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Debris and Shrapnel Mitigation Procedure for NIF Experiments

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Abstract. All experiments at the National Ignition Facility (NIF) will produce debris and shrapnel from vaporized, melted, or fragmented target/diagnostics components. For some experiments mitigation is needed to reduce the impact of debris and shrapnel on optics and diagnostics. The final optics, e.g., wedge focus lens, are protected by two layers of debris shields. There are 192 relatively thin (1-3 mm) disposable debris shields (DDS's) located in front of an equal number of thicker (10 mm) main debris shields (MDS's). The rate of deposition of debris on DDS's affects their replacement rate and hence has an impact on operations. Shrapnel (molten and solid) can have an impact on both types of debris shields. There is a benefit to better understanding these impacts and appropriate mitigation. Our experiments on the Omega laser showed that shrapnel from Ta pinhole foils could be redirected by tilting the foils. Other mitigation steps include changing location or material of the component identified as the shrapnel source. Decisions on the best method to reduce the impact of debris and shrapnel are based on results from a number of advanced simulation codes. These codes are validated by a series of dedicated experiments. One of the 3D codes, NIF's ALE-AMR, is being developed with the primary focus being a predictive capability for debris/shrapnel generation. Target experiments are planned next year on NIF using 96 beams. Evaluations of debris and shrapnel for hohlraum and capsule campaigns are presented.

1. Introduction

The National Ignition Facility (NIF) in the United States and the Laser MegaJoule (LMJ) in France will operate with a large number of optics and many diagnostics exposed to debris and shrapnel from targets and other chamber components. For cost effective operation, it is critical to establish a debris and shrapnel mitigation procedure. There are two main aspects of this mitigation procedure. First is to design the optical assemblies and diagnostics to withstand the impacts of debris and shrapnel in a cost effective manner and second is to modify targets and associated components, as necessary, to reduce debris and shrapnel loading. The plan for both large laser facilities is to use a layered approach to protect the more expensive optics, e.g., wedge focus lens on NIF. The first layer, closest to target chamber center (TCC), are relatively thin (1-3 mm) disposable debris shields (DDS) with the second layer being thicker (10 mm) main debris shields (MDS). The lifetime of the DDS's is expected to be between 1 and 20 shots, depending on target and laser parameters. The lifetime of the MDS's is expected to be between 100 and 200 shots. Diagnostics will use a range of filters and collimators to protect cameras and other vulnerable components to ensure that data is obtained. The focus of this paper is on the second aspect of the mitigation procedure: evaluation of the sources of the debris and shrapnel and the associated impacts on optics and diagnostics.

Our understanding of the generation of debris and shrapnel and the impact on optics and diagnostics is based on past experiments, e.g., Omega and 4-beam NIF shots, dedicated fragmentation experiments on HELEN, JANUS, LIL, etc. laser facilities, and on detailed numerical simulations. For a review of experiments and corresponding simulations see ref. [1]. For information on aspects of a new simulation code, NIF's ALE-AMR, used in the evaluations discussed in this paper see refs. [2-3]. There are three major differences between simulations of debris/shrapnel generation and simulations of ICF capsules/targets: 1) longer time-scale (μs vs. ns), 2) larger spatial scale (μm-m vs. μm-cm), and 3) different physics (ablation and fragmentation vs. LPI, mix, and burn) drives the simulation. Early work focused on the first difference, where it was shown that the majority of the vaporized hohlraum mass is directed towards the waist/equator of the chamber and not towards the optics.[4] To tackle the second difference and the desire to model a "complete target," hohlraum, flanges, shields, cooling rings, and support structure, we use a new code that combines standard ALE hydrodynamics with adaptive mesh refinement (AMR). The initial mesh can be concentrated in structures (hohlraum wall, shields, etc.) with coarser mesh in the vacuum between components. During the simulation the mesh can refine to better resolve shocks or model generation of voids and subsequent fragmentation. The AMR capability also allows different material models to be used at different levels of refinement. The code retains the benefits of ALE codes that allow the mesh to move with the rapidly expanding material with remeshing as needed.

In section 2, we review the constraints placed on debris and shrapnel generation. In section 3, we show some results of our evaluations for the NIF 96-beam energetics campaign, planned for the summer of 2008, and a 96-beam capsule campaign using a keyhole target. We conclude in section 4.

2. Constraints on debris and shrapnel generation

The constraints on debris are primarily associated with loss of transmission through the DDS's and corresponding reduction in their lifetime. The constraints on shrapnel are primarily associated with DDS penetration/breakage, MDS damage/penetration, and diagnostic filter penetration. The DDS's will be held in cassettes with up to 10 DDS's to reduce the replacement time. In contrast, personnel must vent and open a final optics assembly to replace a MDS leading to a more rigid constraint on shrapnel generation associated with MDS lifetimes. The shrapnel constraint associated with DDS breakage places a limit on the mass and velocity of molten material that can strike DDS's. Finally, shrapnel constraints associated with diagnostic filter penetrations depend on the configurations of the diagnostics on a given shot.

There are three main sources of debris in NIF experiments: 1) vaporization of targets components close to TCC, 2) ablation of material by unconverted laser light, 3) ablation of material from target x-rays. (One of the major differences in the design of NIF and LMJ is that unconverted light does not enter the LMJ chamber so LMJ experiments do not have the second source of debris.) For NIF, the first and second sources are often comparable. The third source is only important for very high energy or yield shots where the x-ray fluence on the first-wall if of order 1 J/cm^2 or greater. Ablation from the first-wall, by unconverted light and x rays, is reduced by approximately a factor of 10 by the use of stainless-steel louvers. The allowed mass depends on the level of DDS transmission loss that is allotted to debris.
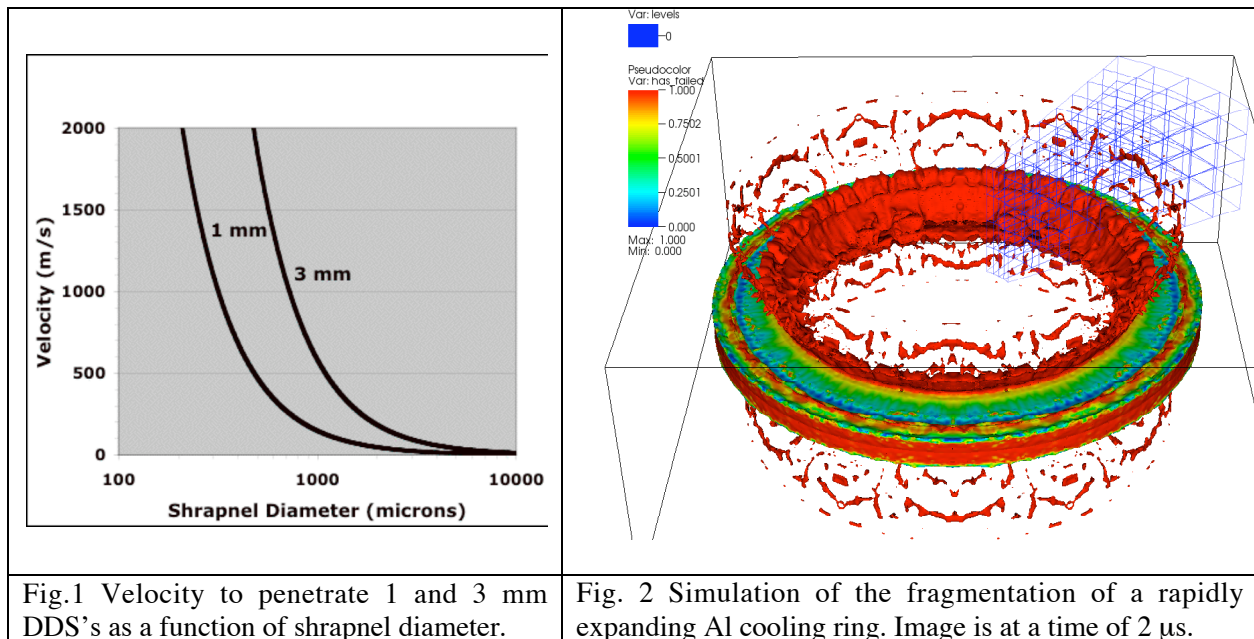
On early NIF shots we observed a type of DDS transmission loss that is not associated with debris. This loss is associated with reactions in the DDS borofloat glass when exposed to a combination of 1ω and 3ω laser light. After approximately 25 shots with 3ω energies of order 2 kJ/beam or less, we observed a drop in transmission from this effect to be of order 2%. We have a goal of ~10 shots prior to DDS replacement with a transmission loss of order 3%. We assign ~1% of this to reactions in the DDS from 1ω + 3ω and 2% to the effects of debris. To relate this transmission loss to mass of debris,

we use Nova measurements that showed a debris mass density of 1 $\mu g/cm^2$ gave a 6% drop in transmission out of the beam. Inside the beam, a transmission loss of 2% was measured for the same debris loading. If we assume similar beam cleaning for NIF, the allowed mass density is 1 $\mu g/cm^2$. Given that the DDS's are ~7 m from TCC, this corresponds to a total mass of 6 g. If beam-dump ablation contributes ~1/3 of the total mass, the allowed vaporized target mass per shot is 400 mg assuming 10 shots per DDS.

One shrapnel constraint is to avoid penetration of DDS's. This assures that shrapnel does not impact MDS's. We have developed simple models of DDS penetration based on the formation of Hertzian cracks going through the thickness of the DDS. In Fig. 1 we show the calculated velocity that a steel shrapnel fragment would need to cause a penetration. We give results for 1 and 3 mm thick DDS's as a function of the fragment diameter. For our default thickness of 1 mm, a shrapnel fragment with a diameter of 200 μm would have to impact with a velocity of slightly more than 2000 m/s. Another shrapnel constraint, which has a greater impact than the penetration of a DDS, is to avoid breakage of a DDS by a molten shrapnel spray. We observed that molten shrapnel can break DDS glass during an Omega shot to test redirection of shrapnel by tilting Ta foils.[5] If a spray having the same kinetic energy as a 200 um diameter fragment moving at 2000 m/s impacts a DDS, our simple model predicts breakage. Curving sources of molten spray can cause divergence of the spray and reduce the mass striking a particular DDS. We don't have a constraint on small solid fragments that produce a large number of small damage sites on DDS's. While these sites can grow in size, for the relatively few number of shots (of order 10) that DDS's are in place we don't expect the growth to be significant and the scatter from these sites should be significantly less than 1%.

3. Evaluations for the NIF 96-beam campaigns
The 96-beam energetics campaign will use scale 0.7 cryogenic hohlraums with the radiation temperature measured by the Dante diagnostic. Other primary diagnostics measure properties of the backscatter light. None of these diagnostics place tighter constraints than those associated with the optics. The vaporized target mass is expected to be 340 mg, which is below the 400 mg limit discussed above. The expected mass ablated by unconverted light and x rays that enters the chamber is less than the 200 mg limit. It is necessary to confirm that the hohlraum is vaporized for the lowest energy being considered for this campaign. This energy of 33 kJ is associated with truncating the pulse after 6 ns corresponding to the 3rd shock. The current cryogenic hohlraum design has an outer layer of Al that is 150 μm thick. We did a 1D simulation, with a model for leakage out of the laser entrance holes, to calculate the temperature of the coolest Al zone as a function of time. The coolest zone is above the vaporization temperature (~2800°K) for over 500 ns allowing the hohlraum to be vaporized. The Si cooling rings are not expected to be completely vaporized for any of the shots and must be evaluated for shrapnel generation. The rings are forced to rapidly expand because of the expanding vaporized hohlraum pushing the rings outward. We estimate that the rings expand at ~1/10 the velocity of an expanding hohlraum or ~1000 m/s. We model the expansion of Si rings using a brittle failure model and also model Al rings using a ductile failure model. We calculate that Si breaks into smaller fragments than Al as expected. CEA is considering Al rings for LMJ targets and Al is interesting as a bounding case for Si, which can become more ductile when heated by neutrons. (During these 96-beam experiments, neutrons will not be generated.) In Fig. 2 we show results of a simulation using NIF's ALE-AMR code for a scale 0.7 Al cooling ring at a time of 2 μs. The color bar denotes how close a zone is to failure with red denoting complete failure. The initial ring is 500-μm thick and 2000-μm wide in the radial direction. At 2 μs, we see that the inner portion of the ring is shooting out the sides in very small fragments/droplets and the ring is in the process of failing. This process continues and we don't calculate any large (>100 μm) fragments that would penetrate a 1-mm thick DDS based on the curve given in Fig. 1.

Fig.1 Velocity to penetrate 1 and 3 mm DDS's as a function of shrapnel diameter.	Fig. 2 Simulation of the fragmentation of a rapidly expanding Al cooling ring. Image is at a time of 2 μs.

The 96-beam shock timing campaign will use keyhole targets that contain a cone filled with liquid D_2, which penetrates the capsule and extends outside the hohlraum. The portion of the cone inside the hohlraum is Au and the portion outside is Al. We determined that the VISAR diagnostic is adequately protected by its blast window. We are evaluating how many spare windows will be required based on the number and sizes of damage sites caused by shrapnel impacts. Another component for this target is a very large outer cone to block unconverted laser light from striking the quartz window holding in the D_2. The current design for this cone is ~50 μm-thick CH with a thin Al coating. Initial evaluation shows that this cone meets debris and shrapnel constraints. The relatively large amount of CH requires an evaluation of the impact of associated non-volatile residue (NVR) on the sol-gel antireflection coating on the DDS's. This was determined not to be a problem given the relatively short time DDS's are exposed to the chamber environment.

4. Conclusion

We have a debris and shrapnel mitigation procedure in place and have applied it to 96-beam campaigns. The goal of the procedure is to manage generation of debris and shrapnel so as to reduce the probability of data loss and allow optimization of optics use. We have defined a set of constraints for debris and shrapnel and have shown that the 96-beam campaigns meet these constraints. Our evaluations use a range of simulation tools including a new code, NIF's ALE-AMR, that has unique capabilities relevant to debris and shrapnel modeling. We will apply the mitigation procedure to the wide range of planned experiments on NIF to achieve ignition and study high-energy density physics.

5. References

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