TRIUMF	**UNIVERSITY OF ALBERTA EDMONTON, ALBERTA**	
	Date 1996/03/22	*File No.* TRI-DNA-96-6
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Subject A revised design for the 27.5° dipoles for beam line 2A		

1. Introduction

Protons are to be extracted from extraction port 2A to deliver beam to an external ISAC facility. The current beamline design calls for two 27.5° dipoles to be located in the cyclotron vault. This report presents a design for an H-magnet that would be suitable for the beamline.

2. Design Parameters

The TRANSPORT calculations for the beamline require a magnet with an effective length 1.246 m that is capable of producing a field of 14 kG at 500 MeV. We design the magnet for a maximum energy of 520 MeV and field of 14.35 kG in order to have adequate provision for the required field. We also add the following additional parameters.

B_g	=	Maximum magnetic field	=	14.344 kG
g	=	Maximum air gap	=	10.160 cm
θ	=	Maximum bend angle	=	27.500°
s	=	Length of the central trajectory	=	1.246 m

We first calculate quantities that are particular to the magnet.

$$\rho_0 = \text{radius of curvature of the central trajectory} = \frac{s}{\theta} = \frac{(180.0)(1.24595)}{(27.5)(\pi)} = 2.59592 \text{ m} = 102.201 \text{ in.}$$

$$\boxed{\text{Radius of curvature of the central trajectory} = \rho_0 = 2.596 \text{ m} = 102.20 \text{ in.}}$$

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

$$l_e = 2\,\rho_0 \sin\frac{\theta}{2} = 2(2.59592)(0.23769) = 1.23403 \text{ m} = 48.58366 \text{ in.}$$

$$\boxed{\text{Straight-line effective length of the magnet} = l_e = 1.234 \text{ m} = 48.584 \text{ in.}}$$

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

$$l_e = l_i + g$$

so that

$$l_i = l_e - g = 1.23403 - 0.1016 = 1.13243 \text{ m} = 44.584 \text{ in.}$$

$$\boxed{\text{Iron length of the magnet} = l_i = 1.133 \text{ m} = 44.600 \text{ in.}}$$

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

$$\Delta = \rho_0 \left[1 - \cos\frac{\theta}{2}\right] = 2.59592(1 - 0.97134) = 0.07439 \text{ m} = 2.92888 \text{ in.}$$

$$\boxed{\text{Maximum deviation of central trajectory from straight line} = \Delta = 0.0744 \text{ m} = 2.930 \text{ in.}}$$

3. Ampere-turns per coil

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

$$NI \text{ per pole} = \frac{1}{2}\left[1.1\,\frac{B_0\,g}{\mu_0}\right] = \frac{1}{2}\,\frac{(1.1)(1.43442)(0.1016)}{4\pi\times10^{-7}} = 63,786 \text{ A-t}$$

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

$$\boxed{NI \text{ per pole} = 64{,}000 \text{ Ampere-turns}}$$

and generate the following table

I (Amperes)	100	200	300	400	500	600	700	800	900	1000
N (turns)	640	320	213	160	128	107	91	80	71	64

Because a relatively low-cost, 100 V 600 A supply is available, we choose

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

4. 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 0.5160 in. conductor; its parameters are listed as

OD	0.5160	in.	13.106	mm
ID	0.2870	in.	7.290	mm
Copper area	0.1940	in.^{2}	125.161	mm^2
Cooling area	0.06469	in.^{2}	41.735	mm^2
Mass	0.7495	lb/ft	1.115	kg/m
Resistance at 20° C	41.99	$\mu\Omega$/ft	137.762	$\mu\Omega$/m
k (British units)	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	0.516 in. + 0.022 in. − 0.004 in.	=	0.534 in. = 13.56 mm
Nominal	0.516 in. + 0.028 in.	=	0.544 in. = 13.82 mm
Maximum	0.516 in. + 0.034 in. + 0.004 in.	=	0.554 in. = 14.07 mm

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

	Maximum		Minimum	
	in.	mm	in.	mm
Wrapped conductor	4.986	126.644	4.806	122.072
Gapping (8x0.10)	0.080	2.032		
Ground wrap (4x0.178x2)	0.056	1.422	0.056	1.422
Total (mm)	5.122	130.099	4.862	123.495

The average coil width is 4.992 in. = 126.8 mm. We take

Maximum coil width	=	5.200 in.	=	132.1 mm.
Nominal coil width	=	5.000 in.	=	127.0 mm.

The *height* of the coil is

	Maximum		Minimum	
	in.	mm	in.	mm
Wrapped conductor	6.648	168.859	6.408	162.763
Gapping (11x0.010)	0.110	2.794		
Keystoning (12x0.010)	0.120	3.048	0.060	1.524
Ground wrap (4x0.178x2)	0.056	1.422	0.056	1.422
Total (mm)	6.934	176.124	6.524	165.710

The average coil height is 6.729 in. = 170.9 mm. We take

Maximum coil height	=	7.000 in.	=	177.8 mm.
Nominal coil height	=	6.800 in.	=	172.7 mm.

We take the conductor dimension D to be

$$\begin{aligned} D &= \text{Nominal dimension} + 4(\text{Insulation thickness}) + \text{Turn separation} \\ &= 0.516 \text{ in.} + 0.028 \text{ in.} + 0.010 \text{ in.} \\ &= 0.554 \text{ in.} = 14.07 \text{ mm} \end{aligned}$$

and further assume a pole-coil gap of $G = 0.75$ in. = 19.05 mm and that the pole corners are rounded with a radius

$$\text{Pole radius} = R_{pole} = 4\,D - G = 4(0.554) \text{ in.} - 0.750 \text{ in.} = 1.466 \text{ in.} = 37.24 \text{ mm.}$$

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

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

We now consider specific properties of the magnet.

5. H-magnet design

5.1 Pole width

We allow for a maximum beam width, x, of ± 1 in. (± 2.54 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

$$W_{iron} = 2\,g + \Delta + x + 2\,c = 2(4.000)\text{ in.} + 2.929\text{ in.} + 2.000\text{ in.} + 2(0.625) = 14.179\text{ in.}$$

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

Substituting the following values into equation (1)

$$\begin{aligned} L_{iron} &= 44.600\text{ in.} &\approx&\ 1132.8\text{ mm} \\ W_{iron} &= 14.250\text{ in.} &\approx&\ 362.0\text{ mm} \\ R_{pole} &= 1.466\text{ in.} &\approx&\ 37.2\text{ mm} \\ G &= 0.750\text{ in.} &\approx&\ 19.1\text{ mm} \\ D &= 0.554\text{ in.} &\approx&\ 14.1\text{ mm} \\ \text{Insulation} &= 0.007\text{ in.} &\approx&\ 0.2\text{ mm} \end{aligned}$$

we find that the length of a 9-turn layer is 1236 in. [31,400 mm] = 103.0 ft [31.39 m]. We take

$$\boxed{\text{Length of a 9-turn layer} = 110\text{ ft} \approx 33.5\text{ m}}$$

and the length per coil becomes

$$\boxed{\text{Length per coil} = 1{,}320\text{ ft} \approx 405\text{ m.}}$$

Because two coils are required per dipole, then

Total length per dipole	2640 ft	≈	805 m
Allow 10% for winding losses	264 ft	≈	81 m
Total	2904 ft	≈	886 m

Then order

$$\boxed{\text{Total length of copper} = 2900\text{ ft} \approx 885\text{ m}}$$

of conductor of mass 0.7495 lb/ft for a total mass of

$$\boxed{\text{Total mass} = 2200\text{ lb} \approx 1000\text{ kg.}}$$

5.2 Power requirements

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

$$R_{20^\circ} = 41.99\times10^{-6}\ \Omega/\text{ft}\times1320\ \text{ft} = 0.05543\ \Omega$$

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:

$$\begin{aligned} R_{hot} &= R_{20^\circ}[1 + (\text{Temp. coeff}/^\circ\text{C})dT(^\circ\text{C})] \\ &= 0.05543[1 + (0.00393)(30)] \\ &= 0.06197\ \Omega \text{ per coil} \end{aligned}$$

Thus, at a current of 600 A, we obtain

$$\text{Voltage per coil} = 37.18 \text{ Volts}$$

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

$$\boxed{\begin{array}{rcrl} I & = & 600 & \text{A minimum} \\ V & = & 82.5 & \text{V minimum} \\ P & = & 49.5 & \text{kW minimum} \end{array}}$$

5.3 Cooling requirements

In these calculations we use the British system of units.

The power required per coil is:

$$\text{Power per coil} = I^2 R_{hot} = (600)(600)(0.06197) = 22.31\ \text{kW}.$$

The required flow rate is given by:

$$\begin{aligned} v\ (\text{ft/sec}) &= \frac{2.19}{\Delta T(^\circ\ \text{F})}\times\frac{P(\text{kW})}{\text{Cooling area (in}^2)} \\ &= 0.47019\times P(\text{kW}) \end{aligned}$$

for $\Delta T = 72°\text{F} = 40°\text{C}$ and $A = 0.06469\ \text{in}^2 = 41.735\ \text{mm}^2$. Choosing $v = 2.50$ ft/sec to define the maximum power dissipation per water circuit we have:

$$P_{max} = \frac{(2.50)(72)(0.06469)}{2.19} = 5.317\ \text{kW/water circuit}$$

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

$$\begin{array}{lcccc} P & = & \text{Total power per coil} & = & 22.31\ \text{kW} \\ \text{Number of circuits} & = & P\ /\ P_{max} & = & 4.20 \end{array}$$

Thus we take

$$\boxed{\text{Number of cooling circuits per coil} = 6}$$

This requires a flow rate of $v = 1.748$ ft/sec per water circuit.

The volume of flow required per circuit is

$$\text{Volume/circuit} = v\,\frac{\text{ft}}{\text{sec}} \times A_{H_2O}\ (\text{in}^2) \times 60\,\frac{\text{sec}}{\text{min}} \times \frac{1}{144}\,\frac{\text{ft}^2}{\text{in}^2} \times 62.4\,\frac{\text{lb}}{\text{ft}^3} \times \frac{1}{10}\,\frac{\text{IG}}{\text{lb}} \times \frac{1}{0.832675}\,\frac{\text{USG}}{\text{IG}}$$

so that

$$\begin{aligned}\text{Volume/circuit} &= 3.12247\, v\,(\text{ft/sec}) \times \text{Cooling area}\,(\text{in}^2)\\ &= 3.12247(1.748)(0.06469) = 0.3531 \text{ USGPM}\end{aligned}$$

Thus we have the following volumes of flow.

Volume per cooling circuit	=	0.353 USGPM	=	1.336 ℓ/min
Volume per coil	=	2.118 USGPM	=	8.019 ℓ/min
Volume per magnet	=	3.535 USGPM	=	16.038 ℓ/min

5.4 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 $k = 0.0152$ we obtain:

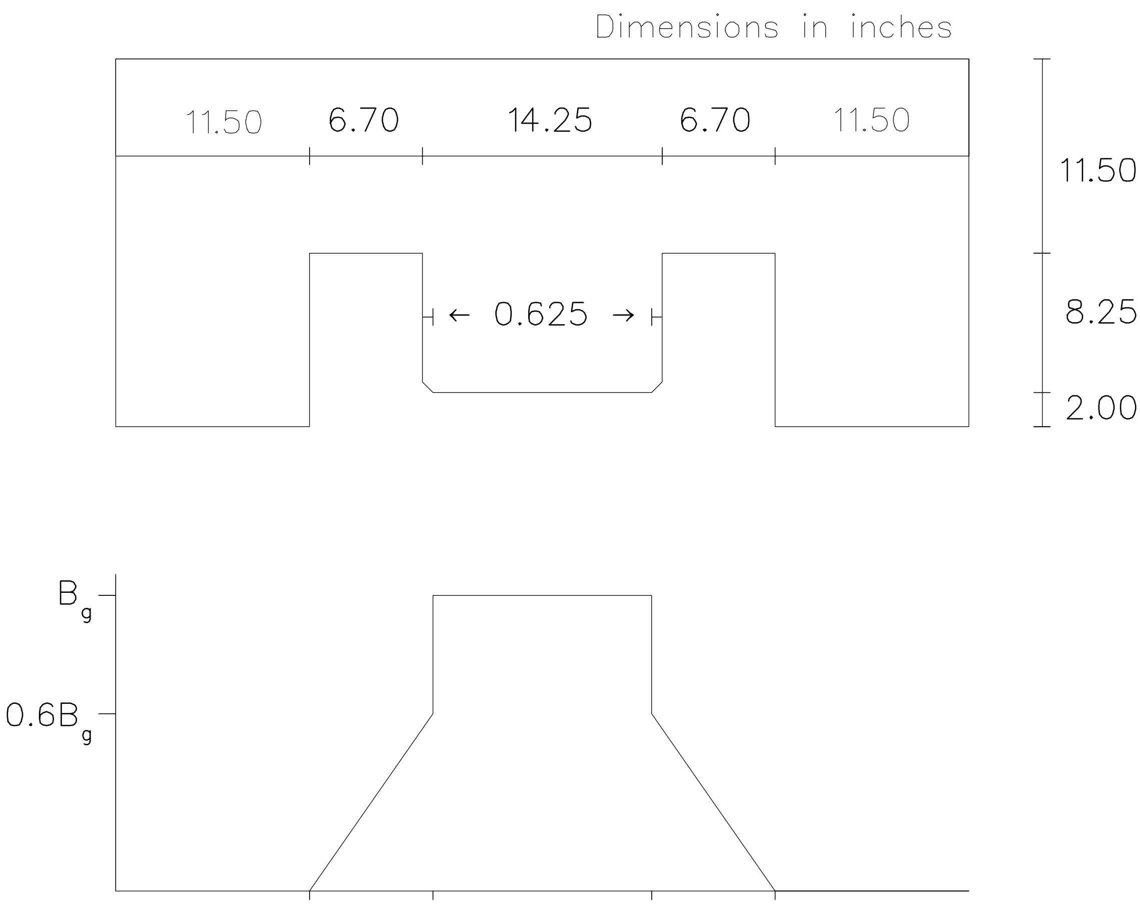
$$\Delta P = (0.0152)(1.748)^{1.79} = 0.0413 \text{ psi/ft} = 0.1355 \text{ psi/m}$$

and the total pressure drop across one cooling circuit is:

$$\boxed{\text{Pressure drop per cooling circuit} = 0.0413 \text{ psi/ft} \times 220 \text{ ft} = 9.09 \text{ psi}}$$

5.5 Iron dimensions

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



Cross section of dipole and the assumed field distribution.

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 a maximum coil width of 5.200 in. 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 6.700 in. To this we add $c = 0.625$ in. for the chamfer to find that the edges of the flat portion of the pole are a distance $l_1 = 7.325$ in. from the inside edges of the yoke.

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. We have

$$\begin{aligned}
2\,B_y\,t &= \frac{l_1}{2}\,(0.6B_g) + (W_{iron} - 2c)B_g + \frac{l_1}{2}\,(0.6B_g) \\
&= \left[\frac{7.325(0.6)}{2} + (14.250 - 2(0.625)) + \frac{7.325(0.6)}{2}\right] B_g \\
&= 17.395\,B_g = (17.395)(14.34422) \text{ kG-in.} \\
&= 249.518 \text{ kG-in.} = 0.63378 \text{ T-m}
\end{aligned}$$

We thus make the following table.

B_y (kG)	10.	11.	12.	13.
t (in.)	12.476	11.342	10.397	9.597

We choose

Yoke field	=	B_y	=	10.849 kG	=	1.085 T
Yoke thickness	=	t	=	11.500 in.	=	0.292 m

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

$$\begin{aligned}
\text{Coil-slot width} &= \text{Maximum coil width} + 2(\text{Pole-coil separation}) \\
&= 5.200 \text{ in.} + 2(0.750) \text{ in.} \\
&= 6.700 \text{ in.} = 170.2 \text{ mm.}
\end{aligned}$$

Also, the total dipole width is

$$\begin{aligned}
\text{Dipole width} &= 2(\text{Coil-slot width} + \text{Yoke thickness}) + \text{Pole width} \\
&= 2(6.700 \text{ in.} + 11.500 \text{ in.}) + 14.250 \text{ in.} \\
&= 50.650 \text{ in.} = 1286.5 \text{ mm,}
\end{aligned}$$

the overall length of the dipole is

$$\begin{aligned}
\text{Dipole length} &= 2(\text{Pole-coil separation} + \text{Maximum coil width}) + \text{Pole length} \\
&= 2(0.750 \text{ in.} + 5.200 \text{ in.}) + 44.600 \text{ in.} \\
&= 56.500 \text{ in.} = 1435.1 \text{ mm,}
\end{aligned}$$

and the pole-height is obtained from

$$\begin{aligned}
\text{Pole height} &= \text{Maximum coil height} + \text{Chamfer} + 15 \text{ mm} \\
&= 7.000 \text{ in.} + 0.625 \text{ in.} + 0.591 \text{ in.} \\
&= 8.216 \text{ in.} = 208.7 \text{ mm,}
\end{aligned}$$

and, using a pole height of 8.250 in., the lengths of the side yokes are

$$\begin{aligned} \text{Side-yoke height} &= 2(\text{Pole height}) + \text{Gap} \\ &= 2(8.250 \text{ in.}) + 4.000 \text{ in.} \\ &= 20.500 \text{ in.} = 520.7 \text{ mm.} \end{aligned}$$

We take

Coil-slot width	=	6.700 in.	=	170.2 mm
Pole height	=	8.250 in.	=	209.6 mm
Side-yoke height	=	20.500 in.	=	520.7 mm
Dipole width	=	50.650 in.	=	1286.5 mm
Dipole length	=	56.500 in.	=	1435.1 mm

5.6 Iron weight

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

Section	Height		Width		Area	
	(in.)	(m)	(in.)	(m)	(in.^{2})	(m^2)
Top yoke	11.500	0.2921	50.650	1.2865	582.475	0.3758
Bottom yoke	11.500	0.2921	50.650	1.2865	582.475	0.3758
Vertical Yoke	20.500	0.5207	11.500	0.2921	235.750	0.1521
Vertical Yoke	20.500	0.5207	11.500	0.2921	235.750	0.1521
Top pole	8.250	0.2096	14.250	0.3620	117.563	0.0758
Bottom pole	8.250	0.2096	14.250	0.3620	117.563	0.0758
Total area					1871.576	1.2074

The total volume of iron is then

$$\begin{aligned} \text{Volume of iron} &= (\text{Total area})(\text{Iron length}) \\ &= (1871.576)(44.600) \text{ in.}^3 \\ &= 83{,}475 \text{ in.}^3 = 48.306 \text{ ft}^3 = 1.3679 \text{ m}^3 \end{aligned}$$

$$\boxed{\text{Volume of iron} = 48.5 \text{ ft}^3 = 1.373 \text{ m}^3}$$

and the iron mass at 7900 kg/m^3 is

$$\begin{aligned} \text{Iron mass} &= (\text{Iron volume})(\text{Density}) \\ &= (1.373 \text{ m}^3)(7900 \text{ kg/m}^3) \\ &= 10.850 \times 10^3 \text{ kg} \\ &= 23.925 \times 10^3 \text{ lb} \end{aligned}$$

We take

$$\boxed{\text{Iron mass} = 24.0 \times 10^3 \text{ lb} = 10.9 \times 10^3 \text{ kg}}$$

5.7 Summary of H-magnet design parameters

A summary of the design parameters of this H-frame dipole is given on the next page as table 1.

Table 1

Summary of H-magnet design parameters for Anaconda 0.5160 conductor

Yoke:	Iron length	44.600 in.	1132.8 mm
	Iron width	50.650 in.	1286.5 mm
	Iron thickness	11.500 in.	292.1 mm
	Coil-slot width	6.700 in.	170.2 mm
	Side-yoke height	20.500 in.	520.7 mm
Pole:	Width	14.250 in.	362.2 mm
	Height	8.250 in.	209.6 mm
	Chamfer at 45°	0.625 in.	15.9 mm
Iron:	Total mass	24.0×10^3 lb	10.9×10^3 kg
Dipole:	Overall width	50.650 in.	1286.5 mm
	Overall height	43.500 in.	1104.9 mm
	Overall length (incl. coil)	56.500 in.	1435.1 mm
Coil:	Anaconda conductor		
	Conductor OD	0.516 in.	13.1 mm
	Conductor ID	0.287 in.	7.3 mm
	Nominal coil width	5.000 in.	127.0 mm
	Nominal coil height	6.800 in.	172.7 mm
	Total coolant flow	4.237 USGPM	16.0 ℓ/min
	Turn configuration	9 wide $\times$ 12 high	
	Resistance (hot) per coil	62.0×10^{-3} Ω	
	Number of cooling circuits per coil	6	
Copper:	Total length per magnet	2640 ft	810 m
	Total mass per magnet	1980 lb	900 kg
	Total length to order	2900 ft	890 m
	Total mass to order	2200 lb	1000 kg
Power:	Total current	600.0	A
	Total Voltage	82.5	V
	Power	49.5	kW