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ABSTRACT

During the years before the National Ignition Facility (NIF) laser system, a set of generally accepted cleaning procedures had been developed for the large 1ω amplifiers of an ICF laser, and up until 1999 similar procedures were planned for NIF. Several parallel sets of test results were obtained from 1992 to 1999 for large amplifiers using these accepted cleaning procedures in the Beamlet physics testbed and in the Amplifier Module Prototype Laboratory (AMPLAB) four-slab-high prototype large amplifier structure. Both of these showed damage to their slab surfaces that, if projected to operating conditions for NIF, would lead to higher than acceptable slab-refurbishment rates. This paper tracks the search for the "smoking gun" origin of this damage and describes the solution employed in NIF for avoiding flashlamp-induced aerosol damage to its 1ω amplifier slabs.

Keywords: Flashlamp-induced aerosols, Laser amplifier environment, Laser slab damage

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I. INTRODUCTION

Cleanliness and contamination control is important in both the 1ω and 3ω sections of the NIF laser in order to avoid reduction of transmission at coatings and surfaces and to avoid laser damage to optical surfaces. This paper will deal with avoiding damage to slabs in the large 1ω amplifiers. In general, flaws on laser slabs do not grow under laser illumination. Rather, their impact can be felt in terms of the obscurations or phase perturbations they present to the propagating laser beams.

Obscurations on slabs were expected to have two important impacts. The first and more obvious impact was scattering of light out of the beam. It is not the loss of light that is important; rather it is the impact that the scattered light can have on reducing the uniformity of the laser-intensity profile by increasing the spatial contrast of the propagating beam. The flowdown requirement for fluence contrast of the 1ω NIF amplifier is < 10%. The scattering contribution to contrast can build up fast because the contribution by each surface is given by $(2F)^{0.5}$, where F is the single-surface scattered fraction; i.e., the fraction of the laser beam area obscured by the scattering sites. To illustrate both this point and the long-term understanding of this point at LLNL, data in Fig. 1 is taken from a 1981 paper by Simmons et al.[1] that describes 1977 results for the Argus laser, which had spatial filtering and image relaying similar to that for NIF and that shows an increase in contrast of about 25% in the range of F between $3x10^{-5}$ and $3x10^{-4}$. The information in Fig. 1 is consistent with approximately 7% contrast due to surface-finishing phase errors typical of laser components manufactured in that period and ~50 slab surfaces, each with the value of scattered fraction, F, (due to obscurations on the optics) given on the horizontal axis.

There are at least four differences between conditions important for Argus and those typically important for NIF. One is that the maximum length of an Argus pulse was only about 2 ns. The second is that Argus amplifiers used a silicate glass instead of the phosphate glass used in NIF. The combination of these two conditions resulted in operation of Argus amplifiers in a less saturated regime than is typical for NIF. The third is that an Argus beamline was operated at higher intensity than a NIF beamline; intensity levels for Argus were as high as 8.3 GW/cm^2 (in silicate amplifier slabs with their slightly higher value of n_2). NIF amplifiers at the peak of a 1.8 MJ pulse reach an intensity of ~4.2 GW/cm^2 at 1.053 μm. The fourth is that the coatings on Argus lenses and mirrors were less damage resistant than the coatings of NIF optics. As a result of these four differences, the importance of obscurations for regular ICF shots on target during NIF operations is less than for Argus. Pulse lengths for NIF beamlines to be used for shots to the advanced radiography capability (ARC) backlighter will be shorter, at about ~1 ns, but with frequency-bandwidth-to-pulse-length compression, the peak power in the ARC beams is estimated to be ~3.6 GW/cm^2, and even allowing for some additional intensification caused by dispersion of the chirped pulses, ARC pulses should still have lower intensity than Argus pulses did.

As NIF was being designed, various specifications were proposed for the maximum scattered fraction allowable for its large 1ω amplifier slabs. These ranged from $1x10^{-5}$ up to < $2.5x10^{-4}$. After internal review, the NIF specification was set at $2.5x10^{-5}$. (Ref. 2)

The second impact of obscurations on slabs is that if sites are large enough, they can lead to damage of downstream optics by a mechanism known as pseudoscopic or holographic imaging.[3] Additional information on downstream impact of flaws can be found in “Damage Mechanisms Avoided or Managed for NIF Large Optics” also in this issue of *FS&T*. Because amplifiers designed for use in an ICF laser operate at intensity levels high enough for the index of refraction to be modified by the local intensity of the propagating beam, beating between the spherical wave created by a scattered site and the approximately plane wave of the main beam can result in generation of the equivalent of a Fresnel lens that can focus a fraction of the main beam to damaging levels on a downstream optic such as shown in Fig. 2. For the particular design of the components in the NIF beamline, the diameter of an obscuration that can lead to downstream pseudoscopic damage is anything larger than ~1 mm.[4] The Ref 4 analysis relates the size of an obscuration on an upstream optic to the risk of damage to a downstream optic that is often several meters away. The risk to the exit surface of an optic (when exposed to a high power laser beam) due to an obscuring particle on the input surface of the same optic has also been studied for both NIF and LIL/LMJ.[5, 6] For the NIF geometry and intensity in the 1ω section of the laser, analysis and experience in previous ICF lasers at LLNL indicated that the highest threat for damage is that due to an ~1 mm obscuration on a slab that could lead to pseudoscopic imaging on a downstream optic. Propagation modeling has shown that the most threatened downstream optics are the Cavity Spatial Filter (CSF) input lens, SF1, and the Transport Spatial Filter (TSF) input lens, SF3. See "A Description of the NIF Laser" in this issue of *FS&T* for more information on spatial filters and their pinholes. Currently NIF uses a 100-μrad TSF pass 1 input pinhole, CSF pinholes are 200 μrad and a 150-μrad pinhole is in the output pass of the TSF.

Prior to NIF, it was the general practice for the design and operation of an ICF 1ω laser to first precision clean the components of the large amplifiers, assemble these components under clean conditions, fill and maintain the volume containing the amplifier slabs with an over-pressure of clean-dry nitrogen, and then fire the flashlamps for each laser shot, counting on slow leakage out of the amplifier volume to keep out all sources of new contamination. This is the procedure that was followed for the Nova Laser.[7]

Review of the replacement rate of Nova amplifier slabs was completed as part of the risk analysis for NIF. It was found that over its 15-year lifetime, on average 7% of the Nova slabs were replaced per year for various reasons. Because such a high failure rate could not be tolerated for NIF, intense study was directed toward uncovering all of the reasons for these failures and to providing design features for NIF that would eliminate these mechanisms. Over half of the Nova slab-failure rate was the result of flashlamp explosions, a problem that was eliminated for NIF by improving the design of the flashlamp electronics. Another failure mode, described briefly in Section IV, indicated that mechanical shock associated with repeated flashlamp firings led to damage near the edges of the slabs. Many other sites on Nova slabs had no discernable mechanical cause and were rather uniformly scattered around on the slabs. These are the flaws addressed here.

Working through the problem of characterizing flaws on laser slabs and understanding their origins had features of a classical use of the scientific method: 1) observing and collecting data, 2) forming early hypotheses for the cause of the observations, 3) designing new experiments and studying the literature for information that could test the hypotheses, and 4) repeating 2) and 3) until an adequately tested understanding of events can emerge. But during the NIF design, fabrication, installation, and activities of early operations, this process was interrupted by the need for decision-making necessary for keeping the NIF facility on schedule. Thus cleanliness-related decisions for the 1ω laser had to be made incrementally, based on the best data and hypotheses available at the point in time they were made.

II. COLLECTION OF DATA

II.A. Early Observations

Maintenance activities on Cyclops, Janus, Argus, Shiva, Nova, and Beamlet[8] provided many opportunities for observation of various types of damage on laser amplifier slabs. Even before Argus (1973–80), a common type of damage was found to occur without the need for laser illumination; that is, damage was observed after flashlamp exposure only.[9] When a flashlamp fires, the radiation environment within the slab region rapidly approximates a blackbody rising to a temperature of ~1eV or ~10,000 K. Any contaminant particle that absorbs within the radiation spectrum of this environment is expected to have a surface temperature that rises, approaching thermal equilibrium with the flashlamp plasmas. As a contaminant particle heats up, the particle itself can become a small local plasma. Fig. 3 shows a magnified image of a slab damage site induced during a single flashlamp firing.[10] This crazed surface characteristic was found to be typical when small particles resting on (or near) the surface of the slab were subjected to flashlamp exposure; it has a very recognizable appearance, or "signature." A crazed spot such as that shown in Fig. 3 becomes a scattering site for the laser light, where to the laser it appears to be an obscuration.

Neodymium (Nd):phosphate glass was selected as the laser medium for Nova and NIF for its laser properties, a low non-linear refractive index (for good propagation of a high-intensity beam), relatively good platinum solubility (for low bulk damage in a high-fluence beam), and an acceptable saturation fluence (for good extraction efficiency). These same glasses, however, also have poor mechanical properties, with high thermal-expansion coefficient, low thermal conductivity, and low tensile strength. In addition, they absorb strongly in the UV. Thus, they are subject to surface crazing when exposed to the UV emitted by small plasmas arising when particles on the slab surface absorb flashlamp radiation.

Cumulative optical damage size distributions measured on laser amplifier slabs withdrawn from LLNL lasers prior to NIF typically followed a power law distribution with a slope of –2. (Ref. 1,10) In fact, for many years prior to the introduction of scanners, all inspections involved counting sites under a microscope. Smaller sites were undercounted and the cumulative distribution reported, *c(a)*, was proportional to $1/a^2$. Obscuration fractions in Argus were reported to obey $F = \pi A \ln (a_L/a_o)^2$ where a_0 and a_L were observed lower and upper size limits on each optical surface in the laser.[1] The parameter A, a measure of the concentration of obscuring sites, was determined by counting the number of sites found within the laser irradiated area, with diameters larger than $a_o = 5$ μm; typically A ranged from 1×10^{-5} to 2.5×10^{-4}, and a_L ranged from ~0.1 to 1 mm. Improvements provided by high-resolution scanners made it apparent that the distributions were steeper than observed by the microscope-aided eye. Use of flatbed scanners to measure damage distribution on LLNL laser glass showed that the damage obeyed a pseudo-log-normal law as described by Honig.[11] The expression for MIL Std 1246, defines a surface cleanliness Level (valid only for just-cleaned surfaces) for particles larger than 1μm. Honig developed a more general expression to define a pLevel for damage found on surfaces that had been illuminated by flashlamps in a typical laser amplifier. He chose to write his expression, as given by the following, in a form that closely resembles the MIL-Std-1246 expression. The value of C in the Honig expression can vary with exposure time of the optic surface.

$$f_d(x) = e^{C \ln^2 (pLevel)} e^{-C_s \ln^2 (x)}$$

where $f_d(x)$ = damage obscurations/ft$^2 \geq x$
x = obscuration diameter in μm
$C = 0.926/\ln(10)$, and
$C_s = slope/\ln(10)$ where for MIL-STD 1246, the $slope \approx 0.5$

Cumulative damage distributions found on laser slabs can also be fit using a power law. (This will be seen to be convenient for comparison of the power laws of damage distributions with those for aerosols typically found in the volume of a laser amplifier.)

One of the important lessons learned from previous ICF lasers at LLNL regarding maintenance of a large 1ω amplifier is that it is necessary to provide an in-situ ability to monitor the damage status of the slabs. The NIF system assigned this responsibility is called the Large Optics Inspection System (LOIS); it is capable of tracking the obscuration status of every one of the laser slabs. More about LOIS can be found in "Description of the NIF Laser," also in this issue of *FS&T*.

II.B. Alternatives to Freon for Cleaning of Large 1ω Amplifiers

The 1ω amplifier structures for lasers up to and including Nova had been cleaned using Freon. After the environmental hazard of Freon became recognized, several alternate cleaning procedures were considered for Beamlet, AMPLAB, and NIF. Options considered included CO_2 spray wash, high-pressure detergent-aided water wash and rinse, isopropyl-alcohol wipe, steam cleaning, and vacuuming. High-pressure detergent-aided water wash/rinse was selected after it was found to provide surfaces as clean as or cleaner than any of the other options and was otherwise relatively benign. With this cleaning approach, measurements indicated that residues of volatile organics could be reduced to $0.1 \mu g/cm^2$ ($0.1 mg/ft^2$) or less and numbers of particulates could be reduced to IEST-STD-CC1246D Level 83 or less,[12] surface cleanliness levels deemed acceptable for precision-cleaned portions of the NIF.[13]

II.C. Obscuration Size Is Linearly Related to Contamination Size

Menapace[10] found that particles (from 1 to 100 μm in diameter) of many different materials (with emphasis given to hydrocarbon materials that might be found in a cleanroom) resting on a laser slab surface and subjected to 1 to 3 flashlamp firings would lead to crazing with an average diameter equal to ~7.8 times the diameter of the original particle (a linear relationship). Because the scattered fraction depends on the area of a site, on average, the amount of light scattered by the crazed site would be a factor of >50 times higher than by the original particle. Materials tested by Menapace included carbon black, clean-room garment fibers, clean-room wipers, Kapton, lens tissue, Plexiglas, polyethylene, polystyrene spheres, paint, skin flakes, Teflon, Voranol and Arizona road dust (as a particulate standard).[10,14] After collection of this data, it became generally accepted that foreign particles resting on slabs would definitely lead to slab damage. The question then revolved around identifying the source of the particulates that could arrive on the slab surfaces. Suspects included contaminants left by manufacturing or installation/removal activities, impurities caught in small surface scratches, sol-gel particles coming from the flashlamp windows (located between the flashlamps and the slabs), and aerosols generated from elastomeric materials that might be used for purposes of electrical insulation or sealing the amplifier from outside contaminants. After Emmett's rule[15] forbidding their use in 1973, elastomers were avoided in amplifier design to the maximum extent possible.

A short time later, in a separate experiment, it was found that SiO_2 particles did not lead to crazing of the slab surface, and one of the suspects, sol gel (small SiO_2 particles) was eliminated. Contaminants from manufacturing, installation, or removal activities fell out of favor as tests for cleanliness regularly showed their absence.

II.D. Aerosols Within a Laser Pump Cavity

Stowers first reported aerosols that appeared immediately following the firing of the flashlamps in the Shiva laser, circa 1980.[16] More detailed studies of this phenomenon began on the Beamlet laser in 1997. In Beamlet, the background (during a quiescent time in the amplifier) particulate level under conditions with a slow rate of nitrogen flow was found to be US FED-STD 209E Class 1–10 (1–10 particles/ft^3 >0.5μm). Immediately after firing of the flashlamps, the aerosol level rose from Class 100,000 to Class 1,000,000. More Beamlet observations will be discussed in Sections II.E and II.F.

Aerosol studies were continued in 1997 and 1998 in a facility called AMPLAB built for prototyping a four-slab-high unit cell of the NIF 1ω power amplifier.[10] A photograph of AMPLAB firing is shown in Fig. 4(a). AMPLAB was a cooperative venture with the French team working toward their planned Laser MegaJoule (LMJ) facility.

Aerosol generation in AMPLAB was measured using a multiport Climet airborne particle counter that could sample the particle distribution as it existed at various vertical locations (heights, measured in units of length) within the amplifier. The particle count was found to be invariant with height. Fig. 4(b) gives a typical aerosol measurement taken for a “clean” amplifier constructed without the use of elastomers. The multiport particle counter generated a nitrogen flow through the amplifier of ~4 ft^3/min, believed to account for the decrease in particle concentration with shot number. This flow rate of ~4 ft^3/min is consistent with ~10 volumetric exchanges of nitrogen between shots on the AMPLAB amplifier test unit. Thus very few of the particles generated during one shot remained in the amplifier volume by the time of the next shot.

Particles from the AMPLAB aerosol were also collected using a cascade impactor, providing material for study of their composition and morphology. The SEM image in Fig. 5(a) shows collected material with a morphology that became known as "dust bunnies," consisting of loosely connected clusters made up of nodules of nearly pure carbon. (The non-carbon constituency is unknown). The dimensions of the nodules were generally found to lie in the range between ~20–30 nm. Larger particles, the clusters, found in the Climet filter were found to be agglomerations of the small 20-30 nm nodules. The density of the clusters was found to be about ~1/10 the density of an individual nearly-pure-carbon nodule. In general the clusters were small and light enough to be affected by Brownian motion of the molecules of the surrounding gas.

As shown in Fig. 5(b), all measured aerosol particle size distributions were found to roughly follow a negative power law. These AMPLAB aerosols were observed to exist within 1 min after the flashlamp firing. The slope of their cumulative size distribution is roughly –3, slightly steeper than the slope (–2.23) of the aerosols described in Federal Standard 209 used to define the classification of clean rooms. The similarity of these two negative power laws led us to expect that the probability density of large particles could be found by extension of the data found for the small particles. The threat of damage to downstream optics by the small coagulated particles (and their resulting obscurations on the laser slabs) is modest, and occurs via degradation of the spatial contrast of a transiting laser beam. A much larger concern exists for the impact of the very rare but larger particles that can lead to ~1 mm obscurations on slabs, large enough to threaten downstream optics by pseudoscopic imaging.

Obscuration data for AMPLAB slabs were also collected but were somewhat difficult to interpret, given that even before the slabs were installed in the elastomer-free AMPLAB housing, they had already collected a significant amount of surface damage. It was still found, however, that the increase in the number of slab obscurations with the number of flashlamp firings was high enough to cause concern regarding the shot life of slabs in NIF. It is noted that the AMPLAB prototype amplifier had gas flow cooling across the flashlamps, but no significant flow through the slab volume.

Subsequent studies of flashlamp exposure of settled airborne particles on slabs were found to (nearly) always induce slab obscurations. With this new understanding, new suspects were added to the list of foreign particles that could lead to slab damage. The list was expanded to include airborne fallout of aerosol particles that were carried into the amplifiers or generated internally by non-volatile residues (NVRs) on surfaces, and outgassing of elastomers or the presence of cleaning residue.

II.E. Observations of Both Aerosol and Slab Obscuration Distributions

Some of the most complete data sets (up to that point in time) for both aerosol and slab-obscuration distributions were collected using the Beamlet physics testbed.[11]

Beamlet cumulative particle size distributions from several locations such as that displayed in Fig. 6(a) were found to fall with a slope of between approximately –3 and –3.5. As the time after an individual shot increased, (with slow leakage out of the Beamlet amplifiers), the measured distributions decayed and steepened slightly. Each curve in Fig 6.(a) represents the aerosol distribution measured for a 1 mn interval of time. As time progressed, many fewer large particles were drawn into the particle counter, perhaps because many of the larger particles had already fallen to the bottom of the amplifier. Also, because it is unlikely that the smaller particles had settled out by the time of the measurement, the observed reduction in their number density with time implies that the purge through the amplifier was effective in sweeping out those aerosol particles that continued to be present.

After disassembly, Beamlet amplifier slabs that had experienced 1,500 lamp exposures each were scanned using a flat-bed optical scanner able to resolve 60-μm damage sites. An example of this data is shown in Fig. 6(b).

The cumulative size distributions of the damage (or surface obscurations) on slab surfaces were measured many times, and in all cases were found to have a slope of approximately –2.5. (Ref. 14)

II.F. INSIGHTS GAINED DURING THE YEARS OF OPERATING BEAMLET AND AMPLAB

With the experience of Beamlet, AMPLAB, and previous large amplifiers in hand, guidelines for amplifier design and cleaning procedures were developed.[17] The first guideline was to eliminate elastomers to the extent possible. Where elastomers could not be avoided, elastomeric materials were required to be baked out to the extent possible and tested for their response to their expected flashlamp load in NIF. Shielding was provided for any elastomers that could not be replaced by smooth welds or other metal-to-metal joints. A flashlamp window is necessary between the flashlamp enclosure and the slab enclosure. In order to keep these two volumes separate, the flashlamp window (Schott B270) must have a gas-tight elastomeric seal. This seal is deeply buried to provide shielding from flashlamp irradiation. In addition, the slab enclosure must be held at a somewhat higher pressure than the outside world to keep out contaminants. Any of the structural joints of the large laser enclosures that were fitted with flat silicone gaskets also required labyrinth metal shields for blocking the majority of the flashlamp light.

A second guideline covered the cleaning method of all walls of structures that would eventually enclose the laser beams, including the 1ω amplifier enclosures. They were cleaned in large room-sized stations using a high-pressure hot-water-spray washing system as shown in Fig. 7. Detergents from the Brulin Corporation[18] were applied hot and thoroughly rinsed with high-pressure DI water at 3,500 psi. Tests of this approach had shown that they could consistently produce surfaces with organic levels of <0.1 μg/cm^2, equivalent to only a few monolayers of organic material. Once clean and dry, the enclosures were triple wrapped in low-outgassing plastic to keep them as clean as possible during transit and installation in the laser bays. The first wrap included separate individual covers of the openings to other sections of the beampath to allow joining with the other large structures in the laser bays using a technique known as "Fast Connections."[19] Fig. 7(b) is a photograph of the arrival of one of the triple-wrapped clean vessels.

Beamlet and AMPLAB data were consistent with expectations gained from earlier amplifiers in that the number of obscurations on a slab would increase with the number of shots on that slab. The flowdown slab-refinishing rate requirement reported to the review by SEAB (Secretary of Energy Advisory Board) in 2000 was ≤10% per year. Several estimates were made using Beamlet data to predict damage rates and refurbishment costs that would then be expected for NIF amplifier slabs. The cumulative size distribution extrapolated from the Beamlet slab damage was used for projection of the failure rate for NIF slabs. Data from Fig. 6 indicates that if NIF were to behave like Beamlet, there could be slab damage of 2-mm size or greater on each surface of 10 to 35% of the NIF slabs after only 1,500 flashlamp firings (roughly 2 years). In internal memoranda, Stowers used historical maintenance records along with aerosol measurements collected up until 1999 to estimate a credible NIF amplifier slab refurbishment rate of 9% per year (or 270 slab refurbishments per year) unless historical trends could be altered substantially.[14] The NIF amplifier design team viewed these estimates as unacceptable.

III. A WORKING HYPOTHESIS FOR THE ORIGIN OF FLASHLAMP-INDUCED DAMAGE

III.A. The Hypothesis

As Beamlet, AMPLAB, and other off-line aerosol and obscuration data were repeatedly reviewed, a working hypothesis was developed. This hypothesis assumed that slab obscurations are formed in a two-step or two-shot process. During the first step (or shot), light from the flashlamps pyrolyzes any residual organic material, in particular, non-volatile residues (NVRs). that may be present in the slab enclosure. These residues, typically dioctal phthalate and dibutyl phthalate, are converted into vapor-like finely divided material by exposure to the light. Within a short period of time (certainly less than a minute), nanometer clumps of mostly dense carbon have agglomerated loosely to form an aerosol such as those described earlier in Figs. 5 and 6. The aerosol class formed is a function of the "cleanliness" of the enclosure before the shot and often ranged around Class 100,000 after the shot. Before the next shot, these aerosol particles can settle out on nearby surfaces. Vertical surfaces were noted to collect particles at about 10% of the rate collected by horizontal surfaces, no doubt observed years earlier when the output amplifier slabs began to be mounted vertically. The second step begins with the next firing of the flashlamps. Aerosol particles that have settled on slabs between shots (or that happen to be floating nearby a surface) are turned into small UV-emitting plasmas that are able to craze the slab surface producing a scald that is approximately eight times the diameter of the original particle, thus creating an obscuration.

In keeping with this hypothesis, internal memoranda noted that very clean structural surfaces with only a few monolayers of NVR will have 0.1 mg/ft^2 (0.1µg/cm^2) and that a NIF amplifier with 56 ft^2 of internal surface area with a similar coating will be able to hold nearly 6 mg of NVR. When compared with a typical aerosol of Class 100,000, that represents only 0.5 μg/ft^3 (12 μg/amplifier volume). It is apparent that very clean structural surfaces can be a source of aerosols even after many flashlamp firings.

It was also noted that Beamlet cumulative particle-size and cumulative obscuration-size distributions could both be fit by power laws that differed by between approximately one-half to one. This difference in slope was studied as part of the search to find out if the aerosol findings could be definitively connected to the obscuration findings on the basis of coagulation and sedimentation theory. Our work along these lines, following the lead of Chandrasekhar[20] and others, has not identified a unique linkage. Very different cumulative distribution time histories have been observed for different lasers that often show a relative decline in the number of larger particles compared with smaller ones, as might be expected if sedimentation is at work.

An alternate phenomenological description is the following: consider two extremes for the relationship between the cumulative distribution of particles in a volume and the manner in which the volume distribution could lead to a cumulative distribution of obscurations on a slab surface. We assume that the size of the obscuration is linearly related to the size of the aerosol particle leading to the obscuration. If the sticking coefficient for a particle hitting the slab surface is very small—close to zero—then the obscuration distribution will be determined by the cumulative distribution of particles that happen to be at a distance that is within approximately their diameter of the slab surface at the instant the flashlamps fire. This distribution will have a slope that is one less than the slope of the cumulative number of particles within the volume.[14] On the other hand, consider the possibility that the sticking coefficient of a particle with respect to the slab is unity. In that case, all of the particles that hit the slab will stay there, and, given enough time, the cumulative distribution on the surface will have the same slope as that for the particle counter; i.e., for the particles in the volume. If consideration of these two extremes is used to interpret the slope differences found, then one can conclude that either the sticking coefficient of the particles with the slabs falls between the values of zero and one or the particles remained in the gas or were deposited elsewhere and never reached the slab during the time frame of the observation.

It is also noted that this interpretation of the slope differences is consistent with an additional hypothesis that suggests the particle size distribution is formed rapidly, very near the walls (that hold the NVRs) during the ~0.5 ms the flashlamps are firing, where due to differing population velocities the particle distributions are quite likely not in thermal equilibrium. The observation that, as time goes on (long after flashlamp firing is complete), the slope of the volume cumulative distribution steepens somewhat is consistent with a hypothesis that larger particles settle out faster than smaller particles, consistent with sedimentation models and inconsistent with expectations from coagulation models. Flushing of the amplifier cavity soon enough after a shot might entrain the aerosol and remove it before it comes into contact with the glass.

III.B. Impact of the Working Hypothesis

At this point, with a fresh and yet unproven hypothesis regarding the origin of slab obscurations, it became time for finalizing decisions for the gas-flow plumbing and other mechanical features of the Frame Assembly Units (FAUs), part of the Beampath Infrastructure of NIF. These were the structures that would, in the future, be accepting the amplifier-slab Line Replaceable Units (LRUs). The Beampath Infrastructure System (BIS), the FAUs, and the LRUs are described in more detail in "Description of the NIF Laser," also in this issue of *FS&T*. The FAUs had already been designed following concepts that had been established by previous lasers; their design-freeze date was imminent and their design at that point in time would seal in any gas contained in the volume enclosing the amplifier slabs. The hypothesis described above led to an urgent need to change the designs of the FAUs, their plumbing, and their corresponding LRU interfaces to ones that would allow the aerosols to be swept out of the amplifier volume before they could settle on the slab surfaces. Operational economics then led to the need for a second change: using clean-dry air in the environment of the slabs rather than dry nitrogen as had historically been done. Clean-dry air was judged to be acceptable because a new technique had just been developed for protecting the silver-plated surfaces of flashlamp reflectors. (See Section VI.D.1 of "A Description of the NIF Laser" also in this issue of *FS&T* for more information on flashlamp reflector design.) Previously, nitrogen had been required to prevent tarnishing of these silver-plated surfaces.

A new, alternative design described in Figs. 8 and 9 was proposed for the slab LRUs and their supporting FAUs. The economics of making this decision were daunting for a project struggling with costs. The NIF Change-Control-Board Three was able to accept this recommendation because the UK Shot Rate Improvement Program for NIF was able to fund the incremental cost.

IV. DATA COLLECTION AFTER BEAMLET AND AMPLAB: RETROSPECTIVE STUDY OF NOVA SLAB "DATA"

Sometime after the decisions described above had been settled for the slab LRUs and their FAUs, it became time for the Nova Laser to be retired. Nova had been operated for approximately 15 years, from 1984 to 1999. During this time, the laser system was fired approximately 10,000 times. The group of us who were working to understand the relationships that might exist between cleanliness, gas flow through an amplifier, and slab damage began to see Nova operations in a new and different light: as a cleanliness experiment that had been underway for 15 years with data records held on the surfaces of its slabs just waiting to be extracted. A plan was put together for taking Nova apart without disturbing this data before it could be collected and archived.[11, 14]

The input and output nitrogen flow rates were measured for each of the Nova slab amplifier beamlines before it was taken apart. Flow rates were relatively small, ranging from 3 to 6 ft^3/min through a chain of typically 5 amplifiers in a series with apertures that varied over 9.4, 15, 20.8, 31.5, and 46 cm. In addition, information on the number of flashlamp firings experienced by each slab was retrieved from Nova records.

Damage data for each slab was obtained using an 800-dpi flatbed scanner and data acquisition software developed by Doug Ravizza. Significant effort was given to validation of the ability of the flatbed scanner to accurately record crazing damage including test scans of a mask imprinted with well-defined shapes and sizes around 200 μm. A typical obscuration site map for a Nova disk is shown in Fig. 10(a).

A typical cumulative obscuration density plot for one of the Nova 31.5-cm disks is given in Fig. 10(b); similar plots were obtained for many of the Nova amplifier slabs. These cumulative distributions of damage-site diameters followed an approximately –2.5 power law. All of the Nova slab amplifiers (46-cm, 31.5-cm, 20.8-cm, 15-cm, and 9.4-cm) were studied in this fashion. More details on these studies are given in Ref. 11. Obscuration densities for the various slabs were studied as a function of flow rate and number of shots experienced. No correlation was found between obscuration density and flow rate, which was not particularly surprising because all flow rates were low. To our surprise, however, it was also found that there was no correlation between obscuration density and number of shots. These results led us to conclude that damage on Nova slabs was correlated with some initial or early condition and did not appear to increase after 200 shots. In general, the number of obscurations was not found to increase between 200 and 8,000 shots. There were no Nova damage data for fewer than 200 shots, and by the end of Nova's life, there were no pristine Nova slabs to be used for comparison.

Inspection of damage data from the Nova slabs also provided important insight regarding details of the mechanical structure to be used for supporting NIF slabs. Upon close examination of Fig. 10(a), more obscurations are found near the edge of the slab in areas that are nominally covered by a mask (by approximately a factor of two) compared with the number of observations in the center of the slab.[14]

An examination of one of the 31.5-cm masks showed sharp and burred edges on the step edge and the mask edge as well as a direct mask contact onto the laser glass due to an inherent overlap in the mask design. The evidence indicated that during a flashlamp pulse, an acoustic shock is generated in both the mask and the slab. The vibration generated by the shock could lead to contact of the mask with the slab surface, chipping the glass and leading to increased damage density. Evidence was also found of evanescent coupling between the slab and the metal contact points on the slab periphery. Erosion of the mask by the high fluorescent fluence, over 0.3 J/cm^2 and subsequent ejection of mask material was able to account for surface-damage-site concentration falling off with distance away from the mask contact points.

V. INSIGHT GAINED FROM THE RETROSPECTIVE STUDY OF NOVA SLAB "DATA"

Data gleaned from the careful disassembly of Nova yielded one more important insight regarding steps for reducing slab damage on NIF. Nova data implied that flashlamp firings during the very early time after a slab had been installed were responsible for much of the damage incurred during its overall shot lifetime. The guidance then given to the NIF commissioning crews was the following:

- Prior to installation of any slabs, fire the flashlamps multiple (40) times and run the purge flow after every shot to remove residual "start-up" NVRs from the surrounding walls. The choice of 40 shots was made on the basis of early testing of this "flashlamp cleaning" concept.
- Monitor particle counts before and after flashlamp firing, during flashlamp cleaning, and continuing into full systems operation. Continuing records of aerosol formation would be used for monitoring the cleanliness "health" of the amplifiers.

Typical data from NIF particle counters during flashlamp cleaning (with no slabs installed) is given in Fig. 11, showing the clean-up process underway. Note that aerosol production falls by a factor of about 30 during the first ~40 shots taken over ~2 days. Also note that flashlamp cleaning was done only during the commissioning period of NIF; it has not continued during NIF operation.

VI. SMALL SCALE TEST FACILITIES

Despite the evidence that slab damage occurred whenever a variety of airborne particles (with the exception of SiO_2) were placed on laser glass and exposed to flashlamps, it was extremely difficult to field a set of experiments that could clearly identify the "smoking gun" leading to conditions that involved 1) creating the aerosol, 2) transporting of the aerosol to the glass surface, and 3) subsequent damage at the surface. The postulate for definitive experiments was simple to state: for the positive-result case, a flashlamp exposure creating an aerosol should always lead to damage on a nearby glass surface; for the negative-result case, if no aerosol is observed upon flashlamp exposure, then negligible damage to the nearby glass should always be found. Setting up conditions for the negative-result experiment, where no aerosol was formed upon flashlamp firing in a sufficiently cleaned vessel proved to be very difficult to do. In pursuit of these experiments, a number of ever-smaller test chambers were built and tested.

The first small-scale test chamber had an exposed face of about 30cm by 30cm.; this chamber was designed to fit inside the Shiva 15-cm laser amplifier flashlamp half-shell that had often been used for materials testing. It was constructed of sheet stainless steel, bent, and welded to form a nearly seamless enclosure. Several sealing options were studied; the option that produced the fewest airborne particles and that had a leakage rate of about 10% of the inlet flow rate was made from expanded Teflon foam wrapped with aluminum foil to protect it from the flashlamp light. This chamber was routinely cleaned using 10% isopropyl alcohol (IPA) and 90% water supplied in a pre-moistened clean-room wiper. Although particle counter tests showed this chamber to be quite clean after approximately 30 flashlamp firings, producing less than about 40 particles per ft^3 of > 0.5 µm per ft^2 of chamber area, the particle count even after hundreds of shots never went appreciably below this value and thus this chamber failed to pass the test of zero aerosol production.

The next small-scale chamber constructed was cylindrical, 8 in. diameter by 2.5 in. high. In physical appearance it looked similar to the chamber that will be described next. The window was made of Pyrex with a Kovar graded glass-to-metal seal. Chemical analysis of material that remained after solvent-wipe cleaning revealed that the most common organic species on the wall was dibutyl phthalate (DBP), a common plasticizer. We consistently found this material or its homologue dioctal phthalate (DOP) on every surface studied in both small-scale and large-scale structures despite our best cleaning efforts and procedures used to protect clean surfaces during transport and handling.

After bake-out under nitrogen purge, the empty chamber was exposed to flashlamp light. The particle production by the baked chamber was essentially the same as the solvent-wiped chamber. Generally, the initial particle generation rate was about 10,000 particles ≥ 0.5 μm diameter dropping to about 100, and occasionally to 10, particles per shot over a 20-shot sequence. The level of 100 to 10 particles ≥ 0.5 μm produced per shot was the lowest that could be achieved in tests with this chamber.

With the experience gained from these tests, a new set of experiments using a somewhat smaller chamber was set up to allow the study of obscurations on small coupons of phosphate laser glass (1 in. by 1 in. by 1/8 in. thick) under various conditions of gas flow and flashlamp irradiation. This chamber is shown in Fig. 12. The conditions for these tests allowed multi-shot experiments to be completed without handling or removing the samples as they were exposed to an increasing number of flashlamp shots. These experiments studied the creation of obscurations with flows of clean-dry air or dry nitrogen and flows seeded with contaminants of NVRs and flakes of silicon. Experiments with the glass supported and held by clips in a stainless steel holder always produced obscurations even with high purge rates of either dry nitrogen or clean-dry air and no seeded contaminants.

Finally after switching to an aluminum holder for the glass sample, one with no clips, conditions were found where a very clean baked-out chamber with no elastomers and no detectable NVRs would produce no aerosols under flashlamp irradiation and no obscurations on the glass samples. The null case of no surface contamination, no aerosol, and no damage had finally been observed.[11]

It is worthwhile at this point to note that the guide rails of the LRU structure that supports the slabs depicted in Fig. 8 are made of aluminum.

VII. MAINTAINING THE OPERATIONAL CLEANLINESS OF THE LARGE 1ω AMPLIFIERS OF NIF

NIF has now been operating for four years. During that time, it has accumulated ~ 2,400 system shots with high 1ω fluence, resulting in (as of February 3, 2014) an integrated delivery of over 1.2 GJ. During this time, the slabs have been continuously monitored for the presence of slab obscurations and some phase objects using the Large Optics Inspection System (LOIS) diagnostic system. LOIS is capable of locating and tracking obscurations with diameter 1 mm or greater on all of the slabs. Because the LOIS inspection beam can follow the four-pass architecture of the NIF amplifier, a single obscuration can show up as many as four times in the LOIS camera. Identification of the location of the flaw can be made to plus or minus one slab position by measurement of the spacing of the multiple images. Fig. 13 includes the sensor image for one of the two obscuration flaws that have been found in NIF (this one in Beamline 122). The shape of the cloverleaf pattern identifies it as located on the slab in the Main Amplifier (MA) at Position 5. After removal of the Position 5 slab, examination of the site revealed that it did not have the characteristic signature of aerosol damage. Rather it appears to have been the result of a small piece of plastic wrap or clean-room glove that managed to be transported to this location just before the damaging shot. One other slab (in MA Position 6 of Beamline 432), also with a damage signature uncharacteristic of that for aerosols was found and removed during the early days of NIF operation.[21] [22]

In the 11-5 configuration with 11 slabs in the Main Amplifier (MA) and 5 slabs in the Power Amplifier (PA), there are 3,072 large amplifier slabs. Since 2009, when NIF went into regular operation, each slab has been exposed to an average of ~5,000 flashlamp firings including over 2,400 full-system shots. Other shots were used for laser conditioning of crystals, calorimeter calibration, alignment, and a variety of testing purposes. During that time, a total of 13 slabs have been replaced. Eleven of these replacements were made because of small polishing flaws that had not been detected before their installation. Only two have been replaced because of obscurations in their aperture, discussed above.

Visual inspections were made of all 13 of these slabs as they were removed. Except for the two slabs already discussed, they were reported to look very clean with no indication of obscuration damage. It has now been over two years since any slab amplifier LRU has been removed for any reason. Since 2009, as reported in the "National Ignition Facility Laser System Performance" article also in this issue of *FS&T*, many high fluence shots have been taken.

As NIF has been operated, particle counts continue to be monitored; they are collected after every shot for all of the NIF main-amplifier and power-amplifier bundles. Stowers' prediction that aerosol sources would not "clean up" has proven to be true even though NIF amplifiers are filled with clean-dry air rather than dry nitrogen—i.e., combustion has not eliminated aerosols. Comparisons of particle counts from NIF amplifiers between 2008 and today show no significant differences.

Since NIF began operations 4 years ago, the inherent laser beam contrast measured at the 1ω main laser output for each of the 192 beamlines has remained steady at ~6 to 7%, well below the 10% design requirement. (This lower value is good because it reduces the initiation rate on the costly downstream 3ω optics, allowing experimentalists more freedom in designing their shots.) Thus, as of the time of writing, there is still no evidence of aerosol damage on the NIF slabs, and no slabs have been replaced because of flashlamp-aerosol-induced damage. If the predictions in the year 2000 for slab damage had been correct, by now, on average, it would be necessary to exchange an amplifier LRU about every 1.5 working days. It appears that the strict cleaning procedures used before the assembly of the Beampath Infrastructure System, the use of flashlamp cleaning prior to slab installation, and the continued use of the vertical purge flow across the slabs after every shot has been successful in eliminating this threat to the reliability of NIF. As a result, significant maintenance time and cost has been avoided.

LOIS inspection continues to be done on a regular basis.[21] Fortunately, LOIS image analysis and data archiving is carried out almost entirely by NIF computers and these have only very rarely had cause to alert a human operator of a possible damage event.

NIF is now meeting user requests at a rate that is projected to be over 300 shots per year for fiscal year 2015. Meeting these requests is also creating flashlamp-induced aerosols in the slab-amplifier volumes on every shot. Today, NIF can be viewed as continuing the set of amplifier-cleanliness experiments that began with measurements on Shiva in ~1980. This current cleanliness "experiment" uses the full NIF 1ω amplifier hardware in Laser Bay 1 and Laser Bay 2. If our current experience continues, the data from this experiment will be collected around 30 years from now; in the meantime, so far, so good.

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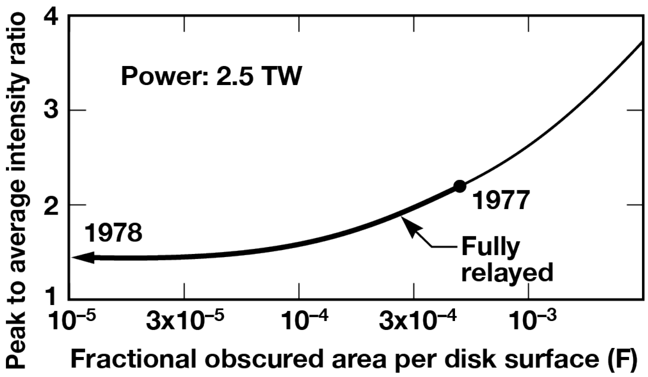


Fig. 1. Impact of scattered fraction observed for the Argus laser, with spatial filtering and image relaying similar to NIF. Data was extracted from information in Ref. 1.

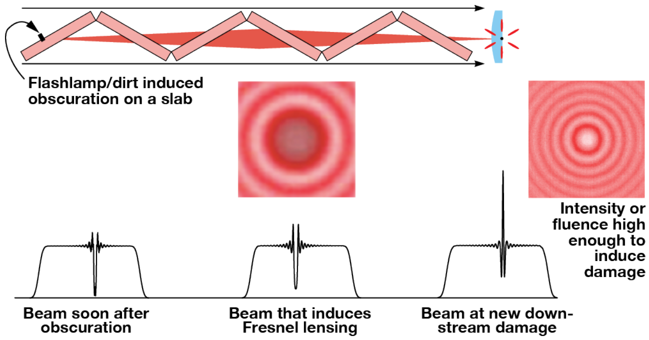


Fig. 2. Illustration of the impact that scattering by a small upstream obscuration (flaw) can have on a downstream optic. (Ref. 3)

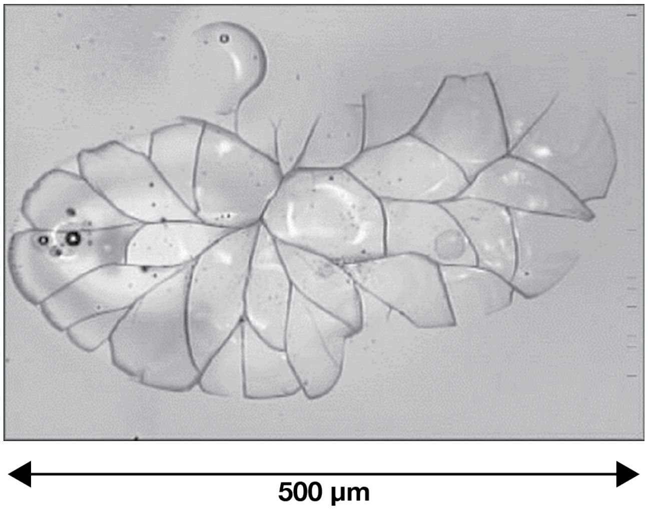
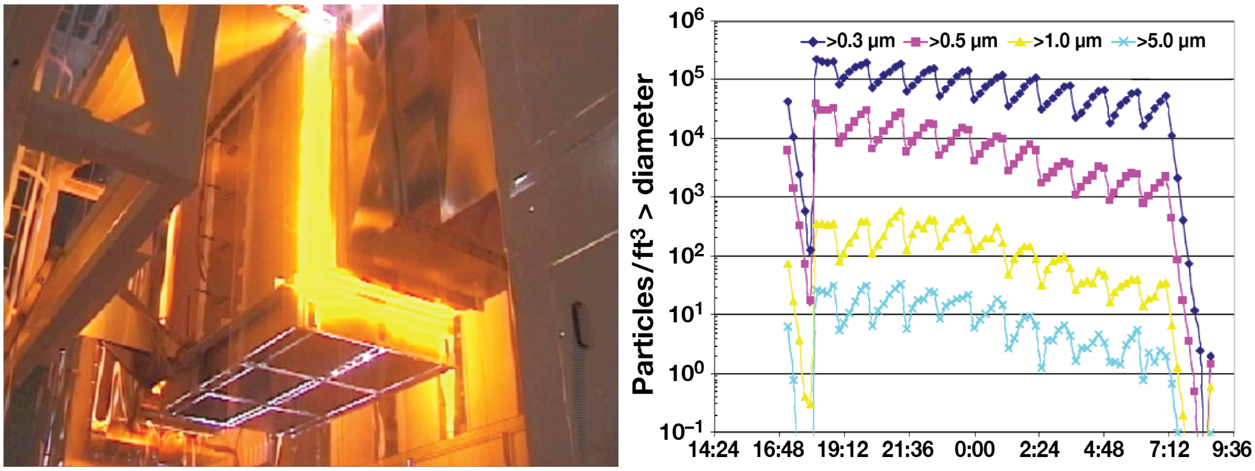
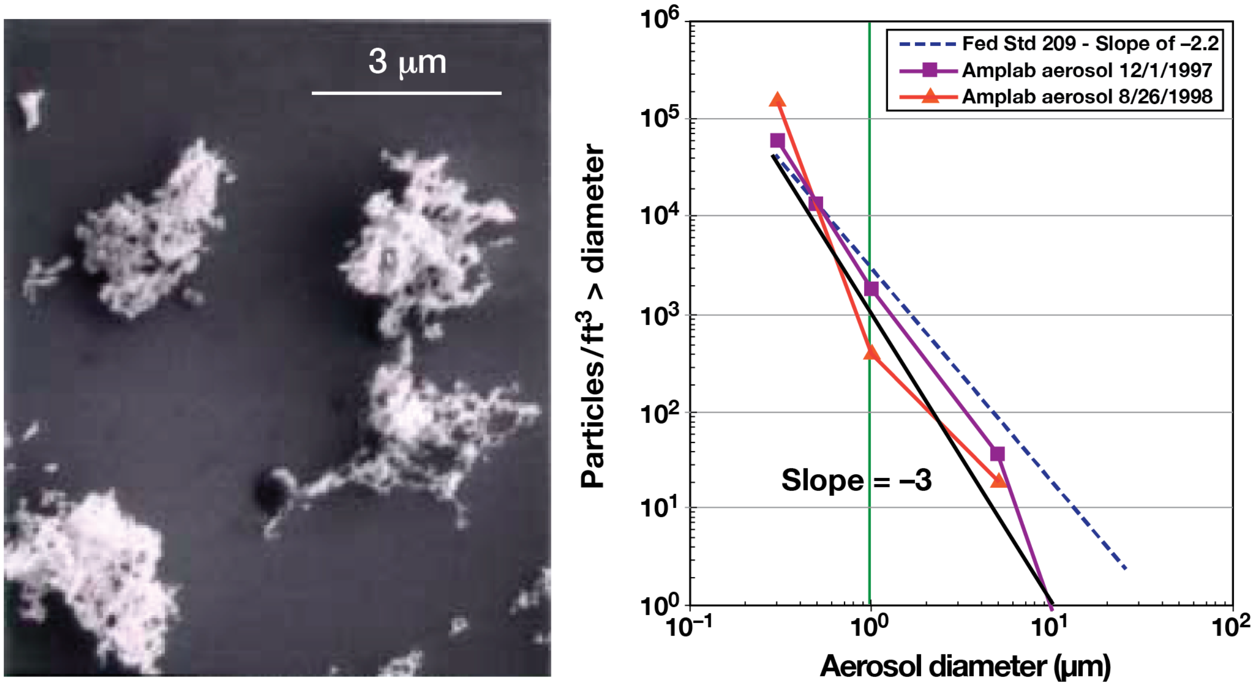


Fig. 3. Microscopic image of laser slab damage resulting from purposeful contamination of neodymium phosphate glass by a small piece of low-density polyethylene and then exposure to a single flashlamp firing. (Ref 10)



(a) (b)

Fig. 4. AMPLAB (a) Photograph of the AMPLAB amplifier with its flashlamps firing; (b) aerosol measurement for 10 shots in AMPLAB.



(a) (b)

Fig. 5. (a) High-magnification SEM photograph of aerosol particles from the AMPLAB amplifier. These dust bunnies are typically composed of 20–30-nm nodules that are nearly pure carbon. (Ref. 14) (b) Cumulative size distribution of aerosol generated after typical flashlamp shot. The flashlamp-generated aerosol is plotted along with the aerosol size distribution used to define naturally occurring aerosols in clean rooms as defined by Federal Standard 209. The data for the aerosol labeled 8/26/98 was taken from Fig. 4(b).

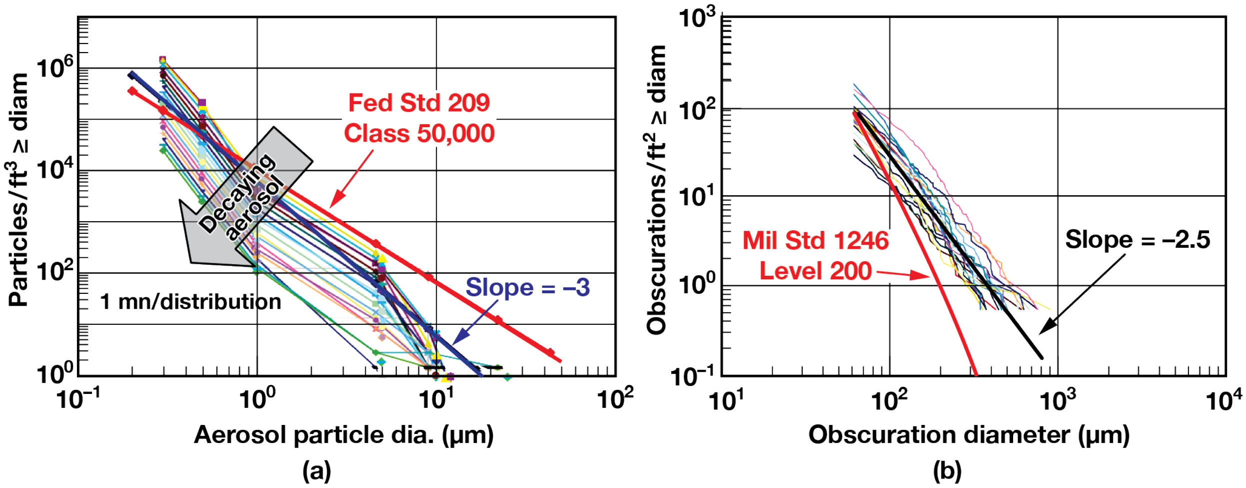
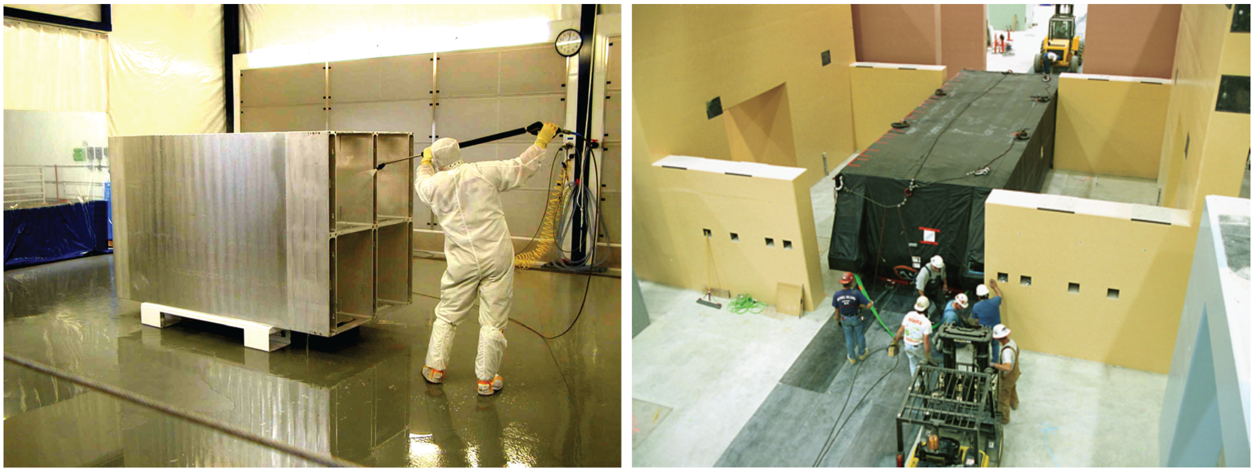


Fig. 6. (a) Aerosol concentration vs. size, after flashlamp firing in Beamlet, June 2000. (b) Obscuration size distribution of a slab after 1,500 flashlamp firings in Beamlet. (Ref. 11)



(a) (b)

Fig. 7. (a) Hot high-pressure surfactant spray washing of a FAU (Frame Assembly Unit) in a temporary off-site cleaning facility operated by Astro Pak of Downey, CA. The clean FAU became the housing for the large amplifier slabs. (b) One of the triple-wrapped spatial-filter end vessels arriving in NIF after off-site high-pressure Brulin water/rinse cleaning.

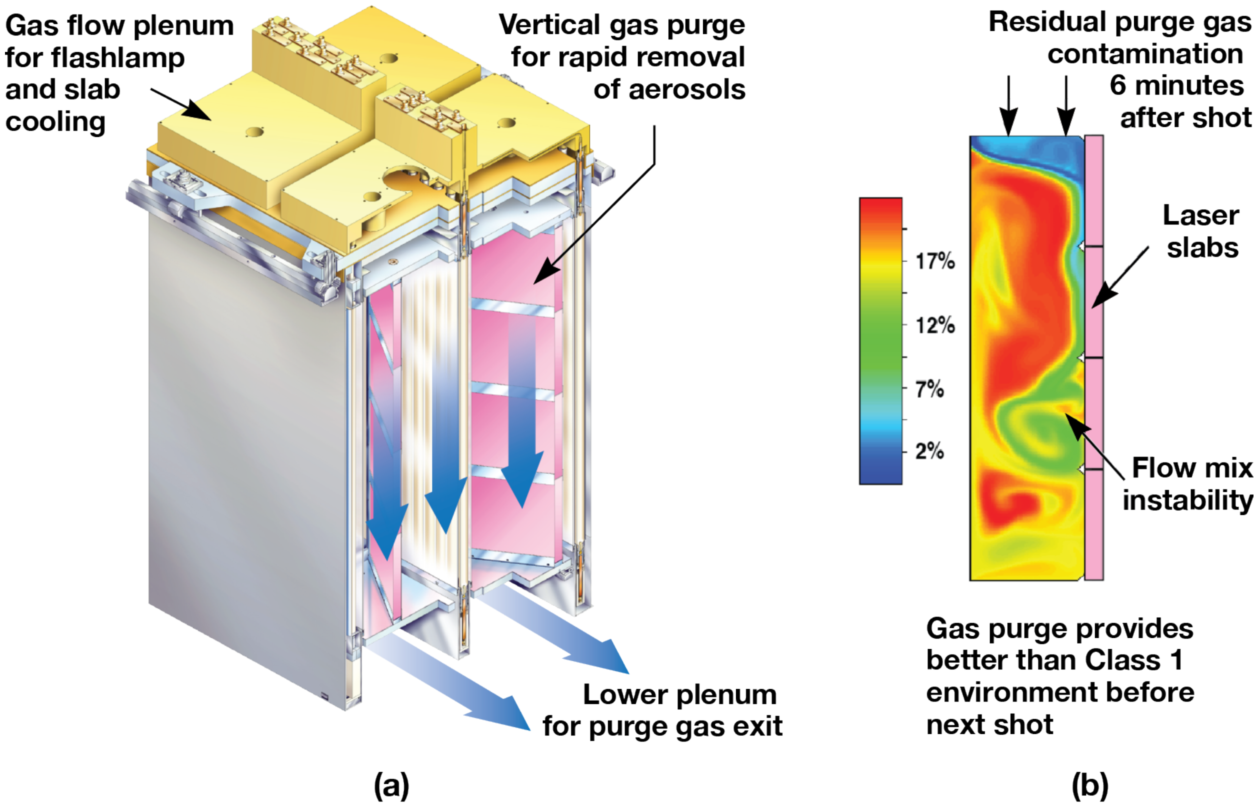


Fig. 8. (a) Vertical gas flow at a rate of 30% of the enclosure volume per minute (10% of the flashlamp cooling supply) is turned on shortly after every flashlamp shot to remove any aerosol particles that may have been created during that shot. (b) Computational-fluid-dynamics modeling had shown early reduction of particle counts near the slabs and an exceptionally clean slab environment by the time of the next shot.[23]

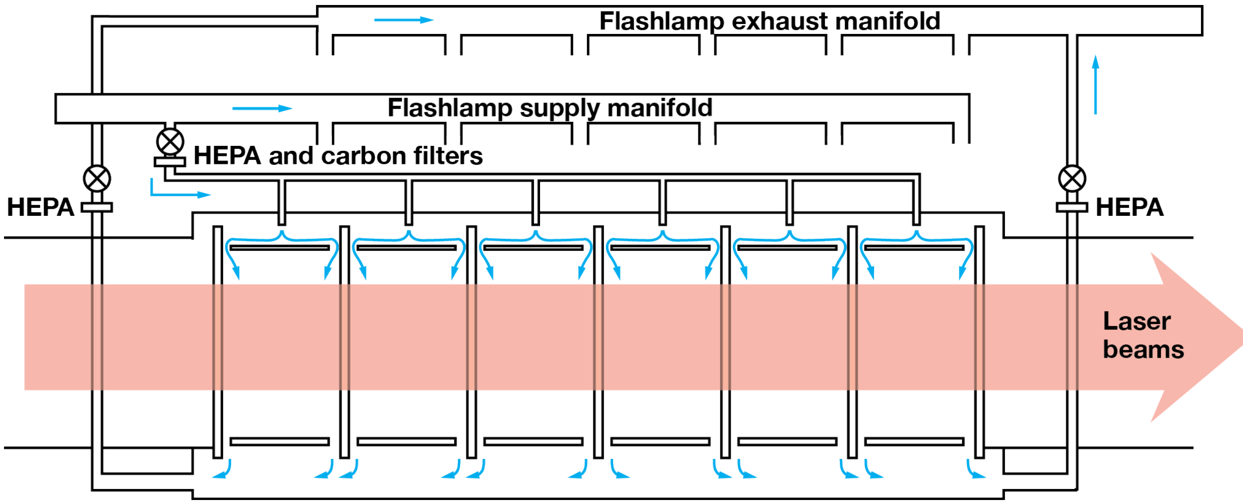


Fig. 9. Side-on view of the Amplifier Frame Assembly Units, part of the Beampath Infrastructure, that holds and supports the laser slab LRUs.

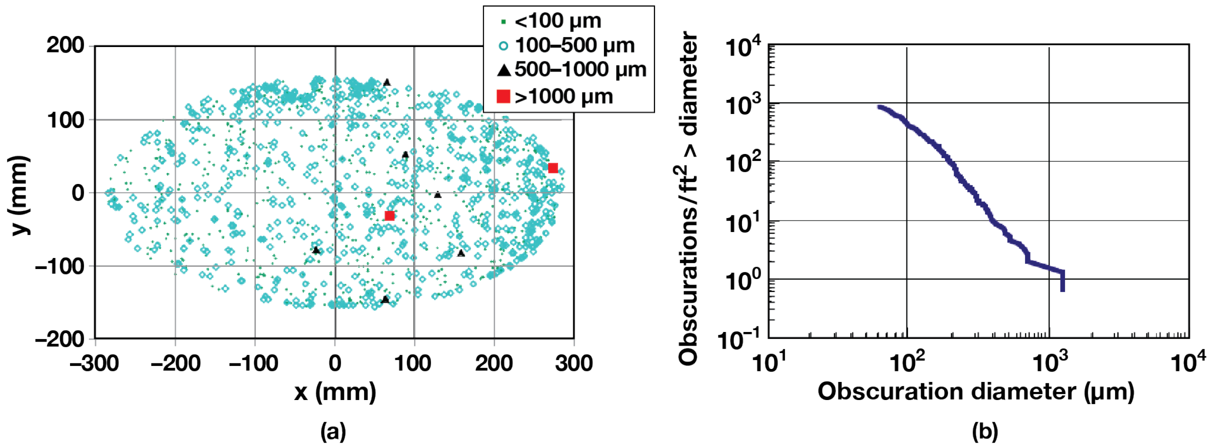


Fig. 10. (a) Obscuration site map for a typical Nova 31.5-cm disk, showing the location of the obscurations and their relative sizes. (b) Cumulative obscuration density plot of Nova disk SP4-416 showing cumulative obscuration densities vs. diameter. (Ref. 11 for both (a) and (b))

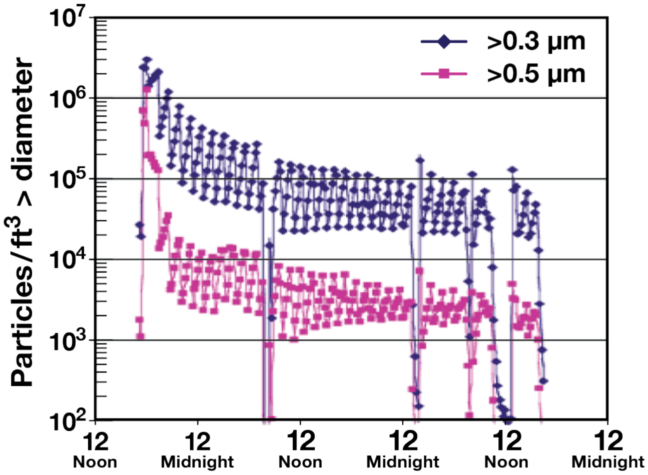
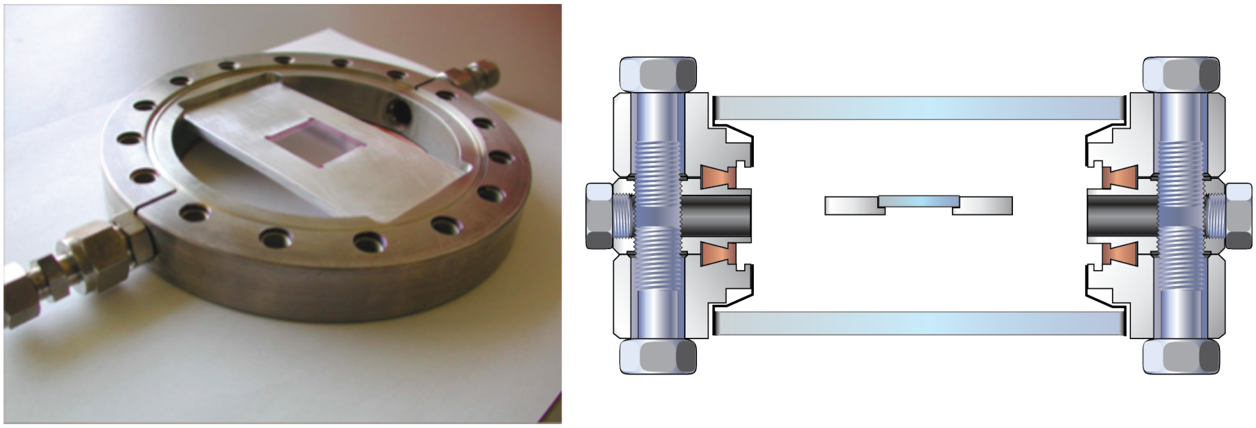


Fig. 11. Flashlamp-cleaning time history of aerosol production. Note that aerosol production falls by a factor of about 30 during the first ~ 40 shots taken over ~2 days.



(a) (b)

Fig. 12. The second small-scale (6 in. diameter) cylindrical test chamber used for proof of principle that flashlamp-created aerosols can be eliminated. (a) Photograph of the center body and aluminum sample support. (b) Cross-section drawing of the entire chamber showing the copper gaskets and window flanges with their graded glass-to-metal seals.

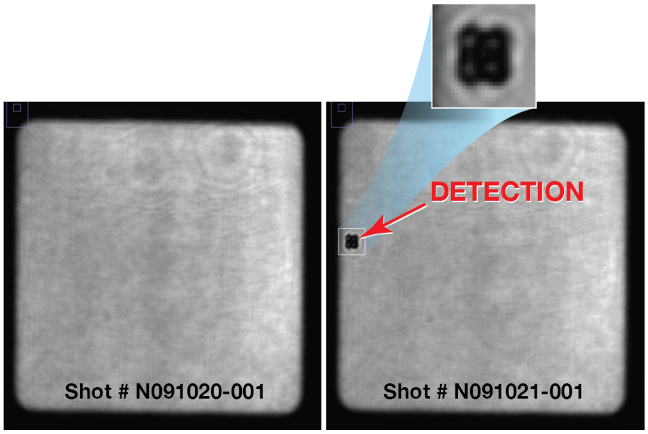


Fig. 13. LOIS sensor images, one taken just before shot N091021, and one taken just after. The cloverleaf pattern identifies an obscuration at location MA6.

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