MERIT - The High Intensity Liquid Mercury Target Experiment at the CERN PS

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***Abstract*—The MERIT experiment is a proof-of-principle test of a target system for high power proton beams to be used as front-end for a neutrino factory complex or a muon collider. The experiment took data in autumn 2007 with the fast extracted beam from the CERN Proton Synchrotron (PS) to a maximum intensity of about 30×10^{12} protons per pulse. The target system, based on a free mercury jet, allows to investigate the interseption of a 4-MW proton beam inside a 15-T magnetic field required to capture the low-energy secondary pions as the source of the required intense muon beams. Particle detectors have been installed around the target setup capable to measure the secondary particle flux out of the target and probe cavitation effects in the mercury jet when exited with a beam of variable intensity. With the analysis of the data ongoing, results will be presented here that demonstrate the validity of the liquid target concept.**

I. Introduction

IN the design of future Neutrino Factory or Muon Collider facilities, the generation of intense muon beams suitable for pursuing advanced physics experiments is foreseen. For the Neutrino Factory case, the muons will let to decay in suitably placed long straight sections around the ring of the accelerator, thus creating intense neutrino beams for the far experimental areas. In the Muon Collider the counter-circulating muon beams will be brought into collision at the center of the experiments. In both cases the muon beams are generated from the decay of hadrons (pions and kaons) produced when intense proton beams impinge on a target system. For the Neutrino Factory, primary proton beams of multi-megawatt power (4-MW) are the baseline option.

The design and operation of target stations coupled to intense proton drivers poses significant technological challenges. In past and present installations with less than 1-MW of beam power, passive solid targets (or rotating-wheel targets), water or air cooled, have been used. Beyond that, such solid targets become problematic in view of effects such as: melting/vaporization of components, embrittlement by beam-induced pressure waves for pulsed beams, and extensive radiation damage. To overcome such effects, the use of liquid targets using mercury, or molten lead, molten Pb/Bi, etc. is proposed.

Liquid target systems offer the advantage of continuously re-generating the target volume that may be affected by the impact of the proton beam. However new challenges need to be addressed: design of the containment vessels and beam windows, effect of beam-induced pressure waves and resulting pitting corrosion in the containment walls and cavitation formation. The use of a free flowing liquid in the form of a jet is a promising design option to address these issues.

The MERIT experiment represents an important milestone in the R&D program of high-power targetry for a future neutrino factory or muon collider [1]. It comes as a continuation of previous studies with encouraging results done at BNL [2] and CERN [3], combining for the first time a free mercury jet and a focusing/capturing solenoid for secondary pions or muons as proposed in design studies for future facilities [4]. The focus of the experiment is the study of the impact of intense single proton pulses on the jet. The observation of the jet target dispersal by the mechanical shock and sudden energy deposition accompanied with material vaporization and cavitation formation and how much such effects are influenced by the strong magnetic field are important scientific questions that the experiment addresses with results presented here.

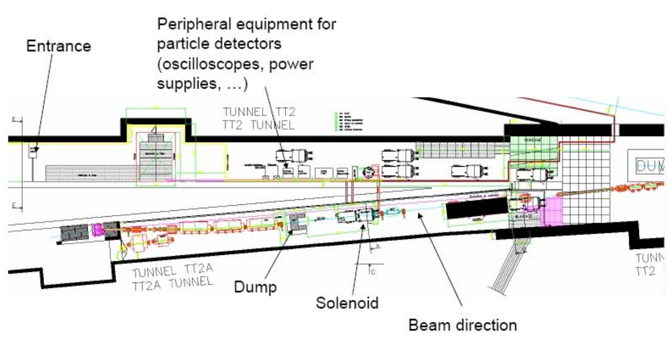

Fig. 1. The experimental setup in the TT2/TT2A tunnels of CERN PS. The beam arrives from the right side of the figure and after traversing the experiment is stopped in an iron dump before reaching the nTOF target shown on the left.

II. The experimental setup

The MERIT experiment was installed in the TT2A extraction line of CERN PS that delivers proton beam to the

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nTOF facility. The beam line was specially modified to best fit the requirements of the test. The layout of the experiment is shown in Fig 1. The magnetic elements of the line allow for the transport of proton beams with energies up to 24 GeV. In addition, the PS is capable of multiple-turn extractions for beams up to 14 GeV. Due to the radiation environment constraints, a total limit of 3×10^{15} protons on target to the experiment was imposed, corresponding to about 100 beam shots at the maximum intensity of 30×10^{12} protons per pulse, the PS machine can deliver. Part of the physics program was done at 14 GeV and part at 24 GeV, profiting also from the variable beam time structure the PS machine could offer.

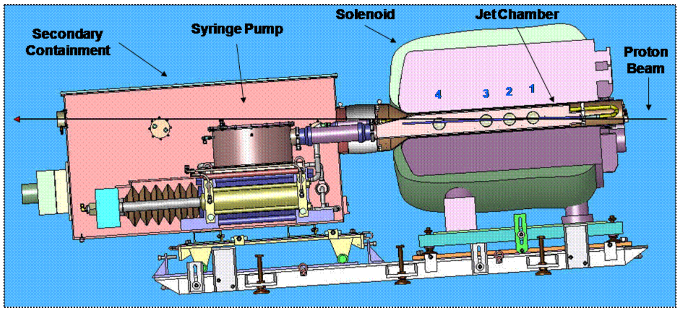

Fig. 2. Schematic view of the experimental apparatus. The mercury delivery system with its sump and syringe pump is shown on the left. On the right is the solenoid with the special primary titanium container inserted from the downstream part.

In Fig. 2 a cut-away view of the experimental apparatus is shown. The experiment comprises of two major components: the 1-m long 15-cm bore diameter solenoid capable of delivering a 15-T field [5], and the mercury loop system that generates a 1-cm diameter free mercury jet moving with velocities up to 20 m/s [6]. The mercury delivery system, due to the particular safety hazards, was designed with a double containment: a primary volume that is in touch with the mercury, and a secondary that acts as retention volume in case of leak, also equipped with special filters to block the mercury vapors escaping in the tunnel. The whole system is tilted by 67 mrad to the horizontal plane, as will be in a final configuration for a Neutrino Factory in order to improve the yield of soft pions. Due to the lack of adequate installation at CERN to handle the mercury, the system was designed such that it could be inserted inside the solenoid bore without opening the primary containment.

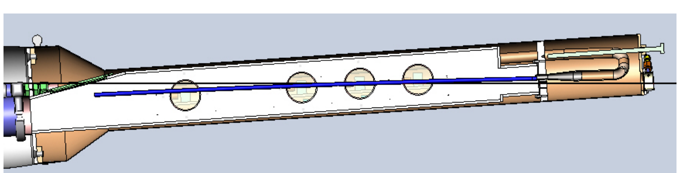

Fig. 3. View of the primary container inside the solenoid bore. The mercury jet (blue line) is generated at the upstream end of the primary container on top of the nominal beam trajectory (red line). The four circular viewports along the axis are for the optical diagnostics system that allows viewing the mercury/jet interactions. The interaction center is at the middle of the solenoid, centered on the second viewport. The first three ports are set 15 cm apart while the last one is 45 cm downstream the interaction center.

In Fig. 3 a view of the primary container is shown. The free jet is generated upstream and intercepts the beam axis at the center of the solenoid at an angle close to 50 mrad. Due to the constraint of not opening the primary container at CERN, a 180-deg turn was introduced in the piping of the mercury which adds to the complexity of the system and is likely to affect the quality of the jet. For the nominal mercury jet diameter, the beam interaction region is about 30 cm and varies with the jet speed and shape which is also affected by the magnetic field.

To observe the mercury jet/beam interaction, special optical diagnostics with high-speed cameras were developed [7]. The system using fast response cameras is capable of taking photos at four locations along the mercury jet inside the solenoid bore. Detectors placed at six locations around the target assembly and behind the thick beam attenuator allowed measuring the flux of the secondary charged particles produced. At each location a detector assembly consisting of an Aluminum Cathode Electron Multiplier (ACEM) detector and a Polycrystaline Chemical Vapour Deposition diamond (pCVD) detector were mounted, as shown in Fig. 4.

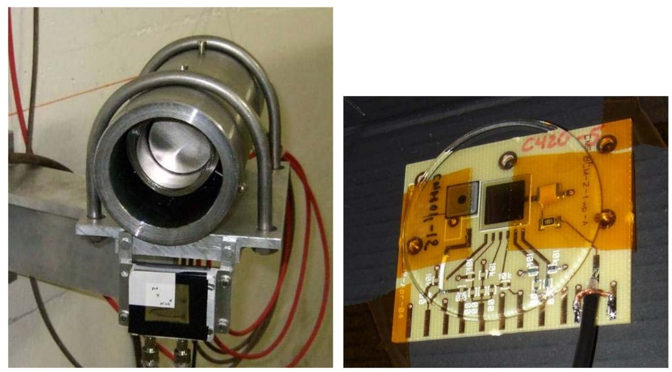

Fig. 4. Left: photo showing one detector assembly: the ACEM detector is located at the top with the pCVD diamond box at the bottom. Right: the board housing the pCVD diamond detector (center) and a pin diode (top left).

The pCVD diamond detectors are of a similar type as those used as beam loss monitors around the interaction regions of the LHC. They are known to be radiation hard and capable of measuring high particle fluxes such as those expected close to the MERIT target [8]. The expected particle flux (charged hadrons) per square centimeter around the experimental setup at the locations of the detector assemblies is shown in Fig 5. For the maximum beam intensity it corresponds to about 10^8 MIP per detector (active area $0.75\,\mathrm{mm} \times 0.75\,\mathrm{mm}$, $0.5\,\mathrm{mm}$ thickness) generating a huge instantaneous current of several amps. A large discharge capacitor of 100 nF was added in the readout circuit to maintain the bias voltage at the detector and allow to extract the signal at all cases. The detectors were read-out using digital oscilloscopes.

The ACEM detectors are extensively used as beam loss monitors in the CERN accelerator complex and are also tested to high fluxes [9] similar to those expected at MERIT.

III. Experimental results

For the needs of the experiment the last part of the TT2A beam line that normally delivers beam to the nTOF target

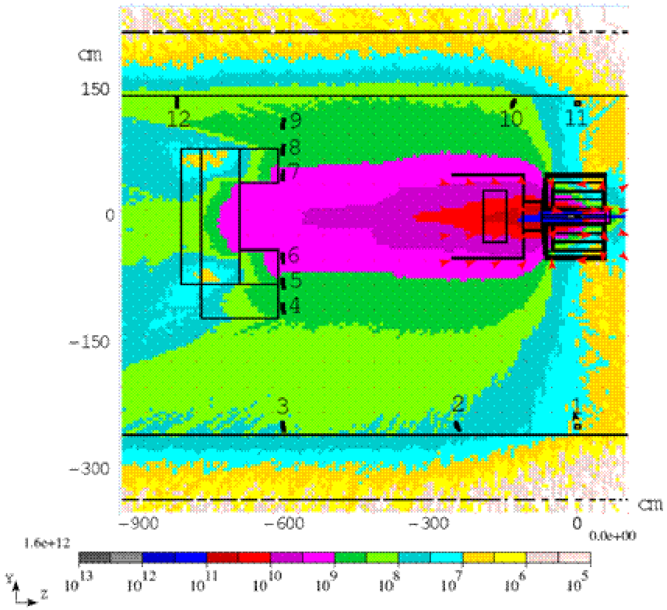

Fig. 5. MARS simulation showing the charged hadron flux per square centimeter for an incident proton beam of 24 GeV with 30×10^{12} protons on the MERIT target and with the solenoid field at 15 T. The location of the particle detectors around the experimental setup is shown.

facility was modified with the magnetic elements reconfigured such to provide a small beam spot at the MERIT target. Beam optics calculations predict beam spot sizes on the target to be of the order of $10.3\,\mathrm{mm}^2$ and $5.7\,\mathrm{mm}^2$ for the 14 GeV and 24 GeV beams respectively. The resulting energy deposition on the target can reach 170 J/g matching the value in future neutrino beam facilities validating the observations at the experiment for future use. The maximum extracted intensity of 30×10^{12} protons at 24 GeV/c to the MERIT expriment corresponds to a new record for the PS machine.

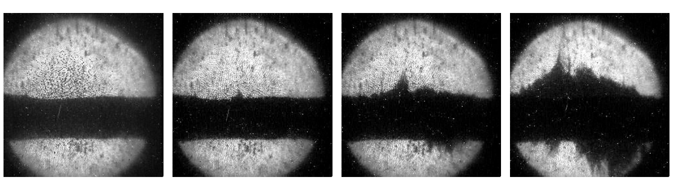

Fig. 6. A 1-cm diameter, 15-m/s Hg jet at 0, 75, 175, and 375 μs after interaction with 10×10^{12} 24-GeV protons in a 10-T solenoid field.

The MERIT experiment is a single pulse experiment, with the PS beam extracted upon request at variable intensity and timing structure. For most of the pulses the PS machine was configured to harmonic 16, i.e. filled with up to 16 bunches spaced at 131 ns while other configurations of harmonic 8 were used as well. The proton beam intensity was varied from 0.25 to 30×10^{12} protons per pulse. The field of the solenoid magnet was varied from 0 to 15 T. The mercury jet was typically injected with velocities of 15 and 20 m/s. The images of the interaction of a 15-m/s jet with a 24-GeV, 10×10^{12} proton beam in a 10-T solenoid field are shown in Fig. 6. These images were taken with a 25-μs frame rate and an exposure time of 150 ns.

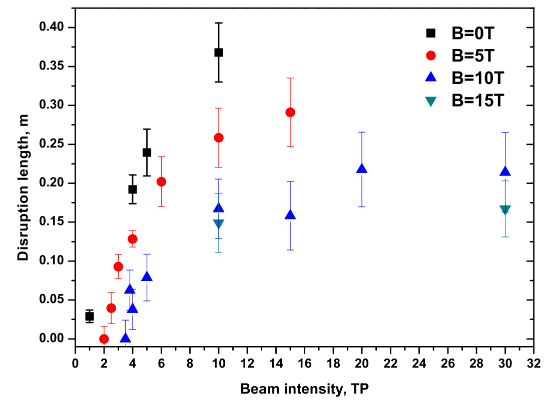

Fig. 7. The observed disruption length of the Hg jet for various beam intensities and solenoid field strengths for an incoming proton beam energy of 24 GeV.

Complete dispersal of the Hg jet resulting from the impact of the proton beam is observed at the 3rd view port located 15cm downstream of the center of the solenoid. After the beam/jet impact, the full extent of the jet breakup can be observed as the jet streams past the view port. Fig. 7 shows the observed lengths of disruption of the Hg jet along its axis from the proton beam at 24 GeV. A dependency of the jet breakup on the proton beam intensity and magnetic field was observed. The high magnetic field contributes to the reduction of the jet dispersal at high beam intensities as well as increasing the threshold for disruption at lower intensities. The observed dispersal length of about 30 cm correspond to roughly 2 interaction lengths for mercury (one interaction length in mercury is 14 cm) which is also compatible with the optimal beam/jet overlap length predicted from particle production simulations for future facilities under study. For a jet moving with 20 m/s, replacing 30 cm requires 14 ms thus allowing for operations with a repetition rate of up to 70 Hz. A key experimental result is the finding that, for the extreme case of an incoming proton beam of 30×10^{12} and a solenoid field of 15 T, the extent of the Hg jet breakup is confined to less than 20 cm, thus preserving the 70 Hz beam rep-rate option. For this 24-GeV, 30×10^{12}beam, the total energy content of the beam is 115 kJ, which coupled with a 70 Hz beam rep-rate, would correspond to a total beam power of 8 MW. Additional results from the analysis of the optical diagnostics system can be found in [10].

Fig. 8 shows the linearity of the pCVD diamond detectors signal with increased beam intensity in the target for different settings of the solenoid magnet. The detectors were connected to a fast sampling digital oscilloscopes synchronized with the beam timing. Both detectors types are quite fast and able to distinguish the signal from the individual beam bunches separated by 131 ns. According to simulations for the detectors the charged particle flux can reach up to 5×10^7 particles/cm ^{2}/bunch which creates a current of 1.6 A in the $0.75\,\mathrm{mm} \times 0.75\,\mathrm{mm}$ diamond detectors. The integrated charge per bunch is then corrected for the variations of the beam intensity measured with current transformers along the beam line.

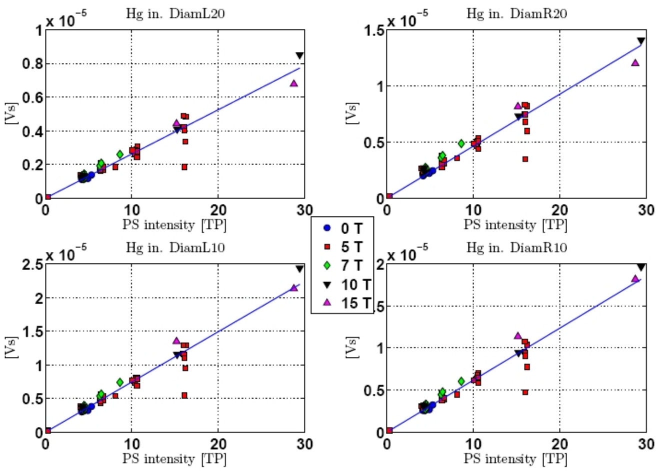

Fig. 8. The response linearity of the pCVD diamond detectors for increased beam intensity.(1 TP corresponds to 10^{12} protons on target).

Fig. 9 shows the signal from the four particle detectors located at different angles around the target showing good agreement with the MARS [11] simulation predictions.The relatively small ratio between the target-in and target-out case can be attributed to the material from beam windows in the beam line. These results represent our present understanding of the target, beam shape and particle detector response. Extensive studies are ongoing in to include effects like the variations in the mercury jet shape, the effect of gravity or misalignment errors as well as improved calibration and beam intensity corrections for the particle detector response.

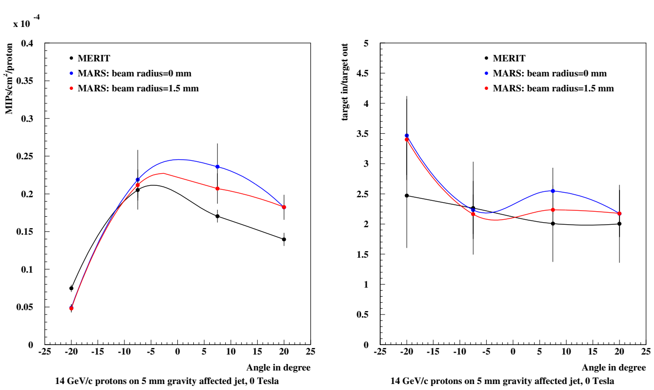

Fig. 9. Left: The response of the pCVD diamond detectors installed at different angles around the mercury target for a 14 GeV/c proton beam compared to MARS simulation predictions. Right: The ratio of the response with and without the mercury jet for experimental data and simulations. The MARS simulation was done for a pencil like proton beam and for a beam with radius of 1.5 mm.

IV. SUMMARY

The MERIT experiment successfully took data in the autumn of 2007 at the CERN PS. The successful operation of the experiment during the three weeks of the experiment combining for the first time a free mercury jet inside a strong magnetic field for a total of about 700 pulses (100 with high-intensity beam) demonstrate the validity of the principle as proposed for future accelerator facilities. The observations of the mercury jet disruption at the impact of the high-intensity beam support its use for multi-MW target systems and provide an important feedback in the design parameters for future applications. The first analysis results of the particle flux detectors provide useful input in understand the mercury jet-beam interaction, while the rest of the analysis is ongoing and further results will be reported at a future occasion.

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