BENT SOLENOID SIMULATIONS FOR THE MUON COOLING EXPERIMENT

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ABSTRACT

The muon collider captures pions using solenoidal fields. The pion are converted to muons as they are bunched in an RF phase rotation system. Solenoids are used to focus the muons as their emitance is reduced during cooling. Bent solenoids are used to sort muons by momentum. This report describes a bent solenoid system that is part of a proposed muon cooling experiment. The superconducting solenoid described in this report consists of a straight solenoid that is 1.8 m long, a bent solenoid that is 1.0 m to 1.3 m long and a second straight solenoid that is 2.6 m long. The bent solenoid bends the muons over an angle of 57.3 degrees (1 radian). The bent solenoid has a minor coil radius (to the center of the coil) that is 0.24 m and a major radius (of the solenoid axis) of 1.0 m. The central induction along the axis is 3.0 T There is a dipole that generates an induction of 0.51 T, perpendicular to the plane of the bend, when the induction on the bent solenoid axis is 3.0 T.

INTRODUCTION

The proposed muon cooling experiment[1,2] consists of a pair of S shaped solenoid bends each of which has two bent solenoids, and straight solenoids for four TPC detectors and an 805 MHz RF cavity[3]. Between the two S shaped bend sections is a straight muon cooling section. The energy and momentum of the muon beam are analyzed by the S shaped bent solenoid systems before and after the straight solenoidal muon cooling section. A schematic representation the muon cooling experiment is shown in Figure 1.

After the beam goes through first S shaped solenoid for energy and momentum analysis, the muon beam enters a muon cooling section that is about 15 meter long. The cooling section consists of ten alternating solenoids with a peak induction of 15 T. The muons are cooled by a liquid hydrogen section that is about 400 mm long and 70 mm in diameter. After the muon momentum has been reduced by about 25 MeV/c, the muon are re-accelerated by a 900 mm long 805 MHz RF cavity section back to their original energy of about 180 MeV. The second S shaped solenoid section analyzes the energy and momentum of the muons after they have gone through cooling.

The bent solenoid separates muons by momentum spatially across the bore of the solenoid following the bent solenoid. A coil that generates a dipole field in the bent solenoid moves the momentum separated muons so that their momentum separation is distributed around the center of the solenoid following the bent solenoid.
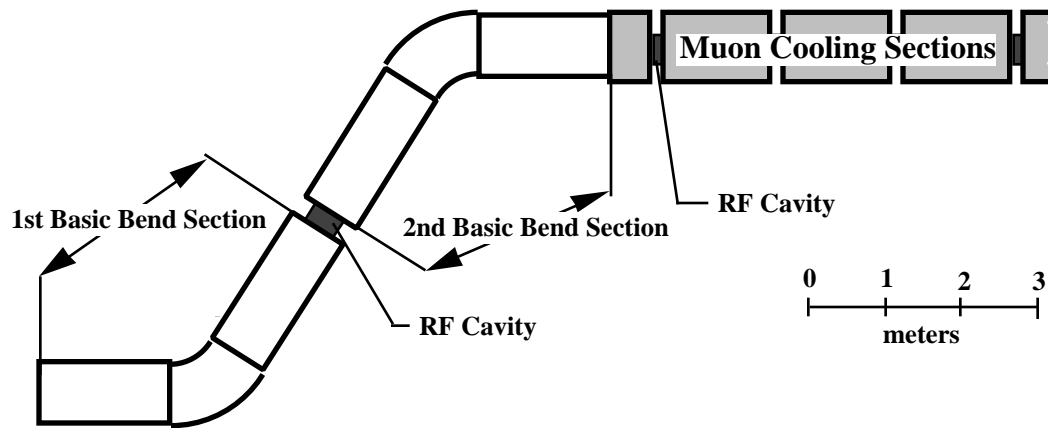
Fig. 1 The S Bend Bent Solenoid System at the Start of the Muon Cooling Channel

THE BENT SOLENOID SYSTEM DESIGN

The following design assumptions were used for the preliminary design of the superconducting bent solenoid system: 1) Magnetic flux is conserved in the solenoids. Magnetic flux conservation means that all of the solenoid coils have the same average current radius. This minimizes the leakage flux into the TPC detectors. 2) The warm bore diameter for the for the two TPC solenoids and the bent solenoid need only be about 320 mm. The solenoid around the RF cavity must have a warm bore diameter of about 440 mm. 3) The solenoid bend angle used for this study is 57.3 degrees (1 radian). The exact bend angle required for the muon cooling experiment will depend on the average momentum of the muons cooled and the muon momentum spread that will be measured. 4) The average bend radius for the bent solenoid axis will be 1000 mm. Simulations of particle motion within the solenoid suggest that the bend radius should be variable with a longer radius at the beginning and end of the bend and a shorter radius for the center of the bend. The variable bend radius may improve the efficiency of the transfer of the muons through the solenoid. 5) The bent solenoid induction on axis will be 3.0 T. 6) In order to have momentum separation at the center of the solenoid, a bent solenoid dipole is of 0.51 T is needed on the axis. The on axis dipole field can be provided using separate dipole winding or by tilting the bent solenoid coils. 7) Standard MRI superconductor has been assumed for the solenoid windings. The solenoids are hooked together electrically in series. 8) In the TPC, the integral of the r component of field over the integral of the z component of field is less than 0.0002 within the TPC active volume. The TPC active volume is assumed to be 160 mm in diameter by 500 mm long near the center of the TPC solenoid. 9) The TPC cables are fed out of the solenoid through room temperature slots between coils that are located at the ends of the TPCs away from the bent solenoid. 10) The two TPC solenoids, the bent solenoid and the RF solenoid share a common cryostat vacuum vessel. The two straight solenoids and the bent solenoid are assumed to have separate cold mass support systems. The cryostat ends at the center of the RF cavity so that the RF wave guide can enter the cavity between the solenoids. 11) The superconducting coils are assumed to be cooled by conduction to a system of pipes attached to the outside of the magnet, which carry two-phase helium.

The first basic bend section shown in Figure 1 is shown in Figure 2. This section goes from the first TPC solenoid to the solenoid that covers half of the RF cavity. The average coil diameter for the magnets shown in Figure 2 is 480 mm. The smallest coil diameter in the TPC magnet section is about 450 mm. The coils around the RF coil clear the warm bore of the cryostat by about 10 mm. The coils around the RF cavities are located inside of an aluminum support structure that has the helium cooling tube attached to it. The bent solenoid shown in Figure 2 is a constant bending radius solenoid. The dipole coils for the bent solenoid are not shown in Fig. 2. The solenoidal coils parameters are shown in Table 1. All of the solenoidal coil shown in Fig. 2 and described in Table 1 are designed to be powered by a single power supply. The total stored energy in the string shown in Fig. 2 is 3.06 MJ. The high current density magnet coils (163.3 A per square mm) would require that the coils be subdivided so that they can be protected by cold diodes and resistors.
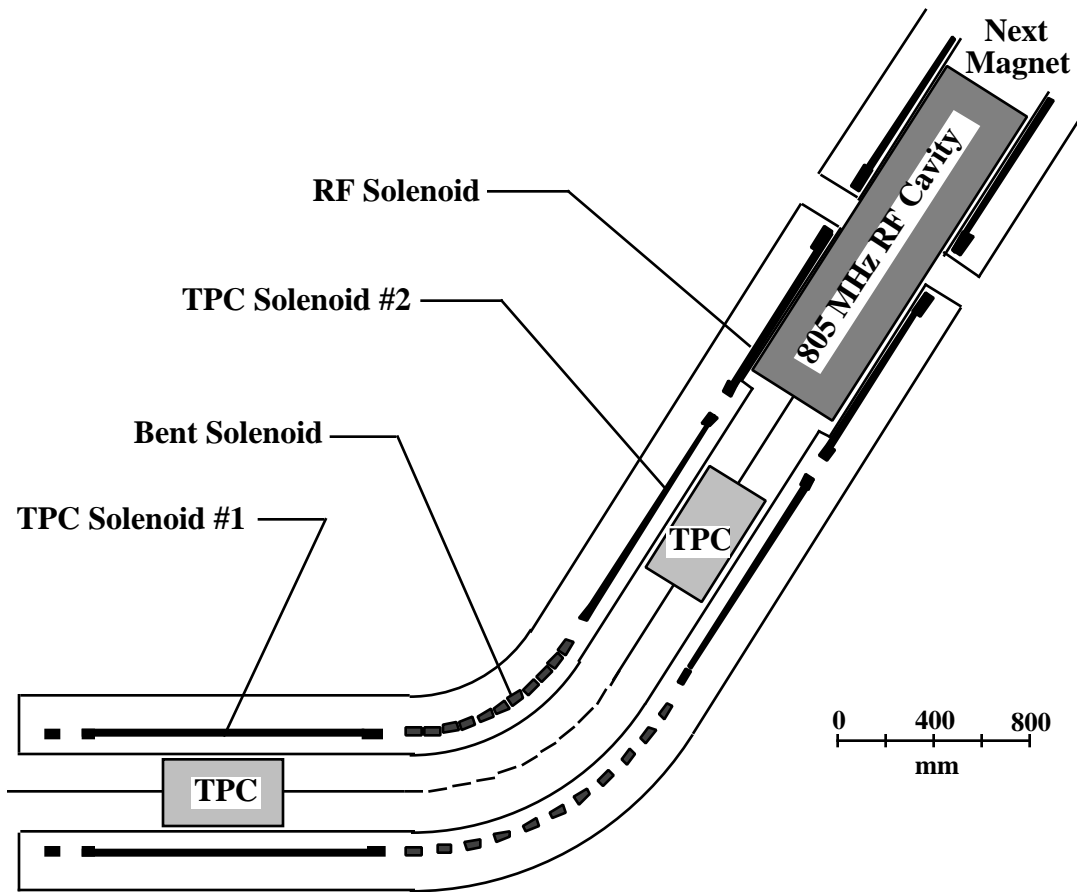
Fig. 2 Cross-section of One Bend Magnet Section for the muon Cooling Experiment
Showing the Locations of the TPC Detectors and the 805 MHz RF Cavity

Table 1 Parameters for the Solenoids in the Bent Solenoid Assembly Shown in Figure 2

	TPC # 1	Bent Sol.	TPC #2	RF Sol.
Warm Bore Diameter (mm)	320	320	320	440
Cryostat Outer Diameter (mm)	800	800	800	800
Cryostat Section Length on axis (m)	1.6	1.2	1.1	0.8
Number of Coils	2	11	1	1
Coil Average Diameter (mm)	480	480	480	480
Coil Thickness (center) (mm)	17.9	25.7	17.9	17.9
Coil Thickness (ends) (mm)	34.8	NA	34.8	34.8
Center Coil Length (mm)	1100	50	870	550
End Coil Length (mm)	50	NA	50	50 & 100
Number of layers (center)	16	31	16	16
Number of Layers (ends)	32	NA	32	32
Number of Turns per Layer Center	686	30	544	344
Number of Turns per Layer Ends	31	NA	31	31 & 62
Central Induction on axis (T)	3.0	3.0	3.0	3.0
Coil Design Current (A)	257.3	257.3	257.3	257.3
Coil Section Stored Energy (MJ)	1.04	0.78	0.72	0.52
Coil Section Inductance (H)	31.4	23.7	21.7	15.7
Conductor Current Density (A mm^{-2})	163.3	163.3	163.3	163.3
EJ (10^{22} J A^2 m^{-4})*	2.8	2.1	1.9	1.4

* Quench protection must be supplied to each magnet. Cold diode and resistor quench protection is attractive for these
   magnets. A separate power supply can be used for each string of magnets. HTS current leads could be used.

THE BENT SOLENOID THE ASSOCIATED DIPOLE

The bent solenoid is used to separate charged particles by momenta. A bent solenoid will cause the charged particles to be separated along a line away from the solenoid axis. It is desirable to have the separated particles centered on the solenoid axis. A dipole field that perpendicular to the bend plane is used to center the separated charged particles in the solenoid at the end of the bend. The magnitude of this dipole field is proportional to the axial field at the center of the bent solenoid, the particle charge, and the mean charged particle momentum. An expression for the required dipole induction on the bend solenoid axis, perpendicular to the plane of the bend can be given as follows:

$$B_d = G(p_c,q)\frac{B_s}{r_s} \tag{1}$$

where B_d is the dipole induction required to center the separated charged particles on the solenoid axis; B_s is the on axis solenoidal induction; r_s is the local bend radius (given in SI units) for the bent solenoid; and $G(p_c,q)$ is the fitting parameter that is a function of the mean particle momentum pc and the particle charge q. For a muon with a charge q = 1 or q =-1 and a mean momentum p_c of 180 MeV/c, the value of $G(p_c,q)$ is about 0.17.

A dipole field can be generated using a cosine theta distribution of currents flowing in a direction parallel to the solenoid axis, on the surface of the solenoid. The highest current (where cosine theta = 1) must be on the bend plane that includes the bent solenoid axis. This distribution of current will produce a perfect dipole superimposed on the solenoidal field if a cosine theta distribution of current is put around a straight solenoid. When the solenoid is bent, a cosine theta current distribution will no longer produce a perfect dipole. The magnitude of the dipole will vary as r over r_s. Near the bent solenoid axis one will have a dipole plus a quadrupole field in the direction perpendicular to the plane of the solenoid bend. Studies indicate that one can alter the cosine theta distribution of the current only a few degrees to achieve a pure dipole in a bent solenoid.

Particle tracking studies were done with a dipole superimposed on a bent solenoidal field. The greatest efficiency of particle transport through the bent solenoid occurred when the impressed dipole had a small amount of quadrupole added to the dipole field in the bent solenoid. The amount of this quadrupole term is between the quadrupole produced when a cosine theta distribution of currents is used to generate the dipole and no quadrupole at all (the perfect bent dipole case). This suggests that the bent solenoid dipole winding may be more complicated than originally thought.

The original bent solenoid studies were done using bent solenoids with a constant bend radius. Particle tracking studies show that the efficiency of particle transmission through the solenoid can be improved considerably by varying the radius of curvature in the solenoid so that the kick in the particles in the horizontal direction increases adiabatically as the particle enters the bent solenoid and decreases adiabatically as the particles leave the bent solenoid. This also means that the impressed dipole B_d must vary along the length of the bent solenoid. This further complicates the design of the bend solenoid and the dipole needed to center the particles spread by momentum.

One way to produce the dipole in a bent solenoid with a variable bend is to tilt the coils in the bent solenoid. Tilting the coils a small angle will produce a dipole field that will vary as r over rs. A small angle tilt will cause the on axis solenoidal field to be reduced as the cosine of the tilt angle . This reduction can be compensated for by increasing the current in the coils that make up the bent solenoid. The tilt angle can be estimated using the following expression:

$$= \sin^{-1}[\frac{B_d}{B_s}] \tag{2}$$

where Bd and Bs have been previously defined. The only extra windings needed are quadrupole windings used to tune the bent solenoid for maximum through put of charged particles. Figure 3 shows a cross-section of a bent solenoid with a variable bend radius. The variable bend sections are coils 1 through 5 and 11 through 15. The first and fifteenth coils have the same axis as the adjacent solenoids. The first five coils and last five coils each produce a total bend of 11.46 degrees. The middle five coils bend of 34.38 degrees.

Coil #15

Coil #1

Number of Coils = 15
Total Bend Angle = 57.3 degrees
Coil Average Radius = 240 mm
Coil Radial Thickness = 32.7 mm
Coil Physical Length = 56 mm
Inside Coil Spacing = 17.5 mm
Outside Coil Spacing = 70.5 mm
Number of Coil Layers = 31
Number of Turns per Layer = 30
Number of Turns per Coil = 930
Design Current = 256.7 A
Design on axis Induction = 3.0 T
Bend Length on Axis = 1300 mm
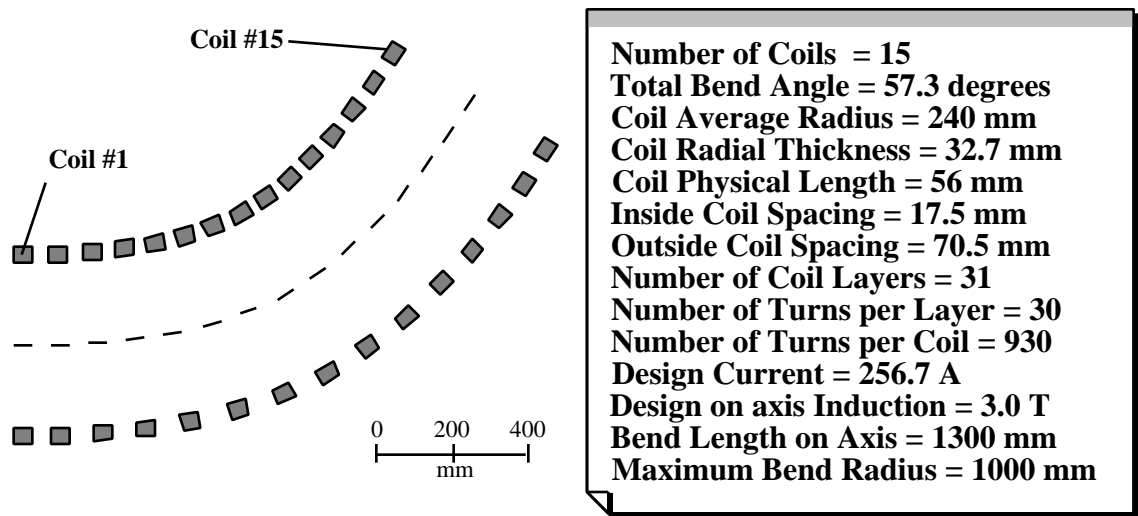**Maximum Bend Radius = 1000 mm**

0   200   400
mm

Fig. 3 A Cross-section View of a 57.3 Degree Bend Magnet Section with Variable Bend Radii
Coils 1 through 5 and 11 through 15 Variable, Coils 6 through 10 Bend R = 1000 mm

The cross-section shown in Figure 3 is in the plane of the bend of the bent solenoid. Each of the 15 coils shown in Figure 3 has the same cross-section and the same number of turns. The table next to Figure 3 is a parameter list for the coils and the variable bend radius bent solenoid. Each coil is assumed to be wound using a 0.955 x 1.65 mm MRI superconductor with 155 filaments about 51 microns in diameter in a copper matrix. The copper to superconductor ratio is 4. This conductor is designed to carry a minimum current of 760 A at 5 T and 4.22 K. The J_c at 5 T and 4.22 K is at least 2400 A mm^{-2}. There is enough margin in the coil to permit the central induction of the bent solenoid to be increased to over 4 T and still have a current margin of 85 percent of critical current along the load line

The bent solenoids shown in Figure 2 and 3 can be built using identical coil packages. The bend and tilt for the solenoid coils is achieved by machined spacers between the standard coil packages. These spacers can be welded to the coil winding forms. The coils can be wound on aluminum winding forms and have aluminum spacers between the coils. Once the coils are assembled into a bent solenoid and welded, the coils can be connected together in series. The spacers allow one to vary the bend radius and tilt angle of the coils to produce the needed dipole field as well as the solenoidal field. Table 2 below shows the parameters of the variable bend radius solenoid shown in figure 3. The dipole is produced by tilting the superconducting coil packages. Table 2 shows the dipole needed in various parts of the bent solenoid shown in Figure 3 along with the coil tilt angle needed to produce that dipole field. At a current of 256.7 A, the solenoid produces and integrated solenoid induction of 3.859 Tm with an average solenoidal induction of 2.969 T. An increase of the bent solenoid current by 1.06 percent will bring the average solenoidal field up to 3.0 T.

Table 2 Parameters for the Variable Bend Angle Bent Solenoid Shown in Figure 3

	Bend R (mm)	Coil Bend Angle (Degrees)	Dipole B (T)	Coil Tilt Angle (Degrees)
Coils 1 and 15*	infinite	0.00	0.000	0.00
Coils 2 and 14	5000	1.15	0.102	1.95
Coils 3 and 13	2500	2.29	0.204	3.90
Coils 4 and 12	1667	3.44	0.306	5.85
Coils 5 and 11	1250	4.58	0.408	7.82
Coils 6 through 10	1000	5.73	0.510	9.79

* Coils 1 and 15 are part of the straight solenoids before and after the bent solenoid.

BENT SOLENOID FIELD UNIFORMITY STUDIES

A study was done to see what effect the bent solenoid would have on the field uniformity within the straight solenoids where the TPC are to be installed. The integral of the r component of field over the length of the TPC over the length of the axial component of field over the length of the TPC should be less than a few parts in 10000. This field uniformity should be occur within the 150 mm in diameter by 400 mm long active volume of the TPC. The following can contribute to the field errors in the two TPC detectors: 1) the holes in the coil were the TPC electronic cables pass out of the cryostat, 2) the field error due to the field from the bent solenoid and 3) the field non uniformity due to the dipole in the bent solenoid. The field uniformity along the axis of the bent solenoid is nominally set to be better than one part in 1000. The off axis solenoidal field is nominally proportional to 1 over R from the center of the solenoid bend. At 75 mm from the axis, on the inside of the bend, the induction is 3.243 T. On the outside of the bend, 75 mm from the solenoid axis, the induction is 2.791 T. In the non bent sections of the solenoid, the solenoid field is supposed to be uniform across the solenoid.

A computer model of the TPC magnets and the bent solenoid was made. The model has the following characteristics: 1) TPC solenoid and the bent solenoid have an average coil diameter of 400 mm. The coils were assumed to be 20 mm thick sheets. 2) The bent solenoid had a constant radius bend of 1000 mm, and it consists of ten straight coils that are 80 mm long. On the inner part of the bend the ten straight coils touch each other and on the outer part of the bend (in the plane of the bend) the coils are separated by a gap of 40 mm. 3) The dipole is located outside of the bent solenoid. The current distribution in the dipole coils is a skewed cosine theta current distribution that produces a perfect dipole at the center of the bent solenoid. The point of zero current is moved a few degrees toward the outside of the solenoid bend. The ends of the dipole make a simple up and over curve over the ends of the bent solenoid, so that the ends of the bent dipole correspond to the ends of the bent solenoid. Figure 4 is a plot of field error defined as 1-BR/BoRo on axis and on curves ± 75 mm from the axis on the plane of the bend. R is the radius of the line from the bending axis and Ro is the radius of curvature of the bend. B is the calculated induction; and Bo = 3.00 T. Within the straight solenoid sections, R over Ro is assumed to be one.
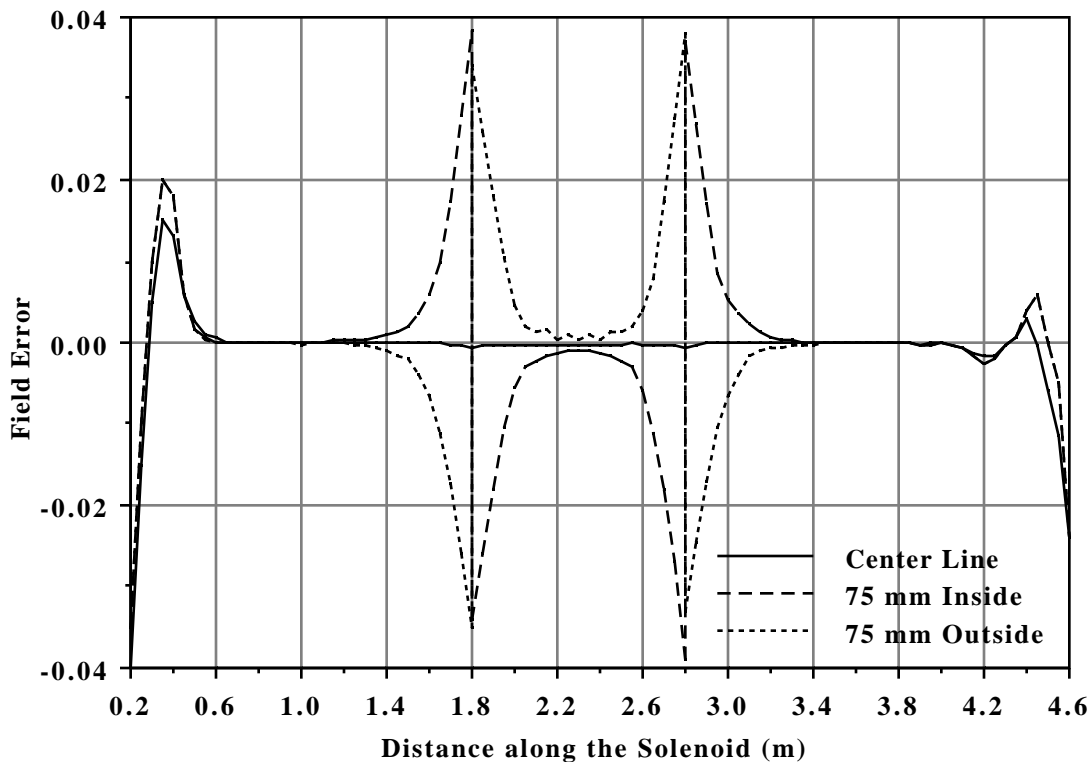

Fig. 4 Field Uniformity Versus Distance along the Solenoid and Distance from the Solenoid Axis
in the Bend plane (Note: The field uniformity is corrected for radius in the bent solenoid.)

The two regions of near zero field error in the solenoid between z = 0.7 and z = 1.2 m and between z = 3.3 m and z = 3.9 m are the regions where the TPC detectors would be located. Within these regions, the maximum field error is ±0.0002 (2 parts in 10000), which is good enough for TPC detectors. The integrated field error within both TPC detectors is less than ±0.0001. The field error excursions at z < 0.6 m and z > 4.1 m are due to field fall off at the physical ends of the straight solenoids.

The bent solenoid extends from z = 1.8 m to z = 2.8 m in the model studied. At the ends of the bent solenoid, the field error approaches ±4 percent. The large excursions of the field error curves shown in Figure 4 are caused by the round ends of the bend dipole, that is mounted on the outside of the bent solenoid. The ends of the dipole cause the largest field errors observed in the study. In the central region of the bent solenoid, one can see that the field error curve for 75 mm inside of the solenoid axis is rather smooth whereas the field error curve for 75 mm outside of the axis has a number of oscillations with a period of about 0.1 m. The amplitude of the field error oscillations is less than 0.001 peak to peak. The oscillations are due to the 40 mm gap between the coils on the outside of the bent solenoid. The field error curve inside the axis of the solenoid does not exhibit these oscillations because there are no gaps between the coils.

Moving the average current radius from 200 mm to 240 mm from the solenoid axis will improve the field uniformity (maybe a factor of two) both in the TPC detectors and in the bent solenoid. Using a variable bend radius bent solenoid, with tilted coils to produce the dipole, should also improve the field uniformity in the bent solenoid. The quadrupole windings needed to correct the dipole generated by the tilted coils should produce a far smaller field error than the separate dipole windings used in the study. The end effect due to the quadrupole windings will be shorter. One should be able to reduce the field errors in the bent solenoid by over an order of magnitude by using a combination of a larger diameter solenoid, a variable bend radius, and tilted coils to produce the dipole.

CONCLUSION

A combination of two straight solenoids on the ends of a bent solenoid was studied. The bent solenoid can be fabricated from a number of identical straight superconducting coils. The bent solenoid can be fabricated so that its bend radius can be variable. A bent solenoid must also have a dipole to move the center of the particle momentum spread to the center of the solenoid following the bend. This dipole can be provided by a separate winding, or it can be provided by tilting the bent solenoid coils. If this dipole is produced by tilting the solenoid coils, separate quadrupole windings must be used. Field errors studies indicate that the field in a straight solenoid near a bent solenoid can be made good to a few parts in 10000, which is suitable for a TPC detector. The magnitude of the field error due to individual bent solenoid coils can be made to be less than one part in 1000 in a region that is 150 mm in diameter within a 400 mm diameter bent solenoid. It appears that the field uniformity can be improved by using larger solenoid coils, a variable bend radius in the bent solenoid and tilted bent solenoid coils to produce the dipole.

ACKNOWLEDGMENTS

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