1. Introduction

A 90° dipole is required for the beamline in which the charge-state booster (CSB) is located. Space is limited where the dipole is to be installed; consequently, a compact design is required.

This report presents a conceptual design for a rectangular H-frame dipole that will meet the specified requirements.

2.1 Dipole specifications

The calculations of this report are based on the following design requirements for the dipole [1].

Bend angle θ	=	90	degrees
Radius of curvature ρ	=	400	millimeters
Air gap g	=	51	millimeters
Atomic weight of ion A_i	=	150	
Charge state of ion q_i	=	+5	
Ion energy T_i	=	60	keV

The dipole can be designed as an H-frame, C-frame, or 'banana' shaped magnet. The only restriction placed on the dipole is that it fit into a constricted space.

2.2 Basic design parameters

If we take the rest mass of the ion E_{i_0} to be

$$E_{i_0} = (A_i \text{ amu})(0.9315\text{GeV/amu}) = 0.9315\, A_i \text{ GeV} ,$$

then its momentum p_i and that of an equivalent proton p_p are given by

$$p_i = T_i \sqrt{1 + \frac{2\, E_{i_0}}{T_i}} \qquad \text{and} \qquad p_p = \frac{p_i}{q_i} .$$

Using the above relationships we calculate the following quantities.

A_i	=	150 amu		
E_{i_0}	=	150 amu(0.9315 GeV/amu)	=	139.725 GeV
T_i	=	60 keV	=	6.0×10^{-5} GeV
p_i	=	$6\times10^{-5}\sqrt{1 + (2\times139.725/6\times10^{-5})}$	=	0.12949 GeV/c
p_p	=	(0.12949/5)	=	0.025898 GeV/c
T_p	=	$\sqrt{(0.025898)^2 + (0.93826)^2} - 0.93826$	=	3.574×10^{-4} GeV
$(B\,\rho)$	=	3.3356×0.025898 GeV/c	=	0.086385 T-m

For the design of the dipole the following parameters have been used.

p_i	=	0.140 GeV/c
p_p	=	0.028 GeV/c
T_p	=	4.177×10^{-4} GeV
$(B\,\rho)$	=	0.093397 T-m

Thus for the given radius of curvature $\rho = 0.4$ m the required field of the dipole is

$$B = \frac{0.093397\ \text{T-m}}{0.400\ \text{m}} = 0.23349\ \text{T} = 2.33493\ \text{kG}\ .$$

3. Derived design parameters

From the above the following quantities are derived.

Radius of curvature	=	Effective length / Bend angle	15.748 in.	=	0.4000 m
Straight-line length	=	$2\,\rho\sin(\theta/2)$	22.271 in.	=	0.5657 m
Iron length	=	Straight-line length − full aperture	20.250 in.	=	0.5143 m
Maximum field			2.335 kG	=	0.2335 T

3.1 Ampere-turns per coil

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

$$\text{NI per pole} \;=\; \frac{1}{2}\left[1.1\,\frac{B_0[\text{T}]\,g[\text{m}]}{4\pi{\times}10^{-7}}\right] \;=\; 5191.4\ \text{A-t}$$

where we have allowed for a 10% flux leakage. Based on the POISSON results that follow we take

$$\boxed{\text{NI per pole} = 4{,}860\ \text{A-t}}$$

and generate the following table.

I (Amperes)	100	200	300	400	500	600	700	800	900	1000
N (Turns)	49	24	16	12	10	8	7	6	5	5

We choose

I	=	maximum current	=	200	Amperes
N	=	number of turns per coil	=	24	

in a coil configuration 4 turns wide and 6 layers high.

3.2 Pole parameters

The deviation of the central trajectory from a line parallel to the entry and exit points (the sagitta of the trajectory) is

$$\Delta \;=\; \rho[1-\cos(\theta/2)] \;=\; 4.6125\ \text{in.} \;=\; 117.16\ \text{mm}.$$

Further, the full width of the beam is given as 0.394 in. = 10.000 mm and we assume Laxdal approximation [2)] of a Rogowski chamfer is machined on the pole sides and ends. This approximation consists of two straight cuts, the first $0.68g$ gap units in the horizontal plane and $0.5g$ gap units in the vertical plane. The second is $0.5g$ gap units in the horizontal plane and $1.0g$ gap units in the vertical plane.

Then the pole width is calculated as

$$\begin{aligned}\text{Pole width} &= 2(\text{Chamfer}) + \text{Beam width} + \Delta + 2(\text{gap}) \\ &= 2(2.18g) + 0.394 + 4.612 \\ &= 13.727\ \text{in.} = 348.7\ \text{mm}.\end{aligned}$$

We take

$$\boxed{\text{Pole width} = 14.000\ \text{in.} = 355.60\ \text{mm.}}$$

3.3 Coil design

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

$$\text{Conductor area} = \frac{200\text{ A}}{3000\text{ A/in.}^2} = 0.06667\text{ in.}^2 = 43.01\text{ mm}^2.$$

This is satisfied within 10% by Anaconda 0.2893 inch-square conductor. Its parameters are listed as:

OD	0.28930 in.	=	7.34822 mm
ID	0.16100 in.	=	4.08940 mm
Copper area	0.06117 in.^{2}	=	39.46444 mm^2
Cooling area	0.02036 in.^{2}	=	13.13546 mm^2
Mass	0.23636 lb/ft	=	0.35174 kg/m
Resistance at 20°C	133.20 $\mu\Omega$/ft	=	437.01 $\mu\Omega$/m
k (British units)	0.03050		

We assume that each conductor is double-wrapped with insulation such that the *total* insulation per conductor has the following dimensions.

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	0.3083 in. = 7.83 mm,
Nominal	0.3173 in. = 8.06 mm,
Maximum	0.3263 in. = 8.29 mm.

We further allow

a) a gap between layers of 0.010 inch maximum,

b) a gap for keystoning of 0.010 inch,

c) a 4-turn ground wrap of 0.007 inch-thick tape.

Then the *width* of the coil is

	Maximum		Minimum	
	in.	mm	in.	mm
Wrapped conductor	1.305	33.152	1.233	31.323
Gapping (3×0.010)	0.030	0.762		
Ground wrap (4×0.007×2)	0.056	1.422	0.056	1.422
Total	1.391	35.336	1.289	32.746

The maximum coil width is 1.391 in. = 35.34 mm. We take

Maximum coil width	=	1.400 in.	=	35.560 mm.
Nominal coil width	=	1.300 in.	=	33.020 mm.

The *height* of the coil is

	Maximum		Minimum	
	in.	mm	in.	mm
Wrapped conductor	1.958	49.728	1.850	46.985
Gapping (5×0.010)	0.050	1.270		
Keystoning (6×0.010)	0.060	1.524	0.030	0.762
Ground wrap (4×0.007×2)	0.056	1.422	0.056	1.422
Total	2.124	53.945	1.936	49.169

The maximum coil height is 2.124 in. = 53.95 mm. We take

Maximum coil height	=	2.100 in.	=	53.340 mm.
Nominal coil height	=	2.000 in.	=	50.800 mm.

We take the conductor dimension D_{nom} to be

$$\begin{aligned} D_{nom} &= \text{Nominal dimension} + 4(\text{Insulation thickness}) + \text{ Turn separation} \\ &= 0.2893 + 0.028 + 0.010 \\ &= 0.327 \text{ in.} = 8.31 \text{ mm} \end{aligned}$$

and further assume a pole-coil gap of 0.375 in. = 9.525 mm and that the pole corners are rounded with a radius R_{pole} of

$$R_{pole} = 4\,D_{nom} - \text{Pole-coil gap} = 0.934 \text{ in.} = 23.73 \text{ mm.}$$

Then the nth conductor is a distance

$$D_n = n\,D_{nom} + \text{Pole-coil separation} + (\text{Pole width})/2 + 4(\text{insulation thickness})$$

from the (longitudinal) center-line of the pole. The (outer) radius of curvature of this nth turn is

$$R_n = R_{pole} + g + n\,D_{nom} + 4(\text{insulation thickness}) .$$

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 nth turn is

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

and the length of an N-turn layer is

$$L_N = \sum l_n = 2\,N\,[L_{iron} + W_{iron} + (\pi - 4)R_{pole} + \pi(4(\text{insulation}) + g)] + \pi\,N(N+1)\,D_{nom}$$

In our case with $N = 4$ and

$$L_{iron} = 20.250 \text{ in.} = 514.35 \text{ mm,}$$

$$
\begin{array}{lllll}
W_{iron} & = & 14.000 \text{ in.} & = & 355.60 \text{ mm,} \\
R_{pole} & = & 0.934 \text{ in.} & = & 23.73 \text{ mm,} \\
\text{Pole-coil gap} & = & 0.375 \text{ in.} & = & 9.52 \text{ mm,} \\
D_{nom} & = & 0.327 \text{ in.} & = & 8.31 \text{ mm,} \\
\text{Insulation} & = & 0.007 \text{ in.} & = & 0.18 \text{ mm,}
\end{array}
$$

we find that the length of a 4-turn layer is 297.5 in. = 7556.8 mm. We take

$$\text{Length of 4-turn layer} = 30 \text{ ft} = 9.1 \text{ m},$$

and the length per coil becomes

$$\text{Length of copper per coil} = 180 \text{ ft} = 55 \text{ m}.$$

Because 2 coils are required per dipole, then

Total length per dipole	360 ft	=	110 m
Allow 10% for winding losses	36 ft	=	11 m
Total	396 ft	=	121 m

Then, for a conductor of mass 0.2364 lb/ft, we should order

A total length of	400 ft	=	130 m,
A total mass of	100 lb	=	50 kg.

3.4 Power requirements

At 20°C, the resistance of the coil is:

$$R_{20^\circ C} = (133.20 \times 10^{-6} \Omega/\text{ft}) \times (180 \text{ ft}) = 0.0240 \ \Omega \ .$$

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:

$$
\begin{aligned}
R_{hot} &= R_{20^\circ C}[1 + (\text{Temperature coefficient}/^\circ\text{C}) dT(^\circ\text{C})] \\
&= 0.0240[1 + 0.00393(30)] \\
&= 0.0268 \ \Omega \text{ per coil.}
\end{aligned}
$$

Thus at a current of 200 A we obtain

$$\text{Voltage per coil} = 5.36 \text{ Volts}$$

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

I	=	200.0 A maximum
V	=	15.0 V total
P	=	3.0 kW total

3.5 Cooling requirements

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

$$\text{Power per coil} = I^2 R_{hot} = (200)(200)(0.02680) = 1.07 \text{ kW} \ .$$

The required flow rate is given by:

$$v(\text{ft/sec}) \;=\; \frac{2.19}{\Delta T} \times \frac{P(\text{kW})}{\text{Cooling area (in.}^2)} \;=\; 1.49394 \times P(\text{kW})$$

for $\Delta T = 72°\text{F} = 40°\text{C}$ and $A_{H_2O} = 0.02036$ in.^{2} = 13.135 mm^2. Choosing $v = 2.50$ ft/sec to define the maximum power dissipation per water circuit we have

$$P_{max} \;=\; \frac{(2.50)(72)(0.02036)}{2.19} \;=\; 1.673 \text{ kW/water circuit}$$

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

$$\begin{array}{lcccl} P & = & \text{Total power per coil} & = & 1.072 \text{ kW} \\ \text{Number of circuits} & = & P \;/\; P_{max} & = & 0.64 \end{array}$$

Thus we take

$$\boxed{\text{Number of cooling circuits per coil} = 1 \text{ .}}$$

This requires a flow rate of $v = 1.60$ ft/sec per water circuit. The volume of flow required per circuit is

$$\text{Volume/circuit} \;=\; 2.6(v(\text{ft/min}))(\text{Cooling area(in.}^2)) \;=\; 2.6(1.602)(0.02036) \;=\; 0.085 \text{ IGPM.}$$

Thus

Volume per cooling circuit	=	0.085 IGPM	=	0.385 ℓ/min	=	0.102 USGPM
Volume per coil	=	0.085 IGPM	=	0.385 ℓ/min	=	0.102 USGPM
Volume per magnet	=	0.170 IGPM	=	0.771 ℓ/min	=	0.204 USGPM

3.6 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, with $k = 0.0305$ we obtain:

$$dP \;=\; (0.0305)(1.602)^{1.79} \;=\; 0.071 \text{ psi/ft} \;=\; 0.233 \text{ psi/m,}$$

and the total pressure drop across one cooling circuit is:

$$\boxed{\text{Pressure drop per cooling circuit} = 12.8 \text{ psi .}}$$

3.7 Iron dimensions

If B_y and t are the yoke flux and thickness, respectively, and it is assumed that the field rises from zero at the outer edge of the coil to $0.6B_0$ at the pole edge and is constant at B_0 across the pole. If we further assume that the flux divides equally between the side yokes, we then have

$$\begin{aligned} B_y t \;&=\; \frac{1}{2} \times \frac{2[2(0.375) \text{ in.} + 1.400 \text{ in.} + 2.000 \text{ in.})](0.6)(2.33 \text{ kG})}{2} \\ &\quad + \frac{1}{2} \times [14.000 \text{ in.} - 2(2.000 \text{ in.})](2.33 \text{ kG}) \\ &=\; 14.582 \text{ kG-in.} \;=\; 0.03704 \text{ T-m ,} \end{aligned}$$

where the coil-slot width is calculated as

$$\begin{aligned}\text{Coil-slot width} &= \text{Maximum coil width} + 2(\text{Pole-coil gap}) \\ &= 1.40000 \text{ in.} + 2(0.375 \text{ in.}) \\ &= 2.15000 \text{ in.} = 54.610 \text{ mm.}\end{aligned}$$

Because we wish to keep the yoke flux to approximately 10 kG = 1 T, we take

Yoke thickness	=	1.500 in.	=	0.038 m ,
Yoke flux	=	9.721 kG	=	0.972 T .

The total width of the dipole is

$$\begin{aligned}\text{Dipole width} &= 2[(\text{Coil-slot width}) + \text{Yoke thickness})] + \text{Pole width} \\ &= 2(2.150 \text{ in.} + 1.500 \text{ in.}) + 14.000 \text{ in.} \\ &= 21.300 \text{ in.} = 0.541 \text{ m} ,\end{aligned}$$

and the total length of the dipole is

$$\begin{aligned}\text{Dipole length} &= 2[(\text{Pole-coil separation}) + (\text{Maximum coil width})] + \text{Pole length} \\ &= 2(0.375 \text{ in.} + 1.400 \text{ in.}) + 20.250 \text{ in.} \\ &= 23.800 \text{ in.} = 0.605 \text{ m.}\end{aligned}$$

Allowing for 0.125 in.-thick insulation between the yoke and the coil, the pole height becomes

$$\begin{aligned}\text{Pole height} &= \text{Maximum coil height} + \text{Vertical chamfer} + 0.125 \text{ in.} \\ &= 2.100 \text{ in.} + 2.500 \text{ in.} + 0.125 \text{ in.} \\ &= 4.725 \text{ in.} = 0.120 \text{ m} .\end{aligned}$$

The lengths of the side yokes are

$$\begin{aligned}\text{Length of side yoke} &= 2(\text{Pole height}) + \text{Gap} \\ &= 2(4.725 \text{ in}). + 2.000 \text{ in.} \\ &= 11.450 \text{ in.} = 0.291 \text{ m} .\end{aligned}$$

We take

Pole height	=	4.725 in.	=	0.120 m
Overall width of magnet	=	21.300 in.	=	0.541 m
Overall length of magnet	=	23.800 in.	=	0.605 m
Length of side yoke of magnet	=	11.450 in.	=	0.291 m

3.8 Iron mass

From the preceding data we have (with metric units in brackets)

	Height		Width		Area	
Top yoke	1.500 in.	[0.038 m]	21.300 in.	[0.541 m]	31.950 in.^{2}	[0.021 m^2]
Top pole	4.725 in.	[0.120 m]	14.000 in.	[0.356 m]	66.150 in.^{2}	[0.043 m^2]
Side yoke	11.450 in.	[0.291 m]	1.500 in.	[0.038 m]	17.175 in.^{2}	[0.011 m^2]
Total					115.275 in.^{2}	[0.074 m^2]

Thus

$$\text{Area of yoke} = 2(115.275\ \text{in.}^2\ [0.074\ \text{m}^2]) = 230.550\ \text{in.}^2 = 0.149\ \text{m}^2$$

and

$$\text{Volume of iron} = (\text{Pole length})(\text{Area}) = (20.250)(230.550)\ \text{in.}^3 = 2.702\ \text{ft}^3 = 0.077\ \text{m}^3$$

so that the mass of iron at 0.2833 lb/in.^{3} (489.54 lb/ft^3) is 1322.6 lb = 599.9 kg. We take

$$\boxed{\text{Mass of iron} = 1{,}350\ \text{lb} = 615\ \text{kg}\ .}$$

3.9 Discussion

The conductor size that was used in the above calculations is unusual and it is unlikely that it is available at TRIUMF. However, we believe that some Anaconda 0.4600 inch-square conductor is available. Its parameters are listed as:

OD	0.46000 in.=	11.68400 mm
ID	0.25500 in.=	6.47700 mm
Copper area	0.15290 in.^{2}=	98.64496 mm^2
Cooling area	0.05107 in.^{2}=	32.94832 mm^2
Mass	0.59100 lb/ft=	0.87950 kg/m
Resistance at 20°C	53.25 $\mu\Omega$/ft=	174.70 $\mu\Omega$/m
k (British units)	0.01760	

A coil of this conductor could be wound 3 conductors wide by 4 conductors high and would carry a current of 400 A. If the calculations of §3.3 through §3.6 are repeated for this conductor we find the following results.

Maximum coil width	=	1.550 in.	=	39.370 mm.
Nominal coil width	=	1.500 in.	=	38.100 mm.
Maximum coil height	=	2.100 in.	=	53.340 mm.
Nominal coil height	=	2.050 in.	=	52.070 mm.
Total copper length required per dipole	=	220.0 ft	=	70.0 m.
Total copper mass required per dipole	=	140.0 lb	=	60.0 kg.
Maximum current I	=	400.0 A.		
Maximum voltage V	=	10.0 V.		
Maximum power P	=	4.0 kW.		
Number of cooling circuits per coil	=	1.		
Volume per cooling circuit	=	0.329 ℓ/min	=	0.087 USGPM.
Volume per coil	=	0.329 ℓ/min	=	0.087 USGPM.
Volume per magnet	=	0.657 ℓ/min	=	0.174 USGPM.
Pressure drop per cooling circuit	=	0.6 psi .		

Because of the slightly larger width (0.15 in.) of s coil made of the 0.4600 inch-square conductor, each coil slot will be increased by that amount. Thus the overall width and length of the dipole will be increased by 0.30 in.

Table 1 gives a summary of the parameters of a dipole designed with the 0.289 in. and 0.460 in. conductors. Figure 1 shows in a quarter-section view the dimensions of a dipole using the smaller conductor.

4. POISSON calculations

The program POISSON [3)] was used to test the suitability of the design presented in §3. Several runs were made with various yoke and pole widths. The results of these runs led to the conclusion that the design shown in figure 1 was adequate.

4.1 Calculations for a dipole with a yoke thickness of 1.5 inches

This dipole is operated at a (relatively) low field and it was noted that the predicted field in the gap increased slightly with distance from the centerline of the pole. This phenomenon can be explained by reference to figure 2 which is the POISSON output showing the field lines in the pole and yoke of the dipole. Field lines are squeezed together as they enter the pole from the yoke. The result is that some enter the air gap at a slight angle, causing a variation of uniformity across the gap.

This effect can be reduced by introducing an air gap between the pole and the yoke, a technique known as a Purcell filter. It may also be reduced by increasing the pole width such that any non-uniformity lies outside of the region traversed by the beam and/or increasing the depth of the pole so as to allow the field lines to straighten out before they enter the air gap. As will be seen, however, we feel that the slight non-uniformity predicted for this design is of little consequence.

Table 2(a) lists the control program *pois.com* used to run the POISSON program; input data for the program from the file *csbdipole.dat* is given in table 2(b). In a Linux environment the command *./pois.com csbdipole* initiates execution of POISSON.

Figure 3 shows the POISSON prediction for the field contours in the pole and the yoke of this dipole with a yoke thickness of 1.50 inches. It is seen that the fields in the pole are reasonably uniform but those in the side yoke and connecting link to the pole are relatively high. However, there is no indication of saturation effects in the yoke.

Figure 4 shows the POISSON prediction for the field contours in the gap of this dipole. It is seen that in the region bounded by $-2.8\,\text{in.} \leq x \leq +\,2.8\,\text{in.}$ and $-0.38\,\text{in.} \leq y \leq +\,0.38\,\text{in.}$ the predicted field variation in the gap is small—0.3 G in 2333.8 G or 0.013%.

The most important aspect of field uniformity, however, is not that of the field in the gap of the magnet but that over the beam as it traverses the dipole. Given that a beam 1 cm in diameter is expected, it is clear that if the field uniformity over the region occupied by the beam in transit is predicted to be 0.013%, then the uniformity over the beam itself at any point should also be better than that. If this POISSON calculation is to be believed, figure 4 indicates that the field variation over a 0.5 inch-square region should be about 0.1 G or 0.0043%.

4.2 Calculations for a dipole with a yoke thickness of 2.5 inches

As noted above, the increase of field from the center of the pole to its side may be reduced in several ways. We have repeated the above POISSON calculation with the only change being an increase of the yoke thickness from 1.5 inches to 2.5 inches. The intent of this experiment is to how the fields in the pole, yoke, and gap are influenced by this change.

Figure 5 shows the predicted field contours in the pole and yoke of the dipole of §4.1 if its yoke thickness were increased to 2.5 inches. It is seen that the field contours in the main portion of the pole are not changed significantly. As is to be expected, fields in the vertical yoke and its connection to the pole are reduced by the ratio of the yoke thicknesses, that is, by a factor of 1.5/2.5.

Figure 6 shows the predicted field contours in the gap of this magnet. In the region bounded by $-2.8\,\text{in.} \leq x \leq +\,2.8\,\text{in.}$ and $-0.38\,\text{in.} \leq y \leq +\,0.38\,\text{in.}$ the predicted field variation in the gap is of the order of 0.22 G in 2367.9 G or 0.0093%. The variation over a beam diameter is about 0.05 G or 0.0021%.

Thus the increase of the yoke thickness by one inch has resulted in an twofold increase in the uniformity of the field in the (useable) portion of the gap of the magnet.

5. Discussion

This report has presented a conceptual design of a 90° dipole for the CSB beamline. Two variations of on a theme are given: one for a dipole with a yoke thickness of 1.5 inches and one with a yoke thickness of 2.5 inches. A dipole manufactured with the thicker yoke will produce a marginally more uniform field than one made with the thinner yoke. However, either dipole would be suitable for use in the beamline.

For each of these, two conductor sizes, 0.289 and 0.460 inch-square, were considered. A coil made from the smaller conductor would be easier to fashion than one made from the larger conductor.

If space is available we suggest that the yoke of the dipole be made 2.5 inches thick. This would add 2 inches to the overall width of the dipole and approximately 400 lbs to its weight.

In passing, we point out that if the entrance and exit edge angles are changed from 45° (as for a rectangular dipole) to 26.56505°, we would have a double-focusing dipole. Such a dipole focuses from a point 2ρ (= 0.8 m) upstream of the effective edge of the dipole to a point the same distance downstream of its exit effective edge. The magnification in each of the horizontal and vertical planes is -1 and the dispersion in the horizontal plane is 1.60 cm/%($\delta p/p$). If this were done winding of the coils of the magnet would be easier with a smaller conductor. It also might be advisable to use a field clamp to define the field boundary better.

References

1. P. Bricault, *Private communication*, TRIUMF, August, 2004.
2. R. E. Laxdal, *M. Sc. Thesis*, University of Saskatchewan, Saskatoon, Saskatchewan, 1980.
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.

Table 1

Summary of the parameters calculated for the 90° CSB dipole

		Conductor size (in. square)	
		0.289	0.460
Yoke:	Iron length	20.250 in.	20.250 in.
	Iron width	21.300 in.	21.600 in.
	Iron Thickness	1.500 in.	1.500 in.
	Coil-slot width	2.150 in.	2.300 in.
	Side yoke height	11.450 in.	11.450 in.
	Total height	14.450 in.	14.450 in.
Pole:	Width	14.000 in.	14.000 in.
	Height	4.725 in.	4.725 in.
	Width of pole flat	9.300 in.	9.300 in.
Iron:	Total weight	1,350 lb	1,350 lb
Coil:	Conductor OD	0.289 in.	0.460 in.
	Turn configuration (wide × high)	4 × 6	3 × 4
	Nominal width	1.300 in.	1.500 in.
	Nominal height	2.000 in.	2.050 in.
	Resistance (hot) per coil	0.027 Ω	0.006 Ω
	Number of cooling circuits	1	1
	Flow per circuit	0.102 USGPM	0.087 USGPM
	Pressure drop per circuit	12.757 psi	0.569 psi
Copper:	Length per magnet	360 ft	192 ft
	Weight per magnet	86 lb	53 kg
Power:	Maximum current	200.0 A	400.0 A
	Maximum voltage	15.0 V	10.0 V
	Total power	3.0 kW	4.0 kW
Magnet:	Total height	14.450 in.	14.450 in.
	Overall length	23.800 in.	24.100 in.
	Total flow	0.204 USGPM	0.174 USGPM
	Total weight per magnet†	1,435 lb	1,463 lb

† Exclusive of power and cooling headers.

Table 2(a)

Listing of the command file *pois.com*

```
NAME=$1
front ¡¡ EOF1
$NAME.dat
EOF1
chmod +x runpsf
./runpsf
psfplot ¡¡ EOF
0 0 0 s
s
go
1 0 20 s
s
go
−1 s
EOF
mv plot.ps $NAME.ps
mv outfro.lis $NAME.fro
mv outlat $NAME.lat
mv outpoi $NAME.poi
```

Table 2(b)

Listing of the data file *csbdipole.dat*

```
title
90 Deg H-magnet for CSB – Pole 14 in, Yoke 1.5 in, 4860 A-t, 2 in Gap
run
pois
mode 0
xmax=10.875
ymax=7.375
xmesh 0.125
ymesh 0.125
symm 6
nseg 6
conv=2.54
zseg 0. 7.00 9.150 10.875 10.875 0.
rseg 0. 0. 0. 0. 7.375 7.375
matpro 1
nseg 7
conv=2.54
zseg 0. 7.0 9.15 9.15 10.65 10.65 0.
rseg 5.725 5.725 5.725 0.0 0.0 7.225 7.225
matpro 2
nseg 6
conv=2.54
zseg 0. 4.65 6.00 7.00 7.00 0.
rseg 1. 1. 1.50 3.50 5.725 5.725
matpro 2
nseg 4
conv=2.54
zseg 7.375 8.775 8.775 7.375
rseg 5.6 5.6 3.5 3.5
current=-4860.
matpro 1
kbot=1
lbot=1
ltop=41
fieldmap 2
begin
end
```

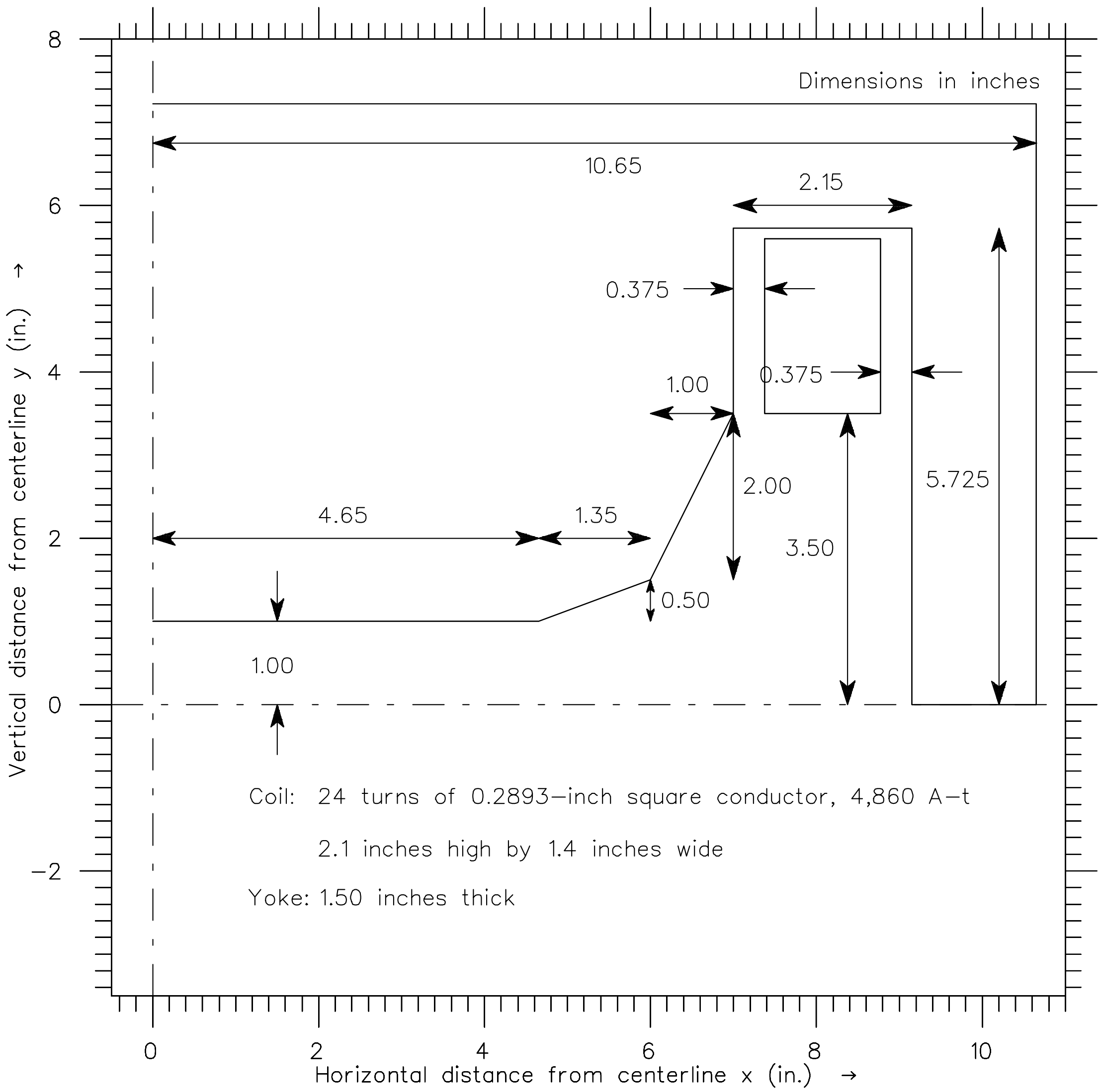

Fig. 1. Quarter-section cross-section of the 90° CSB dipole.

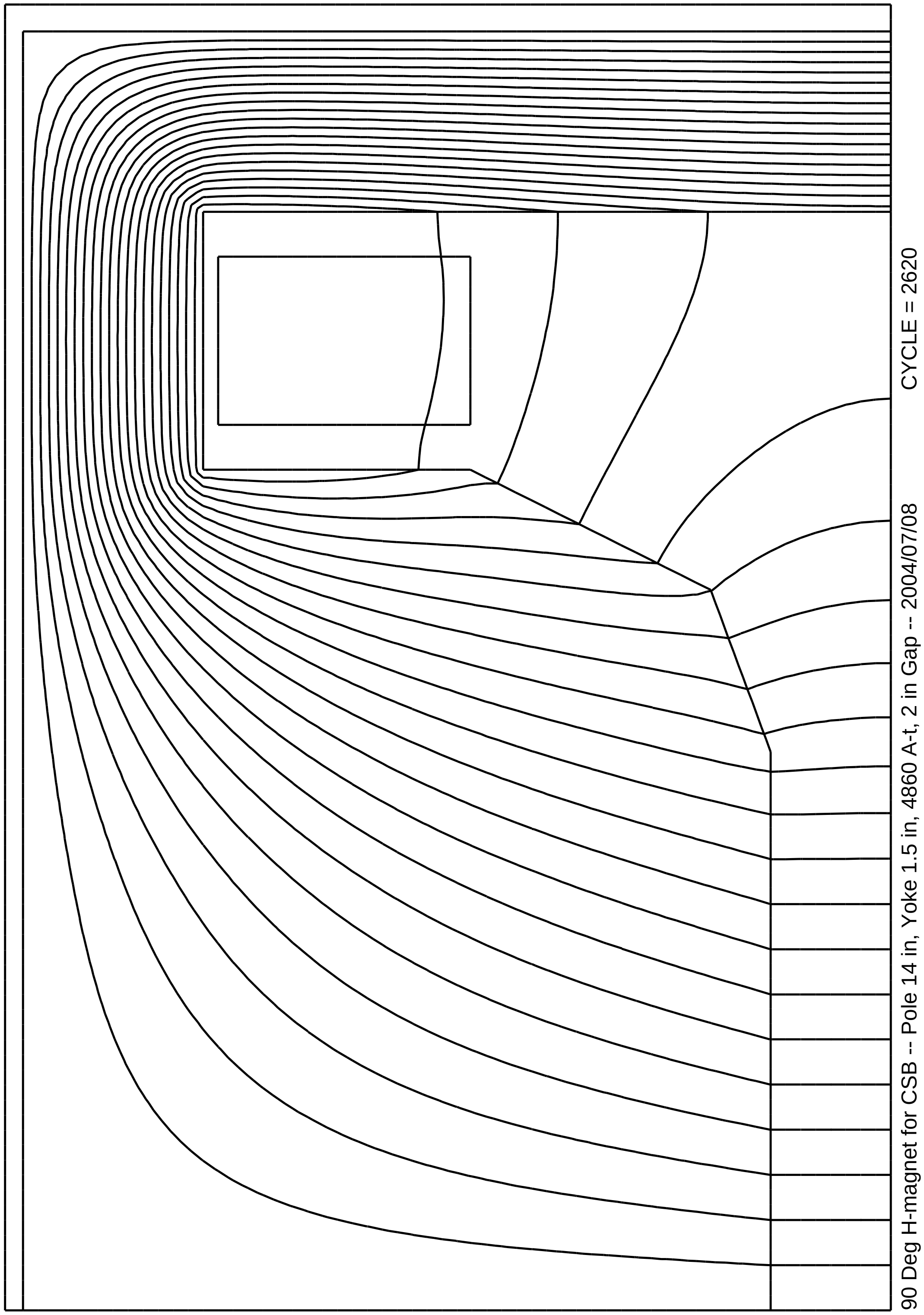

Fig. 2. Illustration of flux concentration in connection between the yoke and the pole.

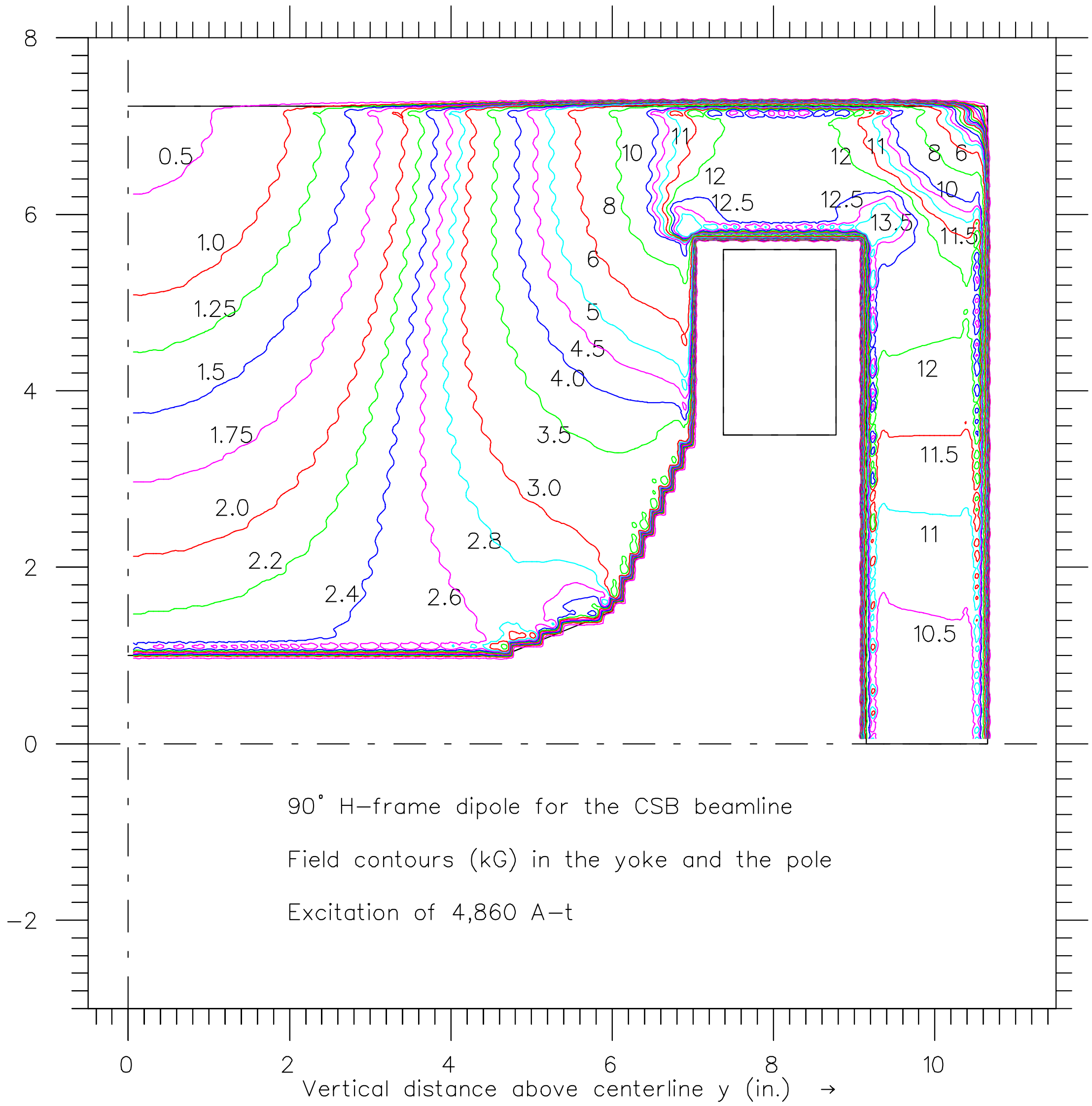

Fig. 3. Field contours in the yoke and pole of the CSB 90° dipole with 1.5 inch yoke thickness.

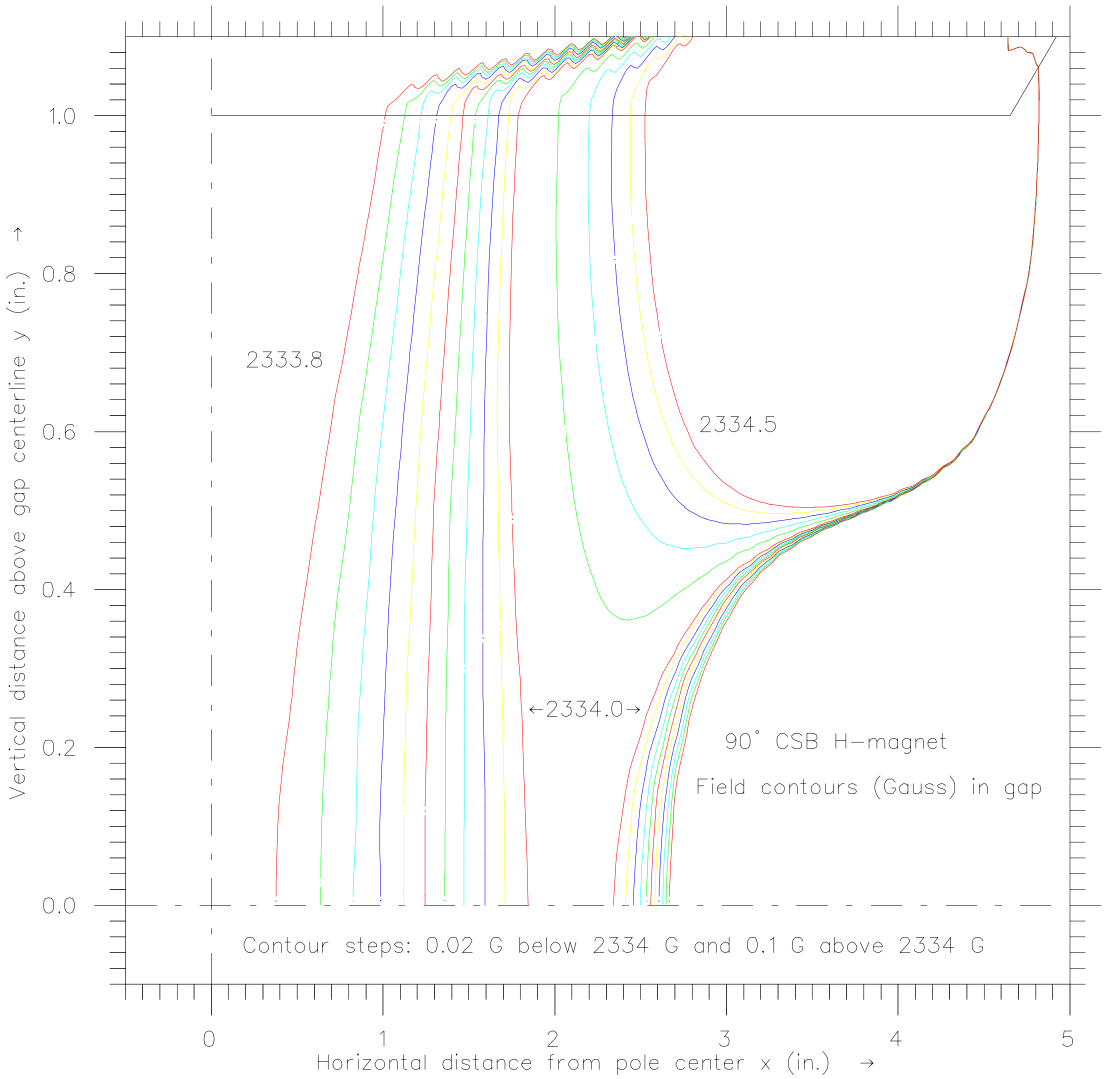

Fig. 4. Field contours in the gap of the CSB 90° dipole with 1.5 inch yoke thickness.

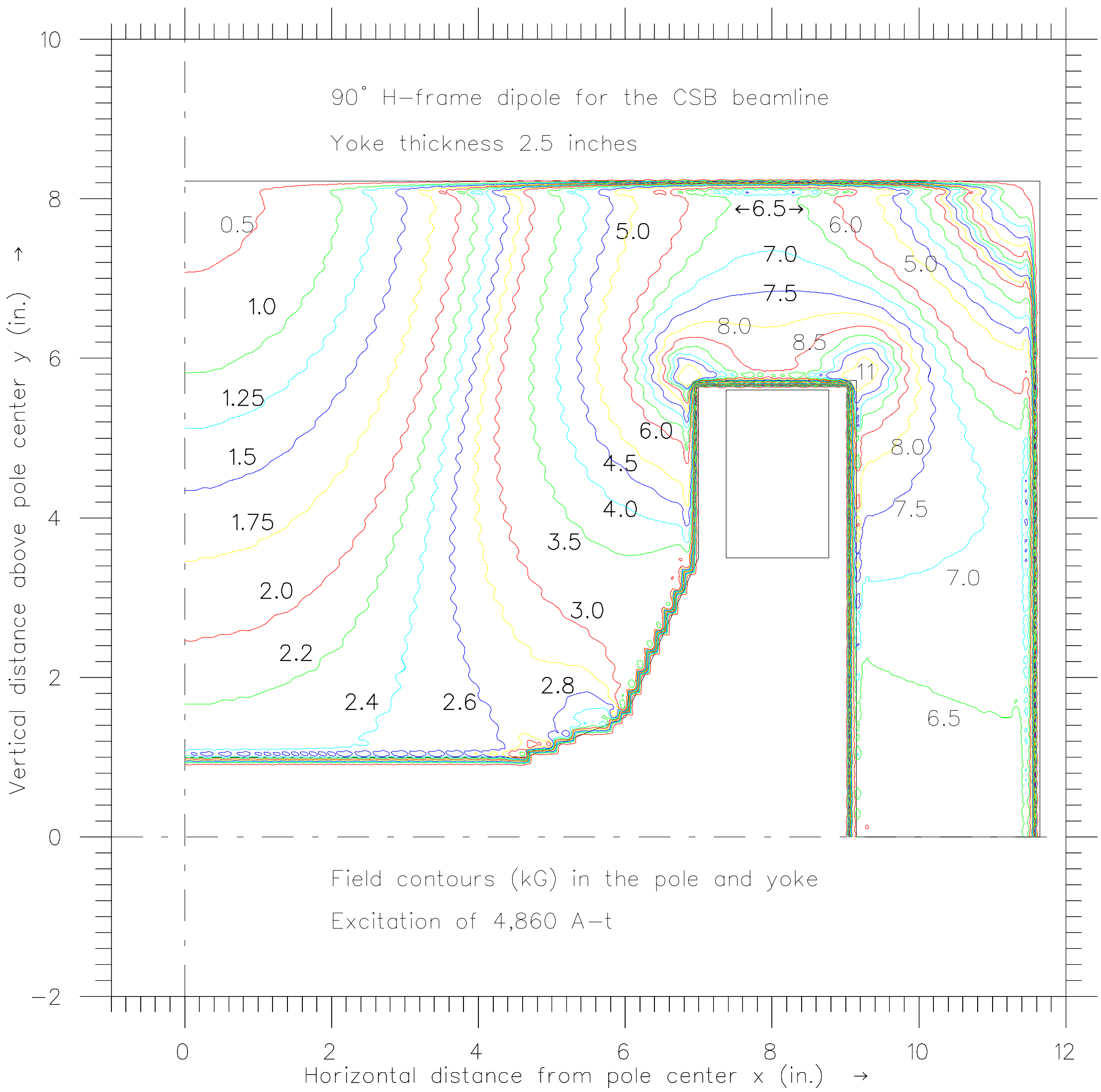

Fig. 5. Field contours in the yoke and pole of the CSB 90° dipole with 2.5 inch yoke thickness.

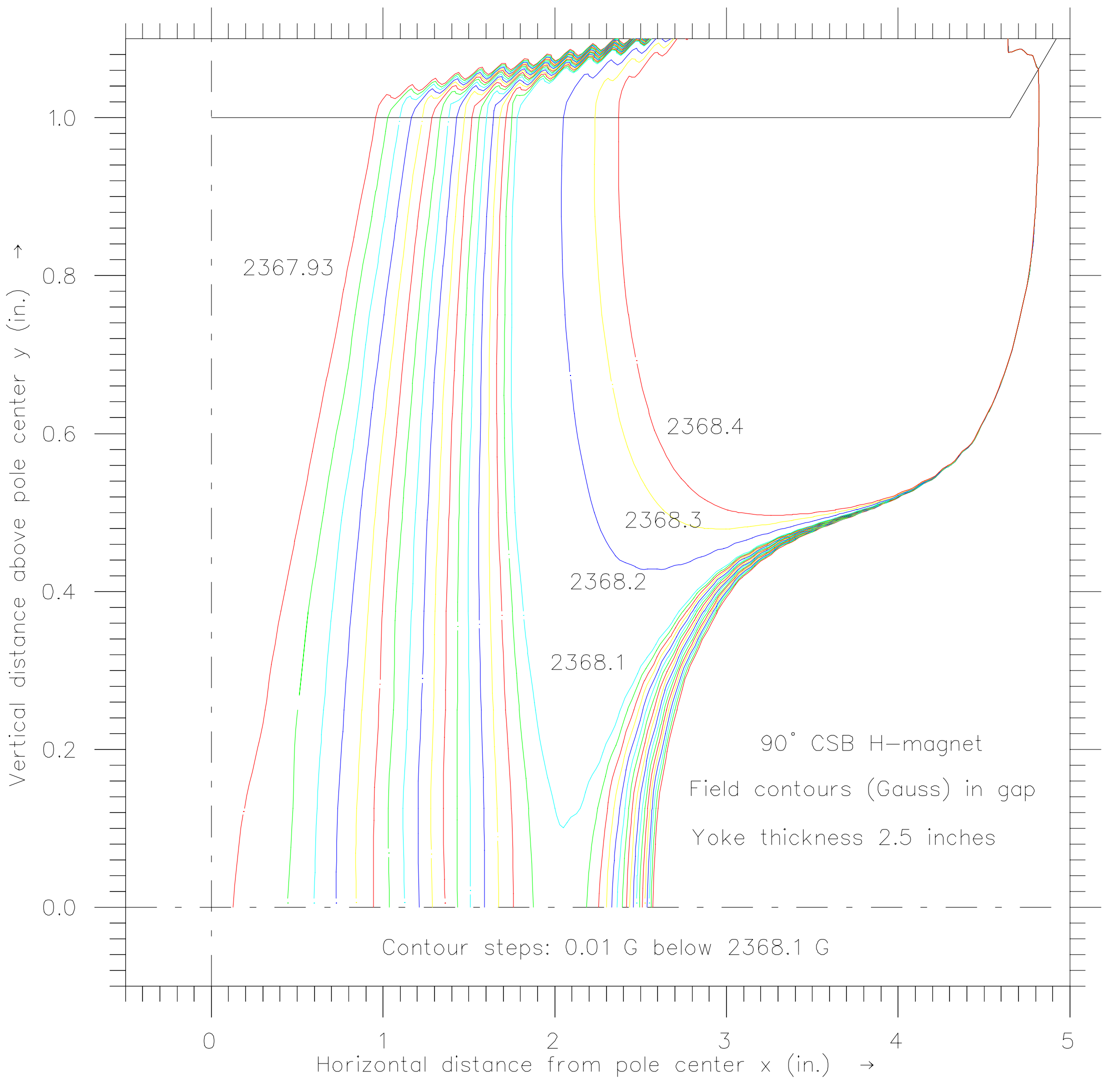

Fig. 6. Field contours in the gap of the CSB 90° dipole with 2.5 inch yoke thickness.