NOVEL MUON COOLING CHANNELS USING HYDROGEN REFRIGERATION AND HIGH TEMPERATURE SUPERCONDUCTOR *

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Abstract

Ionization cooling, a method for shrinking the size of a muon beam, requires a low Z energy absorber, high-field magnets, and high gradient RF. We have studied the use of hydrogen systems to provide ionization energy loss for muon beam cooling, breakdown suppression for pressurized high-gradient RF cavities, and refrigeration for superconducting magnets and cold RF cavities. We report progress on the designs of cryostat and refrigeration systems for different sections of muon cooling channels to achieve safe and robust means to enable exceptionally bright muon beams. We find that engineering designs can be greatly simplified if high temperature superconductor can be used that has the capability to carry adequate current in fields above 10 T for temperatures above 33 K for the use of integrated pressurized RF cavities, or for temperatures above 16 K for designs where the RF and cooling sections are sequential.

INTRODUCTION

The concept of a Helical Cooling Channel (HCC) [1] with a continuous homogeneous absorber has already shown considerable promise to cool the 6D emittance of a muon beam [2]. A recent extension of the HCC concept is to use z or momentum-dependent field strengths for new beam cooling applications [3]. Thus, the number of uses of a HCC has increased. Examples of these new applications of a HCC that we have examined so far include: 1) a precooling device to cool a muon beam as it decelerates by energy loss in a continuous, homogeneous absorber, where the cooling can be all transverse, all longitudinal, or any combination; 2) a device similar to the precooler above, but used as MANX [3], a muon cooling demonstration experiment; 3) a transition section between two HCC sections with different dimensions as when the RF frequency can be increased once the beam has been cooled sufficiently to allow smaller and more effective cavities and magnetic coils, and 4) as an alternative to the original HCC filled with pressurized RF cavities. In this case, muons would lose a few hundred MeV/c by ionizing liquid hydrogen in a HCC section with momentum dependent fields and then pass through several RF cavities to replenish the lost energy. This sequence could be repeated several times.

These possibilities are in addition to the original HCC design [1], where RF cavities pressurized with gaseous hydrogen inside 20 meter long HCC sections may provide the most efficient 6D cooling possible. In this design the RF gradient should be the highest possible, the constant momentum can be the optimum for beam cooling, and, with one dense hydrogen gas energy absorber from the decay region to the end of the last HCC segment, the beam need only pass through absorber containment windows at each end of the cooling channel.

Thus we have five separate potential applications for a HCC. Additionally, depending on the initial beam conditions, each of these applications has a range of possible operating parameters. For example, the original HCC design was imagined to have 3 twenty meter long sections, where the RF frequency would be increased in succeeding sections as the beam cooled. The smaller, higher frequency RF cavities would be more efficient and would allow magnets with smaller bore and higher fields, leading to better beam cooling.

We have begun the systematic investigation and development of the materials, construction limitations, and operating parameters that are needed for HCC components: 1) The superconducting coils (e.g. HTS or Nb3Sn), 2) The normal conducting RF cavities (e.g. copper or beryllium, with or without RF windows to improve performance) [4,5], 3) The refrigeration method (e.g. LH2, GH2, LHe, or GHe), and beam heat loading, 4) The absorber containment windows (e.g. Be, Al, or AlBeMet, and thickness profiles for low mass and safety) [6].

The outcome of these studies will be the basis for the choice of cryostat operating temperature(s) to achieve the necessary magnetic and RF fields and to handle the heat load of the beam passing through the energy absorber for each HCC application. The first example will be the design of the cryostat for the MANX 6D cooling demonstration experiment.

HCC CONTAINING RF CAVITIES

In the HCC cases where the helical magnets and RF cavities are integrated, operation should be above the critical temperature of hydrogen, 33 K, so that the gas will not liquefy at any pressure. Since RF breakdown suppression depends on the density of the gas, lower operating temperature implies that a lower pressure is possible for the same density, which in turn simplifies the beam window and RF power feedthrough designs. A lower temperature may also allow us to take advantage of the lower resistivity of most metals that can be considered as cavity construction or surface coating materials, where lower resistivity implies a higher quality factor so that less power is required to achieve the required RF. At 33 K the use of HTS is a possibility that could simplify the cryostat design since the temperature of the magnet coils can be the same as the energy absorber and the RF

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cavities. However, it may turn out that we will value the HTS more for its high-field characteristics than its high-temperature capabilities and choose to have another imbedded cryostat for the magnet coils to operate at a lower temperature than the RF cavities and gas absorber.

SEQUENTIAL HCC AND RF SECTIONS

In the HCC designs such as for a precooler or MANX, where the RF cavities follow the helical magnets rather than are imbedded in them, a liquid energy absorber is possible. For liquid hydrogen the temperature should be above 14 K in order that the hydrogen not solidify and less than 20 K to prevent boiling. The large aperture, high field superconducting magnets can be made of HTS or a conventional superconductor like Nb3Sn. For Nb3Sn there will have to be a magnet cryostat compartment separate from the hydrogen absorber, since hydrogen solidifies at 14 K and this superconductor will not work in the fields that we need at this temperature or above.

However, for the precooler or MANX HCC designs, which do not incorporate RF, liquid helium may be an acceptable alternative to liquid hydrogen since its perceived safety advantages may outweigh its reduced beam cooling efficiency. And the possibility of operating at 2 or 4 K may make the use of either HTS or Nb3Sn fairly straight-forward with a very simple cryostat.

The most reasonable absorber choices are hydrogen and helium, where helium is roughly a factor of two less effective for ionization beam cooling. For pressurized RF cavities the use of hydrogen is preferred since it has a breakdown suppression factor that is six times better than helium at the same pressure and temperature.

Estimate of Technical Feasibility

Compared to the original HCC that uses pressurized RF cavities imbedded in the fields of the channel, the MANX HCC is considerably easier to build. In particular, the 200 MHz pill box RF cavities that were originally considered imply a HCC diameter of about 1.3 m, which implies very large helical magnet fields at the coils that would be difficult to achieve. While the optimization of the magnet system and cooling parameters and their measurement are subjects of other projects, we can make some estimates of the technical feasibility of constructing a MANX device that will work as modeled in the simulations described above.

The first MANX HCC that has been examined with simulations is a 32 cm radius, 5 m long cylinder containing liquid hydrogen (or helium) with three magnet circuits. The strengths of the magnets depend on the momentum of the beam. For the case that starts with 400 MeV/c muons, the upstream solenoid field is -8.72 T, and the helical dipole and helical quadrupole field and gradient are 2.81 T and -3.04 T/m, respectively, at the equilibrium orbit of 15.9 cm. The maximum field value is 9.71 T at the coils, which we believe is the factor most likely to determine the difficulty of the magnet system.

Compared to the 10% cooling effect expected with MICE, the 540% effect of the first MANX simulations implies a lot of room for compromise. That is, some of the parameters such as the beam momentum range, the magnet aperture, or channel length could be reduced considerably and there would still be an impressive measurement to be made. For example, if we chose to cool in the momentum range of 300 MeV/c to 200 MeV/c, all of the maximum fields in the previous paragraph would be reduced by a factor of 75%. In short, we believe that the parameters for a real MANX experiment are sufficiently flexible that there is no doubt that a design of an outstanding experiment is technically achievable.

The first set of coils and cryostat that we wish to design as part of this general HCC study is for MANX, a particular use of a HCC. Fig. 1 shows an example which serves as an effective 6D cooling demonstration experiment and as a prototype of a precooling device.

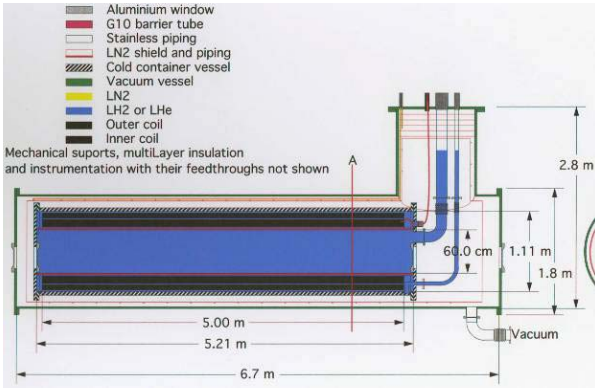

Figure 1: MANX cryostat schematic. Here, liquid H_2 or He is forced through the HTS (16 K) or Nb3Sn (2 K) coils before entering the region where the beam can heat the liquid. A G10 insulating barrier tube keeps the coils at constant temperature, independent of the beam heating in the central volume. The inner coil structure has both helical dipole and quadrupole windings.

FIRST HTS STUDIES

A comparison of the performance at 4.2 K of state-of-the-art HTS materials is shown in Fig. 2, where the engineering critical current density, J_E, is plotted as a function of magnetic field. The J_E is calculated over the entire cross section of the wire.

First Results

We have tested BSCCO-2223 tape in both a hairpin and a spiral configuration. In these experiments the sample is immersed in helium (liquid or vapor) in the cryostat Variable Temperature Insert, which is itself located in a solenoidal magnetic field. Voltages are measured at different points of the sample by means of voltage taps. These measurements are carried out at different magnetic fields, up to 15 T, and at various temperatures. The magnetic field was in the long transverse direction parallel to the tape surface. Fig. 3 shows J_c results as a function of magnetic field for a BSCCO tape sample tested from 4.2 K up to 38 K. After

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comparison of these results with the manufacturer's data, it was found that strain affects J_c performance in the low field and low temperature range only. The J_c excess degradation due to strain was 17% at 22 K and 0 T, but only about 3% at larger fields. At 38 K no excess J_c degradation was observed due to strain.

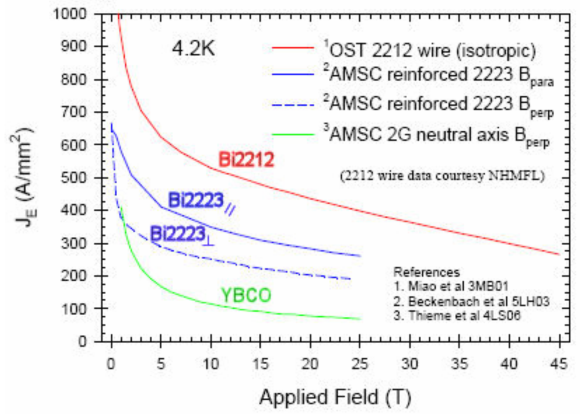

Figure 2: The engineering critical current density, J_E, at 4.2 K as a function of magnetic field for various HTS materials, from various sources as noted.

In order to make the best-informed decision on the superconductor to be used, the performance of HTS and of Nb_3Sn can be compared using engineering critical current density, J_E, for the field and temperature ranges of interest. Fig. 4 shows such a comparison at 14 K. From these plots, the superiority of HTS materials is obvious at higher temperatures, whereas at 4.2 K Nb_3Sn performs better at least up to magnetic fields of 17 T. The operating temperature for a particular HCC application will involve a cost and risk assessment involving the properties of the superconductors, the rf cavities, and the beam and rf heat loads .

CONCLUSIONS

A systematic study of the materials and operating parameters needed for various HCC designs has started. The optimization of the various designs and the choice of alternate approaches will depend on the interplay of these studies and the cooling simulations. Our goal is to produce an end-to-end simulation of a muon beam cooling system for a muon collider with achievable technology. As a concrete example, we will do the engineering design of MANX, a 6D cooling demonstration experiment.

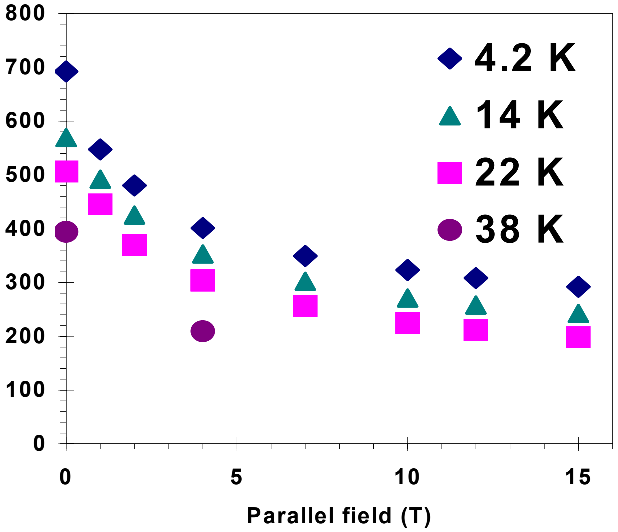

Figure 3: Critical current J_c(A/mm^2) as a function of magnetic field for a BSCCO tape sample tested in a parallel field configuration from 4.2 K up to 38 K.

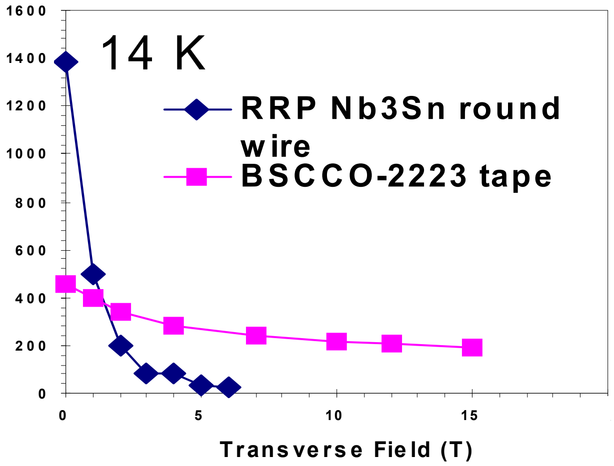

Figure 4: Comparison of the engineering critical current density, J_E, at 14 K as a function of magnetic field between BSCCO-2223 tape and Nb_3Sn round wire.

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