MEUDON, NOVEMBER 23RD 2016

ARWEN, A RHD 2D CODE FOR LABORATORY PLASMAS

MANUEL COTELO FERREIRO

Instituto de Fusión Nuclear

Universidad Politécnica de Madrid

HIGH-ENERGY DENSITY PHYSICS GROUP IN MADRID

- Pedro Velarde: team leader
- Agustín Gonzalez: HHG
- Eduardo Oliva: Lasers
- Manuel Cotelo: Numerical methods
- David Portillo: Numerical methods
- Alberto García: Atomic physics

THANKS TO OBSERVATOIRE DE PARIS

OUTLINE

1. Plasma as a fluid
    - Hydrodynamics
    - Radiation transport
    - Heat conduction: laser absorption
2. Hydrodynamic simulation code: ARWEN
3. Applications

PLASMA AS A FLUID

- On plasma physics: begin with collections of individual particles, to determine how to describe their behavior statistically using the Boltzmann equation, and then to average their behavior in ways that produce simpler models of plasma dynamics.
- Here we take the reverse path, beginning with the very simple averaged equations that are useful in many high-energy-density contexts, and working our way toward more-complex descriptions that are more powerful but also less-often necessary.
- The moments of the Botzmann equations give us the Euler equations: hydrodynamics of a plasma
- The moments of the Boltzmann equation are not enough, we need the constitutive equations: Equation of State.

SINGLE FLUID, THREE TEMPERATURE

- Identify a distinct *temperature* for the electrons, the ions, and the radiation.
- The value of the temperature of an equilibrium thermodynamic system that would have the same mean energy as that of the actual system being described.
- The actual system, which might be an energy distribution of electrons or photons, typically is not in equilibrium and very often has an energy spectrum that departs significantly from the equilibrium energy spectrum.
- The 3T description of a single-fluid plasma is particularly useful, especially for computer simulations.
- Identifying three temperatures in a plasma is a particularly paradoxical action, because the thermodynamic definition of temperature only strictly applies when they are all equal.

- Electron thermalization time:

$$t_e = 0.2896 \frac{(mc^2)^{1/2} T_e^{3/2}}{n_e c e^4 log(\Lambda)}$$

- Electron-ion equilibration time:

$$t_{ei} = \frac{3 m_e c^2 m_i c^2}{8(2\pi)^{1/2} n_i (Ze^2)^2 c log(\Lambda)} \left(\frac{T_e}{m_e c^2} + \frac{T_i}{m_i c^2} \right)^{3/2}$$

- For Hydrogen, $t_{ei}/t_e \gg 1$
- In the initial stages of a laser created plasma, electron and ion temperatures could be very different.
- Laser energy is deposited mainly in free electrons that will transfer energy to ions later

HYDRODYNAMICS

- Density ρ
- Momentum $\rho\mathbf{v}$
- Total energy $\rho E = \rho(e + \frac{1}{2}v^2)$
- Closure relation (incomplete EOS): $p = p(\rho, e)$

$$u = \begin{bmatrix} \rho \\ \rho\mathbf{v} \\ \rho E \end{bmatrix}, F = \begin{bmatrix} \mathbf{v}\rho \\ \mathbf{v}\rho\mathbf{v}^t - Ip \\ \mathbf{v}(\rho E + p) \end{bmatrix}, S = \begin{bmatrix} 0 \\ \rho\mathbf{g} \\ \rho\mathbf{v}\cdot\mathbf{g} \end{bmatrix}$$

Non-linear system of hyperbolic PDE

JUMP CONDITIONS: RANKINE-HUGONIOT

$$\rho_1 v_{n1} = \rho_2 v_{n2}$$

$$(\rho_1 v_{n1}) v_{t1} = (\rho_2 v_{n2}) v_{t2}$$

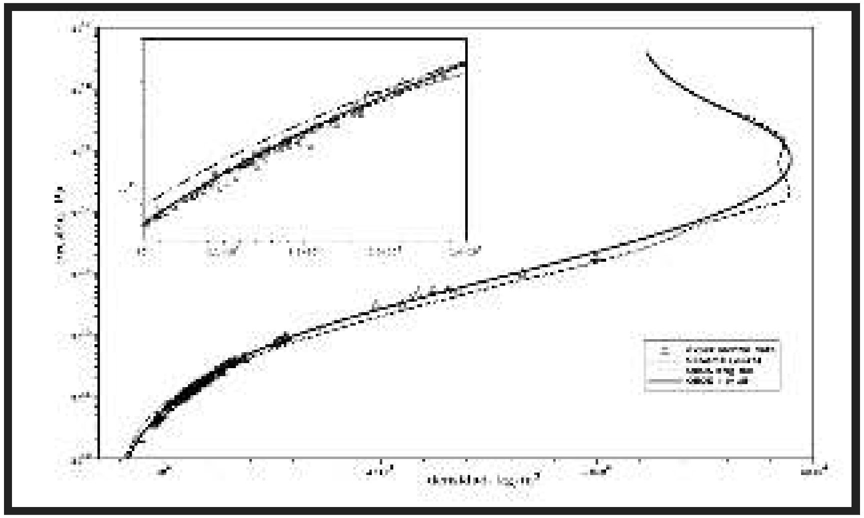
$$p1 - p2 = \rho_2 v_{n2}^2 - \rho_1 - v_{n1}^2$$

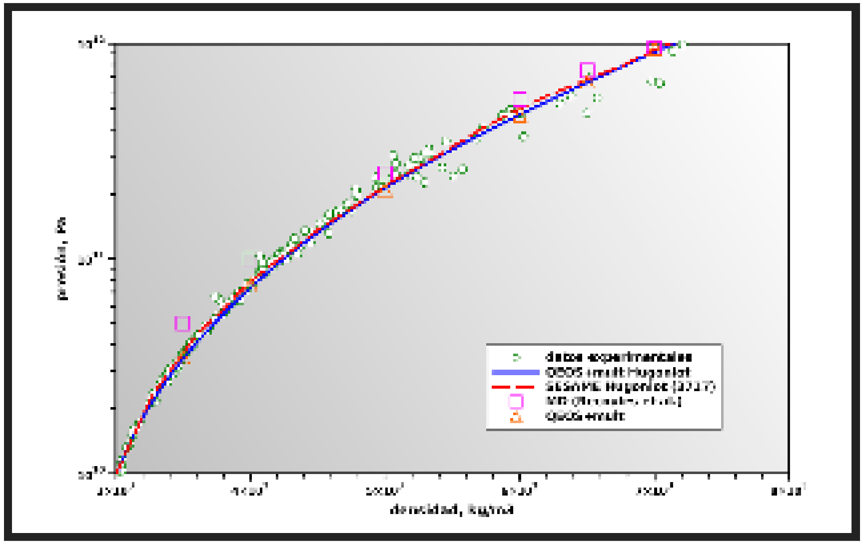
$$v_{n1} \left(p_1 + \rho_1 e_1 \rho_1 \frac{v_{n1}^2}{2} \right) = v_{n2} \left(p_2 + \rho_2 e_2 + \rho_2 \frac{v_{n2}^2}{2} \right)$$

Hugoniot equation

$$e_2 - e_1 = \frac{1}{2}(p_2 + p_1) \left(\frac{1}{\rho_1} - \frac{1}{\rho_2} \right)$$

HUGONIOT CURVE

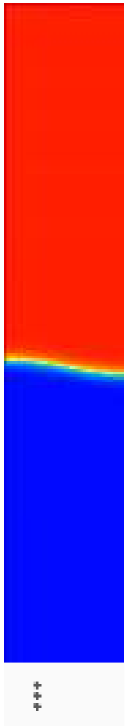


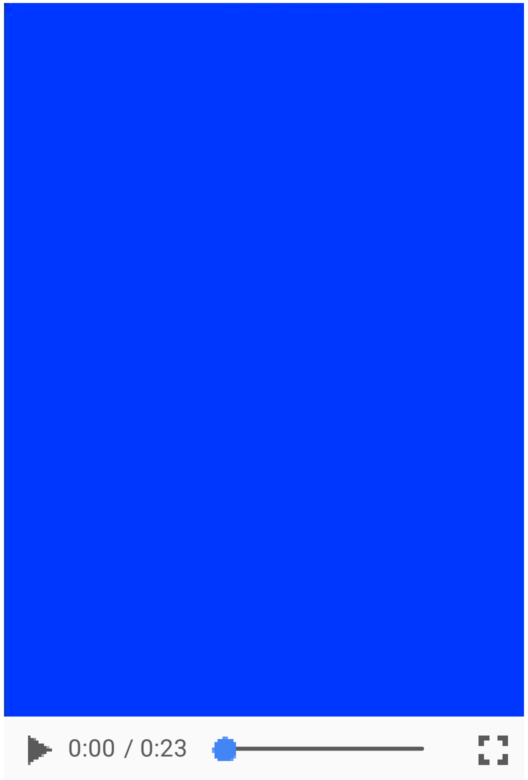


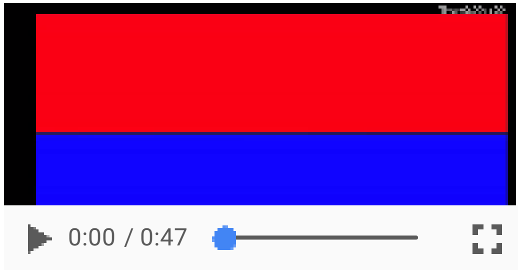
Left, Fe Hugoniot. Right, Al Hugoniot

Cotelo et al. APHSS 2011

HIDRODYNAMIC INSTABILITIES







Rayleigh-Taylor: density gradient against pressure gradient.

Rytchmyer-Meshkov: Shock wave interacting with contact discontinuity (jump in density)

Kevin-Helmholtz: Material in the interface have different velocities

D. Portillo PhD Thesis presentation.

RADIATION TRANSPORT

- Transport of energy in the plasma by the photons
- Transport equation for particles with no charge (Boltzmann e

$$\frac{1}{v(E)}\frac{\partial}{\partial t}\Psi\left(\mathbf{x},\mathbf{\Omega},E,t\right)+\mathbf{\Omega}\cdot\nabla\Psi\left(\mathbf{x},\mathbf{\Omega},E,t\right)+$$
$$\Sigma_t\left(\mathbf{x},E,t\right)\Psi\left(\mathbf{x},\mathbf{\Omega},E,t\right)=S\left(\mathbf{x}\right.$$

- Ψ depends on seven variables: space $\mathbf{x}$ (3), direction $\mathbf{\Omega}$ (2), er and time t (1).
- Numerical methods: diffusion (approx.), momentum method discrete ordinates
- Need to know spectral properties of materials: opacities and emissivities

RADIATION TRANSPORT COEFFICIENTS

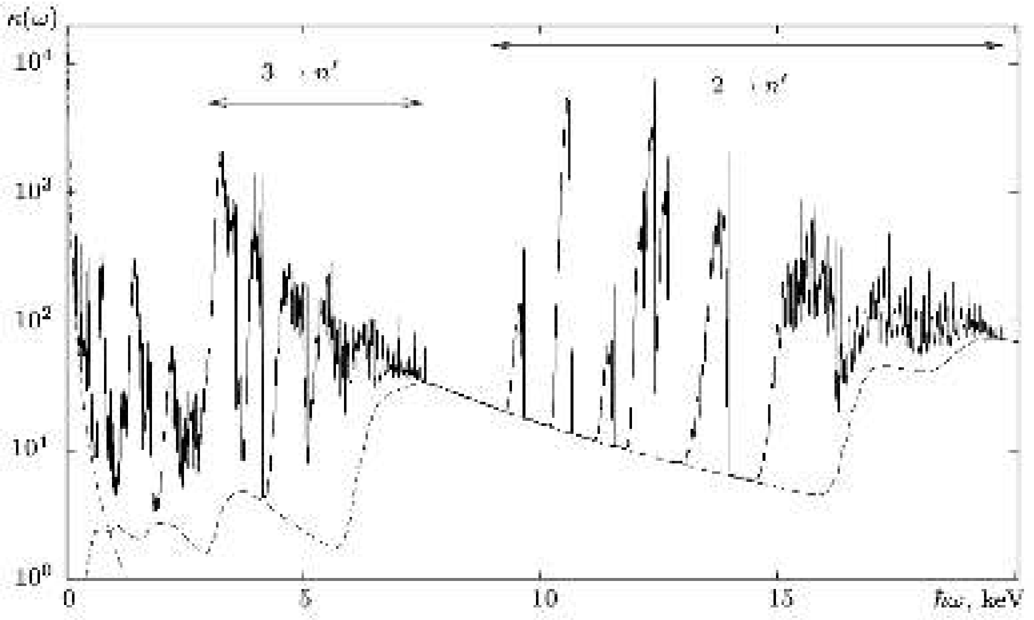


Figure 5.8: Contribution of various processes to the spectral absorption coefficient for a gold plasma ($Z = 79$, $T = 1$ keV, $\rho = 0.1$ g/cm^3). The solid curve corresponds to the total absorption coefficient $\kappa(\omega)$; also shown are the contributions of photoionization (dashed curve), bremsstrahlung (dashed-dotted curve), and the domains of influence of the main transitions $n \to n'$

Quantum Statistical Models of Hot Dense Matter, A.F. Nikiforov, V. B. Uvarov

ELECTRON HEAT CONDUCTION

- Transport of energy in the plasma by electrons
- Approximation by flux-limited electron heat diffusion:

$$\frac{\partial E_e}{\partial t} = \nabla\left(k_e(T_e)\nabla T_e\right) + S_e$$

$$\frac{\partial E_i}{\partial t} = \nabla\left(k_i(T_i)\nabla T_i\right) + S_i$$

- Highly non-inear diffusion coefficient: $k_e \propto T^{5/2}$
- The diffusion equation do not have any limit in the flux, $\mathbf{F} = k_e \nabla T$ and in some cases the energy flux will became too high: flux limiter.

COMPLETE MODEL

$$\frac{\partial \rho}{\partial t} + \nabla\left(\rho \mathbf{v}\right) = 0$$

$$\frac{\partial \rho \mathbf{v}}{\partial t} + \nabla\left(\mathbf{v} \rho \mathbf{v}^t\right) = -\nabla\left(P_{th} + P_r\right)$$

$$\frac{\partial \rho E}{\partial t} + \nabla\left(\rho E \mathbf{v}\right) = -\nabla\left[\left(P_{th} + P_r\right)\mathbf{v}\right] + S_{laser} + \nabla \mathbf{q}_C + \nabla \mathbf{q}_r$$

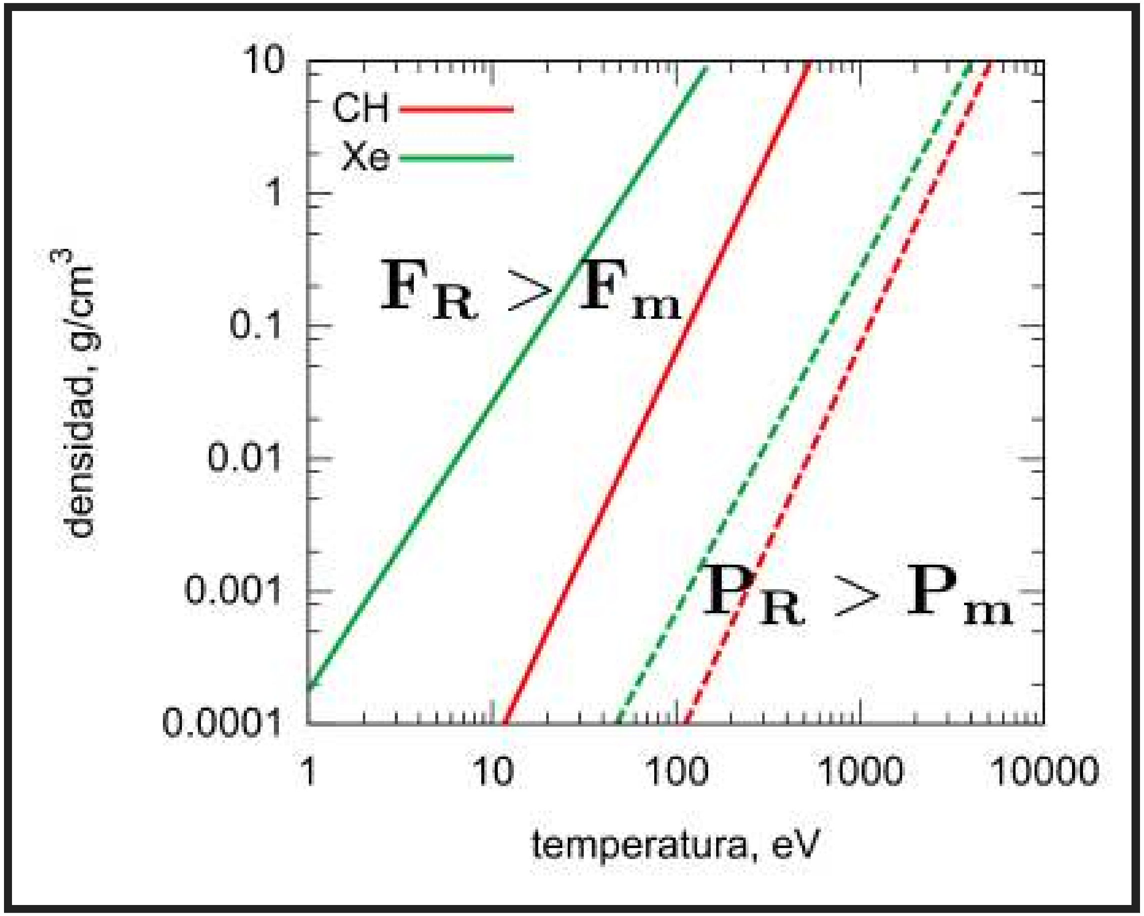
$$\frac{1}{c}\frac{\partial I}{\partial t} + \boldsymbol{\Omega} \nabla I + \kappa I = \epsilon$$

$$\nabla \mathbf{q}_C = -\nabla(k_e \nabla T)$$

$$\nabla \mathbf{q}_r = \int (\kappa I - \epsilon) d\nu$$

$$E_r = \frac{1}{c}\int I d\boldsymbol{\Omega} d\nu$$

$$P_r = \frac{1}{3} E_r$$



Modified from Highe-Energy-Density Physics, R. P. Drake

LASER ABSORPTION IN PLASMAS

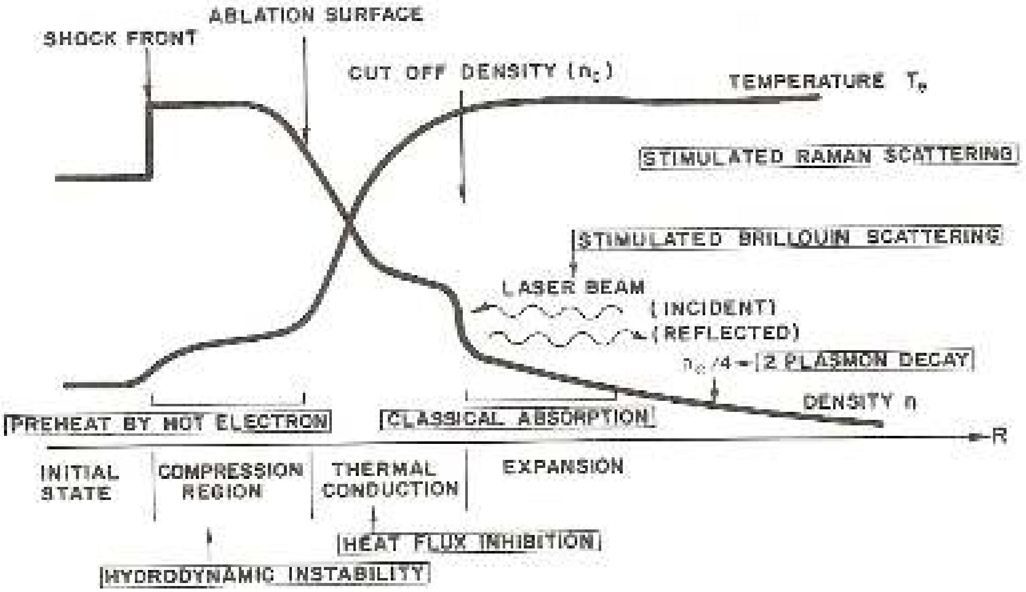


FIGURE 1. Radial distributions of the temperature and the electron density of the laser-irradiated target. Some important physical processes of the laser-target coupling are also shown. (From Yamanaka, C., in *Proc. 19th Eur. Conf. Laser Interaction with Matter*, Villarde, G. et al., Eds., World Scientific, Singapore, 1989, 3. With permission.)

LASER RAYTRACING

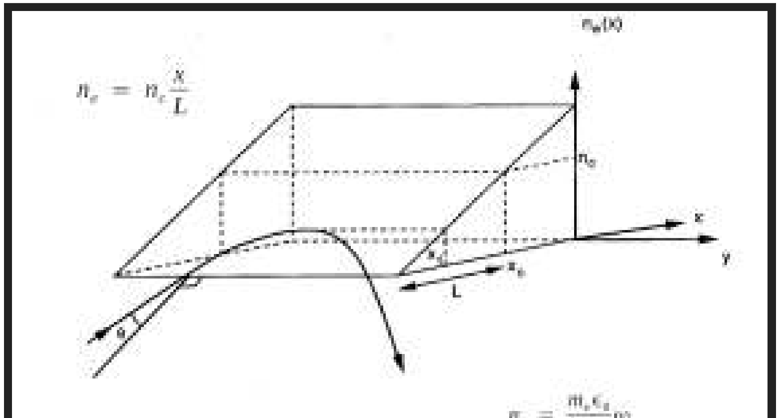


Fig. 4 An incident laser ray trace.

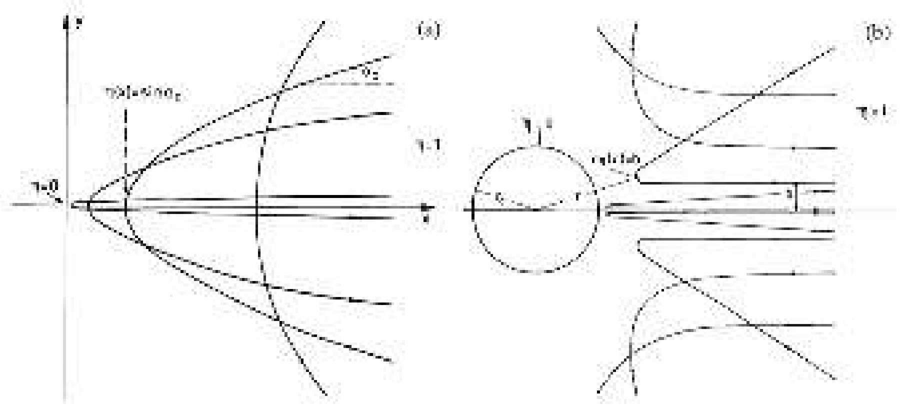


Fig. 3.2 Raytracing. (a): Plane layered medium. A ray incident from vacuum at the angle α_0 has its turning point at $\eta(x) = \sin\alpha_0$. The y-component $\hbar k_y = \hbar k_0 \eta \cos\alpha = \hbar k_0 \cos\alpha_0$ of the photon momentum is conserved in the stationary medium. (b): Deflection of a parallel beam by a spherical plasma cloud. In the stationary medium the angular momenta $\hbar k_0 \eta r \sin\alpha = \hbar k_0 b$ of the photons are conserved along their trajectories

Laser Plasma Theory and Simulation, K. Mima

High Power Laser-matter interaction, P. Musler, D. Bauer

$$\frac{d}{ds}\left(n\frac{d\mathbf{r}}{ds}\right) - \nabla n = 0$$

LASER-PLASMA COUPLING

- Laser absorption in the plasma and energy losses in the low density coronal plasma
- Heat transport to the dense plasma not reached by the laser
- Generation of the ablation pressure that will accelerate the target
- Compression work done by the shock

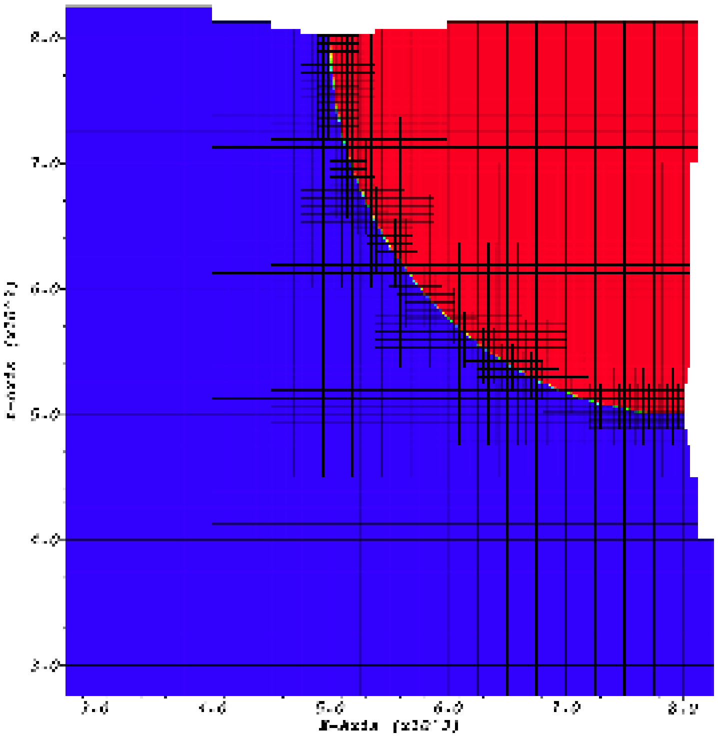
ARWEN: DESCRIPTION

ARWEN code is a simulation program for plasma hydrodynamics in 2D. It includes:

- Eulerian structured mesh in 2D
- Multimaterial hydrodynamics: high-order Godunov method (fully conservative)
- Radiation transport: discrete-ordinates algorithm with energy multigroups
- Laser energy deposition: raytracing algorithm for energy deposition in the plasma.
- Electron heat conduction: able to use a 2-temperature plasma model with electronic heat diffusion.
- Can work with either cartesan (XY) or cylindrical (RZ) coordinates.

And everything using an **AMR** (Adaptive Mesh Refinement) scheme.

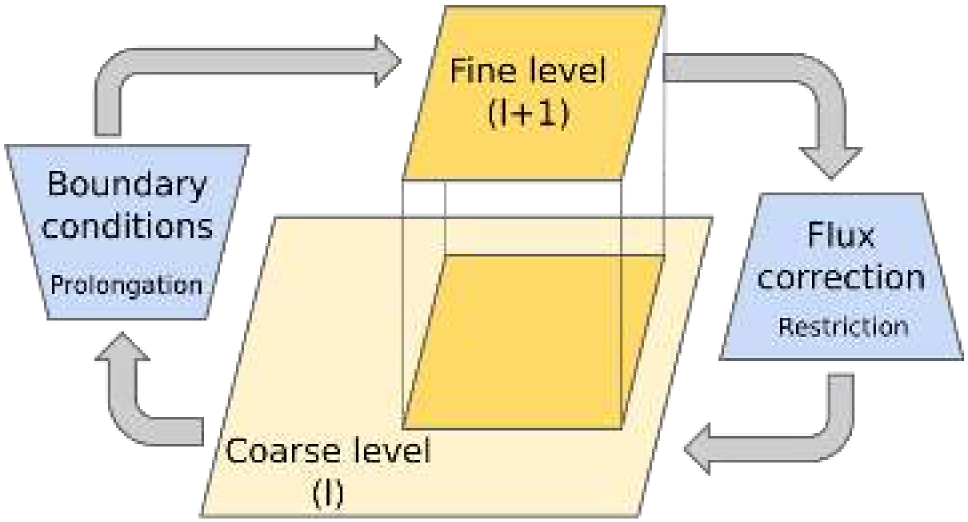
AMR



Example: density discontinuity.

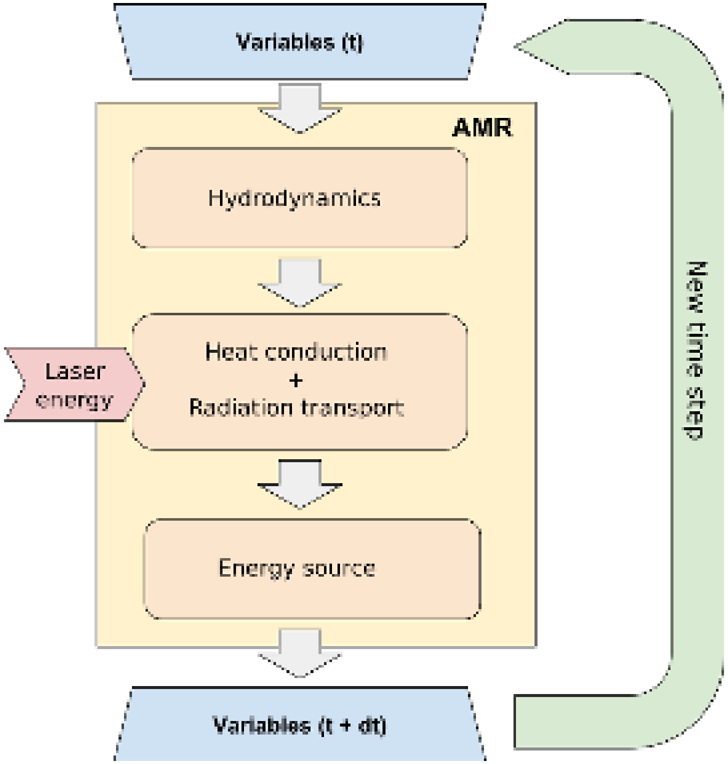
- Hierachy of levels with higher resolutions to cover the *marked* regions.
- Use boxes of cells with higher resolution where we need more precision. Homogeneous error in the solution for the whole system.
- Reduce the number of cells to speed up the calculations: make the computational effort where we really need it.

A SCHEME OF AMR ALGORITHM



Relation between two consecutive levels in the AMR scheme.

A SCHEME OF ARWEN



Basic scheme of the ARWEN program flow.

ARWEN INPUT DATA

- Equation of State:
  - Real EOS using tabulated data: we have developed method to generate EOS tables (1)
- Radiation transport coefficients: load tables with the opacity and emissivity data.
  - Opacity table generation using BigBART code (2)
- Simulation parameters:
  - Target description
  - Laser parameters
  - Parameters for the numerical methods

(1) Cotelo et al, APHSS (2011)
(2) Alberto García et al, HEDP (2013)

APPLICATIONS

The simulation code **ARWEN** can deal with systems in the high energy density regime.

The applications go from target design and optimization to experimental analysis.

- Laser-created plasmas
- X-Ray secondary sources
- ICF targets: target compresion, fast ignition scheme, ...
- Laboratory Astrophysics (LA): radiative shocks, astrophysical jets, supernovae remnants, ...

HIGH-ENERGY DENSITY REGIME

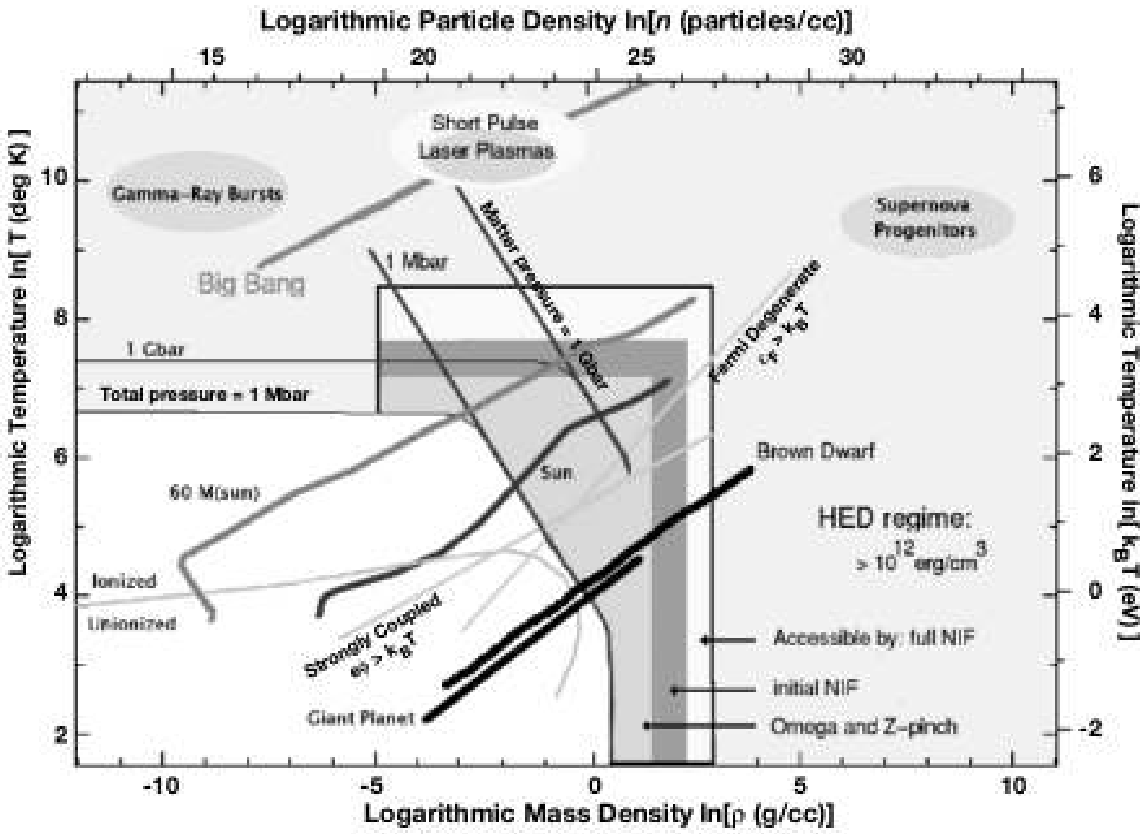
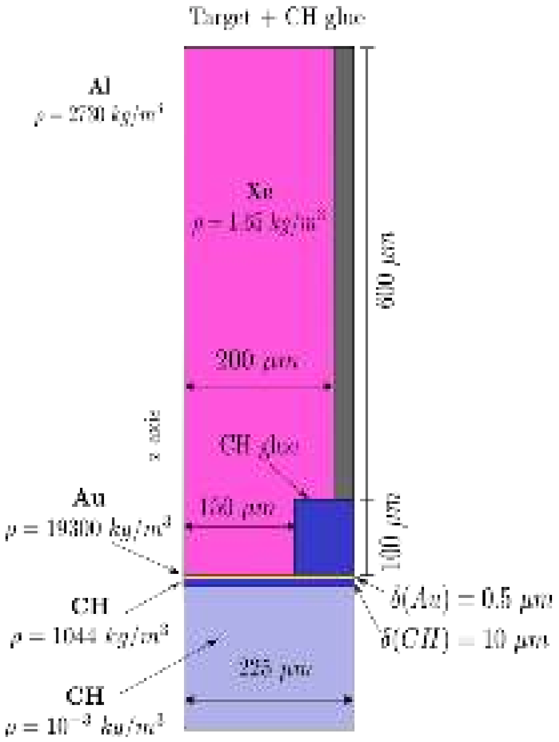
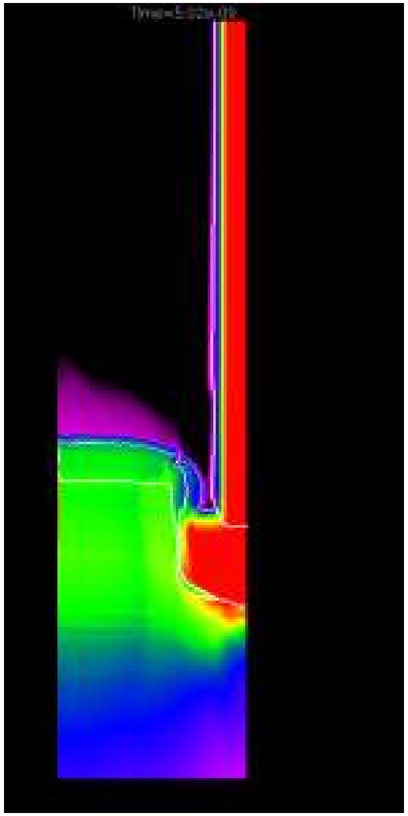


Fig. 1.1. Regimes of high-energy-density physics. Adapted from the NRC Report: *High Energy Density Physics: The X-Games of Contemporary Science*

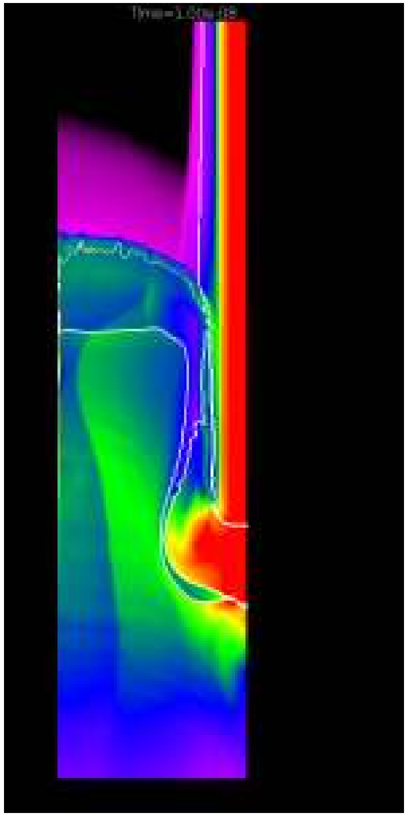
LABORATORY ASTROPHYSICS



Target scheme for PALS simulations



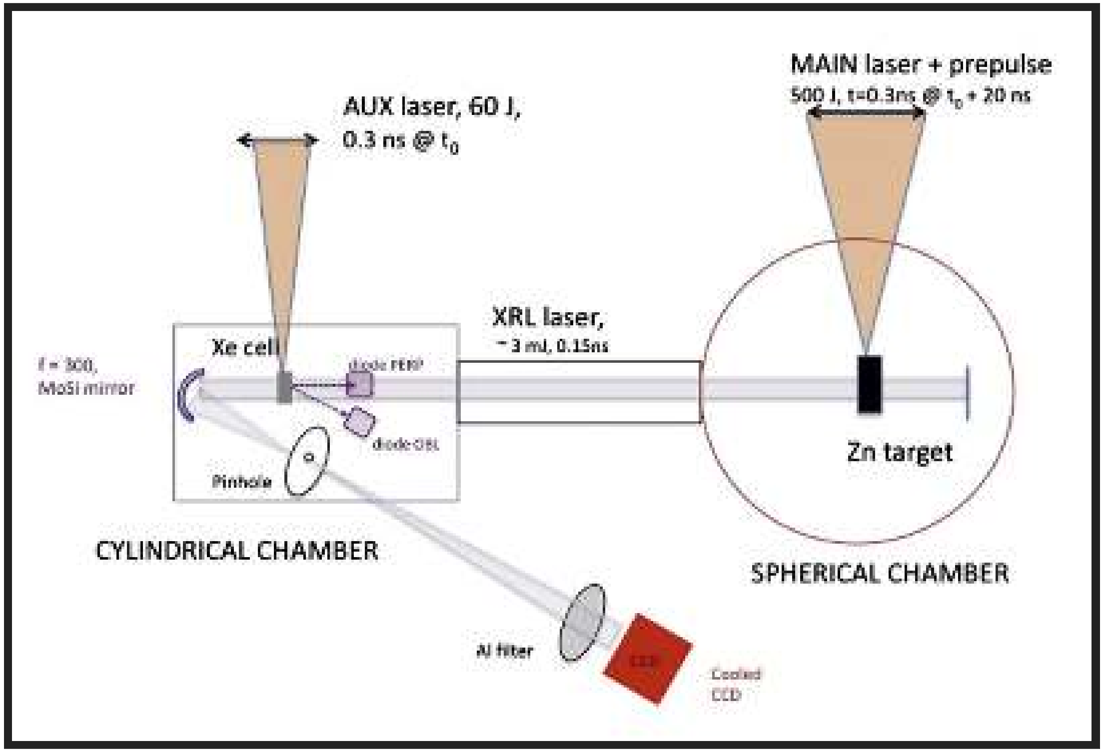
Radiative shock at 5 ns

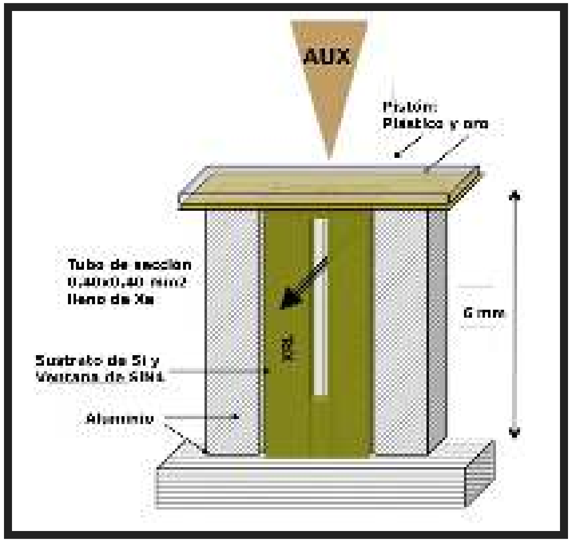


Radiative shock at 10 ns

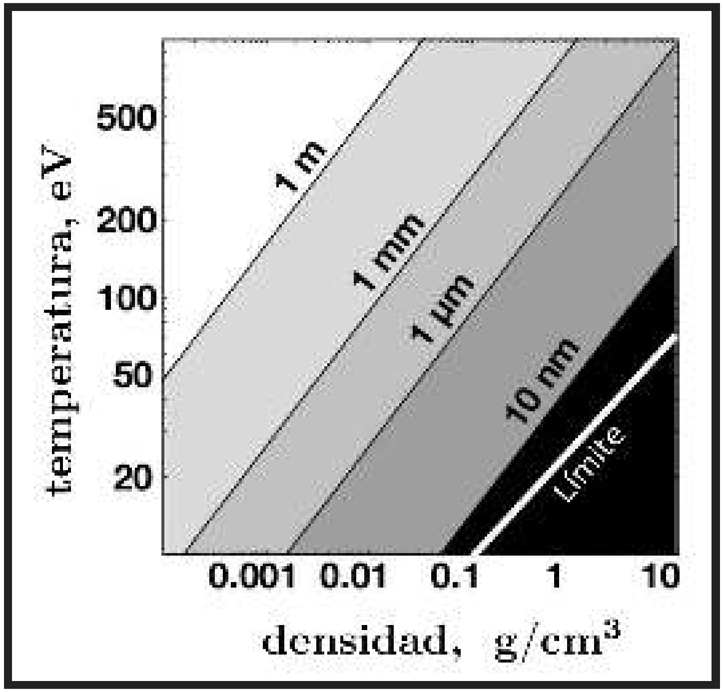
Cotelo et al. HEDP (2014)
Chaulaghain et al. HEDP (2015)

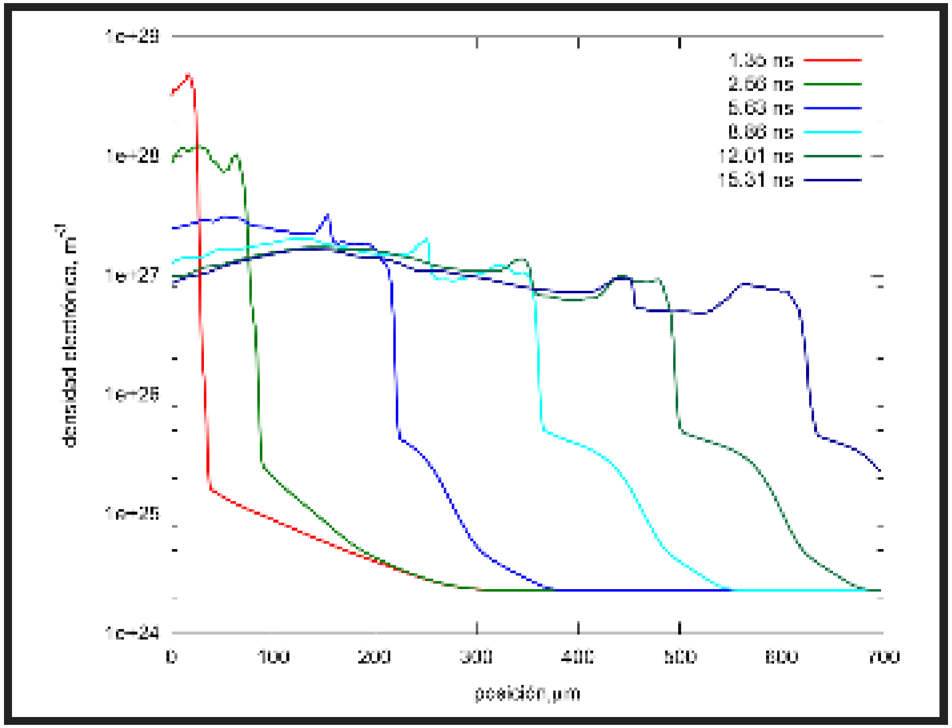
EXPERIMENTAL SETUP

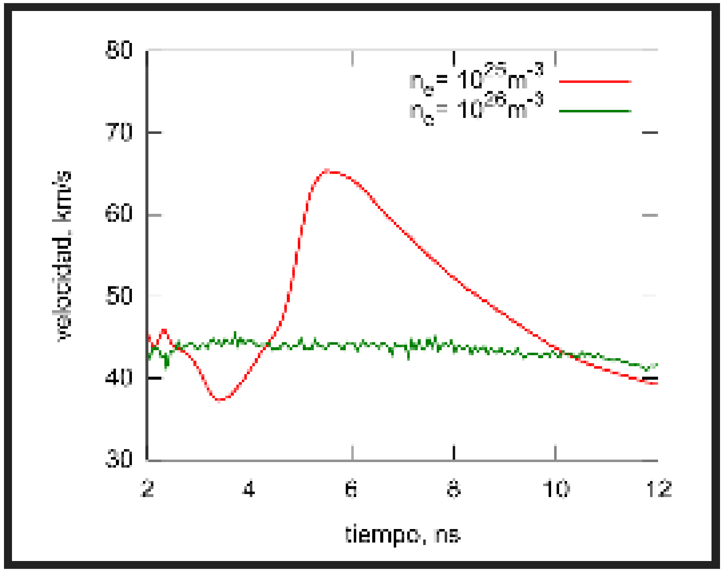




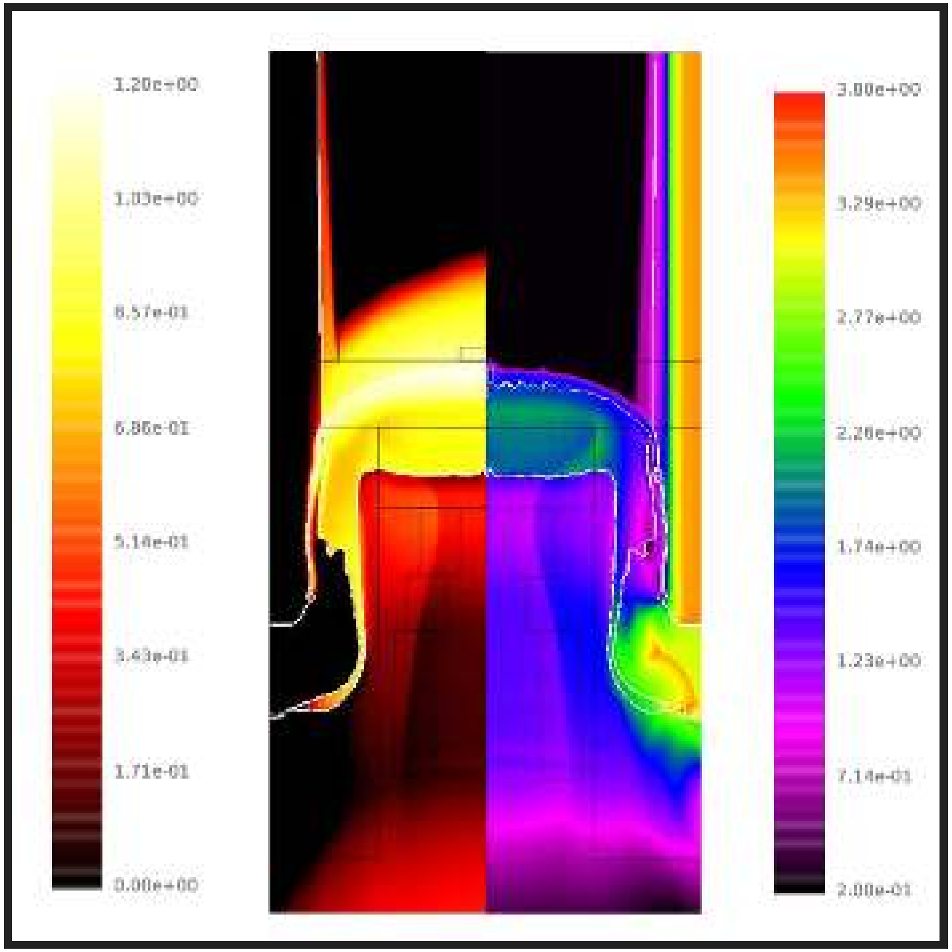
LABORATORY ASTROPHYSICS



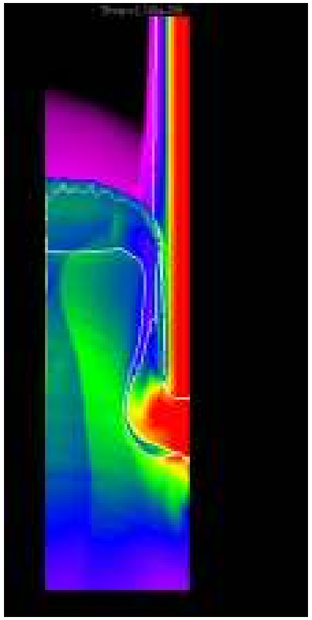


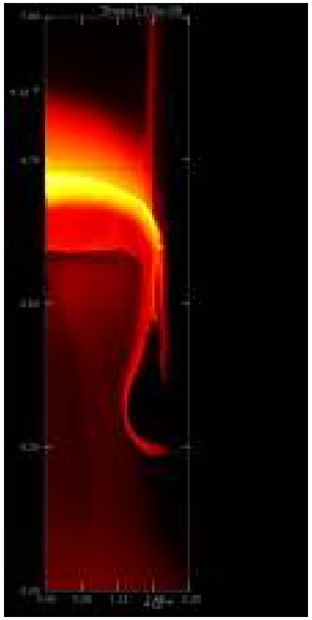


80
70
60
50
40
30
velocidad, km/s
2
4
6
8
10
12
tiempo, ns
n_e= $10^{25}$$m^{-3}$
n_e= $10^{26}$$m^{-3}$



1.20e+00
1.03e+00
8.57e-01
6.86e-01
5.14e-01
3.43e-01
1.71e-01
0.00e+00
3.80e+00
3.29e+00
2.77e+00
2.26e+00
1.74e+00
1.23e+00
7.14e-01
2.00e-01



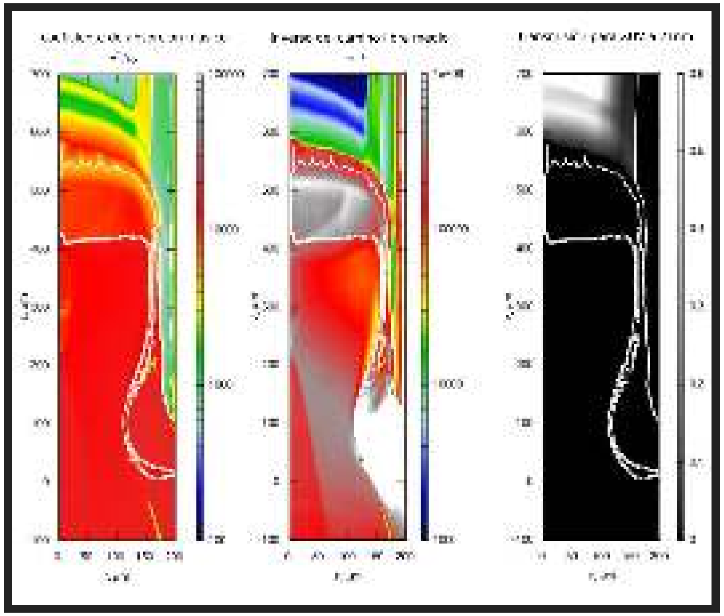


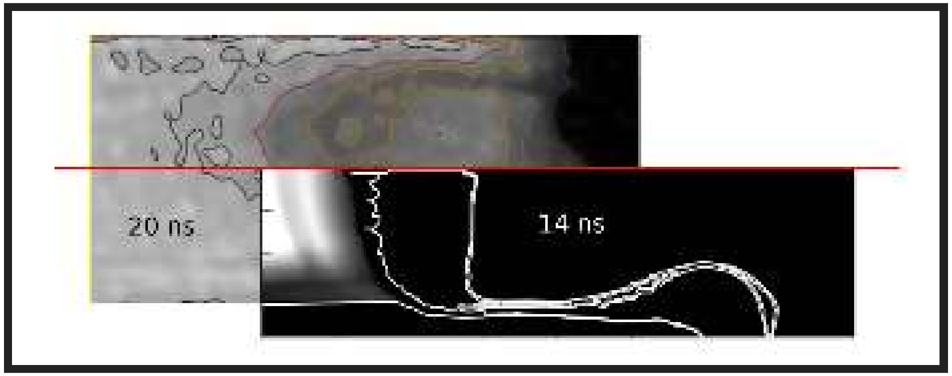
- Left: electron density, white lineas are material interfaces
- Right: temperature, radiative shock is around $16\ eV$

Play

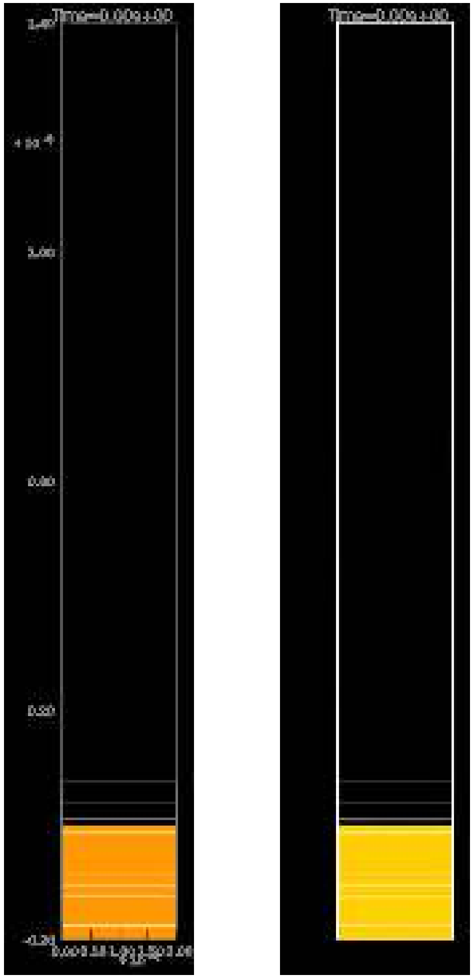
Pause

Resume




20 ns
14 ns

RADIATIVE SHOCK FORMATION

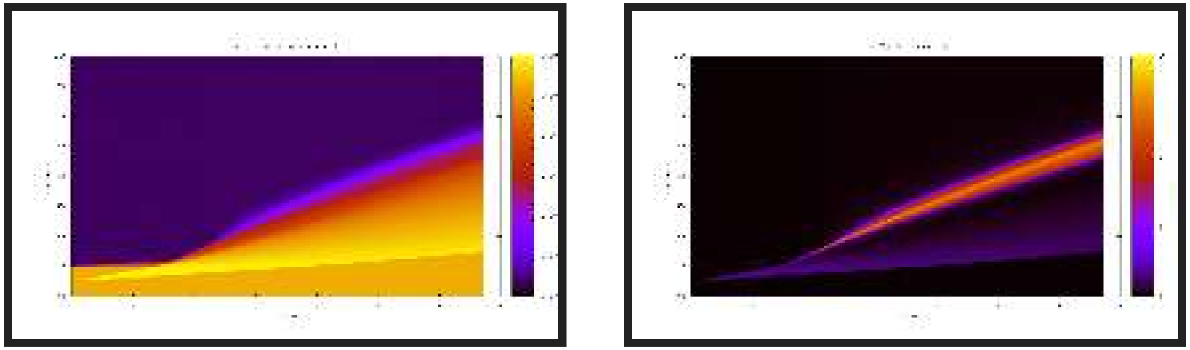


- Left: density
- Right: electron density, black lines are material interfaces
- White lines are AMR boxes with different resolutions

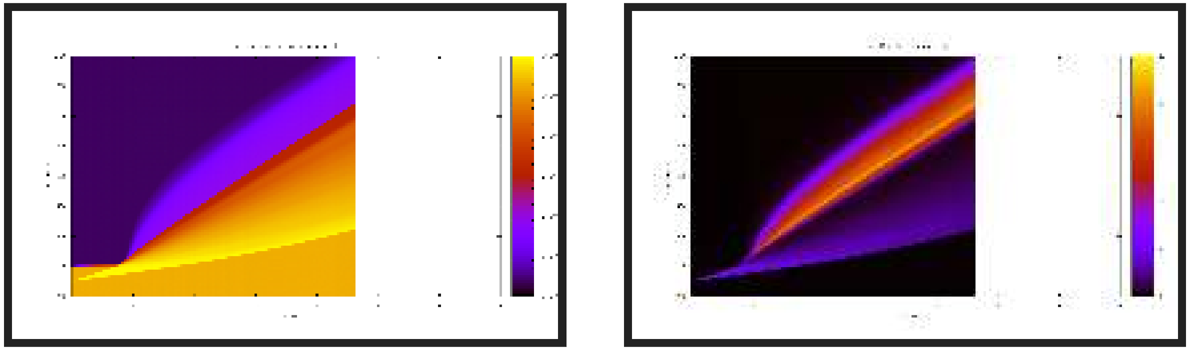
Play

Pause

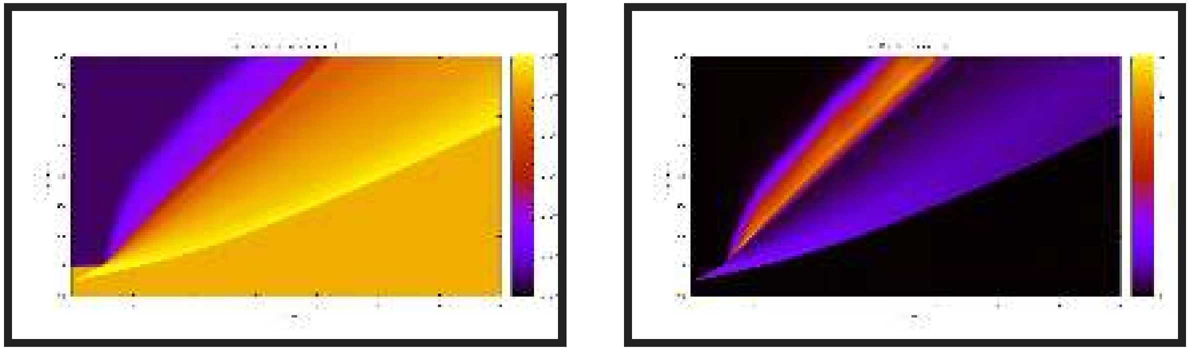
Resume



$u_0 = 20km/s$

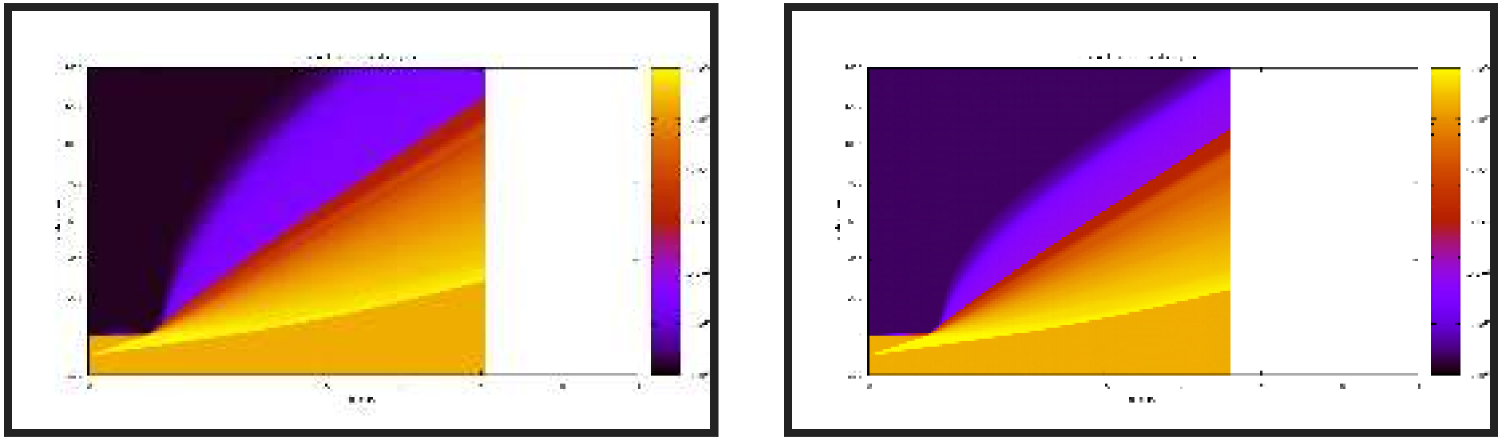


$u_0 = 40km/s$

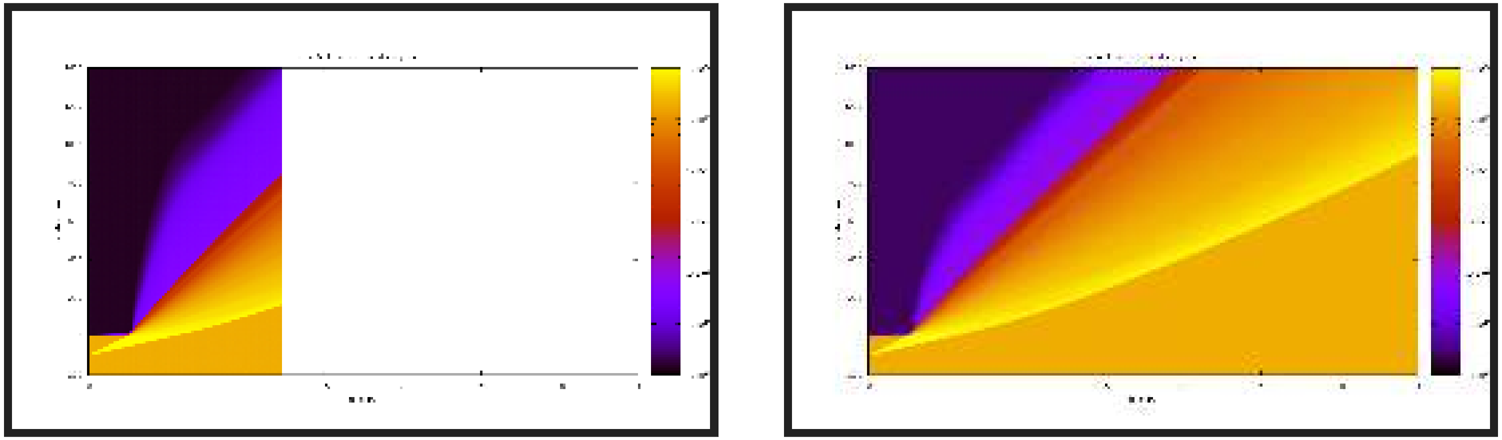


$u_0 = 60km/s$

- Left: electron density, $\rho_{Xe} = 1.65\ kg/m^3$
- Right: temperature, $\rho_{Xe} = 1.65\ kg/m^3$



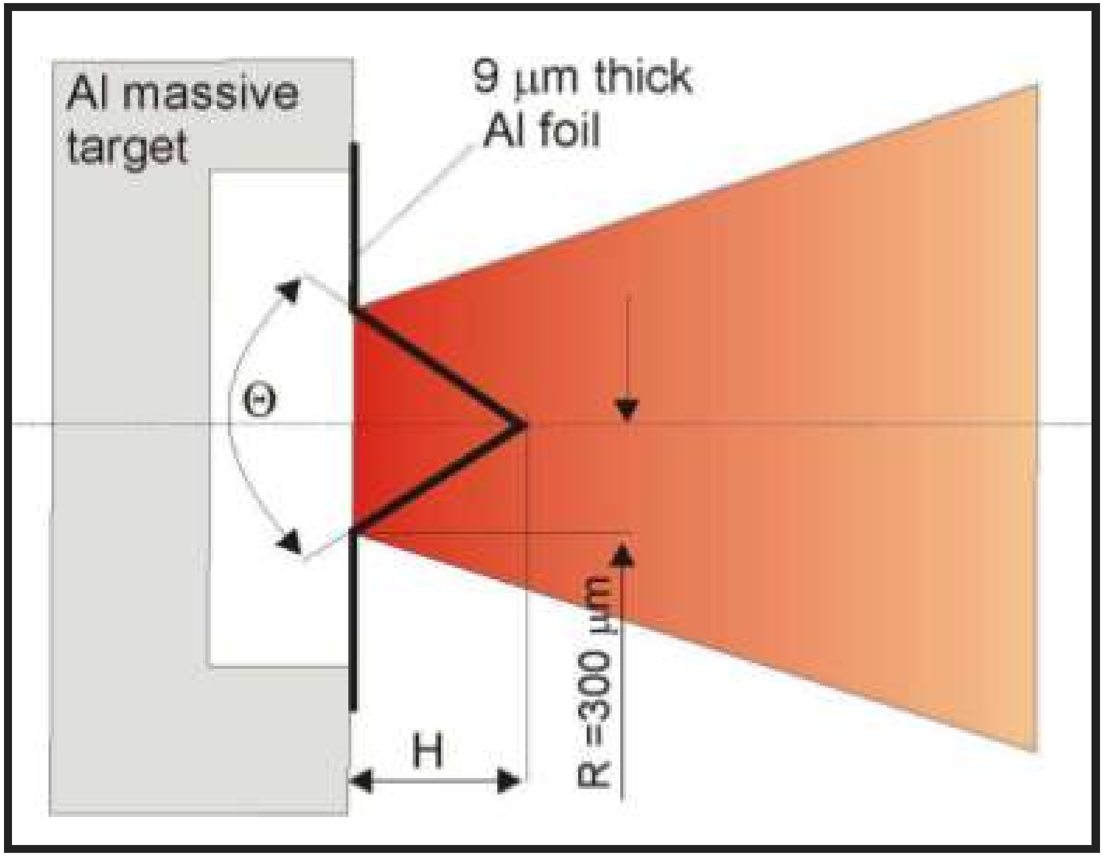
$u_0 = 40km/s$



$u_0 = 60km/s$

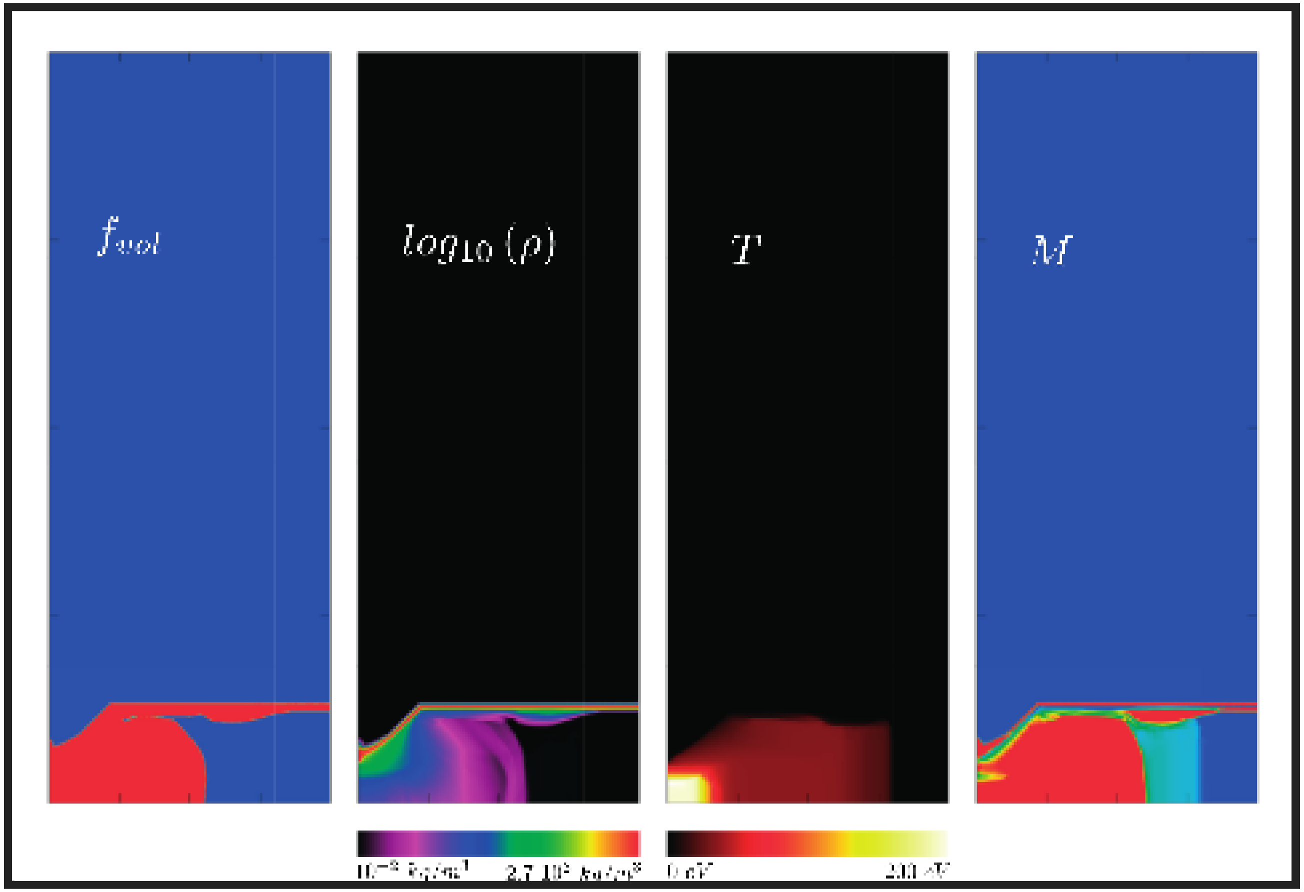
- Left: $\rho_{Xe} = 0.90\ kg/m^3$
- Right: $\rho_{Xe} = 1.65\ kg/m^3$

PLASMA JETS

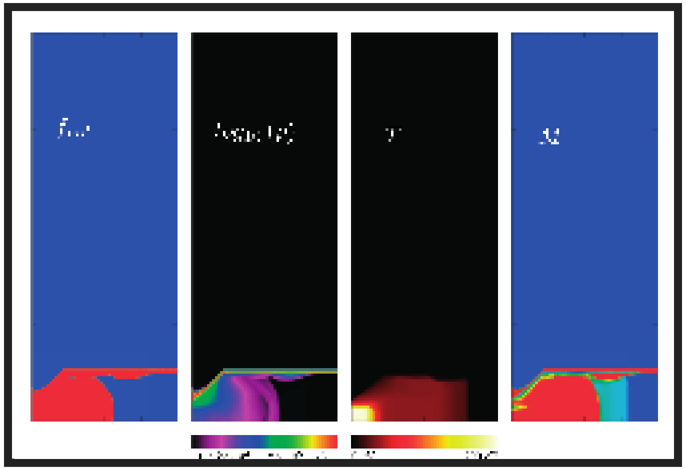
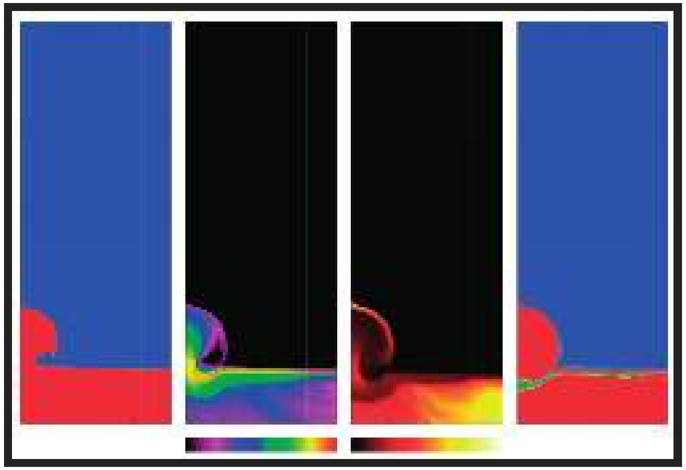
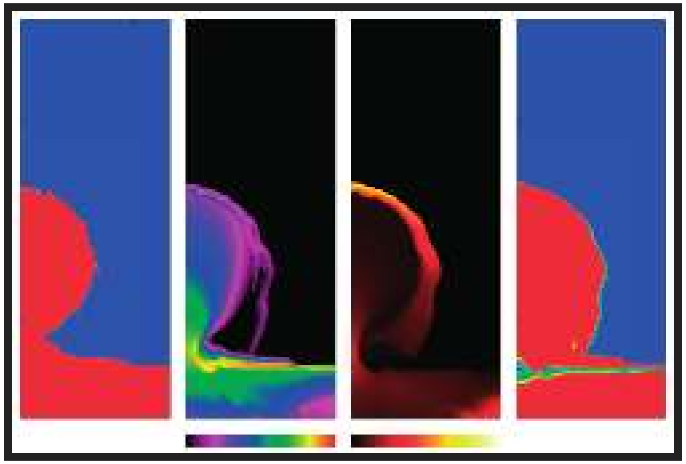
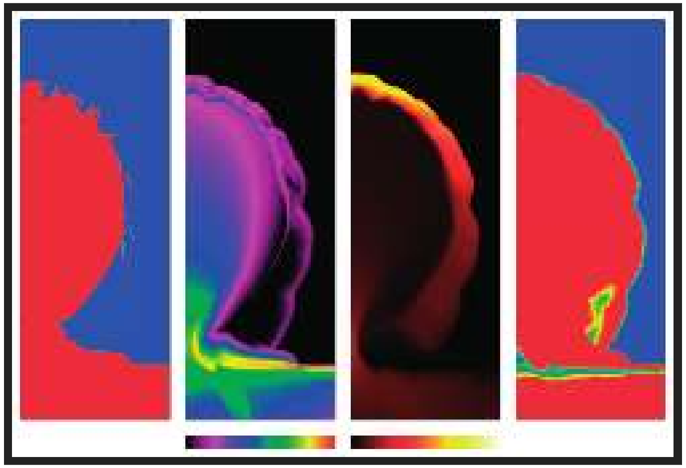


D. Portillo, "*Development of a numerical scheme for multimaterial fluxes in 2D for ARWEN*"

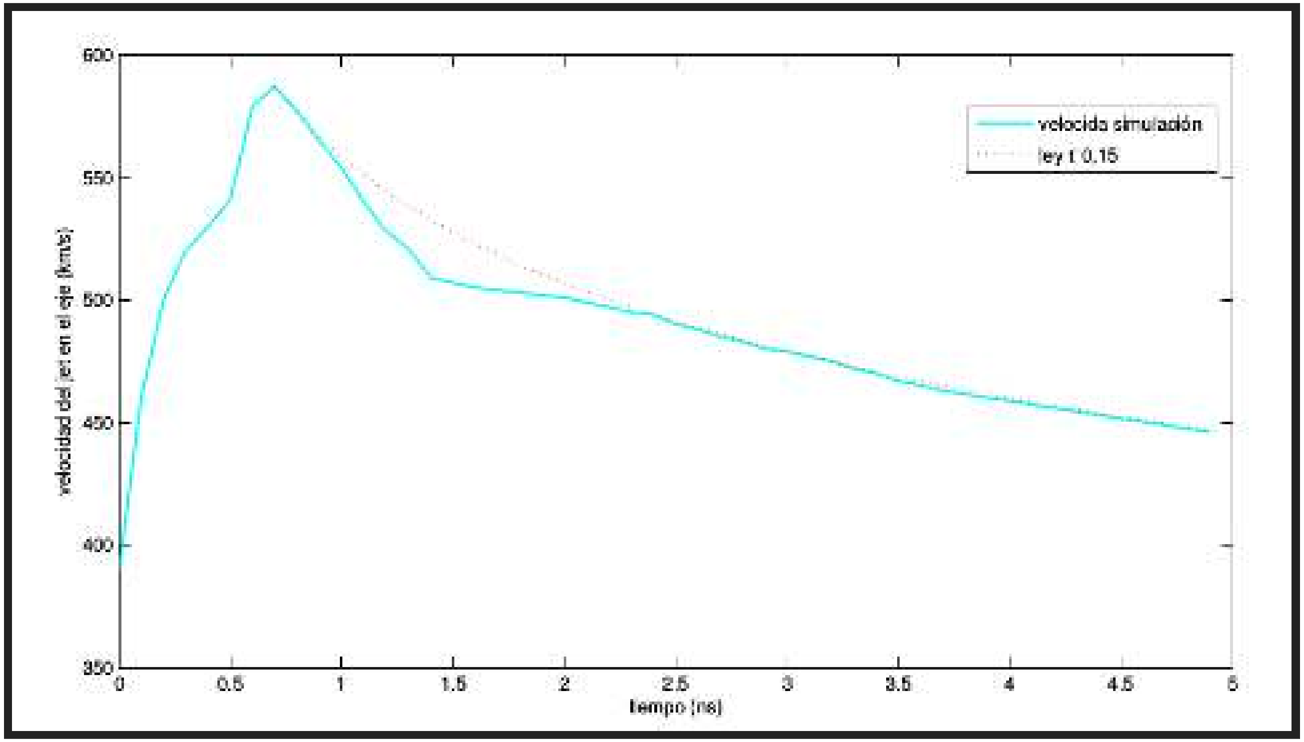
JETS



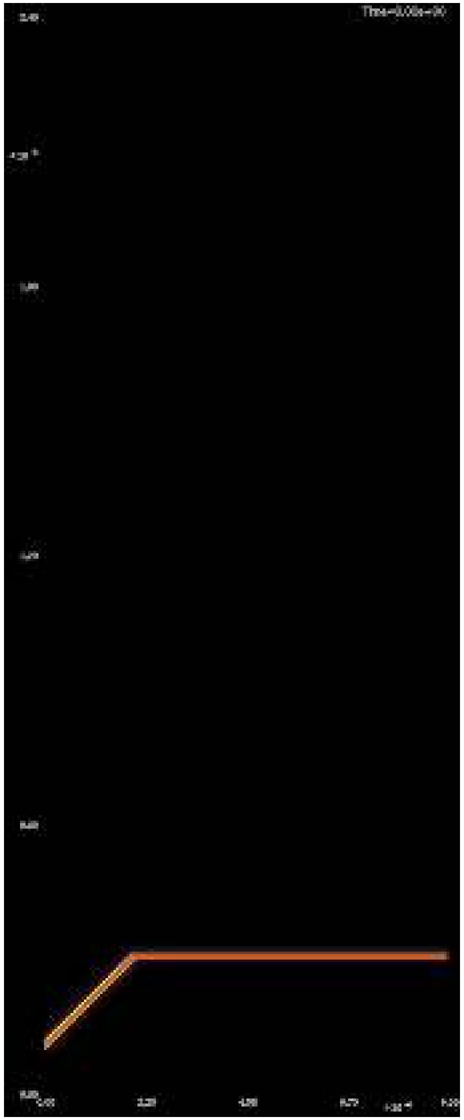
$t = 0.0$ (at laser peak intensity)

JETS



Evolution of the jet velocity in km/s compared to a decay power law $t^{-0.15}$.

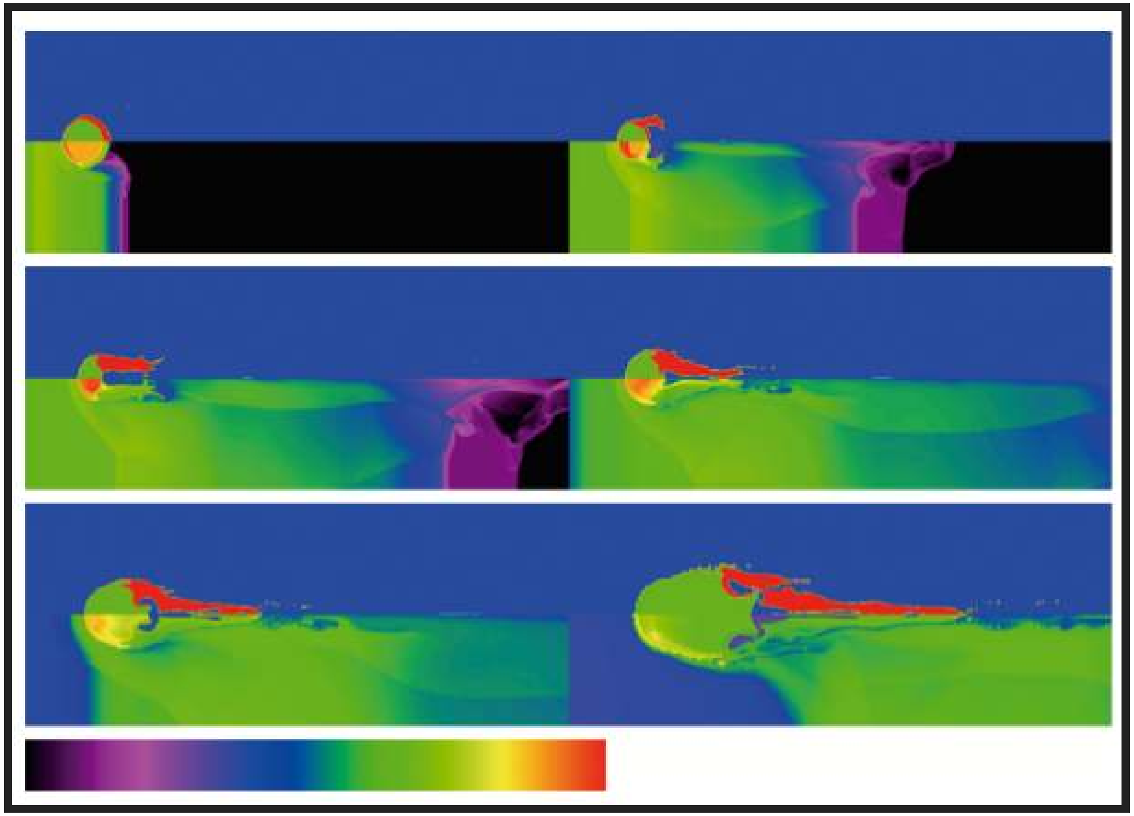


Play

Pause

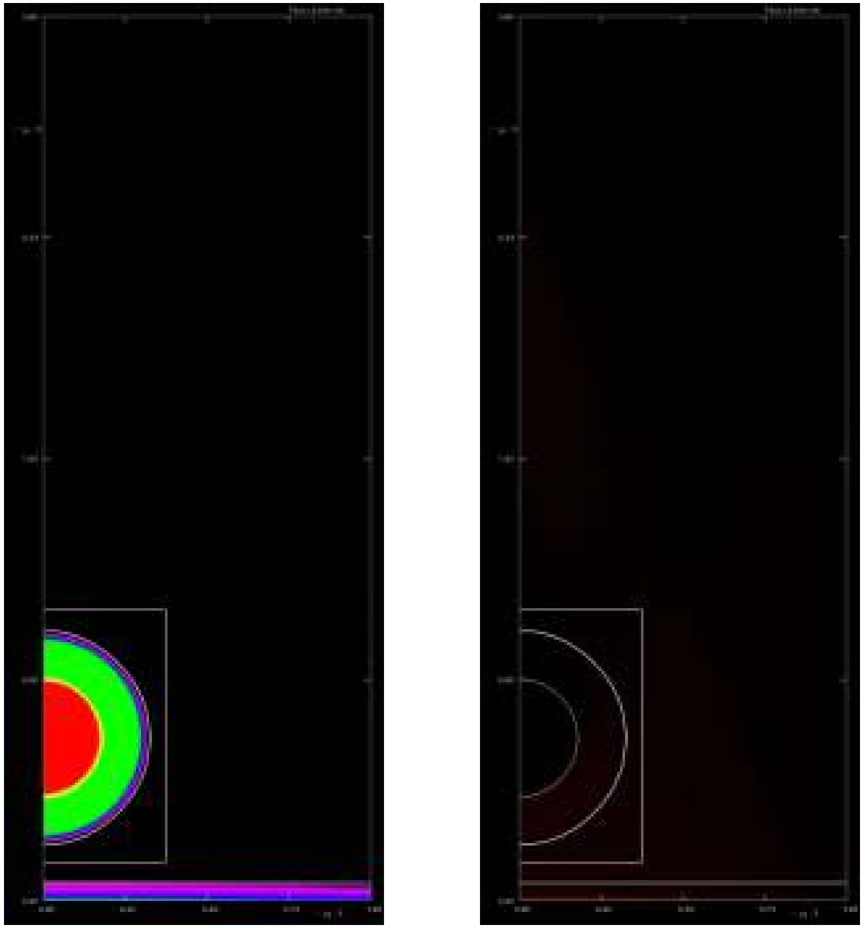
Resume

SUPERNOVAE REMNANTS



Six different snapshots of the evolution of the system that shows the density and the volumetric fraction.

The sopernovae remnant impacts the companion star and pulls out part of the mass of the atmosphere (low density envelope in our target).



- Left: density
- Right: temperature
- White lines are AMR boxes with different resolutions

Play

Pause

Resume

CONCLUSIONS

- Rad-Hydro coupling with AMR
- Robust methods
- Versatile: successfull application to LA, X-Ray secondary sources, ICF studies, etc.
- Continuous evolution and development

REFERENCES

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THANKS

ANY QUESTION?

This presentation has been made using free software:

- reveal.js
- git

Author, Manuel Cotelo Ferreiro (manuel.cotelo@upm.es)

Instituto de Fusión Nuclear - UPM

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