# MUCOOL TEST AREA AT FERMILAB*

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*Abstract*

A new experimental area designed to develop, test and verify muon ionization cooling apparatus using the 400-MeV Fermilab Linac proton beam began construction in spring, 2002. This area will be used initially for cryogenic tests of liquid-hydrogen absorbers for the MUCOOL R&D program and, later, for high-power beam tests of these absorbers and other prototype muon-cooling apparatus. The experimental scenarios being developed for muon facilities involve collection, capture, and cooling of large-emittance, high-intensity muon beams--~1013 muons at a repetition rate of 15Hz, so that conclusive tests of the apparatus require full Linac beam, or 1.6 x 1013 p at 15 Hz. To support the muon cooling facility, a new primary beamline will divert beam from the Linac to the test facility. Located southwest of Wilson Hall between the Linac berm and parking lot, implementation of the facility and associated beamline takes advantage of civil construction and resources that remain from the 400-MeV Linac Upgrade Project. The design concept for the MuCool facility is taken from an earlier proposal[1], but modifications to the existing proposal were necessary to accommodate high-intensity beam, cryogenics, and the increased scale of the cooling experiments. This paper reports on the initial low-intensity (Phase I) implementation of the MuCool Test Area (MTA).

## INTRODUCTION

A new experimental area designed to develop, test and verify muon ionization cooling apparatus using the 400-MeV Fermilab Linac proton beam began construction in spring, 2002 and civil construction is now complete (Figure 1). This area will be used for cryogenic tests of liquid-hydrogen absorbers for the MUCOOL R&D program and, later, for high-power beam tests of these absorbers and other prototype muon-cooling apparatus. Since the experimental scenarios being developed for muon facilities involve collection, capture, and cooling of large-emittance, high-intensity muon beams--$\sim 10^{13}$ muons at a repetition rate of 15Hz, conclusive tests of the apparatus require full Linac beam, or $1.6 \times 10^{13}$ p at 15 Hz. However, given the budget and installed shielding constraints, the initial phase of the facility will be restricted to 10% of full Linac intensity or even lower. The present proposal is to divert Linac beam at a $\leq 1$ Hz repetition rate to begin initial experiments on a gas-filled rf cavity[2] and preliminary tests of liquid hydrogen absorbers.

A new primary beamline is required to divert beam from the Linac to the test facility is presently under design. Located southwest of Wilson Hall between the Linac berm and parking lot, implementation of the facility and associated beamline takes advantage of civil construction and resources that remain from the 400-MeV Linac Upgrade Project (making the project considerably more economical). The design concept for the MuCool facility is from an earlier proposal[1], with modifications to accommodate high-intensity beam, cryogenics, and the increased scale of the cooling experiments.

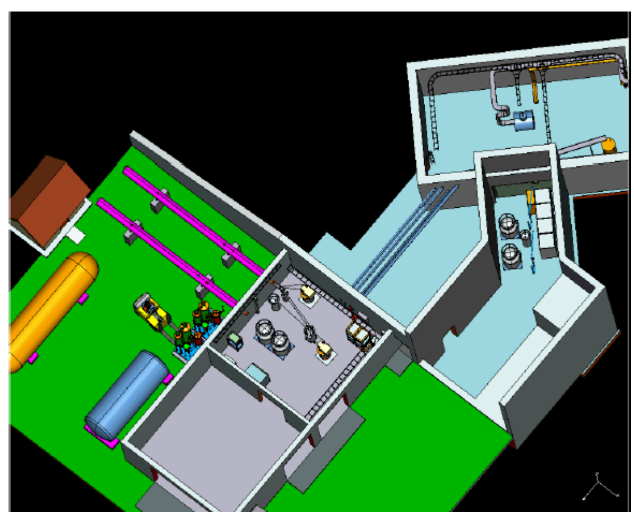

Figure 1. Exterior photograph and drawing of the (finished) civil construction for the MTA facility.

## THE FACILITY

Operational conditions and work environment for the MuCool experiment have been defined by the experimenters. Table 1 documents the operational parameters as submitted by the experimenters for beam requirements in the initial phase of the facility. To

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distinguish the experiment's beam absorber (which is essentially a target) from the beam absorber for the facility (which is designed to contain the primary Linac beam), future references will be to either the experiment's absorber or Device Under Test (D.U.T).

Table 1. Phase I beam parameters for the MTA facility

| **Beam Specifications** | **Min** | **Max** |
|---|---|---|
| Beam Size (±3σ) at D.U.T. | 1 cm | 5-7 cm |
| Beam Divergence (±3σ) at D.U.T. | 0.1 mr | 1 mr |
| Number of Pulses per Second | - | 1 Hz |
| Number of Proton/pulse x $10^{12}$ | 0.64 | 16 |
| Pulse Duration | 2 μs | 50 μs |

### *Facility specifications*

Complete specifications for the MTA must further include the expected occupation of the experimental hall, hands-on maintenance tasks on irradiated components, and establishing a limit on the total number of protons per year that can be delivered to the facility. Such constraints are nominally interrelated and specifications must be self consistent to achieve an optimal facility design.

Normally, the total number of protons delivered is dictated by the physics of an experiment, and since experiments conventionally use orders of magnitude less intensity and highly-irradiated components—such as beamline elements and targets—are rarely worked on or modified, hands-on restrictions are not generally a defining issue for an experiment, but rather a shielding one. Generally, there is low residual activation of experimental detectors, and, once an experiment is up and running, accesses, work, and occupation of the hall is automatically limited.

This is not the case for the high-intensity facility proposed for MuCool R&D. Although full Linac beam has been requested in the final stage of the facility (in one-hour intervals), the integrated intensity or total number of protons required cannot be readily calculated for these proposed R&D projects. The total number of protons the facility can accept, or operational envelope, must be specified using other criteria. Further, the occupancy of the hall is expected to be frequent as modifications naturally follow the development of the experimental apparatus, with maintenance on and change-out of irradiated components potentially routine. The guidelines and administrative control over radiation and dose levels, then, is very similar to those established for accelerator operation and maintenance, but with the added complication of high occupancy. It is these considerations that the facility design—optics, shielding, beam absorber, and rate limitations, etc.—must satisfy.

In consideration of the above, the following list indicates the development and logic of the constraints used to define the operational envelope and specifications for this facility.

- **Hands-on maintenance** implies administrative controls must limit the equivalent dose received by users and employees to a maximum 100 mr/week (FNAL limit). Irradiated components must show activation levels well below this to avoid increased supervision and monitoring of the facility.
- **Unlimited occupancy** for R&D means work and access to the facility cannot be limited by the general radiation profile of the hall. Work areas (most of the hall) will be <5mr/hr, (the defined limit for a radiation area) allowing a normal 40 hr week.
- **Total number of Protons per year** is set by the activation of components to levels tolerable for hands-on maintenance. At the 1 Hz rate at full Linac intensity, there appear to be no limitations from radiological concerns, either environmental or work related as discussed in a following section.
- **Beam parameters** as currently defined by the users (Table 1), are sufficient for a complete beamline design: optics and component specifications including easily-achievable requirements on shielding and radiation control.

## EXPERIMENTAL PROGRAM

A number of R&D experiments are already slated with components in place and ready for beam. These experiments include:

- **Liquid Hydrogen (LH2) absorber tests** will represent the first tests in beam of the thin-window, liquid hydrogen absorber developed for ionization cooling, first at low intensity and later at high intensity (Phase II of the MTA);
- **201 and 805 MHz rf cavities** will be tested using rf power derived from the Fermilab Linac. Ultimate beam tests will involve the hydrogen absorber, rf cavity, and a large-aperture SC solenoid in a cooling channel configuration;
- **Gaseous hydrogen-filled rf cavities** demonstrating an ultra-high-gradient will undergo final testing using beam[2].

Power sources, cryogenics, an rf cavity, and SC solenoid have already been installed in the MTA facility. The gaseous hydrogen-filled rf cavities[2] have been gradient tested and are ready for beam also (Figure 2).

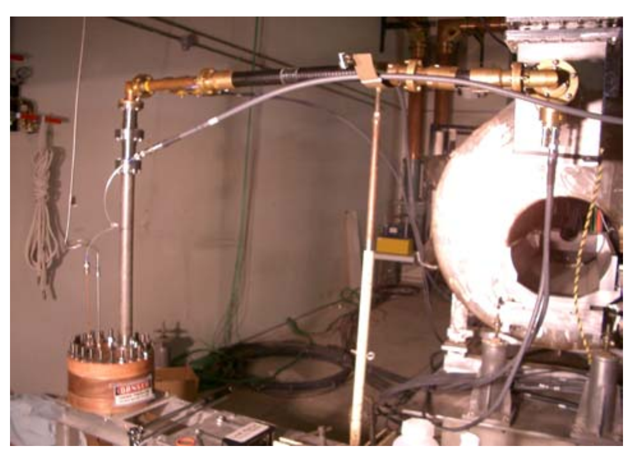

Figure 2. Muons Inc. rf cavity and SC solenoid in MTA.

## RADIATION ASSESSMENTS

A comprehensive radiation shielding study using MARS[3] has been performed for the MuCool Test Area at normal operating and accident conditions[4]. Initially, the full MARS simulation was performed on the MuCool experimental configuration for a 400-MeV (kinetic energy) incident proton beam of 2 x $10^{13}$ protons per pulse at 15 Hz and on a specific test hydrogen absorber. (The test hydrogen absorber includes four 0.2 mm Al windows and 21 cm of liquid hydrogen and is enveloped by a superconducting NbTi solenoid with Bz = 3 T.)

For the purposes of a more complete study of operational radiation levels, residual activation, and ground and surface water contamination, two target models were considered: the liquid hydrogen as designed for MuCool and a copper disk 1 cm in thickness. The targets correspond to 2% and 10% of the 400-MeV proton total interaction length, respectively. Finally, the actual gas-fill rf cavity of the Muons Inc. experiment[2] has also been simulated. Power density, absorbed dose, and residual dose were calculated for components and particle fluxes in the experimental hall were also determined. There is little sensitivity of the results to the variation in beam size. Energy thresholds were set at 0 for neutrons and 0.1 MeV for all other particles.

Within the framework of a credible accident scenario, a beam accident at the MTA is less severe than normal operation. It is the normal operating conditions that determine the level of shielding required, i.e. for 1-15 Hz operation at full Linac intensity (50μs pulse, 1.6 x $10^{13}$ protons/sec).

### *Phase I*

Recently it was suggested to perform the first tests in the MTA at a reduced pulse length and repetition rate, namely at 2 μs pulse length @ 1 Hz or, in other words, 5.2 × $10^{11}$ protons per second. It represents a significant reduction in beam intensity, within a factor of 25×15 = 375, when compared to the maximum beam intensity previously studied and what the facility could, in theory, provide. The request suggests also that the beam absorber should be placed in the target hall instead of the cave initially designed for the absorber in the berm downstream of the experimental hall.

Given the 2 μs pulse length @ 1 Hz and the existing shielding, 11 ft of dirt, the calculated prompt dose rate atop the berm approximately is equal to 0.02 mrem/hr. At this level the top of the berm qualifies as an area of unlimited occupancy with no controls required.

The beam absorber was designed with a copper interior to dissipate the heatload generated by the full Linac intensity and is surrounded by interleaved steel shielding for final attenuation of the radiation. When the beam absorber is disassembled and reassembled in its final position, the residual activation of the absorber is a concern. After 30 days irradiation and 1 day cooling the residual dose at the external surface of the absorber approximately will be approximately 2 mrem/hr. The surrounding steel blocks (170 cm × 170 cm × 270 cm) weigh about 62 × $10^3$ kg, and must be un-stacked before relocation. The hottest part will be the copper wedge-shaped insert. A calculation with a detailed spatial mesh reveals that the residual activation of the copper insert immediately after an irradiation (one or two 10-hr shifts) will be about 1.2 × $10^4$ mrem/hr (see Figure 3 below). However, after a one-week cooling the residual activation falls to 50 mrem/hr. After cooling, a relocation of the beam absorber to its final position is feasible from the standpoint of radiation safety.

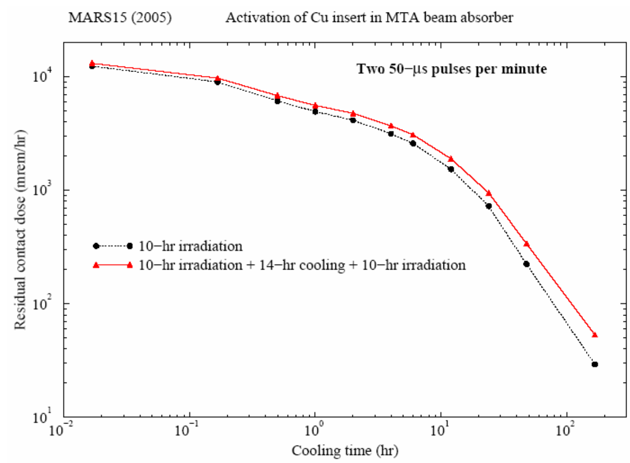


Figure 3. Residual activation of Cu insert in beam absorber. (Two 50-μs pulses provide 4.3 × $10^{11}$ p/sec.)

### *Phase II*

At full Linac capability (the safety envelope), this facility will require substantial upgrades in both shielding and radiological controls[4]. In particular, it has been shown that shielding sandwiches of high-density concrete and dirt provide a much improved dose attenuation above the MTA than the originally-proposed iron-dirt sandwiches when considering the load capacity of the hall enclosure and the low energy of the Linac beam. The present berm will be removed and replaced with 10.5 ft of heavy concrete and 2 ft of soil on top of the enclosure for Phase II and some interior shielding will also be required.

## SUMMARY AND PROSPECTS

The Phase I beamline is presently under design and fabrication. The expectation is to install many of the components in the 2005 October shutdown and potentially deliver low-intensity beam to the facility in 2006.

## REFERENCES

[1] FERMILAB-PUB-95-078 (Mar 1995).
[2] R. Johnson, et. al., to be published LINAC 2004, K. Yonehara, et. al., to be published NuFact04, see also http://www.muonsinc.com
[3] Fermilab-FN-628 (1995)
[4] Fermilab TM-2248, May 2004 and TM-2305-AD.