Recent results on fast ignition jet impact scheme

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Abstract: We present recent developments in the design of the fast ignition jet impact concept [1, 2]. This scheme, unlike the previous designs proposed so far, need only one driver for the whole process to ignition. In the jet impact case, the ignition of the compressed core is produced by hypervelocity jets[3, 4] generated during the process. The collision of jets converts their kinetic energy into thermal energy of the nuclear fuel, which is expected to produce ignition under proper design. Recently we have improved the design, increasing the efficiency of the jet production process and we have explained theoretically the production of jets with the small angle liner cones, seen in some numerical simulations. Now we explore the use of low Z materials for the jets, with better properties for the interaction between the jet and the compressed core. First laser experiments of jet production by collapsing a Al cone target are presented, and jet velocities of 1.5×10^7 m/s with laser intensities of 3.5×10^{14} W/cm^2 are measured.

1 Introduction

Fast ignition [5, 6] targets usually require two energy sources, one for the compression of the target and the other to start the ignition in the compressed target. The idea is to transform part of the X-ray energy from the hohlraum cavity[7] or to use directly the laser driver to generate a high speed, medium density jet. This jet will collide with the compressed target starting the ignition of the DT fuel. The *FIG.1* shown the schematic designs, with the 2-cone structure, one for guiding the target, and the other one inside for producing the cumulative jet. The cone angle is the first parameter to fit, because if this value is increased, the obtained jets will have higher mass but lower velocity. For gold cones, angles smaller than 27^o usually produce low mass irregular jets. For low Z cones, we have observed the production of jets below the critical angle, an effect that we can explain in terms of the dynamics of the jet production. The other parameter is the separation between the conical liner and the center of the target. The timing is important, as the jet impact is to take place when the target reaches an acceptableρR value. The optimal cone angle and gap width is not clear by now, as preheating of the cone walls reduces dramatically the efficiency of the jet production process.

We have use an Adaptive Mesh Refinement (AMR)[8] 2D CFD radiation transport code (ARWEN) [9] to simulate both the jet production and the interaction with the compressed target. Because the code use a full radiation transport formulation[10], the preheating is well simulated. The AMR technique allows to keep constant the numerical error by concentrating refining locally the mesh in the more complicated part of the flow. All the simulations give velocities and momentum of the jet below the limits for fast ignition ($1-2\times10^6$m/s), but we are continuously increasing these numbers as we modify the design. Another way to improved

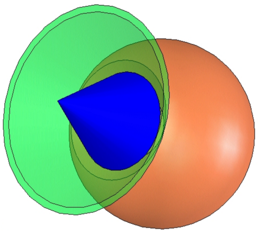

Figure 1: Schematic view of the jet impact fast ignition target with the conical liner (blue) and guiding Au cone (green)

the production and coupling between jet and target is to use the second structure produce when the jet is first produced. This structure consist of higher mass but lower velocity of the jet, but with its velocity can be increased changing the cone profile. The limiting case is to join both structures, making a direct mass accelerated with cumulative effect. This double structure has been observed since the fast ignition jet impact scheme was first proposed[11].

First section describe the types jets produced in laboratory, attempting an explanation for the lower limiting angles found in simulations. Next section describes the jet experiments recently performed in the PALS iodine laser facility. The last section describes the conditions for the jets to produce the ignitor.

2 Jet production

The jets produced in laser facilities are usually radiative jets, as a result of the collision of plasmas on an axis[12, 13]. Adiabatic jets are obtained as a cumulative effect, when shcok accelerated matter collapses on an axis. The production of adiabatic jets by collapsing a conical liner have been known and theoretically explained since 1940's[14, 15, 16]. Jets velocities higher than 10 km/s were easily obtained. This kind of jets have been obtained too accelerating the liner using a electrically exploded conductor[17]. But only recently have been obtained adiabatic jets by laser driven collapsing of a conical liner. The velocity and temperature of adiabatic jets tend to be lower that the radiative jets, but with higher density.

Adiabatic jets can be easily produced by collapsing a hollow cone on its axis. In this case a jet will be formed if cone angle is higher than some critical value that depends of the velocity and temperature of the collapsing cone. According to the *FIG.2*, the Rankine-Hugoniot conditions of the oblique shock structure are

$$\begin{aligned}
U_0 \cos(\phi+\chi) &= U \cos\chi \\
\rho_0 U_0 \sin(\phi+\chi) &= \rho U \sin\chi \\
p - p_0 &= \rho_0 U_0 \sin(\phi+\chi) - \rho U \sin\chi \\
e - e_0 &= -\frac{1}{2}(p+p_0)\left(\frac{1}{\rho}-\frac{1}{\rho_0}\right)
\end{aligned}$$

Solving these equations in ϕ and u we get the condition for the existence of the oblique shock wave

$$M = \frac{u}{c_0} = \sqrt{\Pi}\tan\phi_c \sqrt{\frac{2(1+\tan\phi_c)}{1-\tan\phi_c}}$$

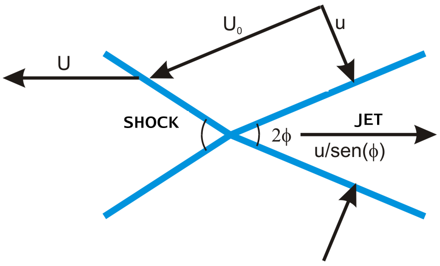

Figure 2: Sketch of the regular reflection case for 2 plate collision. u is the plate velocity and ϕ the semiangle of the cone.

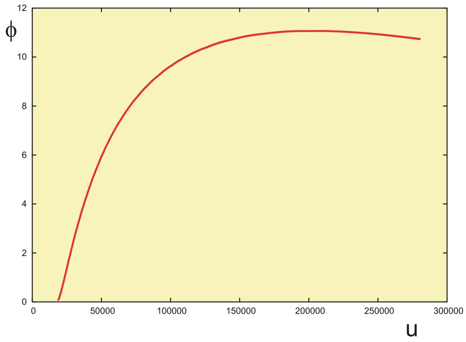

Figure 3: Critical angle as a function of the maximum cone (plate) velocity allowed to produce a jet.

where $u = U_0 \tan\phi$ is the plate (cone) velocity and c_0 is the sound velocity of the plate and $\Pi = \frac{p-p_0}{c_0^2(\rho-\rho_0)}$ measures the shock intensity. For low intensity shocks, $\Pi \approx 1$ and

$$M \approx \sqrt{2}\tan\phi_c \tag{1}$$

For high intensity shocks, Π is higher and critical angle ϕ_c increases at lower rate than shown in 1. The decreasing in the critical angle will be even higher if we take in account the real equation of state (EOS), when dissociation and ionization produce a kink in the Hugoniot, increasing the value of Π. Using a real EOS and supposing that the initial state is the final state of a shock crossing the cone, we obtain the curve shown in *FIG.3*, where the critical angle increases slower for higher plate velocities. It could explain why in some simulations we obtain jets with lower cone angle than ϕ_c deduced for low intensity shocks. Because the velocity of the jet is close to

$$v_j = u(1/\tan\phi + 1/\sin\phi) \tag{2}$$

lower angles means higher velocities, but lower densities too. By combining cone profiles and pulse shaping, we expect obtain in simulations velocities higher than 1000 km/s for 290 eV holhraums. In *FIG.4* we show the density and velocity profiles of a jet produce by a 30^o Al cone. By decreasing the angle to 15^o, keeping the rest of the parameter, we obtain 850 km/s of jet velocity, but extremely low densities ($\approx 10^{-2}$ kg/m^3). This data is consistent with the result of classical conical jet theory

$$m_j = m\sin^2\frac{\phi}{2} \tag{3}$$

being m_j the jet mass and m liner mass per unit length.

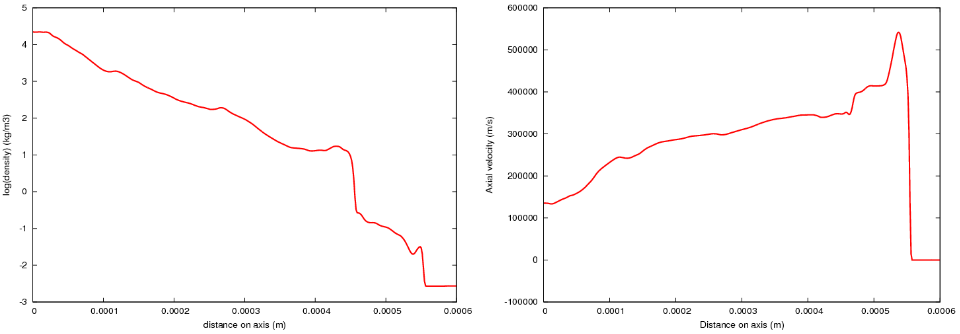

Figure 4: (left) Density in log scale (kg/m^3) and V_z (m/s) for AL 30^o cone with an illumination of 290 eV radiation temperature

3 Jet experiments

Experiments are being done at PALS iodine laser that could check some of the computational results done up to now. This laser provided a 0.4ns (FWHM) pulse with the energy of 100J at the first harmonic ($\lambda = 1.315\mu m$) and focal spot radius of 150 μm on the target (the focal point was located inside the target). In this case the laser intensity on the flat target surface was 3.5×10^{14}W/cm^2. The cones were made of a 9μm thick Al foil and their radius at the basis was set to 300μm. Two cone semiangles were used: 30^o and 45^o. The average cone wall thickness were 5.2μm and 6.4μm for the 30^o cone and the 45^o cone, respectively. The electron density was measured and plotted in *FIG.5*, where we the sequence of jet production is clearly seen after 3 ns. According to these plots, average jet velocities are $100 - 200$ km/s. This is the first time that adiabatic jets are obtained by irradiating cone targets.

The jet structure es better former in the 45^o case that in the 30^o, result consistent with the simulations, but we expect much higher velocities in the 30^o case, something that is not observed in the experiments.

4 Jet parameters

The parameters of the jet, velocity and mass, are described in [18]. For energy fluence of 200 MJ/cm^2, energy needed to heat the ignitor of 0.25 g/cm^2 to 7.5 KeV, the density ρ_j and velocity v_j of the jet are related to the density ρ of the ignitor by

$$\frac{\rho_j}{\rho} = \left(\frac{410\ \mathrm{km/s}}{v_j}\right)^3 \qquad (4)$$

so for a ratio of 100 in density between ignitor and jet, we need a velocity of the jet higher than 1900 km/s, and for a ratio of 20, we need velocities higher than 1100 Km/s. In our numerical simulations we have not get jets with these characteristics, but with the double structure shown at [11] and in 4, it seems feasible to get closer to these numbers. In the fig. 6 both jet production and shell implosion are simulated with ARWEN code. The target 1 is driven by 290 eV hohlraum temperature, heating up to 2 KeV the compressed shell. In all the simulations we have found the low density jet follows by a higher density matter (*FIG.4*) with slightly lower velocity than the jet. We also have obtain jets with laser energies range from 15J to 100 kJ,

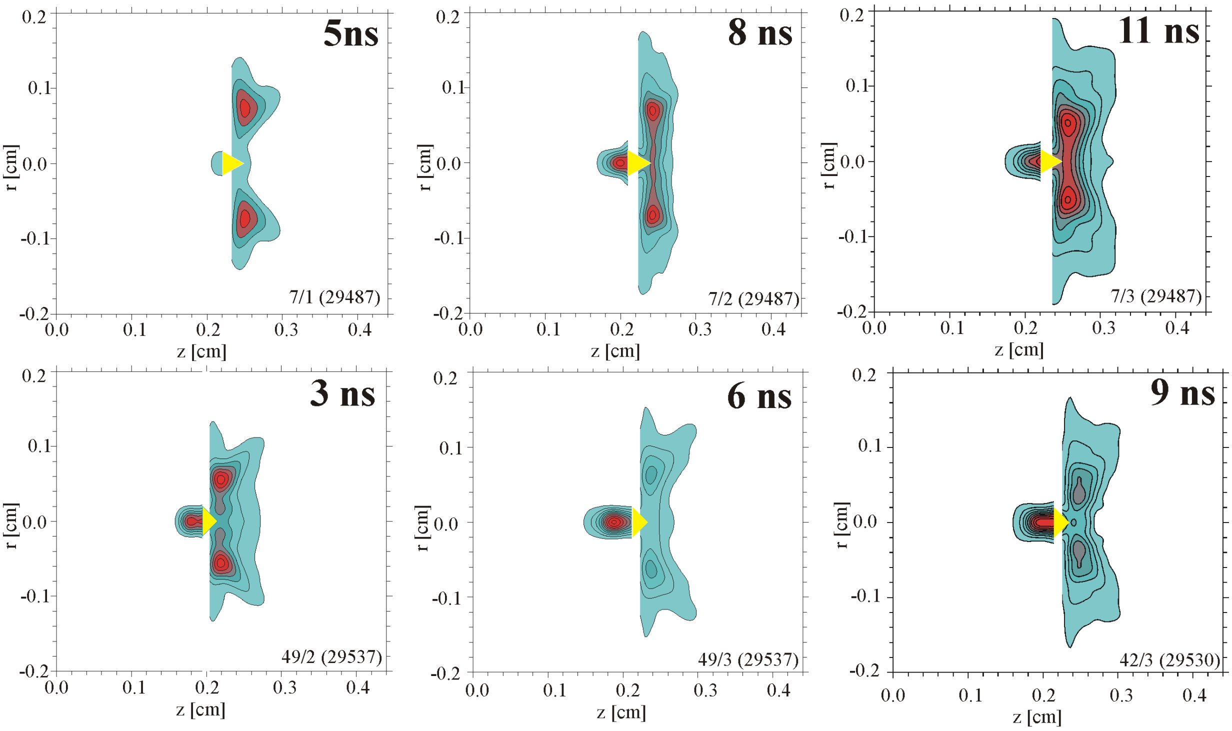

Figure 5: The sequences of the measured electron density isocontours for the 30^o cone (top) and the 45^o cone (bottom). Before 2ns no jet is detected.

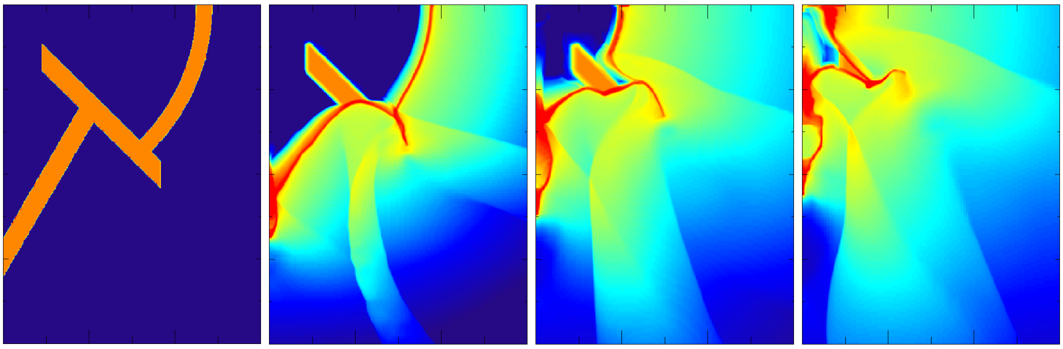

Figure 6: Temporal evolution of the jet production and target compression of the 1 target, for 290 eV hohlraum.

both direct and indirect drive. Uniformity of the laser illumination in the direct drive case is important for producing stable jets, as the collapsing process should be as uniform as possible.

5 Conclusions

Results from numerical simulation of the jet impact fast ignition concept explain the reduction of the critical angle for jets produced by strong shocks. It could open the possibility to increase even more the velocity of the jets by reducing the angle of the cone. By first time, experimental results have demonstrate the production of adiabatic jets by externally illuminate a cone target. The jet velocities measured are still well below the minimum to be practical for fast ignition scenario, but shaping the cone profile and material should increase the jet velocity and density.

Acknowledgements

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References

[1] VELARDE, P. et al., Laser and Part. Beams **23** (2005) 43.

[2] VELARDE, P. et al., Nuclear Inst. and Meth. in Phys. Research **544** (2005) 329.

[3] ZABABAKHIN, E. et al., *Unlimited cumulation phenomena*, Nauka publishers, Moscow, 1990.

[4] ET AL., P. V., Laser Interac. and Rel. Plasma Phen. **406** (1997) 182.

[5] ET AL., M. T., Phys. Plasmas **1** (1994) 1626.

[6] DEUTSCH, C., Eur. Phys. J. Apply Phys. **24** (2003) 95.

[7] LINDL, J., Phys. Plasmas **2** (1995) 3933.

[8] BERGER, M. et al., J. Comp. Phys. **82** (1989) 64.

[9] OGANDO, F. et al., JQSRT **71** (2001) 541.

[10] ADAMS, M. et al., Progress in nuclear energy **1** (2002) 3.

[11] VELARDE, P. et al., Target ignition by jet interaction, in *Inertial fusion sciences and applications 2003*, edited by HAMMEL, B. et al., pages 88–91, American Nuclear Society, 2004.

[12] SHIGEMORI, K. et al., Phys. Rev. E **62** (2000) 8838.

[13] KASPERCZUK, A. et al., Phys. of Plasmas **13** (2006).

[14] BIRKHOFF, G. et al., J. Appl. Phys. **19** (1948) 563.

[15] WALSH, J. M. et al., J. Appl. Phys. **24** (1953) 349.

[16] CHOU, P. C. et al., J. Appl. Phys. **47** (1976) 2975.

[17] AULUCK, S. et al., IEEE transactions on Plasma Science **31** (2003) 725.

[18] ET AL., J. M.-V., Laser Interac. and Rel. Plasma Phen. **406** (1997) 206.