1. Introduction

The High Energy Beam Transport (HEBT) system of ISAC requires two trim quadrupoles in each of its achromatic sections[1]. These are specified short ($L_{eff} = 8$ cm), low-field ($B_{max} = 0.8$ kG) quadrupoles. As such, the use of quadrupoles already designed for the triplets in the DTL section *could* be contemplated. However, these latter quadrupoles have a smaller bore than requested and, because they are designed to produce high field gradients, are costly.

This report is the result of a study to produce a less costly quadrupole that would be suitable for the required purposes.

2. Design Parameters

In reference 1 the following parameters are specified for the required trim quadrupoles.

Maximum pole-tip field	0.8 kG		
Full aperture	5.2 cm	=	2.05 in.
Peak gradient	3.0 T/m	=	0.78 kG/in.
Effective length	8.0 cm	=	3.15 in.

The peak gradient listed above is based on a 50% 'safety margin'. Following subsequent discussions with R. Laxdal[2], he changed the above specifications to an effective length of 10 cm (3.937 in.) with a nominal gradient of 180 G/cm (1.8 T/m). Consequently, allowing for this safety factor, we design the quadrupole for a peak gradient of 2.7 T/m. Further, in the following calculations we assume a full aperture of 2.25 in. The resultant design parameters are then as follows.

Full aperture	5.715 cm	=	2.25 in.
Peak gradient	2.7 T/m	=	0.69 kG/in.
Effective length	10.0 cm	=	3.94 in.
Maximum pole-tip field	0.776 kG		

3. Iron length of the quadrupoles

In the design of a typical quadrupole one normally assumes that its effective length, L_{eff}, and its iron length, L_{iron}, are related by

$$L_{eff} = L_{iron} + k\,a$$

where a is the half-aperture and k lies between 0.9 and 1.1[3]. Historically, this has worked well for TRIUMF-designed quadrupoles. For the standard 4Q14/8 quadrupoles, for example, with $L_{iron} = 14$ in. and $a = 2.03$ in., the measured $L_{eff} = 15.87$ in., corresponding to a value of 0.92 for k. Similarly, the 4Q8.5/8.5 quadrupoles on beam line 2A have $L_{iron} = 8.5$ in. and $a = 2.03$ in. with a measured $L_{eff} = 10.35$ in. This corresponds to a k-value of 0.91. In each case, the nominal design value of k was unity.

We note that the ratio of effective length to half-aperture for the 4Q14/8 quadrupoles is 7.8 and that for the 4Q8.5/8.5 quadrupoles is 5.1.

The ratio of effective length to half-aperture of the quadrupoles considered here is $L_{eff}/a = 3.50$. Consequently, these quadrupoles might be designated 'short' quadrupoles. At TRIUMF there are no quadrupoles that have this ratio of effective length to aperture radius. The shortest (in the above sense) are the 12Q series. Of these the JUNO I (12Q12/10) quadrupoles have $L_{eff} = 15.66$ in., $L_{iron} = 12$ in. and $2a = 12$ in.;

thus for this type $L_{eff}/a = 2.61$. The 12Q12/5 series of quadrupoles have $L_{eff} = 14.55$ in., $L_{iron} = 12$ in. and $2a = 11.72$ in.; thus $L_{eff}/a = 2.28$ for these types.

One of the designs developed by A. Otter for quadrupoles for the CDS gas-cooled triplet[4)] comes closest to the design considered here. This triplet consists of two quadrupoles of effective length 1.5 in. and one of effective length 3.0 in. The apertures of all quadrupoles were 0.7 in. in radius. No measured data on the performance of these quadrupoles is available. However, the initial design was based on the formula given above with $k = 1$. Iron lengths of 0.875 in. and 2.3 in. were chosen for the shorter and longer quadrupoles respectively. Thus, for the longer quadrupole, the chosen value of L_{eff}/a was 4.29—a value (arguably) closer to the required ratio for these HEBT quadrupoles.

Consequently, following Otter we choose $k = 1$ and calculate

$$L_{iron} = L_{eff} - a = 3.94 \text{ in.} - 1.125 \text{ in.} = 2.815 \text{ in.}$$

We take

$$\boxed{L_{iron} = 3.00 \text{ in.} = 7.62 \text{ cm.}}$$

On the basis of the above, the estimated effective length of a quadrupole will be

$$\boxed{L_{eff} = 4.125 \text{ in.} = 10.48 \text{ cm.}}$$

4. Quadrupole design parameters

Following Banford[3)], we calculate iron parameters (with the nominal design parameters in brackets) as follows.

Yoke thickness (= 0.8 * aperture/2.)	1.000 in.	=	25.40 mm
Pole width (= 1.7 * aperture/2.)	2.000 in.	=	50.80 mm
Pole radius (= 1.15 * aperture/2.)	1.294 in.	=	25.40 mm
Pole length (= effective length - aperture/2.)	3.000 in.	=	76.20 mm

5. Ampere-turns per Coil

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

$$NI \text{ per pole} = \frac{1.1}{2}\,(\text{half aperture (m)})\,\frac{\text{Pole-tip field (T)}}{\mu_0} = \frac{1.1}{2}\,\frac{0.05715}{2}\,\frac{0.0776}{4\,\pi\,10^{-7}} = 971 \text{ A–t}$$

Because of the low number of Ampere-turns required, two designs were considered for the coils of these quadrupoles. A conventional water-cooled coil was first studied. For this a 0.1620 in-square, hollow conductor—the same as that used for some of the steering magnets of the MEBT system—was considered. Because a current of 100 A can easily be accommodated by this conductor, only 10 turns of conductor are required to produce the required Ampere-turns.

As an alternative to a water-cooled conductor the use of an air-cooled solid conductor was investigated. For this, a coil wound with AWG number 10 solid copper wire was chosen—primarily because some was available to make a test coil. A 45-turn coil was chosen so that the current required to provide the required number of Ampere-turns would be 21.6 A.

The results of these studies are presented below.

6. Quadrupole design with air-cooled, solid copper coils

6.1 Coil design

As noted above, AWG number 10 wire was chosen to make the coil. The winding arrangement chosen was a $10 \times 9 \times 8 \times 7 \times 6 \times 5 \times 4 \times 3 \times 2 \times 1$ triangular array as shown on the next page. A gap of 0.125 in. has been allowed between the pole and the coil and between the yoke and the coil.

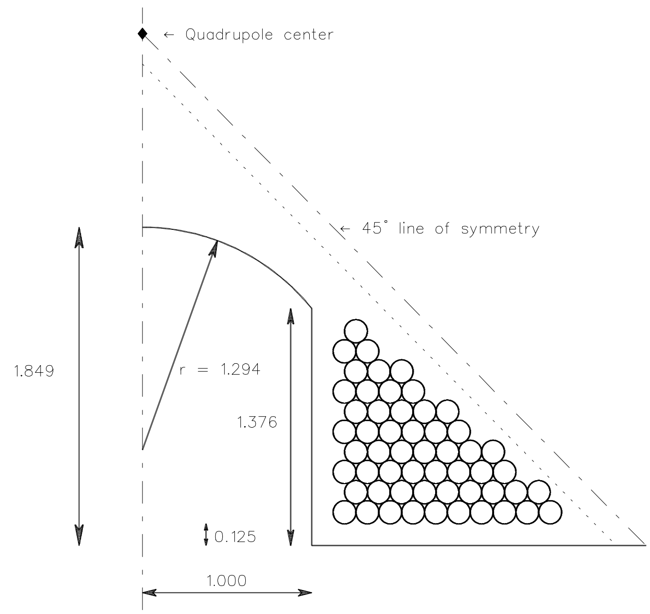

Fig. 1. Coil and yoke cross-sections for AWG #8 wire. Dimensions are inches.

The dotted line in the above figure represents the clearance of 0.125 in. between the coil and the 45° symmetry line. Not indicated is the 0.125 in. pole-coil separation.

In ref [5] this wire is listed as having the following properties.

Listed properties of AWG #8 bare copper wire

Diameter (in.)	0.1288	Area (in.^{2})	0.01297
Ohms/1000 feet at 20°C	0.6282	Ohms/pound at 20°C	0.01257
Feet/pound	20.01	Pounds/1000 feet	49.98

To estimate the length of wire required per coil we assume a gap of $G = 0.125$ in. between the pole and the coil. In addition to this, we note that the even-numbered rows (counting up from the yoke in the above figure) have an additional offset of $\delta = d\cos 60 = 0.0675$ in, where d is the diameter of the wire. Further, we assume that the pole ends are radiused with a radius of $R_{pole} = 0.125$ in.

Then the straight-line length of coil along the length of the pole is

$$L_{straight} = L_{iron} - 2R_{pole}$$

and that along the width of the pole is

$$L_{width} = W_{iron} - 2R_{pole}.$$

To allow for the offset of the different layers we define a new pole-coil gap G' as

$$G' = G + \delta[\mathrm{mod}(L,2) + (-1)^L]$$

where L is again the layer number counting up from the yoke. The *minimum* radius of curvature of the conductor at the pole ends is then

$$R_{min} = R_{pole} + G' + d/2$$

and the radius of curvature of the nth turn of layer L is

$$R_n = R_{min} + (n-1)d.$$

Consequently, the length of this nth turn is

$$\begin{aligned} l_n &= 2[L_{straight} + L_{width}] + 2\pi R_n \\ &= 2[L_{iron} - 2R_{pole} + W_{iron} - 2R_{pole}] + 2\pi[R_{pole} + G' + d\,/\,2 + (n-1)d] \\ &= 2[L_{iron} + W_{iron} - (4-\pi)R_{pole} + \pi(G' + d(n - 1/2))]. \end{aligned}$$

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

$$\begin{aligned} L_N &= \textstyle\sum_{n=1}^{N} l_n \\ &= 2\,N\left[L_{iron} + W_{iron} - (4-\pi)R_{pole} + \pi\left\{G' + d\left(\frac{N+1}{2} - \frac{1}{2}\right)\right\}\right] \\ &= 2\,N\left[L_{iron} + W_{iron} - (4-\pi)R_{pole} + \pi\left\{G' + \frac{N\,d}{2}\right\}\right]. \end{aligned}$$

In our case, W_{iron} has a value of 2.00 in., L_{iron} a value of 3.00 in. and G' takes the value of 0.125 in. for odd-numbered layers and of 0.1925 in. for even-numbered layers. We take the conductor diameter d to be 0.135 in. so as to include its insulation. Recalling that layer numbers are being counted from the yoke upward, the estimated length of conductor required for one coil is calculated as follows.

Layer number	Number of turns	Length (in.)
1	10	148.12
2	9	133.31
3	8	111.71
4	7	97.75
5	6	78.69
6	5	65.58
7	4	49.07
8	3	36.80
9	2	22.84
10	1	11.42
Total		755.29

Thus the estimated length of conductor required is approximately 755 in. or 63 ft. per coil. Allowing 2 ft. for leads, we take

Length of conductor per coil	=	65 ft.
Weight of conductor per coil	=	3.25 lb.

From the data listed in the table of properties of AWG #8 wire we then estimate the resistance of a coil at 20°C to be

$$R_{20} = 65\text{ ft} \times 0.6282\ \Omega/1000\text{ ft} = 0.0408\ \Omega\ .$$

At a maximum current of 20 A the voltage drop per coil is the

$$V_{coil} = (20\text{ A})(0.0408\ \Omega) = 0.816\text{ V}\ .$$

Thus the minimum power supply requirements are

Current	20 A
Voltage	5 V
Power	100 W

To test the feasibility of using this wire for coils for these quadrupoles, a test coil was wound from 39 ft. of AWG #8 wire. The coil was then attached to a power supply such that the coil was suspended in free air. A voltage drop of 0.5 V was noted at a current of 20 A, both values being read from the panel meters of the power supply. At this power level no significant warming of the coil was noted. However, at a current of 24 A and voltage of 0.6 V, a significant warming of the coil was noted. Temperatures of 137°F and 123°F were measured on the inner end surfaces of the coil and a temperature of 128°F was measured at the midpoints of the inner side surfaces of the coil. Corresponding temperatures on the outer coil surface were measured to be 127°F and 116°F at the coil ends and 128°F and 131°F along its sides.

To confirm this calculation, the resistance of the wound coil was measured and the coil was then unwound. The resistance of the unwound wire was then measured. No difference in resistance was noted—implying that no shorted windings had been caused during the winding of the coil. Measurements of the voltage drop across the wire were made for a series of currents with the following results[6)].

Current (A)	Voltage (V)	Resistance (Ω)	Ω/1000 ft (Ω)
6.4	0.166	0.026	0.6667
7.0	0.230	0.032	0.8205
20.0	0.668	0.033	0.8462

The measured resistance of the wire in more in line with the listed resistance of AWG #9 annealed copper wire, listed as having a diameter of 0.1144 in. and a resistance of 0.7921 Ω/1000 ft. If the wire used was indeed AWG #9 it was coated with an insulation thickness of 0.010 in. to bring its size to the measured value of 0.134 in. Regardless, the measured quantities are consistent with either AWG #8 or #9 wires. Consequently, we shall continue with the assumption that AWG #8 wire was used.

6.2 Iron Parameters

Figure 2 shows the geometry of an octant of the proposed HEBT quadrupole with a coil made from AWG #8 wire. Figure 3 shows the overall dimensions of a quadrupole. (For purposes of the POISSON calculations given below, the coils are shown as if they were constructed from rectangular wire.)

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 $R_{pole} = 1.294$ 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

$$\frac{\theta}{2} = \sin^{-1}\left[\frac{1.000}{1.294}\right] = 50.606^\circ = 0.88324 \text{ radian}$$

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

$$\begin{aligned} A_{csp/2} &= R_{pole}^2(\theta - \sin\theta)/4 \\ &= (1.294)[(0.88324)(2) - \sin(2(50.606))]/4 \\ &= 0.3235[1.76648 - 0.98091] = 0.25413 \text{ in.}^2. \end{aligned}$$

The length of the straight side of a pole, L_{str} is

$$\begin{aligned} l_{str} &= \text{Pole length} - (\text{Pole radius})[1 - \cos(\theta/2)] \\ &= 1.849 - 1.294(1 - 0.63456) = 1.37624 \text{ in.} \end{aligned}$$

so that the area of one *full* pole, A_{pole}, is

$$\begin{aligned} A_{pole} &= 2[A_{csp/2}] + (\text{Pole width})(\text{Length of pole side}) \\ &= 2(0.25413) + (2.000)(1.37624) = 3.26074 \text{ in.}^2. \end{aligned}$$

The area of one yoke section, A_{yoke}, is

$$A_{yoke} = (\text{Yoke length})(\text{Yoke thickness}) = (6.948)(1.000) = 6.948 \text{ in.}^2$$

so that the volume of iron per quadrupole, V_{iron}, is

$$V_{iron} = 4(\text{Yoke area} + \text{Pole area})(\text{Iron length}) = 4(3.26074 + 6.948)(3.000) = 122.505 \text{ in.}^3.$$

Using an iron density of 0.2833 lb/in.^{3}, we find the amount of iron per quadrupole, W_{Fe}, to be

$$W_{Fe} = (\text{Iron volume})(\text{Iron density}) = (122.505 \text{ in.}^3)(0.2833 \text{ lb/in.}^3) = 34.71 \text{ lb.}$$

We take

$$\boxed{\text{Weight of iron per HEBT quadrupole} = 35 \text{ lb.}}$$

6.3 POISSON calculations

POISSON[7] runs were made for this quadrupole configuration. Because these quadrupoles operate at low field, it was not thought necessary to use a sloped pole. This assumption is justified by the yoke field contours shown in figure 4. This and other POISSON results were input into the program PLOTDATA[8] to produce the figures showing the results of POISSON calculations. As expected, the largest flux concentration is found at the pole root. Because the flux in the pole will be increased due to leakage, the flux in the pole and yoke will be increased beyond the values shown in the figure. However, even if this increase were a factor of two, the predicted fluxes would be well below saturation.

Figure 5 shows the predicted variation of the field gradient along the x-axis as a function of excitation. It is seen that the required gradient has been reached. Figure 6 shows the calculated value of the gradient radii of 0.5 in. and 1.0 in. as a function of excitation. Both are seen to be predicted to be linear, although the slope at a radius of 1 in. is approximately 3.6% smaller than that at a radius of 0.5 in.

7. Quadrupole design with hollow, water-cooled copper coils

7.1 Coil design

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

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

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

Normally, the minimum bending radius of a conductor is taken to be at least four times the conductor dimension. However, in the design and construction of the steering magnets for the MEBT[9], the minimum bending radius of this particular conductor was 0.50 in. Because these steering magnets work well, we take

$$R_{min,cond} = 0.50 \text{ in.}$$

We allow a separation of $G = 0.250$ in. between the pole and the coil and radius the pole ends by the same amount—that is, $R_{pole} = 0.250$ in. Thus the *minimum* radius of curvature of the conductor at the pole ends is

$$R_{min} = R_{min,cond} + d\,/\,2 = R_{pole} + G + d\,/\,2.$$

Then, applying the previous formulae with $G' = G$, we have the following.

Layer number	Number of turns	Length (in.)
1	4	60.78
2	3	43.20
3	2	27.20
4	1	12.80
Total		143.98

Thus the estimated length of conductor required is approximately 144 in. or 12 ft. per coil. Allowing 2 ft. for leads, we take

Length of conductor per coil	=	14.0 ft.
Weight of conductor per coil	=	1.1 lb.

From the data listed in the table of properties of this 0.162 in. conductor, we then estimate the resistance of a coil at 20°C to be

$$\boxed{R_{20} = 14 \text{ ft} \times 421.1 \times 10^{-6}\ \Omega/\text{ft} = 0.00590\ \Omega\ .}$$

At a maximum current of 100 A the voltage drop per coil is the

$$\boxed{V_{coil} = (100 \text{ A})(0.00590\ \Omega) = 0.590 \text{ V}\ .}$$

Thus the minimum power supply requirements are

Current	100 A
Voltage	3 V
Power	300 W

7.2 Cooling requirement

In these calculations we use the British system of units. Because of the low power dissipation, we assume a temperature rise of 5°C [9°F]. Then the hot resistance of the coil is

$$\begin{aligned} R_{hot} &= R_{20C}\,[1 + (\text{Temp. coeff}/°\text{C})\Delta T(°C)] \\ &= R_{20}\,[1 + 0.00393(5)] \\ &= (0.00590)(1.0197) = 0.00602\ \Omega \text{ per coil.} \end{aligned}$$

The power required per coil is

$$\text{Power per coil} = P = I^2 R_{hot} = (100)(100)(0.00602) = 60.2 \text{ W.}$$

The required flow rate is given by

$$v\ (\text{ft/sec}) = \frac{2.19}{\Delta T(°\text{F})} \frac{P\ (\text{kW})}{\text{Cooling area (in}^2)} = 0.24333 \times \frac{P\ (\text{kW})}{\text{Cooling area (in}^2)}$$

for $\Delta T = 9°\text{F} = 5°\text{C}$. Thus for $P = 0.0602$ kW and a cooling area of 0.006362 in.^{2}, we have

$$v\ (\text{ft/sec}) = \frac{(0.24333)(0.0602)}{0.006362} = 2.301.$$

The volume of flow required per coil is then

$$\begin{aligned}\text{Volume/circuit} &= 2.6\, v(\text{ft/min})\,[\text{Cooling area(in}^2)]\ \text{IGPM} \\ &= 3.12250\, v(\text{ft/min})\,[\text{Cooling area(in}^2)]\ \text{USGPM} \\ &= 0.0457\ \text{USGPM} = 0.173\ \ell/\text{min}.\end{aligned}$$

Thus

Volume per coil	0.046 USGPM	0.173 ℓ/min
Volume per quadrupole	0.184 USGPM	0.692 ℓ/min

7.3 Pressure drop

The pressure drop is given by

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

In our case, with $k = 0.0622$, we obtain

$$\Delta P = 0.0622(2.301)^{1.79} = 0.2765\ \text{psi/ft}$$

and the pressure drop across a single coil is

$$\Delta P\ (\text{psi/coil} = (0.2765\ \text{psi/ft})(14\ \text{ft}) = 3.870\ \text{psi}$$

Pressure drop per coil = 3.9 psi

7.4 Iron parameters

Figure 7 shows the geometry of an octant of the proposed HEBT quadrupole with a coil made from 0.162 in. square conductor. Figure 8 shows the overall dimensions of a quadrupole.

We calculate the amount of iron required for each of the quadrupoles following the method indicated in section 6.2 using the following data.

Pole radius	R_{pole}	1.294 in.
Half-angle	$\theta/2$	50.606°
Pole side	L_{str}	1.12524 in.
Pole width	W_{iron}	2.000 in.
Iron length	L_{iron}	3.000 in.

Using those parameters, we calculate the areas tabulated on the next page.

From this data we take

Weight of iron per HEBT quadrupole = 32 lb.

Area of circular pole segment	$2A_{csp/2}$	0.508 in.^{2}
Area of rectangular pole segment	A_{rect}	2.250 in.^{2}
Area of one yoke	A_{yoke}	6.446 in.^{2}
Area of one quadrant	$A_{quadrant}$	9.204 in.^{2}
Total area of quadrupole	$4A_{quadrant}$	36.816 in.^{2}
Total volume of iron	$4A_{quadrant}L_{iron}$	110.448 in.^{3}
Iron weight	W_{Fe}	31.290 lb

7.4 POISSON results

Again, POISSON were made for this quadrupole configuration. As noted in section 6.3, because these quadrupoles operate at low field, a sloped pole was not used. That this is justified is shown by the yoke field contours shown in figure 9. As with the previous results, the largest flux concentration is found at the pole root and all comments made in section 6.3 are applicable to figure 9.

Figure 10 shows the predicted variation of the field gradient along the x-axis as a function of excitation. Again, the required gradient has been reached. Figure 11 shows the calculated value of the gradient radii of 0.5 in. and 1.0 in. as a function of excitation. Both are seen to be predicted to be linear, although the slope at a radius of 1 in. is approximately 3.6% smaller than that at a radius of 0.5 in. As previously, PLOTDATA was used to produce figures showing the results of the POISSON calculations.

8. Discussion

This report details two possible designs for the HEBT trim quadrupoles. One design uses an air-cooled coil and the other a water-cooled coil. The results of this study might be summarized by saying that there is little difference between the two designs.

The air-cooled design has an advantage in that no cooling circuits are required, thus making assembly and installation easier. In addition, a 5 V, 20 A power supply will be less expensive than a 3 V, 100 A supply. On the other hand, if these quadrupoles are required to run near the design maximum a significant amount of coil heating is to be expected. Consequently, regardless of which design is chosen, it is felt that thermal switches are necessary. Conventional Klixon switches are readily mountable on coils constructed from the 0.162 in.-square conductor. Thermal switches for coils constructed from AWG #8 wire would have to be different—possibly being made of thermocouples.

These designs result in a small, lightweight quadrupole. I have been informed[6)] that a coil-winding mechanism exists at TRIUMF and that this mechanism is capable of winding either type of coil. As a result, either type of quadrupole could be made entirely in-house. Regardless of what type of coil material is selected, it would be necessary to develop a suitable form on which the coil could be wound.

Table 1 following summarizes the results of these calculations. Table 2 lists the input file for POISSON for the calculations for a quadrupole with a coil made from AWG #8 wire. Table 3 is a list of the command file for the program FRONT that automatically generates an input file for POISSON from the data listed in table 4—in this case, input for a quadrupole with a coil made from 0.162 in. square conductor.

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3. A. P. Banford, *The Transport of Charges Particle Beams*, Spon, 1996.

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6. C. Ballard, *Private communication*, TRIUMF, November, 1999.

7. 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.

8. J. L. Chuma, *PLOTDATA Command and Reference Manual*, TRIUMF Report TRI-CD-87-03b, June, 1991.

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Table 1

Summary of the design parameters fro the HEBT trim quadrupole.

		Conductor dimension	
		AWG #8	0.162 in.-square
Yoke:	Iron length (in.)	3.000	3.000
	Iron width (in.)	6.948	6.446
	Iron thickness (in.)	1.000	1.000
Pole:	Width (in.)	2.000	2.000
	Height (in.)	1.849	1.598
	Radius (in.)	1.294	1.294
Iron:	Total weight (lb)	35.0	32.0
Coil:	Conductor OD (in.)	0.135	0.162
	Conductor ID (in.)	—	0.090
	Nominal coil width (in.)	1.350	0.800
	Nominal coil height (in.)	1.350	0.800
	Coolant flow per coil (USGPM)	—	0.05
	Total coolant flow (USGPM)	—	0.20
	Turn configuration	10 wide $\times$ 10 high	4 wide $\times$ 4 high
	Resistance per coil (mΩ)	40.8	5.90
Power:	Maximum current (A)	20.	100.
	Minimum Voltage (V)	5.	3.
	Minimum power (W)	100.	300.
Quadrupole:	Full aperture (in.)	2.250 in.	2.250
	Overall width (in.)	11.240 in.	10.530
	Overall height (in.)	11.240 in.	10.530
	Overall length including coil (in.)	5.950	5.100
	Overall weight including coil (lb)	48.0	36.4

Table 2

Data file for POISSON runs for AWG #8 conductor

```
HEBT trim quadrupole at 1000 A-t, #8 wire in 10x9x8x7x6x5x4x3x2x1 grid, .25 in. pole-coil sep
$reg nreg=6,npoint=5,mat=1
xmin=0.000000,xmax=5.00000,dx=0.05000
,ymin=0.000000,ymax=3.00000,dy=0.05000
$end
$po x=2.809978,y=2.809978 $end
$po x=0.000000,y=0.000000 $end
$po x=4.205742,y=0.000000 $end
$po x=4.912849,y=0.707107 $end
$po x=2.809978,y=2.809978 $end
$reg npoint=7,mat=2 $end
$po x=2.809978,y=2.809978 $end
$po x=0.795495,y=0.795495 $end
$po nt=2,x0=1.7104911,y0=1.7104914,r=1.2940000,theta=-84.3941422 $end
$po x=2.809978,y=1.381371 $end
$po x=4.205742,y=0.000000 $end
$po x=4.912849,y=0.707107 $end
$po x=2.809978,y=2.809978 $end
$reg npoint=23,mat=1,cur=1000. $end
$po x=1.961450,y=0.370459 $end
$po x=2.056909,y=0.275000 $end
$po x=2.141762,y=0.359853 $end
$po x=2.237221,y=0.264393 $end
$po x=2.322074,y=0.349246 $end
$po x=2.417534,y=0.253787 $end
$po x=2.502386,y=0.338640 $end
$po x=2.597846,y=0.243180 $end
$po x=2.682698,y=0.328033 $end
$po x=2.778158,y=0.232574 $end
$po x=2.863011,y=0.317426 $end
$po x=2.958470,y=0.221967 $end
$po x=3.043323,y=0.306820 $end
$po x=3.138783,y=0.211360 $end
$po x=3.223635,y=0.296213 $end
$po x=3.319095,y=0.200754 $end
$po x=3.403948,y=0.285607 $end
$po x=3.499407,y=0.190147 $end
$po x=3.584260,y=0.275000 $end
$po x=3.679719,y=0.179541 $end
$po x=3.764572,y=0.264393 $end
$po x=2.809978,y=1.218988 $end
$po x=1.961450,y=0.370459 $end
$reg npoint=2,mat=1,ibound=0 $end
$po x=0.000000,y=0.000000 $end
$po x=2.809978,y=2.809978 $end
$reg npoint=2,mat=1,ibound=0 $end
$po x=4.912849,y=0.707107 $end
$po x=2.809978,y=2.809978 $end
$reg npoint=2,mat=1,ibound=1 $end
$po x=4.205742,y=0.000000 $end
$po x=4.912849,y=0.707107 $end
```

Table 3

Input file for FRONT for POISSON runs for 0.162 in. square conductor

```
$set def [pois.ps.psxeq]
$dele plot.ps;*
$dele out*.lis;*
$dele tape*.dat;*
$run front
hebt.in
$runpsf
$run psfplot
 0 0 0 s
 s
 go
 1 0 20 s
 s
 go
 1 0 20 s
 s
 go
 -1 s
$rename plot.ps hebt_4x3x2x1_1000.ps
$rename outfro.lis hebt_4x3x2x1_1000.fro
$rename outlat.lis hebt_4x3x2x1_1000.lat
$rename outpoi.lis hebt_4x3x2x1_1000.poi
$pu hebt_4x3x2x1_1000.*
$dele tape*.dat;*
```

Table 4
Data file (hebt.in) for POISSON runs for 0.162 in. square conductor

```
title
HEBT trim quadrupole at 1,000 At with 4x3x2x1 array – 1999/11/04 - 0.162 conductor - 1.0 in yoke
run
pois
mode 0
xmax 4.60
ymax 2.70
xmesh 0.05
ymesh 0.05
symm=4
nseg 4
conv=2.54
matpro 1
zseg 0. 3.850681 4.557788 2.632447
rseg 0. 0. 0.707107 2.632447
nseg 6
conv=2.54
zseg 0.795495 1.836895 2.632447 3.850681 4.557788 2.632447
rseg 0.795495 0.422680 1.218234 0. 0.707107 2.632447
cseg 0. 1.294000 0. 0. 0. 0.
matpro 2
nseg 10
matpro 1
conv=2.54
zseg 2.1127 2.2577 2.4097 2.5547 2.7067 2.8517 3.0037 3.1486 3.3007 2.7208
rseg 0.3450 0.2000 0.3521 0.2071 0.3591 0.2141 0.3662 0.2212 0.3732 0.9531
current=1000.
nseg 2
matpro 1
ibound=0
conv=2.54
zseg 0. 2.632447
rseg 0. 2.632447
nseg 2
matpro 1
ibound=0
conv=2.54
zseg 4.557788 2.632447
rseg 0.707107 2.632447
nseg 2
matpro 1
ibound=1
conv=2.54
zseg 3.850681 4.557788
rseg 0. 0.707107
kbot=1
lbot=1
ltop=41
fieldmap 2
hangle0 45
hangle1 0
hnormalization 1.0
hpoints 30
hradius 1.0
hterms 10
begin
end
```

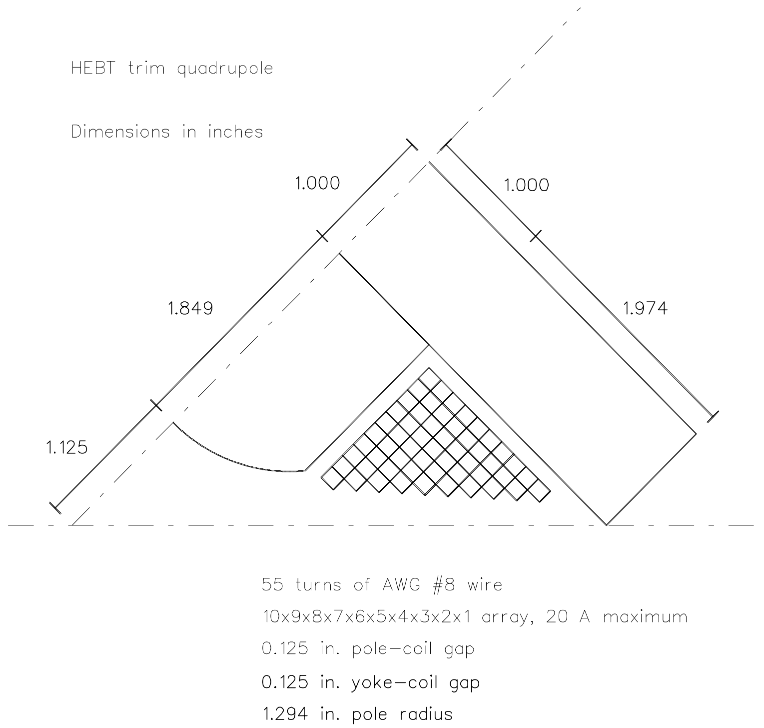

Fig. 2. An octant of a HEBT quadrupole with a coil of 55 turns of AWG #8 wire.

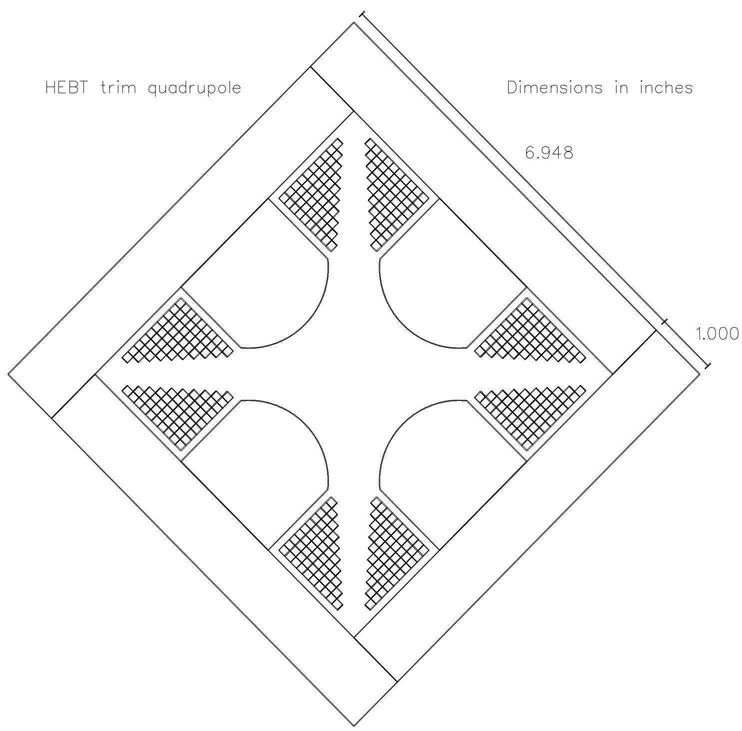

Fig. 3. Overall dimensions of this HEBT quadrupole.

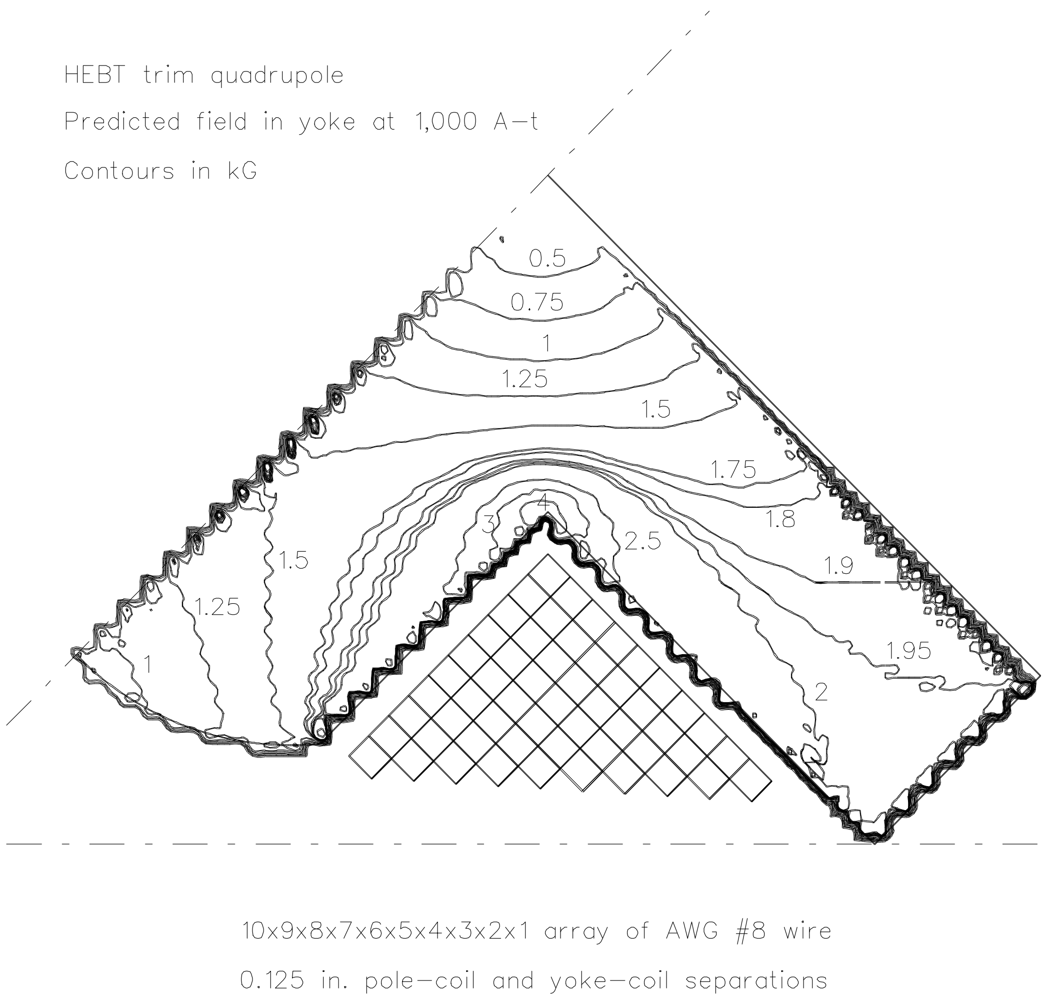

Fig. 4. Predicted fields in the yoke of a HEBT quadrupole at 1,000 A-t. The coil is 55 turns of AWG #8 wire.

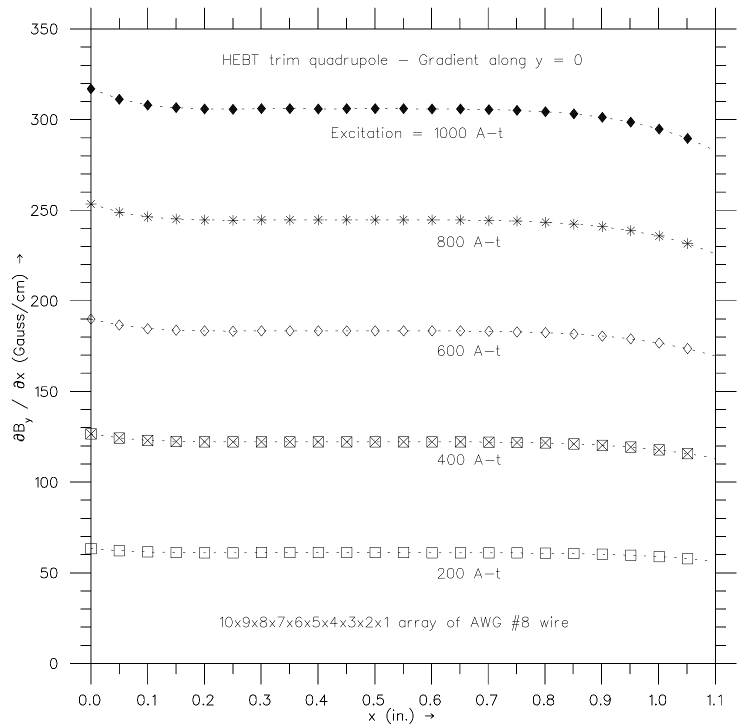

Fig. 5. Calculated gradient as a function of radius and excitation of a HEBT quadrupole with a coil of 55 turns of AWG #8 wire.

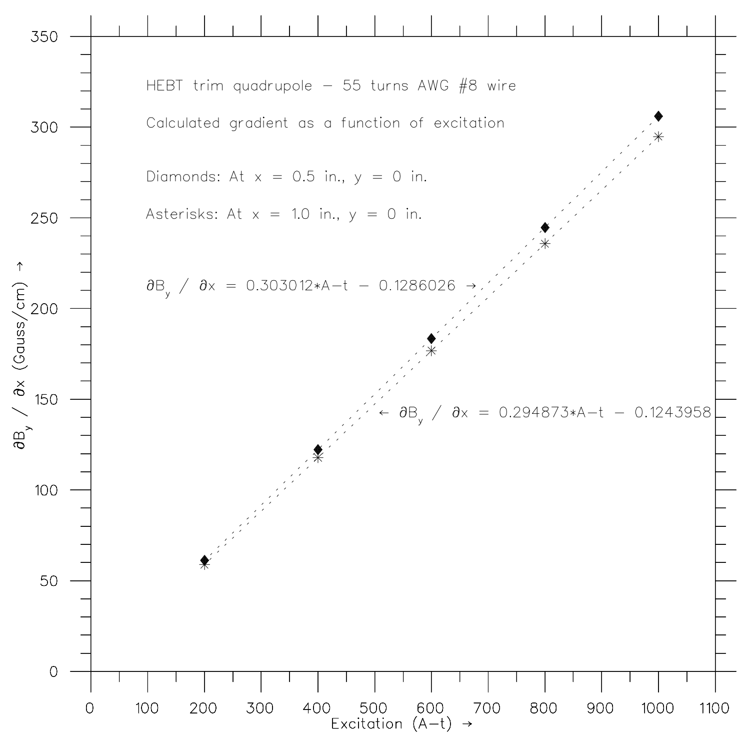

Fig. 6. Calculated gradient as a function of excitation of a HEBT quadrupole with a coil of 55 turns of AWG #8 wire.

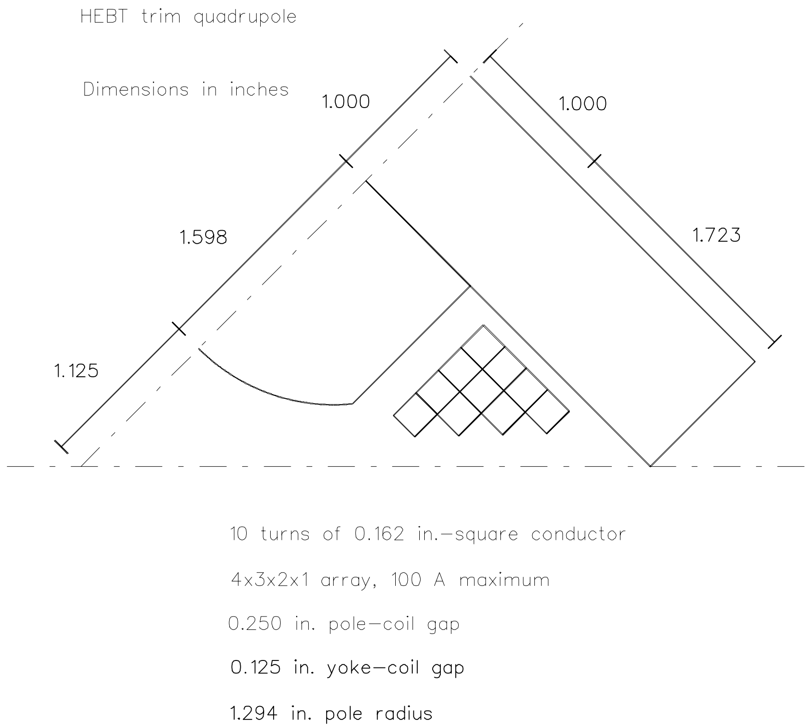

Fig. 7. An octant of a HEBT quadrupole with a coil of 10 turns of 0.162 in. square conductor.

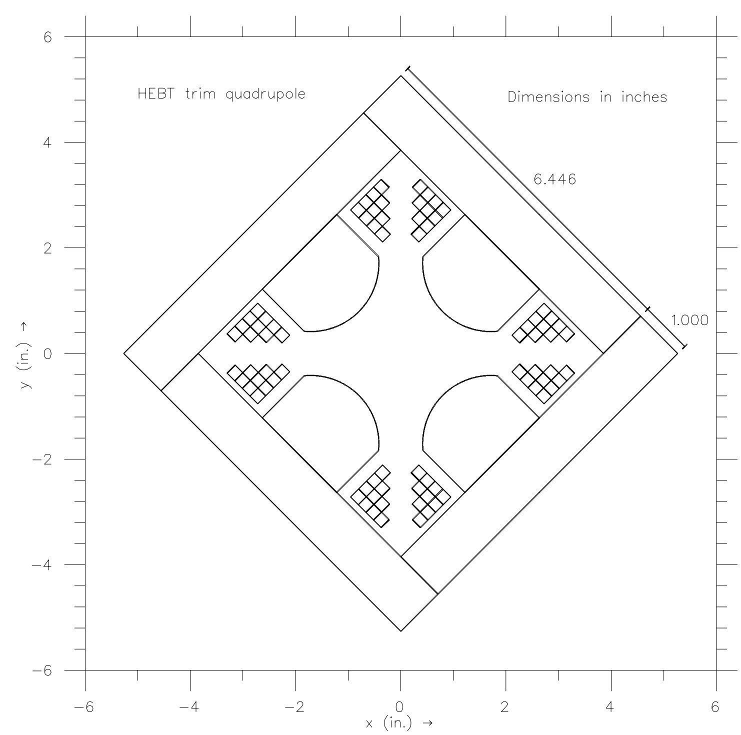

Fig. 8. Overall dimensions of this HEBT quadrupole.

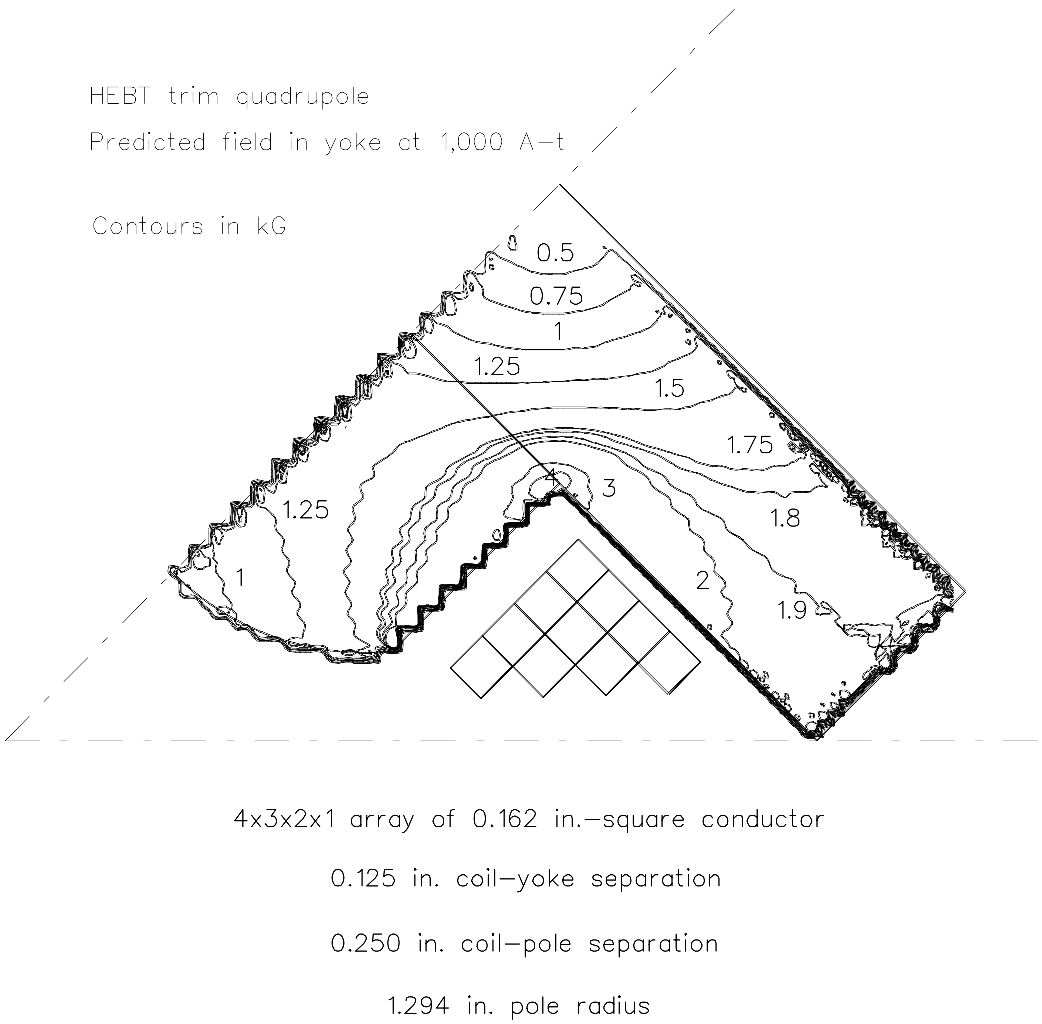

Fig. 9. Predicted fields in the yoke of a HEBT quadrupole at 1,000 A-t. The coil is 10 turns of 0.162 in. square conductor.

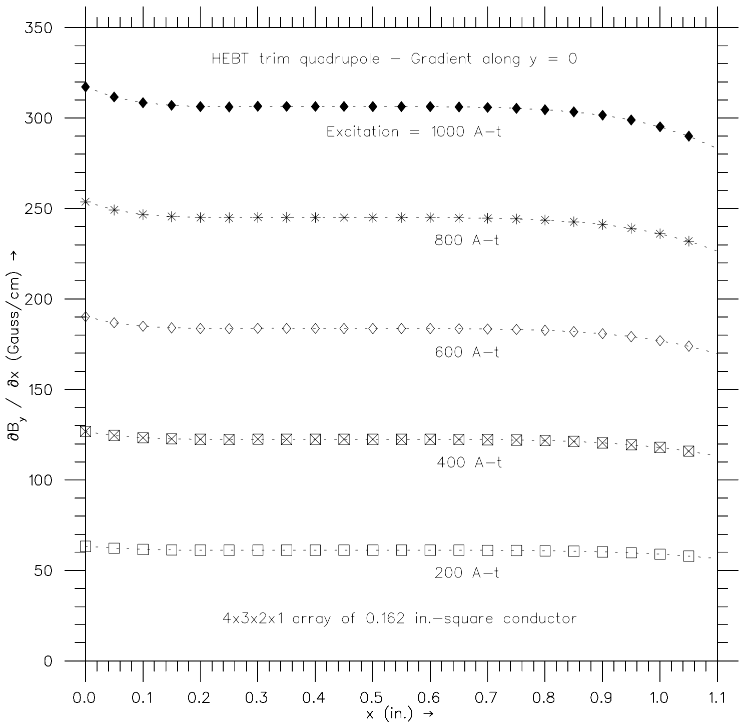

Fig. 10. Calculated gradient as a function of radius and excitation of a HEBT quadrupole with a coil of 10 turns of 0.162 in. square conductor.

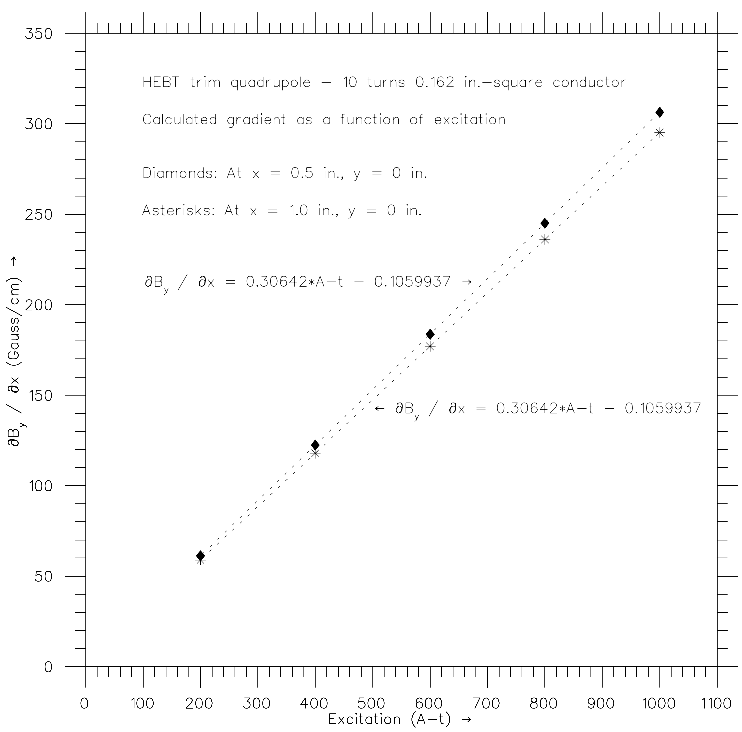

Fig. 11. Calculated gradient as a function of excitation of a HEBT quadrupole with a coil of 10 turns of 0.162 in. square conductor.