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IMPROVED SPATIAL FILTER FOR HIGH POWER LASERS

By:
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IMPROVED SPATIAL FILTER FOR HIGH POWER LASERS

CROSS-REFERENCE TO RELATED APPLICATIONS

This application claims the benefit of U.S. Provisional Application No. 60/048,531, filed June 2, 1997 and which is hereby incorporated by reference herein.

STATEMENT OF GOVERNMENT INTEREST

The United States Government has rights in this invention pursuant to Contract No. W-7405-ENG-48 between the United States Department of Energy and the University of California.

BACKGROUND OF THE INVENTION

1. Field of the Invention. The invention relates to spatial filters, and more particularly, to an improved pinhole configuration for a spatial filter.

2. Prior Art. Spatial filters are essential components of high-energy pulsed laser systems where they are used to remove high spatial-frequency components from a high-energy pulsed laser beam in order to control instabilities in the laser-beam amplification process. See for example, W. W. Simmons, J.S. Guch, F. Rainer and J.E. Murray, Internal Report UCRL-76873, University of California, Lawrence Livermore Laboratory, 1975. A spatial filter includes a focusing, lens-collimating lens pair with a pinhole placed at their common focus. The pinhole clips the wings, or higher spatial frequency components, or modes, of the spatial Fourier-mode spectrum from the laser beam and allows only the lower spatial modes of the Fourier spectrum to be transmitted. Because noise and distorted phase components focusing greater than 100 μrad from best focus have high gain in large solid state lasers, spatial filtering below 100 μrad is required to increase the safe operating region of large solid state lasers systems.

FIG. 1 illustrates operation of a conventional washer-type pinhole element 10 having a pinhole 12 concentric with the axis of a laser beam. The pinhole element 10 in a spatial filter absorbs unwanted rays (typically shown as 14) near normal incidence which heats and ablates the
front surface of the pinhole element 10 to form an expanding plasma 16. A transmitted ray 18 passes through the pinhole.


The design of pinhole spatial filter depends on a number of factors. Usually, for a pinhole to be small enough to clip unwanted light, the intensity of the laser pulse on the rim of the hole is sufficient to ablate the plasma 16 which eventually expands into the beam waist during the pulse as illustrated in FIG. 1. There is an escalating series of problems associated with this process. Initially, plasma in the central regions of the pinhole is a phase object that distorts the wavefront quality of the transmitted beam. The magnitude of the local phase shift, $\delta$, is related to the electron density through the relation:

$$\delta = (\pi/\lambda) \int_0^L (n/n_c) \, dz$$

where $n/n_c$ is the ratio of electron density to the critical density, $\lambda$ is the laser wavelength, and the integral is evaluated along ray paths through the plasma, over the plasma size, $L$. The plasma refractive index is equal to $(1-n/n_c)^{1/2}$ and the critical density is the density where the plasma frequency equals the laser frequency. For $\lambda = 1.05 \mu m$ light, $n_c \approx 10^{21} \text{ cm}^{-3}$. Phase distortions of magnitude $\delta = \pi/2$ can be expected at electron densities of $n = 10^{19} \text{ cm}^{-3}$ depending on the system parameters as discussed herein below. At a threshold level of $n \approx 3 \times 10^{19} \text{ cm}^{-3}$ and higher electron densities, the plasma may become an efficient medium for stimulated Brillouin scattering which can scatter the beam to the side and may also reflect enough light backwards through the laser gain stages such that the backscattered light damages components. Finally, if the plasma density reaches the critical density, it behaves like a metal, and so will reflect the beam totally, which is another mechanism for causing system damage.

Past studies of pinhole closure on washer-type pinholes have demonstrated a plasma closure velocity of around $10^7 \text{ cm s}^{-1}$. See J. M. Auerbach, N.C. Holmes, J.T. Hunt and G.J. Linford, *Appl. Opt.*, 18, pp. 2495-2499, 1979. The simplest way to mitigate against closure is to choose a pinhole diameter large enough so that the beam loading on the pinhole periphery is small (the threshold for plasma generation lies in the range $10^9 - 10^{11} \text{ Wcm}^{-2}$) and so that the plasma does not expand into the beam during the laser pulse. Choice of a sufficiently large $f\#$ allows for a large pinhole diameter while providing filtering down to a small cut-off angle. This reduces the
edge intensity and increases the time required for plasma to reach the pinhole axis. This strategy has been employed for high energy pulsed lasers with pulse durations up to several nanoseconds. However, it has limited efficacy for longer pulse durations, such as the 21 ns pulse required for inertial confinement fusion experiments on the National Ignition Facility (NIF) being developed at Lawrence Livermore National Laboratory (LLNL).

A need exists for a spatial filter which, for example, removes noise sources in a laser beam down to a ±100 μrad divergence at edge intensities exceeding 10^{11} \text{Wcm}^{-2} without closure.

**SUMMARY OF THE INVENTION**

It is therefore an object of the invention to provide a spatial filter with a new pinhole design which incorporates features that reduce the rate of plasma generation.

In accordance with this and other objects of the invention, a novel elongated pinhole aperture is provided for a spatial filter for a long-duration, high-energy laser pulse beam. An apertured body has an elongated aperture formed therethrough for rejecting off-axis rays of the laser pulse beam. The internal surface of the elongated aperture has a diameter which progressively tapers from a larger entrance cross-sectional area at an inlet to a smaller output cross-sectional area at an outlet. The tapered internal surface causes off-axis rays to be refracted in a low density plasma layer that forms on the internal surface or specularly reflected at grazing incidence from the internal surface.

A spatial filter includes a first focusing lens and a second collimating lens aligned with the path of the high-energy laser pulse beam on opposite sides of the apertured body. The axis of the elongated aperture is aligned with the direction of the path of the high-energy laser pulse beam such that the beam waist of the high-energy laser pulse beam coincides with the plane of the outlet of the apertured body. Off-axis rays of the high-energy laser pulse beam are rejected by this design. The external surface of the apertured body adjacent to the larger entrance cross-sectional area at the inlet to the elongated aperture is angled obliquely with respect to the direction of the path of the high-energy laser pulse beam to reflect off-axis rays away from the high-energy pulse beam. Also, plasma formed at the entrance has more vacuum volume to expand into other than into the laser beam with the outer surface tapered back. The aperture is formed as a truncated cone.

Alternatively, the aperture has a rectangular or square cross-section which decreases in cross-
section area from the inlet to outlet. The internal surfaces of the aperture and entrance surface are coated with an ablative material, preferably high-density, which can be deposited with an exploding wire or electroplated.

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BRIEF DESCRIPTION OF THE DRAWINGS

The accompanying drawings, which are incorporated in and form a part of this specification, illustrate embodiments of the invention and, together with the description, serve to explain the principles of the invention:

FIG. 1 is a side cross-sectional view which illustrates the structure and operation of a conventional washer-type pinhole operation where rejected rays are highly absorbed at near normal incidence and ablate the pinhole surface to form an expanding plasma.

FIG. 2 is a side cross-sectional view of a conical pinhole structure according to the invention.

FIG. 3A is a side cross-sectional view of a conventional washer-type pinhole structure for a spatial filter having a gold surface and showing a simulated plasma electron density distribution at a time 0.91 ns after the start of a simulated 5 nanosecond pulse with an incident energy of 250 J.

FIG. 3B is an enlarged view of a portion of FIG. 3A where the gray scale and contour intervals are mapped logarithmically and where the contour interval is one decade in density with the first contour located at 10^{18} \text{cm}^{-3} (0.001 \times \text{critical density}).

FIG. 4A is a side cross-sectional view of conical pinhole structure for a spatial filter having a gold surface according to the invention and showing a simulated plasma electron density at a time 2.00 ns after the start of a simulated 5 nanosecond pulse with an incident energy of 250 J.

FIG. 4B is an enlarged view of a portion of FIG. 4A where the gray scale and contour intervals are mapped logarithmically and where the contour interval is one decade in density with the first contour located at 10^{18} \text{cm}^{-3} (0.001 \times \text{critical density}).
FIG. 5 is a schematic diagram illustrating the experimental arrangement for measurement of incident transmitted and backscattered beams from a spatial filter.

FIG. 6A is an image of the far field (best focus) intensity distribution mapped on a logarithmic gray scale and as recorded on a CCD detector in a far field imager for a spatial filter according to the invention.

FIG. 6B is a graph of horizontal (dotted) and vertical (dash-dot) lineouts of the far field intensity distribution in (FIG. 6A) as well as the azimuthally-averaged (solid) distribution.

FIG. 6C is a plot of integrated energy (azimuthally-averaged) as a function of radius from the spot center.

FIG. 7A shows streaked images of the near field beam imaged at the output lens with no pinhole installed.

FIG. 7B shows streaked images of the near field beam imaged at the output lens of a prior art spatial filter with a 500 μm diameter Ta pinhole.

FIG. 7C shows streaked images of the near field beam imaged at the output lens of a spatial filter with a 500/900 μm Au conical pinhole according to the invention.

FIG. 8A shows streaked images of the near field beam imaged at the output lens of a prior art spatial filter with a 1 mm diameter CH pinhole.

FIG. 8B shows streaked images of the near field beam imaged at the output lens of a prior art spatial filter with a 500 μm diameter CH pinhole.

FIG. 8C shows streaked images of the near field beam imaged at the output lens of a spatial filter with a 500/900 μm CH conical pinhole according to the invention.

FIG. 9A shows plots of incident and transmitted power as functions of time for a prior art 500 μm diameter Ta washer-type pinhole where average incident power level during the 5 ns pulse was 30 GW and where incident power is shown as solid lines, transmitted power is shown as dashed lines, and backscatter signals are shown as dotted lines.
FIG. 9B shows plots of incident and transmitted power as functions of time for a prior art 500 μm diameter CH washer-type pinhole where average incident power level during the 5 ns pulse was 30 GW and where incident power is shown as solid lines, transmitted power is shown as dashed lines., and backscatter signals are shown as dotted lines.

FIG. 10A shows plots of incident and transmitted power as functions of time for a 500/900 μm diameter Au conical pinhole according to the invention, where average incident power level during the 5 ns pulse was 30 GW and where incident power is shown as solid lines, transmitted power is shown as dashed lines, and backscatter signals are shown as dotted lines.

FIG. 10B shows plots of incident and transmitted power as functions of time for a 500/900 μm diameter CH conical pinhole according to the invention, where average incident power level during the 5 ns pulse was 30 GW and where incident power is shown as solid lines, transmitted power is shown as dashed lines, and backscatter signals are shown as dotted lines.

FIG. 11 is a cross-sectional view which diagrammatically illustrates the use of electrodes shaped as concentric rings for providing electric field before and after a pinhole filter.

FIG. 12 is a cross-sectional view which diagrammatically illustrates a pinhole filter having four segments which are aligned along the laser beam path.

FIG. 13 is a cross-sectional view diagrammatically illustrating a hohlraums having truncated cone surfaces.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENTS

Reference will now be made in detail to the preferred embodiments of the invention, examples of which are illustrated in the accompanying drawings. While the invention will be described in conjunction with the preferred embodiments, it will be understood that they are not intended to limit the invention to these embodiments. On the contrary, the invention is intended to cover alternatives, modifications and equivalents, which may be included within the spirit and scope of the invention as defined by the appended claims.
Improved Pinhole Design

FIG. 2. illustrates an elongated-pinhole apertured element 20 according to the invention. The improved pinhole design, shown in FIG. 2, includes a long aperture, or through hole, 22 having a length L formed in the element 20. The aperture 20 has an aperture axis 24 which is aligned coaxially with the central axis or direction along which a transmitted ray 26 of a laser pulse travels. The structure of the aperture 22 is such that its cross section progressively tapers from an entrance opening 30 with a larger cross-sectional area having a diameter d₁ at the inlet of the apertured element 20 to a larger outlet opening 32 with a smaller cross-sectional area 32 having a diameter d₀ at the outlet of the apertured element 20. The beam waist (focus) of the beam coincides with the plane of the outlet of the apertured body. Rays, typically shown as 34, of the high-energy laser pulse which follow trajectories at diameters outside of the exit aperture are rejected. The front lip 36 of the entrance opening 30 is shaped as an external conical surface to direct plasma generated at that surface away from the pinhole axis 24.

While most lasers have circular cross section beams, Beamlet and NIF use square beams in which case a square pinhole filter is optimum. An elongated pinhole according to the invention could be easily made square with the same smooth internal taper. Consequently, the cross sectional area of the aperture 22 can have a number of configurations, including, for example, circular, rectangular, square, etc. One preferred embodiment of the invention includes a circular cross section which provides a truncated conical-shaped, or funnel shaped, aperture with its long axis aligned coaxially to the beam. The structure is oriented with the larger entrance opening 30 facing the incoming beam and positioned such that the beam waist (focus) coincides with the plane of the small opening (exit aperture). Intensities in the central regions of the beam may reach \(10^{17}\) Wcm\(^{-2}\) falling off to much lower levels around the periphery of the beam.

For the aperture shown in FIG. 2, rays following trajectories at diameters outside of the exit aperture are efficiently rejected. The design works three ways. Firstly, it spreads the intensity in the wings of the beam distribution over a large conical surface area, thus reducing the local fluence on the structure. The plasma that is produced is cooler, and expands more slowly than the plasma produced on the outer surface of the washer-type pinhole. Secondly, the geometric structure of the cone is designed such that rejected rays are refracted (in a low density plasma layer that forms on the surface) or specularly reflected at grazing incidence. These reflected rays then pass through the exit aperture along trajectories outside of the collection cone of the downstream collimating lens. Since the unwanted beam energy is rejected by this beam steering process rather
than by absorption, the rate of plasma production is expected to be further reduced. Finally, most of the plasma that is created originates on the front rim at a diameter which is about twice the diameter of an equivalently-sized conventional pinhole, thus increasing by the same factor the distance that the plasma must travel to reach the central regions of the beam, allowing amplification of longer duration pulses.

If we consider the inner surface of the spatial filter to be shielded by a low density plasma layer with a density gradient decreasing away from the surface, then the rays traveling through this layer will be refracted or steered as they progress through the gradient and reach a classical turning point which is determined by the electron density and angle of incidence. See V.L. Ginzburg, *The Propagation of Electromagnetic Waves in Plasmas*, Pergamon Press, Oxford, 1964. In a pinhole the maximum electron density, \( n_{\text{turn}} \), reached by a ray at the classical turning point is \( \sin^2(\theta f) \left( n_c \right) \).

where \( \theta f \) is the angle between the ray and the surface which approaches zero for grazing incidence. For a typical spatial filter with lens \( F\# = 30 \), \( n_{\text{turn}}/n_c \) is about \( 0.0003 \). For 1.05 \( \mu \text{m} \) light, with electron temperature 100 eV, average ionization state Z=40 (gold, tantalum), the inverse bremsstrahlung absorption length is 600 cm. See T. W. Johnston and J. M. Dawson, *Phys. Fluids*, 16, p. 722, 1973. Consequently, very little light is absorbed by the plasma and remains relatively cold as the light is refracted. Since the ray path is mostly through densities smaller than 0.003 \( n_c \), the actual absorption is even smaller. The absorption on the grazing incidence part of the filter becomes smaller as the lens \( F\# \) becomes larger.

The pinhole design is determined by three parameters, namely the entrance and exit aperture diameters, \( d_i \) and \( d_o \) respectively, and the length, \( L \). We simplify the analysis by assuming that all rays entering the pinhole structure are parallel to the axis, which is approximately true in the far field (best focus) near the beam waist. Rays strike the inner conical surface at grazing incidence angle \( \theta f = \arctan \left[ (d_i-d_o)/2L \right] \) relative to the surface, and undergo a deflection angle of \( \theta_d = 2\theta f \). Choice of the pinhole parameters is determined through three criteria: (i) the maximum beam divergence cutoff angle, \( \theta_c \), determine by laser design sets the size of the exit aperture, \( d_o = 2\theta_c F \), where \( F \) is the focal length of the input lens; (ii) the grazing incidence reflection must reject rays to angles outside the collection cone of the collimating lens which is equivalent to the mathematical statement \( \theta f = (d_i-d_o)/2L \geq 1/(2f\#) \), where \( f\# \) is the focal ratio of the spatial filter; and, (iii) the ratio of entrance to exit aperture diameters must be limited such that all rejected rays pass through the exit aperture (i.e. multiple bounces are avoided to avoid trapping of the beam and excessive energy deposition near the exit aperture) leading to the condition \( r = d_i/d_o \leq 3 \). The latter criterion effectively limits \( L \) once \( \theta_c \) and \( \theta f \) are selected. In a practical situation
one would like to choose parameters for $\theta_f$ and $r$ such that there is a safety margin to allow for surface roughness since imperfections in the local surface orientation would tend to spread the rejected energy in a distribution centered around its mean deflection value. For example, a cone angle which matches the focal cone of the input beam, would steer rejected rays out to a deflection angle equal to twice that subtended by the collimating lens. Similarly one should relax $r$ (or length $L$) to a value somewhat less than the maximum allowed to avoid steering too much energy near the edge of the exit aperture. However, this must be balanced by another consideration: energy striking the periphery of the entrance aperture interacts at near normal incidence and will be absorbed strongly to generate much plasma; therefore $d_j$ must also be chosen large enough (and therefore $r$) to limit the intensity loading on the entrance aperture periphery. Clearly, the choice of parameters involves an optimization procedure that requires detailed knowledge of the far field distribution of the input beam in order to balance various considerations.

Simulations

We performed two-dimensional LASNEX simulations of the plasma generation process in the pinholes. See G. B. Zimmerman and W. L. Krueer, Comments on Plasma Physics and Controlled Fusion, 2, p. 51, 1975. LASNEX models hydrodynamics of plasma formation from laser ablation. The simulations described the interaction of the beam with the pinhole structure using a ray propagation algorithm which included the effects of refraction and absorption. The far field (best focus) intensity profile used in the simulation was similar to the experimentally measured profiles presented below. For most of the simulations the incident energies were 125J in a 5 ns rectangular pulse, which matched the incident energies obtained in the experiment. In the simulations, and in the experiments described below, we compared the performance of conventional washer-type pinhole with that of a conical pinhole, and also compared low Z and high Z materials (CH or Au). The conical pinhole structures were 8 mm long with 500/900 $\mu$m diameter exit/entrance apertures. The conventional washer-type structure consisted of a 500 $\mu$m or 1 mm diameter holes drilled through 1 mm thick CH and tantalum disks.

FIGS. 3A and 4A illustrate for comparison purposes a conventional washer-type pinhole spatial filter and a conical pinhole structure, where each has a gold surface.

FIG. 3A illustrates a conventional gold-surfaced washer-type pinhole structure 40 having a length of 1 mm and a diameter of 0.5 mm. A simulated plasma electron density distribution is
illustrated at a time 0.91 ns after the start of a simulated 5 nanosecond pulse with an incident energy of 250 J.

FIG. 3B shows an enlarged view of a portion of the structure of FIG. 3A with the gray scale and contour intervals being mapped logarithmically and where the contour interval is one decade in density with the first contour located at $10^{18}$ cm$^{-3}$ (0.001 x critical density).

FIG. 4A illustrates a gold-surfsed conical pinhole structure 50 according to the invention. The conical pinhole structure 50 has a length of 8 mm, an inlet diameter of 0.9 mm, and an outlet diameter of 0.5 mm. A simulated plasma electron density is illustrated at a time 2.00 ns after the start of a simulated 5 nanosecond pulse with an incident energy of 250 J.

FIG. 4B shows an enlarged view of a portion of the structure of FIG. 4A where the gray scale and contour intervals are mapped logarithmically and where the contour interval is one decade in density with the first contour located at $10^{18}$ cm$^{-3}$ (0.001 x critical density).

For any pinhole structure most of the plasma is generated on surfaces normal to the beam where absorption of the laser light is nearly total. The plasma thereby generated expands towards the axis and interacts with the beam in a plane roughly coincident with the front face. The expanding density profile rises roughly exponentially from the center to the edge, and has a scale length that expands in time consistent with a characteristic speed around $10^7$ cm/s. For the conical pinhole structure of FIG. 4A, FIG. 4B shows that the rate of plasma generation is reduced because less surface area is oriented at near normal incidence to the beam (also the external conical surface on the front face directs plasma generated at that surface away from the pinhole axis) and because the fluence striking the front face at the larger radius is lower. A cool plasma layer is also generated along the inner surface which does not expand significantly into the axial region. In some cases, the simulations also predicted a region of strong plasma generation near the exit aperture after laser light was strongly refracted in the plasma plume at the entrance aperture of the cone to the exit aperture (note different times).

It is evident from a comparison of FIGS. 3B and 4B that there is a much slower convergence of the plasma flow to the axis for the conical design of FIG. 3A than for the equivalent conventional pinhole design of FIG. 4A. In FIG. 4B the 1% of critical density contour is situated 250 $\mu$m away from the axis at 2.0 ns (~$1.6 \times 10^7$ cm/s). Typically, the cone length L is less than the Raleigh range (depth of focus) of the beam, so that the distance from the ablating
surface at the entrance of the cone to the Airy disk (high intensity) in the beam is approximately
twice as big for the conical structures as compared to the washer structure, for an equivalent exit
aperture, thus giving at least two times longer open times.

A useful criterion for determining the plasma conditions that lead to pinhole closure is
provided by examining the deflection angle produced by transverse plasma density gradients in the
central regions of the pinhole. The deflection angle of a given ray is:

$$\phi_d = - \int_0^L \left[ d(n/n_c)/(2dx) \right] dz,$$

where \(x\) is transverse and \(z\) along the ray direction, \(n/n_c\) is the ratio of the plasma electron density
to the critical density, and \(L\) is the path length along the ray through the refracting region. When
the plasma density profile within the Airy disk produces beam deflections comparable to the beam
divergence half-angle of the spatial filter, \(\phi_f\), the pinhole is effectively closed, i.e. \(\phi_d = \phi_f\) over
most of the beam. The plasma density on axis, \(n^*\), required to produce closure depends on the
system parameters (since \(n^*/n_c \approx \phi_f \approx 1/f\)). For beam parameters typical of large laser systems
(\(f/30, \lambda = 1.05 \, \mu m\)) a simple estimate using the above criterion leads to a prediction that pinhole
closure occurs when the plasma electron density in the beam waist near the pinhole axis reaches \(n^*/n_c \approx 0.01\), or 1% of critical density which was confirmed by our simulations. It is difficult to
measure electron densities inside the pinhole; we did not attempt it for this work.

Our simulations also predicted that the high atomic number plasmas (e.g. Cu or Au) expand
at a slower rate than lower Z plasmas (e.g. CH). This comes about through radiative cooling,
which is much more effective for the higher Z plasmas. The higher atomic numbers also produces
a smaller charge to mass ratio which results in lower sound speeds, hence slower plasma motion
and longer closure times.

A summary of the results from these calculations, and from the experiments, is shown in
Table I which lists the times after the start of the laser pulse at which the pinhole "closed." In the
simulations, closure time was determined to be the time when more than 50% of the transmitted
beam energy was deflected to angles outside the angle subtended by the collimating lens (\(f/23\) in
the simulations). In the experiments the closure times were measured directly from streak records
of the beam transmitted through the collimating lens.
**Table I.** Pinhole closure times determined from hydrodynamic simulations and experiments for washer-type and cone-type pinhole structures, made from polystyrene (CH), Ta or Au.

<table>
<thead>
<tr>
<th>Pinhole Structure</th>
<th>Closure time for low Z simulation/experiment</th>
<th>Closure time for high Z simulation/experiment</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 mm washer</td>
<td>3 ns/&gt;5 ns (CH)</td>
<td>&gt;5 ns/&gt;5 ns (Ta)</td>
</tr>
<tr>
<td>500 μm washer</td>
<td>0.6 ns/~2 ns (CH)</td>
<td>1.5 ns/~2.5 ns (Ta)</td>
</tr>
<tr>
<td>500/900 μm cone</td>
<td>2 ns/~4 ns (CH)</td>
<td>4.5 ns/&gt;5 ns (Au)</td>
</tr>
</tbody>
</table>

**Experimental Results**

FIG. 5 shows an experimental arrangement 60 for measurement of incident transmitted and backscattered beams from a spatial filter. An experimental test for pinhole elements 62 was carried out to determine if the conical design allowed much longer open times for a pinhole in a spatial filter. To approximate the NIF design, a spatial filter with an f/23 focus using a pair of 2.21 m lenses 63, 64 was used to build the spatial filter. The focal ratio on the NIF cavity spatial filter is f/27. The arrangement of the spatial filter and various diagnostics around the system are shown in FIG. 5. The incident, transmitted and backscattered light pulses were monitored with respective photodiodes 66, 67, 68 to produce time resolved measurements on an oscilloscope. The transmitted beam was also monitored with an optical streak camera 70 to give a spatially and temporally resolved measurement of the near field distribution in the output beam, and thus to detect the closure time. The optical arrangement relayed the output aperture of the spatial filter onto the input slit of an optical streak camera 68 with an S-1 photocathode.

We used a beam from the Janus laser at LLNL, which was configured to produce 5 ns pulses with pulse energy of approximately 140 J delivered to the experiment in a beam of 95 mm diameter in the near field. The pulse contained a significant level of temporal mode structure which was not reproducible from shot-to-shot; this structure is readily evident in the streak data we display later on. The time integrated beam intensity distribution in the focal plane was measured with a rattle pair 72 and a scientific grade CCD detector 74. The rattle pair 72 consisted of two pairs of reflectors, a pair of 25% reflectivity mirrors placed ahead of a 1.8 m focal length lens, and a pair of 90% reflectivity mirrors placed behind. The separation of the down stream mirrors provided a sampling interval of 100 mm along the beam focus. This arrangement of mirrors could be adjusted to produce an array of images of the far field (best focus) of the beam on the detector.
such that the beam was sampled at selected attenuations and axial positions. We arranged the system to produce a total of 4 images (two attenuations and two axial positions) on the detector. It provided nearly 3 decades of dynamic range to map out the intensity in the wings of the far field (best focus) distribution.

The beam intensity of the Janus beam is shown in FIG. 6A. This beam is far from diffraction limited and included some astigmatic aberrations which were evident from measurements taken at various axial positions (not shown in the figure). The far field (best focus) spot size contained about 70% of the beam energy within a 500 μm diameter aperture, hence a 500 μm diameter pinhole will absorb or reject ~ 30% of the beam energy. The beam intensity at 250 μm radial offset from the beam axis exceeded 3×10^{12} W/cm². Although this beam quality is clearly far different than that expected for NIF operation, this high level of loading in the wings of the spot distribution provided a good test of the new pinhole design. The NIF filters are expected to reject less than 2% of the incident beam energy, but at a comparable loading on the pinhole edge.

We examined the performance of several washer type pinholes to provide a baseline for comparison with the conical design. We fabricated pinholes from 1 mm thick substrates at two diameters 500 μm and 1 mm, and made of polystyrene (CH) and Ta to compare the low Z and high Z cases. The conical pinhole design we tested consisted of a structure of 8 mm length with 500/900 μm diameter exit/entrance apertures identical to the dimensions examined in the simulations. This structure was fabricated from polystyrene (CH) and gold using a specially made tool to machine the inner conical surface.

**Experimental Results**

The experimental tests revealed that the conical pinholes indeed remained open for a significantly longer duration than washer-type pinholes of equivalent diameter. FIG. 7 displays the streak output for the beam incident on: (a) no pinhole; (b) a 500 μm diameter hole in a 1 mm thick Ta plate; and, (c) a Au conical pinhole. The washer-type pinhole clearly closes after about 2.5 ns duration, consistent with a closure velocity of approximately 10^7 cm/s. Among the details evident in the streak records is the temporal variation in the near field beam intensity distribution during the process of pinhole closure. This shows up strongly in FIG. 7B where the whole beam is refracted to produce an enhancement of the near field intensity towards the center line more than 1 ns before the pinhole closed. For comparison FIG. 7A recorded with no pinhole present shows no time variation in the near field spatial intensity profile. Although the Au conical pinhole
transmitted light for the entire duration of the pulse, similar distortions of the near field intensity profile indicate that plasma is filling the structure and distorting the transmitted beam.

The results summarized in Table I show that the simulations systematically underestimate the time the pinholes remain open since the predicted closure times were generally sooner than the observed results. Plasma instabilities, such as stimulated Brillouin scattering, were not included in the simulations and may account for some of this discrepancy since they can alter the energy balance and hydrodynamic motion of the plasma substantially once the plasma density in the pinhole reaches high enough levels to scatter the incident beam out of the pinhole. Observed trends did agree with simulations: washer-type pinholes remained open approximately for 1/3 to 1/2 the duration as the equivalent conical pinholes. The experiments with CH pinholes displayed more beam refraction and earlier closure than the high Z pinholes which was also predicted by the simulations. The strong asymmetries in the transmitted near field intensities which are especially evident in FIG. 8 are related to the astigmatic aberrations in the far field (best focus) profile. In FIG. 8A the 1 mm diameter CH washer pinhole did not close during the pulse, but evidence of beam refraction shows up in the streak records. Experiments with 1 mm diameter Ta washers (not shown in the figures) did not show beam refraction effects, and appeared similar to experiments with no pinholes. In comparison with FIG. 7, both the 500 μm diameter, CH washer, FIG. 8B, and the CH conical pinhole, FIG. 8C, closed earlier than the Ta and Au versions.

Observed backscattering signals depended on the target type and material and on whether plasma closure took place. Several examples of backscattering signals displayed along with incident and transmitted pulses are shown in FIGs. 9 and 10. For 500 μm diameter washer-type pinholes backscatter levels as high as 4% of incident power were observed; the signal appeared after the closure had taken place, i.e. after the transmitted intensity dropped. The temporal response indicated that the backscattering originated from interaction of the laser light with the plasma filling the aperture, with pulsations characteristic of stimulated Brillouin backscatter. No backscattering was observed from the 1 mm diameter washer-type pinholes (data not shown) which did not close during the 5 ns pulse duration. The total backscattered power occurring during these measurements may be much larger than the 4% observed since the backscatter diagnostic only collected the collimated energy propagating down the input beam; sidescattered energy was not collected by the diagnostic system.

The CH conical pinholes, which were observed to close late in the laser pulse than the equivalent washer-type pinholes, also produced a backscattering signal (FIG. 10B) similar to that
produced from the 500 μm diameter washer-type pinholes and consistent with a reflection from plasma filling the pinhole structure. In contrast, the Au conical pinholes produced a low backscatter level of less than 0.4% of peak power. No late time high backscattering signals were observed from these pinholes. In this case the backscattering signal peaked early in the pulse, then diminished rapidly, suggesting that the backscattering signal was caused by low level scattering from surface imperfections on the metal surface along the length of the cone; the signal decreased due to absorption, and possible smoothing effects produced by the cold plasma layer that formed on the surface. Destructive testing of a sample conical pinhole indicated that surface roughness features (grooves and scratches) up to 2 μm in size were observable. Further effort in fabrication techniques can improve this considerably.

Simulations and experiments have demonstrated successfully a strategy for reducing plasma generation in spatial filter pinholes for high energy lasers. The best results were obtained with high Z conical pinholes. The experimental results which examined low Z and high Z washer-type pinholes as well as low Z and high Z conical shaped pinholes confirmed the trends predicted from hydrodynamic simulations of the plasma generation process. The conical pinhole structure appears superior to the washer-type configuration, and was found to remain open longer. Conical pinhole structure can be optimized for future high energy laser systems.

FIG. 11 illustrates that electric fields can be used to accelerate the plasma out of the entrance and exit region. Electrodes 80, 82 in the shape of concentric rings are located respectively before and after the pinhole filter biased and are adapted to having a voltage difference relative to the pinhole impressed thereon to reduce plasma density in the region of light entering and exiting the pinhole.

As illustrated in FIG. 11, alignment is a critical issue. The pinhole must be aligned in x, y, z and θ so that the centerline of the exit pinhole is in the center of best focus and the pinhole is co-linear with the centerline of the laser beam. The angle θ may be aligned by machining a part 84 of the pinhole entrance at large radius with a reflecting plane normal to the centerline 21 in FIG. 2. The alignment laser produces symmetric fringes about this plane when observed with a telescope when θ (the angle between the centerline of the pinhole filter and the laser axis) is zero and the pinhole is concentric with the laser axis.

FIG. 12 diagrammatically illustrates that for large lens f#’s, the Rayleigh length may be long enough to segment the pinhole filter in azimuth into 4 plates, or 4 cylindrical sections 90, 91,
92, 93 tilted with angle of taper described for the solid pinhole above. The sections have non-overlapping positions along the laser propagation path. The advantage is that we avoid cylindrical convergence piling up plasma towards the centerline thus reducing the plasma density in the path of the laser.

Stimulated Brillouin backscattering can reflect light back through the laser chain and damage the laser. One way to reduce Brillouin scattering is a mixture of a high and low atomic number materials so that the light species damps ion acoustic waves of the heavy species. This has the problem that lower atomic weight plasmas ablate and expand faster and thus may not be useful, but we include it for consideration for possible future designs.

Low atomic weight liquids condensing on the filter ablate much more quickly than the high atomic weight solid substrate of the apertured body. Examples of low atomic weight substances are pump oil, water, decomposing plastic from insulators, machining oils, etc. A method to clean the pinhole is to heat the filter to high enough temperatures to evaporate the unwanted liquids as in a self cleaning oven. Tai Ho Tan of Los Alamos National Laboratory and others reduced this to practice several years ago by electrical heating. Another method to remove these substances is to use a medium power laser that defocused just for this purpose. Since the oils can accumulate to significant thicknesses in a few minutes, the cleaning needs to be done within a few minutes of the laser firing.

FIG. 13 illustrates the concept of using grazing incidence to reduce plasma formation by laser light can be extended to other applications. Laser fusion in a hohlraums 100 requires high intensity laser rays typically shown as 102, 103 to enter a small hole 104 in a hohlraum container that cannot close due to plasma formation during the pulse duration. Grazing incidence surfaces in the form of a truncated internal conical surface 106 on an outside surface and an external conical surface on a spaced apart cone 108 near the laser entrance hole 110 reduce plasma formation due to stray light hitting the edges of the hole.

The foregoing descriptions of specific embodiments of the present invention have been presented for purposes of illustration and description. They are not intended to be exhaustive or to limit the invention to the precise forms disclosed, and obviously many modifications and variations are possible in light of the above teaching. The embodiments were chosen and described in order to best explain the principles of the invention and its practical application, to thereby enable others skilled in the art to best utilize the invention and various embodiments with various modifications.
as are suited to the particular use contemplated. It is intended that the scope of the invention be defined by the Claims appended hereto and their equivalents.
IMPROVED SPATIAL FILTER FOR HIGH POWER LASERS

ABSTRACT OF THE DISCLOSURE

A new pinhole architecture incorporates features intended to reduce the rate of plasma generation in a spatial filter for high-energy laser pulse beams. An elongated pinhole aperture is provided in an apertured body for rejecting off-axis rays of the laser pulse beam. The internal surface of the elongated aperture has a diameter which progressively tapers from a larger entrance cross-sectional area at an inlet to a smaller output cross-sectional area at an outlet. The tapered internal surface causes off-axis rays to be refracted in a low density plasma layer that forms on the internal surface or specularly reflected at grazing incidence from the internal surface. Off-axis rays of the high-energy pulse beam are rejected by this design. The external surface of the apertured body adjacent to the larger entrance cross-sectional area at the inlet to the elongated aperture is angled obliquely with respect to the to direction of the path of the high-energy laser pulse beam to backscatter off-axis rays away from the high-energy pulse beam. The aperture is formed as a truncated cone or alternatively with a tapered square cross-section. The internal surface of the aperture is coated with an ablative material, preferably high-density material which can be deposited with an exploding wire.
FIG. 1

expanding plasma

transmitted ray

FIG. 2

transmitted ray

rejected ray
FIG. 4A

8 mm

0.9 mm

Laser

FIG. 4B

radial position (mm)

axial position (mm)

Log (electron density/cm^3)
FIG. 6A
FIG. 6B

![Graph showing energy intensity versus coordinate (μm)]

FIG. 6C

![Graph showing energy fraction contained within r versus radius (μm)]
FIG. 9A

Incident/Transmitted power (arbitrary units)

Backscatter power (GW)

Time (ns)

FIG. 9B

Incident/Transmitted power (arbitrary units)

Backscatter power (GW)

Time (ns)
FIG. 10A

FIG. 10B