Control of Instabilities due to Some Transient Processes in Laser Accelerated Target.

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Abstract:

One of the methods discussed here is to combat the growth of instabilities at the laser induced ablation surface. We refer to our experiments performed by using low density plastic targets embedded with metal particles of micron size and the results were compared with pure plastic targets. The target stability at the rear surface was studied using the optical backlighting technique. Shadowgrams of the seeded targets show a uniform motion of the target rear, whereas pure plastic targets break up under identical conditions. Preliminary investigations reveal the possibility of several simultaneous processes occurring at the ablation surface which can control the growth of the instabilities arising at the ablation surface. There could be several reasons acting for restricting the instabilities and we have tried to analyse the results in the existing knowledge.

1. INTRODUCTION:

Laser induced Direct Drive has the potential to achieve the high gain needed for Inertial Fusion Energy (IFE). One of the major issues in such scheme is a stable ablative compression of spherical fusion pellets filled with DT. Although several alternative schemes have been proposed to over come these instabilities like Indirect drive as discussed in the latest progress report of HiPER [1], fast-ignition proposed by Tabak [2], recent proposal of shock-ignition by Betti [3] etc. are also not free from problems to attain the goal for commercial purpose. Direct Drive is still an attractive proposal and pursued intensely world wide.

Direct Drive scheme can be briefly described as follows. A spherical microballoon filled with Deuterium and Tritium (DT) is symmetrically irradiated by multiple high power laser beams. Laser impact on the surface of the microballoon generates few tens of mega bars of intense pressure which isentropically compresses the DT material to few eV and density of the order of 1000 times the liquid DT density. This forms an envelope around the central low density but high temperature plasma ~ 5 KeV due to shock heating. Actually the core plasma serves as an ignitor. In the case of the directly driven inertial confinement fusion ~ICF scheme, the ignitor size is 2% of initial target radius. Therefore for efficient fusion reactions, ignitor spawned by the imploding fuel needs to be highly uniform for the stability of the compressed core.

There are several reasons to destroy the symmetry of the fuel compression appearing at different stages at the plasma critical density layer (corresponding to laser wavelength) and at the ablation surface etc. These include Laser non-uniformity, Target surface non-uniformity, Preheat (due to fast electrons and hard X-rays), instabilities arising at the ablation surface owing to existing plasma conditions.

Non-uniformities appearing due to laser radiation and target surface non-uniformity can be reasonably overcome with ongoing advancement in the technology. However, existing optical smoothing techniques for reducing laser non-uniformities including RPP, PZP, ISI, SSD etc. offer smoothing of the small scale non-uniformities of the laser beam. For example; using Phase Zone Plates on a large scale laser facility like Prague Asterix Laser System, Prague we can obtain Speckle size ~ (f x λ_L) /beam diameter ~2 µm (for f =100 cm, λ_L =0.44 µm and beam Diameter ≈ 30 cm) and such speckles can be easily smoothened by 2-D effects (thermal conduction) according to the following process. These small scale non-uniformities can be reduced as the beam propagates in laser produced plasma by a factor;

$\Gamma = \exp(- \alpha d 2\Pi/\lambda p)$ where $\alpha \sim 1$, λp= wave-length of the laser non-uniformity.

d= distance between laser deposition layer and ablation layer ~ $I^{14/3} (\lambda_L)^{13/4}$ for planar target.

However, large scale non-uniformities ≥ 2-3 µm persist and imprint on the ablation surface. Smoothing of the non-uniformity profile improves as it propagates the length “d” from laser critical density n_c layer to ablation layer n_a.

Ablation surface layer n_a is also a source for generating certain types of plasma instabilities including Rayleigh-Taylor (RT), Richtmeyer-Meshkov (RM) and Kelvin-Helmholtz (KH) etc. which can not be avoided and we can attempt to reduce their growth rates by adopting appropriate schemes. Low density plasma pushing high density plasma, shock acceleration, and interface shear are the sources for RT, RM and KH instabilities respectively.

Therefore, ablation surface uniformity suffers from non-uniformities introduced by laser and /or target surface and those inherently originating at the ablation surface and mitigating all these simultaneously is a real challenge in direct Drive. To simplify the concept in this work, we assume that the instabilities appear at the ablation-surface are induced either due to laser, heavy ion beam, electron beam interaction etc. as an external source and also due to innate plasma instabilities; thus instabilities are launched at the ablation-surface due to various reasons as shown in fig.1. It is also important to ameliorate these early time imprinting of non-uniformities due to laser radiation or target shell surface in an inertial confinement fusion ~ICF Scheme.

The optical smoothing techniques which produce small scale speckles as discussed above interestingly provide an important clue; if the long wavelength instabilities at the ablation surface can be reduced to smaller wavelengths then we can reasonably smoothen the instability profile due to 2-D expansion. If this is argument is acceptable then the question is how to can we amend the instability wavelength to small scale length at the ablation surface? In this work we propose to modify the pure target structure like low density pure plastic by doping with 1-2 micron size metal particles. Our experimental results show that the accelerated target is smoother in the case of seeded target compared to pure plastic which shows a break up.

These are our preliminary results and presently analysed in some newer light and we plan detail experiments in future based on these analysis.

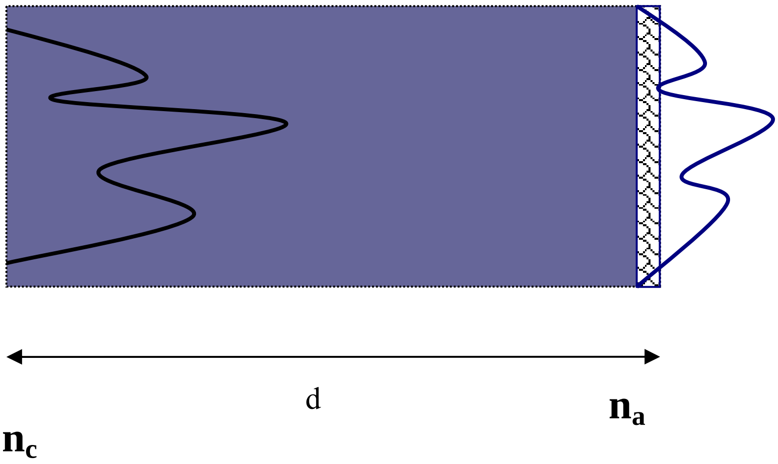

Fig.1. Laser non-uniformities originating at the critical density layer are partially smoothened as they propagate in the plasma up to the ablation surface covering a distance “d”. Various types of plasma instabilities also originate at the ablation surface as shown at na.

2. EXPERIMENTS:

Two types of planar targets were chosen for laser (1.06 μm) irradiation, namely, low density pure plastic target ~ ρ=0.9 gm/cc of thickness 20 μm and the same plastic target containing micro-particles of aluminium or gold or tungsten material. Choice of the low density plastic was to derive the advantage as an ablator that generates few tens of mega bars of pressure isentropically compressing the DT material to few eV and density ~ 1000 times the liquid DT density. Since this forms an envelope around the central low density, high temperature plasma (Te ~5 KeV due to shock heating), high degree of uniformity is required. Therefore the basic interest in the experiments was to study the effect of micro-particles on the hydrodynamic stability of low density plastic target that leads to compression of DT fuel.

Average aluminium particle size was 0.4 μm; gold particles were of diameter ~1–1.2 μm whereas tungsten particles were about 3 μm [4]. Each cc of plastic solution contained up to 50 mg (or as required) material in particle form and the required targets were prepared. Particle size has variation up to 50% and it was not possible to obtain the particles of exact diameter. In the present experiment, Al particle density was about N_{al} ~5.5 x 10^{11}/cc with an average particle diameter ~ 0.4 μm and the average particle spacing was ~ 0.75 μm. Target structure showed not really a uniform placing of the particles but a random distribution in the base plastic target.

Each particle of aluminium, gold and tungsten acts as an X-ray source for primary emission but absorption and reemission plasma zone can not be established for a point source where the dimension of the source is less than the X-radiation mean free path. Therefore X-ray emission from isolated aluminium, gold or tungsten particles will not be similar to that of solid Al/ Au/W slab, high Z buffered foam or high Z coated targets. Due to the presence of fewer gold and tungsten particles (corresponding to their higher density as compared to aluminium), the inter-particle spacing was large for gold and tungsten seeded targets. Experimental arrangement is briefly shown in fig.2 [5].

Targets with micro-particles will form a super-lattice structure. In the present experiment, Au and tungsten particles emit copious soft X-rays $h\nu$ ~1.5 KeV and Al particles which are relatively poor X-ray emitters compared to Au/W material could provide an understanding on the advantage of X-ray in the present experiment. Hence the effect of X-rays on mitigation of the instabilities can be studied by comparing the results of Au/W seeded targets with Al seeded target.

Seeded targets have certain advantages over the pure material targets like;1. Micro-particles are an obstacle to the free flow of plasma and how their presence involves in affecting the growth of the instabilities is an important issue to study. 2. High Z metal particles could be treated as an X-ray source, and hence one can draw some advantage of short wavelength ablation. 3. X-ray emission from such targets is low as compared to pure high-*Z* materials, and thus higher ablation efficiency. 4. Such seeded targets have been used as a shield against the preheating of the plasma due to hot electrons and hard X-rays.

3. RESULTS AND DISCUSSION:

In this report we restrict our discussion to the analysis of the pure plastic and aluminium seeded targets.

We simplify the behaviour of the micro-particle with the following assumption.

1. Micro-particles are mechanical obstacles and they are relatively stationary and the plasma flows freely through the inter-particle spacing.

2. Ionization of the micro-particles is negligible with the on-set of the instability.

3. There is no “particle-particle and particle-surrounding plasma” interaction. Situation will be complex if we involve interaction of the particles and with surrounding plasma as they get ionized at the ablation surface and during the growth of the instabilities.

However, other processes like the following may appear simultaneously in the ablation surface.

4. Plasma revolving around the particles may give rise to vortex formation and related process including generation of magnetic field.

5. High density and low temperature plasma in the vicinity of the ablation surface may turn out to be Non-ideal.

6. Many unknown processes may appear during the growth of the instabilities and could be important.

7. Of course, the process may be very complex if it involves interactions between the incident shock and the reflected rarefaction with the front/rear sides of the target. The problem of this transient phase in which the shock is travelling inside the target, followed by the reflected rarefaction is not yet solved even for the simpler case of uniform materials.

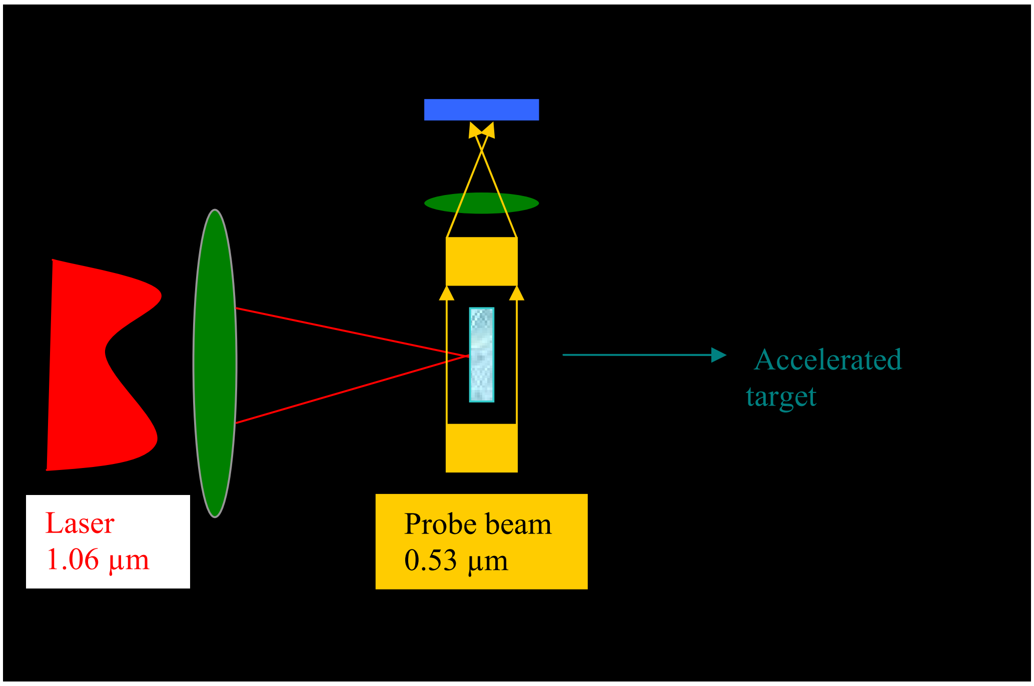

Fig.2. Experimental setup showing the optical shadowgraphy technique using 0.53 µm probe beam for recording the target front and accelerated target rear surface simultaneously.

Shadowgrams shown in fig. 3 a,b were recorded at 35 ns after the laser interaction with the target surface. Laser intensity on the target surface was about 5x10^{12} W/cm^2. Motion of the target rear surface carries the information of the ablated target and it represents the processing taking place at the ablation surface. Therefore, rear surface expanding structure is a signature of the instabilities existing at the ablation surface. Fig. 3a is the ablatively accelerated pure plastic target. Fig. 3b is aluminum seeded plastic target which shows a near uniform structure of the accelerated target and a small coronal plasma expansion as compared to pure plastic target under identical conditions. These images clearly show that seeded targets show a better stability of the accelerated target as compared to pure plastic target.

There could be several processes acting simultaneously at the ablation surface in space and time. This is a complex situation for the analysis. Some of these processes can be based on the effect of micro-particles as mechanical obstacle, role of X-rays, vortex formation, amplitude saturation due to wave breaking etc. Contribution from these individual processes occurring in time/space domain is difficult to point out. However, the final effect is observed as shown in fig.3.

At present our interest is to investigate all these individual effects contributing to final experimental observations. In this report we discuss the role of micro-particles at the ablation surface. In reality target behavior at the ablation surface and its vicinity is turbulent.

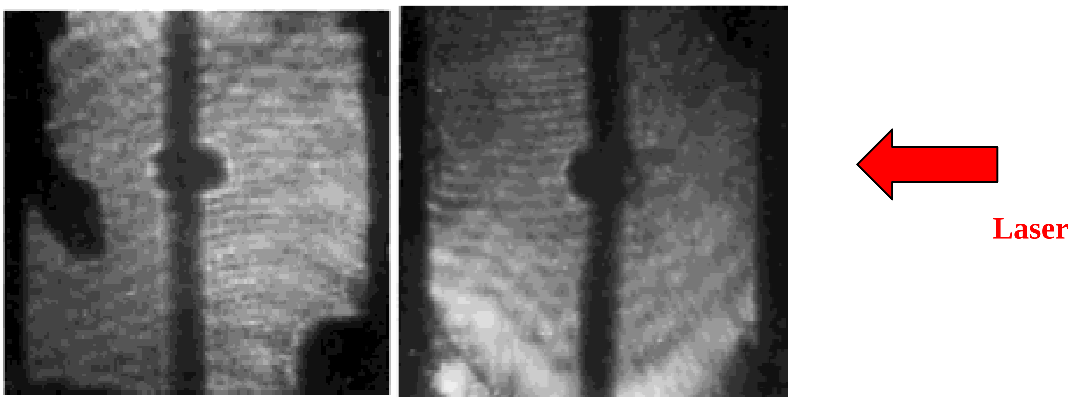

Fig.3. a) Shadowgram of the ablatively accelerated pure plastic target $\rho t \sim 18.0$ g/cm^2.
b) Aluminum seeded plastic target; $\rho t \sim 18.4$ g/cm^2.

We treat the presence of the aluminum particles as a mechanical obstacle. We assume particles are heavy and remain stationary during and after the interaction to all types of instabilities appearing at the ablation surface. Their ionization is neglected. Growth of the instabilities is limited due to the restriction imposed by the spacing set by the micro-particles.

By appropriate use of the micro-particles density (n) we can approximately define the spacing between the two micro-particles in the target structure. We have performed numerical -

calculations to estimate the resultant amplitudes of the instabilities growing at different wavelengths for a given inter-particles spacing in the seeded targets. Here the particle dimension is not considered which will be important when we apply the motion of these micro-particles. We consider a plasma disc of 100 micron in diameter and introduce micro particles of 1 μm at a distance of 5, 10 and 20 μm which represent the inter-spacing of the micro-particles.

We generate all the possible sinusoidal waves and estimate their resultant. The resultant profile of all these modes provides the amplitude of the instability in the fluid. Preliminary results show that the resultant amplitude of the instability is about 3 μm when the inter-particle spacing is 10 μm and lower for smaller micro-particle spacing. As the spacing increases to 20 μm, amplitude is about 3.5 μm and smoothing of the instabilities above this amplitude is difficult due to 2-d effects. Therefore we restrict our calculation to 20 μm inter-particle spacing. Depending upon the material characteristics of the micro particles including diameter, density, electron configuration etc, we can estimate the particle density (n) required for maintaining the spacing between micro-particles.

Gold and tungsten are good emitter of X-rays as compared to aluminum and the present results show a good smoothing of the accelerated target with aluminum seeded targets also. Hence the role of X-radiation transport and the amount of X-radiation needed for transport is to be understood. Although role of X-radiation transport in increasing the distance between critical density layer and ablation layer resulting in enhancing the non-uniformity smoothing is known, its importance and impact are required to be understood in seeded targets.

Vortex formation in the plasma is another possible mechanism which can reduce the growth of the instabilities. Vortices are self organized structures in the turbulent medium and they are generated due to the velocity shear. At the interface, high density plasma extends in to low density plasma and such fluid interchange decreases the potential energy content of the system. At the interface, micro-particle could be in an ionized state and the interaction between the ionized micro-particles and the surrounding plasma is also unknown. Although it is well-recognized that the vortex formation reduces the growth of the instabilities, its role needs to be established in seeded targets. In our present experimental conditions, the spacing between two micro-particles is of the order of wavelength of the incident laser. At present the relevance of the inter-particle spacing and laser wavelength is unknown to us.

In our experiments we can not really differentiate whether instabilities were due to laser / target surface or due to plasma behaviour at the ablation surface. What we see is, the accelerated rear target surface is smoothened in seeded plastic target as compared to pure plastic target. This implies seeded plastic target physics is certainly different than pure plastic target behaviour.

We would like to emphasize that the behavior of seeded particles in the coronal region during laser interaction and up to the ablation region and, there after are still unclear to us. Above report is our effort in understanding one of the possibilities in restricting the growth of the instabilities. We need to perform the experiments by changing various parameters including laser intensity profile, micro-particle properties. This will help us in isolating the contribution from the individual processes mentioned above.

4. CONCLUSION:

Laser accelerated thin plastic and plastic target seeded with high z material particles of micron size were experimentally studied. “ρt” (target density x thickness) in all these targets were nearly constant for comparing the results. Optical shadowgraphy technique was adopted to record the accelerated target motion. Experimental results show that aluminum seeded target show a better target stability as compared to pure plastic target under identical conditions. In the present knowledge it is difficult to identify the exact process involved in smoothing the accelerated seeded-targets. However, we expect several processes to act in restricting the growth of the instabilities. It is also difficult to know the exact instability growing at the ablation surface and contributing to the breakup of the accelerated pure plastic target. We have tried to analyze the result due to presence of micro-particles as an obstacle and other possible processes mentioned in the articles need further experiments. When inter-particle spacing is ≤ 10 μm, the resultant amplitude of the instability is ≤ 3 μm which can be smoothened by 2D effects. Is it really micro-particles act as only physical obstacle or there is more physics to be investigated?

Aluminum is a poor emitter compared to gold and Tungsten and the present results show a good smoothing of the accelerated target with aluminum seeded targets also. Hence the role of X-radiation transport and the amount of X-radiation needed for transport is to be understood.

The exact role of X-radiation transport in increasing the distance between critical density layer and ablation layer and its impact are required to be understood in seeded targets.

We wish to address the contribution of all these individual issues in our future experiments.

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