A PROOF-OF-PRINCIPLE EXPERIMENT FOR A HIGH-POWER TARGET SYSTEM

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Abstract

The MERIT experiment, to be run at CERN in 2007, is a proof-of-principle test for a target system that converts a 4-MW proton beam into a high-intensity muon beam for either a neutrino factory complex or a muon collider. The target system is based on a free mercury jet that intercepts an intense proton beam inside a 15-T solenoidal magnetic field.

INTRODUCTION

A muon collider or neutrino factory requires intense beams of muons, which are obtained from the decay of pions. Pion production by a proton beam is maximized by use of a high-Z target such as mercury. A liquid jet target has the advantages over a solid target that a flowing jet can readily remove heat and that it is immune to radiation damage. However the proton beam energy disrupts the jet and the system could be operationally unstable.

Efficient capture of low-energy secondary pions (for transfer into the subsequent muon accelerator complex) requires that the target system be immersed in a strong magnetic field of solenoidal geometry. This magnetic field should stabilize the mercury flow in regions of nearly uniform field, but it perturbs the liquid metal jet as it enters the field. Hence, the behavior of the mercury jet plus an intense proton beam inside a strong magnetic field needs to be understood better before resources are committed to a larger facility. The MERIT experiment is to be conducted at CERN in 2007 for this purpose.

TARGET ISSUES

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 ($\geq$ 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.

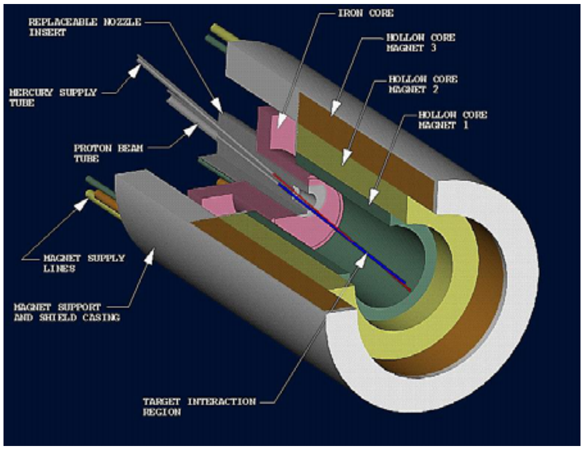

Figure 1: Concept of a continuous mercury jet target for an intense proton beam. The jet and beam are tilted by 100 mrad and 67 mrad, respectively, with respect to a 20-T solenoid magnet that conducts low-momentum pions into a decay channel.

Simulations [2] show that maximal pion production occurs for small radii for both the target and the proton beam. Furthermore, it is advantageous to tilt the target and proton beam by an angle of ≈ 100 mrad to the solenoidal axis so that soft pions that leave the side of the target are not reabsorbed after one turn on their helical trajectory.

The proton beam deposits $\approx$ 15% of its energy in the target, leading to an instantaneous rise in the temperature of the target, which in turn causes large transient stresses that can crack a solid target [3]. In the case of a liquid jet target, its dispersal by the beam should not be destructive to the surrounding target system components. Furthermore, the dispersal of the liquid jet should not reduce the pion production during subsequent beam pulses (nominally 20 msec apart for 50-Hz operation), or during the various bunches of a single macropulse. For the liquid jet to present a new target of two interaction lengths each macropulse, the mercury velocity must be ≈ 20 m/s.

The mercury target should be in the form of a free jet, rather than confined in a pipe, since the beam-induced cavitation of the liquid metal is extremely destructive to any

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solid wall in the immediate vicinity of the interaction region.

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.

PREVIOUS STUDIES

Initial tests involving the interaction of proton beams on mercury targets were performed at the BNL AGS Gradient Synchrotron [4], 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. Proton bunch intensities of 2-4×10^{12} (2-4 TP) protons were delivered into a spot size of σ_x = 0.3 mm and σ_y = 0.9 mm and 100 ns duration. This resulted in a peak energy deposition of 80 J/g, which is comparable to that expected from a 4-MW proton driver delivering a 24-GeV proton beam at 15 Hz. These initial tests did not have a magnetic field on the target.

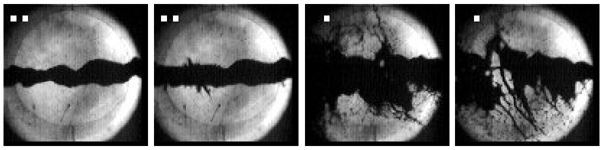

Figure 2: A 1-cm-diameter, 2.5-m/s Hg jet at 0, 0.75, 10, and 18 ms after interaction with 3.8×10^{12} 24-GeV protons.

This experiment had several key observations:

- The dispersal velocity of Hg droplets with 4 TP on target, seen in Fig. 2 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 μs after arrival of the proton beam pulse.
- The Hg jet showed surface-tension instabilities; its diameter varied from 0.5 to 1.5 cm.

These results validate numerical simulations [5] that include cavitation in the interior of the jet by the proton beam, and the formation of filamentary instabilities on the surface of the jet, as shown in Fig. 3.

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. 4. No perturbation of the jet on scales larger than 1 mm were observed when the jet was introduced into magnetic fields of 10-20 T at an angle of 100 mrad to the solenoid axis.

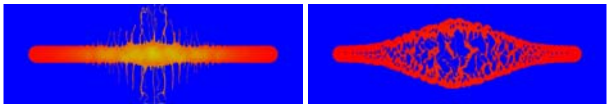

Figure 3: Numerical simulation of the evolution of a free mercury jet after exposure to an intense proton beam [5]. Left: Growth of surface filaments. Right: Growth of cavitation bubbles inside the jet.

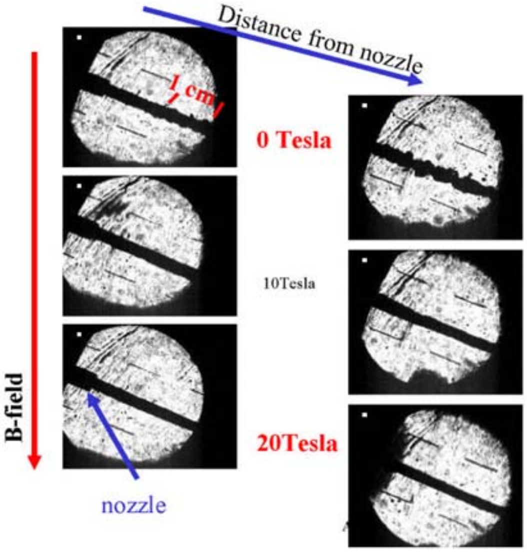

Figure 4: The Rayleigh instability of a mercury jet (4-mm diameter and 12-m/s velocity) is suppressed by high magnetic fields [6].

THE MERIT EXPERIMENT

We have proposed [7] and been approved to perform a proof-of-principle experiment at the CERN Proton Synchrotron (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-16 mode and we will be able to fill 1-8 of the 16 rf buckets with 2.5-3 $\times 10^{12}$ 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 30×10^{12} protons on the mercury target within a 2-μs spill, thus generating a peak energy deposition of 180 J/g.

The experiment will be performed in the TT2A tunnel at CERN (also used for the nToF beamline), as sketched in Fig.5.

For this experiment, we have designed and built a high-field pulsed solenoid with a warm bore of 15 cm [8]. This

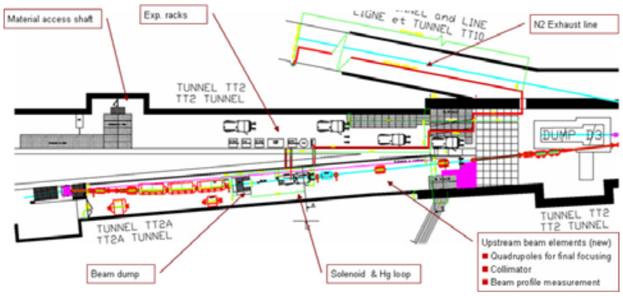

Figure 5: Layout of the MERIT experiment in the TT2A tunnel at CERN.

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.

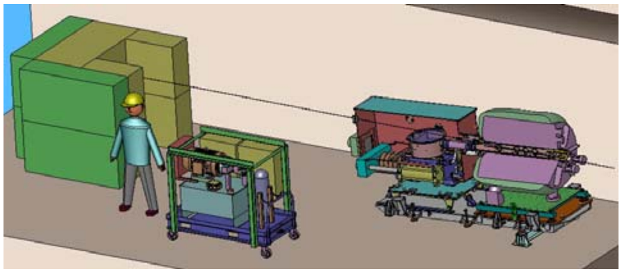

Figure 6: Cutaway view of the MERIT experiment. The solenoid/Hg jet system is tilted by 100 mrad with respect to the beam/floor.

The Hg jet delivery system [9] 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. 6.

The primary diagnostic of the beam-jet interaction is optical. A set of four viewports along the interaction region, shown in Fig. 7, will be connected by imaging fiberoptic bundles to four high-speed cameras. In addition, charged-particle detectors will monitor the flux of secondary pions produced during each of the 1-8 bunches of a beam pulse to provide a measure of possible beam-induced reduction of density of the liquid jet.

Each pulse of the 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. Most pulses will be at 24 GeV, but studies of pulses separated by 2 μs to 20 ms will be performed at 14 GeV due to limitations of the PS kicker. 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.

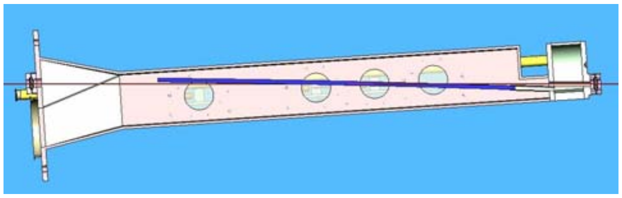

Figure 7: A vertical section through the bore of the solenoid magnet, showing the mercury jet crossing the magnetic axis from right to left at an angle of 100 mrad. A set of four optical viewports along the beam-jet interaction region will permit high-speed imaging of the history of the jet.

ACKNOWLEDGMENTS

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