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Superconducting Magnet System for Muon Beam Cooling

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***Abstract*—A helical cooling channel has been proposed to quickly reduce the six-dimensional phase space of muon beams for muon colliders, neutrino factories, and intense muon sources. A novel superconducting magnet system for a muon beam cooling experiment is being designed at Fermilab. The inner volume of the cooling channel is filled with liquid helium where passing muon beam can be decelerated and cooled in a process of ionization energy loss. The magnet parameters are optimized to match the momentum of the beam as it slows down. The results of 3D magnetic analysis for two designs of magnet system, mechanical and quench protection considerations are discussed.**

***Index Terms*—Muon cooling, superconducting magnet, solenoid, helical magnet**

I. Introduction

THE helical muon cooling channel is being designed at Fermilab. Investigations of the cooling channel physics demonstrated the high efficiency of such system [1-2]. Proposed by Muons, Inc. MANX experiment [3] is to experimentally verify this approach. To achieve the maximum 6D emittance reduction, the MANX magnet system should produce longitudinal and transverse field components on the beam orbit. In addition, all field components should have appropriate gradients in the longitudinal direction.

During the physics investigation phase, the beam optics analysis was based on magnetic field analytically described by Bessel functions that automatically satisfies the Laplace equation in the current-free region, but gives no warranty that a particular field distribution is feasible from a practical viewpoint. The main goal of the work being described is to determine if it is possible to generate the necessary fields by an unambiguous magnet system via a reasonable number of coils.

The design principles employed for the helical magnets have been known for decades [4]-[5]. Normal-conducting helical dipoles with the operating field of 1.7 T were constructed at IHEP [6]. A superconducting helical dipole magnet with the operating field of 3 T was built at BNL [7]. Those magnets, however, had a constant helical field component in the longitudinal direction. The requirement of having longitudinal field gradients brings an additional design challenge that has not been addressed before.

Two approaches to the magnetic system of muon cooling channel have been studied. The first one has a large cylindrical bore encompassing the beam helix. The second one has twice smaller helical bore that follows the beam orbit.

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II. Muon Cooling Channel Parameters

The muon cooling channel parameters were carefully optimized to obtain the maximum beam cooling effect in the MANX experiment [3]. Table 1 summarizes the latest generation of geometrical constraints and magnetic field requirements on the beam orbit in cylindrical coordinates, where B_τ is the transverse tangential field component and B_z is the longitudinal field component. The second transverse field derivative was not considered in this study due to its small effect on the beam cooling factor.

TABLE I
Reference Parameters of Muon Cooling Channel

Parameter	Unit	Large bore	Small bore
Length of the good field region	m	4.0	3.2
Helix twist pitch	m	2.0	1.6
Radius of the reference orbit	m	0.25	0.25
Initial B_τ	T	1.045	1.249
$\partial B_\tau/\partial z$	T/m	-0.133	-0.170
Initial $\partial B_\tau/\partial r$	T/m	0.603	-0.882
$\partial^2 B_\tau/\partial r/\partial z$	T/m^2	-0.052	0.069
Initial B_z	T	-3.753	-3.859
$\partial B_z/\partial z$	T/m	0.467	0.544

III. Large Bore Cooling Channel

The relatively small field level in the cooling channel encourages implementation of well-known NbTi technology. The NbTi superconducting wire with J_c(5 T, 4.2 K) = 3000 A/mm^2 was used in the design of the cooling channel. In order to provide the good field quality over the necessary length, the accelerator magnet design typically requires adding at least one bore radius to each end of the good field region that for the given channel results in the straight section length of 5 m.

A. Helical Dipole

After weighting different design approaches in terms of simplicity and efficiency, a layered design concept was developed. In that concept, the coil consists of a number of layers; each layer has a uniform cross-section and a constant current throughout the entire length. The upstream end of each layer is located at the same longitudinal coordinate, while the downstream end coordinate varies along the channel, providing the longitudinal gradient.

In the current iteration of the cooling channel design the helical dipole consists of six layers. The first layer has 5 m long straight section that results in the total coil length of ~7 m. Each next layer straight section is shorter than the previous one by the half-period of helix (1 m) with the last layer having zero straight section length. Fig. 1 shows the layered helical dipole coil designed with the help of OPERA 3D code to match the B_τ and $\partial B_\tau/\partial z$ components in Table I and the field it produces on the beam orbit. It is possible to see that the required helical dipole component and its longitudinal gradient are reproduced relatively well. Also, the initial $\partial B_\tau/\partial r$ component is pretty close to the required value. Thus, only the average longitudinal gradient $\partial^2 B_\tau/\partial r/\partial z$ needs correction that can be achieved with the help of a dedicated quadrupole coil.

B. Helical Quadrupole

The helical quadrupole coil design is based on the same layered concept as the helical dipole coil. Since the initial transverse field derivative produced by the dipole is close to the required value, the current in the quadrupole coil should start from zero at the upstream end that allows trimming the coil length. Fig. 2 shows the eight-layer helical quadrupole coil around the dipole coil and their combined fields. The first layer of the quadrupole coil has 3.5 m long straight section and is shifted by 1 m towards the downstream end. Each next layer is shorter than the previous one by the quarter-period of helix (0.5 m), while the downstream end of each layer is located at the same longitudinal coordinate as the downstream end of the first layer. One can see that the average $\partial^2 B_\tau/\partial r/\partial z$ component is close to the required. Also, it is clear that the helical coils produce the B_z component with the opposite sign and longitudinal gradient than the one required for the beam cooling. It has to be corrected by the main solenoid.

C. Main solenoid

According to Table I, the solenoid should produce the largest field component of all. Thus, it makes sense to place it between the dipole winding and the bore tube: first – to maximize its efficiency, and second – to avoid unnecessary exposure of other coils to strong longitudinal field. The sectioned design was used to generate the field gradient in the longitudinal direction. Since the solenoid has no geometrically distinguished ends (like a dipole), an extra two bore radii were added to the criterion mentioned earlier to compensate the field decay. The solenoid has a total length of 6 m and consists of 12 sections with a varying number of ampere-turns. It can be achieved by changing the winding pitch or powering each section from a separate power supply. Each section has a uniform current density. Fig. 3 shows the helical dipole, quadrupole and solenoid coils and their combined field. One can see that in average all field components and their longitudinal gradients are close to the required values.

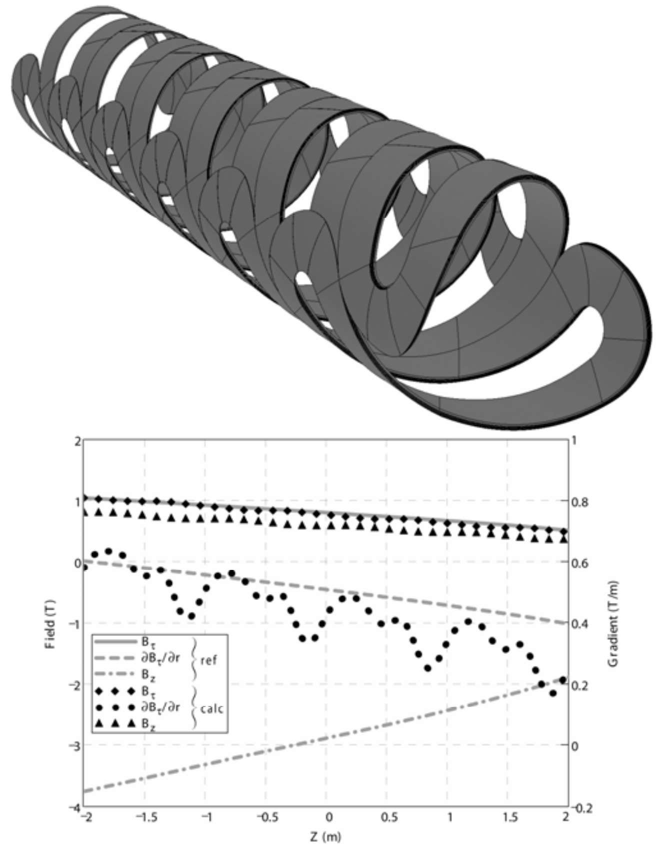

Fig. 1. Upstream end view on the layered helical dipole coil (top) and the field it produces (bottom).

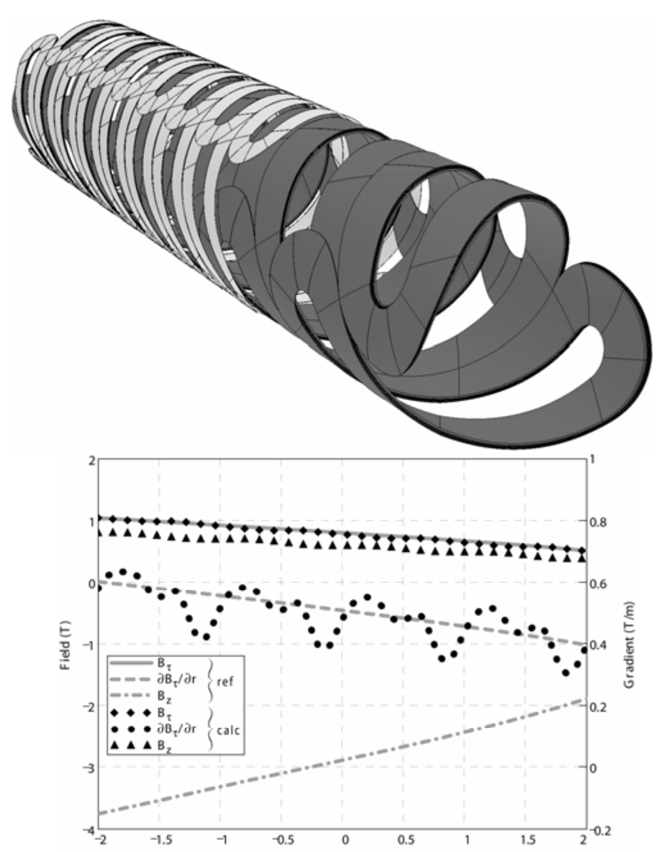

Fig. 2. Upstream end view on the layered helical dipole and quadrupole coils (top) and the field they produce (bottom).

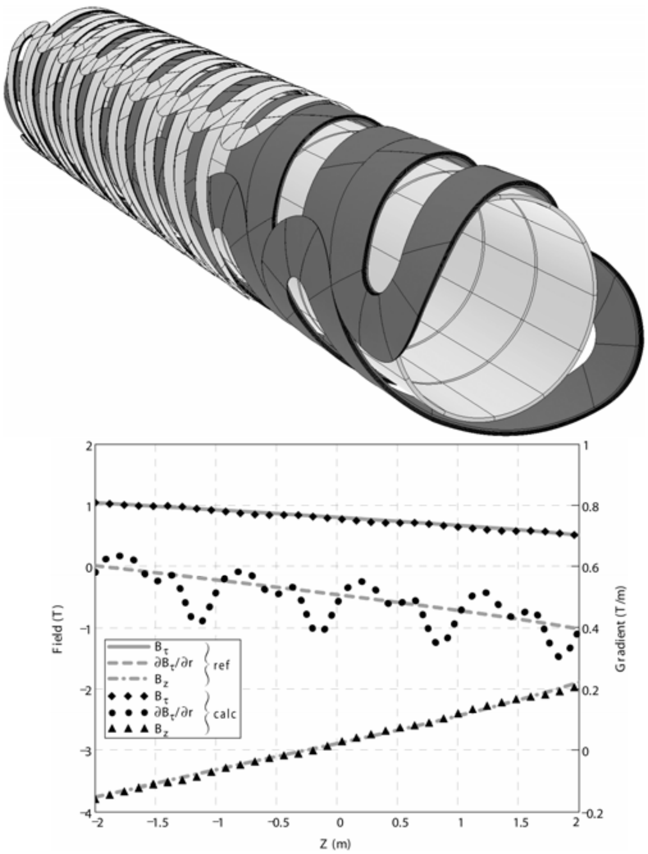

Fig. 3. Upstream end view on the layered helical dipole, quadrupole and solenoid coils (top) and the field they produce (bottom).

Table II lists the parameters of the large bore system. One can see that the dipole and quadrupole coils have large (30-50%) field margins to quench that offsets the unknown factors related to complicated helical coil geometries. The solenoid, on the other hand, has a simple axisymmetric geometry with a large bending radius that may reliably operate with the 10% margin. Otherwise, the radial thickness of several upstream sections can be increased to gain the necessary margin.

TABLE II
PARAMETERS OF LARGE BORE COOLING CHANNEL

Parameter	Unit	Dipole	Quad	Solen
Inner radius	m	0.55	0.58	0.50
Radial thickness: innermost layer	mm	10.00	1.00	20.00
Radial thickness: all other layers	mm	2.72	1.00	-
Radial space between layers	mm	1.00	1.00	-
Operating current density†	A/mm^2	174.3	61.3	253.6
Operating peak field	T	6.41	2.49	7.60
Quench peak field‡ at 4.2 K	T	8.56	3.66	8.37
Operating stored energy	MJ		31.84	

†Calculated as the total current over the total conductor cross-section.

‡Calculated in assumption that the non-Cu fraction of superconductor spans 30% of the total conductor area and the current density in other coils remains at the operating value.

IV. Small Bore Cooling Channel

Another novel approach is to use a helical solenoid to generate the needed fields. The solenoid consists of a number of ring coils shifted in the transverse plane such that the coil centers follow the helical beam orbit. The current in the rings changes along the channel to obtain the longitudinal field gradients. Apart from the large bore system, where the longitudinal and transverse field components are controlled by independent windings, the small bore system has a fixed relation between all components for a given set of geometrical constraints. Thus, to obtain the necessary cooling effect, the coil should be optimized together with the beam parameters.

Fig. 4 shows the optimum initial transverse field gradient $\partial B_\tau/\partial r$ from the beam simulations and the one calculated in the helical solenoid as a function of helix period. One can see that the optimum gradient for the helical solenoid is -0.8 T/m, corresponding to the period of 1.6 m. Besides that, the system has other variables, one of which is the inner coil radius. For example, 0.2 m radius increase corresponds to -1 T/m change in the transverse field gradient. At the same time, it has a small influence on the dipole and longitudinal field components that provides another effective way of transverse gradient optimization. Fig. 5 presents the optimized helical solenoid with 1.6 m period consisting of 73 coils and its field. Table III lists the parameters of the small bore system.

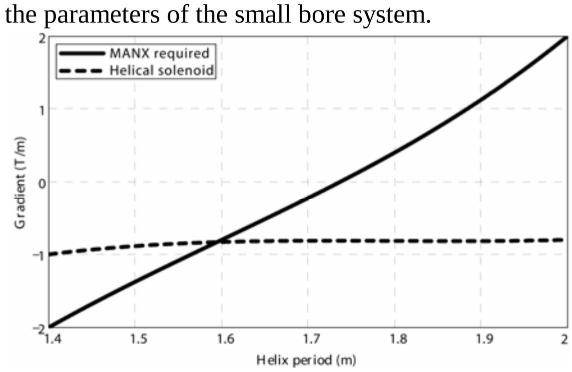

Fig. 4. Initial transverse field gradient as a function of helix period.

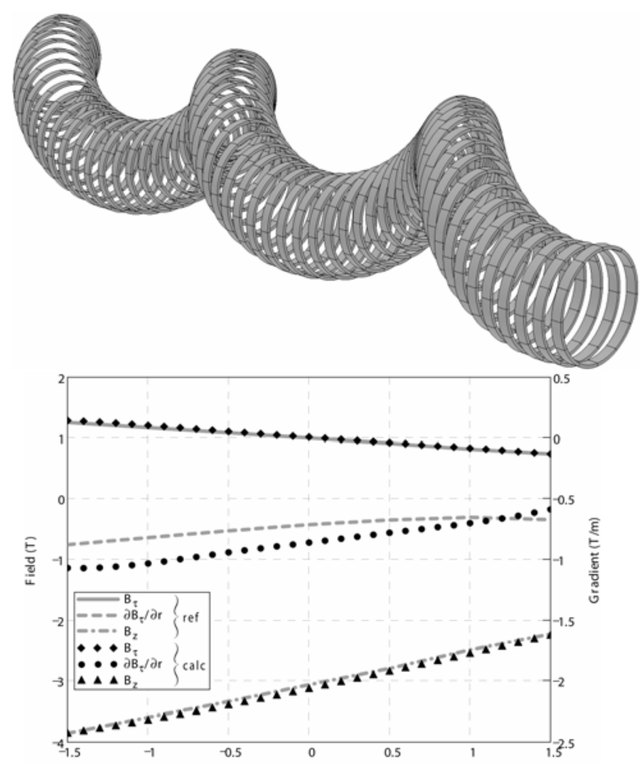

Fig. 5. Helical solenoid coil (top) and the field it produces (bottom).

TABLE III
PARAMETERS OF SMALL BORE COOLING CHANNEL

Parameter	Unit	Value
Inner radius	m	0.25
Radial thickness	mm	15.00
Operating current density†	A/mm^2	268.0
Operating peak field	T	4.43
Quench peak field‡ at 4.2 K	T	7.38
Operating stored energy	MJ	2.65

†Calculated as the total current over the total conductor cross-section.

‡Calculated in assumption that the non-Cu fraction of superconductor spans 30% of the total conductor area.

V. MECHANICS AND QUENCH PROTECTION

A. *Mechanics*

The magnet systems generate 4-7 T fields in the coils. Large Lorentz forces should be intercepted by a strong support structure to provide the conductor mechanical stability. The large bore solenoid should have ~25 mm thick stainless steel support cylinder. Forces applied to the dipole and quadrupole coils are relatively small because they are mounted outside of the solenoid in a lower field area and a simple aluminum shrinkage cylinder can provide the needed support.

The helical solenoid has more complicated forces and torques between the coils. The maximum forces are at the beginning of the cooling channel. The forces are both compressing the magnet in the longitudinal direction and acting to straighten the helical coil.

B. *Quench Protection*

The magnet systems store 3-30 MJ of in magnetic field and should have an active quench protection. In spite of the large stored energy, the sectioned design approach allows independent energy extraction from the coil sections that offers a great flexibility in limiting voltages and temperatures. The relevant conductor parameters and system configuration will be determined during the quench protection analysis to limit the turn to turn and turn to ground voltages at <1 kV and coil hot spot temperature at <300 K.

VI. MUON COOLING PERFORMANCE

While the mechanics and quench protection issues seem solvable at the present level of understanding, the question about adequacy of the field quality produced by the sectioned coils for the beam cooling remains open.

In order to address this question, the beam simulation was performed by the Monte Carlo beamline simulation code, G4Beamline [8] for the OPERA 3D field map of the large bore system. The initial average momentum of 300 MeV/c degrades to 150 MeV/c at the end of the cooling section via the ionization energy loss with the liquid helium absorber. The initial momentum spread of ±13 MeV/c shrinks down to ±10 MeV/c at the end of the cooling section. On the other hand, the initial beam radius of 7 cm slightly increases to 8 cm at the end of the cooling section via the multiple scattering.

The result of beam tracing shown in Fig. 6 demonstrates the six-dimensional emittance decrease along the channel. The cooling factor, defined as the ratio between initial and final six-dimensional emittances, is 3.14 for the cooling section of the large bore system. This performance is close to the cooling factor of 3.4 obtained from the analytical field simulations by Bessel functions. Based on these results, the field quality produced by the large bore magnet system seems to be adequate for the muon cooling application.

Investigation of the small bore system with the beamline simulation has recently begun. In the first step, a single particle motion was traced and found that it successfully reproduces the designed orbit. The cooling performance study will be performed after the precise matching of the helical solenoid design with the beam parameters.

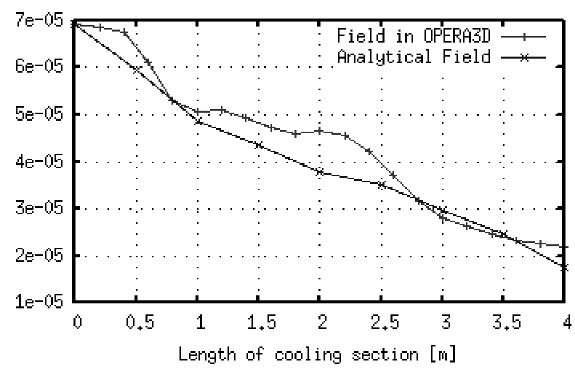

Fig. 6. 6D emittance evolution in the large bore cooling channel.

VII. CONCLUSION

The proposed NbTi magnet systems are technically feasible. The advantages of the large bore system are flexibility in dealing with uncertainties of the beam travel through the cooling channel and independent adjustment of field parameters. The advantages of the small bore system are lower cost, mass and stored energy, but it has a fixed relation between all field components. The next step will be optimization of the matching sections for both systems. A short model and prototype fabrications and tests would be a viable approach towards verifying the magnet system performance.

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