A few studies of symmetry and stability of inertial fusion targets

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Summary

• Simulation code, philosophy and methods

• Deceleration-phase RTI: principle
  - Simulation results
    • Linear stage
    • Nonlinear, single wavelength (Legendre mode)
    • Nonlinear, multiwavelength
    • Nonlinear, localized perturbations (divots)

• A very short summary on symmetry and stability issues for HiPER targets
our (Rome group) DUED code, a fluid code for ICF target simulations: “philosophy”

3-D fluid codes now feasible (e.g., HYDRA at LLNL, Livermore)
However, only available at a few sites, use restricted,
medium-resolution runs require hundred of hours on powerful parallel computers
==> for validation of point designs only

==> flexible, fast, portable code needed for
• physical insight
• wide parametric studies (hundreds of runs)
• preliminary test of new concepts

==> DUED code
• 2-D
• for each “basic process”, simplest model still adequate to semi-quantitative studies
• each model cross-checked vs better models (on the same code, on other codes, ..)
• general purpose (i.e., same code for implosion, instabilities, ignition, shock-waves, ...)
• flexible, highly interactive output
DUED Code (*) physical model model

• 2D Lagrangian fluid scheme + rezoning
• 2 – temperatures +
• single group diffusion ==> 3-temperatures
• multigroup diffusion
• real matter equation of state
• collisional transport
• LTE or non-LTE opacities (MPQ’s SNOP code)
• laser-matter interaction: ray tracing; inverse-bremsstrahlung absorption
• ion beam-matter interaction (binary collisions, deterministic)
• hot-electron matter interaction (binary + collective; Monte Carlo)
• thermonuclear fusion reactions
• non-thermal fusion reactions of
  • fusion products T(1 MeV) and ³He (0.8 MeV)
  • D, T, and ³He scattered by neutrons
• fuel burn-up (D, T, ³He)
• multi-group diffusion of charged fusion products of DD, DT, D ³He e
• Montecarlo neutron transport:
  • Elastic scattering, (n,2n), ³He(n,p)T, (n,g)
  • diffusion of neutron-knocked ions (several energy groups each)

(*) S. Atzeni and coworkers (1986 – 2010)
Drawback of the Lagrangian approach: mesh distortion

Cured by an *automatic* rezoning / remapping algorithm

New mesh generated automatically
By a variational algorithm (according to some user defined criteria)

Physical quantity remapping globally conservative, second order accurate

(see pictures:
left: before rezoning
right: after rezoning)

Main drawback: intrinsically sequential

earlier version: S. Atzeni and A. Guerrieri, 1992, 1993
key issue for central ignition: Rayleigh-Taylor instability

deceleration-phase instability at the hot spot boundary (2D simulation)
Deceleration phase Rayleigh-Taylor instability

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Deceleration-phase Rayleigh-Taylor instability

- standard picture
  (Bell, Plesset, 1950’s + Lindl, 1995)

\[
\gamma = \sqrt{ak} \sqrt{1 + kL_m}
\]

linear growth rate

\[a = \text{acceleration}\]
\[k = l / R_h\]
\[l = \text{spherical mode number}\]
\[L_m = \text{minimum density scale length } \rho / \nabla \rho\]

- in ICF, dense shell ablated by heat flux and fusion \(\alpha\)-particles from the hot spot
  (Guskov and Rozanov 1976, Atzeni and Caruso 1981; 1984)

- Lobatchev and Betti [PRL, 85 (2000)]:
  ablation stabilizes dp-RTI, just in the same way as at a radiation/laser-driven front

\[
\gamma = \alpha \sqrt{ak} \sqrt{1 + kL_m} - \beta ku_a
\]

\[\alpha = 0.95; \beta \approx 1.5\]
\[k = l / R_h\]
\[u_a = \text{ablation velocity}\]
**Inner surface ablation velocity, \( u_a \)**

**Role of electron thermal conductivity and \( \alpha \)-particle transport**

\[
  u_a = \frac{d m}{4 \pi R_h^2 \rho_s} = \frac{d m}{d t} \quad \text{ablation rate}
\]

\[
  \frac{d m}{d t} = \frac{W_e + W_\alpha}{C_v T_h} \quad \text{power from hot spot to shell: thermal conductivity + \( \alpha \)-particles}
\]

\[
  \frac{d m}{d t} = \frac{1}{4 \pi R_h^2 \rho_s} \quad \text{dense shell density}
\]

\[
  R_h \quad \text{hot spot radius}
\]

\[
  \rho_s \quad \text{hot spot density (g/cm\(^3\))}
\]

\[
  T_h \quad \text{hot spot temperature (keV)}
\]

\[
  C_v \quad \text{specific heat}
\]

• from simple model, using dimensional arguments

\[
  u_a \approx 1.6 \times 10^4 \left( \frac{\rho_h}{\rho_s} \right) \frac{T_h^{5/2}}{\rho_h R_h} + 1.6 \times 10^7 f \left( \frac{\rho_h}{\rho_s} \right) \rho_h R_h T_h \quad \text{cm/s}
\]

• in a typical target

\[
  \propto R_h^{-0.2}
\]

\[
  \propto R_h^{-3}
\]

(confirmed by simulations; see later; the effect of ablation on RTI can be tested by switching transport processes on/off)
High resolution 2D study (DUED code) of deceleration-phase RTI of a NIF-size (or LMJ-size) capsule

radiation driven NIF capsule

1D SARA(*) simulation (courtesy of J. Honrubia)

1D flow features (full DUED physics model)

\[ \text{motion of front through the fuel: ABLATION} \]

(only a few Lagrangian trajectories shown here)

for \( 200 \leq t \leq 290 \) ps

- deceleration \( a = 2 \rightarrow 5 \times 10^{17} \) cm/s\(^2\)
- ablation velocity \( u_a = 0.7 \rightarrow 1.6 \times 10^6 \) cm/s
- \( L_m = \min(\rho/\nabla\rho) \approx 0.4 \mu\text{m} \)

at \( t = 250 \) ps:

\[ R_h = 37.7 \mu\text{m} \]
unstable layer \( 37.2 \leq r \leq 37.8 \mu\text{m} \)
a) linear evolution

(S. Atzeni and M. Temporal, PRE, 2003;
2D simulation (starts at $t_{1D} = 17.02$ ns) with imposed mesh deformation around the shell inner surface

\[ \delta R(r, \theta) = P_\ell [\cos(\theta)] A_0 e^{-\ell |r-r_0|/r_0} \]

here
\[ A_0 = 2 \, \mu m \]
\[ l = 48 \]

in the linear RTI study
\[ A_0 = 10^{-3} \, \mu m \]
\[ l = 4, \ldots, 200 \]

Meshes much finer then this used to test accuracy of results

Problems also run with Initial perturbations centred at different locations and with different shape
• without any transport process

1D flow vs full physics model

initially cryogenic fuel

hot spot front = burn wave front

we only plot selected Lagrangian curves; actual simulation achieves much better resolution
**no conduction, no reactions**  $$\implies$$  **Classical RTI**  

**with conduction, no reactions**  $$\implies$$  **ablation** (with constant $a, L, u_a$)  

$$\implies$$  **growth reduction**,  
in agreement with modified-Takabe formula

\[
\gamma = 0.95 \sqrt{\frac{ak}{1 + kL_m}}
\]

\[
\gamma = 0.95 \sqrt{\frac{ak}{1 + kL_m}} - 1.5ku\]

N.B.: $a$, and $L_m$ take different values in the two cases

**NEW FEATURES APPEAR;**  
these are  more apparent when fusion reactions and $\alpha$-particle diffusion are included  
$$\implies$$  see next viegraphs
Ablation => advection of perturbation into the ablated fuel.
RTI modes peak inside the hot-spot and move relatively to the hot spot boundary (this is largely independent of the initial location of the perturbation).

perturbation peaks at \( R_p < R_h \)

\[
\Delta R = R_h - R_p
\]

- grows with time
- decreases with \( l \) (up to \( l = 96 \))

(simulation with thermal conduction, DT reactions, \( \alpha \)-diffusion)
• In classical RTI modes are “frozen” in the fluid, growth is the same at any fluid element
• In ablative RTI modes move relative to the fluid

amplitude of perturbation at fixed lagrangian location

simulation with
• thermal conduction off;
• fusion reactions off
• Perturbations grow classically in the unstable layer;
• Growth reduction results from advection: ablated elements soon exit the unstable layer

Element “deep” in the gas: very weak growth

INSTABILITY GROWTH
What should one measure?
What is relevant to ICF?

• “global growth” growth of the peak of the perturbation
• growth at hot spot front, in general different from global growth
• Hot spot $\rho R$ perturbation?
• **Global** growth in agreement with modified-Takabe expression for $l \leq 80$, but not at higher $l$.

• Growth at the hot spot surface smaller

• Relative hot spot $\rho R$ perturbation grows at intermediate rate

**GENERAL RESULTS:**

• Significant ablative stabilization

• No quantitative agreements with models
• An igniting capsule is less unstable than a non-igniting one, despite larger acceleration

• Reducing thermal conductivity increases RTI growth

Triangles here refer to “global growth”, as defined previously.
b) single-mode nonlinear evolution

Single mode nonlinear evolution

• Saturation

• Bubble and spike evolution

• Spikes reduce hot spot size

• Ignition delayed with increasing initial perturbation
Movie: Initial perturbation with $l = 16$; amplitude 4 µm
Ion temperature map evolution
Initial perturbation with $l=16$; amplitude 4 µm
Density and temperature maps (times: 225, 250, 275 ps)
Initial perturbation with $l = 16$; amplitude 4 $\mu$m

Density and temperature maps (times: 300, 325, 340 ps)
c) multi-mode nonlinear evolution

(S. Atzeni, A. Schiavi and M. Temporal, Plasma Phys. Contr. Fusion 2004,

and more recent, unpublished materials)
multimode perturbations

Different spectra with modes 2 - 72 with random amplitudes

A few, general, qualitative results:
  • Short wavelengths still clearly visible close to ignition
  • Hot spot size reduced by penetration of spikes
  • Ignition and gain delayed
Perturbation with even modes \( l = 2, 4, \ldots, 72 \)

Density and temperature maps around ignition
As the amplitude of the perturbation (at the end of the coasting stage) increases

- Gain decreases (same trends for different spectra)
- Ignition is delayed
Rayleigh-Taylor instability hinders hot spot formation and ignition (multimode perturbation with rms amplitude at the end of the coasting stage = 1.5 µm)

Ion temperature (eV) map evolution
RTI limits the size of the hot spot

Below: density maps at the same time (290 ps) for cases with different perturbation amplitude:
The size of the hot spot [see the 10 keV (red) and 5 keV (orange) contours] is reduced by the penetration of the RTI spikes.
A too large initial corrugation amplified by RTI, makes hot spot formation impossible

Ion temperature (eV) map evolution
d) single-mode, non linear 3D evolution

(A. Schiavi and S. Atzeni, Phys. Plasmas, 2007)
- what about individual, large amplitude perturbations? [why interesting? asymptotic evolution essential ingredient of models for weakly non linear evolution (e.g., Haan, 1989)]

• planar geometry: Layzer (1955)
• spherical: Clark & Tabak (2004, 2005); ablation NOT included; selfsimilar reference flow
  Goncharov and Li (2005): ablation not included
• planar, ablative: Sanz and Betti

• HERE:
  Spherical,
  ICF igniting shell,
  transport processes included ==> ablation, ignition (conductivities, e-i exchange, multi-group $\alpha$-particle diffusion)
Can we study 3D perturbations with a 2D code?

(question: when 2D acceptable?)
Single mode, 3D Gaussian spike perturbation

![Graph and diagram showing 3D Gaussian spike perturbation with FWHM labeled as 5 FWHM.](image)
Movie:
evolution of a fan of spikes (Classical case)
Movie:
evolution of a fan of spikes (Fusion case)
Spike evolution: classical vs fusion: ablation induced growth reduction (Fusion)
spikes at stagnation (large initial amplitude, different $\sigma$): ablative stabilization for small $\sigma$
bubbles at stagnation
ablation less effective than on spikes
\( I = 36 \) bubbles with large initial amplitude
Time evolution of **spike** amplitudes - classical vs fusion

===> ablative stabilization of small-scale divots

(large initial amplitude ($10^{-2}$), in order to observe non linear evolution)
spikes vs bubble, classical vs fusion (\(\sigma = 1.5^\circ\))

classical: spikes larger than bubbles
fusion: bubbles larger than spikes
2D vs 3D, Classical late evolution:
2D spikes slowed down by KH mushrooms
3D spike (spike on axis) nearly unaffected;
anyhow,
3D effects only important for very large amplitude perturbations.

\[ t = 210 \text{ ps} \quad t = 300 \text{ ps} \]
Conclusions

Linear stage:
• Ablative stabilization confirmed; clear qualitative picture
• Different possible measures of RTI growth, agreement with models questionable

Nonlinear, multimode evolution
• Hot spot size limited by spike penetration, small wavelength features still present at ignition (not much swallowing)
• RTI delays ignition, decreases gain

Localised perturbations (divots)
• 2D vs 3D: 3D effects only important in the deep non-linear stage
• Ablation reduces growth of both spikes and bubbles
• For large amplitude initial perturbations:
  spike growth substantially reduced: the smaller the divot width $\sigma$, the smaller the non linear growth; bubbles growth reduced less effectively

Questions/issues
2D vs 3D, detailed understanding of stabilizing and destabilizing mechanisms, interaction RMI-RTI, … non local transport, …
A few pictures on
Symmetry and stability studies
of HiPER targets

S. Atzeni for the HiPER Work Package 9
Irradiation geometry

Energy balance 94%,
Illumination asymmetry $I_{\text{rms}} = 0.15\%$
Main low l-modes: 12, 8 and 10 (< 0.004)

L. Hallo et al., 2009; Feugeas et al.
Implosion driven by 48 beams

Imploding capsule asymmetry

L. Hallo et al., 2009
Asymmetries at ignition time are large!

$t = 11.450 \text{ ns}; 1 \text{ ps after start of ignition pulse}$

S. Atzeni & A. Schiavi, 2009
Same beam non-uniformity as before + 10 micron target horizontal displacement!

S. Atzeni & A. Schiavi, 2009
Instability at ablation front

Weakened by using adiabat shaping

A. Amarocchino, S. Atzeni, A. Schiavi, 2010, to be published
Adiabat shaping drastically reduces RTI growth

Adiabat shaping RX2 technique
(Anderson & Betti, 2004)

Atzeni, Schiavi, Bellei 2007
Output of the analysis:
- tolerance of 1D target to fabrication uncertainties and laser pulse
- target and laser specifications and basis for developing an implosion risk assessment

A. Schiavi, 2010
<table>
<thead>
<tr>
<th>Target injection</th>
<th>Tolerance</th>
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<tr>
<td>lateral displacement at TCC</td>
<td>1-5%</td>
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<tr>
<td>DT ice density</td>
<td>10%</td>
</tr>
<tr>
<td>inner/outer radius</td>
<td>2%</td>
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<td>Laser drive</td>
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<tr>
<td>Total energy</td>
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<td>Pulse shape accuracy (time)</td>
<td>...</td>
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<tr>
<td>Pulse shape accuracy (power)</td>
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</table>

A. Schiavi, 2010