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# A NUMERICAL INVESTIGATION OF THE LLNL/AWE/CEA FRAGMENTATION EXPERIMENTS ON HELEN

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## ABSTRACT

High-speed fragments and their impacts on diagnostics, optics, and first wall components are of concern in high power laser facilities such as the future National Ignition Facility (USA) and Laser Mégajoule (France). In recent years, the Lawrence Livermore National Laboratory (USA), along with AWE (UK), and CEA (France) designed and conducted experiments on AWE's laser HELEN to characterize fragments generated in cylindrical targets irradiated by laser. CEA developed an original numerical strategy to model the experiments, intimately coupling two in-house codes: the one-dimensional radiation hydrodynamics code Delpor for a fine description of the laser-target interaction and the three-dimensional hydrodynamics code Hésione for a fully-coupled modeling of shock wave propagation, fracturing, and fragmentation. Simulations are run until three-dimensional fragments are visible. A comparison between experimental and numerical results is presented along with a parametric study on laser energy and target material composition.

*Key Words*: fragmentation, shock dynamics, laser, Delpor, Hésione

## 1. INTRODUCTION

In high power laser facilities, laser and x-ray interaction with matter can induce strong compressive and tensile waves that can lead to the formation of high-speed liquid and solid shrapnel. Adequate protection of the first wall, optics, and near-field diagnostics in such facilities requires a better characterization of the mechanisms that lead to fragment formation and subsequent shrapnel-induced damage of sensitive materials. Experiments [1] recently conducted on the National Ignition Facility (NIF) at the Lawrence Livermore National Laboratory (LLNL, USA) and on Omega at the Laboratory for Laser Energetics (USA) reemphasize needs for better design and modeling of actual experiments. During the former experiment, a tantalum foil was perforated by solid shrapnel; during the latter, a glass piece was shattered, apparently by a molten fragment. CEA is en route towards characterizing shrapnel formation in a series of experiments of increasing laser energies and geometrical complexities in order to gain a validated three-dimensional simulation of the disassembly of the Laser Mégajoule targets. The experiments conducted on the HELEN laser facility at AWE (UK) were designed to measure fragment size distribution as a function of laser energy and target material. Reduced data were

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implemented in CEA's IMPACTOR software, which can be employed to evaluate debris shield lifetime as a function of shot schedule.

Usually, hydrodynamics codes are run up to an early time (somewhat arbitrarily chosen) when the material has been shocked, but before fragmentation has occurred [2]. A post-processor is then used to estimate the particle size distribution, as a function of the thermodynamic state of the shocked material. Increased computing power, advanced fracturing and interface reconstruction algorithms, as well as better multi-phase equations of state, enable the Hésione/Delpor tandem to be run up to the time three-dimensional fragments are visible, for the first time in the ICF/IFE arena, and, possibly, the impact and fragmentation community. Examples of such simulations were reported in a previous paper [3], in which the Hésione/Delpor approach was compared to an LLNL model with a radiation hydrodynamics code and a fragmentation post-processor. This write-up expands upon the simulation novelties and includes a parametric study conducted to exhibit the influence of laser energy and target material.

## 2. EXPERIMENTAL SET-UP

A thick (compared to laser penetration depth) cylindrical target is irradiated by laser, causing a thin layer to be ablated over short time scales. The layer rapidly expands off the cylinder and, as a result, a shock is generated and propagates into the solid cylinder. When the shock reaches the rear surface of the cylinder, it is reflected back as a tensile pulse, which can induce fractures and fragmentation. An aerogel catcher is placed in front of the rear surface, on or slightly off the axis of symmetry of the cylindrical target. Analysis of the catchers via synchrotron radiation can yield the particle size distribution as a function of depth, which may be used to estimate the speed of the fragments. The set-up is illustrated in Fig. 1 and details can be found in Ref. [4].

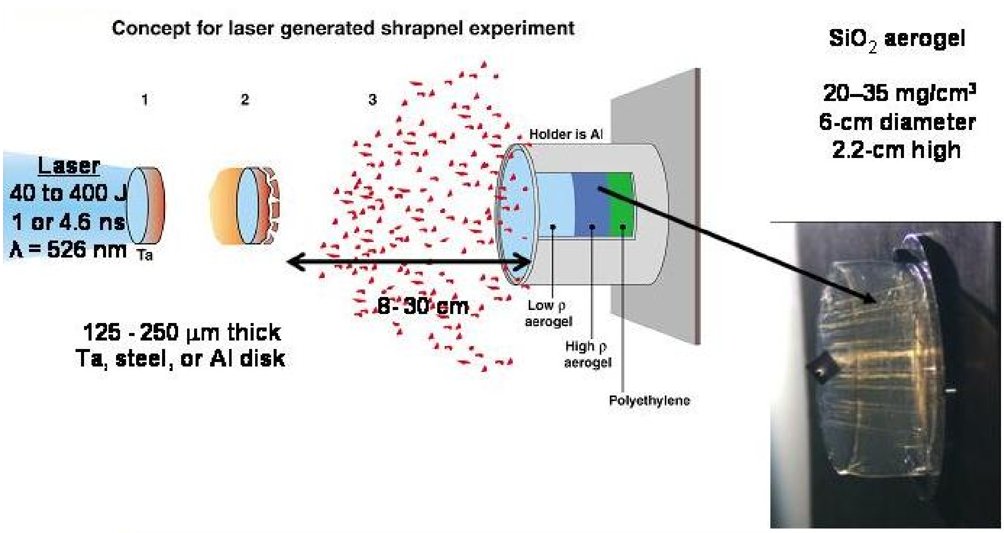


**Figure 1. Schematic of the experimental set-up and a picture of a catcher after a shot.**

An impacted aerogel is shown in Fig. 1. The paths followed by the solid shrapnel into the aerogel can be observed. The picture shows that, during that particular experiment, several fragments went through the catcher completely and what remained of the target itself impacted the aerogel.

## 3. SIMULATION STRATEGY

Typically, 1-D or 2-D radiation hydrodynamics codes are used to model laser energy deposition and initialize multidimensional shock dynamics codes, which then treat solid dynamics over the longer time scales of shock propagation [2]. A more intimate coupling was developed in the course of this study. For the rather moderate fluences of interest, radiative transfer is weakly coupled to one-temperature hydrodynamics and radiative pressure can be neglected. Operator splitting may then be employed. The hydrodynamics step is performed from the beginning of laser irradiation with CEA's code Hésione. The laser energy deposition, radiative transfer, and electronic heat conduction are not treated outside of the laser energy deposition volume. Inside that zone, and during a time slightly greater than the laser pulse duration, these phenomena are treated with the in-house 1-D radiation hydrodynamics code Delpor. For simplicity, Delpor is not called at each time step, but only at the initial time; temporal interpolation is performed to map the results onto the Hésione mesh at each hydrodynamics time step. Additionally, 1-D spatial interpolation (along the axis of symmetry of the cylinder) is performed since Delpor typically uses a finer mesh than Hésione. After the first few nanoseconds, the Delpor results are no longer employed and the Hésione code, soon afterwards, is switched to Eulerian mode, which has better fracture models. The massively paralleled simulations are run on CEA's supercomputer Tera.

The Hésione/Delpor coupling was checked by comparing a Delpor simulation to a Hésione/Delpor calculation, along the axis of symmetry of a cylindrical target and during the laser pulse duration. The agreement is excellent. A straightforward refinement would consist of performing several 1-D Delpor simulations to model the beam transverse non-uniformity. A next step, which can be envisaged with current computing power, would be to call Delpor from within Hésione, on the fly, to perform one or several 1-D simulations (almost) at each hydrodynamics time step.

## 4. COMPARISON BETWEEN NUMERICAL AND EXPERIMENTAL RESULTS

Fig. 2 shows various snapshots of the component of velocity along the target axis at various times. After the plasma has expanded sufficiently, its influence on shock formation and propagation inside the solid target is neglected and it is artificially removed from the simulation to save on computing time. The Eulerian mesh size is small enough to match the experimental resolution of small fragments. At t = 55 ns, the shock emerges and is reflected at the rear surface of the cylindrical target. The formation of a cloud of fragments then becomes apparent. Significant lateral shrapnel emission was first exhibited by Hésione/Delpor simulations.

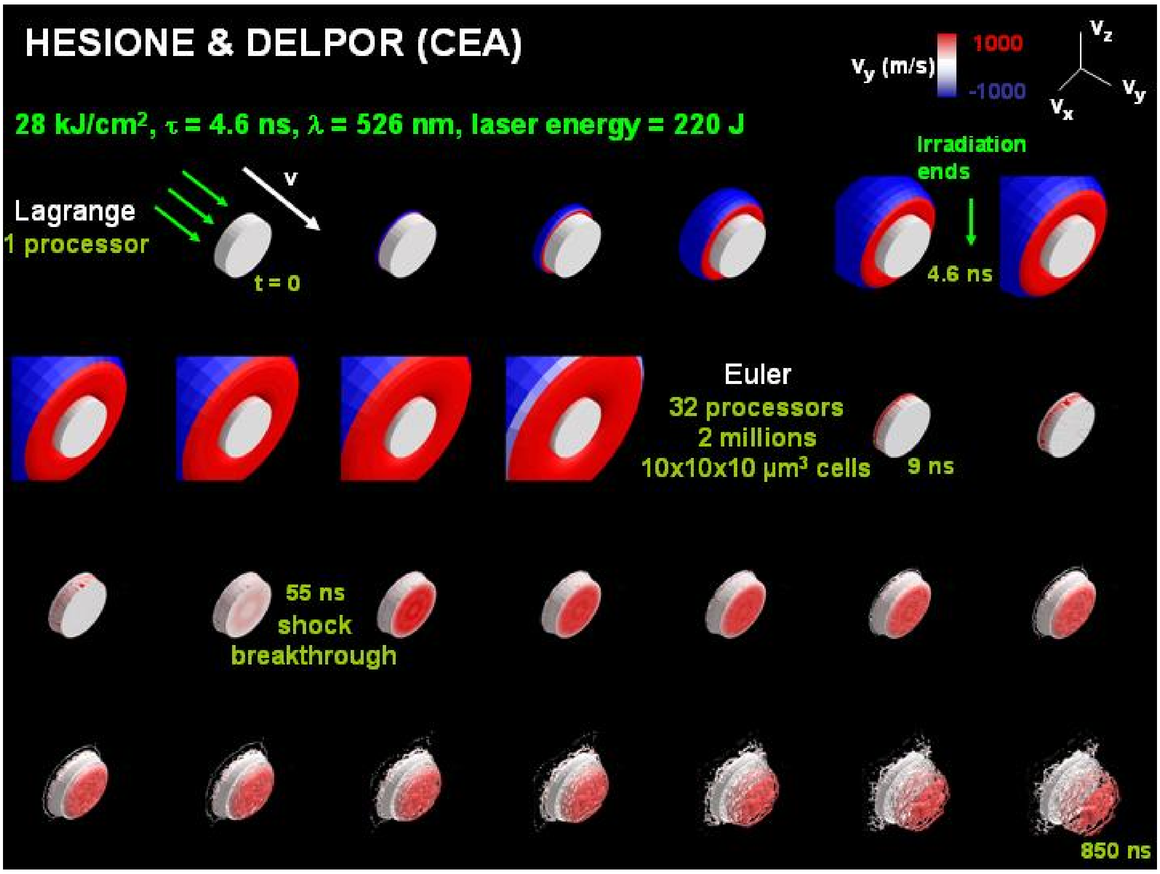


**Figure 2. Evolution of the profile of the component of velocity along the axis of the cylinder (Tantalum target, thickness is 250 microns and diameter is 1 mm.)**

When the Hésione/Delpor tandem shows that a given HELEN target is fragmented into a majority of solid shrapnel, the agreement between the numerical and experimental results is excellent for our purposes. For instance, Table I summarizes our comparison of numerical and experimental results for an iron target illuminated with 371 J during 1 ns. Liquid droplets are not collected adequately by the HELEN aerogel catcher; when Hésione/Delpor indicates that a significant fraction of liquid fragments is formed, the comparison with experimental results is not pursued.

**Table I. Comparison simulation/experiment for an iron target (371 J, 1 ns.)**

| | Hésione/Delpor Simulation | HELEN Experiment |
|---|---|---|
| Fragment volume ($mm^3$) | $1.96\ 10^{-3}$ | $1.44\ 10^{-3}$ |
| Fragment speed ($m\ s^{-1}$) | 250 – 2450 | 150 – 3000 |
| Fragment mass / target mass (%) | 10 | 7.34 |

## 5. PARAMETRIC STUDY: LASER ENERGY AND TARGET COMPOSITION

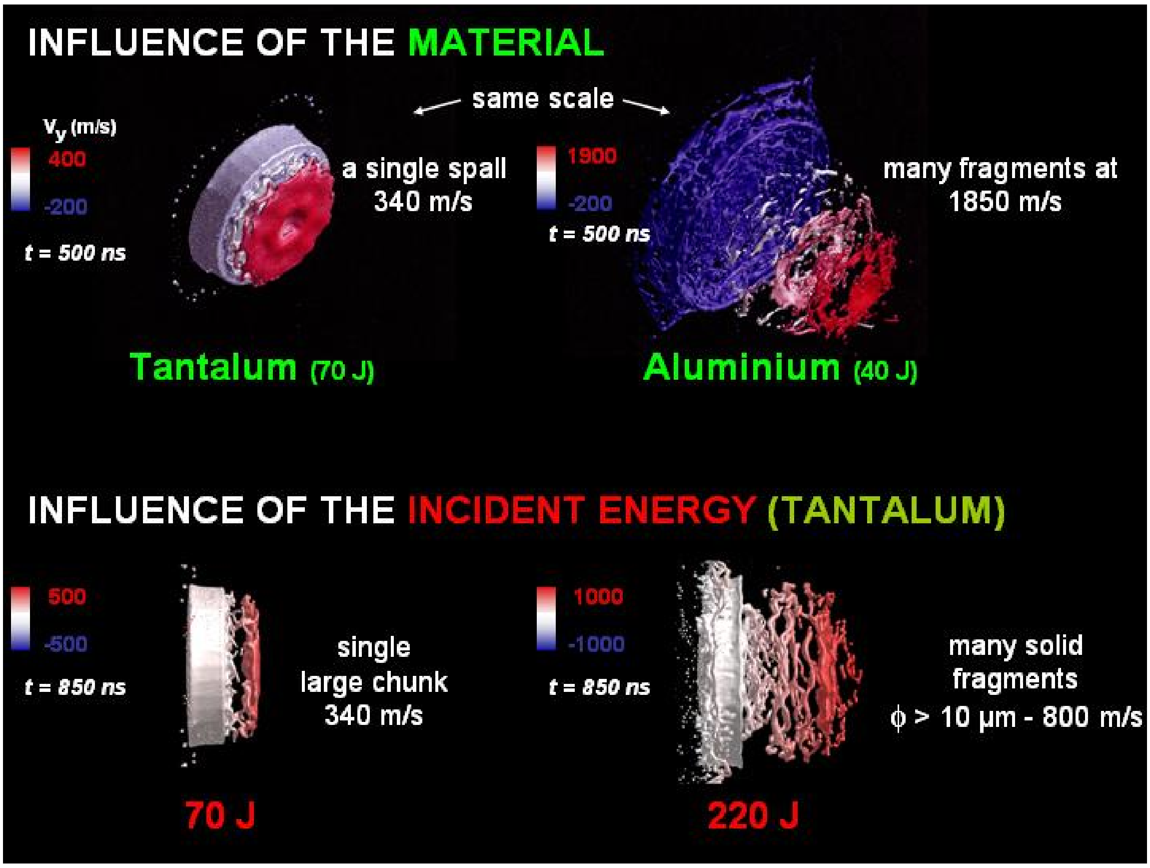


**Figure 3. Parametric study (material and incident energy.)**

Tantalum targets are irradiated at different laser intensities to illustrate different fragmentation patterns, which are shown in the lower part of Fig. 3. At low energy, the cylinder essentially fractures with an onion-like spallation pattern. At high laser energy, the fragments become gravel-like; they are smaller and faster. The fragmentation of tantalum and aluminum targets is also compared. As expected, the aluminum target breaks into a small-fragment cloud with much less laser energy than that made of tantalum, which is the tougher material.

## 6. CONCLUSIONS

The Hésione/Delpor code was successfully applied to model the fragmentation experiments conducted on Helen by the LLNL/AWE/CEA team. The Hésione/Delpor strategy (from laser-target interaction to shock dynamics to fragmentation) was validated for a range of material and laser energy. The comparison between numerical and experimental results are limited by the (in)ability to capture liquid droplets. Several experiments---designed to study geometrical effects---are being planned and the associated modeling is underway and will contribute to the development of a reliable, high-fidelity three-dimensional model of the fragmentation of high power laser targets.

## ACKNOWLEDGMENTS

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