ELSEVIER

Journal of Nuclear Materials 318 (2003) 109–112

journal of nuclear materials

www.elsevier.com/locate/jnucmat

Experimental observation of proton-induced shocks in free surface liquid metal targets

A. Fabich, M. Benedikt, J. Lettry *

CERN-PS Division, Geneva 23 CH-1211, Switzerland

Abstract

Tests on the response of liquid metal targets to high-power proton beams have been performed at ISOLDE/CERN. During these tests, a so-called thimble geometry and an extended version, the trough, filled with liquid mercury were exposed to a 1.4 GeV proton beam with intensities up to 33×10^{12} protons/pulse. In order to extrapolate the behaviour of a liquid metal target from the kilowatt to the megawatt-scale as required for a neutrino factory, various measurements were carried out with the aim of establishing scaling laws of the splash velocity as a function of beam size, intensity and time structure. The mercury volume was placed in a steel frame, while the region above the mercury level was observed through two quartz windows with a high-speed camera. For the highest intensity available at the PS Booster (33×10^{12} protons/pulse), the mercury expanded with velocities up to 50 m/s. The splash velocity scaled with the power density of the proton pulse. Increasing the beam size or the pulse duration reduced the velocity.

1. Introduction

The use of a liquid metal target is a natural solution to avoid the stresses and fatigue, induced by a high-power proton beam that eventually lead to the destruction of most solid targets. A liquid jet provides a new target for each proton pulse if the material disrupted by the proton beam can be evacuated within the proton pulse interval.

For the tests described here, mercury, a room temperature liquid metal, was chosen as target material. The experimental setup is based on the recording of the shadow of the mercury intercepting a laser light source, using a high-speed camera. Sets of mirrors and telescopes allow the installation of the sensitive pieces of electronics behind a few metres thick radiation shielding.

Previous experiments concerning proton-induced shocks have been performed in the E951 experiment at BNL [1,2]. Similar tests in ISOLDE at CERN followed to study the target behaviour as a function of various beam parameters such as pulse intensity, spot size and time structure. The scaling laws obtained through these latter experiments at ISOLDE are described here.

2. Experimental setup

The thimble and trough experiments provide a simple setup to study the impact of proton beams on liquid targets with free surface. The volume of the thimble excavated in a stainless steel frame is 1.2 cm^3. It consists (from bottom to top) of a half sphere ($r = 6$ mm), a vertical cylinder ($r = h = 6$ mm), and a meniscus, which has a free surface of 1.2 cm^2 (Fig. 1). The trough is an extension of the thimble containing about 7.5 cm^3 volume, where the mercury is extended to a length $l = 6$ cm coaxial to the proton beam (Fig. 2). The cross section of the trough perpendicular to the beam is similar to the one of the thimble. Fig. 1 shows the basic geometry of the thimble. In Fig. 2 the trough, which is placed in the steel frame similar to the thimble, with its viewing windows is visible. Both targets were placed separately

* Corresponding author. Tel.: +41-227 672658; fax: +41-227 678990.

E-mail address: jacques.lettry@cern.ch (J. Lettry).

0022-3115/03/$ - see front matter © 2003 Elsevier Science B.V. All rights reserved.
doi:10.1016/S0022-3115(03)00008-4

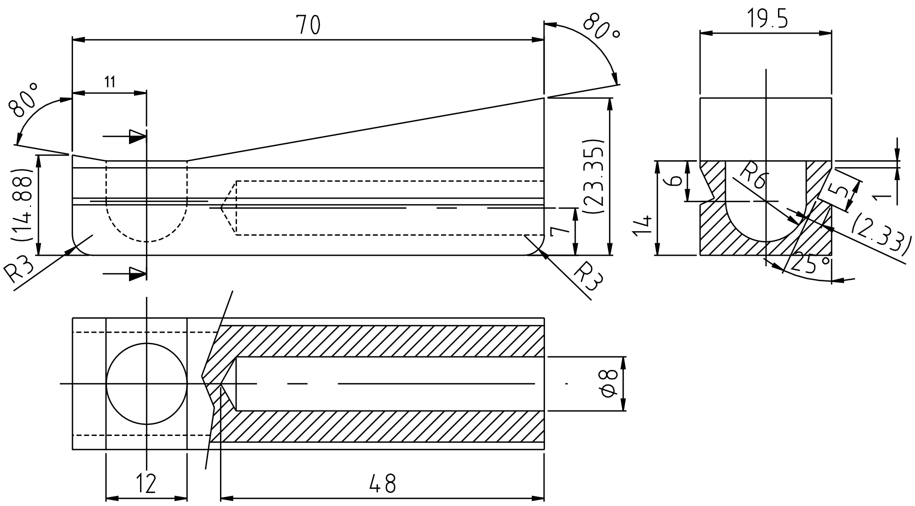

Fig. 1. Technical drawing of thimble. Downstream of the thimble the steel frame is excavated in beam direction in order to minimise the activation of steel.

at the GPS beam line of ISOLDE and exposed to single pulses with varying beam parameters; the quantity measured was the splash velocity of the mercury. The errors of the shutter time ($t = 12.5$ μs) and the spatial resolution of the camera (0.89 mm/pixel) result in an uncertainty of the velocity measurement of ≈10%.

The kinetic energy of the proton beam was 1.4 GeV. The beam parameters such as intensity per bunch, number of bunches per pulse, spot size and pulse length were varied within the limits of the PS Booster machine as follows: intensity per bunch from 1×10^{12} to 9×10^{12} protons; number of bunches per pulse from 1 to 4; spot size (radius r.m.s., Gaussian distribution) from 1.2 to 4.2 mm, where the lower limit is given by the intensity per bunch and the upper limit by the dimension of the mercury target. The pulse length is given by the number of bunches and the peak-to-peak bunch distance, which was varied between 0.286 and 19 μs. The bunch length was kept constant at 230 ns.

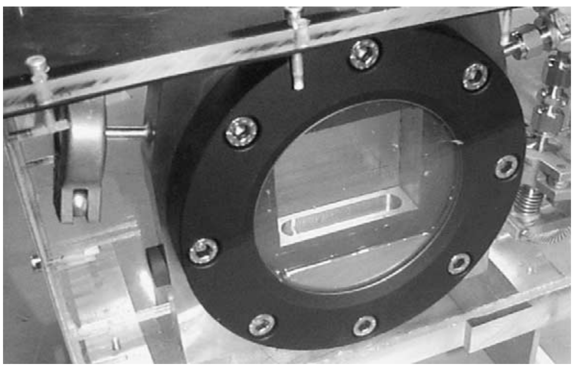

Fig. 2. Trough setup. The mercury volume is placed in a steel frame, where the area above can be viewed trough the window frames. The proton beam arrived from the left coaxially to the trough axis.

The splash of the mercury was recorded with a high-speed CCD camera (4000 frames/s, shutter time 12.5 μs). The flight path as a function of time was extracted via digital image processing. The height of the mercury level as a function of time was fitted with

$$y(t) = \mathrm{p1} * (1 - \mathrm{e}^{-\mathrm{p2}*t}) + \mathrm{p3} * t - \frac{a}{2} * t^2, \qquad (1)$$

where the first and second term correspond to the initial velocity caused by the proton beam and the drag force on the splash in the atmosphere, the third term expresses gravity ($a = 9.81$ m/s) and p1, p2 and p3 are the fit parameters. Deceleration due to the surface tension is negligible. The maximum velocity at $t = 0$ is then given by $v(t = 0) = \mathrm{p1} * \mathrm{p2} + \mathrm{p3}$.

3. Observations

The maximum splash velocity is plotted in Fig. 3 as a function of the proton pulse intensity. The quadrupole settings for beam focusing were kept constant during this measurement series, corresponding to a spot size of $r_{\mathrm{r.m.s.}} = 2.1$ mm at maximum intensity. The splash velocity scales linearly with the beam intensity. The experiments of trough and thimble show very equivalent behaviour for these conditions. The maximum velocities for the trough were extracted from the region $z = 1$–3 cm after the beam entrance window, where the splash velocity is almost constant in this region. For the trough, Fig. 4 shows the propagation of the mercury splash

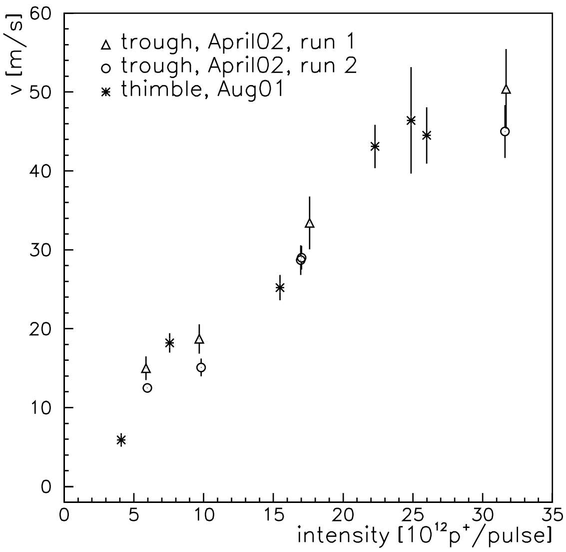

Fig. 3. The maximum splash velocity scales linearly with the proton intensity. Indicated are measurements from the thimble and the trough, where the same maximum splash velocities are observed. Run 1 and 2 are similar exposures of the trough to the proton beam at different times of the experiment.

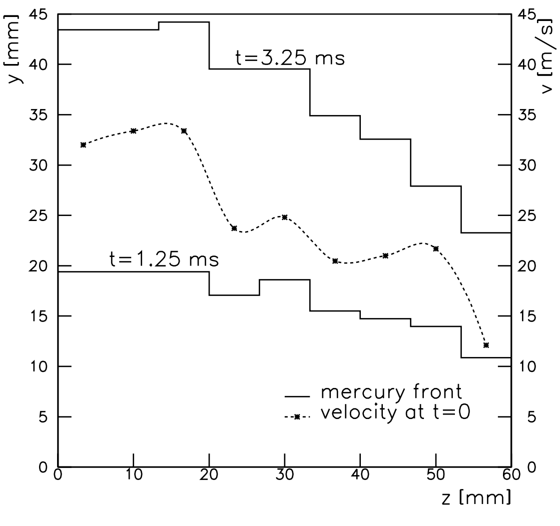

Fig. 4. The trough is a mercury target with a length $l = 60$ mm along the beam axis. The proton beam is passing in positive z-direction. Indicated here is the propagation of the mercury splashes along the beam axis for two different times after proton impact. The movement is averaged over slices each ≈7 mm long. Also indicated is the initial splash velocity due to proton impact.

along the beam axis at certain times after the proton impact, where the beam intensity was $I = 20 \times 10^{12}$ protons/pulse. All recorded trough events show similar qualitative behaviour. The splash velocity at a distance of $z = 60$ mm after the beam window is about half the maximum splash velocity, which occurs close to the beam entrance. This shape corresponds to the distribution of energy deposition in numerical simulations [1]. Also indicated is the initial splash velocity, which shows the same shape as the propagation of the mercury front.

Fig. 5 shows the behaviour of the mercury target as a function of the spot size of the proton beam. All events with a spot size different to $r_{\mathrm{r.m.s.}} = 0.5$ mm are due to a pulse with two bunches within $t_{\mathrm{pulse}} = 0.5$ μs and an intensity of $I = 17 \times 10^{12}$ proton/pulse recorded at ISOLDE. The splash velocity for a spot size $r_{\mathrm{r.m.s.}} = 0.5$ mm (pulse length 150 ns) is derived from the events recorded at BNL [2]. There, the beam intensity was $I = 3.8 \times 10^{12}$ protons/pulse and the splash velocity was extrapolated to an intensity of $I = 17 \times 10^{12}$ protons/pulse according to the measured scaling shown in Fig. 3. The splash velocity is as well corrected for the energy loss of protons $\mathrm{d}E/\mathrm{d}x$ (according to Bethe-Bloch) differing at 1.4 and 24 GeV.

The PS Booster allows the extraction of up to four bunches from its four rings at adjustable bunch-to-bunch distance, which is variable from a minimum of $t_{\mathrm{d}} = 286$ ns to several microseconds in multiples of t_{d}. To simulate various bunch lengths at fixed intensity and spot size, two bunches with varying spacing were

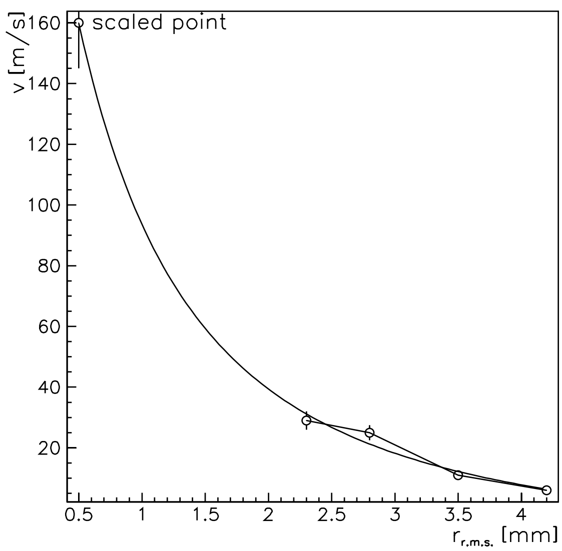

Fig. 5. Increasing the spot size of the proton beam results in a decrease of the splash velocities. The target was exposed to a proton pulse with an intensity of $I = 17 \times 10^{12}$ protons/pulse. Events with a spot size different to $r_{\mathrm{r.m.s.}} = 0.5$ mm are recorded in ISOLDE. The events with a spot size $r_{\mathrm{r.m.s.}} = 0.5$ mm were performed at BNL. The splash velocity measured for events at an intensity $I = 3.8 \times 10^{12}$ protons/pulse were extrapolated according to the linear scaling with the proton pulse intensity.

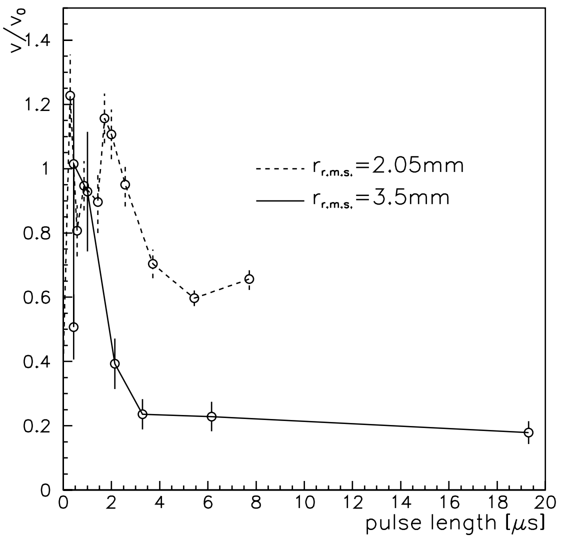

Fig. 6. Splash velocity vs. pulse length for two beam spot sizes. The pulse length was varied from a minimum distance between two bunches of 0.286 μs up to 8 and 19 μs respectively. The velocities are normalised to a typical figure for each of the two data series.

extracted from the PS Booster. The behaviour of the mercury target as a function of the pulse length for two different spot sizes is indicated in Fig. 6.

The splash velocities shown here are derived from the experiments with the thimble and the trough and are not directly valid for the behaviour of a free surface jet. The splash velocities for the free jet are about a factor two below those observed with thimble and trough [1]. This has to be taken into account when estimating the impact of a proton beam on a jet target as foreseen for a Neutrino Factory.

4. Conclusion

- The maximum splash velocity measured was 50 m/s for a pulse intensity of 33×10^{12} protons/pulse.
- The initial splash velocity scales with the deposited power density:
  - The splash velocity scales linearly with the proton intensity.
  - The splash velocity depends on the spot size $r_{\mathrm{r.m.s.}}$ like $(1/r_{\mathrm{r.m.s.}})^2$.
  - When increasing the distance between two bunches to more than ≈3 μs (peak-to-peak), the maximum splash velocity drops to the values measured with a single bunch.
- These scaling laws of the splash velocity for a liquid mercury target enable extrapolation to a 4 MW proton beam as required for a ν-Factory.

References

[1] A. Fabich, J. Lettry, Proceedings NuFact'01, Japan, Nucl. Instr. and Meth. A, 2001.
[2] H. Kirk et al., Proceedings PAC'01, Chicago, 2001.