THE MERIT HIGH-POWER TARGET EXPERIMENT AT THE CERN PS

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Abstract

We report on the analysis of data collected in the MERIT experiment at CERN during the Fall of 2007. These results validate the concept of a free mercury jet inside a high-field solenoid magnet as a target for a pulsed proton beam of 4-MW power, as needed for a future Muon Collider and/or Neutrino Factory.

INTRODUCTION

A future Muon Collider and/or Neutrino Factory [1, 2] requires a target station in which a proton beam of energy ≈ 8 GeV, repetition rate ≈ 50 Hz and average power ≈ 4 MW generates pions that later decay to muons and neutrinos. No existing target system would survive in the extreme conditions of a pulsed 4-MW proton beam, where the target will have to dissipate large amounts of energy, survive the strong pressure waves induced by the short beam pulses, and also survive long-term effects of radiation damage.

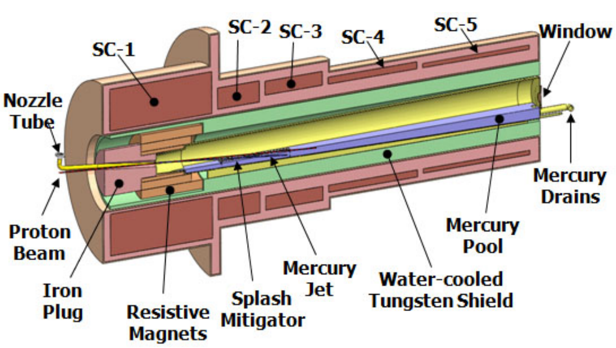

Figure 1: Concept of a 4-MW target station based on a free-mercury jet inside at 20-T solenoid. Both the proton beam and the mercury jet are tilted with respect to the magnet axis to maximize collection of low-energy pions. The mercury is collected in a pool that serves as the proton beam dump.

A concept that potentially meets all these requirements is a free liquid jet target that is replaced every beam pulse, as sketched in Fig. 1. For operation at 50 Hz, replacement of two-interaction lengths of mercury (28 cm) every pulse requires a jet velocity of 20 m/s. The mercury is not contained in a pipe in the region of interaction with the proton beam, because the intense pressure waves, and consequent cavitation of the mercury, induced by the proton beam would eventually fracture such a pipe.

The novel concept of a free mercury jet target has led to an R&D program designed to validate its key features. Encouraging results from the first phase of this program [3] led to a proposal [4] for a proof-of-principle demonstration of a mercury jet in a solenoid magnet in a proton beam whose single pulse intensity would be equivalent to that at a 4-MW Muon Collider or Neutrino Factory. That proposal was approved in 2004 as CERN experiment nToF11, also known as the MERIT experiment.

THE MERIT EXPERIMENT

The MERIT experiment was performed in the CERN TT2A tunnel. Proton beams of energies up to 24 GeV could be transported into this area, but multiple extractions of individual bunches during several turns of the PS was possible only at energies up to 14 GeV.

A cutaway side view of the MERIT apparatus is shown in Fig. 2. The proton-beam/mercury-jet interaction occurred inside the 15-cm-diameter bore of a 1-m-long solenoid magnet precooled with LN_2. The solenoid could be pulsed to fields up to 15 T with a 30-min cycle via a 5-MW power supply [5]. The mercury injection system [6] provided a free Hg jet with a nominal diameter of 1 cm, velocities up to 20 m/s, and durations up to 7 seconds.

Diagnostics for the experiment were obtained mainly from two systems: 1) An optical system with high-speed cameras that observed the region of the proton-beam/mercury-jet interactions through four viewports installed on the primary containment vessel (Fig. 2) [7]; and 2) A set of charged-particle detectors placed downstream of the interaction region [8].

Each of the 267 pulses of the CERN PS onto a mercury jet was a separate experiment in the overall program.). The proton beam intensity was varied from 0.25 to 30 $\times 10^{12}$ (Tp) protons per pulse (the latter at 24 GeV being a record

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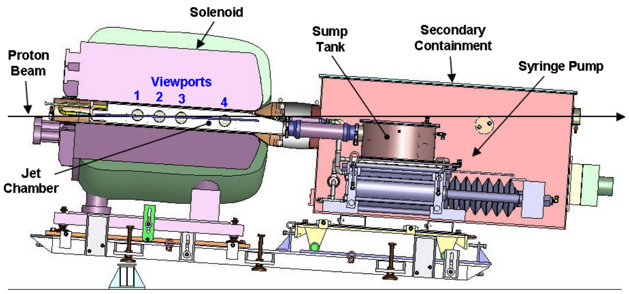

Figure 2: Cutaway side view of the MERIT experiment.

intensity for a single CERN PS pulse). The field of the solenoid magnet was varied from 0 to 15 T. A total of 2.2×10^{15} protons were delivered to the mercury target.

EXPERIMENTAL RESULTS

Jet Behavior without Proton Beam

The surface profile of the jet was significantly perturbed in zero magnetic field (Fig. 3, top left). These surface perturbations were greatly reduced, but not eliminated, in higher magnetic fields.

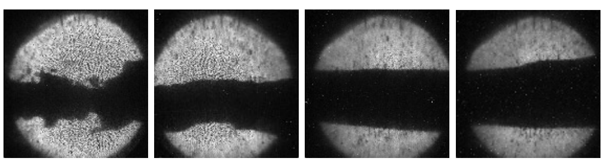

Figure 3: Images of jets with velocities of 15 m/s in magnetic fields of 0, 5, 10 and 15 T, without proton beam.

The surface velocity of the jet varied little with position, but the height of the jet was observed to grow significantly, from 1 cm at the nozzle to $\approx$ 2 cm at viewport 4, largely independent of the magnetic field strength. This undesirable feature may have been due to flow perturbations induced in the 180° bend in the mercury delivery pipe 15 cm from the nozzle.

Length of Disruption of the Jet by the Beam

Figure 4 shows images collected at viewport 3 with a 2-ms frame interval of an interaction of a 15-m/s jet and a 24-GeV, 10×10^{12} proton pulse in a 10-T solenoid field.

Figure 5 shows the observed disruption lengths of the Hg jet along its axis for both 14 and 24 GeV proton beams, and for various magnetic fields. Stronger magnetic fields reduced the extent of dispersal of the Hg jet at high beam intensities, and increased the threshold for disruption at lower intensities.

For pulses of 30×10^{12} protons and a solenoid field of 15 T, the extent of the Hg jet disruption was less than 28 cm, thus permitting a 70-Hz beam repetition rate with a 20-m/s velocity jet. For such a 24-GeV, 30×10^{12} proton

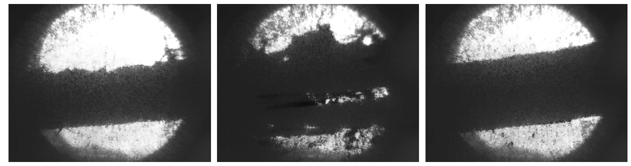

Figure 4: A proton beam/jet interaction as viewed in viewport 3: Left: Image of the jet before interaction; Middle: Image of the interaction aftermath; Right: Image of the reformed jet stream.

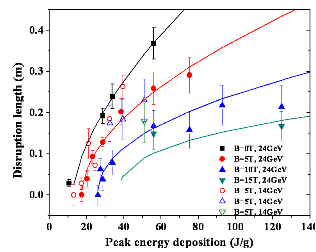

Figure 5: Extent of the proton-beam-induced disruption along the jet axis for various beam energies and magnetic fields as a function of peak energy density deposited in the mercury jet by the proton beam. The smooth curves are fits.

pulse, the total energy was 115 kJ, corresponding to a total beam power of 8 MW at 70 Hz.

Velocity of Filaments Ejected from the Jet

Figure 6 shows images at viewport 2 of the same beam pulse already depicted in Fig. 4. These images were taken with a 25-μs frame interval and an exposure time of 150 ns.

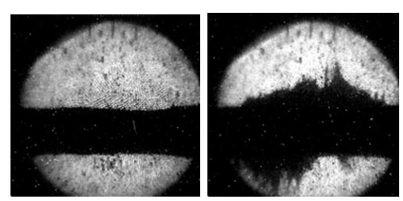

Figure 6: The proton beam/jet interaction of Fig. 4 as viewed in viewport 2: Left: Before interaction; Right: 350 μs after proton beam arrival.

Fits to the position of the tips of mercury filaments as a function of time determined the filament velocity, and the earliest time of appearance of the filament after the proton beam interaction. The highest-velocity filaments were associated with the earliest times of appearances, with results for the maximum observed filament velocities shown in Fig. 7.

In a magnetic field, all filament velocities were less than 100 m/s (typical for splashes induced by a stone thrown into a liquid), and the velocities were reduced in higher

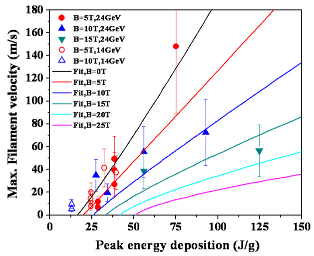

Figure 7: Maximum filament velocities for various beam energies and magnetic fields, as a function of peak energy deposition. The smooth curves are fits.

magnetic fields. The onset of jet filamentation occurred 25-100 μs after the beam interaction, with longer times in higher magnetic fields. This unexpected phenomenon is under further investigation.

Pump-Probe Studies

In another study [8] with “probe” proton bunches up to 700 μs after an initial set of “pump” pulses, the rate of secondary particle production in the diamond detectors was observed to be little affected by the disruption of the mercury jet on these time scales. Either 6 or 12 bunches of 14-GeV protons were first ejected from the CERN PS during one turn, and then the remaining 2 or 4 bunches were ejected during a subsequent turn, 40, 350 or 700 μs later.

The effect of disruption of the mercury target by the pump bunches on the rate of particle production during the pump bunches was gauged by the following ratio,

$$\mathrm{Ratio} = \frac{\frac{\mathrm{Probe_{targetin}} - \mathrm{Probe_{targetout}}}{\mathrm{Pump_{targetin}} - \mathrm{Pump_{targetout}}}}{\frac{\mathrm{Probe_{targetout}}}{\mathrm{Pump_{targetout}}}}.$$

The observed values of this ratio, shown in Fig. 8, are consistent with no reduction in particle production for bunches 40 or 350 μs after a first set of bunches, and about 5% reduction for bunches delayed by 700 μs. This indicates that a mercury jet target, although disrupted by intense proton bunches, would remain fully effective in producing pions during a bunch train of up to 300 μs, as may be desirable for operation of a 4-MW proton driver at a Neutrino Factory.

CONCLUSIONS

The MERIT high-power-target experiment was run using a primary proton beam from the CERN PS, and established the proof-of-principle of a proposed system for generating an intense muon beam by interaction of a megawatt proton beam with a free mercury jet target. The length of disruption of the mercury jet by the proton beam was less than the region of overlap, and was reduced in high magnetic fields. The velocity of mercury ejected from the jet by the proton beam was low enough that damage to the

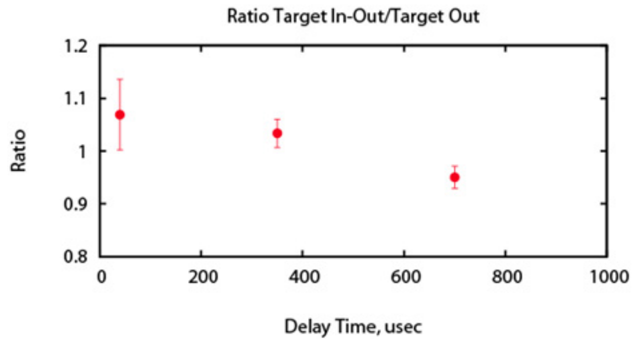

Figure 8: The probe/pump ratio for target-related particle production as a function of delay of the probe bunches.

containment vessel was negligible. Although short segments of the mercury jet were completely disrupted on the scale of several ms, secondary particle production was little affected for several hundred μs after arrival of the first bunches of a train.

ACKNOWLEDGMENTS

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