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Vacuum Spatial Filter Lenses**

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Damage and Fracture in Large Aperture, Fused Silica, Vacuum Spatial Filter Lenses

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ABSTRACT

Optical damage that results in large scale fracture has been observed in the large, high-fluence, fused-silica, spatial filter lenses on the Nova and Beamlet lasers. In nearly all cases damage occurs on the vacuum side of the lenses and because the vacuum side of the lens is under tensile stress this damage can lead to catastrophic crack growth if the flaw (damage) size exceeds the critical flaw size for SiO_2 . The damaged 52 cm Nova lenses fracture into two and sometimes three large pieces. Although under full vacuum load at the time they fracture, the Nova lenses do not implode. Rather we have observed that the pieces lock together and air slowly leaks into the vacuum spatial filter housing through the lens cracks. The Beamlet lenses have a larger aspect ratio and peak tensile stress than Nova. The peak tensile stress at the center of the output surface of the Beamlet lens is 1490 psi versus 810 psi for Nova. During a recent Beamlet high energy shot, a damage spot on the lens grew to the critical flaw size and the lens imploded. Post shot data indicate the lens probably fractured into 5 to 7 pieces, however, unlike Nova, these pieces did not lock together. Analysis shows that the likely source of damage is contamination from pinhole blow-off or out-gassing of volatile materials within the spatial filter. Contamination degrades the anti-reflection properties of the sol-gel coating and reduces its damage threshold. By changing the design of the Beamlet lens it may be possible to insure that it fails safe by locking up in much the same manner as the Nova lens.

1. INTRODUCTION

Large aperture vacuum spatial filters (52 to 61 cm diameter) are used on the LLNL Beamlet and Nova lasers to image relay the beam through the system and remove high spatial frequency noise [1-5]. In addition, the spatial filters on Nova are used to expand the beam between the various amplifiers stages; Nova's final spatial filter lenses are 52 and 80 cm diameter and support round beams about 46 and 74-cm in diameter, respectively. In contrast Beamlet's multi-pass design employs a constant beam size (34 x 34 cm^2 square) through the main amplifier cavity and output section of the laser; therefore, the two large spatial filters have identical lens sizes (61-cm diameter) (Fig. 1).

Figure 1. Side and end view of the large aperture spatial filter lens assembly used on Beamlet. The lens is 61-cm (2 ft.) in diameter and 3.5 cm thick.

Apart from their optical function, the spatial filter lenses also serve as vacuum barriers; the spatial filters are evacuated to avoid optical breakdown due to the high beam intensities at the pinhole plane. The lenses need to be made sufficiently thick that the tensile stress of the vacuum surface remains far below the tensile strength of the polished glass. However, making the lens too thick has adverse effects on beam quality due to the increased non-linear phase retardance that occurs at high intensities. The magnitudes of this non-linear effect is quantified via the so called "B integral" [5-7]:

$$B = \frac{2\pi}{\lambda} \int_0^L \gamma I dx \quad (1)$$

where B is the cumulative phase retardance (in radians) due to the index non-linearity (γ) (cm^2/GW) of the optical materials in the propagation path of length L and λ is the operating wavelength of the laser. The B integral is taken over the optical path length between spatial filters and therefore, both γ and I may vary along the path due to the different optical materials and the optical gain or loss from various components, respectively. The design criteria for ICF high peak-power lasers is that $B \leq 2$ radians [8]. It is clear that in the high intensity stages of the laser, the thicknesses of optical materials need to be minimized. This is particularly true for the final spatial filter lenses.

During the course of high fluence laser operation we have observed laser induced damage on the vacuum surface of certain lenses of both Nova and Beamlet. In particular the input lenses of the final spatial filters see the highest 1ω fluence and experience the most damage. The laser induced damage often grows on subsequent laser shots until it exceeds the critical flaw size for the material causing the lens to catastrophically fail. In the case of Nova, the lenses fracture into 2 or 3 pieces that lock in place by "bridging" across the opening of the spatial filter (Fig. 2). In this failure mode the vacuum then slowly comes up to ambient pressure by air leaking through the fractures. No mechanical damage is experienced during these failures and over more than 10 years of operation on Nova approximately 20 lenses have fractured in this fashion. In stark contrast however, is our experience on Beamlet; we recently observed fracture and failure of a large (61-cm) spatial filter lens in which the fracture pieces did not lock in place by imploded causing severe damage to the mechanical and optical assemblies in the spatial filter.

Figure 2. Photograph of a broken Nova spatial filter lens (SF-7) showing the damage spot that served as the critical flaw site and the resultant catastrophic crack.

In the sections that follow we first compare the Nova and Beamlet lenses, the maximum operating fluences at that the lenses and the expected damage threshold. The possible mechanisms for damage are presented in section 3 followed by a discussion of the mechanism of brittle failure for the two lens types (i.e. Nova and Beamlet). Finally, we consider the design of a "final-safe" lens for Beamlet (and NIF) and its implication on overall system design.

2. COMPARISON OF BEAMLET AND NOVA SPATIAL FILTER LENSES

Table 1 compares the Nova and Beamlet spatial filter lenses including the maximum flaw (damage) size needed for lens failure. This flaw size is based on the well known Griffith fracture criteria for brittle materials [9]:

$$a = \frac{1}{2\pi} \left(\frac{K_{1c}}{\sigma_t} \right)^2 \quad (2)$$

where a is the radius of a "half-penny" shaped crack (flaw), K_{1c} the fracture toughness ($\text{m}^{1/2} \cdot \text{Pa}$) and σ_t the tensile strength (Pa) of the brittle material. We have used the "half-penny" fracture shape because it gives a conservative estimate of the maximum flaw size compared to other flaw geometries.

The critical flaw size is based on the peak tensile stress that occurs at the center of the lens. The two components of stress (radial and tangential) fall off toward the edge of the lens; the radial stress drops to zero at the edge and (for our case) the tangential stress approaches a value of approximately one-half the peak stress. Figure 3 shows a flat-plate approximation of the stress distribution for the simply supported Nova and Beamlet lenses. (Because of the large f-number for these lenses the flat-plate approximation is good to within 5-10% of the stress values predicted by finite element analysis.) Also shown are the corresponding critical flaw sizes that would produce catastrophic failure of the lens. Note that crack growth occurs normal to the direction of the maximum principle stress and therefore, the cracks tend to grow diagonally across the lens, i.e. on the diameter (for example, see Fig. 2).

The Beamlet spatial filter lens has a peak tensile stress about 85% greater than Nova's. This is because the Beamlet lens was made purposely thinner to reduce the B-integral in the final amplification stage of the system. Nevertheless, the Beamlet lens was designed with a factor of 5 safety margin (if undamaged).

Table 1 Characteristics of Beamlet and Nova spatial filter lenses that receive the highest 1 ω fluence

<u>Characteristic</u>	<u>Beamlet (L3)</u>	<u>Nova (SF-7)</u>
Diameter (cm)	61	52
Center thickness (cm)	3.5	3.7
Aspect ratio (d/t)	17.4	14.1
SiO ₂ tensile strength (psi)	7100	7100
Peak tensile stress (psi)	1490	810
Safety factor	4.8	8.8
Critical flaw size (mm)		
– lens center	2.1	5.5
– lens edge ($r_o=0.1$)	5.7	14.5
1 ω damage limit (J/cm ²)	~34 (@ 3 ns)	~ 20 (@ 1ns)
Peak operating fluence (J/cm ²)	~ 20(@ 3 ns)	~ 13 (@ 1ns)
No. major fractures on failure	~4-5 (est.)	~1-2

Figure 3. Comparison of radial and tangential stress distributions for (a) Nova and (b) Beamlet lenses calculated with a simply supported, circular flat plate model and the corresponding critical flaw size at various r/r_0 locations ($r/r_0 = 0$ is the lens center). The critical flaw size is calculated using the Griffith fracture model assuming a "half-penny" fracture shape (Eqn. 2)

The error made in the Beamlet lens design was the failure to predict the number of fractures that would be produced on failure. Based on post fracture analysis, we estimate that 3-4 major fractures were generated producing about 6-8 major fragments. Unfortunately, these fragments were destroyed during the implosion so this estimate is based only on the major abrasions clearly seen on the inner wall of the stainless steel spatial filter vessel. (This identification was enhanced by the fact the walls were electro-polished.) In our initial design we assumed that the Beamlet lens would fail in only 2 or 3 major fragments. Furthermore, based on our Nova experience we assumed the lens would not implode. In a later section we address why more fractures (i.e. fragments) were produced during failure of the Beamlet lens.

Both the Nova and Beamlet lasers are designed such that the peak operating fluence at the final spatial filter lens is well below the damage threshold for fused silica coated with a single layer SiO_2 sol-gel anti-reflection (AR) coating. This is shown in Fig. 4 where the nominal peak operating fluences of both the Beamlet and Nova laser are plotted versus the optical component location. Note that the highest 1ω fluences occur at the lens locations that experience failure. The expected damage thresholds are about 50% greater than this peak fluence based on laboratory damage measurements. Specifically the 1ω damage threshold for sol-gel AR coated fused silica is about 20 J/cm^2 at the nominal Nova operating pulse length of 1-ns and 34 J/cm^2 at the Beamlet 3-ns pulse length (Table 1).

3. REASONS FOR DAMAGE AND FAILURE OF NOVA AND BEAMLET SPATIAL FILTER LENSES

There are a number of proposed mechanisms for damage to the output (vacuum) side of Nova and Beamlet final spatial filter lenses. In general, these can be grouped into three main ideas:

- (i) degradation of the sol-gel coating;
- (ii) hot spots in the beam due to either self-focusing or conjugate image formation from an “up stream” imperfection or damage site;
- (iii) decrease in damage threshold due to tensile stress.

Of the three proposed mechanisms the first is the most likely source of damage. This is because we measured degradation with time of both the optical performance and damage threshold of the AR coating. Of course, this does not eliminate the possibility of damage due to the other two mechanisms; for example we have also observed self-focusing damage in Nova lenses (but not on Beamlet). Whether the self-focusing spawns the fractures that eventually grow to failure on Nova is not clear. We believe hot spots generated in the beam in combination with the degradation of the AR coating may be the cause of damage on Beamlet. We feel that the third mechanism (tensile stress effects) is probably the most unlikely because the stresses are low compared to the ultimate strength of the material; also previous studies of stress effects on damage to optical coatings show no improvement in damage threshold with stress reduction [10].

The sol-gel AR coatings used on Nova and Beamlet spatial filter lenses have been observed to degrade with time. This degradation which is visually noticeable as a change in the coating reflectivity, may be due to absorption of contaminants by the highly porous (~50%) high surface area ($\geq 100\text{m}^2/\text{g}$) sol-gel coating. A lens removed from Beamlet spatial filter location L3 prior to the implosion showed an increase in reflectivity from $<0.5\%$ to about 3% over the course of approximately 5 months of high power operation.

The damage threshold of the degraded surface of the Beamlet lens was measured subsequent to its removal from the system. The beam direction through the optic was the same during damage testing as when installed on the system; that is, the vacuum surface was the exit surface for the beam. The damage threshold at 3-ns and 1ω was determined to be $14\text{--}18\text{ J/cm}^2$. This is only 50% of the value expected for a fresh sol-gel coating ($\sim 35\text{ J/cm}^2$) suggesting that the damage threshold degraded about 50% during the time it was installed on the system. More importantly, the damage threshold is less than the peak operating fluence at L3. Therefore, it is not surprising the lens damaged.

The decrease in damage threshold on the output surface of the lens is probably due to two coupled effects. First, the contamination of the surface degrades the damage threshold, and second it enhances the reflectivity, and therefore, the electric field strength, at the output surface. The enhanced field associated with the increase in reflectivity to 3% gives an intensity increase of nearly 40% at the rear surface (11). The combination of enhanced intensity and reduced damage threshold leads to a much higher risk of damage.

Degradation of the sol-gel AR coating by contamination from within the vacuum chamber has been previously observed on Nova. Contamination sources include volatiles released by various components within the vacuum (for example plasticizers from various polymers) as well as particulate blow-off from the pinholes. Although the fraction of energy incident on the edges of the pinhole is very small, the intensity is quite large since the pinhole lies at the focal plane. Therefore, during high energy shots a small portion of the pinhole wall is vaporized and may deposit on the lens causing some decrease in the damage threshold. The Beamlet pinholes are fabricated from graphite. Work is currently underway to further quantify the magnitude and source of contamination of the AR coating.

The morphology of damage sites on Nova and Beamlet lenses has been documented after careful inspection. In general, visual damage is only observed on the output surface of the lens. Also, major damage (>5mm diameter) occurs at only one or two isolated sites. These damage sites have fracture patterns characteristic of an impact event. This suggests that a pressure pulse generated by plasma blow-off during damage may be the cause of initial fracture and subsequent growth to the critical flaw size.

Nova lenses show self-focusing damage as evidenced by the characteristic "angel hair" tracking that occurs in the bulk material. Although this is common in Nova lenses, we have not observed self-focusing in Beamlet spatial filter lenses. Small spots (less than 50 μm) are commonly observed where the self-focusing tracks intercept the output surface of the lens. These spots are typically grouped in clusters containing a number of individual damage spots within a cluster diameter of about 1-2 mm. In general, these spots do not seem to grow on subsequent shots.

The failure of a fused silica lens is caused by growth of a damage spot up to the critical size that then leads to catastrophic fracture. By catastrophic fracture we mean the rapid growth of a small crack into one or more large fractures that traverse the optic. This is the well known mechanism for failure in brittle materials.

Inspection of the fracture surfaces of a failed lens can be used to imply the source, direction and speed of crack growth at the time of failure. Unfortunately, in the case of the failed Beamlet lens the pieces were so badly damaged that this was not possible. However, the recovered fragments of the Nova lenses give an excellent chronology of the material failure (Fig. 5). First a flaw is generated by optical damage. During subsequent shots the crack slowly grows. Surprising, on Nova we have never observed growth to the critical flaw size (and subsequent failure) during a laser shot. Instead we have observed lens failure during the process of removing the lens from the system, specifically while warming up the cryogenic vacuum pumps connected to the spatial filter. As a cost savings device on Nova we omitted the use of isolation valves on the cryo pumps. Therefore, we believe that small amounts of water vapor released during cryo pump warm-up enhanced the slow growth of the damage crack up to the critical flaw size. The effects of minute amounts of water on crack growth rates in glasses is well documented with perhaps the most important study being the classic work by Wiederhorn [12,13].

Once this initial crack reaches the critical flaw size it rapidly grows in a direction normal to the peak tensile stress, in other words nearly diagonal across the lens. This can be determined from the Wallner lines, a faint set of marks left on the fracture surface that result from the interaction of the propagating crack with sonic waves produced during fracture [14,15]. The crack growth, although rapid, is much

slower than that produced by fracture at very high stress as indicated by the very smooth (mirror like) fracture surface of the Nova lenses. After the crack has propagated along the tensile surface of the lens, it then propagates toward the compression surface (see Fig. 5). Wallner lines and other characteristic fractological features (twist hackel) that are representative of typical flat plate failure under uniform loading are observed on the lens fracture surfaces.

Figure 5. Characteristic features of crack formation and growth and during a Nova lens failure: (1) initial flaw generation by laser damage, (2) slow growth to critical size, (3) after reaching critical size, rapid growth along the tensile surface and (4) propagation toward the compressive surface.

4. ESTIMATE OF FRACTURE AREA FOR BEAMLET LENS L3

During fracture of brittle material, the energy used to produce new surfaces is proportional to the elastic stored energy in the material. In turn, the stored energy is related to the stress via the expression:

$$E_s = \int_0^{V_L} \sigma \cdot \varepsilon dV \quad (3)$$

where σ is the stress (Pa) ε , the strain (m) and V_L the integrated volume (m^3) of the elastic material under the applied stress. The strain is related to stress via Hook's law:

$$\sigma = E\varepsilon \quad (4)$$

where E is Youngs modulus (Pa). Therefore, after substituting Eqn. 4 into 3 it is clear that energy is proportional to the square of the stress. This provides a useful scaling relationship to estimate the fracture area for geometrically similar objects under comparable loading conditions. For example, by estimating the fracture area produced under given stress conditions for Nova lenses it should be possible to estimate the area generated during fracture of a Beamlet lens. This is because the Nova and Beamlet lenses are all comparably shaped and have similar vacuum loading (although the stored energy varies significantly).

We measured the crack surface area produced by catastrophic failure of seven Nova lenses under full vacuum load. The peak tensile stress in the lenses was about 810 psi based on finite element calculations and the fracture surface area was measured to be $430 \pm 40 \text{ cm}^2$ per lens (based on the average from all seven lenses that failed). The surface energy for SiO_2 is reported to be about 4.3 J/m^2 so the elastically stored energy required to generate the total fracture area is about 0.2 J. Note that the elastically stored energy in the lens is of the order of a few joules so that only a small amount goes into generating new surfaces. This is typical of brittle failure where only about 10% of the stored energy goes into generating new surfaces (fractures) and the remainder produces noise and heat.

In the analysis given here we assume that the fraction of stored energy used to generate new surfaces in a failed Beamlet lens is similar to that for Nova because of the similar lens shapes and loading.

From the Nova data we can determine the simple relationship:

$$A_f (\text{cm}^2) = \left(6.6 \times 10^{-4} \frac{\text{cm}^2}{\text{psi}^2} \right) (\sigma_p)^2 (V/V_n) \quad (5)$$

where A_f is the generated fracture area on failure, σ_p the peak tensile stress in the lens (psi) and V/V_n a volume normalization factor where V_n is the volume of the Nova lens and V the volume of the lens under test. Therefore in the case of this application, V is the volume of the Beamlet L3 spatial filter lens. The numerical constant in equation 5 was empirically determined from the fracture data for Nova lenses. Equation 5 is plotted in Fig. 6.

The peak stress in the Beamlet lens is 1490 psi and the lens volume is about 30% greater than

Nova's. Thus the total fracture area produced during failure of a Beamlet lens is predicted to be about 1900 cm². The area of a fracture running across the diameter of the Beamlet lens is approximately 430 cm² (compared to 385 cm² for Nova). Therefore, a total of about four to five large fractures are predicted to be produced during the failure of the Beamlet lens giving roughly eight to ten large glass fragments. This implies it would be nearly impossible for the Beamlet lens not to implode on failure because the number of fragments generated is simply too large to expect the pieces to "bridge" the spatial filter opening. Also the estimate of 8 to 10 large fragments generated during fracture of the Beamlet lens is in reasonable agreement with our initial rough estimate of a minimum of 6 to 8 fragments based simply on the observed abrasion pattern on the walls of the spatial filter.

5. DESIGN OF A FAIL-SAFE LENS

Equation 5 and Fig. 6 clearly show that a modest reduction in stress produces a large reduction in fracture area because of the parabolic relationship between the two quantities. If the fracture area could be reduced to the point that only one large fracture is generated (i.e. 2 fragments) then we could be confident the lens would not implode. This probably requires that the stress be reduced to <700 psi. Figure 7 shows the calculated principal stresses and critical flaw size for such a lens. To reach this stress level would require that the thickness be increased to about 5.5 cm. Note that this design does not eliminate the problem of optical damage but instead provides a safety measure such that if the lens does fracture it will not implode. This design also requires that the lens mount be similar to that used on Nova that restrains the radial motion of the fragments thus insuring that they "lock" together.

Figure 6. Fracture area (normalized to the Nova lens volume) vs. stress. The curves were generated from equation 5.

Figure 7. Calculated principal stresses and critical flaw sizes for a round Beamlet spatial filter lens designed not to fracture into more than 2 pieces.

The increase in the B integral for the thicker lens can be computed from the increase in intensity • length product ($2\pi\gamma IL/\lambda$). Here we assume a constant intensity, I , (GW/cm^2) through the added SiO_2 optical path, ΔL , (cm) having a non-linear coefficient, γ ($0.24 \times 10^{-6} \text{ cm}^2/\text{GW}$). For a peak intensity of $6.7 \text{ GW}/\text{cm}^2$ (i.e. $20 \text{ J}/\text{cm}^2$ at 3 ns) the increment in B is about 0.2 radians.

One other mitigating factor in the design of spatial filter lens for NIF is the fact that the lenses are square rather than round. This significantly reduces the peak stress (by about 50%) for similar aperture sizes. Therefore, the thickness required to insure a “fail-safe” design for a square NIF lens will be less than that determined above for the round lenses used on the prototype Beamlet.

Fracture experiments are presently underway on round and square SiO_2 plates in order to further quantify the fracture area vs. stress relationship.

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