Advances in Radiation-Hydrodynamics and Atomic Physics Simulation for Current and New Neutron-Less Targets

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Abstract. We present advances in advanced fusion cycles, atomic physics and radiation hydrodinamics. With ARWEN code we analyze a target design for ICF based on jet production. ARWEN is 2D Adaptive Mesh Refinement fluid dynamic and multigroup radiation transport. We are designing, by using also ARWEN, a target for laboratory simulation of astrophysical phenomena. We feature an experimental device to reproduce collisions of two shock waves, scaled to roughly represent cosmic supernova remnants. Opacity calculations are obtained with ANALOP code, which uses parametric potentials fitting to self-consistent potentials. It includes temperature and density effects by linearized Debye-Hückel and it treats excited configurations and H+He-like lines. Advanced fusion cycles, as the aneutronic proton-boron 11 reaction, require very high ignition temperatures. Plasma conditions for a fusion-burning wave to propagate at such temperatures are rather extreme and complex, because of the overlapping effects of the main energy transport mechanisms. Calculations on the most appropriate ICF regimes for this purpose are presented.

1. Advanced Fusion Reactions in Inertial Fusion

Standard regimes for Inertial Fusion are based on the propagation of a fusion burning waves in a pre-compressed plasma. The onset of the fusion wave can be produced either by the implosion process itself, in the so called spark-ignition model, or by an external beam depositing the required ignition energy into a small volume and in a very short time, in the so called fast-ignition model.

In both cases, a fundamental requirement is to previously achieve a high density in the plasma, in such a way that the fusion burning process can take place before the mechanical disassembly of the capsule. In Deuterium-Tritium plasmas, the design window to meet this requirement (a sort of Lawson's criterion) is very broad, and no specific difficulties arise from it.

When addressing this case for advanced fusion cycles, such as proton-boron11, a main problem appears in relation to the burning temperature to be achieved. In particular for proton-boron 11, reactivity does not reach high enough values until the ion temperature achieves 200 keV. Therefore, this temperature must be reached both in the ignition phase and in burn propagation.

Achieving 200 keV in a central spark in the same implosion process used to compressed the target seems to be beyond feasibility, because the surrounding plasma would be at very high temperatures (above 20 keV) and the energy required to drive such implosion would be enormous. From this viewpoint, fast-ignition by external energy beams seems to be the best model for advanced fusion. Even so, igniting energy values needed for the microexplosion

onset are very high, and they inversely depend on density squared, within some standard assumptions[1]. So, there is a clear benefit in getting very high compressions in the target to be ignited.

Theoretically speaking, if the igniting beam is powerful and short enough, a fast-ignition process can be the onset for a fusion burning wave. However, the propagation of this wave is hampered by important energy losses mechanisms, particularly bremsstrahlung radiation and inverse Compton effect, which pump a lot of plasma energy out of the reacting zone[2].

The picture is significantly modified when the density of the precompressed target is so high that degeneracy effects become relevant. In such a case, bremsstrahlung emission, stopping of charged particles by electrons and other Coulomb collision processes are inhibited to some extent, and energy losses become much smaller [3].

Even so, plasma conditions for a fusion burning wave to propagate are very extreme, and it means that very special Inertial Confinement regimes had to be produced to succeed in burning advanced targets, such as proton-boron. The afore-mentioned conditions would only guarantee wave propagation if the energy loss mechanisms are as moderate as predicted [3] by first calculations on degenerate plasmas. Otherwise, very advanced fusion cycles would not be possible in Inertial Confinement. It is worth remembering that proton-boron 11 can not be exploited in magnetically confined plasmas, according to overall estimates of the energy gain[4].

In order to have better estimates, a work programme has been established inside our Institute, including the development of different approaches to characterize all mechanisms strongly modified by degenerate effects. The aim is to feature the rate of ion-electron energy transfer in such a case, and bremsstrahlung emission when electrons are severely affected by Pauli's exclusion principle.

Ion-electron coulombian interaction can be studied either by collective or individual interaction models, properly integrated by Fermi-Dirac distributions. This means that, in degenerate plasmas, only a minor fraction of the total number of electrons are actually able to gain energy from the hotter ions. Of course, as temperature increases, degeneracy becomes weaker, and the rate of ion cooling increases very much. The main objective of our study is to assess the density/temperature regime that a plasma must reach in precompression so that a fusion burning wave can expand across it, once it is started by a powerful beam of energetic protons.

2. Opacity Calculation

The possibility to obtain fast and accurate opacity data for a wide range of plasma conditions is very useful when we have to study the radiation emitted from laser-produced plasmas or astrophysical bodies. We have used, to determine opacities, analytical potentials reflecting the electronic structure of an ion inmersed in the plasma. This model allows calculate in a very fast way the energy levels in a wide range of ionic configurations. For ultra high-density plasmas we use the dicenter model (Idefix code[5]) to take into account the ionic correlation effects, considering perturbing ions through a quasiestatic external microfield. This model is used here as a reference one to the numerical results obtained with the model using the analytical potentials.

The advantage of the analytical potentials in the calculation of atomic properties for the study of hot plasmas with respect to self-consistent calculations is the considerable reduction in the computing time. This reduction becomes more important when we develop models that handle each configuration into the plasma.

We have developed an opacity code called ANALOP[6] to calculate optical properties for plasmas based on analytical potentials. For an ion having a nuclear charge Z and N bound electrons embedded in the plasma, it was proposed the following effective analytical potential[7,8].

$$U_{eff}(r) = -\frac{1}{r}\left\{(N-1)(\Phi(r)-\eta(r)) + \left[Z - N + (N-1)\eta(0)\right]e^{-ar} + 1\right\} \qquad (1)$$

where

$$\eta(r) = \frac{1}{2}a\int_0^\infty e^{-a|s-r|}\Phi(s)\,ds\,. \qquad (2)$$

a being the inverse of the Debye radius given by

$$a = \left(\frac{\rho Z^*(Z^*+1)}{kT}\right)^{1/2} \qquad (3)$$

Here ρ is the ion density and Φ(r) is a screening function given by[9]

$$\Phi(a_1,a_2,a_3,r) = \begin{cases} e^{-a_1 r^{a_3}} & , for\ \ N > 11 \\ (1-a_2 r)\,e^{-a_1 r} & , for\ \ 8 \le N \le 11 \quad or \quad N = 2,3 \\ e^{-a_1 r} & , for\ \ 4 \le N \le 7 \end{cases} \qquad (4)$$

with

$$a_k = c_{1k}Z^4 + c_{2k}Z^3 + c_{3k}Z^2 + c_{4k}Z + c_{5k}\,. \qquad (5)$$

The coefficients c_{ik} were obtained for the ground state of isolated ions from He-like to U-like[10].

This non-isolated parametric potential (1) has been obtained by solving the Poisson equation, assuming the linearized Debye-Hückel approximation, and taking into account the reaction of the plasma-charge density to the optical electron[7].

For a given ionic stage and into the context of the Independent Particle Model (IPM), the energy levels and orbital functions for each level (bound and free spectrum) are obtained by solving the Dirac equation using the effective potential given by (1). Because total energies are necessary for obtaining the ionic populations, an expression proposed in the Density Functional Theory[11] is used in ANALOP.

The expression of the bound-bound photo-absorption cross section for a given line is as following (in a_0^2, a_0 is the Bohr radius)

$$s_w^{abs} = 2p^2 a\, \overline{f(w)} \sum_l r_l \sum_u f_{u-l}^{abs} \qquad (6)$$

Here r_l stands for the populations of the lower mono-electronic levels involved in the transition, $\overline{\phi(\omega)}$ is the normalized Stark profile of the considered line. These profiles are calculated with the Pim Pam Pum (PPP) code[12] using as input data the energy transitions and oscillator strengths given by the ANALOP code.

In the equation (6), f_{u-l}^{abs} is the absorption oscillator strength, which is given into the context of IPM (the quantities in the equation are expressed in atomic units)

$$f_{ul}^{abs} = \frac{2\Delta E_{u-l}}{3g_l} \left| \langle \psi_u | r | \psi_l \rangle \right|^2 . \qquad (7)$$

Here $\Delta E_{u\text{-}l}$ is the transition energy, ψ_k is the normalized wavefunction associated to the monoelectronic level k, and g_l is the statistical weight of the initial level.

The absorption coefficients for the bound-bound transitions have been evaluated, through the following expressions

$$k_w = N_l s_w^{abs} \qquad (8)$$

where s_w^{abs} stands for the photo-excitation cross section, N_l is the abundance of ions in the initial state of the transition which is calculated with M3R code[13] using ANALOP energies and oscillator strengths.

In figure 1 we present the absorption cross section for aluminum Lyman β for the macroscopic parameters Ne = 5.10^{22} cm^{-3} and Te = 500 eV. The plasma coupling parameter Γ, corresponding to these conditions is 1.1. It can be seen from the figure some discrepancies between the non-isolated analytical potential and the dicenter model. These discrepancies were expected, because of the use of the Debye-Hückel approximation in the determination of the non-isolated potential which is not valid at high densities, i.e. Γ>1. On the same figure we give results from the ion sphere potential model, which are very close to Idefix results.

The analytical potential shows its applicability at low densities, i.e. with a coupling parameter less than one. In this range of density this potential reproduces the main effects of the plasma environment on the atomic magnitudes, such as the continuum lowering and the red shift of the lines with respect to the isolated situations, however, for low density the dicenter model is inapplicable.

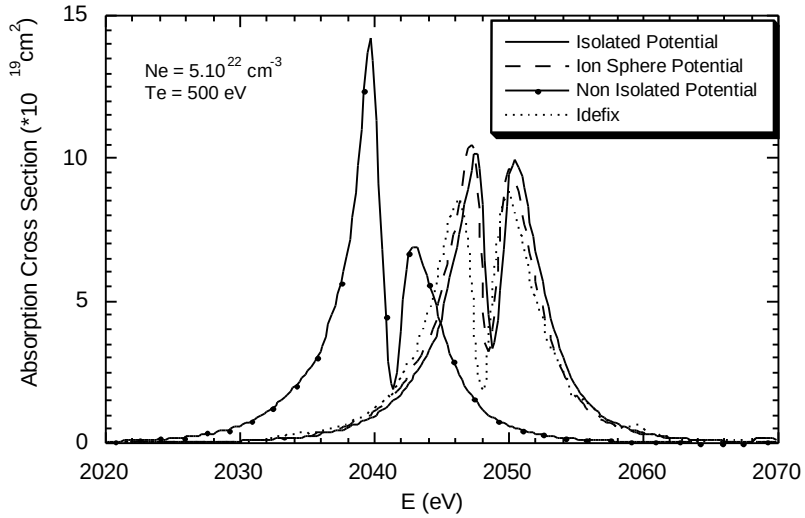

FIG. 1. Absorption cross section for the aluminum Lyman b. G = 1.1.

3. Numerical Simulation of High Energy Processes

The collision of the two supernovae remnants has been observed recently in the DEML-316 object[14,15] at the Large Magellian Cloud. While some data is available about this collision, there are many uncertainties associated with the details of the interaction between the two remnants. We have designed an experimental target to reproduce some details of this interaction. As shown in[16], we have similarity flow when the Euler number ($Eu = v\sqrt{r/p}$) of the remnant and laboratory target are the same. By modifying the materials and densities of the target we can reproduce by similarity supernovae remnants of different ages. In our case, the remnants are quite old and Eu takes values close to 1.

For the simulations we use two computer codes, one for the laboratory target and the other for the supernovae remnant. The ARWEN[17] code, which is suitable for the laboratory simulation, is a 2D Adaptive Mesh Refinement (AMR) fluid dynamic and radiation transport code. It has been used for designing and analysing several experiments and conceptual designs. The radiation intensity is calculated with a discrete ordinates scheme in multigroups of energy[18] coupled to the adaptive algorithm. For the simulation of the supernovae remnants, we use an astrophysical simulation code[19] based in the 3D Smooth Particle Hydrodynamics (SPH) with nuclear burning.

Simulations are done on a SiO2 and Al targets, with 125 J laser at 0.25 μm. Initial densities are adjusted to obtain the double shock strurcture and Euler number close to 1. Previous simulations[20] were done with much lower energy and smaller scales. But we still can use Carbon doping of the target to analyze the collision process. Profiles of density and temperature are very similar to those in[20], being the temperature represented in figure 2. Euler number on both shock waves are represented in fig 3 along the axis of the laser. In this plot we can see that the Euler number is close to 1 in the forward shock.

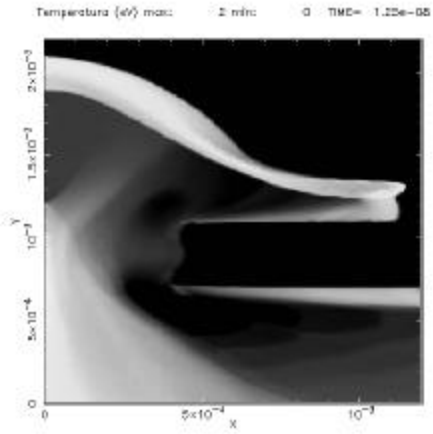

FIG. 2. Electron temperature at 12.5ns.

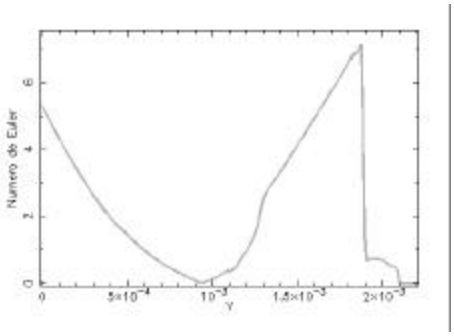

FIG. 3. Euler number along the simmetry axis.

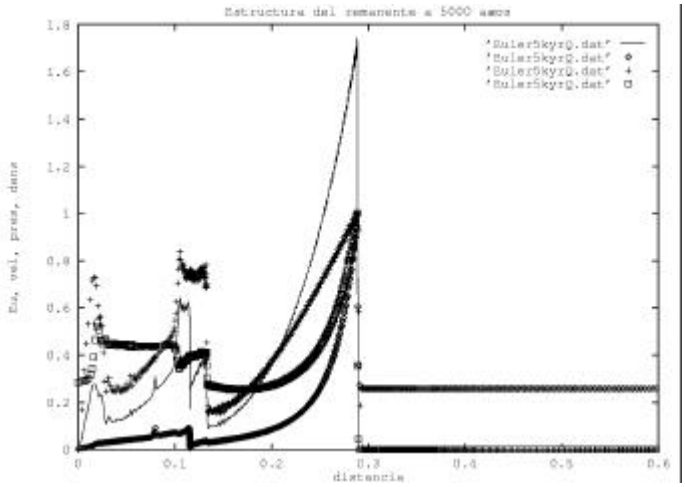

FIG. 4. Density, temperature, velocity and Euler number profiles at 5000 y.

The actual profiles of the 5000 y.o. supernovae remnant are represented in fig 4, and are similar to those of the laboratory target represented in[20]. The profiles resemble those selfsimilar described in[21], with uniform interstelar medium and with a r^{-12} law of the density in the expanding shell.

Our goal in this kind of design is to meassure the temperature and velocity of the collision point, and to determine the stability of the collision plane. In this first proposal, only the

temperature can be meassured, but we are developing more elaborated designs in order to be able to obtain the other above mentioned quantities.

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