Current LH_2-Absorber R&D in MuCool

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The MuCool hydrogen-absorber R&D program is summarized. Prototype absorbers featuring thin aluminum windows and "flow-through" or "convection" cooling are under development for eventual power-handling tests in a proton beam and a cooling demonstration in a muon beam. Testing these prototypes and their components involves application of novel techniques.

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]

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

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 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 low atomic number (high L_R), the optimal choice being hydrogen.

The main absorber design issues are 1) the large amount of heat deposited by a high-intensity beam, 2) the desire to minimize beam "heating" from multiple scattering and 3) the densely-packed and high-radiation environment in which absorbers must operate in a cooling channel. Additionally, the combustive nature of hydrogen imposes safety requirements that drive aspects of the engineering design and will require extensive reviews to ensure that the system is sufficiently robust and failsafe.

Minimizing multiple scattering has led to novel window designs (figure 1) that depart from the standard spherical and torispherical shells. Our first design, a torispherical shell modified with tapered thickness near the "knuckle" for additional strength, achieved a minimum thickness about half that of a standard torispherical shell. A second design incorporated a spherical cap joined to the mounting flange via an inflected, tapered toroidal section, gaining another factor ≈2 in thickness. A more recent design achieves the same strength with the same central thinness and less material at the edges.

Testing these windows presents interesting technical challenges. Confirming that the manufactured window is consistent with design can be cumbersome, since standard coordinate measuring machines (CMM) require physical contact with the window and can only measure one point at a time. The standard technology for measuring strain in pressurized vessels, strain gages, require gluing to the window surface, with a clamping pressure beyond what the unsupported window can withstand. Gluing was accomplished using a mold of the concave side of the window that, when hardened, provided a backing surface to support the window. The first two windows tested at NIU were instrumented with both linear and "rosette" strain gages. Though consistent with FEA predictions, they provided only a limited number of data points.

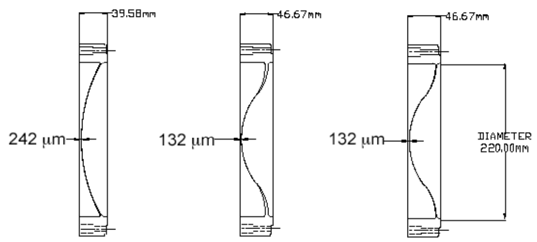

Figure 1: Profiles of three nonstandard window designs: "tapered-torispherical", "inflected", and "thinner-inflected".

Figure 2: Photogrammetry setup at NIU with projector in foreground, camera on right, projected dots on window, and stationary targets on flange

These problems are handled more effectively by a novel application of photogrammetry [2], using optical projection of dots measured via a position-calculating digital camera (see figure 2). Mask plates for the optical projector were designed to project ≈1,000 dots onto the window and flange in a radial pattern, the highest concentration being in the center. Stationary targets on the flange and a standard "optical bar" provided calibration and established the coordinate system. Window-shape measurements required imaging both sides of the window, with common stationary points tying the measurements to a single coordinate frame. For the pressure tests, pictures were taken (from one side only) after each pressure increment, with the change in window coordinates with respect to the stationary targets on the flange giving the displacement and strain of the window due to the pressure. In each test, several pictures from different angles were taken to determine coordinates in three dimensions using parallax. Test measurements on flat targets calibrated the projector. One major source of error was the proper mounting and stabilization of the projector. Measurement resolution improved when the projector and window/flange were mounted firmly to a single optical table.

The advantages of photogrammetry over CMM and strain-gage measurements are (1) non-contact measurements (important for very thin windows), (2) on the order of 100 times the number of measurements, all done simultaneously, (3) for shape measurements, smaller, more mobile equipment, and (4) no lengthy preparation process as with strain-gage application. With such a large number of measured points, the problem of determining the true thinnest part of a window can be realistically approached: fits to spherical caps can give a reasonable estimate and determine the deviation from front/back concentricity in the machining process. Combining the resolution of the projector and camera and the estimated error of the spherical fit, the uncertainty in the "thinnest-point" thickness is less than 2% for 330-μm-thick windows. Table 1 summarizes burst tests of four prototype tapered-torispherical windows. Measured and predicted burst pressures agree within 5%.

Hydrogen targets have been successfully designed for high-intensity beam experiments with heat extraction up to 700 W [3]. The large beam widths in proposed cooling channels require fluid mixing throughout the entire absorber volume, including the regions adjacent to the windows. Two approaches are being considered for quick and uniform removal of deposited heat to avoid boiling and unacceptable density fluctuations. One ("forced-flow") involves heat exchange in a cooling loop external to the absorber, with transverse flow through the absorber; nozzles recessed within the absorber manifold will direct the flow to create sufficient turbulence that "dead" zones (where heat buildup could cause boiling) will be avoided. The other approach relies on natural convection generated by the deposited heat, with heat exchange via cooling fins machined on the inner surface of the absorber manifold. In both cases gaseous-helium refrigerant will be provided using standard helium refrigerators. In a cooling channel, the absorber will be located between RF cavities and inside superconducting solenoid coils, where cavity dark-current radiation could be a challenge, accessibility is limited and forces from a magnet quench could present serious mechanical-stability problems.

Table 1. Burst-test results for tapered-torispherical windows of 15-cm radius. Window 1, thinner than cooling-channel requirements, provided a test of the limits of machinability. Photogrammetry was used to measure window deflection up to bursting and, for window 4, for shape measurement as well.

Window number	Temp.	Burst pressure measured (psi)	Burst pressure FEA (psi)	Design Thickness (μm)	CMM Thickness (μm)	Photogrammetry thickness (μm)
1	room	43.5	48	127	114	na
2	room	119	117	330	357	na
3	room	1	117	330	346	na
4	LN	151	156	330	365	331.6

Both forced-flow and convection absorber designs present substantial technical challenges and pose performance questions that are difficult to answer by simulation alone. Simulations will be used to guide the placement and orientation of nozzles in the forced-flow design to achieve optimal mixing. Computational-fluid-dynamics predictions are under development to predict flow velocities and patterns in the convection design. Experimental tests are planned using optical methods to determine heat flow and convection in test volumes, using water and various cryogenic fluids. In cryogenic absorber operation, temperature probes inside the manifold will be used for monitoring; their exact placement will be determined based on flow tests and flow simulations.

The current schedule calls for cryogenic absorber operation in the FNAL MTA late in 2003. One or more absorber prototypes will be filled with hydrogen and the system will be operated “standalone” to establish the necessary controls and instrumentation. A cryogenic test of an 11-cm-radius absorber inside the existing FNAL Lab G magnet will take place before the beam turns on. The first beam test of an absorber is planned for sometime during or after 2004. Tests are envisioned up to the full Linac intensity of 10^{14} protons/s. The planned MTA program consists of multiple studies, including a complete-cooling-cell test, beam-instrumentation tests, and tests of alternative cooling-channel technologies. The program’s scope will ultimately be determined by funding.

The success of a cooling-channel design cannot be determined without a thorough test of its components in an environment as challenging as that of a full-intensity muon-collider or neutrino-factory beam. Instrumentation and detectors must be developed that can measure beam parameters with enough precision to demonstrate that cooling has occurred. High-power tests at FNAL with protons and a definitive measurement of cooling with a lower-intensity muon beam [4] will provide necessary and complementary input to the design of a cooling channel for an actual neutrino factory.

References

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