MAGNETS FOR THE MANX 6-D MUON COOLING DEMONSTRATION EXPERIMENT

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Abstract

MANX is a 6-dimensional muon ionization-cooling experiment that has been proposed to Fermilab to demonstrate the use of a Helical Cooling Channel (HCC) for future muon colliders and neutrino factories. The HCC for MANX has solenoidal, helical dipole, and helical quadrupole magnetic components which diminish as the beam loses energy as it slow down in a liquid helium absorber inside the magnets. Additional magnets that provide emittance matching between the HCC and upstream and downstream spectrometers are also described as are the results of G4Beamline simulations of the beam cooling behavior of the complete magnet and absorber system.

INTRODUCTION

MANX is a 6-dimensional muon ionization-cooling experiment which is now under design at Fermilab [1-2]. The main system of this experiment is a Helical Cooling Channel. Two HCC concepts have been proposed. 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. That is why this more compact concept of HS was chosen for further investigation as discussed below.

HELICAL SOLENOID

The Helical Solenoid proposed in [3] has the general parameters and geometry shown in Table I and Fig. 1. 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 orbit direction, it simultaneously generates longitudinal and transverse field components.

The entire inner volume of the magnet system is filled with liquid helium (LHe), which is the energy absorber for the ionization-cooling experiment.

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

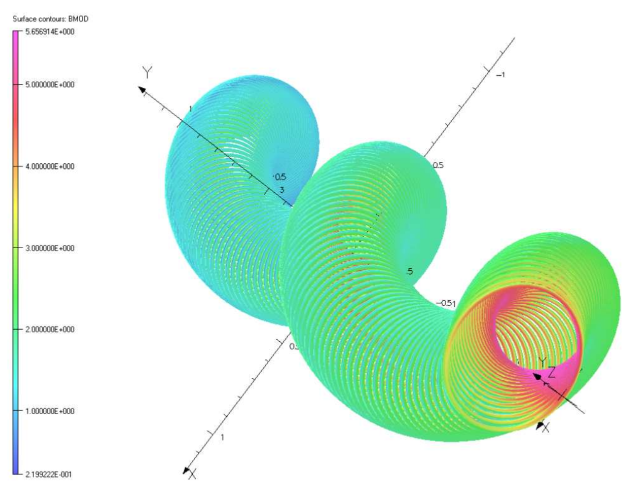

Figure 1: Helical Solenoid geometry and flux density.

The muon momentum is reduced from 300 MeV/c to 160 MeV/c in passing along the helical path through the 5.6 m 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 HS. 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.

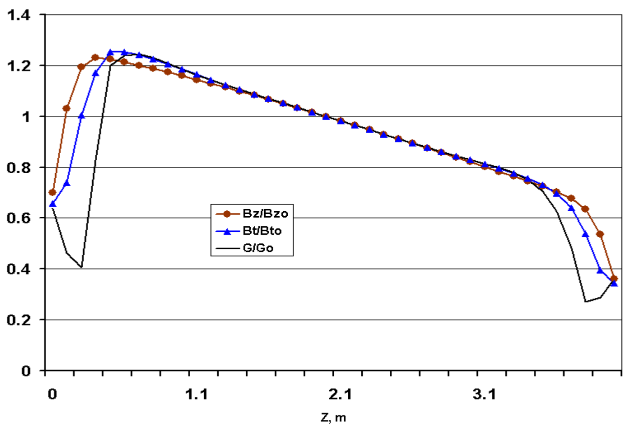

Figure 2: Field distribution related to the values at z=2 m (Bzo=-3.37 T, Bto=1.04 T, Go=-0.9 T/m).

One can see the interesting result that the three important field components, (solenoidal (Bz), helical dipole (Bt), and helical quadrupole (Gz)), scale with coil current.

Fig. 3 shows the dependence of the three field components as a function of coil radius.

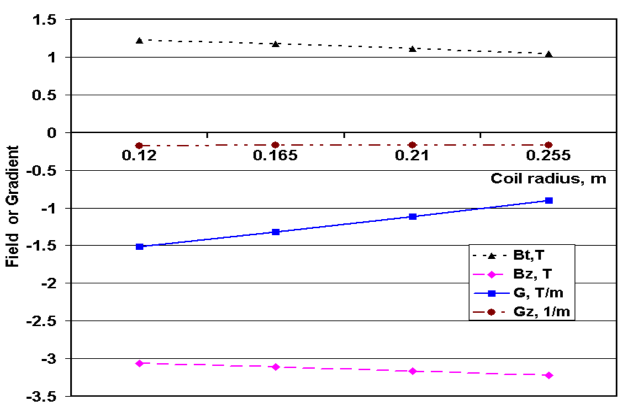

Figure 3: Field and field gradient dependence.

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 HS generates complicated helical field components and corresponding Lorentz forces. These forces are intercepted by the outer collar structure. A mechanical design of a short (80 mm long) solenoid section to be used as a prototype for study is shown in Fig. 4. Coils are continuously wound with NbTi Rutherford SSC type cable on an inner support cylinder, while outer collar rings are correspondingly mounted, section by section. After assembly, the solenoid 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.

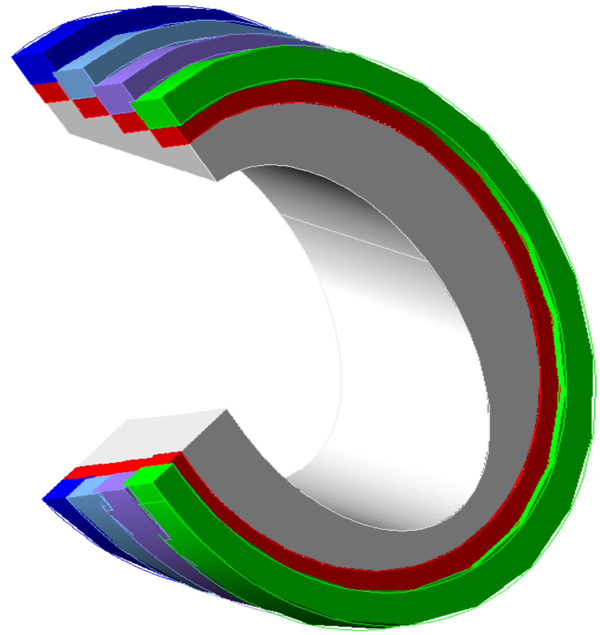

Figure 4: Helical Solenoid short section geometry. Inner support (grey), superconducting coil (red) and outer collar rings (green-blue).

HELICAL SOLENOID WITH RF CAVITIES

In the technique of ionization cooling for muon beams, the muons lose both transverse and longitudinal momentum while passing through a low-Z material. The longitudinal momentum is then restored by acceleration in RF cavities.

The proposed Helical Solenoid for future MANX experiments could be upgraded with the RF accelerating structures. Several types of RF cavities for muon accelerators [4-6] were proposed.

In the basic HCC concept, the accelerating cavities have to be placed inside the magnet system. We have slightly modified an 805 MHz cavity with thin beryllium windows [6], and have managed to fit the cavity inside an HCC using a special spiral waveguide to feed the cavity. The RF design was performed with the use of CST Microwave Studio. However, the development of practical mechanical solutions for placing the cavity inside HCC remains a challenging problem.

A good starting point for this design could be a $\pi/2$ interleaved cavity consisting of 16 pillbox-like cells [10, 11]. This 1.25 meter single coupled multi-cell accelerating cavity is designed to provide an energy gain of ≈22 MeV. The cavity is to be cooled to liquid nitrogen temperature to increase the shunt impedance by about a factor of two and reduce the large peak power requirements. The total RF peak power for the cavity is then ≈11 MW. Unfortunately, this cavity can not be used "as is" – significant design work is needed to make this cavity into a helical shape.

An accelerating cavity of any kind will be exposed in the HCC to a very strong magnetic field. In an evacuated

RF cavity the maximum accelerating gradient degrades substantially in the presence of a focusing magnetic field due to breakdowns induced presumably by well focused dark currents. The idea of filling RF cavities with high-density gas to suppress breakdowns works very well and is applicable to muons [8]. Besides suppressing breakdowns, the gas in the cavities also acts as the energy absorber needed for ionization cooling [9]. By regulating absorber gas pressure the proposed RF system is capable of exactly restoring the muon momentum loss in the absorber. But it is quite clear that this attractive concept needs a strong R&D effort.

IONIZATION COOLING EFFECT

The MANX cooling channel consists of the upstream matching, the helical cooling, and the downstream matching sections, respectively [10]. The beam emittance cooling takes place in the LHe-filled helical cooling section. Figure 5 shows the field strength along the reference orbit in the whole MANX cooling channel.

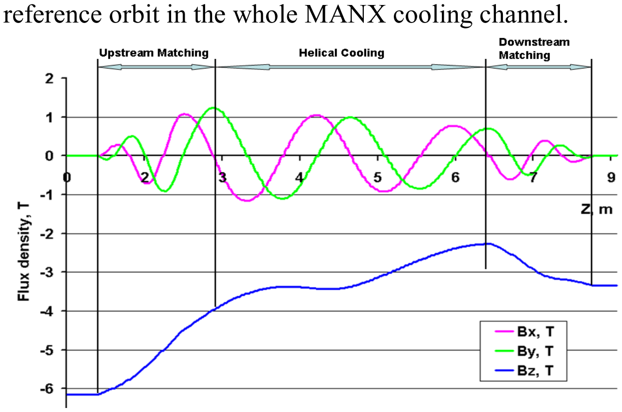

Figure 5: Field along the reference orbit.

The beam trajectory in the helical cooling section is a spiral which follows the centers of the helical solenoid coils. The reference orbit is described by the radius of the reference orbit (a) and the helical period (λ). The tangential pitch of the reference orbit (κ), is determined as $\kappa = 2\pi a/\lambda$ from these parameters. The upstream and downstream matching magnets are made of coils like the basic HS that must transform a coaxial beam with $a=0$ to match the HCC. To do this, the upstream matching coils adiabatically increase helical dipole and quadrupole components. In addition, the beam is stabilized by an adiabatic decrease of the solenoidal component. The downstream matching section has the opposite function from the upstream matching section to reduce a and κ. More detailed discussion about the design of the matching magnet is in reference [10]. Figure 6 shows the simulated normalized 6-dimensional (6D) emittance evolution in the MANX channel with and without the emittance matching sections. The red line shows the 6D emittance evolution of the beam which travels in the whole MANX channel, while the blue one shows that of the beam which passes through only in the helical cooling section. The size of the initial emittance is arbitrary in this plot because the initial condition of the beam in each channel is completely different. The essential point is that the emittance grows at the beginning of both channels since the position-momentum uncorrelated beam is injected into the strongly angular momentum dependent channel. The upstream matching section removes the mismatch with a transverse momentum kick, which is yet to be fully optimized.

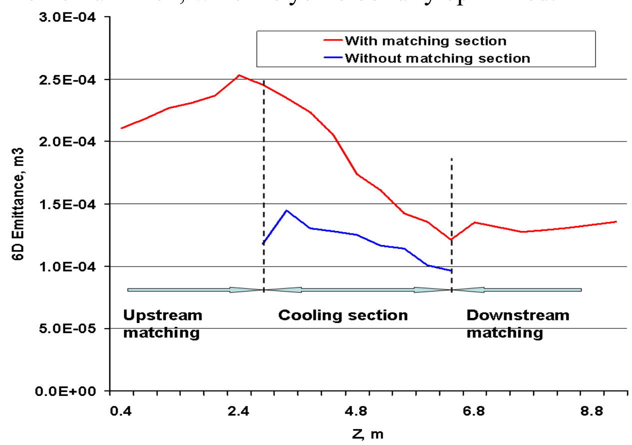

Figure 6: Emittance evolution in the whole channel (red) in only the helical cooling section (blue).

SUMMARY

- The MANX demonstration experiment should be based on the Helical Solenoid magnet system.
- The Helical Solenoid generates the longitudinal and transverse helical magnetic fields for effective ionization-cooling.
- The magnetic and mechanical analyses of the Helical Solenoid have confirmed that the magnet system can be built.
- The Helical Solenoid could be combined with a helical RF cavity to compensate muons energy losses in an absorber.

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