolt holes for assembly of the magnet are indicated but not dimensioned. This will be corrected in the final drawing of the magnet.

The lower portion of the figure is an attempt to show a view looking in at either end of the section shown above it. The radiused portions are the upstream and downstream edges of the pole; the ends have been made rectangular in order to ease assembly.

5. POISSON results

The program POISSON was run to estimate the field to be expected at an excitation current of 200 A. Figure 4 is a large-scale contour plot of the fields predicted at that current when only the horizontal steering coils are powered; the contour levels are in Gauss. The larger circle is drawn with a radius of 1 inch and represents the (nominal) 2-inch diameter beam pipe. The smaller circle is drawn with a radius of 0.75 inch.

Figure 5 is the same plot on an enlarged scale to allow an estimate of the uniformity of the field in the gap. From figure 5 it is seen that the field over a diameter of 1.5 inches is predicted to be ≈(669.5±1.5) Gauss or uniform to within ±0.23%. On the other hand, the uniformity over a 2-inch diameter is worse; it is seen to be ≈(669.5±4.5) Gauss or uniform to within ±0.67%.

In operation in this case—only the horizontal coils excited—the fields in the yokes are, in general, small. This is shown in figure 6, a contour map of the predicted fields in the yokes. In this case the contour levels are in kG and it is seen that except at the corners of the poles the fields in the yoke are 2 kG or less.

In general, then, this design has met the design goal set out in §3. However, it must be remembered that POISSON is a two-dimensional program that treats all magnets as if they were of infinite length, which is certainly not the case for the design in question.

Given that the original design was obtained using this program and that those magnets met their design specifications in actual usage, we suspect a similar result for this new design. Further, this new design is slightly longer in the beam direction than is the original. Consequently, we would expect that its effective length would be slightly longer.

To be safe, however, if we assume that the effective length of the new design is equal to that of the original design, ≈20 cm, then based on the POISSON predictions the $B \cdot \Delta L$ product of this new design would be 13, 400 G-cm.

6. Discussion

An overall summary of the calculations presented here is given in table 12. This table is identical to that of ref[3] *except* that the pressure drop across the two coils in series is taken from Table 11 for an allowed temperature increase of $\Delta T = 54\,^{\circ}\mathrm{F} = 30\,^{\circ}\mathrm{C}$.

In §2 it was noted that TRIUMF has on hand four unopened and two partially used reels of the chosen conductor. The quotation stated that each reel was guaranteed to have a minimum *continuous* length of 127 ft. Shorter lengths might also be wound on the reel. Should this be the case and the shorter lengths are less than 36.6 ft in length this would mean that we could only get three coil-lengths from each reel.

A total of 40 coils are needed for the 10 steering magnets required. Consequently, it will be necessary to purchase additional copper and to have it coated with DDG insulation.

References

1. G. M. Stinson, *A design for a x-y steerer for the* MEBT *beam line*, TRIUMF report TRI-DNA-99-2, February, 1999.
2. M. Marchetti, *Steerers for the ISAC–II S-HEBT*, TRIUMF note, April, 2005.
3. G. M. Stinson, *'Stinson' steerer Mark 2*, Memo to R. Laxdal, TRIUMF, March 4, 2005.
4. G. S. Clark, *Trivial details in your 'Stinson' steerer Mark 2 memo*, E-mail to G. Stinson, TRIUMF, April 13, 2005.
5. G. S. Clark, *A Concept Design for the ISAC-II HEBT (S-Bend) Dipole*, Revision 3, TRIUMF report TRI-03-4, May, 2003.
6. 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 12

Design parameters for ISAC-II $x - y$ steering magnet Mark 2

Yoke piece	Thickness (max.)	1.50 in.
	Width	7.60 in.
	Length	2.50 in.
	Weight	7.03 lb.
Coil	Conductor (DDG insulated)	0.235 in. square
	Length per coil	36.30 ft.
	Weight per coil	5.63 lb.
	Resistance (hot) per coil	8.256 mΩ
	Coolant flow (1 coil, parallel cooling, $\Delta T = 30°C$)	0.042 USGPM
	Coolant flow (2 coils, series cooling, $\Delta T = 30°C$)	0.084 USGPM
	Pressure drop (1 coil, parallel cooling $\Delta T = 30°C$))	1.982 psi
	Pressure drop (2 coils, series cooling $\Delta T = 30°C$))	9.988 psi
Overall magnet	Iron weight per magnet	28.12 lb.
	Copper weight per magnet (4 coils)	22.52 lb.
	Total weight per magnet (4 coils)	50.64 lb.
	Overall width	11.80 in.
	Overall height	11.80 in.
	Overall length	4.95 in.
Power supply	Maximum current	200.0 A
	Minimum voltage (2 coils in series)	3.65 V
	Minimum power (2 coils in series)	0.66 kW
Magnetic	Nominal effective length, l_{nom}	8.0 in.
	Estimated maximum $\int B\,dl$ at l_{nom}	13,400 Gauss-cm.

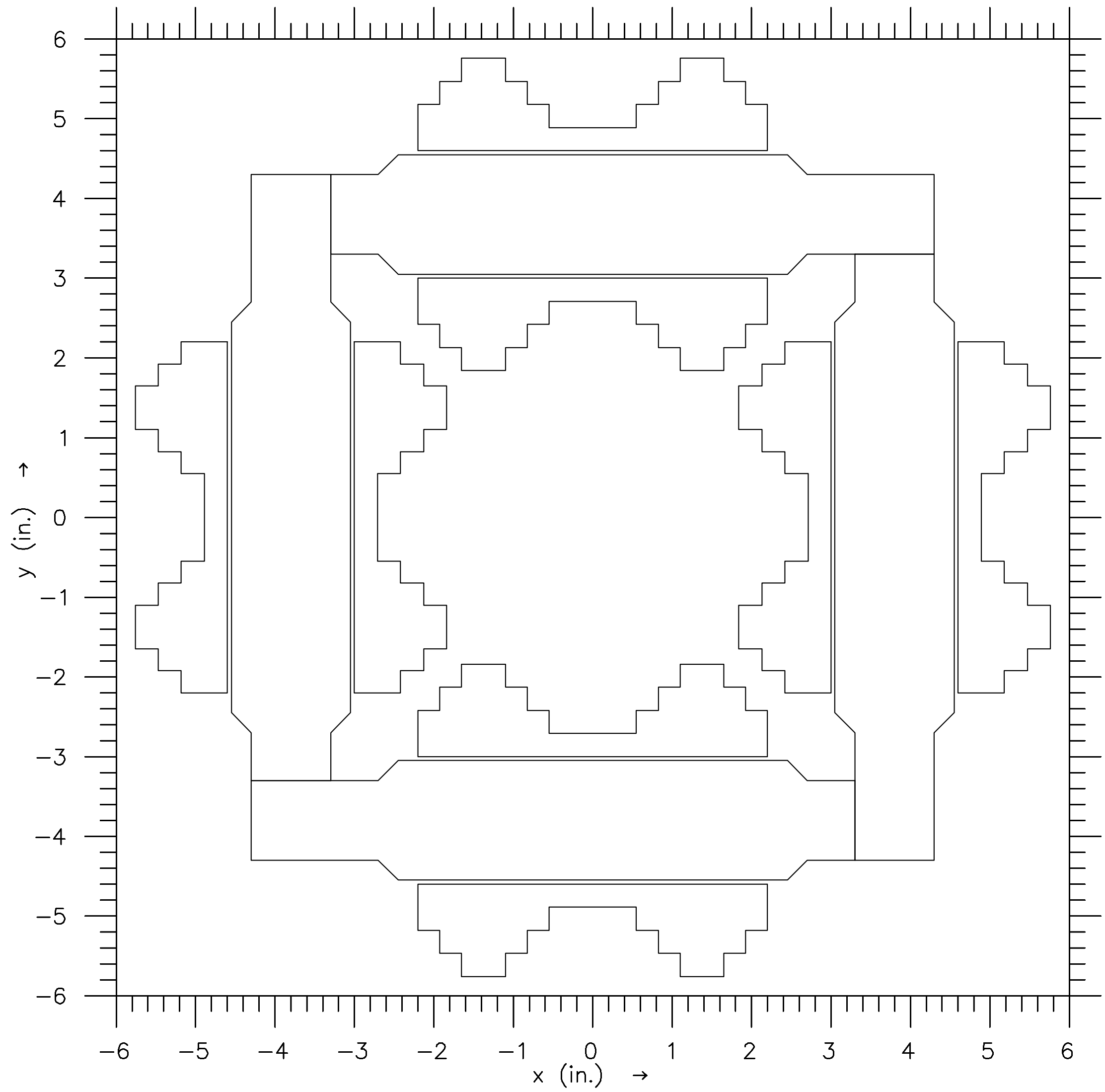

Fig. 1. Proposed design of the ‘Stinson’ steerer Mark 2.

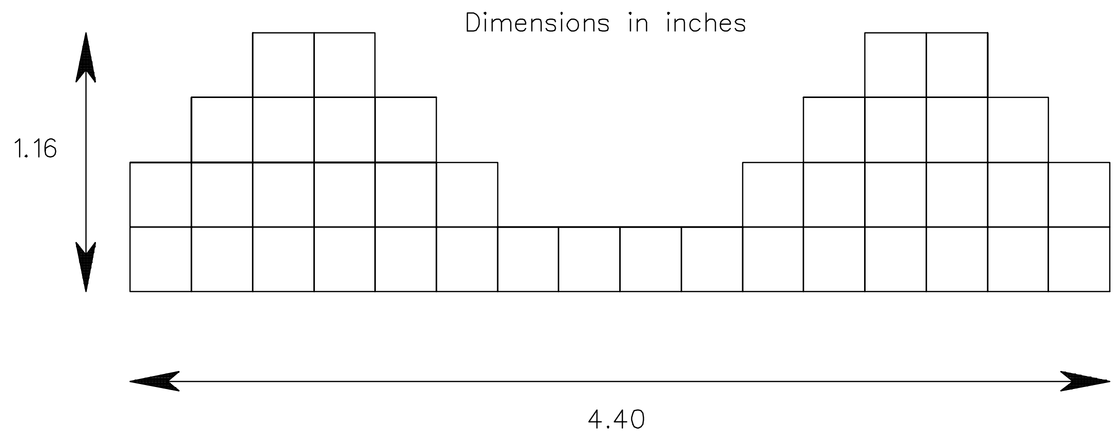

Fig. 2. Overall dimensions of a coil of the steering magnet.

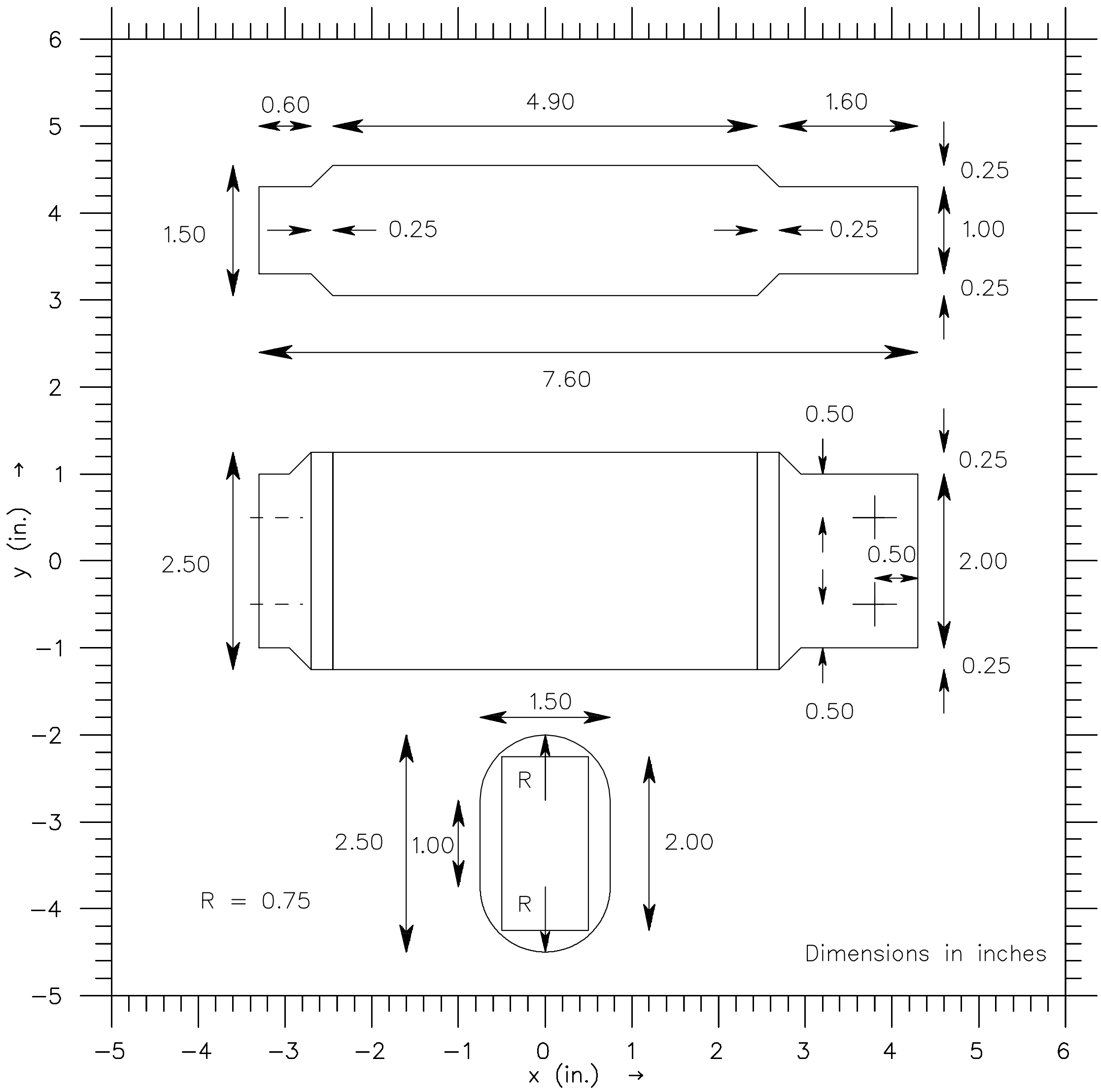

Fig. 3. Dimensions of a yoke section of the proposed $x - y$ steering magnet.

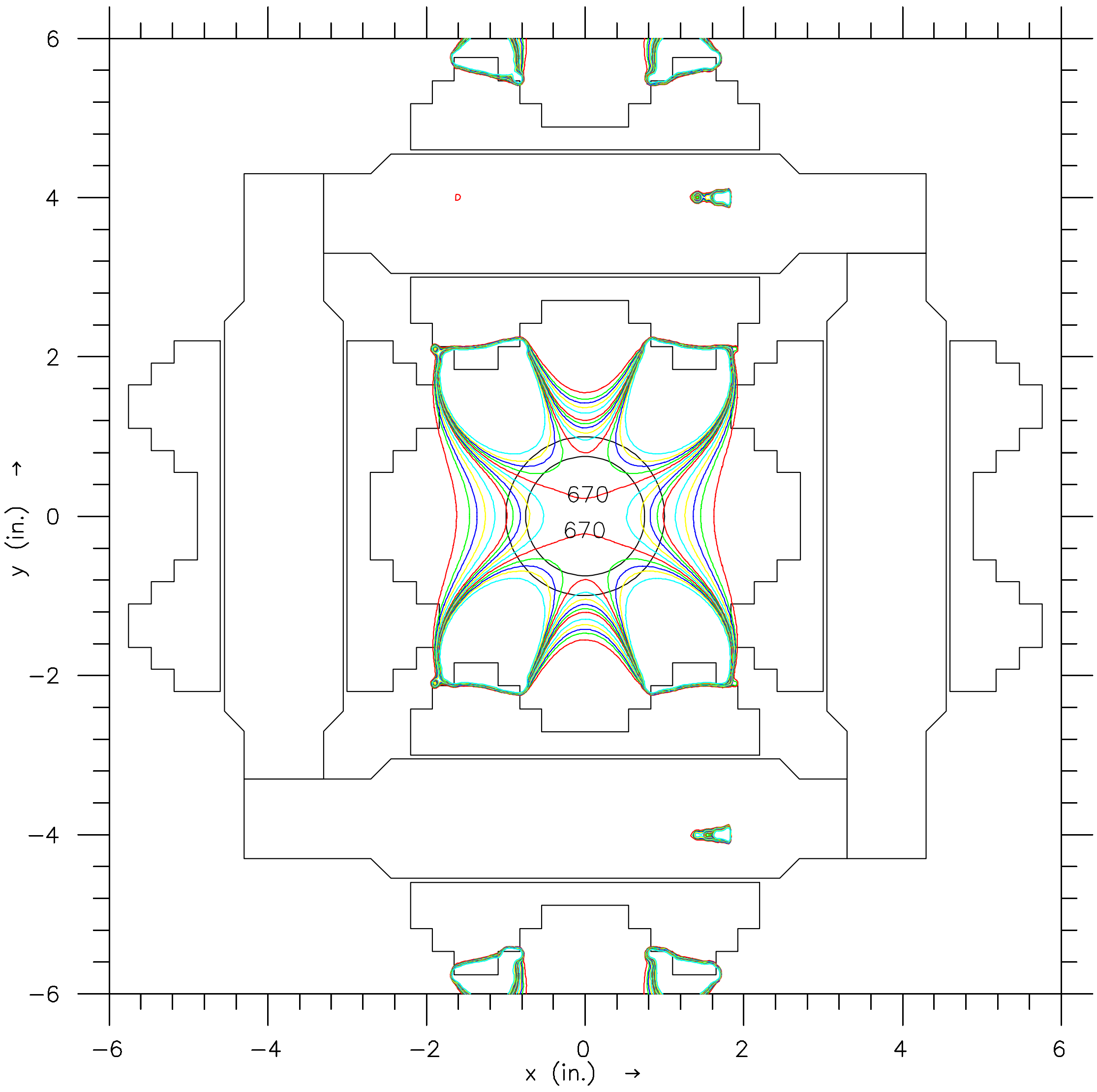

Fig. 4. POISSON prediction of the field in the gap of the proposed $x - y$ steering magnet. Only the horizontal coils are powered.

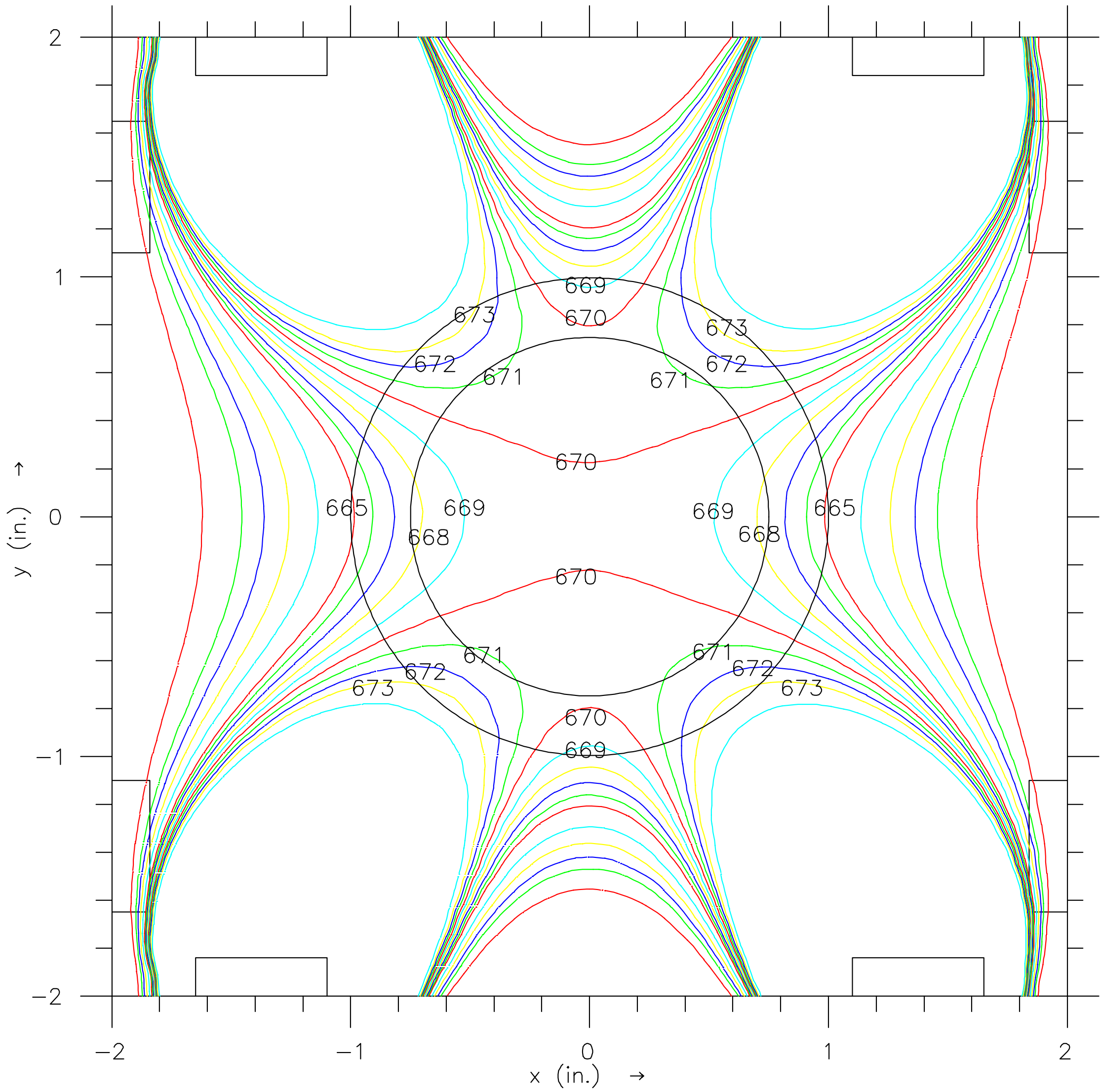

Fig. 5. Enlarged view of the POISSON prediction of the field in the gap of the proposed $x - y$ steering magnet. Contours are in Gauss. Only the horizontal coils are powered. The large circle represents the beam pipe with a diameter of 2 inches. The smaller circle has a diameter of 1.5 inches.

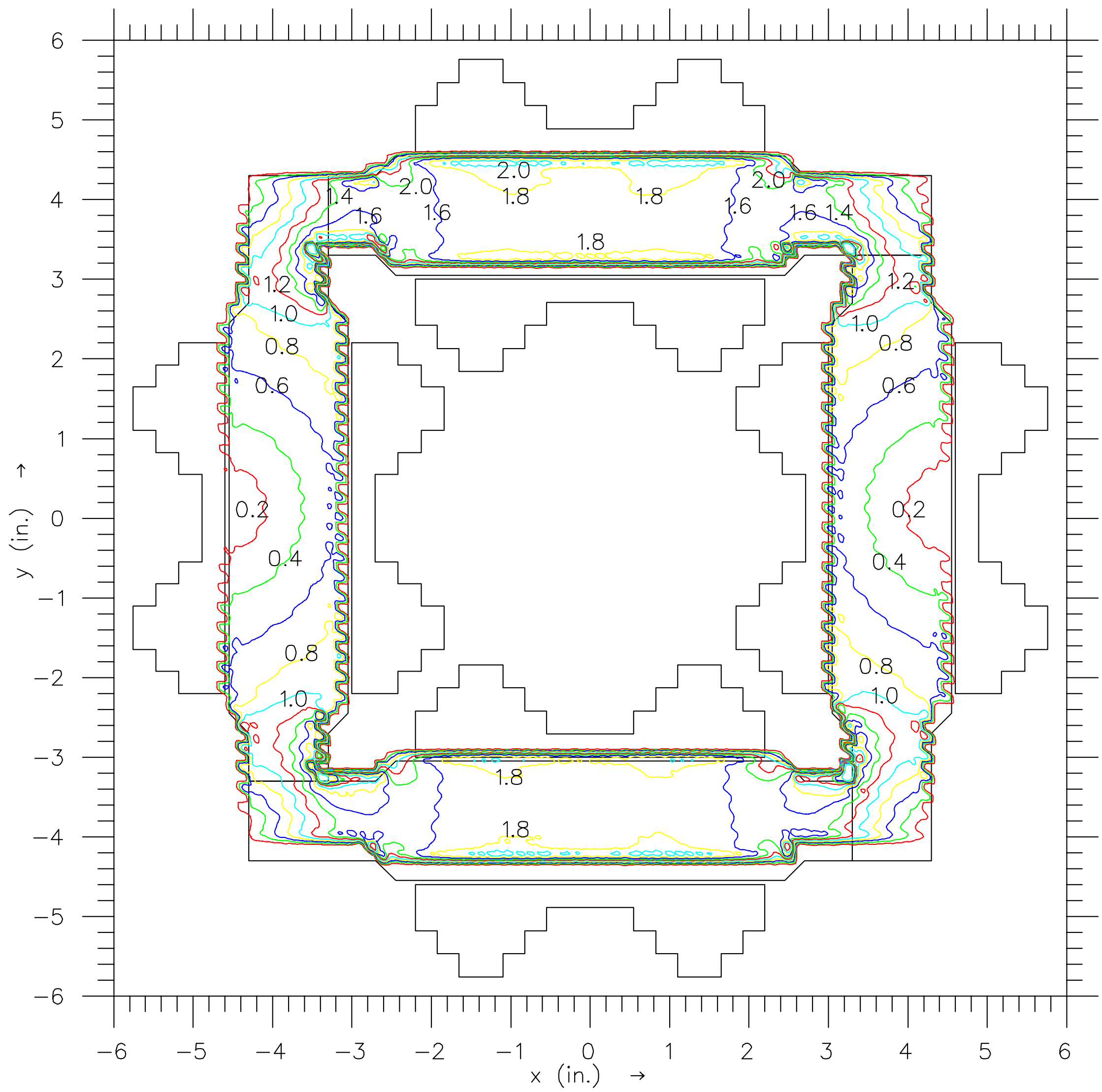

Fig. 6. The POISSON prediction of the field in the iron of the proposed $x - y$ steering magnet. Contours are in kGauss. Only the horizontal coils are powered.