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Subject A revised conceptual design for the 15° dipoles on beamline 2A		

1. Introduction

Because only the west target—designated TGT2 in this report—will be installed initially in the ISAC target area, a revised design for beam line 2A replaces the ±15° switching magnet with a rectangular 15° dipole identical to that located downstream. The two 15° bends then give the 30° deflection required to reach the target. A previous report[1)] presented a conceptual design for an H-magnet that would be suitable for the individual 15° dipoles.

The fastest and simplest method of obtaining these dipoles would be to scale the design for the vault dipoles[2)] down to the size given in ref[1)]. However, in discussions with G. Clark it became apparent that if this were done, the good field region would be over a length of approximately 14 inches in the center of the approximately 28 inch iron length of the dipole. Consequently, another option for the dipole was investigated. This report presents another possible concept for the design of these dipoles. The design has a length midway between that of the vault dipoles and that given in ref[1)] and runs at a lower field.

2. Design parameters for the 15° dipoles

In this version of the beam line, the TRANSPORT calculations require a magnet with an effective length 0.95191 m that is capable of producing a field of 10.00 kG at 500 MeV. We design the magnet for a maximum energy of 520 MeV (or a momentum of 1.11633 GeV/c) and field of 10.241 kG in order that we have sufficient range. We require a clear gap of 3 inches so the gap is specified to be 4.0 inches, thus allowing 1 inch for the vacuum vessel.

B_0	=	Maximum magnetic field	=	10.241 kG
g	=	Maximum air gap	=	10.160 cm
θ	=	Maximum bend angle	=	15.000°
s	=	Length of the central trajectory	=	95.191 cm

We first calculate the basic properties of these magnets.

$$\rho = \text{radius of curvature of the central trajectory} = \frac{s}{\theta} = \frac{(180.0)(0.95191)}{(15.0)(\pi)} = 3.63604 \text{ m} = 143.151 \text{ in.}$$

$$\boxed{\text{Radius of curvature of the central trajectory} = \rho = 3.636 \text{ m} = 143.15 \text{ in.}}$$

We take the effective straight-line length of the magnet to be

$$l_e = 2\rho \sin\frac{\theta}{2} = 2(3.63604)(0.13053) = 0.94772 \text{ m} = 37.31173 \text{ in.}$$

$$\boxed{\text{Straight-line effective length of the magnet} = l_e = 0.945 \text{ m} = 37.312 \text{ in.}}$$

and assume that the the iron length, l_i, is obtained from

$$l_e = l_i + g$$

so that

$$l_i = l_e - g = 0.94772 - 0.1016 = 0.84612 \text{ m} = 33.31173 \text{ in.}$$

$$\boxed{\text{Iron length of the magnet} = l_i = 0.851 \text{ m} = 33.500 \text{ in.}}$$

2.1 Pole width

The deviation, Δ, of the central trajectory from a line drawn through the points of entry and exit is found from the relation

$$\Delta = \rho\left[1 - \cos\frac{\theta}{2}\right] = 3.63604(1 - 0.99144) = 0.03111 \text{ m} = 1.22468 \text{ in.}$$

$$\boxed{\text{Maximum deviation of central trajectory from straight line} = \Delta = 0.031 \text{ m} = 1.225 \text{ in.}}$$

We allow for a maximum beam width, x, of 2.0 in. (50.8 mm) and assume a 0.625 in. (15.875 mm) chamfer, c, at 45° to the each pole edge. Because the field is relatively uniform in an H-frame magnet, we take the pole width, W_{iron}, to be

$$W_{iron} = 2\,g + \Delta + x + 2\,c = 2(4.000) \text{ in.} + 1.225 \text{ in.} + 2.000 \text{ in.} + 2(0.625) \text{ in.} = 12.475 \text{ in.}$$

$$\boxed{\text{Pole width} = W_{iron} = 13.000 \text{ in.} = 330.2 \text{ mm.}}$$

2.2 Ampere-turns per coil

The required Ampere-turns per coil are calculated from the relation

$$NI \text{ per pole} = \frac{1}{2}\left[1.1\,\frac{B_0\,g}{\mu_0}\right] = \frac{1}{2}\,\frac{(1.1)(1.02410)(0.1016)}{4\pi\times10^{-7}} = 45,539 \text{ A-t}$$

where we have allowed for a 10% flux leakage. We take

$$\boxed{NI \text{ per pole} = 46{,}000 \text{ Ampere-turns}}$$

and generate the following table

I (Amperes)	100	200	300	400	500	600	700	800	900	1000
N (turns)	460	230	154	115	92	77	66	58	52	46

Because a low-cost 50 kW supply (80 V at 625 A) is available, we choose

I	=	600 Amperes
Coil configuration		8 turns wide by 10 turns high

3. Coil design

We assume a current density of 3000 A/in^2 = 4.65 A/mm^2 and calculate the required conductor area from

$$\text{Conductor area} = \frac{600\ A}{3000\ A/\text{in}^2} = 0.2000 \text{ in.}^2 = 129.03 \text{ mm}^2$$

This is satisfied within 10% by Ananconda 0.4600 and 0.5160 in.-square conductors; their parameters are given in the table on the next page.

We assume that each conductor is double-wrapped with insulation that is 0.007 in. (0.178 mm) thick with a tolerance of 0.0015 in. (0.038 mm). Then the *total* insulation per conductor has:

Minimum thickness	4(0.007 − 0.0015) in.	=	0.022 in. = 0.559 mm
Nominal thickness	4(0.007) in.	=	0.028 in. = 0.711 mm
Maximum thickness	4(0.007 + 0.0015) in.	=	0.034 in. = 0.864 mm

	Anaconda 0.4600		Anaconda 0.5160	
OD	0.4600 in.	[11.684 mm]	0.5160 in.	[13.106 mm]
ID	0.2550 in.	[6.477 mm]	0.2870 in.	[7.290 mm]
Copper area	0.1529 in.^{2}	[98.645 mm^2]	0.1940 in.^{2}	[125.161 mm^2]
Cooling area	0.05107 in.^{2}	[32.948 mm^2]	0.06469 in.^{2}	[41.735 mm^2]
Mass	0.5910 lb/ft	[0.880 kg/m]	0.7495 lb/ft	[1.115 kg/m]
Resistance at 20°C	53.25 $\mu\Omega$/ft	[174.70 $\mu\Omega$/m]	41.99 $\mu\Omega$/ft	[137.762 $\mu\Omega$/m]
k (British units)	0.01760		0.01520	

The tolerance of the outer dimension of the conductor is listed as 0.004 in. = 0.100 mm so that the dimensions of a *wrapped* conductor are:

Minimum	Conductor dimension + 0.022 in. − 0.004 in.	=	Conductor dimension + 0.018 in.
Nominal	Conductor dimension + 0.028 in.		
Maximum	Conductor dimension + 0.034 in. + 0.004 in.	=	Conductor dimension + 0.038 in.

We further allow

a) a gap between layers of 0.010 in. (0.254 mm) maximum
b) for keystoning, assume 0.010 in. (0.254 mm)
c) a 4-turn ground wrap of 0.007 in. (0.178 mm) tape

Then the *width* of the coil is obtained from

	Anaconda 0.4600		Anaconda 0.5160	
	Maximum	Minimum	Maximum	Minimum
Wrapped conductor	3.984 in.	3.824 in.	4.432 in.	4.272 in.
Gapping (7x0.10)	0.070 in.		0.070 in.	
Ground wrap (4x0.007x2)	0.056 in.	0.056 in.	0.056 in.	0.056 in.
Total (in.)	4.110 in.	3.880 in.	4.558 in.	4.328 in.

The average coil width is 3.995 in. [101.5 mm] for the 0.4600 in. conductor and 4.443 in. [112.9 mm] for the 0.5160 in. one. We take

	Anaconda 0.4600		Anaconda 0.5160	
Maximum coil width	4.200 in.	[106.7 mm]	4.600 in.	[118.1 mm]
Nominal coil width	4.000 in.	[101.6 mm]	4.500 in.	[114.3 mm]

The *height* of the coil is

	Anaconda 0.4600		Anaconda 0.5160	
	Maximum	Minimum	Maximum	Minimum
Wrapped conductor	4.980 in.	4.780 in.	5.540 in.	5.340 in.
Gapping (9x0.10)	0.090 in.		0.090 in.	
Keystoning (10x0.010)	0.100 in.	0.050 in.	0.100 in.	0.050 in.
Ground wrap (4x0.178x2)	0.056 in.	0.056 in.	0.056 in.	0.056 in.
Total	5.226 in.	4.886 in.	5.786 in.	5.446 in.

The average coil height is 5.056 in. [128.4 mm] for the 0.4600 in. conductor and 5.616 in. [142.7 mm] for the 0.5160 in. one. We take

	Anaconda 0.4600		Anaconda 0.5160	
Maximum coil height	5.300 in.	[134.6 mm]	5.850 in.	[148.6 mm]
Nominal coil height	5.100 in.	[129.5 mm]	5.650 in.	[143.5 mm]

We take the conductor dimension D to be

$$D = \text{Nominal dimension} + 4(\text{Insulation thickness}) + \text{Turn separation}$$

so that we then have for the 0.4600 in. conductor

$$\begin{aligned} D &= 0.460 \text{ in.} + 0.028 \text{ in.} + 0.010 \text{ in.} \\ &= 0.498 \text{ in.} \ [12.65 \text{ mm}] \end{aligned}$$

and for the 0.5160 in. conductor

$$\begin{aligned} D &= 0.516 \text{ in.} + 0.028 \text{ in.} + 0.010 \text{ in.} \\ &= 0.554 \text{ in.} \ [14.07 \text{ mm}]. \end{aligned}$$

We further assume a pole-coil gap of $G = 0.500$ in. $= 12.7$ mm and that the pole corners are rounded with a radius

$$\text{Pole radius} = R_{pole} = 4\,D - G$$

so that for the 0.4600 in. conductor we have

$$\begin{aligned} R_{pole} &= 4(0.498) \text{ in.} - 0.500 \text{ in.} \\ &= 1.492 \text{ in.} \ [37.90 \text{ mm}]. \end{aligned}$$

and for the 0.5160 in. conductor

$$\begin{aligned} R_{pole} &= 4(0.554) \text{ in.} - 0.500 \text{ in.} \\ &= 1.716 \text{ in.} \ [43.59 \text{ mm}]. \end{aligned}$$

Then the n^{th} conductor is a distance

$$D_n = n\,D + G + \text{Polewidth}/2 + 4(\text{insulation thickness})$$

from the longitudinal center-line of the pole and its (outer) radius of curvature is

$$R_n = R_{pole} + n\,D + G + 4(\text{insulation thickness})$$

The length of the straight longitudinal section of the winding is

$$L_{length} = L_{iron} - 2\,R_{pole}$$

and that of the straight section along the pole width is

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

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

$$\begin{aligned} l_n &= 2[L_{length} + L_{width}] + 2\,\pi\,R_n \\ &= 2[L_{iron} + W_{iron} + (\pi - 4)R_{pole} + \pi(4(\text{insulation}) + G)] + 2\,\pi\,n\,D \end{aligned}$$

and the length of an N-turn layer is

$$L_N = \sum_{n=1}^{N} l_n = 2\,N[L_{iron} + W_{iron} + (\pi - 4)R_{pole} + \pi(4(\text{insulation} + G)] + \pi\,N(N+1)D \qquad (1)$$

Substituting the following values from the table on the next page into equation (1) we find that the length of an 8-turn layer of the 0.4600 in. conductor is 861.3 in. [21,877 mm] = 71.78 ft [21.88 m] and that of an 8-turn layer of the 0.5160 in. conductor is 870.9 in [22,120 mm] = 72.58 ft [22.12 m]. Because these lengths differ little, we take

	Anaconda 0.4600	Anaconda 0.5160
L_{iron}	33.500 in.	33.500 in.
W_{iron}	13.000 in.	13.000 in.
R_{pole}	1.492 in.	1.716 in.
G	0.500 in.	0.500 in.
D	0.498 in.	0.554 in.
Insulation	0.007 in.	0.007 in.

$$\boxed{\text{Length of 8-turn layer of either conductor} = 75\text{ ft} \approx 23\text{ m},}$$

and the length per coil becomes

$$\boxed{\text{Length per coil of either conductor} = 750\text{ ft} \approx 230\text{ m}.}$$

Because two coils are required per dipole, then

Total length per dipole	1500 ft	≈	460 m
Allow 10% for winding losses	150 ft	≈	46 m
Total	1650 ft	≈	506 m

Then order

$$\boxed{\text{Total length of copper} = 1750\text{ ft} \approx 535\text{ m}}$$

of conductor. The mass of the 0.4600 conductor at 0.5910 lb/ft is approximately 1050 lb [480 kg] and that of the 0.5160 conductor at 0.7495 lb/ft is approximately 1325 lb [600 kg].

$$\boxed{\begin{aligned}\text{Total mass of 0.4600 conductor} &= 1100\text{ lb} \approx 500\text{ kg.}\\ \text{Total mass of 0.5160 conductor} &= 1400\text{ lb} \approx 635\text{ kg.}\end{aligned}}$$

4. Power requirements

At 20°C, the resistance of a coil of the 0.4600 in. conductor is

$$R_{20^\circ} = 53.25\times10^{-6}\ \Omega/\text{ft} \times 750\text{ ft} = 0.03994\ \Omega$$

and that of a coil of the 0.5160 in. conductor is

$$R_{20^\circ} = 41.99\times10^{-6}\ \Omega/\text{ft} \times 750\text{ ft} = 0.03149\ \Omega$$

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:

$$R_{hot} = R_{20^\circ}[1 + (\text{Temp. coeff}/^\circ\text{C})dT(^\circ\text{C})]$$

so that for the coil made of the 0.4600 in. conductor

$$R_{hot} = 0.03994[1 + (0.00393)(30)] = 0.04465\ \Omega \text{ per coil}$$

and that for the coil made of the 0.5160 in. conductor

$$R_{hot} = 0.03149[1 + (0.00393)(30)] = 0.03521\ \Omega \text{ per coil}$$

Thus, at a current of 600 A, we obtain

$$\begin{aligned}\text{Voltage per coil} &= 26.79 \text{ Volts for the 0.4600 in. conductor}\\ \text{Voltage per coil} &= 21.12 \text{ Volts for the 0.5160 in. conductor}\end{aligned}$$

Therefore, allowing for a 10% lead loss, we choose a power supply that has

	Anaconda 0.4600	Anaconda 0.5160
I (A minimum)	600	600
V (V minimum)	65	55
P (kW minimum)	39	33

5. Cooling requirements

In these calculations we use the British system of units.

The power required per coil of the 0.4600 in. conductor is

$$\text{Power per coil} = I^2 R_{hot} = (600)(600)(0.04465) = 16.07 \text{ kW}.$$

and that required per coil of the 0.5160 in. conductor is

$$\text{Power per coil} = I^2 R_{hot} = (600)(600)(0.03521) = 12.67 \text{ kW}.$$

The required flow rate is given by:

$$v \text{ (ft/sec)} = \frac{2.19}{\Delta T(^\circ \text{ F})} \times \frac{P(\text{kW})}{\text{Cooling area (in}^2)} = 0.0304167 \times \frac{P(\text{kW})}{A_c \text{ (in.}^2)}$$

for $\Delta T = 72°\text{F} = 40°\text{C}$. The 0.4600 in. conductor has a cooling area of $A_c = 0.05107$ in.^{2} [32.948 mm^2] and the 0.5160 in. conductor one of $A_c = 0.06469$ in^2 [41.735 mm^2]. Choosing $v = 2.50$ ft/sec to define the maximum power dissipation per water circuit we have:

$$\begin{aligned} P_{max} &= \frac{(2.50)(72)(0.05107)}{2.19} = 4.198 \text{ kW/water circuit [0.4600 in. conductor]} \\ &= \frac{(2.50)(72)(0.06469)}{2.19} = 5.317 \text{ kW/water circuit [0.5160 in. conductor]} \end{aligned}$$

from which we calculate the number of cooling circuits per coil (excluding lead loss) as

			Anaconda 0.4600	Anaconda 0.5160
P	=	Total power per coil	16.07 kW	12.67 kW
Number of circuits	=	$P \;/\; P_{max}$	3.83	2.38

Thus we take for *either* conductor

$$\boxed{\text{Number of cooling circuits per coil} \quad = \quad 5 \text{ for either conductor}}$$

This requires a flow rate of $v = 1.915$ ft/sec per water circuit of the 0.4600 in. conductor and a flow rate of $v = 1.192$ ft/sec per water circuit of the 0.5160 in. conductor. The volume of flow required per circuit is

$$\begin{aligned} \text{Volume/circuit} &= v\,\frac{\text{ft}}{\text{sec}} \times A_{H_2O}\,(\text{in}^2) \times 60\,\frac{\text{sec}}{\text{min}} \times \frac{1}{144}\,\frac{\text{ft}^2}{\text{in}^2} \times 62.4\,\frac{\text{lb}}{\text{ft}^3} \times \frac{1}{10}\,\frac{\text{IG}}{\text{lb}} \times 1.20095\,\frac{\text{USG}}{\text{IG}} \\ &= 3.1225\,v\,(\text{ft/sec}) \times \text{Cooling area}\,(\text{in}^2)\ \text{USGPM} \end{aligned}$$

Thus we have the following volumes of flow.

	0.4600 in. conductor		0.5160 in. conductor	
Volume per cooling circuit	0.305 USGPM	1.156 ℓ/min	0.241 USGPM	0.911 ℓ/min
Volume per coil	1.527 USGPM	5.778 ℓ/min	1.204 USGPM	4.557 ℓ/min
Volume per magnet	3.053 USGPM	11.556 ℓ/min	2.407 USGPM	9.114 ℓ/min

6. Pressure drop

The pressure drop is given by

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

with k a function of the cooling area. In our case, for the 0.4600 in. conductor with $k = 0.0176$ and $v = 1.915$ ft/sec we obtain

$$\Delta P = (0.0176)(1.915)^{1.79} = 0.0563 \text{ psi/ft} = 0.1847 \text{ psi/m}.$$

For the 0.51600 in. conductor with $k = 0.0152$ and $v = 1.192$ ft/sec we obtain

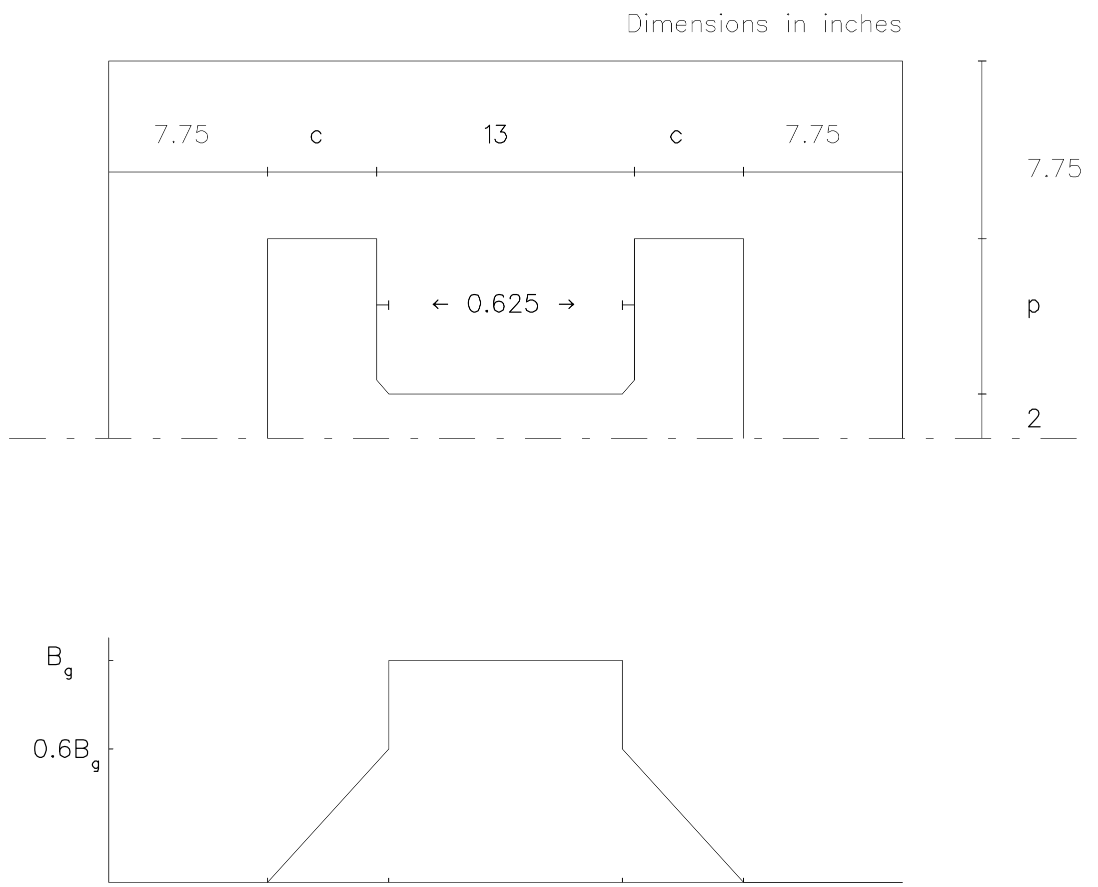
$$\Delta P = (0.0152)(1.192)^{1.79} = 0.0208 \text{ psi/ft} = 0.0683 \text{ psi/m}.$$

and the total pressure drop across one cooling circuit is:

$$\boxed{\begin{aligned} \text{Pressure drop per cooling circuit} &= 0.0563 \text{ psi/ft} \times 2(75) \text{ ft} = 8.45 \text{ psi } [0.4600 \text{ in. conductor}] \\ &= 0.0208 \text{ psi/ft} \times 2(75) \text{ ft} = 3.12 \text{ psi } [0.5160 \text{ in. conductor}] \end{aligned}}$$

7. Iron dimensions

A cross section of the dipole and an assumed field profile is shown in the figure below.



Cross section of the H magnet and assumed field profile for conceptual design.

As is illustrated in the figure, the magnetic field profile has been assumed to rise linearly from zero at the inside edge of the yoke to a value of $0.6B_g$ at the flat part of the pole. At that point the field rises to the full value in the gap B_g and remains at that value to the outer edge of the pole. At that point the field is assumed to abruptly drop to a value of $0.6B_g$ and to fall linearly to zero at the outer edge of the outer coil. This assumption is made for ease of further calculation.

We have assumed maximum coil widths of 4.200 in. and 4.600 in., respectively, for the smaller and larger conductor and allowed 0.500 in. clearance between the coil and the yoke and the coil and the pole. Consequently, the widths of the coil slots are 5.200 in. for the 0.4600 in. conductor case and 5.600 in. for the 0.5160 in. case. To these we add $c = 0.625$ in. for the chamfer to find that the edges of the flat portion of the pole are at distances from the inside edges of the yoke of $l_1 = 5.825$ in. in the case of the smaller conductor and 6.225 in. in the case of the larger conductor.

Calling the field in the yoke B_y and the yoke thickness t and assuming that the flux divides equally between the vertical yokes, we equate the flux densities in the yoke and in the gap to obtain a relation between the yoke field and the yoke thickness. Thus we have

$$2\,B_y\,t \;=\; \frac{l_1}{2}\,(0.6B_g) + (W_{iron} - 2c)B_g + \frac{l_1}{2}\,(0.6B_g)$$

With $B_g = 10.241$ kG, we have for the 0.4600 in. conductor

$$\begin{aligned} B_y\,t &= \frac{1}{2}\left[\frac{5.825(0.6)}{2} + (13.000 - 2(0.625)) + \frac{5.825(0.6)}{2}\right] B_g \\ &= 78.061 \text{ kG-in.} = 0.19828 \text{ T-m} \end{aligned}$$

and for the 0.5160 in. conductor we find

$$\begin{aligned} B_y\,t &= \frac{1}{2}\left[\frac{6.225(0.6)}{2} + (13.000 - 2(0.625)) + \frac{6.225(0.6)}{2}\right] B_g \\ &= 79.290 \text{ kG-in.} = 0.20140 \text{ T-m} \end{aligned}$$

We make the following table.

	0.4600 in. conductor				0.5160 in. conductor			
B_y (kG)	9.	10.	11.	12.	9.	10.	11.	12.
t (in.)	8.673	7.806	7.096	6.505	8.810	7.929	7.208	6.608

We choose

		0.4600 in. comductor		0.5160 in. conductor	
Yoke field	B_y	10.072 kG	1.007 T	10.231 kG	1.023 T
Yoke thickness	t	7.750 in.	196.9 mm	7.750 in.	196.9 mm

In the above, the coil-slot width (c in the figure) was calculated from

$$\begin{aligned} \text{Coil-slot width} &= \text{Maximum coil width} + 2(\text{Pole-coil separation}) \\ &= 4.200 \text{ in.} + 2(0.500) \text{ in.} = 5.200 \text{ in. [0.4600 in. case]} \\ &= 4.600 \text{ in.} + 2(0.500) \text{ in.} = 5.600 \text{ in. [0.5160 in. case].} \end{aligned}$$

Also, the total dipole width is

$$\begin{aligned} \text{dipole width} &= 2(\text{Coil-slot width} + \text{Yoke thickness}) + \text{Pole width} \\ &= 2(5.200 \text{ in.} + 7.750 \text{ in.}) + 13.000 \text{ in.} = 38.900 \text{ in. [0.4600 in. case]} \\ &= 2(5.600 \text{ in.} + 7.750 \text{ in.}) + 13.000 \text{ in.} = 39.700 \text{ in. [0.5160 in. case],} \end{aligned}$$

the overall length of the dipole is

$$\begin{aligned} \text{dipole length} &= 2(\text{Pole-coil separation} + \text{Maximum coil width}) + \text{Pole length} \\ &= 2(0.500 \text{ in.} + 4.200 \text{ in.}) + 33.500 \text{ in.} = 42.900 \text{ in. [0.4600 in. case]} \\ &= 2(0.500 \text{ in.} + 4.600 \text{ in.}) + 33.500 \text{ in.} = 43.700 \text{ in. [0.5160 in. case],} \end{aligned}$$

the pole-height, p in the figure, is obtained from

$$\begin{aligned}\text{pole height} &= \text{Maximum coil height} + \text{Chamfer} + 15\text{ mm}\\ &= 5.300\text{ in.} + 0.625\text{ in.} + 0.591\text{ in.} = 6.516\text{ in. [0.4600 in. case]}\\ &= 5.850\text{ in.} + 0.625\text{ in.} + 0.591\text{ in.} = 7.066\text{ in. [0.5160 in. case]},\end{aligned}$$

and the lengths of the side yokes are

$$\begin{aligned}\text{side-yoke height} &= 2(\text{Pole height}) + \text{Gap}\\ &= 2(6.550\text{ in.}) + 4.000\text{ in.} = 17.100\text{ in. [0.4600 in. case]}\\ &= 2(7.100\text{ in.}) + 4.000\text{ in.} = 18.200\text{ in. [0.5160 in. case]}\end{aligned}$$

where the pole height is taken as 6.550 in. (167.6 mm) in the case of the 0.4600 in. conductor and 7.100 in. (181.6 mm) in the case of the 0.5160 in. conductor. We take

	0.4600 in. conductor		0.5160 in. conductor	
Coil-slot width	5.200 in.	132.1 mm	5.600 in.	142.2 mm
Pole height	6.550 in.	166.4 mm	7.100 in.	180.3 mm
Side-yoke height	17.100 in.	434.3 mm	18.200 in.	462.3 mm
Dipole width	38.900 in.	988.1 mm	41.200 in.	1046.5 mm
Dipole length	42.900 in.	1089.7 mm	43.700 in.	1110.0 mm

8. Iron weight

The cross-sectional areas of the magnet components are tabulated below.

Section	0.460 in. conductor			0.516 in. conductor		
	Height (in.)	Width (in.)	Area (in.^{2})	Height (in.)	Width (in.)	Area (in.^{2})
Top yoke	7.750	38.900	301.475	7.750	39.700	307.675
Bottom yoke	7.750	38.900	301.475	7.750	39.700	307.675
Vertical Yoke	17.100	7.750	132.525	18.200	7.750	141.050
Vertical Yoke	17.100	7.750	132.525	18.200	7.750	141.050
Top pole	6.550	13.000	85.150	7.100	13.000	92.300
Bottom pole	6.550	13.000	85.150	7.100	13.000	92.300
Total area			1038.300			1082.050

The total volume of iron is then

$$\text{Volume of iron} = (\text{Total area})(\text{Iron length})$$

and we obtain

	0.4600 in. conductor	0.5160 in. conductor
Iron length (in.)	33.500	33.500
Iron area (in.^{2})	1038.300	1082.050
Iron volume (in.^{3})	34,783.050	36,248.675
Iron volume (ft^3)	20.129	20.977
Iron volume (m^3)	0.570	0.594

and the iron mass at a density of 7900 kg/m^3 is

$$\begin{aligned}\text{Iron mass} &= (\text{Iron volume})(\text{Density})\\ &= (0.570\text{ m}^3)(7900\text{ kg/m}^3) = 4.505\times10^3\text{ kg} = 9.935\times10^3\text{ lb for the 0.4600 in. conductor}\\ &= (0.594\text{ m}^3)(7900\text{ kg/m}^3) = 4.695\times10^3\text{ kg} = 10.355\times10^3\text{ lb for the 0.5610 in. conductor}\end{aligned}$$

We take

$$\boxed{\begin{aligned}\text{Iron mass} &= 10.0\times10^3\ \text{lb} = 4.56\times10^3\ \text{kg}\ [0.4600\ \text{in. case}]\\ &= 10.5\times10^3\ \text{lb} = 4.80\times10^3\ \text{kg}\ [0.5160\ \text{in. case}]\end{aligned}}$$

9. Discussion

This report has presented a conceptual design for the individual 15° dipoles that are used on beam line 2A. Two possibilities of conductor have been considered. As indicated in table 1, the mass required of the smaller, 0.460 in.-square conductor is approximately 20% less than that of the larger, 0.516 in.-square conductor. At a cost of US$4 per pound, this could represent a saving of US$1,200 in conductor material. On the other hand, a coil constructed of the larger conductor requires approximately 20% less power to operate.

There is no significant cost difference in the iron costs for dipoles made with the different conductors.

Because the 27.5° vault dipoles have been designed with the larger conductor [1,2], it is suggested that use of the larger conductor may be more economical to use for the 15° dipoles. Thus a larger quantity of the conductor would be purchased at, perhaps, a somewhat reduced price. However, based on material costs for the 4Q8.5/8.5 quadrupoles, regardless of the conductor size ordered one is charged by the weight of conductor used. That being the case, an overall saving of US$2,500 may be realized by using the smaller conductor.

References

1. G. M. Stinson, *A revised design for the 27.5° dipoles for beam line 2A*, TRIUMF Report TRI-DNA-96-6, March, 1966.

2. G. S. Clark, *Concept Design for the Beam Line 2A B1/B2 Dipole, Revision 3*, TRIUMF Report, TRI-DN-96-24, November, 1996.

3. 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.

4. G. W. Rodenz, *User's Guide to the Program FRONT*, Los Alamos Accelerator Code Group, June, 1992.

5. J. L. Chuma, *PLOTDATA Command Reference Manual*, TRIUMF Report, TRI-CD-87-03b, August, 1989. 1996.

Table 1

Summary of H-magnet conceptual design parameters for the 15° dipoles on beam line 2A

		Conductor dimension	
		0.460 in.	0.516 in.
Yoke:	Iron length	33.500 in.	33.500 in.
	Iron width	38.900 in.	39.700 in.
	Iron thickness	7.750 in.	7.750 in.
	Coil-slot width	5.700 in.	6.150 in.
	Side-yoke height	17.100 in.	18.200 in.
Pole:	Width	13.000 in.	13.000 in.
	Height	6.550 in.	7.100 in.
	Chamfer at 45°	0.625 in.	0.625 in.
Iron:	Total mass	10.0×10^3 lb	10.5×10^3 lb
		4.55×10^3 kg	4.80×10^3 kg
Dipole:	Overall width	38.900 in.	39.700 in.
	Overall height	32.600 in.	33.700 in.
	Overall length (incl. coil)	42.900 in.	43.700 in.
Coil:	Conductor OD	0.460 in.	0.516 in.
	Conductor ID	0.255 in.	0.287 in.
	Nominal coil width	4.000 in.	4.500 in.
	Nominal coil height	5.100 in.	5.650 in.
	Total coolant flow	3.053 USGPM	2.407 USGPM
	Turn configuration	8 wide × 10 high	8 wide × 10 high
	Resistance (hot) per coil	44.7×10^{-3} Ω	35.2×10^{-3} Ω
	Number of cooling circuits per coil	5	5
Copper:	Total length per magnet	1500 ft	1500 ft
	Total mass per magnet	900 lb	1150 lb
	Total length to order	1750 ft	1750 ft
	Total mass to order	1050 lb	1325 lb
Power:	Total current	600.0 A	600.0 A
	Total Voltage	65.0 V	55.0 V
	Power	39.0 kW	33.0 kW

Addendum: POISSON calculations

Following the conceptual design of the preceding pages the program POISSON[3)], modified by Rodenz[4)], was used in a study of the magnetic fields in both the yoke and the air gap. This modified version of POISSON allows a simpler input of geometric data and automatically produces input for the AUTOMESH routine of the program.

POISSON was used to determine both the pole profile that would provide the required field uniformity ($\leq$0.1% over a two-inch wide band centered about the longitudinal center-line of the pole) and to estimate the effective length of the dipole.

A1. Transverse field calculations

Unless otherwise noted, all of the following calculations were for the case of the larger conductor with a mesh size of 0.125 in. in each of the horizontal and vertical directions. Table A1 lists an input file for the transverse calculations.

The POISSON calculations indicated that 41,150 Ampere-turns were required to produce a field of $\approx$10.065 kG along the mid-plane. Given that the conceptual design was for a field of 10.241 kG with a 10% increase in the Ampere-turns required, one would estimate the required Ampere-turns for a 10.065 kG central field to be

$$\text{Ampere-turns required for 10 kG} = \frac{10.065\ \text{kG}}{10.241\ \text{kG}}\,\frac{46,000\ \text{A-t}}{1.1} = 41,100\ \text{Ampere-turns.}$$

Consequently, the POISSON results are in good agreement with what is to be expected.

Several different pole profiles were studied; some are shown in figure A1. In all cases a 0.125 in. gap was left between the coil slot and the coil. This gap was to allow for that thickness of insulation between the yoke and the coil.

The UL portion of the figure shows the pole geometry initially tried. Based on ref[2)], the pole was shaped with a 0.25-in. horizontal by 0.10-in. vertical slope followed by a horizontal 0.375-in. horizontal flat. The sloped portion began 5.875 in. from the center of the pole. From the end of the flat the pole was tapered to the coil slot 1 in. further horizontally and 6.95 in. vertically below the outer edge of the flat—thus making the pole 6.95 in. deep by 2(7.5) = 15 in. wide at its base and 2(6.5) = 13 in. wide at its top. The POISSON results showed no saturation in the yoke but indicated high saturation in the corner of the pole where the step was located.

To alleviate the pole saturation a 0.625-in. chamfer at 45° was added as is indicated in the UR and LL portions of the figure. In the UR diagram, the pole depth was increased 0.25 in. from that shown in the UL portion; the LL portion is identical to the UL except for the added chamfer. The LR portion of the figure shows a pole profile in which the 0.25-in. by 0.10-in. slope was started a distance of 5.125 in. from the pole center, thus providing a horizontal flat 0.625 in. wide. The addition of the chamfer removed the problem of saturation of the corners of the pole.

For completeness, we show the predicted variation of B_x and B_y, the horizontal and vertical field components respectively, for the pole profile as in the UL portion of figure A1. These are presented as contours (in Gauss) in figure A2 as a function of distance above the mid-plane. Figure A3 shows contours of $B_t = [B_x^2 + B_y^2]^{1/2}$ for the same pole geometry. The contours were obtained using the program PLOTDATA[5)]. From these figures it is seen that the field is uniform within 0.1% (10 G in 10.065 kG) in a region bounded by $x \approx \pm 3.1$ in. horizontally about the pole center and $y \approx \pm 1.5$ in. about the mid-plane. This uniformity is completely acceptable; unfortunately, the pole saturation is not.

For comparison, figures A4 and A5 show similar plots for a pole configuration corresponding to the LR portion of figure 1. In this case the wider flat of the step has increased the horizontal region of uniformity about the pole center to $x \approx \pm 3.7$ in. with no degradation in the vertical direction. The former, of course, is to be expected.

Finally, we show in figures A6 and A7 similar data for the same pole profile but for a coil made from the smaller conductor. This is denoted as case 9. Again, a mesh size of 0.125 in. was used in each direction. For this case a coil size of 4.25 in. wide by 5.25 in. high was used. These dimensions differ slightly from those given in section 3. Figure A8 shows contour lines of the predicted fields (in kG) in the yoke.

A2. Longitudinal calculations

Following ref[2)], a C-shaped dipole was used to estimate the effective length of the dipole. A vertical yoke 20 in. wide by 50 in. high and a (flat) pole width of 24.125 in. were used in this POISSON run. A 0.625 in. taper at 45° was added to each side of the pole. Mid-plane symmetry and a mesh size of 0.4 in. were used. It was found that 41,700 Ampere-turns provided a central field of 10.08 kG. The input file for this calculation is listed in table A2.

The upper portion of figure A9 shows the configuration used; in the lower portion is a plot of the calculated field profile on the mid-plane.

In the geometry used, the center of the pole is 17.885 inches from the inner edge of the yoke. Again following the method of ref[2)], we use PLOTDATA to integrate from the pole center to a point well outside the magnet (60 in.) and obtain

$$\int_{17.885}^{60} B_t \, dx = 151.396 \text{ kG-in.}$$

> [At this point we note that the field predicted across the pole of the C-magnet has, on a small scale, a decided slope. This is illustrated in the upper portion of figure 10. Note that the vertical scale covers only the top 0.1% of the field distribution. Such a phenomenon is to be expected in an unshimmed C-magnet. The lower portion of the figure shows the accumulation of the integral as one goes out from the pole center.]

Because the field produced is 10.08 kG, the effective length of the half-pole, $l_{C,eff}$, becomes

$$l_{C,eff} = \frac{151.396 \text{ kG-in.}}{10.08 \text{ kG}} = 15.019 \text{ in.}$$

As in section 2, we take the effective length to be the iron length, $l_{C,i}$, plus a fringe-field length, $l_{C,ff}$. In the model used we calculate the iron length from

$$\begin{aligned} l_{C,i} &= \text{outer edge of yoke} - \text{pole center} \\ &= 30.625 \text{ in.} - 17.885 \text{ in.} \\ &= 12.740 \text{ in.} \end{aligned}$$

and obtain

$$\begin{aligned} l_{C,ff} &= l_{C,eff} - l_{C,i} \\ &= 15.019 \text{ in.} - 12.740 \text{ in.} \\ &= 2.279 \text{ in.} \end{aligned}$$

Because only one end of the magnet has been modeled with the C-magnet, we have the iron length for the H-frame magnet, $l_{H,i}$,

$$\begin{aligned} l_{H,i} &= l_{H,eff} - 2\, l_{C,ff} \\ &= 37.312 \text{ in.} - 2(2.279 \text{ in.}) \\ &= 32.754 \text{ in.} \end{aligned}$$

where $l_{H,eff}$ is the straight-line effective length of the magnet, l_e, of section 2. In that section the iron length of the H-magnet, l_i, was taken as $l_i = l_e - g = 33.31173$ in. For simplicity, we split the difference and take the iron length of the magnet to be

$$\boxed{\text{Iron length of final } 15^\circ \text{ magnet} = 33.00 \text{ in.}}$$

2.1 Finite length correction

Because of the POISSON calculation is two-dimensional a magnet of finite length will see a slightly larger flux in its steel. To correct for this a POISSON run was made with the field on the mid-plane at the center of the gap set to

$$B_y(0,0) = 10.08 \text{ kG} \frac{l_{H,eff}}{l_{H,i}} = 10.08 \text{ kg} \frac{37.312 \text{ in.}}{32.754 \text{ in.}} = 11.45 \text{ kG}.$$

It was found that for $Ni = 46{,}225$ A-t that the field ot the mid-point of the mid-plane was 11.27 kG. Thus, to obtain a field of 11.45 kG, the required number of Ampere-turns is estimated to be

$$NI = \frac{11.45 \text{ kG}}{11.27 \text{ kG}} \times 46,225 \text{ A-t} = 46,963 \text{ A-t}.$$

For an eighty-turn coil this would require a current of 587 A—a current well within the power supply specification.

A3. The final design of the 15° dipole

As noted in section 9, it is felt that the 0.460 in. conductor is the most suitable for this dipole. Consequently, the following design parameters are based on that conductor size.

A3.1 Final coil design

Using revised figures for the iron length and pole width we recompute the length of copper per layer as was done in section 3 from the following data.

	Anaconda 0.4600
L_{iron}	33.000 in.
W_{iron}	14.000 in.
R_{pole}	1.492 in.
G	0.500 in.
D	0.498 in.
Insulation	0.007 in.

We obtain a length of 871 in. (72.58 ft) per 8-turn layer and of 8710 in. (726 ft) per 10-layer coil. Because these differ only slightly from those lengths calculated in section 3, we use the previously calculated values. Consequently, all power and cooling calculations are unchanged. The relevant coil parameters, extracted from sections 3–6, are summarized on the next page.

A3.2 Final iron weight

Figure A11 shows the final design parameters for the 15° yoke of the 15° H-frame dipole. Here we estimate the mass of iron required based on the calculations presented in this addendum. We first list on the next page the specific yoke parameters that have now been determined; again, these are listed only for a magnet with a coil made from the 0.460 in. conductor.

from the yoke parameters listed in that table, we make an estimate of the weight of the yoke and poles. For simplicity, we take the poles to be 14 in. wide by 6.3 in. high.

Summary of coil parameters for 0.460 in. conductor

Coil:	Conductor (in. square)	0.460
	Length per 8-turn layer (ft)	75
	Length per 10-layer coil (ft)	750
	Length per magnet (ft)	1500
	Allow 10% winding loss (ft)	150
	Total conductor per magnet (ft)	1650
	Length of conductor to order (ft)	1750
	Weight of conductor to order (lb)	1100
	Coil resistance at 20°C (Ω)	0.03994
	Coil resistance at 50°C (Ω)	0.04465
Power:	Minimum current (A)	600
	Minimum voltage (V)	65
	Minimum power (kW)	39
Cooling:	Number of circuits	5
	Volume per coil (USGPM)	3.05
	Pressure drop per circuit (psi)	8.45

Yoke parameters for 0.4600 in. conductor

Coil-slot width	5.25 in.	135.4 mm
Pole width at base	14.00 in.	355.6 mm
Pole width at flat	10.25 in.	260.4 mm
Pole height at step	6.40 in.	162.6 mm
Pole height at flat	6.30 in.	160.0 mm
Pole step height	0.10 in.	2.5 mm
Pole step angle	23.58°	
Pole step width	0.625 in.	15.9 mm
Side-yoke height	16.60 in.	421.6 mm
Dipole width	40.00 in.	1016.0 mm
Dipole length	33.00 in.	838.2 mm

The cross-sectional areas of the magnet components are tabulated below.

Section	0.460 in. conductor		
	Height (in.)	Width (in.)	Area (in.^{2})
Top yoke	7.75	40.00	310.00
Bottom yoke	7.75	40.00	310.00
Vertical Yoke	16.60	7.75	128.65
Vertical Yoke	16.60	7.75	128.65
Top pole	6.30	14.00	88.20
Bottom pole	6.30	14.00	88.20
Total			1,053.70

The total volume of iron for a magnet with a coil constructed from the 0.460 in. conductor is then

$$\begin{aligned}\text{Volume of iron} &= \text{(Total area)(Iron length)}\\ &= (1,053.70\,\text{in.}^2)(33.00\,\text{in.})\\ &= 34,772.10\,\text{in.}^3\end{aligned}$$

and the iron mass of the completed magnet, assuming a density of 0.2833 lb/in.^{3} (7,842 kg/m^3), is 1129.6 in.^{3} for a weight of

$$\begin{aligned}\text{Iron mass} &= \text{(Iron volume)(Density)}\\ &= (34,772.10\,\text{in.}^3)(0.2833\,\text{lb/in.}^3)\\ &= 9.851\times10^3\ \text{lb}\ (4.468\times10^3\ \text{kg})\end{aligned}$$

$$\boxed{\text{Estimated weight of } 15^\circ \text{ dipole} = 9{,}900\text{ lb} = 4{,}500\text{ kg}}$$

If we assume that 8-inch plate that is 60 in. wide is ordered for the construction, then the iron for a complete magnet could be obtained from a length of 70 in. Thus, for two dipoles a length of 150in. of 60 in.-wide 8-in. plate should suffice. The volume of this iron would be (150 in.)(60.00 in.)(8 in.) = 72,000 in.^{3} corresponding to a weight of 20,400 lb (9,252 kg).

$$\boxed{\text{Estimated weight of iron to order for } \textit{two} \text{ magnets} = 20{,}400\text{ lb} = 9{,}252\text{ kg.}}$$

A4. Discussion

The program POISSON has been used to decide the final iron dimensions of the 15° H-frame dipoles for the ISAC beam line 2A. A final design is proposed utilizing a coil formed from a conductor with an outer dimension that is 0.460 in. square.

A summary of the parameters of the proposed design is given in table A3.

Table A1

Input file for POISSON for the transverse case 9

```
title
15.0 deg ISAC dipole – #9 .46 in
run
pois
mode      0
xmax = 20.0
ymax = 16.5
xmesh     0.125
ymesh     0.125
symm = 6
nseg      4
conv = 2.54
zseg     0.0     19.95   19.95    0.0
rseg     0.0      0.0    16.6    16.6
matpro    1
nseg     13
conv = 2.54
zseg     0.0      5.125   5.375   6.0     6.625   7.0    7.5    11.75   12.25   12.25   19.05   19.05    0.0
rseg     2.0      2.0     1.9     1.9     2.525   8.30   8.30    8.30    8.30    0.0     0.0    16.05   16.05
matpro    2
nseg     4.
conv = 2.54
zseg     7.500   11.750  11.750   7.500
rseg     8.175    8.175   8.300   8.300
matpro    1
nseg     4.
conv = 2.54
zseg     7.500   11.750  11.750   7.500
rseg     2.925    2.925   8.175   8.175
matpro    1
current = 41150.
kbot = 1
lbot = 1
ltop = 16
fieldmap   2
begin
end
```

Table A2
Input file for POISSON for the end effect calculations for case 9

```
title
15.0 deg ISAC dipole – #9 0.46 end
run
pois
mode          0
xmax = 60.0
xmin = −20.0
ymax = 50.0
ymin = 0.0
xregion     35.725
yregion     12.0
xmesh        0.4
ymesh        0.4
symm = 2
nseg          4
conv = 2.54
zseg       −20.0     60.0    60.0     −20.0
rseg         0.0      0.0    50.0      50.0
matpro        1
nseg         12
conv = 2.54
zseg       −20.0      0.0     0.0      0.5    4.75   5.25   5.25    5.875   30.0   30.625   30.625   −20.0
rseg         0.0      0.0     8.3      8.3    8.3    8.3    2.625   2.0      2.0    2.625   50.0      50.0
matpro        2
nseg         4.
conv = 2.54
zseg         0.500    4.750   4.750    0.500
rseg         2.925    2.925   8.300    8.300
matpro        1
current = −41700.
nseg         4.
conv = 2.54
zseg        31.125   35.725  35.725   31.125
rseg         2.925    2.925   8.300    8.300
matpro        1
current = 41700.
kbot = 1
lbot = 1
ltop = 8
fieldmap      2
begin
end
```

Table A3

Summary of H-magnet final design parameters for the 15° dipoles on beam line 2A

Yoke:	Iron length	33.00 in.	838.2 mm
	Iron width	40.00 in.	1016.0 mm
	Iron thickness	7.75 in.	196.7 mm
	Coil-slot width	5.25 in.	135.4 mm
	Side-yoke height	16.60 in.	421.6 mm
Pole:	Width at base	14.00 in.	355.6 mm
	Height at flat	6.30 in.	160.0 mm
	Height at step	6.40 in.	162.6 mm
	Height of step	0.10 in.	2.5 mm
	Width of step	0.625 in.	15.9 mm
	Angle of step	23.58°	23.58°
	Chamfer at 45°	0.625 in.	15.9 mm
Iron:	Total mass	9,900 lb	4,500 kg
Dipole:	Overall width	40.00 in.	1016.0 mm
	Overall height	32.10 in.	815.3 mm
	Overall length (incl. coil)	42.50 in.	1079.5 mm
Coil:	Conductor OD	0.460 in.	11.7 mm
	Conductor ID	0.255 in.	6.5 mm
	Nominal coil width	4.250 in.	108.0 mm
	Nominal coil height	5.250 in.	133.4 mm
	Total coolant flow	3.053 USGPM	11.6 ℓ/min
	Turn configuration	8 wide $\times$ 10 high	8 wide $\times$ 10 high
	Resistance (hot) per coil	$44.65 \times 10^{-3}\ \Omega$	$44.65 \times 10^{-3}\ \Omega$
	Number of cooling circuits per coil	5	5
Copper:	Total length per magnet	1500 ft	458 m
	Total mass per magnet	890 lb	405 kg
	Total length to order	1750 ft	535 m
	Total mass to order	1050 lb	474 kg
Power:	Total current	600.0 A	600.0 A
	Total Voltage	65.0 V	55.0 V
	Power	39.0 kW	33.0 kW

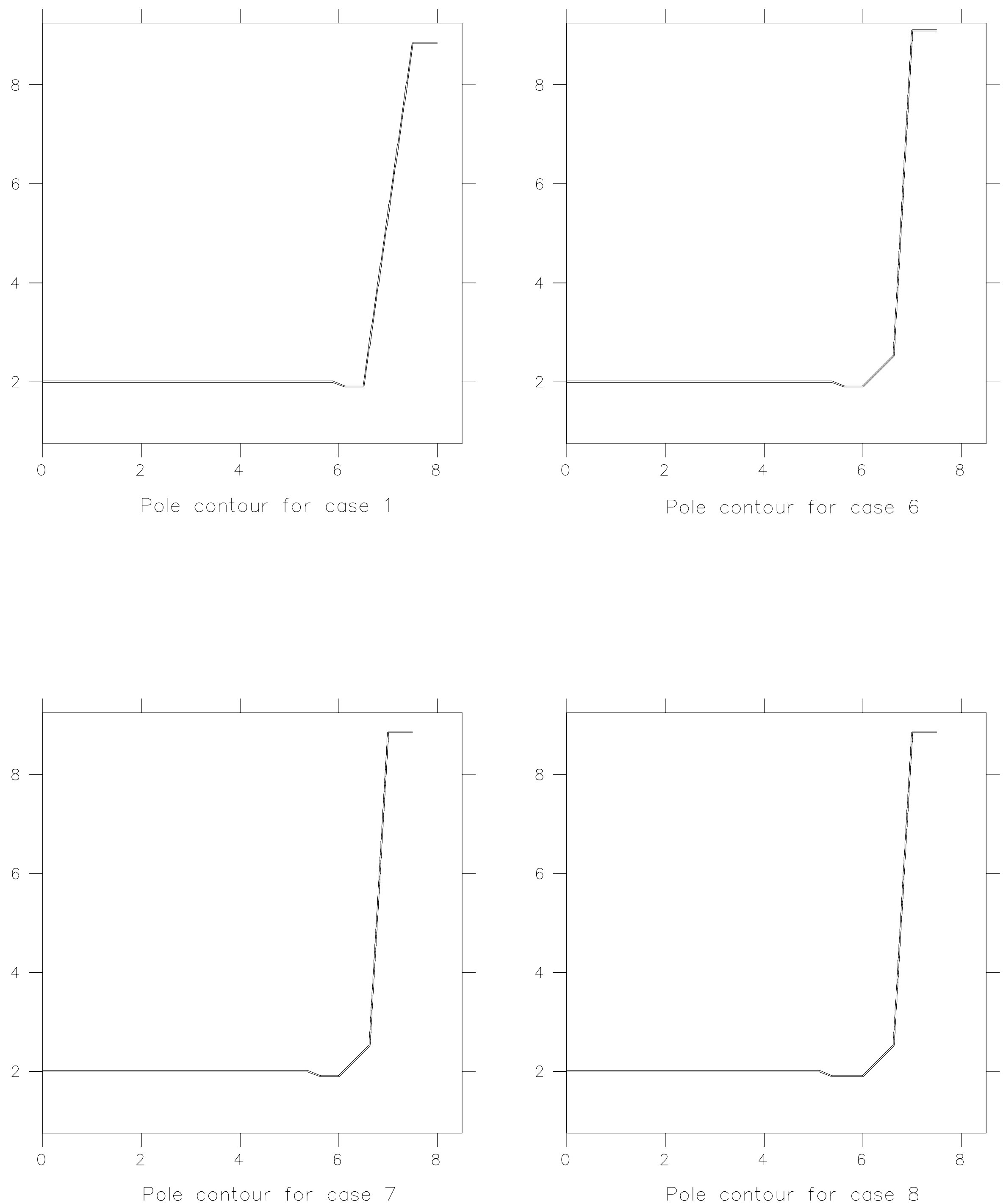
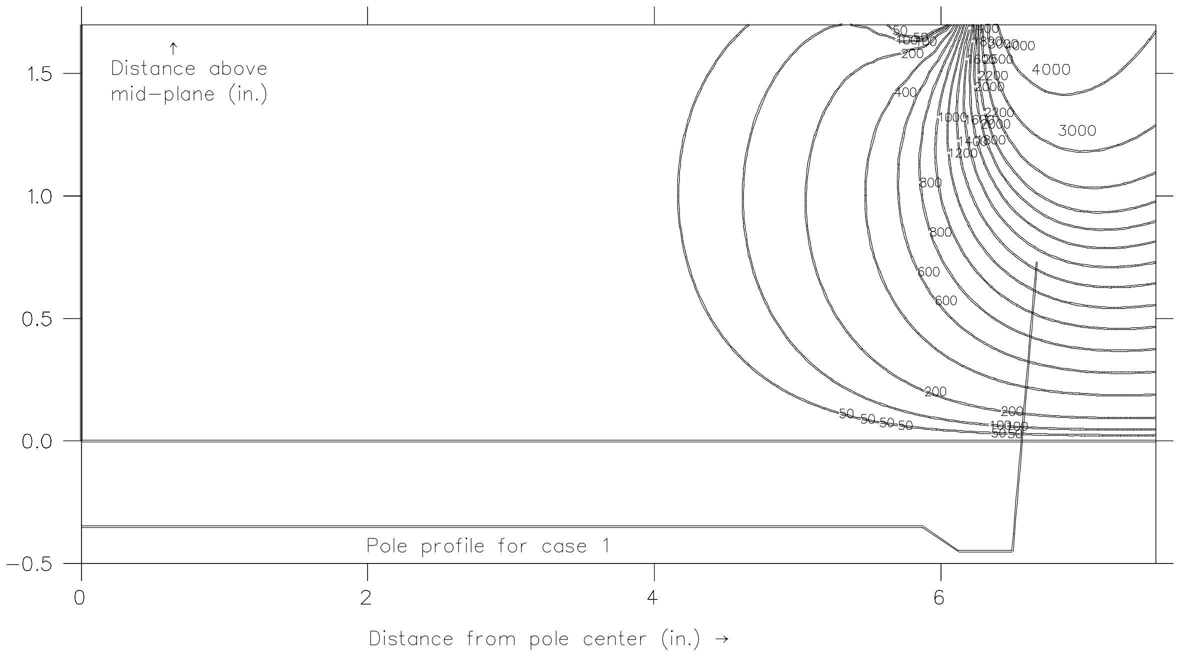


Figure A1. Some of the pole configurations studied.



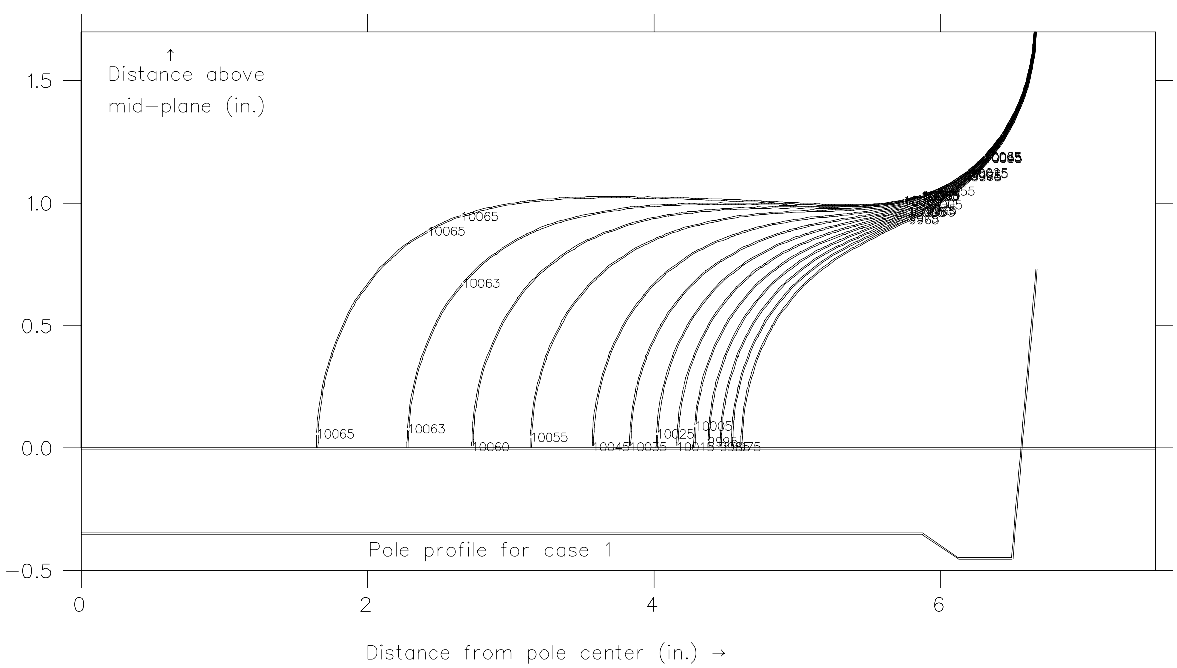


Figure A2. Variation of B_x (upper) and B_y (lower) as a function of height across the pole for case 1.

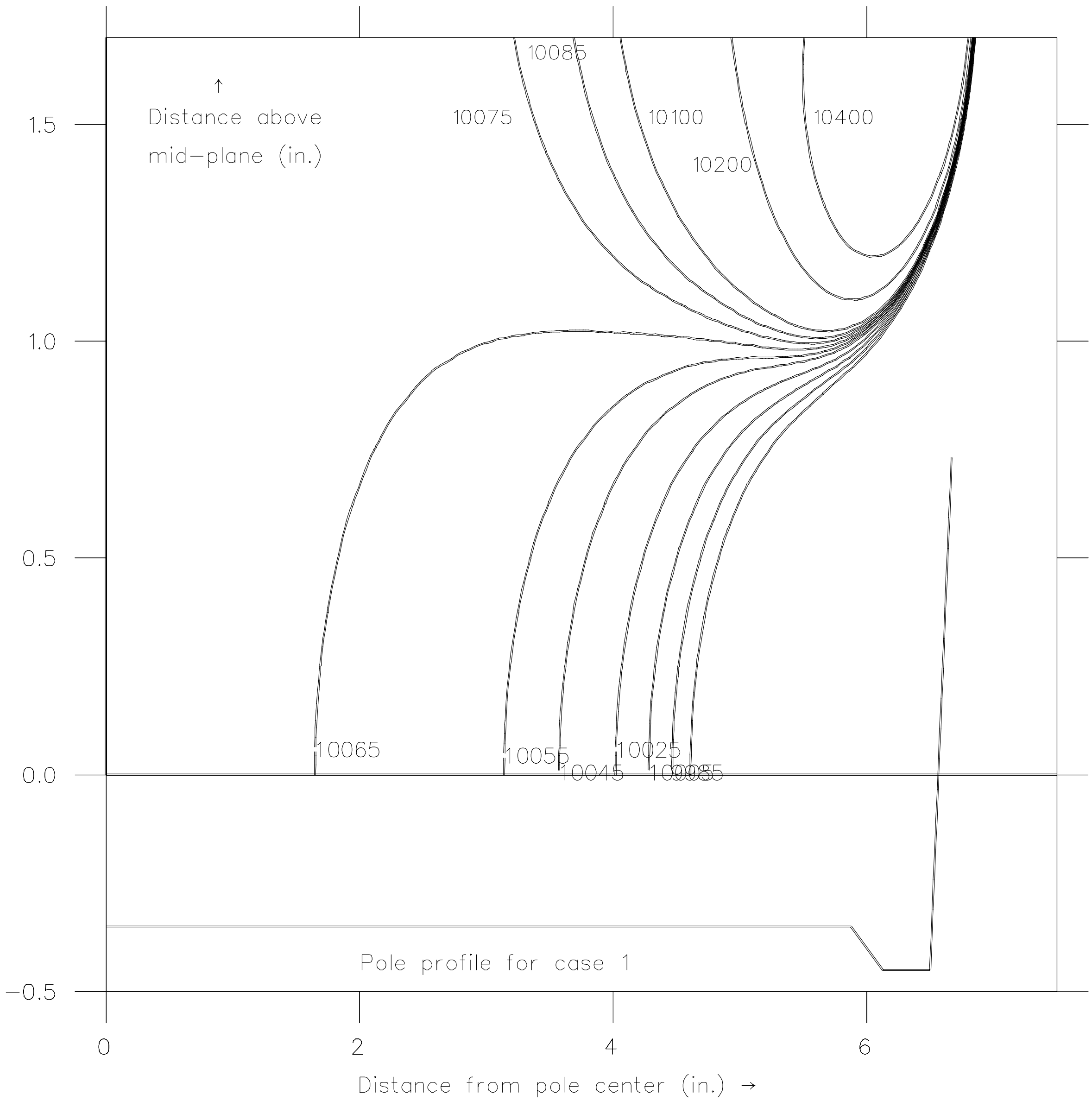
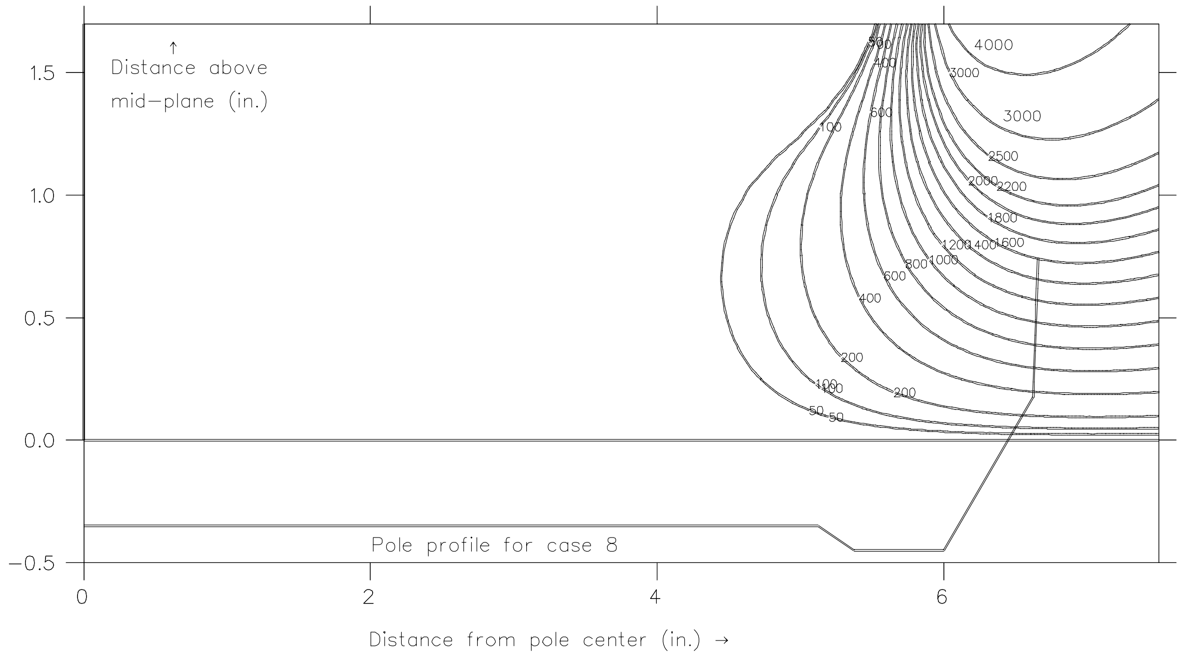


Figure A3. Variation of $B_t = \sqrt{B_x^2 + B_y^2}$ as a function of height across the pole for case 1.



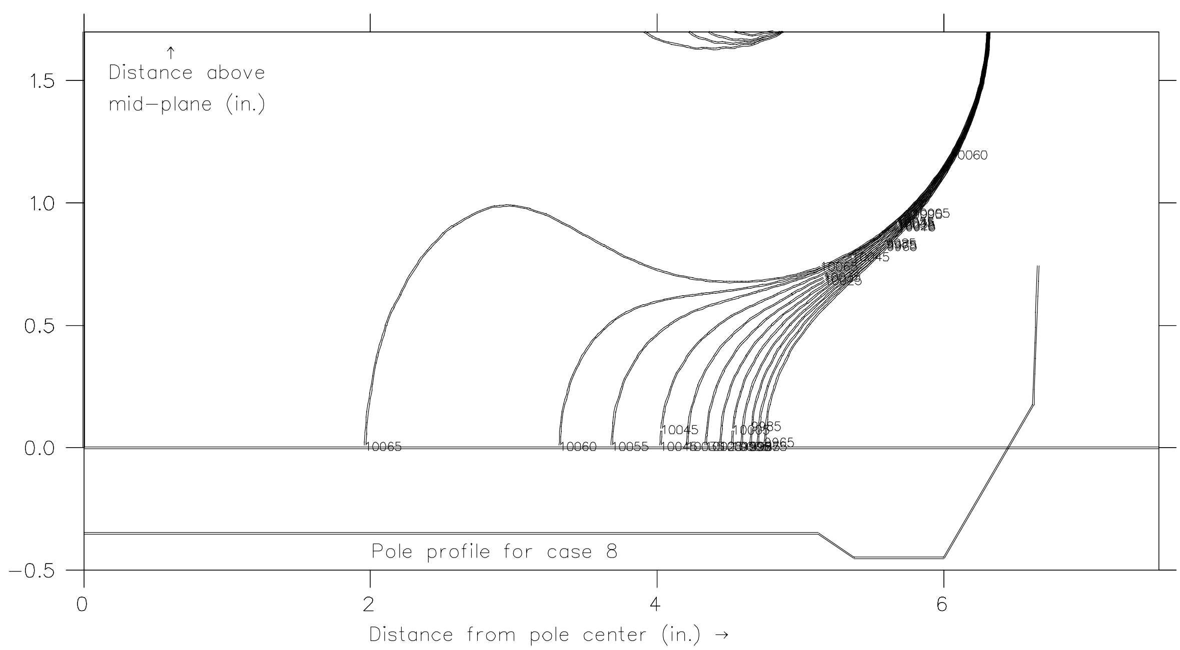


Figure A4. Variation of B_x (upper) and B_y (lower) as a function of height across the pole for case 8.

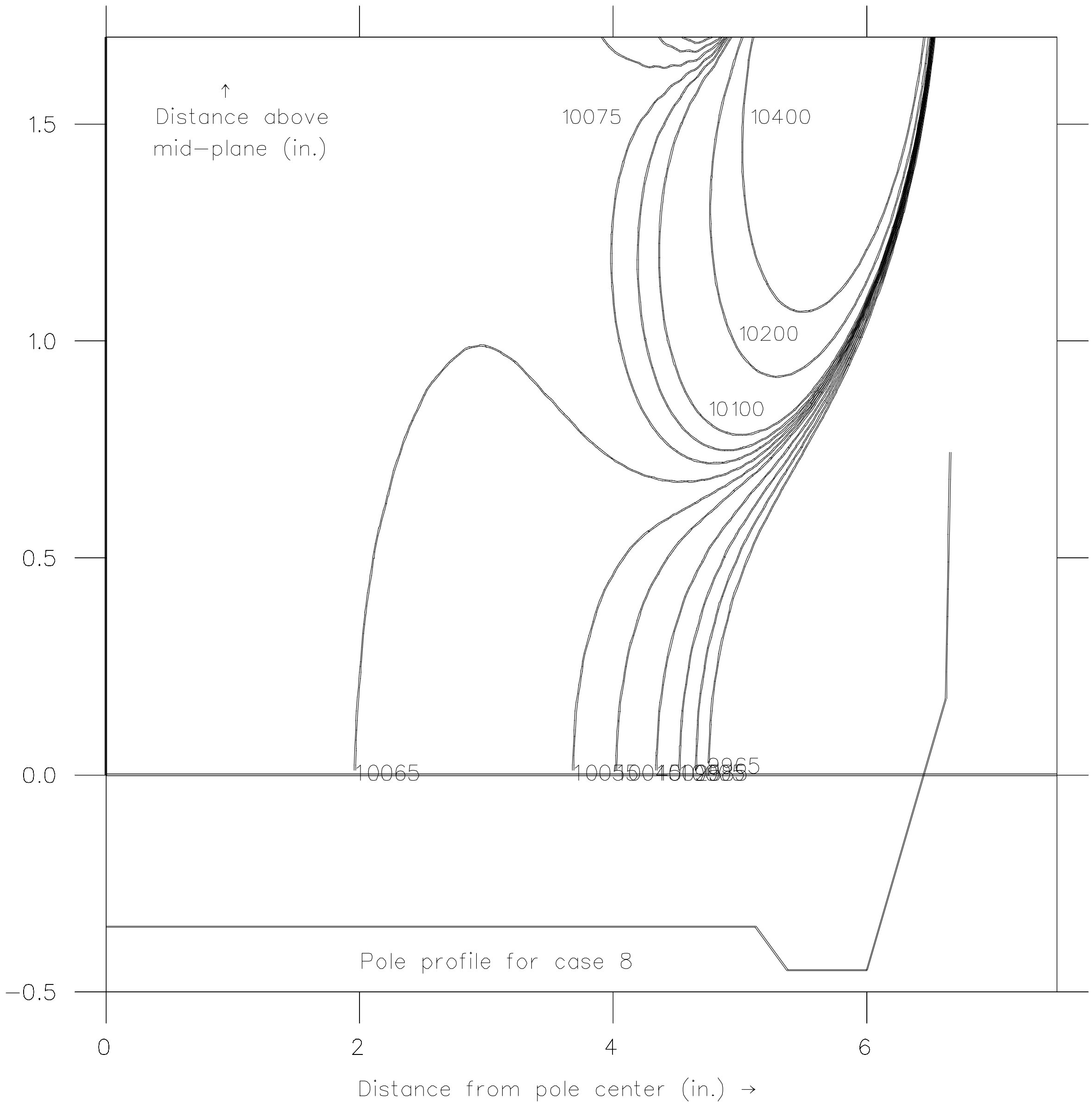


Figure A5. Variation of $B_t = \sqrt{B_x^2 + B_y^2}$ as a function of height across the pole for case 8.

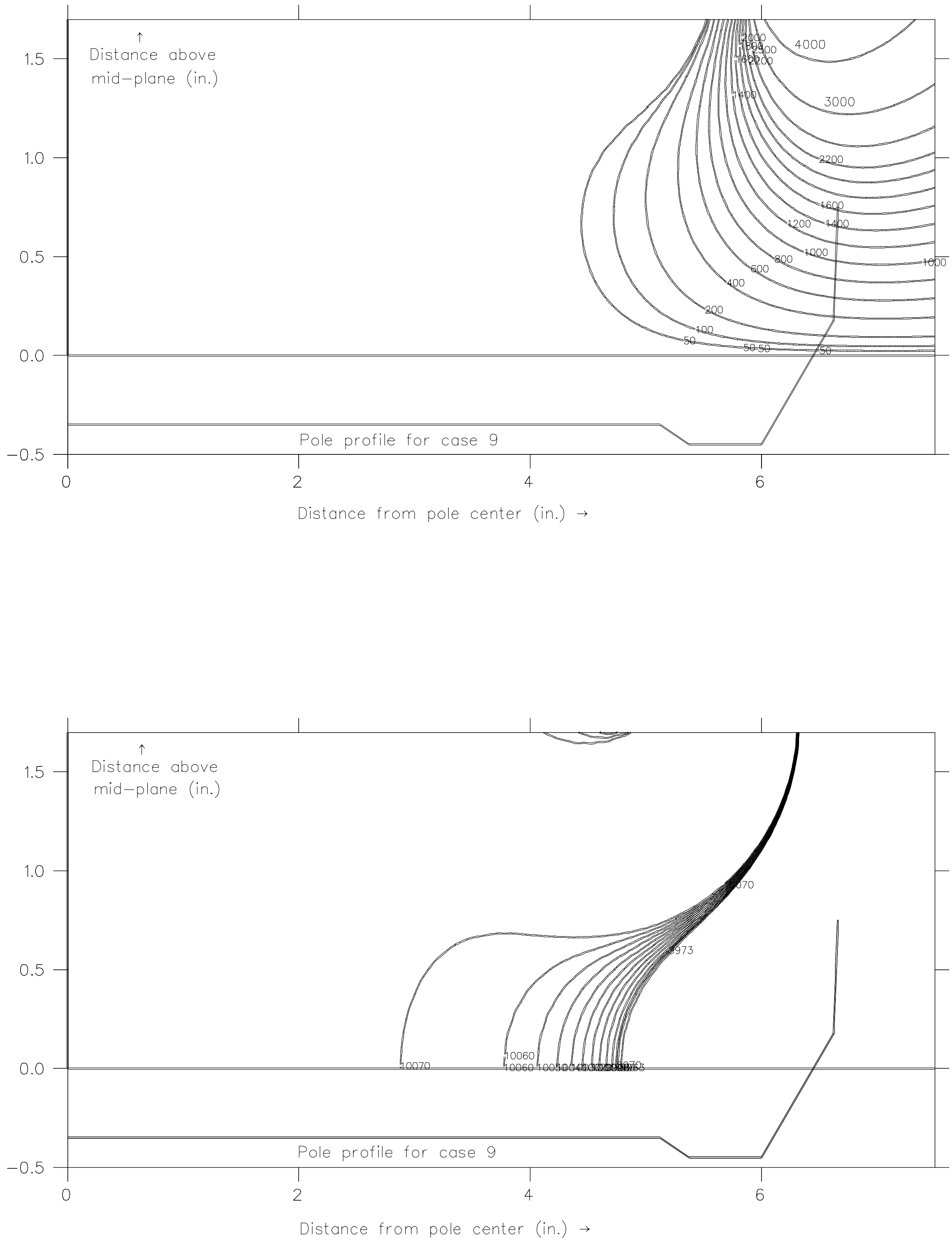


Figure A6. Variation of B_x (upper) and B_y (lower) as a function of height across the pole for case 9.

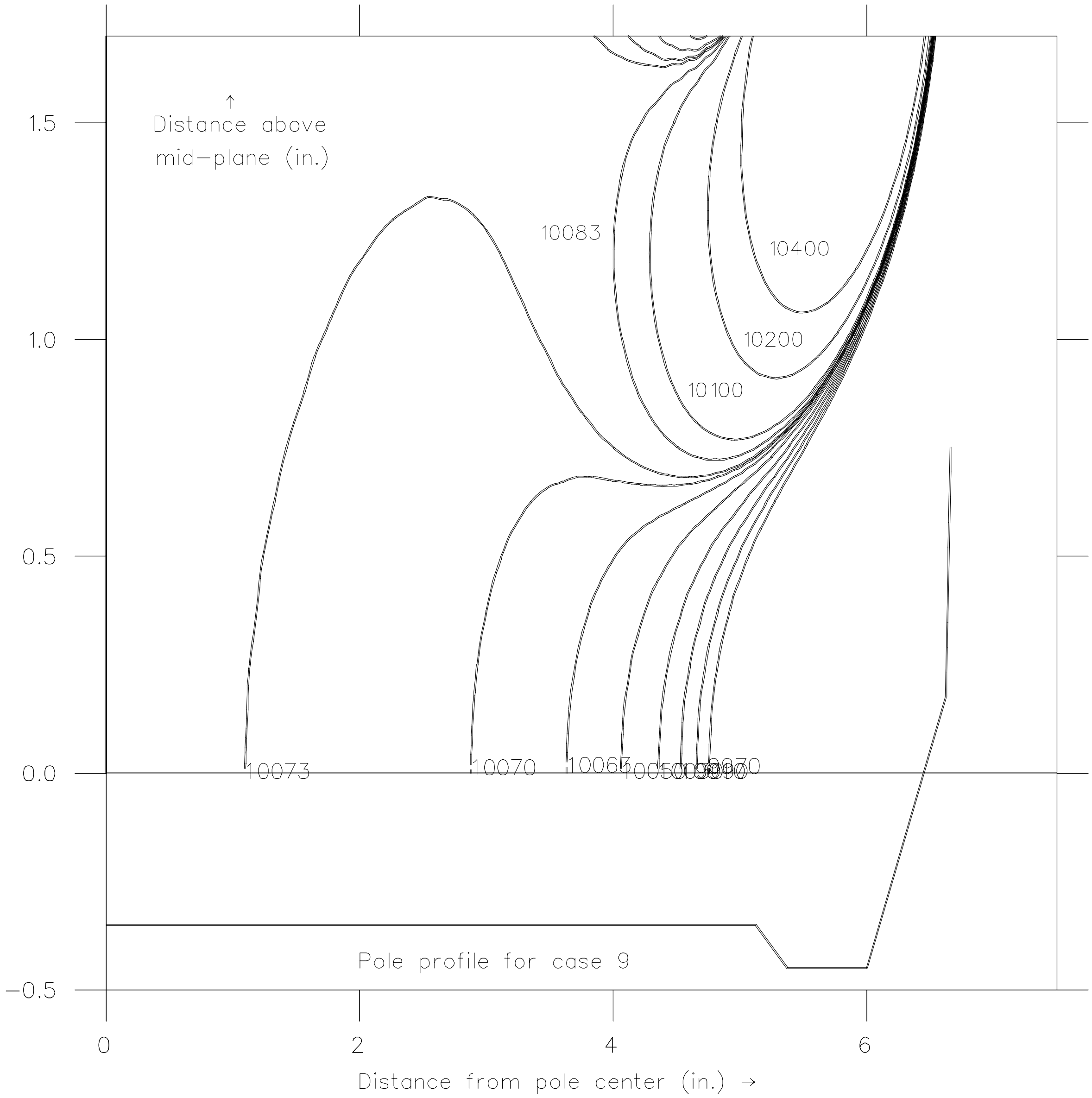


Figure A7. Variation of $B_t = \sqrt{B_x^2 + B_y^2}$ as a function of height across the pole for case 9.

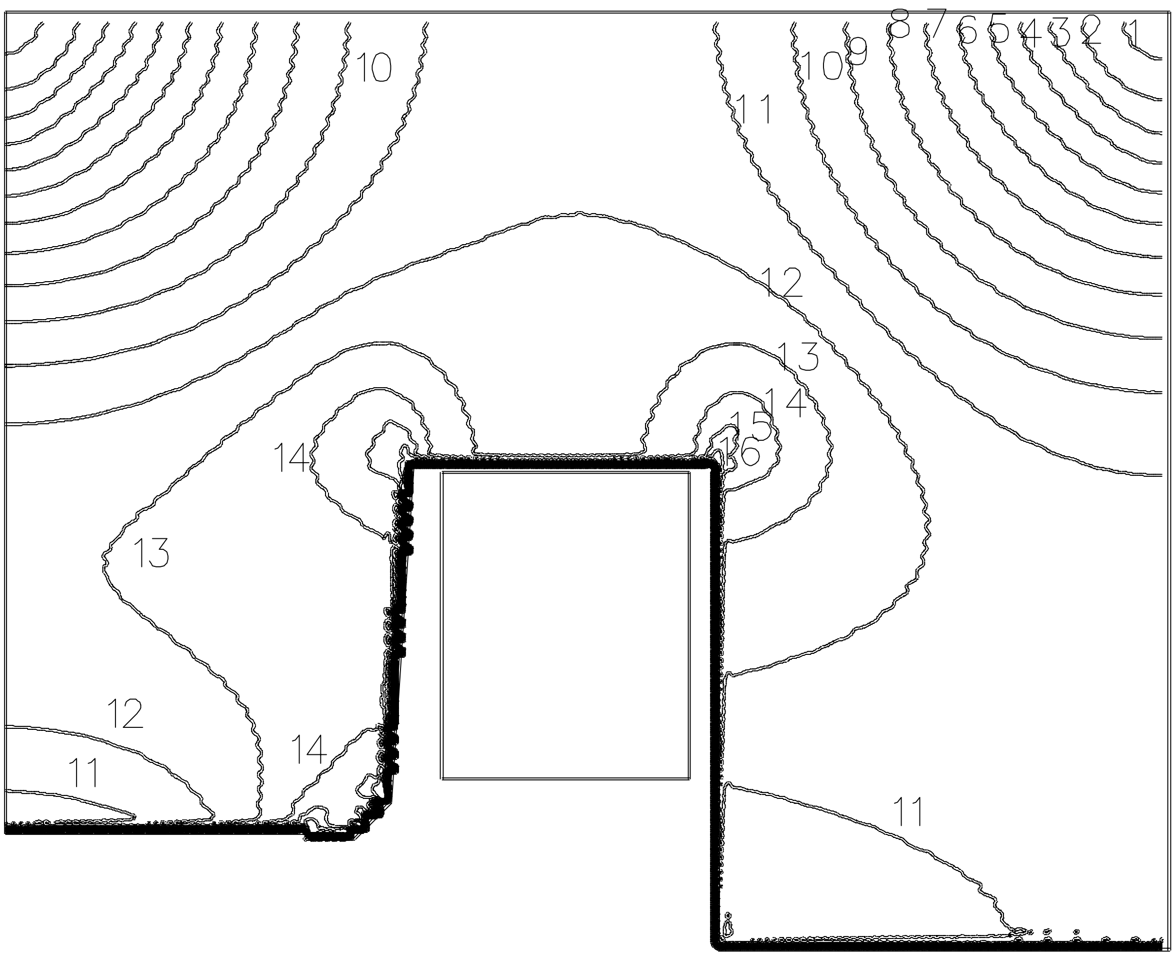


Figure A8. Contours of the yoke fields as predicted by POISSON for case 9.

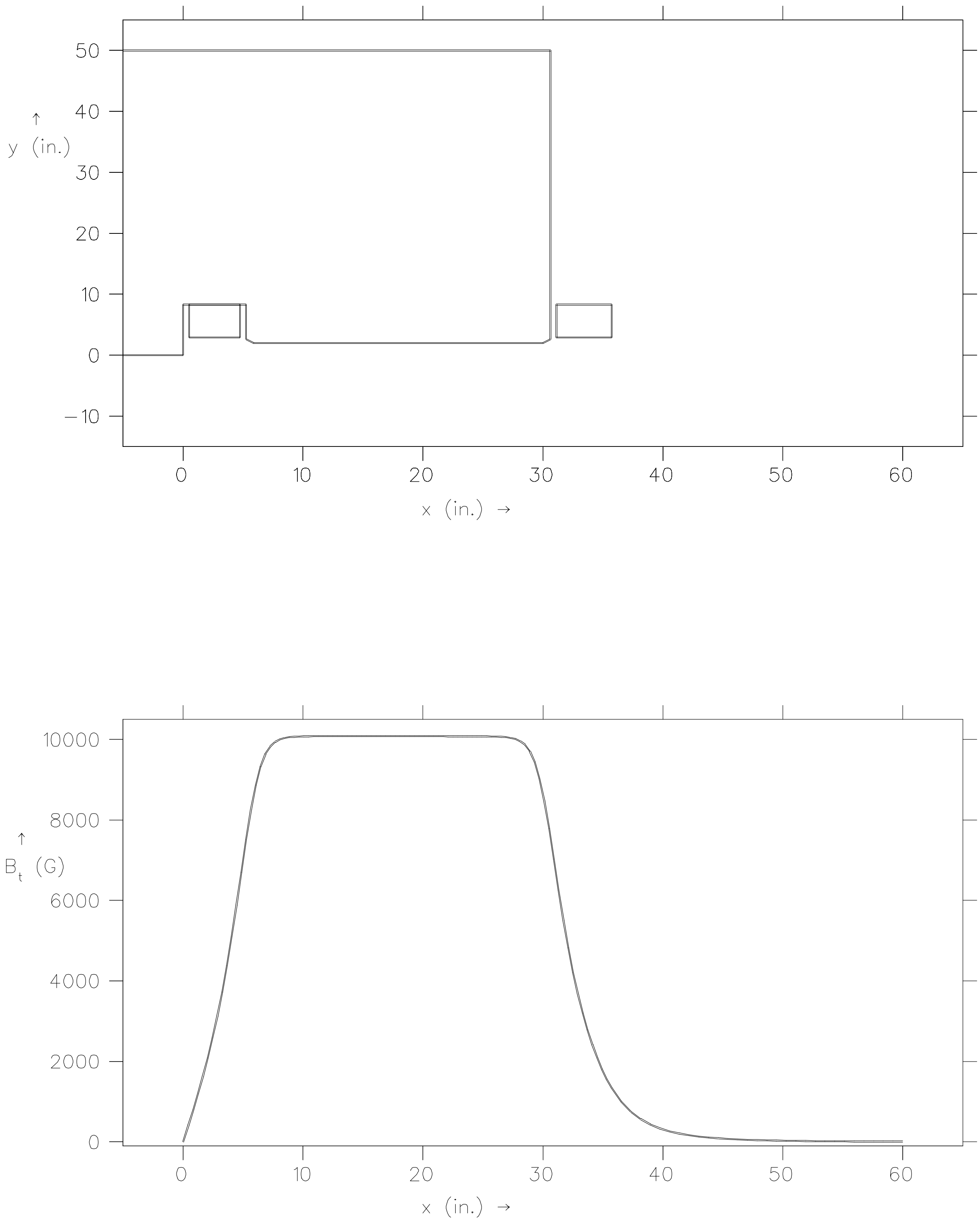
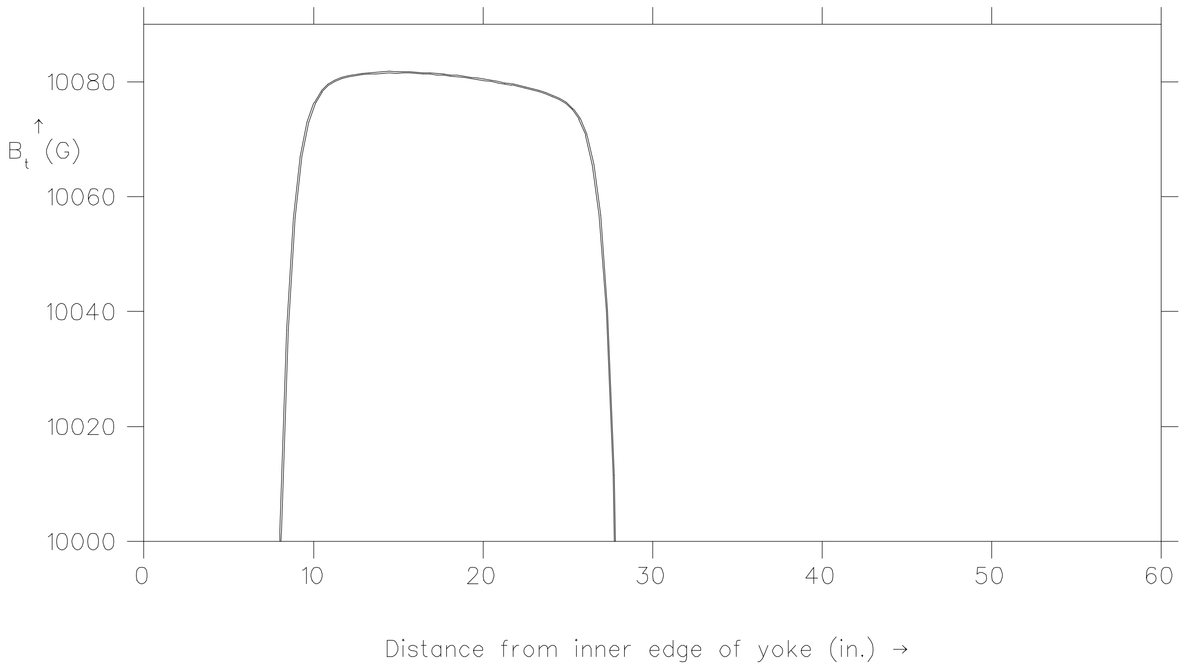


Figure A9. The model used for iron-length calculations for case 9.



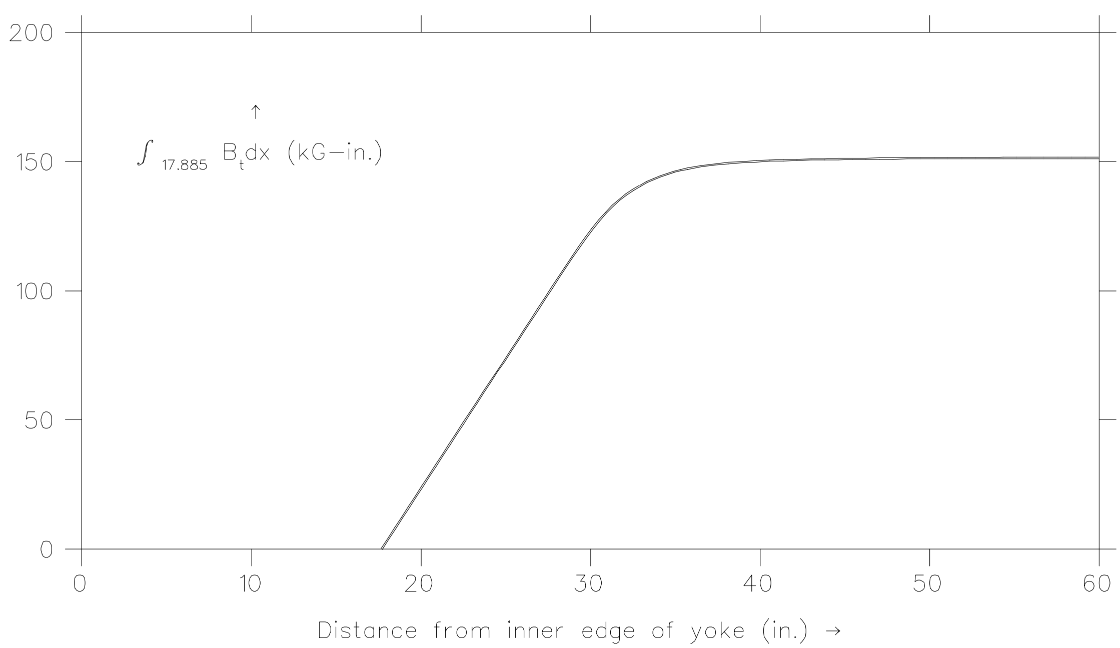
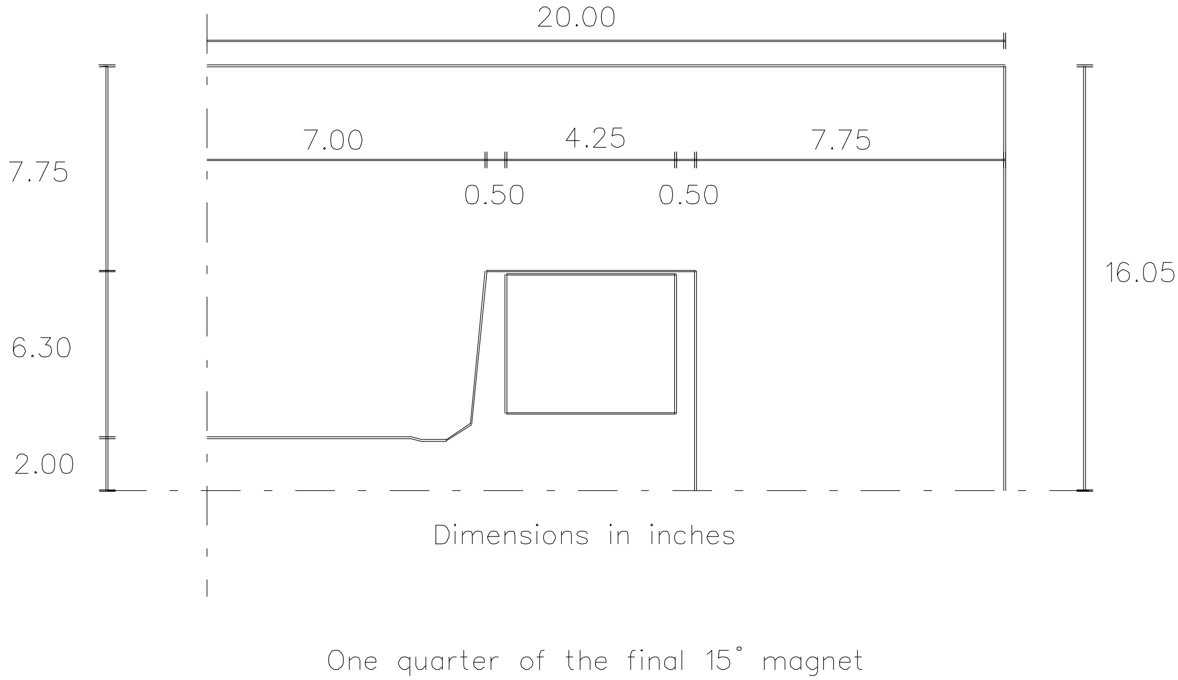


Figure A10. The field shape and integral from the pole center for case 9.



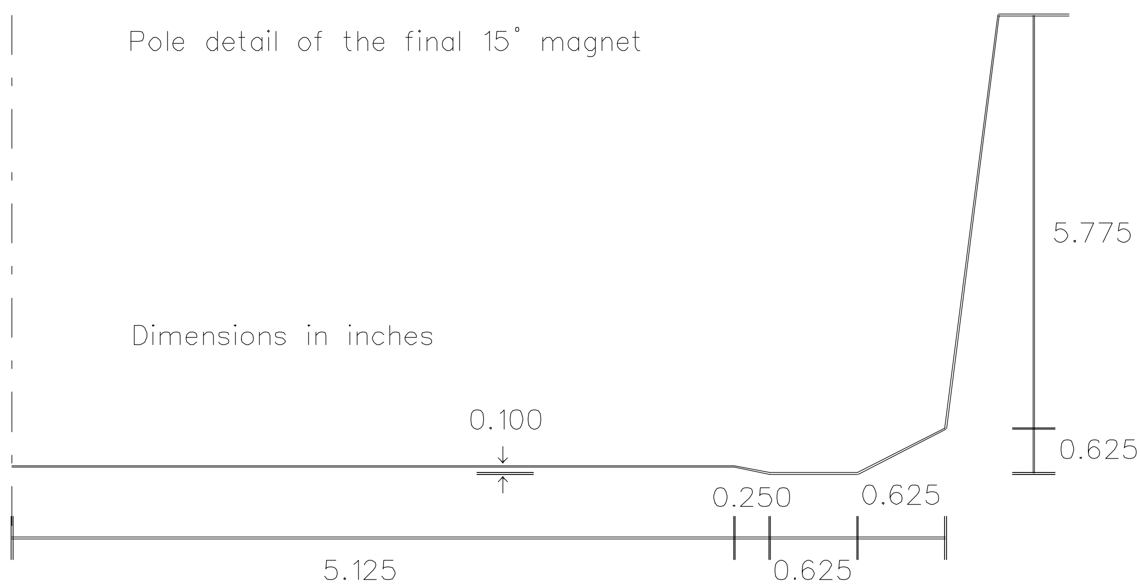


Figure A11. The dimensions of the final 15° magnet.