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Superconducting Helical Solenoid Systems for Muon Cooling Experiment at Fermilab

Vladimir S. Kashikhin, Nikolai Andreev, Rolland P. Johnson, Vadim V. Kashikhin, Michael J. Lamm,
Gennady Romanov, Katsuya Yonehara, Alexander V. Zlobin

Abstract— **Novel configurations of superconducting magnet system for Muon Beam Cooling Experiment is under design at Fermilab. The magnet system has to generate longitudinal and transverse dipole and quadrupole helical magnetic fields providing a muon beam motion along helical orbit. It was found that such complicated field configuration can be formed by a set of circular coils shifted in transverse directions in such a way that their centers lay on the center of the helical beam orbit. Closed beam orbit configurations were also proposed and investigated. This paper describes the magnetic and mechanical designs and parameters of such magnetic system based on a NbTi Rutherford type cable. The helical solenoid fabrication, assembly and quench protection issues are presented.**

***Index Terms*—Helical Solenoid, Magnetic Design, Muon Cooling, Superconducting Magnet System.**

I. INTRODUCTION

THE 6-dimensional muon ionization-cooling experiment is now under design at Fermilab [1-2]. The main magnet system of this experiment is a Helical Cooling Channel (HCC). Two superconducting concepts of HCC were investigated. The first has a large bore (~ 1 m diameter) superconducting solenoid with outer helical dipole and quadrupole coils. The second is a helical superconducting solenoid of 0.5 m diameter with the coil sections shifted in the transverse direction to simultaneously generate solenoidal, helical dipole and helical quadrupole field components. Both magnet system concepts were discussed in [3]. The comparison showed the advantage of the Helical Solenoid (HS) from a magnet system point of view. The HS has half the coil diameter and superconductor volume, seven times lower total magnetic field energy, lower peak field in the superconductor (5.7 T vs. 7.6 T), a correspondingly lower level of Lorentz forces and naturally generated helical dipole and quadrupole fields. This more efficient concept of HS was chosen for further investigation and briefly discussed in [4,5]. This paper summarizes further investigations of the HCC for muon beam cooling. Proposed novel beam closed orbit magnet system configurations.

II. SINGLE HELICAL SOLENOID

The Single Helical Solenoid (SHS) described in [3] has the general parameters and geometry shown in Fig. 1 and Table I.

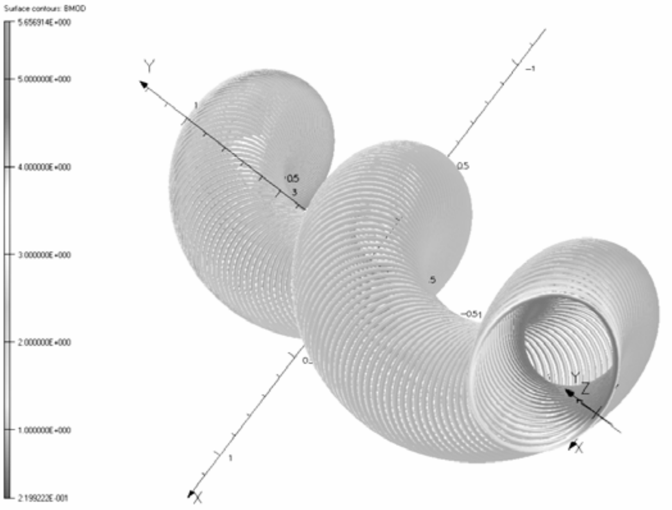

Fig. 1. Helical Solenoid geometry and flux density.

TABLE 1 Helical Solenoid Parameters

Parameter	Unit	Value
Inner bore diameter	m	0.5
Helical Solenoid length	m	4.0
Helix twist pitch	m	1.6
Radius of beam reference orbit	m	0.255
Initial dipole field, B_τ	T	1.25
Dipole field gradient, $\partial B_\tau/\partial z$	T/m	-0.17
Initial quadrupole field, $\partial B_\tau/\partial r$	T/m	-0.88
Quadrupole field gradient, $\partial^2 B_\tau/\partial r/\partial z$	T/m^2	0.07
Initial field, B_z	T	-3.86
Longitudinal field gradient, $\partial B_z/\partial z$	T/m	0.54
NbTi superconductor peak field	T	5.7
Operational current	kA	10
Operating stored energy	MJ	4.4
Coil section length along Z axis	mm	20
Superconducting cable length	km	3.3

The main concept of this approach is to use circular short coils shifted in the transverse direction to the z axis. All coil centers lay on a helical beam orbit and are equally distributed along z. Because each coil is tilted relative to the helical beam

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V. S. Kashikhin, N. Andreev, V. V. Kashikhin, M. J. Lamm, K. Yonehara, A. V. Zlobin are with the Fermi National Accelerator Laboratory, Batavia, IL 60510 USA (corresponding author phone: 630-840-2899; fax: 630-840-3369; e-mail: kash@fnal.gov).

R. P. Johnson is with Muons Inc., Batavia, IL 60510 USA.

orbit direction, it simultaneously generates longitudinal and transverse field components. The inner volume of the magnet system is filled with a liquid helium (LHe) or a hydrogen gas which are energy absorbers for the ionization-cooling experiment.

The muon momentum is reduced from 300 MeV/c to 160 MeV/c in passing along the 5.6 m helical path through the LHe absorber. and the magnetic field strength must diminish with the momentum to provide a stable beam orbit. Magnetic field simulations were performed to investigate the behavior of the SHS. Fig. 2 shows the relative field components for a model in which the current in the coils was decreased linearly as a function of the longitudinal z-coordinate with gradient -13 %/m.

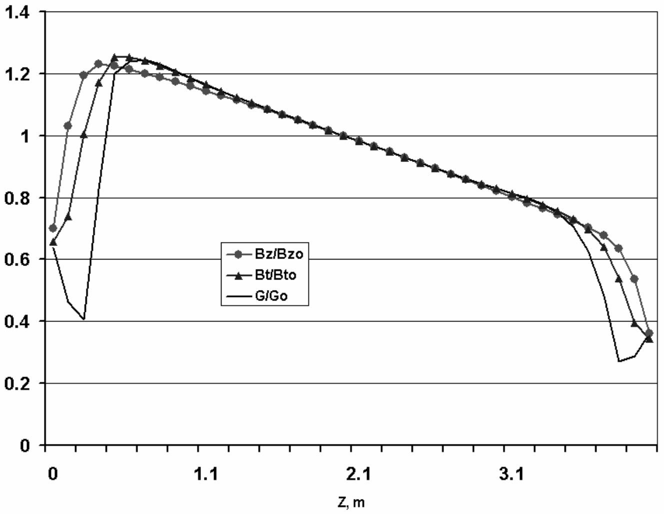

Fig. 2. Field distribution related to the values at z=2 m (Bzo=-3.37 T, Bto=1.04 T, Go=-0.9 T/m).

One can see the interesting result that the three important field components, (solenoidal (Bz), helical dipole (Bt), and helical quadrupole (Gz)), scale with the coil currents. Fig. 3 shows the dependence of the three field components as a function of coil radius.

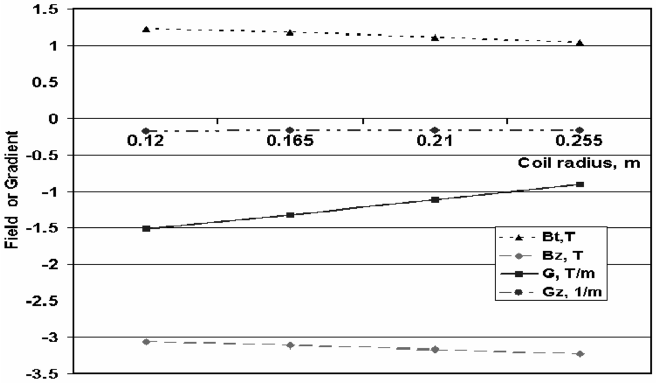

Fig. 3. Field and field gradient dependence.

As follows from Fig. 3 there is a linear dependence of field components and gradient with the coil radius change. At the same time Gz gradient is constant and defined only by coil currents.

The Helical Solenoid have fixed helical dipole and quadrupole fields. The muon cooling experiment will be more attractive if helical dipole and quadrupole fields will be regulated in wide range of helical field levels independently from the Bz solenoidal field. The helical dipole and quadrupole coils should correct ~30 % of corresponding field component.

III. DOUBLE HELICAL SOLENOID

The Single Helical Solenoid will occupy only a spiral space inside cylindrical ~1 meter diameter liquid helium vessel. There is enough space to place the second Helical Solenoid shifted on a half helix twist pitch in longitudinal direction. Fig. 4 shows the Double Helical Solenoid (DHS) of novel configuration. The direction of currents in opposite sections defines if the longitudinal Bz field components have the same or opposite directions. The same Bz field directions for the DHS channels open a possibility to use this system for particles having the same sign of charge. Another more attractive opportunity is to have opposite currents and Bz fields (see Fig. 5) in opposite coils. So, positive and negative muons could be cooled in parallel channels. In this case also both helical channels could be used in a closed orbit configuration. The DHS parameters for this option are shown in Table 2. One can see that in DHS with opposite currents the transverse Lorentz forces goes to the system center and self-compensated. It reduces demands to the outer mechanical support structure and provides better mechanical stability of superconducting coils.

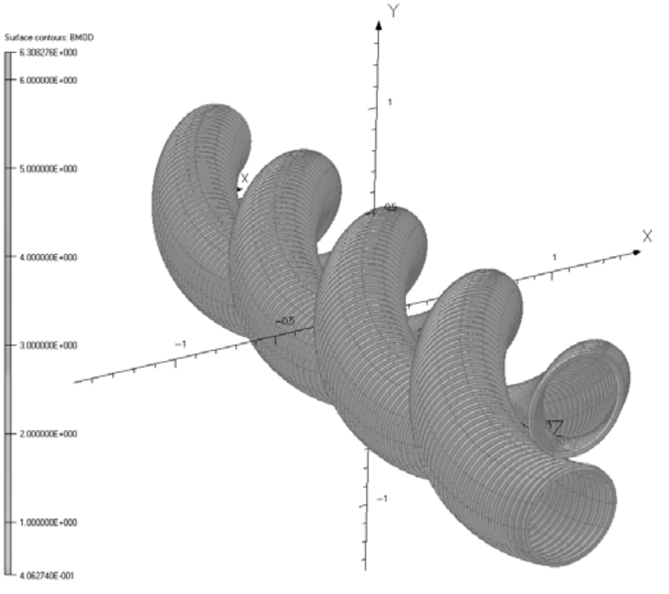

Fig. 4. Double Helical Solenoid geometry and flux density.

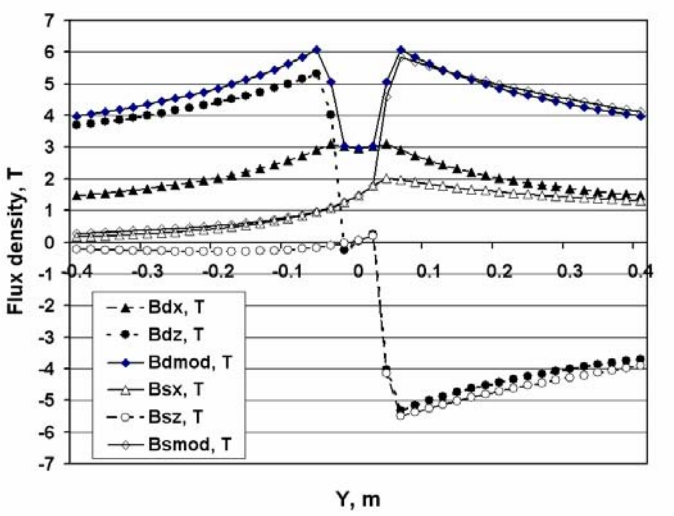

Fig. 5. Field distribution in 3.2 m Single and Double Helical Solenoids at z=1.6 m and x=0. Field components Bsx, Bsz, Bsmod are for single and Bdx, Bdz, Bdmod are for double solenoid.

TABLE II Double Helical Solenoid Parameters

Parameter	Unit	Value
Inner coil diameter	m	0.42
Double Helical Solenoid length	m	1.6
Helix twist pitch	m	1.6
Radius of beam reference orbit	m	0.255
NbTi superconductor peak field	T	6.3
Operational current	kA	10
Operating stored energy	MJ	4
Coil section length along Z axis	mm	20
Superconducting cable length	km	2.2

As follows from Fig. 5 the Bz field components are close for SHS and DHS. The transverse Bx field components in beam area are in range of 1.5 – 2 Tesla but DHS has two times larger $\partial B_r/\partial r$ transverse gradient -3.3 T/m and -1.65 T/m correspondingly. In [3] was shown the linear dependence between SHS optimal transverse gradient for a longitudinal cooling and the helix period. For SHS with 0.5 m coils inner diameter the optimal helix period is 1.6 m. For DHS with 0.42 m coil diameter and larger gradient the helix period should be reduced and optimized.

IV. CLOSED ORBIT MAGNET SYSTEMS

The proposed SHS and DHS muon cooling channels could be used for muon beam cooling in closed orbit configurations. The main advantage of closed orbit systems are to extremely reduce the total future channel cost, incorporate room temperature [6-10] or even superconducting RF cavity to compensate muon energy losses in absorber, and improve the total cooling channel performance using multi turn beam circulation. Fig. 6 shows the view of muon cooling experiment based on SHS.

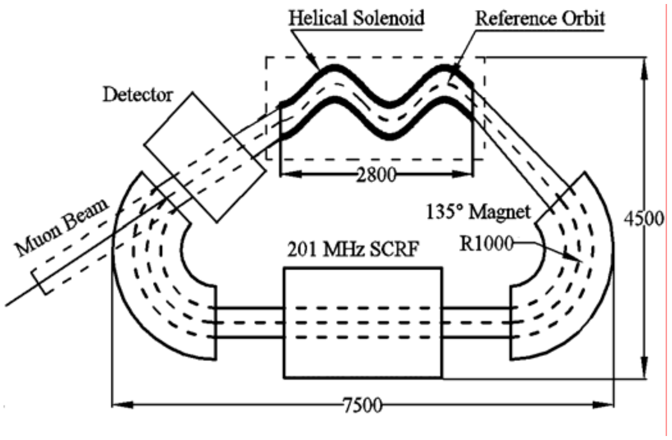

Fig. 6. Schematic view of muon cooling experiment with Single Helical Solenoid. All dimensions in mm.

The system includes: SHS, three combined function magnets which provide beam closed and stable orbit, 201 MHz superconducting or room temperature RF cavity, and muon detector. All magnets and SCRF could have common cryostat and beam pipe. The 320 mm diameter beam pipe could be filled with hydrogen gas used as an absorber. The beryllium foils and wedges used as gas absorber breakers and additional absorbers. The combined function magnets should have ~ 1.1 T dipole magnetic field, plus quadrupole and sextupoles correctors. The SCRF cavity is shielded from external magnetic fields by an iron shield to the level of several μT. During experiments to obtain optimal cooling the absorber gas pressure is regulated to match the RF cavity integrated gradient and the absorber energy losses. The helical solenod has helical dipole and quadrupole correctors to optimize the ionization cooling and provide stable closed orbit. Because muons have a very short life time (~ 5.6 μs at energy 250 MeV/c) the number of turns and particle path length is limited. More compact magnet system could be built on the base of DHS. Fig. 7 shows the view of such system where at the end of the cooling channel the muon beam rotated by 270° and goes in opposite direction through the second helical solenoid in the DHS.

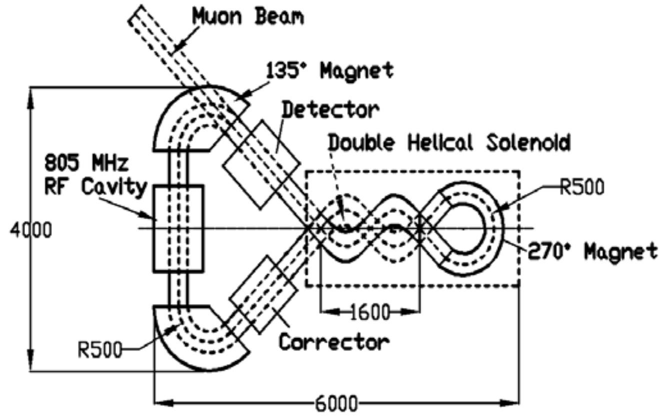

Fig. 7. Schematic view of muon cooling experiment with Double Helical Solenoid. All dimensions in mm.

The closed orbit beam circulation where beam goes in opposite directions in helical channels and turned back at the cooling channel ends by dipole magnets has more compact configuration and better combined with 805 MHz cavity [9]. All magnets have main dipole coils, quadrupole and sextupole correctors. Besides the multipole corrector placed at the exit from the Helical Channel to focus the beam for further transportation. The goal of this section is to propose for investigation closed orbit configurations. The obvious difficulties are: the beam injection and proper matching with the Helical Channel, beam transportation without emittance grouth and losses, correct synchronization RF cavity phase and beam. But all of these overcompensated by substantial cost reduction of cooling channel for future muon accelerators and the experimental possibility to confirm the ionization cooling effect for the muon beam.

V. SHORT MODEL PROTOTYPE

The Helical Solenoid generates complicated helical field components and corresponding Lorentz forces. These forces are intercepted by the outer collar structure. Fig. 8 shows a mechanical design of a short (~100 mm long) solenoid section to be used as a prototype to prove the SHS design and manufacturing technology.

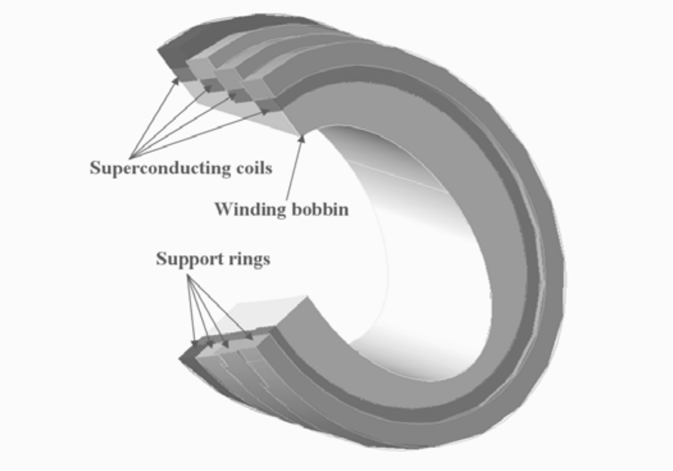

Fig. 8 Helical Solenoid short section geometry.

Single layer coils are continuously hard bend wound with NbTi Rutherford type SSC cable on an inner support cylinder, while outer collar rings are correspondingly mounted, section by section. After assembly, rings are welded to each other, the whole assembly is vacuum impregnated with epoxy, forming a solid mechanical structure. Mechanical stresses at a nominal current in this cold mass assembly are less than 50 MPa. The level of stresses well models the long Helical Solenoid mechanical structure. For the long solenoid a one meter diameter outer stainless steel tube will be used as the solenoid support structure and as an outer wall of liquid helium vessel. This tube will protect the magnet system from longitudinal and transverse motion under Lorentz forces.

VI. CONCLUSION

The proposed magnet system configurations are very promising for further investigations. The careful beam optics analysis with control of total muon cooling effect should be made to confirm the efficiency of closed orbit magnet systems. Also should be designed beams injection, extraction and detection systems for which could be used conventional particle accelerator technology.

Nevertheless, it is possible to highlight the following advantages:

- Single Helical Solenoid provides effective 6-D muon beam ionization cooling (see [4] and [5]);
- Double Helical Solenoid could be used for ionization cooling of two muon beams with opposite particle charge;
- Single and Double Helical Solenoids provide effective way of building the closed orbit cooling channels with open for RF cavity installation structure.
- Dipole magnets at the ends of magnet system combined with gas absorbers or beryllium wedges in addition capable to increase beam cooling efficiency;
- It is convenient at closed orbit system ends inject and extract the beam;
- RF could be mount in a very low magnetic field region and even superconducting RF technology could be used;
- An absorber gas pressure inside the helical channel could be regulated to match RF structure integrated acceleration gradient;
- Closed orbit system configurations extremely reduce the cooling channel cost and improve muon beam cooling efficiency by multi turn passing.

REFERENCES

[1] Y. Derbenev, R.P. Johnson, Phys. Rev. STAB 8, 041002, 2005.

[2] R. Gupta et al., "Letter of intent to propose a six-dimensional muon beam cooling experiment for Fermilab" http://www.muonsinc.com/tiki_download_wiki_attachment.php?attId=36

[3] V.S. Kashikhin, *et al*., "Superconducting magnet system for muon beam cooling", Proceedings of Applied Superconductivity Conference, ASC 2006.

[4] V. S. Kashikhin, *et. al*., "Magnets for the MANX 6-D cooling demonstration experiment", Particle Accelerator Conference, Albuquerque, 2007, to be published.

[5] K. Yonehara *et al*., "The MANX muon cooling demonstration experiment", Particle Accelerator Conference, Albuquerque, 2007, to be published.

[6] A. Moretti, *et. al*., "RF cavities for the muon and Neutrino Factory collaboration study", XX International Linac Conference, Monterey, California.

[7] J. Corlett *et al*., "High-Gradient normal-conducting RF structures for muon cooling channels" PAC2001, Chicago, 2001

[8] J. Corlett *et al*., "RF accelerating structures for the muon cooling experiment ", PAC'99, New York, March 29-April2, 1999.

[9] Derun Li *et al.*, "Design and fabrication of an 805 MHz RF cavity with Be windows for a high RF power testing for a muon cooling experiment", PAC2001, Chicago.

[10] A. Moretti, *et al*., "π/2 interleaved cavity developments for the muon collider cooling experiment", Linear Accelerator Conference, Chicago 1998.