APPLICATION OF PARTICLE ACCELERATORS TO STUDY HIGH ENERGY DENSITY PHYSICS IN THE LABORATORY

N. A. Tahir, Th. Stöhlker, GSI Darmstadt, 64291 Darmstadt, Germany
A. Shutov, A.P. Zharkov, IPCP, Chernogolovka, Russia
A. R. Piriz, University of Castilla-La Mancha, 13071 Ciudad Real, Spain

Abstract

Intense particle beams are a very efficient tool to generate strong shock waves in solid matter, thereby producing large samples of High Energy Density (HED) matter in the laboratory. However, due to the intrinsic cylindrical geometry involved in the typical beam–target configuration used in this problem, the resulting shock front is cylindrical and non–steady which is not very useful for HED physics studies. Recently, we have developed a novel technique based on a Mach type reflection configuration that generates a plane and steady shock wave [1]. This will open up the possibility to investigate numerous HED physics problems, for example, hydrodynamic instability growth studies in solids and ideal fluids in the linear as well as in the non–linear regimes. In addition to that, ion beam driven isentropic compression of solid samples can be carried to investigate the solid constitutive properties under high pressure loading.

INTRODUCTION

High Energy Density Physics (HEDP) is one of the most active areas of research which spans over numerous disciplines of physics. For example, astrophysics, planetary physics, geophysics, inertial fusion and many others. Theoretical investigations have shown that an intense particle beam is an efficient new tool to study HEDP [2, 3, 4]. Moreover, it offers unrivaled flexibility to the scientists as it can be employed to generate HED matter using two very different schemes, namely, by isochoric and uniform heating of solid targets [4] and shock compression [3]. If one uses a simple beam–target interaction set up, a curved and non–steady shock front is generated [3] that is not very useful for studying HED physics problems like the Equation–of–State (EOS) of matter. We have recently developed a novel technique that is based on a Mach type reflection scheme [5] to generate a plane and steady shock wave using an intense ion beam. This technique will open up the possibility of doing novel HED physics experiments using an ion beam driver. For example, hydrodynamic instability growth studies in solids and ideal fluids in the linear as well as in the non–linear regimes and isentropic compression of solid samples that can be used to investigate the constitutive solid properties under dynamic conditions.

The heavy ion synchrotron, SIS100, to be built at Facility for Antiprotons and Ion Research (FAIR) at Darmstadt, will be one of the most powerful accelerators in the world. According to the design parameters, it will generate a uranium beam with an intensity, N = 5×10^{11} ions that will be delivered in a single bunch, 50–100 ns long. We have carried out two–dimensional hydrodynamic simulations using the SIS100 beam parameters to study the possibility of doing the above experiments at the FAIR facility. In the next section we report these numerical simulation results with detailed analysis. These simulations have been carried out using a sophisticated computer code, BIG2 [6].

NUMERICAL SIMULATION RESULTS

The beam–target set up is shown in Fig. 1 which is a multi–layered conical shaped cylindrical target that is irradiated by the beam from the right side. Since the beam intensity at FAIR will increase gradually before achieving the maximum design value of 5×10^{11} ions per bunch, we have also done calculations using a lower beam intensity of 5×10^{10} ions per bunch in order to explore the possibility of doing experiments during the early and the intermediate stages of the project. First, we present the results obtained using this lower intensity. The full width at half maximum (FWHM) of the transverse Gaussian intensity distribution is 2 mm and the pulse length is 50 ns. The pressure produced in the target at t = 50 ns (end of the ion bunch) is presented in Fig. 2. It is seen that the parallel ion beam deposits maximum energy density in the conical region at the location of the Bragg peak. This leads to an inward and an outward moving shock wave. The inward moving shock wave, after reflection at the axis of symmetry, forms a Mach configuration [5]. This leads to an extended, steady and plane shock front with a pressure of about 55 GPa, as shown in Fig. 3 where we present the pressure distribution at t = 500 ns. This scheme therefore provides a very efficient tool to study a variety of problems in HED physics.

To simplify the calculations, the inner part of the target where the shock front exists, is magnified and is presented in Fig. 4. It is seen that at t = 500 ns, the shock front is still in the Cu region, but is close to the Cu–Al interface that is located at L = 0. The pressure in the shock front is about 55 GPa while the temperature in the shock heated Cu is around 900 K which means that the material is still in solid state and possesses solid constitutive properties.

Simulations have also shown that if one uses the highest beam intensity of 5×10^{11} ions / bunch, the shock is

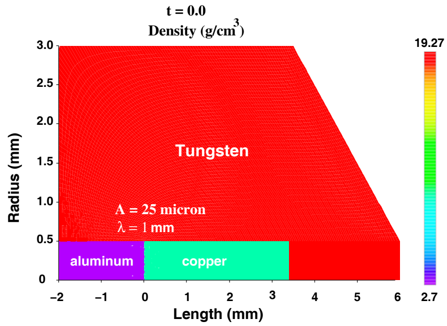

Figure 1: Beam–target geometry to generate a plane steady shock wave using a Mach type reflection scheme. The beam is incident from right to left.

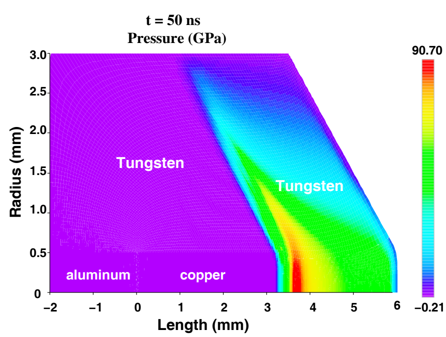

Figure 2: Pressure distribution at t = 50 ns, irradiated by U beam, N = 5 $\times$ 10^{10} ions / bunch, FWHM = 2 mm, particle energy = 400 MeV/u, τ = 50 ns.

driven by a much higher pressure of about 480 GPa and the temperature in the shocked Cu is of the order of 18000 K that corresponds to a fluid state. Moreover, in this case the shock moves faster and arrives close to the Cu–Al interface at an earlier time of about 250 ns.

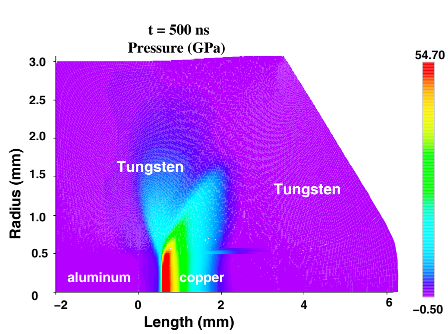

Figure 3: Same as in 2, but at t = 500 ns, a plane shock front has been generated.

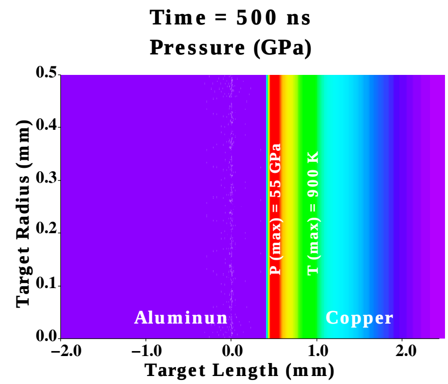

Figure 4: Magnified view of the shock region before the shock propagates across the Cu–Al contact at L = 0.0.

A very interesting application of this tool can be to study the Richtmyer–Meshkov (RM) instability growth in solids and ideal fluids both in the linear as well as non–linear regime if the surface of the contact between Cu and Al is corrugated, as described in the next sub–section.

Richtmyer–Meshkov Instability Studies

To study the RM instability growth across the Cu–Al interface in an ideal fluid (using a beam intensity of 5 $\times$ 10^{11} ions / bunch), a perturbation with wavelength, λ = 100 μm having an initial amplitude, A = 25 μm is applied in the vertical direction. The corresponding wave number, k = 6.28 $\times$ 10^2 cm^{-1}so that the product kA = 1.57, which represents a non–linear regime. Since the interface has a radius of 0.5 mm, five wavelengths will fit in that region. However, for the simplicity of the calculations, we study the behavior of a single wavelength as shown in Fig. 5. The shock travels from right to the left (from copper into the aluminum).

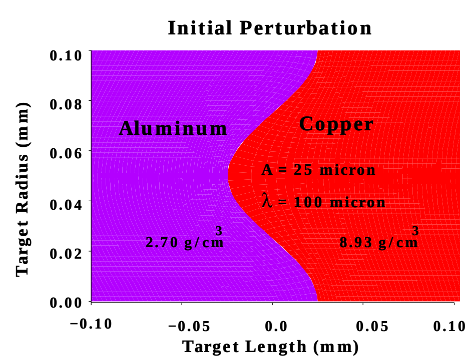

Figure 5: Wavelength, λ = 100 μm and initial amplitude, A = 25 μm.

It is well known that when a shock propagates from a high–density medium (Cu) to a low–density medium (Al) through a corrugated interface, corrugated fronts in the expanding Cu (due to rarefaction wave) and Al that is being compressed by the transmitted shock, are generated.

This process deposits enough vorticity on the contact interface in such a way that it enhances the ripple growth in the opposite direction to that at initial time which leads to inversion of the perturbation phase [7, 8]. This is clearly seen in Fig. 6 which shows a typical non–linear "mushroom type" growth of the interface due to the RM instability with a phase, opposite to that of the initial perturbation. The perturbation amplitude continues to grow as no stabilizing mechanism exists. Experimental studies of the growth rate of the instability in this regime will allow one to understand the non–linear evolution of the RM instability in ideal fluids.

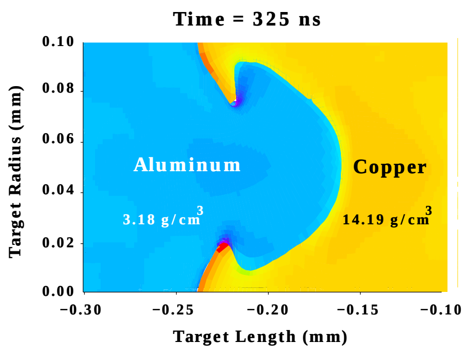

Figure 6: Perturbation amplitude at t = 325 ns in an ideal fluid (N = 5×10^{11} ions / bunch).

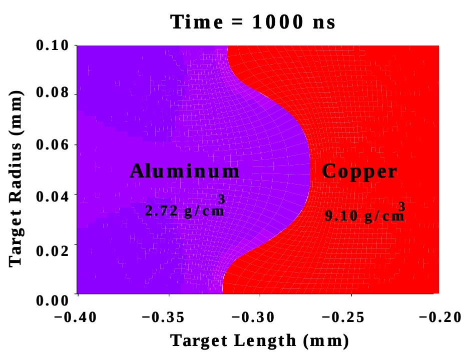

Figure 7: Perturbation amplitude at t = 1000 ns in the solid case (N = 5×10^{11} ions / bunch).

To show the influence of the constitutive properties on the development of the RM instability, we also studied the shock propagation from Cu into Al using the initial conditions presented in Fig. 4 where a lower beam intensity of 5×10^{10} ions per bunch has been used. In this case the target remains in a solid state and therefore maintains its constitutive properties. The hydrodynamic simulations have been carried out using a modified version of the BIG2 code that includes a Prandtl–Reuss model supplemented with von Mises yield criterion [9]. A semi-empirical EOS model [10] has been used to treat the different phases of the target material during the target heating. The results are presented in Fig. 7 which shows that at t = 1000 ns, the perturbation phase has been inverted, but the amplitude is comparable to the initial amplitude of 25 μm and there is no mushroom shaped growth. In fact the perturbation amplitude stabilizes at about t = 750 ns in accordance with the prediction in [11] due to the constitutive properties of the material. However, in the present case, the problem is more involved due to the different values of the yield strength and shear modulus of the two materials, Cu and Al. Similar experiments will be very useful in determining the constitutive parameters of materials in HED state.

Simulations using smaller perturbation amplitude of 1 μm corresponding to a linear regime, have shown that initially the amplitude grows linearly in case of an ideal fluid, but at a later stage it enters into the non–linear regime and loses its sinusoidal structure. In case of a solid, on the other hand, small perturbations do not grow at all but are completely stabilized due to the solid constitutive properties.

CONCLUSIONS

In this paper we present detailed numerical simulations that demonstrate that a strong, steady, plane shock wave can be generated using a wedge shaped multi–layered target that is irradiated with an intense heavy ion beam. This is a new, very important technique that will provide an additional, very efficient tool to study numerous problems in the field of HED physics. One such problem is to study the growth rate of the RM instability in solids and ideal fluids in the linear as well as in the non–linear regimes. Using the beam parameters that will be available at the SIS100 synchrotron at FAIR, we have carried out hydrodynamic simulations to investigate the potential of this facility to study the above problems. It is shown that in case of an ideal fluid, the perturbation amplitude continues to grow without restrictions and develops into a typical mushroom shape. In case of solid material, on the other hand, the perturbation growth is limited due to the solid constitutive properties of the material and the amplitude finally stabilizes.

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