# THE MERIT HIGH-POWER TARGET EXPERIMENT AT THE CERN PS


K.T. McDonald,* *Princeton University, Princeton, NJ 08544, U.S.A.*
H.G. Kirk, H. Park, T. Tsang, *BNL, Upton, NY 11973, U.S.A.*
I. Efthymiopoulos, A. Fabich, F. Haug, J. Lettry, M. Palm, H. Pereira,
*CERN, CH-1211 Genève 23, Switzerland*
N. Mokhov, S. Striganov, *FNAL, Batavia, IL, 60510, U.S.A.*
A.J. Carroll, V.B. Graves, P.T. Spampinato, *ORNL, Oak Ridge, TN 37831, U.S.A.*
J.R.J. Bennett, O. Caretta, P. Loveridge, *RAL, Chilton, OX11 0QX, U.K.*



*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

Requirements for the target station at a future Muon Collider and/or Neutrino Factory [1, 2] are listed in Table 1. 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.

Table 1: Requirements for the target station at a Muon Collider or Neutrino Factory.

| Item | Value |
|---|---|
| Beam power | 4 MW |
| $E_p$ | 8 GeV |
| Rep rate | 50 Hz |
| Bunches/pulse | 3 |
| Bunch spacing | $\approx 100\ \mu$s |
| Bunch width | $\approx 3$ ns |
| $\pi$ Capture system | 20-T solenoid |
| $\pi$ Capture energy | $40 < T_\pi < 180$ MeV |
| Target geometry | Free liquid jet |
| Target material | Mercury |
| Target velocity | 20 m/s |
| Target radius | 4 mm |
| Jet angle | $\approx 60$ mrad |
| Beam angle | $\approx 80$ mrad |
| Beam dump | $< 5$ m from target |
| Dump material | Mercury |

A concept that potentially meets all these requirements (including a proton beam dump located inside the capture magnet system) 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.

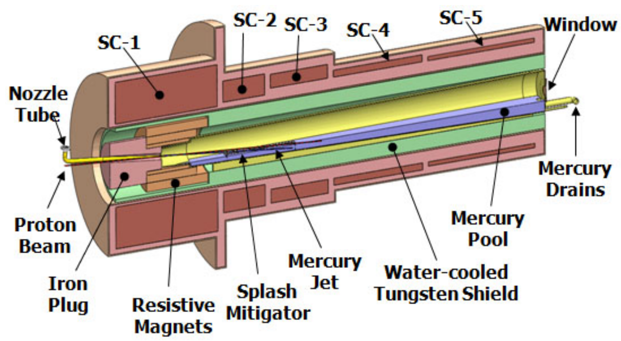


Figure 1: Concept of a 4-MW target station based on a free-mercury jet inside at 20-T solenoid. Both the proton beam and the mercury jet are tilted with respect to the magnet axis to maximize collection of low-energy pions. The mercury is collected in a pool that serves as the proton beam dump.

The geometry of the proton-beam/mercury-jet interaction has been optimized by simulations using the MARS15 code [3]. As shown in the top left of Fig. 2, the yield of pions in the desired kinetic energy range of $40 < T_\pi < 180$ MeV is maximized for proton beam energies near 8 GeV. At this beam energy, the pion yield is maximized for a mercury jet radius of 4 mm (Fig. 2, top right), assuming the proton-beam radius has $\sigma_r = 0.3R_{\rm jet}$. Soft pions emerge from the sides, rather than the end, of the target, so a small radius is favored. Furthermore, the pion yield is maximized when both the proton beam and the mercury jet have small angles with respect to the capture-solenoid axis (Fig. 2, bottom), which geometry reduces reabsorption of the pions on subsequent turns of their helical trajectories.

The desired tilt of the proton beam implies that it does


* kirkmcd@princeton.edu

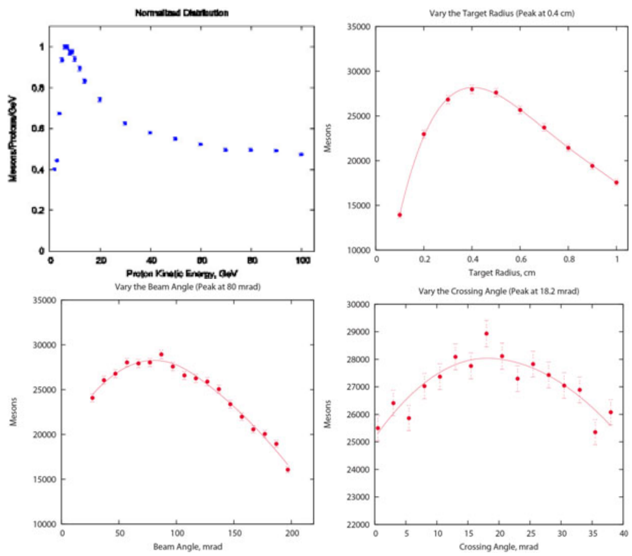


Figure 2: MARS15 simulations to optimize the mercury target geometry.

not point down the pion-capture channel, which includes rf cavities and liquid-hydrogen absorbers for ionization cooling. Instead, the proton beam is dumped a few meters downstream of the target, into shielding inside the capture solenoid. That shielding, if solid and static, would not survive even the proton beam as attenuated by the target. Hence, the proton beam dump will consist of a pool of mercury fed by the target, and drained appropriately to complete the mercury-flow loop.

The novel concept of a free mercury jet target has led to an R&D program designed to validate its key features. In 2001-2002, experiments with small mercury targets in proton beams, without magnetic field, indicated that the disruption of the mercury jet is not severe, and is confined to the region of interaction between the jet and proton beam [4]. Additional studies of a narrow mercury jet in a 20-T solenoid, without proton beam, indicated favorable stabilization of hydrodynamic instabilities by the high magnetic field [4]. These encouraging results led to a proposal [5] 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.

This paper summarizes results from the MERIT experiment, which was very successful in its mission to validate the concept of a mercury jet target for intense proton beams.

## THE MERIT EXPERIMENT

The MERIT experiment was located in the CERN TT2A tunnel, with support equipment located in the TT2 tunnel (previously the ISR injection-line tunnel), as sketched in Fig. 3. 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. As such, the MERIT experiment operated at the two proton-beam energies of 14 and 24 GeV.

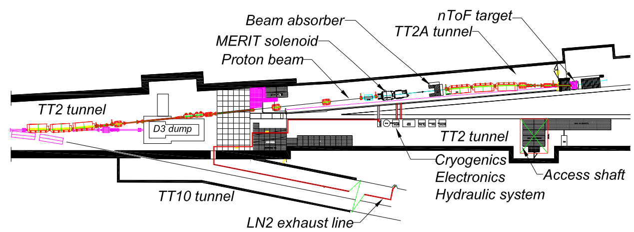


Figure 3: Layout of the MERIT experimental in the CERN TT2/TT2A tunnels. The proton beam goes from left to right in this and all subsequent figures.

A cutaway side view of the MERIT apparatus is shown in Fig. 4. 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 [6]. The mercury injection system [7] provided a free Hg jet with a nominal diameter of 1 cm, velocities up to 20 m/s, and durations up to 7 seconds. The mercury jet and proton beam were both tilted with respect to the magnet axis to maximize the collection of soft pions that later decay into muons.

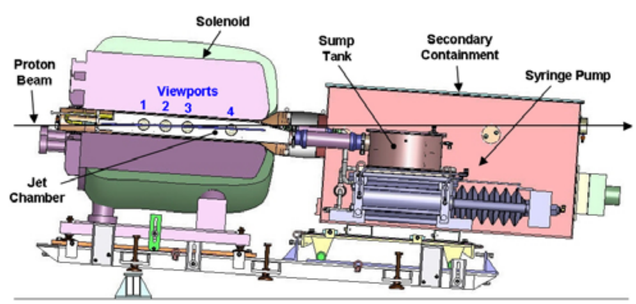


Figure 4: Cutaway side view of the MERIT experiment.

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) [8]; and 2) A set of charged-particle detectors placed downstream of the interaction region [9]. The four optical viewports were aligned such that the upstream three ports were 15 cm apart with the second viewport located at the magnet center; the fourth viewport was displaced 45 cm downstream from the magnet center.

Each of the 267 pulses of the CERN PS onto a mercury jet was a separate experiment in the overall program. For the MERIT experiment, the CERN PS was typically run in a harmonic-16 mode (although several shots were also done with the proton beam in a harmonic-8 mode and a few with a harmonic-4 structure). The proton beam intensity was varied from 0.25 to 30 $\times 10^{12}$ (T$p$) protons per pulse (the latter at 24 GeV being a record intensity for a single CERN PS pulse). The field of the solenoid magnet was varied from 0 to 15 T. The mercury jet was injected with velocities of 15 or 20 m/s. A total of $2.2 \times 10^{15}$ protons were delivered to the mercury target.

## EXPERIMENTAL RESULTS

### *Jet Behavior without Proton Beam*

The Reynolds number of the 1-cm-diameter mercury jet at 15 m/s velocity was about $10^5$, so the flow was turbulent, and the surface profile of the jet was significantly perturbed in zero magnetic field (Fig. 5, top left). These surface perturbations were greatly reduced, but not eliminated, in higher magnetic fields.

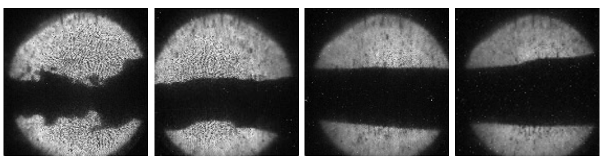

Figure 5: Images of jets with velocities of 15 m/s in magnetic fields of 0, 5, 10 and 15 T, without proton beam.

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 $180^\circ$ bend in the mercury delivery pipe 15 cm from the nozzle.

### *Length of Disruption of the Jet by the Beam*

Figure 6 shows images at viewport 3 of an interaction of a 15-m/s jet and a 24-GeV, $10 \times 10^{12}$ proton pulse in a 10-T solenoid field. A sequence of 200 images was collected at viewport 3 with a 2-ms frame interval .

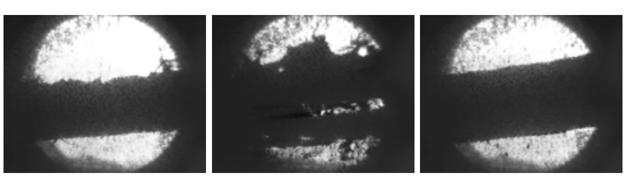

Figure 6: A proton beam/jet interaction as viewed in viewport 3: Left: Image of the jet before interaction; Middle: Image of the interaction aftermath; Right: Image of the reformed jet stream.

The dispersal of the Hg jet resulting from the impact of the proton beam was observed at the third viewport, located

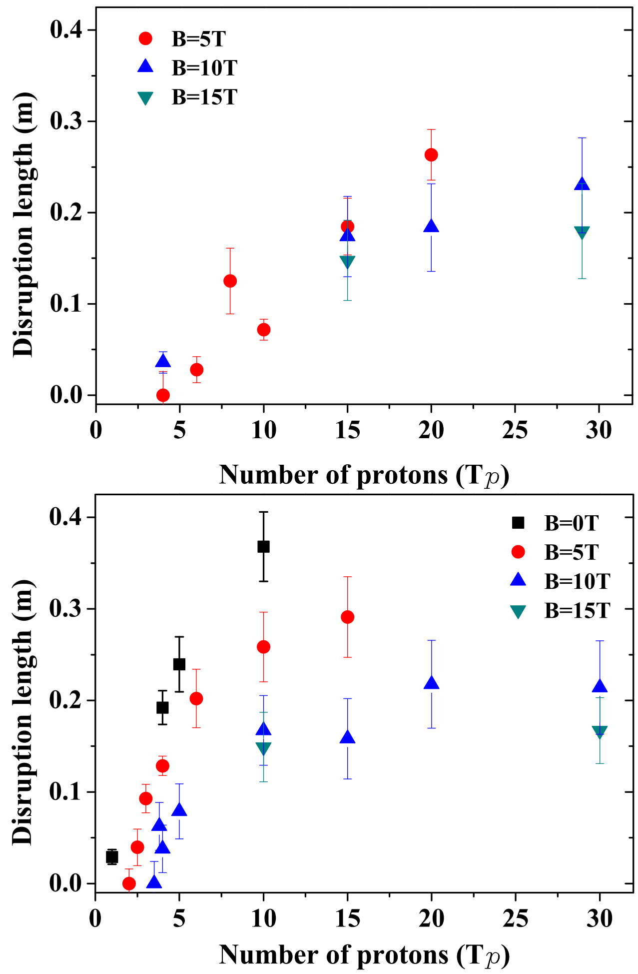


Figure 7: Extent of the proton-beam-induced disruptions: Top: Disruptions resulting from a 14-GeV proton beam; Bottom: Disruptions with a 24-GeV proton beam. In both cases the proton beam intensity and solenoid magnetic field were varied.

15 cm downstream of the center of the solenoid. Figure 7 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 $30 \times 10^{12}$ 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, $30 \times 10^{12}$ proton 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 8 shows images at viewport 2 of the same beam pulse already depicted in Fig. 6. These images were taken with a 25-$\mu$s frame interval and an exposure time of 150 ns.

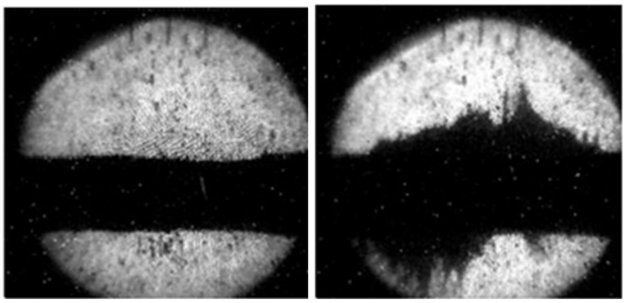

Figure 8: The proton beam/jet interaction of Fig. 6 as viewed in viewport 2: Left: Before interaction; Right: 350 $\mu$s after proton beam arrival.

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. 9.

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 magnetic fields.

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

## *Pump-Probe Studies*

In another study [9] with "probe" proton bunches up to 700 $\mu$s after an initial set of "pump" pulses, the rate of secondary particle production was observed to be little affected by the disruption of the mercury jet on these time scales.

The concept of the pump-probe studies is illustrated in Fig. 10. 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 $\mu$s later. This could only be done with beams of energy up to 14 GeV, and the maximum delay possible was 1 ms.

The relative rates of secondary particles produced by these bunches was recorded in a set of diamond-diode detectors arrayed as shown in Fig. 11. Data from both target-in and -out events showed a rapid reduction of sensitivity of the diamond detectors during a bunch train, with a recovery time of order several hundred $\mu$s. Hence, the effect of disruption of the mercury target by the pump bunches on the rate of particle production during the pump bunches

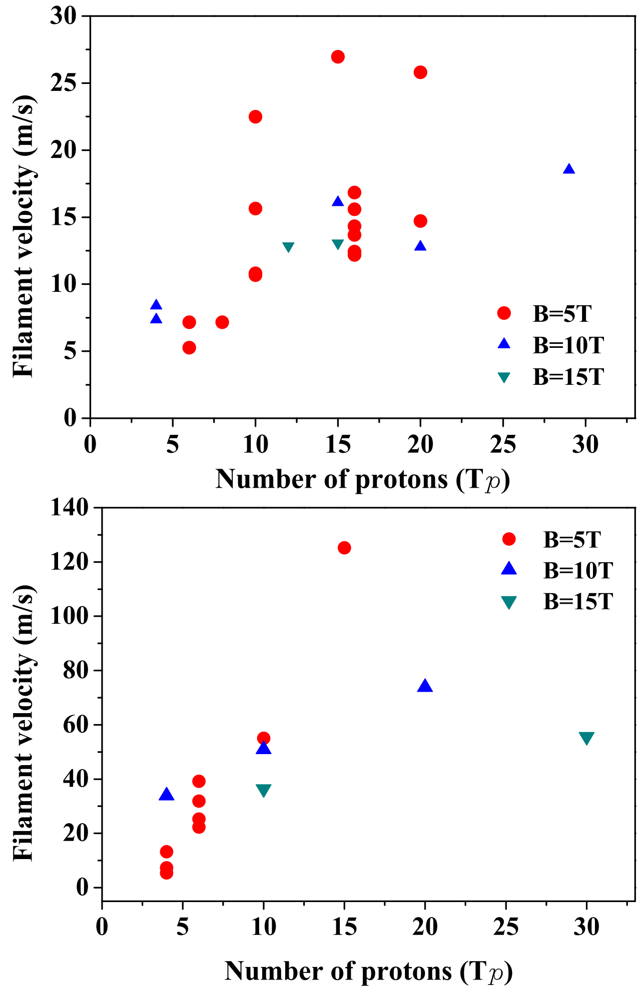


Figure 9: Measured filament velocities: Top: 14-GeV proton beam with various solenoid field strengths; Bottom: 24-GeV protons.

was gauged by the following ratio,

$$\text{Ratio} = \frac{\frac{\text{Probe}_{\text{targetin}} - \text{Probe}_{\text{targetout}}}{\text{Pump}_{\text{targetin}} - \text{Pump}_{\text{targetout}}}}{\frac{\text{Probe}_{\text{targetout}}}{\text{Pump}_{\text{targetout}}}}.$$

The observed values of this ratio, shown in Fig. 12, are consistent with no reduction in particle production for bunches 40 or 350 $\mu$s after a first set of bunches, and about 5% reduction for bunches delayed by 700 $\mu$s. 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 $\mu$s, 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 gen-

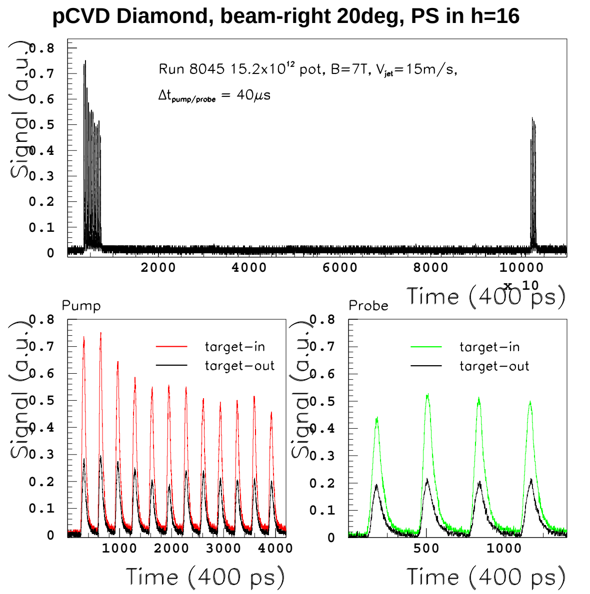


Figure 10: Data a diamond detectors for an event with 12 pump bunches, followed by 4 probe bunches 40 $\mu$s later.

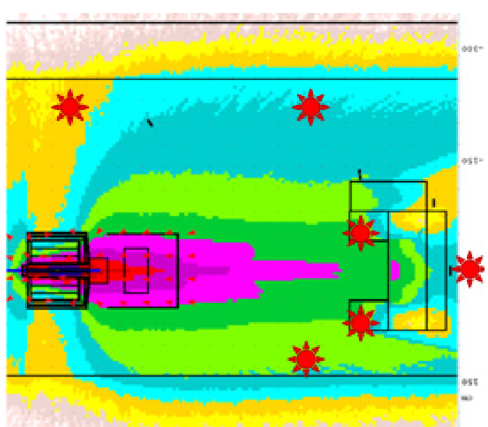

Figure 11: Layout of the secondary particle detectors, which are indicated by stars. The contours are a MARS15 simulation of the intensity of secondary particles.

erating 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 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 $\mu$s after arrival of the first bunches of a train.

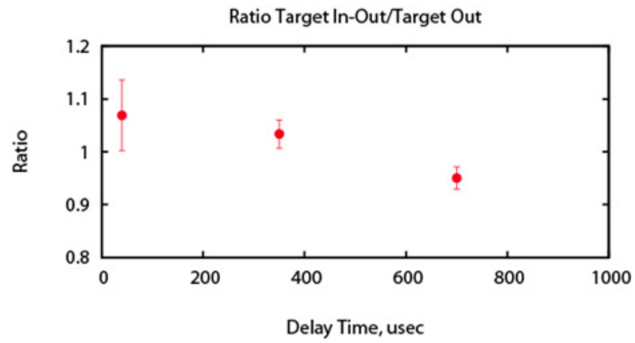


Figure 12: The probe/pump ratio for target-related particle production as a function of delay of the probe bunches.

## ACKNOWLEDGMENTS

We wish to acknowledge the excellent support from the CERN PS staff whose professionalism was indispensable to the successful conclusion of this experiment. This work was supported in part by the US DOE Contract NO. DE-AC02-98CH10886.

## REFERENCES

[1] S. Ozaki *et al.*, *Feasibility Study II of a Muon-Based Neutrino Source* (June 14, 2001), http://www.cap.bnl.gov/mumu/studyii/FS2-report.html

[2] M.M. Alsharo'a *et al.*, *Status of Neutrino Factory and Muon Collider Research and Development and Future Plans*, Phys. Rev. ST Accel. Beams **6**, 081001 (2003).

[3] The MARS Code System: http://www-ap.fnal.gov/MARS/

[4] A. Fabich, *High Power Proton Beam Shocks and Magnetohydrodynamics in a Mercury Jet Target for a Neutrino Factory*, Ph.D. thesis (U. Vienna, Nov. 2002).

[5] J.R.J. Bennett *et al.*, *Studies of a Target System for a 4-MW, 24-GeV Proton Beam*, proposal to the ISOLDE and Neutron Time-of-Flight Experiments Committee, CERN-INTC-P-186 (April 26, 2004).

[6] H.G. Kirk *et al.*, *A 15-T Pulsed Solenoid for a High-power Target Experiment*, Proc. 2008 Eur. Part. Accel. Conf. (Genoa, Italy, July 2008), WEPP170.

[7] V.B. Graves *et al.*, *Operation of a Free Hg Jet Delivery System for a High-Power Target Experiment* (these proceedings), WE6PFP086.

[8] H.G. Kirk *et al.*, *Optical Diagnostic Results for the MERIT High-Power Target Experiment*, (these proceedings), WE6RFP010.

[9] I. Efthymiopoulos *et al.*, *Time Structure of Particle Production in the MERIT High-Power Target Experiment*, (these proceedings), TU6PFP085.