A Mix-Model for One-Dimensional Simulations of Laser-Driven Implosion Experiments

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MéDiC: A tool to mimic hydrodynamic instability effects on laser targets

- Context:
  Design of laser targets for LMJ facility
  Studies upon the reduction of implosion efficiency due to the development of interface and front perturbations
  Usefulness of 1D quick parametric studies

- By previous theoretical, experimental or multidimensional simulation studies, temporal evolution of the ”mixing zone” is known
  (thickness = peak-to-valley distance, exchange area, mass, ...)

- Basic hypothesis:
  Influence of the interpenetration of matter is modelized through diffusion processes although transition to full turbulent mixing do not occur
  (short wavenumber perturbations, in weakly non-linear stage, are still dominant)

Application to the hydrodynamic instabilities at the ablator-fuel interface

- Cumulative effects of various processes: Richtmyer-Meshkov instability, feed-in, Bell-Plesset instability ...

  Preliminary stages of the mixing of two separate fluids

  Main process: mass transport

- Goal: interpretation of the HEP4 experiments at Omega

- Derivation of the mix model from a classical two-fluid formulation

Averaging the Two-Fluid Model $\Longrightarrow$

a mono-fluid model

Hyp. : The 2 fluids have the same presssure

$$\frac{\partial \rho}{\partial t} + \frac{\partial}{\partial x}(\rho u) = 0,$$

$$\frac{\partial}{\partial t}(\rho c) + \frac{\partial}{\partial x}(\rho c u + \rho c (1-c) u_r) = 0,$$

$$\frac{\partial}{\partial t}(\rho u) + \frac{\partial}{\partial x}\left(\rho u^2 + P + \rho c (1-c) u_r^2\right) = 0,$$

$$\frac{\partial}{\partial t}(\rho E) + \frac{\partial}{\partial x}\left(\rho E u + P u + \rho c (1-c)(h_1 - h_2) u_r \quad + \rho c (1-c)\left(u u_r^2 + \left(\frac{1}{2} - c\right) u_r^3\right)\right) = S$$

where ρ, u, P and E are the density, the velocity, the pressure and the total energy of the mixture. c the mass fraction of fluid 1, $h_{1,2}$ are the partial enthalpies of each fluid and u_r the relative velocity between each fluid.

Basic hypothesis: Diffusion type closure $\rho c (1-c) u_r \equiv -\rho \mathcal{D} \dfrac{\partial c}{\partial x} \Longrightarrow$

Equations for the mixing in a monofluid 1D lagrangian code

Extra hypothesis: isothermal mixing ($h_i = \mathcal{F}(\rho_i, T)$)
relative velocity is small ($u_r << u$) $\Longrightarrow$ "green terms" neglected
Source terms for internal energies equations: thermal conduction, thermalization and radiative contributions

$$\frac{\partial \rho}{\partial t} + \frac{\partial}{\partial x}(\rho u) = 0,$$

$$\rho \frac{Dc}{Dt} = \frac{\partial}{\partial x}\left(\rho \mathcal{D} \frac{\partial c}{\partial x}\right),$$

$$\rho \frac{Du}{Dt} = - \frac{\partial P}{\partial x},$$

$$\rho \frac{De_i}{Dt} = -P \frac{\partial u}{\partial x} + \frac{\partial}{\partial x}\left(\rho \left(h_1 - h_2\right) \mathcal{D} \frac{\partial c}{\partial x}\right) + \frac{\partial}{\partial x}\left(\mathcal{K}_i \frac{\partial T_i}{\partial x}\right) + \text{Therm.}$$

$$\rho \frac{De_e}{Dt} = -P \frac{\partial u}{\partial x} + \frac{\partial}{\partial x}\left(\mathcal{K}_e \frac{\partial T_e}{\partial x}\right) - \text{Therm.} + \text{Rad.}$$

with $\frac{D}{Dt}$ the Lagrangian derivative, e_i, e_e, T_i and T_e are the internal energies and temperatures

+ Multigroupe radiative method

$\equiv$ Modelling of the mass transport by "molecular mixing" with diffusion coefficient $\mathcal{D}$

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Determination of the diffusion coefficient

The diffusion coefficient in the mass concentration equation, $\mathcal{D}(t)$, must be adjusted to give the requested mixing zone widening, $L_{mix}(t)$

- For an interface at constant velocity the exact solution is known:
  $\mathcal{D}(t) = \frac{1}{8\,\xi^2} L_{mix} \frac{dL_{mix}}{dt}(t)$, with $\xi = 1.163$ for a 5 - 95 % concentration profile
- For an homogeneous compression in spherical geometry,
  the flow is defined by the evolution of the interface location $\Lambda(t)$
  A good approximation is given by $\mathcal{D}(t) = \frac{1}{8\,\xi^2} L_{mix} \left[\frac{dL_{mix}}{dt} - \frac{L_{mix}}{\Lambda}\frac{d\Lambda}{dt}\right]$

Moreover, the mass of the mixing zone can be approximate by $M_{mix} \approx (\rho_h + \rho_l)\, 4\pi\Lambda^2\, L_{mix}/2$

As, in these ideal flows, we have $\rho(t) \propto \Lambda^{-3}$, we get $M_{mix}(t) \propto \frac{L_{mix}}{\Lambda}(t)$

If we know $M_{mix}(t)$ and $L(t)$, we thus can use the alternative expression

$$\mathcal{D}(t) = \frac{1}{8\,\xi^2} L_{mix}^2 \left[\frac{1}{M_{mix}} \frac{dM_{mix}}{dt}\right]$$

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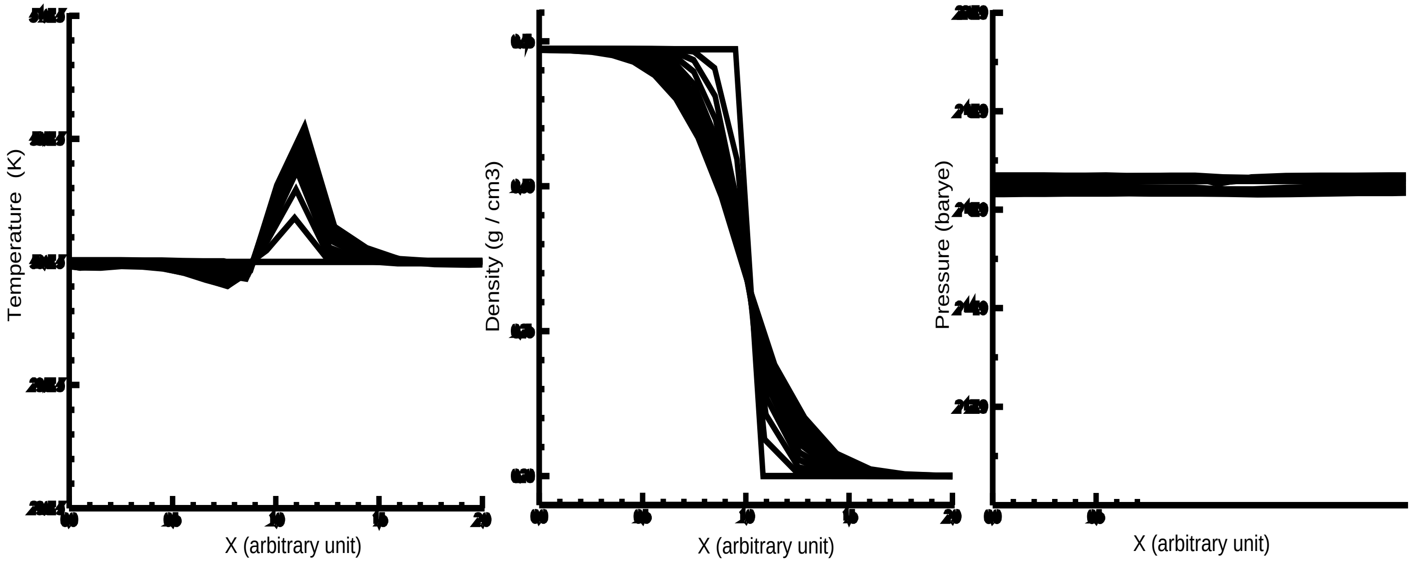
First results

The mix-model is implemented and validated for simple configurations
(two fluids with the same initial temperature mix without global motion)

Example of He / DT mixing at T=30000 K. Evolution of temperature, density and pressure profiles



Future work: application to HEP4 experiments

Application to the hydrodynamic instabilities at the hot spot

Characteristics:

- Development of an ”ablation front like” instability inside the fuel volume between the heavy and cold corona and the light and hot central spot

- Here, the front is not linked to a material interface: its location has to be determined by appropriate criterium

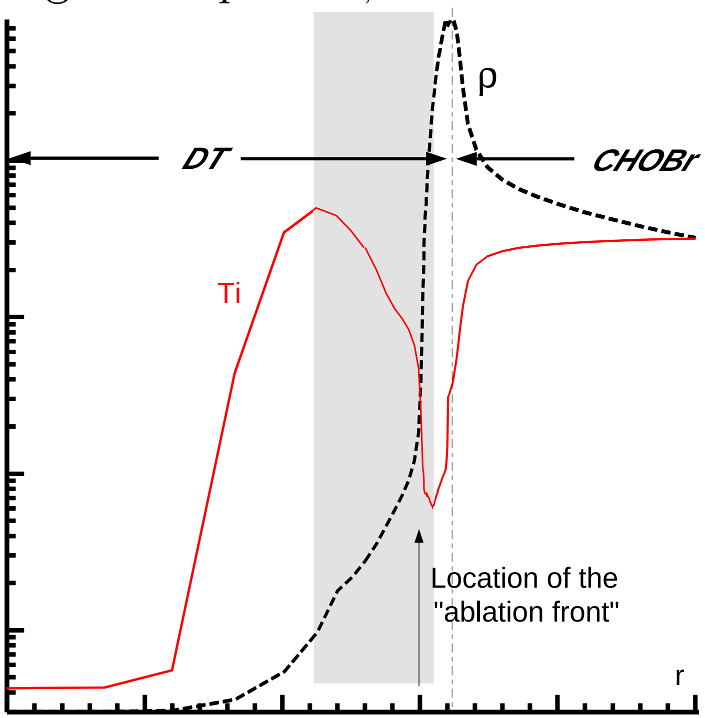
- Partial enthalpy difference transport term is ineffective (same fluid, isothermal mixing)

- Perturbation of the isotherms increase exchange area for thermal conduction

Perturbation at the edge of the "in progress" hot spot

In cryogenic capsules, the DT of the hot spot at ignition is made up of the internal part of cryogenic DT corona

During the implosion, an ablation front propagate into the initially cryogenic DT



Temperature and density profiles during the implosion (1D unperturbed simulation)

We assume identity of hot spot edge, R_{hs}, and ablation front location

Ablation front location determination:

$$Max\left[2\frac{\rho^{I+1}-\rho^{I}}{\rho^{I+1}+\rho^{I}}\times(T_{ion}^{I}-T_{ion}^{I-1})\right]$$

(based upon R-T instability criterium, first part $\longrightarrow$ local Atwood number)

Good agreement with other definitions of the hot spot, within the last ns before the ignition time (see below)

Modelling the instable front perturbation in a 1D code

Previous modelling through a "mass transfer" is inappropriate

(perturbations within the DT, where $\Delta h_i = 0$: added term do not affect energy balance)

The main process is assumed to be the increase of exchange surface for thermal conduction:

within the perturbated zone $(R_{hs} - L_{mix}/2 < x < R_{hs} + L_{mix}/2)$

thermal conduction fluxes will be multiplied by the ratio of areas $Ra(t) = S_{perturb}/S_{sph}$

Modified set of equations (plane geometry):

$$\frac{\partial \rho}{\partial t} + \frac{\partial}{\partial x}(\rho u) = 0,$$

$$\rho \frac{Du}{Dt} t = -\frac{\partial P}{\partial x},$$

$$\rho \frac{De_i}{Dt} = -P \frac{\partial u}{\partial x} + \frac{\partial}{\partial x}\left(Ra\, \mathcal{K}_i \frac{\partial T_i}{\partial x} \right) + \text{Therm.}$$

$$\rho \frac{De_e}{Dt} = -P \frac{\partial u}{\partial x} + \frac{\partial}{\partial x}\left(Ra\, \mathcal{K}_e \frac{\partial T_e}{\partial x} \right) - \text{Therm.} + \text{Rad.}$$

R_{hs} is calculated through above method; $L_{mix}, Ra(t)$ are deduced from 2D simulation

Alternative modelling through a "diffusive model"

Hypothesis: we add "mix" viscous and conductive terms

within the perturbated zone ($R_{hs} - L_{mix}/2 < x < R_{hs} + L_{mix}/2$)

"mix viscosity", $\mathcal{D}_u$, and "mix conductivity", $\mathcal{D}_e$, (homogeneous to l^2/t)

are deduced from $\mathcal{D}(t) = \dfrac{1}{8\,\xi^2} L_{mix}^2 \left[\dfrac{1}{M_{mix}} \dfrac{dM_{mix}}{dt}\right]$ (see above)

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Modified set of equations (plane geometry):

$$\frac{\partial \rho}{\partial t} + \frac{\partial}{\partial x}(\rho u) = 0,$$

$$\rho \frac{Du}{Dt} t = -\frac{\partial P}{\partial x} + \frac{\partial}{\partial x}\left(\frac{4}{3}\rho \mathcal{D}_u \frac{\partial u}{\partial x}\right),$$

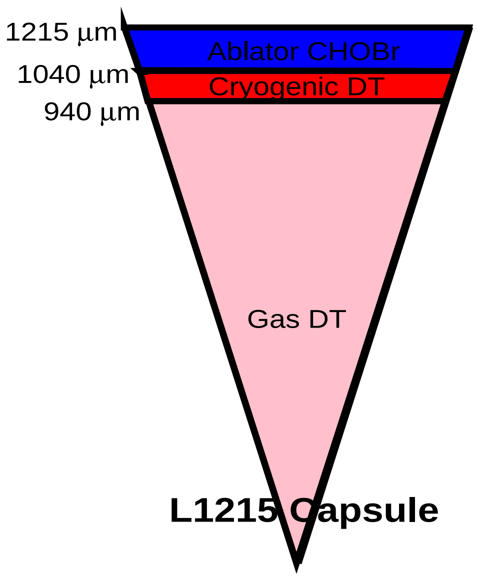
$$\rho \frac{De_i}{Dt} = -P\frac{\partial u}{\partial x} + \frac{\partial}{\partial x}\left(\rho \mathcal{D}_e \frac{\partial e_i}{\partial x}\right) + \frac{\partial}{\partial x}\left(\mathcal{K}_i \frac{\partial T_i}{\partial x}\right) + \text{Therm.} + \left(\frac{4}{3}\rho \mathcal{D}_u \frac{\partial u}{\partial x}\right)\frac{\partial u}{\partial x},$$

$$\rho \frac{De_e}{Dt} = -P\frac{\partial u}{\partial x} + \frac{\partial}{\partial x}\left(\rho \mathcal{D}_e \frac{\partial e_e}{\partial x}\right) + \frac{\partial}{\partial x}\left(\mathcal{K}_e \frac{\partial T_e}{\partial x}\right) - \text{Therm.} + \text{Rad.}$$

Example: simulations of the L1215 capsule

to recover nonlinear multimode 2D simulations

Description of the configuration and simulations (Cherfils *et al.*, APS 43rd Annual Meeting, Long Beach CA, 2001):



Half-spheres simulations

FCI2 code (”driven” ALE method)

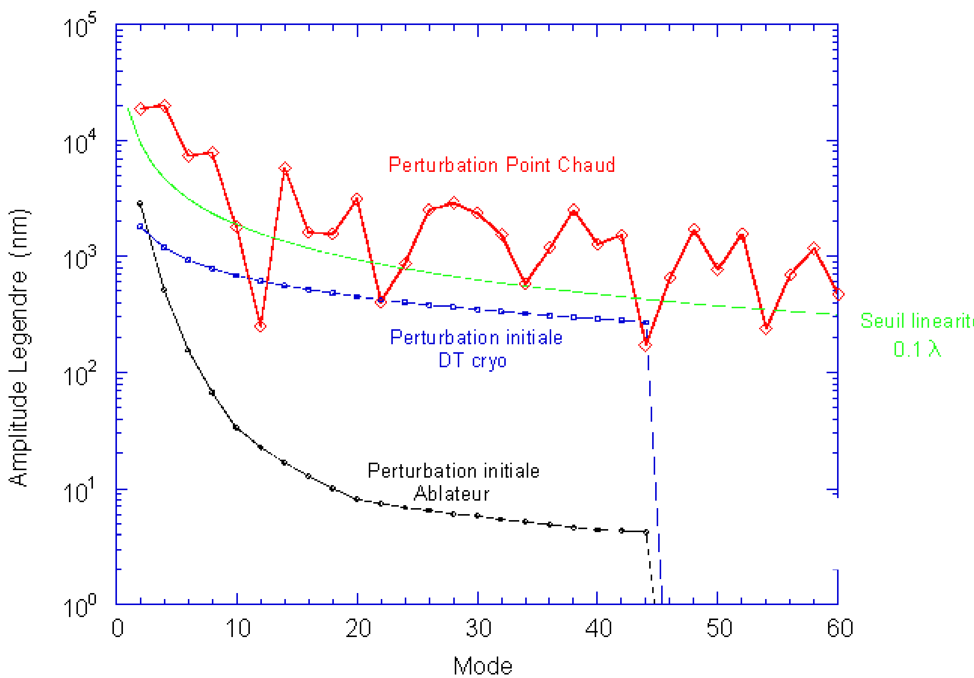
$t_i = 17.45ns$,

$V_{DT}{}^{max} = 3.9\,10^7 cm/s$

Multimode initial perturbations:

Ablation surface $rms(l \geq 10) = 10\,nm$,

Cryogenic DT surface $rms(l \geq 10) = 1\,\mu m$



Hot Spot front tracking

3 ways to track the Hot Spot front :

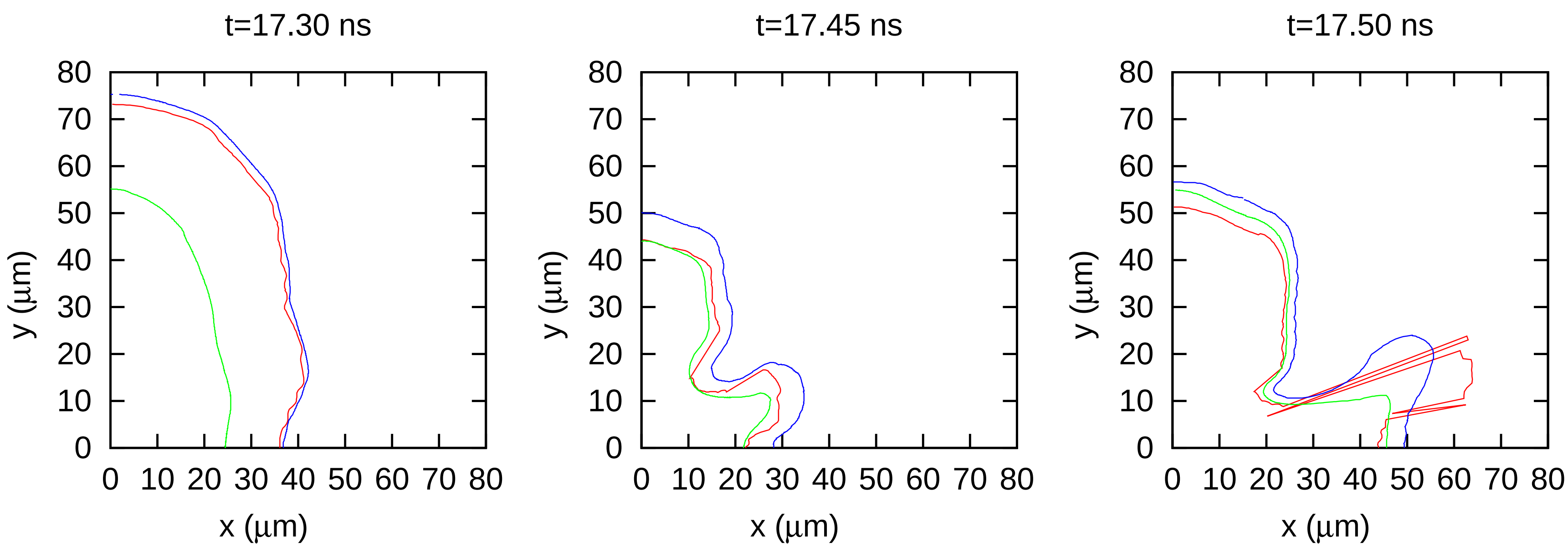
1) Search the isotherm T_{ion}=50 MK (—).

2) Search the isotherm T_{ion}= Max(T_{ion})/10 (—).

3) Search the location of the instable front:

$$\left[2\frac{\rho^{I+1}-\rho^{I}}{\rho^{I+1}-\rho^{I}} \times (T^{I}_{ion} - T^{I-1}_{ion}) \right]$$ maximum, for each angle θ (—)

this last method can be applied even before the converging time of the shock waves



Comparison of Hot Spot fronts for 2D simulation around the ignition time

Post-processing 2D simulation results

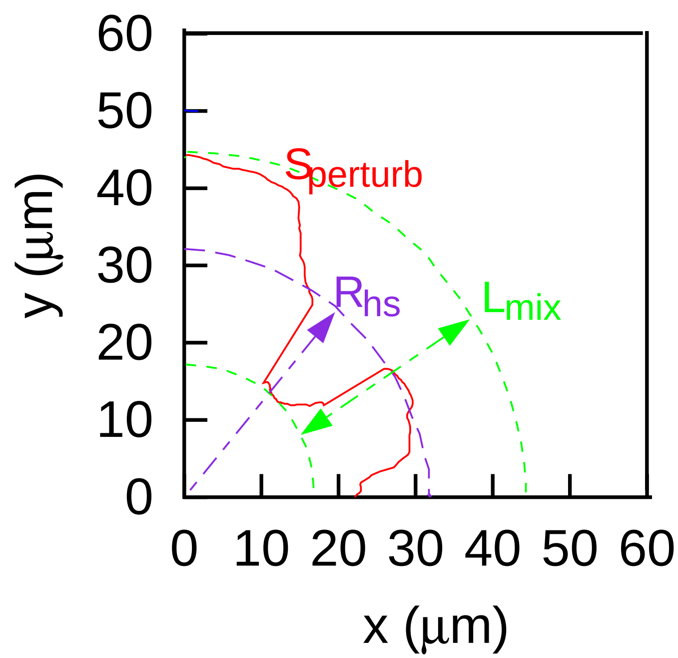
From the instable front contour

Minimal radius and maximal radius of the Hot Spot front

$\Longrightarrow$ 1D mixing length L_{mix} and mean radius R_{hs}

Integration of the Hot Spot front

$\Longrightarrow$ 1D thermal exchange surface in the mixing zone S_{perturb}

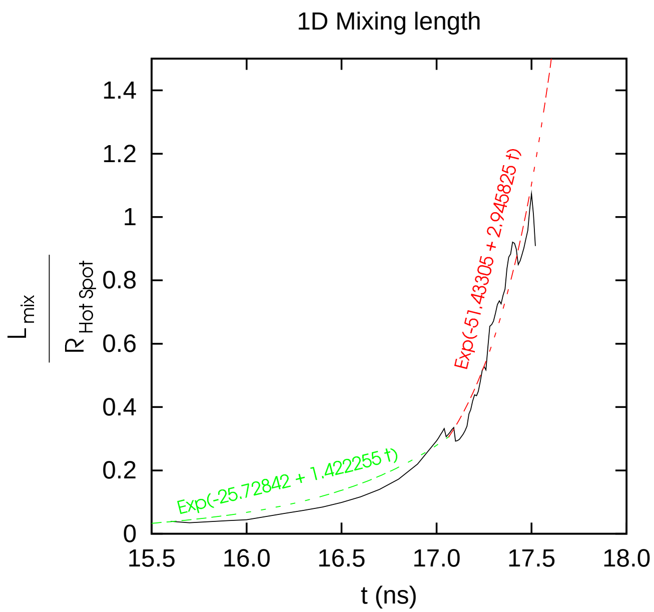


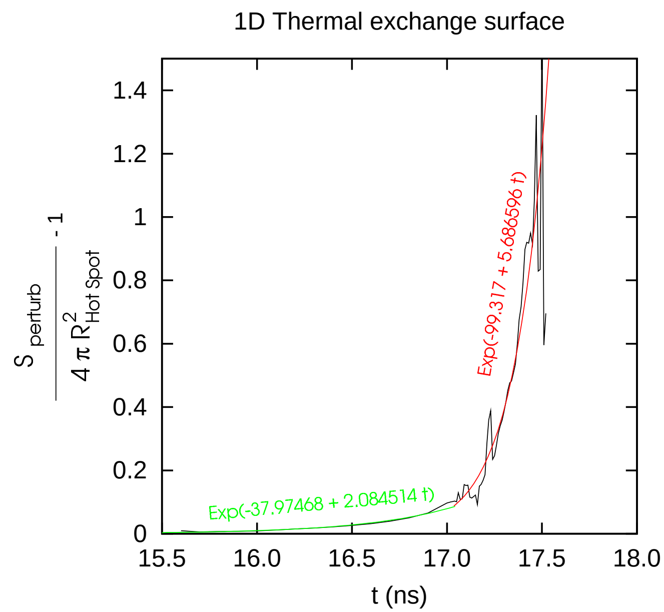
1D Mixing length and thermal exchange surface

2D mixing length and thermal exchange area are fitted to be used in 1D code

Scaling of L_{mix} by the Hot Spot mean radius R_{hs}

Scaling of S_{perturb} by the Hot Spot mean surface $4\pi R_{\text{hs}}^2$

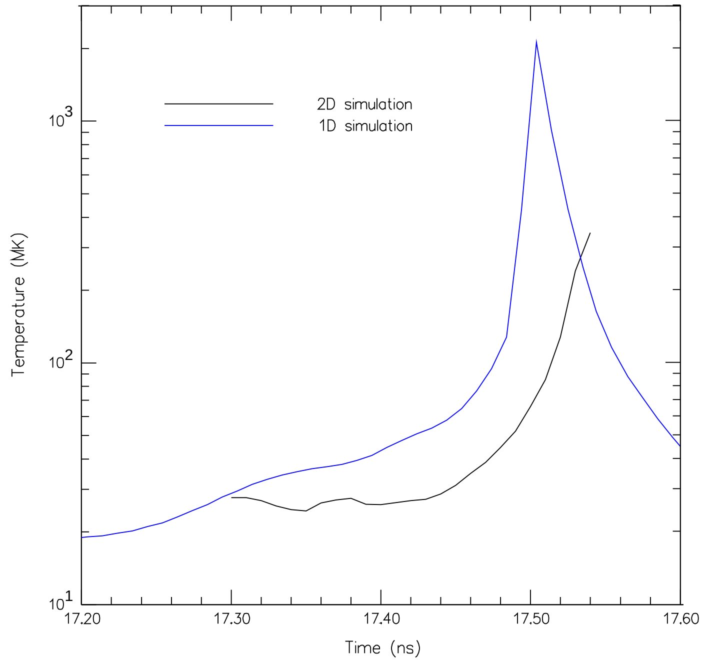


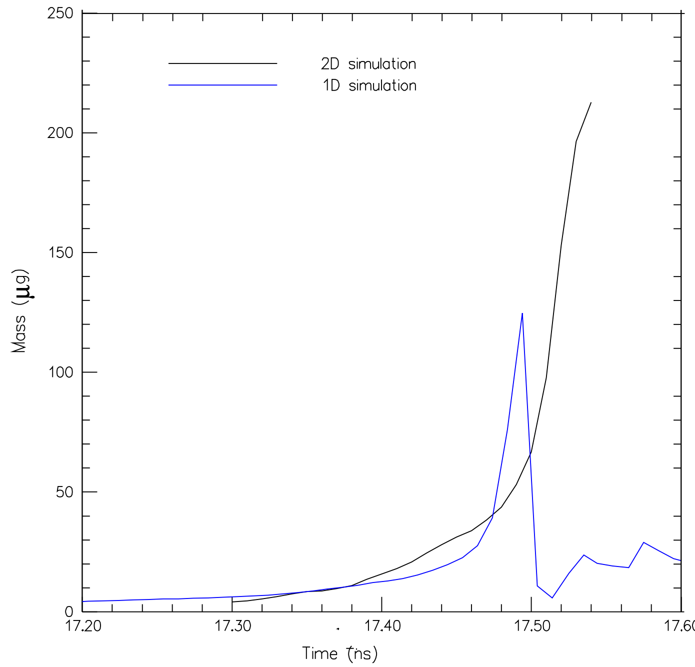


Satisfactory description of the mean hot spot characteristics

The evolution of the mass of DT within the hot spot

and its mean ionic temperature are simulated in 1D calculations





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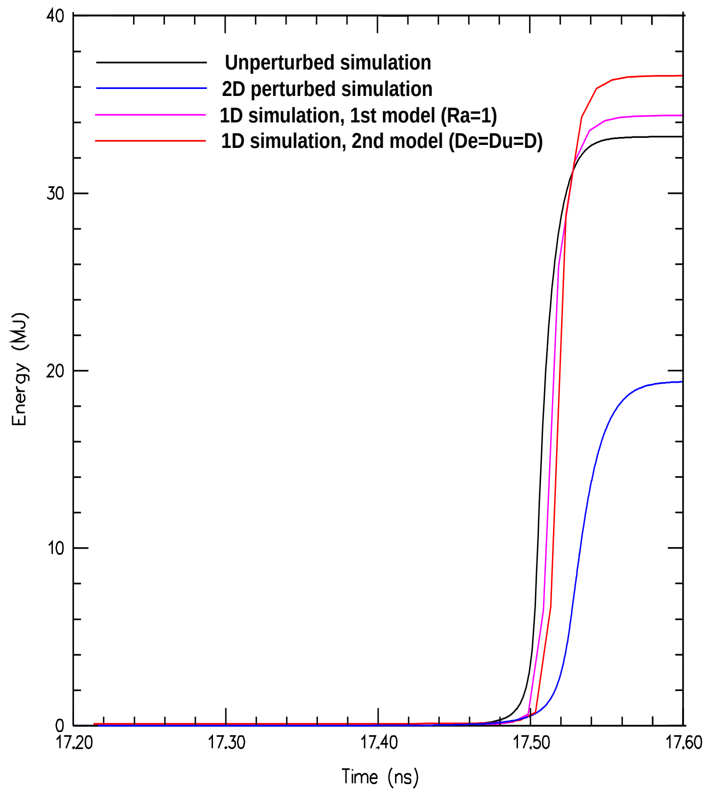
1D models fail to represent all 2D flow complexity



Comparison of energy evolution

With the two mix models,

the relative delay to ignition is underestimated

The implosion is more efficient but closer to the threshold

The non-sphericity of perturbed 2D implosion explain the spread of the energy production

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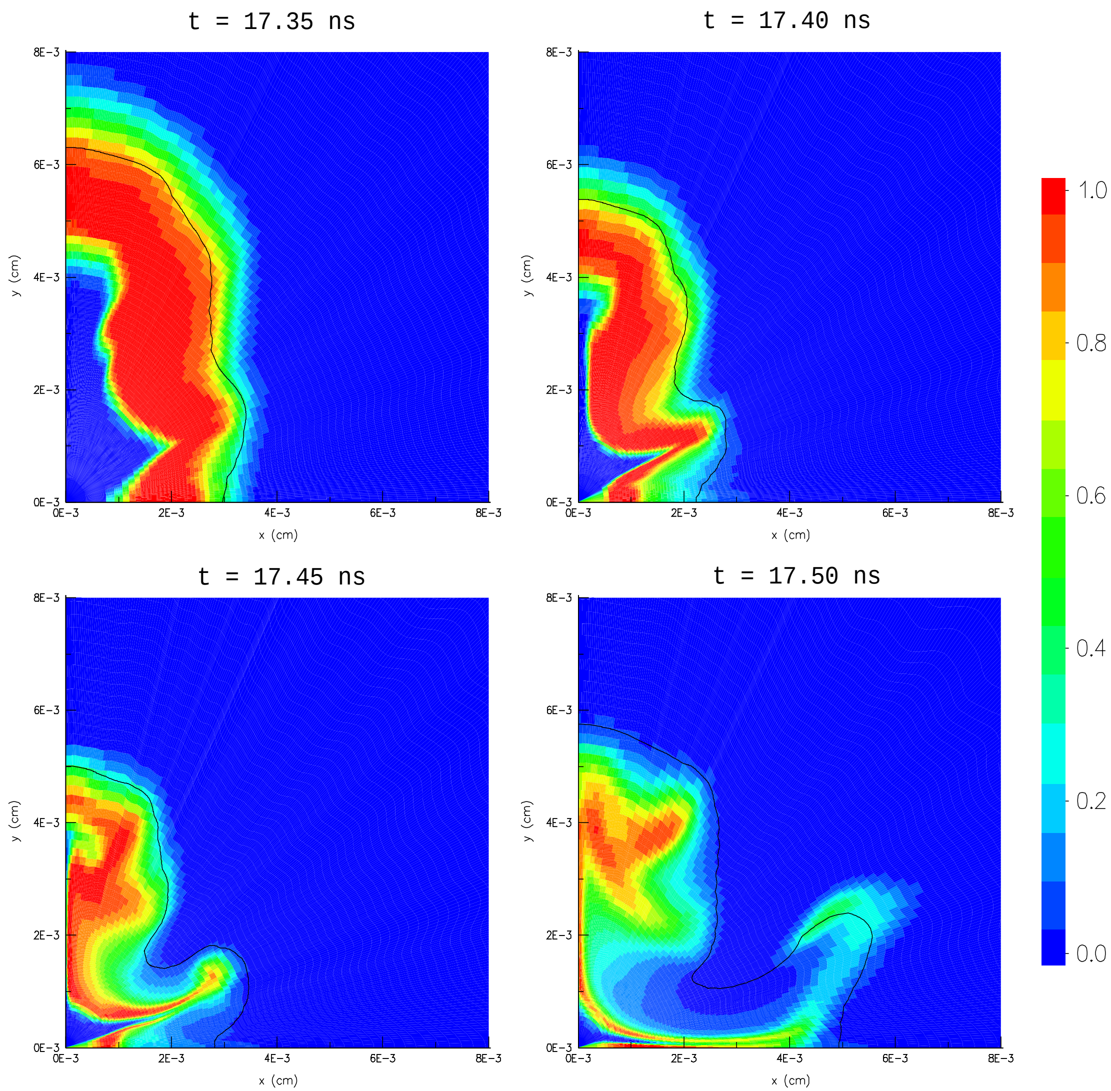
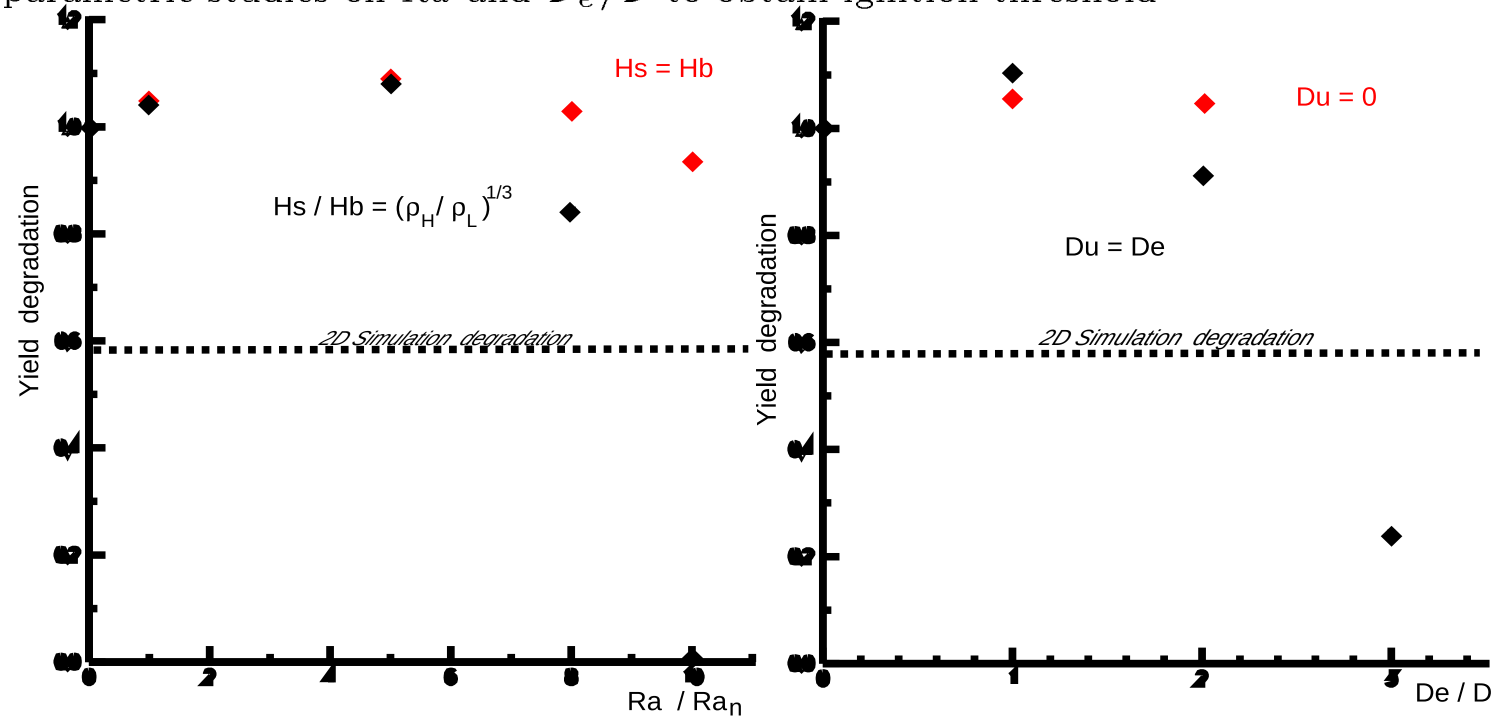


Comparison of the Hot Spot contours ($T = (MaxT_{ion})/10$) with the mass concentrations of the cryogenic DT entering in the Hot Spot at the ignition time.
Iso-concentration contours are more perturbed than Iso-temperature contours

Simulation of the ignition threshold

2D specific behavior (low mode deformation of the Hot Spot contours, possible mean viscous effects,) is not recovered by nominal values of 1D models

We realize parametric studies on Ra and $\mathcal{D}_e/\mathcal{D}$ to obtain ignition threshold



To recover the 2D simulation degradation we need to multiply by 8 the nominal ratio area

$Ra_n \equiv S_{perturb}/S_{sph}$ (with an asymetric development of "spikes" and "bubbles")

The simulation with the "diffusive model" show the importance of the added term in velocity equation

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Prospects

- These preliminary results open several ways
- For Hot Spot perturbations we envisage to model separately low modes and high modes
- The modelling of an ”average viscous effect” on the velocity profiles seems essential
- The modelling of hydrodynamic instabilities at interfaces could take advantage of the above ideas