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A LARGE SUPERCONDUCTING DETECTOR MAGNET WITHOUT AN IRON RETURN PATH

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ABSTRACT

This paper describes a detector magnet which returns flux between the coils rather than through an iron return path. This actively shielded uniform field 2 T magnet can be fabricated in separate parts which can be manufactured on the SSC site. This magnet can be built so that central field is uniform enough to permit a TPC detector to be used without iron poles. The field outside of the coil can be made to fall off as R^{-N} power where N approaches 9. A major advantage of the magnet described in the paper is that there is no pole piece to block the particle jets emanating from the collision region in the forward and backward directions. Inexpensive materials such as earth and concrete can be used to provide the mass needed to analyze particles such as mu mesons. As a result, problems such as experimental hall subsidence can be reduced. Perhaps the cost of such an experiment can also be reduced. This type of magnet would require experimenters to rethink their experimental concepts.

BACKGROUND

The SSC, a large machine, will produce proton collisions of 20 TeV on 20 TeV. The collisions result in many fragments which must be detected in a large number of detectors around the collision point. Large magnetic fields can be used to bend charged particles which will permit the mass and momentum of these particles to be calculated. The volume of the magnetic field must be large (at least 5 meters in diameter and 7 or 8 meters long).

In order to generate a large volume magnetic field, superconducting magnets provide an economical way of generating the magnetic field. A large volume of magnetic field implies that there must be a large ferromagnetic return path. If the magnetic field must be uniform, the iron return path and pole pieces must be machined in order to achieve the desired field uniformity. The conventional approach to building large detector magnets would require up to 30000 tons of iron to shape the magnetic flux and return it.

A large massive iron return path has a number of disadvantages which include: 1) The iron density is high enough to cause serious subsidence problems at the site of the experiment, 2) When the desired field is uniform, the iron blocks particles which travel at low angles in the direction from which the colliding beams come. The disadvantages given above can be modified

somewhat by the proper design of iron return path. The result is a larger iron return path mass and an even more complex design for the iron.

This paper presents an alternative approach to detector magnets. This is a modest proposal for a large superconducting magnet which will produce a uniform field over a volume which is four meters in diameter and four meters in length. The proposed magnet has no iron return path, yet the magnetic induction 20 meters from the collision point is less than 10 Gauss. The no iron detector magnet requires that one rethink the design of SSC physics detectors.

THE IRON FREE DETECTOR MAGNET AND ITS EFFECT ON PHYSICS

For some types of SSC detectors, it may be desirable to eliminate the iron shielding and return yoke. The iron free detector magnet is in principle like the actively shielded magnetic resonance imaging magnets (MRI), which have been built by Oxford¹ and other companies.² Two general designs were looked at for magnets which have a free bore diameter of at least 7.5 meters.

The two designs can be described as follows:

- 1) The first type of magnet is the two solenoid type of actively shielded magnet, which is shaped like a cylinder. This type of magnet is the state of the art actively shielded MRI magnet. This type of magnet, when it has an inside bore of 7.5 m would have an overall length of about 28 to 30 meters and an outside diameter of about 16 meters. Magnets of this type have been built with warm bore diameters of 1 meter. This type of magnet has a peak field which is 10 to 15 percent higher than the central field of the magnet.³ This type of magnet is well suited for use as a high central induction magnet ($>3T$).
2. The second type of actively shielded magnet is a spherical type of magnet which was developed at Stanford University⁴ for MRI imaging of the heart and the circulatory system. This magnet, when it has a minimum warm bore diameter of 7.5 meters, will have an overall length of 14 meters and an outside diameter of about 19 meters. A magnet of this type has a peak induction at the conductor which is 60-80 percent higher than the central induction. This type of magnet is well suited for central inductions below 3.0T.

The advantages of the solenoidal design are: 1) The peak field in the winding is only 15 percent higher than the magnet central field. 2) The field is quite uniform over a region which is up to 6 meters in diameter over a length of about 12 meters without an iron return path. The disadvantages of this type of magnet are as follows: 1) The magnet is large, and it is difficult to fabricate in pieces on the site. The transport of magnets with a warm bore over 5 or 6 meters is difficult under the best conditions. 2) The free solid angle in the forward and backwards directions from the collision point is only about 20 degrees from the proton beam line. 3) Physics is difficult to do outside of the 3.75 m radius over the full length of the solenoid magnet. 4) The 10 Gauss induction line is 38 meters

from the collision point in the radial direction and 48 meters from the collision point along the beam axis.

The advantages of the spherical design are: 1) The field is quite uniform over a diameter of 4 to 5 meters and a length of 6 to 8 meters without an iron return path. 2) The free solid angle in the forward and backwards directions from the collision point is about 35 degrees from the proton beam line. 3) At high solid angles from 60 to 90 degrees from the proton beam around the collision point, physics can be done out to a radius of 5.5 meters. 4) The 10 Gauss line is 18 meters from the collision point in the axial direction. 5) The magnet can be built in pieces on the site and it can be assembled on site. The disadvantages of this type of magnet are as follows: 1) The field rise at the conductor is 65 percent higher than the central field. This is acceptable in a 2.0 Tesla magnet, but it is not acceptable in a 4 or 5 Tesla magnet. 2) The members which carry the forces between the magnet coils must be cold. These forces are much larger than in the solenoid design.

The spherical solenoid design was selected as the candidate for an iron free detector magnet. The use of such a magnet configuration requires one to rethink how one might do the physics. If the magnet has no iron return yoke, one must use other materials such as concrete, heavy concrete with barites, earth and other relatively low density materials to moderate the particles generated at the collision point around which the experiment is being done. This may require one to look at different types of detectors to do the physics.

The advantages of the iron free magnet are: 1) The up to 30000 tons of iron return path can be eliminated. If iron is used in the experiment, the coil design must be altered. 2) Up to 35 degrees in the forward and backwards directions is completely free for looking at the particle jets created at the intersection point. 3) Cheap materials such as concrete and earth can be used to moderate the particles. There is a saving in foundation cost and subsidence is greatly reduced. The disadvantages are: 1) The magnet coils block particles at a radius of 4 meters from the proton beam line at solid angles from 35 to 60 degrees from the proton beam line. This radius goes out to 5.5 meters for an angle of 60 to 90 degrees from the proton beam line. 2) Some kinds of experiments require dense materials to moderate the particle produced at the collision point. Iron is one of the least expensive dense materials to use as a moderator. 3) The stray field from the magnet can have an adverse effect on some types of detectors. The colliding proton beams may have to be carried in superconducting shielded beam pipes.

A DESIGN FOR A SPHERICAL IRON FREE DETECTOR MAGNET

Figure 1 shows a schematic of an eight coil iron free detector magnet using the spherical solenoid coil concept. The good field region, which has a field uniformity of better than one part in 1000 is defined as a spherical region which is 4 meters in diameter with the center of the sphere at the SSC proton beam collision point. The magnet shown in Figure 1 has a nominal design central induction of 2T (if one makes the spherical magnet somewhat smaller, say two-

Figure 1
A SPHERICAL DETECTOR MAGNET
WITHOUT AN IRON RETURN PATH

thirds of the size shown in Figure 1, the central induction could be increased to 3 Tesla).

The magnet design process uses Legendre polynomials of the first kind to expand the field inside of the coil.⁵ Legendre polynomial of the second kind are used for the field outside of the coils (when one looks at the problem, the use of Legendre polynomials of the second kind are not needed). The magnetic field is designed to be axially symmetric. The net magnetic Legendre dipole, sextupole and decapole moments are zero by design (for both the inner and outer fields) and the quadrupole, octupole, 12 pole and so on are zero by symmetry. Since the magnetic moments up to $N = 7$ are zero, the field outside of the magnet coils falls off rapidly (as radius to the minus nine power).

Figure 2 shows a computer drawing of the magnet coils for the actively shielded spherical axially symmetric magnet. The round dot indicates current flow into the paper; the square dot indicates current flow out of the paper. The design shown in Figure 2 produces an axially symmetric dipole of 2 Tesla, with no axially symmetric quadrupole, sextupole, octupole, decapole or 12 pole. The first higher term to appear in either the internal or external field is the axially symmetric 14 pole. A magnetic induction contour map for the magnet is shown in Figure 3 and the magnetic flux line contour map is shown in Figure 4. The flux which is inside the inner coils (coils 1 and 2) is returned between the inner coils and the outer coils (coils 3 and 4). Very little flux escapes from the magnet.

Table 1 presents parameters for the spherical no iron detector magnet shown in Figure 1 and 2. The eight coil magnet system has an overall coil length of 13.6 m and an overall diameter of 18.5 m. When a 2.0 Tesla central field is generated, the peak induction in coil 2 is 3.3 Tesla. The external induction out to a distance of 25 meters from the collision point is shown in Figure 5. The 1 gauss line is about 24 meters from the collision point in the radial direction, and it is about 28 meters from collision point in the axial direction. The shielding achieved can be controlled by thin windings mounted on the outer coils (coils 3 and 4). Table 1 assumes that the inner and outer coils are operated off of a single 12kA power supply. Quench protection can be provided by a single 0.16 ohm external dump resistor.

Table 2 presents the parameters for the four coil types. (There are two coils of each type.) A calculation of hoop stress in the four coil types indicate that the copper based superconductor within the pure aluminum stabilizer can carry the hoop forces in coils one and two. In coils three and four additional hard aluminum (6061 - T6) is required to carry the hoop forces generated in those coils. The large intercoil forces from coils 4 to coils 1 and coils 2 to coils 1 must be carried by cold members between the coils.

The total conductor mass for the eight coils is estimated to be 492 metric tons. The total magnet mass is estimated to be about 900 metric tons (the outer coils which return the flux represents about half the total mass). The total coil surface area would be around 1600 square meters. Based on experience with the TPC magnet,⁶ about 500 W of refrigeration is required at 4.2 K and about 2000 W of

Figure 2

**SUPERCONDUCTING COIL PLACEMENT
FOR A LARGE NO IRON SPHERICAL
DETECTOR MAGNET FOR THE SSC**

Figure 3

**MAGNETIC INDUCTION CONTOUR MAP
FOR A LARGE NO IRON SPHERICAL
DETECTOR MAGNET FOR THE SSC**

Figure 4

**A MAGNETIC FLUX LINE CONTOUR MAP
FOR A LARGE NO IRON SPHERICAL
DETECTOR MAGNET FOR THE SSC**

Table 1
PARAMETERS FOR A LARGE
SUPERCONDUCTING
DETECTOR MAGNET
WITHOUT AN IRON SHIELD

PARAMETER	
Central Magnetic Induction (T)	2.0
Good Field Length (m)	4.0
Good Field Diameter (m)	4.0
Inside Coil Diameter (m)	7.92
Outside Coil Diameter (m)	18.12
Magnet Overall Length (m)	13.60
Magnet Overall Diameter (m)	18.50
Number of Coils	8
Number of Magnet Turns	5720
Magnet Self Inductance (H)	71.62
Magnet Design Current (A)	10126
Magnet Stored Energy* (MJ)	3672
Matrix Current Density* (A/sq cm)	1315
Winding Peak Induction (T)	3.3
Maximum 10 Gauss Distance (m)	20.5
Type of Superconductor	Nb-Ti
Matrix Material	copper
Stabilizer Material	pure Al

Table 2

**PARAMETERS OF THE NO IRON DETECTOR
MAGNET SUPERCONDUCTING COILS**

Coil Parameter	Coil 1	Coil 2	Coil 3	Coil 4
Coil Outside Diameter (m)	12.330	8.636	18.114	13.840
Coil Inside Diameter (m)	11.670	7.914	17.814	12.880
Distance from Center (m)	0.018	3.231	0.024	5.672
Coil Length (m)	3.000	2.160	2.400	0.930
Number of Layers	11	12	5	16
Number of Turns #	1100	864	400	496
Coil Design Current (A)*	10126	10126	-10126	-10126
Conductor Mass (tons)**	93	50	51	52
final Coil Mass (tons)##	145	89	120	84

Conductor matrix size 2.7 by 2.8 centimeters

*** Current to generate an induction of 2.0 tesla at the magnet center**

**** Conductor mass for each coil in metric tons**

Coil plus cryostat mass for each coil in metric tons

Figure 5

**MAGNETIC INDUCTION OUTSIDE OF
A LARGE NO IRON SPHERICAL
DETECTOR MAGNET FOR THE SSC
(The Log10 of the Magnetic induction in Tesla)**

magnet,⁶ about 500 W of refrigeration is required at 4.2 K and about 2000 W of refrigeration is required at 80K in order to keep the magnet cold. A refrigerator equivalent to the LBL 1500 W machine^{7,8} can handle the combined refrigeration liquefaction load required for the no-iron detector magnet with a minimum of 7.5 diameter clear bore.

CONCLUDING COMMENTS

A large superconducting detector magnet can be built with bucking coils to return the magnetic flux. The mass of the bucking coils and the effect on the local environment is smaller than for a similar magnet with an iron return path. The induction at the beam intersection point for a magnet with a clear bore of 7.5 m can be as high as 2.0 Tesla. The field can be uniform (to 1 part in 1000) within a 4 meter diameter sphere centered at collision point. The field 25 meters from the collision point will fall off the 2.5 gauss or less.

The proposed detector magnet should be built on the site and assembled along with the experiment. A no-iron detector magnet requires one to rethink about physics options for the SSC. This type of magnet will not achieve all the physics goals for the SSC, but it will be good for analyzing particle jets up to a solid angle of 35 degrees from the proton beam line.

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