NEW TECHNOLOGY IN HYDROGEN ABSORBERS FOR MUON COOLING CHANNELS

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Abstract

Ionization cooling is the only technique fast enough to cool and focus muons for neutrino factories and muon colliders, and hydrogen is the optimal material for maximum cooling and minimal multiple scattering. Liquid hydrogen absorber R & D for the Muon Colloboration has proceeded on parallel and complementary fronts. The continuing LH_2 absorber engineering and technical developments by the MuCool group conducted by ICAR# institutions (NIU, IIT and UIUC), the University of Mississippi and Oxford University, in cooperation with Fermilab (FNAL), will be summarized, including results from the first hydrogen absorber tests at the newly constructed FNAL Mucool Test Area (MTA). The program includes designs for the high-powered test of an absorber prototype (external heat exchange) at the MTA which are nearing completion to be installed by 2005, an alternative absorber design (internal heat exchange) being finalized for the approved cooling experiment (MICE) at Rutherford-Appleton Laboratory. Finally, a novel idea for gaseous hydrogen absorbers being developed at FNAL for a high-powered test at the MTA in 2006, and new technologies are proposed to be tested as a sequel to MICE.

INTRODUCTION

The possibility of building a muon accelerator has been made more realizable by recent progress in the design of cooling channels. Muon beams at the required intensity for neutrino factories or muon colliders can only be produced into a large phase space and need to be focused fast enough to outlive the 2.2 µs muon lifetime. Ionization cooling, in which muons repeatedly traverse an energy absorbing medium, alternating with accelerating RF cavities within a strongly focusing magnetic lattice, addresses the latter challenge. The ionization energy loss, dE_μ/ds, decreases all three muon momentum components without affecting beam size, reducing the overall phase space by reducing the transverse momentum spread of the beam. The design of ionization cooling channels have been motivated by the following equation for the rate of change of the normalized transverse emittance [1]:

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

where s is the path length, E_μ is the beam energy in GeV, β = v/c, L_R is the radiation length of the absorber material and $\beta_\perp$ is the betatron function describing the size of the beam. The first term describes the cooling from ionization loss. The second term describes beam heating and is minimized when absorbers are placed in a strong focusing field (low $\beta_\perp$) and consist of material of a low atomic number (high L_R). Setting the cooling and heating terms equal defines the equilibrium emittance, the very smallest possible with the given parameters:

$$\varepsilon_n^{(equ)} = \frac{1}{2\beta}\frac{\beta_\perp (0.014)^2}{(dE_\mu / ds) m_\mu L_R} \qquad (2)$$

A figure of merit can be defined as $[L_R dE_\mu/ds)]^2$, the square coming from the two transverse directions. Figure 1 shows this number for several materials, with hydrogen, in its liquid or gaseous state, being optimal for the lowest achievable emittance.

Material	$\langle dE/ds\rangle_{min}$ (MeV g^{-1}cm^2)	L_R (g cm^{-2})	Merit
GH_2	4.103	61.28	1.03
LH_2	4.034	61.28	1
He	1.937	94.32	0.55
LiH	1.94	86.9	0.47
Li	1.639	82.76	0.30
CH_4	2.417	46.22	0.20
Be	1.594	65.19	0.18

Figure 1: Table of cooling figures of merit for various light materials relative to liquid hydrogen.

Superconducting solenoids are the focusing element of choice in most designs, and can give $\beta_\perp$~ 10 cm. Between the absorbers, the high-gradient acceleration from RF cavities replaces the lost longitudinal momentum so that the ionization cooling process can be repeated. Running "off-crest", where the faster muons see less acceleration than the slower muons, rebunches the beam so that a large momentum spread of particles can remain captured in an RF bucket. The RF gradient (~10 MeV/m compared to an ionization energy loss (dE_μ/ds) of 30 MeV/m in liquid hydrogen) determines how much cooling can be achieved before a significant fraction of muons decay. In spite of the relativistic increase of muon lifetime with energy, ionization cooling is optimized at lower beam momentum because of the increase of dE_μ/ds

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below the ionization minimum and because of the lower voltage required for acceleration. Current designs for cooling channels assume a mean muon momentum of 200 MeV/*c*.

THE MUCOOL COLLABORATION

The MuCool Collaboration consists of 18 institutions from the U.S.,Europe and Japan. The mission is 1) to design and prototype cooling channel components; 2) perform a high-power beam test of a cooling cell; and 3) work with the Muon International Cooling Experiment (MICE), particularly with the design and building of cooling channel elements.

Cooling channels come in a variety of configurations, but all share common design challenges. The main questions include: 1) can non-superconducting RF cavities be built to provide the required accelerating fields, and operate within large magnetic fields; 2) can the heat from dE_μ/ds losses (~ several 100 watts) be adequately removed from absorbers, 3) can the channel be engineered with an acceptably low thickness of non-hydrogen material, particularly absorber and RF windows; and 4) can a cost-effective, timely decision be made on the cooling channel technology.

The MuCool R&D efforts have been based on the SFOFO cooling lattice described in the Neutrino Factory Study II [2]. This lattice includes 201 MHz RF cavities (Figure 2). The MICE cooling channel is based on this design, and one goal of the MuCool program is to construct and test elements from this channel together in a high intensity proton beam in the newly completed MuCool Test Area (MTA).

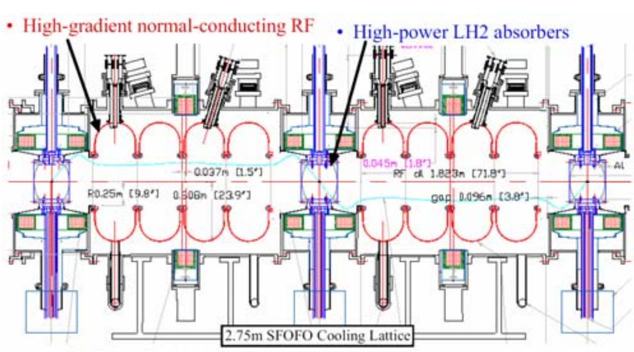

Figure 2: Cooling channel from Neutrino Factory Study II.

THE MUCOOL TEST AREA AT FNAL

In late 2003, construction of the MTA was completed at the site of the old access tunnel to the FNAL Linac, and is now the focus of MuCool activity at FNAL. The MTA is designed to accommodate the full Linac intensity of 1.6×10^{13} protons/pulse at 15Hz or 2.4×10^{14} protons/s, or 600W energy deposition into a 35 cm long liquid hydrogen absorber at 400 MeV. The test area will provide power from the Linac to operate 201 MHz and 805 MHz test cavities. A first LH_2 test has been completed with the KEK convection absorber, and RF testing (both 805 and 201 MHz) is planned. A cryogenic facility is scheduled for completion near the end of 2005 that will provide cooling power to the "forced-flow" LH_2 absorber prototype. Additionally, there is a program for a new gaseous hydrogen absorber system, described below. A beam line for the high power test has been designed and will be under construction by 2005. A FNAL study group

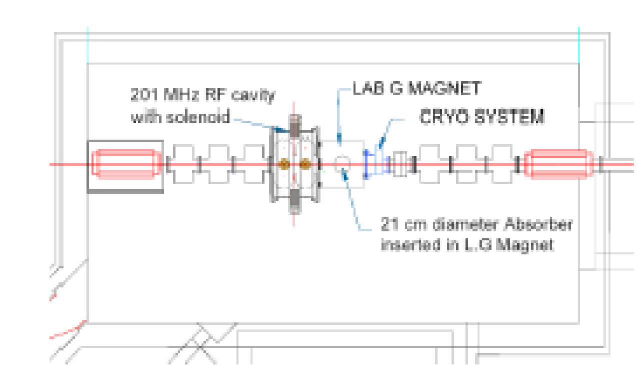

Figure 3: Plan view of a complete cooling cell test at the MTA.

was formed to design the beamline that will be located in the old Linac access tunnel and brought into the MTA for a proposed high-power test of a complete cooling cell (Figure 3). A preliminary beam design with cost and scheduling has been completed, and a safety analysis and shielding assessment has been completed for the MTA. Beam spot enlargement options for the final design, include a large aperture quadrupole design, producing a large beam spot similar in size to that expected for a muon beam entering an initial cooling stage in neutrino factories or muon colliders.

LH_2 ABSORBERS

The issues that drive the absorber design and tests are: 1) the large amount of heat that needs to be extracted from high intensity beams 2) the desire to minimize multiple scattering and 3) the densely-packed and high radiation environment in which absorbers will be operating in a real cooling channel. Additionally, the combustive nature of hydrogen requires special safety considerations that drive much of the engineering and design.

Minimizing the multiple scattering has lead to novel window designs that depart from the standard spherical and torispherical shells [3]. For efficient heat removal, two different absorber designs have been proposed: 1) an internal heat exchange design, where the LH_2 mixing is achieved by natural convection cells, driven by the beam-deposited heat and the cold walls of the heat exchanger (with cold He gas) and 2) an external heat exchange design where the heat exchanger is in an external loop of hydrogen and the LH_2 mixing is achieved with an external pump with nozzles oriented at various angles to establish turbulent flow. These are shown in Figure 4.

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Designs for thin windows have matured, where windows of equivalent strength to standard designs have been realized with less than 30% their minimum thickness. Figure 5 shows the evolution of the window profiles. The current design has a profile with an inflected curvature where the thinnest section (around the center) is membrane-stress dominant: under the ultimate pressure (rupture) the greatest stress is experienced at the center.

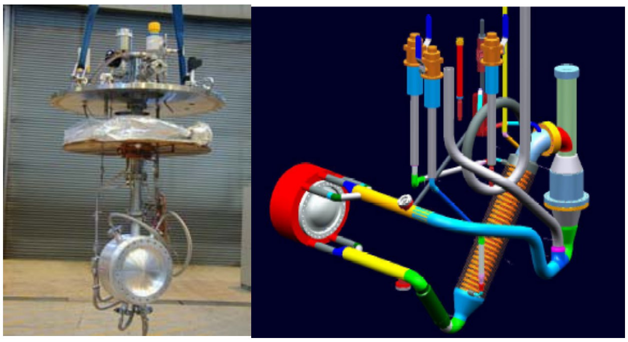

Figure 4: Two LH_2 absorber prototypes, convection type, internal heat exchange (left) and forced-flow, external heat exchange (right).

Earlier burst tests on thin membrane-stress dominated windowed did not produce shards, and demonstrated a window strength that was consistent with predictions from finite element analysis (FEA) predictions. To test the window performance, photogrammetry was used as a non-contact, large sampling method of measuring window profile deformation under pressure. This technique uses points of light projected onto the window surface, whose space locations were determined by a camera programmed to make parallax calculations [4]. The system has been upgraded to include a new projector lens and new camera software. Additionally, new methods of optical coating, including vapor deposition, are under consideration, as the thinness of the windows makes the variations in the thickness of the TiO optical coating manually applied a potential source of error. A set of safety requirements for the window design have been established for the MICE and MuCool experiments, and the MuCool window approach has passed the initial MICE safety review. A certification procedure for windows used in the cooling cells is being developed.

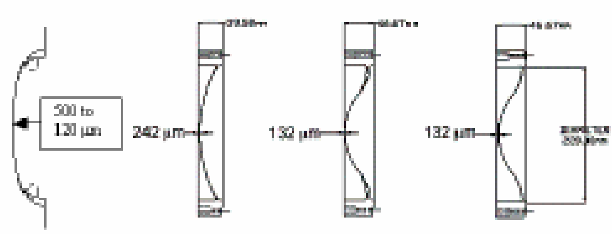

Figure 5: Evolution of thin window profiles. From left to right: standard torispherical shell with tapered ends to a normal surface, tapered torispherical to flange, inflected to flange, and thinned inflected.

The program for the absorber manifolds is proceeding in parallel paths. The external heat exchange, or forced-flow prototype has been built, and is currently set up in Lab P8 at FNAL for room temperature flow tests using an infrared camera. A design for an absorber manifold, cryostat and external hydrogen loop with pump and heat exchange is near completion and will be the first absorber tested in a beam at the MTA (Figure 6). The cryostat is designed to slide into the solenoid from Lab G, with the absorber in the magnets center. This is the absorber planned for the first complete cooling cell test.

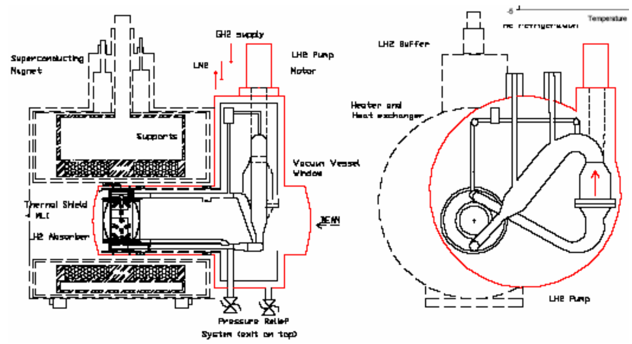

Figure 6: LH_2 forced-flow, external heat exchange prototype, shown inside a cryostat, inserted into the bore of the MTA solenoidal magnet sideview(left) and beam view (right).

A prototype for the convection absorber design has been manufactured and tested by the KEK/Osaka group (shown in Figure 4) [5]. This prototype was delivered to the MTA late in 2003. The absorber is cooled by cold helium gas (~15K) circulated behind the wall of the absorber interior. Heating coils are installed at the bottom of the absorber and in the center using warmer helium gas. An initial test with liquid hydrogen was successfully completed in August 2004, after a lengthy safety review. The hydrogen was cooled and condensed using cold helium from dewars. The absorber was completely filled, with a temperature of 18K maintained stably over a period of several hours. Several operational issues were successfully resolved and the safety and controls system refined with this first run. Initial heat loading tests indicated that heat absorption of 20W or more can be accomplished at a stable temperature. Plans for the next test in 2005 will include upgrades to the absorber instrumentation: new, better resolution temperature probes, a level sensor, and temperature probes placed inside the input and output cold helium for better determination of cooling efficiency.

Results from both the KEK tests and the room temperature flow tests will be compared with flow simulations of both prototype designs to predict performance in a real beam.

HIGH-PRESSURE RF CAVITIES

A novel approach to ionization cooling is being developed that uses high-pressure hydrogen gas at liquid nitrogen temperatures, with a density 0.5 that of liquid hydrogen. This idea of filling RF cavities with gas is new for particle accelerators, and is only possible for muons because they do not scatter as do strongly interacting protons, or shower as do less-massive electrons. Instead of discrete absorbers, the gaseous hydrogen would fill the accelerating RF cavities. Dark currents are suppressed due to Paschen's Law, a property first observed in 19th century when sparking in vacuum tubes was suppressed when the tubes where filled with a pressurized inert gas. Consequently, a much higher gradient is possible in a hydrogen-filled RF cavity than is needed to overcome the ionization energy loss, provided one can supply the required RF power. Hydrogen is also twice as effective as helium in ionization cooling effectiveness, viscosity, and heat capacity.

Measurements by Muons, Inc. and IIT at FNAL have demonstrated that hydrogen gas suppresses RF breakdown very well, about a factor six better than helium at the same temperature and pressure [6]. A small RF cavity test cell was built and run at FNAL's Lab G using power from the Lab G klystron. Figure 6 shows data that was taken at each pressure point by setting the klystron frequency at reduced voltage and raising the voltage until breakdown occurred. The cell was run up to 80MV/m after conditioning and before breakdown with a H_2 gas pressure of 31 atm at 80K. The next tests will be conducted at the MTA at FNAL. Current R & D plans include tests of pressurized RF cavities in magnetic fields and high radiation environments, and the use of new cavity construction materials, including beryllium RF windows for improved cavity performance. A beam test is scheduled for 2006 in the MTA.

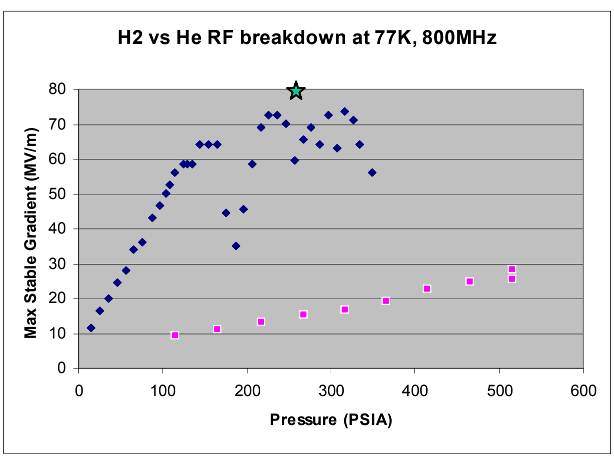

Figure 7: Paschen curve measurements for hydrogen (diamonds) and helium (squares). After a period of conditioning, a maximum gradient of 80MV/m was achieved (star) in GH_2.

6 D COOLING H_2 TECHNOLOGIES

In order to have the full 6-dimensional (6D) cooling that is required for muon colliders, tranverse cooling techniques must be combined with a mechanism for emittance exchange. Conventional schemes employ momentum dispersion and correlate momentum with path length through an absorber (typically wedge-shaped). The idea of pressurized RF cavities led to the concept of a cooling channel filled with a continuous homogeneous absorber. For instance, a magnetic channel with positive dispersion can correlate momentum with path length through the absorber material (ionization energy loss) in a compact and elegant fashion, achieving longitudinal cooling. Figure 8 shows a cartoon conceptualization of this principle.

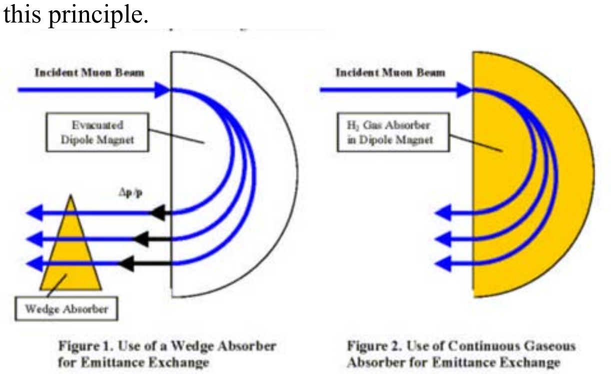

Figure 8: Conceptual drawing of emittance exchange with a homogeneous absorber (right) compared with conventional emittance exchange (left).

Helical Cooling Channels

New ideas are evolving around the continuous absorber concept. Analytical and simulation studies have confirmed that 6D cooling channel based on helical magnets surrounding RF cavities filled with dense hydrogen gas can be used to achieve very small emittances. Using the continuous absorber approach in this helical cooling channel (HCC) achieves a 6D emittance reduction of over 3 orders of magnitude in a 100 m segment. Simulations are being done for a cooling channel design employing a HCC filled with 200 MHz RF cavities pressurized with hydrogen gas to a density corresponding to half the density of liquid hydrogen. The simulations show a factor of 5000 reduction in the 6D emittance [7]. For a complete cooling channel, there would be three or four 20 m long segments, each with higher RF frequency.

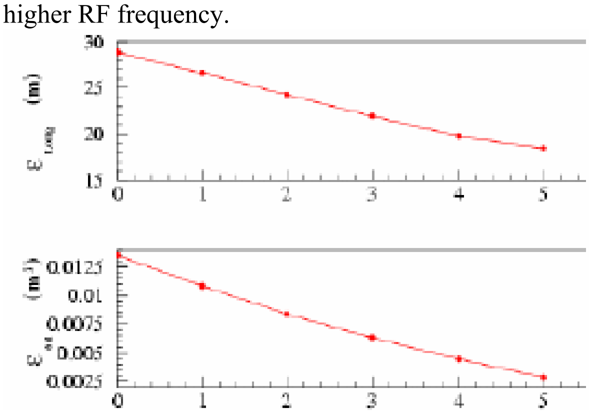

Figure 9: Simulated MANX cooling of normalized longitudinal and 6D emittances in a 5 m long HCC filled with liquid hydrogen.

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Manx Experiment

The HCC concept has been extended to have momentum-dependent magnetic field strengths for several new applications. In such channels the beam is decelerated and cooled by ionization energy loss over more than 100 MeV/c, then reaccelerated by a series of RF cavities (pressurized or conventional). The HCC magnet parameters must be varied to match the momentum of the beam as it slows down. Filled with liquid, the HCC with momentum dependent field parameters followed by RF cavities can be a 6D precooler, a 6D demonstration experiment, or an alternative to the original gas-filled HCC (where the momentum is kept almost constant).

A section of this momentum-dependent HCC can be part of a demonstration experiment for 6D cooling. One such demonstration experiment is being developed to follow MICE, using the same beamline and particle detectors [8]. Simulation results in Figure 9 show that a 5 m long section of the momentum-dependent HCC can reduce the normalized longitudinal emittance by a factor of 1.7 and likewise for each of the transverse emittances for a total 6D emittance reduction of a 5.5. Figure 10 shows a conceptual drawing of two views of the MANX experiment.

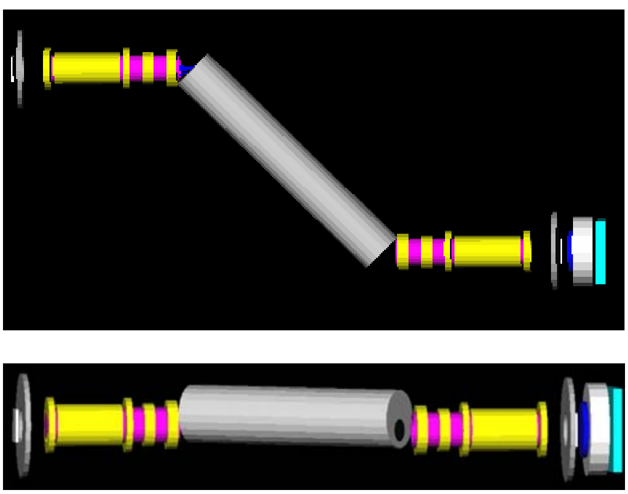

Figure 10: The Manx HCC cooling module between the detector solenoids of MICE.

In addition, two very interesting technological aspects of HCC designs involve the potential use of HTS to achieve very high fields and the use of hydrogen to act simultaneously as refrigerant, ionization energy absorber, and RF breakdown suppressant [9].

SUMMARY

The MuCool collaboration has successfuly built and tested cooling cell components and has resolved many outstanding technical and safety issues surrounding the use of hydrogen. The MTA is complete, on budget and on schedule. A major milestone was accomplished with the first absorber test with liquid hydrogen. The work involved in achieving safe, stable operation of the KEK convection type absorber builds a foundation for all subsequent reviews of absorber operation, including a high-powered run with a complete cooling cell. This test has also pushed the development of absorber instrumentation, and the work on safe operation at FNAL has expedited the successful completion of the first MICE safety review. The window design and testing has also matured, and has been used for the 201 MHz RF cell. An operational beamline is on schedule to run as early as 2006 in the MTA for tests on LH_2 and GH_2 absorber prototypes. Finally, new technology is being developed based on continuous absorber channels that include GH_2 filled RF cavities, and LH_2 or GH_2 filled helical magnetic channels that make neutrino factory and muon collider designs compelling and more affordable.

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