## 1. Introduction

One proposed design for beam line 2A calls for a 15° dipole to be located on each leg of beam line downstream of a ±15° switching magnet. The two 15° bends then give the 30° deflection required to reach either of the two targets. This report presents a conceptual design for an H-magnet that would be suitable for the individual 15° dipoles.

## 2. Design parameters for the vault dipoles

The TRANSPORT calculations for the beamline require a magnet with an effective length 0.68139 m that is capable of producing a field of 13.97 kG at 500 MeV. We design the magnet for a maximum energy of 512 MeV and field of 14.175 kG in order that we have sufficient range. We also add the following additional parameters.

| | | | | |
|---|---|---|---|---|
| $B_0$ | = | Maximum magnetic field | = | 14.175 kG |
| $g$ | = | Maximum air gap | = | 10.160 cm |
| $\theta$ | = | Maximum bend angle | = | 15.000° |
| $s$ | = | Length of the central trajectory | = | 68.139 cm |

We first calculate the basic properties of these magnets.

$$\rho = \text{radius of curvature of the central trajectory} = \frac{s}{\theta} = \frac{(180.0)(0.68139)}{(15.0)(\pi)} = 2.60272 \text{ m} = 102.469 \text{ in.}$$

$$\boxed{\text{Radius of curvature of the central trajectory} = \rho = 2.603 \text{ m} = 102.5 \text{ in.}}$$

We take the effective straight-line length of the magnet to be

$$l_e = 2\rho \sin\frac{\theta}{2} = 2(2.60272)(0.13053) = 0.67945 \text{ m} = 26.750 \text{ in.}$$

$$\boxed{\text{Straight-line effective length of the magnet} = l_e = 0.680 \text{ m} = 26.750 \text{ in.}}$$

and assume that the the iron length, $l_i$, is obtained from

$$l_e = l_i + g$$

so that

$$l_i = l_e - g = 0.67945 - 0.1016 = 0.57785 \text{ m} = 22.74985 \text{ in.}$$

$$\boxed{\text{Iron length of the magnet} = l_i = 0.578 \text{ m} = 22.750 \text{ in.}}$$

The deviation, $\Delta$, of the central trajectory from a line drawn through the points of entry and exit is found from the relation

$$\Delta = \rho\left[1 - \cos\frac{\theta}{2}\right] = 2.60272(1 - 0.99144) = 0.02227 \text{ m} = 0.87664 \text{ in.}$$

$$\boxed{\text{Maximum deviation of central trajectory from straight line} = \Delta = 0.022 \text{ m} = 0.877 \text{ in.}}$$

### 2.1 Pole width

We allow for a maximum beam width, $x$, of 10.16 cm and assume a 0.625 in. (15.875 mm) chamfer, $c$, at 45° to the each pole edge. Because the field is relatively uniform in an H-frame magnet, we take the pole width, $W_{iron}$, to be

$$W_{iron} = 2\,g + \Delta + x + 2\,c = 2(4.000)\text{ in.} + 0.877\text{ in.} + 4.000\text{ in.} + 2(0.625)\text{ in.} = 14.127\text{ in.}$$

$$\boxed{\text{Pole width} = W_{iron} = 14.250\text{ in.} = 361.95\text{ mm.}}$$

### 2.2 Ampere-turns per coil

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

$$NI\text{ per pole} = \frac{1}{2}\left[1.1\,\frac{B_0\,g}{\mu_0}\right] = \frac{1}{2}\,\frac{(1.1)(1.41724)(0.1016)}{4\pi\times 10^{-7}} = 63022\text{ A-t}$$

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

$$\boxed{NI\text{ per pole} = 63500\text{ Ampere-turns}}$$

and generate the following table

| $I$ (Amperes) | 100 | 200 | 300 | 400 | 500 | 600 | 700 | 800 | 900 | 1000 |
|---|---|---|---|---|---|---|---|---|---|---|
| $N$ (turns) | 635 | 317 | 212 | 159 | 127 | 106 | 91 | 79 | 71 | 643 |

Because a low-cost 60 kW supply (60 V at 600 A), we choose

| | | |
|---|---|---|
| $I$ | = | 600 Amperes |
| Coil configuration | | 9 turns wide by 12 turns high |

### 3. Coil design

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

$$\text{Conductor area} = \frac{600\ A}{3000\ A/\text{in}^2} = 0.2000\text{ in.}^2 = 129.03\text{ mm}^2$$

This is satisfied within 10% by Ananconda 0.4600 and 0.5160 in.-square conductors; their parameters are given in the table below.

| | Anaconda 0.4600 | | Anaconda 0.5160 | |
|---|---|---|---|---|
| OD | 0.4600 in. | [11.684 mm] | 0.5160 in. | [13.106 mm] |
| ID | 0.2550 in. | [6.477 mm] | 0.2870 in. | [7.290 mm] |
| Copper area | 0.1529 in.$^2$ | [98.645 mm$^2$] | 0.1940 in.$^2$ | [125.161 mm$^2$] |
| Cooling area | 0.1529 in.$^2$ | [98.645 mm$^2$] | 0.06469 in.$^2$ | [41.735 mm$^2$] |
| Mass | 0.5910 lb/ft | [0.880 kg/m] | 0.7495 lb/ft | [1.115 kg/m] |
| Resistance at 20°C | 53.25 $\mu\Omega$/ft | [174.70 $\mu\Omega$/m] | 41.99 $\mu\Omega$/ft | [137.762 $\mu\Omega$/m] |
| $k$ (British units) | 0.01760 | | 0.01520 | |

We assume that each conductor is double-wrapped with insulation that is 0.007 in. (0.178 mm) thick with a tolerance of 0.0015 in. (0.038 mm). Then the *total* insulation per conductor has:

| | | | |
|---|---|---|---|
| Minimum thickness | 4(0.007 − 0.0015) in. | = | 0.022 in. = 0.559 mm |
| Nominal thickness | 4(0.007) in. | = | 0.028 in. = 0.711 mm |
| Maximum thickness | 4(0.007 + 0.0015) in. | = | 0.034 in. = 0.864 mm |

The tolerance of the outer dimension of the conductor is listed as 0.004 in. = 0.100 mm so that the dimensions of a *wrapped* conductor are:

| | | | |
|---|---|---|---|
| Minimum | Conductor dimension + 0.022 in. − 0.004 in. | = | Conductor dimension + 0.018 in. |
| Nominal | Conductor dimension + 0.028 in. | | |
| Maximum | Conductor dimension + 0.034 in. + 0.004 in. | = | Conductor dimension + 0.038 in. |

We further allow

a) a gap between layers of 0.010 in. (0.254 mm) maximum
b) for keystoning, assume 0.010 in. (0.254 mm)
c) a 4-turn ground wrap of 0.007 in. (0.178 mm) tape

Then the *width* of the coil is obtained from

| | Anaconda 0.4600 | | Anaconda 0.5160 | |
|---|---|---|---|---|
| | Maximum | Minimum | Maximum | Minimum |
| Wrapped conductor | 4.482 in. | 4.302 in. | 4.986 in. | 4.806 in. |
| Gapping ( 8x0.10 ) | 0.080 in. | | 0.080 in. | |
| Ground wrap (4x0.178x2) | 0.056 in. | 0.056 in. | 0.056 in. | 0.056 in. |
| Total (in.) | 4.618 in. | 4.358 in. | 5.122 in. | 4.862 in. |

The average coil width is 4.488 in. [113.995 mm] for the 0.4600 in. conductor and 4.992 in. [126.797 mm] for the 0.5160 in. one. We take

| | Anaconda 0.4600 | | Anaconda 0.5160 | |
|---|---|---|---|---|
| Maximum coil width | 4.625 in. | [117.5 mm] | 5.250 in. | [133.4 mm] |
| Nominal coil width | 4.500 in. | [114.3 mm] | 5.000 in. | [127.0 mm] |

The *height* of the coil is

| | Anaconda 0.4600 | | Anaconda 0.5160 | |
|---|---|---|---|---|
| | Maximum | Minimum | Maximum | Minimum |
| Wrapped conductor | 5.976 in. | 5.736 in. | 6.648 in. | 6.408 in. |
| Gapping (11x0.10 ) | 0.110 in. | | 0.080 in. | |
| Keystoning (12x0.010) | 0.120 in. | 0.060 in. | 0.120 in. | 0.060 in. |
| Ground wrap (4x0.178x2) | 0.056 in. | 0.056 in. | 0.056 in. | 0.056 in. |
| Total | 6.262 in. | 5.852 in. | 6.934 in. | 6.524 in. |

The average coil height is 6.057 in. [153.848 mm] for the 0.4600 in. conductor and 6.729 in. [176.124 mm] for the 0.5160 in. one. We take

| | Anaconda 0.4600 | | Anaconda 0.5160 | |
|---|---|---|---|---|
| Maximum coil height | 6.300 in. | [160.0 mm] | 7.000 in. | [177.8 mm] |
| Nominal coil height | 6.100 in. | [154.9 mm] | 6.750 in. | [170.9 mm] |

We take the conductor dimension $D$ to be

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

so that we then have for the 0.4600 in. conductor

$$\begin{aligned} D &= 0.460 \text{ in.} + 0.028 \text{ in.} + 0.010 \text{ in.} \\ &= 0.498 \text{ in. } [12.65 \text{ mm}] \end{aligned}$$

and for the 0.5160 in. conductor

$$\begin{aligned} D &= 0.516 \text{ in.} + 0.028 \text{ in.} + 0.010 \text{ in.} \\ &= 0.554 \text{ in. } [14.07 \text{ mm}]. \end{aligned}$$

We further assume a pole-coil gap of $G = 0.75$ in. = 19.1 mm and that the pole corners are rounded with a radius

$$\text{Pole radius} = R_{pole} = 4\,D - G$$

so that for the 0.4600 in. conductor we have

$$\begin{aligned} R_{pole} &= 4(0.498) \text{ in.} - 0.750 \text{ in.} \\ &= 1.242 \text{ in. } [31.55 \text{ mm}]. \end{aligned}$$

and for the 0.5160 in. conductor

$$\begin{aligned} R_{pole} &= 4(0.554) \text{ in.} - 0.750 \text{ in.} \\ &= 1.466 \text{ in. } [37.24 \text{ mm}]. \end{aligned}$$

Then the $n^{th}$ conductor is a distance

$$D_n = n\,D + G + \text{Polewidth}/2 + 4(\text{insulation thickness})$$

from the longitudinal center-line of the pole and its (outer) radius of curvature is

$$R_n = R_{pole} + n\,D + G + 4(\text{insulation thickness})$$

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

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

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

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

Substituting the following values into equation (1)

| | Anaconda 0.4600 | Anaconda 0.5160 |
|---|---|---|
| $L_{iron}$ | 22.750 in. | 22.750 in. |
| $W_{iron}$ | 14.250 in. | 14.250 in. |
| $R_{pole}$ | 1.242 in. | 1.466 in. |
| $G$ | 0.750 in. | 0.750 in. |
| $D$ | 0.498 in. | 0.554 in. |
| Insulation | 0.007 in. | 0.007 in. |

we find that the length of a 9-turn layer of the 0.4600 in. conductor is 831.6 in. [21,125 mm] = 69.30 ft [21.13 m] and that of a 9-turn layer of the 0.5160 in. conductor is 844.0 in [21,440 mm] = 70.33 ft [21.44 m]. Because these lengths differ little, we take

$$\boxed{\text{Length of 9-turn layer of either conductor} = 72 \text{ ft} \approx 22.0 \text{ m},}$$

and the length per coil becomes

$$\boxed{\text{Length per coil of either conductor} = 865 \text{ ft} \approx 265 \text{ m}.}$$

Because two coils are required per dipole, then

| | | | |
|---|---|---|---|
| Total length per dipole | 1730 ft | $\approx$ | 530 m |
| Allow 10% for winding losses | 173 ft | $\approx$ | 53 m |
| Total | 1903 ft | $\approx$ | 583 m |

Then order

$$\boxed{\text{Total length of copper} = 1910 \text{ ft} \approx 590 \text{ m}}$$

of conductor. The mass of the 0.4600 conductor at 0.5910 lb/ft is 1130 lb [515 kg] and that of the 0.5160 conductor at 0.7495 lb/ft is 1435 lb [650 kg].

$$\begin{array}{|lcl|}\hline \text{Total mass of 0.4600 conductor} & = & 1130 \text{ lb} \approx 515 \text{ kg.} \\ \text{Total mass of 0.5160 conductor} & = & 1435 \text{ lb} \approx 650 \text{ kg.} \\ \hline \end{array}$$

**4. Power requirements**

At 20°C, the resistance of a coil of the 0.4600 in. conductor is

$$R_{20^\circ} = 53.25\times10^{-6}\ \Omega/\text{ft}\times 865 \text{ ft} = 0.04606\ \Omega$$

and that of a coil of the 0.5160 in. conductor is

$$R_{20^\circ} = 41.99\times10^{-6}\ \Omega/\text{ft}\times 865 \text{ ft} = 0.03632\ \Omega$$

We assume an ambient temperature of 20°C, an inlet water temperature of 30°C and an outlet water temperature of 70°C (thus allowing a 40° C coolant temperature rise). Then the mean coil temperature will be 50°C.

With a 30°C rise above ambient of the coil we then have:

$$R_{hot} = R_{20^\circ}[1 + (\text{Temp. coeff}/^\circ\text{C})dT(^\circ\text{C})]$$

so that for the coil made of the 0.4600 in. conductor

$$R_{hot} = 0.04606[1 + (0.00393)(30)] = 0.05150\ \Omega \text{ per coil}$$

and that for the coil made of the 0.5160 in. conductor

$$R_{hot} = 0.03632[1 + (0.00393)(30)] = 0.04060\ \Omega \text{ per coil}$$

Thus, at a current of 600 A, we obtain

$$\text{Voltage per coil} = 30.90 \text{ Volts for the 0.4600 in. conductor}$$
$$\text{Voltage per coil} = 24.36 \text{ Volts for the 0.5160 in. conductor}$$

Therefore, allowing for a 10% lead loss, we choose a power supply that has

| | Anaconda 0.4600 | Anaconda 0.5160 |
|---|---|---|
| $I$ (A minimum) | 600 | 600 |
| $V$ (V minimum) | 70 | 55 |
| $P$(kW minimum) | 42 | 33 |

**5. Cooling requirements**

In these calculations we use the British system of units.

The power required per coil of the 0.4600 in. conductor is

$$\text{Power per coil} = I^2 R_{hot} = (600)(600)(0.05150) = 18.54 \text{ kW.}$$

and that required per coil of the 0.5160 in. conductor is

$$\text{Power per coil} = I^2 R_{hot} = (600)(600)(0.04060) = 14.62 \text{ kW}.$$

The required flow rate is given by:

$$\begin{aligned} v \text{ (ft/sec)} &= \frac{2.19}{\Delta T(^\circ \text{ F})} \times \frac{P(\text{kW})}{\text{Cooling area (in}^2)} \\ &= 0.0304167 \times \frac{P(\text{kW})}{A_c \text{ (in.}^2)} \end{aligned}$$

for $\Delta T = 72^\circ\text{F} = 40^\circ\text{C}$. The 0.4600 in. conductor has a cooling area of $A_c = 0.05107$ in.$^2$ [32.948 mm$^2$] and the 0.5160 in. conductor one of $A_c = 0.06469$ in$^2$ [41.735 mm$^2$]. Choosing $v = 2.50$ ft/sec to define the maximum power dissipation per water circuit we have:

$$\begin{aligned} P_{max} &= \frac{(2.50)(72)(0.05107)}{2.19} = 4.198 \text{ kW/water circuit [0.4600 in. conductor]} \\ &= \frac{(2.50)(72)(0.06469)}{2.19} = 5.317 \text{ kW/water circuit [0.5160 in. conductor]} \end{aligned}$$

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

| | | | | Anaconda 0.4600 | Anaconda 0.5160 |
|---|---|---|---|---|---|
| $P$ | = | Total power per coil | | 18.54 kW | 14.62 kW |
| Number of circuits | = | $P$ / $P_{max}$ | = | 4.42 | 2.75 |

Thus we take

| | | |
|---|---|---|
| Number of cooling circuits per coil | = | 6 for the 0.4600 in. conductor |
| | = | 3 for the 0.5160 in. conductor |

This requires a flow rate of $v = 1.840$ ft/sec per water circuit of the 0.4600 in. conductor and a flow rate of $v = 2.291$ ft/sec per water circuit of the 0.5160 in. conductor. The volume of flow required per circuit is

$$\begin{aligned} \text{Volume/circuit} &= v \frac{\text{ft}}{\text{sec}} \times A_{H_2O} \, (\text{in}^2) \times 60 \, \frac{\text{sec}}{\text{min}} \times \frac{1}{144} \frac{\text{ft}^2}{\text{in}^2} \times 62.4 \, \frac{\text{lb}}{\text{ft}^3} \times \frac{1}{10} \frac{\text{IG}}{\text{lb}} \times 1.20095 \, \frac{\text{USG}}{\text{IG}} \\ &= 3.1225 \, v \, (\text{ft/sec}) \times \text{Cooling area (in}^2) \text{ USGPM} \end{aligned}$$

Thus we have the following volumes of flow.

| | 0.4600 in. conductor | | 0.5160 in. conductor | |
|---|---|---|---|---|
| Volume per cooling circuit | 0.293 USGPM | 1.111 $\ell$/min | 0.463 USGPM | 1.752 $\ell$/min |
| Volume per coil | 1.760 USGPM | 6.663 $\ell$/min | 1.389 USGPM | 5.255 $\ell$/min |
| Volume per magnet | 3.521 USGPM | 13.327 $\ell$/min | 2.777 USGPM | 10.509 $\ell$/min |

## 6. Pressure drop

The pressure drop is given by

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

with $k$ a function of the cooling area. In our case, for the 0.4600 in. conductor with $k = 0.0176$ and $v = 1.840$ ft/sec we obtain

$$\Delta P = (0.0176)(1.840)^{1.79} = 0.0524 \text{ psi/ft} = 0.1720 \text{ psi/m}.$$

For the 0.51400 in. conductor with $k = 0.0152$ and $v = 2.291$ ft/sec we obtain

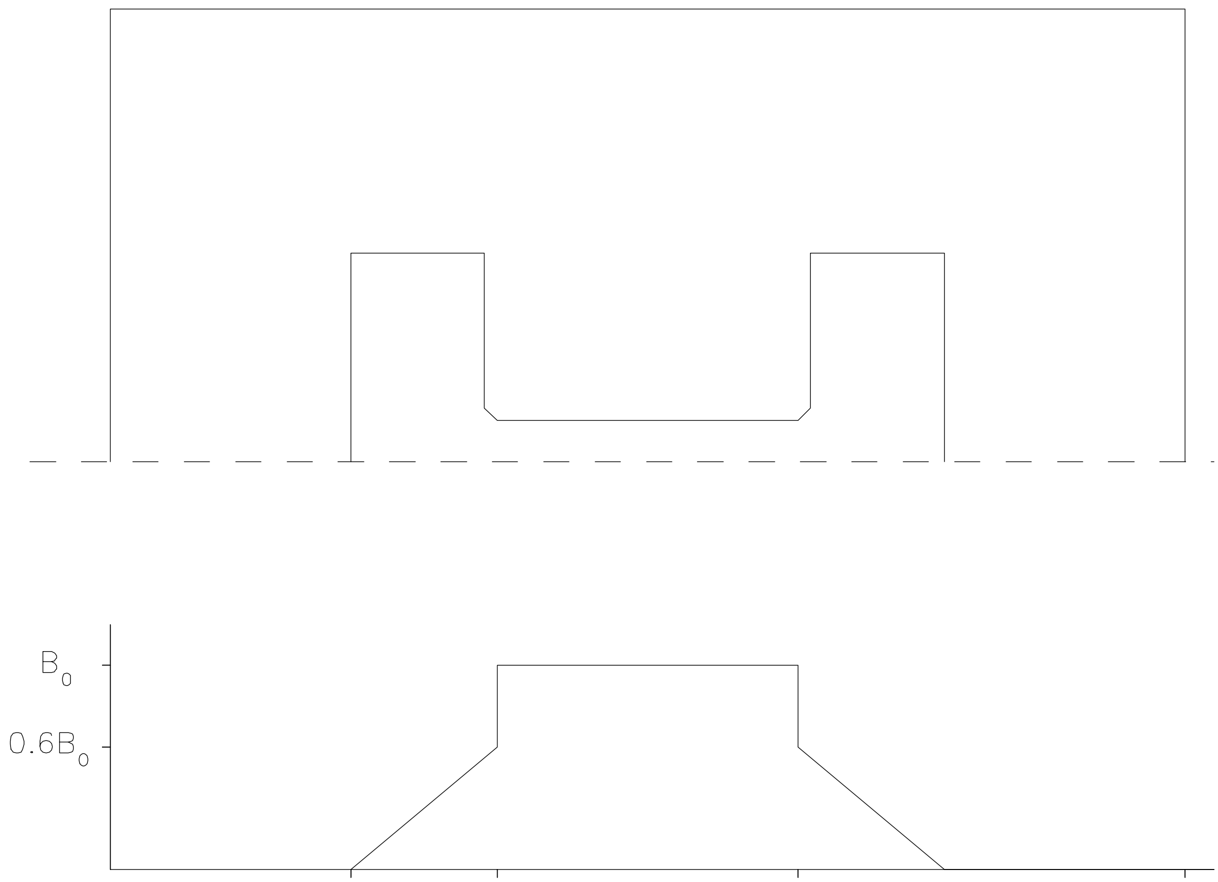
$$\Delta P = (0.0152)(2.291)^{1.79} = 0.0670 \text{ psi/ft} = 0.2199 \text{ psi/m}.$$

and the total pressure drop across one cooling circuit is:

$$\begin{aligned}\text{Pressure drop per cooling circuit} &= 0.0524 \text{ psi/ft} \times 2(72) \text{ ft} = 7.75 \text{ psi [0.4600 in. conductor]} \\ &= 0.0670 \text{ psi/ft} \times 4(72) \text{ ft} = 19.31 \text{ psi [0.5160 in. conductor]}\end{aligned}$$

**7. Iron dimensions**

A cross section of the dipole and an assumed field profile is shown in the figure below.




Cross section of the H magnet and assumed field profile.

As is illustrated in the figure, the magnetic field profile has been assumed to rise linearly from zero at the inside edge of the yoke to a value of $0.6B_g$ at the flat part of the pole. At that point the field rises to the full value in the gap $B_g$ and remains at that value to the outer edge of the pole. At that point the field is assumed to abruptly drop to a value of $0.6B_g$ and to fall linearly to zero at the outer edge of the outer coil. This assumption is made for ease of further calculation.

We have assumed maximum coil widths of 4.625 in. and 5.250 in., respectively, for the smaller and larger conductor and allowed 0.750 in. clearance between the coil and the yoke and the coil and the pole. Consequently, the widths of the coil slots are 6.125 in. for the 0.4600 in. conductor case and 6.750 in. for the 0.5160 in. case. To these we add $c = 0.625$ in. for the chamfer to find that the edges of the flat portion of the pole are at distances from the inside edges of the yoke of $l_1 = 6.750$ in. in the case of the smaller conductor and 7.375 in. in the case of the larger conductor.

Calling the field in the yoke $B_y$ and the yoke thickness $t$ and assuming that the flux divides equally between the vertical yokes, we equate the flux densities in the yoke and in the gap to obtain a relation between the yoke field and the yoke thickness. Thus we have

$$2\,B_y\,t \;=\; \frac{l_1}{2}\,(0.6B_g) + (W_{iron} - 2c)B_g + \frac{l_1}{2}\,(0.6B_g)$$

For the 0.4600 in. conductor we have

$$\begin{aligned} B_y\,t &= \frac{1}{2}\left[\frac{6.750(0.6)}{2} + (14.250 - 2(0.625)) + \frac{6.750(0.6)}{2}\right] B_g \\ &= 120.842 \text{ kG-in.} = 0.30694 \text{ T-m} \end{aligned}$$

and for the 0.5160 in. conductor we find

$$\begin{aligned} B_y\,t &= \frac{1}{2}\left[\frac{7.375(0.6)}{2} + (14.250 - 2(0.625)) + \frac{7.375(0.6)}{2}\right] B_g \\ &= 123.500 \text{ kG-in.} = 0.31369 \text{ T-m} \end{aligned}$$

We make the following table.

| | 0.4600 in. conductor | | | | 0.5160 in. conductor | | | |
|---|---|---|---|---|---|---|---|---|
| $B_y$ (kG) | 10. | 11. | 12. | 13. | 10. | 11. | 12. | 13. |
| $t$ (in.) | 12.084 | 10.986 | 10.070 | 9.295 | 12.350 | 11.227 | 10.292 | 9.500 |

We choose

| | | 0.4600 in. comductor | | 0.5160 in. conductor | |
|---|---|---|---|---|---|
| Yoke field | $B_y$ | 10.986 kG | 1.099 T | 11.227 kG | 1.123 T |
| Yoke thickness | $t$ | 11.000 in. | 0.279 m | 11.000 in. | 0.279 m |

In the above, the coil-slot width was calculated from

$$\begin{aligned} \text{Coil-slot width} &= \text{Maximum coil width} + 2(\text{Pole-coil separation}) \\ &= 4.625 \text{ in.} + 2(0.750) \text{ in.} = 6.125 \text{ in. } [0.4600 \text{ in. case}] \\ &= 5.250 \text{ in.} + 2(0.750) \text{ in.} = 6.750 \text{ in. } [0.5160 \text{ in. case}]. \end{aligned}$$

Also, the total dipole width is

$$\begin{aligned} \text{dipole width} &= 2(\text{Coil-slot width} + \text{Yoke thickness}) + \text{Pole width} \\ &= 2(6.125 \text{ in.} + 11.000 \text{ in.}) + 14.250 \text{ in.} = 48.500 \text{ in. } [0.4600 \text{ in. case}] \\ &= 2(6.750 \text{ in.} + 11.000 \text{ in.}) + 14.250 \text{ in.} = 49.750 \text{ in. } [0.5160 \text{ in. case}], \end{aligned}$$

the overall length of the dipole is

$$\begin{aligned} \text{dipole length} &= 2(\text{Pole-coil separation} + \text{Maximum coil width}) + \text{Pole length} \\ &= 2(0.750 \text{ in.} + 4.625 \text{ in.}) + 22.750 \text{ in.} = 33.500 \text{ in. } [0.4600 \text{ in. case}] \\ &= 2(0.750 \text{ in.} + 5.250 \text{ in.}) + 22.750 \text{ in.} = 34.750 \text{ in. } [0.5160 \text{ in. case}], \end{aligned}$$

the pole-height is obtained from

$$\begin{aligned} \text{pole height} &= \text{Maximum coil height} + \text{Chamfer} + 15 \text{ mm} \\ &= 6.300 \text{ in.} + 0.625 \text{ in.} + 0.591 \text{ in.} = 7.516 \text{ in. } [0.4600 \text{ in. case}] \\ &= 7.000 \text{ in.} + 0.625 \text{ in.} + 0.591 \text{ in.} = 8.216 \text{ in. } [0.5160 \text{ in. case}], \end{aligned}$$

and the lengths of the side yokes are

$$\text{side-yoke height} = 2(\text{Pole height}) + \text{Gap}$$

$$\begin{aligned}\text{side-yoke height} &= 2(7.500\text{ in.}) + 4.000\text{ in.} = 19.000\text{ in.}\ [0.4600\text{ in. case}]\\ &= 2(8.200\text{ in.}) + 4.000\text{ in.} = 20.400\text{ in.}\ [0.5160\text{ in. case}]\end{aligned}$$

where the pole height is taken as 7.500 in. (190.5 mm) in the case of the 0.4600 in. conductor and 8.200 in. (208.3 mm) in the case of the 0.5160 in. conductor. We take

| | 0.4600 in. conductor | | 0.5160 in. conductor | |
|---|---|---|---|---|
| Coil-slot width | 6.125 in. | 155.6 mm | 6.750 in. | 171.5 mm |
| Pole height | 7.500 in. | 190.5 mm | 8.200 in. | 208.3 mm |
| Side-yoke height | 19.000 in. | 482.6 mm | 20.400 in. | 518.2 mm |
| Dipole width | 48.500 in. | 1231.9 mm | 49.750 in. | 1263.7 mm |
| Dipole length | 33.500 in. | 850.9 mm | 34.750 in. | 882.7 mm |

**8. Iron weight**

The cross-sectional areas of the magnet components are tabulated below.

| Section | 0.4600 in. conductor | | | 0.4600 in. conductor | | |
|---|---|---|---|---|---|---|
| | Height (in.) | Width (in.) | Area (in.$^2$) | Height (in.) | Width (in.) | Area (in.$^2$) |
| Top yoke | 11.000 | 48.500 | 533.500 | 11.000 | 49.750 | 547.250 |
| Bottom yoke | 11.000 | 48.500 | 533.500 | 11.000 | 49.750 | 547.250 |
| Vertical Yoke | 19.000 | 11.000 | 209.000 | 20.400 | 11.000 | 224.400 |
| Vertical Yoke | 19.000 | 11.000 | 209.000 | 20.400 | 11.000 | 224.400 |
| Top pole | 7.500 | 14.250 | 99.750 | 8.200 | 14.250 | 116.850 |
| Bottom pole | 7.500 | 14.250 | 99.750 | 8.200 | 14.250 | 116.850 |
| Total area | | | 1684.500 | | | 1777.000 |

The total volume of iron is then

$$\text{Volume of iron} = (\text{Total area})(\text{Iron length})$$

and we obtain

| | 0.4600 in. conductor | 0.5160 in. conductor |
|---|---|---|
| Iron length (in.) | 22.750 | 22.750 |
| Iron area (in.$^2$) | 1684.500 | 1777.000 |
| Iron volume (in.$^3$) | 38,322.375 | 40,426.750 |
| Iron volume (ft$^3$) | 22.177 | 23.395 |
| Iron volume (m$^3$) | 0.628 | 0.663 |

and the iron mass at a density of 7900 kg/m$^3$ is

$$\begin{aligned}\text{Iron mass} &= (\text{Iron volume})(\text{Density})\\ &= (0.628\text{ m}^3)(7900\text{ kg/m}^3) = 4.961\times10^3\text{ kg} = 10.939\times10^3\text{ lb for the 0.4600 in. conductor}\\ &= (0.663\text{ m}^3)(7900\text{ kg/m}^3) = 5.238\times10^3\text{ kg} = 11.785\times10^3\text{ lb for the 0.5610 in. conductor}\end{aligned}$$

We take

$$\begin{aligned}\text{Iron mass} &= 11.0\times10^3\text{ lb} = 5.00\times10^3\text{ kg}\ [0.4600\text{ in. case}]\\ &= 12.0\times10^3\text{ lb} = 5.45\times10^3\text{ kg}\ [0.5160\text{ in. case}]\end{aligned}$$

**9. Discussion**

This report has presented a conceptual design for the individual 15'degr dipoles that are used on beam line 2A. Two possibilities of conductor have been considered. As indicated in table 1, the mass required of the smaller, 0.460 in.-square conductor is approximately 25% less than that of the larger, 0.516 in.-square conductor. On the other hand, the larger conductor requires approximately 25% less power to operate.

Because the 27.5° vault dipoles have been designed with the larger conductor[1)], it is suggested that use of the larger conductor may be more economical to use for the 15° dipoles. Thus a larger quantity of the conductor would be purchased at, perhaps, a somewhat reduced price.

**References**

1. G. M. Stinson, *TRIUMF Report* TRI-DNA-96-6, TRIUMF, March, 1966.

Table 1

Summary of H-magnet design parameters for the 15° dipoles on beam line 2AA

| | | Conductor dimension | |
|---|---|---|---|
| | | 0.460 in. | 0.516 in. |
| Yoke: | Iron length | 22.750 in. | 22.750 in. |
| | Iron width | 48.500 in. | 49.750 mm |
| | Iron thickness | 11.000 in. | 11.000 in. |
| | Coil-slot width | 6.125 in. | 6.750 in. |
| | Side-yoke height | 19.000 in. | 20.400 in. |
| Pole: | Width | 14.250 in. | 14.250 in. |
| | Height | 7.500 in. | 8.200 in. |
| | Chamfer at 45° | 0.625 in. | 0.625 in. |
| Iron: | Total mass | $11.0 \times 10^3$ lb | $12.0 \times 10^3$ lb |
| | | $5.00 \times 10^3$ kg | $5.45 \times 10^3$ kg |
| Dipole: | Overall width | 48.500 in. | 49.750 in. |
| | Overall height | 43.000 in. | 44.000 in. |
| | Overall length (incl. coil) | 33.500 in. | 34.750 in. |
| Coil: | Conductor OD | 0.460 in. | 0.516 in. |
| | Conductor ID | 0.255 in. | 0.287 in. |
| | Nominal coil width | 4.500 in. | 5.000 in. |
| | Nominal coil height | 6.100 in. | 6.750 in. |
| | Total coolant flow | 3.521 USGPM | 2.777 USGPM |
| | Turn configuration | 9 wide × 12 high | 9 wide × 12 high |
| | Resistance (hot) per coil | $51.5 \times 10^{-3}\ \Omega$ | $40.6 \times 10^{-3}\ \Omega$ |
| | Number of cooling circuits per coil | 6 | 3 |
| Copper: | Total length per magnet | 1730 ft | 1730 ft |
| | Total mass per magnet | 1025 lb | 1300 lb |
| | Total length to order | 1910 ft | 1910 ft |
| | Total mass to order | 1130 lb | 1435 lb |
| Power: | Total current | 600.0 A | 600.0 A |
| | Total Voltage | 70.0 V | 55.0 V |
| | Power | 42.0 kW | 33.0 kW |