3D modelling of cylindrical implosion experiments

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AWE has been involved in a series of experimental campaigns to study shock-induced mixing in a convergent geometry. We have studied the flows in these simulations using a three-dimensional hydrodynamic code, Turmoil3D. In this paper, we compare these adiabatic results with experimental results.

Introduction

Laser driven implosions of cylindrical targets offer an opportunity to study the growth of Richtmyer-Meshkov and Rayleigh-Taylor instabilities in a convergent geometry, where the developing flow can be directly measured by axial radiography.

AWE and LANL have been involved in a collaborative experimental programme on the OMEGA laser to study cylindrical implosions, with a range of target geometries. Here, we present results of three dimensional simulations based on two experimental geometries. These targets allow us to study the growth of nonlinear perturbations.

Simulations were done in two and three dimensions, using the Turmoil3D code (Youngs 1982). This code treats the flow of perfect gases, with a adiabatic constant that has a different value in each of two components. While the physics of these simulations is very simplified, comparisons with the results of more physically detailed codes in two dimensions gives us the confidence to use Turmoil3D to investigate three dimensional aspects of the development of turbulence in these experiments.

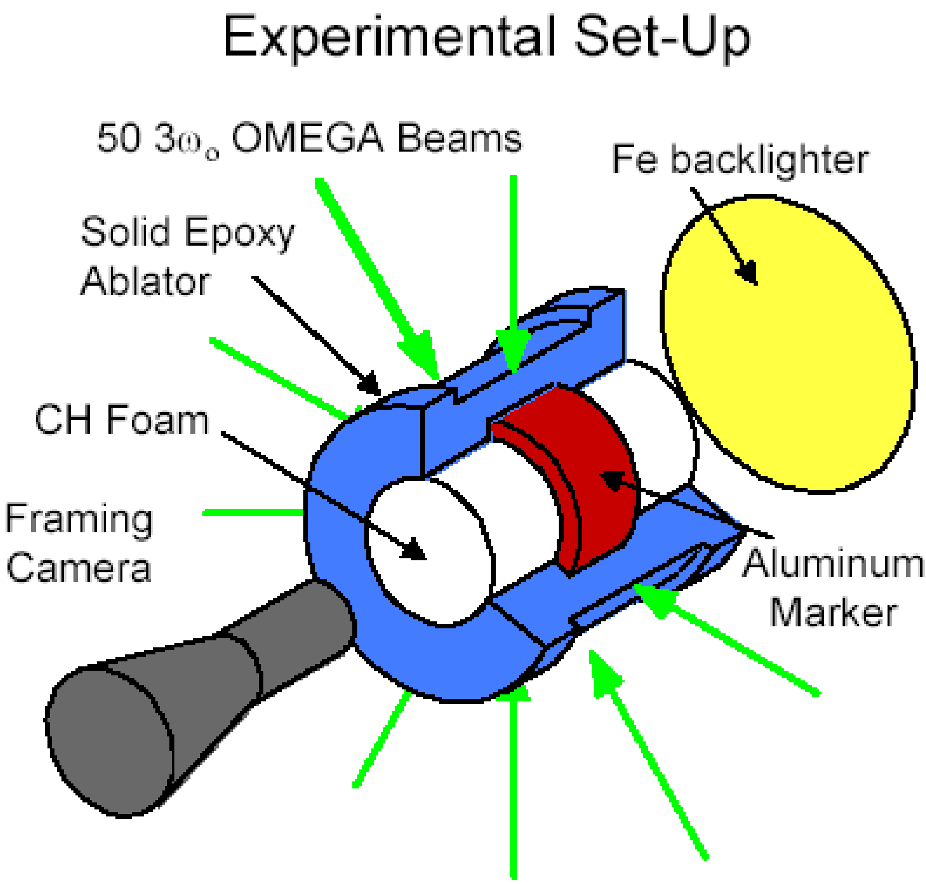


Figure 1: Schematic diagram of the experimental configuration.

Specified roughness target

We present simulations of a target in which the outer surface of the metal marker layer has a periodic screw-thread milling with superposed random variations. The results are for two dimensional and three dimensional simulations of these experiments. We have set the power spectrum of the fluctuations on lines across the surface to be the same in both simulations, matched to the profile measured in one experimental target.

The initial surface perturbation in 3D looks more regular than in the 2D case, as the high wavenumber modes have been averaged around the circumference. The two dimensional results have significant azimuthal structure as a result of the nonlinear growth of the Richtmyer-Meshkov instability (Figure 2).

When projected on the (r,z) plame, the 3D simulation shows material streaming away from the marker layer apparently almost uniformly mixed, except for a rather weak periodic modulation, which is close to radial (Figure 3).

For an single section through the midplane in ϕ, however, the density structure retains a higher contrast, and the influence of the random perturbation in generating asymmetric streamers is clear (Figure 4).

The mean density of the marker layer material in the axial direction is similar in 2D and 3D, Figure 5, although the 3D profile is significantly smoother and somewhat more peaked at the inner radii at late times. The total column density remains smooth even in a two-dimensional projection similar to the axial radiographs used to diagnose the experiment, Figure 6.

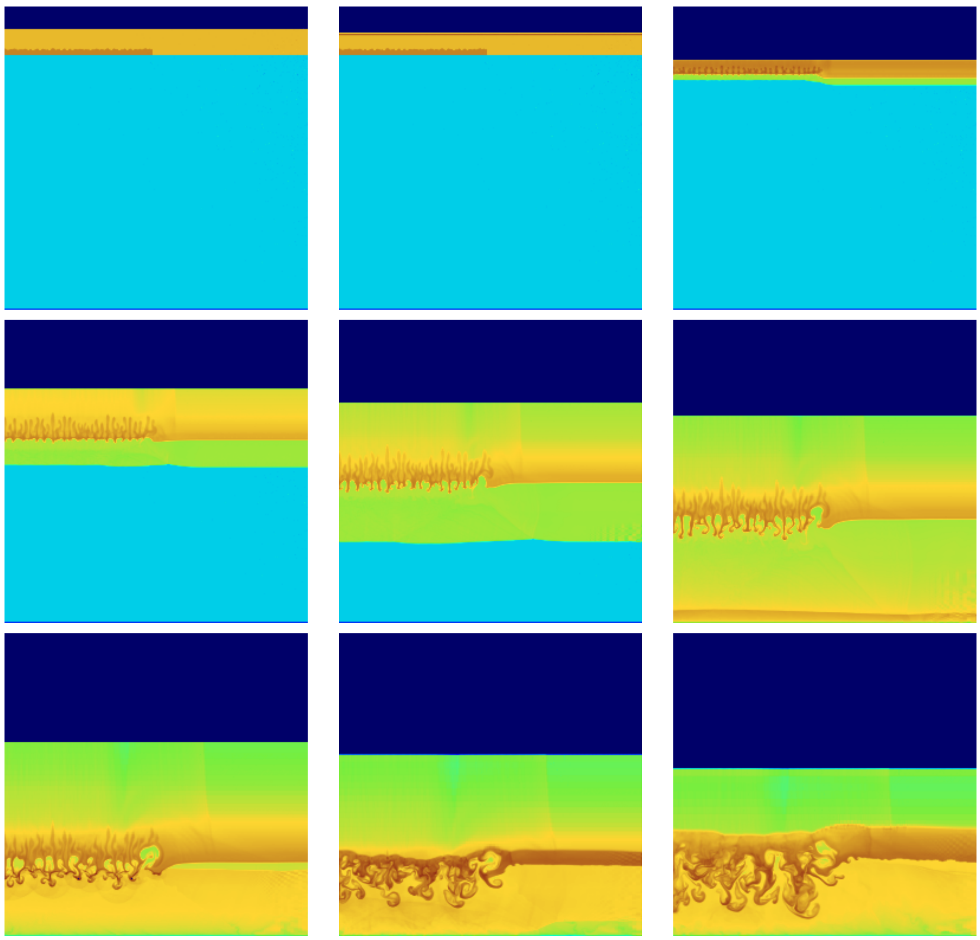


Figure 2: The dynamics of a 2D simulation using Turmoil3D. The plots are of the logarithm of the gas density shown every 1ns. The initial profile of the experimental package is shown in the first frame, with different colours corresponding to different densities the inner radius of the marker layer is 430 μm.

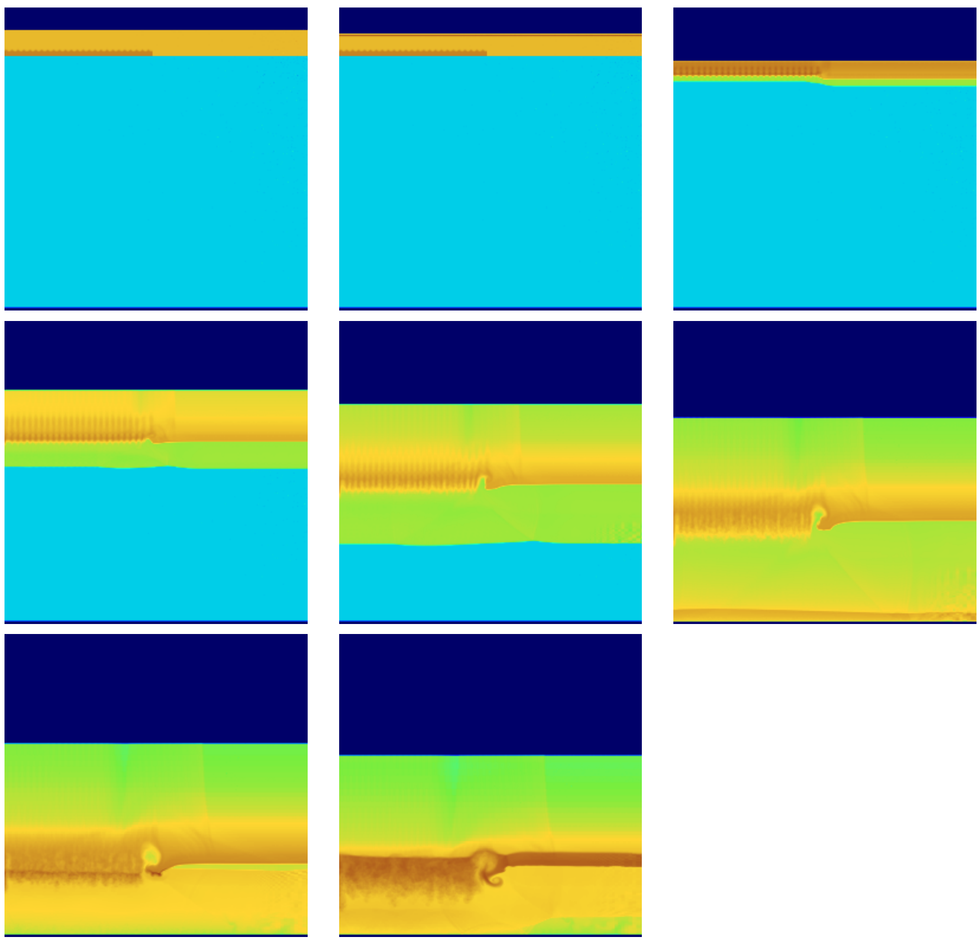


Figure 3: Mean density of the 3D simulation in the (r, z) plane.

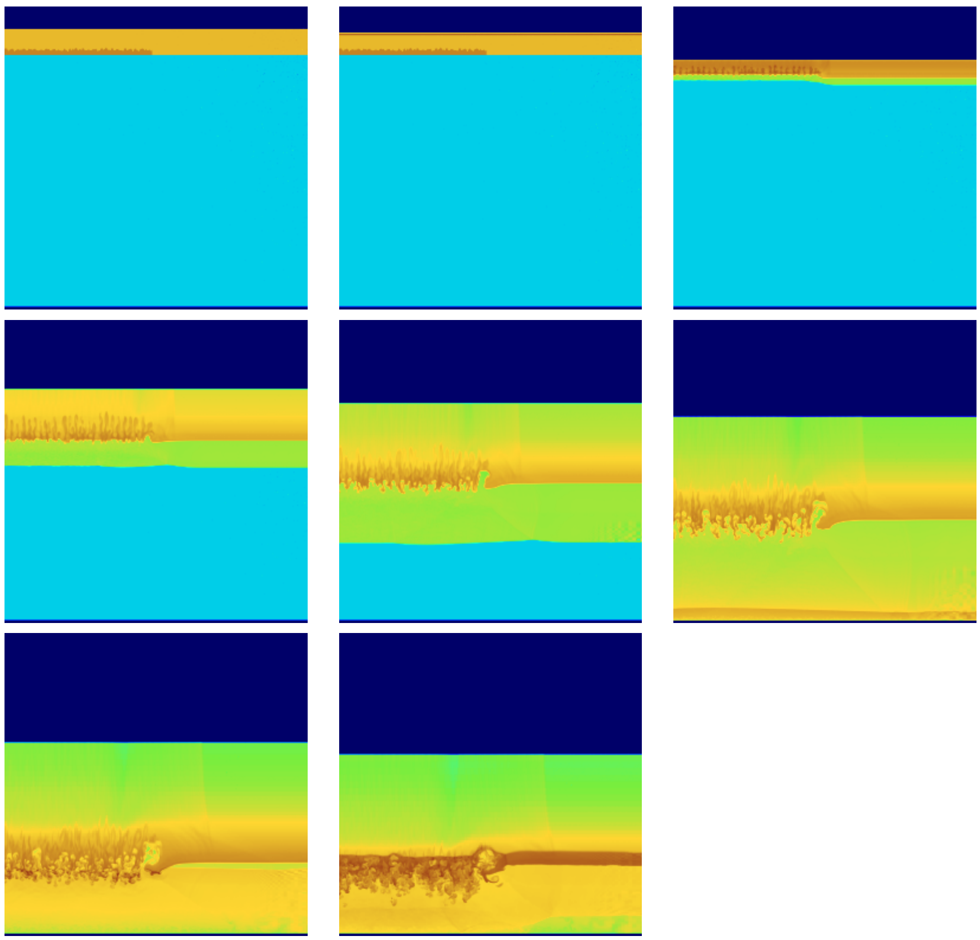
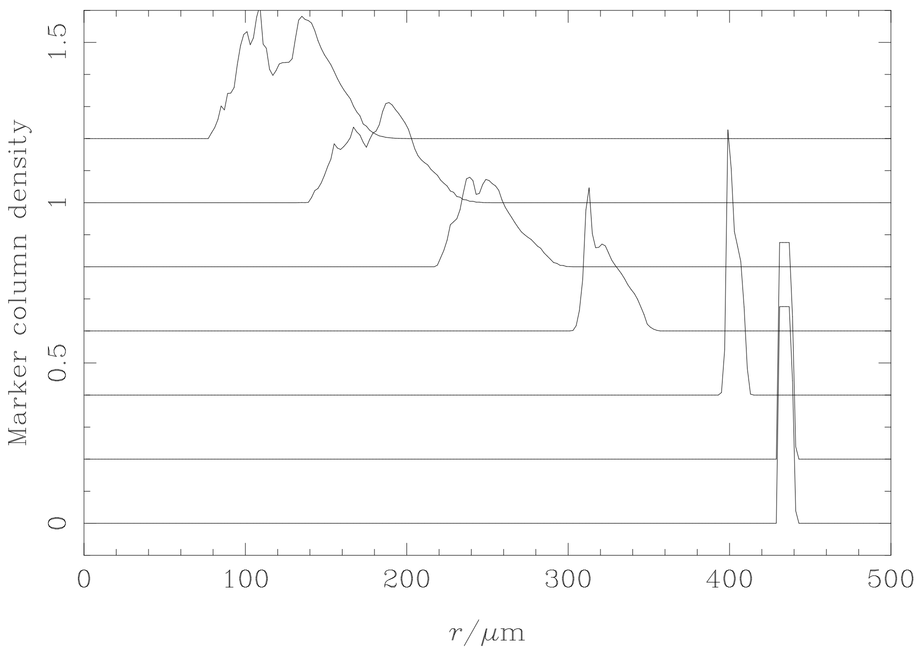


Figure 4: Density of the 3D simulation in the (r, z) plane, at the midplane in ϕ.

(a)



(b)

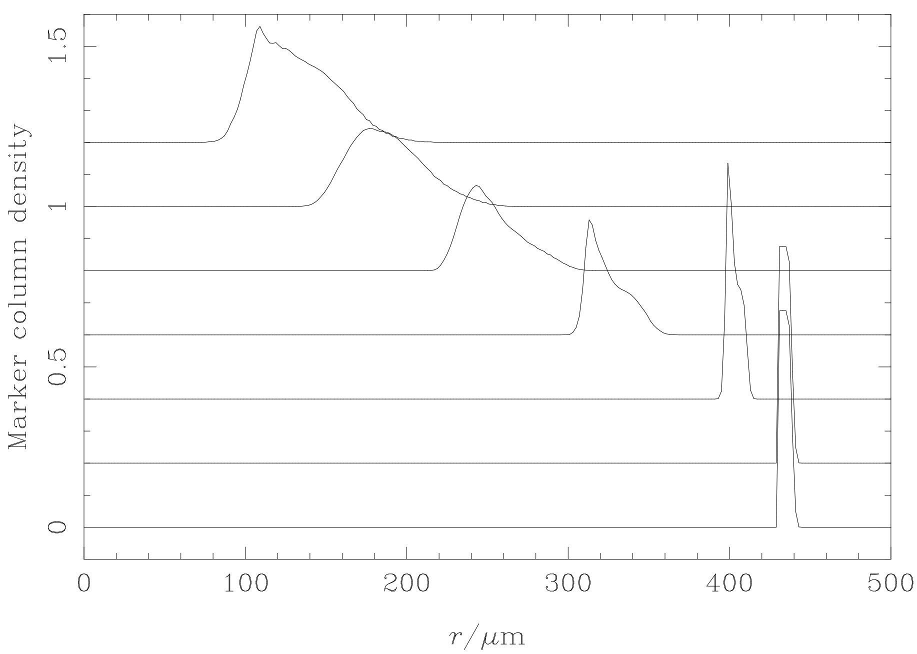


Figure 5: Mean line-of-sight density for marker layer material in (a) 2D and (b) 3D simulations.

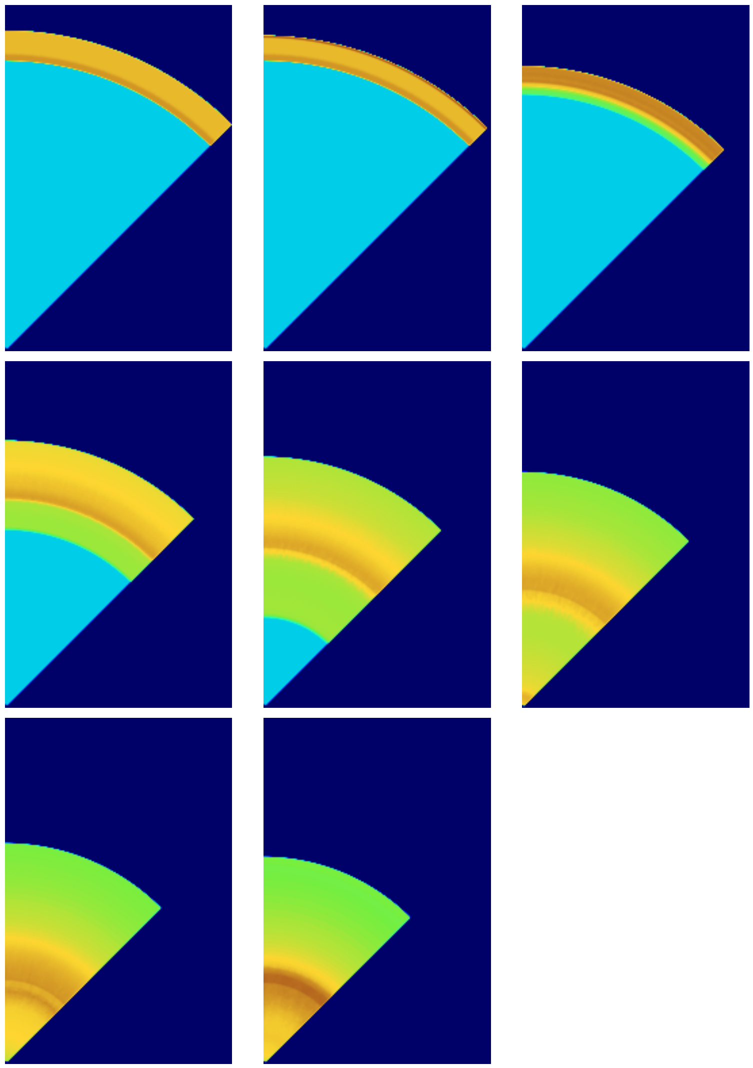


Figure 6: Numerical axial radiograph of the 3D simulation. The flow appears smooth when averaged in this way. The reshock can be seen propagating out towards the mixing region in the later frames.

Belly band defect

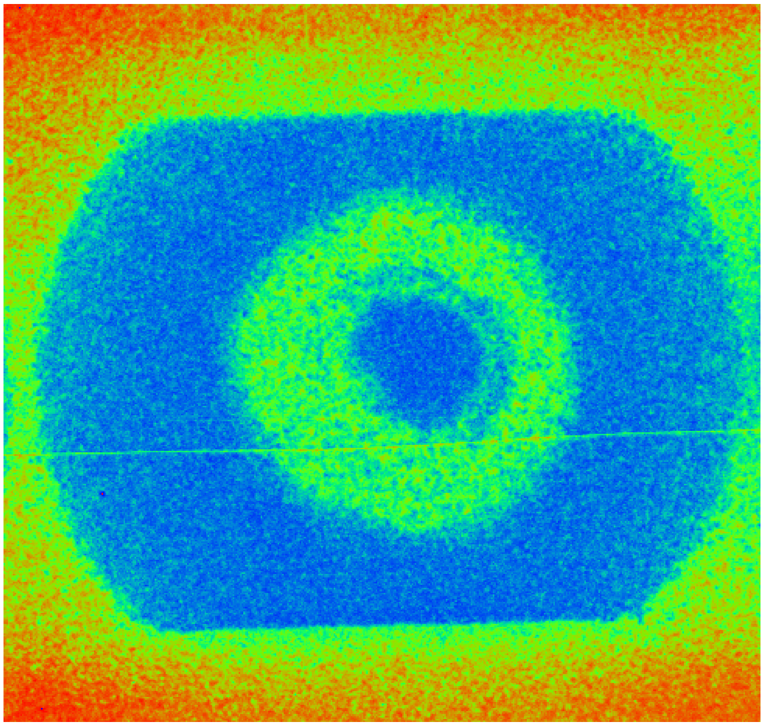
In recent experimental work, the dynamics of imploding cylinders with discrete features has been studied. We have modelled one of these using Turmoil3D, the so-called 'Belly Band defect' in which a region close to the equator of the marker cylinder was substantially thinned. In order to approximate the drive conditions in this case, we found it necessary to include an approximate treatment of the blow-off region. In order to do this, we applied the pressure drive at the outer-most cell above a threshold density chosen so that the overall dynamics of the 2D full-physics simulations were fit adequately.

We present the results of a two- and three-dimensional simulations. In the two dimensional simulation, all surfaces were smooth, while in the three dimensional simulation we have roughened the outer surface of the main cylinder to test how robust the overall dynamics are to this type of perturbation.

In each case the narrowed region of the marker layer moves ahead of the main layer, as found in the experiment. Figure 13 demonstrates this particularly clearly. Jets of material are seen to move out from the inner edge of the thick plate at a speed comparable to the thinned plate (Figure 8).

There is no evidence for these jets in the axial density, either experimentally or numerically, as these are relatively low-contrast features in a plane orthogonal to the viewing angle. Experiments with longitudinal defects have also not shown these jets clearly. However, when the density of the flow is integrated in the azimuthal direction, the jets are seen to be reasonably robust to the influence of the perturbations in the thick region of the marker layer.

In fact, the jet appears to result from the interaction of the shocks which escape into the central foam region the main marker layer and, somewhat earlier, from the thinned region. Where these leading shocks collide, a Mach stem appears. Shear lines appear at the shock intersections, as in complex Mach reflection. These shear lines meet at the surface of the marker layer, and turn to form a jet, also as in complex Mach reflection.



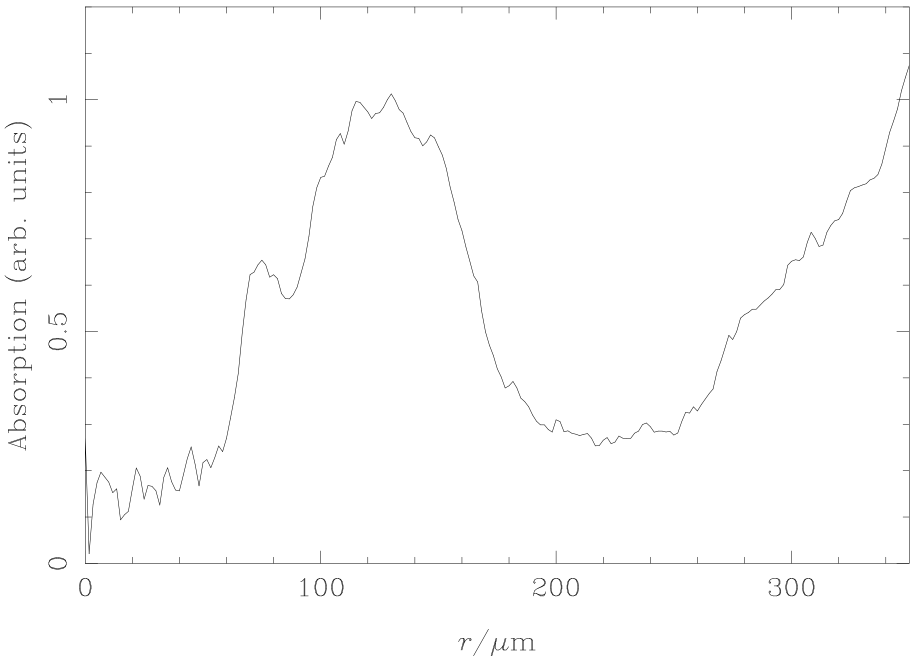


Figure 7: Axial radiograph of the imploded package, and azimuthally averaged absorption profile. (Thanks to S. Rothman and the experimental team.)

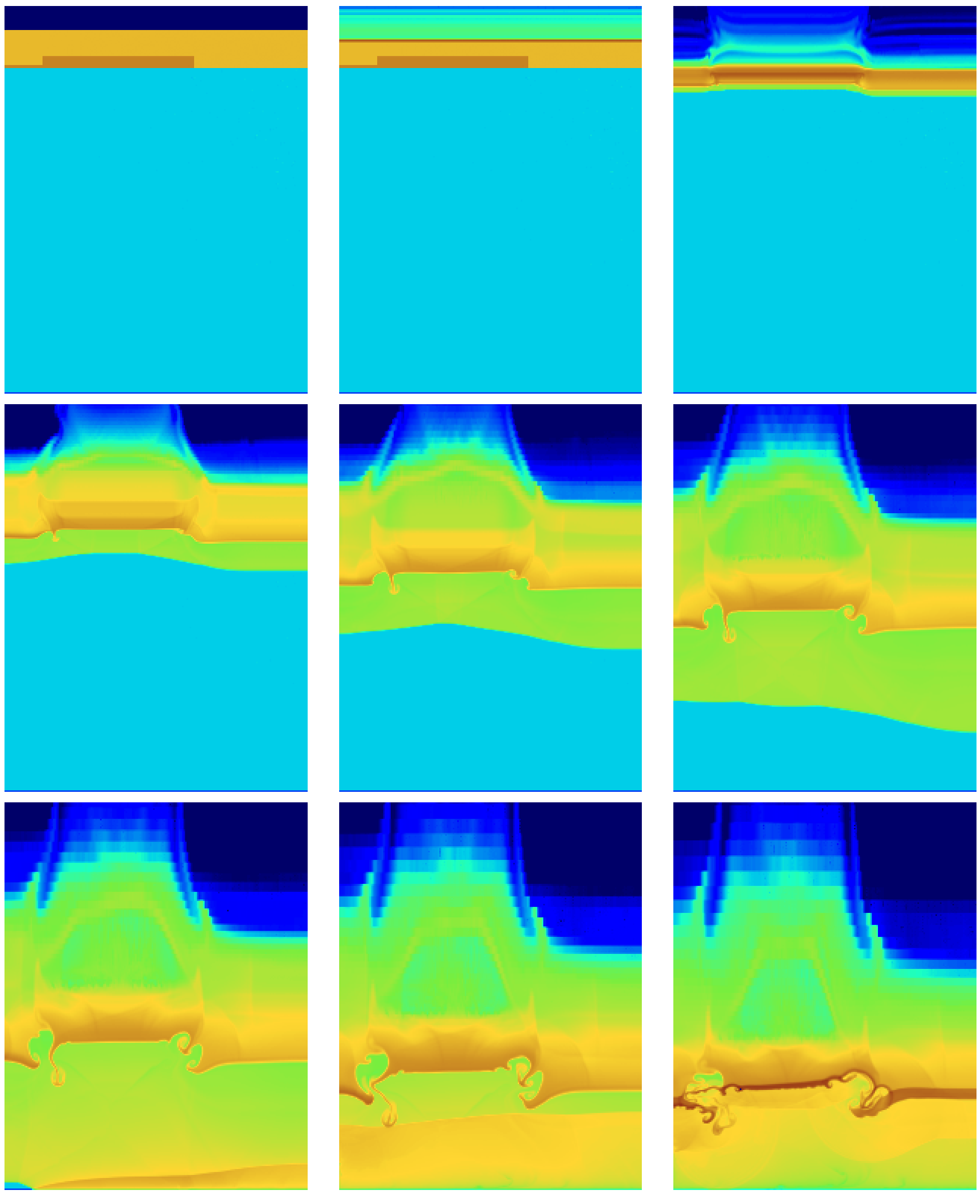


Figure 8: The dynamics of a 2D simulation using Turmoil3D. The plots are of the logarithm of the gas density shown every 1ns. Note the jet feature escaping at the left-hand edge of the thicker region of the marker layer.

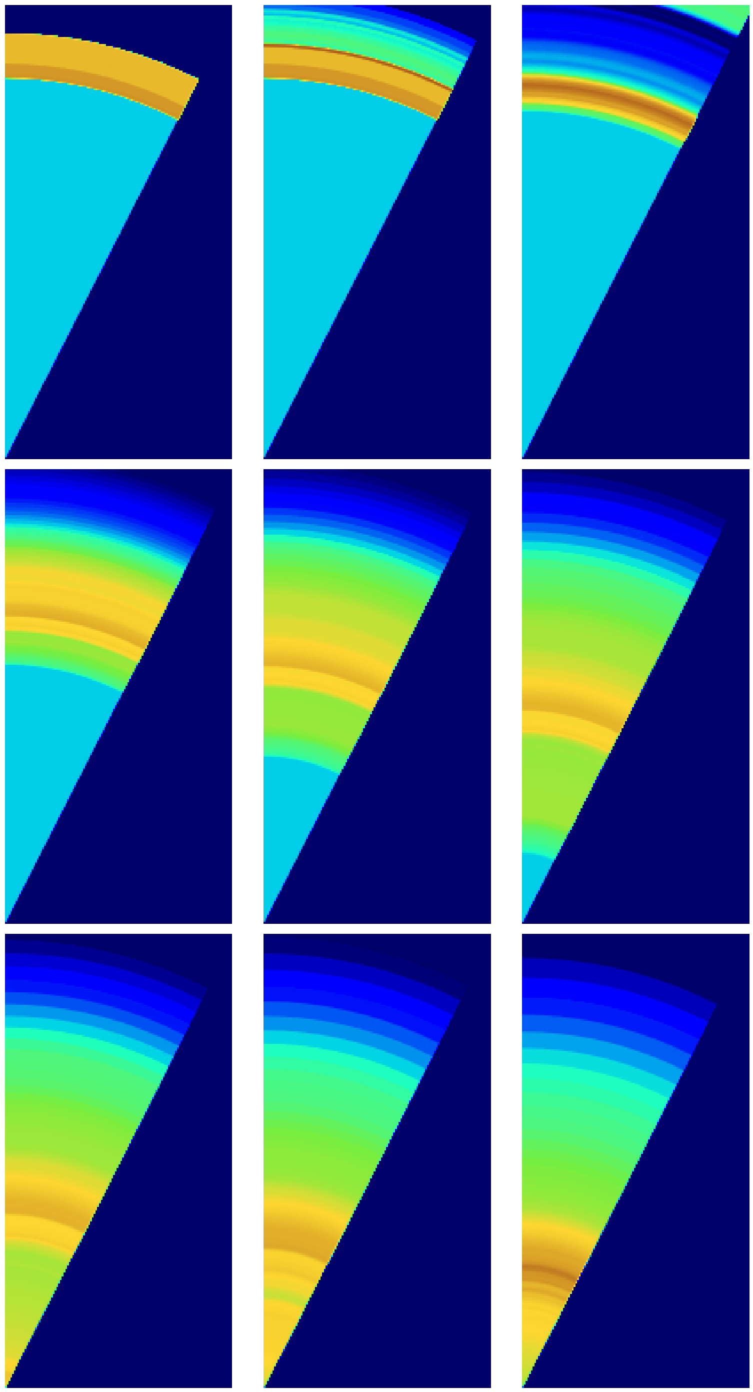


Figure 9: Numerical axial radiograph of the 2D simulation. A shell of high density material is seen inside the main shell, produced by the increased speed of the marker layer material in the thinned region.

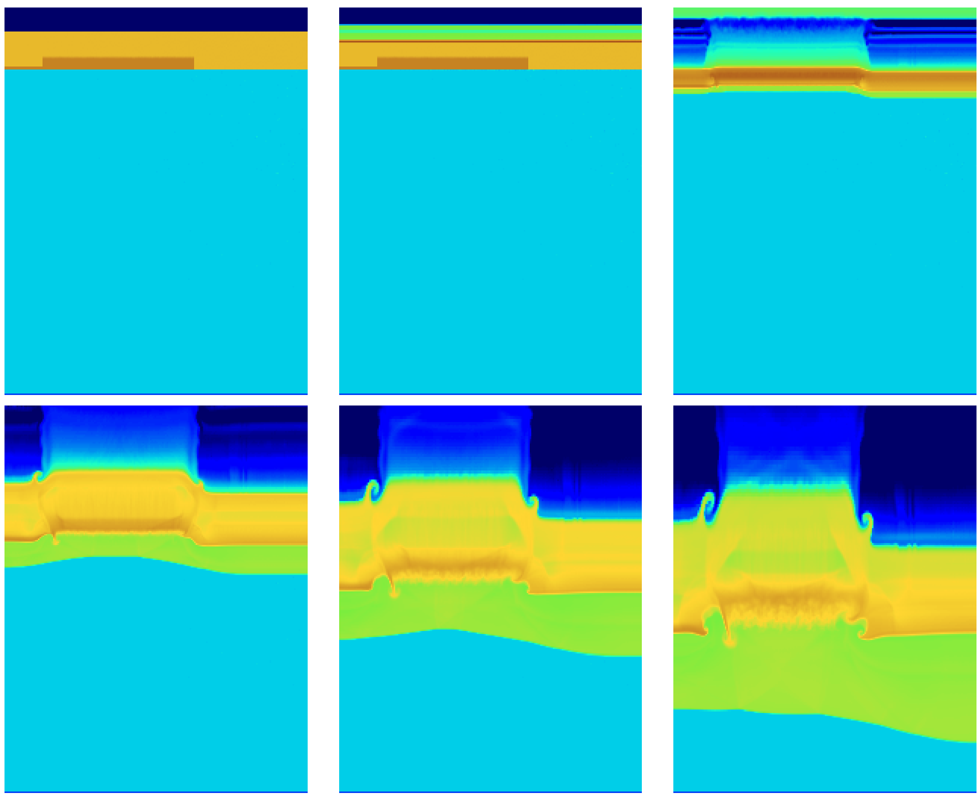


Figure 10: Mean density of the 3D simulation in the (r,z) plane. The overall form of the flow is similar to than in Figure 8, although the inner edge of the main marker layer appears considerably more diffuse. The size of the jet at the side is little changed from the unperturbed case.

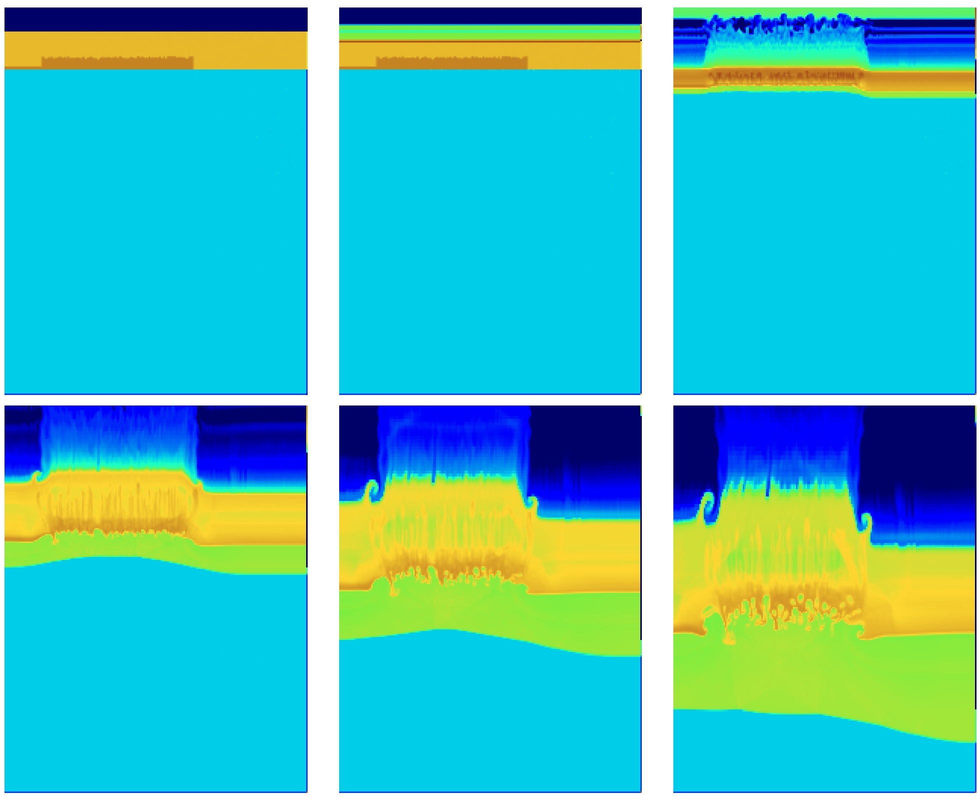


Figure 11: Density of the 3D simulation in a particular (r,z) plane. It is clear that the diffuse region at the front surface of the main marker layer in Figure 10 results from Richtmyer-Meshkov instability, which has broken the layer up by the latest frames.

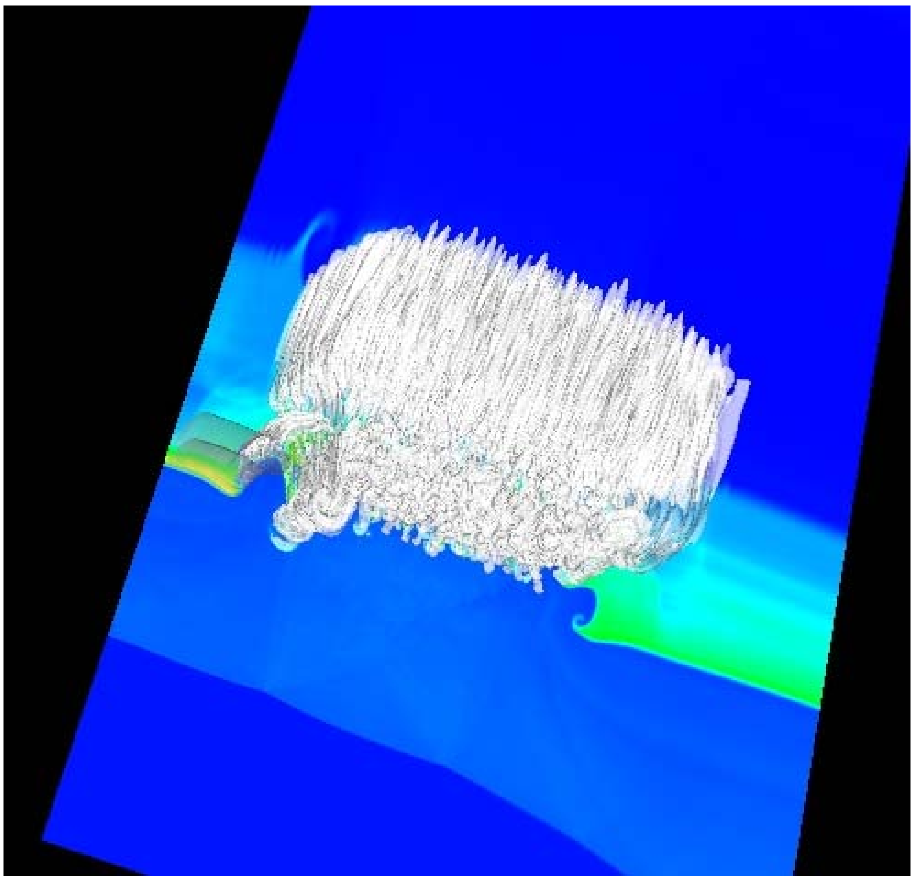


Figure 12: Perspective view of the 3D simulation, including an isosurface showing the region containing marker layer material.

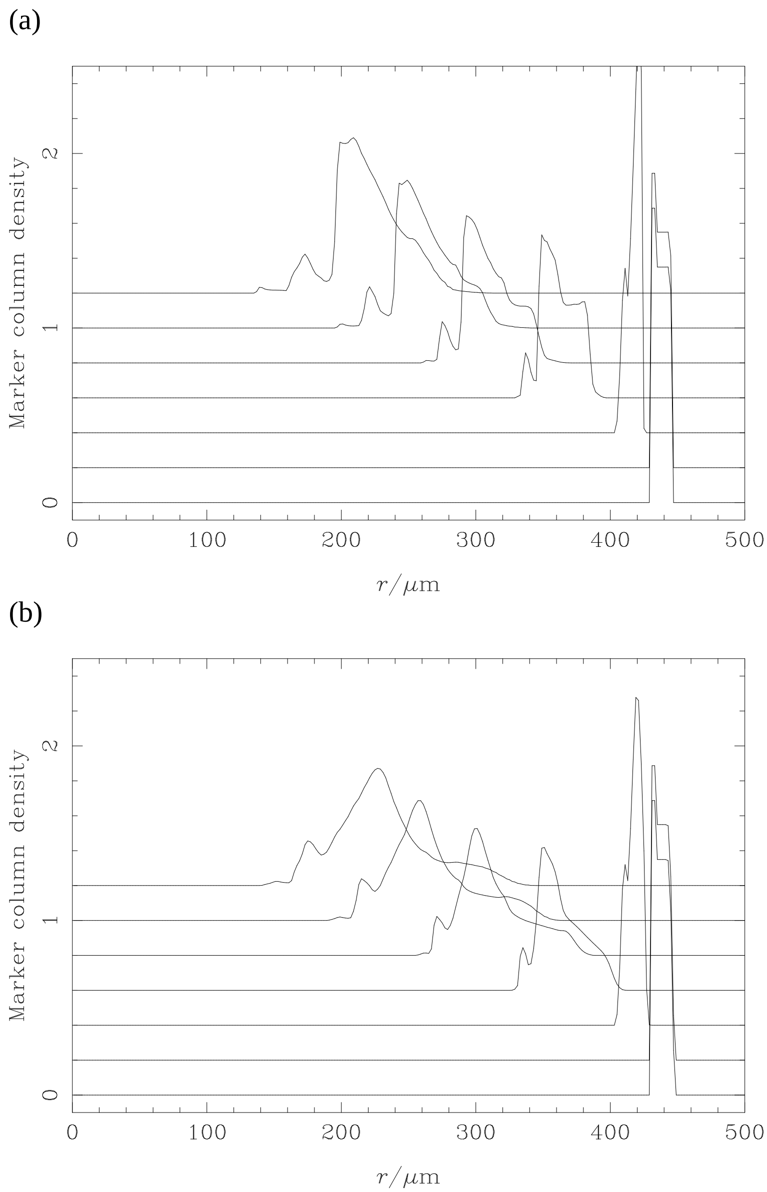


Figure 13: Mean line-of-sight density of marker layer material for (a) 2D and (b) 3D simulations. The inner shell of high density material, which results from the more rapid motion of the thinned region of the cylinder, is offset from the main band, as seen in the experimental results. The roughening of the surface in the 3D simulations broadens the main marker layer, and makes the inner surface less sharp at late times.