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An improved pinhole spatial filter

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Lasers generate phase aberrated light that can damage laser glass, frequency conversion crystals, lenses and mirror coatings and can also reduce extractable energy and power. Spatial pinhole filters can partly eliminate such "hot spots." Problems are that the pinhole closes during the laser pulse and has to be made too large initially to avoid being too small at the end of the pulse. Debris from the pinholecan coat or damage spatial filter lenses. This paper presents a novel design for a more robust pinhole filter. Phase distorted (hot spot) light refracts at grazing incidence by plasma on the wall of a funnel shaped filter resulting in less absorption and debris. Refracted light absorbs at low intensities on the vacuum wall. We present two dimensional hydrodynamic computer simulations compare the two types of filters with experimental comparison.

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Introduction

In solid state laser systems, high intensity spots can damage laser glass, frequency conversion crystals, lenses and mirror coatings, and reduce the extractable energy and power. [1] Focused on the target, [2] hot spots can drive numerous plasma instabilities [3] (thermal filamentation, ponderomotive filamentation, Raman, Brillouin, resonant absorption, magnetic fields etc.) which increase hot electron production, reduce electron heat transport and x ray conversion. Hot spots hamper symmetry requirements. [4]

A common method to reduce the laser hot spots is a spatial pinhole filter (Fig.1). Laser light focuses on such filters at several points in the laser chain. [1] Hot spot light has phaseaberrations which do not focus well enough to go through the pinhole and consequently stop on the solid part of the filter.

Figure 1 shows a problem with presently used spatial pinhole filters. The off angle laser light (the hot spot light) hits the edge of the pinhole and ablates a plume of plasma which rapidly fills in the hole to block further light energy transmission through the pinhole.[1,5] To avoid this, the pinhole radius must be made excessively large to remain transmitting during the laser pulse duration. This increased hole diameter reduces the effectiveness of the spatial filter in reducing hot spots.

The new filter

An inexpensive modification of the spatial filter allows the aperture to remain clear longer permitting smaller holes resulting in reduced hot spots and a longer duration of energy transmission. Unwanted, hot spot light is refracted rather than absorbed in a conical shaped filter. Cone filters help make an out of focus beam more uniform as random phase plates [6] and make the focus smaller.

Figure 2 shows the pinhole geometry for reduced pinhole closure time. The phase distorted (poorly focused) light strikes the ablating funnel plasma at grazing incidence and is therefore only slightly absorbed. It is mostly refracted through the hole beyond the acceptance angle of the far lens to be harmlessly stopped at low intensities on the vacuum chamber wall. The intensities in the hole can easily be 10^17 W/cm^2 because of the focus, but is reduced by many orders of magnitude on the large wall area where it is absorbed. Irradiances below about 10^9 W/cm^2 do not form a plasma in the time scales of interest.

Refraction at low density

In the filter, the maximum electron density, n, reached by a ray is cos^2(alpha)nc where alpha is the angle between the ray in vacuum and the plasma density gradient. Here nc is the critical density where the laser light frequency equals the local electron plasma frequency. For example, if the angle of incidence is 87 degrees, then the turning point density is 0.003 nc. For 1.05 micron light, electron temperature, Te,=100 eV, ionization state zbar=3.5 (plastic), the IB absorption length is 75 cm at the maximum density of 0.003nc. Since the ray path is mostly through densities much smaller than 0.003, the actual inverse bremsstrahlung (IB) absorption length is much longer than 75 cm.

A high f number lens is best since the IB absorption is proportional to (n/nc)^2 ~ cos^4(alpha) ~ 1/(f#)^4 and a high f# makes less intensity on the periphery of focus.

Tradeoffs

A comparison between the old filter and the conical filter are as follows. In the old filters, all the laser light hitting the pinhole absorbs. Small pinholes close too quickly, are damaged and are less effective for the next laser shot. In the conical filters much less plasma is produced because absorption is small. One drawback of the conical filter is that the smaller the pinhole, the more accurately it must be aligned. Typically the angular tolerance is 1/10 the angle of the lens.

Brillouin and Raman backscattering can scatter light in the funnel, but are ineffective at densities less than .01 critical. By the time the density is greater than .001 critical, typical perpendicular density gradients already distort light phase fronts. Brillouin and refraction are a proven problem in existing filters. Raman near forward scattering is a potential problem in either filter even at densities < .001 critical.

Pinhole close time

An overly simplistic but easily diagnosed criterion for pinhole closure is light refraction beyond the acceptance angle of an f/20 lens (0.025 radians half angle). The plasma does not need to be over dense to close the pinhole since the light is lost if the rays refract enough to miss the opposite collection lens. The angle of refraction is 0.5[d(n/nc)/dy]dx radians where dy is in the direction perpendicular to the ray and dx is the distance in the refraction region. Densities of only 0.01 critical (10^19 cm^-3 for 1.05 micron light) and typical gradients are sufficient to refract the light enough to miss the collection lens.

High Z funnel filters stay open about twice as long in LASNEX than CH filters, but Janus experiments by P.Celliers didn't show as much difference but still improvement with gold over CH. Probably the reason is low z gases condensing on the high z filters. Experiments by Ti Ho Tan at Los Alamos using a mass spectrometer showed protons only went away when the beam focused inside a helix of a white hot light bulb filament. P.Celliers found that 100 degrees centigrade did not reduce closing of a high z funnel filter. The optimum temperature is probably less than white hot and greater than 100 degrees centigrade. Alternatively, the pinhole might be cleaned by a rod shot with a diverging lens in front of the filter. Just 3 Joules would clean a circle of radius of 1 cm in a .1 ns pulse.

Isolation by filters

Simulations show that the old style filters tend to stay closed for microseconds and thus isolate the laser chain from light reflected back from the target. The funnel filters probably act similarly although have not been tested and will require more energy at the same opening diameter.

History

Conical pinholes in the form of diamond dies for drawing wire have been tried experimentally[7], but were quite short (2mm) along the axis of the cone. The laser light still hit the pinhole edge at near perpendicular incidence and thus quickly filled with plasma. Cones in the form of metal springs or wires have the same problem. The cross section is a staircase shape and so the angle between the spring and the light is near normal and so the light absorbs rather than refracts. It is important for the funnel to be continuous and for the inside edge to be straight and very smooth. A partial funnel followed by a space to an old style pinhole is not sufficient because, again, the light will strike the pinhole at near normal incidence.

Fabrication requirements

Fabrication of the pinhole funnel requires a very smooth surface finish on the inside since microscopic roughness will cause excessive absorption due to the large angles of incidence on the rough features and non-grazing angles will reflect the light to the other side of the pinhole at higher angles of incidence where it is more likely to be absorbed.

The pinhole funnel will have an angle between angle as the lens and a few times the angle of the lens. For large f numbers, the angle can be larger making a shorter filter. A flared geometry like a trumpet has the problem of reflecting light to the other side where it will be more likely to be absorbed.

The length of the funnel involves some trade offs. As light bounces from one side to another, the angle steepens each bounce. Suppose the light of the first bounce comes from the opposite side of the lens so that the angle is 2 theta where theta is arctan(1/(2 f#)) where f# is the focal length divided by the lens diameter. The angle between the ray and the funnel surface is 2n theta where n is the bounce number. The z distance between bounces becomes shorter rapidly with the number of bounces. A ray trace computer program is available from KGE to quantify the funnel length when ray is likely to absorb as a function of f#. LASNEX simulations show that the funnel should be designed so that without plasma the first bounce is after the exit hole because when the plasma forms in the pinhole entrance it will refract light into the exit pinhole and is the primary mechanism for plasma formation at exit.

Another issue is plasma expansion time to close the front opening. The closing time is roughly the distance between the pinhole edge and the light radius of interest divided by about 3 times the sound speed. This speed depends on the electron temperature, ionization state and hence the absorbed intensity. Some light will still hit the front of the funnel filter and should be simulated with measured intensity vs radius.

Simulations

LASNEX, with laser ray trace, models the refraction and plasma blow off. Figures 3-5 illustrate two dimensional pre-shot LASNEX runs with old and new gold pinhole filters for Janus. In each case, 250 Joules was incident with a FWHM of 0.013 cm spot over 10 nsec with intensity vs radius approximately the same as Janus. The experiment only used half that many Joules however. The diameter of both filters was also 0.052 cm so that 35% of the light was intercepted by the filter (a severe test). By the criterion described below, the old filter closed by ~ 1ns (Fig.3). The conical filter is still open by 1 ns on both ends (Figs.4,5).

Experiments

Peter Celliers streaked the output light from pinhole and washer filters (Fig.6) on the Janus laser where 35% of the beam was intercepted by the 500 micron diameter pinholes (Figs.7,8). This was a rigorous test: Beamlet and NIF pinholes intercept only 2%. LASNEX simulations (Figs.1-3) showed that conical pinholes stayed open >2 times longer than washers. There are several criteria for closure. If we define closure as that time when the image on the collecting lens departs from no pinhole, then we have the arrows on Fig.9. Other experimental streaks are Figs. 10-12. Note that the light on the collecting lens converges towards the center in time as shown by the rays in the simulations (Figs. 3-5) as refraction bends the light towards lower density. Figs. 13,14 describe Brillouin and specular backscattering measurements of < 4%.

Beamlet

Beamlet simulations at 3 ns for Macor ($K_2Mg_6Al_2Si_6O_2F_4$) show closure, whereas the same irradiance on a CH funnel filter (Fig.10) is still marginally open. A re-tune of this filter stayed open ~ 20% longer.

Conclusion

A funnel shaped spatial pinhole filter has a longer closing time than previous washer filters. Grazing incidence between the laser light and the filter allows only a small amount of laser energy to be absorbed hence allowing longer open times and smaller pinholes.

Acknowledgements

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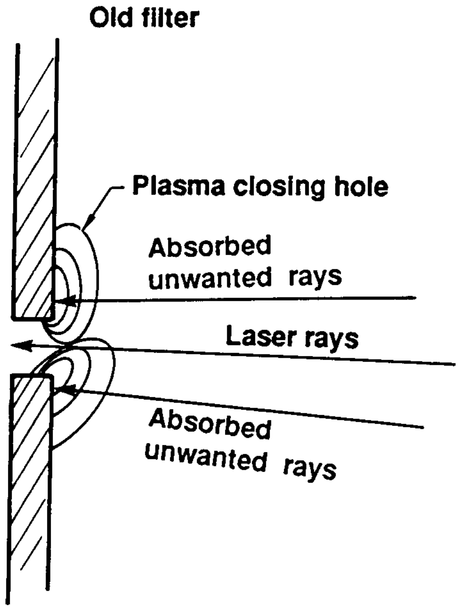
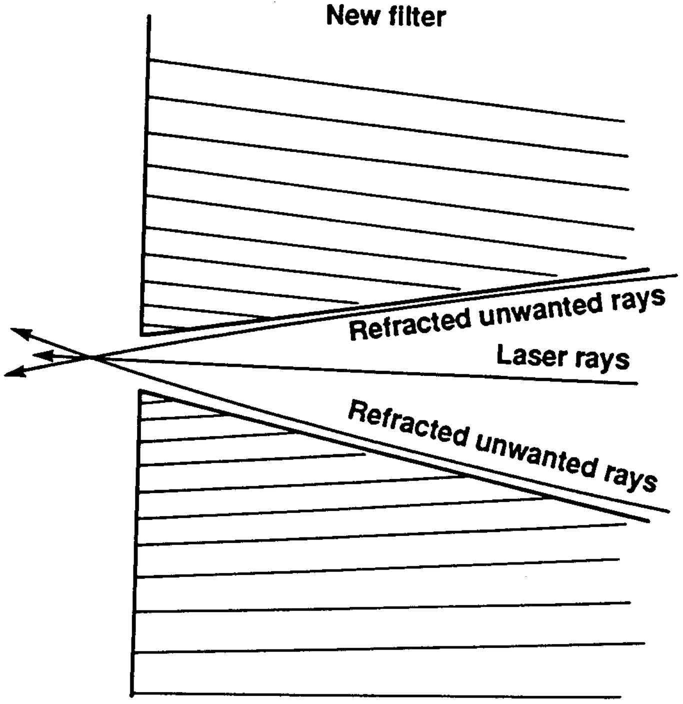


Estabrook
Fig. 1



Estabrook
Fig. 2

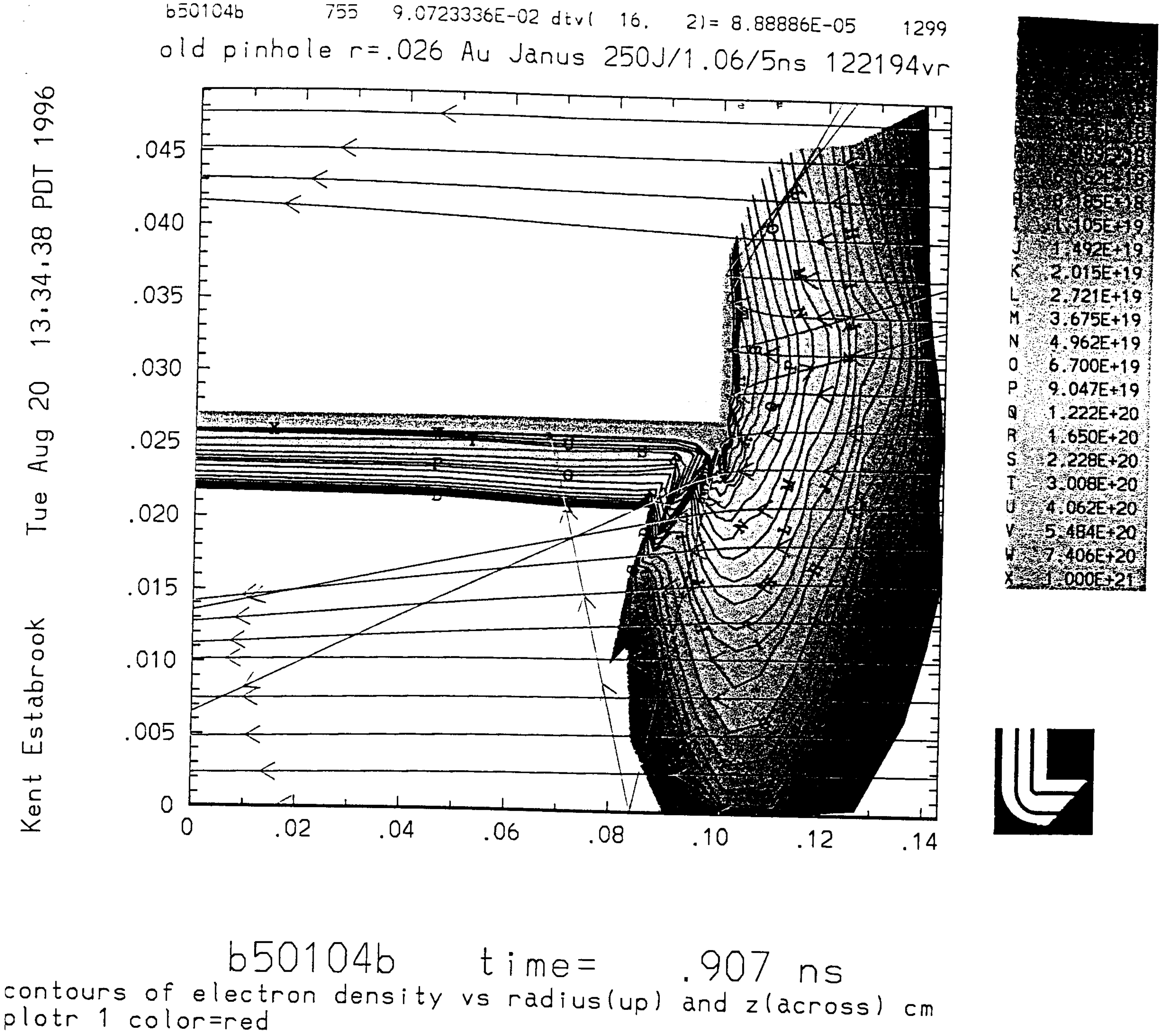


Fig. 3 LASNEX simulation of washer pinhole. The red rays are the laser's 1.06 micron light incident from the right to the left. The filter still transmits and the density is too low for serious Raman and Brillouin backscattering, but beam distortion is enough to degrate beam to possibly damaging downstream optics or miss target.

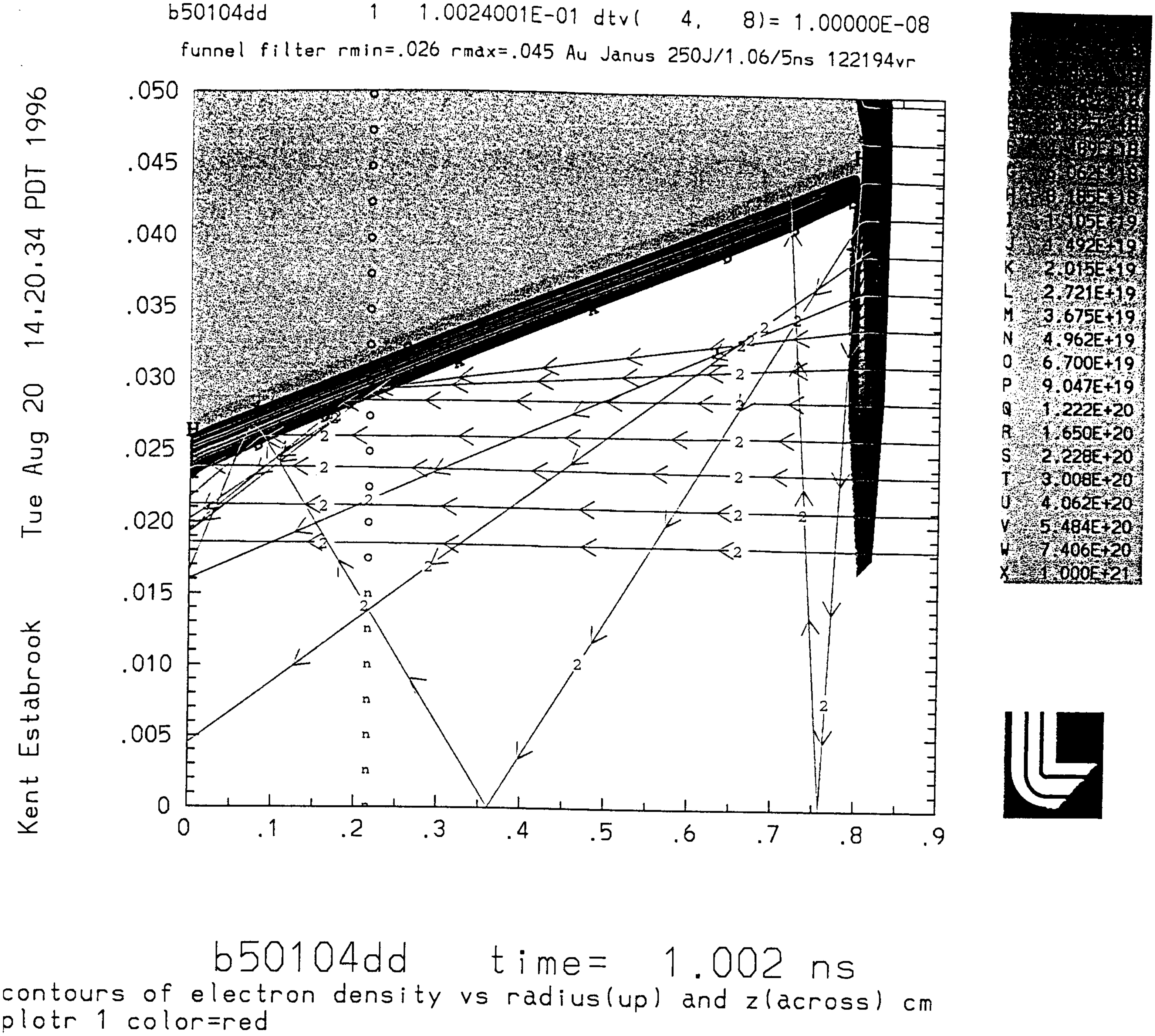


Fig. 4 Funnel filter with same irradiance still open at 1 ns.

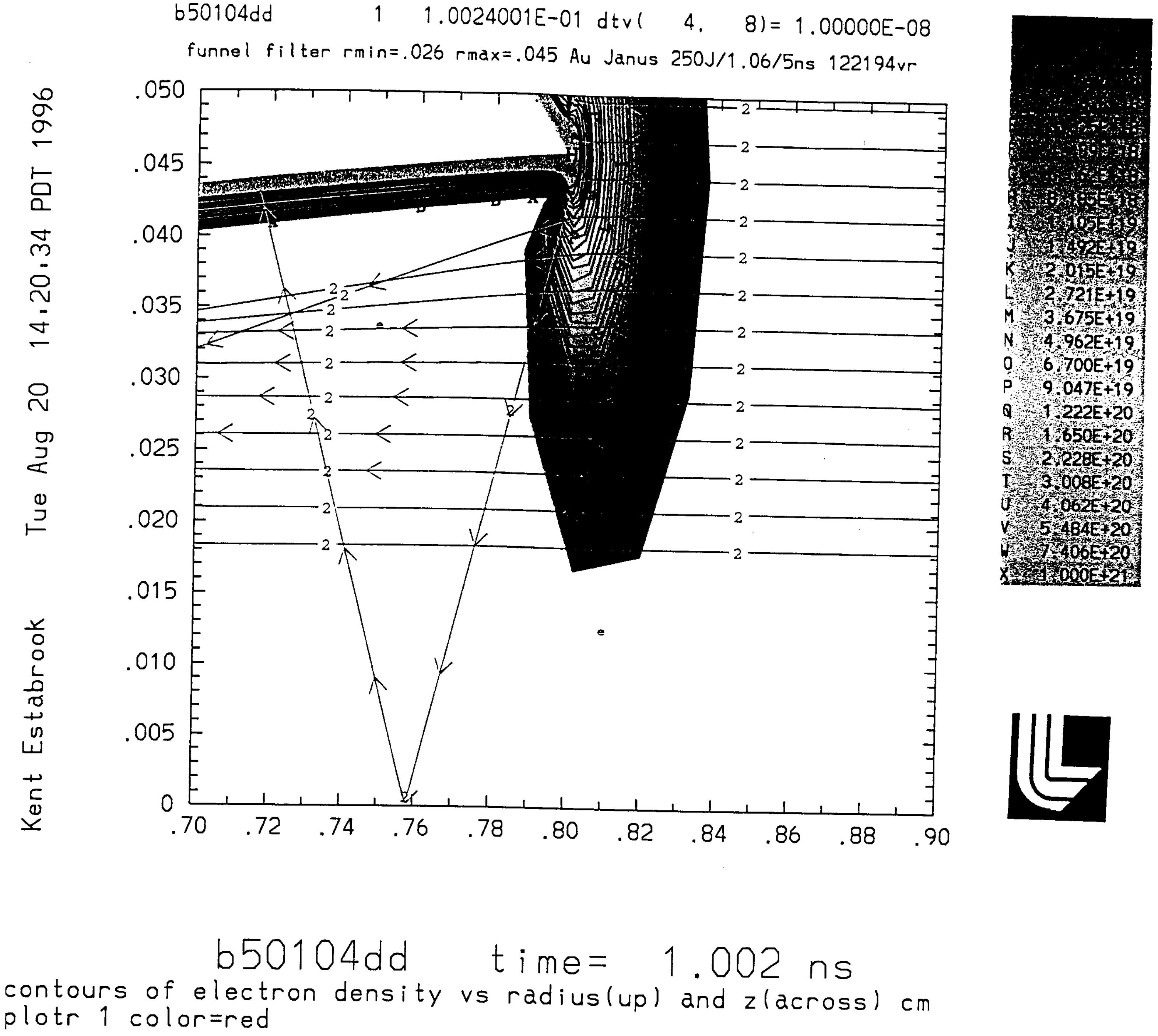
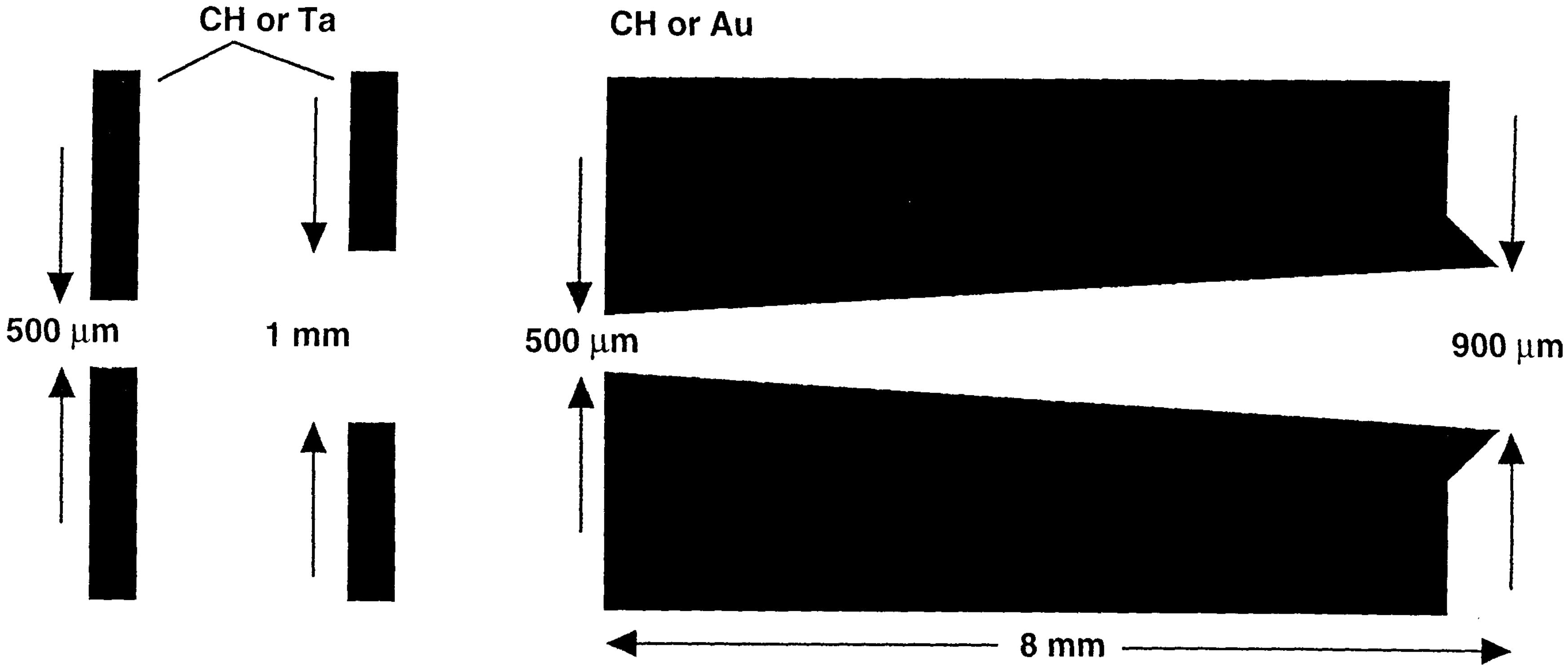


Fig. 5 Enlargement of Fig. 4 near entrance to funnel filter.

Pinholes tested

- 500 μm and 1 mm diameter washer-type pinholes fabricated from 1 mm thick Ta and 1 mm thick polystyrene (CH) slabs
- conical pinhole with 900 μm dia. entrance aperture and 500 μm dia. exit aperture spanning a conical surface of 8 mm length; conical pinholes were fabricated from CH and from gold*

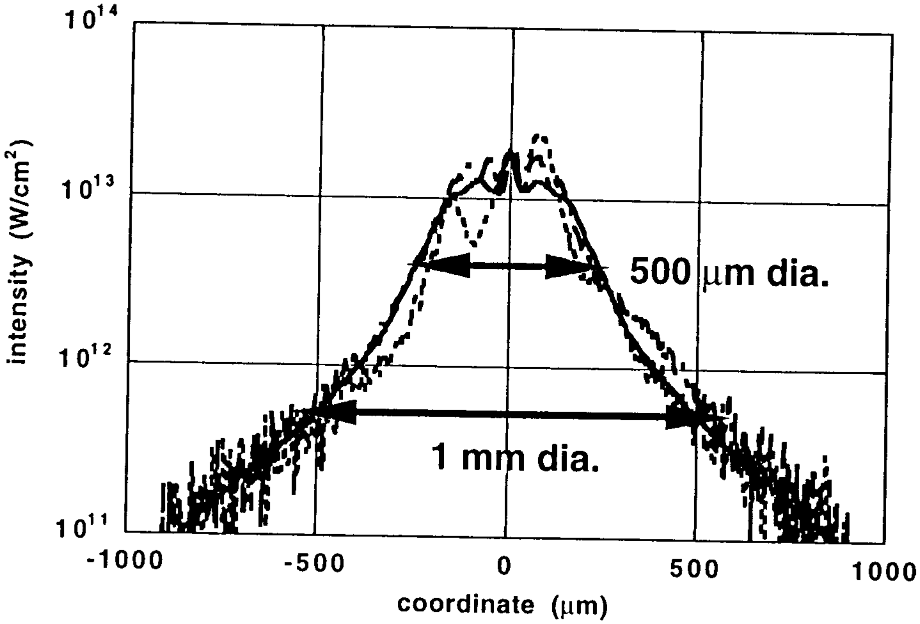


* Angular alignment (pointing) of the cone axis was accomplished accurately by observing the diffraction pattern produced with a collimated HeNe illuminating the cone and adjusting to give a symmetrical arrangement of diffraction rings

FIG. 6

Pinholes were loaded severely

- Only 65% of beam energy was contained within a 500 μm diameter circle: the 500 μm diameter pinholes intercepted approximately 35% of the beam energy
- 1 mm diameter pinholes intercepted approximately 10% of the beam energy at much lower fluences
- peripheral loading on 500 μm diameter pinholes exceeded 5 x 10^{12} W/cm^2
- peripheral loading on 1 mm diameter pinholes was well below 10^{12} W/cm^2



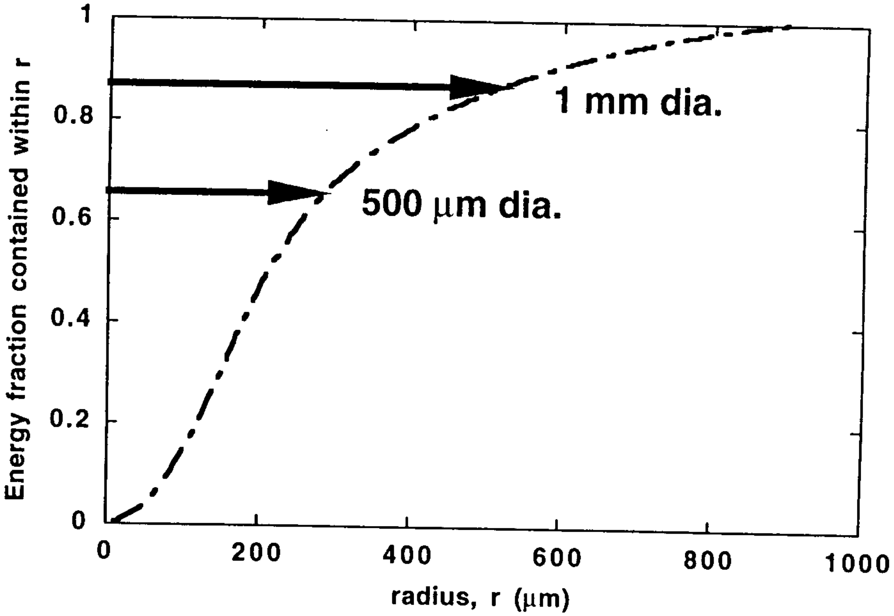


Fig. 7

Characterization of the far field intensity profile (loading on the pinhole)

- CCD readout provided about 3 decades of dynamic range
- The beam intensity was measured accurately out to 2 mm diameter and below 10^{11} W/cm^2 on every shot

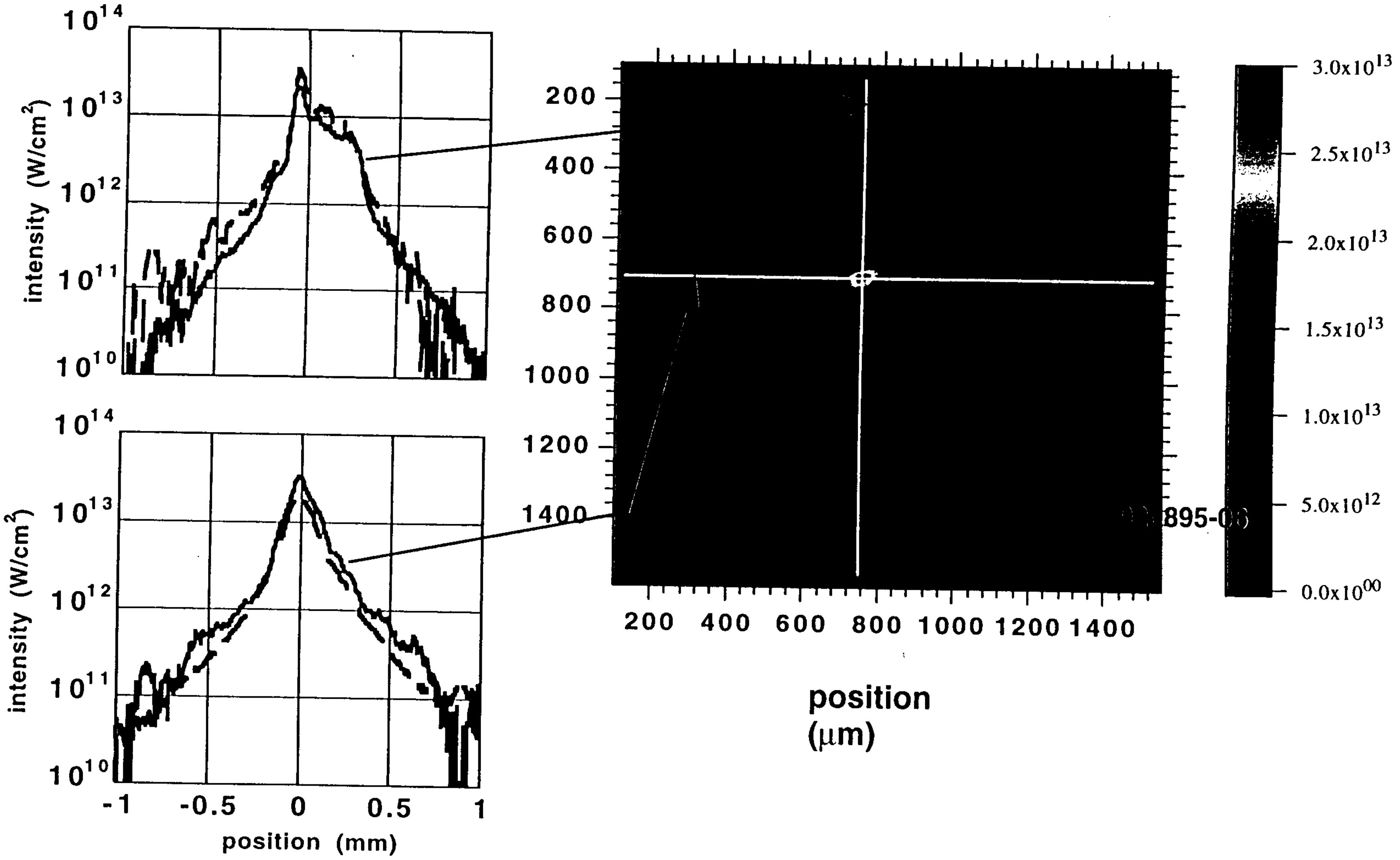
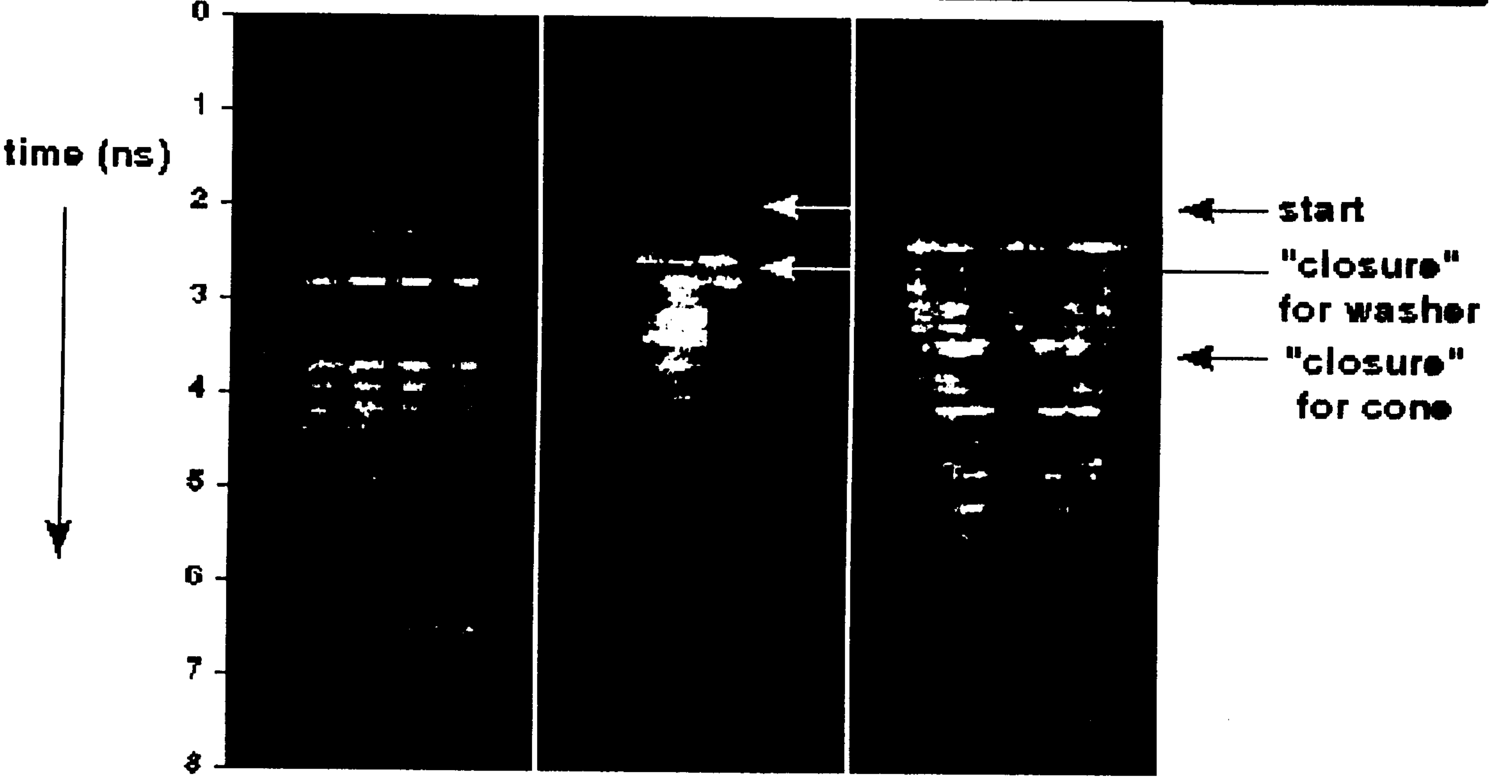


Fig. 8

Celliers' measurements show that the cone pinhole stays open at least 2x longer than a washer pinhole



start

"closure" for washer

"closure" for cone

no pinhole

500 µm Ta washer

900/500 µm Au cone

Fig. 9

Streaks of the output near field reveal strong beam refraction before pinhole closure occurs

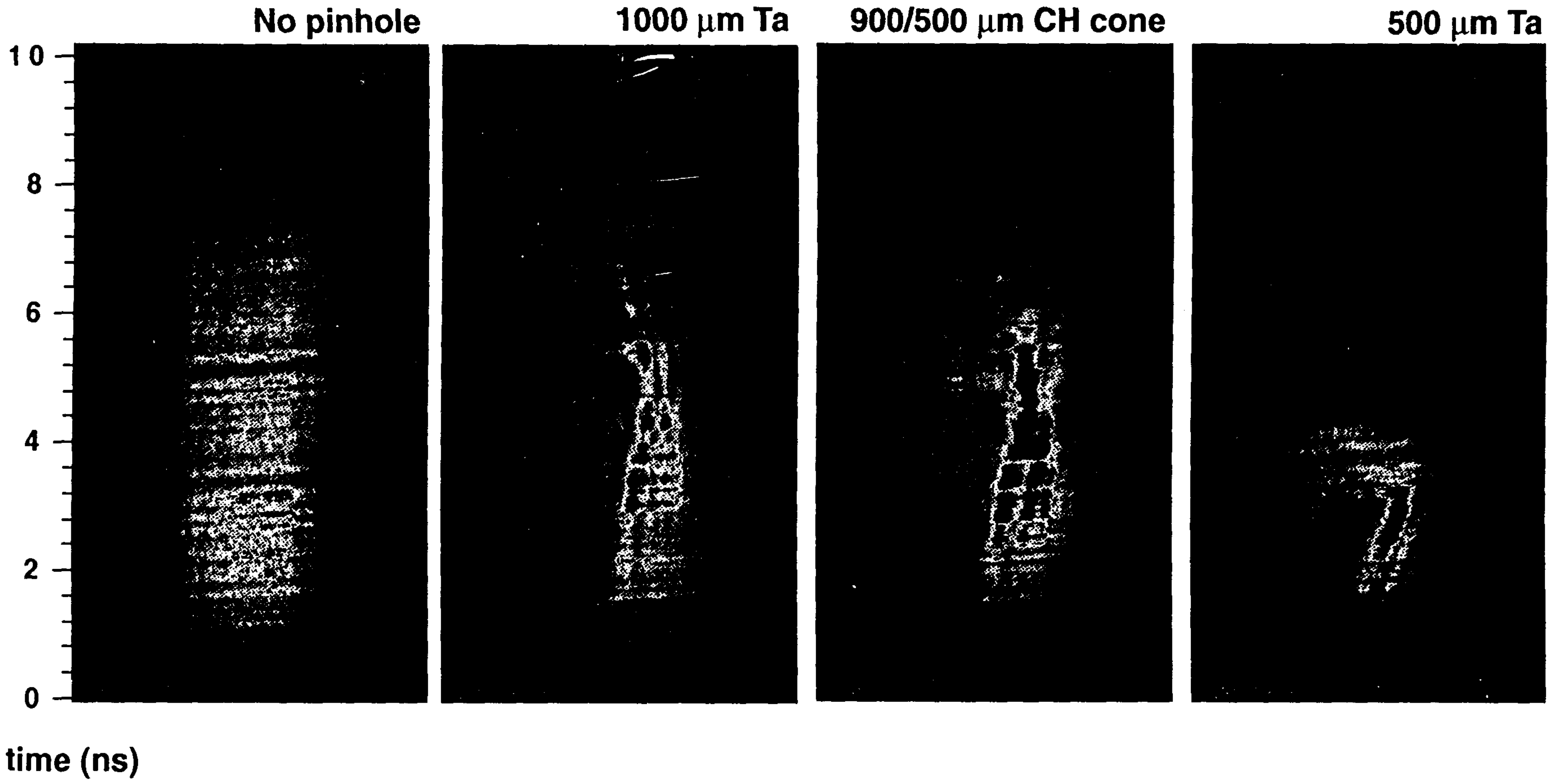
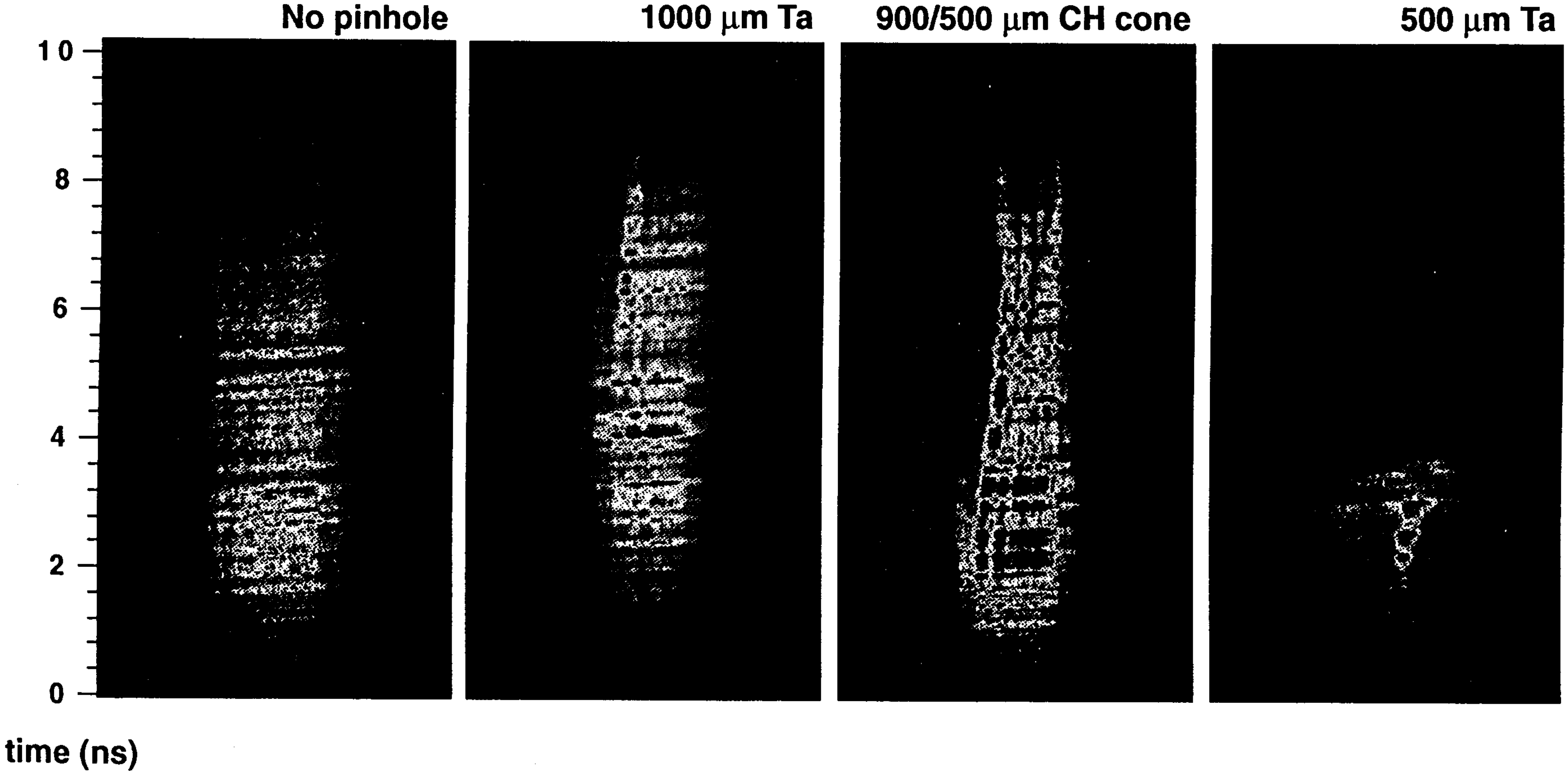


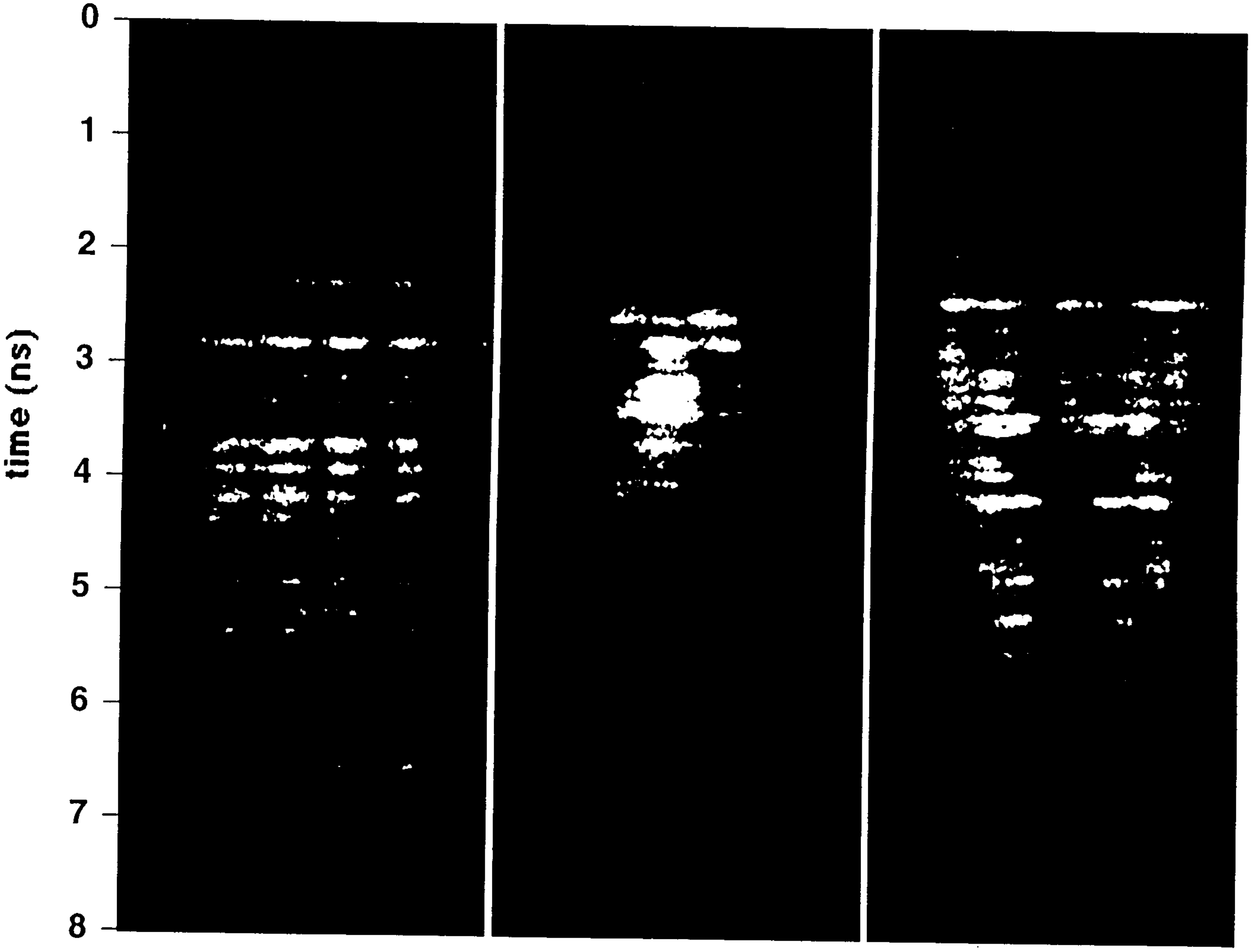
FiG. 10

Conical pinhole design remains open significantly longer than an equivalent diameter disk pinhole



High Z conical pinholes remain open significantly longer than equivalent diameter washer-type pinholes

- Streaks of output lens of the spatial filter (near field beam profile)



no pinhole

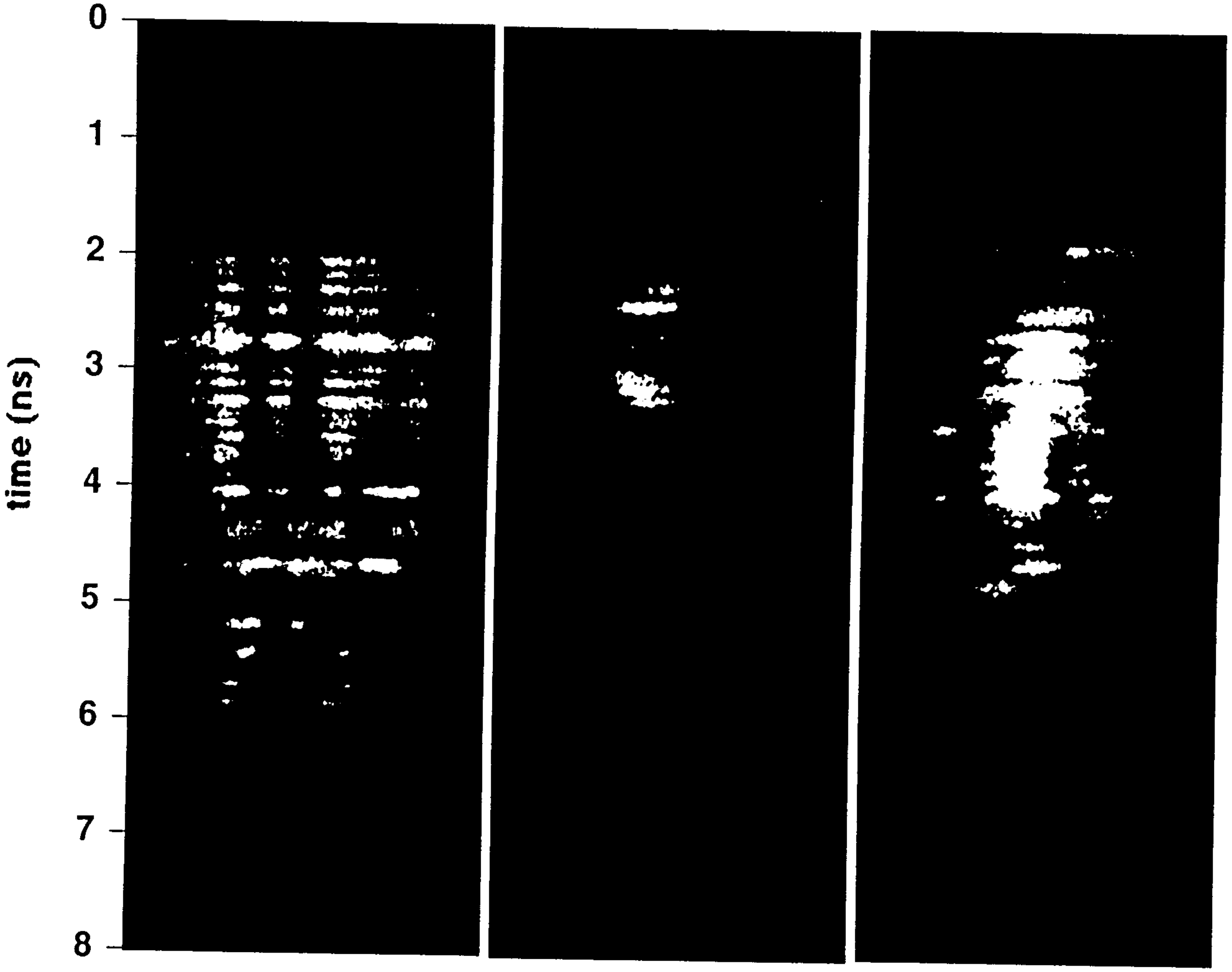
500 μm Ta washer

500/900 μm Au cone

Fig. 11

Low Z pinholes display faster plasma filling of the pinhole aperture

- Streaked spatial profiles vary with time indicating plasma refraction of the transmitted beam



1 mm CH washer

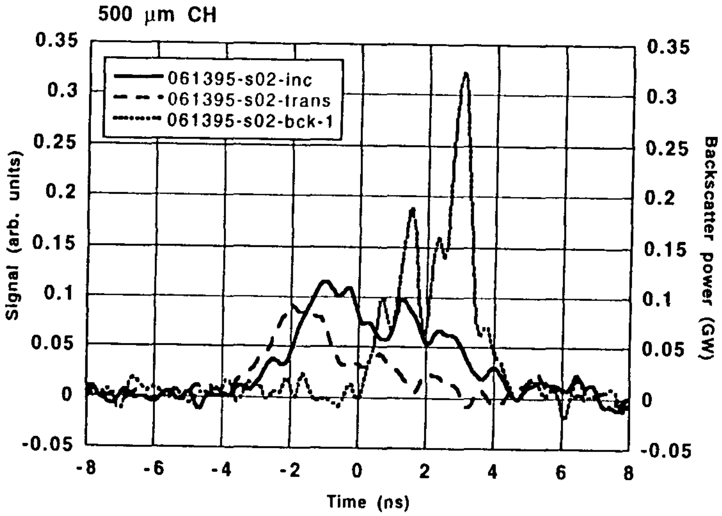
500 μm CH washer

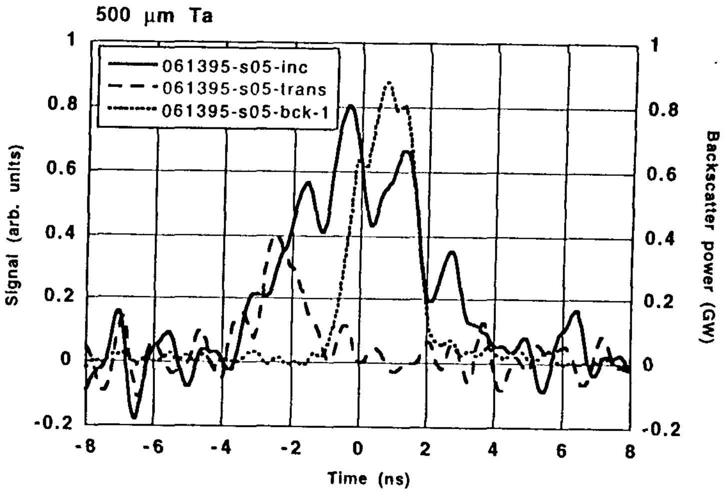
500/900 μm CH cone

FIG. 12

Significant backscatter was observed from 500 µm diameter washer pinholes

- closure occurs in approximately 2 ns
- backscatter powers up to 1 GW - approx. 3 - 4% of peak power

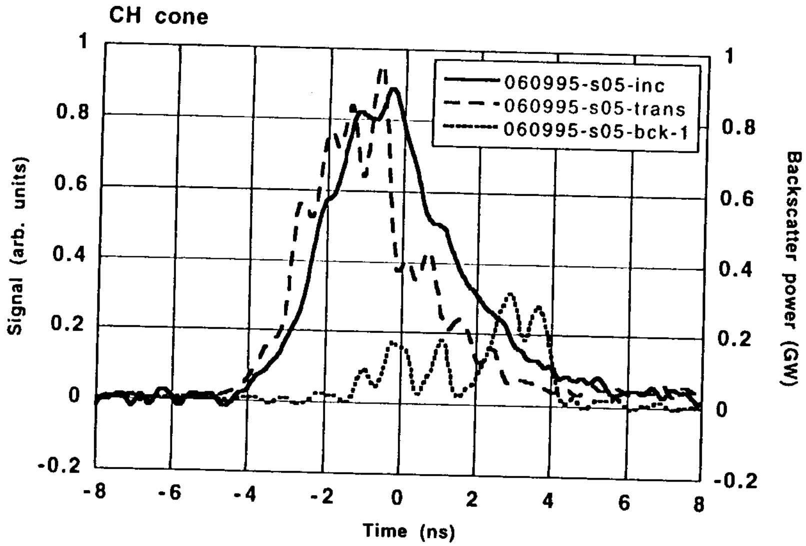


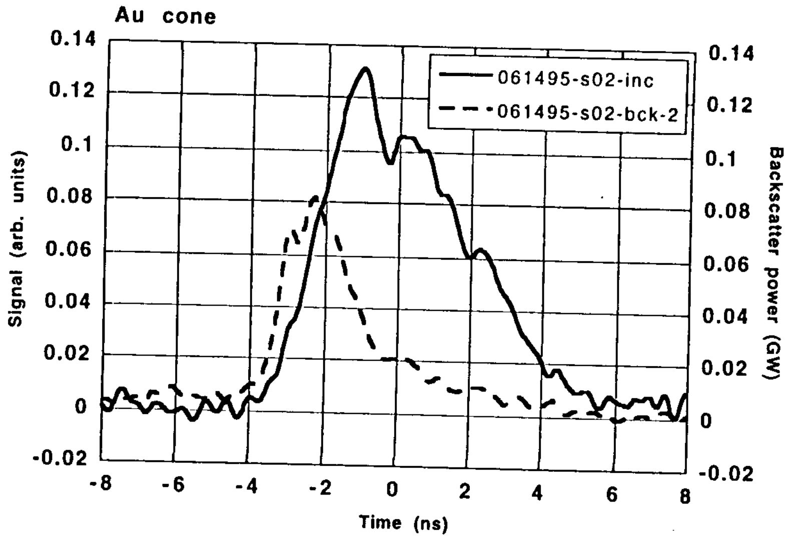


Fi 6.

Backscatter levels from conical pinholes

- **CH cones:**
  - Closure occurs during pulse
  - Backscatter from plasma similar to small diameter washer-type pinholes; power levels up to 1% of average power
- **Au cones:**
  - No closure
  - Backscatter appears to be mainly specular, and diminishes towards the end of the pulse - 0.04 - 0.08 GW => 0.1-0.3% of peak power





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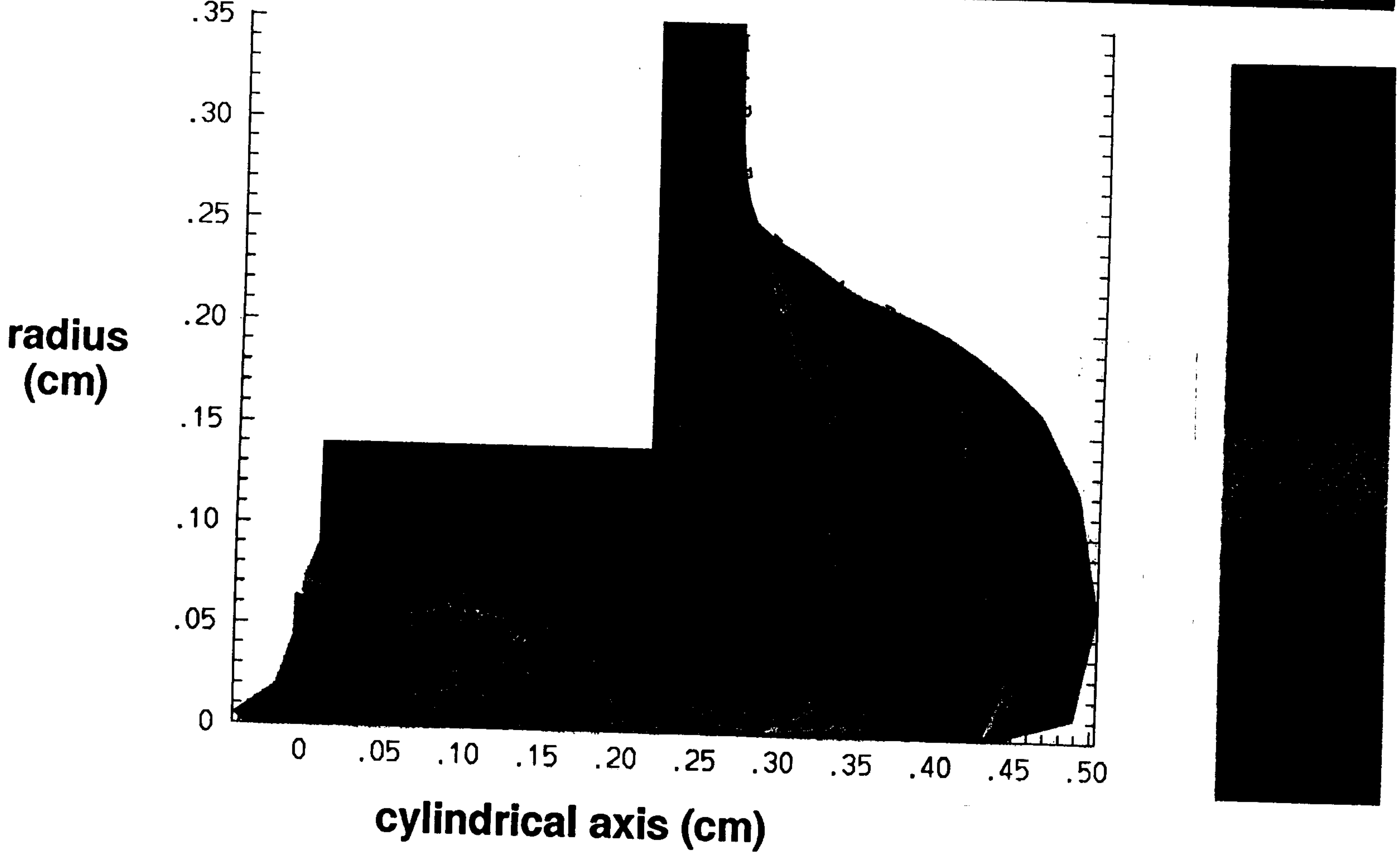
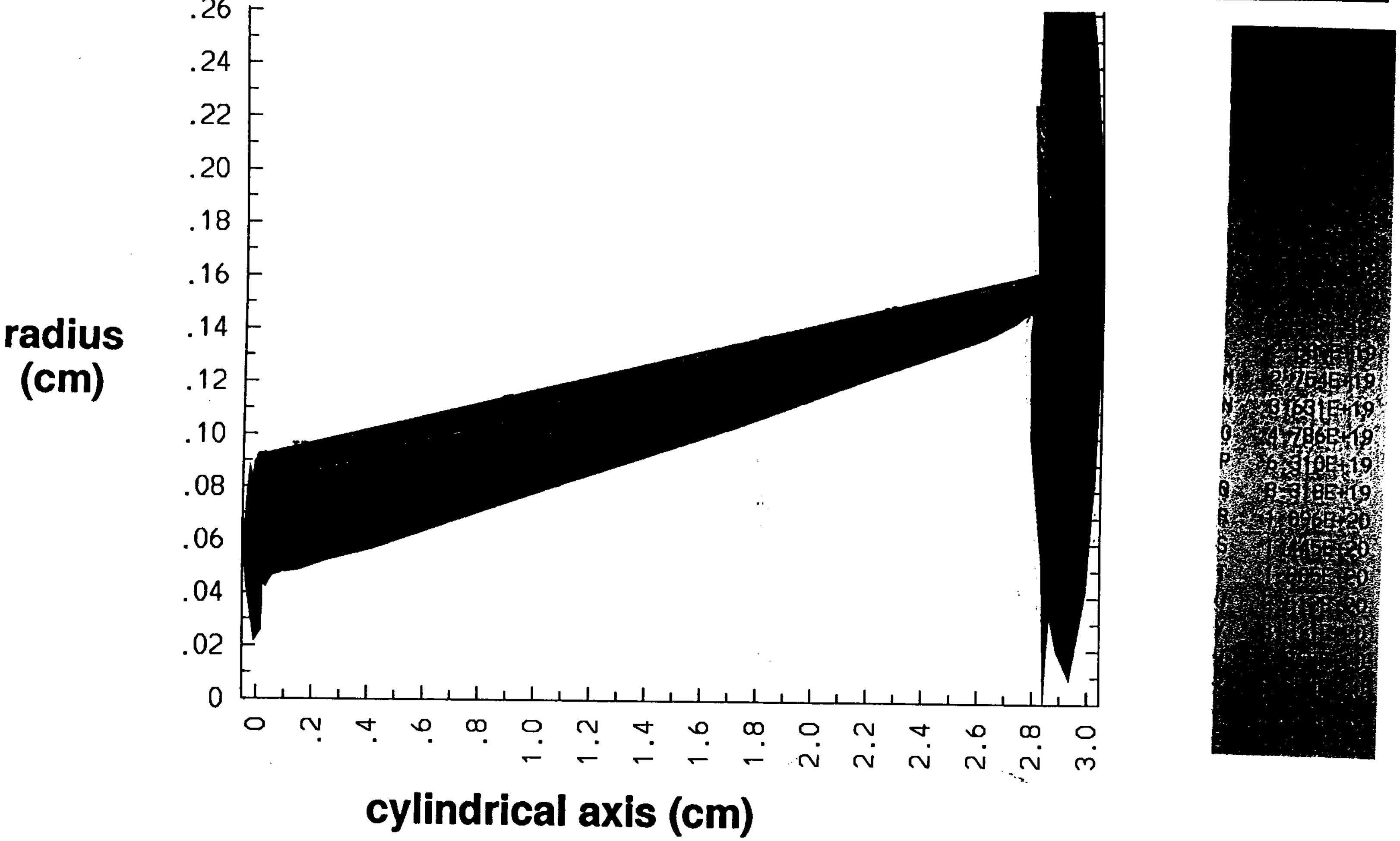
LASNEX shows that a ±100 μrad washer pinhole made of Macor in the Beamlet TSF distorts the beam well before 3 ns



nif\pinholes\tls4-8a

FIG 15

The same LASNEX calculation for a ±100 μrad cone pinhole made of CH shows much less ablation at 3 ns



- Calculated pinholes stay open longer for high-Z materials.
- Square pinholes should further reduce intensity at the pinhole edge.

nif\pinholes\tls4-8b

Fig. 16

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