Spinning Targets for Laser Fusion+

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ABSTRACT

Several techniques for spinning the ICF targets up prior to or in the course of their compression are suggested. Interference of the rotational shear flow with Rayleigh-Taylor instability is briefly discussed and possible consequences for the target performance are pointed out.

I. INTRODUCTION

Mix of the fuel with an imploding shell is a phenomenon that adversely affects pellet performance and eventually sets the limit for the energy yield of the fusion pellets. In the present paper, we suggest a technique of suppressing the mix by spinning the pellet up prior to or in the course of its compression.

Initial rotation of the pellet can be relatively slow because of a considerable enhancement of rotation in the course of compression (by virtue of the angular momentum conservation). Still, as it turns out, in order to produce a non-negligible effect on the pellet performance, initial rotation should have a velocity of order 10km/s. Centrifugal forces corresponding to this velocity are such that structural strength of the shell is insufficient to withstand them. Therefore, it is impossible to gradually spin the pellet up by, e.g., fiber suspension or similar techniques.

We consider two techniques for spinning the pellet up on a time-scale shorter than or comparable with implosion time-scale: i) use of an ablation force with a non-zero azimuthal component (which can be produced even in case of a fully axisymmetric purely radial irradiation of the pellet, by a proper structuring of the pellet surface layers) and, ii) creation of the azimuthal shear flow deep inside the pellet using a pre-formed left-right asymmetric structure (created at the desired depth during the pellet fabrication) which would produce an azimuthal shear flow in the course of absorption of a spherically converging shock wave. As it turns out, these techniques can produce rotation whose velocity varies, in a controlled way, over the radius and the latitude of the pellet. We demonstrate that thus produced shear flow can have considerable stabilizing effect on the Rayleigh-Taylor instability.

There are also two unfavorable effects caused by rotation: i) the loss of spherical symmetry under the action of the centrifugal forces; ii) additional mixing caused by the shear-flow turbulence. However, the first effect can be reduced by reducing the thickness of the spherical layer involved into the rotational motion, while the second could, in principle, be eliminated at all by a proper tayloring of the velocity profile of the shear flow.

A more detailed analysis of some physics issues related to the performance of rotating targets, can be found in Ref.[1].

II. REQUIRED ROTATION VELOCITIES

To make numerical estimates more specific, we present here some parameters of the current Nova experiment [2]. The maximum convergence C in these experiments is approximately 25, so that rotation velocity v_{final} at the moment of the maximum implosion would be 25 times higher than the initial rotational velocity v_0. In order rotation to have a considerable effect on the pellet dynamics near the maximum compression point, the final rotation velocity should be comparable with the characteristic implosion velocity $\sim 3 \cdot 10^7$ cm/s. Accordingly, the required initial rotation velocity is

$$v_0 \cong 10^6 \text{ cm/s} \tag{1}$$

We will use this velocity as a reference value in some of the estimates. Note that final rotation energy is C^2 times larger than the initial one. Therefore, if we assume that the final rotation energy is comparable with the total mechanical energy delivered to the target, this would mean that the initial rotation energy is C^2 times less (i.e., $\sim 2 \cdot 10^{-3}$ of the total mechanical energy).

III. SPINNING THE PELLET UP

A. *Ablation Torque*

To give a conceptual illustration regarding the possibility of generating "ablation torque", we assume that a surface layer of a relatively small thickness has a structure shown in Fig.1, with the "east" slopes of the surface having different chemical composition than the "west" slopes (the height of the "ridges" is grossly exagerated). Such a structure can be, in principle,

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principle, formed by a combination of etching and surface deposition techniques. If the molecular weights on the two slopes are different, then, according to [3], the ablation pressure on the "east" and "west" slopes is unequal and the ablation torque is applied to the surface layers of the pellet.

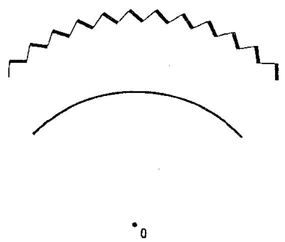

Fig 1. Part of the equatorial cross-section of the pellet; O-pellet center. The "ridges" on the surface are oriented in the North-South direction. East slopes are made of a different material than the West slopes. This is one of possible surface reliefs that would produce an ablation torque. The circle conditionally depicts the inner surface of the shell.

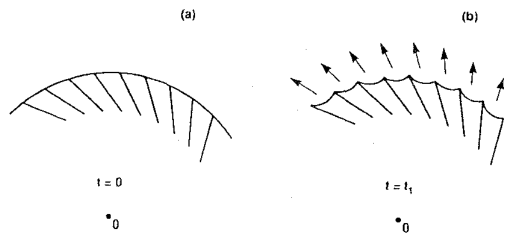

Fig.2 Another method of creating an azimuthal ablation torque: a) initial state; straight stretches depict impregnations with a slower ablation rate; b) later state; ablation is to a certain degree channeled by the impregnations; arrows show the ablation flow which, because of the aforementioned channeling, has a tangential velocity component.

Another conceivable technique for creating an "ablation torque" would be to use structured surface layers, as shown in Fig.2a. Note that, in principle, these surface non-uniformities might have a very small characteristic length and, therefore, would not serve as "seeds" for the Rayleigh-Taylor instability. The azimuthal force would have to be transferred to the deeper layers of the target by one or another kind of the shear forces (see below). This should occur before the structured surface layer would be blown-off by the laser pulse.

For the parameters of the Nova experiment (thickness of the plastic shell ~30 μm and a pulse-width of ~1 ns), it is difficult to find any type of the shear force that would provide a fast enough radial momentum transport. Of course, we can not count on the elastic shear stresses: the time-scale is much shorter than the acoustic time for the transverse acoustic waves; the pellet material at so short time-scales behaves essentially as a fluid. Kinematic viscosity ν~0.1-1 cm^2/s (the value one can expect for the plastic shells in the temperature range from a few to a few hundred eV) also does not provide fast enough momentum transfer. Even the turbulent viscosity is not quite sufficient for that (see [1]).

A possible solution for this problem is a using of an additional laser pulse (preceding the main one) that would have a considerably longer pulse-width and lower energy (according to what has been said above, the energy can be $\sim 2\cdot 10^{-3}$ of that of the main pulse). This would probably require a use of a direct laser irradiation through the holes in the hohlraum shell (Fig. 3). The pulse width should exceed the propagation time of a shear flow perturbation through the pellet shell.

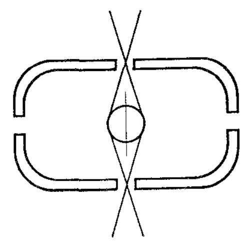

Fig.3 Possible geometry of irradiation of the pellet by a low-power laser beam. To provide conditions when the absorbed power density would be more or less evenly distributed over the surface of the target, one would have to use a beam with a hollow radial distribution of intensity. Main laser beams are supposed to be fired through the holes on the horizontal axis.

For targets with large aspect ratios $A=r_0/\Delta$, the spinning up can be carried out in a much more gentle way, with a reliance on the elastic forces in the target. The maximum shear stress that can be transferred to the solid material without causing a structural failure, is $\alpha\rho c_s^2$, where c_s is velocity of shear acoustic waves, and α (α<1) is some numerical factor. The quantity ρc_s^2 is equal to a so called shear modulus, or modulus of rigidity (see Ref. [4], §§ 5 and 22).To accelerate tangentially the layer of thickness Δ to some velocity v> c_s, one should apply this shear stress for the time

$$t \sim \rho v\Delta/\alpha\rho c_s^2 \sim v\Delta/\alpha c_s^2 \qquad (2)$$

For the pellet rotating with a speed $v \gg c_s$, the centrifugal forces are much larger than the structural strength of the material can maintain. In order to avoid considerable deformation of the pellet during the spinning-up process, the time t should be shorter than ω^{-1} (where $\omega=v/r_0$ is the angular frequency). This, together with (2), gives the following limit on the aspect ratios for which the spinning-up could be carried out by elastic forces:

$$A>v^2/\alpha c_s^2 \qquad (3)$$

For example, to reach rotation velocity of $v=5\cdot 10^5$ cm/s for a shell made of a material with $c_s = 2\cdot 10^5$ cm/s and α=0.3, one would have to use the shells with A>20. The characteristic spinning-up time for a shell of initial thickness 5 μm, according to (2), would be ~15 ns. This "gentle" spinning-up eliminates a problem of an early "smearing out" of the surface structure.

At $v>c_s$, elastic forces are sufficient to transfer the rotational velocity through the thickness of the shell but insufficient to transfer it in the north-south direction: relationships (5) and (6) show that there is not enough time for the elastic shear perturbations to propagate the distance $\sim r_0$ (while there is enough time to propagate the distance $\sim\Delta_0$). Therefore, by a proper variation of the parameters of the surface structure over the latitude, one can control dependence of rotation frequency over the latitude.

"Gentle" acceleration would not allow a considerable variation of the rotation velocity over the thickness of the shell (no considerable radial shear in the flow velocity). To create such a shear, the aforementioned scheme of the turbulent momentum transfer seems more appropriate.

B. *Generation of Shear Flow inside the Shell*

Returning to thick shells and short time-scales, we suggest a possibility of creating azimuthal flow at an arbitrary depth of the shell by using an East-West asymmetry in the reflection of the shock wave (or, more generally, any - initially longitudinal - wave which is created by fast inward motion of the shell surface. To avoid misunderstanding, we emphasize that no special surface structure is to be used in this scheme. This concept is illustrated by Fig. 4 (for a planar geometry): at a certain depth, a series of tilted plates of a material different from the surrounding material, is embedded into the shell. A compression wave that travels across the shell gets (at least partly) reflected in the direction tilted with respect to the initial one. Clearly, impregnated "tiles" then acquire a momentum directed along the slab. The reflected part of the wave gets gradually absorbed in the surrounding material and transfers to it its momentum so that the slab as a whole doesn't acquire any tangential momentum.

In the scenarios with short time-scales and high pressures, when the material behaves like a fluid, the tiles and surrounding matter start flowing in a horizontal direction, forming a submerged jet; the jet, at high speed, becomes turbulent and gradually expands. Initial non-uniformities which served for partial non-normal reflection of the incident wave, get mixed-up with the rest of the fluid. Dimensional arguments similar to the ones used in Ref. [5] show that the jet thickness asymptotically grows as $t^{1/2}$, with the average flow velocity decreasing as $t^{-1/2}$ (we refer here to the case when the broadening of the jet is caused by the turbulent viscosity; somewhat paradoxically, the broadening caused by the ordinary viscosity follows the same scaling, though with different coefficients).

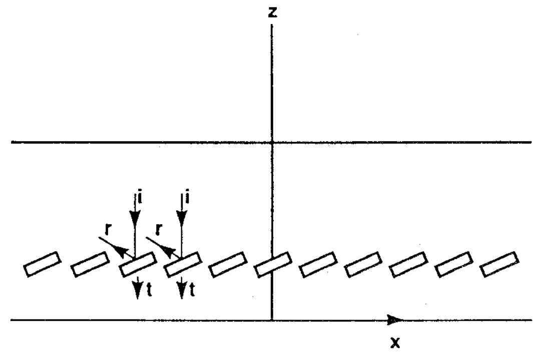

Fig.4 Asymmetric reflection of the compressional wave. Shown by arrows are the directions of propagation of the incident (i), reflected (r) and transmitted (t) waves. The horizontal flow of fluid is set on in the layer containing the tilted tiles. This figure just illustrates the concept: real stucture may look different.

The time during which the submerged jet would considerably broaden and slow down depends on its thickness and fluid viscosity. For the parameters of Nova experiment, considerable broadening can hardly occur within the compression time. Therefore, one can expect that the jet formed on the front part of the compression pulse will exist until the maximum compression point. The presence of such a shear flow near the interface between the plastic outer shell and glass inner shell in the configuration of Nova experiment could smear out the perturbations caused by the most dangerous Rayleigh-Taylor instability.

IV. EFFECT ON PELLET PERFORMANCE

The presence of a rotation of the imploding target has several consequences for the implosion dynamics. The most obvious one is the effect on the shape of the imploding shell: because of the centrifugal forces, the shell should become oblate. Deviation from the spherical symmetry can be roughly characterized by the parameter $\varepsilon=(d_{max}-d_{min})/d_{max}$, where d_{max} and d_{min} are the maximum and minimum diameters, respectively. For a simple model of radial implosion of a thin shell occurring at a constant velocity V_R, parameter ε varies with the convergence C as:

$$\varepsilon\sim C^2 v_0^2/V_R^2 \quad (4)$$

(we assume that ε is small; this estimate "works" until $\varepsilon\sim 1$).

If the shell is filled with a fusion fuel then, at a certain compression ratio, the internal pressure begins to decelerate the shell rapidly. Near this point, a fast Rayleigh-Taylor instability of the inner surface of the shell may develop (see e.g., a survey paper [6]). Centrifugal acceleration is directed in such a way that it reduces or even reverses the effective gravity force "seen" by the shell in the last (and most critical) instants of the pellet implosion and therefore it should reduce the growth rate or eliminate the instability at all. This stabilization technique has been suggested many years ago in conjunction with experiments on the implosion of the cylindrical liners (see, e.g., Ref.[7]). Of course, in case of a quasi-spherical pellet it does not work near the pellet's poles but a considerable part of the fuel-shell interface (not very close to the poles) would be favorably affected by this phenomenon. On the other hand, deviation of the pellet shape from the sphere should have an unfavorable effect on the pellet performance. However, there is no reason to immediately believe that the optimum of the pellet performance necessarily corresponds to the *zero* initial rotation velocity. We believe that the whole issue deserves a more detailed analysis.

If rotation has a considerable shear, especially in the radial direction, this shear can produce another stabilizing effect for the Rayleigh-Taylor instability. Without shear, the growth-rate of this instability can be evaluated as (see, e.g., Ref.[6]):

$$\gamma \sim [kg/(1+kL)]^{1/2} \qquad (5)$$

where L is a scale-length of a radial density variation, k is a tangential wave-number, and g is an effective gravity acceleration. For short wave-lengths the growth rate is $\sim(g/L)^{1/2}$. Assume now that there exists a shear flow with velocity directed azimuthally and varying in the radial direction at the same scale-length as the density. The Rayleigh-Taylor perturbations have, roughly speaking, the same extent ($\sim 1/k$) in the radial as in the azimuthal directions. The shear flow will stretch the perturbations azimuthally. Characteristic stretching time is $1/|\partial v/\partial r| \sim L/v$. One can expect that a considerable stabilization effect would occur if this time would be shorter than the growth time $1/\gamma$. From these considerations we obtain the following condition of a considerable stabilizing effect:

$$v>(gL)^{1/2} \qquad (6)$$

One should also note that the perturbations of the type of the "rolls" oriented azimuthally are not affected by the shear flow at all. But the presence of a strong enough shear flow certainly narrows the class of possible R-T perturbations and is in this sense favorable for the pellet performance.

The other concern is that a shear-flow turbulence would mix-up the shell and the fuel even in the absence of the R-T instability. By exciting a shear flow in such a manner that it does not penetrate to the fuel-shell interface but does exist at some distance from it (in radial direction), one would already produce a stabilizing effect for the R-T perturbations with not too short wavelengths and, at the same time, would not perturb the fuel-shell boundary. Technique of the type shown in Fig. 4 should allow creation of a shear flow at a prescribed location. One should also emphasize that there exist shear flows which are stable with respect to the Kelvin-Helmholtz instability at the arbitrarily high Reynolds numbers and don't produce turbulent pulsations by themselves [1]. Moreover, shear flow should smear out perturbations which otherwise could propagate to the inner surface of the shell and serve as seeds for the R-T instability.

The aforementioned techniques can be used to create also non-axisymmetric flows occupying only part of the pellet surface. The reason why this exercise might be of some interest, consists in that such flow patterns might be formed inadvertently in some of the current experiments, without having known of their presence.

To conclude: we think that there are several ways of setting the laser targets into a fast rotational motion. This motion can be made both more or less uniform (ω=const) and non-uniform (along the radius and/or along the latitude). Rotational motion can have a significant stabilizing effect on the Rayleigh-Taylor instability near the point of the maximum implosion via the favorably directed centrifugal force and/or via the shear flow. Controlled generation of localized non-axisymmetric tangential flows could shed some light on possible role of such perturbations in the current implosion experiments.

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