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A COMPARISON OF SEVERAL DESIGNS OF H TYPE DIPOLE FOR AN ADVANCED HADRON FACILITY

by

J. Liu and S. Greene

ABSTRACT

Several dipole magnets with different features are given and a comparison is made between them. Some possible problems are presented so that a better dipole design could be chosen.

In the design of the dipole magnet for an advanced hadron facility 45 GeV synchrotron, some problems have been encountered, such as a high uniformity requirement within the good field area, the possibility of coil damage due to particle spills and radiation, application of regular current density, eddy current and cooling problems in the A.C. magnet, and manufacture cost, and so on. In order to solve these problems, a comparison has been made between several dipole designs. We are expecting that a better design project of the dipole magnet will be chosen through the comparison and the extensive discussion.

Design 1.

The magnet configuration is shown in Fig.1. Good uniformity of field distribution can be obtained because of the utilization of adjustment coils with contrary current.

Basic parameters of the dipole are below:

Magnet Data

Magnet dimension (m)	1.56 X 1.02 X 8
Pole width (cm)	40
Lamination thickness (cm)	0.1
Steel weight (Ton)	77
Copper weight (Ton)	19.4

Field Data

Field range (T)	0.225 - 1.5 (45 GeV)
	0.225 - 2.0 (60 GeV)(upgrade)
Good field region (W X H cm)	16 X 8.4
Uniformity	0.01 %

Coil Data

	Main coil	Adjustment coil
Coil dimension (cm)	30 X 20	7 X 0.3
Mean length (m)	18.04	16.09
Turns/coil	10 (in series)	23 (in parallel)
Conductors/turn	15 (in parallel)	
Conductor size (cm)	2 X 2	0.3 X 0.3
Wires/cond. (wire dia.)	200 (1mm)	
Coil resistance (mOhm)	2.21	2.67

Operation Data

Magnet:	
Peak stored energy (KJ)	328
Inductance (mH)	20.94
Main coil:	
I _{max} (A)	5600
I _{min} (A)	746
I _{dc} (A)	3173
Peak current density (A/cm ²)	186.67
Peak coil voltage (V)	24.72
Induced voltage (KV)	-2.03
Adjustment coil:	
Peak current (A)	5.22
Peak current density (A/cm ²)	-57.14

Power Data

Iron core loss (W)	943
Main coil A.C. power (KW)	13.02
Main coil D.C. power (KW)	44.50
Eddy loss in main coil	negligible
Adj. coil peak power (W)	39
Eddy loss in adj. coil (W)	197
Total (KW)	< 60

Cooling Data

Temperature rise (F degree)	5
Pressure drop (lb/in ²)	0.47
Water flow/circuit (gal./min)	1.0
Water velocity (ft/sec)	1.72
Water circuits	30

Advantages:

- (1). Good uniformity of field distribution;
- (2). Relatively low power cost;
- (3). No coil damage problems.

Problem and discussion:

- (1). Because low current density and big size coils are used, the magnet dimension is big, so costs are expensive on manufacture and materials. But operation cost should be cheap relatively.
- (2). In this model, we just use current densities of 187 A/cm² (1.5T) and 330 A/cm² (2.0T). A reason why it is so low is that we have no experience about cooling. From the Report of EHF Main Ring Dipole Magnet Design Data, we know their current use is 833 A/cm² (1.3T). And in KEK magnet report, it is estimated that the current density is more than 650 A/cm² at least when the field intensity is 1.5 tesla.
- (3). In order to get high field accuracy, the power supply of the adjustment coil must be synchronous with that of the main coil perfectly.

Design 2.

 In view of those mentioned above, we increase exciting current density up to 2 times. This model has similar configuration to design 1 as shown in Fig. 2.

Basic parameters of the dipole are as follows:

Magnet Data

Magnet dimension (m)	1.26 X 0.88 X 8
Pole width (cm)	40
Lamination thickness (cm)	0.1
Steel weight (Ton)	57
Copper weight (Ton)	8.9

Field Data

Field range (T)	0.225 - 1.5 (45 GeV)
	0.225 - 2.0 (60 GeV)(upgrade)
Good field region (W X H cm)	16 X 8.4
Uniformity	0.01 %

Coil Data

	Main coil	Adjustment coil
Coil dimension (cm)	18 X 16	7 X 0.3
Mean length (m)	17.56	16.09
Turns/coil	12 (in series)	23 (in parallel)
Conductors/turn	6 (in parallel)	
Conductor size (cm)	2 X 2	0.3 X 0.3
Wires/cond. (wire dia.)	200 (1mm)	
Coil resistance (mOhm)	6.32	2.67

Operation Data

Magnet:	
Peak stored energy (KJ)	319
Inductance (mH)	29.29
Main coil:	
Imax (A)	4666.67
Imin (A)	698.60
Idc (A)	2682.64
Peak current density (A/cm**2)	388.89
Peak coil voltage (V)	58.99
Induced voltage (KV)	-2.36
Adjustment coil:	
Peak current (A)	4.78
Peak current density (A/cm**2)	-53.14
Peak coil voltage (V)	0.30
Induced voltage (V)	-41.60

Power Data

Iron core loss (W)	981
Main coil A.C. power (KW)	12.44
Main coil D.C. power (KW)	90.96
Eddy loss in main coil	negligible
Adj. coil peak power (W)	32
Eddy loss in adj. coil (W)	195
Total (KW)	< 104

Cooling Data

Temperature rise (F degree)	5
Pressure drop (lb/in**2)	1.91
Water flow/circuit (gal./min)	2.63
Water velocity (ft/sec)	4.53
Water circuits	12

Advantages:

- (1). Good uniformity of field distribution;
- (2). Smaller magnet dimension, less manufacture cost and saving of 30 ton iron and copper;
- (3). No coil damage problems.

Problem and discussion:

- (1). Though material cost can be reduced 31%, operation cost will be increased up to 2 times as design 1 because of a raise in power consumption;
- (2). In order to get high field accuracy, the power supply of the adjustment coil must be synchronous with that of the main coil perfectly;
- (3). From cooling parameters, we think it is not necessary to worry about water cooling of coils at all. More water circuits can be utilized, so this is not a serious problem and no heat damage will happen.

Design 3.

The magnet configuration is shown in Fig. 3. Usually it is difficult to realize $\pm 0.01\%$ uniformity requirement technologically without any assistant means. After we consulted a lot of reference papers on magnet design and construction, we found that this is the first magnet design with high field accuracy requirement. But it is quite possible to reach $\pm 0.1\%$ accuracy in the case of alternating fields.

Basic parameters of the dipole are as below:

Magnet Data

Magnet dimension (m)	1.26 X 0.8 X 8
Pole width (cm)	40
Lamination thickness (cm)	0.1
Steel weight (Ton)	52
Copper weight (Ton)	8.2

Field Data

Field range (T)	0.225 - 1.5 (45 GeV) 0.225 - 2.0 (60 GeV)(upgrade)
Good field region (W X H cm)	12 X 9
Uniformity	0.1 %

Coil Data

Coil dimension (cm)	20 X 12
Mean length (m)	17.62
Turns/coil	10 (in series)
Conductors/turn	6 (in parallel)
Conductor size (cm)	2 X 2
Wires/cond. (wire dia.)	200 (1mm)
Coil resistance (mOhm)	5.29

Operation Data

Magnet:	
Peak stored energy (KJ)	305
Inductance (mH)	19.18
Main coil:	
Imax (A)	5640

Imin (A)	844.31
Idc (A)	3242.15
Peak current density (A/cm**2)	470
Peak coil voltage (V)	59.69
Induced voltage (KV)	-1.89

Power Data

Iron core loss (W)	531
Main coil A.C. power (KW)	15.43
Main coil D.C. power (KW)	110
Eddy loss in main coil	negligible
Total (KW)	< 126

Cooling Data

Temperature rise (F degree)	5
Pressure drop (lb/in**2)	18.62
Water flow/circuit (gal./min)	6.26
Water velocity (ft/sec)	10.80
Water circuits	12

Advantages:

- (1). Smaller magnet dimension and saving of 36 ton iron and copper;
- (2). No adjustment coil and no coil damage problem;

Problem and discussion:

- (1). A uniformity of 0.1% can be got within +/- 6 cm good field region. Through Fourier analysis, we can reach multipole errors as follows

mean field (Gauss)	15209	20103
dipole error	-5.274 (-0.0346%)	5.096 (0.0253%)
quadrupole error	-6.392 (-0.0420%)	5.080 (0.0253%)
sextupole error	3.248 (0.0214%)	0.266 (0.0013%)
octupole error	-1.773 (-0.0117%)	-0.257 (-0.0013%)
decapole error	1.184 (0.0078%)	0.153 (0.0008%)

- (2). From beam dynamics, dipole field errors will lead to beam spread. Though so, we can correct the distortions through regulating parameters of other components or for example, using a correction dipole.

- (3). We still don't worry about coil cooling.

Design 4.

In this design, we investigate former design work on H-type dipole with four coils. The magnet configuration is shown in Fig. 4. Excellent uniformity of field distribution can be obtained. It has been suggested that in order to avoid damage of coils from spilled particles and synchrotron radiation, some shielding materials can be put into the gap between beam tube and coils to stop beam spills and radiation. We consider it is possible.

Basic parameters of the dipole are below:

Magnet Data

Magnet dimension (m)	1.26 X 0.72 X 8
Pole width (cm)	40

Lamination thickness (cm)	0.1	
Steel weight (Ton)	49	
Copper weight (Ton)	8.7	
Field Data		
Field range (T)	0.225 - 1.5 (45 GeV)	
in the future	0.225 - 2.0 (60 GeV)	
Good field region (W X H cm)	16 X 7.5	
Uniformity	< 0.01 %	
Coil Data		
	Main coil	Small coil
Coil dimension (cm)	20 X 12	10.5 X 3.5
Mean length (m)	17.64	16.80
Turns/coil	10 (in series)	2 (in series)
Conductors/turn	6 (in parallel)	6 (in parallel)
Conductor size (cm)	2 X 2	1.75 X 1.75
Wires/cond. (wire dia.)	200 (1mm)	150 (1mm)
Coil resistance (mOhm)	5.3	1.3
Operation Data		
Magnet:		
Peak stored energy (KJ)	232	
Inductance (mH)	27.60	
Main coil:		
I _{max} (A)	4100	
I _{min} (A)	613.77	
I _{dc} (A)	2356.88	
Peak current density (A/cm**2)	341.67	
Peak coil voltage (V)	43.73	
Induced voltage (KV)	-1.95	
Small coil:		
I _{max} (A)	2250	
I _{min} (A)	336.83	
I _{dc} (A)	1293.4	
Peak current density (A/cm**2)	244.9	
Peak coil voltage (V)	3.03	
Induced voltage (KV)	-1.06	
Power Data		
Iron core loss (W)	619	
Main coil A.C. power (KW)	18.05	
Main coil D.C. power (KW)	58.88	
Eddy loss in main coil	negligible	
Small coil A.C. power (KW)	0.60	
Small coil D.C. power (KW)	4.95	
Eddy loss in small coil (W)	negligible	
Total (KW)	< 82.5	
Cooling Data		
	Main coil	Small coil
Temperature rise (F degree)	5	5
Pressure drop (lb/in**2)	5.23	0.1
Water flow/circuit (gal./min)	3.36	0.52
Water velocity (ft/sec)	5.79	1.16
Water circuits	12	6

Advantages:

- (1). Excellent uniformity of magnetic field distribution;
- (2). Lower current density and good cooling parameters;
- (3). Smaller magnet size and saving of 39 ton iron and copper;

Problem and discussion:

(1). A layout of the dipole shielding is as shown in Fig. 5. Our considerations are based on several facts:

(a). Approximate opening angle of synchrotron radiation equal to wavelength. The radiative opening angle is so small that it is easy to shield radiation.

(b). Usually spilled particles appear possibly when the machine fails to control them. Because of small deviation angle from beam axis, shielding material blocks have enough length to stop them.

(c). Particle spilling happens at the beginning of operation due to some reasons. The stopping power of some materials is strong enough to shield spilled particles with lower potentials.

(d). In fact, there are same problems in vacuum chamber design. Even though a few particles can penetrate beam tube wall, they still can be shielded by stopping blocks because of their energy loss.

(2). No reliable data and experience can be referred.

Fig. 1 A.C. dipole magnet for the AHF synchrotron

Fig. 2

Fig. 3

Fig. 4

Fig. 5 Shielding layout