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Point Design Targets, Specifications, and Requirements for the 2010 Ignition Campaign on the National Ignition Facility

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Abstract

Targets intended to produce ignition on NIF are being simulated and the simulations are used to set specifications for target fabrication. Recent design work has focused on incorporating the implications of NIF experiments that were done in fall 2009, and planning for the campaign in 2010. Near-term experiments will use Ge-doped CH, although Be and diamond are still under active consideration for 2011 and beyond. The emphasis in this article will be on changes in the requirements over the last year, the characteristics of the 2010 CH-ablator design, and the designs for 2011 and beyond. Capsule defects of particular interest are surface perturbations on the CH ablator, and composition variations in the Be shells. Complete tables of specifications are regularly updated for all of the targets. All the specifications are rolled together into an error budget indicating adequate margin for ignition with all of the designs.

I. Introduction.

Experiments have begun on the National Ignition Facility,[1] with the goal of producing fusion ignition. This article updates our description of the targets for the ignition campaign, and the requirements on them. Proceedings articles for previous Target Fabrication Specialists meeting provide background and describe previous targets.[2]

The National Ignition Campaign (NIC) is proceeding in several steps to the ultimate goal of a reliable ignition platform that can be used for experiments on high energy density science. The initial campaign, in 2010, will (i) integrate the required hardware including target diagnostics and cryogenic target positioner, (ii) demonstrate the experimental techniques and targets needed to optimize the capsule implosion without cryogenic fuel layers, and (iii) begin experiments with cryogenic fuel layers. These 2010 experiments will be done with CH-ablator capsules, doped with Ge, in Au hohlraums. The point design target, designated as Rev5, is shown in Figs. 1 and 2. The drive for this target is shown in Fig. 3. The target is essentially the same as that described in Clark;[3] it has been updated to match the measured x-ray spectrum.[4,5]

An alternate design is available in case we cannot achieve 300eV peak drive radiation temperature. This 280eV design is shown in Fig. 4. The experiments in 2009 verified that we can achieve at least 280eV, and indicated that we could get temperatures as high as 300eV.[4,5]

While near-term work will concentrate on these CH designs, the NIC effort continues to consider possible future use of Be and C(diamond) designs, shown in Figs. 5 and 6.

Several features of these targets were set as a result of experiments on NIF in 2009. These are described in Section II. Section III describes a formalism we have developed that is used to characterize the margin of performance of the ignition target. This is used to describe the sensitivity of the performance to the requirements, including probability distributions characterizing the performance. Section IV summarizes the updated requirements, and Section V is a conclusion.

II. Experiments in 2009

The experiments in 2009 were very successful overall, including the fabrication of targets that were more complex than have been previously fielded, with tighter requirements. The target fabrication community deserves thanks and congratulations from the rest of the NIC community for their remarkable contribution to this success.

The primary goal of the 2009 experiments was to characterize the hohlraums and laser-plasma-interactions (LPI).[4,5,6] The experiments demonstrated that we can achieve peak hohlraum temperature of at least 280eV with a 1.0 MJ ignition pulse in a hohlraum of the size shown in Fig. 1, with acceptable LPI. The experiments suggested, with less certainty, that we can hope to heat this size hohlraum to 300eV with about 1.35 MJ. Thus the target shown in Fig. 2, with the pulse shown in Fig. 3, is optimized to be driven at 300eV. If we cannot achieve 300eV, we can do many of the necessary experiments with this target, while planning and fabricating somewhat thinner targets, as shown in Fig. 4, which is optimized for a lower radiation temperature.

The target designs shown in Figs. 1-6 include various updates based on the experiments:

(i) The laser entrance, previously lined with CH, is no longer lined. Simulations and modeling in 2009 had suggested that there may be issues with coupling between the beams as they crossed in the plasma blowing out from the LEH,[7] and the experiments confirmed that overall performance was better without the liner. The LEH needs to be somewhat bigger initially, since the liner was reducing motion of the Au during the pulse.

(ii) The fill-gas in the hohlraum, which was a mixture of H and He, is now pure He, with a density that has been optimized in the experiments.

(iii) Previous designs had boron doping in the innermost Au layer of the hohlraum wall, in order to reduce Stimulated Brillioun Scattering in the blown-out wall material. That proved in the experiments to be unnecessary.

(iv) The amount of Ge-doping in the CH shell has been increased, because the experiments indicated more-than expected x-ray flux in the preheat part of the drive spectrum (around 1.8-2.2 keV). With this higher preheat flux, and the previous level of Ge doping, the x-ray preheat of the ablator would reduce its density and increase the growth of Rayleigh-Taylor instabilities at the CH/DT interface.

We also gained new insight into implosion issues from the 2009 shots. Many of the shots produced x-ray images that showed bright spots within the radiating core, such as for example shown in Fig. 7. (This image is similar to published images;[4,5,6] this previously unpublished image, from those authors, was selected to demonstrate the bright spots.) Spectroscopic analysis established that the bright spots included emission from Ge. Simulations indicate that Ge-emission features generically similar to those seen could result from the dome defects that were typically on the CH shells, as well as from foreign material on the CH outer surface (which we casually call "dust" although its origin and composition may not necessarily correspond to the connotations of that word). Since the experiments in 2009 were primarily intended for hohlraum characterization, it was not a high priority to track the orientation of the characterized surfaces, or the specific locations of dust objects that were generally known to be present. Hence, for these shots, the data is not available to identify particular features seen in the implosion images with pre-shot characterized features on the surface. In a couple of shots, this connection may be evident with photographs of "dust." Although the connection between the pre-shot characterization and the images remains somewhat less definite than one might like, these observations have resulted in increased awareness of both of these issues. Requirements for the isolated defects on the surface have been tightened, as shown in Fig. 8. The tightened requirement is derived from simulations, which we could now regard as being qualitatively validated by the experimental results. The simulations that determine the requirement differ from the simulations that were used to set the earlier requirement primarily in the use of a new CH equation of state. This was updated based on Omega experiments.[8] Requirements have also been tightened for foreign material on the CH surface (historically the requirement for foreign material has been simply that no foreign object can be bigger than the size specified by the curve in Fig. 8. Now we allow features slightly higher than the new curve, if they are small enough laterally.) The requirement for the dust features is that no feature is allowed on the surface with mass more than 30pg, which at density unity corresponds to a cube of side 3.1 μm.

III. Ignition Threshold Factor as figure of merit for implosion

As a measure of ignition implosion robustness, we define a quantity we call the Ignition Threshold Factor (ITF). This builds on previous work on ignition scaling,[9-13] and will be described in detail in a forthcoming publication.[14] The formalism is a fit to our simulation results, with input from the basic physics. It provides a structure for describing and estimating the impact of all deviations from nominal in the ignition experiment. ITF is defined to be the energy that the implosion has divided by the minimum energy that would be required for ignition, where that minimum is defined by scaling the target down in energy (hence target mass) at fixed velocity, adiabat, etc. The ITF is defined to be

$$\mathrm{ITF} = 4.2\left(\frac{M_{\mathrm{DT}}}{0.20\ \mathrm{mg}}\right)\left(\frac{v}{366\ \mu\mathrm{m/ns}}\right)^{8}\left(\frac{\alpha}{1.38}\right)^{-4}\left(1-1.2\frac{\Delta R_{\mathrm{hotspot}}^{K_{\mathrm{wtd}}}}{R_{\mathrm{hotspot}}}\right)^{4.5+\varepsilon}\left(1-F_{\mathrm{mix}}\right)^{0.5} \qquad (1)$$

where M_{DT} is the fuel mass; v is the implosion speed; α the fuel adiabat; $\Delta R_{\mathrm{hotspot}}^{K_{\mathrm{wtd}}}$ is a weighted rms perturbation of the hot-spot shape, with mode weighting according to Kishony and Shvarts,[12] as described in more detail elsewhere;[14] and F_{mix} is the fraction, by mass, of fuel that is >5at% contaminated by CH mix. Each term includes as a denominator its nominal value for the Rev5-CH target. The overall prefactor of 4.2 is the amount of margin that the Rev5-CH target has, scaled up to 1.5 MJ, if everything is perfect and symmetrical. That factor of 4.2 is then used up by reduction of the other terms, until ITF reaches unity at which the ignition fails (see Fig. 9). The ITF is linear in M_{DT} by definition, so that it scales with laser energy × coupling efficiency, all else being equal. For a given laser energy and hohlraums, one could not change M_{DT} significantly without changing the speed v. The ITF is very sensitive to speed v, which is determined by variables such as drive temperature, ablator composition, shell thickness, etc. We have set requirements and design the campaign so that the velocity will be known to about 2%, and is expected to vary by about 2%. The power on the hot-spot shape term is a function of how much ablator mix penetrates into the hot-spot, designated m_{HSmix} and of the DT age:

$$\varepsilon = 0.6\frac{m_{\mathrm{HSmix}}^2 - (45\ \mathrm{ng})^2}{(45\ \mathrm{ng})^2} + 0.12\frac{A - 30\ \mathrm{h}}{30\ \mathrm{h}} \qquad (2)$$

Isolated defects, such as those that probably caused the bright spots in Fig. 7, cause hot-spot mix and would be an important source of failure. The hot-spot mix is normalized to 45ng because that much mix into the hot-spot is expected from the fill tube.

The ITF formalism is used to evaluate the impact of the various requirements, and of any failure to meet them. As is indicated in Fig. 9, the baseline scenario is that ITF reduces from 4.5 to 1.5±0.4, because various aspects of the experiment increase α, cause hot-spot perturbations $\Delta R_{\mathrm{hotspot}}^{K_{\mathrm{wtd}}}$, and cause mix F_{mix} and m_{HSmix}. Variations and uncertainty in the various quantities lead to the uncertainty and shot-to-shot variability in ITF

IV. Summary of Rev5 requirements

The requirements have been updated because of updates to the design, the experimental results, and updated simulations. Several issues have already been described; following are a few other changes.

The Rev5 surface roughness requirements are shown in Fig. 10. These are actually unchanged since Rev3.1 but have not been previously published. The outer surface of the CH is known to be considerably smoother than this requirement, except for the presence of the isolated features discussed above. This curve remains as the requirement, as a representation of the low modes and of the average features for higher modes. Specific requirements for the isolated features are being updated as described above.

The fill hole profile has been refined as shown in Fig. 11. This takes into account the actual geometry of the holes as they are being fabricated.

Other requirements remain essentially the same as described previously.[2]

V. Conclusion

The 2009 experiments led to several refinements of the requirements for ignition target fabrication. They verified that we will get above 280eV, in a gas-filled hohlraums with appropriate pulse-shaping, and that we will probably get 300eV. Along with the decision to proceed with CH(Ge) for the near term, this narrows considerably the parameter space of designs to be considered, at least for the near future. The preheat flux determined the optimum Ge profile, and we will proceed with the Rev5 capsule design described herein. Several features of the hohlraum design were refined. Upcoming shots will fine-tune the laser pulse and test whether any other aspects of the target design need to be adjusted. Overall we are positioned to get into the ignition campaign in late 2010, and the NIC program of experimentally validating and tuning the ignition target is well underway.

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Figure Captions

Figure 1. Baseline target for the 2010 ignition campaign. Hohlraum specifications are called out in detail. This is the target Rev5-CH.

Figure 2. Capsule specifics for Rev5-CH target.

Figure 3. (i) Laser power to drive the Rev5 target; (ii) the resulting temperature in the hohlraum (right scale); (iii) pressure in the capsule; (iv) fraction of x-ray energy above 1.8keV (right scale, x1000, i.e. peak fraction is 18%). This baseline target uses 1.35 MJ of 0.3 μm light absorbed in the target, at peak power 420 TW. The step in power in the first ns is the turning on of the outer cone, the pulse for which begins 300ps later than the inner cone.

Figure 4. Alternate CH(Ge) design that is optimized to be driven at peak radiation temperature 280eV. This design will be used if LPI makes it impossible to get to 300eV. Experiments in 2009 verified that we will get radiation temperature at least 280eV.

Figure 5. Updated Be(Cu)design. Be still looks the most likely to be the best ablator for long-term applications. This capsule size would require 1.3 MJ, at 290eV, in a hohlraum with diameter 5.88mm.

Figure 6. Diamond doped with Ta or W has potential to be the best ablator of all, but still has open issues with homogeneity of melt.

Figure 7. Image of x-ray emission from the core of shot 2009117. (Ref. 5) The radius of the image radius is about 50 microns. Bright features, which were spectroscopically established to be Ge emission, are thought to result from perturbation growth seeded by features on the CH shell. Simulations indicate that known features can grow to cause perturbation of this size—both bumps on the CH, and foreign material on the outside of the shell.

Figure 8. Requirement on maximum allowed defect on the CH ablator surface. Requirement has been tightened both because of changes in the simulations, as well as the experimental evidence that features on the shell can cause bright spots as shown in Fig. 7.

Figure 9. Expected statistics of margin, for the 1.5 MJ scale of Rev5. The horizontal axis is the Ignition Threshold Factor, defined as the energy the implosion has, divided by the minimum needed for ignition at the same velocity, adiabat, etc. In 1D, with all nominal drive and dimensions, the implosion has ITF 4.2, as indicated. For this target with the assumed statistics the expected ITF is 1.5±0.4, while the ITF that is needed for ignition is 1±0.25.

Figure 10. Maximum allowed surface roughness power spectra for trace circumferential lineouts of the indicated surfaces. Surfaces are defined relative to the centroid of the inner surface, so mode 1 is not defined for that surface.

Figure 11. Hole and tube profile defined as nominal configuration. Note that the vertical scale is expanded relative to horizontal. The glue profile is actually a circular torus. Requirements define the size of the tube, the maximum volume of the hole, any tilt of the hole, and the maximum glue mass.