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Subject Design of 12 Degree Dipole for Parity

1. Introduction

The relocation of the Parity experiment to a site other than on beamline 4A is discussed in ref[1]. Of the locations considered, relocation to a line on the 12° port of beamline 4C is the most attractive. Were this to occur, it is necessary add a 12° dipole that is centred at the present LD_2 target location. This note presents a design for such a magnet.

2. Parameters

Because this dipole could be useful for other TRIUMF experiments, the magnet is designed to bend 500 MeV protons through 12°. The basic parameters are then:

Bend angle	$\theta =$	12°
Energy	$T =$	500 MeV
Momentum	$p =$	1.09007 GeV/c
Magnetic rigidity	$(B\rho)_0 =$	36.360375 kG-m
Magnet Gap	$g =$	0.10 m

3. Derived Quantities

We choose the maximum operating field to be 1.4 T.

$$\boxed{B_{max} = 1.4 \text{ T} = 14 \text{ kG}}$$

Then

$$\rho = (B\rho)_0 / B_{max} = 2.59717 \text{ m}$$

$$\boxed{\rho = 2.6 \text{ m} = 102.362 \text{ in}}$$

and

$$s = \rho\,\theta = 2.6(12\pi)/180 = 0.54454 \text{ m}$$

$$\boxed{s = 0.55 \text{ m} = 21.653 \text{ in}}$$

To calculate the *iron* length of the magnet we assume that, because of the small bend angle, the *effective* length of the magnet is equal to the arc length s. Then

$$\boxed{L_{iron} = L_{eff} - g = 0.45 \text{ m} = 17.717 \text{ in}}$$

The deviation of the central trajectory of the beam from a line parallel to the exit and entrance points is

$$\boxed{\Delta = \rho[1 - \cos(\theta/2)] = 0.01424 \text{ m}}$$

We assume a champfer of 12.5 mm on each pole edge and calculate the *pole-width* W as

$$\begin{aligned} W &= 2 \text{ champfers} + \text{beam width} + \Delta + 2 \text{ gaps} \\ &= 2(12.5\text{mm}) + 60\text{mm} + 14.24\text{mm} + 2(100\text{mm}) \\ &= 299.24 \text{ mm} \end{aligned}$$

$$\boxed{W = 0.300 \text{ m} = 11.811 \text{ in}}$$

4. Ampere-turns Required

We allow for a flux leakage of 10% and obtain

$$\text{Ampere-turns per coil} = NI = \frac{1}{2}(1.1)\frac{B_{max}g}{\mu_0} = 6.13\text{x}10^4$$

$$\boxed{NI/\text{coil} = 6.15\text{x}10^4}$$

5. Coil Configuration and Conductor

For NI/coil = 6.15x10^4 we have the following table:

I (Amperes)	100	200	300	400	500
N (Turns)	615	308	205	154	123

We choose

$$\boxed{\begin{aligned} I_{max} &= 500A \\ N &= 120 \end{aligned}}$$

Although a 12x12 array is dictated, the choice of a 10x12 or 12x10 array produces a smaller coil. The 'safety' factor for flux leakage is reduced by ≈2%; however, it is not felt that this would be detrimental to the magnet's performance.

Coil configuration chosen as 10x12 or 12x10 array.

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

$$\text{A} = \frac{500A}{3000A/\text{in}^2} = 0.16667 \text{ in}^2 = 107.53 \text{ mm}^2$$

This is satisfied by **Anaconda 0.5160 inch-square** conductor whose properties are listed as:

Copper area	=	A_{Cu}	=	0.1940 in^2	=	125.161 mm^2
Cooling area	=	A_{H_2O}	=	0.06469 in^2	=	41.735 mm^2
Weight			=	0.7495 lb/ft	=	1.11538 kg/m
Resistance at 20° C	=	R_{20}	=	41.99x10^{-6} Ω/ft	=	137.76x10^{-6} Ω/m
Cooling factor	=	k	=	0.0152		

With this conductor the current density is $(500\ A/0.194\ \text{in}^2) = 2577\ A/\text{in}^2$ and is within specifications.

6. Coil Design

Figure 1 shows the coil construction.

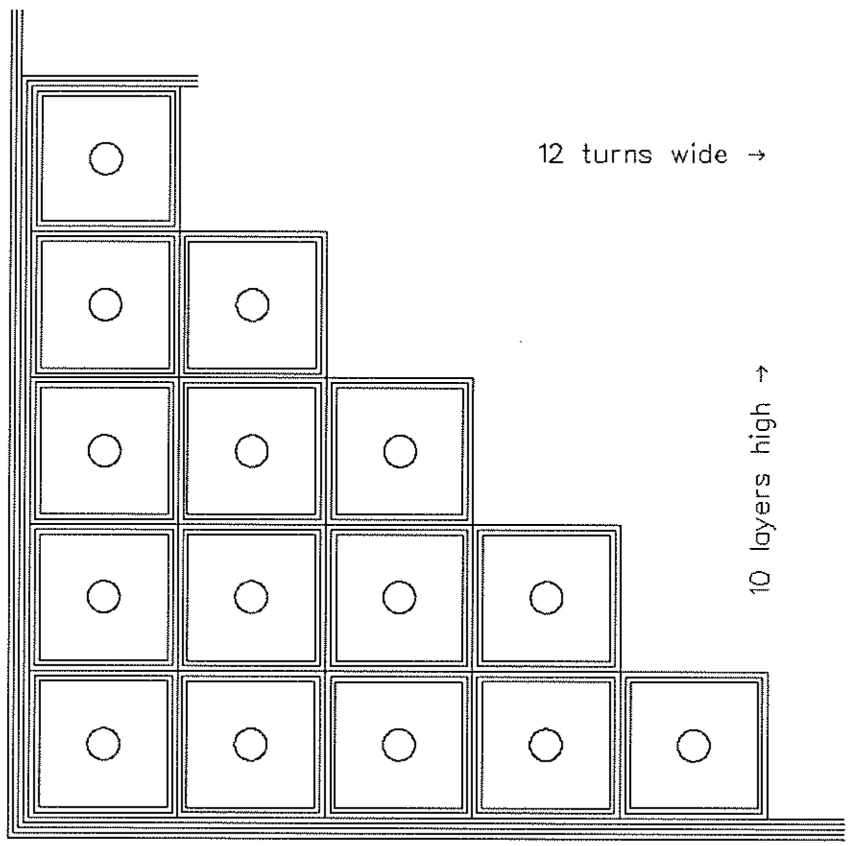


Figure 1: Construction of the coil with cooling circuit of 5 layers.

In its design we assume:

1. a 12.7 mm (0.50 in) gap G between the coil and the yoke and pole.
2. each turn is double-wrapped in insulation $t_i = 0.1778$ mm (0.007 in) thick.
3. there is a 0.254 mm (0.010 in) separation between adjacent turns.
4. each cooling circuit is double-wrapped with 0.1778 mm insulation.
5. the entire coil is double-wrapped with the 0.1778 mm insulation.

6. that the minimum bending radius of the conductor is four times its dimension.

We then take the conductor dimension D to be

$$\begin{aligned} D &= \text{nominal dimension} + 4(\text{insulation thickness}) + \text{turn separation} \\ &= 0.5160 \text{ in} + 4(0.007 \text{ in}) + 0.010 \text{ in} \\ &= 0.5540 \text{ in} = 14.0716 \text{ mm} \end{aligned}$$

As a result of item 6 above, we make the further simplifying assumption that the pole corners are rounded with a radius of $R_{pole} = 4\,D - G = 43.5864$ mm = 1.716 inches in order that the coil-pole separation be maintained.

Figure 2 is a diagram from which the length of each layer is calculated.

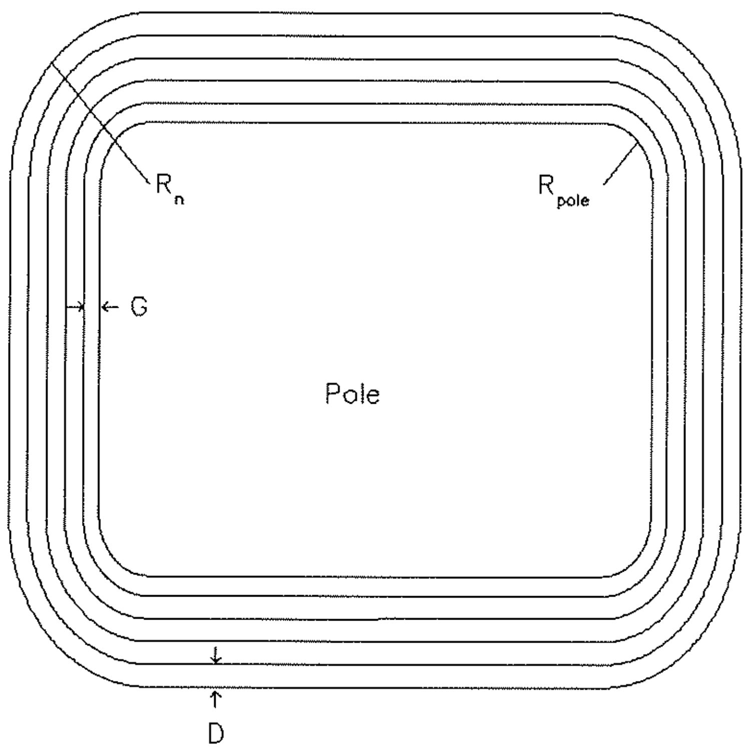


Figure 2: Diagram for the calculation of layer length.

The outer edge of the n^{th} conductor is a distance

$$d_n = n\,D + G + W/2 + 4\,t_i$$

from the (longitudinal) centreline of the pole; the term $4\,t_i$ represents the thickness of the ground wrap nearest the pole. The (outer) radius of curvature of this n^{th} turn is

$$R_n = R_{pole} + G + n\,D + 4\,t_i$$

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 width is

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

The length of the n^{th} turn is then

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

and the length of an N-turn layer is

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

For our case with

$$\begin{aligned} L_{iron} &= 450.\ \text{mm} \\ W_{iron} &= 300.\ \text{mm} \\ R_{pole} &= 43.5864\ \text{mm} \\ G &= 12.7\ \text{mm} \\ D &= 14.0716\ \text{mm} \\ t_i &= 0.1778\ \text{mm} \end{aligned}$$

the length of an N-turn layer becomes

$$L_N = 1510\,N + 44.25\,N(N+1)$$

and the lengths of 10- and 12-turn layers become $L_{10} = 19968$ mm and $L_{12} = 25010$ mm respectively. We take

Length of 10-turn layer	=	20.5 m ≈ 68 ft
Length of 12-turn layer	=	25.5 m ≈ 84 ft

Then the length of copper per coil is 12(68) = 246 m for the 10x12 coil and 10(25.5) = 255 m for the 12x10 coil. Because these lengths are the same to all intent and purpose, we take the *total* length of copper per coil as the larger of the two. Thus

Copper per coil	=	255 m	≈	285 kg	=	630 lb
Total copper per magnet	=	510 m	≈	570 kg	=	1260 lb

7. Power Requirement

In this section we assume

ambient temperature	20° C
inlet water temperature	30° C
outlet water temperature	70° C

so that the *mean* coil temperature is 50° C, an elevation of 30° C above ambient. Using a temperature coeffient of $\alpha = 0.00393\Omega/°\text{C}$ we then have

$$R_{50} = (1 + \alpha\,\Delta T)R_{20} = 1.1179\,R_{20}$$

For either coil configuration we then have

$$
\begin{aligned}
R_{20} &= (137.76\text{x}10^{-6}\Omega/\text{m})(255\text{m}) &&= 0.03513\ \Omega \\
R_{50} &= (1.1179)(137.76\text{x}10^{-6}\Omega/\text{m})(255\text{m}) &&= 0.03927\ \Omega \\
V &= I_{max}R_{50} &&= 19.65\ \text{V}
\end{aligned}
$$

and with an allowance for a 10% voltage drop in the cabling we obtain

$$
\begin{aligned}
V/\text{coil} &= 1.1V &&= 21.6\ \text{V} \\
P/\text{coil} &= (V/\text{coil})I_{max} &&= 10.8\ \text{kW}
\end{aligned}
$$

Thus the specifications of the power supply are

Maximum current	=	500	*A*
Total voltage	=	44	*V*
Total power	=	22	kW

8. Cooling Requirement

In the British system of units the required flow rate of the coolant is given by

$$v(\text{ft/sec}) = \frac{2.19}{\Delta T(^o\text{F})}\frac{P(\text{kW})}{\text{A}_{H_2O}(\text{in}^2)}$$

so that for $\Delta T = 40^o$ C $= 72^o$ F and $\text{A}_{H_2O} = 0.06469$ in^2 we have

$$v(\text{ft/sec}) = 0.47019\ P(\text{kW})$$

We choose a flow rate of $v = 2.25$ ft/sec to define the maximum power dissipation P_{max} allowed per water circuit. Thus

$$P_{max} = \frac{(2.25)(72)(0.06469)}{2.19} = 4.785\ \text{kW/water circuit}$$

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

$$
\begin{aligned}
P &= \text{Total power per coil} &&= 9.825\ \text{kW} \\
\text{Number of circuits} &= P/P_{max} &&= 2.05
\end{aligned}
$$

We thus take

Number of cooling circuits per coil = 2

With 2 cooling circuits per coil, each circuit contains 6 layers in a 10x12 configuration and 5 layers in a 12x10 configuration. Assuming the initial layer is wound inward from the outside, with an even number of layers the final layer ends at the outside of the coil wheras with an odd number of layers it ends at the inside. Consequently we choose

Coil configuration as a 10x12 array.

The volume of flow required per circuit is

$$
\begin{aligned}
\text{Volume/circuit} &= v\frac{\text{ft}}{\text{sec}}\ \text{x}\,\text{A}_{H_2O}(\text{in}^2)\ \text{x}\ 60\frac{\text{sec}}{\text{min}}\ \text{x}\ \frac{1}{144}\frac{\text{ft}^2}{\text{in}^2}\ \text{x}\ 62.4\frac{\text{lb}}{\text{ft}^3}\ \text{x}\ \frac{1}{10}\frac{\text{IG}}{\text{lb}} \\
&= 2.6\,v(\text{ft/min})\,\text{A}_{H_2O}(\text{in}^2)\ \ \text{IGPM} \\
&= 0.378\ \text{IGPM}
\end{aligned}
$$

Thus

Volume per cooling circuit	=	0.40 IGPM = 1.62 ℓ/min
Volume per coil	=	0.80 IGPM = 3.24 ℓ/min
Volume per magnet	=	1.60 IGPM = 6.48 ℓ/min

9. Pressure Drop

The pressure drop over a water circuit is given by

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

so that for one water circuit of length 6(25.5 m) = 153 m ≈ 502 ft we have for $k = 0.0152$ and $v = 2.25$ ft/sec

$$\boxed{\Delta p/\text{circuit} = (0.0152)(2.25)^{1.79}(502) = 32.6\ \text{psi}}$$

which is well within an allowed pressure drop of 60 psi.

10. Iron Dimensions

Figure 3 shows a cross-section of the dipole and an approximation of the field to be expected.

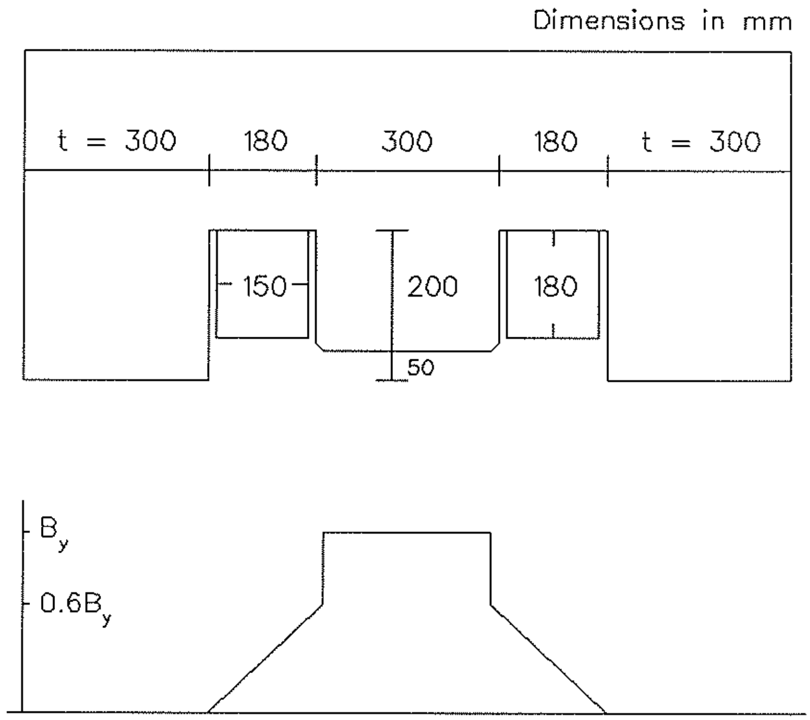


Figure 3: Cross-section of dipole and field approximation.

If B_y and t are the yoke flux and thickness respectively and it is assumed that the flux divides equally between the side yokes, we then have

$$\begin{aligned} 2\,B_y t &= 2[(0.180\text{m} + 0.0127\text{m})(0.6)(1.4\text{T})/2] + (0.300\text{m} - 0.0254\text{m})(1.4\text{T}) \\ &= (0.1619 + 0.3844)\ \text{T-m} \\ &= 0.5463\ \text{T-m} \end{aligned}$$

$$\boxed{B_y t = 0.2732\ \text{T-m}}$$

Because we wish to keep the yoke flux to ≈1 T and the pole-width has already been chosen to be 0.300 m, we choose

$$t = 0.300 \text{ m} \approx 12 \text{ in}$$
$$B_y = 0.911 \text{ T}$$

11. Iron Mass

From figure 3 we have

	Height	Width	Area
Top yoke	0.300 m	1.260 m	0.378 m^2
Top pole	0.200 m	0.300 m	0.060 m^2
Side Yoke	2x0.250 m	0.300 m	0.150 m^2
Total			0.588 m^2

Area of yoke = 2 x 0.588 m^2 = 1.176 m^2.

Volume of yoke = (0.450 m)(1.176 m^2) = 0.5292 m^3.

Mass of iron = (0.5292 m^3)(7.9x10^3 kg/m^3) = 4181 kg.

Mass of iron per magnet = 4185 kg ≈ 9230 lb

12. Summary

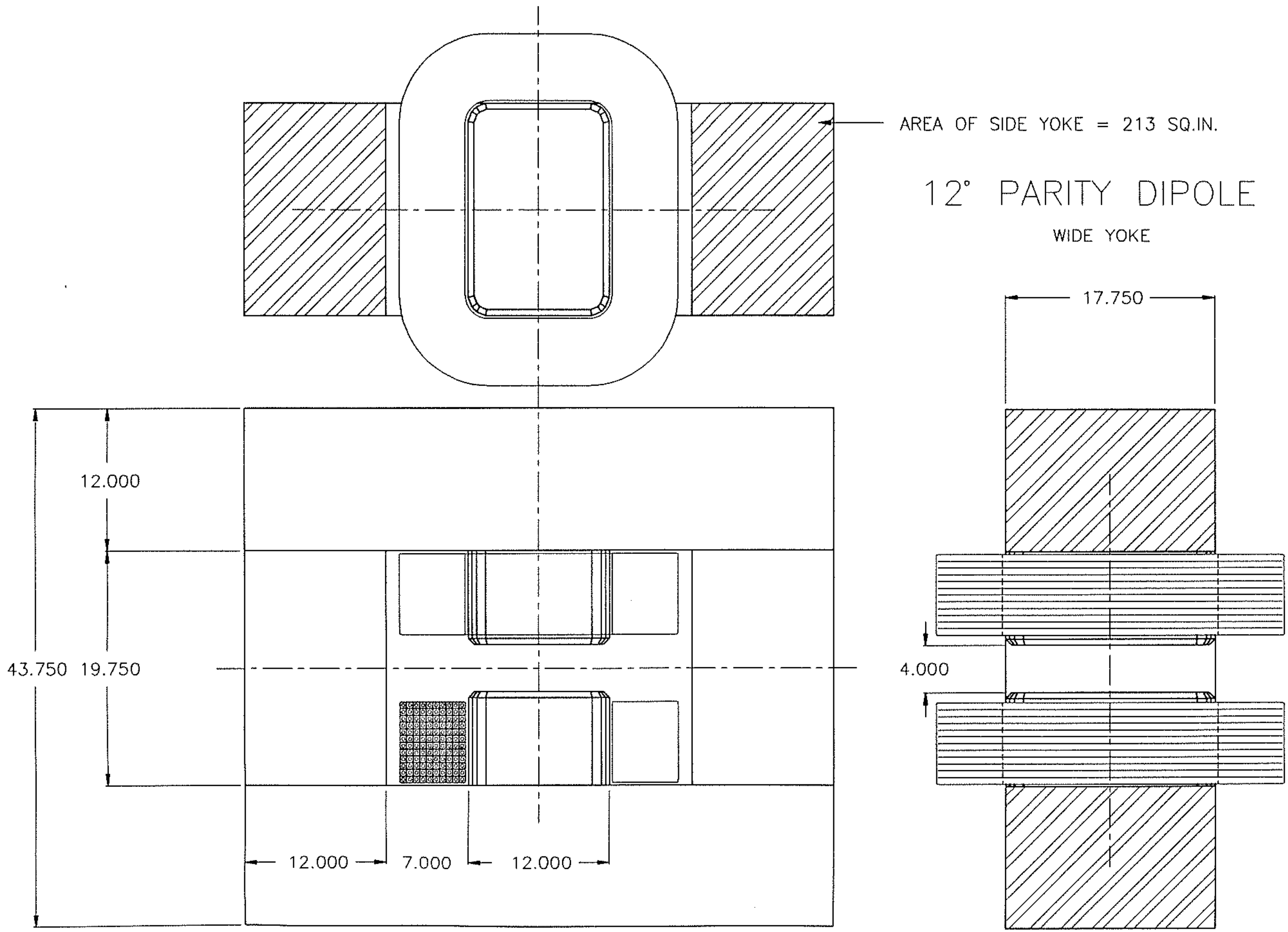
Yoke:	Iron length	0.450 m
	Iron width	1.260 m
	Coil slot	0.180 m wide
Pole:	Width	0.300 m
	Height	0.200 m
	Champfer	0.0127 m at 45°
Iron:	Total mass	4185 kg ≈ 9160 lb
Coil:	Conductor	13.11 mm (0.5160 in) square
	Turn configuration	10 wide x 12 high
	Nominal width	0.150 m
	Nominal height	0.180 m
	Total coolant flow	1.6 IGPM = 6.5 ℓ/min
	Number of cooling circuits per coil	2
Copper:	Total length	510 m ≈ 1675 ft
	Total mass	570 kg ≈ 1260 lb
Power:	Maximum current	500 A
	Maximum voltage	44 V
	Power	22 kW

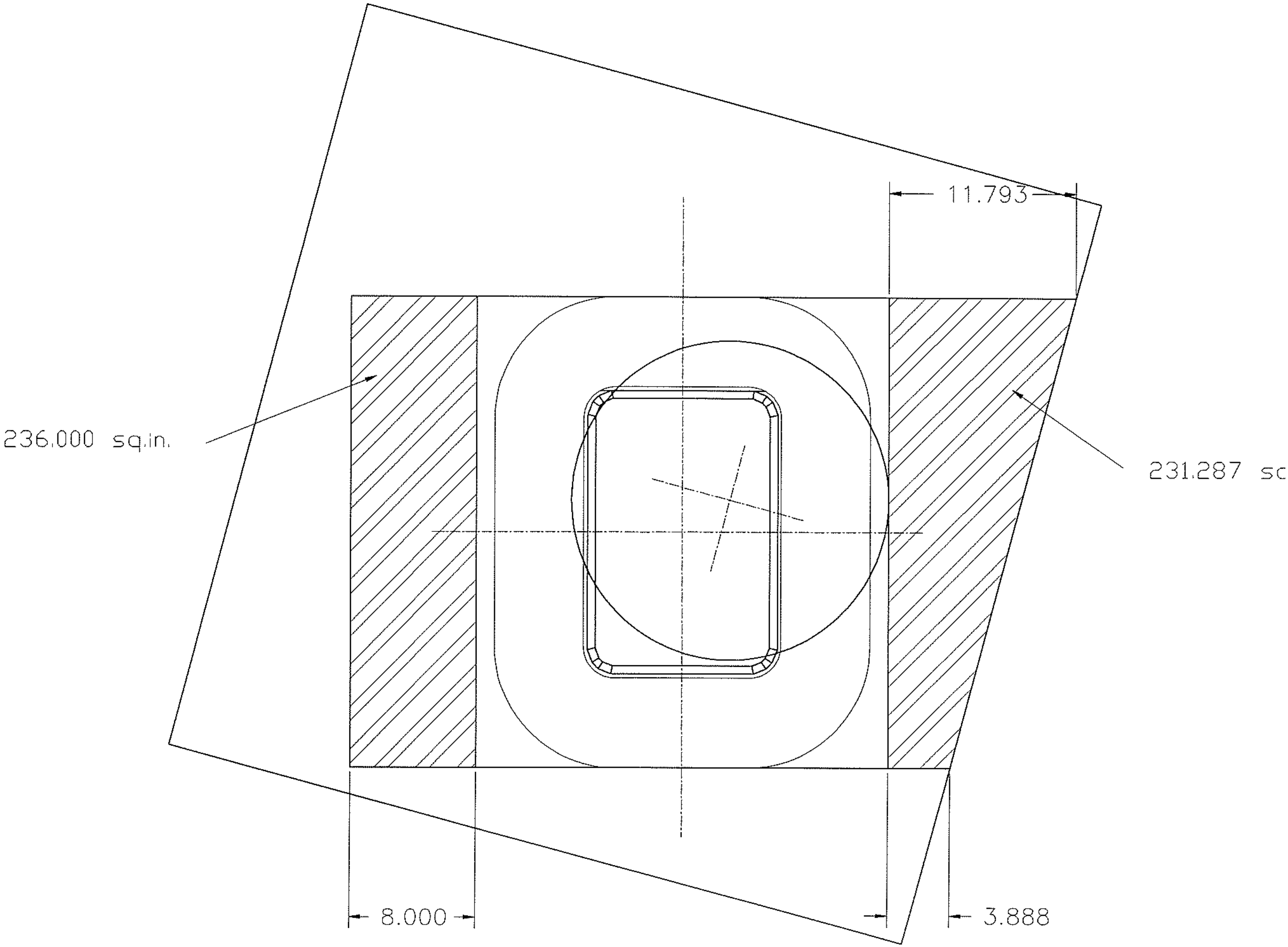
References

[1] GM Stinson, *Possible Areas for the Relocation of the Parity Experiment*, **TRI-DNA-90-2**, August, 1990.

12° PARITY DIPOLE

WIDE YOKE




11.793
236.000 sq.in.
231.287 sc
8.000
3.888