Beam Port Reduction Schemes for Laser Fusion Reactors

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Beam Port Reduction Scheme
for a Laser Fusion Reactor

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Abstract

A device is described which reduces and recollimates a laser beam in order to minimize the penetration of a neutron shield in a laser fusion reactor. Reflective optics are used throughout to allow operation in high neutron fluxes. Fraunhofer diffraction is calculated at a line focus for both a square and a circular aperture. The results show that evacuation is required in either case to handle the very large focal irradiances that occur under reactor conditions.

I. Introduction

An inherent difficulty in designing a laser fusion reactor is the excessive neutron leakage through the large optical apertures in the reactor cavity. For example, in the SOLASE design[1] over 10^4 cm^2 of aperture area is required to keep the 1 MJ, 1 nsec laser pulses from damaging the mirrors. Neutronics calculations reveal very high radiation levels ($\sim 10^6$ Rem/hr) even after two reflections back through the optical train.[2] Ample amounts of shielding have failed to substantially reduce these levels. One approach to this problem entails locating the final mirrors a large distance (50-100 m) from the target.[3] However, this scheme poses difficult alignment problems.[4] In another design study,[5] annular beams are reflected via toric optics, a central reflector effectively plugging the aperture.

In this paper we propose a beam port reduction scheme employing a pair of parabolic reflectors to condense and recollimate an initially collimated beam. A pair of off-axis paraboloids reduces the wall penetration to a small circular hole, as sketched in Fig. 1, while a pair of parabolic cylinders gives a line focus and a slot penetration, as depicted in Fig. 2. Either of these configurations would dramatically reduce the neutron leakage out of the primary containment volume. The point focus arrangement arose in fusion design meetings at Wisconsin[2] and also independently at Livermore.[3] The line focus scheme was recently proposed by M. Monsler as a means of avoiding gas breakdown. The present study is much more quantitative and differs in several important respects from the design described in Ref. 3.

Most laser fusion reactor designs involve a low pressure (0.1 - 1.0 torr) gas either in the form of lithium vapor[6] or a buffer gas such as neon or xenon.[7] As is well-known, gas breakdown will occur in the presence of high intensity laser radiation.[8] To this end we have calculated the irradiance in the focal

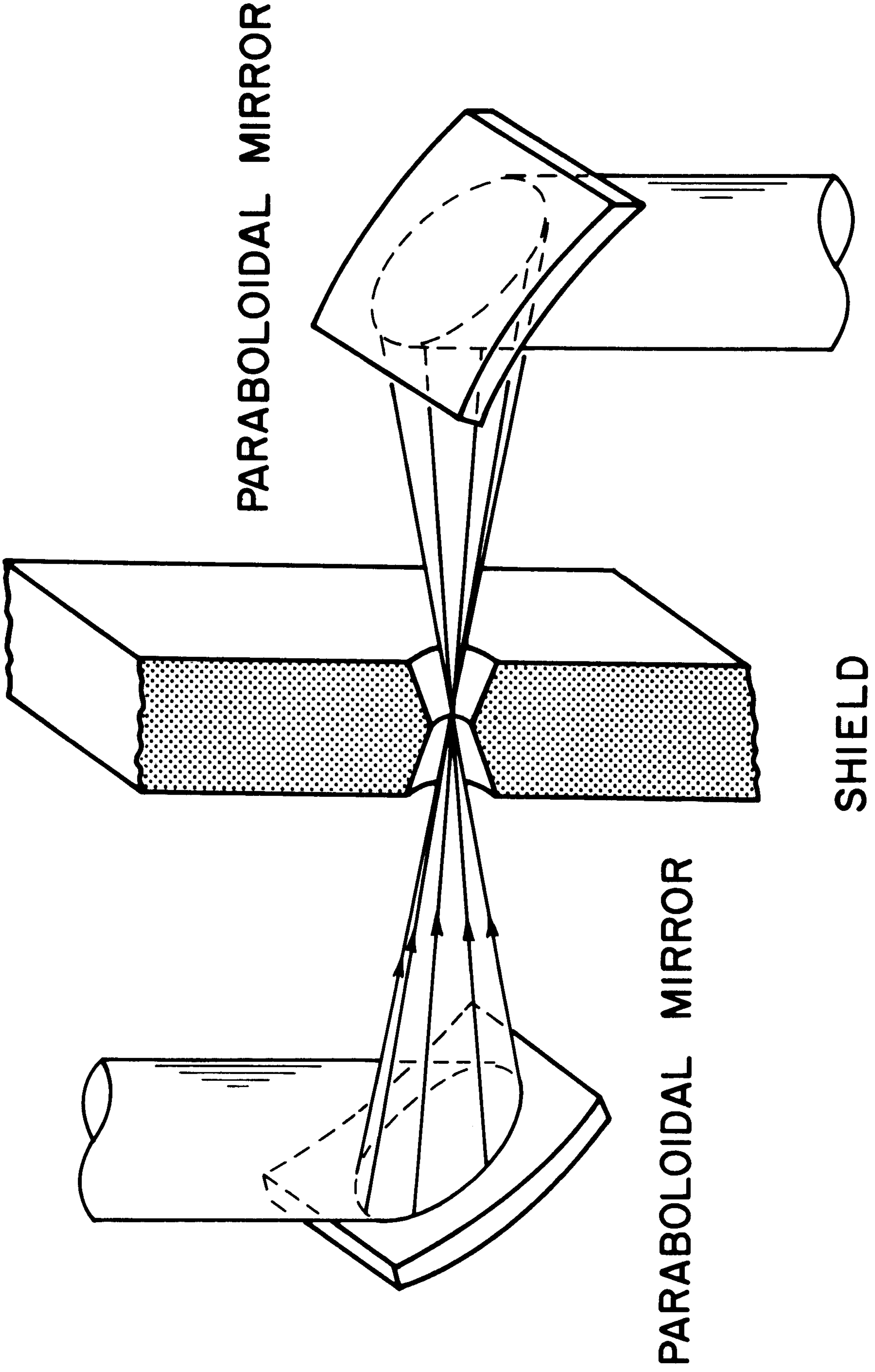

Figure 1

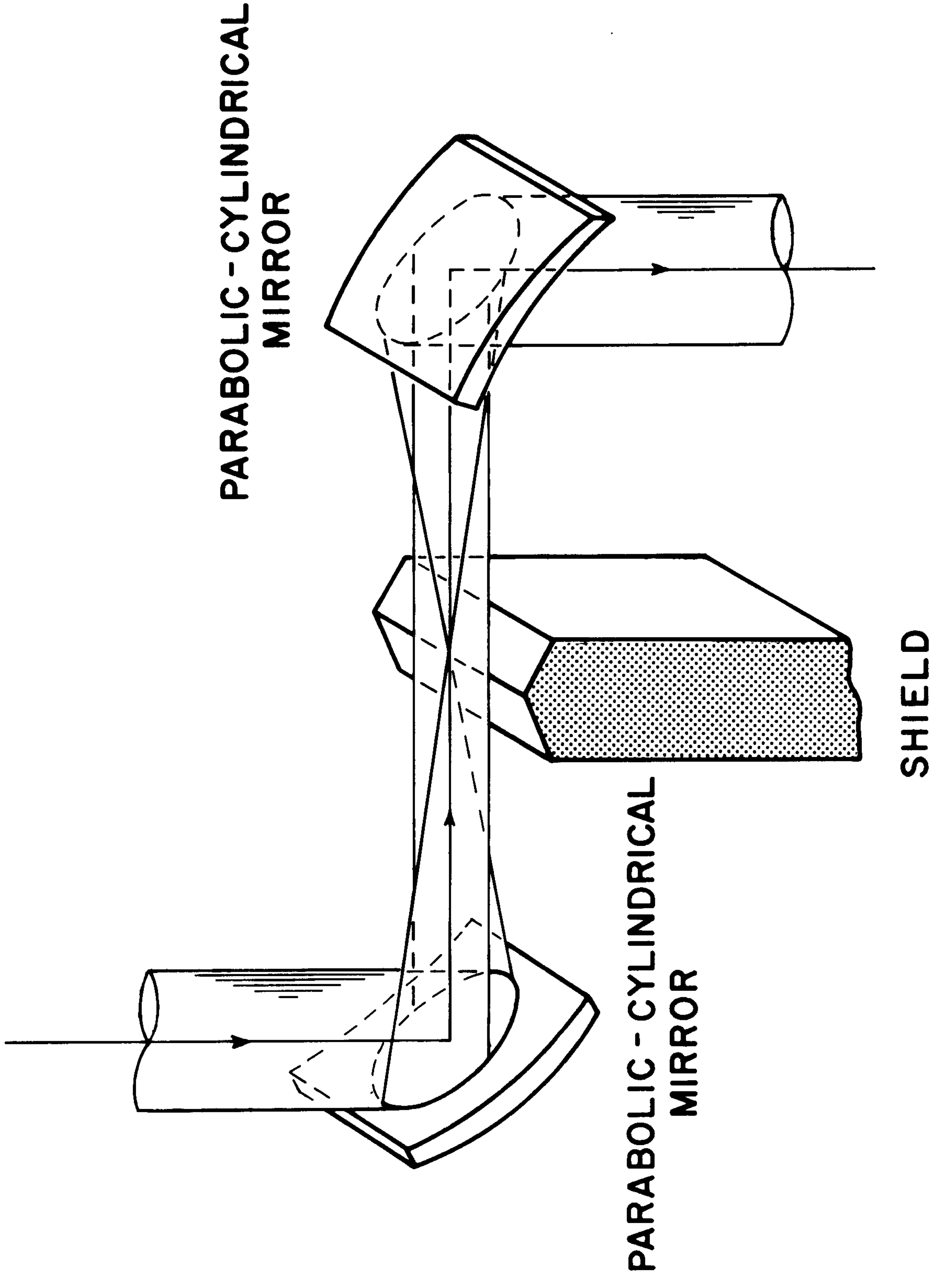
PARABOLIC-CYLINDRICAL MIRROR
SHIELD
PARABOLIC-CYLINDRICAL MIRROR

Figure 2

plane of a circular and a cylindrical focusing element using Fraunhofer diffraction theory. The resulting formulas are applied to a square aperture typical of an HF laser and reflecting our emerging fusion-fission hybrid design, and also to the more familiar case of a circular beam. Although the very high irradiance at a point focus is substantially reduced by going to a line focus, the peak irradiance is still large enough to cause gas breakdown at pressures on the order of one torr of neon or xenon.

Thus, using cylindrical mirrors doesn't really alleviate the breakdown problem and it is necessary to pump down the focal region to a low enough pressure that negligible refraction[9] and stimulated Raman scattering[10] occur. To accomplish this, it is desirable to enclose the mirrors in a vacuum chamber and install quartz windows (in the case of HF) to admit the beams. Following the example of the spatial filters installed in the SHIVA laser chains,[11] we estimate that a pressure of 10^{-5} torr would more than suffice.

Since evacuation is required in either case, one may ask whether a line focus is preferable to a point focus. It may turn out to be more difficult to align two mirrors at a common focal line than at a "point." One clear advantage is cost; cylindrical mirrors are cheaper to make than paraboloids. On the other hand, if it is desired to run the device as a spatial filter, a point focus would be appropriate. We elect to leave this option open, as it doesn't affect the basic features of our design.

We also consider briefly the possibility of a "fuzzy focus" system, in which aberrations are deliberately introduced into a first reflector, producing a lower focal irradiance. The second collector would hopefully compensate for these aberrations, producing a uniform collimated beam.

II. Irradiance in the Focal Plane of a Paraboloidal Mirror

This problem is formally the same as the well-known problem of calculating the irradiance in the focal plane of an ideal converging lens. Figure 3 depicts collimated light incident on an aperture and focused onto the image plane at distance f along the optical axis 0-0'. The diffracted wave for a rectangular aperture of dimensions 2a x 2b is given by the Fraunhofer integral[12]

$$U(x,y) = C \int_{-b}^{b} \int_{-a}^{a} e^{ik(x\xi+y\eta)/f} \, d\xi \, d\eta \;, \tag{1}$$

where (x,y) is the image point, (ξ,η) is a source point within the aperture and $k = 2\pi/\lambda$. The irradiance is then

$$I = U^2 \;. \tag{2}$$

Using Parseval's theorem or conservation of energy to determine the constant C, we obtain the familiar result,

$$U = \frac{\sqrt{PA}}{\lambda f} \frac{\sin(kxa/f)}{kxa/f} \cdot \frac{\sin(kyb/f)}{kyb/f} \tag{3}$$

from which

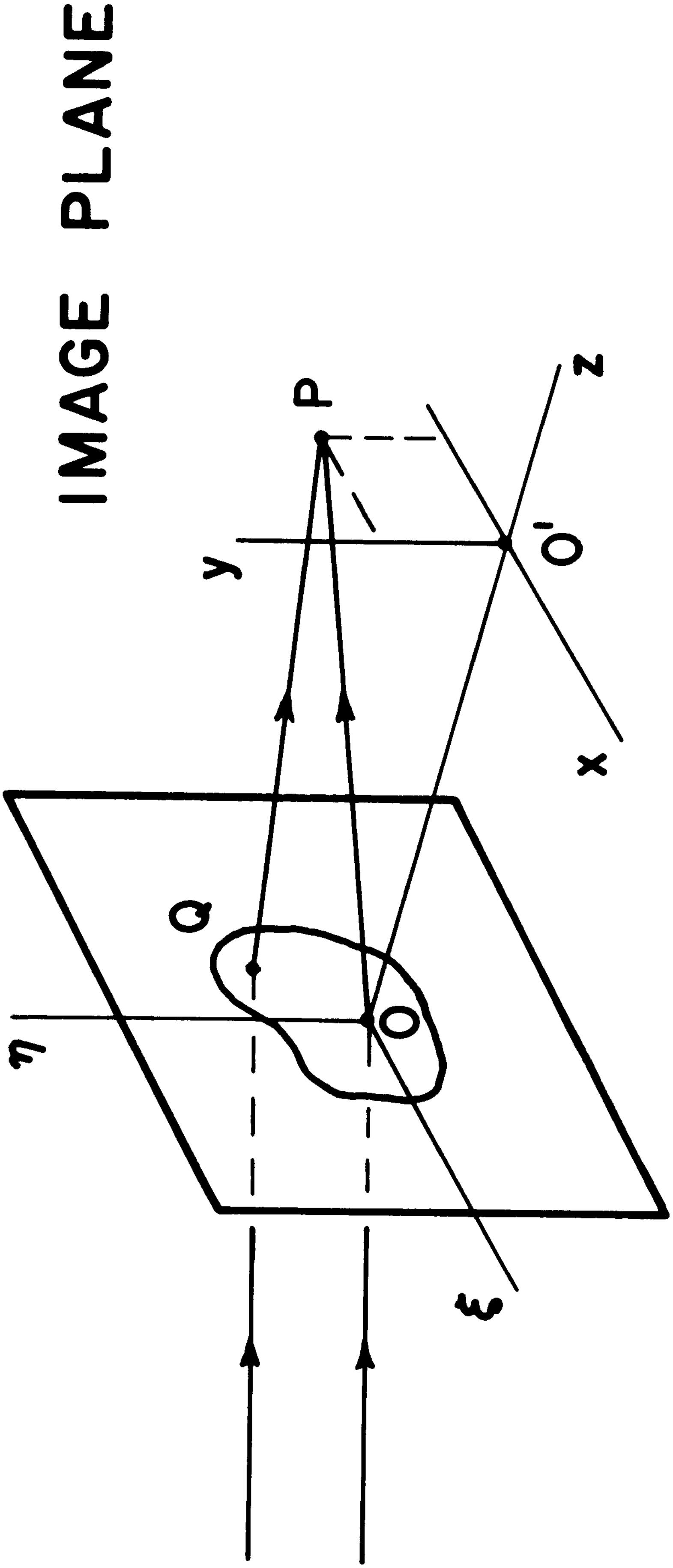

Figure 3

$$I_{max} = \frac{PA}{\lambda^2 f^2} \quad . \tag{4}$$

Here $P = \iint U^2 \, dx \, dy$ is the total beam power and $A = 4ab$ is the aperture area.

For our HF conceptual design,[13] $\lambda = 3$ μm, $P_{max} = 300$ TW, and $a = b = 70$ cm. Taking $f = 2$m then gives

$$I_{max} = 4 \times 10^{20} \text{ W/cm}^2 \ ,$$

a very large irradiance indeed, far above the gas breakdown threshold of $\sim 10^{12}$ W/cm^2 for $\sim$ 1 torr of neon or xenon.

III. Irradiance in the Focal Plane of a Parabolic Cylinder Mirror

This problem, formally identical to the cylindrical lens case, does not seem to be treated in the standard literature, so we shall derive it from basic principles.

A. Rectangular Aperture

As convergence occurs only in one direction, say the y-direction, the Fraunhofer integral becomes

$$U(y) = C \int_{-b}^{b} e^{iky\eta/f} \, d\eta \ , \tag{5}$$

where we have assumed uniform irradiance on the aperture. This is a Fourier integral, to which Parseval's theorem applies:

$$C^2 \int_{-b}^{b} d\eta = \frac{1}{\lambda f} \int_{-\infty}^{\infty} |U(y)|^2 \, dy = \frac{P}{\lambda f} \quad . \tag{6}$$

Thus,

$$C^2 = \frac{P}{2b\lambda f} \quad . \tag{7}$$

Carrying out the integral in Eq. (5), we obtain

$$U(y) = \sqrt{\frac{bP}{a\lambda f}} \quad \frac{\sin(kby/f)}{kby/f} \quad . \tag{8}$$

The peak irradiance is therefore

$$I_{max} = \frac{b}{a}\frac{P}{\lambda f} \quad , \tag{9}$$

independent of area. In terms of the incident irradiance I_o this takes the dimensionless form

$$I_{max} = \frac{b}{a}\left(\frac{A}{\lambda f}\right) I_o \ . \tag{10}$$

Putting in numerical values we find

$$I_{max} = 5 \times 10^{15} \ \mathrm{W/cm^2} \ .$$

This is still large enough to induce gas breakdown in 1 torr of neon or xenon.

B. Circular Aperture

Figure 4 illustrates the formation of the line focus, from a circular aperture of radius a. Since we are focusing in the y-direction only, we need only consider rays originating in a particular y-z plane and identify $x = \xi$. Rays from other ξ-values contribute only a little near-field Fresnel

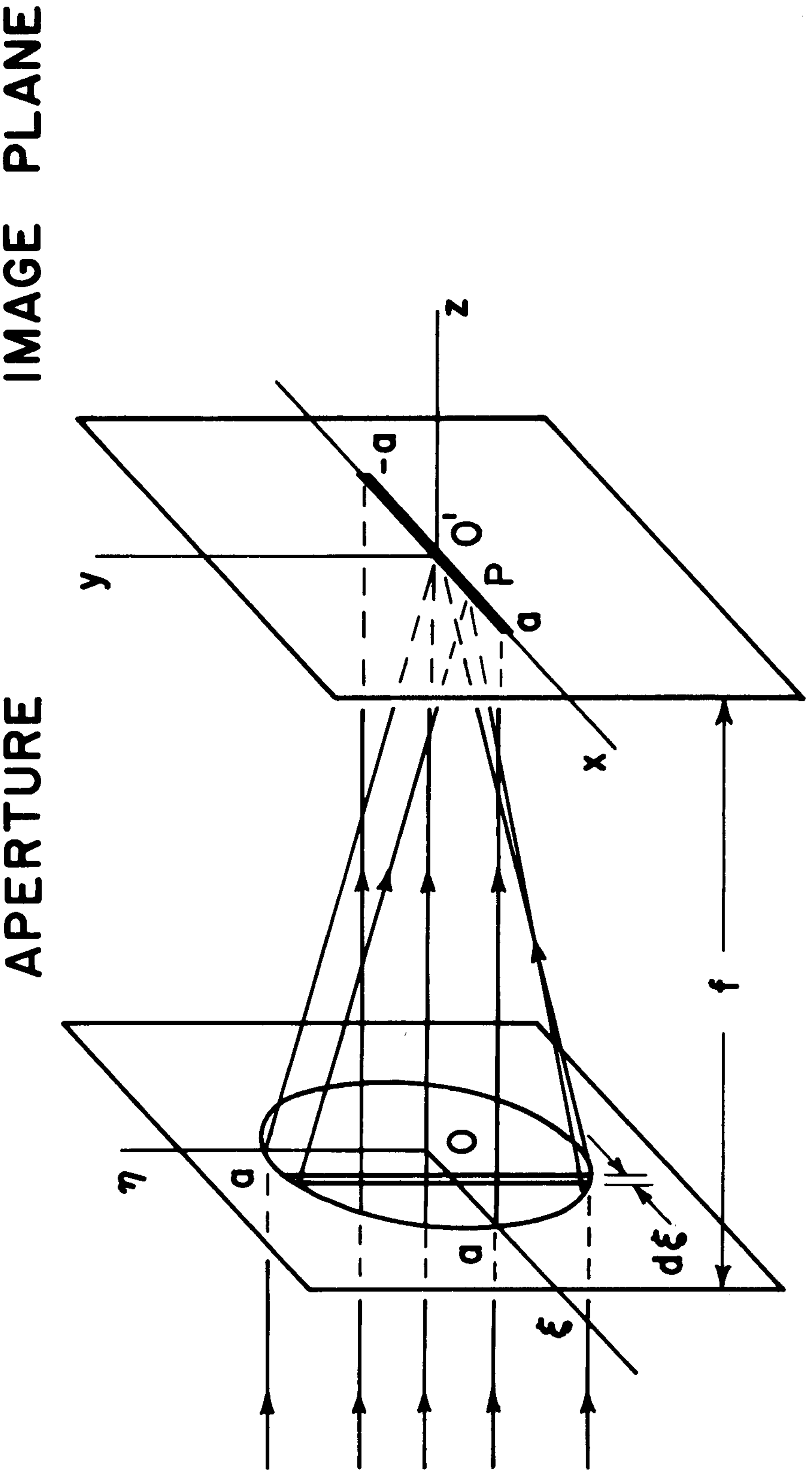

Figure 4

diffraction, which we neglect. From Fig. 4, the relevant Fraunhofer integral is

$$U(x,y) = C \int_{-\sqrt{a^2-x^2}}^{\sqrt{a^2-x^2}} e^{ik\eta y/f} \, d\eta \tag{11}$$

or

$$U(x,y) = \frac{2Cf}{ky} \sin \left(\frac{ky}{f} \sqrt{a^2-x^2}\right) . \tag{12}$$

The Parseval relation is not applicable in this case so we must use conservation of energy directly to determine C:

$$P = \iint U^2 \, dx \, dy = \left(\frac{2Cf}{k}\right)^2 \int_{-a}^{a} F(x) \, dx , \tag{13}$$

where

$$F(x) = \int_{-\infty}^{\infty} \frac{1}{y^2} \sin^2 \left(\frac{ky}{f} \sqrt{a^2-x^2}\right) dy \tag{14}$$

or

$$F(x) = \frac{\pi k}{f} \sqrt{a^2-x^2} . \tag{15}$$

Carrying out the x-integration then gives

$$P = \lambda f A C^2 . \tag{16}$$

Using this result in Eq. (12) we obtain

$$U(x,y) = \sqrt{\frac{4P}{\pi\lambda f}}\ \frac{\sin(\frac{ky}{f}\sqrt{a^2-x^2})}{kya/f} \ , \qquad (17)$$

from which

$$I_{max} = \frac{4}{\pi}\left(\frac{A}{\lambda f}\right) I_o \ . \qquad (18)$$

Figure 5 illustrates the irradiance $I = U^2$ in the x-y plane. Note that the central peak broadens as $x \to a$, the first null being given by

$$y^* = \frac{\lambda f}{2a\sqrt{1-x^2/a^2}} \quad . \qquad (19)$$

Applying Eq. (18) to the Livermore conceptual design[3] which calls for P_{max} = 500 TW, λ = 1.06 μm and f = 2m (say), we find $I_{max} = 3.2 \times 10^{16}$ W/cm^2.

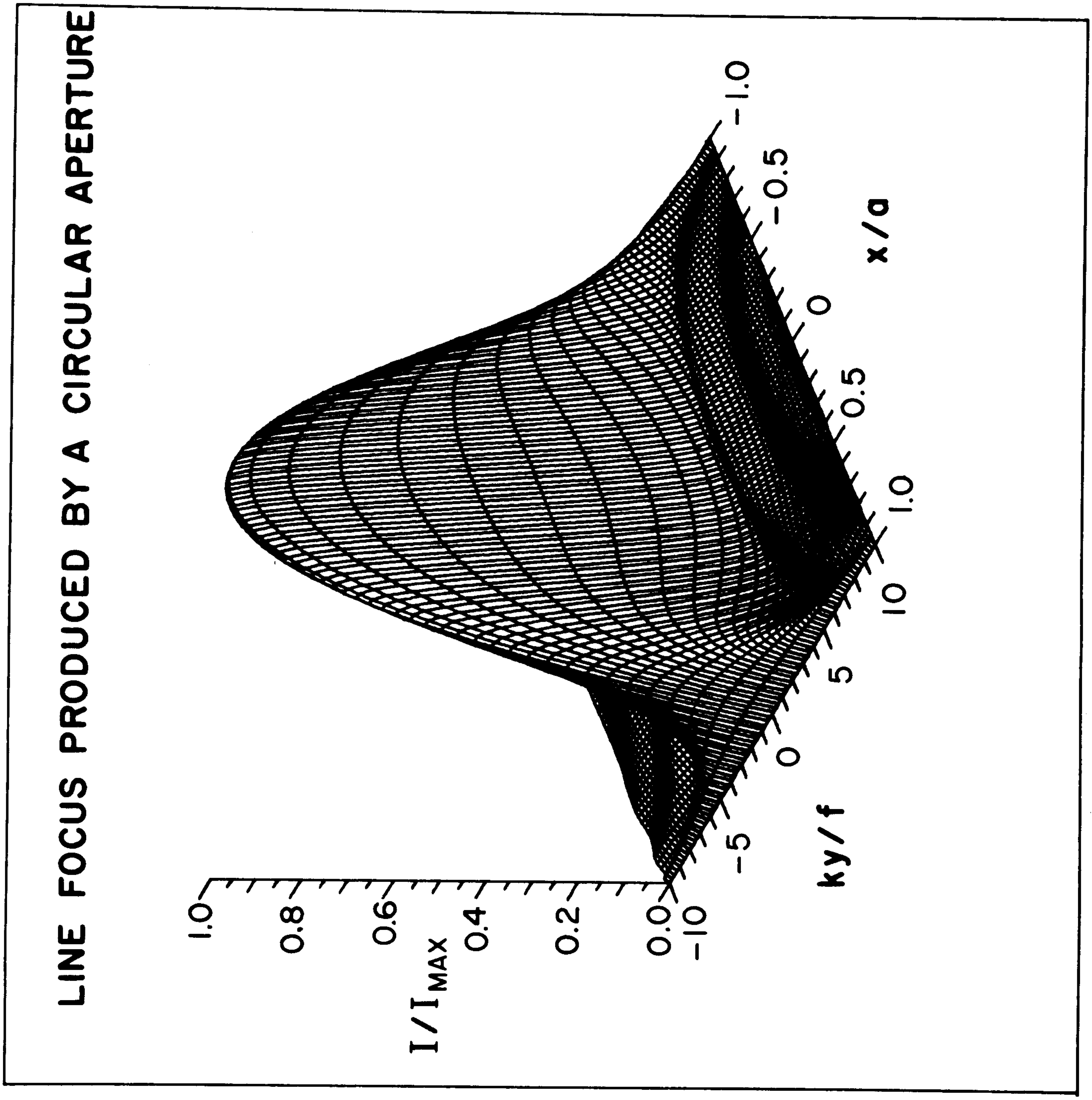
LINE FOCUS PRODUCED BY A CIRCULAR APERTURE
I/I_MAX
1.0
0.8
0.6
0.4
0.2
0.0
-10
-5
0
5
10
ky/f
1.0
0.5
0
-0.5
-1.0
x/a

Figure 5

IV. Schematic Design

Figure 6 is an overhead view of the proposed device. A 70 cm square beam is assumed incident from the laser some meters distant. After striking flat F_1 it is turned through 45^o, passing through a 2.5 cm thick quartz window. The window must be thick enough to ensure tritium containment but thin enough to hold down nonlinear optical effects. The beam is then simultaneously turned and focused by parabolic mirror P_1 of 3.5 m focal length, passing through the 2 m thick shielded primary containment wall. The wall would be of structural concrete with additional shielding placed behind flat F_2. The port is tapered to a diameter of approximately 1 cm. A fast acting valve could be installed in the port throat to ensure tritium containment in case of window failure. Next the beam is turned and recollimated by parabolic mirror P_2, exiting from the vacuum chamber through window W_2. Finally, the beam is turned by flat F_2 and directed to the reactor chamber some 20 m distant.

The entire region outlined in black and enclosing mirrors P_1 and P_2 is evacuated to 10^{-5} torr to avoid breakdown at the (point or line) focus. The region outside the chamber is at a pressure of about one torr. The beams would be enclosed in evacuated beam tubes (not shown) to maintain clean optical surfaces.

It should be noted that 45^o turning mirrors have been used rather than 90^o mirrors. This choice is based on our studies of the imaging properties of parabolic mirrors, which show that for the same tilt error

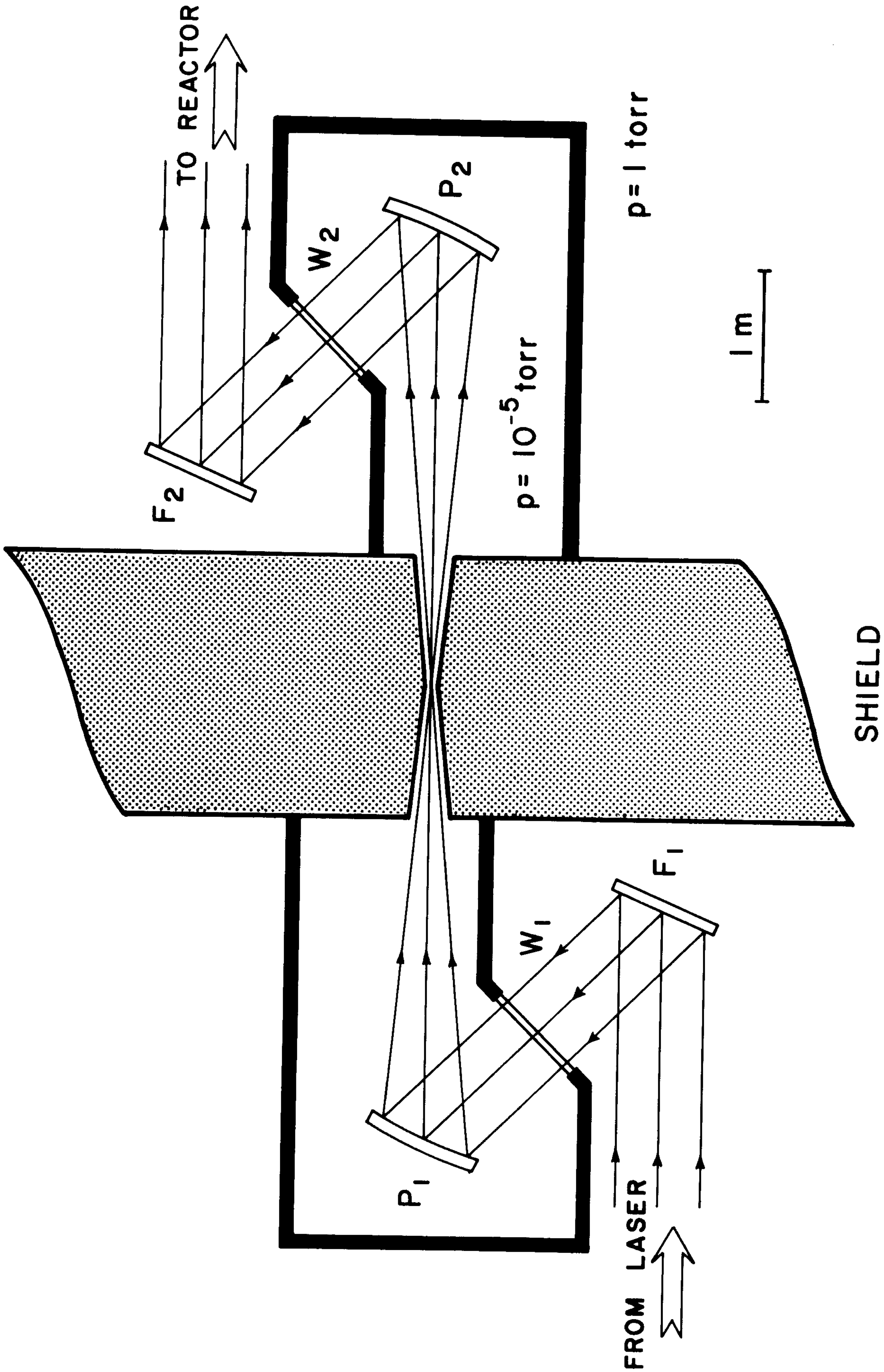
TO REACTOR
FROM LASER
SHIELD
$p = 10^{-5}$ torr
$p = 1$ torr
1 m
F_1
F_2
P_1
P_2
W_1
W_2

Figure 6

much larger irradiance distortions occur at larger deflection angles. Naturally space must be provided for rigid mirror mounts and automatic alignment systems. Also note that quartz window W_2 is not directly exposed to the neutron flux from the reactor chamber located to the right. This is an important feature of the design, since quartz is vulnerable to loss of transparency by neutron damage.

It would be very desirable to place beam reduction units closer to the target chamber in order to limit the high neutron flux in the immediate vicinity of the first wall and blanket. It seems fairly certain that an evacuated system such as the one described above could not be so installed due to the very short expected window lifetimes under intense neutron bombardment.

Assuming a gas breakdown threshold of 10^{12} W/cm^2, it is straightforward to show that a 10 cm focal radius would allow transmission of up to 300 TW peak power without evacuation. A spot of this size could in principle be produced by employing nonparabolic surfaces to deliberately induce aberrations in the focal region. Another possibility would be to tilt the parabolic mirrors a prescribed amount, which would also spread out the focal region. In both cases caustic formation would have to be investigated.

In summary, we have presented a schematic design for a beam reduction device, similar to a conventional spatial filter except for the use of reflective optics. Maintaining mirror alignment is expected to be difficult but not unattainable. The vacuum requirements are modest. Probably the

Achilles' heel of this design is the optical response of the quartz windows to neutrons and X-rays. We are currently engaged in a study of these effects which will hopefully lead to a quantitative estimate of window lifetimes.

Acknowledgement

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Figure Captions

Fig. 1. Beam reduction using off-axis paraboloids,

Fig. 2. Beam reduction using parabolic cylindrical mirrors. Only the lower half of the wall is shown for clarity.

Fig. 3. Fraunhofer diffraction geometry in the focal plane of a converging lens or mirror (not shown).

Fig. 4. Formation of line focus from a circular aperture and cylindrical focusing element.

Fig. 5. Fraunhofer diffraction pattern produced by a circular aperture and a cylindrical focusing element.

Fig. 6. Schematic design of proposed beam port reduction scheme, using effective f/5 off-axis paraboloids or parabolic cylinders. The minimum wall penetration width can be as small as 1 cm or less.