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Progress On Establishing Guidelines For National Ignition Facility (NIF) Experiments To Extend Debris Shield Lifetime

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Progress on Establishing Guidelines for National Ignition Facility (NIF) Experiments to Extend Debris Shield Lifetime

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Abstract

The survivability and performance of the debris shields on the National Ignition Facility (NIF) are a key factor for the successful conduct and affordable operation of the facility. The improvements required over Nova debris shields are described. Estimates of debris shield lifetimes in the presence of target emissions with 4 - 5 J/cm^2 laser fluences (and higher) indicate lifetimes that may contribute unacceptably to operations costs for NIF. We are developing detailed guidance for target and experiment designers for NIF to assist in minimizing the damage to, and therefore the cost of, maintaining NIF debris shields. The guidance limits the target mass that is allowed to become particulate on the debris shields (300 mg). It also limits the amount of material that can become shrapnel for any given shot (10 mg). Finally, it restricts the introduction of non-volatile residue (NVR) that is a threat to the sol-gel coatings on the debris shields to ensure that the chamber loading at any time is less than 1 μg/cm^2. We review the experimentation on the Nova chamber that included measuring quantities of particulate on debris shields by element and capturing shrapnel pieces in aerogel samples mounted in the chamber. We also describe computations of x-ray emissions from a likely NIF target and the associated ablation expected from this x-ray exposure on supporting target hardware. We describe progress in assessing the benefits of a pre-shield and the possible impact on the guidance for target experiments on NIF. Plans for possible experimentation on Omega and other facilities to improve our understanding of target emissions and their impacts are discussed. Our discussion of planned future work provides a forum to invite possible collaboration with the IFE community.

1. Introduction

The National Ignition Facility needs to have established guidelines for experiment and target design that provide affordable operations costs. These guidelines should describe, for proposed experiment, what magnitude of operation cost the debris and shrapnel production and consequent impacts to debris shields create. In addition, the impact of non-volatile residue, that can degrade the performance of anti-reflection coatings, must be controlled. We are evolving these guidelines with users on a quarterly basis by developing adequate target effects modeling supported by experimental data. This effort contributes to the overall ability to plan NIF shot costs using the future Laser Performance Operations Model (LPOM) that includes a model developed for the chamber. This effort also impacts design of actual in-chamber systems such as diagnostics. This model must integrate a great deal of information for each shot in order to predict costs. It must be capable of detailed modeling of target emissions and their effects on the debris shield such as shrapnel, molten droplets, x-rays and particulate. It must keep track of laser damage initiation and growth in the presence of the target emissions. It must take into account beam self-cleaning. Finally, it must model the subsequent impact on beam balance, energy, ability to focus, and pulse duration. The final optics assemblies are mounted on the chamber and hold the debris shields 7.3 m from chamber center, as shown in Figure 1. The NIF planned debris shield performance is compared to Nova debris shield performance in Table 1.

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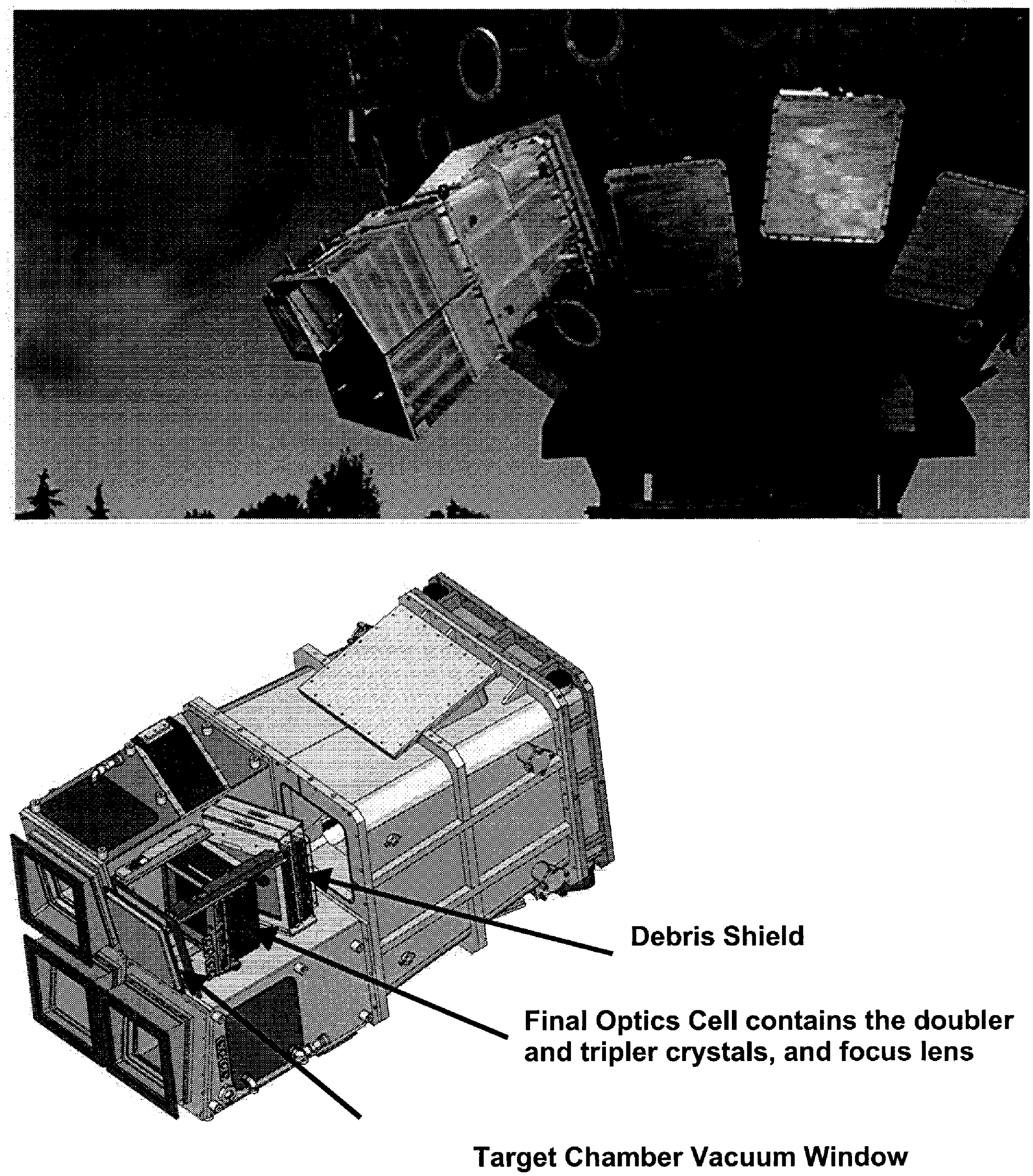


Figure 1. The Final Optics Assembly is attached to the chamber exterior and contains the optics to frequency convert the beam as well as focus it to chamber center.

Feature	Nova	NIF
Size	65 cm dia (round)	43 x 43 cm (square)
Number	10	192
# Changed per Week	5	192
Transmission (new)	99.5%	99.5%
Transmission (reject)	95%	95%
Shield Lifetime	~6 months	~2 months
Refurbishment Rate	~ one time per shield	unknown
Installation Time (each)	~1 hour	15 minutes (goal)
Total Install Time	~5 man-hours	~48 man-hours (goal)
Beam Balance	Few %	<8% RMS
Beam Focus	80% in 150 μm spot	80% in 500 μm spot
Particulate Obscuration	1.25% / week	2.5% / week
Damage Site Obscuration	0.2% / week	0.3% / week
Disposable Debris Shield	None	Changed each shot

Table 1. A comparison between Nova and NIF debris shield performance illustrates the stringent requirements on the NIF debris shields.

2. Guidelines

Designs for experiments on NIF, including both targets and diagnostics, are currently in progress. Therefore, it is necessary to identify a process for reducing debris and shrapnel impacts of experiments while allowing designs to go forward. We have set an initial, simple, experiment plan (shot energies, generic targets) and will evaluate the shrapnel and laser-induced damage growth with models benchmarked against data. Shrapnel reduces debris shield effectiveness by creating damage sites that obscure or scatter the beam. We have set an initial shrapnel criteria by allowing debris shields to become obscured 2.5% due to shrapnel craters over 120 shots, or approximately an 8 week period of operations. The growth of these craters due to laser fluence effects must also be considered. Further, since refurbishment of debris shields is less expensive than a new shield, removal of a shield at a point in time and state of damage that supports cost effective refurbishment should also be determined. Debris particulate also degrades a shield's performance by scattering laser light out of the focus. We have likewise set a criteria for particulate that after 15 shots, or about a week of shots, ≤ 0.7 nm layer of material will be deposited on the main debris shield, causing 2.5% transmission loss.

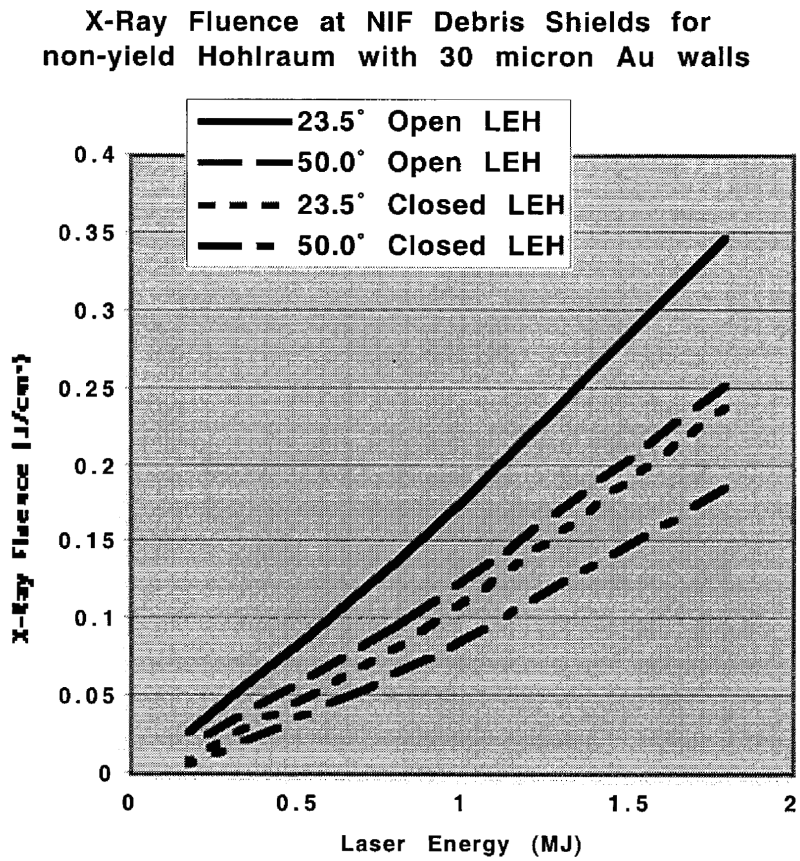
After determination of whether or not a baseline, or generic design meets these criteria or not, we would then modify (in our analyses) the target design until all criteria are met. The results of these analyses are then fed back to experiment planners as a guide to address such aspects as target material choices, stand-off distances, total mass, etc. that meet the economical criteria discussed above. This process continues iteratively expanding considered experiments and targets.

Although this process is still being developed to an acceptable capability, interim guidelines are needed now. Therefore, we have proposed a current guideline for a particulate limit of 300 mg. This includes that particulate generated by the target, the beam dumps, any diagnostics, the target positioner, the first wall, and takes credit for 50% of the particulate being removed by the laser beams actually cleaning the glass surface. We have proposed a current guideline for a shrapnel limit of 10 mg. For shots that can use the somewhat broadened beam spot that results, a disposable debris shield may be used that substantially reduces or eliminates the particulate and shrapnel effects. There will also be a restriction on the specific velocity – radius space to limit damage to a disposable debris shield as well as the main shield. Finally, the NVR level in the chamber must remain below 1 $\mu g/cm^2$. These levels of particulate and shrapnel suggested here do not yet include the growth of these target-induced damage sites by the laser fluence. This must be included in the future.

The particulate level was determined by investigation of Nova's debris shield surface contamination. Measurements of 3ω transmission through debris shields after two weeks on Nova were made. The composition of the surface contamination was measured using wipes and Inductively Coupled Plasma-Optical Emission and Mass Spectroscopy techniques with nano-gram-level accuracy. A simple laser ablation model was constructed in an effort to predict the expected quantity of contamination just by using the shot energies and target configurations. This effort revealed some surprising results. The efforts to model the particulate thickness initially seemed quite good -- results were better than a factor of 2 to the measured data for two debris shields that were near the top of the Nova chamber. Later, data compared across all 10 shields showed variations ***within the same polar angle from the target*** of more than a factor of 10. Horizontally positioned debris shields had *substantially* more material than any others. Cleaning of particulate from the surface of the glass by the laser was an average of 50% at 0.75 J/cm^2. This was determined by comparing the particulate quantities measured in and out of the beam. This result would indicate that beam balance was impacted due to debris alone by as much as 5%. Therefore, predictive models of particulate deposited on the main debris shield must include this demonstrated anisotropy. The total quantity predicted released as debris (on average) was consistent with the data, even if the distribution was not.

Material removal due to x-rays from all proximate surfaces such as the diagnostics and the target positioner must be calculated to be included with the particulate budget. The LLNL-developed ABLATOR code calculates x-ray ablation for fluences up to ~10 J/cm^2. This upper limit exists because the code uses cold opacities. The LLNL code LASNEX or the CEA code DELPHOR can be used to predict material removal for higher x-ray fluences. Once a quantity of material is modeled as being ablated, a major issue that remains is the calculation of its condensation and transport to determine what material in what state actually makes contact with the optic. Since there is some limited data that suggests that laser damage of particulate-coated optics may be Z and state of the material dependent, this is a key issue. These aspects, taken together, will drive examination of new materials and new target designs. The University of Madrid will address condensation and transport over the next few years and experiments on Omega, and/or Helen are critical to resolving these issues.

Accurate x-ray emission predictions are essential to assessing experimental impacts. For a hohlraum with a 30-micron thick Au wall, the code LASNEX has been used to predict x-ray emissions. These are shown in Figure 2. Due to difficulties with completing the late-time 2-D computations, 1-D predictions were used. When 2-D predictions were attempted, the material expanding into the laser entrance hole (LEH) from the hole edges and the material moving



450 kJ @ 5 cm (J/cm²) 30-μm wall			
Case	**23.5°**	**50°**	**90°**
30 μm closed LEH	740	575	170
30 μm open LEH	1425	1000	33

Figure 2. X-ray emission predictions bound the expected value by comparing the 'open' LEH case to the 'closed' LEH case. At 450 kJ laser energy, the difference is as much as a factor of 5.

through the same location, combined with material that was expanding from the exterior surface of the hohlraum causing numerical problems that terminated the calculation. Two sets of 1-D calculations were done to study the issue of hole closure. The first kept the LEH open for the duration of x-ray emission to provide a worst case estimate of x-ray fluence at the 23° beam angle and maximum radiation cooling of the hohlraum. Then, a rather conservative closing assumption was made where the LEH was half closed at 20 ns, and fully closed at 30 ns, where the duration indicates the time after the initiation of the laser pulse in the hohlraum. This provided a much smaller fluence at the 23° angle (about half as large as for the open LEH case) but a much larger fluence at 90° -- larger by a factor of five. Further 2-D computations are in progress to resolve this issue.

3. Disposable Debris Shield

If a sufficiently inexpensive thin glass sheet, that produces acceptable beam distortion, can be placed in front of the main debris shield on each shot, the life of the expensive optic can be extended. Substantially all of the particulate and most of the shrapnel is expected to be intercepted by such a disposable debris shield. The amount of shrapnel intercepted depends on the disposable shield thickness. Figure 3 shows the relationship between particle size and velocity and the thickness of shield needed to stop it. For example, a 50-micron particle traveling at 1 km/s would need a thickness of about 100 microns of glass to prevent the particle from passing through and striking the main shield. A 200-micron particle traveling 2 km/s would need a 1-mm thick glass shield.

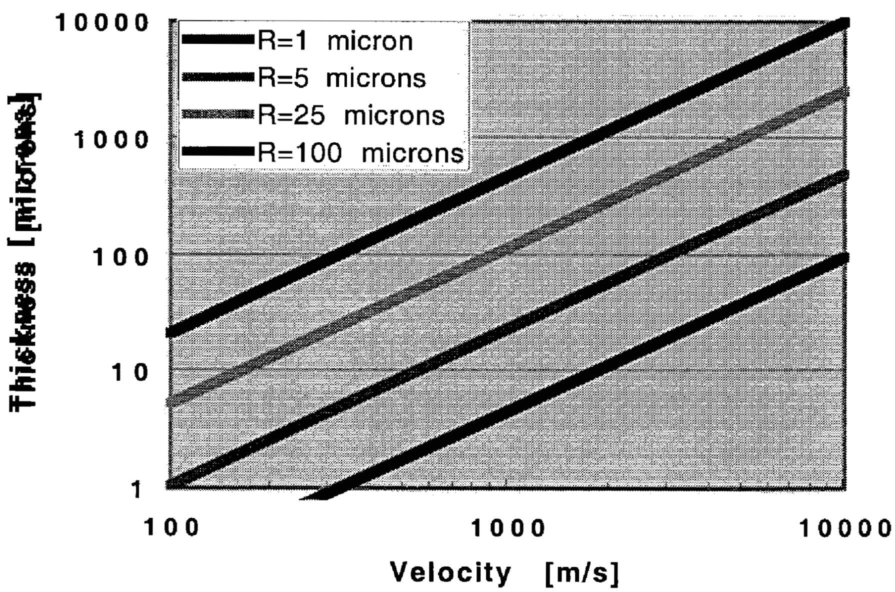


Figure 3. A glass disposable debris shield thickness can be chosen to stop a particular size and velocity of shrapnel. These calculations assume that the particle is steel.

There is concern, however, of such a shield shattering due to shrapnel impacts, or spalling as much or more material (glass shards) onto the main shield than it is intended to stop. This is because for a brittle material, the spall zone tends to be a cone shaped section with an included angle of approximately 90°. The thicker the shield, the more shrapnel is stopped, but also the more material is spalled for those particles that can damage the disposal shield in this way. When disposable shield thicknesses are chosen for use, this will imply the need for an additional guideline to experimenters to limit or eliminate penetration and spalling by shrapnel. An example of such a limit is shown in Figure 4. Predictions of shrapnel generation for a particular experiment would be compared to a plot like this to ensure the particles produced would lie below line representing the thickness of the disposal debris shield to be used. For example, for a 1-mm thick shield, a size limit on 1 km/s particles would be about 200 microns.

On-going analyses of disposal debris shield candidates continues with examination of optical properties, total weight, impact experiments for to examine shatter and penetration, examination of the characteristics of the ejecta, gravity induced stress, laser heating thermal stresses, and thermal stresses due to x-ray deposition.

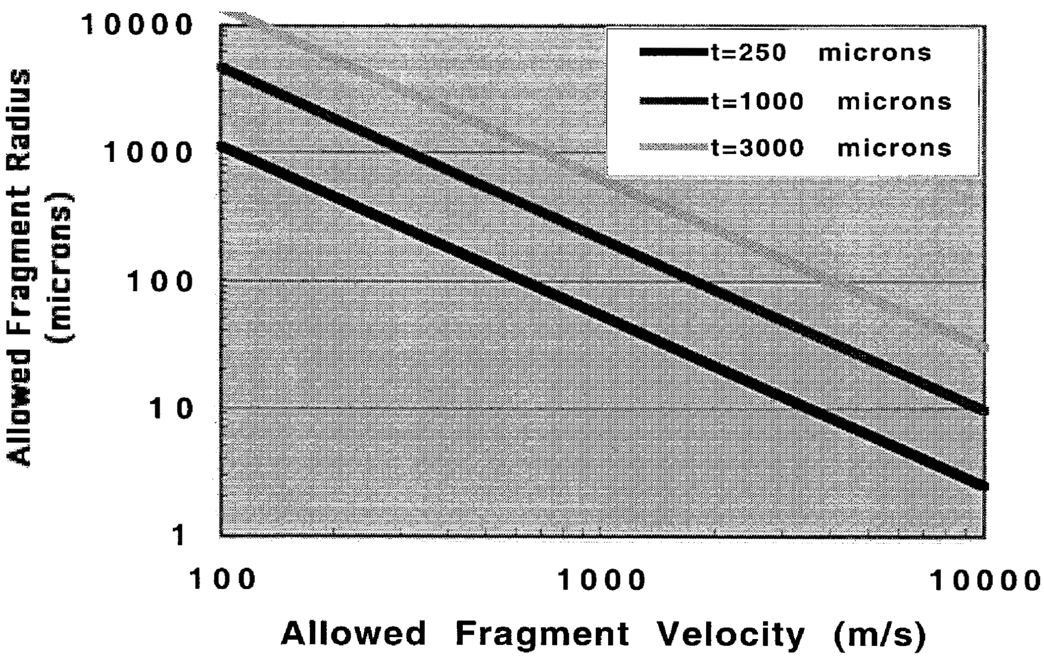


Figure 4. To prevent penetration of the disposal debris shield and subsequent damage to the main shield, targets would have to be designed to produce shrapnel below the line corresponding to the disposal shield thickness. The size-velocity region for fragments below each line will not penetrate that thickness. Penetration is defined as any cracking NOT reaching the back surface of the shield.

4. Experiments to Define and Models to Predict NIF Target Emissions

Key to the process of guiding NIF experimenters to conduct experiments that minimize operations costs on NIF is the ability to model sufficiently accurately target emissions and their impacts. This includes the x-ray emission and subsequent ablation, the debris emission and subsequent condensation, the shrapnel generated and its impacts, and the growth of damage due to the laser beam itself. ***Substantial*** code development is needed to do self-consistent 3D calculations in these areas. Detailed modeling of NIF target/diagnostic configurations will evolve during the years. The long-term goal is to have one 3-D code that calculates x rays, debris, and shrapnel. The code, KULL, one of the ASCII codes at LLNL, is a potential candidate. The short-term goal is to calculate x rays, debris, and shrapnel and effects for a few simple target designs, using existing codes such as LASNEX, HYDRA, CALE, and AMR. An example of such as simple target design is shown in Figure 5.

There is a substantial need for many types of data to validate and guide the modeling. While significant experimentation was done to establish the modeling that was developed to set the NIF chamber radius in the early 1990's, much more is needed now. For example, there is a

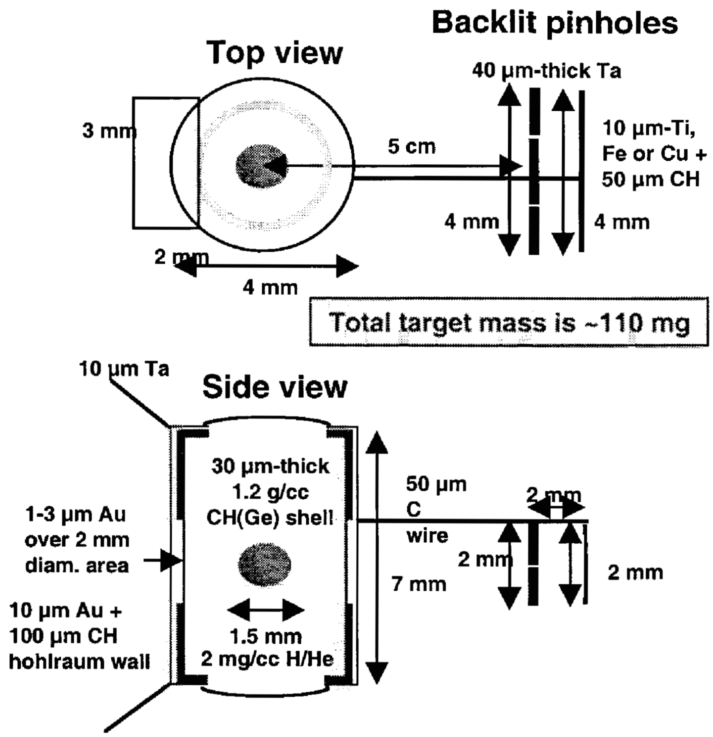


Figure 5. A non-yield implosion experiment is a good candidate to develop predictive capabilities for target emission impacts.

need to measure the growth rate of shrapnel induced craters in case it is different from the growth rate of laser indued damage. As mentioned earlier, measurements of x-ray emission need to be made to contribute to resolution of the hole closure issue for hohlraums. When a disposable debris shield cannot be used for a particular shot due to beam fidelity concerns, data is needed to validate the evolving modeling of the state of condensed target debris and its impact on the main shield, that is the damage rates of fused silica coated with debris that is in the state expected for NIF. Data to validate predictions of shrapnel emission of target assemblies is essential. This will be done on experiments using a material such as aerogel to trap emitted particles and allow their tracks to indicate their velocities. More data on laser cleaning of particulate both above and below that measured on NIF is needed. Data for confirmation of material removal at high x-ray fluences is needed to compare to LASNEX predictions. One of the advantages of a disposable debris shield is that the characteristic shrapnel emissions may possibly be reduced to more benign condition by increasing the overall mass of the target or using different materials in the target. The disposable shield will intercept (in theory) the increased debris loading. Therefore, data on new target material behavior is anticipated. We have learned that the debris from a target is not emitted isotropically – but more data is needed to quantify this anisotropy. There are certainly dynamic effects, such as a debris cloud that redirects ablated material from the direction x-rays have sent it, that will be needed and some means to collect data related to such phenomena must be developed.

Conclusions

Target guidance is being developed to aid in the economical operation of NIF. Specifically, we will extend the life of the main debris shield by modifications to target designs and possibly by using a pre-shield to the debris shield that is inexpensive enough to be disposable. Substantial modeling and supporting data collection needed to support this effort offers many opportunities for collaborations with the Inertial Fusion Energy community.