DESIGN OF HELICAL SOLENOID COMBINED WITH RF CAVITY*

V. S. Kashikhin#, N. Andreev, V. V. Kashikhin, M. J. Lamm, A. Makarov, G. Romanov, K. Yonehara, M. Yu, A. Zlobin, FERMILAB, Batavia, IL 60510, U.S.A.

Abstract

Helical Solenoids (HS) were proposed for a muon beam ionization cooling. There are substantial energy losses, up to 30 MeV/m, during the passing of the muon beam through the absorber. The main issue of such a system is the muon beam energy recovery. A conventional RF cavity is too large to be placed inside HS. In the paper the results of a dielectric-filled RF cavity design is presented. The proposed RF cavity has a helical configuration. Helical Cooling Channel (HCC) module design which includes high pressure vessel, RF cavity, and superconducting HS is presented. The parameters of these module sub-systems are discussed, and the results of muon beam tracking in combined magnetic and electric 3D fields are shown.

INTRODUCTION

One of the critical issues of Muon Collider design is a muon beam ionization cooling. An effective 6-dimensional muon cooling was proposed in [1]. The cooling channel should include a helical magnet system combined with RF cavities to recover the beam energy loss in an absorber. Helical Cooling Channel parameters were investigated in [2-3]. Helical magnet systems [4-5] should generate a wide range 4 T – 30 T magnetic fields. A short Helical Solenoid 4 T field model was built and successfully tested [6]. The second model with improved fabrication technology is under construction now.

Nevertheless, a still open question is how to combine HS and RF cavity. In this paper the approach of mounting RF cavity inside HS is presented. The RF cavity outer diameter is substantially reduced by ceramic filler as proposed in [7]. Cavities are filled in by a high pressure hydrogen gas absorber which provides also a better cavity performance in high magnetic fields.

HELICAL SOLENOID

The Helical Solenoid should generate the combination of helical fields: solenoidal, transverse dipole, and transverse quadrupole [1-4].

Magnetic Design

The magnetic design for a 200 MeV muon beam energy is based on parameters presented in the Table 1. The superconducting coil centers are shifted in transverse direction to be on the helical beam orbit. These coil shifts generate helical dipole and quadrupole field components along with the primary solenoid field. The Variant 1 (V.1) has a 1.6 m helix period (See Fig. 1) and was proposed for MANX experiment [4]. For this magnet the solenoidal and transverse helical dipole and quadrupole fields needed for the cooling could be accomplished without any correction. In [3] it was shown that even better HCC performance could be obtained with a smaller 1 m long HS helix period. But in this V.2 case in order to match the needed field, a demagnetization solenoid (DS) should be placed outside of HS.

Table 1: Helical Solenoids

Parameter	Unit	V. 1	V. 2
Helix orbit radius	m	0.255	0.16
Helix period	m	1.6	1.0
HS coil radius	m	0.315	0.3
DS coil radius	m	-	0.5
RF cavity OD	m	0.44	0.36
Coil width in Z direction	m	0.02	0.02
Number of coils/section		80	50
Distance between sections	m	0.24	0.2
Total HS coil current	kA	100	100
Total DS current/meter	kA	-	25
Coil peak field	T	6.8	7.1
B_z – field at orbit centre	T	-4.8	-4.9
B_τ - tangential field	T	1.33	0.88
d B_τ/dr – field gradient	T/m	-0.96	-0.06

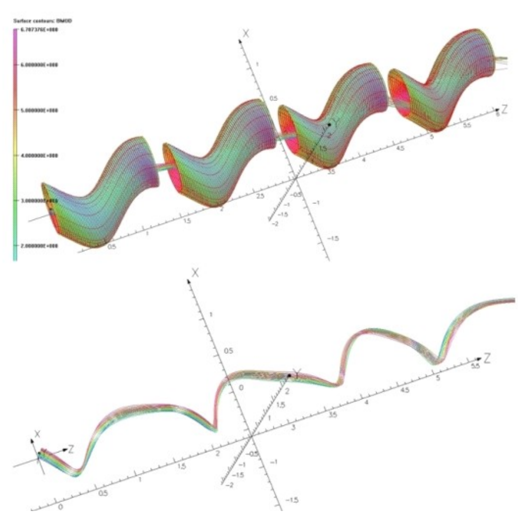

Figure 1: Helical solenoid V.1 geometry, flux density on the coils, and muon beam tracks at 200 MeV.

*Work supported by US Department of Energy

#kash@fnal.gov

Muon beam tracking studies confirmed the possibility of beam transport through the HCC even with 240 mm wide slots between HS sections (See. Fig. 1). Further beam transmission improvement could be obtained by proper HS end field corrections. It should be noted that each HS section is shifted in such a way to provide a maximum channel acceptance.

Mechanical Design

The HS mechanical design is based on the HS short model successfully tested at FNAL [6]. For long HS sections in addition support flanges are used as shown in Fig. 2.

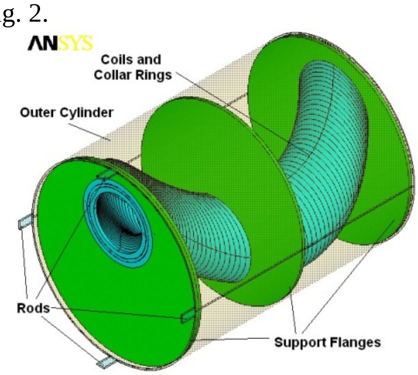

Figure 2: HS mechanical structure.

The stress analysis by ANSYS showed that peak stresses in this mechanical structure are below 60 MPa and the mechanical structure is efficient to intercept large Lorentz forces from the superconducting coils.

DIELECTRIC FILLED RF CAVITY

Design of accelerating cavities mounted inside the HS presents many challenges. The most important issues are:

1) Limited space for RF system.

2) Large beam transverse size. Large bore reduces achievable accelerating gradient and accelerating field uniformity in conventional pillbox-type RF cavities. Fortunately beryllium grids or windows solve this problem since beryllium is almost transparent for muons. But it creates a number of other problems. One of them is electrical isolation of RF cavities. That requires an individual power coupler for each of them.

3) Large RF power needed for an efficient ionization cooling.

4) Low RF cavity performance in presence of magnetic field [8]. Filling a cavity with high pressure hydrogen gas restores the performance, but rises up engineering issues.

In this paper is proposed the way to develop an RF cavity that can mechanically fit inside HS. It was shown [3] that the optimum helical period should be equal the RF system wavelength. Consequently, the 1.0-1.6 m helix period range corresponds to 200-300 MHz frequency range. Let us consider two widely used operating frequencies of 200 and 325 MHz to cover this range. The conventional pillbox cavities for these frequencies would have diameters ≈1.2 m and ≈0.7 m respectfully. They only could be placed between HS sections. Another option is to use ceramic filler material inside cavity to reduce about 2.5 times the cavity diameter [7]. In this paper ceramic Alumina955 (ε=9.6, tanδ=0.0002) is considered as a filler because of its availability, though there are known better ceramics with extremely low tanδ.

The length of cavity cannot be larger than the coil width due to simple geometrical considerations. So, the overall length of cavity is 20 mm. A beam aperture does not affect the cavity size directly since the cavity is supposed to be closed with beryllium foils of 0.126 mm thickness or grids. But space for beam must be free of dielectric, so a larger aperture leads to a larger cavity. In our case beam aperture diameter is 150 mm. The resultant cavity RF design is shown in Fig. 3. The cavity volume is filled completely with ceramic except the beam bore to reduce the cavity outer diameter as much as possible. A substantial fraction of RF losses occurs in ceramic and the problem of cooling the ceramic will limit the acceptable RF power. Calculations show that it is possible to remove 10 kW/m from ceramic using a pressurized hydrogen gas flow. So, the duty factor of RF system was chosen to keep losses in the ceramic below this limit.

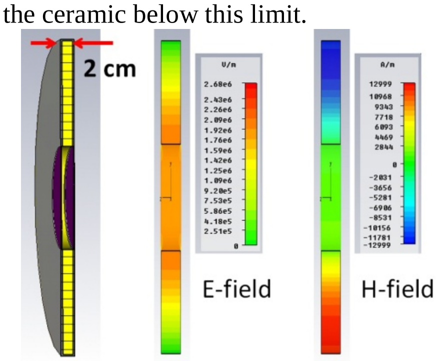

Figure 3: RF design of dielectric loaded cavity and field distributions.

Very high RF power losses per cavity require development of compact and powerful couplers; this is likely to be unfeasible taking into account very limited space. Also, due to high RF losses the duty factor, which is determined by our capability to remove heat from ceramic, is extremely low for both frequencies.

The problem of multiple high power couplers can be solved by combining short single cavities into a coupled cell structure as shown in Fig. 4. Coupled cell structure operating at 0-mode may help to reduce number of transmission lines and couplers to two units.

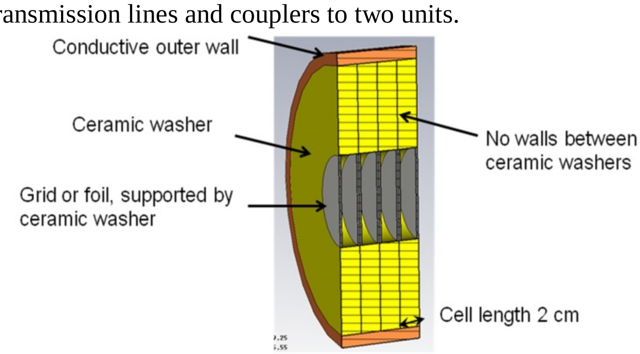

Figure 4: Design of coupled cell dielectric loaded cavity.

We can break the whole structure into two cavities and then the general layout of helix period will be as shown in Fig. 5. So, one helix period will contain either two 80 cm long cavities instead of 80 short ones at frequency 200 MHz, or two 50 cm long cavities instead of 50 of short ones at frequency 325 MHz.

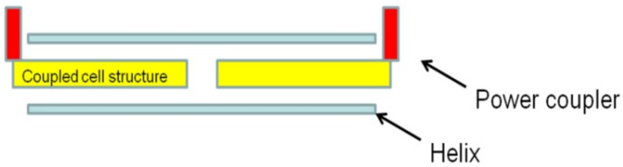

Figure 5: Principal layout of HCC period with coupled cell cavities.

The parameters of such long cavities loaded with ceramic washers and beryllium foils (grids) under the same requirements are shown in the Table 2.

Table 2: RF Cavity Parameters

Parameter (per cavity)	**Unit**	**200MHz**	**325MHz**
Cavity outer diameter	mm	440	316
Accelerating gradient	MV/m	10	10
Energy gain for β=0.9	MeV	8	5
Q-factor		4425	4360
Eff. Shunt impedance	MΩ	0.38	0.293
Pulsed losses in copper	MW	25	17.5
Pulsed losses in ceramic	MW	143	67.5
Total pulsed power losses	MW	168	85
Duty factor	%	0.006	0.007
Losses in ceramic	kW	8	5

The fixed lengths of helix period (1.6 and 1 m) do not allow using cavities of optimal length. Due to transit time effect the optimal choice of cavity length would be 50 cm for 200 MHz cavity and 30 cm for 325 MHz cavity. One more complication is that the losses in ceramic reach up to 80% of total losses in longer cavity making heat removal even more problematic.

Coupled cell cavity loaded with ceramic solves just a few problems. But it seems that it also has a potential for optimization.

COOLING CHANNEL CONCEPT

The HCC concept is shown in Fig. 6. RF cavity sections mounted inside a high pressure helical vessel filled with a high pressure (100 atm) hydrogen gas. This helical tube placed inside sections of HS. The space between HS sections is used for ports. These ports service both RF couplers and gas flow. RF system works at room temperature and cooled by a hydrogen gas flow. The HS superconducting coils mounted inside cryostats and cooled by liquid helium.

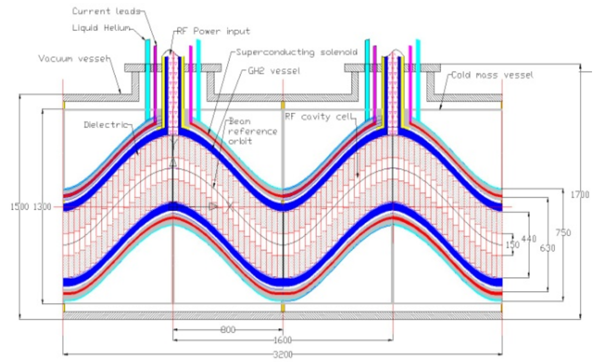

Figure 6: HCC conceptual design.

SUMMARY

The muon beam cooling channel concept is proposed. The RF system is placed inside Helical Solenoid, and a high pressure vessel. The RF system outer dimensions are reduced by filling the cavity with ceramic material. A Helical Solenoid model was successfully built and tested. The second improved HS model is fabricated and is ready for the test.

The proposed conceptual design opens a possibility for further HCC tuning to optimize main RF and HS dimensions to minimize the RF power, losses, and HS field.

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