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RF CAVITY DESIGN ASPECTS FOR A HELICAL MUON BEAM COOLING CHANNEL*

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Abstract

A Helical Cooling Channel (HCC) promises efficient six-dimensional ionization cooling of muon beams by utilizing high-pressurized gas as a continuous absorber within a magnetic channel embedding RF cavities. The progress on cavity design, tailored for such a cooling channel, is discussed.

INTRODUCTION

Muon accelerators bear unique potential for the high energy physics community supporting the US Intensity Frontier research program and - when relying on the infrastructure developed - the Energy Frontier using one or more muon colliders as a subsequent stage [1]. Muon beam ionization cooling is deemed the only solution to provide the very high beam intensities required for a neutrino factory or muon collider. Cooling channels generally demand strong magnetic fields enclosing RF cavities that compensate for the energy loss due to ionization. Cooling by at least a factor of $\sim 10^6$ - defined as the ratio of initial to final six-dimensional beam emittance - is necessary for a muon collider [2]. E.g., to achieve this reduction for a 250 MeV/c muon beam necessitates about seven times that much energy loss, which means an equivalent accelerator of about 1.75 GeV. This represents a multi-billion dollar expense based on large diameter superconducting magnets, pillbox-like cavities, and present RF power source technology. The HCC is considered a cost-saving solution for muon cooling, though its engineering design remains challenging. After briefly introducing the HCC concept and the benefit of gaseous absorbers, the paper focuses on the development of RF cavity concepts.

HCC CONCEPT

The cooling technique utilized in an HCC has been under study since several years both analytically [3] and numerically (e.g. [4], [5]). The most effective approach to implement the desired magnetic field is a low-temperature (4 K), superconducting helical solenoid (HS) channel composed of short solenoid coils arranged in a helical pattern [6]. In addition, a helical quadrupole field is used to provide beam stability. Solenoidal and transverse helical dipole field components provide a constant dispersion along the cooling channel for emittance exchange to allow longitudinal cooling. Whereas the helical dipole component creates an outward radial force due to the longitudinal momentum, the solenoidal component creates an inward force due to the transverse momentum. This yields a beam motion with helical period ($\lambda = 2\pi/k$) at constant radius (a) as depicted in Fig. 1, i.e. unlike the motion in a pure solenoidal field, where the radius would diminish. The momentum of the equilibrium orbit obeys eq.(1) [3]. Herein B is the solenoidal magnetic field component, b the transverse helical component, and $\kappa = k\cdot a$.

$$p(a) = \sqrt{\frac{1+\kappa^2}{\kappa}} \cdot \left[B - \frac{1+\kappa^2}{\kappa} \cdot b \right] \tag{1}$$

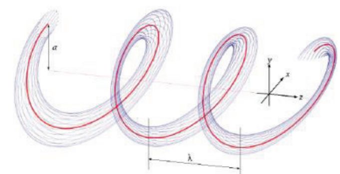

Figure 1: Theoretical helical muon beam motion in an HCC. Red is the equilibrium orbit obeying eq. (1) [3].

The presently conceived HCC concept makes use of a series of six different cooling segments, wherein a and λ decreases as the muon beam is cooled, but not within the same segment [7]. The pitch angle is 45 deg. throughout ($\tan^{-1}(\kappa = p_t/p_z = 1)$). Two operating frequencies are envisaged to cover all six segments, i.e. 325 MHz and 650 MHz. The frequencies derive from Project-X (now PIP-II) at Fermilab, which could serve as a proton driver. Within the magnetic channel, high-pressurized, gas-filled normal-conducting RF cavities have to be embedded. The high pressure gas serves as a homogeneous absorber for continuous ionization cooling. The energy lost is replenished by the RF cavities to maintain the total beam momentum (p_μ). A momentum around $p_\mu = 200$ MeV/c ($\beta = v/c_0 = 0.88$) has been found optimal for cooling.

GASEOUS ABSORBER

Hydrogen (H_2) is the most promising gaseous absorber, since it has the largest product of ionization loss and radiation length. Moreover, H_2 has the largest heat capacity and lowest viscosity of all gases making it well suited as a coolant. Thin beryllium (Be) windows are foreseen to close the cavities electrically on each side, which reduces the surface peak fields compared to cavities with open beam tubes. The windows are almost transparent for the muon beam. At $p_\mu = 200$ MeV/c, the ionization losses in H_2 are $\sim$4.4 MeV$\cdot$cm^2/g and $\sim$1.75 MeV$\cdot$cm^2/g in Be, respectively. This determines the required accelerating field (E_{acc}) in a cavity. As the helical period decreases along the segments during cooling, the

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required E_{acc} rises and may exceed 20 MV/m depending on design. (This considers the synchronous phase). The cavities have to operate within multi-Tesla fields generated by the magnets, while avoiding RF breakdown and multipacting. These phenomena have been a prevalent problem in vacuum cavities. Pressurized gas-filled cavities have so far not revealed a significant difference whether or not an external magnetic field was applied [8]. Common to all tests is the characteristic that the RF breakdown threshold field linearly increases with pressure since the mean free path for ions and electrons is reduced with higher gas density. This in turn lowers the achievable collision energy. Thus, higher fields are required to initiate a breakdown shower in the gas (Paschen effect). At sufficiently high pressures however, the onset of RF breakdown is determined by the metal surface, whereas the gas pressure plays a negligible role. Overall, the gas combines multiple functions as a benefit:

- Continuous, homogeneous ionization cooling
- Elevation of RF breakdown limit as compared to vacuum cavities, particularly important in presence of external multi-Tesla magnetic fields
- Mitigation of multipacting and dark current phenomena
- Thermal cooling of cavity walls and Be windows

RF CAVITIES

The engineering design of the RF cavities is challenging since the HS channel limits the usable size. Several cavity candidates were investigated towards a realistic HCC concept. While peak power (P_{peak}) levels per cavity may be in the MW-range depending on the design, the thermal power dissipation is reasonably low (few hundred Watts) thanks to the low duty factor. Yet, the cavities require adequate thermal management since these operate at room temperature in close vicinity of the superconducting magnets. To cope with the envisioned gas pressures beyond 100 bar, pressure-resistant walls (~1/2" stainless steel) have to be employed. More recently it has been proposed to share a common pressure vessel among all cavities within a thermodynamically independent HS cryostat as sketched in Fig. 2 [7]. This does not save space, but simplifies cavity fabrication (only few mm thin copper walls required), thermal management and avoids cryostat penetration by RF feeds.

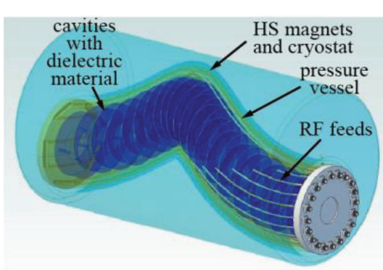

Figure 2: Concept of an HCC module using RF cavities enclosed in a pressure vessel within a HS cryostat [7].

H_2 gas may flow through the interior and exterior of the cavities for cooling. The pressure vessel itself can implement channels for circulating water, LN_2 or gaseous Helium. Each cavity is offset radially with respect to the preceding unit to smoothly follow the helical path. One requires additional space for input coupler and instrumentation feeds to be attached to each individual unit. Pillbox-like cavities will not fit into the cooling lattice. Thus, measures have to be provided to reduce the cavity size and to limit RF losses to acceptable levels.

Dielectric-loaded Cavities

Since the early stage of the HCC design, RF cavities filled with a dielectric material have been conceived to minimize the cavity diameter at a given frequency, whereas magnetic materials are not a viable option [9]. Depending on the material and volume filled, the diameter can be halved, making the cavity sufficiently small to fit into the HCC lattice, but RF power requirements are significantly enhanced at the same time. Note that Ohmic wall losses increase with decreasing diameter for the same cavity shape and same frequency, while dielectric (volumetric) losses are added according to the product of loss tangent (tan δ) and permittivity (ε') of the ceramic. One of the initial concepts consisted of 24 cavity units per helical period (similar to Fig. 2) that implemented ceramics filling the upper volume of a cavity unit along its full length [10]. Despite the small cavity diameter, the input couplers pointed out radially. This claims significant space and complicates the practical usage for an HCC. A large number of cavities implies rather short cavities (few cm). This reduces the stored energy (W_s), hence P_{peak} per unit, but increases the peak power per active length (P_{peak}/L) on the other hand. The latter determines the overall power demands. To reduce P_{peak}/L, 12 instead of 24 cavities are considered for the arrangement depicted in Fig. 3. Short drift tubes are used between the cavities, which is advantageous to not disrupt the HCC. The magnets enclosing the cavities are not shown for clarity. The interior ceramics are depicted on the right hand side. Technical Alumina (Al_2O_3) is the preferred choice since readily available in high purity offering low dielectric losses (tan δ ~ 1e-4, ε'~9-10 at room temperature in the considered frequency regime).

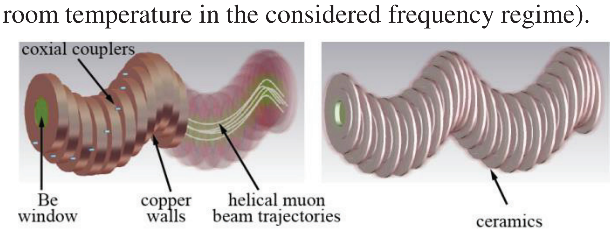

Figure 3: Schematic showing RF copper cavities for one HCC segment (solid color, left). The cavities are filled with low-loss Alumina ceramic rings (right).

A ceramic placed at the outer perimeter of the cavity has the least influence on frequency since the electrical fields decrease with distance from the axis. Therefore, instead of filling the cavity along its full length, a ceramic ring - centered in the cavity - with a bulge at the lower end and a neck at the upper end is utilized. This design

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sacrifices diameter to reduce P_{peak}/L, but space is regained since coaxial antenna couplers can be attached to the cavities' front plates. The couplers do not interfere with the ceramics inside. The RF cables can be fed sideward through the ends of the HS cryostat to yield a practical concept. Moreover, the typical electric field enhancement at the ceramic-metal-gas interface is mitigated as best as practicable. Potential RF breakdown at the ceramics is a separate issue. The breakdown is initiated by electron avalanche at the ceramic surface, which determines its dielectric strength. An experiment with a special 805 MHz cavity holding an Alumina (99.8% purity) rod along its center confirmed that RF breakdown can be prematurely initiated in accordance with the materials' dielectric strength [11]. For the proposed design however, the electrical fields at the ceramic surfaces are comparably small and would allow operation beyond the envisioned field levels before breakdown occurs (e.g. $E_{acc} > 30$ MV/m). A dielectric-loaded cavity prototype based on the present layout will be built and tested at Fermilab to verify this statement. Potential charge build-up at the ceramic surface due to the traversing beam is another concern, which will be addressed.

Re-entrant Cavities

An HCC with dielectric-loaded cavities requires a large amount of ceramics. This adds costs and complicates the engineering design compared to conventional cavities (e.g. how to integrate the ceramics). As an alternative, re-entrant cavities are proposed omitting the ceramics. Re-entrant cavities enhance the shunt impedance by introducing nose cones on each side, which focus the electrical field. Since the capacitance (C) is increased, the frequency is lowered ($f \sim \sqrt{(L \cdot C)}$) at a given cavity diameter. One may also consider that the inductance (L) is enlarged due to a broader dome at a given accelerating gap. In fact, re-entrant cavities as shown in Fig. 4 have been designed to yield the same diameter at the same frequency as the dielectric-loaded cavities above.

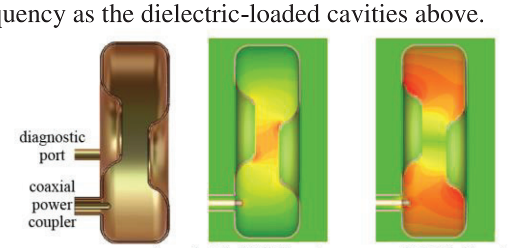

Figure 4: Cross-sectional view of a re-entrant cavity unit. Electric and magnetic RF field contours are shown (a.u.).

The broad dome provides ample space for a coaxial coupler and a diagnostic probe. One crucial feature is that the nose cones (holding the Be windows) are offset from the cavity axis to follow the helical path such that the equilibrium orbit crosses the center of each Be window. This provides the maximum clearance for the beam. The radii of the Be windows can be minimized to merely the size of the beam envelope passing through. This is better visualized in the perspective view of Fig. 5. The front view illustrates the idea how the instrumentation cables can be attached avoiding conflict with neighbouring cavities. As for pillbox-like cavities, the muons will experience longitudinal and transverse fields along the helical path. Yet, reasonable field uniformity is achieved along the orbit.

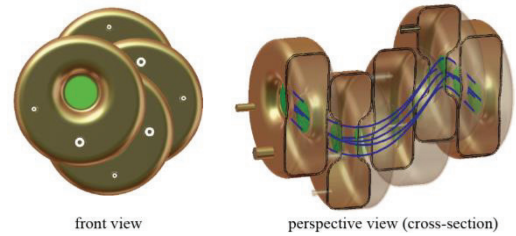

Figure 5: Re-entrant RF cavity design for the HCC.

Note that the number of cavities is only four per helical period (cavity center to center), which is a factor six reduction compared to the design in ref. [9] and a factor three compared to Fig. 3. The peak power requirement per cavity has actually been reduced despite the larger gap due to the re-entrant cell shape. This is crucial to minimize costs for the RF system. E.g., P_{peak} can be limited to a few hundred kW instead of operating in the MW regime (per unit), and P_{peak}/L has been reduced at the same time (several factors). All technical and operational issues associated with the ceramics are eliminated. The disadvantage of the design is that the fill factor of the accelerator (active/passive length) is reduced, which impacts beam dynamics. The effects will be studied numerically. Also, the required E_{acc} is increased (up to ~25 MV/m), however, fields still remain below the RF breakdown limit based on past experimental tests [8].

CONCLUSION

RF cavities concepts have been discussed for usage in an HCC, which imposes strict space constraints given by the surrounding magnets. Cavities filled partially with ceramic as well as exhibiting a re-entrant shape (no ceramics) have been proposed as candidates to be embedded in the channel, while allowing for space of input couplers, pickup probes, and a pressure vessel. The number of cavities employed per helical period is still a matter of trade-off between space and power requirements (cost driver). Alternative designs, e.g. cavities with elliptical cross-section, helical outline, tilted nose cones, or nested cavities have been investigated as well, but not presented here. The work is considered as in progress.

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