

A HIGH-POWER TARGET EXPERIMENT

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Abstract

We describe an experiment designed as a proof-of-principle test for a target system capable of converting a 4-MW proton beam into a high-intensity muon beam suitable for incorporation into either a neutrino factory complex or a muon collider. The target system is based on exposing a free mercury jet to an intense proton beam in the presence of a high-strength solenoidal magnetic field.

Previous studies [2] have indicated that the most efficient pion production will be achieved with small radii for both the target and the proton beam. Furthermore, it is advantageous to place the target and proton beam at an angle of ≈ 100 mrad to the solenoidal axis. This permits the pions, whose trajectories in the solenoidal field are spirals, to leave the side of the target with a minimal probability for re-entering the target volume where they might be absorbed.

THE TARGET CONCEPT

Key elements of the target system [1] are: an intense proton source, copious soft-pion production off a high- Z target that is replaced every beam pulse, and capture of the generated low- P_{\perp} pions in a high-field (≥ 15 T) solenoidal magnet, as shown in Fig. 1. An important byproduct of this approach is that π^+ 's and π^- 's are equally produced and both particle types can be conducted down the solenoidal decay channel.

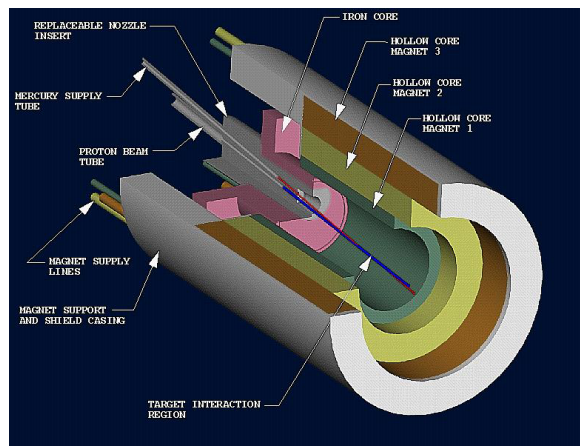


Figure 1: Concept of a continuous mercury jet target for an intense proton beam. The jet and beam are tilted by 100 mrad and 67 mrad, respectively, with respect to a 20-T solenoid magnet that conducts low-momentum pions into a decay channel.

TARGET ISSUES

To avoid the issues of radiation damage to a solid target in an intense proton beam, the target is replaced every beam pulse. While schemes for moving solid targets can be envisaged [3], a flowing liquid target is simpler, and mercury presents itself as the unique high- Z room-temperature liquid metal. An alternative is a eutectic Pb-Bi alloy that melts at 125 °C. The liquid target should be in the form of a free jet, rather than being confined in a pipe, since the beam-induced cavitation of the liquid metal is extremely destructive to any solid wall in the immediate vicinity of the interaction region. For, say, a 50-Hz beam pulse rate, and a new target of two interaction lengths each pulse, the mercury velocity must be ≈ 20 m/s. Another issue associated with the proton beam is the effect of the energy that it deposits in the target. The temperature of the target rises almost instantaneously after a beam pulse, resulting in large internal stresses that might crack a solid target [4] or disperse a liquid target. In the case of a liquid jet target, the dispersal of the jet by the beam should not be destructive to the surrounding target system components. Furthermore, the dispersal of the liquid jet should not adversely effect the pion production during subsequent beam pulses, either on the microsecond scale if several micropulses are extracted from a proton synchrotron, or on the scale of the macropulse period (nominally 20 msec for 50-Hz operation).

The operation of a liquid metal jet inside a strong magnetic field raises several magnetohydrodynamic issues as to possible deformation of the jet's shape and trajectory, as well as the effect of the magnetic field on the beam-induced dispersal of the jet.

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THE EXPERIMENTAL PROGRAM

Initial tests involving the interaction of proton beams on mercury targets were performed with experiment E951 at the Brookhaven Alternating Gradient Synchrotron [5], and continued at the CERN ISOLDE facility [6]. The BNL tests featured a 24-GeV proton beam interacting with a free mercury jet with a diameter of 1 cm and velocity of 2.5 m/s. The AGS was operated in a harmonic-12 mode and the extraction kicker configured so that only one of the 12 proton bunches could be extracted within a 30-msec interval. Proton bunch intensities of $2\text{--}4 \times 10^{12}$ (2-4 TP) protons were delivered into a spot size of $\sigma_x = 0.3$ mm and $\sigma_y = 0.9$ mm. This resulted in a peak energy deposition of 80 J/g, which is comparable to that expected from a 1 MW proton driver delivering a 24-GeV proton beam at 15 Hz [7]. These initial tests did not have a magnetic field on the target. Some images of the dispersal of the mercury jet are shown in Fig. 2.

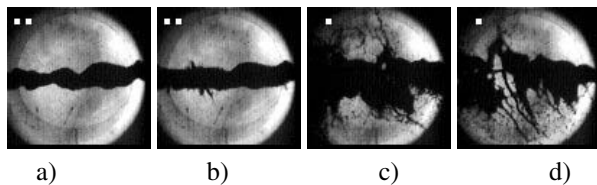


Figure 2: Hg jet interaction with 3.8×10^{12} 24-GeV protons; $t =$ a) 0 ms; b) 0.75 ms; c) 10 ms; d) 18 ms.

This experiment had several key observations:

- The dispersal velocity of Hg droplets with 4 TP on target was on the order of 10 m/s.
- The Hg dispersal was largely confined to the transverse direction and did not extend outside the region of overlap with the proton beam.
- The visible manifestation of Hg dispersal occurred 40 μ s after arrival of the proton beam pulse.
- The Hg jet showed surface-tension instabilities; its diameter varied from 0.5 to 1.5 cm.

A parallel effort was undertaken to study the effects of high-velocity mercury jets in the presence of high-magnetic fields [6], but with no proton beam. The Hg jet had a diameter of 4 mm and a velocity of 12 m/s. Magnetic fields up to 20 T were utilized. The main result was the observation of jet stabilization (damping of surface tension waves) as the magnetic field was increased, as shown in Fig. 3. The jet was introduced into the magnetic field at an angle of 100 mrad with no perturbation of the jet on scales larger than 1 mm.

PROOF-OF-PRINCIPLE EXPERIMENT

We have proposed [8] and been approved to perform a proof-of-principle experiment at the CERN Proton Syn-

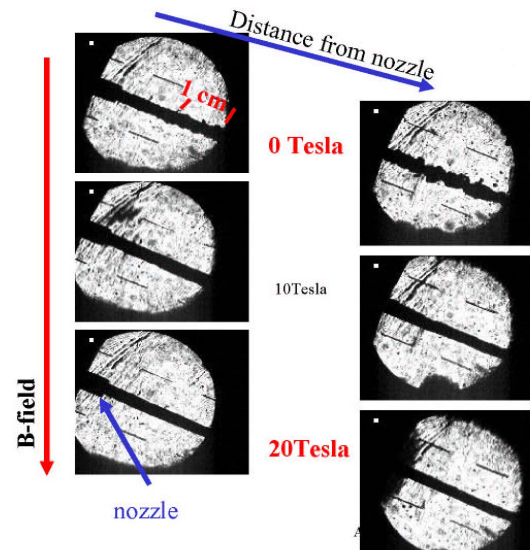


Figure 3: The Rayleigh instability of a mercury jet (4-mm diameter and 12-m/s velocity) is suppressed by high magnetic fields.

chrotron (PS) that will combine a free mercury jet target with a 15-T solenoid magnet and a 24-GeV primary proton beam. The PS will run in a harmonic-8 mode and we will be able to fill 1-4 of the 8 rf buckets with $5\text{--}7 \times 10^{12}$ protons/bunch at our discretion. The achievable spot size at the experiment will be $r \geq 1.2$ mm (rms). This will allow us to place up to 28×10^{12} protons on the mercury target within a 2- μ s spill, thus generating a peak energy deposition of 180 J/g. For this experiment we have designed and built a high-field pulsed solenoid with a warm bore of 15 cm [9]. This magnet is capable of delivering a peak field of 15 T with a 1-s flattop after a 9-s ramp. The magnet will be cooled to 77 K by liquid nitrogen to reduce the resistance of its copper coils. Nonetheless, a 5-MVA power supply is required to achieve the 15-T peak field. The Hg

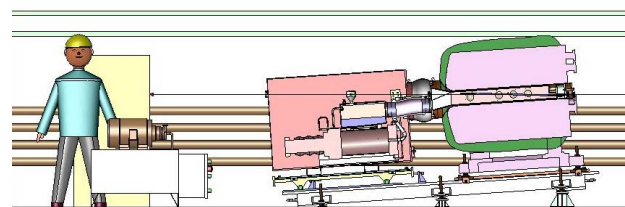


Figure 4: A vertical section of the proof-of-principle experiment at CERN. The solenoid/Hg jet system is tilted by 100 mrad with respect to the beam/floor.

jet delivery system [10] is being designed, built, and tested at ORNL. This system will generate a 1-cm-diameter mercury stream with velocities up to 20 m/s. In order to obtain the required 100-mrad angle between the mercury jet and the axis of the solenoid, we will tilt the combined magnet

and Hg jet system as shown in Fig. 4. The primary diagnostic of the beam-jet interaction is optical. A set of four viewports along the interaction region, shown in Fig. 5, will be connected by imaging fiberoptic bundles to four high-speed cameras. Scintillation counters will monitor the flux of secondary pions produced during each of the 1-4 bunches of a beam pulse to provide a measure of possible beam-induced reduction of density of the liquid jet. Each pulse of the

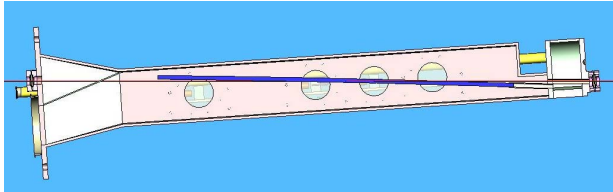


Figure 5: A vertical section through the bore of the solenoid magnet, showing the mercury jet crossing the magnetic axis from right to left at an angle of 100 mrad. A set of four optical viewports along the beam-jet interaction region will permit high-speed imaging of the history of the jet.

proton beam delivered to this system constitutes a separate experiment. It will take about 30 min to recool the solenoid each time it is energized. About 100 beam pulses will be utilized in a parasitic, beam-on-demand mode over a two-week period at CERN in the Spring of 2007. These pulses will span a range of intensities, and a range of time intervals between the multiple extracted bunches per pulse. The magnet will be operated over a range of field strengths of 0-15 T. This program will explore the full variety of beam/target conditions anticipated in the design of neutrino factories driven by proton linacs or synchrotrons of 1-4 MW beam power.

CONCLUSION

We will perform a proof-of-principle experiment at CERN in the Spring of 2007 in order to validate the target concept for producing an intense secondary source of muons. This experiment will combine in one setup a high-field 15-T pulsed solenoidal field, an intense 24-GeV proton beam, and a free flowing 1-cm-diameter, 20-m/s mercury jet.

ACKNOWLEDGMENTS

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