

## A FREE-JET MERCURY SYSTEM FOR USE IN A HIGH-POWER TARGET EXPERIMENT\*

P.T. Spampinato<sup>†</sup>, V.B. Graves, T.A. Gabriel, M.J. Rennich, ORNL, Oak Ridge, TN 37831, U.S.A.  
H. Kirk, N. Simos, T. Tsang, BNL, Upton, NY 11973, U.S.A.  
K. McDonald, Princeton University, Princeton, NJ 08544, U.S.A.  
P. Titus, MIT Plasma Science and Fusion Center, Cambridge, MA 02139, U.S.A.  
A. Fabich, H. Haseroth, J. Lettry, CERN, Geneva, Switzerland

### Abstract

A proof-of-principle experiment to investigate the interaction of a proton beam, high magnetic field, and high-Z target is planned for testing at CERN in 2007. The experiment is a multi-laboratory, international endeavor underwritten by the Muon Collider Collaboration. A free-jet mercury target system that interacts with a high-power (1-MW) proton beam in a high magnetic field (15 T) is being designed. The mercury jet target is configured for insertion into the 15-cm-diameter bore of a high-field solenoid. The target features a hermetically sealed primary-containment volume that is enclosed in a secondary containment to ensure isolation of mercury vapors from the surrounding environment. The jet diameter is 1 cm, and the jet velocity will be up to 20 m/s. An optical diagnostic is incorporated into the target design to permit observation of the dispersal of the mercury as a result of interaction with a 24-GeV proton beam with up to  $20 \times 10^{12}$  protons per pulse. The target system also includes titanium alloy beam windows for the primary and secondary containments.

### INTRODUCTION

The mercury jet target system is part of the proof-of-principle experiment to investigate the interaction of a proton beam, high magnetic field, and high-Z target planned for testing at CERN in 2007. In principle, it is similar to a high-power production target needed for a neutrino factory or muon collider. The system consists of a free-jet mercury target situated inside a 15-T solenoid, fitted with a laser optic system to observe the interaction of the jet and the proton beam in the magnetic field [1]. The experiment is planned for 2007 in the TT2A tunnel at CERN. The target system will have double containment and be capable of delivering a minimum of 100 jet cycles into a proton beam line. Figure 1 shows the target system; the protruding end is that which is inserted into the bore of the solenoid.

The target system consists of four subsystems: the primary-containment structure, a secondary-containment structure, a hydraulically actuated syringe pump system, and the support base structure. The design for each subsystem must take into account the requirements for dealing with mercury, a toxic heavy metal that will

become mildly activated once testing commences, and the requirements for dealing with a mildly radioactive structure at the completion of testing.

The system will operate in a 1-atm environment of air for both the primary and secondary containments. Air activation (i.e.,  $^{13}\text{N}$ ,  $^{15}\text{O}$ , and  $^{41}\text{Ar}$ ) will not be an issue

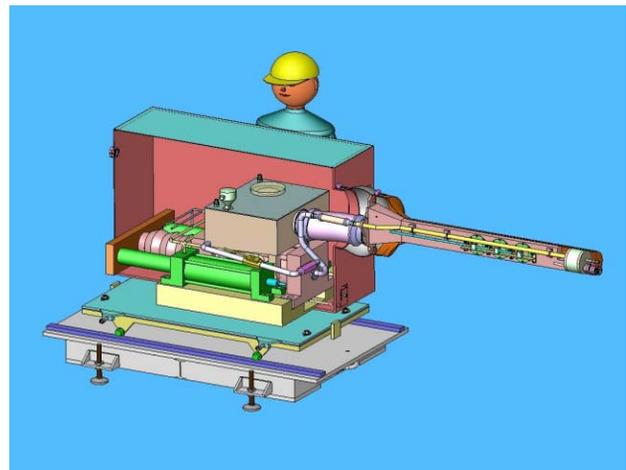


Figure 1: Cutaway view of the target system.

for this system since the air environment is not purged after each pulse and the containment boundaries remain intact for the duration of testing. If there is a need to breach either barrier after test operations commence, 1 h of waiting will be sufficient for the decay of these isotopes. This approach is simpler than incorporating equipment to evacuate and backfill with helium.

### TARGET SYSTEM DESIGN

The target system consists of the equipment to operate and contain a continuous mercury jet that can be sustained for a maximum of 12 s. The jet is produced by a syringe pump that is hydraulically driven. The target system is being designed such that the elemental mercury in the target is double contained and mounted on a base structure that supports the target equipment and the solenoid system as an integrated unit. The support structure will be capable of being manually maneuvered into or out of the axis of the proton beam line, and it has provisions for adjusting the elevation and pitch of the integrated system.

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<sup>†</sup>spampinatop@ornl.gov

The target system is initially assembled and tested “hands on” but must be maintained and operated with minimal personal contact after beam operations commence. Therefore, design of the target system takes into account the eventual disassembly and decontamination of the equipment. Design features are incorporated into the target system to simplify the handling of mildly activated components that are mercury contaminated as well as the handling of activated mercury, so as to minimize exposure to personnel. At the completion of the CERN tests, the target system and the mercury will be returned to Oak Ridge National Laboratory (ORNL) for future use in developing high-power targets. Figure 2 is a schematic diagram of the target system and the containment boundaries.

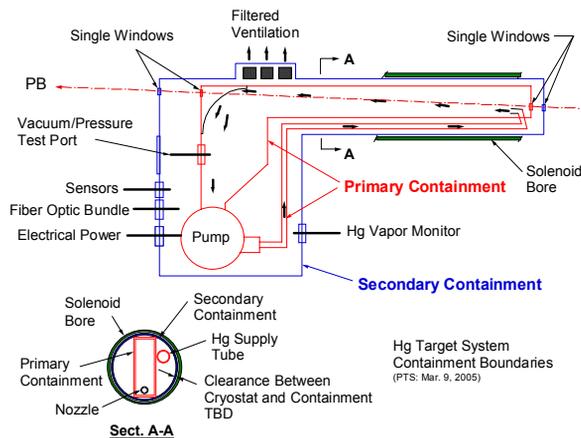


Figure 2: Schematic diagram of the target system.

### Design Specification

The fundamental requirement for the target system is to deliver a 1-cm-diameter jet of mercury with a velocity of up to 20 m/s, fully interacting with protons along 30 cm of beam line. A flow rate of 95 L/m (25 gpm) is required to meet the velocity specification. In addition, the target system is being designed to meet the criteria of ISO 2919, “Table 2–Classification of Sealed Source Performance–Class 2,” since the elemental mercury will become mildly activated. These requirements are as follows:

- temperature:  $-40^{\circ}\text{C}$  (20 min),  $+80^{\circ}\text{C}$  (1 h);
- external pressure: 25 kPa absolute (60 psi) to atmospheric;
- impact: 50 g dropped from 1 m, or equivalent imparted energy;
- vibration: 3 times at 10 min. each, 25–500 Hz at  $49\text{ m/s}^2$  ( $5 g_n$ , acceleration maximum amplitude); and
- puncture: 1 g dropped from 1 m, or equivalent imparted energy.

### Geometry

The geometric requirement for the target system is based on the following criteria:

- The proton beam is parallel to the horizontal tunnel floor and  $121\text{ cm} \pm 5\text{ mm}$  ( $47.64 \pm 0.20\text{ in.}$ ) above the floor.
- The proton beam, solenoid axis, and mercury jet all reside in a common vertical plane.
- The service end of the solenoid (i.e., the location of electrical and cryogenic connections) is “up-beam.”
- The solenoid axis is tilted 67 milliradians ( $3.84^{\circ}$ ) with respect to the proton beam, with the up-beam end of the solenoid elevated above the beam.
- The mercury jet flows from the “up-beam” to the “down-beam” direction, the same direction as the proton beam.
- The mercury jet begins below the proton beam at an angle of 33 milliradians ( $1.89^{\circ}$ ) to the beam.
- The jet nozzle is positioned so that the jet center crosses the beam center at  $Z = 0$ , the center of the solenoid.

### Instrumentation

The target system will be instrumented with the following sensors, each having readout capability remotely located in a control room  $\sim 50\text{ m}$  away:

- a mercury vapor sensor to monitor the atmosphere in the secondary containment,
- a temperature sensor to monitor mercury temperature in the sump tank,
- a position sensor on the syringe pump cylinder to monitor mercury flow in the supply line,
- a level sensor to monitor the quantity of mercury in the sump tank,
- a conductivity sensor to detect mercury that could collect in the base of the secondary containment, and
- leak detection of the interstitial space in the secondary-containment beam windows.

### Optical Diagnostic

A pulsed laser optical diagnostic connected to a high-speed charge-coupled device (CCD) camera will be used to view the behavior of the mercury jet as it interacts with the proton beam. Three viewing ports will be incorporated into the primary containment, each consisting of a quartz window where laser light is directed perpendicular to the jet. A spherical mirror will be mounted on the opposite side of each port, also mounted on the primary containment. Because the jet is opaque, the images obtained are the shadow of the jet. The ports will be located at  $Z = 0$  (center of the solenoid) and at  $Z = \pm 13\text{ cm}$ . The diagnostic system is being designed at Brookhaven National Laboratory (BNL).

### Beam Windows

Proton beam windows will be mounted to the primary and secondary containments of the target system. The windows will be fabricated from titanium alloy, Ti6Al4V. The up-beam and down-beam windows of the primary

containment will be single-thickness material, while the secondary-containment windows will be double thickness to permit interstitial leak detection to be used to monitor for a possible window failure. The windows are being designed at BNL.

## TEST PLAN

The target system will undergo a series of functional and operating tests before being shipped to CERN for the beam experiment. Systems testing will be done at ORNL after the equipment has been fabricated and assembled; the equipment will then be shipped to Massachusetts Institute of Technology (MIT) for integrated system tests with the solenoid.

The completely assembled system includes the pump equipment, the primary and secondary containments, the control system, the laser optics, the beam windows, and up to 23 L of mercury. (Twenty-three liters is based on a system capable of delivering 12 s of jet.) The tests at ORNL will be used to characterize the performance of the equipment, verify the leak tightness of the equipment, calibrate and verify the timing of the controls, and confirm operation of the sensors and optical diagnostic system.

The testing at MIT will repeat all of the tests listed above but under varying magnetic fields up to 15 T. These tests will verify operation of the target system prior to shipment to CERN and also verify the integrity of the target interfaces with the magnet system.

The experiment at CERN will repeat all of the tests listed above but with the addition of the proton beam. Up to 100 pulses (tests) will be done at CERN for the proof-of-principle testing. At the completion of these tests the target system and the mercury will be mildly activated. Therefore, the equipment will remain in the TT2A tunnel for a cool-down period sufficient to permit hands-on dismantling of the components. Figure 3 shows the target/solenoid equipment installed in the beam-line path. (Note the angle of the target/solenoid components relative to the horizontal beam line shown in red.)

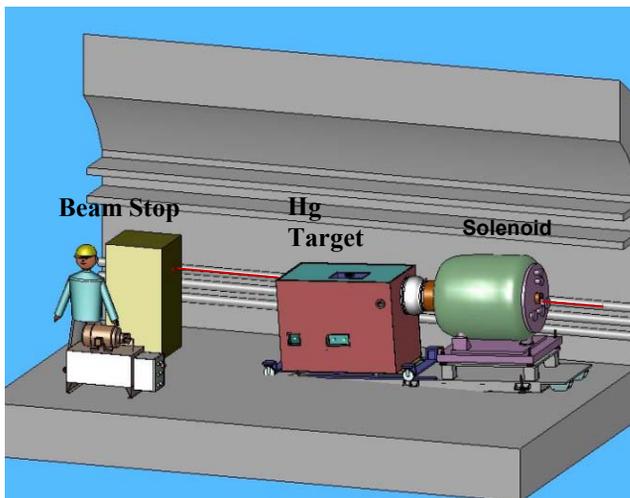


Figure 3: Target and solenoid installed in the tunnel.

## SAFETY CONSIDERATIONS

The primary safety considerations focus on transporting and handling elemental mercury before and after it becomes activated, containing mercury and its vapors during testing, and decommissioning the activated equipment and preparing it for shipment back to ORNL. Packaging and shipping requirements for the activated equipment and the mercury will be met for transport within the United States and the European Union. A preliminary estimate of activation [2] indicates that after 200 pulses with  $16 \times 10^{12}$  protons per pulse and 30 days of operation, a contact dose at  $Z = 0$  on the outer surface of the solenoid will be as follows:

- 40 mrad/h after 1 h,
- 21 mrad/h after 1 day,
- 13 mrad/h after 1 week,
- 5 mrad/h after 1 month, and
- 1 mrad/h after 1 year.

It is expected that dose-rate levels at other locations around the equipment will be lower. Therefore, limited access to the equipment during the CERN tests, although not anticipated, is possible after a cool-down period of days. Access for removing the mercury, dismantling the target equipment, and packaging the equipment for shipment appears possible after a cool-down period of at least 1 month.

## CONCLUSION

A free-jet mercury target system is being designed at ORNL to support a proof-of-principle experiment planned for 2007 at CERN. The mercury jet will have a velocity of up to 20 m/s at a flow of 95 L/m and will be powered by a hydraulically driven syringe pump. The amount of mercury needed for a 12-s jet is 23 L of elemental mercury. The jet will interact with a 24-GeV proton beam in a 15-T magnetic field. A laser optical diagnostic coupled to a high-speed CCD camera will be used to record the interaction of the jet and the beam.

## REFERENCES

- [1] J.R.J. Bennett et al "Studies of a Target System for a 4-MW, 24-GeV Proton Beam," A Proposal to the ISOLDE and Neutron Time-of-Flight Experiments Committee, CERN-INTC-2004-016, INTC-P-186, April 26, 2004.
- [2] H. Kirk, "The High-Power Target Experiment," May 24, 2004, p. 31, [http://puhep1.princeton.edu/mumu/target/hkirk/kirk\\_intc.pdf](http://puhep1.princeton.edu/mumu/target/hkirk/kirk_intc.pdf).