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 45° dipoles for each of the two energies.

2. Dipole specifications

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

Bend angle θ	45.000 °		
Radius of curvature ρ	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°.

Given that the bend angle θ of the dipole, its full gap g and the radius of curvature ρ 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	$s = \rho\theta$	23.19089 in.	0.58905 m
Straight-line length L_{str}	$L_{str} = 2\,\rho\sin(\theta/2)$	22.59942 in.	0.57403 m
Iron length L_{Fe}	$L_{Fe} = L_{str} - g$	20.59942 in.	0.52323 m

We take **Iron length $L_{Fe} = 20.600$ in. $= 0.52323$ 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

$$\Delta \;=\; \rho[1-\cos(\theta/2)] \;=\; 2.24765\,\text{inches}\ (57.09\,\text{mm}).$$

Then the pole width is calculated as

$$\begin{aligned}\text{Pole width} &= 2(\text{Chamfer}) + \text{Beam width} + \Delta \ + 2(\text{gap})\\ &= 2(0.650)+0.157+2.248+2(2.000)\\ &= 7.705\,\text{inches}\ (195.7\,\text{mm}).\end{aligned}$$

Based on (later) POISSON runs we take

$$\boxed{\text{Pole width} = 9.000\,\text{inches}\ (228.6\,\text{mm}).}$$

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

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

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

I	=	maximum current	=	200 Amperes
N	=	number of turns per coil	=	24 for 50 MeV e^-
		in a coil configuration 6 turns wide and 4 layers high		
N	=	number of turns per coil	=	36 for 75 MeV e^-
		in a coil configuration 6 turns wide and 6 layers high		

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		

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	1.958	49.728	1.850	46.985
Gapping (5×0.010)	0.050	1.270		
Ground wrap (4×0.007×2)	0.056	1.422	0.056	1.422
Total	2.064	52.421	1.906	48.407

We take

Maximum coil width	=	2.050 in.	=	52.100 mm.
Nominal coil width	=	2.000 in.	=	50.800 mm.

The *height* of the coil depends on the energy of the electron beam. For a 50 MeV e^- beam we have the following.

	Maximum		Minimum	
	in.	mm	in.	mm
Wrapped conductor	1.305	33.152	1.233	31.323
Gapping (3×0.010)	0.030	0.762		
Keystoning (4×0.010)	0.040	1.016	0.020	0.508
Ground wrap (4×0.007×2)	0.056	1.422	0.056	1.422
Total	1.431	36.352	1.309	33.254

For the height of the coil for the 45° dipole bending a 50 MeV electron beam we take

Maximum coil height	=	1.430 in.	=	36.320 mm.
Nominal coil height	=	1.400 in.	=	35.560 mm.

The maximum height of a coil for a dipole bending a 75 MeV electron beam through 45° is increased by two widths of wrapped conductor, two gapping widths and two keystoning widths. Thus the increase in coil height Δh is

$$\Delta h \;=\; 2[0.3262 + 0.010 + 0.010]\,\text{in.} \;=\; 0.6924\,\text{inches}\;.$$

We take $$\Delta h = 0.700\,\text{inches}.$$

Thus for the coil height of the dipole bending a 75 MeV beam through 45° we take

Maximum coil height	=	2.130 in.	=	54.100 mm.
Nominal coil height	=	2.100 in.	=	53.340 mm.

We take the conductor dimension D_{nom} to be

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

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 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

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

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 on the next page together with our case of $N = 6$ we find that the length of a 6-turn layer is 410 inches (34.2 ft). We take

$$\text{Length of 6-turn layer} = 36\,\text{ft}\;(11\,\text{m}).$$

Thus the length of copper in a coil of a magnet that bends 50 MeV electrons through 45° is

$$
\begin{array}{lclcl}
L_{iron} & = & 20.600 \text{ in.} & = & 523.24 \text{ mm}, \\
W_{iron} & = & 9.000 \text{ in.} & = & 228.60 \text{ mm}, \\
R_{pole} & = & 0.800 \text{ in.} & = & 20.32 \text{ mm}, \\
G & = & 0.500 \text{ in.} & = & 12.70 \text{ mm}, \\
D_{nom} & = & 0.327 \text{ in.} & = & 8.31 \text{ mm}, \\
\text{Insulation} & = & 0.007 \text{ in.} & = & 0.18 \text{ mm},
\end{array}
$$

$$\text{Length of copper per coil of dipole for } 50\,\text{MeV electrons} = 144\,\text{ft}\ (44\,\text{m}),$$

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

$$\text{Length of copper per coil of dipole for } 75\,\text{MeV electrons} = 216\,\text{ft}\ (66\,\text{m}),$$

Because 2 coils are required per dipole, then

	50 MeV e^-	75 MeV e^-
Total length per dipole	288 ft (88 m)	432 ft (132 m)
Allow 10% for winding losses	28 ft (8 m)	44 ft (12 m)
Total	316 ft (96 m)	476 ft (144 m)

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

	50 MeV e^-	75 MeV e^-
A total length of	320 ft (98 m)	480 ft (148 m)
A total mass of	80 lb (37 kg)	115 lb (53 kg)

7. Power requirements

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

$$R_{20^\circ C} = \begin{cases} (133.20\times10^{-6}\Omega/\text{ft})\times(144\ \text{ft}) = 0.0192\ \Omega \text{ for a dipole coil for } 50\,\text{MeV e}^- , \\ (133.20\times10^{-6}\Omega/\text{ft})\times(216\ \text{ft}) = 0.0288\ \Omega \text{ for a dipole coil for } 75\,\text{MeV e}^- . \end{cases}$$

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

$$
\begin{aligned}
R_{hot} &= R_{20^\circ C}[1 + (0.00393/^\circ\text{C})(30^\circ\text{C})] \\
&= \begin{cases} 0.0192[1.1179] = 0.0214\,\Omega/\text{coil for } 50\,\text{MeV e}^- , \\ 0.0288[1.1179] = 0.0322\,\Omega/\text{coil for } 75\,\text{MeV e}^- . \end{cases}
\end{aligned}
$$

Thus at a current of 200 A a (minimum) voltage/coil of 4.3 V is required for the 50 MeV dipole and 6.5 V is required for the 75 MeV dipole. Therefore, allowing for 2V lead loss, we choose a power supply that has

	50 MeV dipole	75 MeV dipole
Current I	200.0 A maximum	200.0 A maximum
Voltage V	12.0 V minimum	15.0 V minimum
Power P	2.4 kW minimum	3.0 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

$$\text{Power per coil} \ = \ I^2 R_{hot} \ = \ (200)(200)(0.02144) \ = \ 0.86\,\text{kW} \ .$$

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°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

$$\begin{array}{lcllcl} P & = & \text{Total power per coil} & = & 0.858 \text{ kW} \\ \text{Number of circuits} & = & P \ / \ P_{max} & = & 0.51 \end{array}$$

Thus we take

Number of cooling circuits per coil = 1 .

This requires a flow rate of $v = 1.28$ ft/sec per water circuit. The volume of flow required per circuit is

$$\text{Volume/circuit} \ = \ 2.6(v(\text{ft/min}))(\text{Cooling area(in.}^2)) \ = \ 2.6(1.281)(0.02036) \ = \ 0.068\,\text{IGPM.}$$

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

Volume per cooling circuit	=	0.068 IGPM	=	0.309 ℓ/min	=	0.082 USGPM
Volume per coil	=	0.068 IGPM	=	0.309 ℓ/min	=	0.082 USGPM
Volume per magnet	=	0.136 IGPM	=	0.618 ℓ/min	=	0.163 USGPM

For the 75 MeV dipole the power requirement per coil is

$$\text{Power per coil} \ = \ I^2 R_{hot} \ = \ (200)(200)(0.0322) \ = \ 1.30\,\text{kW} \ .$$

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

$$\begin{array}{lcllcl} P & = & \text{Total power per coil} & = & 1.30 \text{ kW} \\ \text{Number of circuits} & = & P \ / \ P_{max} & = & 0.78 \end{array}$$

Thus we take

Number of cooling circuits per coil = 1 .

This requires a flow rate of $v = 1.94$ ft/sec per water circuit. The volume of flow required per circuit is

$$\text{Volume/circuit} \ = \ 2.6(v(\text{ft/min}))(\text{Cooling area(in.}^2)) \ = \ 2.6(1.943)(0.02036) \ = \ 0.103 \text{ IGPM.}$$

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

Volume per cooling circuit	=	0.103 IGPM	=	0.468 ℓ/min	=	0.124 USGPM
Volume per coil	=	0.103 IGPM	=	0.468 ℓ/min	=	0.124 USGPM
Volume per magnet	=	0.206 IGPM	=	0.936 ℓ/min	=	0.247 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 $v = 1.28\,\text{ft/sec}$ we obtain for the 50 MeV dipole

$$dP = (0.0305)(1.281)^{1.79} = 0.048\ \text{psi/ft} = 0.156\ \text{psi/m},$$

and the total pressure drop across one cooling circuit (one coil of length 144 ft) is

$$\boxed{\text{Pressure drop per cooling circuit of the 50 MeV dipole} = 6.8\ \text{psi}\ .}$$

In the case of the 75 MeV dipole for which $v = 1.94\,\text{ft/sec}$ we have

$$dP = (0.0305)(1.943)^{1.79} = 0.100\ \text{psi/ft} = 0.328\ \text{psi/m},$$

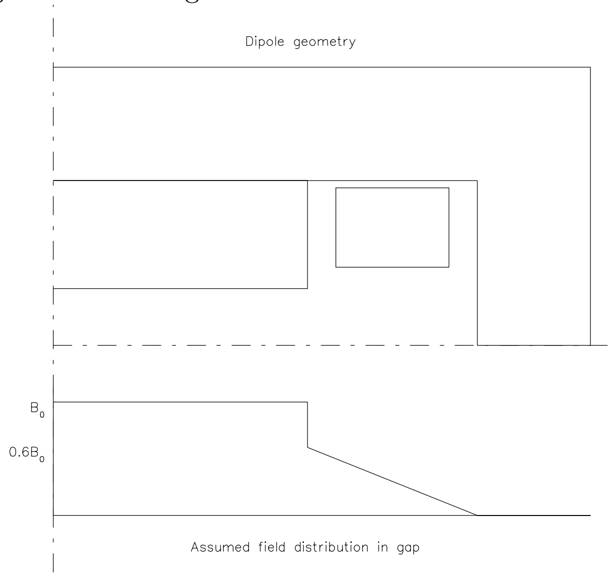
and the total pressure drop across one cooling circuit (one coil of length 216 ft) is

$$\boxed{\text{Pressure drop per cooling circuit of the 75 MeV dipole} = 21.6\ \text{psi}\ .}$$

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 below. Note that the chamfer on the pole edge has been ignored in the figure.



Dipole geometry and assumed field distribution

The half-width of the pole is 4.500 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

$$B_y t = \frac{[3.000\,\text{inches}](0.6)(3.500\,\text{kG})}{2} + (4.500\,\text{inches})(3.500\,\text{kG}) = 18.9\,\text{kG-in.} = 1.89\,\text{T-m}\ ,$$

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	9.450 kGauss	0.945 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 $B_y t = 13.5$ 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

$$\begin{aligned}\text{Dipole width} &= 2[(\text{Coil-slot width}) + \text{Yoke thickness})] + \text{Pole width} \\ &= 2(3.000\,\text{inches} + 2.000\,\text{inches}) + 9.000\,\text{inches} \\ &= 19.000\,\text{inches}(0.483\,\text{m}).\end{aligned}$$

The total length of the dipole is

$$\begin{aligned}\text{Dipole length} &= 2[(\text{Pole-coil separation}) + (\text{Maximum coil width})] + \text{Pole length} \\ &= 2(0.500\text{ in.} + 2.000\text{ in.}) + 20.600\text{ in.} \\ &= 25.600\text{ in.} = 0.650\text{ m.}\end{aligned}$$

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	19.000 inches	19.000 inches
Overall length of magnet	25.600 inches	25.600 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.	19.000 in.	38.000 in.^{2}
Top pole	1.900 in.	9.000 in.	17.100 in.^{2}
Side yoke	5.800 in.	2.000 in.	11.600 in.^{2}
Total			66.700 in.^{2}

Thus

$$\text{Area of yoke} = 2(66.700\,\text{in.}^2 = 133.400\,\text{in.}^2$$

and

$$\text{Volume of iron} = (\text{Pole length})(\text{Area}) = (20.600\,\text{in.})(133.400\,\text{in.}^2) = 1.590\,\text{ft}^3$$

so that the mass of iron at 0.2833 lb/in.^{3} (489.54 lb/ft^3) is 778.5 lb (353.1 kg). We take

Mass of iron in 50 MeV dipole = 785 lb = 356 kg .

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

Section	Height	Width	Area
Top yoke	2.000 in.	19.000 in.	38.000 in.^{2}
Top pole	2.600 in.	9.000 in.	23.400 in.^{2}
Side yoke	7.200 in.	2.000 in.	14.400 in.^{2}
Total			75.800 in.^{2}

Thus

$$\text{Area of yoke} = 2(75.800\,\text{in.}^2 = 151.600\,\text{in.}^2$$

and

$$\text{Volume of iron} = (\text{Pole length})(\text{Area}) = (20.600\,\text{in.})(151.600\,\text{in.}^2) = 1.810\,\text{ft}^3$$

so that the mass of iron at 0.2833 lb/in.^{3} (489.54 lb/ft^3) is 884.7 lb (401.2 kg). We take

Mass of iron in 75 MeV dipole = 890 lb = 405 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 1.8 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 2.25 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 ± 1.125 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. The region of uniformity of the 75 MeV dipole is predicted to be the same as that of the 50 MeV dipole. 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 45° 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 incease 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 gioven here specifies wrapping the conductor with half-lapped fiberglass insulation. A further suggestion is to consider 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. Although this would increase the coil sizes slightly, it would allow the potting compound to infiltrate the coil form, thus further insulating the conductor.

References

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

Table 1

Summary of the calculated dipole parameters

Parameter		50 MeV dipole	75 MeV dipole
Yoke:	Iron length	20.600 in.	20.600 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	785 lb	890 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	0.0214 Ω	0.0322 Ω
	Number of cooling circuits	1	1
	Flow per circuit	0.081 USGPM	0.123 USGPM
	Pressure drop per circuit	6.842 psi	21.633 psi
Copper:	Length per magnet	320 ft	480 ft
	Weight per magnet	76 lb	115 lb
Power:	Maximum current	200.000 A	200.000 A
	Minimum voltage	12.000 V	15.000 V
	Minimum power	2.400 kW	3.000 kW
Magnet:	Total height	9.800 in.	11.200 in.
	Overall length	25.600 in.	25.600 in.
	Total flow	0.163 USGPM	0.246 USGPM
	Total weight per magnet†	861 lb	1,005 lb

† Exclusive of power and cooling headers.

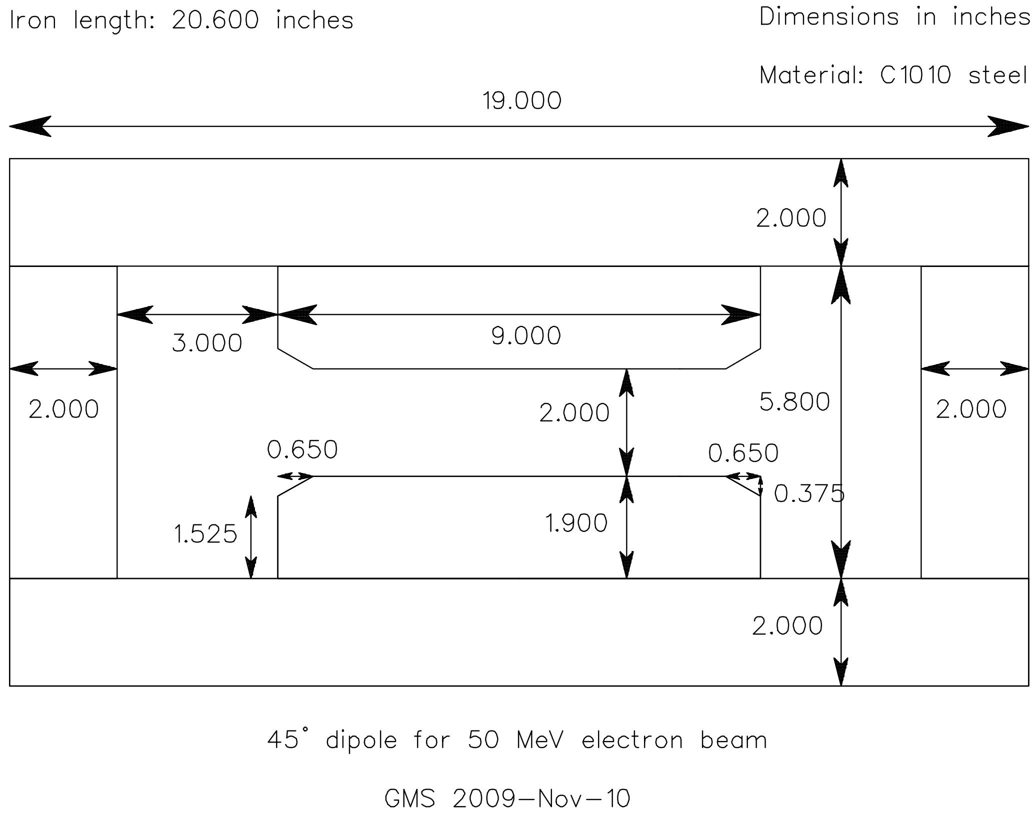


Figure 1. Cross-section geometry of the 50 MeV, 45° dipole magnet.

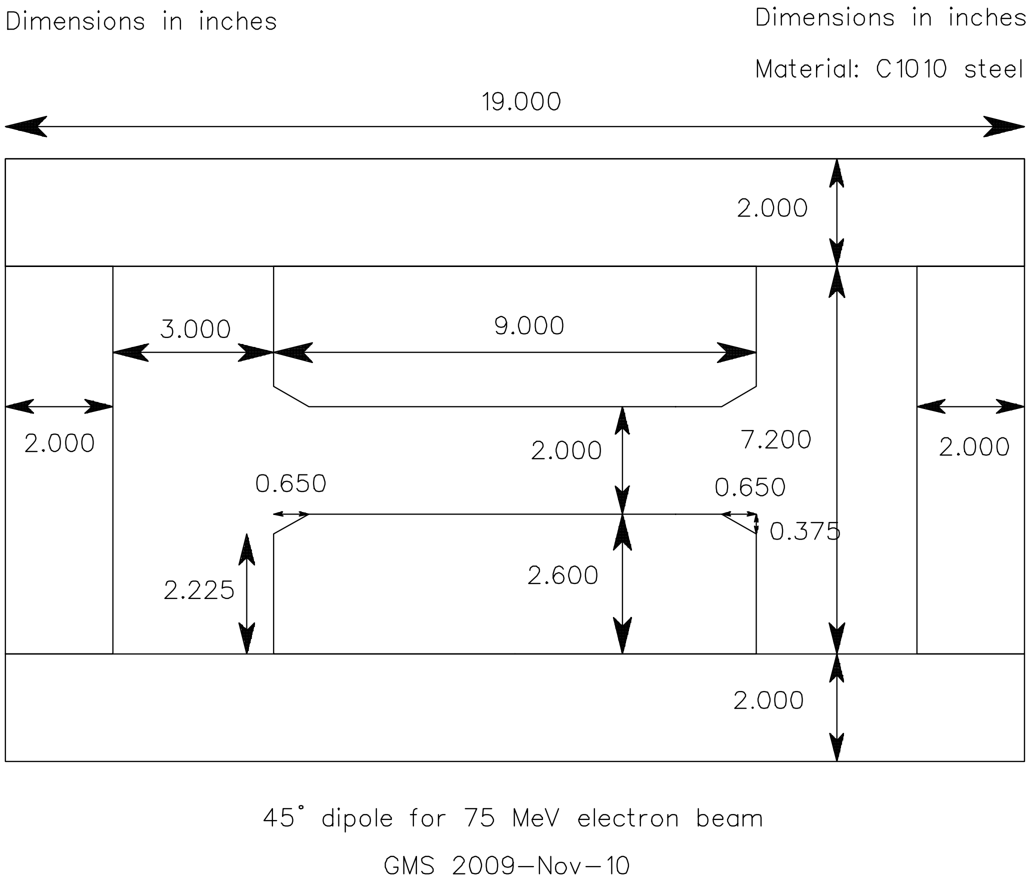


Figure 2. Cross-section geometry of the 70 MeV, 45° dipole magnet.

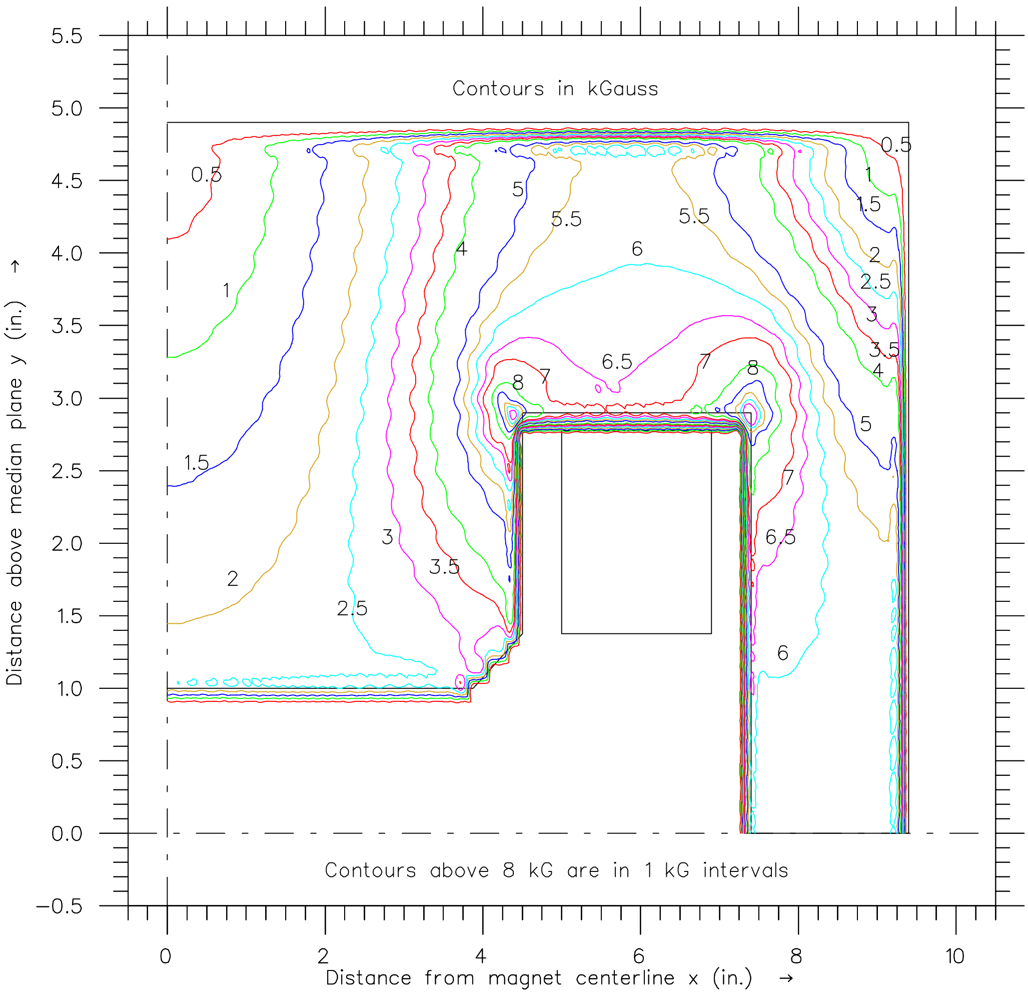


Figure 3. Predicted field in the yoke of the 50 MeV, 45° dipole magnet.

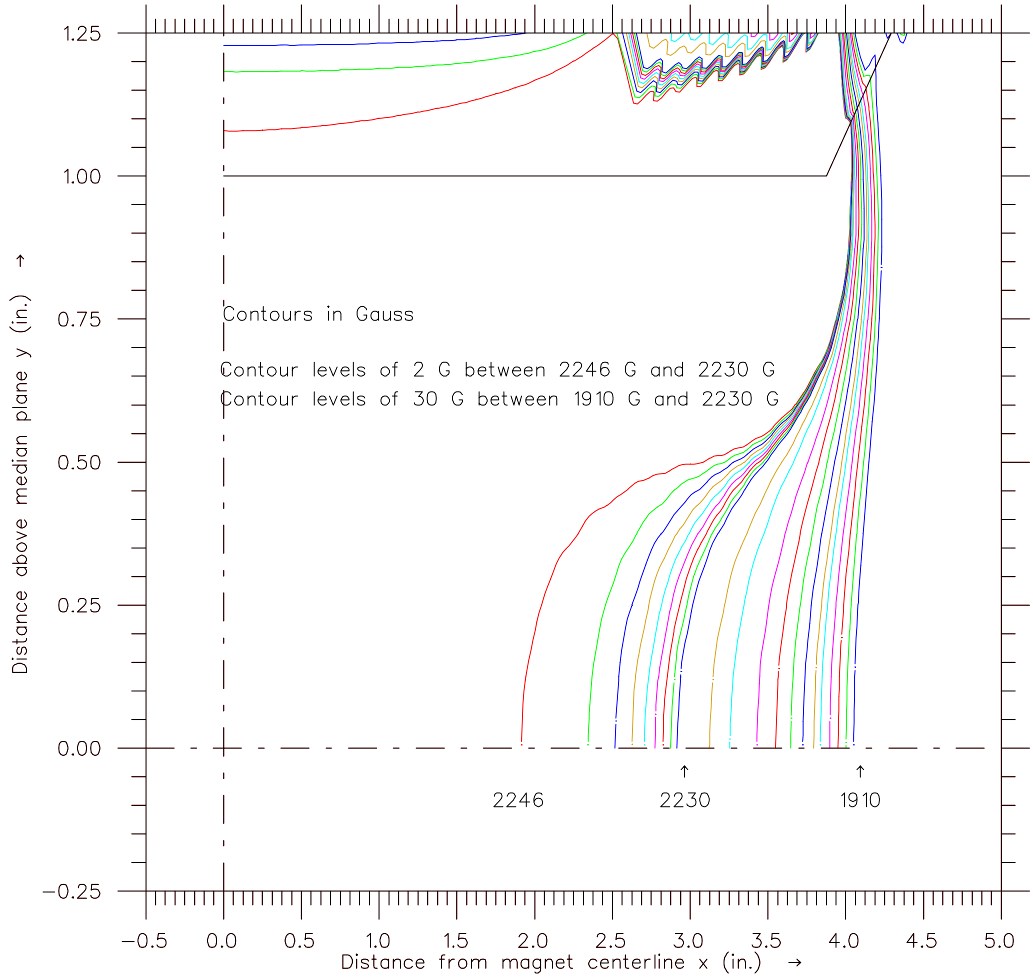


Figure 4. Predicted field in the gap of the 50 MeV, 45° dipole magnet.

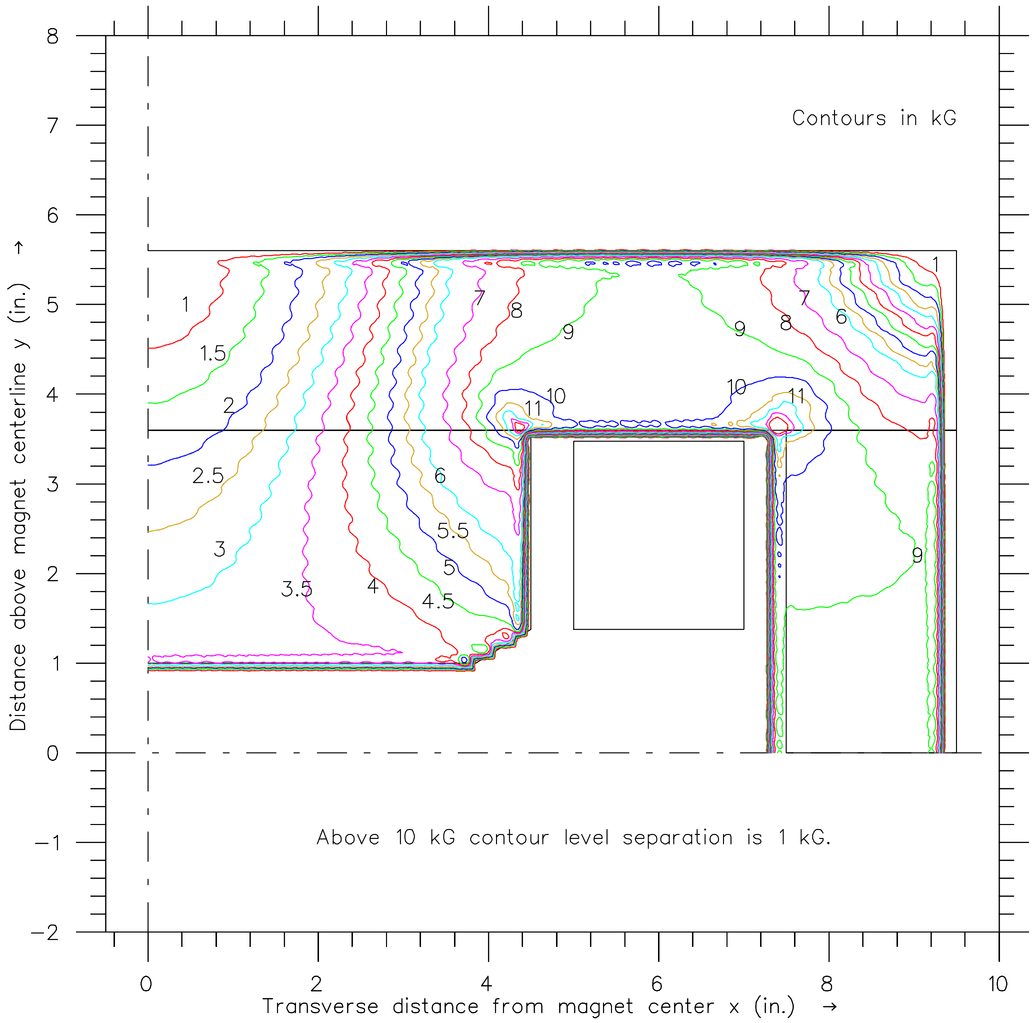


Figure 5. Predicted field in the yoke of the 75 MeV, 45° dipole magnet.

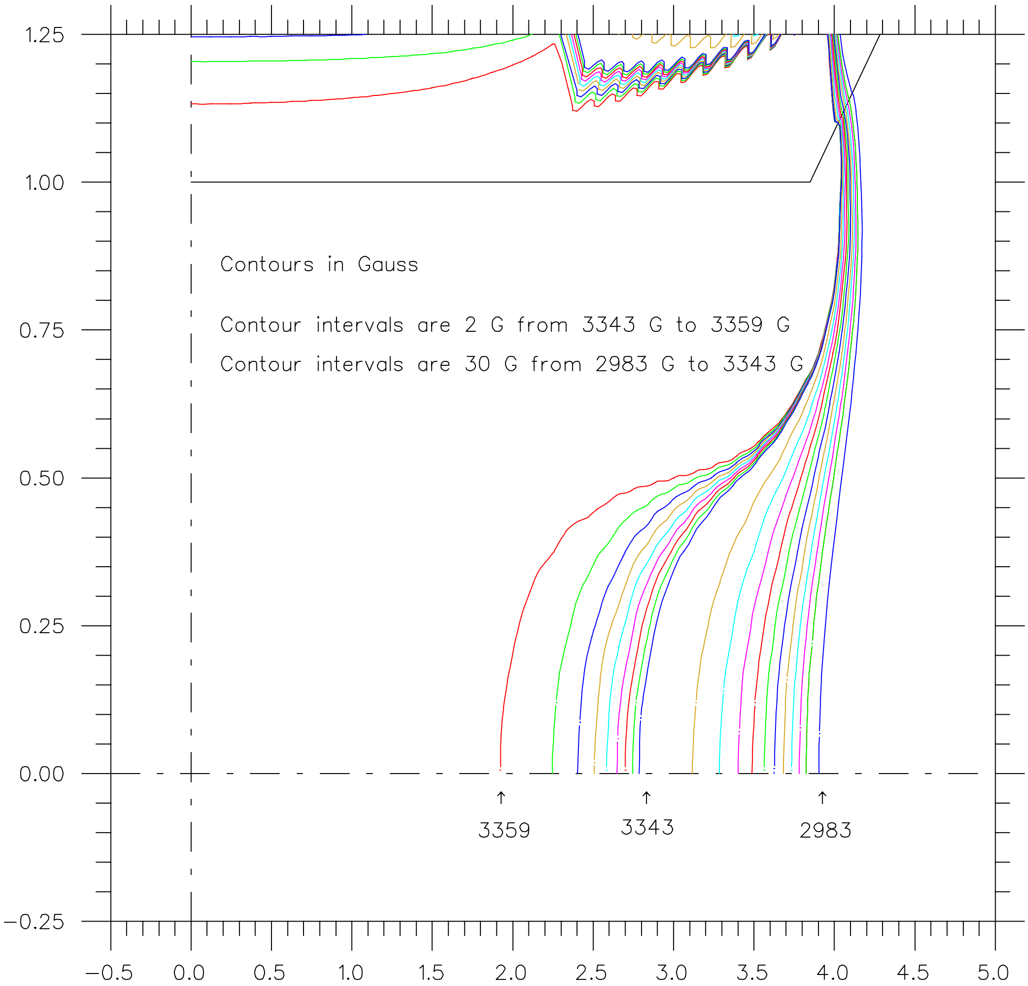


Figure 6. Predicted field in the gap of the 75 MeV, 45° dipole magnet.