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. The concept we present includes a decoupling of the RF and magnetic channels and 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.

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 [2,3] 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

We have reported progress on the design and testing of dielectric loaded cavities for a HCC in detail elsewhere [3,4]. Here we give a summary and then devote more time to the alternative technology of re-entrant cavities (see next section). The key idea behind using dielectric loaded cavities is the reduction of cavity radius and the associated easing of engineering demands that comes along with it. One can decouple the RF and magnetic channels.

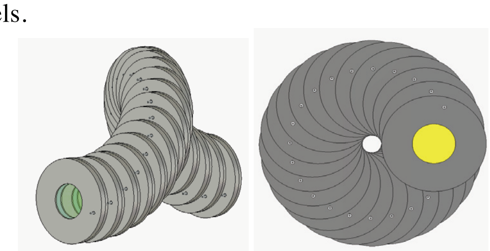

Figure 1: (Left) Illustration of RF cavities aligned to fit inside a HS magnet and cryostat. (Right) The end view shows the dielectric-filled region of the cavity (gray), where the yellow area corresponds to the region that the beam passes through. The small holes indicate the locations of the power feeds. Beryllium grids separate the cavities to make them RF pillboxes while not impeding oxygen-doped hydrogen flow. These are some of the building blocks of the integrated channel (see Figures 4 and 5).

RE-ENTRANT RF CAVITY ALTERNATIVE

As an alternative to using dielectric inserts for reducing the size of the RF cavities in order to fit them into a magnetic channel, we also consider a re-entrant RF structures. It is known that the cavity frequency can be lowered if one employs a half/quarter wave type upper torso. This increases the magnetic field at the perimeter.

*Work supported under U.S. DOE Grant Application Number DE-SC0006266
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Alternatively, one can argue this is a re-entrant structure with capacitive loading.

Both ways lower the frequency for a given radius. The benefits of this approach are:

- Reduced power requirements, even though some real estate length is lost due to smaller gap than cavity length.
- Reduced capital costs for cavities.
- Reduced operational costs for cavities.
- Reduced number of RF sources and cavities per helical period.
- Reduced costs for the RF system
- Required peak power in range of what can be done with magnetrons (< 1MW).
- Structure is easy to build, i.e. with the aforementioned idea of utilizing an outer pressure vessel (no pressure difference across cavities) we can use 3mm thin copper sheets and deep-draw cavity shape similar to SRF cavities, then EBW parts (full penetration welds). Tune and weld.
- High Q0, several factors higher than when using a ceramic.
- No triple joint junction and thus no associated field enhancement.
- Performance not limited by dielectric strength of the ceramic but RF breakdown limit in GH2.
- Mitigation of cross talk between cavities through gridded windows.
- The cavity design makes use of offset windows and re-entrant shapes to follow the helical path. Enough clearance for beam while minimizing Be-window radius. Field asymmetry along helical path is small as re-entrant shape (planar front) homogenized and concentrated field along gap and path of interest.
- More space for instrumentation etc.

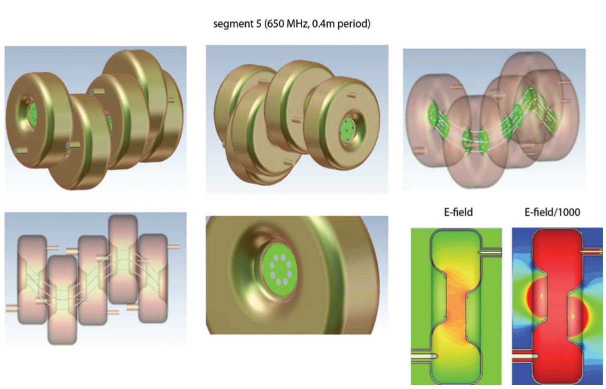

Figure 2. 3D conceptual design and initial simulations for the re-entrant cavities that could be used in mid-section of an HCC.

Currently we have explored two options for reducing the RF cavity sizes. Both options allow the cavities to be embedded in the helical magnetic/high pressure channel. The final technology choice will be made once the detailed simulation of the full cooling channel has been performed.

10 T NB_3SN HELICAL SOLENOID

Details of the magnet design effort to date have been reported elsewhere [4]. Here we give a summary for completeness. The invention of the Helical Solenoid (HS) magnet provides a simple configuration of coils to generate the solenoid, helical dipole, and helical quadrupole field components required for the HCC. The HS overcame the difficulty of very high coil currents required to produce the quadrupole field component in an ordinary magnet design. Note that the HS is not a bent solenoid. In a HS the coil planes are normal to the z axis, while a bent solenoid would have the coil planes normal to the equilibrium orbit.

Multi-coil HS magnet sections have been designed, constructed, and tested using NbTi [5] for the lowest field (5T, four coil) and YBCO for the highest field (15 T, 6 coil) HCC segments [6]. The coil design for the intermediate HCC section (10 T, continuous coil) is being made to provide a technology demonstration and develop practical experience with the construction and performance of a Nb_3Sn helical solenoid.

Figure 3: Conceptual drawing (left) and 3d printer version (right) of the Nb_3Sn HS spool and conductor that will be fabricated and tested in the Fermilab Vertical Magnet Test Facility. The test will use two layers of cable.

Additional studies are being performed with elliptical coil configurations. These are beyond the baseline studies designed to see if we can further ease overall engineering burden and improve performance (these studies are presented at this conference [7].

INTEGRATED HCC DESIGN

Figure 4 shows the essential features of a compact design of an HCC module where hydrogen-pressurized, dielectric-loaded RF cavities fit inside HS magnet coils. In this concept, the HS magnet and its 4 K cryostat are thermodynamically independent of the RF cavities and their power sources. Figure 4 shows a cut-away view of a module with 20 RF cavities that could be the first device to be built and tested. Figure 5 shows a three-dimensional view of the same module

ISBN 978-3-95450-138-0

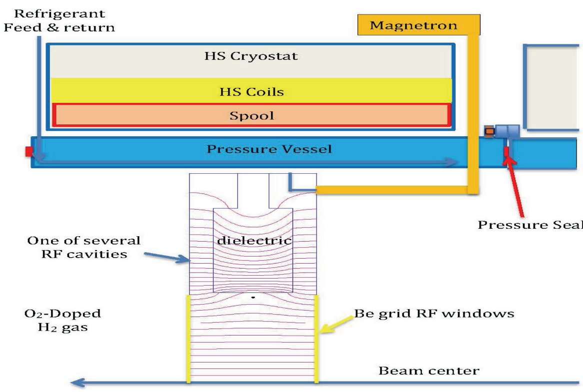

Figure 4: Conceptual diagram showing the features of a beam-cooling module with dielectric-loaded RF cavities, Be RF windows, pressure vessel, HS coil, and its cryostat.

The coax feed for each cavity comes from a magnetron power source fed through a break in the magnet structure where the magnet cryostats end [4]. The pressure vessel wall is refrigerated by circulating liquid or gas (water, LN2, or gaseous Helium), and could be machined to contain the coax power leads. Compared to earlier design concepts, this one has only one break between coils per module and no penetrations of the cryostat by RF feeds.

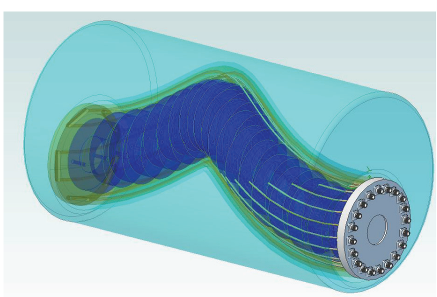

Figure 5: Three-dimensional visualization of Figure 4.

SIMULATION AND OPTIMIZATION

The design will be validated for muon cooling performance via G4Beamline [8] 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 (and re-rentrant 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 [9], a HS magnet [10], hydrogen-pressurized RF cavities [11], phase and frequency-locked magnetron power sources [12], emittance exchange using a continuous absorber [9], 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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