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Subject Conceptual designs for dipoles in the ISAC1 to ISAC2 transfer line – H-frame design		

1. Introduction

The transfer beamline from the ISAC1 DTLs to the medium-β section of the ISAC2 accelerator complex requires four identical 59.56° rectangular dipoles. Their design is complicated somewhat by the tight spatial constraints in both the ISAC1 HEBT beamline and the ISAC2 complex. In the former it is desired that the Prague magnet and its object slits remain in their present locations; in the latter space is restricted between the low-β and medium-β portions of the accelerators.

This report presents the first of two possible conceptual designs for the dipoles. Here we consider an H-frame design. A subsequent report will present the details of an arc-shaped design—that is, a dipole that has curved yokes.

2. Design parameters

The basic design of the ISAC1 to ISAC2 transfer beamline is given in ref[1]. In that report the following specifications are given.

Beam parameters:	Maximum beam height y_{max}	1.5 cm (0.5906 in.)
	Maximum beam width x_{max}	2.0 cm (0.7874 in.)
Dipole parameters:	Bend angle of dipole θ	59.56°
	Radius of curvature ρ_0	0.920 m (36.220 in.)
	Maximum $(B\rho)_0$	1.2 T-m
	Maximum dipole field B_0	1.3 T
	Magnet air gap g	5.0 cm (1.9685 in.)

3. Derived iron parameters

We choose to design the dipole for a maximum field of 13.5 kG (1.35 T) and an air gap of 2.0 inches (5.08 cm). Combining these values and those given above we obtain the derived parameters listed below.

Maximum *proton* momentum	=	$[B_0(\mathrm{T})\rho_0(\mathrm{m})]/3.3356$	=	0.37235 GeV/c
Maximum *proton* energy			=	71.182 MeV
Effective length along arc of trajectory	=	$\rho_0\theta$	=	0.95636 m (37.652 in.)
Straight-line effective length	=	$2\rho_0\sin(\theta/2)$	=	0.91388 m (35.979 in.)

3.1 Iron length

We take the iron length to be the straight-line effective length minus the full aperture. Thus

$$\text{Iron length} = 0.91388 \text{ m} - 0.0508 \text{ m} = 0.8631 \text{ m} = 33.980 \text{ in.}$$

We take

$$\boxed{\text{Iron length} = 0.8636 \text{ m} = 34.000 \text{ inches.}}$$

3.2 Ampere turns

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

$$\text{NI per pole} \;=\; \frac{1}{2}\left[1.1\,\frac{B_0(\mathrm{T})\,g(\mathrm{m})}{\mu_0}\right] \;=\; \frac{1}{2}\left[1.1\,\frac{(1.35)(0.0508)}{4\pi\times 10^{-7}}\right] \;=\; 30,020 \text{ A-t}$$

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

$$\boxed{\text{NI per pole} = 28{,}500 \text{ A-t.}}$$

3.3 Pole width

The deviation of the central trajectory from a line joining the entrance and exit points is found from

$$\Delta \;=\; \rho_0[1 - \cos(\theta/2)] \;=\; 0.12150 \text{ m} \;=\; 4.783 \text{ in.}$$

On each of the pole sides we assume a shim of 0.25 inch at 45° plus a 0.625 inch flat plus a 0.625 inch at 45°. From that point the pole tapers 0.50 inch to the pole root. Thus each pole side has a shim 2.0 inches wide. The nominal pole width is then

$$\begin{aligned} \text{Pole width} &= 2(\text{Shim} + \text{Gap}) + x_{max} + \Delta \\ &= 2(2.00 \text{ in.} + 2.00 \text{ in.}) + 0.7874 \text{ in.} + 4.783 \text{ in.} \\ &= 13.570 \text{ inches} \;=\; 0.34470 \text{ m.} \end{aligned}$$

We will require a field uniformity of better than 0.1% over the area traversed by the beam. If we assume that the dipole is installed such that the (longitudinal) geometric center of the magnet lies midway between the entrance and exit points of the central trajectory and its maximum deviation from those points, then this uniformity is required over a band of width $(\Delta + x_{max})/2$ either side of the central trajectory. The required uniformity, again anticipating the POISSON results below, is obtained if we choose

$$\boxed{\text{Base width of pole} = 18.00 \text{ inches} = 0.4572 \text{ m.}}$$

4. Coil design

In §3.2 above we determined that the required Ampere=turns per pole were 28,500. From this we have the following table of Amperes versus turns.

I (Amperes)	100	200	300	400	500	600	700	800	900	1000
N (Turns)	285	142	95	71	57	47	41	36	32	28

We choose

$$\boxed{\begin{array}{lcl} \text{I} & = & \text{maximum current} & = & 500 \quad \text{Amperes} \\ \text{N} & = & \text{number of turns per coil} & = & 56 \end{array}}$$

in a coil configuration 7 turns wide and 8 layers high.

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

$$\text{Conductor area} \;=\; \frac{500 \text{ A}}{3000\text{A/in.}^2} \;=\; 0.17 \text{ in.}^2 \;=\; 110 \text{ mm}^2.$$

This is satisfied within 10% by Anaconda 0.460 and 0.516 inch-square conductors. Their parameters are listed below.

OD (in.)	0.460	0.516
ID (in.)	0.255	0.287
Copper area (in.^{2})	0.1529	0.1940
Cooling area (in.^{2})	0.05107	0.06469
Mass (lb/ft)	0.5910	0.7495
Resistance at 20°C ($\mu\Omega$/ft)	53.25	41.99
k (British units)	0.01760	0.01520

We assume that each conductor is double-wrapped with insulation such that the *total* insulation per conductor has a minimum thickness of 0.022 inch, a nominal thickness of 0.028 inch, and a maximum thickness of 0.034 inch. With the tolerance of the outer dimension of the conductors listed as 0.004 inch, the dimensions of *wrapped* conductors are as follows.

	0.460 square	0.516 square
Minimum	0.478 inch	0.534 inch
Nominal	0.488 inch	0.544 inch
Maximum	0.498 inch	0.554 inch

Then the *width* of the coil is

	0.460 square		0.516 square	
	Maximum	Minimum	Maximum	Minimum
Wrapped conductor (inches)	3.486	3.346	3.878	3.738
Gapping (6×0.010) (inch)	0.060		0.060	
Ground wrap (4×0.007×2) (inch)	0.056	0.056	0.056	0.056
Total (inches)	3.602	3.402	3.994	3.794

We take

	0.460 square	0.516 square
Maximum coil width	3.500 inches	3.900 inches
Nominal coil width	3.400 inches	3.800 inches

The *height* of the coil is

	0.460 square		0.516 square	
	Maximum	Minimum	Maximum	Minimum
Wrapped conductor (inches)	3.984	3.824	4.432	4.272
Gapping (6×0.010) (inch)	0.060		0.060	
Keystoning (8×0.010) (inch)	0.080	0.040	0.080	0.040
Ground wrap (4×0.007×2) (inch)	0.056	0.056	0.056	0.056
Total (inches)	4.190	3.920	4.638	4.368

We take

	0.460 square	0.516 square
Maximum coil height	4.100 inches	4.500 inches
Nominal coil height	4.000 inches	4.400 inches

We take the conductor dimension D_{nom} to be

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

and further assume a pole-coil gap of 0.375 inches and that the pole corners are rounded with a radius R_{pole} of

$$R_{pole} = 4\,D_{nom} - \text{Pole-coil gap}$$

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 $N = 7$ and

Parameter	0.460 square	0.516 square
L_{iron} (inches)	34.000	34.000
W_{iron} (inches)	18.000	18.000
R_{pole} (inches)	1.617	1.841
Pole-coil gap (inch)	0.375	0.375
D_{nom} (inch)	0.498	0.554
Insulation (inch)	0.007	0.007

we find that the length of a 7-turn layer of 0.460-inch square conductor is 813 inches and that of 0.516-inch square conductor is 820 inches. For either case we take

Length of 7-turn layer = 75 ft (23 m),

and the length per coil becomes

Length of copper per coil = 600 ft (184 m).

Because 2 coils are required per dipole, then for either conductor we have

Total length per dipole	1200 ft	(368 m)
Allow 10% for winding losses	120 ft	(36 m)
Total	1320 ft	(404 m)

Then, for the 0.460-inch square conductor (of mass 0.5910 lb/ft) or for the 0.516-inch square conductor (of mass 0.7495 lb/ft) , we should order

	0.460-inch square		0.516-inch square	
A total length of	1350 ft	(415 m)	1350 ft	(415 m)
A total mass of	800 lb	(365 kg)	1025 lb	(465 kg)

5. Power requirements

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

$$R_{20^\circ C} = (\text{Resistance per foot})(\text{Coil length})$$

so that

$$\begin{aligned} R_{20^\circ C} &= (53.25\times10^{-6}\Omega/\text{ft})\times(600\text{ ft}) = 0.0320\ \Omega\ [0.460\text{-inch conductor}]. \\ &= (41.99\times10^{-6}\Omega/\text{ft})\times(600\text{ ft}) = 0.0252\ \Omega\ [0.516\text{-inch conductor}]. \end{aligned}$$

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:

$$\begin{aligned} R_{hot} &= R_{20^\circ C}[1 + (\text{Temperature coefficient}/^\circ\text{C})dT(^\circ\text{C})] \\ &= \begin{cases} 0.0320[1 + 0.00393(30)] = 0.0357\ \Omega \text{ per coil } [0.460\text{-inch conductor}]. \\ 0.0252[1 + 0.00393(30)] = 0.0282\ \Omega \text{ per coil } [0.516\text{-inch conductor}]. \end{cases} \end{aligned}$$

Thus at a current of 500 A we require a voltage of 17.9 V per coil of the smaller conductor and of 14.1 V per coil of the larger conductor. Therefore, allowing for lead loss, we choose power supplies that have

	0.460 square	0.516 square
I (A maximum)	500.0	500.0
V (V total)	45.0	40.0
P (kW total)	22.5	20.0

6. Cooling requirements

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

$$\begin{aligned} \text{Power per coil} &= I^2 R_{hot} \\ &= \begin{cases} (500)(500)(0.03572) = 8.93\text{ kW } [0.460\text{ conductor}]. \\ (500)(500)(0.02816) = 7.04\text{ kW } [0.516\text{ conductor}]. \end{cases} \end{aligned}$$

The required flow rate is given by:

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

For $\Delta T = 72^\circ\text{F} = 40^\circ\text{C}$ and choosing $v = 2.50$ ft/sec to define the maximum power dissipation per water circuit, we have

$$P_{max} = \begin{cases} \frac{(2.50)(72)(0.05107)}{2.19} = 4.198\text{ kW/water circuit of 0.460 conductor}. \\ \frac{(2.50)(72)(0.06469)}{2.19} = 5.317\text{ kW/water circuit of 0.516 conductor}. \end{cases}$$

From these we calculate the number of cooling circuits per coil (excluding lead loss) as

		0.460 square	0.516 square
P	Total power per coil	8.93 kW	7.04 kW
Number of circuits	$P\ /\ P_{max}$	2.13	1.32

Thus we take

$$\text{Number of cooling circuits per coil} = \begin{cases} 2\ [0.460\text{-inch conductor}] \\ 2\ [0.516\text{-inch conductor}] \end{cases}$$

This requires a flow rate of $v = 2.66$ ft/sec per water circuit of a coil of the smaller conductor and one of 1.66 ft/sec per water circuit of a coil of the larger conductor. The volume of flow required per circuit is found from

$$\begin{aligned}\text{Volume/circuit} &= 2.6(v(\text{ft/min}))(\text{Cooling area(in.}^2)) \text{ IGPM}\\ &= \begin{cases} 2.6(2.659)(0.05107) = 0.353 \text{ IGPM [0.460 conductor]}.\\ 2.6(1.655)(0.06469) = 0.278 \text{ IGPM [0.516 conductor]}.\end{cases}\end{aligned}$$

Thus the calculated flow requirements for the two types of coils are as follows.

	0.460 conductor			0.460 conductor		
	IGPM	ℓ/min	USGPM	IGPM	ℓ/min	USGPM
Volume per cooling circuit	0.353	1.605	0.424	0.278	1.266	0.334
Volume per coil	0.706	3.210	0.848	0.557	2.531	0.669
Volume per magnet	1.412	6.420	1.696	1.114	5.062	1.337

7. 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 $k = 0.0176$ for the 0.460 conductor and $k = 0.0152$ for the 0.516 conductor we obtain:

$$dP = \begin{cases} (0.0176)(2.659)^{1.79} = 0.101 \text{ psi/ft [0.460 conductor]},\\ (0.0152)(1.655)^{1.79} = 0.037 \text{ psi/ft [0.516 conductor]},\end{cases}$$

and the total pressure drop across one cooling circuit is

$$\boxed{\text{Pressure drop per cooling circuit} = \begin{cases} 30.4 \text{ psi [0.460 conductor.]}\\ 11.2 \text{ psi [0.516 conductor.]}\end{cases}}$$

8. Iron dimensions

We begin by taking the width of the coil slot as

$$\begin{aligned}\text{Coil-slot width} &= \text{Maximum coil width} + 2(\text{Pole-coil gap})\\ &= \begin{cases} 3.50 \text{ inches} + 2(0.375 \text{ inch}) = 4.25 \text{ inches [0.460 conductor]}.\\ 3.90 \text{ inches} + 2(0.375 \text{ inch}) = 4.65 \text{ inches [0.516 conductor]}.\end{cases}\end{aligned}$$

We assume that the field rises from zero at the outer edge of the coil slot to $0.6B_0$ at the pole flat and is constant at B_0 across the pole flat. In this context the pole flat is taken as the outer edge of the flat portion of the pole shim and the coil slot as the width of the coil slot plus the 0.5 inch and 0.625 inch tapers of the pole shim. We further assume that the flux divides equally between the side yokes. Setting B_y and t as the yoke flux and thickness, respectively, we then may calculate the flux in each yoke by setting it equal to one-half of that through the gap region. Thus

$$B_y t = \frac{1}{2} \times \frac{2[\text{Coil-slot + pole shim}][0.6B_0]}{2} + \frac{1}{2} \times [\text{Width of pole flat}]B_0$$

In our case with

	0.460 square	0.516 square
Coil slot (inches)	4.250	4.650
Shim (inches)	1.125	1.125
Width of pole flat (inches)	15.750	15.750

we find the following values for $B_y t$.

$$B_y t = \begin{cases} \frac{13.5}{2}[(4.250+1.125)(0.6)+15.750] = 128.1 \text{ kG-inches [0.460-inch conductor]}. \\ \frac{13.5}{2}[(4.650+1.125)(0.6)+15.750] = 129.7 \text{ kG-inches [0.516-inch conductor]}. \end{cases}$$

For either case we choose $t = 10.00$ inches thus making the yoke flux approximately 13 kG.

Yoke thickness	10.00 inches
Yoke field	≈13.0 kG

The total width of the dipole is

$$\begin{aligned} \text{Dipole width} &= 2[(\text{Coil-slot width}) + \text{Yoke thickness})] + \text{Pole base width} \\ &= \begin{cases} 2(4.25+10.00)+18.00 = 46.500 \text{ inches [0.460 conductor]}, \\ 2(4.65+10.00)+18.00 = 47.300 \text{ inches [0.516 conductor]}, \end{cases} \end{aligned}$$

and the total length of the dipole is

$$\begin{aligned} \text{Dipole length} &= 2[(\text{Pole-coil separation}) + (\text{Maximum coil width})] + \text{Pole length} \\ &= \begin{cases} 2(0.375+3.50)+34.00 = 41.750 \text{ inches [0.460 conductor]}. \\ 2(0.375+3.90)+34.00 = 42.550 \text{ inches [0.516 conductor]}. \end{cases} \end{aligned}$$

The pole height is

$$\begin{aligned} \text{Pole height} &= \text{Maximum coil height} + \text{Insulation pad} + 0.75 \text{ inch} \\ &= \begin{cases} 4.100+0.125+0.750 = 4.975 \text{ inches} \Longrightarrow 5.00 \text{ inches [0.460 conductor]}, \\ 4.500+0.125+0.750 = 5.375 \text{ inches} \Longrightarrow 5.40 \text{ inches [0.516 conductor]}, \end{cases} \end{aligned}$$

and the lengths of the side yokes are

$$\begin{aligned} \text{Length of side yoke} &= 2(\text{Pole height}) + \text{Gap} \\ &= \begin{cases} 2(5.000 \text{ inches} + 2.000 \text{ inches} = 12.000 \text{ inches [0.460 conductor]}. \\ 2(5.400 \text{ inches} + 2.000 \text{ inches} = 12.800 \text{ inches [0.516 conductor]}. \end{cases} \end{aligned}$$

9. Iron mass

From the preceding data we have

	0.460-inch square			0.516-inch square		
	Height (in.)	Width (in.)	Area (in.^{2})	Height (in.)	Width (in.)	Area (in.^{2})
Top yoke	10.00	46.50	465.00	10.00	47.30	473.00
Top pole	5.00	18.00	90.00	5.40	18.00	97.20
Side yoke	12.00	10.00	120.00	12.80	10.00	128.00
Total			675.00			698.20

Thus, using an iron density of 0.2833 lb/in.^{3} we find

	0.460 square	0.516 square
Area of yoke (in.^{2})	1,350	1,396
Volume of iron (in.^{3})	45,900	47,464
Mass of iron (lb)	13,005	13,447

We take

Iron mass for 0.460-inch square conductor	13,100 lb	(5,940 kg) .
Iron mass for 0.516-inch square conductor	13,500 lb	(6,125 kg) .

Table 1 presents a summary of these calculations. Figure 1 shows the overall geometry of the magnet as well as the detail of the pole shim.

9. POISSON results

As noted previously, the program POISSON[2)] was used to test the validity of the above calculations. The program was run only for the case of a coil constructed from the 0.460-inch square conductor, the assumption being that results would be similar for the case of the larger conductor. The output from the POISSON runs were analyzed using the programs PLOTDATA[3)] and PHYSICA[4)].

POISSON was run with a mesh of width 0.125 inch in each of the horizontal and vertical planes. Figure 2 is a contour map of the predicted field distribution in the yoke and pole of the magnet. Figure 3 is a similar map of the field distribution in the magnet gap. In this figure field contours in the pole should, of course, be ignored because they are figments of the contouring process.

From figure 2 it is seen that the field in the yoke is more-or-less as calculated in §8—that is, in the order of 13 kG. However, regions of (near) saturation are predicted at the corners of the coil slot and in the shims along the side of the pole.

Similarly, figure 3 shows that the field is predicted to be reasonably uniform at $(13{,}678.5 \pm 3.5)$ G ($\pm 0.026\%$) over a region bounded by $x = \pm 3$ inches from the transverse centerline of the pole and $y = \pm 0.5$ inch from the (vertical) midplane of the dipole.

It should be remembered that the results shown in figures 2 and 3 are for the design field of 13.5 kG, a value approximately 5% larger than the maximum field at which the magnet is expected to be run. Consequently, one may expect the fields in the (unsaturated sections) of the yoke to be reduced proportionately when operating at the expected maximum field. This is *not* to be expected in the saturated regions.

10. Discussion

This report has presented a study of an H-frame dipole that could be used in the ISAC1 to ISAC2 transfer beamline. The study considered magnets with coils fabricated from different sizes of conductor. As indicated in the summary (Table 1), there is little to choose between the two.

If the smaller, 0.460-inch square conductor is used, the overall size of the dipole is slightly smaller than that of a dipole constructed with coils made with a 0.516-inch square conductor. However, the smaller conductor requires four cooling circuits per coil as opposed to two circuits per coil made from the larger conductor. Also, coils made from the smaller conductor require a larger power supply than is necessary for coils made from the larger conductor. Consequently, a magnet fabricated with the larger conductor would be slightly less expensive to operate.

The design of the magnet is such that portions of the pole will be at or close to saturation when the dipole is operated at its maximum field. This, however, should not cause operational problems.

POISSON calculations indicate that the field uniformity of the dipole should be reasonable. However, a more detailed three-dimensional analysis should be made—particularly near the entrance and exit of the dipole.

References

1. R. E. Laxdal and M. Pasini, *ISAC-II Optics Specifications*, TRIUMF report TRI-DN-01-xx, March, 2002.
2. M. T. Menzel and H. K. Stokes, *User's Guide fro the POISSON/SUPERFISH Group of Codes*, Los Alamos National Laboratory Report LA-UR-87-117, January, 1987.
3. J. L. Chuma, *PLOTDATA Command and Reference Manual*, TRIUMF Report TRI-CD-87-03b, June, 1991.
4. J. L. Chuma, *PHYSICA User's Guide*, TRIUMF Report TRI-CD-98-01, February, 1998.

Summary of the calculated dipole parameters

		0.460-inch conductor	0.516-inch conductor
Yoke:	Iron length (inches)	34.00	34.00
	Iron width (inches)	46.50	47.30
	Iron Thickness (inches)	10.00	10.00
	Coil-slot width (inches)	4.25	4.65
	Side yoke height (inches)	12.00	12.80
	Total height (inches)	32.00	32.80
Pole:	Width (inches)	18.00	18.00
	Height (inches)	5.00	5.40
	Shim (each side of pole) (inches)	1.50	1.50
Iron:	Total weight (lb)	13,100	13,500
Coil:	Conductor OD (inch)	0.460	0.516
	Turn configuration (wide × high)	7 × 8	7 × 8
	Nominal width (inches)	3.40	3.80
	Nominal height (inches)	4.00	4.40
	Resistance (hot) Ω per coil	0.036	0.028
	Number of cooling circuits	2	2
	Flow per circuit (USGPM)	0.424	0.334
	Flow per circuit (ℓ/min)	1.61	1.27
	Pressure drop per circuit (psi)	30.40	11.24
Copper:	Length per magnet (ft)	1,200	1,680
	Weight per magnet (lb)	710	900
Power:	Maximum current (A)	500.0	500.0
	Maximum voltage (V)	45.0	40.0
	Total power (kW)	22.5	20.0
Magnet:	Gap (inches)	2.00	2.00
	Total height (inches)	32.00	32.80
	Overall length (inches)	41.75	42.55
	Total flow (USGPM)	1.70	1.34
	Total flow (ℓ/min)	6.42	5.06
	Total weight per magnet† (lb)	13,110	14,400

† Exclusive of power and cooling headers.

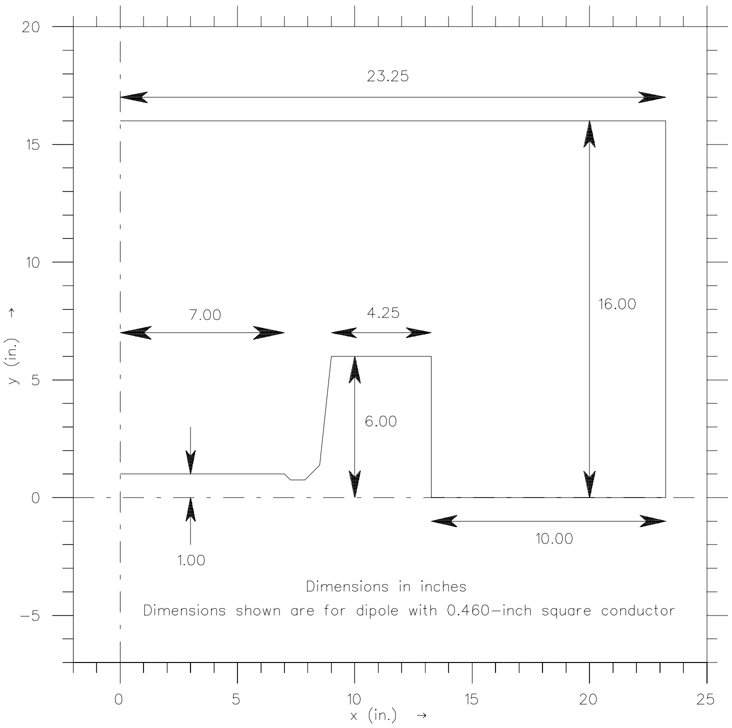

Fig. 1(a). Estimated yoke dimensions for the H-frame dipole. The coil-slot dimension is for the 0.460-inch square conductor.

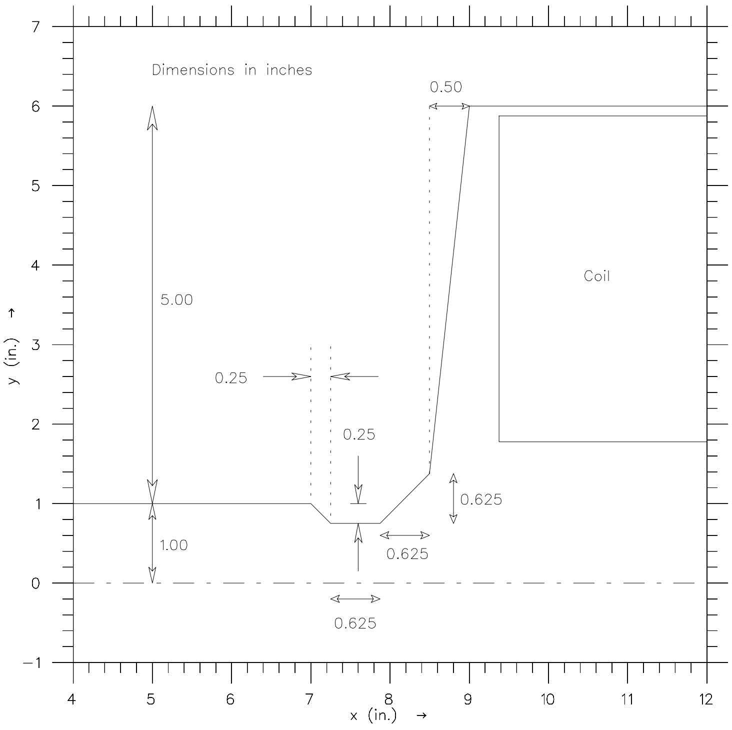

Fig. 1(b). Detail of the shim on the pole edge of the dipole.

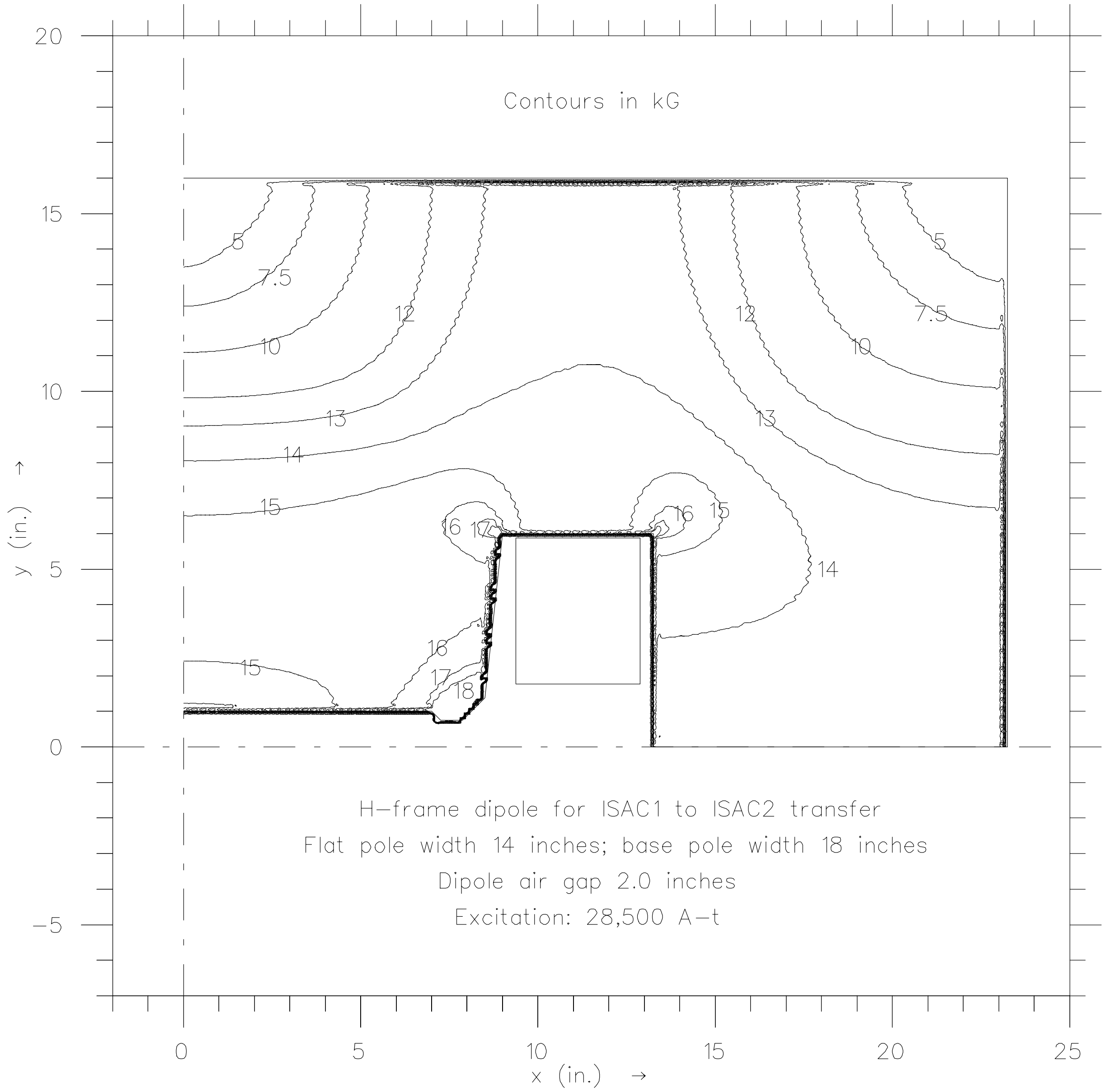

Fig. 2. The POISSON prediction of the field in the yoke of the dipole.

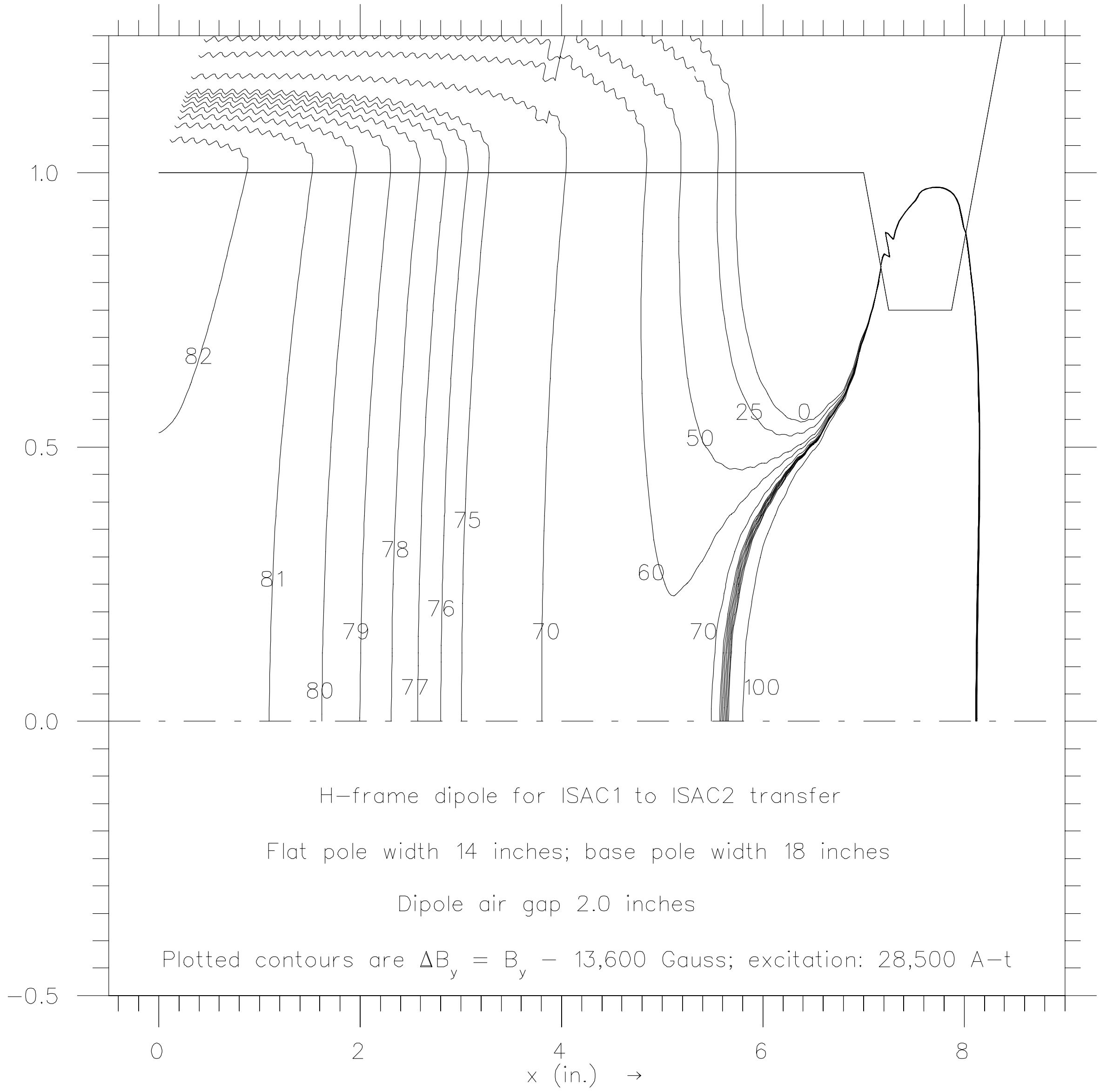

Fig. 3. The POISSON prediction for the field in the gap of the dipole.