Design Study for Diverging Supernova Explosion Experiment on NIF

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Introduction

We report on design simulations for the DivSNRT experiment, which is a spherically-diverging Rayleigh-Taylor experiment scaled to the physical conditions in core-collapse supernovae and which will be carried out at the National Ignition Facility (NIF). The simulations are done in cylindrical geometry, using the block-AMR multi-group radiative diffusion hydrodynamics codes CRASH and FLASH. We assess the sensitivity of the Rayleigh-Taylor instability growth on numerical discretization effects, variations in the laser drive energy and the manufacturing noise at the material interface. Future simulations will be used to study the self-generation of magnetic fields and how these affect the experimental outcome.

Numerical Setup

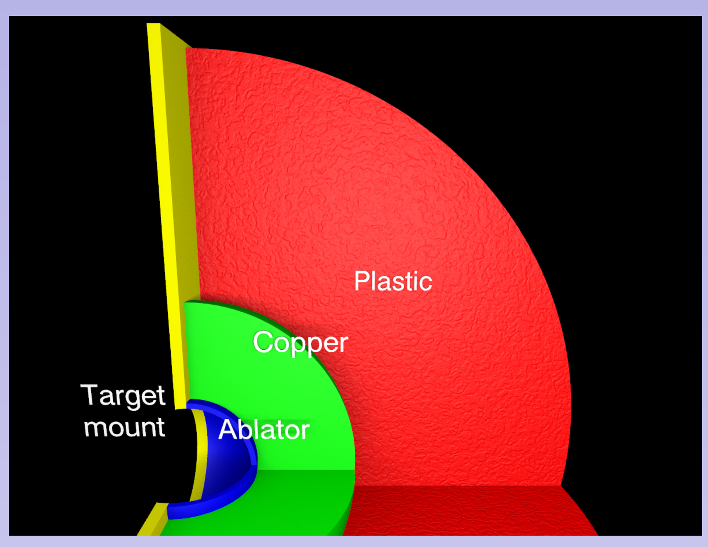

Fig. 1: Sketch of experimental setup.

Parameter	Value	
ρ(ablator)	1.410	$\mathrm{g\,cm^{-3}}$
ρ(layer 1)	8.960	$\mathrm{g\,cm^{-3}}$
ρ(layer 2)	0.959	$\mathrm{g\,cm^{-3}}$
ρ(target mount)	10.49	$\mathrm{g\,cm^{-3}}$
Δr(ablator)	25	µm
Δr(layer 1)	446	µm
Δr(layer 2)	1112	µm
Δx(target mount)	50	µm

Table 1: Basic physical parameters.

Experimental setup: Two spherical shells (copper/plastic) + ablator (plastic), mounted on a metal plate (see Fig. 1, Table 1). Masses are scaled to the 15 solar mass progenitor of Kifonidis et al. (2003).

Effect of numerical resolution: Mixing of material due to Rayleigh-Taylor and related instabilities depends on numerical resolution (Fig. 2). For practical reasons, we mostly restrict ourselves to a numerical resolution of 2 micron.

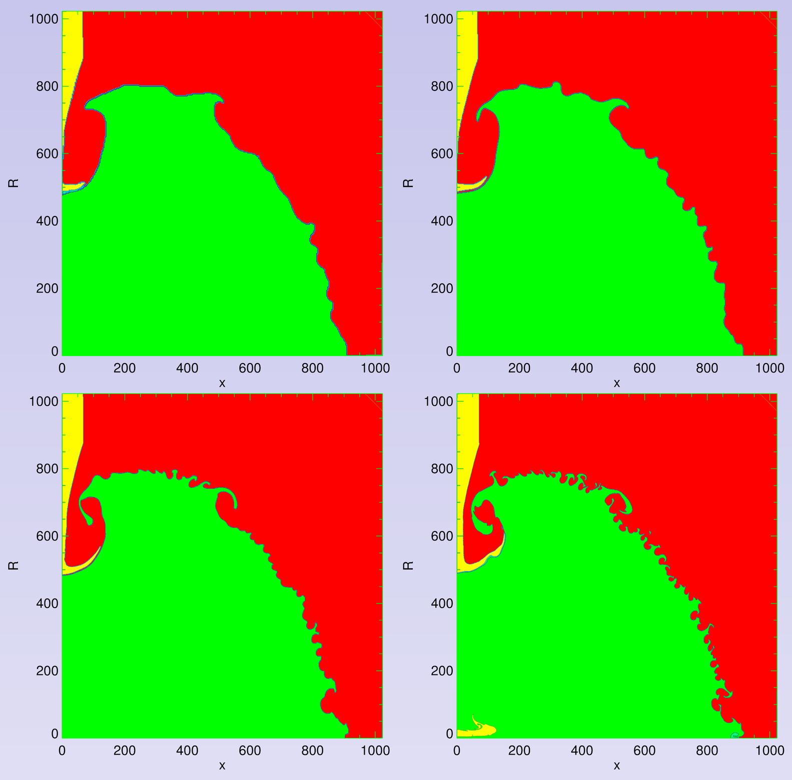

Fig. 2: Plots of the materials at $t = 100$ ns for a series of simulations with resolutions (left to right, top to bottom): $8, 4, 2$ and $1\,\mu$m. Colors as in Fig. 1.

Variation of laser energy: The peak velocity $v_{\rm peak}$ of the blast wave scales approximately as $v_{\rm peak} \sim \sqrt{P_{\rm L}}$ (where $P_{\rm L}$ is the laser power), as is to be expected.

Target mount: Inhibits the flow of material in the negative axial direction. In the region where $30° \lesssim \theta \lesssim 60°$, ($\theta$ being the angle with the z direction), the flow is reasonably spherical, with $v_{\rm lat}/v_{\rm rad} \lesssim 0.1$ (Fig. 4).

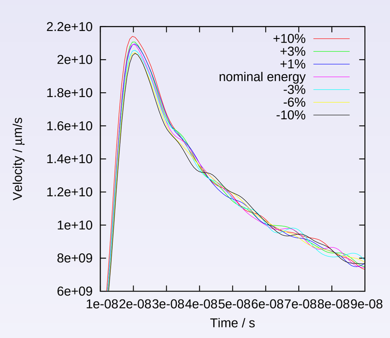

Fig. 3: Dependence of blast wave velocity on the laser energy. The peak nominal laser energy is $3.3333 \cdot 10^{13}$ W.

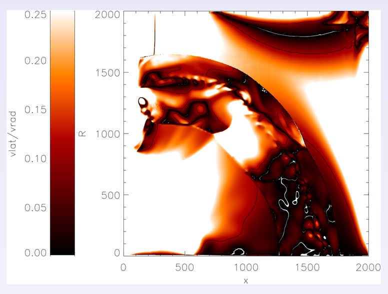

Fig. 4: Ratio of lateral over radial velocity (time-averaged). The black contour line corresponds to $v_{\rm lat}/v_{\rm rad} = 0.1$

Machining Noise

Material mixing: The process of target machining introduces small perturbations at the interfaces, which seed the Rayleigh-Taylor growth. In the following, the *mixing length* is defined as the width of the region which on average contains 5 % or more of the material of both shells, where the average goes over the region defined above (Fig. 4).

Resolvability of perturbation amplitude: We perform a series of simulations with a sinusoidal perturbation on the material interface, where the amplitude is varied. It is found that perturbations with amplitude as small as the size of one grid cell are properly resolved (Fig. 5).

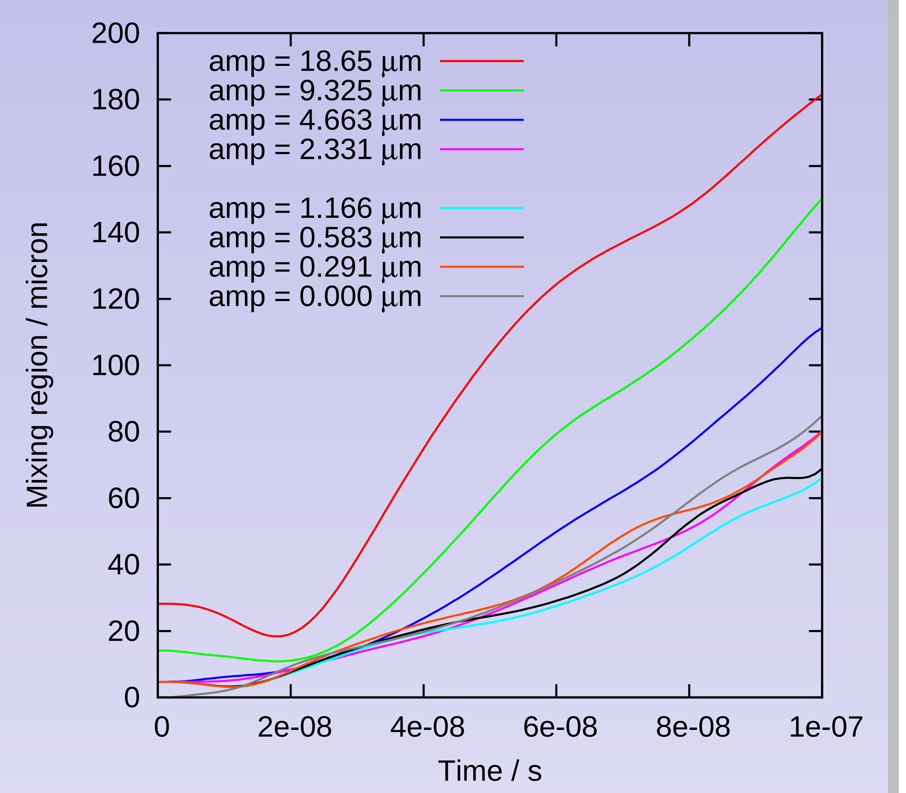

Fig. 5: Mixing length vs. time. Perturbations at the material interface, with wavelength 40 micron and amplitude "amp".

Nonlinear interactions: We consider the possibility of nonlinear interactions between perturbations on the ablator and the material interface. To this end we compare the mixing length for the case where only the ablator/the material interface contain perturbations ("$d_{\rm A}$"/"$d_{\rm I}$") vs. the case where perturbations are seeded on both layers ("$d_{\rm A+I}$", see Fig. 6). It is found that $\sqrt{d_{\rm I}^2 + d_{\rm A}^2} \approx d_{\rm A+I}$, i.e. no evidence for nonlinear interactions.

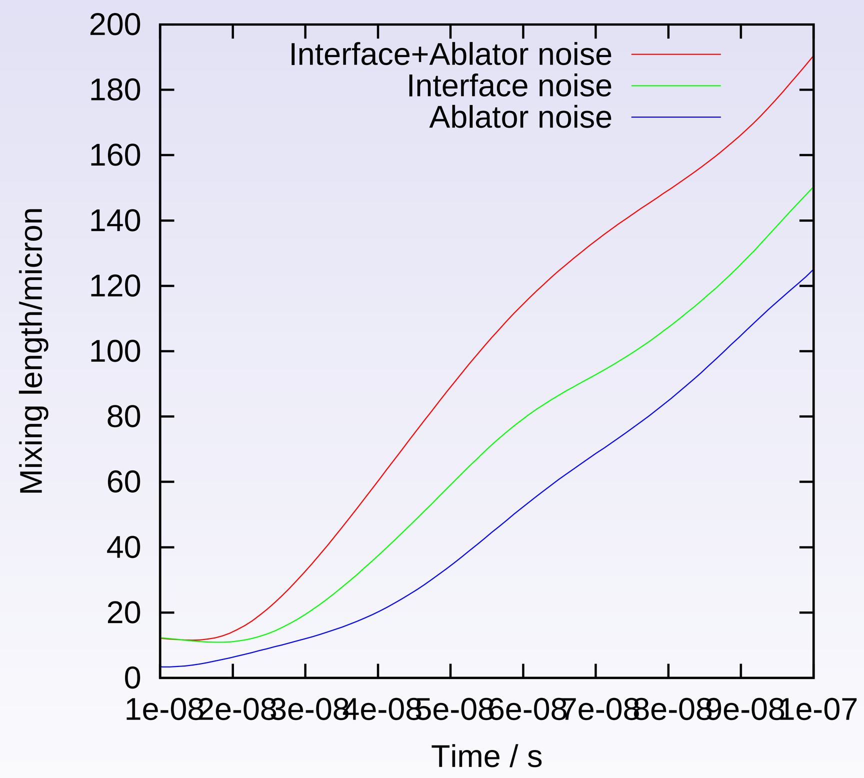

Fig. 6: As above, with perturbations on both ablator and material interfac, as well as ablator/material interface only.

Planar Target

Setup: The first few shots will be done using a planar version of the design, which consists of a cylindrical tube with radius 1500 µm, made of 25 µm ablator, 200 µm Copper followed by Br doped plastic (Fig. 7).

Copper tube: We study the option of putting the target inside a tube made of Copper, in order to better retain the pressure and achieve a more planar shock wave. Contrary to what is expected, the Copper tube does not help to reduce the non-planarity of the shock wave, even if it is made very thick (Fig. 8). Even worse, it will severely impact the diagnostics, since already a 5 µm thick layer of Copper reduces the X-ray radiography signal by half.

Self-magnetization: Magnetic fields can be generated in plasmas by the so-called "Biermann battery" mechanism when the gradients of the electron density $n_{\rm e}$ and the electron temperature $T_{\rm e}$ are not aligned. In our case, the generated magnetic fields are of the order of mG (Fig. 9).

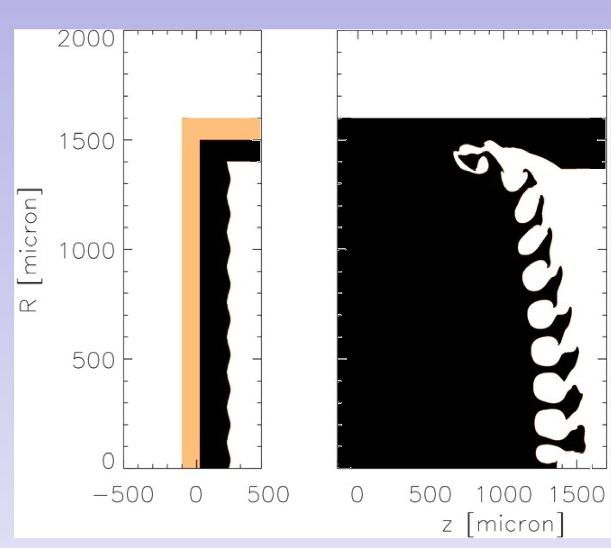

Fig. 7: Plot of the materials at 0 (left) and 100 ns (right). Significant mixing of material has occured due to the Rayleigh-Taylor growth.

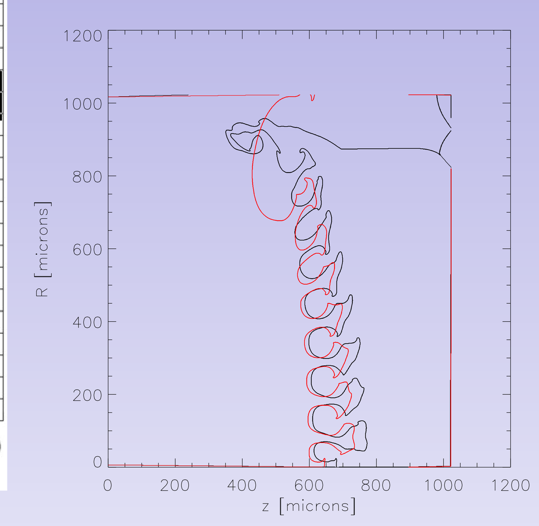

Fig. 8: Comparison of the material interface contours for the case without (black) and with 100 µm Copper tube.

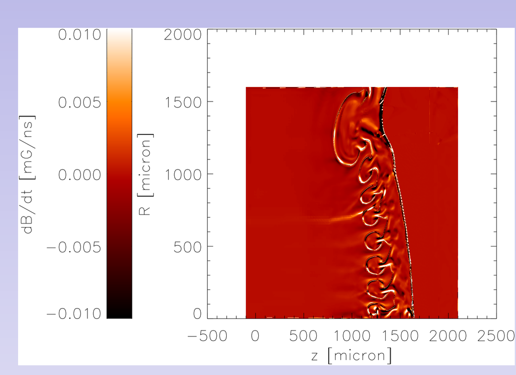

Fig. 9: *Left:* Rate of magnetic field generation $\partial \boldsymbol{B}/\partial t = \frac{ck_{\rm b}}{e}\nabla T_{\rm e} \times \nabla \ln n_{\rm e}$ due to the Biermann battery term at $t = 100$ ns.

Conclusion

We have carried out design simulation for a diverging Rayleigh-Taylor experiment relevant to core collapse supernovae using two different codes. We find that for perturbations with well resolved wavelength, the CRASH code is able to account for the effects of the target manufacturing noise as long as its amplitude is larger than a single grid cell. The present work will serve as the basis for more detailed, multi-interface target design optimization studies in the future which will also include the effect of the self-generation of magnetic fields. This research was supported by the DOE grant DE-SC0008823. The research used resources of the National Energy Research Scientific Computing Center, which is supported by the U.S. DOE Office of Science under Contract No. DE-AC02-05CH11123.