330
8-18-75
LA-5986-MS, Vol. II

Informal Report

Dr-1551

UC-20 and UC-34

Reporting Date: May 1975

Issued: June 1975

**Optical Design of a Reaction Chamber for
Weakly Absorbed Light.
II. Parallel Mirrors, Multitravel**

by

J. J. Devaney
F. T. Finch

los alamos
scientific laboratory
of the University of California
LOS ALAMOS, NEW MEXICO 87545

An Affirmative Action/Equal Opportunity Employer

UNITED STATES
ENERGY RESEARCH AND DEVELOPMENT ADMINISTRATION
CONTRACT W-7403-ENG. 36

MASTER

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

In the interest of prompt distribution, this report was not edited by the Technical Information staff.

**Printed in the United States of America. Available from
National Technical Information Service
US Department of Commerce
5285 Port Royal Road
Springfield, VA 22151
Price: Printed Copy \$4.00 Microfiche \$2.25**

This report was prepared as an account of work sponsored by the United States Government. Neither the United States nor the United States Energy Research and Development Administration, nor any of their employees, nor any of their contractors, subcontractors, or their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights.

--NOTICE--

This report was prepared as an account of work sponsored by the United States Government. Neither the United States nor the United States Energy Research and Development Administration, nor any of their employees, nor any of their contractors, subcontractors, or their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness or usefulness of any information, apparatus, product or process disclosed, or represents that its use would not infringe privately owned rights.

OPTICAL DESIGN OF A REACTION CHAMBER FOR WEAKLY ABSORBED LIGHT

II. PARALLEL MIRRORS, MULTITRAVEL

by

J. J. Devaney and F. T. Finch

ABSTRACT

This report outlines the possibilities to be found using one or more diffraction-limited high-quality light beams to activate a weakly absorbing gas in a regime where the diffraction spread can be controlled by converging optical devices to within a ratio of $\sqrt{2}$ of the minimum at the beam waist (corresponding lengths between converging elements are within twice the Rayleigh range). Our designs use plane or cylindrical parallel mirrors down which a light beam is repeatedly reflected. In the first design variation, the beam is re-reflected up the parallel mirrors to the entrance aperture where it can be returned repeatedly for a number of multiply reflecting "travels" up and down the parallel mirror reaction chamber. In the second variation, the return of the beam after each multiply reflecting "travel" down the chamber is external to the chamber and is achieved by two mirror reflections. For diffraction control the return mirrors can be made converging.

For multiple laser excitation, any of the external return mirrors can be replaced by a laser.

The advantages of these designs are a high degree of uniformity of chamber illumination with a reasonably high number of passes. Drawbacks of the designs are the large space needed for beam return (many tens of meters for some parameters) and (common to all high optical quality chambers) the figuring and reflectivity demands on the mirrors.

I. INTRODUCTION

This is the second in a series of reports¹ dealing with illumination of a reaction chamber by weakly absorbed light which, as a specific example, we will take here to be $0.4\text{-}\mu\text{m}$ wavelength with a small fractional absorption of $\lambda \approx 3.675 \times 10^{-6} \text{ cm}^{-1}$. However, our results are general and not limited to these particular values, nor does this work specifically depend on the first report, designated Vol. I.

We suppose an active chamber size of width, W , across which we shall pass a beam of light of height, h . The length of the chamber is ℓ (see Fig. 1). We place plane or cylindrical mirrors of size $h \times \ell$ (or slightly larger) at the ends of the chamber at a separation, W . We suppose that the major vertical beam divergence is easily controlled by making one mirror (or if W is very large and/or h/λ is not large, making both mirrors) cylindrical; see the pertinent discussion in Vol. I. We further suppose

Fig. 1. Reaction chamber.

that we have unlimited access to certain regions beyond the active chamber in which can be located as many (converging) mirrors as we please.

Under such circumstances we can highly absorb a sufficiently wide diffraction-limited beam with

RECEIVED

a high degree of uniformity of illumination within the chamber. Moreover these ends are achieved with the simplest optical elements, namely plane elements, when beam size is large enough, λ small enough, and/or the beam path short enough to neglect diffraction, and by cylindrical elements otherwise. As a consequence the designs in this paper are appropriate for large cross-section diffraction-limited beams where plentiful space is available.

II. INTERNAL BACK REFLECTION DESIGN, SINGLE LASER General

For the moment we take the beam to be uniform and of constant width a , height h , and leave diffraction and beam shape for later discussion. The beam is introduced into the chamber at an angle θ_1 so as to just clear the entrance after one reflection (Fig. 1). θ_1 is given by

$$\sin \theta_1 = \frac{a}{2W}. \quad (1)$$

The number of passes, n , across the chamber is then two for progression $a' = a/\cos \theta_1$ down the chamber, giving a total

$$n_1 = 2 \frac{\ell}{a'} + 1 = 2 \frac{\ell \cos \theta_1}{a} + 1, \quad (2)$$

for a chamber of length, ℓ , which must either be divisible by a' or else ℓ is the least number in the original length which is divisible by a' . In any case the position of the mirror M is the least divisible number, ℓ . In practice the position and angle of the incident laser beam and the angle ϕ of M are adjusted to fit this requirement. The additional reflection, the 1 in Eq. (2), is the last pass traversing W to the mirror M in Fig. 1.

At the end of the chamber at precisely a multiple of a' , namely ℓ , we place a mirror, M , of size a' or greater, at an angle ϕ to the parallel mirrors. Later, M will be made concave to compensate for diffraction, but for simplicity we now consider a beam of constant width and a plane mirror will do. At $\phi = 0$ the beam is simply lost beyond the edge, with less and less lost as ϕ increases. For M of width greater than a' , one can obtain multiple reflections with eventual return of the beam down its incident path. Alternatively one gets split beams, both returning to the entrance side of the

chamber but at different angles. Neither of these possibilities is advantageous. We begin with $\phi = \theta_1$ which is the case of normal incidence and was discussed in Vol. I, paragraph 2a. This choice gives a total of

$$n_{2T} = 2(2 \frac{\ell}{a'} + 1) = 2 \left(\frac{2\ell \cos \theta_1}{a} + 1 \right) \quad (3)$$

passes and is completely uniform for a beam of constant width and low absorption, each position in the chamber except the ends receiving precisely four passes, two originating from the incident side and two from the reflected side, so compensating somewhat for any absorption. For sufficient absorption (cross section, density, and width), or sufficiently large ℓ , this is the design of choice. Note that diffraction limits the improvement in absorption obtained by making a as small as we please.

If the combination of chamber size and cross section does not give enough absorption from the double travel of Eq. (3), we can increase the number of travels by increasing ϕ and including additional mirrors. We define travel, t , to be the number of progressions down or up chamber in the dimension ℓ . To better visualize the geometry, we expand Fig. 1 by "unfolding" the successive image spaces of the parallel mirrors, much as a tailor's mirrors repeatedly reflect the buyer. Figure 2 shows part of the beam for a travel, $t = 4$; Fig. 4 shows six travel.

Four Travel

In Fig. 2 four travels are achieved by choosing ϕ such that the first reflection from M exits at A_2 and then placing M_2 sufficiently beyond A_2 (which is also aperture A_1 in real space) so as not to interfere with the incident beam and the laser source. Mirror M_2 is normal to the beam and therefore returns it through the entire optical system giving a total of four travels. However, exiting at A_2 rather than at A_1 gives two passes less across W per travel. Consequently the total number of passes is

$$n_{4T} = 2n_1 + 2(n_1 - 2) = 8\ell/a' = 8\ell \cos \theta_1/a. \quad (4)$$

The beam retains its width, a , throughout so that at the slightly greater angle θ_2 that the beam has exiting at A_2 , the coverage begins to be

Fig. 2. Expanded parallel mirrors (of Fig. 1). The beam for $t = 4$ is partially illustrated.

lattice-like with slight gaps in volume coverage for a relative total average coverage during travels 2 and 3 of

$$a/(2W \sin \theta_2) = \text{relative coverage.} \quad (5)$$

In the gaps, the total intensity drops to 50 or 75% of maximum light intensity. The gaps can be somewhat removed by making the mirror M slightly convex and the mirror M_2 slightly concave, but we judge the slight improvement gained thereby not worth the additional complexity except for greater angles θ_2 or for multiple laser input. Moreover when diffraction is included the beam will vary in cross section and the mirrors will in fact be concave to control diffraction. From Fig. 2 the entrance angle θ_1 at A_1 is given by

$$\tan \theta_1 = \frac{l + (a'/2)}{n_1 W} = \frac{a'}{2W}, \quad (6)$$

which checks (1) and (2), but the exit angle θ_2 at A_2 is given by

$$\tan \theta_2 = \frac{l + (a'/2)}{(n_1 - 2)W} = \frac{a'}{2W} \left(\frac{2l + a'}{2l - a'} \right). \quad (7)$$

The normal of the mirror, M , bisects the center lines at θ_1 and θ_2 so

$$\phi = \frac{1}{2}(\theta_1 + \theta_2) \quad (8)$$

sets the mirror M angle.

In order to know where the mirrors M_2 and M_3 in Fig. 2 must be placed, we must calculate the minimum distance b along the incident beam from the entrance aperture to where the first reflected beam out of the aperture just clears the entrance beam. Indeed we will need such calculations in general throughout this paper and will therefore solve the problem in general. Consider Fig. 3: two beams of width a issue from the same aperture at angles α and β . We wish to calculate the distances x , h , and b which locate the closest point at which the two beams are just entirely separated.

$$a = a(\alpha) \cos \alpha \quad (9)$$

$$x = h \tan \alpha \quad (10)$$

$$x + a(\alpha) = h \tan \beta \quad (11)$$

$$h = b \cos \alpha \quad (12)$$

Eliminating x in Eqs. (10) and (11)

$$h = a(\alpha) / (\tan \beta - \tan \alpha), \quad (13)$$

$$x = a(\alpha) \tan \alpha / (\tan \beta - \tan \alpha), \quad (14)$$

Fig. 3. Diagram for calculation of the beam separation distance, b .

$$b = [a(\alpha)]^2 / [a(\tan \beta - \tan \alpha)]. \quad (15)$$

Applying Eq. (15) to our present case, setting $\theta_2 \equiv \beta$ and $\theta_1 \equiv \alpha$, and using (6), (7) and (9) we have

$$b = \frac{W}{a}(2\ell - a') \quad (16)$$

$$a' \equiv a / \cos \theta_1;$$

b is the minimum distance at which the normal mirror, M_2 , can be located from the chamber aperture.

The minimum distance of mirror M_2 from the chamber, b , can be large. Suppose $a = 0.5$ cm, $\ell = 10$ cm, and $W = 200$ cm for instance, then $b \sim 80$ m, to be compared with a total travel of $n_{4T}W \sim 8\ell W/a = 320$ m (160 passes) within the chamber. One must therefore definitely control diffraction as discussed below, and must allow for considerable beam room at the chamber entrance. Indeed a 0.5-cm-wide beam has a Rayleigh range of 49 meters and so is too narrow to be used precisely as the foregoing (without additional converging optical elements). However, the 0.5-cm-wide beam can be used in the External Return Design (see Sec. III) for these parameters.

By giving up both some uniformity and some number of passes in the second and third travel, one may shorten the mirror M_2 distance, b , to the chamber. Thus if (Fig. 2) the beam exits at some aperture A_m in place of A_2 the exit angle is now:

$$\tan \theta_{2m} = \frac{\ell + (a'/2)}{(n_1 - 2m + 2)W}$$

$$= \frac{a'}{2W} \cdot \frac{(2\ell + a')}{[2\ell + (3 - 2m)a']}. \quad (17)$$

The new angle for the mirror M is $\theta = \frac{1}{2}(\theta_1 + \theta_{2m})$. The total four-travel number of passes is now

$$n_{4mT} = 2n_1 + 2(n_1 - 2m + 2)$$

$$= 4\left(\frac{2\ell}{a'} + 2 - m\right) \quad m \geq 2. \quad (18)$$

The gaps now will be larger, but the light intensity in the gaps will again be 50 and 75% of maximum. To calculate b we put $\alpha = \theta_1$ and $\beta = \theta_{2m}$ in (15) and use (6) and (17) to get

$$b_m = \frac{W}{a} \cdot \frac{[2\ell + (3 - 2m)a']}{(m - 1)}, \quad (19)$$

where, for m as large as we please, b_m is as small as we please. Equation (16) is a special case of (19) for $m = 2$. By using the parameters above, if we take $m = 9$, we are reduced to 132 passes in place of 160, but b_9 has been reduced to ~ 6.3 m in place of ~ 80 m.

Six Travel

In Fig. 4, as shown, one can achieve $t = 6$, six travel, by exiting at A_1 or higher m and placing mirrors M_2 and M_3 at a distance, b , sufficiently far from the chamber that the return beam neither interferes with the incident laser beam, nor with the originally exiting beam through A_3 . The purpose of mirrors M_2 and M_3 is to return the beam down the center normal of the mirror M where the beam is re-reflected through its previous path for a total of six travels. The number of passes is

$$n_{6T} = 2n_1 + 2(n_1 - 4) + 2(n_1 - 2) = 6\left(2\frac{\ell}{a'} - 1\right)$$

$$= 6\left(2\frac{\ell \cos \theta_1}{a} - 1\right). \quad (20)$$

The angle θ_2 of the first reflection at M is given by Eq. (17) with $m = 3$:

$$\tan \theta_2 = \tan \theta_{23} = \frac{a'}{2W} \frac{(2\ell + a')}{(2\ell - 3a')}. \quad (21)$$

Fig. 4. Expanded parallel mirrors (of Fig. 1). The beam for $t = 6$ is partially illustrated.

and, as before,

$$\phi = \frac{1}{2}(\theta_1 + \theta_2). \quad (8)$$

The angle θ_3 from mirror M_3 is precisely ϕ ;

$$\theta_3 = \phi. \quad (22)$$

The minimum distance b is determined from the greater of the distances b of Eq. (15) for the angle pairs θ_3, θ_1 and θ_3, θ_2 , namely:

$$b_{31} = a'^2/[a(\tan \theta_3 - \tan \theta_1)], \quad (23)$$

$$b_{32} = a''^2/[a(\tan \theta_2 - \tan \theta_3)]. \quad (24)$$

Since by (8) and (22), $\theta_3 = (\theta_1 + \theta_2)/2$, $\Delta \tan \theta = -\Delta \theta / \cos^2 \theta$, and $a'' = a / \cos \theta_2$, $a' = a / \cos \theta_1$; the former expression is proportional to $\sim \cos^{-3} \theta_1$, the latter to $\sim \cos^{-3} \theta_2$ and $\theta_2 > \theta_1$ in the first quadrant so that $b_{32} > b_{31}$, and therefore $b_{32} = b$ is the closest distance of the mirrors, M_2 and M_3 .

The precise value b is obtained by substituting (1) and (21) in (24), a somewhat complicated algebraic procedure. We can get a simplified relation when $a' \ll W$, which is usually true, for then the angles are small enough so we can replace tangents by their angles. Then

$$b \approx 2a''^2/[a(\theta_2 - \theta_1)], \quad (25)$$

where, to the same accuracy, $a' \approx a''$ so that:

$$b \approx \frac{W}{a} (2\theta_2 - 3a'). \quad (26)$$

Compare with the four-travel mirror (M_2) distance given by (16). Again we need plenty of external beam space for the six travel just as for the four travel. As in four travel, one may accept some degradation in uniformity and some loss in total passes in order to effect a reduction in the distances of the mirrors M_2 and M_3 from the chamber.

Higher Travel

In Fig. 4, note that the apertures, A_m , are not equally spaced about a circle whose center is at M . Thus one cannot indefinitely take the apertures A_m to be sufficiently symmetric about the mirror normal and so continue in the above manner to many travel designs. For example, the angle $\angle A_6 M A_4$ is obviously far greater than the angle $\angle A_4 M A_2$. Therefore a beam through A_6 for an M mirror normal at A_4 will miss exiting at A_2 , (indeed also A_1), by a large margin. Consequently higher travel is limited to a $\ll l$ and a $\ll W$. Already that may be sufficient for some purposes, since, for example, high travel means a large number of passes and consequent high

transit time, which may not be tolerable for other reasons. However, it is possible to achieve very high travel by the method of external return of the beam which we now study.

II'. EXTERNAL BEAM RETURN DESIGN, SINGLE LASER

In this design the beam is "travelled" down the chamber to a complete exit and is then rerouted externally to reenter the chamber for as many times and thus travels as desired, (within some limitations discussed below).

The advantages of this design are that it yields as many passes as desired, provided the chamber dimensions are sufficiently large, and that the average uniformity of illumination is perfect as in Section II. The limitations of this design as with the internally reflected beam design are the considerable space needed for beam separation and return, and the high-quality beams needed. Figure 5 shows the general plan view with a highly contracted width, W . The upper mirror is of length ℓ , the lower of length $\ell + a$. Again the beam is of width a . As before, the angle θ_1 is set by the requirement that the beam just clear the entrance upon return after one reflection:

$$\sin \theta_1 = \frac{a}{2W}. \quad (1)$$

Again the number of passes is two for every progression $a' = a/\cos \theta_1$ down the chamber giving a total for the first travel of (Fig. 5)

Fig. 5. Reaction chamber, External Return (the mirrors M_m' could be combined to one plane mirror and placed closer to the exit aperture).

$$n_1' = 2\left(\frac{\ell}{a} + 1\right) = 2\left(\frac{\ell \cos \theta_1}{a} + 1\right). \quad (26)$$

(The prime distinguishes n_1' from the passes of the internal-reflection design.) Equation (26) incorporates one additional pass more than (2) because we exit at the top rather than at the bottom. ℓ is required to be divisible by a' , i.e. $(\ell \cos \theta_1)/a$ must be an integer. In practice, with a fixed beam width, a , and mirror length, ℓ , one adjusts θ_1 to make ℓ/a' an integer (see beam B_m of Fig. 6).

For the maximum number of passes and travels, one chooses the smallest angle that just permits full clearance of the next beam B_2 from the first or laser beam B_1 . Let $m = 1$ in Fig. 6 and compare B_m with B_{m+1} . As before, maximum passes implies the smallest angular difference between beams which implies the greatest distance, b_m , of the mirror M_m , see Figs. 5 and 6. It is clear from Fig. 6 that θ_m is determined from

$$\tan \theta_m = \frac{\ell + a^{(m)}}{n_m' W}, \quad (27)$$

where

$$n_m' = 2\left(\frac{\ell}{a'} + 2 - m\right), \quad (28)$$

and

$$a^{(m)} = a/\cos \theta_m, \quad (29)$$

because for the smallest angle change ($\neq 0$) a beam exiting "cleanly" through the aperture at the bottom of Fig. 6 must leave at the next highest exit which is precisely two passes less. Equations (27), (28) and (29) for $m = 1$ give Equation (1).

The maximum $m = \bar{m}$ occurs for

$$\frac{\ell}{a'} + 2 - \bar{m} = 1 \text{ or } \bar{m} = \frac{\ell}{a'} + 1 \quad (30)$$

since $n_m' = 2$ (Fig. 5). (We omit passes along the flow having but one reflection at the bottom mirror in Fig. 5 although in principle, these can be made as often as desired so $\bar{n}$ can be made infinite, but these passes are usually an impractical means of illumination.) Thus the total number of passes is

$$\bar{n}' = \sum_{m=1}^{\frac{\ell}{a'} + 1} n_m' = 2 \sum_{m=1}^{\frac{\ell}{a'} + 1} \left(\frac{\ell}{a'} + 2 - m\right), \quad (31)$$

Fig. 6. Expanded Fig. 5 (parallel mirrors). Beams B_m and B_{m+1} illustrated. m is travel number.

$$\bar{n}' = \left(\frac{l}{a'} + 1\right)\left(\frac{l}{a'} + 2\right).$$

This number for $a' = 0.5$ cm, $l = 10$ cm is 462 passes, for example, of which the first travel is

$n'_1 = 42$ passes of perfect uniformity for a perfect beam, each succeeding travel having two less passes (and therefore gaps unless broadened). The number of travels is 21, requiring a total of 42 (or 22) mirrors of the type M and M' .

These mirrors, M_m , must be located at least a distance b_m from the entrance aperture so as to selectively reflect but one beam. The same distances apply to the exit mirrors, M'_m , except that an alternative design is to combine the mirrors M'_m into a single plane mirror M' located near the exit aperture and rely on the mirrors M_m for selection and redirection of the beam.

IV. CHAMBER EXCITATION BY MULTIPLE LASERS

The foregoing designs are immediately applicable to multiple laser excitation of the reaction cavity by simply replacing the mirrors M_2 in Fig. 2, M_3 in Fig. 4, etc., or mirrors M_m in Fig. 6, with lasers directing their beams into the chamber. The location of the lasers are given, just as for the mirrors by Equations (13), (14), and (15) (minimum distances). The angle of inputs θ_1 are given by (1), (6), (7), (17), (21), or (27), depending on just what paths the beams are to follow. The discussion of coverage and gaps is identical, except that for higher angles of insertion θ_1 it is easy to prevent gaps in the first travel by widening the laser beam itself by an amount:

$$a_i = a \cos \theta_1 / \cos \theta_1. \quad (32)$$

However, as Figs. 2 or 4 show (with a laser in place of M_2) the internal return mirror, M , can only be precisely set for one laser (in size and angle). Incidentally for larger diameter beams, the input angles θ_1 are slightly larger for a clean, i.e., no beam splitting, exit. That angle is given by Equations (27), (28), and (29) but with the larger beam width substituted.

Thus for fully equivalent multi-travel paths in the chamber from multiple lasers, it is necessary to use external return. If the widths are varied as Eq. (32), the first travel of each laser beam will illuminate the chamber uniformly and without gaps (assuming negligible diffraction). Later travels of each beam will have gaps (or diffractive overlaps) unless appropriate optics are inserted in the return paths.

V. THE EFFECTS OF DIFFRACTION, NON-PERFECT BEAMS

The foregoing designs are described using a beam with constant cross-section; actual beams expand because of diffraction and imperfect sources. We discuss (to first order) in this section the effect of real beams on the foregoing designs.

Vertical diffraction control by the chamber mirrors has been discussed in Vol I. Because of differing diffraction width versus depth it is possible that one may want to invoke the techniques suggested in that report in addition to the vertical diffraction control obtainable through use of vertically concave mirrors M , M_1 , and M'_1 of Figs. 1-6. In such a case the reader is referred to Vol. I, or to an optics text. We assume here that sufficient control is possible through the smaller mirrors, M , M_1 , M'_1 . Moreover, since the theory is identical vertical or horizontal, we do not even discuss vertical control separately but concentrate on horizontal control exclusively with no loss of generality thereby.

The differing diffraction-limited beams ranging from uniform intensity to soft aperture-truncated to a gaussian intensity profile have the same dominant angular diffraction spread, namely the far field angle, θ , given by

$$\sin \theta \sim \lambda/a, \quad (33)$$

where a is the (initial) aperture and λ the wavelength. The differing beams have different constants depending primarily on the ease of defining a spread parameter. Thus, for the position of the first minima from the axis in the Fraunhofer (far field) pattern of an initially uniform beam, (33) is precisely the appropriate relation. Such a beam and equation [(33)] were used in Vol. I. For the gaussian beam, the 1/e intensity position spreads in the far field as $2\lambda/\pi a$. The smaller spread of the gaussian is apparent rather than real, for first of all 1/e is not much reduction of the beam magnitude, higher reductions having larger angles; and second, Terrell, Suydam, and Goldstein, et al, have shown² truncated gaussians spread to a greater degree than pure gaussian beams do, and are similar to uniform beams of the same truncation. For high power, soft aperture-modulated beams will likely be used; they may be considered (initially) as intermediate between gaussian and uniform. We note that the far-

field pattern of all beams, widely truncated or not,³ is centrally peaked; i.e., gaussian-like. We are therefore perhaps justified in using a somewhat smaller divergence than that of (33) for the spread of the central peak ($\sim 89\%$ energy in a one-dimension uniform beam), but complementarily we may not take the beam as uniform. Of course, Eq. (33) gives the angular spread of just the central peak; for a truncated uniform beam the k th minimum spreads as

$$\sin \theta = k\lambda/a.$$

At the moment these considerations are but second order in importance, so we do approximate the beam as roughly uniform and of divergence given by Eq. (33).

We need to know how far and within what limits a beam can be controlled. That requirement is derived from the relation:³

$$2\omega = 2\omega_0 \sqrt{1 + (\lambda Z/\pi\omega_0^2)^2} = 2\omega_0 \sqrt{1 + (Z/Z_R)^2}, \quad (34)$$

where 2ω is the width of the beam, $2\omega_0$ being the width at the waist, and Z the distance from the waist. Within a variation of $\sqrt{2}$ times the width at the waist, (going from $\sqrt{2} 2\omega_0$ to $2\omega_0$ to $\sqrt{2} 2\omega_0$), the total distance, D , of the beam is two Rayleigh ranges, Z_R , to wit:

$$D = 2Z_R = \frac{2\pi\omega_0^2}{\lambda}. \quad (35)$$

D is therefore the upper practical bound on the distance that a beam can travel without need of refocusing. Table I gives a listing of such distances as a function of waist diameter, $2\omega_0$, and wavelength, λ .

These are the distances within which a (diffraction-limited) beam may be considered to be controlled. Wherever distances between converging optical devices equal or exceed these distances, the designs of this report are not in general appropriate. See rather Vol. I, re: canted mirror designs.

Between converging mirrors we want the beam restored as much as possible to the original waist, $2\omega_0$ which acts now as the distance a of Figs. 1, 2, 4, 5, and 6. Consequently we require that the radius of curvature of the concave mirrors, M , M_1 , M'_1 of these figures be given by

$$R(Z) = Z[1 + (\pi\omega_0^2/Z)^2] = Z[1 + (Z_R/Z)^2] \quad (36)$$

TABLE I
CONTROLLED (TO WITHIN $\sqrt{2}$ OF WAIST)
BEAM SPREAD DISTANCE, D (m)

Wavelength λ (μm)	Waist Diameter, $2\omega_0$ (cm)				
	0.25	0.5	1.0	2.0	4.0
0.4	24.5	98.2	393.	1570.	6283.
0.6	16.4	64.4	262.	1047.	4188.
0.8	12.3	49.1	196.	785.	3142.
1.0	9.82	39.3	157.	628.	2513.
2.0	4.91	19.6	78.5	314.	1257.
4.0	2.45	9.82	39.3	157.	628.
8.0	1.23	4.91	19.6	78.5	314.
10.0	0.98	3.93	15.7	62.8	251.
16.0	0.62	2.45	9.82	39.3	157.

where, for best control, Z is half the beam distance from one converging element to the next.

Table I gives twice the Rayleigh range, $2Z_R$. Thus (Fig. 4) for travel, $t \approx 6$, we would choose radii for M and say M_2 from (36), substituting

$$Z = \frac{1}{2} [b + (n_1 - 2)W];$$

M_3 would then be left planar. Also, where possible the mirrors should considerably exceed our nominal beam width for diffraction control.

At the maximum recommended distance between focusing elements ($2Z_R$), the radius of curvature of a concave element is Z_R and the beam diameter is $2\sqrt{2}\omega_0$ leading to a depth of concavity of $1/\sqrt{2}$. For smaller or larger distances, Z, the radius is larger, Eq. (36). Larger distances than $2Z_R$ are unacceptable against diffraction; much smaller do not need converging elements for the diffractive loss is usually negligible. One must also allow for a scattering loss (mirrors, condensate, density variations, etc.) from the beam as well as absorptive and diffractive loss. It is not the purpose of this early study to include all effects to all possible accuracy; rather we present these designs as exploratory for the purposes of comparison with other designs, with the intent to include parameter ranges from pessimistic to optimistic.

We conclude our discussion with an example. Suppose our illumination chamber is 300-cm wide (W of Figs. 1 or 5), 10-cm long (l), and 1-cm deep with a beam waist, $2\omega_0$ ($\approx a$), of 1 cm; θ_1 , the angle of the beam to the mirror normals is given by (1) to be 0.00167 radians. Our laser must be at least 57 m from the entrance aperture, using Eq. (16), and furnishes a diffraction-limited beam. We expect 22 passes, n_1 , from Eq. (26) for a total in-chamber distance of 6.6 m plus a return distance to mirror M_1 of Fig. 5 of greater than 57 m (with or without separate mirrors M'). The total distance, laser to M_1 , is about 125 m which, for 0.4- μm light, gives an excursion of 1.19 to 1 to 1.19 cm from laser to mirror M_1 . So the beam is within $\pm 10\%$ of constant cross section. The total possible number of passes is given by (31) and is 132 for these parameters.

ACKNOWLEDGMENTS

It is a pleasure to acknowledge conversations with the following: L. A. Booth, L-5, W. H. Reichelt, L-1, D. Morelli, OCLI, and D. Romero, L-5.

REFERENCES

1. J. J. Devaney and D. E. Jackson, "Optical Design of a Reaction Chamber for Weakly Absorbed Light, I. Canted and Parallel Mirrors," Los Alamos Scientific Laboratory report LA-5986-MS, Vol. 1. (1975).
2. N. J. Terrell, Jr., Los Alamos Scientific Laboratory, private communication (1974).
A. J. Campillo, J. E. Pearson, S. L. Shapiro, and N. J. Terrell, Jr., "Fresnel Diffraction Effects in the Design of High-Power Laser Systems," Appl. Phys. Lett. **23**, 85 (1973).
A. J. Campillo, D. H. Gill, B. E. Newnam, S. L. Shapiro, and J. Terrell, "Reduction of Fresnel Diffraction Effects by Soft Apertures," 8th Int. Quant. Elect. Conf., Paper D7 (1974).
3. See, for example, A. E. Siegman, "An Introduction to Lasers and Masers," (McGraw-Hill, New York, 1971), pp. 339-340 and p. 309.
4. Concave mirror surfaces can be figured to as little as 50 Å and then uniform coatings can be applied; D. Morelli, OCLI, private communication (November 1974).