Fluid simulations
of exploding pusher experiments

Stefano Atzeni

Dipartimento di Scienze di Base e Applicate per l'Ingegneria (SBAI)
Università di Roma “La Sapienza” and CNISM

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Collaborators
- A. Marocchino, A. Schiavi (Dip. SBAI, U. Roma “La Sapienza”)
- G. Inchingolo (MS student, U. Pisa) and G.M. Rossi (MS student, “Sapienza”)

- M. Rosenberg, R. Petrasso

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Refs:
YOC (expt vs DUED) and Knudsen number: fluid, kinetic, intermediate regimes (*)

DDn YOC vs Knudsen number

Rosenberg et al (PRL 2014)
- D³He filled glass shells
- $R = 430 \, \mu m$, $\Delta R = 2.3 \, \mu m$
- fill density 0.4 – 3.2 mg/cm³
- OMEGA d.d. square pulse
- $E_L = 14.6 \, kJ$ in 0.6 ns

other OMEGA:
- D₂ filled glass shells
- 61085 (Rindernecht slides 2/20/13)
- 30981 (Kurebayashi et al, PoP 2005)
- 54853 (Shvydky, SIWorkshop 2010)

Le Pape et al (PRL 2014)
- D₂ or DT filled, doped CH shell
- $R = 1055 \, \mu m$, $\Delta R = 120 \, \mu m$
- D (DT) density 6.33 (7.66) mg/cm³
- NIF, rad. drive (2 steps),
- 900 kJ, 325 TW, $T = 290 \, eV$

the rest of the presentation is restricted to fluid and intermediate regimes
Simulations with the fluid code DUED
“A standard ICF code”

Is really everything standard, validated and established in the area of ICF fluid codes? What about red items below?

• 2D, mainly used as 1D for the present study
• Lagrangian hydrodynamics, with artificial viscosity
• 2 temperatures, e-i exchange
• flux-limited e-conductivity (or non local e-transport, Schurtz et al, PoP 2000)
• flux-limited ion conductivity
• ion viscosity (1D only)
• our EOS
• multi-group flux-limited radiation diffusion
• LTE or nonLTE opacities (in-house modified SNOP code by Eidmann et al.)
• nuclear reactions
• charged fusion product multigroup diffusion (not used here)
• Monte Carlo neutron transport
• 2D or 3D laser raytracing (2D used here), with inverse bremsstrahlung absorption
Ion viscosity in ICF fluid codes

- Shock thickness $\approx$ ion mean free path $\lambda_{ii}$
- In most ICF situations $\lambda_{ii} \ll \Delta R$ (mesh size)
  $\Rightarrow$ artificial viscosity needed to stabilize inviscid hydrodynamics;
  all ICF codes include artificial viscosity;
  a few also include ion viscosity (e.g. LASNEX, DRACO, IMPLO=old 1D-DUED)

- When $\lambda_{ii}$ comparable to mesh size, ion viscosity is effective and artificial viscosity can be gradually switched off

- However, as $\lambda_{ii}$ approaches velocity gradient scale-length a fluid approach is no more adequate; ion momentum transfer becomes non local.

  To save causality, momentum transfer must be limited $\Rightarrow$ flux-limited viscosity
  (just as flux-limited electron conductivity), but what about the flux limiter ($vfl$)?

\[
\mu = \frac{\mu_i}{\max(1, \xi)}, \quad \xi = \frac{|\mu_i (\partial u / \partial r)|}{(vfl) p_i}
\]
At moderate Knudsen numbers (0.3 – 3), ion viscosity

- smooths shocks,
- reduces return shock strength,
- reduces peak ion temperature, reduces yields

Also: $T$, Yield, etc. become independent of zoning

D$^3$He fill density: 3.2 mg/cm$^3$; $K_n = 0.3$
viscosity flux limiter dramatically affects burn profiles

Limiter in the range 0.2 – 0.5 produces moderately peaked profiles, as inferred by neutron penumbral imaging

Simulations always underestimate size of burning region (next vg)

• Overall hydro unaffected by limiter
• reaction yields unaffected
As initial density increases (and *Kn decreases*) YOC raises, but
- burn radii disagree
- simulated ion temperatures become smaller than measured ones

M. J. Rosenberg *et al.*, PRL. **112**, 014022 (2014)

Kinetic physics or something else?

Discrepancies simulations – observations at low–intermediate $Kn$:  
- (slightly) lower ion temperature (in the sims)  
- smaller burn region  
- shorter burn duration  
- higher ratio DDn/D$_3^3$He yield

really due to kinetic effects (in the shocked gas)

or, instead, to

1) modeling of drive?  
2) preheating?  
3) diagnostic interpretation?

1) Drive is usually “adjusted”  
2) Hot electrons neglected  
3) E.g., do we all measure neutron-averaged temperature in the same way?
Kinetic physics or something else?

1. modeling of drive?
2. preheating?
3. large scale 2D effects? [Assuming RTI does not affect such low aspect ratio implosions]

1. and 2.: simulation of reference EP_0044 case (3.2 mg/cm³) with some preheating and non-local electron transport (and again laser power adjusted to get observed absorption), give
   • YOC_DD = 0.55,
   • YOC_DHe = 0.8,
   • R_burn = 70–75 µm,
   • R_shell = 125 µm,
all in better agreement with measured values,
but
• ion temperatures a bit lower than in previous sims,
• worst ratio of yields
Neutron-averaged temperatures

Current DUED simulations (*):

**Monte Carlo generated spectra, taking into account both ion thermal motion and fluid motion** (and scattering, irrelevant for the present targets)

We measure the averaged temperature from the FWHM of the spectrum (*note that since the time- and space-integrated spectrum is not Gaussian, the FWHM is no more proportional to rms deviation*).

For case EP_0044 exploding pusher we obtain $T_i \approx 10 \text{ keV}$, (8.5 keV neglecting fluid motion(#{})). From the spectrum rms we would obtain about 12 keV.

(#) An approximate estimate of fluid motion effects on temperature measurement

\[ T_{DT} \simeq T_{DT\text{no motion}}(1 + 0.176u_7^2/T); \quad T_{DD} \simeq T_{DD\text{no motion}}(1 + 0.14u_7^2/T), \]

with temperatures in keV and \( u_7 = u/10^7 \) m/s.

(*) SA and GM Rossi, *EPS 2015*, P1.203, and to be published
2D long scale-length effects unlikely to drastically change the overall picture

- identical yields, identical burn histories
- same as in 1D with same physical model
- same size of the hottest region (different shape)

uniform spherical irradiation, radial rays (power adjusted to give same absorption as 1D with 2D ray-tracing), flux-limited e-conduct. (0.07), artificial viscosity
Low-$Kn$ limit:
radiation driven exploding pusher [Le Pape et al. (*)]
well reproduced by DUED (#)
(= DUED seems nearly OK in the fluid purely fluid limit)

(*) PRL 112, 225002 (2014)]

DUED simulations
YOC = 1; burn history, neutron burn radius, compressed shell radius, $\rho R$ in agreement with experimental data (and HYDRA simulations). Neutron averaged temperature 10% lower.
With slightly different drive, temperature OK, but YOC = 0.6, and slightly stronger compression

(#) with drive properly adjusted: DUED cannot simulate hohlraums; we impose radiation spectrum at the outer boundary
Conclusions

Fluid simulations

- reproduce overall implosion dynamics (collapse time, implosion velocity) of exploding pushers, once the absorbed power is adjusted
- not surprisingly, cannot reproduce the lowest density imploded cores ($Kn >> 1$)
- at moderate $Kn$ (0.3–3) reasonable agreement on integrated quantities ($YOC = 0.3–0.5$, temperatures within 15%), still large difference on burn radii, strong model dependence of burn profiles, wrong DD/D$^3$He yield ratio (worst as YOC improves) [note that codes with ion mixing have better YOC, but even smaller burn radii]

Just kinetics, or are $Kn$ something else? What about drive?

- At low $Kn$ very good agreement with experiments. But (not discussed here for lack of time) why codes cannot reproduce the measured difference between DD and DT averaged neutron temperatures in DT implosions (Hurricane et al., Nature (2014))?