MUON COOLING RESEARCH AND DEVELOPMENT

M.A.C. Cummings*, Northern Illinois University, Dekalb, IL 60115, USA
Daniel M. Kaplan, Illinois Institute of Technology, Chicago, IL, 60616, USA

Abstract

The MuCool Collaboration is engaged in a program of research and development on hardware for ionization cooling of a muon beam. The aim of MuCool is to develop the key pieces, including high-gradient normal-conducting RF cavities and high-power liquid-hydrogen energy absorbers. This effort will lead to a more detailed understanding of the construction and operating costs of such hardware, as well as to optimized designs that can be used to build a Neutrino Factory or Muon Collider. This work is being undertaken by a broad collaboration including accelerator and particle physicists and engineers from many national laboratories and universities in the U.S. and abroad. The intended schedule of work will lead to ionization cooling being well enough established that a construction decision for a Neutrino Factory could be taken before the end of this decade based on solid technical foundations.

INTRODUCTION

The concept of a muon collider has been given serious consideration in recent years to extend the energy reach of particle physics machines. The larger muon mass, compared to electrons, suppresses bremstrahlung and synchrotron radiation, resulting in high-resolution mass and energy measurement. The challenges of muons are their short lifetime (~10^{-6} s) and their production into a diffuse phase space from pions. The phase space can be reduced via ionization cooling sufficiently within the muon lifetime to store a muon beam.

Cooling is based on the principle that the density of a beam can be increased only by non-conservative interactions such as ionization energy loss, as phase space is otherwise conserved by Liouville's Theorem. The evolution of transverse beam emittance ε_n within matter is given by [1]:

$$\frac{d\varepsilon_n}{ds} \approx -\frac{1}{\beta^2}\frac{dE_\mu}{ds}\frac{\varepsilon_n}{E_\mu} + \frac{1}{\beta^3}\frac{\beta_\perp(0.014)^2}{2E_\mu m_\mu L_R}, \qquad (1)$$

where s is path length, E_μ is beam energy in GeV, $\beta = v/c$, L_R is the radiation length of the absorber material and $\beta_\perp$ is the betatron function describing the focusing strength of the lattice. The two terms of Eq. 1 reflect the competition between multiple scattering of the muons within the absorber (a heating effect) and the ionization loss. The second, "heating" term is minimized when absorbers are placed in a strong focusing field (low $\beta_\perp$) and consist of material of low atomic number (high L_R), the optimal choice being hydrogen.

*macc@fnal.gov

IONIZATION COOLING CHANNELS

In an ionization-cooling channel, the dE/dx ionization loss of the muons in the medium decreases all three of their momentum components without changing the size of the beam. The longitudinal momentum of the beam is then restored through RF cavities placed between the absorbers. These have to achieve sufficient accelerating gradients so that the muons go through the cooling channel before a significant fraction of them decay. It is also desired that the maximum acceleration of the cavities exceed that required to restore the longitudinal momentum to allow "off-crest" operation; this results in continuous rebunching so that even with large momentum spreads the beam can remain captured in the RF bucket. The cooling effect can be rotated between transverse and longitudinal phase space by inserting wedge-shaped absorbers into dispersive regions of the cooling channel lattice ("emittance exchange"); longitudinal ionization cooling as such is impractical due to energy loss straggling.

COOLING CHANNEL R&D

An effective ionization cooling channel will require low-Z absorbers with sufficient cooling capacity to handle heat loads on the order of hundreds of watts. These absorbers need to be placed in low beta regions, requiring high magnetic fields or large field gradients, with sufficient accelerating gradient to achieve cooling in the shortest practical distance. The MuCool Collaboration is engaged in R&D on all three technology fronts.

Figure 1: Photogrammetry setup for window tests..

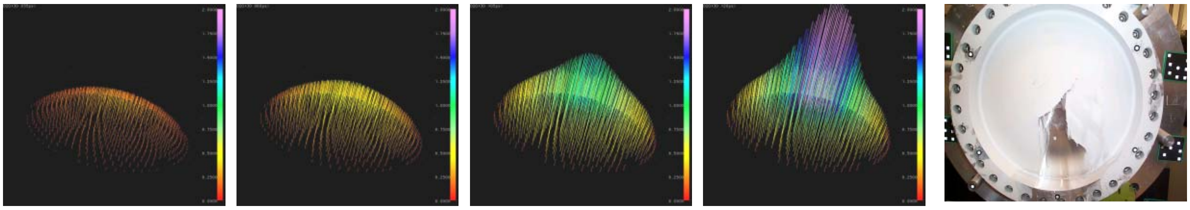

Figure 2: Successive photogrammetry measurements for a window pressure test to bursting (the far right-hand picture). Hundreds of points can be measured without coming into contact with delicate window surfaces.

High-Power Hydrogen Absorbers

The development of high-power liquid-hydrogen (LH_2) absorbers has been a critical goal in the MuCool program. The driving issues are to minimize the multiple scattering (beam heating) and to handle large heat loads while maintaining uniform temperature, and hence density, within the absorber volume. To handle the former requirement, we have developed new shapes for the ends of the hydrogen flasks that allow for significant reductions in their thickness (particularly near the center where the beam intensity is maximum) [2]. We have successfully fabricated tapered, curved windows out of disks of an aluminum alloy (6061-T6) using a numerically controlled lathe. We also devised novel means to test these non-standard windows and demonstrate that they meet design specifications and satisfy applicable safety requirements. By optimizing the maximum stress as a function of volume pressure, one of our designs, the inflected "thinned bellows" window, was able to achieve a minimum central thickness one fourth that of the ASME-standard "torispherical" window of equivalent strength and diameter [2].

We developed photogrammetric techniques to measure the shape of the windows and their performance in pressure tests. The advantages of photogrammetry are the non-contact nature of the measurement (projected points of light, with parallax calculations to determine the space points within a calibrated coordinate system), and that ~1000 points could be measured simultaneously. This represents almost 2 orders of magnitude improvement over CMM measurements (about 30 discrete points) for shape measurement and strain gages (about 16 measurements) for the pressure tests [2].

We have completed manufacture and pressure tests of the first series of non-standard window, the "tapered torispherical" design, establishing testing and certification procedures, including finite element analysis (FEA) predictions for window performance [2]. Fabrication of the next series non-standard window type, of the "thinned bellows" design, is now underway, including windows for the vacuum vessels surrounding the absorber (mandated by the Fermilab safety code). We will be considering the use of lithium-aluminum alloys, such as the 2195 alloy used in the Space Shuttle; the resulting thinness could challenge the current fabrication technique, and any new alloy will have to be certified for machinability and high-radiation application.

The power to be dissipated in these absorbers in the cooling channel designs considered so far is within the limits of what has been achieved in LH_2 targets developed for and operating within the high-power environments of current experiments. However, the highly turbulent fluid dynamics involved in the heat-exchange process necessitates R&D for each new configuration. We are pursuing two approaches to heat extraction: a conventional flow-through design with an external heat exchanger, similar to that used for high-powered LH_2 targets, and a convection-cooled design with an internal heat exchanger built into the absorber vessel. The convection design has desirable mechanical simplicity and minimizes the total hydrogen volume in the cooling channel (a significant safety concern), but is expected to be limited in the amount of power it can handle compared to the flow-through design. To study and optimize the fluid mixing and heat transfer properties of these designs, we have been exploring ways to visualize the flow patterns and temperature distributions within the fluid [3].

High-Gradient Normal-Conducting RF Cavities

An ionization-cooling channel requires insertion of high-gradient RF cavities into a lattice employing strong solenoidal magnetic fields. This precludes using superconducting cavities. The cooling channels under consideration will use normal-conducting 201-MHz cavities, but the R&D is more readily carried out with smaller, higher-frequency devices.

Radio-frequency cavities normally contain a minimum of material in the path of the beam. However, the penetrating nature of muons allows the use of closed-cell ("pillbox") cavities, provided that the cell closures are constructed with thin material of long radiation length. Eq. 1 implies that this material will have little effect on cooling performance as long as its thickness L per cooling cell (at the $\beta_\perp$ of its location in the lattice) has $\beta_\perp\, L/L_R$ small compared to that of the absorber. Closing the RF cells approximately doubles the on-axis accelerating gradient for a given maximum surface electric field, allowing operation with less power and less "dark current" emission. Two alternatives have been considered for the design of the cell closures: thin beryllium foils and grids of gas-cooled, thin-walled aluminum tubing.

The tests of a 6-cell open cavity, designed at Fermilab, and a closed, single-cell cavity, designed at LBNL, both at 805 MHz, are being carried out in Fermilab's Laboratory G. The dedicated test area includes a high-power 805-MHz klystron transmitter (12-MW peak pulsed power with pulse length of 50 μs and a repetition rate of 15Hz), an x-ray-shielded cave, remote-readout test probes, safety-interlock systems, and a control room and workshop area for setup of experiments [4]. The cave also contains a high-vacuum pumping system and water cooling for the cavity. To allow tests of the cooling-channel RF cavities and absorbers in a high magnetic field or high field gradient, a superconducting 5 Tesla solenoid with a room-temperature bore of 44 cm was constructed by LBNL and installed in the Lab G cave, with two separate coils that can be run in "solenoid" mode (currents flowing in the same direction) or "gradient" mode (currents flowing in opposite directions).

A primary challenge in high-gradient RF cavity development is the suppression of dark currents (electrons emitted from the cavity surface via quantum tunnelling as described by the Fowler-Nordheim formalism) and their associated x rays. Our tests show that exposed copper surfaces appear to be problematic at high field [5]. A variety of window and cavity surface preparations and coatings remain to be explored, including TiN-coated copper at the locations of maximum surface field. Alternatives to flat, pre-stressed foils are receiving attention, and we expect to prototype and test several solutions at 805 MHz; the 805 MHz pillbox-cavity prototype was designed with just this type of test program in mind. Design studies indicate that both pre-curved Be foils and grids of gas-cooled, thin-walled Al tubes should be feasible and may be cheaper and induce less scattering than flat foils.

The design of the 201 MHz closed-cell cavity for muon cooling is complete [6]. We intend to build a first prototype in the next year.

MuCool Test Area at Fermilab

In order to rigorously test the heat capability and radiation hardness of our cooling channel components, we are building a MuCool Test Area (MTA) off the end of the Fermilab Linac. This location combines the availability of multi-megawatt RF power at both 805 and 201 MHz, and a 400 MeV proton beam at high intensity. Cryogenic facilities are being constructed for LH_2 absorber and superconducting magnet operation. The underground enclosure will provide the needed radiation shielding for a high-power beam test of a single prototype cooling cell. We anticipate the first stand-alone LH_2 absorber test towards the end of 2003, and tests for the 201-MHz cavity when it becomes available. Beam tests will happen within the next three years, to explore the possible effects on cavity breakdown and absorber power-handling. This is only a high-power engineering test, and not a cooling demonstration. A complementary cooling experiment (MICE) has been approved and will operate at Rutherford Appleton Laboratory in England [7].

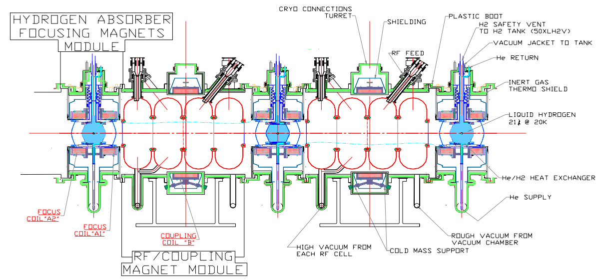

Figure 3. Cooling channel design: Absorbers between 201 MHz RF cavities, surrounded by high-field solenoidal coils.

Acknowledgements

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REFERENCES

[1] D. Neuffer, Part. Acc. **14** 75 (1983).

[2] M.A.C. Cummings *et al*, "Current LH_2 Absorber Research in MuCool", NuFact '02, Imperial College, London, UK, 2002.

[3] J. Norem *et al*, "Measurement of Beam Driven Hydrodynamics" , these proceedings.

[4] D. Li *et al*, "RF Tests of an 805 MHz Pillbox Cavity at Lab G of Fermilab", these proceedings.

[5] J. Norem *et al*, "Dark Current and X Ray Measurements of an 805 MHz Pillbox Cavity", these proceedings.

[6] D. Li *et al*, "A 201 MHz RF Cavity Design with Non-Stressed and Pre-Curved Be Windows for Muon Cooling Channels", these proceedings.

[7] Y. Torun *et al*, "MICE: Muon International Cooling Experiment", these proceedings.