Uniform Hydrogen Fuel Layers for Inertial Fusion Targets by Microgravity

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Abstract

A critical concern in the fabrication of targets for inertial confinement fusion (ICF) is ensuring that the hydrogenic (D_2 or DT) fuel layer maintains spherical symmetry. Solid layered targets have structural integrity, but lack the needed surface smoothness. Liquid targets are inherently smooth, but suffer from gravitationally induced sagging. One method to reduce the effective gravitational field environment is freefall insertion into the target chamber. Another method to counterbalance the gravitational force is to use an applied magnetic field combined with a gradient field to induce a magnetic dipole force on the liquid fuel layer. Based on time dependent calculations of the dynamics of the liquid fuel layer in microgravity environments, we show that it may be possible to produce a liquid layered ICF target that satisfies both smoothness and symmetry requirements.

Introduction

In the Inertial Confinement Fusion (ICF) concept,[1] multiple high power laser or ion beams are focused on a small spherical target containing condensed hydrogen fuel. The intense pressure generated by the incident beams cause the target to implode to high density (~1000x liquid density) and temperature (>100 million K) with the subsequent release of thermonuclear energy. For ICF to be economically attractive, the gain (thermonuclear energy out divided by beam driver energy in) must be large enough to overcome driver inefficiencies.

The ultimate goal of ICF research is the development of an Inertial Fusion Energy Power Plant.[2] Such a plant would most likely utilize a 2 ~ 5 MJ driver with a 500 MJ yield/target (gain >100). Using a 5-10 Hz shot rate, this would produce 1000 MW electrical power. With reasonable progress, a demonstration inertial fusion power plant could be expected to be operational in 2020 ~ 2030.

Cryogenic targets planned for ICF experiments are in the form of a liquid or solid hydrogen fuel layer which coats the inner surface of a low-Z (e.g., polystyrene) microballoon. The region interior to the fuel layer (the "bubble") contains low pressure hydrogen gas at the vapor pressure of the liquid or solid fuel layer.

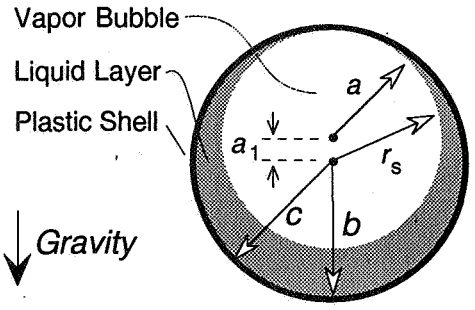

Fig. 1. Liquid layer in a spherical shell. a is the radius of the vapor bubble, a_1 the amplitude of the $\ell = 1$ harmonic, b is the inner radius of the shell and c is the outer radius of the shell.

A critical concern in the fabrication of these targets is ensuring that the hydrogenic fuel layer maintains smooth, spherically symmetric uniformity with peak-to-valley variations on the 1000Å scale. Non-uniform or rough surfaces in the target or fuel can instigate Rayleigh-Taylor instabilities.[3] These instabilities can grow—allowing the cold condensed fuel to mix with the inner hot gaseous region and damp out the fusion reaction. To prevent Rayleigh-Taylor growth, the smoothness of the (plastic) shell surface must be less than 500Å.

Solid fuel layers have the advantage of being able to support the condensed hydrogen fuel layer naturally. However, surface smoothness is a problem. To date, no solid layering technique has been able to produce a smooth inner layer at the 1000Å level. Because of surface tension, liquid

fuel layers will have a smooth inner surface. However, an unacceptable departure from uniformity arises by gravity-induced sagging of the liquid. Hence, the layer thickness will vary from thin at top to thick at bottom (Fig. 1).

There are almost a dozen suggested layering methods for both liquid and solid fuel layers. For example fast refreeze, beta-decay heating,[4] thermally induced gradients using helium gas jets,[5] graded intensity laser beams,[6] and microwave plasma heating.[7] The beta-layering technique is a volumetric heating process which relies on tritium beta-decay to produce a uniform layer, hence it is only good for DT layers. Thermal gradient methods induce dynamic circulating flow patterns in liquid fuels. The fuel can be distributed around inside the capsule by adjusting the temperature profile to produce a uniform thick layer. Only beta-layering has demonstrated 100 μm thick fuel layers. The best beta-layered surface to date has a surface roughness on 2 μm, an order of magnitude larger than desired.

Plastic foams[8] can be used to trap liquid fuel. The foam density must be low (< 30 mg/cc) to minimize the amount of higher Z materials (the carbon in the plastic). The foam cell size must also be small (≤ 1 μm) to minimize surface irregularities. If the volume of the liquid significantly exceeds the volume of the foam pores (overfilled), thick overfill layers will sag due to gravity. Thin overfilled layers (< 1 μm) may conform to irregularities commensurate with the foam cell size.[9] A rough estimate of the minimum overfill thickness to avoid surface imprinting (and Rayleigh-Taylor instabilities) would be about three times the foam cell size.

Microgravity Methods

There are two microgravity layering methods that have the potential to produce adequate liquid targets. These methods work by reducing the gravitational force, preventing the liquid layer from slumping to the bottom of the target.

One method for reducing the gravitational force is to use the simple freefall method. In the absence of other forces, surface tension will drive the inner surface of the liquid to a spherical shape. AS will be shown, short range forces will center the bubble after an appropriate damping time. Unfortunately, for an ordinary liquid layer, the damping times are much longer than a typical ~1 second drop time. However, if we consider an overfilled foam target with a thin ~1 μm liquid layer, by virtue of its smaller inertia, the thin liquid layer will approach a stable, more symmetric, equilibrium in a relatively short time.

The other technique[10,11] uses an applied magnetic field to support the liquid fuel layer against gravity. The method proposed here makes use of the diamagnetic nature of hydrogen. The magnetic dipole force per unit volume is $\chi\, B\cdot\nabla B/\mu_0$. Balancing this against the gravitational force per unit volume $F_g = \rho g$ yields the required product of field strength with field gradient:

$$B\frac{\partial \vec{B}}{\partial z} = \frac{\mu_o \rho \vec{g}}{\chi} \qquad (1)$$

Taking $\chi = -2.2 \times 10^{-6}$ (SI), $\rho = 200$ kg/m^3, $g = 9.8$ m/sec^2, one obtains 1.12×10^3 T^2/m or 11.2 T^2/cm for deuterium, a value achievable with commercially available superconducting magnets.

In the following we investigate the degree of symmetry attained by each of the two layering methods described above, *i.e.*, the concentricity of the inner surface of the liquid fuel layer and examine the time-dependent motion of the liquid fuel layer. A more complete version of the

analysis presented here is given in ref. 11. We first note that the amplitudes of the perturbations on the inner fuel layer are extremely small compared to the radius of the target so that a perturbative approach is warranted.

Assuming axial symmetry, we can then describe the radial coordinate of the inner surface of the liquid fuel layer, $r_s(\theta,t)$, by expanding it in Legendre polynomials:

$$r_s(\theta,t) = a_0(t) + \sum_{\ell=1}^{\infty} a_\ell(t)\, P_\ell \cos\theta \tag{2}$$

where t is time, θ is the polar angle in a spherical polar coordinate system (Fig. 1), and a_ℓ is the perturbation amplitude of the ℓ^{th} spherical harmonic ($a_\ell << a_0 \leq b < c$). In the case of overfilled foam targets, b is replaced by d, the inner radius of the foam layer. This method of decomposition of surface nonuniformities (as well as absorbed laser energy and pressure nonuniformities) into spherical harmonics, is traditionally used in target performance and fusion gain calculations.

We study the liquid fuel layer beginning with the energy equation:

$$\frac{\partial}{\partial t}(E + P_{gm} + P_\gamma + P_{LV}) + \dot{Q}_{vis} = 0 \tag{3}$$

with E being the kinetic energy of the whole layer, $\dot{Q}_{vis}$ is the viscous dissipation rate, and the three potential energies considered here being P_{gm}, the potential energy in the combined gravitational and applied B-fields or net gravitational field in the case of freefall, P_γ the free energy stored in the liquid/vapor interfacial surface, and P_{LV} is the potential energy stored in the long range attractive forces between the molecules of the liquid fuel layer and the outer shell or foam matrix. Since all the molecules are neutral and non-polar, only the potential associated with the London-Van der Waals force is relevant. Each of these components can be analyzed separately. By using the orthogonal properties of the Legendre polynomial, all the terms in Eq. 3 can be reduced to functions of the mode amplitudes.

The surface tension energy at the liquid/vapor interface (with constant surface tension γ) can be written as:

$$P_\gamma = 2\pi\gamma \sum_{\ell=1}^{\infty} (\ell-1)(\ell+2)(2\ell+1)^{-1} a_\ell^2 \tag{4}$$

It is noteworthy that the first $\ell = 1$ mode results in no change of the surface area or its potential energy, P_γ. This simply means that the interior "vapor bubble" can undergo a vertical shift without changing its liquid/vapor surface area; accordingly, surface tension forces alone cannot counterbalance the gravitational forces. A similar conclusion was reached in Ref. 12 using the extended Young-Laplace equation of capillarity.

The other energy terms depend on the velocity perturbations within the fluid layer. Assuming incompressible and irrotational flow, the velocity field is represented by $\vec{v} = -\nabla\phi$. The volume integrals can then be converted to surface integrals, viz:

$$E = \frac{1}{2}\rho \int \phi\, \nabla\phi \cdot \hat{n}\, dS \qquad \dot{P}_{gm} = \int \Phi_{gm}\, \vec{v} \cdot \hat{n}\, dS \tag{5a, b}$$

$$\dot{P}_{LV} = \int \Phi_{LV}\, \vec{v} \cdot \hat{n}\, dS \qquad \dot{Q}_{vis} = \eta \int \nabla v^2 \cdot \hat{n}\, dS \tag{6a, b}$$

where $\hat{n}$ is the surface normal,

$$\hat{n} = \frac{\nabla (r - r_s)}{|\nabla (r - r_s)|} \approx -\hat{r}_u - \frac{\hat{\theta}_u}{r} \sum_{\ell=1}^{\infty} a_\ell(t) (1-\mu^2)^{1/2} P_\ell'(\mu) \tag{7}$$

where $P_\ell'(\mu) = dP_\ell / d\mu$, η is the viscosity of the liquid fuel, and $\Phi_{gm} = U_g + U_m$ is the combined gravitational and magnetic dipole potentials per unit volume; $U_g = \rho g z$, $U_m = |\chi| \vec{B} \cdot \vec{B} / 2\mu_o$.

The attractive interaction energy between a liquid hydrogen molecule and a shell (or foam) molecule is due to the long range dipole-induced dipole interaction for non-polar molecules such as glass or plastic. In the electrostatic ($c \rightarrow \infty$ limit), the interaction potential obeys the London-Van der Waals inverse sixth power law formula. However, since the dipole moments of the individual atoms are fluctuating at a frequency characteristic of the electronic motions ω_o, there will be a time between the fluctuating dipole that radiated the electromagnetic field and the reradiated field when it arrives back at the fluctuation and interacts with it. When the distance between two molecules, d, is such that the propagation time d/c exceeds the fluctuation period $\sim 2\pi/\omega_o$, the "retardation effect" is significant and reduces the range of the Van der Waals forces.[13] The retardation effect can be quantified by multiplying the Van der Waals interaction energy between the molecules with the empirical expression $f(p) \approx 2.45\, p^{-1} - 2.17\, p^{-2} + 0.59\, p^{-3}$, where $p = \omega_o d/c$.

The total interaction energy between a single liquid molecule of mass m at position $\vec{r}$ and the entire plastic sphere (or foam) layer is given by the pairwise approximation.[13] With $d = |\vec{r}' - \vec{r}|$ this is:

$$\Phi_{LV}(\vec{r}) = \frac{N^{eff} \mathsf{B}^{eff}}{m} \int_{volume\ of\ shell\ (foam)} \frac{d^3 r'\, f(p)}{|\vec{r}' - \vec{r}|^6} \tag{8}$$

and B^{eff} is the effective London constant defined through the weighted product for foam-filled fuel layers as $N^{eff}\, \mathsf{B}^{eff} = \mathsf{B}_s N_s\, (1 - f_{void}) + \mathsf{B}_H N_H f_{void}$, where N_s is the number density of the solid (s) portion (the plastic shell) and N_H is the number density of the liquid isotope (H) filling the void, with f_{void} being the volume void fraction, typically $f_{void} = 0.95$.

The equilibrium amplitude of the first mode, a_1^{eq}, results from a balance between the net vertical force and the strength of the London-Van der Waals force. The layer concentricity a_1^{eq}/a is then given by

$$\frac{a_1^{eq}}{a} = \frac{-3\, a\, c^3\, m\, \varepsilon\, g}{4\pi N^{eff} \mathsf{B}^{eff}} \left[x\, \tilde{\phi}'(x) + \mathbf{E}_1(x)\, \tilde{\phi}(x) \right]^{-1}_{x = a/b} \tag{9}$$

where $\tilde{\phi}'(x)$ is the derivative of $\tilde{\phi}(x) = \Phi_{LV} \times 3\, m\, c^3 / 4\pi N^{eff} \mathsf{B}^{eff}$ with respect to $x = r/b$. This result can also be obtained by setting the time derivatives $\dot{a}_1$ and $\ddot{a}_1$ to zero in Eq. (3).

For freefall (assuming no turbulence or vibration), surface tension drives the higher order equilibrium amplitudes to zero. In the case of magnetic field assisted microgravity for which $\mathbf{B} \cdot \nabla \mathbf{B}$ has small non-vertical components, these higher order amplitudes, a_ℓ^{eq}/a, are proportional to $a^2 \gamma^{-1} (a/L)^{\ell - 1}$ where L is the scale length of the magnetic field gradient. Fortunately, the higher order modes are less than 0.01% if $L \geq 5$ cm and $a \approx c \sim 500\mu$m.

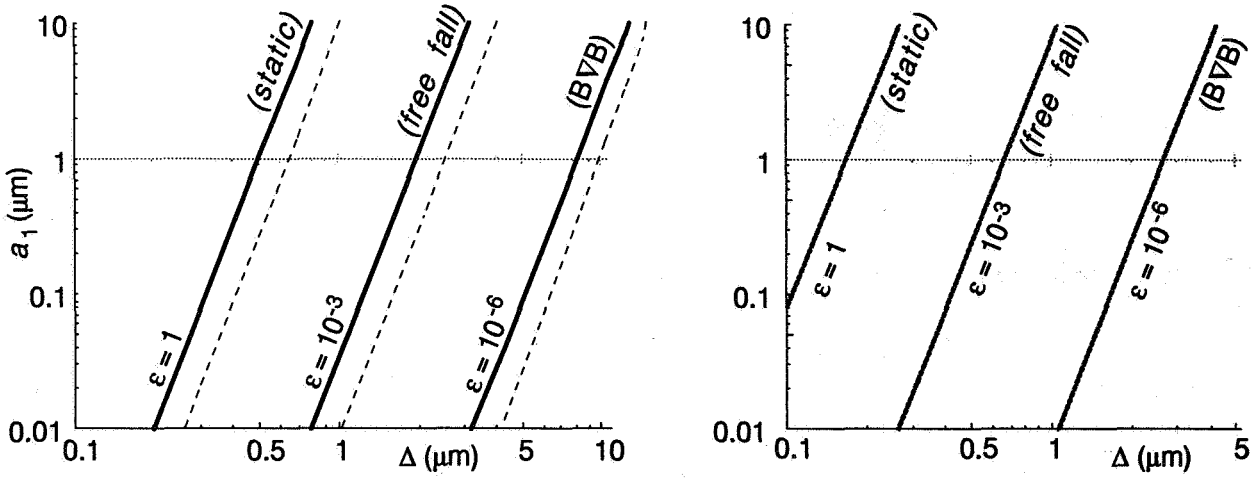

Fig. 2a a_1^{eq} for hollow plastic shells: the solid line is for a 1 000 μm dia., the dashed line a 250 μm dia.
Fig. 2b a_1^{eq} for a 100 μm thick foam shell having a density of 50 mg/cc (f_{void} = 0.95).

As can be seen (Fig. 2a), a_1^{eq} is directly proportional to the reduced gravitational field, εg. Its dependence on the thickness of the liquid layer, $a_1^{eq} \sim \Delta^5$ comes from taking the limit as $\Delta/a \ll 1$ in Eq. (9).

Fig 2b. shows that a 1 mm diameter overfilled foam target can support a liquid layer ~0.2 μm thick in a 1 g environment. For a given nonconcentricity, $\Delta \sim \varepsilon^{-1/5}$; for $a_1^{eq}/a = 1\%$, $\Delta \sim 0.7$ μm for $\varepsilon = 10^{-3}$ (free fall) and ~3 μm for $\varepsilon = 10^{-6}$ (B·∇B).

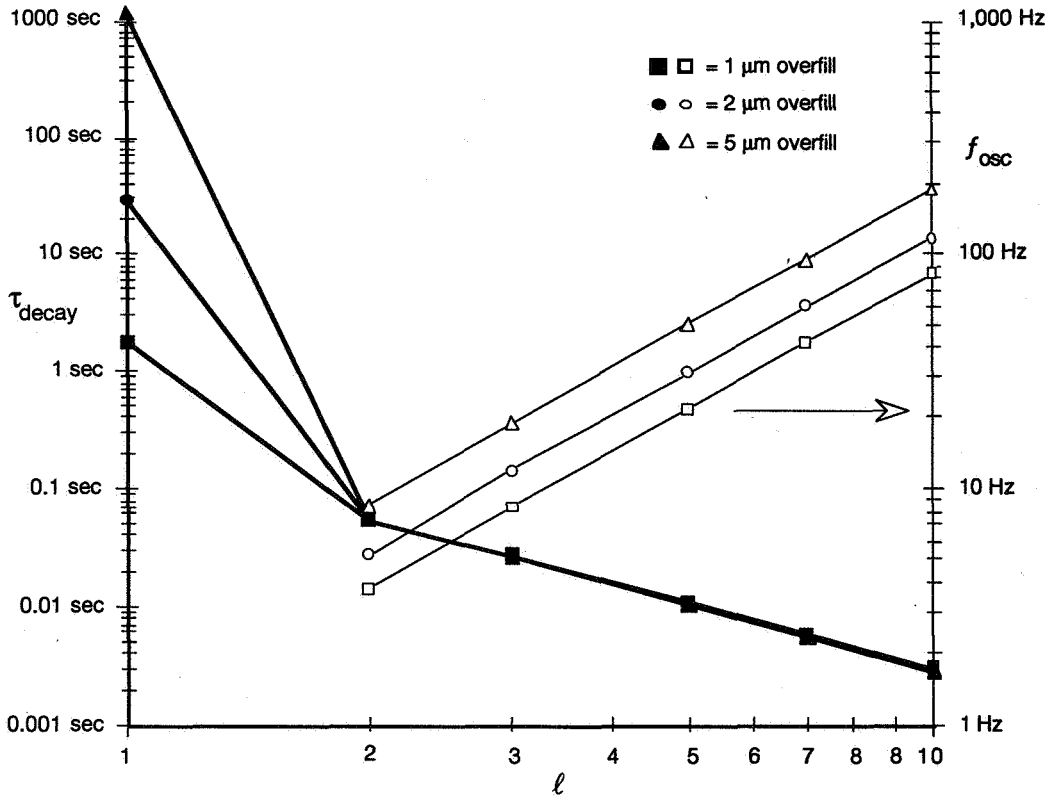

Fig. 3 Time constants and oscillation frequencies as a function of mode number for an overfilled foam target.

Figure 3 displays the time constants as a function of liquid fuel layer thickness Δ for a large shell (c = 500 μm) with an ordinary liquid D_2 layer in conditions typical of B·∇B experiment (10^{-6} g) and an overfilled foam target in freefall and stationary situations (10^{-3} g and 1 g). The long damping times for the $\ell = 1$ modes are due to the extremely weak Van der Waals[14] attractive forces between the liquid and the plastic shell or foam material.

In the case of the overfilled foam layers, the decay times for all modes can be short enough to consider the simple freefall method, where drop times from height h, $t_{drop} = (2h/g)^{1/2}$, can be manifestly longer (nearly 1 sec for a 2 meter drop).

Conclusions

Symmetric cryogenic targets are critical for inertial confinement fusion. To date, no layering method has demonstrated the needed symmetry and surface smoothness. Microgravity techniques may achieve the required symmetry, but development is needed. Specifically we need to measure the London-Van der Waals Forces between liquid deuterium and plastic and observe the actual time dependent behavior of liquid layers in microgravity environments. This should lead to an accurate model of the liquid layer interaction that will allow the ICF community to design present and future ICF targets.

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