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EVIDENCE OF RAYLEIGH-TAYLOR INSTABILITIES IN TRI-LAYER TARGETS

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EVIDENCE OF RAYLEIGH-TAYLOR INSTABILITIES IN TRI-LAYER TARGETS

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INTRODUCTION

In laser fusion, the Rayleigh-Taylor (RT) instability represents a major obstacle by destroying the spherical symmetry of the imploding shell, thus leading to a degradation of target performance [1,2,3,4]. During implosion process, this instability may occur at the ablation layer on the outer surface, at an internal interface, or at the fuel-pusher interface during the deceleration phase. If the instability grows enough, it will buckle or break the shell and will cause fuel mix.

Experiments have been carried out at Limeil on P102 laser system in order to investigate the problem of target stability under ablative acceleration and to get direct evidence of RT instability [5]. Main experimental results are reported here.

Numerical simulation have been performed with the 1-D hydrocode FCI1 coupled with a simple mixing model. We present, in the following text, part of our numerical investigations which support the occurrence of a mixed layer.

I - EXPERIMENTS

I.1 - Experimental set-up

Tri-layer targets Au/Al/Au are accelerated by a main laser beam. The RT instability is thought to occur at the rear interface Al/Au where the pressure and density gradients are opposed. The front Au layer function is to smooth the energy deposition and to avoid a straight heating of the Al layer by the laser.

To evidence an Al-Au mixing, the rear surface composition of the target is diagnosed by using a probe laser beam being delayed with respect to the main beam. If the Al-Au mixing is quite developed, this probe beam heats up the rear mixing boundary; Al X-ray lines are excited and are observed with a spectrograph [6].

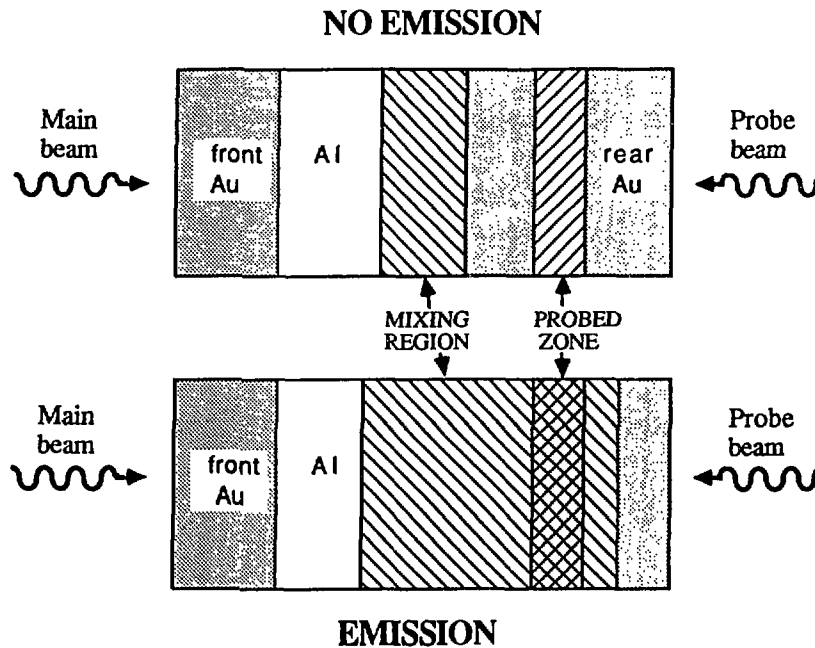


FIGURE 1
Schematic of experiment principle : Al emission is observed when the mixing region is well developed.

The main laser beam is at $0.35 \mu\text{m}$ and is focused from 10^{13} to 10^{14} W/cm^2 on target in a $180 \mu\text{m}$ diameter spot (its energy ranges from 1 to 11 J). The pulse is a sum of two gaussians with a 0.8-1 ns FWHM (full width at half maximum).

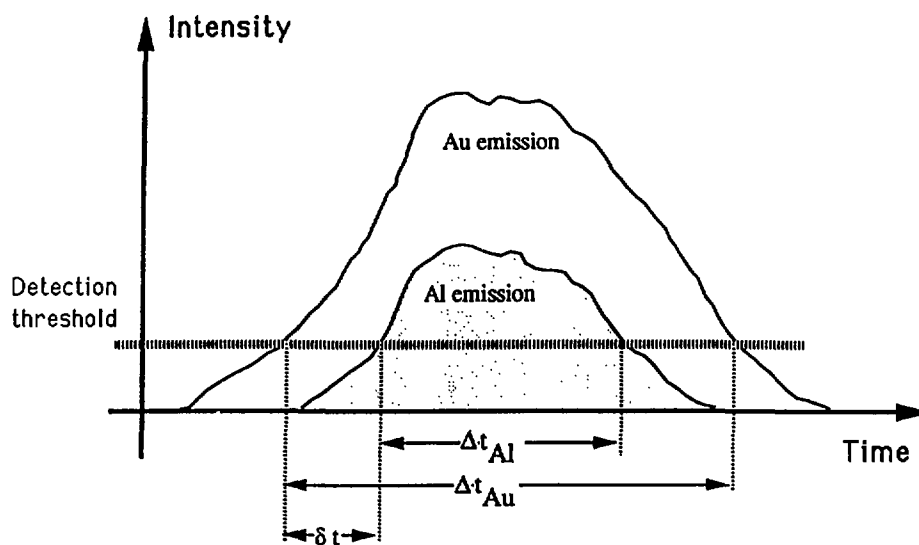
The probe beam is at $1.06 \mu\text{m}$ and is focused to $3 \cdot 10^{13} \text{ W/cm}^2$ in a $180 \mu\text{m}$ diameter spot (its energy is 11 J); it is delayed by 1 ns relative to the main beam, and has a similar pulse shape with a 900 ps FWHM.

The X-ray spectrum from the rear target surface is measured in the range 1.4-2.7 keV with two spectrometers : the first one (TIS) temporally integrates the Al-lines, and the second one (TRS) gives the temporal resolution.

Typically the thickness is $0.3 \mu\text{m}$ for Au foils and 1 or $2 \mu\text{m}$ for Al foil.

1.2 - Benefit of time-resolved spectrometer (TRS)

The TRS supplies us with the intensity of lines emissions in the range 1.5-1.7 keV for Al ions and in the range 2.3-2.5 keV for Au ions; in addition, it gives us the durations and the shift between both emissions. Only the intensities higher than the detection threshold are experimentally observed.



($\delta t > 0$, if Au emission occurs before Al emission)

FIGURE 2
Schematic illustration of experimental data obtained with the time-resolved spectrograph (TRS).

The temporal shift δt gives informations about the depth of the mixing zone : δt is all the higher as the non-polluted Au thickness is large. For a small unmixed Au layer, the Al line emission may start before the Au emission, so that δt is negative.

X-ray lines emissions should enable us to get an evaluation of the mixing zone composition. To this end, it has been necessary to calibrate the intensity of emission for mixed Al and Au samples of which ions ratios were known. This step was followed by an other set of samples covered with Au, in order to point out the effect of a non-polluted Au layer.

Emission durations may drive numerical simulations. Comparisons between experiments and computations require the knowledge of emission threshold, and are proving hard to deal with.

Au emission in the Al lines range has to be subtracted. As signals are noisy, this systematic correction is approximate and we have to be very cautious in temporal shifts and lines intensities interpretation.

The advantage we should reap from TRS is illustrated at Figure 3 where results obtained with three samples are presented :

- two mixed Al-Au samples with different ions ratios are well characterized by emission levels and by temporal shift.
- two identical mixed Al-Au samples, one of which is covered with a Au layer, yield very different results.
- in spite of similar emissions, the temporal shift let us differentiate the (20%Al, 80%Au) sample to the (50%Al, 50% Au)+0.04 μm Au sample.

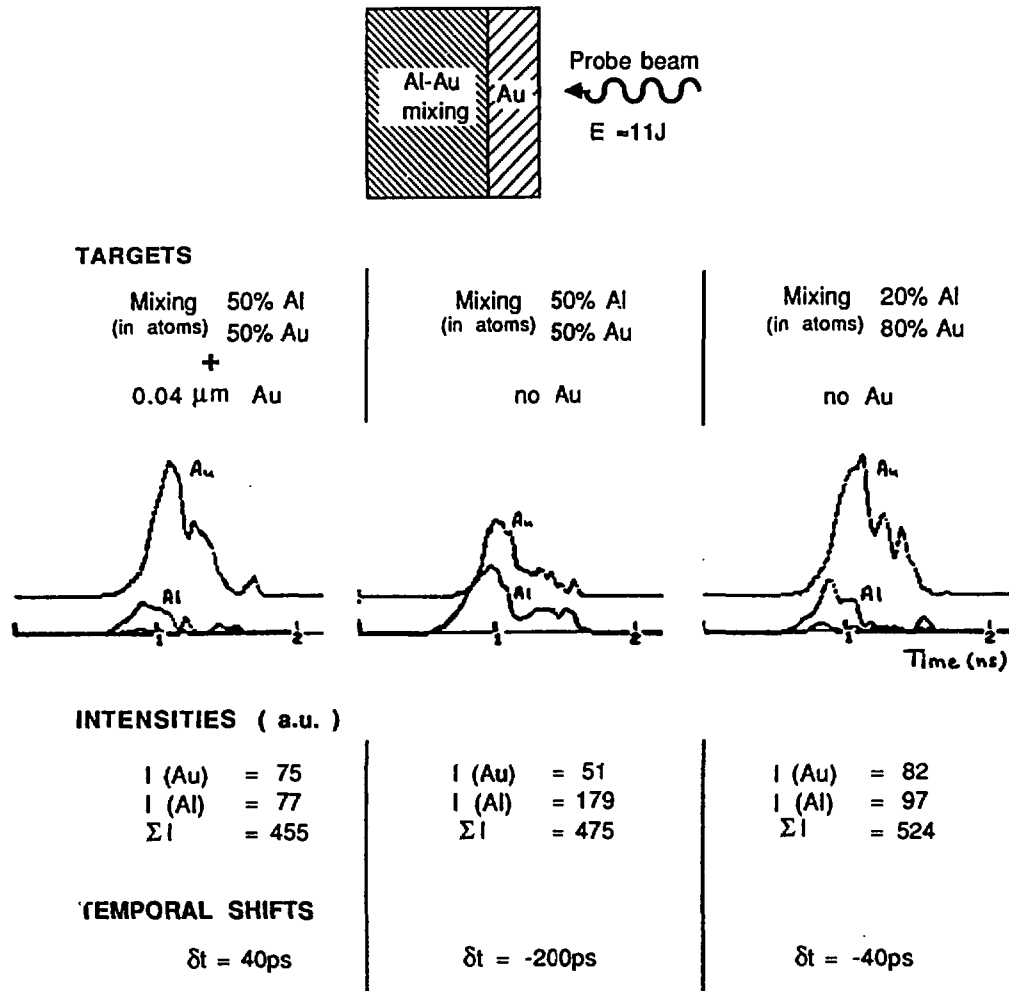


FIGURE 3

Experimental spectra obtained with the TRS. The intensities of Au emission, Al emission and the whole emission, and the temporal shift between Au and Al emissions are given for three different targets.

1.3 - Experimental results

The front gold layer prevents the Al layer from a direct heating and smooths the energy deposition by radiation. Former experiments carried out at Limeil have shown that for a 0.3 μm gold layer the pressure asymmetries at the ablation surface are reduced by a factor 3-4 [7], which may ensure the absence of large-scale instabilities due to irradiation non-uniformity. In the present experiment, optical smoothing with the "Random Phase Plates" technique (RPP) has been realized during last shots; as results obtained with and without RPP are similar, it has confirmed that large-scale illumination non-uniformities are not responsible for the apparent mixing.

Preliminary experiments have been realized to determine the ablation depth in order to make sure that, in the initial configuration, the Al layer cannot be heated by the probe laser beam. Two-layer targets have been irradiated with the probe beam : over 0.1 μm gold thickness, the Al He_{α} line emission is below the experimental threshold. A 0.3 μm rear gold thickness assures us that there will be no emission in the absence of mixing.

Figure 4 gives the Al line energy versus the main laser energy with a 2 μm Al foil tri-layer target. Despite the 0.3 μm gold thickness, the Al line appears, therefore some mixing occurs. Dispersion of the data is due to the very small signals receive on the spectrograph. Al line emission, which is our mixing signature, appears between 2 and 4 J, and increases with the main beam energy.

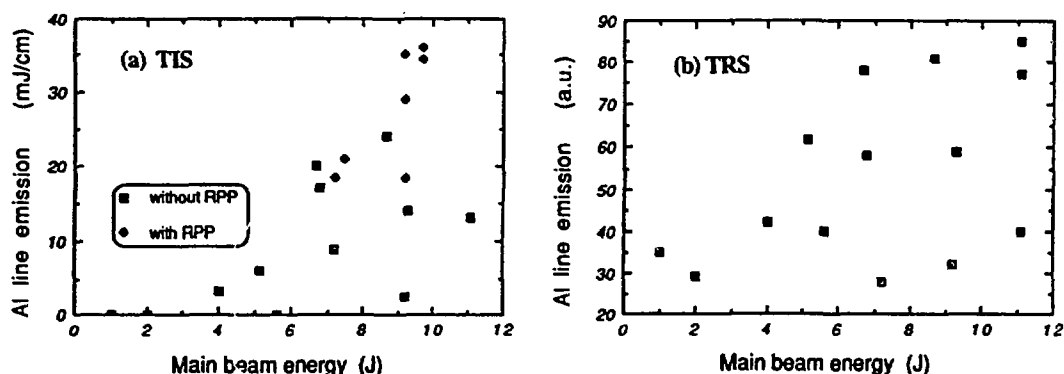


FIGURE 4
Al line energy versus main laser energy : experimental results obtained from the TIS (a) and the TRS (b) (for the TRS, Au emission has not be subtracted so that emission is not zero at small energy).

Temporal shifts between Au and Al emissions obtained with the TRS scatter close to $\delta t = 0$, which means that both emissions occur quite simultaneously whatever is the main beam energy.

In order to assess quantitatively the mixing composition, we measured the Al line emission by irradiating samples with pre-made mixing layers of variable Al-Au ions densities. As the rear Au layer may

be non-totally polluted, we made measurements again with these samples coated with Au. With the help of TRS signals, for a main beam energy in the region of 10 J, the composition of the probed zone seems to correspond to a 20 % Al ions density mixing zone with a Au layer in the range 0-40 nm.

We made another set of experiments with 1 μm Al foils instead of 2 μm . Data obtained with these tri-layer targets exhibit an opposite behavior : the mixing becomes smaller as the main energy increases from 5 to 10 J. In the same time, the temporal shift grows: Al emission starts before Au emission at low energy , in a less and less marked way as the energy increases, till the Au emission occurs first at high energy.

The distinct behaviors of 1 μm and 2 μm are analysed in the next section.

II - NUMERICAL RESULTS

Numerical simulations have been performed with the monodimensional hydrocode FCI1 coupled with a mixing code which is a rough modeling of ordered energy conversion into disordered energy. This mixing code is a static model and evaluates masses of mixed Al and Au as a postprocessor at each step of the calculation.

FCI1 is run with the ionization model MM (Mixed Model /8/) to obtain relevant Au emission.

The temporal shape of the interface velocity depends strongly on the energy and on the shape of both laser pulses, and on the delay of the probe beam. Typical interface velocity and acceleration plots are shown in Figures 5 and 6. In this case, the Al layer thickness is 2 μm and main and probe beam energies are respectively 6.7 J and 10.7 J.

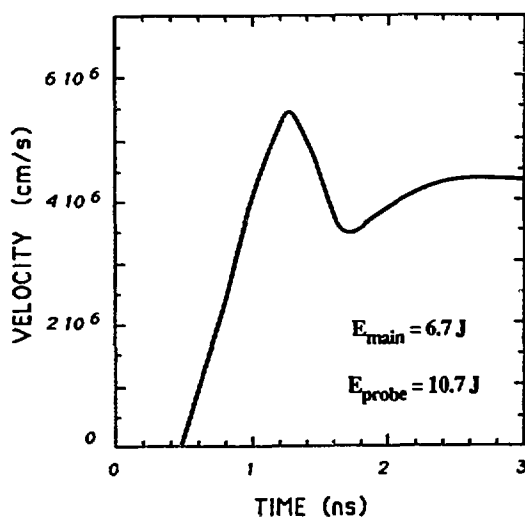


FIGURE 5
Al/rear Au interface velocity
versus time.

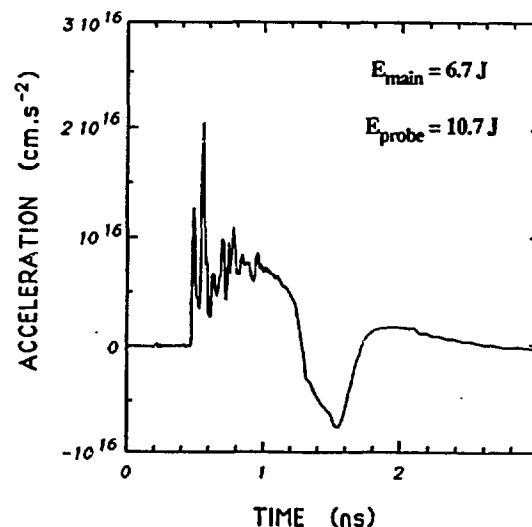


FIGURE 6
Al/rear Au acceleration
versus time.

The probe beam is responsible for the deceleration; this slowing down of the interface is followed by another positive acceleration phase due to the decompression of target material related to the deposition of rear Au X-ray energy. The Richtmyer-Meshkov (RM) stage (when the shock goes across the interface) is short, and the RT stage plays a prominent part. As long as the velocity increases, we may consider that the acceleration process is RT unstable. We recall that we do not use grooved targets, but the instability growth originates from the interface roughness. As the probe beam is delayed, perturbations have time to develop and induce turbulent mixing.

The evolution of mixed materials masses is shown in Figure 7. The unstable phase starts as soon as the first strong shock goes across the interface. The rear Au pollution expands very quickly and is almost entire. The Al pollution develops more slowly and affects half of the whole Al layer.

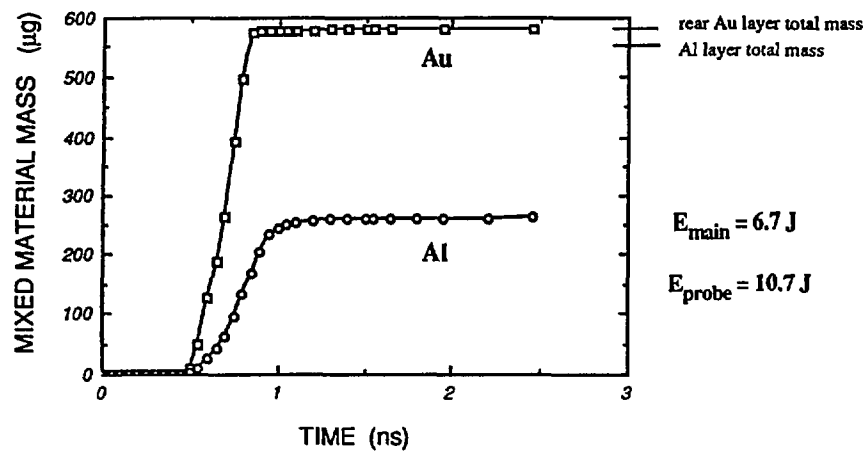


FIGURE 7
Temporal evolution of masses of mixed Au and Al.

The X-rays coming from the front Au layer induces a more or less important preheating, so the matter expands and the mixing is reduced as material density is decreased, although Atwood number has not much changed. Simulations pointed out that this radiation preheating, which is very sensitive to the pulse rise time, can become large enough when the beam energy is increased so that the rear Au expands very much and the mixing mass is reduced. Main beam energy and radiative preheating are strongly correlated but have opposite influence on the growth of the mixing, as the first one increases the acceleration of the target and the other lessens the material densities.

Our numerical investigations lead us to the following remarks :

- the mixing process is not much sensible to the main beam pulse shape as long as we consider gaussian (or sum of gaussians) pulses (i.e. smooth pulses)
- the delay of the probe beam is a major factor; it is all the more determinant as the main beam energy is small, because the unstable phase starts later and develops more slowly
- Al and Au emission levels are very sensitive to the value of the probe energy.

For 2 μm Al tri-layer targets, the rear Au layer is nearly wholly polluted in the range of energy 2 J to 12 J : entire mixing for 12 J, and some nanometers of the initial Au layer unmixed for 2 J. The disappearance of this unmixed layer could validate the experimental growth of Al emission as the energy is increased.

The weak scattering in temporal shift δt data is relevant too as pollution of rear Au layer is quite complete in most cases : for low energies, a small non-polluted Au layer may induce a little delay of Al emission; for high energies, front Au radiative preheating may set before the Au emission. Both behaviors could explain a non-modified shift between emissions.

Numerical results for various main beam energies gives a remarkably stable mixing composition. Assuming an homogeneous mixing layer, the composition is close to 25 % Au ions and 75 % Al ions densities. It is quite the reverse of the experimental proportion, but in the experiment only a small region of the mixing layer is probed. The existence of a concentration gradient is a possible explanation.

Experiments with 1 μm Al layer, performed without the probe beam, displayed that front Au X-rays can go through the target. Simulations assert the major role of front Au preheating with these structures. With both laser beams, numerical spectra obtained at the rear side of the tri-layer targets exhibit precursory signals connected to front Au radiation. This supports the experimental increase of the temporal shift δt .

From the mixing code, according to the growing reduction of Al layer density, polluted Al mass is shown to lessen when the main beam energy is increased; in the same time, Au layer mixing is not much disturbed and remains total. Therefore the experimental decrease of Al emission is coherent.

The competition between radiative preheating and target acceleration drive the opposite behavior observed with 2 μm and 1 μm Al foil tri-layer targets.

III - CONCLUSIONS

Tri-layer experiments assert the validity of X-ray spectroscopy measurements as experimental method to investigate the problem of target stability under ablative acceleration. A mixing zone is evidenced and general trends of mixing development versus target acceleration are coherent with numerical simulations (emission level, shift between emissions).

Results obtained with optical smoothing demonstrate that the apparent mixing is not due to large-scale illumination non-uniformities. As numerical simulations have confirmed, the Rayleigh-Taylor instability seems to be the dominant process responsible for the mixing.

Benefit of time-resolved spectroscopy appears very attractive and should supply us with a real knowledge of the mixing layer (span and composition). Its ability to discriminate between distinct mixing compositions with or without remaining Au layer is most valuable. Yet, under our present experimental conditions, especially dispersion of the data, it remains difficult to make full use of this diagnostic. We got

an estimate of the probed zone composition which is consistent with our numerical results. More numerical runs are necessary, and we intend to realize an additive set of simulations with other turbulence models.

Improving this experiment needs more beam energy in order to get higher emission intensities. Acquisition of repetitivity should enable us to get real quantitative results : with reproductive shots, by varying the probe energy, we could probe the mixing zone at different depths, and display (perhaps!) a concentration gradient.

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