HELICAL MUON BEAM COOLING CHANNEL ENGINEERING DESIGN *

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Abstract

The Helical Cooling Channel (HCC), a novel technique for six-dimensional (6D) ionization cooling of muon beams, has shown considerable promise based on analytic and simulation studies. However, the implementation of this revolutionary method of muon cooling requires new techniques for the integration of hydrogen-pressurized, high-power RF cavities into the low-temperature superconducting magnets of the HCC. We present the progress toward a conceptual design for the integration of 805 MHz RF cavities into a 10 T Nb_3Sn based HCC test section. We include discussions on the pressure and thermal barriers needed within the cryostat to maintain operation of the magnet at 4.2 K while operating the RF and energy absorber at a higher temperature. Additionally, we include progress on the Nb_3Sn helical solenoid design.

INTRODUCTION

A HCC consisting of a pressurized gas absorber imbedded in a magnetic channel that provides solenoid, helical dipole and helical quadrupole fields has shown considerable promise in providing six-dimensional cooling for muon beams. The energy lost by muons traversing the gas absorber needs to be replaced by inserting RF cavities into the lattice. Replacing the substantial muon energy losses using RF cavities with reasonable accelerating fields will require a significant fraction of the channel length be devoted to RF. However, to provide the maximum phase space cooling and minimal muon losses, the helical channel should have a short period and length. Demonstrating the technology of such a cooling channel would represent enormous progress toward the next energy frontier machine. We propose to design and build the 10 T, 805 MHz segment of a HCC. This corresponds to the second section of the HCC design discussed in [1].

KEY TECHNOLOGICAL BARRIERS

The key technological barriers include cooling of the helical solenoid coils made of the low temperature superconductor (LTS) in the presence of RF cavities embedded in the channel and operation of RF cavities in the presence of a magnetic field. Recent results [2] show pressurizing the RF cavities may solve the latter challenge. The first challenge, we believe, can be addressed by reducing the size of each RF cavity utilizing a low loss dielectric insert to ease physical constraints for a given frequency. This allows enough room between the cavities and the coils for the magnet coils, the magnet cryostat, the hydrogen pressure vessel, and the RF coaxial feeds to the individual cavities. Calculations show that the heat loads will be tolerable and RF breakdown of the inserts will be suppressed by the pressurized hydrogen gas. The work done on this problem is one of the key accomplishments of the project and has led to a solution to the engineering problem of feeding the RF power through the magnet cryostat.

The following sections describe more fully the dielectric cavity design concepts and the design concept for an integrated 10 T, 805 MHz HCC.

DIELECTRIC LOADED CAVITIES

Previous simulations have shown the admittance of HCC that are determined from the strength of a HCC magnetic field and the RF frequency that can be used to contain the beam longitudinally [3]. This imposes strict dimensional constraints for the RF cavities embedded within the magnetic system of the HCC. In fact, the use of conventional, merely gas-filled pillbox-like cavities yields prohibitively large radii. Therefore, we load each cavity with ceramic material to reduce the radial size to tolerable values at the given (L-Band) frequency, corresponding to the HCC segment under consideration. To find an optimum RF cavity and engineering design, we have performed rigorous numerical investigations for cavities loaded with various ceramic shapes revealing quantitative relationships of critical RF operational parameters taking into account temperature-dependent material properties. The study particularly yields absolute input peak power and thermal power levels that can be expected at any operating temperature, while the temperature of choice is important to limit the heat transfer to the surrounding superconducting coils at 4 K. We considered a range from room temperature down to ~33 K for the cavity operation. In case pressurized hydrogen can be used for muon cooling, this lower temperature limit coincides with the critical point of hydrogen, where it will not liquefy at any given pressure.

A major design objective is to lower the required peak power (P_{peak}) level to sustain the envisaged effective field levels - in the order of E_{acc} = 16 MV/m - while employing contemporary, affordable, pulsed (μs pulse length) magnetron power sources. Such magnetron sources typically provide several ten to several hundred kW at L-Band frequencies. This is yet much smaller than the cavities would require for operation at a typical active length of $L_{act} = \beta\lambda/2$, with $\beta = v_\mu/c$ denoting the normalized

*Work supported under U.S. DOE Grant Application Number DE-SC0006266
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muon velocity and λ=c/f the RF wavelength where c is speed of light and f is frequency). Consequently, the peak power can only be diminished by a significant reduction of L_{act}. In fact, multiple rather short cavity cells (few centimeters long) fit into our proposed scheme to position cavities smoothly along the helical equilibrium orbit, thereby providing optimum replenishment of the longitudinal particle momentum lost during helical cooling. Using affordable power sources, the cavities then can be powered separately providing each an optimum phase for acceleration. Moreover, the transit-time factor along the short L_{act} is close to unity for the 200-250 MeV/c muon beams. The key design issue is how to integrate the RF cavities in the helical solenoids. The most desirable and efficient way would be to completely integrate the cavities inside of the helical coils. A first conceptual design of this was proposed earlier for the last stage of the HCC [1].

The conceptual engineering design is shown in Fig. 1. Hereby a single metal body (segment) can be easily machined to accommodate the Be windows on either side. Each segment is part of two neighboring cavities. Note that the windows will include small openings (not shown) for the pressurized gas, such that the gas can flow through the cavity chain serving as a coolant of cavity walls and ceramics, while there is no pressure difference stressing the windows. The segment exhibits a recess to hold the ceramic in place, while the following body - of identical shape - can hold the ceramic in place, thereby completing the resonator.

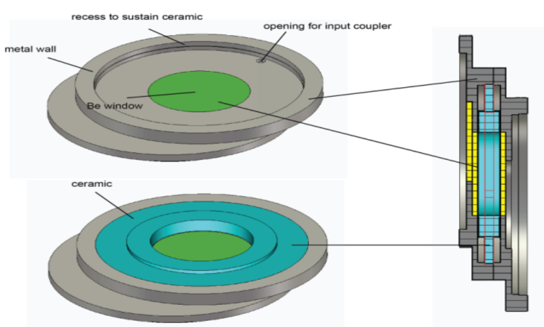

Figure 1: Conceptual engineering design for the RF cavities showing one segment (left) of the helical channel without (top) and with the ceramic placed inside (bottom). The next segment would hold the ceramic in place and complete the cavity resonator as depicted right.

The cooling demand per cavity cell is relatively low (<< 1kW), yet the concept allows to choose the wall thickness adequately to allow the incorporation of cooling channels (if required) and to provide the proper pressure barrier for the envisioned up to 200 atm levels (at room temperature). Several options can be pursued to bolt different segments together based on our experience with the pressurized test cavities in the MuCool Test Area at Fermilab built to sustain similar pressure levels [2]. Fig. 2 eventually shows one period of the helical RF section. It also depicts the positions of the input power antenna, while pickup antenna for RF control can be located for each cavity on the opposing side. With this dielectric-loaded cavity solution, the coaxial feeds for the 24 cavities in a 1 m long HCC unit can run parallel to the muon beam to a gap between magnet cryostats where they all can be taken out radially at one point to be attached to power sources.

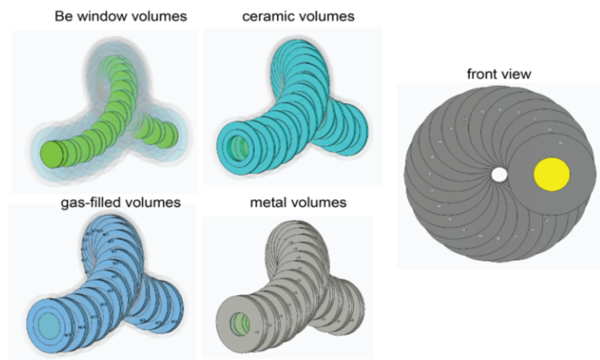

Figure 2: Conceptual engineering design of one period of the helical RF channel illustrating separately the different material volumes (leftmost) and a front view (right).

10 T NB_3SN HELICAL SOLENOID

Future work will include a four-coil short section of helical solenoid. The four-coil short section is intended to provide a technology demonstration and develop practical experience with the construction and performance of Nb_3Sn helical solenoid. As was done with the NbTi test coils, the coil size will be limited to the 640 mm inner diameter of the test dewar at the Fermilab Vertical Magnet Test Facility (VMTF). The four-coil model should be sufficient to explore all of the coil fabrication complexities and structural stresses of a long helical solenoid, while allowing fairly large aperture rings and generating a peak field of order 10 T (on coil, ~4 T on axis). The lessons learned during the fabrication and testing will be fed back into the 1m, 10 T, 805 MHz, HCC system design. The Nb_3Sn helical solenoid coil fabrication will build upon previous Muons, Inc. and FNAL work (Fig. 3).

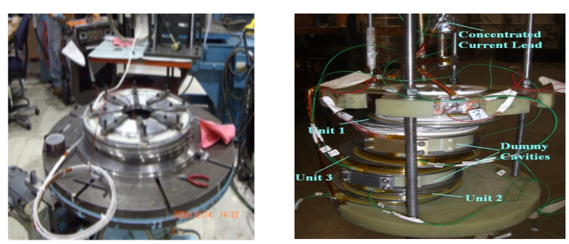

Figure 3: NbTi HS (left) [3] and YBCO HS (right) [4] models.

INTEGRATED HCC DESIGN

Based on recent developments, including high pressure RF results, conceptual design for dielectric loaded cavities, and extrapolating from the NbTi helical solenoid experience we are currently moving toward an engineering design for an integrated 1m segment of a 10 T, 805 MHz HCC. The conceptual basis of the design can be seen below.

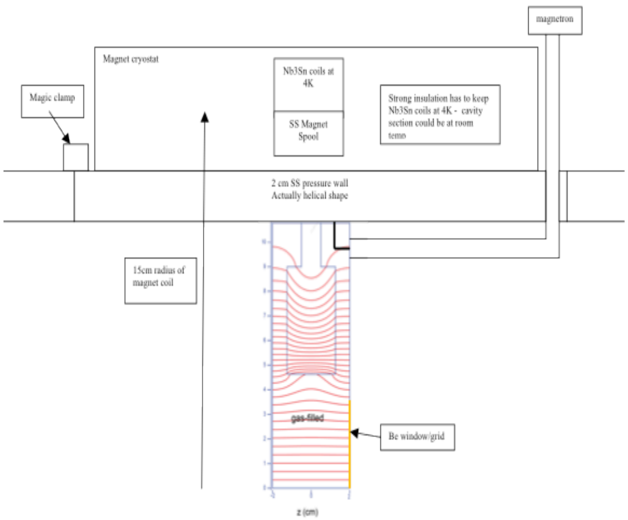

Figure 4. Conceptual picture of the geometry of a dielectric-loaded cavity, pressure vessel wall, and the HS solenoid coil and its cryostat.

The coax feed for each cavity in one helix period comes from a magnetron power source fed through a common 1or 2-inch break in the magnet structure where the magnet cryostat ends. All feeds go between magnet cryostats that each enclose 20 cavities. The pressure vessel wall is cooled by circulating liquid or gas (water, LN2, or gaseous Helium), and could be machined to contain the coax power leads. Compared to figure 4 above, this concept has only one break in the coil spacing instead of 20 and no penetrations of the cryostat by the RF feeds. The colder the RF cavity operates implies more engineering advantages: 1) less temperature difference between the pressure wall and the magnet spool for easier cryostat insulation. Additionally, we will be considering RF power solutions for the HCC, this work will include the consideration of using magnetrons as the power source. Recent stability studies [6] have shown that magnetrons may be a viable technology. The peak power handling of the RF distribution system from the magnetron to the cavities will be designed with a factor of two in mind to assure reliability under various reflected power conditions.

The modular conceptual scheme presented above will be the basis of the engineering design.

SIMULATION AND OPTIMIZATION

The design will be validated for muon cooling performance via G4Beamline [7] simulations. Of key importance will be the effect of the gaps between cryostats on the cooling performance. From the engineering design we will have detailed understanding of the fields within and between modules. The effect of the gap on the field will be propagated into G4Beamline and the effects studied. It is expected that any ill-effects of the gap can be overcome, at least in part, by having increased fields at the end of the modules. This study will be part of a larger study of field error tolerances.

The details of the dielectric cavities will also be ported to the simulation code. Additionally, all known details including RF coupling scheme will be taken into account in the simulation effort.

The G4beamline simulation will be used synergistically with the RF and magnet design tools to ensure the engineering design is able to provide a system optimized for cooling performance.

SUMMARY

Based on recent results we are moving toward combining several Muons, Inc. SBIR-STTR-developed inventions in an innovative practical engineering solution for a 10 T, 805 MHz muon-cooling channel suitable for a muon collider. The design will incorporate the HCC [8], a HS magnet [9], hydrogen-pressurized RF cavities [10], phase and frequency-locked magnetron power sources, emittance exchange using a continuous absorber [8], and be optimized using G4beamline muon beam cooling simulations. The goal of the project is to optimize beam cooling for maximum collider luminosity while including all known engineering constraints, from material properties to affordable RF power sources and cryogenic loads, and to generate an engineering design of a segment of a channel as a prototype to build and test.

Demonstrating the technology of such a cooling channel would represent enormous progress toward the next energy frontier machine. We propose to design and build the 10 T, 805 MHz segment of a helical cooling channel.

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