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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 x-ray-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 when the fuel reaches peak velocity. The specifications also require that the implosion bang time, a surrogate measurement for implosion velocity, be known to ± 50 ps RMS. These specifications guard against several capsule failure modes associated with low implosion velocity or low residual mass. 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. Alternative techniques to measure residual mass using activated Cu debris collection and proton spectrometry have also been developed. These developing techniques, together with bang time measurements, will 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 an 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 experimentally observe and adjust both the residual mass and the peak velocity in order to accommodate ablation rate uncertainties.

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 , which reaches 300 eV in Revision 1 point designs. The radiation is absorbed due to the finite ablator opacity, μ . The absorption of the radiation drive sets up an ablation front that propagates into the capsule ablator. As the front evolves, low density mass is ejected from the capsule surface, compressing the capsule in reaction.

This process, known as spherical rocket compression, is described by the ordinary differential equations in (1). These equations result from basic conservation of mass and momentum. They are dependent on the hohlraum drive T_r and the opacity through the mass flux term, \dot{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 .

$$\begin{aligned}\dot{M} &= 4\pi R^2 \dot{m}_a(T_r, \mu) \\ M\dot{v} &= -4\pi R^2 \dot{m}_a v_x(T_r, \mu)\end{aligned}$$

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. Successful implosions depend strongly on peak implosion velocity. To ensure that the minimum acceptable velocity is achieved, ignition specifications [2] 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. Further reduction of the residual mass reduces the x-ray barrier that shields the DT fuel. This leads to fuel preheat and entropy deposition. The ignition specifications allow the implosion to avoid these failure regions of phase space.

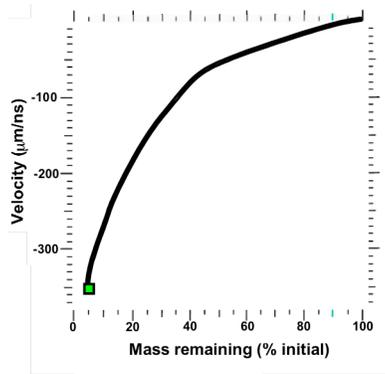


Figure 1: The HYDRA code provides detailed simulations of ignition point designs. Shown here is the capsule implosion trajectory in mass-velocity phase space.

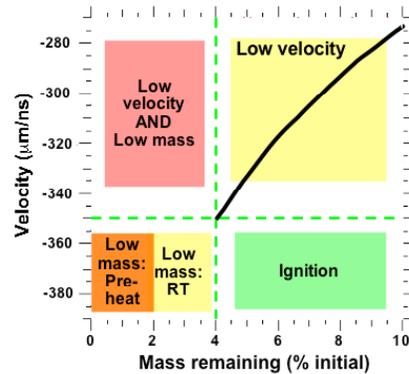


Figure 2: Ignition implosions are designed to avoid low velocity and low residual mass failure modes.

3. Tuning mass ablation

The National Ignition Campaign will tune experimentally the residual mass and peak velocity. Systematic physics uncertainties perturb the residual mass and peak velocity. 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. A similar effect is achieved by varying the initial capsule thickness (Figure 4). Decreasing the initial thickness, increases the velocity and decreases the residual mass. 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.

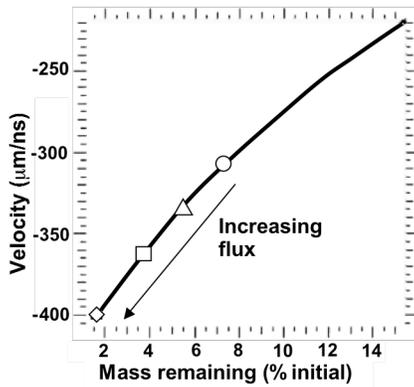


Figure 3: Adjusting the peak laser flux alters the residual mass and peak implosion velocity.

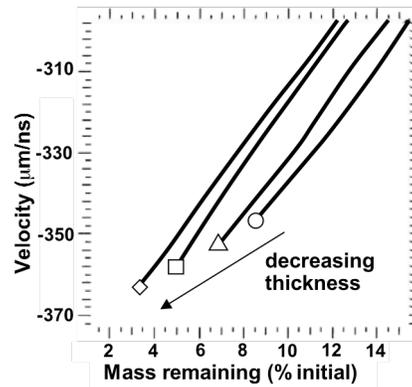


Figure 4: Adjusting the initial capsule thickness also alters the residual mass and peak implosion velocity. Together with peak laser flux, the pair of parameters provides the ability to tune both mass and velocity.

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. These include techniques based on streaked x-ray imaging of implosions, collection of activated ablator Cu dopant, and observation of proton slowing in unablated capsule material.

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 image is time resolved using a streak camera to produce a spatiotemporal history of the x-ray transmission. 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 final result is a time history of an approximate capsule density profile. This reduced data provides time-resolved mass and velocity data for tuning, as well as additional useful areal mass, shell aspect ratio, and x-ray bang time data. Initial tests have been performed at the Omega laser facility. These experiments demonstrated the measurement principle. Experimental errors due to data reduction schemes are currently larger than NIF specifications. However, it is expected that modifications to the reduction technique can bring this measurement in specification.

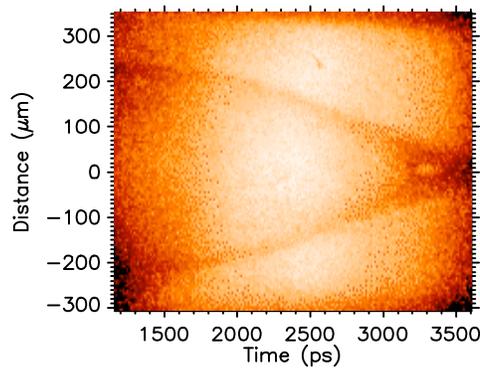


Figure 5: Streaked radiographs can be used to estimate capsule density profiles at each instant of the implosion. Fully reduced data provides time histories of both capsule mass and velocity.

4.2. Copper Activation

Capsule residual mass may also be inferred by measuring the amount of activated Cu produced in an implosion. [3] 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 $^{65}\text{Cu}(n,2n)^{64}\text{Cu}$ reaction. The number of ^{64}Cu atoms produced per ^{65}Cu per neutron is proportional to the residual mass in implosion simulations (Figure 6). 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}Cu atoms is measured by γ -ray counting. The number of ^{65}Cu is measured by isotope dilution mass spectrometry. Initial tests of the collection scheme for this technique have shown that the collection of unactivated Cu is challenging due to background laboratory Cu levels. Modified handling protocols have been developed to reduce background contamination.

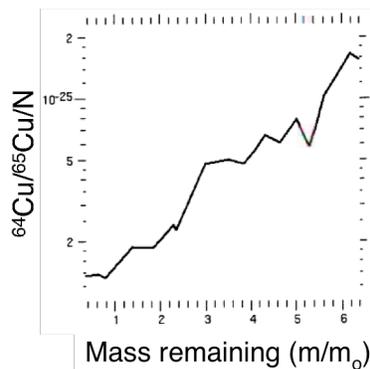


Figure 6: Collection of Cu debris provides a measurement of capsule areal mass and residual mass.

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 $\text{D}_2\text{-}^3\text{He}$ 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 7). The proton spectra and associated shift are measured using CR-39 wedge range filters placed near the target. [4] 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.

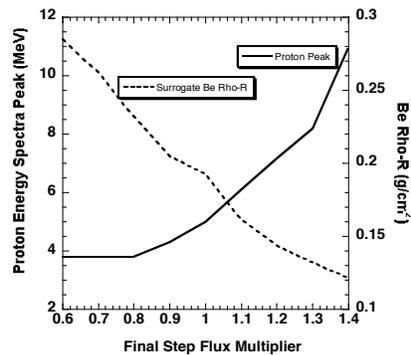


Figure 7: Shifts of the spectral peak of protons generated in D23He filled tuning capsules are proportional to the residual mass of the ablator.

5. Conclusion

NIC ignition capsules are designed to achieve a target residual mass and implosion velocity. Physics uncertainties, principally x-ray drive and ablator opacity uncertainties, can perturb the residual mass and velocity. The NIC has developed a tuning strategy to adjust the implosion physics in response to these 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 initially tested. The techniques include streaked radiography, Cu activation, and proton spectrometry. When optimized, the techniques allow tuning to within NIC specifications.

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