Relativistic Fluid Dynamics for Modelling Inertial Confinement Fusion

Prof. Laszlo P. Csernai, *Department of Physics and Engineering, Univ. of Bergen, csernai@ift.uib.no*
Prof. Daniel D. Strottman, *Fellow, Los Alamos National Laboratory, danstrottman@gmail.com*

Keywords: Relativistic Detonation Fronts, Volume Ignition, Radiation dominated implosion

Recent considerations [1] on the applicability of relativistic theory of time-like detonations for advances in fusion research. Experimental and theoretical efforts to achieve Inertial Confinement Fusion (ICF) have focussed on the compression of the fuel in a fuel capsule [2, 3]. An ablator layer was placed on the external surface to achieve larger compression. The outcome of these experiments was that most of the pellet broke into pieces due to Rayleigh-Taylor surface instabilities.

Already in the classical literature [4] it is mentioned that the way to avoid these instabilities is to make the compression and the detonation front a high temperature radiation dominated front, which works to smooth out the Rayleigh-Taylor (RT) instabilities propagating with the sound-speed, while the radiation is propagating with the speed of light. The radiation dominated, high temperature process must be described with relativistic fluid dynamics, wherein the pressure is not neglected compared with the energy density, and the propagation of radiative energy is described in a consistent way with all other dynamical processes.

In the present work, we concentrate on the "volume ignition" of the fuel by neglecting compression. We use a relativistic Rankine-Hugoniot description originally described by A. Taub in 1948 [5], which description was then corrected by L.P. Csernai 39 years later [6], and used since then widely in the field of relativistic heavy ion collisions [7]. The relativistic shock relations are based on the energy-momentum tensor, $T^{\mu\nu}$, and baryon charge current, N^{μ}, conservation across a hyper-surface with a normal 4-vector Λ^{μ}, where the change of a quantity a across the hyper-surface is denoted by $[a] = a_2 - a_1$:

$$[R^{\mu}] = [T^{\mu\nu}\Lambda_{\nu}] = 0 \quad \text{and} \quad [j] = [N^{\mu}\Lambda_{\mu}] = 0. \qquad (1)$$

These conservation laws lead to the relativistic shock or detonation equations for the energy density, e, pressure, p, and generalized specific volume, $X = (e + p) / n^2$: $\quad j^2 = \Lambda^{\mu}\Lambda_{\mu}\, [p] / [X]$, and $[p](X1+X2) = [(e+p)X]$. (2)

This description treats detonations also across hypersurfaces with time-like normal vectors ($\Lambda^{\mu}\Lambda_{\mu} = +1$), and therefore has the name time-like detonation, which actually means simultaneous volume ignition. Taub's description could be applied to "slow", space-like fronts only.

The presented model became relevant and applicable to the recently published ICF experiments performed at the National Ignition Facility (NIF). To achieve a rapid volume ignition the needed total ignition energy should be radiated inward in a time interval, $t_{in} < 1$ or $t_{in} << 1$ (in units of $[R_0/c]$).

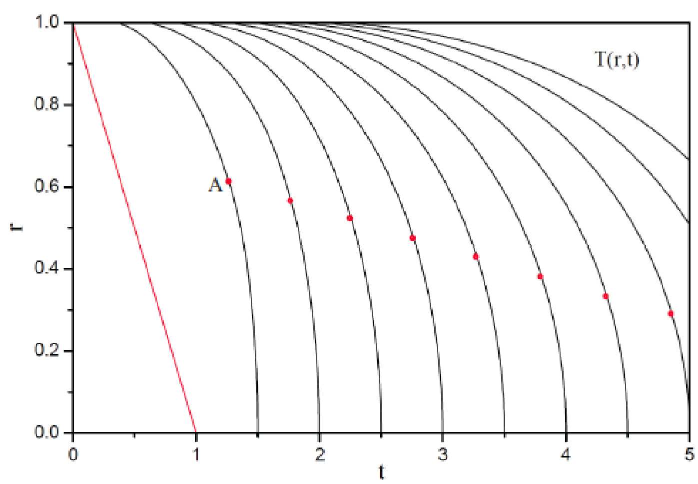

Fig. 1 Acceleration of the detonation fronts, characterized by T = const. contour lines, due to radiation from the outer surface at $r = 1$ inwards to $r = 0$. The heating by radiation leads to a smooth transition from space-like to time-like front at the red points A, where the front propagates with the speed of light.

The longer is tin the greater probability we have for RT instability. If $t_{in} > 3$, the RT instability can hardly be avoided, and the possible volume ignition domain size becomes negligible. Thus for an R0 = 3 mm pellet the ideal irradiation time for volume ignition would be $t_{in} < 10$ ps (while for an $R_0 = 30$ cm target it would be $t_{in} = 1$ ns).

References:

[1] L.P. Csernai and D.D. Strottman, in preparation.
[2] O.A. Hurricane et al. Nature, 506, 343 (2014).
[3] H.-S. Park et al. Phys. Rev. Lett 112, 055001 (2014).
[4] Ya.B. Zel'dovich and Yu.P. Raizer: *Physics of Shock Waves and High-Temperature Hydrodynamic Phenomena* (Nauka, Moscow, 1969)
[5] A.H. Taub, Phys. Rev. 74, 328 (1948).
[6] L.P. Csernai, Zh. Eksp. Teor. Fiz. 92, 379 (1987); Sov. JETP 65, 216 (1987).
[7] L.P. Csernai: *Introduction to Relativistic Heavy Ion Collisions* (Wiley, Chichester, 1994).