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Subject A design for short quadrupoles for the ISAC MEBT beam line		

1. Introduction

For the ISAC charge selection portion of the Medium Energy Beam Transport MEBT line, the suggested MEBT optimization requires four short quadrupoles[1]. This note presents a conceptual design and a POISSON[2,3] study of a quadrupole that would be suitable for this purpose.

2. Design Parameters

The calculations of ref[1] require quadrupoles with an effective length of 0.180 m with a 2.0 in. full aperture that is capable of producing a pole-tip field of 3.0 kG. Subsequent analysis of the transport system suggested that a higher pole-tip field might be required. Although this is now known not to be the case, we proceed with a design for the higher field and establish the following parameters for the quadrupole design.

Maximum pole-tip field	5.00 kG		
Full aperture	2.100 in.	=	5.334 cm
Effective length	7.087 in.	=	18.0 cm
Maximum current	185 A		

The aperture chosen leaves room for the beam tube.

During this study several different sizes of conductor were considered. We illustrate the design procedure using an Anaconda 0.2294 and 0.2576 inch-square conductors. Results for the other conductor sizes are not given here because either of the above conductors would be suitable.

3. Ampere-turns per Coil

Allowing 10% for stray fields, we obtain the required Ampere-turns per pole from

$$NI \text{ per pole} = \frac{1.1}{2}\,(\text{half aperture})\,\frac{\text{Pole-tip field}}{4\,\pi\,10^{-7}} = 5,837$$

For a current of 185 Amperes we choose

$$\boxed{N = \text{number of turns per coil} = 32}$$

in the configuration shown below.

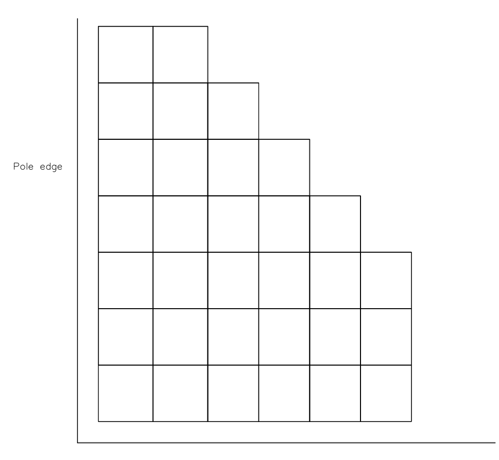

Fig. 1. Illustration of the coil configuration.

Following Banford[4)], we calculate the iron parameters (with the nominal design parameters of Banford in brackets) as

Yoke thickness [= 0.8(aperture/2.)]	1.000 in.	=	25.40 mm
Pole width [= 1.7(aperture/2.)]	1.800 in.	=	45.72 mm
Pole radius [= 1.15(aperture/2.)]	1.210 in.	=	30.734 mm
Pole length [= effective length − aperture/2.]	6.100 in.	=	154.94 mm

4. Coil Design

The copper parameters for these conductors are given in Anaconda data as follows.

	0.2294	0.2576
OD (in.)	0.2294	0.2576
ID (in.)	0.1280	0.1430
Copper area (in.^{2})	9.03838	0.04852
Cooling area (in.^{2})	0.01287	0.01606
Mass (lb/ft)	0.1438	0.18748
Resistance at 20° C ($\mu\Omega$/ft)	212.20	167.90
k (British units)	0.400	0.03540

We assume that each conductor is double-wrapped with insulation 0.007 inch thickness such that the *total* insulation per conductor has:

Minimum thickness	=	0.022 in.	=	0.559 mm
Nominal thickness	=	0.028 in.	=	0.711 mm
Maximum thickness	=	0.034 in.	=	0.864 mm

The tolerance of the outer dimension of the conductor is listed as 0.003 in. [= 0.076 mm] so that the dimensions of a *wrapped* conductor are:

	Conductor dimension	
	0.2294 in.	0.2576 in.
Minimum	0.2484 in.	0.2766 in.
Nominal	0.2574 in.	0.2856 in.
Maximum	0.2664 in.	0.2946 in.

We further allow

1. a gap between layers of 0.010 in. maximum.
2. for keystoning, assume 0.010 in.
3. a 4-turn ground wrap of 0.007 in. tape.

Then the lengths in inches of the coils along the *yoke* are

	Conductor dimension			
	0.2294 in.		0.2576 in.	
	Maximum	Minimum	Maximum	Minimum
Wrapped conductor	1.598	1.490	1.768	1.660
Gapping (5x0.010)	0.050		0.050	
Keystoning (6x0.010)	0.060	0.030	0.070	0.030
Ground wrap (4x0.007x2)	0.056	0.056	0.056	0.056
Total (in.)	1.764	1.576	1.944	1.746

The nominal widths of the coils along the yoke are 1.670 in. for the 0.2294 in. conductor and 1.845 in. for the 0.2576 in. conductor. We take

$$\begin{aligned}\text{Coil width along yoke} &= 1.70 \text{ in. for the } 0.2294 \text{ in. conductor}\\ &= 1.90 \text{ in. for the } 0.2576 \text{ in. conductor}\end{aligned}$$

The lengths in inches of the *pole* sides of the coil is obtained in a similar manner. We have

	Conductor dimension			
	0.2294 in.		0.2576 in.	
	Maximum	Minimum	Maximum	Minimum
Wrapped conductor	1.865	1.739	2.062	1.936
Gapping (6x0.010)	0.060		0.060	
Ground wrap (4x0.007x2)	0.056	0.056	0.056	0.056
Total (in.)	1.981	1.795	2.178	1.992

The nominal heights of the coils along the pole are 1.888 in. for the 0.2294 in. conductor and 2.085 in. for the 0.2576 in. conductor. We take

$$\begin{aligned}\text{Coil height along yoke} &= 1.90 \text{ in. for the } 0.2294 \text{ in. conductor}\\ &= 2.10 \text{ in. for the } 0.2576 \text{ in. conductor}\end{aligned}$$

To calculate the amount of copper required per coil we proceed as follows. We allow a *minimum* bending radius of the conductor to be four times its nominal dimension. Thus we have

$$R_{min} = 4(0.2294 \text{ in.}) \approx 0.92 \text{ in.}$$

for the smaller conductor and

$$R_{min} = 4(0.2576 \text{ in.}) \approx 1.05 \text{ in.}$$

For simplicity we choose

$$R_{min} = 1.00 \text{ in.}$$

for either conductor. Normally we would choose a pole-gap clearance and round the pole ends such that the clearance is maintained at the pole ends. In this case, if a pole-coil clearance of $G = 0.125$ in. is chosen, the pole-ends would be rounded with a radius of $R_{pole} = (R_{min} - G) = 0.875$ in. Because this is done at each pole corner and the pole is only 1.8 in. wide, this procedure will not work. Rather, we choose a clearance at the pole corners x, leave the pole end square and calculate what clearance this requires along the pole sides. We have, for $x = 0.125$ in.,

$$\begin{aligned}G &= R_{min}(1 - \cos 45) + x \cos 45\\ &= 0.381 \text{ in.}\end{aligned}$$

We take

$$\begin{aligned}R_{min} &= 1.000 \text{ in.}\\ x &= 0.151 \text{ in.}\\ G &= 0.400 \text{ in.}\\ R_{pole} &= 0.000 \text{ in.}\end{aligned}$$

We simplify the calculation by assuming *square* corners on the coil. Then the length of conductor of dimension d_{nom} in the n^{th} turn of a layer along the length of the pole, $L_{n,long}$, is

$$L_{n,long} = L_{iron} + 2(G + n\, d_{nom})$$

and that along the width of the pole, $L_{n,wid}$, is

$$L_{n,wid} = W_{iron} + 2(G + (n-1)d_{nom}).$$

Thus the length of the n^{th} turn of a layer, l_n, is

$$\begin{aligned} L_n &= 2(L_{n,long} + L_{n,wid}) \\ &= 2[L_{iron} + 2(G + n\,d_{nom}) + W_{iron} + 2(G + (n-1)d_{nom})] \\ &= 2[L_{iron} + W_{iron} + 4\,G - 2\,d_{nom} + 4\,n\,d_{nom}] \end{aligned}$$

and the length of an N-turn layer, L_N, is

$$\begin{aligned} L_N &= \sum_{n=1}^{N} L_n \\ &= 2\,N\,[L_{iron} + W_{iron} + 4\,G - 2\,d_{nom}] + 4\,N(N+1)\,d_{nom} \end{aligned}$$

In our case, we have $L_{iron} = 6.100$ in. and $G = 0.400$ in. and we take the maximum wrapped conductor dimension for $d_{nom} = 0.295$ in. In a later section we consider both a straight and a tapered pole. The base width of the latter is 3.05 in. and we use this for the pole width W_{iron}. Assuming that the coil is wound from the pole outward, the following table is generated for the coil configuration considered here.

	Conductor dimension			
	0.2294 in.		0.2576 in.	
Number of turns/layer	Length of layer	Accumulated length	Length of layer	Accumulated length
3	74.090	74.090	75.106	75.106
4	103.050	177.140	104.854	179.960
5	134.140	311.280	136.960	316.920
6	167.362	478.642	171.422	488.342
7	202.714	681.356	208.242	696.584
7	202.714	884.070	208.242	904.826

Thus the length of copper per coil is estimated to be approximately 890 in. for the smaller conductor and 910 in. for the larger. Although we have overestimated this length, we take for either conductor

Length of copper per coil = 924 in. = 77 ft.

Because four coils are required per quadrupole, we calculate the amount of copper to order, using the densities listed previously, from

	Conductor dimension			
	0.2294 in.		0.2576 in.	
Length of copper per quadrupole	310 ft	45.97 lb	310 ft	58.12 lb
Allow 10% winding loss	31 ft	4.60 lb	31 ft	5.81 lb
Total	342 ft	50.57 lb	342 ft	63.93 lb

Thus

$$\begin{aligned} \text{Amount of copper to order per quadrupole} &= 350 \text{ ft} \approx 52 \text{ lb. of } 0.2294 \text{ in. conductor} \\ &= 350 \text{ ft} \approx 66 \text{ lb. of } 0.2576 \text{ in. conductor} \end{aligned}$$

5. Power requirements

At 20°C the resistance of a coil made of the smaller conductor, $R_{s,20}$, is

$$R_{s,20°C} = (212.20 \times 10^{-6}\Omega/\text{ft})(77\text{ ft}) = 0.01634\ \Omega$$

and that of a coil made of the larger conductor, $R_{l,20}$, is

$$R_{l,20°C} = (167.90 \times 10^{-6}\Omega/\text{ft})(77\text{ ft}) = 0.01293\ \Omega$$

We assume an ambient temperature of 20°C, an inlet water temperature of 30°C and an outlet water temperature of 70°C (thus allowing a 40°C coolant temperature rise). Then the mean coil temperature will be 50°C. With a 30°C rise above ambient of the coil we then have

$$\begin{aligned} R_{hot} &= R_{20°C}\,[\,1 + (\text{Temp. coeff}/°\text{C})\times\Delta\text{T}(°\text{C})\,] \\ &= R_{20}\times[1 + 0.00393\times30] \\ &= 1.1179\,R_{20}\ \Omega \text{ per coil} \end{aligned}$$

Thus for the two conductors we find

$$\begin{aligned} R_{hot} &= 0.01827\,\Omega \text{ for the 0.2294 in. conductor} \\ &= 0.01445\,\Omega \text{ for the 0.2576 in. conductor} \end{aligned}$$

and at a current of 185 A we obtain

$$\begin{aligned} \text{Voltage per coil} &= 3.380 \text{ Volts for the 0.2294 in. conductor} \\ &= 2.674 \text{ Volts for the 0.2576 in. conductor} \end{aligned}$$

Therefore, allowing for a 10% lead loss, we choose a power supply that has the following minimum requirements

		Conductor dimension			
		0.2294 in.		0.2576 in.	
I	=	185	A	185	A
V	=	14.00	V total	11.0	V total
P	=	2.59	kW total	2.04	kW total

6. Cooling requirements

In these calculations we use the British system of units. The power required per coil is

$$\begin{aligned} \text{Power per coil} &= I^2\,R_{hot} \\ &= (185)(185)(0.01827) = 0.6253 \text{ kW for the 0.2294 in. conductor} \\ &= (185)(185)(0.01445) = 0.4946 \text{ kW for the 0.2576 in. conductor} \end{aligned}$$

The required flow rate is given by

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

For $\Delta T = 72°\text{F} = 40°\text{C}$ and $A = 0.01287\text{ in}^2$ we have for the smaller conductor

$$v = \frac{(2.19)(0.6253)}{(72)(0.01287)} = 1.4778 \text{ ft/sec}$$

and for $\Delta T = 72°\text{F} = 40°\text{C}$ and $A = 0.01606\text{ in}^2$ we have for the larger conductor

$$v = \frac{(2.19)(0.4946)}{(72)(0.01606)} = 0.9367 \text{ ft/sec}$$

The volume of flow required per circuit is

$$\begin{aligned} \text{Volume/circuit} &= v\,\frac{\text{ft}}{\text{sec}} \times A_{H_2O}\,(\text{in}^2) \times 60\,\frac{\text{sec}}{\text{min}} \times \frac{1}{144}\,\frac{\text{ft}^2}{\text{in}^2} \times 62.4\,\frac{\text{lb}}{\text{ft}^3} \times \frac{1}{10}\,\frac{\text{IG}}{\text{lb}} \times \frac{1}{0.832675}\,\frac{\text{USG}}{\text{IG}} \\ &= 3.12247\,v\,(\text{ft/sec}) \times \text{Cooling area}\,(\text{in}^2)\ \text{USGPM} \end{aligned}$$

We then find for the smaller conductor

$$\text{Volume/circuit} = 3.12247(1.4778)(0.01287) = 0.0594\ \text{USGPM} = 0.2248\ \ell/\text{min}.$$

and for the larger conductor

$$\text{Volume/circuit} = 3.12247(0.9367)(0.01606) = 0.0470\ \text{USGPM} = 0.1778\ \ell/\text{min}.$$

$$\begin{aligned} \text{Total flow volume per quadrupole} &= 0.24\ \text{USGPM} = 0.908\ \ell/\text{min for the 0.2294 in. conductor} \\ &= 0.19\ \text{USGPM} = 0.712\ \ell/\text{min for the 0.2576 in. conductor} \end{aligned}$$

7. Pressure drop

The pressure drop is given by

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

with k a function of the cooling area. In our case, with $k = 0.0400$ we obtain for the smaller conductor

$$\Delta p = (0.0400)(1.4778)^{1.79} = 0.0805\ \text{psi/ft}$$

and for the larger conductor we find

$$\Delta p = (0.0354)(0.9367)^{1.79} = 0.00315\ \text{psi/ft}$$

Thus the total pressure drop across the coil is

$$\begin{aligned} \text{Pressure drop per coil} &= 6.20\ \text{psi for the 0.2294 in. conductor} \\ &= 2.43\ \text{psi for the 0.2576 in, conductor} \end{aligned}$$

8. Iron dimensions

In the calculation of the iron dimensions, two pole configurations were considered. The two configurations studied are shown in figure 2; they were chosen so that the yoke fields would be compared later using the program POISSON to see if saturation occurred in either (or both).

The upper portion of the figure shows an octant of a quadrupole with a straight pole 1.80 in. wide. The coil is located 0.40 in. from the pole and is placed such that the *minimum* distance between the coil and the horizontal symmetry axis is 0.25 in. Clearance between the coil and the yoke is 0.125 in.

The lower portion of the figure shows an octant of a quadrupole with its pole flared at a 35° angle with respect to the horizontal symmetry axis. In this case the base width of the pole is required to be 3.044 in. Again, the minimum distance between the coil and the horizontal symmetry axis is 0.25 in., the clearance between the coil and the pole is 0.40 in. and that between the coil and the yoke is 0.125 in.

Because of the insistence that the minimum distance between the coil and the horizontal symmetry axis be 0.25 in. (thus assuring a coil-to-coil separation of 0.50 in.) we list in the following table the coordinates of pertinent locations for these cases. These coordinates were calculated analytically and are given in a Cartesian system centered at the center of the quadrupole. Locations are identified in the notation A:B with the meaning 'The coordinates of the intersection of A and B'. All coordinates are given in inches.

At this point we take the prerogative of the designer and choose the 0.2576 in.-square conductor for the coil material. *All subsequent calculations presented here are with the use of this conductor.*

Location	Straight pole		Sloped pole	
	x	y	x	y
Curved pole : 45° symmetry axis	0.7425	0.7425	0.7425	0.7425
Curved pole : pole side	1.6626	0.3898	1.6626	0.3898
Pole side : inner yoke	3.8471	2.5743	4.5981	2.4453
Inner yoke : 45° symmetry axis	3.2107	3.2107	3.5217	3.5217
Outer yoke : 45° symmetry axis	3.9178	3.9178	4.2288	4.2288

From the above data, we may calculate the iron dimensions. We have

	Straight pole	Sloped pole
Length of pole side (in.)	3.1758	3.6851
Overall height of pole (in.)	3.4907	3.9304
Width of pole at curve-side intersection (in.)	1.800	1.800
Width of pole at base (in.)	1.800	3.044

Figure 3 shows the dimensions of an octant of a quadrupole with a straight pole. A completed quadrupole is shown in figure 4. Note that the yoke is asymmetric relative to the center-line of the pole. One side is 1 in. longer than twice the dimension shown in figure 3 in order to allow the yokes to be bolted (or welded) together. Figures 5 and 6 are similar diagrams for a quadrupole with a sloped pole.

We are now in a position to calculate the amount of iron required for each of the quadrupoles. We begin by noting that the area of the circular segment portion of the pole, A_{csp}, is given by

$$A_{csp} = \frac{1}{2} R_{pole}^2(\theta - \sin\theta)$$

where $R_{pole} = 1.210$ in. is the radius of curvature of the pole end and θ is the angle between the lines that join the points of intersection of the curved pole and the pole sides to the center of curvature of the pole end. In our case we have

$$\frac{\theta}{2} = \sin^{-1}\left[\frac{0.900}{1.210}\right] = 48.056° = 0.83874 \text{ radian}$$

so that the area of *one half* of the curved segment of the pole is

$$\begin{aligned} A_{csp/2} &= R_{pole}^2(\theta - \sin\theta)/4 \\ &= (1.210)[(0.83874)(2) - \sin(2(48.056))]/4 \\ &= 0.3025[1.67748 - 0.99432] \\ &= 0.20666 \text{ in.}^2 \end{aligned}$$

Then the area of one half of a pole of a quadrupole with a straight pole, $A_{str/2}$, is

$$\begin{aligned} A_{str/2} &= A_{csp/2} + [(\text{pole width})/2](\text{length of pole side}) \\ &= 0.20666 + (1.800)(3.1758)/2 \\ &= 3.06488 \text{ in.}^2. \end{aligned}$$

The area of one half of a pole of a quadrupole with a sloped pole, $A_{slope/2}$, is the above plus the triangular area A_{tri}

$$\begin{aligned} A_{tri} &= [(\text{length of sloped side})\sin(10°)][(\text{length of sloped side})\cos(10°)]/2 \\ &= (3.6851)(0.17365)(3.6851)(0.98481)/2 \\ &= 1.16116 \text{ in.}^2 \end{aligned}$$

so that

$$\begin{aligned} A_{slope/2} &= A_{str/2} + A_{tri} \\ &= 3.06468 + 1.16116 \\ &= 4.22584 \text{ in.}^2. \end{aligned}$$

Because the yoke thickness is one inch, the area of a yoke piece is (numerically) equal to its length. Thus, using an iron density of 0.2833 lb/in.^{3}, we find

			Straight pole	Sloped pole
Pole area (in.^{2})	=	8(pole area/2)	24.519	33.807
Yoke area (in.^{2})	=	4(area of yoke piece)	40.324	43.844
Total area (in.^{2})			64.843	77.651
Iron volume (in.^{3})	=	(6.1 in.)(Total area)	395.543	473.669
Iron weight (lb)			112.057	134.191

we take

Weight of a quadrupole with straight poles	=	115 lb
Weight of a quadrupole with sloped poles	=	140 lb

9. POISSON calculations

As was noted in previous sections, POISSON runs were made on each of these two designs in order to see if either or both would be unsuitable because of yoke saturation. Table 1 gives the input for the case of a quadrupole with a straight pole to the FRONT program that generates input for the AUTOMESH routine of POISSON. Similar input for the sloped-pole case is given in table 2. In each case the mesh for calculation was based on a 0.05 in. grid in each of the horizontal and vertical directions. We remind the reader that these calculations are for a nominal pole-tip field of 5 kG.

As in the case of the design of the 4Q8.5/8.5 quadrupoles[5,6)], if saturation were to occur it would be expected to show up at the pole-yoke interface. Figure 7 is POISSON output of the field in region of the pole-yoke intersection for the case of a quadrupole with straight poles. The values of K and L are the horizontal and vertical locations, respectively, of the mesh points of the field grid set up by POISSON. They may be converted to (approximate) x-y coordinates relative to the quadrupole axis by multiplying the K and L values by 0.05 in. Similar output for the sloped-pole case is shown in figure 8.

Figure 9 shows the POISSON prediction for the fields in the iron in the region of the pole tip for a quadrupole with poles that are straight-sided. A similar prediction for a quadrupole with sloped sides is shown in figure 10. As is indicated in these figures, the field in the iron at the pole-tip is approximately 5 kG along the pole edge.

POISSON creates a triangular mesh that is divided into an upper and a lower triangle group for each cut along the horizontal axis. The upper portion of figure 11 shows the POISSON prediction for the field in the iron of the upper triangle group for a quadrupole with straight-sided poles. The lower portion of the figure shows the prediction for the lower triangle group. It is seen that even for a nominal pole-tip field of 5kG the predicted fields in the iron are below saturation in general. The upper and lower portions of figure 12 show similar predictions for a quadrupole with poles that have sloped sides.

Finally, the upper portion of figure 13 shows the predicted field in the gap of a quadrupole with straight-sided poles. The lower portion of the figure shows similar data for a quadrupole with poles that have sloped sides. Because the field at which these quadrupoles are to be run is quite low, it is not expected that any significant saturation should occur. Indeed, this was confirmed by the POISSON runs. The quadrupole with the straight pole shows higher fields in the iron at the pole-yoke junction then does a quadrupole with a sloped pole at the same location.

For a quadrupole with a straight pole it is seen from figure 7 that in the region of the pole-yoke interface the field in the iron predicted to reach a maximum value of 16.1 kG at one point only. There are a few points in this region at which fields in the order of 15 kG are predicted. Otherwise the field is predicted to be lower than approximately 14.3 kG. Field values in the yoke and pole average approximately 8.5 kG. In contrast, the field in the iron of a quadrupole with a sloped pole is predicted to reach a maximum of 17.0 kG at one point only in the region of the pole-yoke interface. A field of 16.0 kG is predicted at another and a field greater than 15 kG is predicted at two other points. In general, however, the predicted field in the yoke is significantly lower for the sloped-pole case.

10. Discussion

This report presents two possible designs for a short quadrupole for the MEBT. Either design would be suitable.

The first design, that with a pole with straight sides, would be the simplest to manufacture. The second design, that with a pole with sloped sides, would require somewhat more machining, is approximately 17% heavier and approximately 10% larger in cross section. Also, because of the sloped pole, either the coil would have to be wound on a slant or an insulating wedge would be required between the coil and the yoke. However, neither of these is of any great concern; for example, the coils of the 4Q8.5/8.5 quadrupoles are wound on a slant.

The fields in the region of the pole-interface are slightly lower in the second design than those in the same region of the first design. Nowhere do these fields approach saturation. However, because the quadrupole is designed to have a maximum pole-tip field of 5 kG and, in all likelihood, the quadrupole would be run at lower fields, it is felt that the differences in fields in the iron are of no practical significance.

Table 3 summarizes the parameters of these designs. It is the opinion of the author that in order to have 'good' quadrupole the sloped-pole design should be adopted.

References

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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. G. W. Rodenz, *User's Guide to the Program FRONT*, Los Alamos Accelerator Code Group, June, 1992.
4. A. P. Banford, *The Transport of Charged Particles*, SPON, 1966.
5. G. M. Stinson, *A design for the quadrupoles for beam line 2A*, TRIUMF Report TRI-DNA-96-7, April, 1996.
6. M. Dehnel, *A revised design for the Beamline 2A quadrupole magnets*, TRIUMF Report TRI-DN-ISAC-6, August, 1996.

Table 1

POISSON input for a quadrupole with straight pole

```
title
Short quad for MEBT – Straight pole, 0.2576 in. conductor, 5,280 A-t
run
pois
mode 0
xmax=7.15
ymax=4.00
xmesh 0.05
ymesh 0.05
symm=4
nseg 4
conv=2.54
matpro 1
zseg        0.         6.421474   7.128581                           3.917844
rseg        0.         0.         0.707107                           3.917844
nseg 6
conv=2.54
zseg        0.742462   1.662575   3.847133                           6.421474   7.128581   3.917844
rseg        0.742462   0.389783   2.574341                           0.         0.707107   3.917844
cseg        0.         1.210000   0.                                 0.         0.         0.
matpro 2
nseg 5
matpro 1
conv=2.54
zseg        2.585513   3.015340   4.746634                           5.370666   4.041587
rseg        0.747036   0.317209   0.250000                           0.874032   2.203110
current=5280.
nseg 2
matpro 1
ibound=0
conv=2.54
zseg        0.         3.917844
rseg        0.         3.917844
nseg 2
matpro 1
ibound=0
conv=2.54
zseg        7.128581   3.917844
rseg        0.707107   3.917844
nseg 2
matpro 1
ibound=1
conv=2.54
zseg        6.421474   7.128581
rseg        0.         0.707107
kbot=1
lbot=1
ltop=15
fieldmap 2
begin
end
```

Table 2

POISSON input for a quadrupole with sloped pole

```
title
Short quad for MEBT – Slanted pole, 0.2576 in. conductor, 5,280 A-t
run
pois
mode 0
xmax=7.80
ymax=4.25
xmesh 0.05
ymesh 0.05
symm=4
nseg 4
conv=2.54
matpro 1
zseg          0.         7.043400   7.750507                          4.228807
rseg          0.         0.         0.707107                          4.228807
nseg 6
conv=2.54
zseg          0.742462   1.662575   4.598124                          7.043400   7.750507   4.228807
rseg          0.742462   0.389783   2.445277                          0.         0.707107   4.228807
cseg          0.         1.210000   0.                                0.         0.         0.
matpro 2
nseg 5
matpro 1
conv=2.54
zseg          3.094558   3.524385   5.387521                          6.110434   4.781356
rseg          0.904158   0.474332   0.250000                          0.756189   2.085267
current=5280.
nseg 2
matpro 1
ibound=0
conv=2.54
zseg          0.         4.228807
rseg          0.         4.228807
nseg 2
matpro 1
ibound=0
conv=2.54
zseg          7.750507   4.228807
rseg          0.707107   4.228807
nseg 2
matpro 1
ibound=1
conv=2.54
zseg          7.043400   7.750507
rseg          0.         0.707107
kbot=1
lbot=1
ltop=15
fieldmap 2
begin
end
```

Table 3
Summary of quadrupole parameters for the different pole shapes

Parameter		Straight pole	Sloped pole
Conductor:	OD (in.)	0.2576	0.2576
	ID (in.)	0.1430	0.1430
	Copper area (in.^{2})	0.0485	0.0485
	Cooling area (in.^{2})	0.0161	0.0161
	Weight (lb/ft)	0.1875	0.1875
	Resistance at 20° C ($\mu\Omega$/ft)	167.90	167.90
	k (British units)	0.0354	0.0354
Coil:	Number of turns	32	32
	Number of layers	7	7
	Nominal width along yoke (in.)	1.900	1.900
	Nominal height along pole (in.)	2.100	2.100
	Length per coil (ft)	77.0	77.0
	Weight per coil (lb)	15.0	15.0
	Weight per quadrupole (lb)	60.0	60.0
	Resistance per coil (hot) (mΩ)	14.45	14.45
	Coolant flow rate (ft/sec)	0.94	0.94
	Volume per coil (USGPM)	0.047	0.047
	Pressure drop per coil (psi)	2.43	2.43
Iron:	Yoke thickness (in.)	1.000	1.000
	Yoke width (in.)	10.081	10.961
	Yoke length (in.)	6.100	6.100
	Pole radius (in.)	1.210	1.210
	Pole width at curve-side intersection	1.800	1.800
	Pole width at base (in.)	1.800	3.044
	Overall pole height (in.)	3.491	3.930
	Weight (lb)	120.	140.
Power:	Current (A minimum)	185.	185.
	Voltage (V minimum)	11.	11.
	Power (kW minimum)	2.04	2.04
Quadrupole:	Aperture (in.)	2.100	2.100
	Width (in.)	15.671	16.915
	Height (in.)	15.671	16.915
	Length (in.)	10.700	10.700
	Assembled weight† (lb)	180.	200.

† Excluding power and coolant connections.

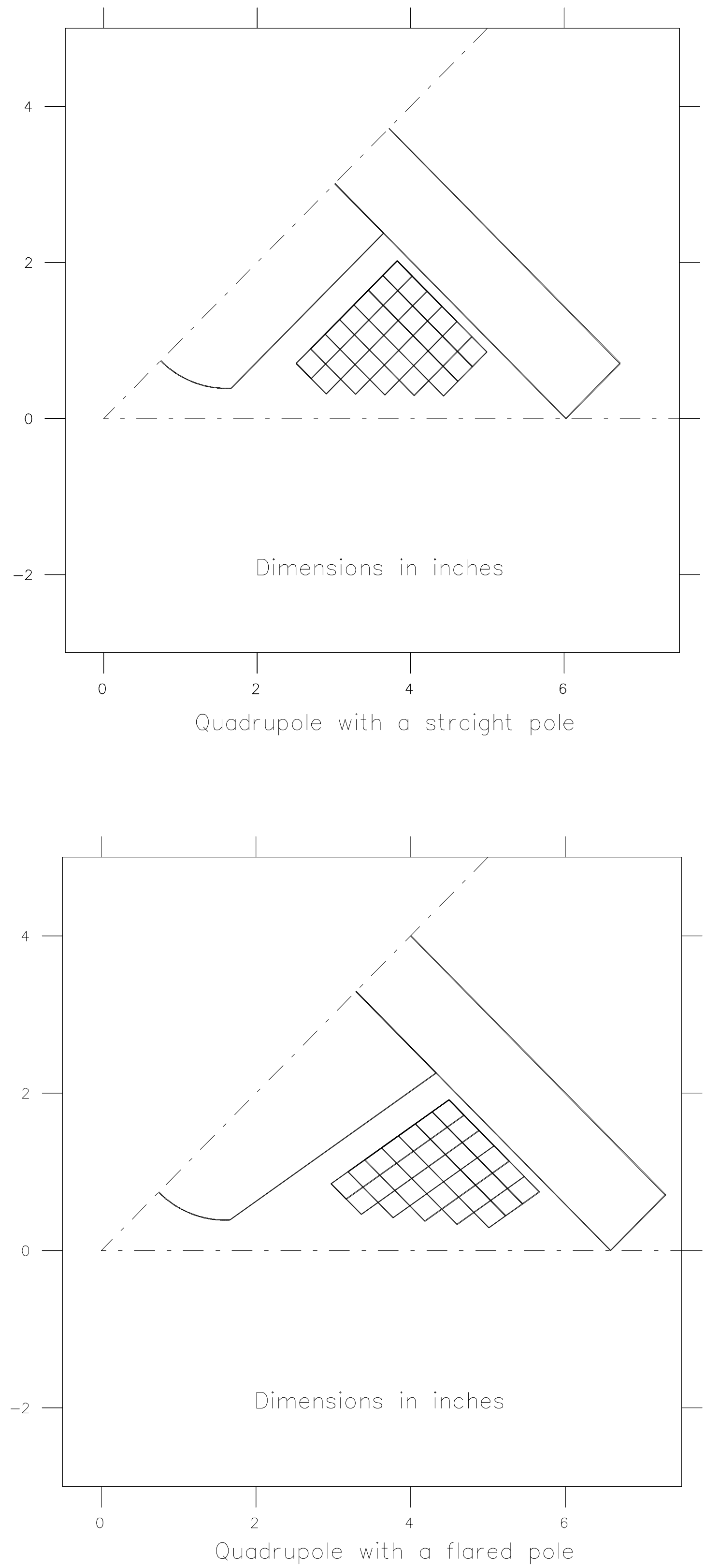

Fig. 2. The two pole-coil configurations studied.

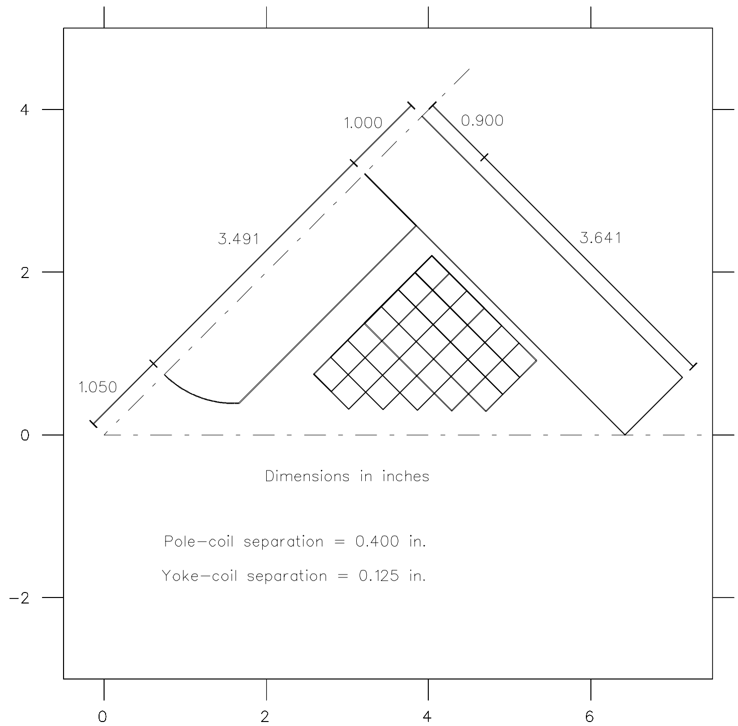

Fig. 3. Dimensions of an octant of a quadrupole with a straight pole.

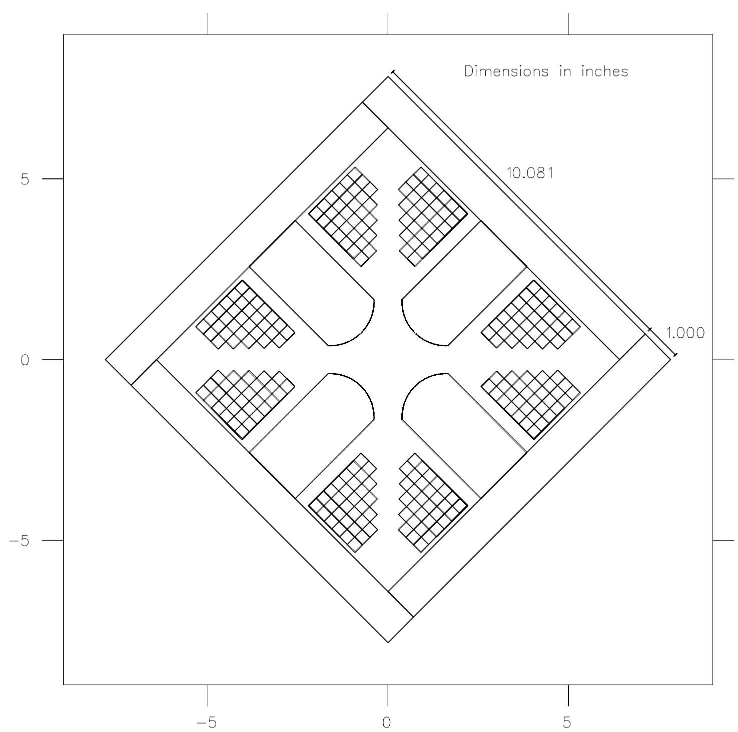

Fig. 4. Dimensions of a quadrant of a quadrupole with a straight pole.

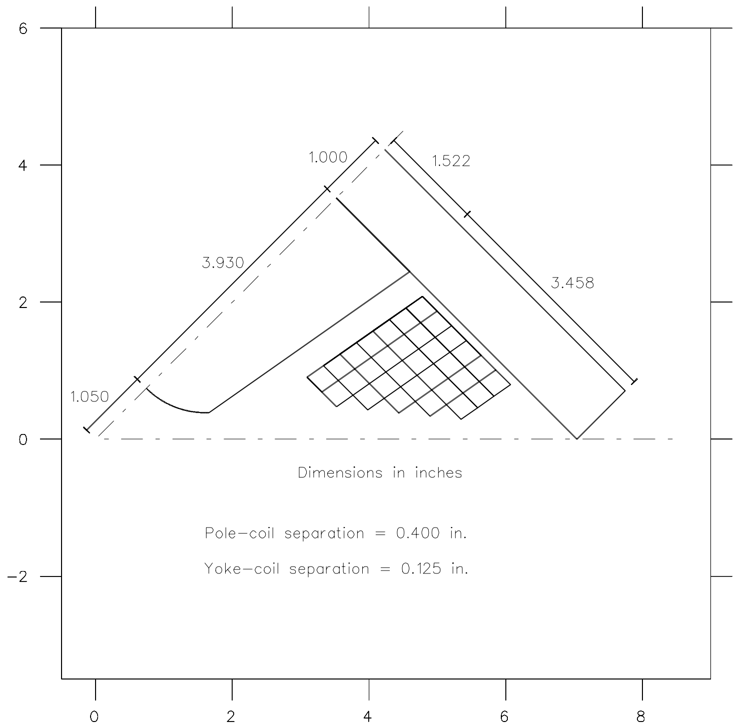

Fig. 5. Dimensions of an octant of a quadrupole with a sloped pole.

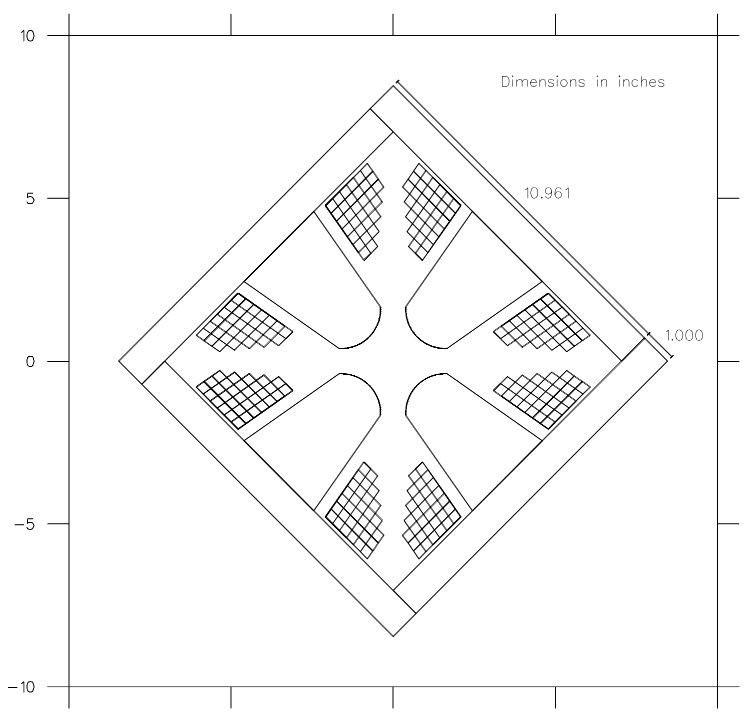

Fig. 6. Dimensions of an quadrant of a quadrupole with a sloped pole.

```
THE FOLLOWING IS A MAP OF /B/(KG) UPPER --- CYCLE 1390   Short quad for HEBT - Straight pole, 0.2576 in. conductor, 5,280 A-t
                          /B/(KG) LOWER
 L
 .         .
 .    K .......
...        .
 .
```

		67	68	69	70	71	72	73	74	75	76	77	78	79	80	81	82	83	84	85	86	87	88
79	U																						
	L													0.00									
78	U													0.39	0.78								
	L												0.00	1.10	1.65								
77	U											1.47	0.70	0.91	1.36								
	L											2.82	1.40	1.86	2.63	0.00							
76	U											2.60	1.78	1.57	1.67	1.94	2.53						
	L										0.00	2.59	2.50	2.44	2.68	2.30	3.51						
75	U									3.96	1.94	2.25	2.32	2.42	2.61	2.93	3.42						
	L									5.50	3.16	3.68	3.55	3.53	3.53	3.93	5.54	0.00					
74	U									5.22	3.88	3.45	3.36	3.37	3.44	3.60	3.84	4.17	4.86				
	L								0.00	4.83	4.70	4.37	4.43	4.40	4.41	4.55	4.83	4.10	5.68				
73	U							6.36	4.01	4.45	4.35	4.26	4.23	4.26	4.35	4.52	4.79	5.19	5.73				
	L							7.97	5.31	5.81	5.45	5.27	5.23	5.21	5.25	5.36	5.42	6.04	8.43	0.00			
72	U							7.57	6.31	5.55	5.26	5.11	5.05	5.04	5.09	5.19	5.38	5.66	6.01	6.39	6.98		
	L						0.00	7.23	7.01	6.43	6.31	6.14	6.03	5.98	5.97	6.02	6.12	6.39	6.84	5.83	7.54		
71	U					8.33	6.18	6.74	6.48	6.16	5.95	5.84	5.80	5.81	5.87	5.99	6.19	6.46	6.81	7.23	7.69		
	L					10.03	7.42	7.91	7.43	7.12	6.93	6.78	6.69	6.65	6.66	6.74	6.89	7.10	7.22	7.93	10.83	0.00	
70	U					9.50	8.56	7.63	7.27	6.99	6.76	6.59	6.50	6.48	6.51	6.59	6.74	6.95	7.22	7.54	7.90	8.23	8.67
	L				0.00	9.52	9.13	8.48	8.24	7.93	7.68	7.50	7.38	7.31	7.28	7.31	7.40	7.56	7.77	8.10	8.59	7.29	9.01
69	U			9.90	8.10	8.80	8.55	8.10	7.77	7.50	7.31	7.19	7.13	7.12	7.17	7.27	7.43	7.65	7.91	8.20	8.52	8.88	9.22
	L			11.70	9.21	9.79	9.34	8.97	8.67	8.42	8.22	8.07	7.96	7.91	7.90	7.94	8.04	8.19	8.41	8.67	8.75	9.44	12.67
68	U			11.01	10.40	9.48	9.17	8.85	8.51	8.23	8.02	7.87	7.77	7.73	7.74	7.81	7.93	8.09	8.29	8.54	8.81	9.10	9.38
	L		0.00	11.47	10.87	10.30	10.03	9.68	9.38	9.13	8.90	8.71	8.58	8.49	8.45	8.45	8.51	8.62	8.79	8.98	9.18	9.49	9.96
67	U	11.08	9.67	10.46	10.32	9.88	9.52	9.22	8.94	8.70	8.51	8.38	8.30	8.29	8.32	8.40	8.52	8.69	8.89	9.11	9.35	9.59	9.83
	L	12.86	10.57	11.29	10.94	10.64	10.34	10.06	9.79	9.55	9.36	9.21	9.09	9.02	8.99	9.00	9.06	9.16	9.31	9.48	9.70	9.92	9.91
66	U	12.11	11.76	10.97	10.75	10.50	10.18	9.88	9.60	9.34	9.14	8.99	8.89	8.84	8.84	8.89	8.97	9.09	9.25	9.43	9.62	9.83	10.04
	L	13.02	12.17	11.73	11.47	11.20	10.95	10.67	10.42	10.19	9.99	9.81	9.66	9.56	9.50	9.47	9.49	9.56	9.66	9.80	9.94	10.11	10.26
65	U	11.68	11.66	11.29	11.03	10.77	10.49	10.22	9.98	9.76	9.58	9.45	9.37	9.34	9.35	9.40	9.49	9.62	9.76	9.92	10.08	10.25	10.42
	L	12.35	12.12	11.96	11.72	11.47	11.25	11.03	10.79	10.58	10.40	10.25	10.12	10.03	9.97	9.95	9.97	10.02	10.10	10.21	10.34	10.48	10.64
64	U	11.99	11.88	11.76	11.52	11.29	11.06	10.82	10.58	10.35	10.16	10.02	9.91	9.85	9.84	9.86	9.92	10.00	10.10	10.21	10.34	10.47	10.61
	L	12.68	12.48	12.30	12.15	11.96	11.77	11.56	11.36	11.17	10.99	10.82	10.67	10.55	10.46	10.40	10.37	10.38	10.42	10.49	10.58	10.69	10.80
63	U	12.24	12.08	11.94	11.76	11.57	11.35	11.14	10.93	10.74	10.57	10.44	10.35	10.30	10.30	10.32	10.37	10.44	10.52	10.61	10.71	10.82	10.92
	L	12.81	12.65	12.50	12.36	12.21	12.06	11.90	11.73	11.55	11.39	11.23	11.10	10.98	10.88	10.81	10.78	10.77	10.79	10.83	10.89	10.97	11.05
62	U	12.53	12.41	12.27	12.15	12.00	11.84	11.67	11.48	11.29	11.11	10.97	10.86	10.79	10.76	10.76	10.78	10.81	10.85	10.90	10.95	11.02	11.09
	L	12.95	12.91	12.81	12.70	12.60	12.48	12.36	12.23	12.10	11.95	11.80	11.64	11.50	11.36	11.24	11.15	11.09	11.07	11.08	11.10	11.15	11.21
61	U	12.63	12.55	12.47	12.37	12.26	12.13	11.98	11.82	11.66	11.50	11.37	11.28	11.22	11.18	11.17	11.16	11.16	11.17	11.19	11.22	11.26	11.31
	L	13.08	13.03	12.97	12.90	12.83	12.76	12.70	12.61	12.49	12.35	12.20	12.04	11.88	11.72	11.58	11.46	11.38	11.34	11.32	11.34	11.36	11.40
60	U	12.79	12.75	12.70	12.65	12.60	12.53	12.45	12.33	12.19	12.03	11.88	11.77	11.69	11.64	11.60	11.56	11.51	11.47	11.45	11.44	11.45	11.46
	L	13.25	13.20	13.17	13.13	13.10	13.07	13.05	13.03	12.98	12.90	12.77	12.60	12.42	12.21	12.00	11.82	11.69	11.61	11.56	11.53	11.53	11.54
59	U	12.90	12.88	12.86	12.85	12.83	12.81	12.77	12.67	12.54	12.40	12.27	12.17	12.10	12.04	11.95	11.86	11.77	11.71	11.66	11.63	11.62	11.62
	L	13.34	13.32	13.31	13.31	13.32	13.34	13.37	13.42	13.41	13.33	13.19	12.99	12.75	12.48	12.20	11.99	11.85	11.76	11.71	11.68	11.67	11.67
58	U	13.01	13.00	13.01	13.02	13.05	13.08	13.11	13.13	13.05	12.92	12.78	12.67	12.58	12.50	12.39	12.23	12.07	11.95	11.86	11.80	11.76	11.74
	L	13.42	13.42	13.43	13.44	13.47	13.51	13.58	13.69	13.84	13.87	13.78	13.61	13.35	13.00	12.59	12.32	12.11	11.97	11.88	11.82	11.78	11.77
57	U	13.08	13.09	13.12	13.16	13.22	13.31	13.42	13.52	13.44	13.30	13.16	13.07	12.99	12.87	12.61	12.39	12.20	12.06	11.96	11.89	11.84	11.82
	L	13.48	13.50	13.52	13.56	13.62	13.71	13.85	14.03	14.32	14.36	14.23	14.00	13.60	13.00	12.61	12.37	12.18	12.05	11.96	11.90	11.87	11.85
56	U	13.11	13.14	13.17	13.22	13.29	13.40	13.55	13.74	13.95	13.83	13.67	13.55	13.49	13.39	13.02	12.68	12.44	12.25	12.11	12.01	11.94	11.90
	L	13.51	13.54	13.57	13.61	13.68	13.77	13.92	14.11	14.39	14.88	14.87	14.67	14.29	13.38	12.92	12.59	12.38	12.21	12.09	12.01	11.96	11.92
55	U	13.16	13.19	13.24	13.30	13.40	13.56	13.76	14.06	14.46	14.21	14.03	13.96	14.00	13.41	12.97	12.64	12.42	12.24	12.12	12.03	11.98	11.94
	L	13.55	13.59	13.63	13.70	13.79	13.92	14.11	14.37	14.77	15.50	15.31	15.08	13.79	13.20	12.81	12.54	12.35	12.21	12.11	12.04	11.99	11.97
54	U	13.16	13.19	13.23	13.29	13.37	13.49	13.67	13.93	14.35	15.01	14.53	14.39	14.66	13.77	13.20	12.80	12.54	12.35	12.21	12.11	12.04	11.99
	L	13.56	13.59	13.63	13.69	13.77	13.89	14.05	14.27	14.65	15.36	15.85	15.62	14.34	13.47	12.99	12.69	12.47	12.31	12.20	12.12	12.06	12.02
53	U	13.18	13.22	13.26	13.33	13.42	13.55	13.74	14.02	14.52	15.58	14.79	15.32	14.00	13.32	12.90	12.62	12.42	12.27	12.17	12.09	12.04	12.00
	L	13.58	13.62	13.67	13.74	13.83	13.97	14.16	14.36	14.98	17.36	11.14	16.11	13.76	13.08	12.81	12.57	12.39	12.27	12.18	12.11	12.07	12.04
52	U	13.17	13.20	13.24	13.29	13.35	13.44	13.57	13.74	13.98	14.31	15.15	14.90	13.74	13.27	12.91	12.64	12.45	12.31	12.21	12.13	12.07	12.03
	L	13.57	13.60	13.65	13.70	13.78	13.87	14.03	14.31	13.90	15.13			14.01	12.67	12.96	12.64	12.44	12.32	12.23	12.16	12.11	12.08
51	U	13.18	13.21	13.25	13.30	13.36	13.44	13.55	13.71	13.89				13.13	12.85	12.61	12.45	12.32	12.22	12.15	12.10	12.06	12.03
	L	13.58	13.62	13.66	13.72	13.80	13.83	14.11	15.54	10.06				9.19	14.13	12.71	12.42	12.36	12.27	12.19	12.14	12.11	12.08
50	U	13.16	13.18	13.22	13.26	13.30	13.36	13.43	13.51	13.67					12.76	12.54	12.42	12.31	12.22	12.16	12.11	12.07	12.05
	L	13.55	13.59	13.63	13.67	13.75	13.89	13.33	14.18							12.80	11.96	12.45	12.30	12.21	12.17	12.13	12.11
49	U	13.16	13.19	13.22	13.26	13.30	13.36	13.41								12.37	12.28	12.21	12.16	12.11	12.08	12.06	12.04
	L	13.55	13.59	13.63	13.61	13.81	15.05	9.75								8.68	13.59	12.35	12.17	12.19	12.15	12.12	12.11
48	U	13.14	13.16	13.19	13.22	13.26	13.29	13.35									12.25	12.19	12.14	12.11	12.08	12.06	12.05
	L	13.52	13.55	13.60	13.71	13.12	13.93											12.44	11.72	12.27	12.17	12.13	12.12
47	U	13.14	13.16	13.19	13.22	13.25												12.13	12.10	12.08	12.06	12.05	12.04
	L	13.53	13.49	13.66	14.83	9.67												8.50	13.42	12.23	12.08	12.14	12.12
46	U	13.11	13.14	13.16	13.19	13.22													12.08	12.08	12.06	12.05	12.05
	L	13.50	13.59	13.01	13.82															12.33	11.64	12.22	12.14
45	U	13.11	13.14	13.16																12.06	12.05	12.05	12.05
	L	13.57	14.68	9.64																8.44	13.38	12.20	12.07
44	U	13.09	13.11	13.14																	12.04	12.06	12.05
	L	12.93	13.75																			12.30	11.63
43	U	13.09																				12.05	12.05
	L	9.63																				8.44	13.38

Figure 7. POISSON prediction along pole-yoke interface of a quadrupole with straight sides. The nominal pole-tip field is 5 kG (5,280 A-t).

```
THE FOLLOWING IS A HAP OF /B/(KG) UPPER --- CYCLE 1360   Short quad for HEBT - Straight pole, 0.2576 in. conductor, 5,280 A-t
                          /B/(KG) LOWER
 L
 .         .
 .    K .......
...        .
 .
```

		81	82	83	84	85	86	87	88	89	90	91	92	93	94	95	96	97	98	99	100	101	102
85	U					0.00																	
	L					0.65																	
84	U					0.53	0.41																
	L				0.00	0.91	1.15	0.00															
83	U			1.12	0.51	0.61	0.73	1.00															
	L			1.85	0.96	1.08	0.94	1.50															
82	U			1.75	1.17	0.96	0.99	1.13	1.35														
	L		0.00	1.70	1.54	1.36	1.38	1.60	2.36	0.00													
81	U	2.43	1.22	1.40	1.34	1.30	1.36	1.48	1.66	1.96													
	L	3.18	1.75	1.88	1.76	1.72	1.81	1.98	1.74	2.50													
80	U	3.16	2.09	1.77	1.68	1.65	1.66	1.74	1.88	2.10	2.39												
	L	2.42	2.38	2.20	2.18	2.15	2.18	2.28	2.36	2.70	3.85	0.00											
79	U	2.24	2.20	2.11	2.07	2.07	2.12	2.23	2.37	2.56	2.78	3.19											
	L	3.00	2.84	2.76	2.75	2.77	2.81	2.88	3.02	3.25	2.79	3.83											
78	U	2.85	2.75	2.70	2.67	2.67	2.70	2.75	2.83	2.94	3.11	3.37	3.73										
	L	3.31	3.31	3.26	3.23	3.24	3.28	3.34	3.45	3.58	3.66	4.07	5.71	0.00									
77	U	3.23	3.17	3.15	3.15	3.17	3.21	3.28	3.38	3.52	3.70	3.91	4.18	4.63									
	L	3.81	3.78	3.76	3.76	3.79	3.84	3.90	4.00	4.12	4.33	4.67	3.99	5.26									
76	U	3.75	3.70	3.67	3.67	3.69	3.72	3.77	3.84	3.93	4.07	4.25	4.50	4.82	5.20								
	L	4.28	4.22	4.19	4.19	4.21	4.26	4.33	4.42	4.55	4.71	4.89	4.99	5.54	7.68	0.00							
75	U	4.14	4.11	4.10	4.11	4.14	4.19	4.26	4.36	4.48	4.64	4.84	5.07	5.36	5.67	6.11							
	L	4.69	4.66	4.65	4.67	4.71	4.77	4.85	4.95	5.08	5.24	5.43	5.73	6.14	5.24	6.69							
74	U	4.60	4.57	4.56	4.57	4.60	4.64	4.71	4.78	4.88	5.01	5.18	5.39	5.65	5.95	6.30	6.69						
	L	5.09	5.06	5.05	5.07	5.10	5.15	5.23	5.33	5.45	5.61	5.79	6.01	6.26	6.40	7.04	9.63	0.00					
73	U	4.97	4.96	4.96	4.99	5.03	5.09	5.16	5.26	5.39	5.55	5.74	5.96	6.22	6.51	6.84	7.15	7.59					
	L	5.45	5.44	5.45	5.49	5.54	5.62	5.71	5.83	5.97	6.12	6.32	6.55	6.80	7.15	7.63	6.49	8.10					
72	U	5.37	5.35	5.35	5.37	5.42	5.48	5.55	5.65	5.77	5.90	6.07	6.27	6.50	6.78	7.08	7.40	7.76	8.15				
	L	5.85	5.83	5.84	5.87	5.91	5.98	6.06	6.17	6.30	6.45	6.64	6.86	7.09	7.37	7.67	7.81	8.50	11.52	0.00			
71	U	5.74	5.74	5.76	5.79	5.85	5.91	6.00	6.10	6.24	6.40	6.59	6.81	7.05	7.33	7.63	7.96	8.29	8.59	9.00			
	L	6.17	6.17	6.20	6.24	6.31	6.39	6.50	6.63	6.78	6.96	7.15	7.38	7.63	7.91	8.18	8.56	9.08	7.70	9.44			
70	U	6.08	6.07	6.09	6.12	6.18	6.25	6.33	6.44	6.57	6.73	6.90	7.10	7.33	7.59	7.88	8.18	8.49	8.82	9.17	9.52		
	L	6.50	6.50	6.53	6.57	6.64	6.73	6.83	6.95	7.09	7.25	7.44	7.66	7.90	8.16	8.43	8.74	9.06	9.17	9.90	13.32	0.00	
69	U	6.40	6.42	6.46	6.51	6.58	6.67	6.77	6.90	7.03	7.20	7.39	7.61	7.86	8.12	8.41	8.71	9.03	9.34	9.66	9.94	10.30	
	L	6.83	6.85	6.90	6.96	7.03	7.13	7.24	7.38	7.54	7.73	7.94	8.16	8.41	8.68	8.97	9.25	9.53	9.92	10.44	8.80	10.64	
68	U	6.73	6.75	6.78	6.83	6.90	6.97	7.07	7.19	7.33	7.49	7.68	7.89	8.12	8.37	8.64	8.94	9.23	9.54	9.84	10.14	10.46	10.76
	L	7.12	7.14	7.18	7.24	7.31	7.41	7.53	7.67	7.83	8.01	8.21	8.42	8.66	8.93	9.19	9.47	9.76	10.06	10.36	10.42	11.15	14.87
67	U	7.03	7.06	7.11	7.18	7.26	7.36	7.48	7.62	7.78	7.96	8.15	8.37	8.62	8.89	9.16	9.45	9.74	10.04	10.33	10.61	10.89	11.12
	L	7.41	7.45	7.51	7.59	7.69	7.81	7.95	8.10	8.27	8.47	8.68	8.92	9.17	9.42	9.69	9.98	10.25	10.53	10.78	11.12	11.63	9.76
66	U	7.30	7.33	7.38	7.45	7.54	7.64	7.76	7.90	8.05	8.22	8.41	8.63	8.88	9.12	9.39	9.67	9.96	10.23	10.51	10.79	11.05	11.29
	L	7.66	7.71	7.77	7.85	7.95	8.07	8.20	8.35	8.53	8.72	8.94	9.17	9.41	9.66	9.93	10.19	10.45	10.72	10.98	11.24	11.49	11.48
65	U	7.60	7.65	7.72	7.81	7.91	8.02	8.15	8.30	8.48	8.67	8.89	9.12	9.36	9.62	9.90	10.17	10.44	10.71	10.97	11.22	11.45	11.68
	L	7.95	8.01	8.09	8.18	8.30	8.43	8.59	8.77	8.98	9.18	9.41	9.65	9.91	10.15	10.41	10.67	10.92	11.16	11.40	11.63	11.81	12.10
64	U	7.85	7.90	7.96	8.04	8.14	8.26	8.39	8.55	8.73	8.93	9.13	9.35	9.60	9.86	10.12	10.38	10.65	10.92	11.16	11.39	11.62	11.82
	L	8.17	8.22	8.30	8.39	8.51	8.65	8.82	9.01	9.20	9.41	9.64	9.89	10.14	10.39	10.64	10.89	11.13	11.36	11.58	11.79	11.98	12.18
63	U	8.11	8.18	8.26	8.36	8.49	8.63	8.79	8.97	9.15	9.36	9.59	9.84	10.09	10.34	10.61	10.88	11.12	11.36	11.58	11.79	11.97	12.15
	L	8.42	8.49	8.59	8.71	8.86	9.03	9.21	9.41	9.63	9.88	10.13	10.37	10.63	10.88	11.12	11.34	11.57	11.77	11.95	12.13	12.30	12.46
62	U	8.31	8.38	8.46	8.57	8.70	8.85	9.01	9.18	9.37	9.59	9.83	10.06	10.31	10.58	10.84	11.09	11.34	11.57	11.78	11.96	12.14	12.29
	L	8.60	8.68	8.78	8.90	9.05	9.21	9.39	9.60	9.84	10.09	10.35	10.61	10.88	11.12	11.35	11.58	11.78	11.96	12.14	12.30	12.44	12.57
61	U	8.56	8.65	8.76	8.89	9.04	9.19	9.38	9.58	9.81	10.04	10.28	10.55	10.81	11.07	11.32	11.57	11.79	11.98	12.15	12.31	12.45	12.56
	L	8.84	8.94	9.06	9.20	9.36	9.55	9.77	10.02	10.28	10.56	10.84	11.11	11.37	11.61	11.82	12.01	12.18	12.33	12.46	12.58	12.69	12.80
60	U	8.73	8.82	8.93	9.06	9.20	9.37	9.56	9.78	10.00	10.24	10.50	10.77	11.03	11.30	11.57	11.80	12.01	12.20	12.36	12.49	12.60	12.70
	L	9.00	9.09	9.20	9.33	9.49	9.69	9.92	10.17	10.45	10.75	11.06	11.35	11.63	11.87	12.08	12.26	12.41	12.53	12.63	12.73	12.82	12.91
59	U	8.97	9.07	9.19	9.34	9.52	9.72	9.94	10.18	10.43	10.71	10.98	11.26	11.55	11.80	12.04	12.26	12.44	12.57	12.67	12.76	12.83	12.90
	L	9.21	9.31	9.44	9.60	9.80	10.03	10.29	10.58	10.91	11.25	11.58	11.88	12.14	12.37	12.53	12.64	12.74	12.81	12.89	12.96	13.02	13.08
58	U	9.09	9.19	9.31	9.46	9.64	9.85	10.07	10.32	10.60	10.89	11.19	11.49	11.77	12.05	12.31	12.52	12.68	12.79	12.87	12.93	12.98	13.03
	L	9.31	9.41	9.54	9.70	9.89	10.11	10.36	10.67	11.02	11.40	11.78	12.13	12.43	12.66	12.82	12.92	12.97	13.01	13.05	13.08	13.12	13.16
57	U	9.29	9.41	9.56	9.74	9.95	10.17	10.44	10.74	11.05	11.37	11.69	12.00	12.31	12.57	12.79	12.96	13.04	13.08	13.11	13.12	13.14	13.16
	L	9.50	9.62	9.77	9.95	10.16	10.40	10.71	11.07	11.48	11.94	12.36	12.72	12.99	13.15	13.21	13.20	13.19	13.19	13.20	13.22	13.25	13.27
56	U	9.37	9.49	9.64	9.81	10.01	10.24	10.51	10.82	11.16	11.53	11.89	12.23	12.55	12.85	13.09	13.24	13.28	13.28	13.27	13.26	13.25	13.24
	L	9.57	9.68	9.82	10.00	10.19	10.42	10.71	11.06	11.48	12.00	12.54	13.00	13.33	13.51	13.56	13.46	13.39	13.35	13.33	13.32	13.33	13.34
55	U	9.55	9.69	9.86	10.05	10.27	10.54	10.86	11.21	11.63	12.05	12.44	12.79	13.11	13.40	13.59	13.57	13.51	13.44	13.39	13.35	13.33	13.31
	L	9.74	9.87	10.02	10.20	10.41	10.67	11.01	11.40	11.92	12.58	13.22	13.67	13.92	13.95	13.70	13.58	13.50	13.45	13.42	13.40	13.40	13.41
54	U	9.60	9.73	9.89	10.06	10.27	10.52	10.84	11.19	11.64	12.14	12.61	13.02	13.38	13.71	13.96	13.86	13.73	13.61	13.52	13.45	13.40	13.37
	L	9.78	9.90	10.04	10.20	10.39	10.62	10.92	11.28	11.75	12.35	13.28	14.00	14.37	14.42	13.94	13.74	13.63	13.56	13.51	13.48	13.46	13.46
53	U	9.75	9.90	10.06	10.25	10.48	10.78	11.11	11.55	12.07	12.73	13.22	13.62	14.01	14.40	14.17	13.93	13.76	13.63	13.53	13.47	13.43	13.40
	L	9.93	10.05	10.19	10.36	10.56	10.82	11.13	11.52	12.04	12.76	14.16	14.83	14.98	14.14	13.89	13.74	13.65	13.58	13.54	13.52	13.50	13.50
52	U	9.77	9.90	10.04	10.21	10.42	10.68	10.99	11.38	11.87	12.51	13.41	13.82	14.25	14.89	14.47	14.12	13.87	13.71	13.60	13.52	13.47	13.44
	L	9.95	10.06	10.18	10.32	10.50	10.71	10.98	11.31	11.74	12.30	13.09	15.22	15.64	14.20	14.02	13.84	13.72	13.65	13.60	13.56	13.54	13.54
51	U	9.89	10.02	10.17	10.35	10.58	10.86	11.18	11.61	12.16	12.93	14.09	14.39	15.40	14.73	14.24	13.94	13.75	13.63	13.55	13.50	13.46	13.44
	L	10.07	10.18	10.30	10.44	10.62	10.84	11.10	11.44	11.85	12.53	12.96	17.01	13.74	14.22	13.93	13.78	13.70	13.64	13.60	13.58	13.57	13.56
50	U	9.88	9.99	10.12	10.28	10.47	10.70	10.98	11.33	11.78	12.36	13.21	14.56	16.04	14.87	14.23	13.94	13.76	13.64	13.57	13.52	13.48	13.46
	L	10.08	10.18	10.28	10.39	10.53	10.71	10.92	11.16	11.57	11.66	13.57	10.22	10.73	15.48	14.09	13.78	13.75	13.69	13.64	13.61	13.60	13.59
49	U	9.96	10.07	10.21	10.37	10.56	10.80	11.08	11.42	11.86	12.41	13.23		14.27	13.99	13.85	13.73	13.63	13.57	13.52	13.49	13.47	13.46
	L	10.19	10.27	10.36	10.47	10.60	10.75	11.02	10.97	12.46	9.36				14.52	13.36	13.88	13.74	13.67	13.64	13.62	13.61	13.61
48	U	9.94	10.03	10.14	10.28	10.44	10.63	10.85	11.12	11.43	11.85					13.78	13.69	13.61	13.56	13.52	13.49	13.48	13.47
	L	10.21	10.28	10.34	10.42	10.50	10.69	10.57	11.85	8.88						9.85	15.10	13.84	13.64	13.68	13.65	13.64	13.63
47	U	10.00	10.09	10.20	10.33	10.48	10.66	10.86	11.12							13.65	13.57	13.54	13.51	13.49	13.48	13.47	13.47
	L	10.30	10.35	10.38	10.51	10.33	11.48	8.61									14.08	13.18	13.78	13.69	13.65	13.65	13.65
46	U	9.96	10.04	10.13	10.23	10.36	10.49	10.66										13.52	13.50	13.49	13.48	13.47	13.47
	L	10.37	10.38	10.46	10.23	11.27	8.46											9.62	15.01	13.78	13.62	13.68	13.67

Figure 8. POISSON prediction along pole-yoke interface of a quadrupole with sloped sides. The nominal pole-tip field is 5 kG (5,280 A-t).

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THE FOLLOWING IS A MAP OF /B/(KG) UPPER --- CYCLE 1390   Short quad for HEBT - Straight pole, 0.2576 in. conductor, 5,280 A-t
                          /B/(KG) LOWER
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		16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37
24	U										9.87	9.06	8.82	9.04	9.24	9.40	9.56	9.71	9.86	10.01	10.15	10.28	10.40
	L									0.00	9.41	9.00	8.98	9.23	9.39	9.56	9.72	9.88	10.04	10.18	10.32	10.46	10.58
23	U								8.58	7.21	8.38	8.70	8.83	9.01	9.19	9.36	9.53	9.69	9.84	9.99	10.13	10.26	10.39
	L								9.27	7.59	8.73	8.80	8.97	9.16	9.34	9.51	9.68	9.85	10.01	10.16	10.30	10.44	10.57
22	U								9.17	8.31	8.13	8.37	8.59	8.78	8.97	9.16	9.34	9.51	9.67	9.83	9.99	10.13	10.26
	L							0.00	8.57	8.23	8.25	8.53	8.72	8.91	9.11	9.30	9.48	9.65	9.82	9.99	10.14	10.29	10.42
21	U						7.87	6.49	7.62	7.95	8.12	8.33	8.54	8.74	8.95	9.14	9.32	9.50	9.67	9.83	9.99	10.13	10.27
	L						8.50	6.88	7.98	8.04	8.23	8.45	8.66	8.86	9.07	9.27	9.46	9.64	9.81	9.98	10.14	10.28	10.42
20	U						8.32	7.46	7.35	7.60	7.85	8.07	8.29	8.51	8.72	8.93	9.13	9.32	9.50	9.68	9.85	10.00	10.15
	L					0.00	7.69	7.40	7.43	7.74	7.94	8.16	8.39	8.61	8.83	9.05	9.25	9.45	9.63	9.81	9.98	10.14	10.29
19	U				7.05	5.74	6.78	7.11	7.32	7.56	7.80	8.04	8.27	8.49	8.72	8.94	9.14	9.34	9.52	9.70	9.87	10.03	10.17
	L				7.70	6.13	7.16	7.20	7.39	7.63	7.87	8.11	8.35	8.58	8.81	9.04	9.25	9.45	9.64	9.82	10.00	10.16	10.30
18	U				7.31	6.52	6.78	7.11	7.32	7.56	7.80	8.04	8.27	8.49	8.72	8.94	9.14	9.34	9.52	9.70	9.87	10.03	10.17
	L			0.00	7.06	6.53	7.16	7.20	7.39	7.63	7.87	8.11	8.35	8.58	8.81	9.04	9.25	9.45	9.64	9.82	10.00	10.16	10.30
17	U		6.08	4.96	5.88	6.21	6.46	6.72	6.98	7.24	7.50	7.76	8.02	8.27	8.51	8.76	9.00	9.21	9.42	9.62	9.80	9.98	10.12
	L		7.26	5.35	6.31	6.26	6.43	6.68	6.95	7.23	7.51	7.79	8.06	8.32	8.58	8.84	9.08	9.31	9.51	9.71	9.90	10.08	10.23
16	U		5.87	5.48	5.60	5.87	6.15	6.42	6.69	6.96	7.23	7.49	7.76	8.03	8.29	8.55	8.81	9.06	9.28	9.50	9.70	9.89	10.05
	L	0.00	8.22	5.46	5.54	5.80	6.03	6.29	6.59	6.90	7.20	7.50	7.78	8.07	8.34	8.61	8.88	9.14	9.36	9.58	9.78	9.97	10.15
15	U	5.09	4.98	5.29	5.57	5.85	6.13	6.40	6.68	6.96	7.23	7.50	7.78	8.06	8.33	8.61	8.89	9.14	9.38	9.60	9.81	9.99	10.14
	L		3.81	5.39	5.23	5.60	5.87	6.20	6.55	6.89	7.21	7.50	7.80	8.09	8.38	8.67	8.95	9.21	9.44	9.67	9.88	10.05	10.31
14	U			4.94	5.30	5.56	5.84	6.12	6.40	6.68	6.96	7.23	7.51	7.81	8.10	8.39	8.69	8.99	9.27	9.52	9.75	9.97	10.12
	L				4.09	5.35	5.39	5.82	6.17	6.57	6.93	7.24	7.52	7.82	8.13	8.44	8.74	9.04	9.31	9.56	9.81	10.00	10.02
13	U				5.19	5.57	5.85	6.13	6.41	6.69	6.97	7.24	7.53	7.84	8.15	8.46	8.80	9.14	9.44	9.72	9.95	10.17	10.25
	L					4.44	5.57	5.74	6.25	6.67	7.01	7.25	7.52	7.85	8.20	8.52	8.84	9.17	9.46	9.73	10.06	10.18	9.31
12	U						5.50	5.89	6.16	6.43	6.70	6.97	7.25	7.55	7.87	8.19	8.55	8.96	9.35	9.73	10.01	10.20	10.36
	L							4.91	6.00	6.37	6.89	7.05	7.18	7.51	7.92	8.27	8.60	8.97	9.34	9.68	9.92	10.65	
11	U							5.86	6.21	6.45	6.69	6.97	7.26	7.55	7.87	8.22	8.65	9.15	9.69	10.25	10.32		
	L								5.61	7.04	7.13	6.81	7.03	7.62	8.00	8.30	8.65	9.12	9.67	10.01	10.01		
10	U									6.22	6.43	6.64	6.98	7.25	7.49	7.79	8.16	8.69	9.46	10.45	10.89		
	L												5.97	7.44	7.77	7.94	8.19	8.69	9.52	10.38			
9	U												6.96	7.14	7.32	7.52	7.80	8.33	9.79				
	L																						

Figure 9. POISSON prediction along pole face of a quadrupole with straight sides. The nominal pole-tip field is 5 kG (5,280 A-t).

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THE FOLLOWING IS A MAP OF /B/(KG) UPPER --- CYCLE 1360   Short quad for HEBT - Sloped pole, 0.2576 in. conductor, 5,280 A-t
                          /B/(KG) LOWER
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		16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37
24	U										9.72	8.28	8.05	8.22	8.37	8.49	8.61	8.73	8.84	8.94	9.04	9.13	9.22
	L									0.00	10.09	8.36	8.16	8.43	8.54	8.66	8.78	8.90	9.01	9.12	9.23	9.32	9.42
23	U								8.14	6.60	7.73	7.98	8.07	8.21	8.35	8.49	8.61	8.74	8.85	8.97	9.07	9.16	9.25
	L								8.85	6.73	8.16	8.13	8.23	8.38	8.51	8.64	8.77	8.90	9.02	9.14	9.25	9.35	9.45
22	U								9.17	7.72	7.53	7.73	7.91	8.06	8.21	8.35	8.49	8.63	8.76	8.88	9.00	9.10	9.20
	L							0.00	9.46	7.80	7.62	7.92	8.06	8.21	8.36	8.50	8.64	8.78	8.91	9.04	9.16	9.28	9.39
21	U						7.56	6.06	7.15	7.41	7.55	7.72	7.89	8.06	8.21	8.37	8.51	8.66	8.79	8.92	9.04	9.14	9.24
	L						8.24	6.20	7.60	7.57	7.69	7.86	8.03	8.19	8.35	8.50	8.65	8.79	8.93	9.07	9.20	9.32	9.44
20	U						8.48	7.03	6.94	7.14	7.34	7.53	7.71	7.89	8.07	8.23	8.39	8.55	8.70	8.84	8.97	9.09	9.20
	L					0.00	8.78	7.14	7.01	7.33	7.48	7.65	7.83	8.01	8.19	8.35	8.51	8.67	8.82	8.97	9.11	9.25	9.38
19	U				6.88	5.46	6.47	6.75	6.93	7.13	7.32	7.52	7.71	7.91	8.09	8.27	8.44	8.60	8.75	8.90	9.04	9.15	9.26
	L				7.60	5.63	6.96	6.91	7.04	7.24	7.43	7.63	7.82	8.01	8.19	8.37	8.53	8.70	8.86	9.01	9.16	9.31	9.45
18	U				7.58	6.26	6.24	6.47	6.69	6.91	7.12	7.32	7.53	7.74	7.94	8.13	8.32	8.49	8.67	8.83	8.98	9.11	9.23
	L			0.00	8.28	6.43	6.30	6.61	6.78	6.98	7.20	7.41	7.62	7.82	8.03	8.22	8.40	8.57	8.74	8.91	9.07	9.23	9.38
17	U		6.03	4.83	5.71	6.01	6.22	6.45	6.68	6.90	7.12	7.34	7.56	7.78	7.99	8.19	8.39	8.57	8.75	8.92	9.07	9.20	9.32
	L		7.32	5.04	6.26	6.14	6.26	6.48	6.70	6.94	7.18	7.41	7.63	7.85	8.06	8.26	8.44	8.62	8.80	8.97	9.13	9.30	9.48
16	U		6.21	5.38	5.48	5.72	5.97	6.21	6.44	6.68	6.92	7.14	7.37	7.60	7.83	8.06	8.27	8.47	8.67	8.86	9.03	9.18	9.30
	L	0.00	10.01	5.52	5.47	5.74	5.93	6.14	6.40	6.67	6.94	7.19	7.43	7.66	7.89	8.11	8.31	8.51	8.69	8.87	9.04	9.20	9.38
15	U	4.85	4.92	5.21	5.47	5.72	5.97	6.21	6.46	6.70	6.94	7.18	7.42	7.66	7.90	8.14	8.37	8.59	8.80	9.00	9.16	9.30	9.43
	L		3.81	5.43	5.20	5.55	5.78	6.07	6.38	6.68	6.97	7.22	7.46	7.71	7.95	8.18	8.39	8.58	8.77	8.95	9.10	9.26	9.45
14	U			4.91	5.24	5.48	5.74	5.99	6.24	6.49	6.73	6.98	7.22	7.47	7.73	7.99	8.24	8.49	8.74	8.97	9.15	9.31	9.45
	L				4.04	5.35	5.33	5.74	6.06	6.42	6.75	7.03	7.26	7.51	7.77	8.04	8.27	8.48	8.67	8.86	9.02	9.17	9.31
13	U				5.16	5.51	5.77	6.03	6.28	6.52	6.78	7.03	7.27	7.53	7.81	8.09	8.37	8.66	8.94	9.16	9.35	9.50	9.62
	L					4.35	5.54	5.66	6.15	6.54	6.87	7.08	7.29	7.57	7.87	8.14	8.37	8.58	8.79	8.97	9.12	9.26	9.28
12	U						5.47	5.82	6.08	6.32	6.57	6.82	7.07	7.33	7.60	7.89	8.20	8.53	8.89	9.18	9.42	9.59	9.73
	L							4.78	5.97	6.29	6.82	6.96	7.03	7.31	7.68	7.99	8.24	8.47	8.71	8.93	9.12	9.25	9.49
11	U							5.83	6.15	6.37	6.60	6.86	7.11	7.37	7.64	7.96	8.31	8.75	9.22	9.52	9.78	9.89	9.91
	L								5.46	7.07	7.19	6.73	6.85	7.49	7.85	8.09	8.31	8.59	8.89	9.15	9.43	9.47	
10	U									6.19	6.40	6.61	6.91	7.15	7.37	7.63	7.95	8.37	9.03	9.87	10.02	10.10	
	L												5.63	7.41	7.82	7.94	8.07	8.30	8.78	9.34	9.82		
9	U												6.95	7.13	7.30	7.48	7.70	8.09	9.27	11.11			
	L																						

Figure 10. POISSON prediction along pole face of a quadrupole with sloped sides. The nominal pole-tip field is 5 kG (5,280 A-t).

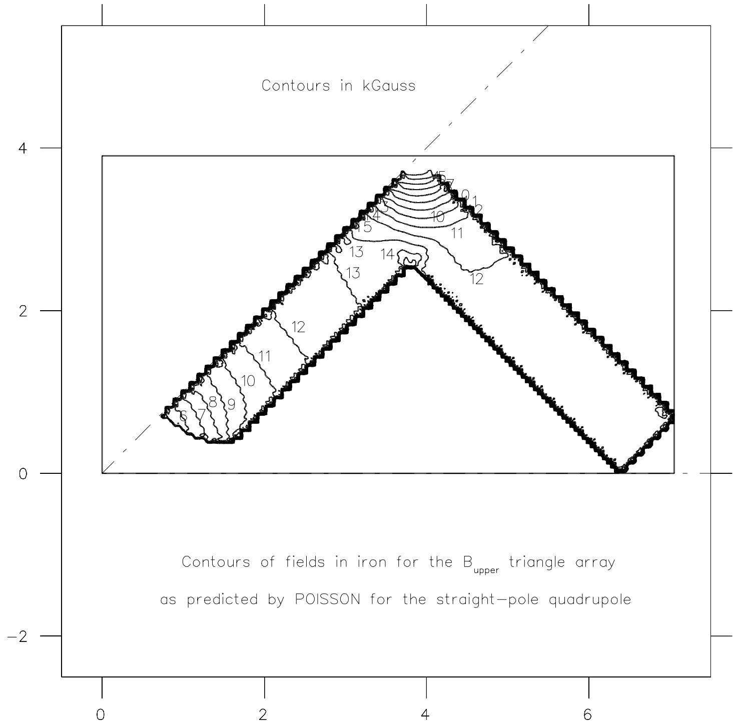

Fig. 11a. POISSON prediction of the field in the iron for the upper triangle group of a quadrupole with a straight-sided pole.

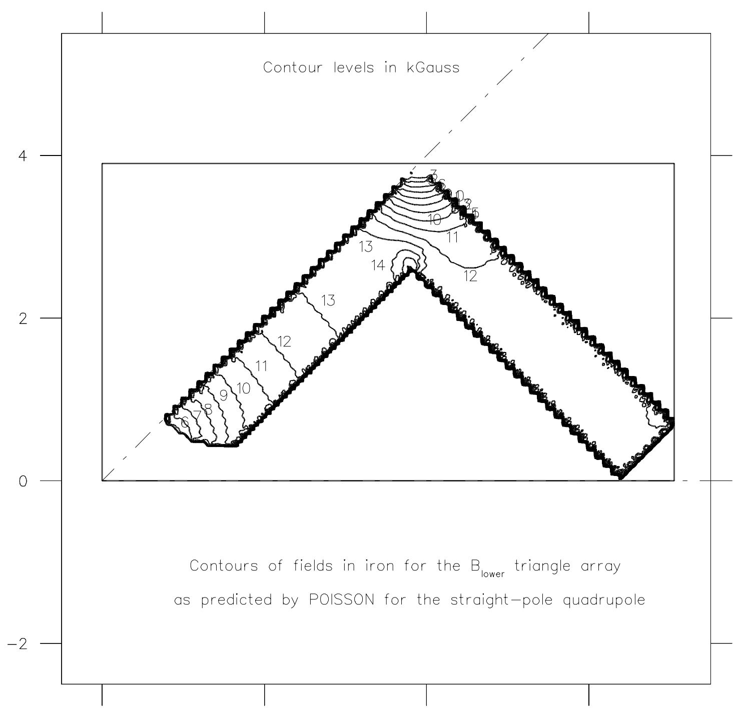

Fig. 11b. POISSON prediction of the field in the iron for the lower triangle group of a quadrupole with a straight-sided pole.

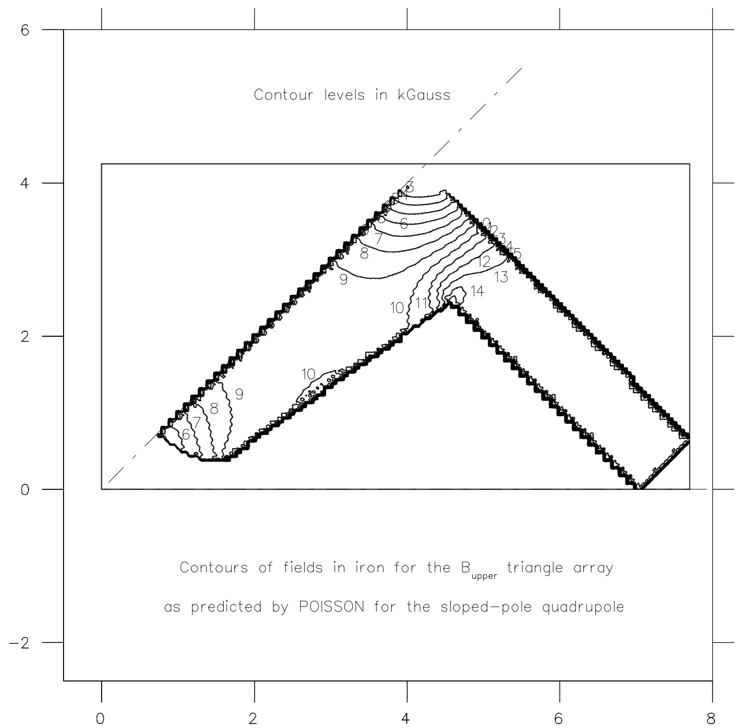

Fig. 12a. POISSON prediction of the field in the iron for the upper triangle group of a quadrupole with a sloped pole.

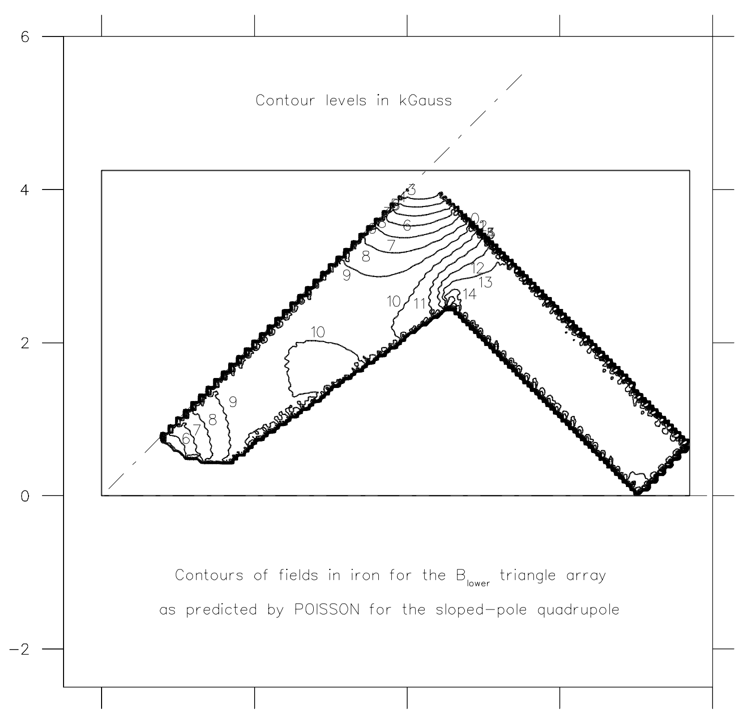

Fig. 12b. POISSON prediction of the field in the iron for the lower triangle group of a quadrupole with a sloped pole.

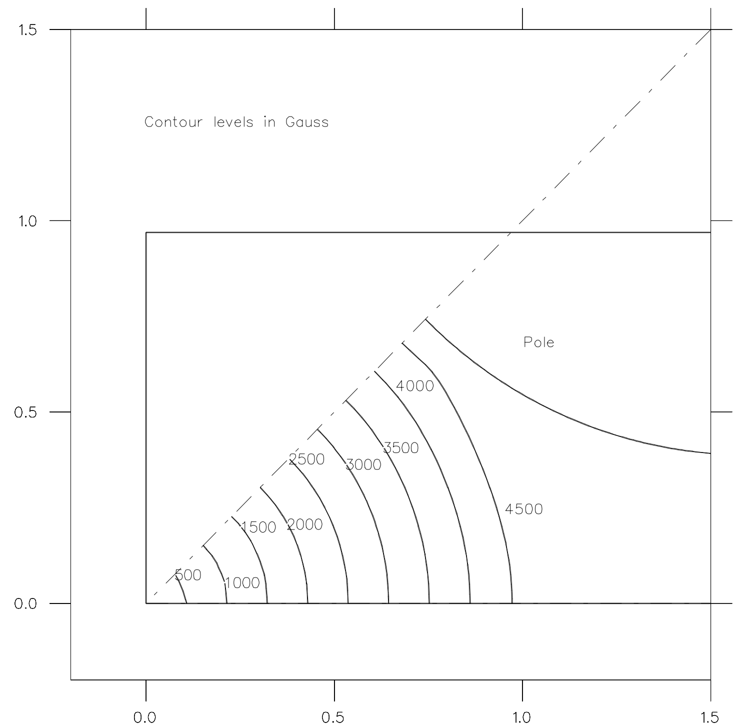

Fig. 13a. POISSON prediction of the field in the gap of a quadrupole with a straight-sided pole.

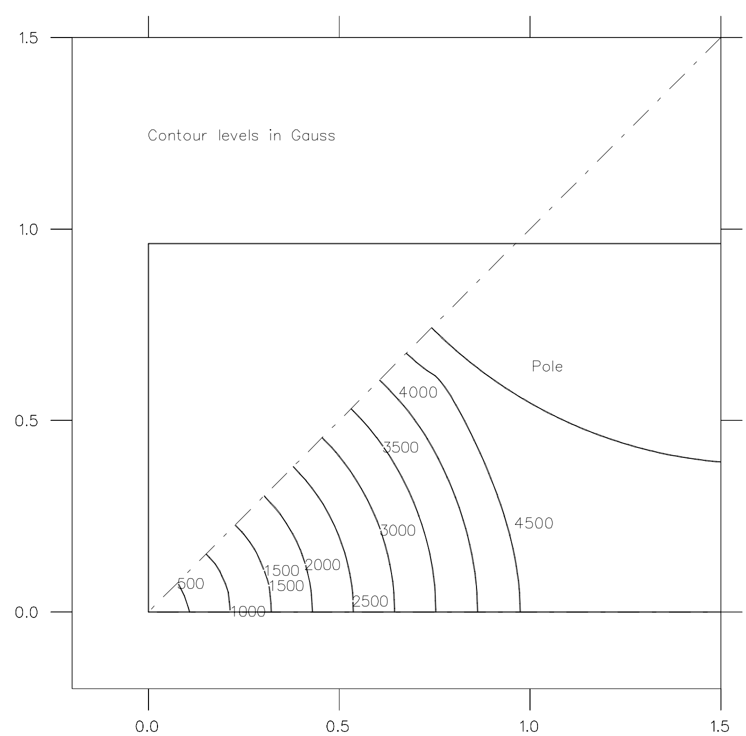

Fig. 13b. POISSON prediction of the field in the gap of a quadrupole with a sloped pole.