## 1. Introduction

For the new electron beam line at TRIUMF 45° and 30° dipoles are required. Initially the maximum energy of the electrons was proposed to be 50 MeV and preliminary designs for each type of dipole were made on this basis. Recently, however, a request was made for the upgrade of these dipoles to an electron energy of 75 MeV [1)]. This report presents conceptual designs for 30° dipoles for each of the two energies.

## 2. Dipole specifications

The following design parameters were also given by R. Baartman.

| | | | |
|---|---|---|---|
| Bend angle $\theta$ | 45.000 ° | | |
| Radius of curvature $\rho$ | 29.52756 in. | = | 0.750 m |
| Full gap $g$ | 2.000 in. | = | 0.0508 m |
| Electron energy | 50.000 MeV | and | 75.000 MeV |

## 3. Derived quantities

From the above the following quantities are derived for a bend angle of 45°.

Because the bend angle $\theta$ of the dipole, its full gap $g$ and the radius of curvature $\rho$ of the beam in it are defined, the following parameters are *independent* of the energy of the electron beam.

| Parameter | Definition | Value | |
|---|---|---|---|
| Arc length $s$ | $s = \rho\theta$ | 15.46060 in. | 0.39270 m |
| Straight-line length $L_{str}$ | $L_{str} = 2\,\rho \sin(\theta/2)$ | 15.28459 in. | 0.38823 m |
| Iron length $L_{Fe}$ | $L_{Fe} = L_{str} - g$ | 13.28459 in. | 0.33743 m |

We take $\boxed{\text{Iron length } L_{Fe} = 13.400\,\text{in.} = 0.34036\,\text{m}}$

Other parameters that depend on the energy of the electrons are listed below. The parameters for an equivalent proton are calculated by setting its momentum equal to that of an electron of the appropriate energy. The notation $p^+$ below refer to that equivalent proton.

| Parameter | Definition | 50 MeV $e^-$ | 75 MeV $e^-$ |
|---|---|---|---|
| $e^-$ momentum | $p_{e^-}$ | 50.508414 MeV/c | 75.509270 MeV/c |
| $p^+$ momentum | $p_{p^+}$ | 50.508414 MeV/c | 75.509270 MeV/c |
| $p^+$ energy | $E_{p^+}$ | 1.684759 MeV | 3.033474 MeV |
| Magnetic rigidity $(B\rho)_0$ | $(B\rho)_0 = 33.356\, p_{p^+}$ | 1.684759 kG-m | 2.518687 kG-m |
| Maximum field $B_{max}$ | $B_{max} = 33.356\, p_{p^+}/\rho$ | 2.24635 kG | 3.35825 kG |

Note that in the calculation of $(B\rho)_0$ and $B_{max}$ that the proton momentum is to be entered in GeV/c.

**4. Pole parameters**

We assume a chamfer of 30° along the sides and ends of the pole and a beam full-width of 0.157 inch (4.000 mm). The deviation of the central trajectory from a line parallel to the entry and exit points is

$$\Delta \;=\; \rho[1-\cos(\theta/2)] \;=\; 1.0063\,\text{inch}\ (25.556\,\text{mm}).$$

Then the pole width is calculated as

$$\begin{aligned}\text{Pole width} &= 2(\text{Chamfer}) + \text{Beam width} + \Delta\ + 2(\text{gap})\\ &= 2(0.650) + 0.157 + 1.0063 + 2(2.000)\\ &= 6.463\,\text{inches}\ (164.2\,\text{mm}).\end{aligned}$$

Based on (later) POISSON runs we take

$$\boxed{\text{Pole width} = 8.000\,\text{inches}\ (203.2\,\text{mm}).}$$

**5. Ampere-turns per coil** The required Ampere-turns per pole are calculated from the relation

$$\text{NI per pole} \;=\; \frac{1}{2}\left[1.1\,\frac{B_{max}[\text{T}]\,g[\text{m}]}{4\pi\times10^{-7}}\right] \;=\; \begin{cases} \dfrac{1}{2}\left[1.1\,\dfrac{0.224635(0.0508)}{4\pi\times10^{-7}}\right] = 4995\ \text{A-t for } 50\,\text{MeV e}^- \\[2ex] \dfrac{1}{2}\left[1.1\,\dfrac{0.335825(0.0508)}{4\pi\times10^{-7}}\right] = 7467\ \text{A-t for } 75\,\text{MeV e}^- \end{cases}$$

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

$$\text{NI per pole} = \begin{cases} 5,000\ \text{A-t for } 50\,\text{MeV e}^- \\[2ex] 7,500\ \text{A-t for } 75\,\text{MeV e}^- \end{cases}$$

and generate the following table.

| I (Amperes) | 100 | 200 | 300 | 400 | 500 | 600 | 700 | 800 | 900 | 1000 |
|---|---|---|---|---|---|---|---|---|---|---|
| N (Turns) | 50 | 25 | 17 | 12 | 10 | 8 | 7 | 6 | 6 | 5 |

We choose

$$\boxed{\begin{array}{lll} \text{I} = \text{maximum current} & = & 200\,\text{Amperes} \\ \text{N} = \text{number of turns per coil} & = & 24\ \text{for}\ 50\,\text{MeV e}^- \\ \quad\ \text{in a coil configuration 6 turns wide and 4 layers high} & & \\ \text{N} = \text{number of turns per coil} & = & 36\ \text{for}\ 75\,\text{MeV e}^- \\ \quad\ \text{in a coil configuration 6 turns wide and 6 layers high} & & \end{array}}$$

These, of course, are the same values that were obtained for the 45° dipole[2)].

**6. 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 inch | = | 7.34822 mm |
| ID | 0.161 inch | = | 4.08940 mm |
| Corner radius | 0.050 inch | = | 1.27 mm |
| Copper area | 0.06117 inch$^2$ | = | 39.46444 mm$^2$ |
| Cooling area | 0.02036 inch$^2$ | = | 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 | | |

By using this conductor calculation of the coil cross-sectional dimensions for the 30° dipole will be the same as those of the 45° dipoles of ref[2]. There it was assumed that each conductor was insulated with half-lapped fiberglass tape 0.007 inch thick and the ground wrap was provided by overwrapping the entire coil in the same manner. Details of these calculations are given in ref[2] and are not repeated here; we quote only the final results.

| Parameter | Width (inches) | Height (inches) 50 MeV dipole | Height (inches) 75 MeV dipole |
|---|---|---|---|
| Maximum coil width | 2.050 | 1.430 | 2.130 |
| Nominal coil width | 2.000 | 1.400 | 2.100 |

Because 50 MeV and 75 MeV dipoles are each 6 turns wide their coil widths are the same. Thus in ref[2] the dimensions of a coil for the 50 MeV dipole were taken as 2.000 inches wide and 1.400 inches high; those of a coil for the 75 MeV dipole were taken as 2.000 inches wide and 2.100 inches high.

An alternate method of insulating the conductor using double Dacron glass (DDG) was also mentioned in ref[2]. We illustrate this here using the technique noted on pages 2 and 3 of ref[3]. This assumes that the conductor has been coated a double layer of Dacron glass insulation that according to page 44 of the Essex Magnet Wire Engineering Data book gives a *minimum increase* (over the [bare] copper OD) of 0.012 inch. A spiral wrapping of fiberglass, 0.007 inch thick and spaced 0.25 inch apart, is assumed to be applied over the DDG-wrapped conductor. An estimate of the maximum conductor obtained by using the nominal conductor size plus the maximum tolerance on the conductor size (0.003 inch) plus the *minimum increase* for the DDG (0.012 inch). Thus we estimate the maximum size of a DDG-wrapped conductor to be (0.2893 + 0.003 + 0.012) inch = 0.3043 inch and make the following table.

| Parameter | Width (inches) | Height (inches) 50 MeV dipole | Height (inches) 75 MeV dipole |
|---|---|---|---|
| DDG-wrapped conductor 6(4)[6]×0.3043 | 1.826 | 1.217 | 1.826 |
| Fiberglass overwrap 12(8)[12]×0.007 | 0.084 | 0.056 | 0.084 |
| Inter-turn spacing 5(3)[5]×0.010 | 0.050 | 0.030 | 0.050 |
| Keystoning 0(4)[6]×0.010 | 0.000 | 0.040 | 0.060 |
| Ground wrap 4(4)[4]×0.007 | 0.028 | 0.028 | 0.028 |
| Total | 1.988 | 1.371 | 2.048 |

These coil dimensions are consistent with those obtained by assuming that the conductors were overwrapped with half-lapped fiberglass tape. Consequently, we continue using the dimensions calculated that way—that is, we assume that the dimensions of a coil for the 50 MeV dipole are 2.000 inches wide and 1.400 inches high and those of a coil for the 75 MeV dipole are 2.000 inches wide and 2.100 inches high.

To calculate the lengths of the coils we follow the method used in ref[2]. The conductor dimension $D_{nom}$ is taken to be

$$\begin{aligned} D_{nom} &= \text{Nominal dimension} + 4(\text{Insulation thickness}) + \text{ Turn separation} \\ &= 0.2893 + 0.028 + 0.010 \\ &= 0.327\,\text{inch}\ (8.313\,\text{mm}) \end{aligned}$$

and further assume a pole-coil gap $G$ of 0.500 inch (12.700 mm) and that the pole corners are rounded with a radius $R_{pole}$ of

$$R_{pole} \;=\; 4\,D_{nom} - G \approx 0.800\,\text{inch}\ (20.32\ \ \text{mm})\ .$$

Then the $n$th 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 $n$th 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 $n$th turn is

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

and the length of an $N$-turn layer is

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

Using the values tabulated below

| | | | | |
|---|---|---|---|---|
| $L_{iron}$ | = | 13.400 in. | = | 340.36 mm, |
| $W_{iron}$ | = | 8.000 in. | = | 203.20 mm, |
| $R_{pole}$ | = | 0.800 in. | = | 20.32 mm, |
| $G$ | = | 0.500 in. | = | 12.70 mm, |
| $D_{nom}$ | = | 0.327 in. | = | 8.31 mm, |
| Insulation | = | 0.007 in. | = | 0.18 mm, |

together with our case of $N = 6$ we find that the length of a 6-turn layer is 312 inches (26.0 ft). We take

$$\text{Length of 6-turn layer} = 28\,\text{ft}\ (8.5\,\text{m}).$$

Thus the length of copper in a coil of a magnet that bends 50 MeV electrons through 30° is

$$\text{Length of copper per coil of dipole for 50 MeV electrons} = 112\,\text{ft}\ (34\,\text{m}),$$

and that in a coil of a dipole for 75 MeV electrons is

$$\text{Length of copper per coil of dipole for 75 MeV electrons} = 168\,\text{ft}\ (51\,\text{m}),$$

Because 2 coils are required per dipole, then

| | 50 MeV $e^-$ | 75 MeV $e^-$ |
|---|---|---|
| Total length per dipole | 224 ft (68 m) | 336 ft (102 m) |
| Allow 10% for winding losses | 22 ft ( 7 m) | 34 ft (10 m) |
| Total | 246 ft (75 m) | 370 ft (113 m) |

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

| | 50 MeV e⁻ | 75 MeV e⁻ |
|---|---|---|
| A total length of | 250 ft (76 m) | 370 ft (104 m) |
| A total mass of | 60 lb (27 kg) | 88 lb (40 kg) |

**7. Power requirements**

At 20°C, the resistance of a coil is:

$$R_{20^\circ C} = \begin{cases} (133.20\times10^{-6}\Omega/\text{ft})\times(112\text{ ft}) = 0.0149\ \Omega \text{ for a dipole coil for } 50\,\text{MeV e}^- , \\ (133.20\times10^{-6}\Omega/\text{ft})\times(168\text{ ft}) = 0.0224\ \Omega \text{ for a dipole coil for } 75\,\text{MeV e}^- . \end{cases}$$

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

$$\begin{aligned} R_{hot} &= R_{20^\circ C}[1 + (0.00393/^\circ\text{C})(30^\circ\text{C})] \\ &= \begin{cases} 0.0149[1.1179] = 0.0167\,\Omega/\text{coil for } 50\,\text{MeV e}^- , \\ 0.0224[1.1179] = 0.0250\,\Omega/\text{coil for } 75\,\text{MeV e}^- . \end{cases} \end{aligned}$$

Thus at a current of 200 A a (minimum) voltage/coil of 3.4 V is required for the 50 MeV dipole and 5.0 V is required for the 75 MeV dipole. Therefore, allowing 2V for lead loss, we choose a power supply that has the minimum parameters.

| | 50 MeV dipole | 75 MeV dipole |
|---|---|---|
| Current I | 200.0 A maximum | 200.0 A maximum |
| Voltage V | 9.0 V minimum | 12.0 V minimum |
| Power P | 1.8 kW minimum | 2.4 kW minimum |

**8. Cooling requirements**

In these calculations we use the British system of units. The power required per coil of the 50 MeV dipole is

$$\text{Power per coil} = I^2 R_{hot} = (200)(200)(0.0149) = 0.596\,\text{kW} .$$

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 $\Delta T = 72^\circ$F (40°C) and $A_{H_2O} = 0.02036$ inch$^2$ (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

$$\begin{aligned} P &= \text{Total power per coil} = 0.596\text{ kW} \\ \text{Number of circuits} &= P \,/\, P_{max} = 0.36 \end{aligned}$$

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

This requires a flow rate of $v = 0.890\,\text{ft/sec}$ per water circuit. The volume of flow required per circuit is

$$\text{Volume/circuit} \;=\; 2.6(v(\text{ft/min}))(\text{Cooling area}(\text{in.}^2)) \;=\; 2.6(0.890)(0.02036) \;=\; 0.047\,\text{IGPM}.$$

Thus for the 50 MeV dipole we have the following coolant flow requirements.

| | | | | | | |
|---|---|---|---|---|---|---|
| Volume per cooling circuit | = | 0.047 IGPM | = | 0.214 $\ell$/min | = | 0.057 USGPM |
| Volume per coil | = | 0.047 IGPM | = | 0.214 $\ell$/min | = | 0.057 USGPM |
| Volume per magnet | = | 0.094 IGPM | = | 0.427 $\ell$/min | = | 0.113 USGPM |

For the 75 MeV dipole the power requirement per coil is

$$\text{Power per coil} \;=\; I^2 R_{hot} \;=\; (200)(200)(0.0250) \;=\; 1.00\,\text{kW}\ .$$

For a maximum power dissipation of 1.673 kW per water circuit required for a flow rate of 2.50 ft/sec we calculate the number of cooling circuits per coil (excluding lead loss) as

$$\begin{array}{lcll} P & = & \text{Total power per coil} & = \; 1.00\ \text{kW} \\ \text{Number of circuits} & = & P\ /\ P_{max} & = \; 0.60 \end{array}$$

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

This requires a flow rate of $v = 1.494\,\text{ft/sec}$ per water circuit. The volume of flow required per circuit is

$$\text{Volume/circuit} \;=\; 2.6(v(\text{ft/min}))(\text{Cooling area}(\text{in.}^2)) \;=\; 2.6(1.494)(0.02036) \;=\; 0.079\ \text{IGPM}.$$

Thus for the 75 MeV dipole we have the following coolant flow requirements.

| | | | | | | |
|---|---|---|---|---|---|---|
| Volume per cooling circuit | = | 0.079 IGPM | = | 0.359 $\ell$/min | = | 0.095 USGPM |
| Volume per coil | = | 0.079 IGPM | = | 0.359 $\ell$/min | = | 0.095 USGPM |
| Volume per magnet | = | 0.158 IGPM | = | 0.718 $\ell$/min | = | 0.190 USGPM |

**9. 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 $k = 0.0305$ and $v = 0.890\,\text{ft/sec}$ we obtain for the 50 MeV dipole

$$dP \;=\; (0.0305)(0.890)^{1.79} \;=\; 0.025\ \text{psi/ft} \;=\; 0.081\ \text{psi/m},$$

and the total pressure drop across one cooling circuit (one coil of length 112 ft) is

$$\boxed{\text{Pressure drop per cooling circuit of the 50 MeV dipole} = 2.8\ \text{psi}\ .}$$

In the case of the 75 MeV dipole for which $v = 1.494\,\text{ft/sec}$ we have

$$dP \;=\; (0.0305)(1.494)^{1.79} \;=\; 0.063\ \text{psi/ft} \;=\; 0.207\ \text{psi/m},$$

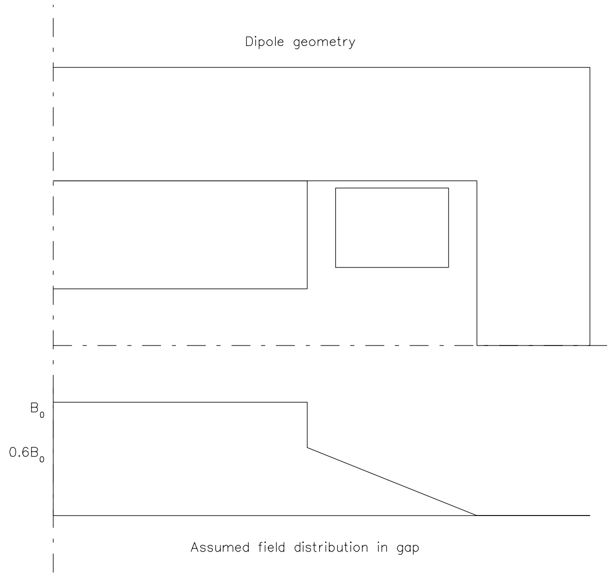
and the total pressure drop across one cooling circuit (one coil of length 168 ft) is

$$\boxed{\text{Pressure drop per cooling circuit of the 75 MeV dipole} = 10.5\ \text{psi}\ .}$$

**10. Iron dimensions**

**10.1 Yoke thickness**

We assume that in the gap the field rises from zero at the outer edge of the coil slot to $0.6B_0$ at the pole edge and that it is constant at $B_0$ across the pole as is shown in the figure on the next page. Note that




Dipole geometry and assumed field distribution

the chamfer on the pole edge has been ignored in the figure.

The half-width of the pole is 4.000 inches and we take the width of the coil slot to be

$$\begin{aligned}\text{Width of coil slot} &= 2(\text{pole-coil separation} + \text{maximum coil width}) \\ &= 2(0.500\,\text{inch}) + 2.000\,\text{inches} \;=\; 3.000\,\text{inches}\end{aligned}$$

Let $B_y$ and $t$ be the yoke flux and thickness respectively, and assume that the flux divides equally between the side yokes. Equating the flux through the pole and coil gap to that in the yoke we have

$$B_y t \;=\; \frac{[3.000\,\text{inches}](0.6)(3.500\,\text{kG})}{2} + (4.000\,\text{inches})(3.500\,\text{kG}) \;=\; 17.15\,\text{kG-in.} \;=\; 1.715\,\text{T-m}\ ,$$

in which we have used the maximum 3.50 kG field of the 70 MeV dipole. Because we wish to keep the yoke flux to approximately 10 kG = 1 T, we take

| | | |
|---|---|---|
| Yoke thickness | 2.000 inches | 0.051 m , |
| Yoke field | 8.575 kGauss | 0.858 T . |

At this point we note that had the above calculation been made for the 50 MeV dipole with a gap field of, say 2.50 kG the $B_y t$ product is found to be $B_y t = 13.15$ kG-m. Requiring that $B_y$ be less than 10 kG then leads to a yoke thickness of greater than 1.35 inches—say 1.50 inches. Because most of the cost of the iron is in the cost of machining and not in the cost of the raw material, we would use a yoke thickness of 2.000 inches for this magnet, if for no other reason than a magnet with a more uniform field would result.

**10.2 Magnet width and length**

The total width of the dipole is

$$\begin{aligned}\text{Dipole width} &= 2[(\text{Coil-slot width}) + \text{Yoke thickness})] + \text{Pole width} \\ &= 2(3.000\,\text{inches} + 2.000\,\text{inches}) + 8.000\,\text{inches} \\ &= 18.000\,\text{inches}(0.457\,\text{m}).\end{aligned}$$

The total length of the dipole is

$$\begin{aligned}\text{Dipole length} &= 2[(\text{Pole-coil separation}) + (\text{Maximum coil width})] + \text{Pole length} \\ &= 2(0.500\text{ in.} + 2.000\text{ in.}) + 13.400\text{ in.} \\ &= 18.400\text{ in.} = 0.417\text{ m}.\end{aligned}$$

### 10.3 Pole height

The pole height of these magnets depends on the maximum energy of the electrons for which they are designed. In general we define the pole height to be

$$\text{Pole height} = \text{Nominal coil height} + \text{Vertical chamfer} + 0.125\text{ inch}$$

in which the 0.125 inch is an allowance for insulation between the coil and the iron of the coil slot. Addition of the depth of the vertical chamfer (0.375 inch) assures that the coil will be positioned in the coil slot at or above the chamfer of the upper pole (or at or below the chamfer of the lower pole). Thus we have

$$\text{Pole height} = \begin{cases} 1.400\text{ inches} + 0.375\text{ inches} + 0.125\text{ inches} = 1.900\text{ inches for the 50 MeV dipole} \\ 2.100\text{ inches} + 0.375\text{ inches} + 0.125\text{ inches} = 2.600\text{ inches for the 75 MeV dipole} \end{cases}$$

### 10.4 Length of side yokes

The lengths of the side yokes are

$$\begin{aligned} \text{Length of side yoke} &= 2(\text{Pole height}) + \text{Gap} \\ &= \begin{cases} 2(1.900\text{ inches}) + 2.000\text{ inches} = 5.800\text{ inches for the 50 MeV dipole} \\ 2(2.600\text{ inches}) + 2.000\text{ inches} = 7.200\text{ inches for the 75 MeV dipole} \end{cases} \end{aligned}$$

### 10.5 Summary

| | 50 MeV dipole | 75 MeV dipole |
|---|---|---|
| Yoke thickness | 2.000 inches | 2.000 inches |
| Pole height | 1.900 inches | 2.600 inches |
| Overall width of magnet | 18.000 inches | 18.000 inches |
| Overall length of magnet | 18.400 inches | 18.400 inches |
| Length of side yoke of magnet | 5.800 inches | 7.200 inches |

### 11. Iron mass

From the preceding data we have the following for the 50 MeV dipole.

| Section | Height | Width | Area |
|---|---|---|---|
| Top yoke | 2.000 in. | 18.000 in. | 36.000 in.$^2$ |
| Top pole | 1.900 in. | 8.000 in. | 15.200 in.$^2$ |
| Side yoke | 5.800 in. | 2.000 in. | 11.600 in.$^2$ |
| Total | | | 62.800 in.$^2$ |

Thus

$$\text{Area of yoke} = 2(62.800\text{ in.}^2) = 125.600\text{ in.}^2$$

and

$$\text{Volume of iron} = (\text{Pole length})(\text{Area}) = (13.400\text{ in.})(125.600\text{ in.}^2) = 0.975\text{ ft}^3$$

so that the mass of iron at 0.2833 lb/in.$^3$ (489.54 lb/ft$^3$) is 477.3 lb (216.5 kg). We take

$$\boxed{\text{Mass of iron in 50 MeV dipole} = 485\text{ lb} = 220\text{ kg}\ .}$$

Similarly, for the 75 MeV dipole we find the following.

| Section | Height | Width | Area |
|---|---|---|---|
| Top yoke | 2.000 in. | 18.000 in. | 36.000 in.$^2$ |
| Top pole | 2.600 in. | 8.000 in. | 20.800 in.$^2$ |
| Side yoke | 7.200 in. | 2.000 in. | 14.400 in.$^2$ |
| Total | | | 71.200 in.$^2$ |

Thus

$$\text{Area of yoke} \ = \ 2(71.200\,\text{in.}^2 \ = \ 142.400\,\text{in.}^2$$

and

$$\text{Volume of iron} \ = \ (\text{Pole length})(\text{Area}) \ = \ (13.400\,\text{in.})(142.400\,\text{in.}^2) \ = \ 1.104\,\text{ft}^3$$

so that the mass of iron at 0.2833 lb/in.$^3$ (489.54 lb/ft$^3$) is 540.6 lb (245.2 kg). We take

$$\boxed{\text{Mass of iron in 75 MeV dipole} = 550\,\text{lb} = 250\,\text{kg}\ .}$$

Table 1 gives a summary of the parameters calculated for the 50 MeV and 75 MeV dipoles.

Figure 1 details the geometry of the 50 MeV dipole and figure 2 shows that of the 75 MeV dipole.

**12. POISSON calculations**

The program POISSON was used to obtain an estimate of the field distributions in the iron and in the gap of the two species of dipole.

Figure 3 shows the calculated field distribution in the yoke of the 50 MeV dipole; that in its gap is shown in figure 4. Each of these distributions were calculated for $NI = 4,584$ A-t (or a current of 191 A) in the 24-turn coil. We note here that these calculations (inadvertently) were performed for a coil of width 1.9 inches rather than the of 2 inches as specified in the design above. However, the 0.100 inch difference will not significantly affect the field distributions shown.

From figure 3 it is seen that the calculated fields in the pole and yoke are quite low. No saturation is predicted at the pole root. It could be argued that the yoke could be thinner—say, 1.5 inches—without causing the fields in it to become too large. This would reduce the magnet weight somewhat but would also change the field distribution in the pole. If this is important a recalculation is required. Regardless, we still propose that a yoke thickness of 2 inches be used.

Figure 4 shows that the field in the gap is predicted to be uniform over the full gap height and a region approximately 1.60 inches either side of the pole center. Again it could be argued that the pole is too wide. However, in the calculation of the pole width it is seen that maximum deflection of the center of the beam is 1.00 inches. If it is assumed that the beam trajectory is centered about the longitudinal center-line of the pole, then the maximum excursion of the beam center is 0.500 inches either side of the pole center. Thus taking into account the beam width the chosen pole width ensures that the entire beam lies within the most uniform portion of the gap field.

Figures 5 and 6 show the predicted field distributions in the iron and gap, respectively, of the 75 MeV dipole. These calculations were made assuming a coil width of 2 inches and an excitation of $NI = 6,870$ A-t (or a current of 191 A) flowing in the 36-turn coil).

Figure 5 shows that the field in the magnet yoke is approximately 50% larger than that in the 50 MeV dipole—not an unexpected result because this is the same percentage increase in the excitation of the 75 MeV dipole. Again, there is no indication of saturation around the pole root, although the predicted field in that region is slightly greater that 15 kG. The average field in the yoke is of the order of 10 kG as desired.

Similarly, the field in the pole of the 75 MeV dipole is roughly 50% larger than that in the pole of the 50 MeV dipole, but it is well within a tolerable value.

Figure 6, which shows the predicted field distribution in the gap of the 75 MeV dipole, shows similar properties to that of the 50 MeV dipole. However, the region of uniformity of the 75 MeV dipole is predicted to be somewhat less than that of the 50 MeV dipole—approximately 0.90 inch rather than 1.60 inches either side of the longitudinal center-line. Given that the maximum excursion either side of the pole center is

0.500 inch there should be adequate room for the beam to remain within the uniform field region. Consequently, comments made above concerning the latter apply equally to the 75 MeV dipole.

**13. Discussion**

This report presents designs that would be suitable for 30° dipoles for the TRIUMF electron beam line. Designs are given for dipoles for a energies of 50 MeV and 75 MeV of the electron beam. Yoke designs for the dipoles are identical with the only differences being that the pole thicknesses and the coils are smaller for the lower energy.

It is suggested that the design for the higher energy be adapted because such a dipoles could be operated at 50 MeV. Such a decision would slightly increase the raw material costs of the iron and copper. Machining cost of the iron should be the same but that of winding the coil would increase somewhat. However, should it be decided at some time to increase the beam energy of the electron beam to 75 MeV an appropriate dipole would be on hand.

The coil design given here specifies coating the bare conductor with a layer of double Dacron glass (DDI) insulation and overwrapping that with a spiral lap, spaced 0.25 inch, of fiberglass insulation. This was done for illustrative purposes only; no significant increases in the coil sizes were found. It would, however, allow the potting compound to infiltrate the coil form, thus further insulating the conductor.

It was noted above that there might be a concern regarding the chosen pole width (8.000 inches). Were that the case the pole width could be increased to 8.500 or 9.000 inches. If the larger value were chosen the cross-sections of the 50 and 75 MeV dipoles would be the same as those of the 45° dipoles of ref[2]. Because of the wider poles and top and bottom yokes, the iron weights of the two dipoles would increase. The top and bottom yokes of the 50 MeV dipole, which are 2 inches in thickness and 13.4 inches long, would increase in volume by 2(1 inch)(2 inches)(13.4 inches) = and its poles increases in volume by 2(1 inch)(1.9 inches)(13.4 inches) = 50.9 inch$^3$ for a total volume increase of 104.5 inch$^3$. This corresponds to an increase of weight of approximately 30 lb. The increase in volume of the top and bottom yokes of the 75 MeV dipoles is 53.6 inch$^3$ (as for the 50 MeV dipole) and its increase in pole volume is 2(1 inch)(2.6 inches)(13.4 inches) = 69.7 inch$^3$ for a total volume increase of 123.3 inch$^3$. This corresponds to an increase of weight of approximately 35 lb of the 75 MeV dipole.

There would also be a modification of the masses, cooling and power supply requirements, and pressure drops because of the wider poles of the two dipoles. Table 2 lists the revised data for 50 and 75 MeV dipoles with poles 9 inches wide.

The cross-sections of these two dipoles would be the same as given in figures 1 and 2 of ref[2] and are reproduced here as figures 7 and 8. Similarly, the field distributions in the yokes and gaps would be the same as shown in figures 3 through 6 of that reference—to which the reader is referred.

*References*

1. R. Baartman, *E-mail to G. Stinson*, TRIUMF, October 17, 2009.

2. G.M. Stinson, *Conceptual design for a 45° H-frame dipole magnet for the electron beam line*, TRIUMF, TRI-DNA-09-1, November, 2009.

3. G.M. Stinson, *Conceptual design for a 'Stinson' Mark $2x-y$ steering magnet for the ISAC-II HEBT beamline*, TRIUMF, TRI-DNA-05-2, April, 2005.

Table 1

Summary of the calculated dipole parameters for 30° dipole with pole width of 8.000 inches

| Parameter | | 50 MeV dipole | 75 MeV dipole |
|---|---|---|---|
| Yoke: | Iron length | 13.400 in. | 13.400 in. |
| | Iron width | 18.000 in. | 18.000 in. |
| | Iron Thickness | 2.000 in. | 2.600 in. |
| | Coil-slot width | 3.000 in. | 3.600 in. |
| | Side yoke height | 5.800 in. | 7.600 in. |
| | Total height | 9.800 in. | 11.600 in. |
| Pole: | Width | 8.000 in. | 8.000 in. |
| | Height | 1.900 in. | 2.600 in. |
| | Chamfer (high×wide) | 0.375 in.×0.650 in. | 0.375 in.×0.650 in. |
| Iron: | Total weight | 485 lb | 550 lb |
| Coil: | Conductor OD | 0.289 in. | 0.289 in. |
| | Turn configuration (wide × high) | 6 × 4 | 6 × 6 |
| | Nominal width | 2.000 in. | 2.000 in. |
| | Nominal height | 1.400 in. | 2.100 in. |
| | Resistance (hot) per coil | 0.0167 Ω | 0.0250 Ω |
| | Number of cooling circuits | 1 | 1 |
| | Flow per circuit | 0.057 USGPM | 0.095 USGPM |
| | Pressure drop per circuit | 2.800 psi | 10.512 psi |
| Copper: | Length per magnet‡ | 250 ft | 370 ft |
| | Weight per magnet | 60 lb | 88 lb |
| Power: | Maximum current | 200.000 A | 200.000 A |
| | Minimum voltage | 9.000 V | 12.000 V |
| | Minimum power | 1.800 kW | 2.400 kW |
| Magnet: | Total height | 9.800 in. | 11.200 in. |
| | Overall length | 18.400 in. | 18.400 in. |
| | Total flow | 0.113 USGPM | 0.190 USGPM |
| | Total weight per magnet† | 545 lb | 638 lb |

† Exclusive of power and cooling headers.
‡ Based on the amount of copper ordered.

Table 2

Summary of the calculated dipole parameters for 30° dipole with pole width of 9.000 inches

| Parameter | | 50 MeV dipole | 75 MeV dipole |
|---|---|---|---|
| Yoke: | Iron length | 13.400 in. | 13.400 in. |
| | Iron width | 19.000 in. | 19.000 in. |
| | Iron Thickness | 2.000 in. | 2.600 in. |
| | Coil-slot width | 3.000 in. | 3.600 in. |
| | Side yoke height | 5.800 in. | 7.600 in. |
| | Total height | 9.800 in. | 11.600 in. |
| Pole: | Width | 9.000 in. | 9.000 in. |
| | Height | 1.900 in. | 2.600 in. |
| | Chamfer (high×wide) | 0.375 in.×0.650 in. | 0.375 in.×0.650 in. |
| Iron: | Total weight | 515 lb | 585 lb |
| Coil: | Conductor OD | 0.289 in. | 0.289 in. |
| | Turn configuration (wide × high) | 6 × 4 | 6 × 6 |
| | Nominal width | 2.000 in. | 2.000 in. |
| | Nominal height | 1.400 in. | 2.100 in. |
| | Resistance (hot) per coil | 0.0179 Ω | 0.0268 Ω |
| | Number of cooling circuits | 1 | 1 |
| | Flow per circuit | 0.068 USGPM | 0.102 USGPM |
| | Pressure drop per circuit | 4.100 psi | 12.800 psi |
| Copper: | Length per magnet‡ | 250 ft | 400 ft |
| | Weight per magnet | 60 lb | 95 lb |
| Power: | Maximum current | 200.000 A | 200.000 A |
| | Minimum voltage | 10.000 V | 13.000 V |
| | Minimum power | 2.000 kW | 2.600 kW |
| Magnet: | Total height | 9.800 in. | 11.200 in. |
| | Overall length | 18.400 in. | 18.400 in. |
| | Total flow | 0.136 USGPM | 0.204 USGPM |
| | Total weight per magnet† | 575 lb | 680 lb |

† Exclusive of power and cooling headers.
‡ Based on the amount of copper ordered.

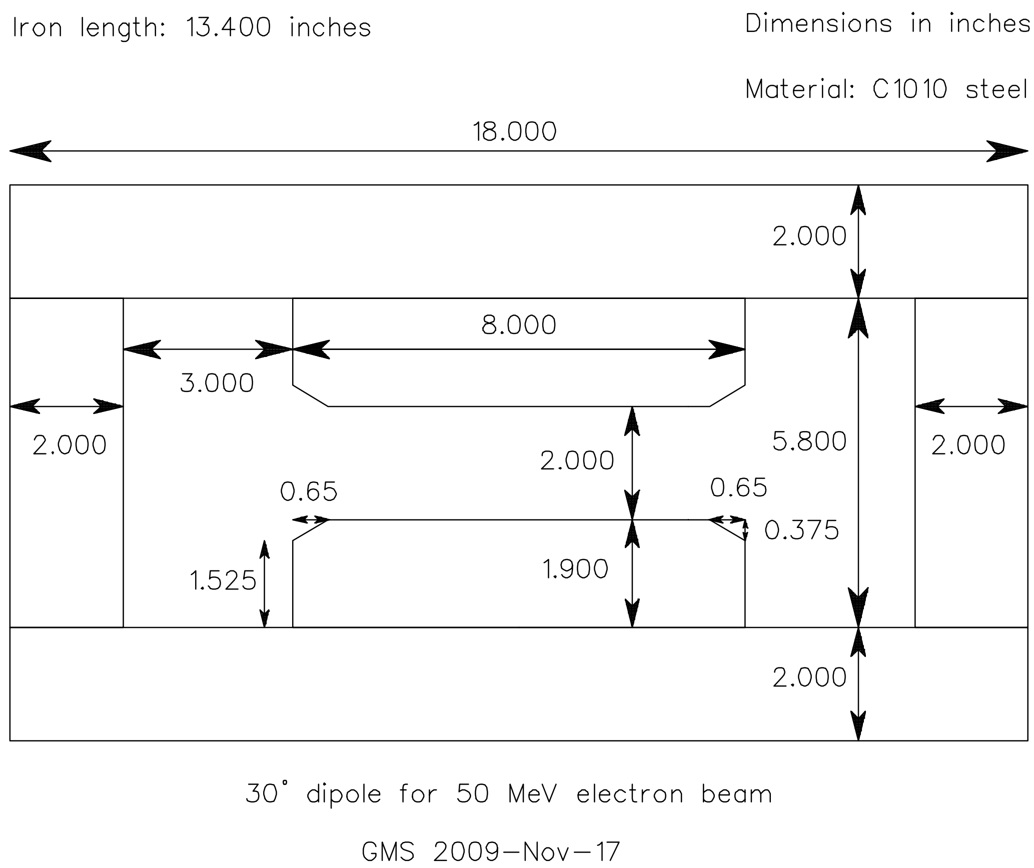



Figure 1. Cross section geometry of the 50 MeV, 30° dipole

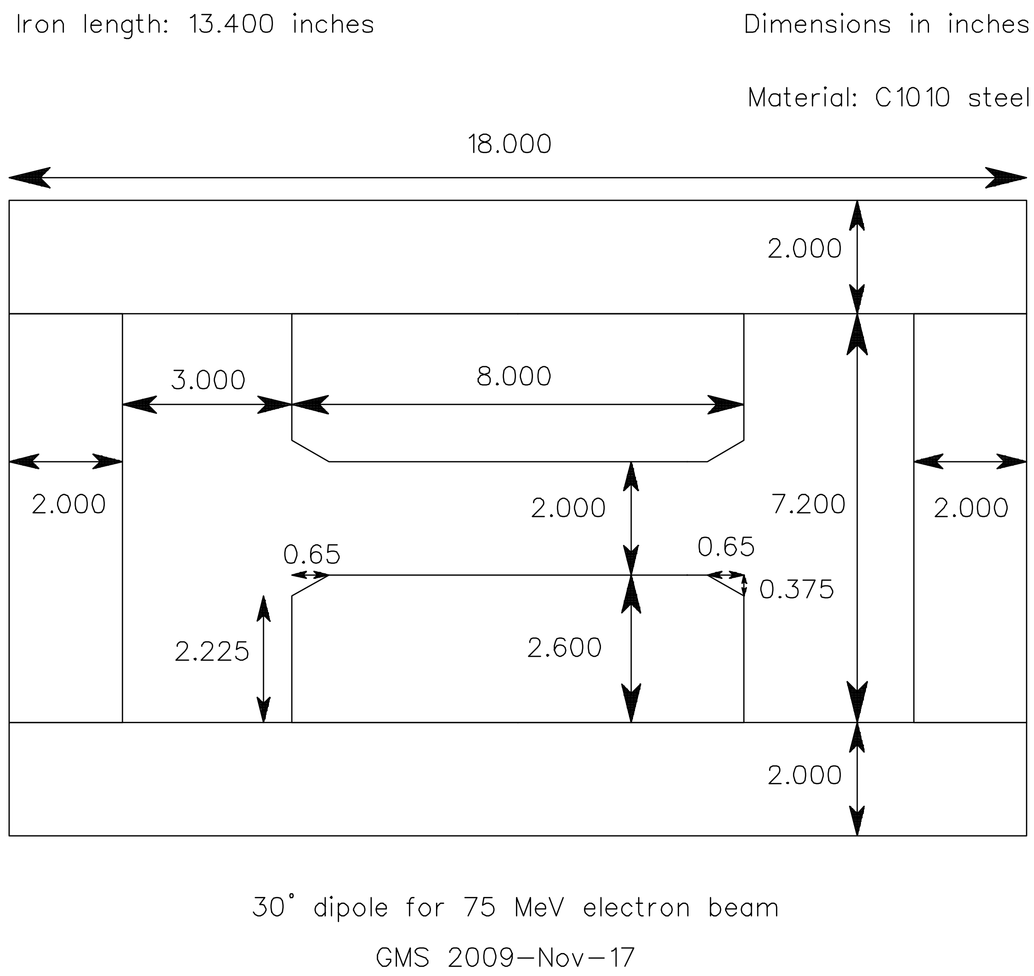



Figure 2. Cross section geometry of the 70 MeV, 30° dipole

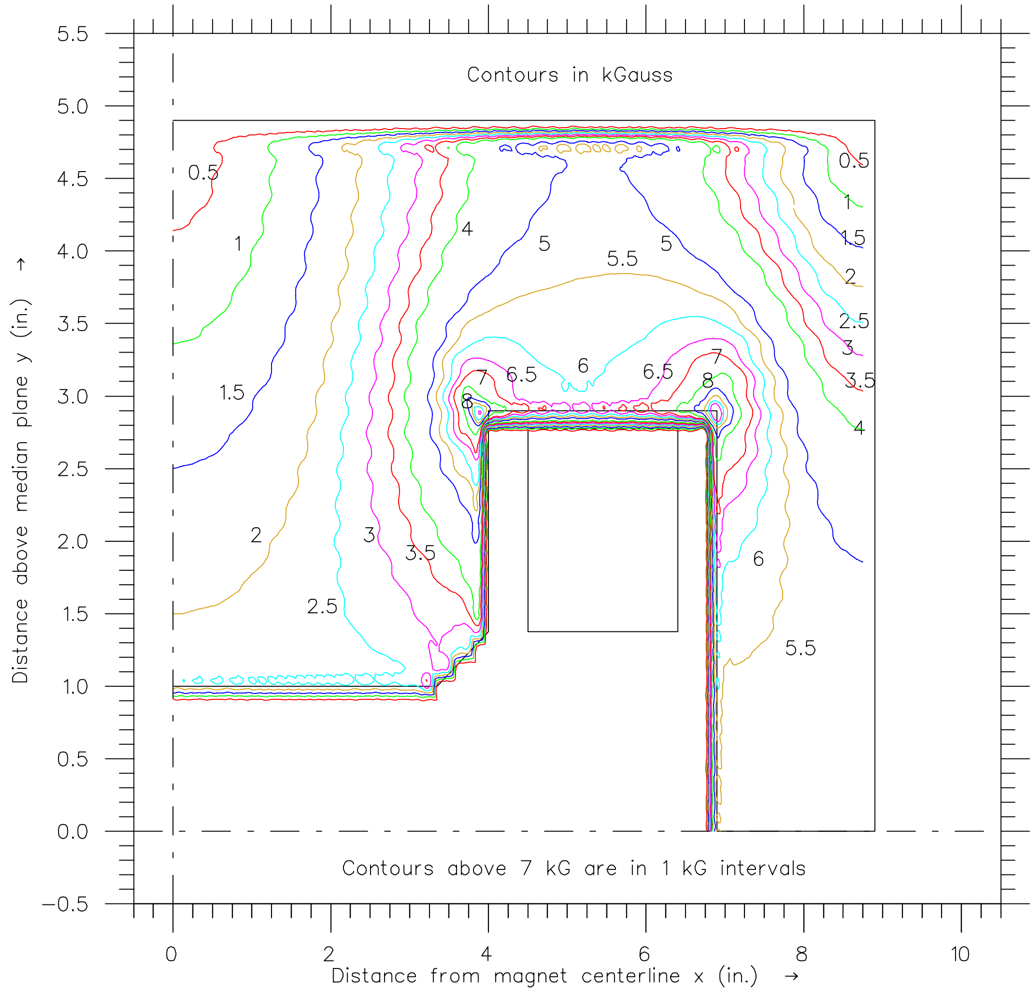



Figure 3. Predicted field in the yoke of the 50 MeV, 30° dipole magnet at an excitation of 4,584 A-t (or a current of 191 A).

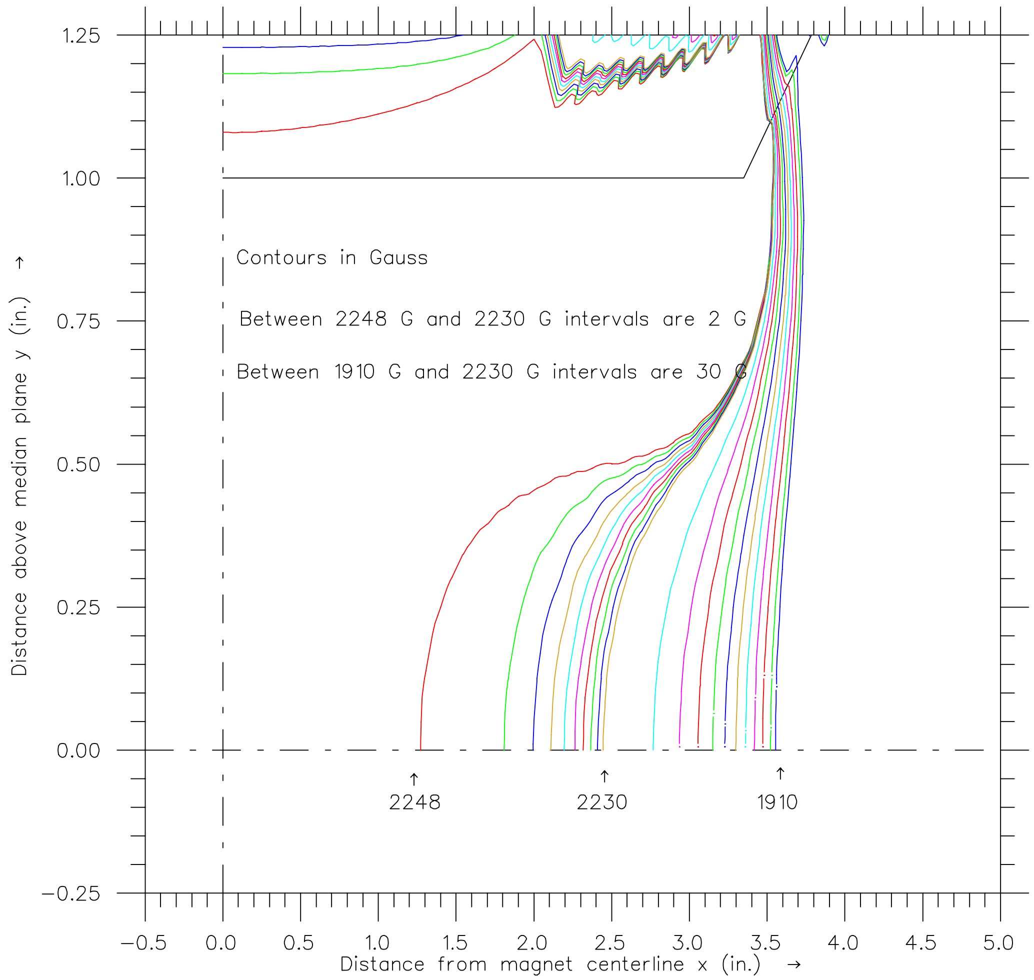



Figure 4. Predicted field in the gap of the 50 MeV, 30° dipole magnet at an excitation of 4,584 A-t (or a current of 191 A).

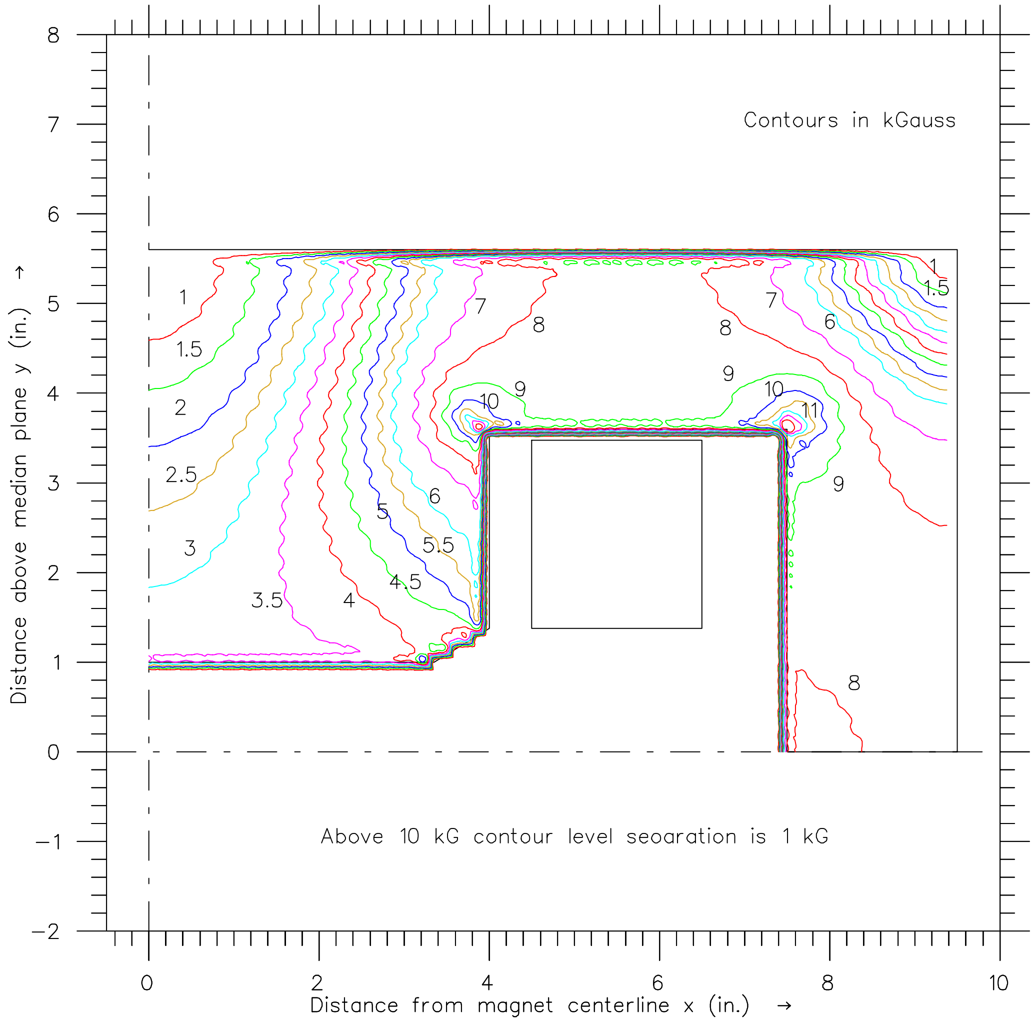



Figure 5. Predicted field in the yoke of the 75 MeV, 30° dipole magnet at an excitation of 6,870 A-t (or a current of 191 A).

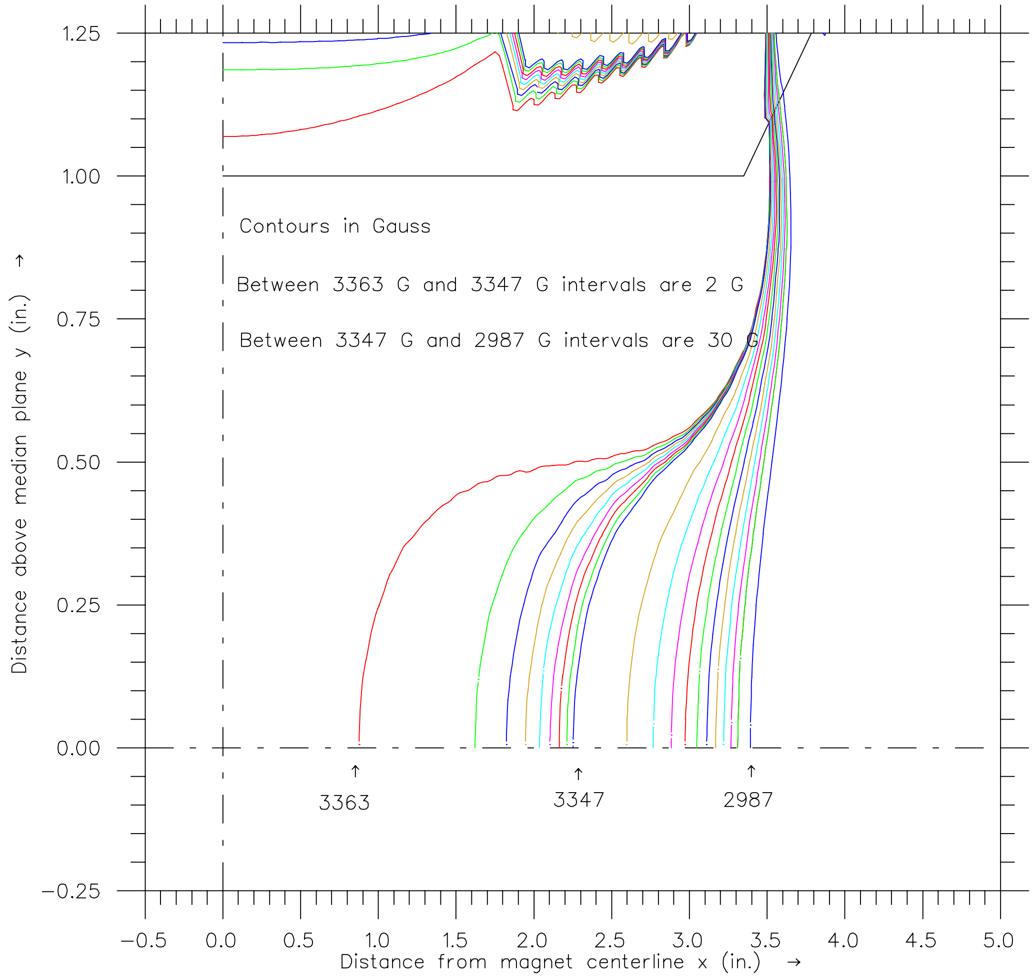



Figure 6. Predicted field in the gap of the 75 MeV, 30° dipole magnet at an excitation of 6,870 A-t (or a current of 191 A).

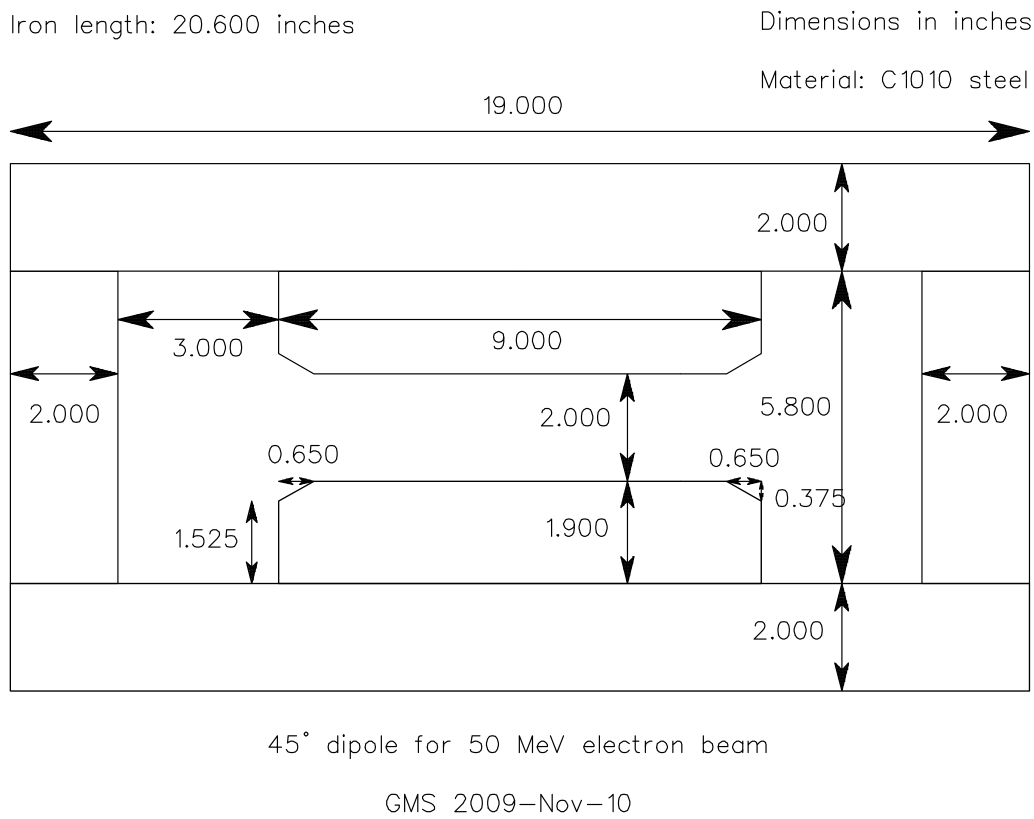



Figure 7. Cross-section geometry of the 50 MeV, 30° dipole magnet with a 9.000 inch pole width.

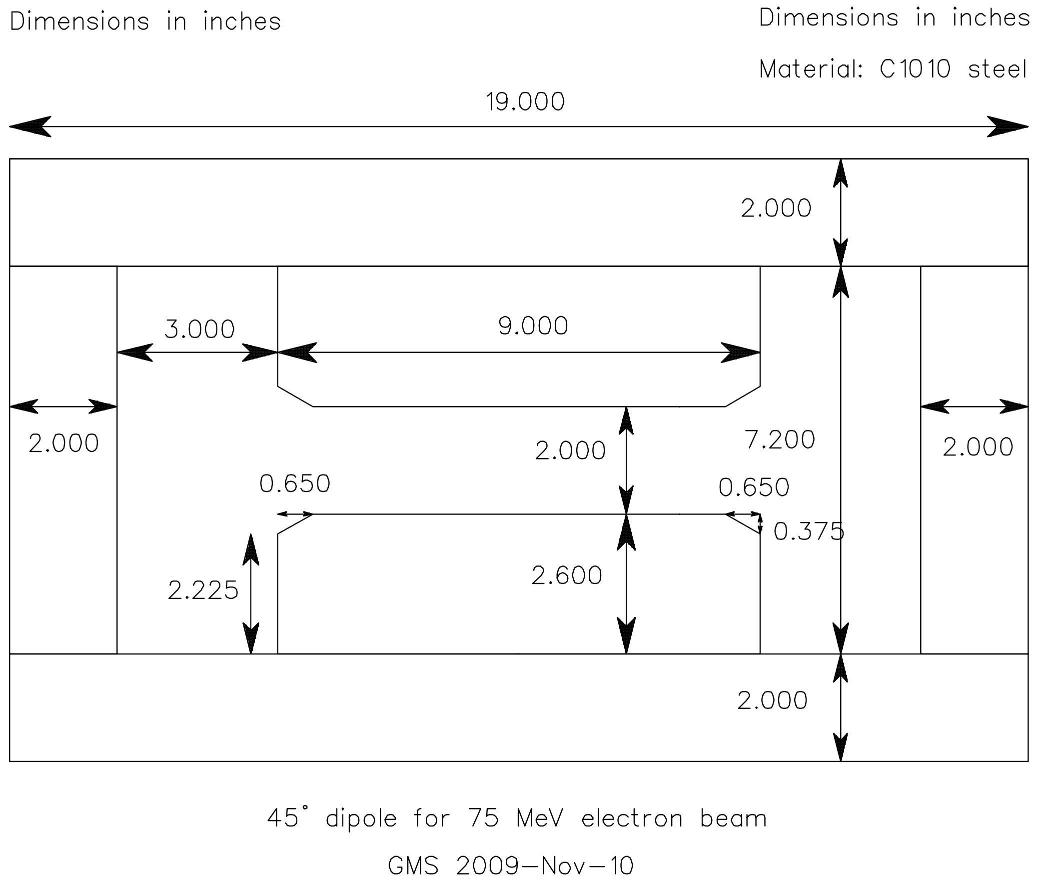



Figure 8. Cross-section geometry of the 70 MeV, 30° dipole magnet with a 9.000 inch pole width.