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5 T MAGNETS WITH IRON AT AN INTERMEDIATE TEMPERATURE BETWEEN AMBIENT AND 4.5°K

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I N D E X

LIST OF DRAWINGS

5 T MAGNETS WITH IRON AT AN INTERMEDIATE TEMPERATURE BETWEEN AMBIENT AND 4.5°K

1. INTRODUCTION:

The Tevatron at Fermilab is equipped with ambient temperature iron. In order for the iron to contribute significantly to the field, the gap or hole in the iron should be as small as is possible. The requirement of small bore in the iron is not compatible with the cryogenic requirement of low heat leak to the magnets. Consequently, warm iron superconducting magnets have exhibited high heat leak.

Isabelle (CBA) was based on the use of cold iron magnets. A small number of these magnets was built; heat leaks reported in March-April, 1983 during the CBA review were of the order of 4.5 W per magnet (.9 W/meter). It appears that a large fraction of this heat is generated by the warm bore tube. A cold bore tube will improve the CBA magnets by approximately a factor 2. It appears then that it is necessary to improve on the warm iron and cold iron magnets in terms of heat leak.

A preliminary analysis of some cryogenic aspects of the 5 T magnet for the SSC, utilizing cold iron at 4.5°K, indicates that cooldown and warmup of the large cold mass (at present of the order of 2,600 lbs per meter) may require a large amount of time and massive amounts of refrigeration. Although initial cooldown can be carried out slowly, subsequent warmups and cooldowns for replacement of magnets should be reasonably fast.

In this report it is proposed to investigate the possibility of operating the iron at an intermediate temperature between ambient and 4.5°K. The most interesting temperature range is probably from 80-20°K. Although the hole in the iron needs to be larger than for a 4.5°K iron temperature, insulation between magnet and the iron at 80-20°K probably may not exceed 1/4 in. in radial direction.

2. ASSUMPTIONS:

The following assumptions have been made:

2.1 The ring is 86.4 km long.

2.2 There are 24 refrigeration stations located at 3.6 km intervals.

2.3 Heat load caused by synchrotron heating has been assumed to be 20 kW for the total system.

2.4 Heat load from ramping has been assumed to be 100 Joules per meter per ring or 200 Joules per meter total. Refrigeration load is then a function of the number of ramps per unit of time. It has been assumed that a ramp occurs occasionally and that ramping takes 15 minutes.

2.5 Heat load from shield through radiation and magnet supports will be intercepted at a temperature level of 4.5°K.

2.6 System cooldown will be accomplished without the need for warm piping in parallel with the collider.

3. DESCRIPTION OF PROPOSED ARRANGEMENT:

Drawing 7503-E shows the cross section of the two dipoles, iron, shield, and outer vessel between supports. Drawing 7504-D shows some details of a proposed magnet support. The two dipole magnets with collars and bore tube are carried in a thin wall vacuum-tight tube of approximately 4-5/8 in. O.D. This tube only carries single phase flow. The cross sectional flow area is large enough for rapid cooldown and warmup, and the tube can easily withstand fairly high fluid pressures during cooldown and warmup and during a quench.

The iron surrounds a tube of approximately 5-1/4 in. in diameter. This tube serves as a vacuum barrier and support tube for the magnet. Drawing 7504-D shows a potential support system. It consists of stainless steel rings located on the magnet shell which support a 5 in. O.D. stainless steel tube. This tube in turn is supported at its midpoint by stainless steel rings between the 5 in. diameter tube and the iron. It is necessary that there is some capability for sliding, either between magnet tube and support tube or support tube and vacuum shell inside the iron. The amount of sliding is determined by the relative rates of cooldown and warmup of magnet and shield. Under steady state conditions, both shield system and magnet shrink the same amount.

The iron and magnets are carried in a 21-1/2 in. diameter stainless steel vessel with a 1/8 in. thick wall. The total assembly of 21-1/2 in. vessel with contents is supported on three columns, each of which carries approximately 10,000 to 11,000 pounds of weight. At a spacing of 14-1/2 ft from the center, deflection of the iron and magnet assembly is at worst .012 in.

The 21-1/2 in. diameter vessel is equipped with flat ends or, if there is space, dished heads. A number of pipes penetrate through the end plates, as follows:

1) Two bore tubes.

2) Two magnet cryostats.

3) Two-phase flow tube. This tube is carried in a vacuum jacket of its own.

4) Liquid nitrogen or cold helium gas shield tube.

5) Helium gas tube connecting contents of 21 in. vessel with adjacent vessels.

6) Possibly a 1 Ø tube.

7) Any other tubes that may be required.

To make sure that non-uniform cooldown of these tubes and vessel can be accommodated, some bellow sections may have to be used.

The 21-1/2 in. diameter vessel is surrounded by superinsulation. The thickness of this insulation will be a function of steady state temperature level of the shield system. At 60-80°K, the thickness of the superinsulation will be of the order of 1-1/4 in. or 75-80 layers of aluminized mylar with Dexter paper. The exact thickness may be determined by making an economic analysis of cost of insulation versus savings in power consumption of the refrigeration system.

The support of the shield system consists of two or three column supports. These will be stiff structures, probably 6 in. O.D. thin wall tubes. If three supports are used, the center one will be used as an anchor. The two outside supports then need to accommodate 1/2 in. of motion between warm and cold conditions. This motion may be accommodated by linear bearings or slide pads located at the bottom of the support or by potentially some other means. The vacuum vessel surrounding the total assembly may be decoupled from the support system by means of bellows in the warm support legs. In that case, the vacuum vessel will have a separate anchor to ground.

4. FEATURES OF THE DESIGN:

4.1 By selecting a proper temperature of the shield system, heat leak to the 4.5°K temperature level may be reduced to any desirable low level.

4.2 The heat leak of the shield system can be controlled by providing more or less superinsulation and by making the support columns longer or shorter.

4.3 Magnet cooldown can be accomplished independently from iron cooldown. There is some coupling, and the magnets may not be capable of operation with room temperature iron. Since the magnets are housed in small diameter tubes, a high pressure rating is achievable, and cooldown may be accomplished by putting all the magnets of half a refrigerator system in series.

4.4 Cooldown of iron is not pressure drop limited since an enormous cross section for flow is available. Shields can be cooled in a series arrangement at a high rate.

4.5 By providing internal cooling of the shield, either with liquid nitrogen flowing in a pipe or helium flow, transmission of heat from the shield surface to the coolant is straight forward.

4.6 With a shield system filled with helium gas, excess fluid from a quench can be discharged into the shield system. Its volume is large, and the shield can accommodate a substantial increase in mass. Also, recooling of the magnet after a quench can be accomplished by simply pushing the warm gas from the magnet into the shield system.

4.7 The shield system has a tremendous thermal inertia. Shield refrigeration could be turned off for a number of days without affecting the operation of the system.

4.8 Sometime after the system is in operation, additional refrigeration may be supplied to the shield system to reduce its temperature if so desired.

5. HEAT LEAKS:

5.1 Shield System:

5.1.1 Superinsulation:

Assume 75-80 layers of insulation with a thermal conductivity of 1 x 10^{-6} W/cm °K. Surface area of the shield per 40 ft magnet is approximately 220 ft^2. At a shield temperature of 65°K, heat input is:

$$Q_{rad} = \frac{1 \times 10^{-6} \times 220 \times 930 \times 235}{1.25 \times 2.54} = 15.2 \text{ W}$$

5.1.2 Shield Support System:

Total weight is of the order of 32,000 lbs per 40 ft length. Assume 2 sq in. of stainless steel for support cross section and an effective length of 12 in. between ambient and 65°K. Then:

$$Q_{supp} = \frac{2 \times 6.45 \times \int_{65}^{300} KdT}{12.0 \times 2.54} = .423 \int KdT \text{ W}$$

For stainless steel $\int_{65}^{300} KdT = 28.3$ W/cm

Q_{supp} = 12.0 Watts/maget

5.1.3 Total for shield system is then 27.2 W/magnet or 2.23 W/meter.

5.2 Magnet System:

5.2.1 Radiation:

Surface area of the magnets is of the order of:

$$\frac{2 \times 4.5 \times \pi \times 40}{12} = 94.25 \text{ ft}^2.$$

Surface area of the 2 Ø pipe (2 in. IPS, Schedule 5) is of the order of 24.9 ft^2. Total 4.5°K surface area is of the order of 120 ft^2. Assume an emissivity of .04 and a warm wall temperature of 65°K. Radiation from a 77°K surface area is .0045 w/ft^2.

$$\text{Then } Q_{rad} = \left(\frac{65}{77}\right)^4 \times .0045 \times 120 =$$

$$= .274 \text{ W/magnet}$$

$$= .0225 \text{ W/meter}$$

5.2.2 Conduction through Supports:

Drawing 7504-D shows the support system to consist of a 5 in. I.D., .035 in. wall stainless steel tube with alternate stainless steel rings on inside and outside of the tube.

By keeping tolerances between rings and tubes small, the .035 in. wall tube will remain round and will be subjected to bending from the load represented by the magnet and the unbalanced force exerted by the iron on the magnet. The close tolerances also will position the magnet in the center of the iron. This will reduce the unbalanced force to a small value. Support tube thickness and distance between support rings are related when the maximum deflection is fixed. It turns out (See Appendix A) that the heat leak is proportional to L^{+2} where L is distance between rings on the magnet tube. It appears that we need to decrease the length between support points by decreasing wall thickness of the intermediate tube.

A typical support system as shown on Drawing 7504-D consists of a .035 in. wall tube of 5 in. diameter with support points at 60 in. intervals. Deflection at the midpoint due to magnet weight is then less than .010 in. Heat leak to the 4.5°K system from a 65°K shield system is then approximately 1.75 W per magnet. For the total system heat leak is 3.5 W per 40 ft or .288 W/meter. This heat leak is not a real low number, but is reasonable. It can be reduced very significantly by reducing the shield temperature. For instance, a change from 65 to 50°K will reduce the heat leak to the magnets through the support system by 42% to .165 W/meter. It can also be reduced by reducing support tube wall thickness. A reduction of 25% in heat leak will be achieved by using a wall thickness of .020 in.

5.2.3 Ramping:

It has been assumed that the heat generated in the 4.5°K system will amount to 100 Joules/meter per magnet. This heat may be generated at various rates, dependent on ramp rate. If we assume the ramp to occur over a 900 second period, then rate of heating is $\frac{200}{900} = .222$ W/meter.

5.2.4 Synchrotron Heating:

This heat occurs only when the system operates as a storage system after ramping essentially is complete. The assumed load for the total system at this time is 20,000 kW or .231 W/meter.

6. REFRIGERATION SYSTEM FOR STEADY STATE OPERATION:

6.1 Shield System:

Total load to be removed at 65°K is 2.23 - .31 = 1.92 W/meter or 165,888 W total. Without going into detail about the refrigeration system, it may be assumed that a system with 20% of Carnot efficiency can be designed. Power required to remove 167.6 kW at 65°K is then of the order of:

$$\frac{1}{.2} \times \frac{300 - 65}{65} \times 165.9 = 2{,}998.7 \text{ kW}$$

$$= 3.0 \text{ MW}$$

6.2 Magnet System:

Total heat load will be of the order of .0225 + .288 + .231 = .542 W/meter. This assumes that ramping occurs infrequently and that the system mostly operates at full beam. For the complete system, heat load is 46,830 W. Again, assuming 20% Carnot efficiency, power required to deliver this refrigeration will be of the order of:

$$\frac{1}{.2} \times \frac{300 - 4.5}{4.5} \times 46.83 = 15{,}376 \text{ KW}$$

$$= 15.38 \text{ MW}$$

6.3 Optimization of Refrigeration System:

It appears that lowering of the shield temperature may reduce overall power. Assume that a shield temperature of 50°K will reduce heat leak of the magnet support system to .404 W/meter. Then total power of the system will be (20% of Carnot efficiency).

$$\text{At } 50°\text{K} \quad \frac{1}{.2} \times 205.0 \times \frac{300 - 50}{50} = 5{,}125 \text{ kW}$$

$$= 5.13 \text{ MW}$$

$$\text{At } 4.5°\text{K} \quad \frac{1}{.2} \times 34.9 \quad \frac{300 - 4.5}{4.5} = 11{,}461 \text{ KW}$$

$$= 11.46 \text{ MW}$$

Total for System = 16.59 MW

This is somewhat less than the 18.41 MW calculated for the 65°K shield system.

It appears that at this time some flexibility should be maintained in selecting the steady state operating temperature of the shield system. It is obvious that a major reduction of the heat load at 4.5°K can be obtained through lowering of the shield temperature. A refrigeration system which allows "add-ons" at some future date can provide the necessary safety factor of the overall refrigeration system.

6.4 Shield System Refrigeration:

The design of the shield allows for a very convenient application of refrigeration. With refrigerator stations at 3.6 km intervals refrigeration load of 1.8 km of shield is approximately 3,700 W. To remove this heat, helium gas will flow from the refrigerator through a pipe (LIN pipe on Drawing 7503-E) to the end of the magnet string and return through the 21-1/2 in. diameter shield pipe. If the gas is allowed to rise 10°K in temperature over the 1.8 km length, flow rate will be of the order of 70 g/sec. This flow rate can be accommodated by a 2 in. IPS pipe (2.375 in. O.D.). The pipe needs to be insulated from the shield system to prevent heating of the gas in the pipe. The gas removes heat through direct contact with the 21-1/2 in. diameter pipe.

The shield system represents an enormous thermal mass. If shield system weight is 2,000 lbs per meter, then a temperature rise from 65 to 75°K requires addition of 1.75 J/gr or 2.86 x 10^9 Joules total. With complete absence of shield refrigeration, time required is then of the order of 215 hours.

Shield refrigeration load can be reduced in a straight forward manner. Lengthening the support columns will cost very little, as long as the tunnel size need not be increased. Addition of superinsulation is simple and can be priced quite accurately. Trade-offs in terms of capital versus operating cost need to be evaluated in the near future.

6.5 Magnet Refrigeration:

The proposed design of the magnets shows cooling of the windings by single phase flow. There will be some temperature rise in the single phase fluid. Heat will be removed in 1 Ø to 2 Ø heat exchangers located at regular intervals. The frequency will be determined by heat loads, ramp rates, etc.

The two phase helium stream returns to the refrigerator through a 2 in. IPS pipe which is insulated from the shield system by means of vacuum. Pressure drop in this pipe is low. If necessary or desired, the pipe size may be increased. This would accommodate operation at lower temperature.

7. TRANSIENT CONDITIONS:

7.1 Magnet Quench:

It is proposed that helium ejected during a magnet quench will be discharged to the shield refrigeration system. The shield system contains a large gaseous atmosphere. The volume of the shield system will be of the order of 2 cft per meter length. Mass in 1,800 meters of system at 1 ata and 65°K is then 76,585 grams (equivalent to 610 liters of liquid). It is obvious that a number of quenching magnets could discharge into the shield system with a resultant slight pressure change. Because of thermal mass in the shield, magnet cooldown after a quench can be carried out as fast as liquid helium can be made available. The warm fluid from the magnet will be discharged into the shield system.

7.2 Replacement of a Magnet:

It is essential that a magnet can be replaced in a reasonable length of time. In order to accomplish this, it is necessary that the total string of magnets need not be warmed to ambient temperature before vacuum is broken. Drawings 7505-E and 7506-E show a concept which allows opening of the vacuum system on either side of the magnet to be removed. Before breaking the vacuum system, magnets and shield system with iron will have been warmed to 80°K.

The procedure is basically as follows:

a) With electric heat, warm all of the shield systems from operating temperature to 80°K.

b) Warm magnets also to 80°K after liquid helium has been removed. This can be done by electric heating also.

c) When the string (1,800 m long) is at 80°K, break the vacuum with bone dry nitrogen gas. Drawing 7506-E shows that the 21-1/2 in. diameter vessel has an insulating vacuum which is separate from the rest of the vacuum system. These vacua will not be broken.

d) With vacuum broken, heat leak to the magnets increases, but at a low rate. This is achieved by covering the flat end plates of the shield system with foam or a similar material of a few inches thickness. Since all connecting boxes between magnets are equipped with superinsulation, heat leak from the environment is determined by the thermal conductivity of the nitrogen gas and the thickness and total surface area of the insulation.

e) Open the connecting boxes at both ends of the magnet to be removed. To reduce the condensation and freezing of water, dry nitrogen gas will flow at a low rate into the open box connection from the magnet string.

f) Break both bore tube connections, and immediately blank off the bore tubes of the magnets remaining in place.

g) Break the 3 in. connection between shield vessels, and immediately cover the 3 in. pipes of the remaining magnets.

h) Break 2 Ø tube connections, and again cover immediately.

i) Break 2 in. shield flow tube, and cover holes with blanks.

j) At this time, only the single phase tubes with superconductors are still connected. Each one of these will be broken, the conductor severed, and the tube closed.

While the above is going on, heat leak to the remaining magnets will slowly increase the temperature of all of these magnets. The rate of rise will be very slow because mass to be heated is enormous, and heat added is at a low rate. This rate is also low for both magnets facing the magnet to be removed. This is achieved by the foam covering the flat end plates of the magnet system.

k) The next step is removal of the magnet and immediate replacement with the replacement magnet. This replacement magnet has been charged with helium gas in order to reduce the contamination level of the circuits after the various tubes have been connected.

l) After tubes have been connected, vacuum integrity, of the newly made joints needs to be made before the vacuum shell is closed up. A technique needs to be developed by means of sniffing the joints. All joints, except those made to the bore tubes, have helium gas on the inside of the joint. It should be possible to perform the vacuum integrity test adequately. The bore tube connections are not critical since the insulating vacuum surrounds these connections.

m) The external vacuum shells will now be installed, and the insulating vacuum will be reestablished. Leak checking of the external shell will be performed.

At this point, the system consists of magnets with a temperature of 90-100°K, except for the replacement magnet which is at ambient temperature.

7.3 Cooling of the Replacement Magnet:

Cooling the shield and magnet by flowing cold helium through the string will cool the magnet, but will not remove the heat from the string. It is merely moved along from magnet to magnet. Cooling the magnets proper with helium flow from the upstream magnets will be feasible when the warm gas at the end of the magnet may be dumped into the shield system of the magnet to be cooled.

It appears then that an external source of refrigeration needs to be applied in order to cool the magnet shield. The amount of cooling required to change the shield temperature from 300°K to 80-100°K is of the order of 1.1 10^9 Joules (32,000 lbs of metal total, including magnets). If liquid nitrogen can be used in some way, a total of 7,000 liters of liquid nitrogen is required. If done in 48 hours, rate of refrigeration application is of the order of 6,400 W.

Although wasteful, it might be worth considering to consume helium gas by pushing gas from the upstream shield system into the warm shield and out into the atmosphere downstream of the shield being cooled. In that case, cooling can be accomplished quickly in a matter of 12 hours or less. Consumption of helium would be of the order of 250,000 scft (9,000 to 10,000 liters of liquid). Cost is of the order of $20,000. Although this sounds expensive, it may not be all that bad when compared to the cost of having the system inoperational for 1.5 to 2 days or the cost of liquid nitrogen and the extra equipment necessary to apply the refrigeration properly. The anticipated frequency of the operation also will have a bearing on the economics of throwing helium gas away.

Once the replaced magnet has been cooled to the same temperature as the other magnets, final cooldown may be started. The magnets will be filled with liquid helium at the fastest possible rate. The vaporized liquid will be returned through the shield system. Additional cooling of the shield system will be provided by the refrigerator.

It should be noted that magnets may be made operational before the iron has been cooled to final steady state conditions. Heat leak to the 4.5°K level will be somewhat higher, but extra refrigerator capacity or stored liquid helium can provide the extra required for the few days necessary to cool the shield to steady state condition.

APPENDIX A

Support System for Magnets in Iron (Reference Drawing 7504-D)

Moment of inertia of tube located between magnet and iron is:

$$I = .049\ (D^4 - d^4)$$

Where: D = O.D. in inches.

d = I.D. in inches.

$$t = \frac{D - d}{2}$$

Then:

$$I = .049\ D^4\ \left[1 - \left(\frac{D - 2t}{D}\right)^4\right]$$

When t is much smaller than D, we may substitute as follows:

$$1 - \left(\frac{D - 2t}{D}\right)^4 = \frac{8t}{D}$$

Then:

$$I = .392\ D^3\ t \qquad (1)$$

Deflection of the support tube needs to be limited to a maximum value. The deflection for the particular arrangement is given by:

$$Y = \frac{7}{768}\ \frac{w\ L^4}{EI}$$

Where: Y = maximum deflection in inches.

L = distance between support points.

w = load per inch of length of magnet.

Substitution of (1) leads to:

$$Y = \frac{7}{768}\ \frac{w\ L^4}{E \times .392\ D^3\ t} =$$

$$= .02325\ \left(\frac{w}{E\ D^3}\right)\ \left(\frac{L^4}{t}\right)$$

By fixing the maximum deflection, we find that:

$$\frac{L^4}{t} = 43.0 \frac{Y_m E D^3}{w} = C_1 \qquad (2)$$

Heat leak through the support tube is defined by:

$$Q = \frac{N A}{1/2 L} \int Kdt$$

Where: N = number of parallel tubes.

A = cross section of tube for heat flow.

L = distance between supports.

$$A = \pi D t$$

$$N = \frac{480}{1/2 L} = \frac{960}{L}$$

Then:

$$Q = \frac{2 \times 960}{L^2} \times \pi D t \int KdT$$

$$= 6032 \frac{Dt}{L^2} \int KdT \qquad (3)$$

Substitution of (2) in (3) yields:

$$Q = \frac{6032 D L^2}{C_1} \int KdT \qquad (4)$$

Equation (4) states that the length of the support tube between rings should be as short as possible. The significant parameter is t, the thickness of the support tube. There probably is a reasonable minimum thickness which determines the shortest reasonable length, L.

Table I shows various numbers for a wall thickness of .020 in. and .035 in. respectively:

TABLE I

Wall Thickness (inch):	.020	.035
Tube Diameter (inch):	5.000	5.000
Maximum Deflection (inch):	.010	.010
Magnet Weight (lb/inch):	4.5	4.5
Length Between Rings (Inch):	76.72	88.23
Number of Parallel Support Tubes:	12-1/2	11
Heat Leak:	.1025 $\int K dt$	.1356 $\int K dT$
Ratio of Heat Leaks:	.756	1.0