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Author GM Stinson		*Page* 1 *of* 18
Subject A conceptual design for the 4-inch diameter quadrupoles for the DRAGON facility		

1. Introduction

For the DRAGON facility of ISAC three types of quadrupoles are required. Of these, a design exists for Q9 and Q10 exists (the 6-in. SMIT quadrupoles).

The remaining quadrupoles are of two varieties [1)]. Quadrupoles Q1 and Q6 have apertures of 10.8 cm, effective lengths of 26 cm and maximum field gradients of 5 T/m (0.5 kG/cm). The balance of the quadrupoles are specified to have apertures of 15.9 cm, effective lengths of 35 cm and maximum field gradients of 3.6 T/m (0.36 kG/cm). Quadrupole Q2 is to have a special pole-tip shape so as to provide sextupole and octupole components (calculated at a radius of 7.5 cm) that are 0.029 and −0.008, respectively, of the quadrupole component.

This report presents a conceptual design for the 10.8-cm diameter quadrupoles. Included is a POISSON [2,3)] study of a design that would be suitable.

2. Design Parameters

Quadrupoles Q1 and Q6 will be termed quadrupoles of type 1. For them we choose an aperture of 4.25 in. (10.795 cm). With a field gradient of 0.5 kG/cm, a pole-tip field of $(0.5 \text{ kG/cm}) \times (5.4 \text{ cm}) = 2.5$ kG is required. We design these quadrupoles with a pole-tip field of 2.75 kG.

Thus the following parameters are defined for the quadrupole design.

Parameter	Type 1 (4 in.) quadrupole		
Maximum pole-tip field	2.75 kG		
Full aperture	4.25 in.	=	10.8 cm
Effective length	10.24 in.	=	26.0 cm

3. Ampere-turns per Coil

Allowing 10% for stray fields, we obtain the required Ampere-turns per pole for the type 1 quadrupoles from

$$NI_{type1} \text{ per pole} = \frac{1.1}{2}(\text{half aperture (m)})\frac{\text{Pole-tip field (T)}}{4\,\pi\,10^{-7}} = \frac{1.1}{2}\,\frac{(0.054)(0.275)}{4\,\pi\,10^{-7}} = 6{,}500 \text{ A-t}$$

We choose a current of 325 Amperes so that

$$\boxed{N_{type1} = \text{number of turns per coil of type 1 quadrupoles} = 21}$$

in the $5 \times 5 \times 4 \times 4 \times 3$ configuration shown on the next page.

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

Yoke thickness [= 0.8(aperture/2.)]	1.700 in.	=	43.18 mm
Pole width [= 1.7(aperture/2.)]	3.613 in.	=	91.77 mm
Pole radius [= 1.15(aperture/2.)]	2.450 in.	=	62.23 mm
Pole length [= effective length − aperture/2.]	8.250 in.	=	209.55 mm

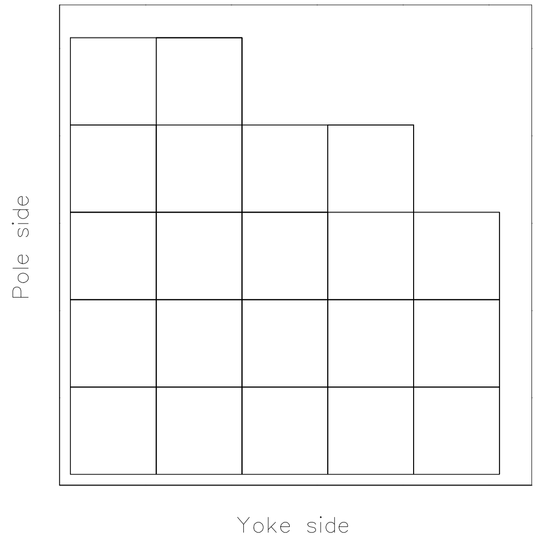

Fig. 1. The coil configuration of the DRAGON 4-inch quadrupole.

4. Coil Design

For the type 1, 4-inch quadrupoles (and for the type 2, 6-inch quadrupoles) we choose an Anaconda 0.3648-inch square conductor. The copper parameters for this conductor are given in Anaconda data as follows.

	British	Metric
OD	0.3648 in.	9.266 mm
ID	0.2040 in.	5.182 mm
Copper area	0.09730 in.^{2}	62.774 mm^2
Cooling area	0.03269 in.^{2}	21.090 mm^2
Mass	0.3760 lb/ft	0.5595 kg/m
Resistance at 20° C	83.70 $\mu\Omega$/ft	274.61 $\mu\Omega$/m
k (British units)	0.02320	

Thus the current density in the conductor is 325 A/0.09730 in.^{2} = 3,340 A/in.^{2} (= 5.18 A/mm^2) and is conservative.

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:

Minimum	=	0.3838 in.	=	9.75 mm
Nominal	=	0.3928 in.	=	9.98 mm
Maximum	=	0.4018 in.	=	10.21 mm

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 length of the coil along the *pole* are

	Maximum (in.)	Maximum (mm)	Minimum (in.)	Minimum (mm)
Wrapped conductor	2.009	51.029	1.919	48.743
Gapping (4x0.010)	0.040	1.016		
Keystoning (5x0.010)	0.050	1.270	0.025	0.635
Ground wrap (4x0.007x2)	0.056	1.422	0.056	1.422
Total (in.)	2.155	54.737	2.000	50.800

We take

$$\boxed{\text{Nominal coil height} = \text{coil length along pole} = 2.10 \text{ in.}}$$

The length of the *yoke* side of the coil is obtained in a similar manner. We have

	Maximum (in.)	Maximum (mm)	Minimum (in.)	Minimum (mm)
Wrapped conductor	2.009	51.029	1.919	48.743
Gapping (4x0.010)	0.040	1.016		
Ground wrap (4x0.007x2)	0.056	1.422	0.056	1.422
Total (in.)	2.105	53.467	1.975	50.165

We take

$$\boxed{\text{Nominal coil width} = \text{coil length along yoke} = 2.05 \text{ in.}}$$

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

$$R_{min} = 4(0.3648 \text{ in.}) \approx 1.5 \text{ in.}$$

and we choose a clearance, G, of 0.250 in. along the pole sides between the pole and the coil. It is then clear the pole ends must be chamfered to provide clearance for the coil, as is illustrated in figure 2 below.

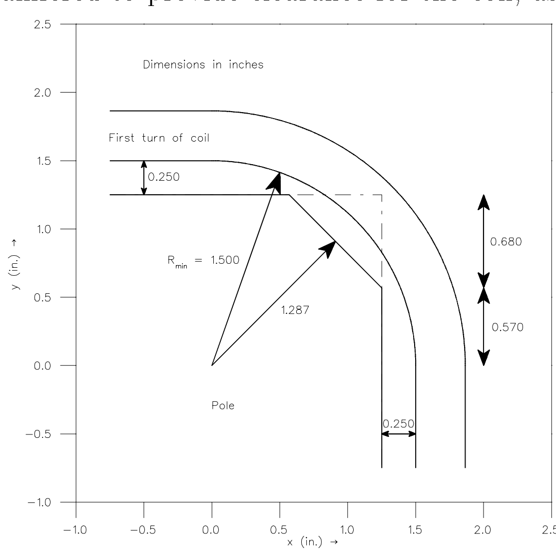

Fig. 2. Illustration of the pole-end chamfer of the DRAGON 4-inch quadrupole.

We choose a minimum pole-end to coil clearance of 0.125 in. Consequently, using the coordinate system of fig. 2 with the center of curvature of the first turn at (0, 0), we require the intersection of the pole-side (defined by the equation $x = 1.250$ in.) and a circle centered at the origin and of radius $r = R_{min} - 0.125 = 1.375$ in. This occurs at the coordinate $(x, y) = (1.250$ in., 0.5728 in.). We then choose the pole chamfer to be 0.680 in. at 45° so that the perpendicular distance from the center of curvature of the coil to the chamfer is 1.287 in.

We now take the conductor dimension D to be

$$\begin{aligned} D &= \text{Nominal dimension} + 4(\text{Insulation thickness}) + \text{Turn separation} \\ &= 0.365 + 0.028 + 0.010 \\ &= 0.403 \text{ in.} = 10.24 \text{ mm.} \end{aligned}$$

We note that the straight section of the n^{th} conductor along the longitudinal portion of the coil is a distance

$$D(n) = n\,D + G + (\text{pole width})/2$$

from the (longitudinal) centre-line of the pole. The (outer) radius of curvature of this n^{th} turn is

$$R(n) = R_{min} + n\,D\ ,$$

the length of the straight longitudinal section of the winding is

$$L_{length} = L_{iron} - 2(R_{min} - G)$$

and that of the straight section along the pole-width is

$$L_{width} = W_{iron} - 2(R_{min} - G)\ .$$

Thus the length of the n^{th} turn is

$$\begin{aligned} l(n) &= 2[L_{length} + L_{width}] + 2\,\pi\,R(n) \\ &= 2[L_{iron} + W_{iron} + 4\,G - (4 - \pi)R_{min} + \pi\,n\,D] \end{aligned}$$

and the length of an N-turn layer is

$$L(N) = \sum_{n=1}^{N} l(n) = 2\,N\,[L_{iron} + W_{iron} + 4\,G - (4 - \pi)R_{min}] + \pi\,N\,(N+1)\,D$$

Using the following parameters

	in.	mm
L_{iron}	8.250	209.6
W_{iron}	3.613	91.8
G	0.250	6.4
D	0.403	10.3
R_{min}	1.500	38.1

and counting from the bottom up, we find the following lengths of the coil layers.

Layer	N	$L(N)$ (in.)	$L(N)$ (mm)
1	5	153.8	3,906
2	5	153.8	3,906
3	5	153.8	3,906
4	4	118.0	2,997
5	2	54.0	1,372
Total		633.4	16,087

Thus the length of copper per coil is estimated to be approximately 635 in. We take

$$\boxed{\text{Length of copper per coil} = 660 \text{ in.} = 55 \text{ ft } [\approx 17 \text{ m}]}$$

Because four coils are required per quadrupole, we calculate the amount of copper to order, using the density of 0.376 lb/ft^3, from

	Length	Weight
Length of copper per quadrupole	220 ft	82.72 lb
Allow 10% winding loss	22 ft	8.27 lb
Total	242 ft	90.99 lb

Thus

$$\boxed{\text{Amount of copper to order per quadrupole} = 250 \text{ ft} \approx 94 \text{ lb of } 0.3648 \text{ in. conductor.}}$$

5. Power requirements

At 20°C the resistance of a coil, R_{20}, is

$$R_{20°C} = (87.70 \times 10^{-6}\Omega/\text{ft})(55 \text{ ft}) = 0.004824\ \Omega$$

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

$$\begin{aligned} R_{hot} &= R_{20°C}\ [\ 1 + (\text{Temp. coeff}/°\text{C}) \times \Delta\text{T}(°\text{C})\ ] \\ &= R_{20°C} \times [1 + 0.00393 \times 30] \\ &= 5.392 \times 10^{-3}\ \Omega \text{ per coil} \end{aligned}$$

and at a current of 325 A we obtain

$$\begin{aligned} \text{Voltage per coil} &= (325 \text{ A})(5.392 \times 10^{-3}\ \Omega) \\ &= 1.753 \text{ Volts} \end{aligned}$$

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

$$\boxed{\begin{array}{ccrl} \text{I} & = & 325 & \text{A} \\ \text{V} & = & 10 & \text{V total} \\ \text{P} & = & 3.25 & \text{kW total} \end{array}}$$

6. Cooling requirements

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

$$\text{Power per coil} = I^2 R_{hot} = (325)(325)(0.005392) = 0.5696 \text{ kW}$$

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 $\Delta T = 72$°F = 40°C and $A = 0.03269$ in^2 we have

$$v = \frac{(2.19)(0.5696)}{(72)(0.03269)} = 0.530 \text{ ft/sec}$$

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 find

$$\text{Volume/circuit} = 3.12247(0.530)(0.03269) = 0.0541\ \text{USGPM} = 0.2006\ \ell/\text{min}.$$

$$\boxed{\text{Total flow volume per quadrupole} = 0.22\ \text{USGPM} = 0.802\ \ell/\text{min}}$$

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 $k = 0.0232$ we obtain

$$\Delta p = (0.0232)(0.530)^{1.79} = 0.0075\ \text{psi/ft}\quad .$$

Thus the total pressure drop across the coil is

$$\boxed{\text{Pressure drop per coil} = 0.41\ \text{psi.}}$$

8. Iron dimensions

In the calculation of the iron dimensions, two yoke thicknesses were considered. The first—determined by Banford's criteria—was a yoke thickness of 1.70 in.; the second was a thinner yoke of thickness 1.25 in. This was done following POISSON runs with the thicker yoke in which it was found that the yoke and pole were well below saturation. A decision was made to find the effect of using a thinner yoke. Note, however, that the pole thickness of 3.6125 in. was used for either yoke thickness. Note further that because of the low field in the pole, the pole was *not* tapered at the usual 10° angle; the pole was left straight.

Regardless of the yoke thickness, in each case, clearance between the coil and the pole side was 0.250 in. and that between the coil and the yoke was 0.125 in. A minimum clearance of 0.125 in. between the coil and the horizontal symmetry axis was required.

We list in the following table the coordinates of pertinent points of the quadrupole geometry. 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.

Location	1.25 in. yoke		1.70 in. yoke	
	x	y	x	y
Curved pole : 45° symmetry axis	1.5026	1.5026	1.5026	1.5026
Curved pole : pole side	3.3418	0.7873	3.3418	0.7873
Pole side : inner yoke	5.3092	2.7548	5.3092	2.7548
Inner yoke : 45° symmetry axis	4.0320	4.0320	4.0320	4.0320
Outer yoke : 45° symmetry axis	4.9159	4.9159	5.2341	5.2341
Length of outer yoke	12.6543		13.1043	

From the above data, we may calculate the iron dimensions. Because the pole is independent of the yoke thickness we have

Length of pole side	2.7824 in.
Overall height of pole	3.5771 in.
Half-width of pole	1.8065 in.

Figure 3 shows the dimensions of an octant of a quadrupole with a yoke thickness of 1.25 in. 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 longer by the yoke thickness 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 yoke thickness of 1.70 in.

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 $R_{pole} = 2.450$ 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

$$\frac{\theta}{2} = \sin^{-1}\left[\frac{1.8053}{2.450}\right] = 47.464^\circ = 0.82841 \text{ radian}$$

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

$$\begin{aligned} A_{csp/2} &= R_{pole}^2(\theta - \sin\theta)/4 \\ &= (6.0025)[(0.82841)(2) - \sin(2(47.464))]/4 \\ &= 1.50063[1.65682 - 0.99630] \\ &= 0.99119 \text{ in.}^2 \end{aligned}$$

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

$$\begin{aligned} A_{str/2} &= A_{csp/2} + [(\text{pole width})/2](\text{length of pole side}) \\ &= 0.99119 + (3.613)(2.7824)/2 \\ &= 6.01760 \text{ in.}^2 \end{aligned}$$

The area of a yoke piece is the yoke length times the yoke thickness. Thus, using an iron density of 0.2833 lb/in.^{3}, we find

			Yoke thickness	
			1.25 in.	1.70 in.
Pole area (in.^{2})	=	8(pole area/2)	48.141	48.141
Yoke area (in.^{2})	=	4(area of yoke piece)	63.272	89.109
Total area (in.^{2})			111.412	137.250
Iron volume (in.^{3})	=	(8.25 in.)(Total area)	919.151	1132.312
Iron weight (lb)			260.395	320.312

we take

Weight of a quadrupole with a yoke thickness of 1.25 in.	=	270 lb
Weight of a quadrupole with a yoke thickness of 1.70 in.	=	330 lb

9. POISSON calculations

As noted in previous sections, POISSON runs were made on each of these two designs in order to determine the extent of pole and yoke saturation. Table 1 gives the input for the case of a quadrupole with a yoke thickness of 1.250 in. to the FRONT program that generates input for the AUTOMESH routine of POISSON. Similar input for the case of a yoke thickness of 1.70 in. 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 2.75 kG.

If saturation were to occur it would be expected to show up at the pole-yoke interface. In its calculations POISSON creates a triangular mesh that is divided into an upper and a lower triangle group for each cut along the horizontal axis. These are indicated by the letters 'U' and 'L' in its output. This is illustrated in figures 7-10. Figure 7 shows the POISSON output of the predicted field in region of the pole-yoke intersection for the case of a quadrupole with a yoke thickness of 1.25 in. 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 case of a yoke thickness of 1.70 in. is shown in figure 8.

Comparison of these figures shows that, as one would expect, a quadrupole with a yoke thickness of 1.25 in. is predicted to have a slightly higher concentration of flux at the intersection of the pole and the yoke than is predicted for one with a yoke thickness of 1.70 in. However, this is a local phenomenon and, in either case, is not predicted to exceed 16 kG. Similarly, the field in the yoke of a quadrupole with the thinner yoke is predicted to be $\approx$10.25 kG, a value approximately 20% higher than that in a quadrupole with the thicker yoke. Again, however, this value is relatively low. The predicted fields in the pole are seen to be approximately the same—as one would expect because the pole thicknesses are the same for each case. It is for this reason that it was concluded that it is not necessary to construct the poles with sloped sides.

Figure 9 shows the POISSON prediction for the fields in the iron in the region of the pole tip for a quadrupole with a yoke thickness of 1.25 in. A similar prediction for a quadrupole with a yoke thickness of 1.70 in. is shown in figure 10. As is indicated in these figures, the field in the iron at the pole-tip is approximately 3.5 kG along the pole edge.

Figure 11 shows a contour plot of the predicted fields in the pole and yoke of a quadrupole with a yoke thickness of 1.25 in. A similar plot for a quadrupole with a yoke thickness of 1.70 in. is shown in figure 12. These diagrams were produced using the program PLOTDATA [5)] with input taken from POISSON output. It is seen that, except for regions around the pole-yoke interface, that predicted fields in the iron are relatively low. These figures show the increased flux concentration in the yoke of a quadrupole with a yoke thickness of 1.25 in. relative to that in the yoke of a quadrupole with a yoke thickness of 1.70 in. Again, however, the field in the yoke of the quadrupole with a thinner yoke does not exceed 11 kG on average.

Finally, figures 13 and 14 show the predicted field in the gaps of the quadrupoles. Clearly, there is little difference predicted. In each case, a field of 2.75 kG is predicted at a radius of 2 in. from the quadrupole center. The 'squiggle' of the 2.9 kG contour near the 45° symmetry line results, I believe, because of the proximity of the contour interval to the iron of the pole. Regardless, a specified pole-tip field of 2.5 kG is requested and it is clear that this can be attained with either yoke thickness.

10. Discussion

This report presents two possible designs for a 4-in. quadrupole for the DRAGON facility. The designs differ only in their yoke thicknesses.

A design with a yoke thickness of 1.25 in. would be the slightly less bulky and have a slightly smaller footprint than that with a yoke thickness of 1.70 in.

In preliminary layouts of the DRAGON facility it was assumed these 4-in. quadrupoles would be similar to the HERA quadrupoles—approximately 12.4 in. long by 18.5 in. square. These dimensions are close to those predicted for quadrupoles constructed with a yoke thickness of 1.25 in. Quadrupoles constructed with yoke thicknesses of 1.70 in. are approximately 1.25 in. larger in transverse dimensions but, of course, have the same length.

Table 3 summarizes the parameters of these designs. If space considerations are of importance, quadrupoles should be constructed with yoke thicknesses of 1.25 in. If, however, an extra inch of width and height do not constitute a problem, it is recommended that they be constructed with yoke thicknesses of 1.70 in.

It should be remembered that quantities of copper and iron calculated in this note are estimates only. Exact quantities will be determined in the engineering phase from ACAD analysis.

References

1. V. Verma, *Private communication*, FAX of 1998/07/22 quoting specifications listed by D. A. Hutcheon dated 1998/07/21, TRIUMF, July, 1998.
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. J. L. Chuma, *PLOTDATA Command Reference Manual*, TRIUMF Report, TRI-CD-87-03b, August, 1989. 1996.

Table 1

POISSON input for a quadrupole a yoke thickness of 1.250 in.

```
title
DRAGON Q1 at 6,500 At with 5x5x4x4x3 array – 1998/07/23 – 0.3648 conductor - 1.25 in. yoke
run
pois
mode 0
xmax= 9.00
ymax= 5.00
xmesh 0.05
ymesh 0.05
symm=4
nseg 4
conv=2.54
matpro 1
zseg        0.          8.064056    8.947940    4.915912
rseg        0.          0.          0.883884    4.915912
nseg 6
conv=2.54
zseg        1.502602    3.341763    5.309240    8.064056    8.947940    4.915912
rseg        1.502602    0.787341    2.754817    0.          0.883884    4.915912
cseg        0.          2.450000    0.          0.          0.          0.
matpro 2
nseg 8
matpro 1
conv=2.54
zseg        3.906       4.488       4.789       5.369       5.668       5.959       6.854   5.398
rseg        0.998       0.415       0.714       0.131       0.429       0.138       1.033   2.490
current=6500.
nseg 2
matpro 1
ibound=0
conv=2.54
zseg        0.          4.915912
rseg        0.          4.915912
nseg 2
matpro 1
ibound=0
conv=2.54
zseg        8.947940    4.915912
rseg        0.883884    4.915912
nseg 2
matpro 1
ibound=1
conv=2.54
zseg        8.064056    8.947940
rseg        0.          0.883884
kbot=1
lbot=1
ltop=41
fieldmap 2
begin
end
```

Table 2

POISSON input for a quadrupole a yoke thickness of 1.700 in.

```
title
DRAGON Q1 at 6,500 At with 5x5x4x4x3 array – 1998/07/23 - 0.3648 conductor - 1.7 in yoke
run
pois
mode 0
xmax= 9.50
ymax= 5.50
xmesh 0.05
ymesh 0.05
symm=4
nseg 4
conv=2.54
matpro 1
zseg          0.          8.064056    9.266138    5.234110
rseg          0.          0.          1.202082    5.234110
nseg 6
conv=2.54
zseg          1.502602    3.341763    5.309240    8.064056    9.266138    5.234110
rseg          1.502602    0.787341    2.754817    0.          1.202082    5.234110
cseg          0.          2.450000    0.          0.          0.          0.
matpro 2
nseg 8
matpro 1
conv=2.54
zseg          3.906       4.488       4.789       5.369       5.668       5.959       6.854     5.398
rseg          0.998       0.415       0.714       0.131       0.429       0.138       1.033     2.490
current=6500.
nseg 2
matpro 1
ibound=0
conv=2.54
zseg          0.          5.234110
rseg          0.          5.234110
nseg 2
matpro 1
ibound=0
conv=2.54
zseg          9.266138    5.234110
rseg          1.202082    5.234110
nseg 2
matpro 1
ibound=1
conv=2.54
zseg          8.064056    9.266138
rseg          0.          1.202082
kbot=1
lbot=21
ltop=41
fieldmap 2
begin
end
```

Table 3
Summary of the 4-in. quadrupole parameters for the different yoke thicknesses

Parameter		Yoke thickness	
		1.25 in.	1.70 in.
Conductor:	OD (in.)	0.3648	0.3648
	ID (in.)	0.2040	0.2040
	Copper area (in.^{2})	0.0973	0.0973
	Cooling area (in.^{2})	0.0327	0.0327
	Weight (lb/ft)	0.376	0.376
	Resistance at 20° C ($\mu\Omega$/ft)	83.70	83.70
	k (British units)	0.0232	0.0232
Coil:	Number of turns	21	21
	Number of layers	5	5
	Nominal width along yoke (in.)	2.050	2.050
	Nominal height along pole (in.)	2.100	2.100
	Length per coil (ft)	55.0	55.0
	Weight per coil (lb)	21.0	21.0
	Weight per quadrupole (lb)	85.0	85.0
	Resistance per coil (hot) (mΩ)	5.40	5.40
	Coolant flow rate (ft/sec)	0.53	0.53
	Volume per coil (USGPM)	0.06	0.06
	Pressure drop per coil (psi)	0.41	0.41
Iron:	Yoke thickness (in.)	1.250	1.700
	Yoke width (in.)	12.654	13.104
	Yoke length (in.)	8.250	8.250
	Pole radius (in.)	2.450	2.450
	Pole width (in.)	3.613	3.613
	Overall pole height (in.)	3.577	3.577
	Weight (lb)	115.	140.
Power:	Current (A minimum)	325.	325.
	Voltage (V minimum)	10.	10.
	Power (kW minimum)	3.25	3.25
Quadrupole:	Aperture (in.)	4.250	4.250
	Width (in.)	19.663	20.936
	Height (in.)	19.663	20.936
	Length (in.)	12.850	12.850
	Assembled weight† (lb)	355.	415.

† Excluding power and coolant connections.

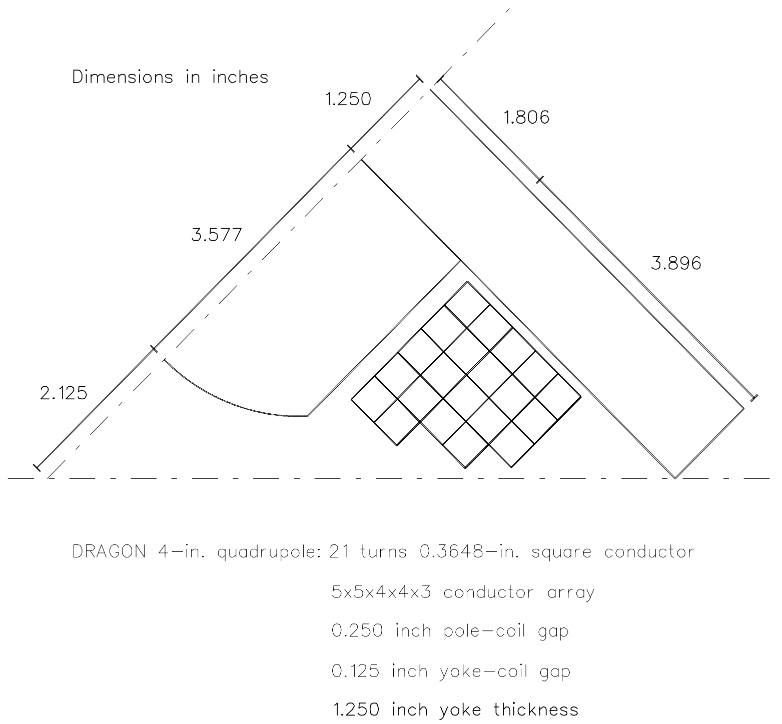

Fig. 3. Dimensions of an octant of a quadrupole with a yoke 1.25 in. thick.

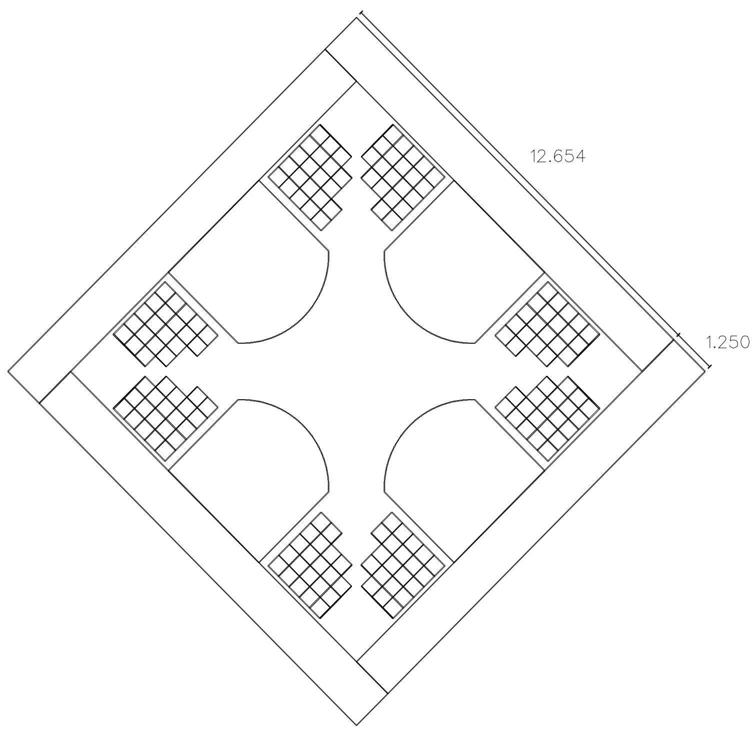

Fig. 4. Overall dimensions of a quadrupole with a yoke 1.25 in. thick.

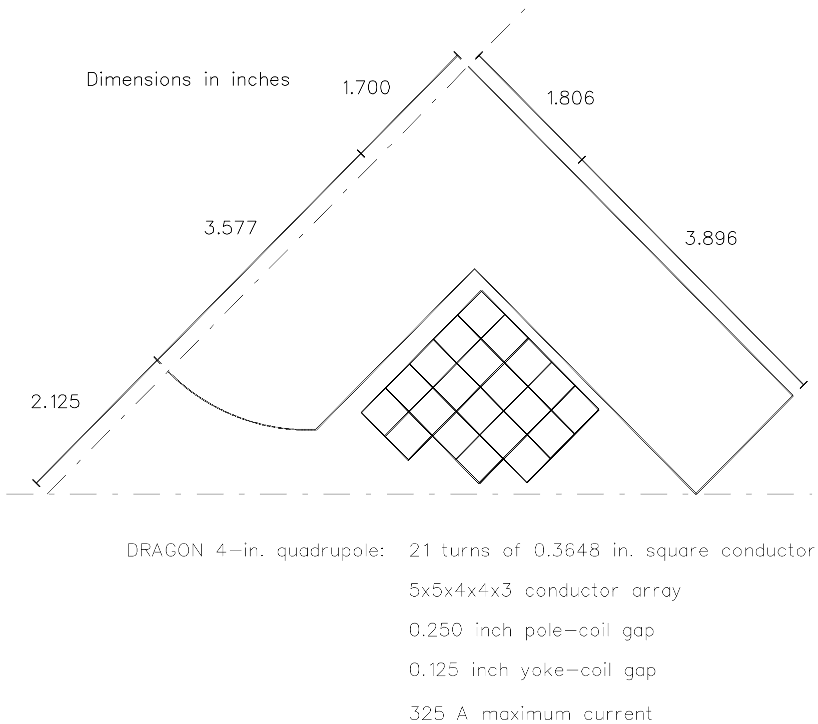

Fig. 5. Dimensions of an octant of a quadrupole with a yoke 1.70 in. thick.

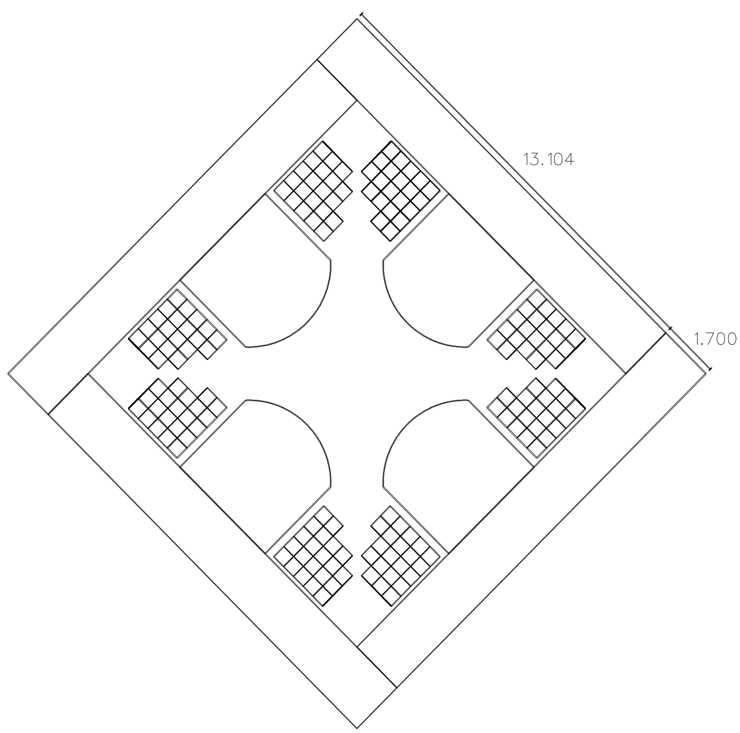

Fig. 6. Overall dimensions of a quadrupole with a yoke 1.70 in. thick.

```
 THE FOLLOWING IS A MAP OF /B/(KG) UPPER ---CYCLE 2110
                           /B/(KG) LOWER
  L                                DRAGON Q1 at 6,500 A-t with 5x5x4x4x3 array -- 1998/07/23 - 0.3648 conductor - 1.25 in yoke
  .            .
  .     K .......
 ...           .
  .
        98    99   100   101   102   103   104   105   106   107   108   109   110   111   112   113   114   115   116   117
 60 U  8.33  8.59  8.89  9.22  9.60 10.04 10.52 10.95 11.27 11.48 11.60 11.55 11.26 10.98 10.73 10.51 10.34 10.20 10.10 10.01
    L  8.36  8.63  8.94  9.30  9.73 10.25 10.89 11.71 12.41 12.70 12.46 11.65 11.18 10.86 10.62 10.43 10.28 10.17 10.08 10.02
 59 U  8.54  8.83  9.16  9.55 10.01 10.56 11.19 11.69 11.99 12.19 12.24 11.76 11.34 11.00 10.74 10.52 10.35 10.22 10.12 10.04
    L  8.54  8.83  9.17  9.56 10.06 10.66 11.48 12.72 13.60 13.66 12.13 11.50 11.10 10.82 10.60 10.43 10.29 10.19 10.11 10.05
 58 U  8.48  8.75  9.06  9.42  9.87 10.41 11.11 12.03 12.53 12.81 13.15 12.29 11.70 11.25 10.93 10.68 10.48 10.33 10.22 10.12
    L  8.44  8.70  9.01  9.35  9.79 10.33 11.05 12.09 14.07 15.33 12.68 11.77 11.31 10.99 10.75 10.56 10.41 10.29 10.20 10.13
 57 U  8.64  8.93  9.25  9.65 10.14 10.79 11.67 13.09 13.41 14.21 12.74 11.96 11.44 11.07 10.80 10.59 10.43 10.30 10.20 10.12
    L  8.56  8.83  9.14  9.50  9.95 10.53 11.24 12.52 15.70 14.29 12.05 11.44 11.15 10.88 10.67 10.51 10.38 10.28 10.20 10.13
 56 U  8.52  8.77  9.07  9.41  9.82 10.34 11.03 12.01 13.82 15.27 12.74 12.03 11.52 11.15 10.87 10.66 10.49 10.36 10.25 10.17
    L  8.43  8.66  8.92  9.22  9.58 10.03 10.68 10.77 12.05       12.87 11.19 11.33 10.98 10.75 10.59 10.45 10.34 10.26 10.19
 55 U  8.63  8.88  9.17  9.51  9.91 10.41 11.10 12.00             11.82 11.46 11.13 10.88 10.69 10.53 10.40 10.29 10.21 10.14
    L  8.50  8.72  8.98  9.26  9.54 10.00 11.64  7.44              8.36 12.30 11.10 10.77 10.65 10.51 10.40 10.31 10.24 10.18
 54 U  8.48  8.70  8.95  9.22  9.55  9.91 10.32 11.02                   11.35 11.02 10.84 10.68 10.54 10.42 10.32 10.24 10.17
    L  8.35  8.54  8.75  8.99  9.31  9.11  9.89                               11.36 10.42 10.75 10.56 10.43 10.35 10.28 10.22
 53 U  8.54  8.75  8.98  9.23  9.54  9.84                                     10.77 10.65 10.52 10.41 10.33 10.25 10.19 10.13
    L  8.38  8.56  8.71  8.99 10.12  6.59                                      7.64 11.66 10.63 10.42 10.38 10.31 10.25 10.20
 52 U  8.39  8.57  8.77  8.97  9.18  9.51                                           10.61 10.47 10.39 10.32 10.25 10.19 10.14
    L  8.24  8.40  8.61  8.36  9.04                                                       10.81 10.06 10.46 10.34 10.26 10.22
 51 U  8.42  8.58  8.76  8.94                                                             10.36 10.30 10.24 10.19 10.15 10.11
    L  8.21  8.43  9.34  6.17                                                              7.34 11.37 10.40 10.24 10.24 10.20
 50 U  8.29  8.42  8.56  8.75                                                                   10.29 10.21 10.18 10.14 10.11
    L  8.18  7.92  8.55                                                                               10.56  9.88 10.32 10.23
 49 U  8.30  8.42                                                                                     10.16 10.13 10.10 10.08
    L  8.85  5.92                                                                                      7.20 11.22 10.28 10.15
 48 U  8.16  8.30                                                                                           10.12 10.09 10.07
    L  8.22                                                                                                       10.43  9.79
```

Fig. 7. POISSON prediction along pole-yoke interface of a quadrupole with a yoke thickness of 1.25 in. The nominal pole-tip field is 2.75 kG (6,500 A-t).

```
 THE FOLLOWING IS A MAP OF /B/(KG) UPPER ---CYCLE 2250
                           /B/(KG) LOWER
  L                                  DRAGON Q1 at 6,500 At with 5x5x4x4x3 array -- 1998/07/23 - 0.3648 conductor - 1.7 in yoke
  .            .
  .     K .......
 ...           .
  .
        98    99   100   101   102   103   104   105   106   107   108   109   110   111   112   113   114   115   116   117
 60 U  8.06  8.27  8.52  8.81  9.13  9.48  9.87 10.19 10.39 10.47 10.41 10.19  9.83  9.45  9.13  8.84  8.59  8.38  8.20  8.05
    L  8.12  8.34  8.60  8.92  9.29  9.74 10.30 10.97 11.54 11.70 11.29 10.42  9.84  9.39  9.06  8.78  8.55  8.35  8.19  8.05
 59 U  8.26  8.51  8.80  9.13  9.52  9.99 10.52 10.91 11.10 11.12 10.94 10.37  9.88  9.45  9.11  8.81  8.57  8.36  8.19  8.05
    L  8.28  8.53  8.83  9.19  9.61 10.18 10.90 11.97 12.75 12.62 11.01 10.21  9.69  9.29  8.98  8.72  8.51  8.33  8.17  8.04
 58 U  8.23  8.46  8.73  9.06  9.44  9.94 10.55 11.35 11.79 11.91 11.96 11.00 10.29  9.76  9.35  9.02  8.74  8.51  8.32  8.16
    L  8.21  8.44  8.71  9.03  9.41  9.91 10.56 11.52 13.39 14.62 11.69 10.55  9.94  9.50  9.16  8.88  8.65  8.45  8.29  8.15
 57 U  8.38  8.63  8.94  9.29  9.73 10.31 11.13 12.47 12.80 13.32 11.62 10.67 10.03  9.55  9.18  8.89  8.64  8.44  8.27  8.13
    L  8.33  8.57  8.85  9.18  9.59 10.14 10.80 12.03 15.30 13.31 10.83 10.08  9.67  9.30  9.01  8.77  8.56  8.39  8.24  8.12
 56 U  8.30  8.52  8.78  9.10  9.47  9.95 10.60 11.57 13.45 14.72 11.75 10.83 10.16  9.67  9.29  8.99  8.74  8.53  8.36  8.21
    L  8.23  8.43  8.67  8.95  9.27  9.69 10.30 10.40 11.64       11.59  9.87  9.86  9.41  9.10  8.86  8.65  8.47  8.32  8.19
 55 U  8.40  8.63  8.90  9.21  9.58 10.05 10.72 11.62             10.62 10.12  9.67  9.32  9.04  8.80  8.60  8.42  8.27  8.14
    L  8.30  8.50  8.73  9.00  9.24  9.68 11.28  7.18              7.35 10.69  9.51  9.11  8.92  8.71  8.53  8.38  8.25  8.14
 54 U  8.29  8.48  8.70  8.96  9.26  9.60  9.99 10.65                   10.00  9.53  9.28  9.03  8.82  8.63  8.46  8.31  8.19
    L  8.18  8.35  8.53  8.76  9.06  8.84  9.57                                9.71  8.80  9.00  8.76  8.57  8.43  8.30  8.19
 53 U  8.35  8.53  8.74  8.98  9.26  9.55                                      9.18  8.99  8.79  8.62  8.47  8.34  8.21  8.11
    L  8.21  8.37  8.50  8.77  9.87  6.39                                      6.43  9.76  8.80  8.55  8.46  8.33  8.22  8.13
 52 U  8.22  8.38  8.56  8.75  8.95  9.24                                            8.94  8.71  8.59  8.46  8.34  8.22  8.12
    L  8.09  8.24  8.43  8.17  8.81                                                        8.93  8.24  8.52  8.36  8.24  8.15
 51 U  8.25  8.40  8.57  8.73                                                              8.54  8.43  8.32  8.22  8.13  8.04
    L  8.07  8.27  9.16  6.02                                                              5.99  9.25  8.39  8.21  8.17  8.09
 50 U  8.14  8.26  8.39  8.56                                                                    8.41  8.27  8.19  8.12  8.04
    L  8.05  7.78  8.37                                                                                8.49  7.91  8.22  8.10
 49 U  8.16  8.26                                                                                      8.16  8.10  8.03  7.97
    L  8.72  5.82                                                                                      5.74  8.95  8.14  7.99
 48 U  8.04  8.16                                                                                            8.08  8.00  7.95
    L  8.09                                                                                                        8.23  7.70
```

Fig. 8. POISSON prediction along pole-yoke interface of a quadrupole with a yoke thickness of 1.70 in. The nominal pole-tip field is 2.75 kG (6,500 A-t).

```
THE FOLLOWING IS A MAP OF /B/(KG) UPPER ---CYCLE  750
                          /B/(KG) LOWER
 L                                DRAGON Q1 at 6,500 At with 5x5x4x4x3 array -- 1998/07/23 - 0.3648 conductor - 1.25 in yoke
 .               .
 .     K .......
...              .
 .
        16    17    18    19    20    21    22    23    24    25    26    27    28    29    30    31    32    33    34    35    36    37
24 U                                                        6.55  5.18  5.05  5.16  5.28  5.39  5.51  5.63  5.75  5.87  5.98  6.10  6.22
   L                                                  0.00  5.47  5.05  5.01  5.23  5.33  5.43  5.55  5.67  5.80  5.92  6.04  6.16  6.29
23 U                                            5.46  3.94  4.76  4.94  5.05  5.17  5.29  5.42  5.55  5.68  5.81  5.93  6.06  6.18  6.31
   L                                            5.73  4.14  5.05  5.00  5.08  5.21  5.33  5.45  5.58  5.72  5.85  5.98  6.11  6.24  6.37
22 U                                            6.13  4.75  4.67  4.79  4.92  5.05  5.18  5.32  5.46  5.60  5.74  5.88  6.01  6.14  6.27
   L                                      0.00  5.19  4.65  4.63  4.86  4.97  5.09  5.22  5.35  5.49  5.63  5.77  5.91  6.05  6.18  6.32
21 U                                5.03  3.60  4.33  4.53  4.66  4.79  4.93  5.07  5.21  5.36  5.51  5.66  5.81  5.95  6.09  6.23  6.37
   L                                5.27  3.77  4.64  4.61  4.69  4.84  4.97  5.10  5.24  5.38  5.53  5.68  5.84  5.98  6.13  6.27  6.42
20 U                                5.64  4.28  4.23  4.36  4.51  4.66  4.80  4.95  5.10  5.25  5.41  5.57  5.74  5.89  6.04  6.18  6.33
   L                          0.00  4.84  4.24  4.21  4.45  4.56  4.69  4.84  4.98  5.12  5.27  5.43  5.59  5.75  5.91  6.06  6.22  6.37
19 U                    4.52  3.20  3.89  4.08  4.22  4.36  4.51  4.67  4.83  4.98  5.14  5.31  5.48  5.66  5.83  5.98  6.13  6.29  6.43
   L                    4.81  3.36  4.23  4.18  4.27  4.41  4.55  4.70  4.85  5.00  5.15  5.32  5.48  5.66  5.84  6.00  6.16  6.32  6.48
18 U                    5.01  3.75  3.79  3.92  4.07  4.21  4.37  4.53  4.70  4.86  5.03  5.20  5.38  5.57  5.75  5.92  6.09  6.25  6.40
   L              0.00  4.67  3.80  3.78  4.01  4.12  4.25  4.40  4.55  4.71  4.87  5.03  5.20  5.37  5.56  5.75  5.92  6.09  6.26  6.43
17 U        3.93  2.82  3.41  3.62  3.77  3.92  4.07  4.23  4.39  4.56  4.74  4.91  5.09  5.27  5.47  5.67  5.86  6.04  6.21  6.37  6.53
   L        4.54  2.99  3.78  3.72  3.81  3.95  4.10  4.25  4.40  4.56  4.73  4.90  5.07  5.26  5.45  5.65  5.85  6.02  6.20  6.38  6.56
16 U        3.99  3.23  3.31  3.46  3.62  3.78  3.93  4.09  4.25  4.42  4.60  4.78  4.96  5.16  5.36  5.57  5.79  5.98  6.17  6.35  6.52
   L  0.00  6.00  3.31  3.30  3.49  3.63  3.78  3.93  4.09  4.25  4.42  4.59  4.77  4.94  5.13  5.33  5.54  5.75  5.95  6.14  6.34  6.52
15 U  3.02  2.98  3.16  3.32  3.48  3.64  3.79  3.95  4.11  4.27  4.45  4.64  4.83  5.03  5.24  5.46  5.70  5.92  6.13  6.32  6.51  6.68
   L              2.34  3.33  3.19  3.41  3.58  3.77  3.94  4.11  4.27  4.44  4.62  4.80  4.99  5.20  5.42  5.65  5.87  6.08  6.29  6.50
14 U                    3.02  3.21  3.34  3.50  3.66  3.82  3.97  4.13  4.31  4.49  4.69  4.89  5.10  5.33  5.59  5.85  6.08  6.30  6.51
   L                          2.47  3.31  3.31  3.59  3.79  3.97  4.13  4.29  4.47  4.65  4.84  5.05  5.28  5.53  5.78  6.01  6.24  6.46
13 U                          3.18  3.38  3.52  3.69  3.84  4.00  4.16  4.34  4.53  4.74  4.94  5.18  5.44  5.74  6.02  6.29  6.53  6.73
   L                                2.67  3.49  3.62  3.89  3.99  4.15  4.33  4.48  4.66  4.88  5.13  5.39  5.66  5.93  6.19  6.44  6.59
12 U                                      3.36  3.56  3.71  3.86  4.03  4.19  4.37  4.56  4.77  4.99  5.26  5.58  5.94  6.27  6.56  6.82
   L                                            3.03  4.04  3.89  3.92  4.25  4.36  4.44  4.67  4.95  5.23  5.51  5.82  6.12  6.48  6.70
11 U                                            3.57  3.71  3.91  4.05  4.20  4.38  4.58  4.79  5.03  5.33  5.75  6.22  6.63  6.95  7.05
   L                                                        3.19  4.30  4.44  4.20  4.32  4.77  5.05  5.32  5.65  6.02  6.42  7.12
10 U                                                              3.93  4.06  4.19  4.39  4.58  4.77  5.00  5.36  5.95  6.80  7.10
   L                                                                          3.49  4.63  4.93  5.08  5.34  5.84  6.49  7.05
 9 U                                                                          4.40  4.52  4.65  4.82  5.15  6.16  7.91
```

Fig. 9. POISSON prediction along pole face of a quadrupole with a yoke thickness of 1.25 in. The nominal pole-tip field is 2.75 kG (6,500 A-t).

```
THE FOLLOWING IS A MAP OF /B/(KG) UPPER ---CYCLE  780
                          /B/(KG) LOWER
 L                                DRAGON Q1 at 6,500 At with 5x5x4x4x3 array -- 1998/07/23 - 0.3648 conductor - 1.7 in yoke
 .               .
 .     K .......
...              .
 .
        16    17    18    19    20    21    22    23    24    25    26    27    28    29    30    31    32    33    34    35    36    37    38    39    40
24 U                                                        6.82  5.18  5.06  5.18  5.29  5.41  5.53  5.65  5.77  5.89  6.00  6.12  6.23  6.35  6.47  6.60
   L                                                  0.00  6.13  5.11  5.02  5.26  5.36  5.47  5.59  5.71  5.83  5.95  6.07  6.19  6.31  6.43  6.56  6.69
23 U                                            5.46  3.96  4.78  4.96  5.06  5.18  5.31  5.43  5.56  5.69  5.82  5.95  6.07  6.19  6.32  6.44  6.57  6.70
   L                                            5.78  4.06  5.11  5.04  5.11  5.24  5.36  5.49  5.61  5.75  5.88  6.01  6.13  6.26  6.39  6.52  6.66  6.80
22 U                                            6.39  4.75  4.68  4.80  4.94  5.06  5.20  5.33  5.47  5.61  5.75  5.89  6.02  6.15  6.28  6.41  6.54  6.67
   L                                      0.00  5.87  4.71  4.64  4.89  5.00  5.12  5.25  5.38  5.52  5.66  5.80  5.94  6.07  6.21  6.34  6.48  6.62  6.76
21 U                                5.03  3.61  4.35  4.54  4.67  4.80  4.94  5.08  5.22  5.37  5.52  5.67  5.82  5.96  6.10  6.23  6.37  6.50  6.64  6.77
   L                                5.32  3.69  4.69  4.64  4.72  4.86  4.99  5.13  5.27  5.41  5.56  5.71  5.86  6.01  6.15  6.29  6.43  6.58  6.72  6.87
20 U                                5.89  4.27  4.24  4.37  4.52  4.67  4.81  4.96  5.11  5.27  5.42  5.58  5.75  5.90  6.04  6.19  6.33  6.47  6.61  6.74
   L                          0.00  5.52  4.29  4.23  4.47  4.59  4.72  4.86  5.00  5.15  5.30  5.45  5.61  5.78  5.93  6.08  6.23  6.38  6.53  6.68  6.83
19 U                    4.52  3.21  3.91  4.09  4.22  4.37  4.52  4.68  4.84  4.99  5.15  5.32  5.49  5.67  5.83  5.99  6.14  6.29  6.44  6.58  6.72  6.85
   L                    4.85  3.30  4.28  4.21  4.29  4.44  4.58  4.72  4.87  5.02  5.18  5.34  5.51  5.68  5.86  6.01  6.17  6.33  6.49  6.65  6.80  6.96
18 U                    5.25  3.76  3.79  3.93  4.07  4.22  4.38  4.54  4.71  4.87  5.04  5.21  5.39  5.57  5.76  5.93  6.09  6.25  6.41  6.56  6.70  6.84
   L              0.00  5.37  3.85  3.80  4.04  4.15  4.28  4.42  4.58  4.74  4.89  5.05  5.22  5.40  5.58  5.77  5.94  6.11  6.28  6.44  6.61  6.77  6.91
17 U        3.93  2.84  3.43  3.63  3.78  3.93  4.08  4.23  4.40  4.57  4.74  4.92  5.09  5.28  5.48  5.68  5.87  6.04  6.21  6.38  6.54  6.69  6.83  6.95
   L        4.62  2.94  3.84  3.76  3.83  3.98  4.12  4.27  4.43  4.59  4.76  4.92  5.10  5.28  5.47  5.67  5.86  6.04  6.22  6.40  6.57  6.75  6.91  6.88
16 U        4.22  3.24  3.32  3.47  3.63  3.78  3.94  4.09  4.25  4.42  4.61  4.79  4.97  5.16  5.37  5.58  5.80  5.99  6.17  6.35  6.52  6.68  6.83  6.96
   L  0.00  6.95  3.37  3.32  3.52  3.65  3.80  3.96  4.12  4.28  4.44  4.61  4.79  4.96  5.15  5.35  5.56  5.77  5.97  6.16  6.35  6.54  6.70  6.95  7.24
15 U  2.93  2.98  3.17  3.33  3.48  3.65  3.80  3.96  4.11  4.28  4.46  4.65  4.84  5.03  5.24  5.47  5.71  5.93  6.13  6.33  6.51  6.69  6.84  6.98  7.06
   L        2.36  3.37  3.21  3.44  3.60  3.79  3.97  4.13  4.29  4.46  4.64  4.82  5.01  5.21  5.43  5.67  5.89  6.09  6.30  6.51  6.70  6.74  7.39
14 U              3.02  3.21  3.35  3.51  3.67  3.82  3.98  4.14  4.31  4.50  4.70  4.90  5.11  5.34  5.59  5.86  6.09  6.31  6.52  6.70  6.87  6.97
   L                    2.49  3.34  3.34  3.62  3.82  4.00  4.15  4.32  4.49  4.67  4.86  5.07  5.30  5.54  5.80  6.02  6.25  6.47  6.75  6.99  6.03
13 U                    3.18  3.38  3.53  3.69  3.85  4.00  4.17  4.35  4.54  4.74  4.95  5.18  5.45  5.75  6.03  6.30  6.54  6.74  6.91  7.01
   L                          2.69  3.51  3.64  3.91  4.01  4.17  4.35  4.50  4.68  4.90  5.15  5.40  5.68  5.94  6.20  6.45  6.60  7.25
12 U                                3.37  3.57  3.72  3.87  4.03  4.20  4.37  4.57  4.78  5.00  5.27  5.59  5.94  6.28  6.57  6.83  6.95
   L                                      3.05  4.06  3.91  3.94  4.27  4.37  4.46  4.68  4.97  5.24  5.53  5.83  6.14  6.49  6.71  6.29
11 U                                      3.58  3.71  3.91  4.06  4.21  4.39  4.59  4.80  5.03  5.34  5.76  6.23  6.64  6.96  7.06
   L                                                  3.20  4.32  4.46  4.22  4.34  4.78  5.07  5.33  5.66  6.04  6.43  7.13
10 U                                                        3.94  4.07  4.20  4.40  4.59  4.78  5.01  5.36  5.96  6.81  7.11
   L                                                                          3.50  4.65  4.95  5.10  5.35  5.85  6.50  7.06
 9 U                                                                          4.41  4.53  4.66  4.83  5.16  6.17  7.92
   L
```

Fig. 10. POISSON prediction along pole face of a quadrupole with a yoke thickness of 1.70 in. The nominal pole-tip field is 2.75 kG (6,500 A-t).

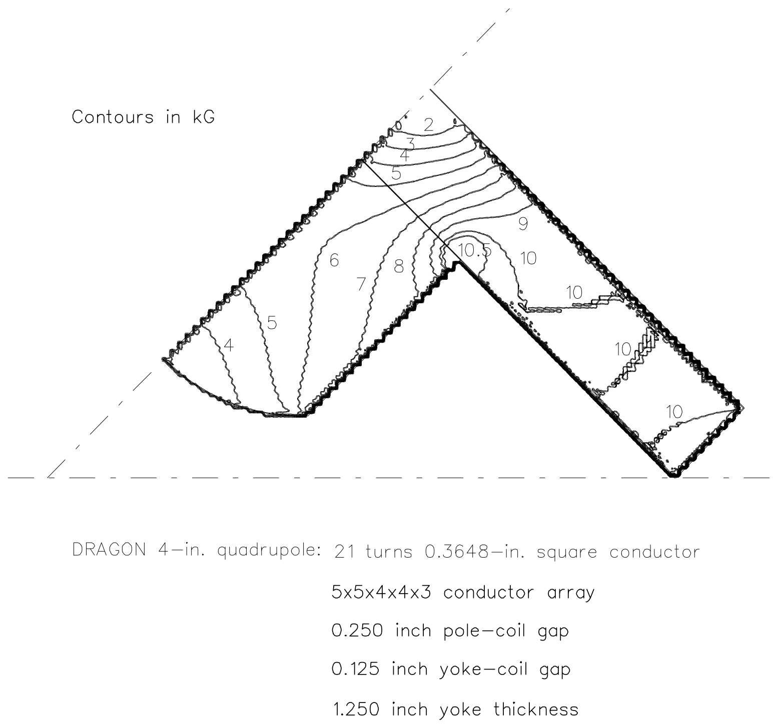

Fig. 11. POISSON prediction of the field in the iron for the upper triangle group of a quadrupole with a 1.25 in. yoke thickness.

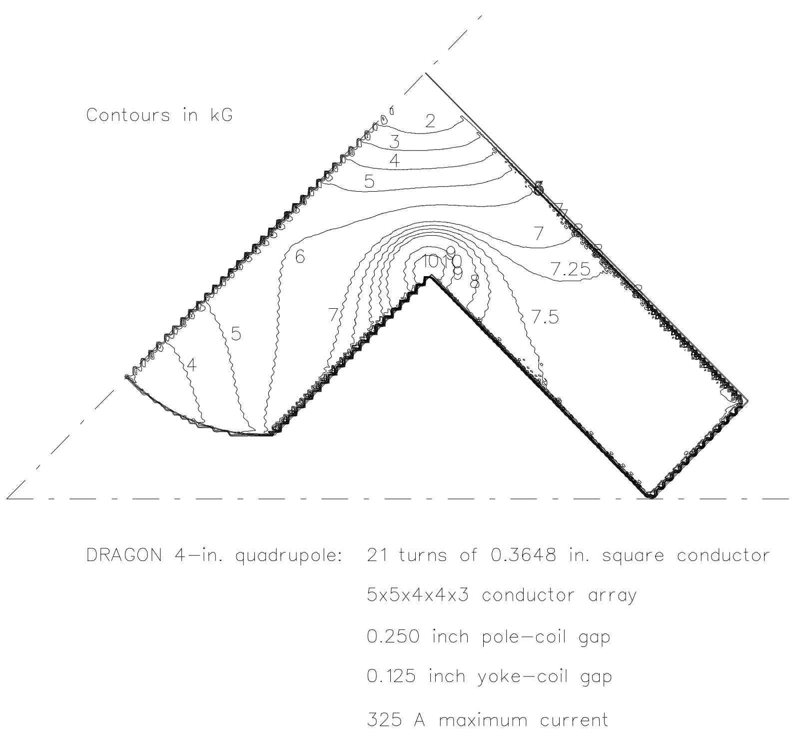

Fig. 12. POISSON prediction of the field in the iron for the upper triangle group of a quadrupole with a 1.70 in. yoke thickness.

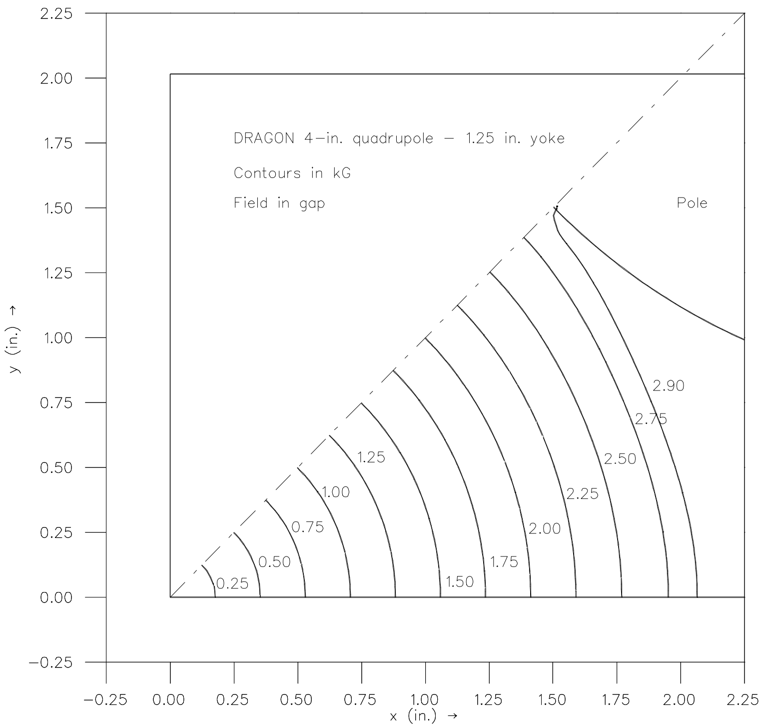

Fig. 13. POISSON prediction of the field in the gap of a quadrupole with a 1.25 in. yoke thickness.

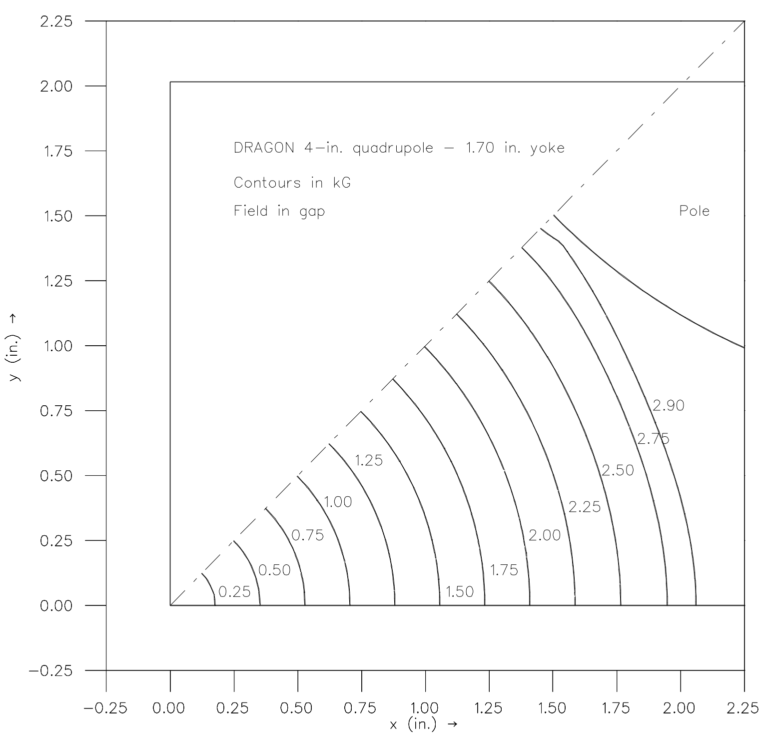

Fig. 14. POISSON prediction of the field in the gap of a quadrupole with a 1.70 in. yoke thickness.