Influence and measurement of mass ablation in ICF implosions*

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Abstract. Point design ignition capsules designed for the National Ignition Facility (NIF) currently use an xray-driven Be(Cu) ablator to compress the DT fuel. Ignition specifications require that the mass of unablated Be(Cu), called residual mass, be known to within 1% of the initial ablator mass. The specifications also require that the implosion bang time, a surrogate measurement for implosion velocity, be known to +/- 50 ps RMS. Experiments designed to measure and to tune experimentally the amount of residual mass are being developed as part of the National Ignition Campaign (NIC). Tuning adjustments of the residual mass and peak velocity can be achieved using capsule and laser parameters. We currently plan to measure the residual mass using streaked radiographic imaging of surrogate tuning capsules. This technique, together with bang time measurements, should allow us to tune ignition capsules to meet NIC specs.

1. Introduction

National Ignition Campaign point designs use a graded, doped beryllium-copper (BeCu) ablator to compress Deuterium-Tritium (DT) fuel. The laser-heated hohlraum generates and x-ray bath which ablates the surface of the capsule. Physics uncertainties in the hohlraum drive and its coupling with the capsule produce associated uncertainties in the mass ablation rate. The NIC has developed a tuning strategy and an associated set of tuning experiments to observe and adjust the the residual mass and the peak velocity.

2. Ignition specifications for mass ablation rate

X-rays generated by the hohlraum irradiate the beryllium-copper (BeCu) ablator in NIF ignition point designs. The radiation is characterized by a radiation temperature, $T_r$, that reaches 300 eV in Revision 1 point designs [1]. The radiation is absorbed due to the finite ablator opacity, $\mu$, setting up an ablation front that propagates into the ablator. Low density mass is ejected from the capsule surface, compressing the capsule in reaction. This spherical rocket compression process is described by the ordinary differential equations in (1). They are dependent on the hohlraum drive $T_r$ and the opacity through the mass flux term, $m_a$, and the exhaust velocity, $v_x$. An essential feature of the rocket
equations is the coupling of the unablated capsule mass, or residual mass, $M$, and the implosion velocity, $v$.

$$\dot{M} = 4\pi R^2 \dot{m}_s(T_s, \mu)$$

$$M \dot{v} = -4\pi R^2 \dot{m}_v v_s(T_s, \mu)$$

More detailed solutions of ignition capsule implosion dynamics are provided by the radiation-hydrodynamics code HYDRA [1]. HYDRA simulations of ignition point design capsules set the nominal implosion trajectory in mass-velocity space (Figure 1). Ignition specifications also set tolerances on the mass and velocity trajectories to avoid known failure modes (Figure 2) that result from mistuning. To ensure that the minimum acceptable velocity is achieved, ignition specifications [3] require measurement of the implosion bang time to 50 ps RMS. The residual mass must also be known to 1%. This prevents the occurrence of two failure modes. Insufficient residual mass leads to enhanced Rayleigh-Taylor instability growth and eventually to DT fuel preheating by x-rays. Excess residual mass leads to low velocity implosions with insufficient kinetic energy to initiate fusion burn. The ignition specifications allow the implosion to avoid these failure regions of phase space.

![Figure 1: The HYDRA code provides detailed simulations of ignition capsule trajectories in mass-velocity phase space.](image1)

![Figure 2: Ignition implosions are designed to avoid low velocity and low residual mass failure modes.](image2)

3. Tuning mass ablation

The National Ignition Campaign will tune experimentally the residual mass and peak velocity to correct for systematic physics uncertainties. The chief uncertainties affecting the implosion dynamics are hohlraum x-ray flux, believed to be known to 5%, and ablator opacity, known to 10%. Two parameters have been identified to allow tuning of implosions suffering from physics uncertainties. The first parameter, peak laser flux, adjusts the peak $T_r$ and associated x-ray flux. Increasing the peak flux increases the peak velocity and reduces the residual ablator mass (Figure 3). The flux adjustment creates a family of final mass and velocity states that span a 1-dimensional subspace. Similarly, decreasing the initial thickness increases the velocity and decreases the residual mass (Figure 4). However, the locus of final states now spans a different 1-dimensional subspace. Thus, the pair of tuning parameters provides a non-orthogonal basis for simultaneously adjusting both the residual mass and the peak velocity.
4. Experimental measurement techniques for tuning campaigns
To accomplish the tuning operations described in section 3, experimental measurement techniques are required for both residual mass and bang time as a surrogate for velocity. The bang time will be measured using either x-ray or γ-ray bang time detection. Three candidate techniques are being developed to measure residual mass and are described below.

4.1. Streaked radiography
Streaked radiography is currently the baseline ablation rate measurement technique for the NIC. The streaked radiography technique uses an x-ray backlighter and a slit imaging system to view a radial slice of imploding capsules. The implosion data (Figure 5) is reduced by iteratively estimating the spatial intensity profile of the backlighter and the spatial density profile of the object required to produce the observed image. The reduced data provides time-resolved mass data and an x-ray bang time. Initial tests performed at the Omega laser facility demonstrate the measurement principle.

Figure 5: Streaked radiographs can be used to estimate capsule density profiles at each instant of the implosion. Fully reduced data provides time histories of both capsule mass and velocity.

4.2. Copper Activation
Capsule residual mass may also be inferred by measuring the amount of activated Cu produced in an implosion. [4] This technique serves as risk mitigation for the streaked radiography technique. It
exploits the fact that Cu dopant in ignition point designs will be activated via the $^{65}\text{Cu}(n,\text{2n})^{64}\text{Cu}$ reaction. The number of $^{64}\text{Cu}$ atoms produced per $^{65}\text{Cu}$ per neutron is proportional to the residual mass in implosion simulations. The experimental measurement would be made by collecting solid Cu debris, both activated and unactivated, on solid Si plates placed near the target. The number of $^{64}\text{Cu}$ atoms is measured by $\gamma$-ray counting. The number of $^{65}\text{Cu}$ is measured by isotope dilution mass spectrometry.

4.3. Proton Spectrometry
A final, alternate mass ablation rate technique uses proton spectrometry to infer the ablator areal mass. This areal mass is strongly correlated with residual mass in suites of ignition implosion simulations. This diagnostic requires that the surrogate tuning capsule have the DT fuel removed and replaced with D$_2$-3He gas. The fill pressure is chosen so that the surrogate implosion kinematics are similar to those in an ignition capsule. The imploding surrogate produces 14.7 MeV protons whose spectral peak is shifted in proportion to the areal mass of the unablated Be (Figure 6). The proton spectra and associated shift are measured using CR-39 wedge range filters placed near the target. [5] The technique has been tested at the Omega laser facility. The measurement is feasible, however, the substituted gas fill makes certification of surrogacy between tuning and ignition capsules difficult.

![Figure 6: Shifts of the spectral peak of protons generated in D$_3$He filled tuning capsules are proportional to the residual mass of the ablator.](image)

5. Conclusion
NIC ignition capsules are designed to achieve a target residual mass and implosion velocity. The NIC has developed a tuning strategy to adjust the implosion physics in response to physics uncertainties. The initial capsule thickness and peak laser flux provide a pair of tuning parameters that can steer the residual mass and peak implosion velocity within ignition specifications. A set of candidate ablation rate measurement techniques has been developed and, when optimized, should allow tuning to within NIC specifications.

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