SIMULATION OF HIGH-POWER MERCURY JET TARGETS FOR NEUTRINO FACTORY AND MUON COLLIDER*

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Abstract

Hydrodynamic behavior of high power targets for future particle accelerators, in particular for the proposed neutrino factory and muon collider, has been investigated via numerical simulations. The target will contain a series of mercury jet pulses of about 1 cm in diameter, interacting with intense proton pulses in 15 – 20 T magnetic fields. Simulations used a smoothed particle hydrodynamics code designed to accurately resolve free surface 3D hydrodynamic flows. Simulation results have been compared with existing experimental data and previous simulations performed with the front tracking code FronTier. New target parameters have also been investigated.

INTRODUCTION

The key element of the target system being designed for the future muon collider and / or neutrino factory is a liquid mercury jet interacting with powerful proton pulses inside a 15 – 20 T magnetic solenoid. The stability of the mercury jet after the proton pulse disruption is a major concern for the target design. The proof-of-principles experiment for high-power mercury target system was conducted at CERN in 2007 [1].

The problem of the slow distortion of the mercury jet entering the solenoid has been evaluated numerically using the FronTier code [2, 3]. FronTier is a hydro- and magnetohydrodynamic code that resolves material interfaces using the method of front tracking. FronTier simulations of the mercury jet cavitation and disruption caused by interaction with proton pulses were presented in [4] and previous works referenced therein. Previous studies have demonstrated that modeling of cavitation and surface dynamics is critical for the simulation of the mercury jet interaction with proton pulses. Cavitation is intrinsically a multiscale phenomenon involving scales from micron-size at the cavitation onset to global scales in later phases of the evolution of bubbles. In FronTier, cavitation was modeled by creating numerically grid-dependent initial cavitation bubbles with tracked surfaces in rarefaction waves of critical strength. Such a cavitation model depends on a number of artificial parameters and makes it difficult to resolve small scales typical for clouds of cavitating bubbles. It is also non-conservative in nature as it removes the liquid and replaces the corresponding volume with gas bubbles. Difficulties with cavitation models prevented us from simulating long time dynamics of mercury jets in 3D.

To improve the modeling of small scales and simulation of long time dynamics of free surfaces flows, we have developed a parallel code based on the smoothed particle hydrodynamics (SPH) [5]. The code has been applied for the simulation of mercury jet targets in the parameter range typical for the muon collider, neutrino factory, and other experimental designs. The present paper only deals with hydrodynamic effects. The study of influence of MHD on the mercury jet cavitation and disruption using particle methods is in progress and will be reported in forthcoming work.

NUMERICAL METHODS

SPH [5] is a Lagrangian particle method in computational fluid dynamics in which deforming Lagrangian cells are replaced with particles. SPH eliminates the main mesh tangling difficulty of the original Lagrangian method while retaining many of its advantages. Due to its Lagrangian nature, SPH is strictly mass-preserving and capable of robustly handling interfaces of arbitrary complexity in the simulation of free surface and multiphase flows. It has known accuracy issues in the numerical approximation of differential operators but these are compensated by the SPH properties of nonlinear stability and conservation, enabling successful usage of SPH for a wide class of problems. We have also developed necessary physics models pertinent to the mercury target problem.

To model properties of mercury, we use the stiffened polytropic equation of state (EOS) [6]

$$P = (\gamma_l - 1)\rho(E + E_\infty) - \gamma_l P_\infty$$

with the adiabatic exponent $\gamma_l = 6.0$ and the stiffening constant $P_\infty = 47$ kbar . The stiffened polytropic EOS extends the range of pressure to negative values in order to account for the transient effect of tension in liquids. When the pressure falls below the cavitation threshold, the interaction between the corresponding particles is eliminated. This causes internal liquid breakups or cavitation. Using this method, cavities can appear on particle-scale length. The particle interactions are resumed if the pressure equilibrates and particles move close to each other causing the merger of fluid fragments.

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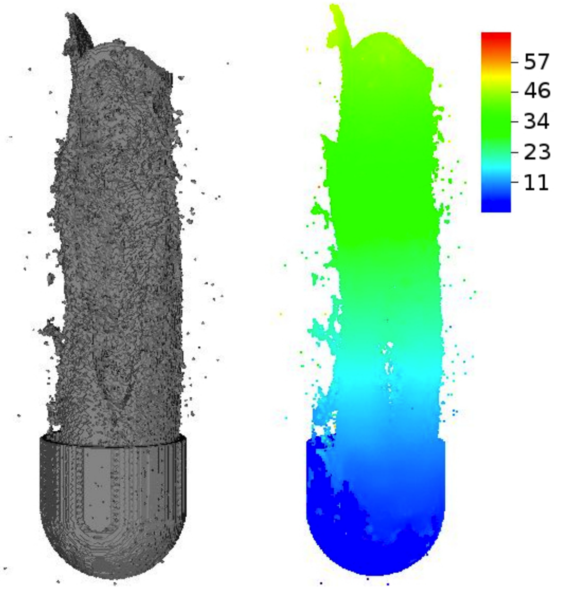


(a) Mercury surface (b) z-velocity, m/s

Figure 1: Mercury thimble. Shape (left) and vertical velocity (right) of mercury splash column after 0.85 ms.

RESULTS AND DISCUSSION

Mercury Thimble Experiments

We have validated SPH simulations of the interaction of mercury with proton pulses using data of the mercury thimble experiments [7]. The volume of the thimble excavated in a stainless steel bar is 1.3 cm^3. It consists from bottom to top of a half sphere (r = 6 mm) and a vertical cylinder (r = h = 6 mm). The mercury has a free surface in up-direction, where it can expand to. The proton pulse has approximately Gaussian distribution and the intensity range of $0.6 - 17 \cdot 10^{12}$ protons at energy 24 GeV. We have performed numerical simulations of the thimble splash and observed that the splash velocity is sensitive to the value of the critical pressure used in the capitation model. Good agreement with experimental data was obtained for the critical pressure of 100 bar. This value was then used in all mercury jet simulations. Figure 1 depicts the shape of the mercury column in the thimble simulation.

Mercury Targets for Neutrino Factory and Muon Collider

In this section, we report simulation results of the mercury jet interaction with proton pulses in the neutrino factory and muon collider power regimes. The 4 MW beam of 8 GeV protons will be delivered in 150 bunches per second for the neutrino factory and in 15 bunches per second for the muon collider. 20.8 teraproton bunches arrive at the neutrino factory target with the 6.67 ms interval that is large compared to hydrodynamic time scales of the mercury splash. In the case of the muon collider, 208 teraproton bunches arrive with the time interval of 66.7 ms. Therefore, it is sufficient to consider the interaction of the mercury jet with only one proton pulse. We use the corresponding energy deposition tables calculated at FNAL with the Monte Carlo code MARS. Assuming the isochoric regime of the energy deposition (the deposition time scale is mush smaller than the hydrodynamic time scale), the peak pressure is approximately 110 kbar in the muon collider target and 11 kbar in the target for the neutrino factory. Figure 2 shows the increase of pressure in mercury with the increase of internal energy. The proton pulse enters the jet under small angle and the energy deposition is not axially symmetric. The pressure profile in the jet is shown in Fig. 3.

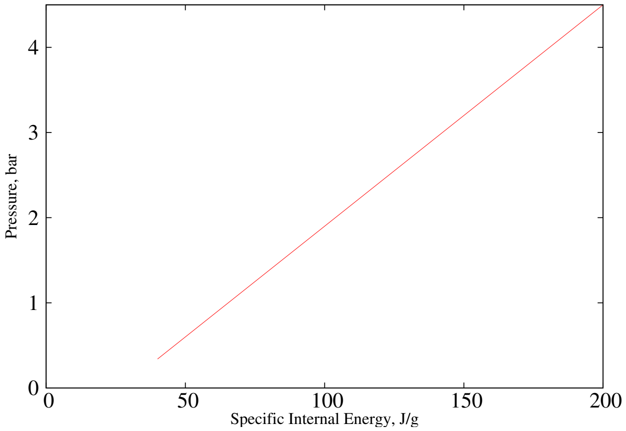


Figure 2: Isochoric increase of mercury pressure with increase of internal energy (cortesy Sandia National Lab).

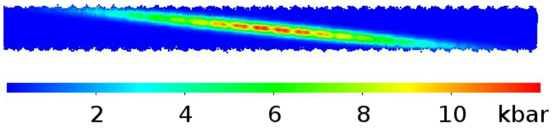
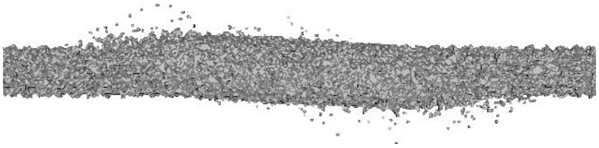
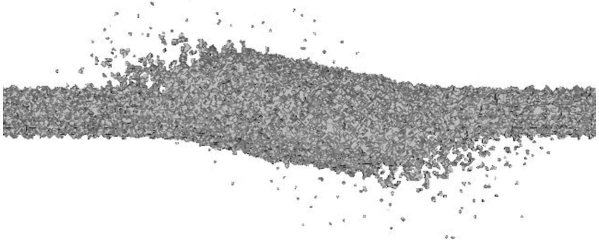


Figure 3: Initial pressure distribution in cross-section of the mercury jet due to neutrino factory beam energy deposition.

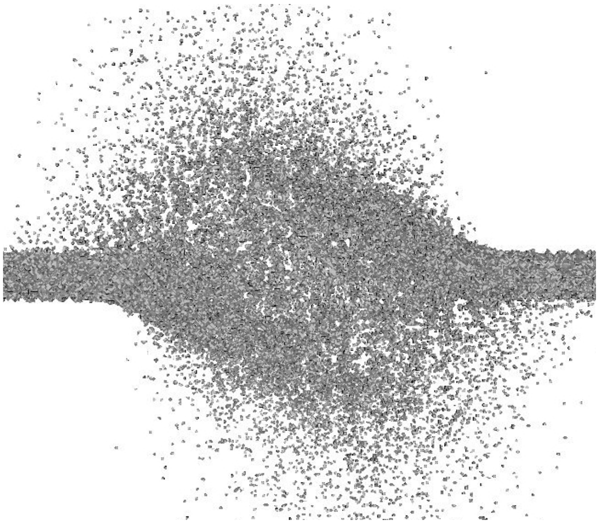
After the energy deposition, strong pressure wave propagates to the jet surface and reflects from the mercury - vacuum interface as a rarefaction wave. Rarefaction waves focus in the center of the jet, break the liquid and create an extensive cavitation zone. After the jet is disintegrated by cavitation and surface instabilities, fragments of jet freely fly apart. The velocity of the neutrino factory target splash is in the range of 15 - 35 m/s, with some small droplets reaching velocities of the order of 40 - 50 m/s. These velocities are in the same range as ones observed in MERIT experiments. The exact comparison is not possible because of uncertainties in the energy deposition and spot sizes. In the muon collider case, main jet fragments disperse with the velocity of 90 - 110 m/s with some droplets reaching much higher velocities (see Fig. 4).



(a) Neutrino factory, 0.35 ms



(b) Neutrino factory, 1.0 ms



(c) Muon collider, 0.35 ms

Figure 4: Mercury jet dispersal after deposition of 4 MW beam of 8 GeV protons. State of the neutrino factory target at 0.35 ms (a) and 1 ms (b), and the muon collider target at 0.35 ms (c).

Evaluation of Gallium Targets

The targetry group of the MAP collaboration is interested in evaluating the performance of lower-Z materials as targets for future accelerators / storage rings. We performed initial hydrodynamic simulations of the interaction of gallium jets with proton pulses. The density of gallium is $6.1\, g/cm^3$ and the sound speed is 2879 m/s. Detailed thermodynamic properties of gallium were not available at the time of simulations. Based on lower gallium density, we assumed that the pressure and internal energy density increase will be 50% of that in mercury for the same proton pulse. Using the muon collider proton beam parameters, the dispersal of the gallium jet was similar to that of the mercury jet (see Fig. 5). This observation is consistent with a simple extimate using the energy balance law. For the case of the neutrino factory proton beam, the jet expansion velocities were lower compared to the mercury jet and the gallium jet exhibited little distortion at 1 ms. This result could have been affected by inaccurate thermodynamic properties of gallium and the cavitation model. This issue will be addressed in the future work.

Figure 5: Gallium jet dispersal after proton beam energy deposition.

CONCLUSIONS AND FUTURE WORK

Hydrodynamic response of high power mercury targets interacting with proton pulses have been studies computationally using a smooth particle hydrodynamics (SPH) code. The mercury thimble experiments have been used for the validation of physics models, in particular cavitation, implemented in the SPH code. Simulated velocities of the mercury splash agree with experimental values. Furthermore, the sensitivity of the splash velocity to the value of the critical pressure has again demonstrated the importance of cavitation modeling for target simulations. With the critical pressure selected in the benchmark process, simulations of the neutrino factory and muon collider targets have been performed and mercury dispersal velocities have been calculated. Preliminary studies of gallium targets have also been performed. Future work will focus on MHD effects using the SPH code and its modifications.

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