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Very High Intensity Reaction Chamber Design

by

J. J. Devaney

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

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VERY HIGH INTENSITY REACTION CHAMBER DESIGN

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ABSTRACT

The problem of achieving very high intensity irradiation by light in minimal regions is studied. Three types of irradiation chamber are suggested: the common laser-reaction chamber, the folded concentric or near-concentric resonator, and the asymmetric confocal resonator. In all designs the ratio of high-intensity illuminated volume to other volume is highly dependent (to the $3/2$ power) on the power and fluence tolerances of optical elements, primarily mirrors. Optimization of energy coupling is discussed for the common cavity. For the concentric cavities, optimization for both coherent and incoherent beams is treated. Formulae and numerical examples give the size of chambers, aspect ratios, maximum pass number, image sizes, fluences, and the like. Similarly for the asymmetric confocal chamber, formulae and numerical examples for fluences, dimensions, losses, and totally contained pass numbers are given.

I. INTRODUCTION

To achieve light intensities in a reaction chamber exceeding the tolerance of optical elements, it's clear that the light must be focused beyond the optical elements. For highest absolute efficiency, the light should be repeatedly refocused as much as losses permit, and the source-to-absorber coupling should be maximum. For the highest relative efficiency, the reaction volume exclusively should be strongly and completely illuminated. When absorber depletion is important, the refocusing should be on new absorber material. Accordingly, our objectives are:

1. Maximum source-to-absorber coupling,
2. Periodic refocusing of the light beam,
3. Minimum superfluous volume (i.e., least unilluminated or weakly illuminated volume), and
4. Optimization of reaction-illuminated volume and beam intensity to prevent overdepletion of reactants.

For really high intensities one is naturally drawn to laser sources and this report, therefore, considers only those. For lesser intensities, particularly

when the intensities needed are comparable to or less than mirror tolerances, the designs of this report are not optimum; for such intensities see rather Vols. I, II, and III.^{1,2,3}

We suggest three chamber designs to achieve our ends: a common laser-reactor cavity, in Sec. II; folded near-concentric and concentric resonators in Sec. III; and the asymmetric confocal resonator in Sec. IV. In the common cavity design the reaction chamber is part of the laser resonator. Partial or full decoupling of laser and reaction chamber is also possible. In the fully coupled common cavity every pass of light through the laser is focused in the reaction chamber, thus utilizing the higher circulating power of the laser itself. Moreover, the efficiency of coupling the laser light to the cavity approaches 100%. However, if the reaction chamber absorption is appreciable, optimum light intensities will be attained by decoupling the lasing from the reacting medium. The folded near-concentric resonator and the asymmetric confocal resonator use external laser beams. The common and the folded resonators refocus on every pass, the confocal resonator on every other pass, but in addition compresses

the beam itself to possibly useful intensities. Both the common and the confocal refocus to the same region, whereas the concentric refocuses at a different place along a Lissajous figure, one limiting form of which could be just two points. Each design has advantages and disadvantages which we discuss in detail below.

II. COMMON CAVITY

As shown in Fig. 1., the reaction chamber is an intrinsic part of the laser resonator and forms, together with it, a stable resonator. From left to right the resonator consists of a regular fully reflecting laser end mirror M_1 ; the lasing medium A (e.g., $\text{CO}_2 + \text{N}_2$ gas); an optional partially reflecting mirror, either M_2 or M'_2 ; a converging lens L, which may also serve as the reaction chamber entrance window, of diameter equal to that of the desired laser high-intensity mode; an optional partially reflecting mirror and/or optional window M'_2 ; two conical frusta apex to apex with an apex opening equal to the effective spot size, bounded by the lens L, and by the final laser-cavity mirror M_3 . The reaction-chamber walls are formed by either the lens L or the partial mirror/window M'_2 , the conical frusta and the mirror M_3 . For highest specific reactivity in the chamber, mirror (window) M'_2 , if used, and mirror M_3 are of the minimum size that optical tolerance will permit. The purpose of the partially reflecting mirrors M_2 or M'_2 is to manipulate the effective (lasing) Q of the smaller resonator consisting of M_1 , A, M_2 . Mirror M_2 (M'_2) may be needed if chamber absorption is large to obtain lasing at the desired frequency. The mirror M_2 (M'_2) may be dispensed with and control achieved with the plano-convex lens/window L used either with partial silvering, no coating, or antireflection coatings as alternative methods of manipulating the lasing Q.

Fig. 1. High-intensity common reaction chamber.

If the losses in the reaction part of the resonator are small compared to the net gain in the laser part, the mirror M_2 (or M'_2) is not needed, that is, the transmission of M_2 (M'_2) and L should be as close to unity as possible in order to get the maximum light into the reaction chamber, i.e., to attain maximum coupling. On the other hand, for large absorption per pass in the reaction part, one wants to decouple the reaction part to a large extent, in fact to decouple the lasing part so as to make it effectively a complete laser, using regular laser techniques for maximizing the output and neglecting the small chamber return. For intermediate cases when the reaction-chamber net absorption is neither large nor negligible one needs to know what reflection in M_2 or M'_2 is optimum. The problem is not simply the determination of the transmission T of the mirror M_2 (or M'_2 or L) for now the chamber return beam can itself induce lasing, and several timelike modes can propagate in the system to the detriment of the maximum intensity obtained from a single mode. The reaction-chamber return beam must therefore match in time and phase with the reflected beam. Moreover, one must be careful that absorption does not "pull" the lasing to an undesired frequency.

For illustration we choose the simplest case, that of a steady-state laser and make the laser part and the reaction part have the same optical length measured from the mirror M_2 (or M'_2 , or L). Let the initial gain of the laser be δ_{m0} per round trip (2 passes), the laser saturation energy be E_{sat} and the laser energy be E_L so that the laser gain per round trip, δ , is given by:⁴

$$\delta_m = \delta_{m0} / (1 + E_L / E_{sat}). \quad (1)$$

Let the intrinsic fractional loss of the laser part be δ_0 per round trip and that of the reaction chamber be δ_r per round trip with a window or mirror transmission of T. Of course $0 \leq T \leq 1$. (Window losses are included in δ_r or δ_0 or both, as appropriate.) If E_r is the energy in the reaction part of the resonator, then the energy increments per round trip are:

$$\Delta E_L = [\delta_m - (\delta_0 + T)]E_L + TE_r \quad (2)$$

for the laser part, and

$$\Delta E_r = -(\delta_r + T)E_r + TE_\ell \quad (3)$$

for the reaction part.

For the steady state the net energy flow is nil so $\Delta E_\ell = 0 = \Delta E_r$ and we get the relations:

$$[\delta_m - (\delta_o + T)]E_\ell + TE_r = 0, \quad (4)$$

and

$$(\delta_r + T)E_r = TE_\ell. \quad (5)$$

Substituting Eqs. (1) and (5) into (4) and solving for E_ℓ we get:

$$E_\ell = [(\delta_{mo}/D) - 1]E_{sat}, \quad (6)$$

where

$$D \equiv \delta_o + T - [T^2/(\delta_r + T)]. \quad (7)$$

For lasing we must have $E_\ell > 0$ or

$$\delta_{mo} > D = \delta_o + T - [T^2/(\delta_r + T)], \quad (8)$$

which is, for our case, the usual lasing condition that the round trip gain exceed the loss. Unless condition (8) is satisfied the common cavity will fail to lase at all. Equation (6) agrees with Eq. (3) of Siegman⁴ in the limits $T = 0$, or for $T = 1$ and $\delta_r + \delta_o$. Equations (5) and (6) give:

$$E_r = \left[\frac{\delta_{mo}}{(\delta_o \delta_r / T) + \delta_o + \delta_r} - \frac{1}{(\delta_r / T) + 1} \right] E_{sat}, \quad (9)$$

which we want to maximize subject to the condition $0 < T \leq 1$. Since we usually will have already reduced the loss parameters δ_o and δ_r to their minimum and the gain parameter δ_{mo} to its maximum, the remaining parameter at our disposal is T , so we maximize Eq. (9) with respect to T by setting $\partial E_r / \partial T = 0$ and rearrange to get:

$$T_1 = \frac{\delta_r (\sqrt{\delta_{mo} \delta_o} - \delta_o)}{\delta_r - (\sqrt{\delta_{mo} \delta_o} - \delta_o)} \quad (10)$$

for $0 < T \leq 1$ only.

The transmission, T_1 , is that value of T which maximizes the energy E_r in the reaction chamber for the given parameters. The range of usefulness of Eq. (10) is limited and one should generally refer to Eq. (9). Thus, for example, in the optimum case that $\delta_{mo} \gg \delta_o, \delta_r$; T_1 is negative and Eq. (10) does not apply. One sets $T = 1$ and Eq. (9) gives the maximum reaction chamber energy, E_r . In general when T_1 of Eq. (10) is negative the maximum E_r from Eq. (9) is obtained by putting $T = 1$. A case when Eq. (10) is useful in determining the optimum transmission occurs when the absorption in the reaction chamber is large, then

$$T_1 \sim \sqrt{\delta_{mo} \delta_o} - \delta_o \text{ for } \delta_r \gg (\sqrt{\delta_{mo} \delta_o} - \delta_o), \quad (11)$$

and since $1 \geq \delta_r$, then $T_1 \ll 1$, and we have a highly decoupled laser. That is, the laser is automatically isolated from the highly absorbing chamber which otherwise would quench lasing if T were large.

Assuming the laser lases in a single coherent mode of radius ω , parallel to the optical axis, the focal fluence per pass, n , is given by (Ref. 4, p. 316):

$$I_o = E_n / \pi \omega_o^2 = \pi E_n^2 / f^2 \lambda^2,$$

where E_n is the pass beam energy (circulating laser power for $T = 1$, or equals E_r otherwise), ω_o is the focused spot radius; f is the focal length of lens L ; and λ is the wavelength. If the lasing medium does not quench for a time τ , the optical path length of the whole common cavity is d , the cavities are nearly fully coupled, and the average circulating laser energy is E_A , then the total average fluence delivered at the focus is:

$$I_{tot} = \pi E_A^2 V_c \tau / f^2 \lambda^2 d \approx \pi E_A^2 v^2 \tau / f^2 V_c d,$$

where V_c is the velocity of light and v the frequency. The total number of passes is $n = V_c \tau / d$. For the laser we want to maximize the product $E_A^2 \tau$ for maximum fluence I_{out} ; that is, we want to have a broad beam of high average energy lasting for a long time. The other parameters are the well-known geometric factors of short focal length, high frequency or short wavelength, and short optical path.

The apparent advantages of the common-cavity design are:

1. Use of the (higher) circulating laser power rather than the external beam power. For weak absorbers, a higher cavity Q is possible than for external beam operation.
2. Maximum output coupling. Laser and absorber form a common stable resonator.
3. Very small useless reaction medium volume.
4. Very high light intensities.
5. A high number of passes, e.g., for say about 1.3 m total chamber length, M_1 to M_2 and non-quench for 200 ns one gets 46 passes through the focal point.

With disadvantages:

1. Refocus is at the same place which may deplete or bleach the reacting medium. However, one can compensate by exciting multimodes in the laser (or increase lasing gain) and thereby enlarge the active focal reaction region.
2. If the coupling is tight ($T \sim 1$), absorption chamber changes affect laser operation, requiring careful tuning.
3. For maximum production we have shown double duty elements such as a window performing also as a partial mirror. Efficiency is gained at the cost of some complexity.
4. Early medium quench implies inefficient use of the available light. External cavities are then indicated.

III. FOLDED NEAR-CONCENTRIC AND CONCENTRIC RESONATORS

General

The designs discussed in Secs. II and IV refocus either in precisely the same region (II) or nearly so (IV); we now suggest a design that refocuses in different regions in space, indeed dispartate regions if desired. We use a stable optical resonator for periodic refocusing and introduce the beam off-axis, forming thereby a folded optical delay line.^{5,6} Our requirement that the light be refocused into a small spot on each pass forces the delay line resonator to be near concentric. For example, a confocal resonator would refocus on every other pass, permitting useless absorption in the nonfocused pass and leading to excess superfluous volume in the reaction chamber. Of course the

confocal design (and others) could be used for weaker focusing on every pass with coherent beams; in our theory this corresponds to δ not small compared to d . For coherent beams our resonator will be just short of concentric; for poor beams there are advantages to the precisely concentric chamber.

Refer to Fig. 2. The reaction chamber is formed by two squashed pie segments of triangular cross section in elevation, bounded by spherical end mirrors, M_1 and M_2 , spaced d apart, which are of rectangular-like cross section. The mode-matching insertion lens, L , may either be external to the chamber proper or may actually form the entrance window. Generally mirrors withstand higher beam intensities than lenses or windows so the entrance window or lens L will, therefore, usually be further than $d/2$ from the line of foci. For a given spot size the minimum useless volume is achieved for d made as small as the damage threshold of the mirrors will permit. The foci lie along a straight line perpendicular to the optic axis in the x - z plane. The origin is located where mirror M_1 extended intersects the initial beam center, with x in the long mirror dimension and y in the short. The z -axis is in the initial cross-chamber dimension. The beam is of diameter $2w$, and for a diffraction-limited beam enters the chamber through a lens of diameter greater than $2w$. Usual practice is to have an

Fig. 2. Near-concentric spherical resonator reaction chamber.

aperture 50% greater than beam width in order to avoid severe truncation and diffraction. For poor-quality beams the chamber aperture actually should approach the width of the beam. For high-quality beams wider apertures might be indicated, but not much wider, as our arguments below indicate. For our purposes the diameter 2ω is taken as simply the desired beam truncation by the mirror M_1 , regardless of actual beam size. This parameter is a user option, but it is a critical parameter controlling pass number in a chamber of given geometry. The smaller 2ω , the more passes can be packed into the chamber. So it is, therefore, usually best to allow 2ω to be close to the effective beam diameter. Indeed near-superradiant lasers typically have a high-intensity core beam with weak wings, (i.e., sort of hat shaped). However if 2ω is made too small, the beam is truncated and diffracted excessively. One should not in any case allow the lens L to be an aperture stop of the system but rather make the mirror M_1 the limiting aperture. Mirror M_1 is at the minimum distance ω from the beam center at one point only, thus introducing a minimum of diffraction and that in the x-z plane. Thus, for many beams 2ω can actually be the beam diameter for optimum chamber illumination. The mirrors M_1 and M_2 are spherical, of focal length f , and the dimension A gives their effective arc length beginning at a distance δ from the optic axis (see Fig. 3).

Our objectives are to refocus the beam on each pass and to closely pack as many refocused images into the chamber as space will allow. To meet the former objective requires a concentric or near-concentric resonator. For both we utilize the theory of Herriott et al. on folded optical delay lines.^{5,6} We will first discuss the theory appropriate to coherent or nearly so beams; the treatment for poor-quality beams follows as a limit to the coherent case.

Fig. 3. Near-concentric cavity.

Coherent or Diffraction-Limited Beams

We set

$$d + \delta = 4f, \text{ with } 0 < \delta \ll d \text{ or } f, \quad (12)$$

thus forming a stable resonator. The mirror radius satisfies

$$R = 2f. \quad (13)$$

The usual coherent Gaussian beam-waist relation gives the focused spot radius ω_o :⁷

$$\omega_o^2 = \frac{\lambda}{2\pi} \sqrt{d(2R - d)} = \frac{\lambda d}{2\pi} \sqrt{\frac{\delta}{d}}, \quad (14)$$

which is to be compared with the spot radius from a coherent (parallel) beam of radius ω , focused by a lens of focal length f_1 , to a minimum radius ω_o (Ref. 4, p. 316):

$$\omega_o \sim f_1 \lambda / \pi \omega. \quad (15)$$

The spot size required (and wavelength) fix the product $d \sqrt{\delta/d}$. The corresponding beam radius ω at the entrance and on the mirrors must be:

$$\omega^2 = \frac{\lambda R}{\pi} \sqrt{2 \frac{R}{d} - 1} = \frac{\lambda d}{2\pi} \left(1 + \frac{\delta}{d}\right) \sqrt{\frac{\delta}{d}}, \quad (16)$$

thus,

$$\omega_o / \omega \sim \sqrt{\delta/d}. \quad (17)$$

Note that the power tolerances of mirrors, windows, and lenses limit the smallness of ω .

So much for beam resonance, now for insertion. The insertion lens should match the curvature of the incoming light-phase front to the curvature of the resonator wave front, i.e., to the radius of mirror curvature R , so that for a distant source or a parallel beam, $f_1 = R = 2f$, where f_1 is the focal length of the insertion lens if located at the entrance aperture. The intersection of the mirrors with the optic axis defines the origin of our Cartesian coordinate system whose x,y dimensions are in a plane perpendicular to the optic axis (see Fig. 3). Let the (central) entrance beam position be at some x_o, y_o , with slope x'_o ($x'_o \equiv dx_o/dz$) which is the slope of the beam center relative to the chamber

optic axis, z . Take $y'_0 \equiv 0$, which is no loss of generality. Each succeeding reflection on the mirrors will have successive integer indices so that x_1, y_1 is the position of the beam center at the first reflection on mirror M_2 , etc. Then from Herriott, Kogelnik, and Kampfer⁵ we have for the successive beam positions:

$$x_n = A \sin(n\theta + \alpha), \quad y_n = B \sin(n\theta + \beta), \quad (18)$$

where n is the pass number. In general, therefore, the repeated reflections fall on an ellipse which may in fact be converted to any Lissajous figure by making one mirror slightly astigmatic or by adding a small beam-sized deflecting mirror.⁶ Both for simplicity of reaction chamber design and for the gain in specific high-intensity reactivity obtainable from having the beam overlap itself, we will squash the ellipse of Eq. (18) into a straight line and thus consider a reaction chamber of the form of Fig. 2. Following Ref. 5 and Eq. (12) we have:

$$\cos\theta = 1 - (d/2f) = -1 + (\delta/2f), \quad (19)$$

and using $\delta \ll 2f$:

$$\theta \approx \pi - 2\sqrt{\delta/d}, \quad (20)$$

so that for $\delta \ll d$, the beam crosses to nearly the opposite, or 180° , position on a mirror at each pass. From Ref. 5 and Eq. (12), A and α are given by:

$$A^2 = (1 + d/\delta)(x_0'^2 + dx_0'x_0'' + dfx_0''^2), \quad (21)$$

$$\tan\alpha = \sqrt{\delta/d} / [1 + 2f(x_0'/x_0'')] \quad (22)$$

similarly for B and β . However, as we noted above, we will squash the ellipse to a line (in the x direction) by choosing $y_0', y_0'' = 0$ so that we put $\beta = 0$.

For irradiation of maximum intensity we want to pack as many passes into the chamber as possible without premature beam leakage through the entrance. Accordingly we calculate the spacing $\Delta_2 x_n$ between reflection spots on a given mirror:

$$\Delta_2 x_n = x_{n+2} - x_n = 2A \cos[(n+1)\theta + \alpha] \sin\theta$$

$$\Delta_2 x_n \approx (-1)^{n+1} 4A\sqrt{\delta/d} \cos[-\alpha + 2\sqrt{\delta/d}(n+1)], \quad (23)$$

$$\delta \ll d,$$

using Eqs. (18) and (20).

In order to just miss the entrance aperture we must spread the beam paths (i.e., make $\Delta_2 x_0 > 0$) but as little as possible. As discussed above we define our aperture to be 2ω and so we set

$$2\omega = \Delta_2 x_0. \quad (24)$$

Again as discussed above, for a high-quality beam one might want the aperture greater than the beam diameter, but usually not much more, for best absorption. We also want to insert the beam at such a phase α in Eq. (18) where the spacing $\Delta_2 x_0$ is a relative maximum so that the rest of the beam spacings are correspondingly as close as possible. Clearly, from Eq. (23), that optimum occurs in $\Delta_2 x_0$ for $\alpha = 0$, ($\delta \ll d$), i.e.,

$$\Delta_2 x_n \approx (-1)^{n+1} 4A\sqrt{\delta/d} \cos[2\sqrt{\delta/d}(n+1)],$$

$$\Delta_2 x_0 \approx -4A\sqrt{\delta/d}. \quad (25)$$

We thus achieve gradually increasing beam overlap elsewhere which is complete at the turning point, pass number $n+1 = (\pi/4)\sqrt{d/\delta}$. Achieving both above objectives results in maximum passes in the available geometry.

Thus we insert our beam at $x_0' = 0 = y_0' = y_0''$ with $\alpha = 0$ so that $x_0' \neq 0$ and

$$A^2 = (1 + d/\delta)dfx_0'^2 = (d^2/4)(1 + \frac{d}{\delta})(1 + \frac{\delta}{d})x_0'^2,$$

or

$$A = (dx_0'/2)(\sqrt{d/\delta} + \sqrt{\delta/d}). \quad (26)$$

Equations (24) and (25) then give, for the insertion slope, x_0' of beam center:

$$x_0' = \omega/d, \quad (27)$$

which is hardly surprising, for Eq. (27) simply says that to move 2ω in the x coordinate while moving $2d$

in the z coordinate, we get an average slope $dx/dz = 2\omega/2d$. Equation (27) fixes the insertion slope x'_0 in terms of chamber and beam parameters.

Referring to Eq. (26), the remaining parameter to be fixed is δ , or δ/d , and it determines or is determined by the extent, A , of the beam reflection position's travel on the mirrors. To maximize the number of refocussed passes, A will equal the arc length of mirror available, and thus, by Eq. (26), will fix δ . We now can compute our beam center reflection positions from Eqs. (18), (20), and (26) to be:

$$x_n = (-1)^{n+1} A \sin 2n\sqrt{\delta/d},$$

and

$$x_n = (-1)^{n+1} (\omega/2) \sqrt{d/\delta} \sin 2n\sqrt{\delta/d}, \quad \delta \ll d. \quad (28)$$

In our configuration the beam has effectively leaked out of the entrance aperture when $x_n = x_0$, giving an effective maximum pass number $\bar{n}$ from Eqs. (23), (27), and (26):

$$2\bar{n}\sqrt{\delta/d} = \pi \text{ or } \bar{n} = (\pi/2) \sqrt{d/\delta} = \pi A/\omega. \quad (29)$$

Although n in Eq. (28) is an integer, $\bar{n}$ is not necessarily an integer. Noninteger values of $\bar{n}$ simply describe the situation when a portion of the beam completes two extra passes more than the rest, so $\bar{n}$ is a useful effective pass number. We observe that $\bar{n}$ is a maximum for the largest mirror, A , and the smallest beam radius or entrance aperture radius,

Equation (29) gives the maximum effective pass number for one-half a squashed ellipse. If we let $y_0 = \omega$, then the return elliptic path will just miss the entrance and we can get a full ellipse. However, for a given mirror size this corresponds to central beam insertion with swings of only one-half the amplitude A which by Eq. (26) means $\sqrt{d/\delta} \rightarrow 1/2 \sqrt{d/\delta}$ and the expected doubling of $\bar{n}$ from Eq. (29) is therefore precisely removed or compensated, so the full ellipse offers no advantage over the half ellipse. However, there may be insertion conveniences of one versus the other.

The beam-center focused positions, x_{fn} , may be obtained from Eq. (28) by:

$$\begin{aligned} x_{fn} &= (x_n + x_{n-1})/2 \\ &= (-1)^{n+1} (\omega/2) \cos[(2n-1)\sqrt{\delta/d}] \end{aligned} \quad (30)$$

where n is the n th focus.

Thus the line of foci in Figs. 2 and 3 have length $\omega + 2\omega_0$. From Eq. (30) we observe that as n increases from the value 1, the focused beams overlap more and more until at $(2n-1)\sqrt{\delta/d} = \pi/2$ or $x_{fn} = 0$, the overlap is complete; then the overlap again decreases with higher n . For some purposes it may be desired to have concentrated foci or to have no mirror beam overlap. Our theory also describes such a situation. Totally disparate images may also be obtained by describing a circle in place of a squashed ellipse, or increasing ω and using an ellipse. The treatment is identical to the foregoing except that x_0 , y_0 , y_n , and $\beta = \alpha - \pi/2$ are no longer zero. For the case of a circle:

$$x_n \sim (-1)^n x_0 \cos[(2n-1)\sqrt{\delta/d}] \text{ (circle),}$$

and

$$y_n \sim (-1)^{n+1} x_0 \sin[(2n-1)\sqrt{\delta/d}],$$

$$\delta \ll d, \text{ (circle).} \quad (31)$$

Note that we need mirrors of diameter $2(x_0 + \omega)$ and that we describe a circle of radius x_0 on the mirrors. The foci are evenly spaced around a circle of radius

$$r = x_0 \sqrt{\delta/d} (1 + \delta/d), \quad (32)$$

and are disparate when

$$x_0(1 + \delta/d)\sqrt{\delta/d} > \lambda d/2\pi, \quad (33)$$

or roughly for $x_0 > \omega$, a condition usually met or meetable in practice. The maximum pass number obtained from full travel around the circle is given by

$$\bar{n} = \pi\sqrt{d/\delta} \text{ (circle);} \quad (34)$$

just twice half an ellipse [see Eq. (29)] as it should be (but the mirrors are twice the linear

extent and much bigger in area). Beyond these summary remarks and Fig. 4, we say no more on the circular cavity. Unless disparate images are desired, the complexity of the chamber depicted in Fig. 4 argues against its use.

Coherent Beam — Concentrated Foci

In Figs. 2 and 3 let us replace the mirror lengths A by L and reserve A to be solely the amplitude of beam excursion in Eq. (28). Take the limit $A \rightarrow \infty$; then Eq. (26) implies $\delta \rightarrow 0$, and Eq. (26) further implies in Eq. (23) that

$$\Delta_2 x_n \rightarrow (-1)^{n+1} 2\omega; \quad (35)$$

that is, the beam spacing along each mirror is constant with n and equal to the original mirror spot diameter. The total number of passes is:

$$\bar{n} = L/\omega, \quad (36)$$

and is quite a bit less than half the passes (precisely $1/\pi$ of the passes) obtainable through mirror overlap, Eq. (29). Equation (30) ($\delta \rightarrow 0$) shows that the foci are concentrated at the positions $x_f = \pm \omega/2$, with half the passes, namely $\bar{n}/2 = L/2\omega$, in each.

Poor Quality Beams

The foregoing theory treated a coherent beam; now suppose that the beam quality is poor, but a well-defined focus of diameter S_1 is possible. All the foregoing theory of beam-center location, pass numbers, beam spacing, insertion angle, and the like, remain the same. New to this case is the image size, no longer determined by Eq. (14) or (17), and also not necessarily constant. The

Fig. 4. Circular, near-concentric spherical-resonator reaction chamber.

insertion lens provides the first focus, diameter S_1 , at the center of the chamber, $Z = d/2$. The first image by the mirror M_2 (Fig. 2) of S_1 is of diameter S_2 . Let the object distances be U_n , the image U'_n , n is the image number, then the well-known relation

$$1/U_n + 1/U'_n = 1/f \quad (37)$$

obtains, where n is the pass number in object space. The ratio of image size to image distance then leads to:

$$S_{n+1}/S_n = U'_n/U_n = f/(U_n - f) = \frac{d - U_{n+1}}{U_n} \quad (38)$$

For $n = 1$, $U_n = d/2$, we then have:

$$S_2/S_1 = 1 + (2\delta/d), \quad \delta \ll d, \quad (39)$$

and

$$U_2 = (d/2)\{1 - (2\delta/d)\}, \quad \delta \ll d. \quad (40)$$

We must solve Eq. (38); Eq. (40) suggests that U_n is of the form

$$U_n = d/2(1 - \Delta_n). \quad (41)$$

Substituting in Eq. (38) and using Eq. (12), we find that Δ obeys

$$\Delta_{n+1} = \Delta_n + 2(\delta/d), \quad (42)$$

and, from Eq. (40), $\Delta_2 = 2(\delta/d)$ so that

$$\Delta_n = 2(n-1)(\delta/d), \quad (43)$$

and we have then from Eqs. (38) and (12) again:

$$S_{n+1}/S_n = 1 + 2(2n-1)(\delta/d). \quad (44)$$

Whence for $\delta \ll d$,

$$S_n/S_1 = (S_n/S_{n-1})(S_{n-1}/S_{n-2}) \dots (S_2/S_1),$$

$$S_n/S_1 \approx 1 + 2(\delta/d) \sum_{n=1}^{n=n-1} (2n-1), \text{ or}$$

$$S_n/S_1 \approx 1 + 2n^2(\delta/d), \quad \delta \ll d; \quad (45)$$

and from Eq. (41) and $z_n = U_n$ for n even, and $z_n = d - U_n$ for n odd:

$$z_n \sim (d/2)[1 + (-1)^{n+1} 2(n-1)(\delta/d)],$$

$$\delta \ll d, \quad (46)$$

giving the relative size and location of the n th image. Equation (45) shows that the image grows quadratically in linear dimensions with pass number. We can decrease the image growth, improve image location control, and increase the pass number by making (δ/d) small [Eq. (29)], that is, by making A/ω large:

$$\sqrt{\delta/d} = \omega/2A. \quad (29a)$$

Because the mirrors are spherical we can approach total enclosure with $A \rightarrow \pi d/2$ (we ignore spherical aberration for these small beams). The amount that ω can be reduced is limited by intensity and heat tolerance of the mirrors.

Poor Quality Beams — Constant Image Size

The above theory optimizes irradiation of a narrow linear region by maximizing the number of passes and therefore gives up constancy of the refocused image size. We also have the option of holding the image size strictly constant by giving up a bit over 1/3 the passes obtainable above. We obtain the latter case in the limit $A \rightarrow \infty$. Then Eq. (29a) shows that $\delta \rightarrow 0$ and so by Eqs. (45) and (46) the image sizes and positions are constant. Since Eq. (27) does not contain A , it applies as written and determines the insertion slope x'_0 for the returning beam so as to just miss the entrance aperture. Moreover, Eq. (27) is predicated on an initial 2-pass progression in the x direction of one beam width, namely 2ω . For $A \rightarrow \infty$ this becomes a uniform progression for all paths amounting, therefore, to ω per pass. Thus the total number of passes for mirror length L is again given by:

$$\bar{n} = \text{mirror length times two/beam diameter at entrance (constant image size)}. \quad (36)$$

Table I lists a few examples of what can be done with a poor-quality beam. The very large curved

mirror lengths A (or L) there form a nearly totally enclosed spherical mirror cavity in the plane of the two beams, and these cavity sizes are included primarily to show the maximum absorption. Column 6 gives the maximum passes in the given chamber, but its highly favorable results for near concentric (odd rows), must be tempered a bit by the results of succeeding columns which give the pass number at which the image linear size has doubled (Column 7) and the central image location at that pass number measured from the center of the chamber (Column 8). The even-numbered rows show what can be done for constant image size and spacing obtained by using a spherical concentric cavity. The pass numbers for concentric cavities are indeed very respectably high and therefore strict concentric is a useful option.

Systems Analysis for the Near-Concentric Chamber — Coherent Beam Examples

Normally in designing an irradiation chamber, a known fixed laser energy or fluence, I , is available and one wants to achieve a maximum focused reaction energy or fluence I_0 ; thus the parameter ω_0 is fixed by $I_0 = I\omega_0^2/\omega^2$. Refer to Eqs. (14) and (16). The damage limitations of optical devices will limit the beam radius ω , and physical sizes and optics will limit d and the ratio A/d or L/d . Thus starting with ω_0 and (say) A/d , one gets an array of possible values for ω , d , n , I , etc., which we exhibit in Table II. However the systems analysis can be simplified considerably by rearranging the foregoing theory. Define:

$$a \equiv \lambda d/2\pi, \quad b \equiv \sqrt{\delta/d}. \quad (47)$$

Then, per Eq. (14),

$$\omega_0^2 = ab, \quad (48)$$

and using Eq. (17),

$$b = \omega_0/\omega. \quad (49)$$

Thus,

$$a = \omega_0 \omega. \quad (50)$$

Equations (29) or (29a) yield

TABLE I
POOR BEAM CONCENTRIC AND NEAR CONCENTRIC REFOCUSING EXAMPLES
(0.6-cm diam laser beam focused to 0.2-cm diam at the center of the chamber by a 50-cm lens)

Example Number	Chamber Width d (cm)	Beam Diameter at Entrance 2ω (cm)	Mirror Length A (or L) (cm)	δ/d Eq. (15)	Maximum Passes [Eq. (9) or Eq. (17)]	Pass Number at which Image Diameter has Doubled from Eq. (13)	Doubled Image Location from Center Line from Eq. (14) (cm)	Remarks
1	40	0.36	30	9 (-6)	523.6	235.7	0.085	
2	40	0.36	30	0	166.7	---	---	Constant Images (A $\rightarrow \infty$)
3	40	0.36	10	8.1 (-5)	174.5	78.6	0.25	
4	40	0.36	10	0	55.6	---	---	Constant Images
5	40	0.36	5	3.24(-4)	87.3	39.3	0.51	
6	40	0.36	5	0	27.8	---	---	Constant Images
7	10	0.24	7.5	6.4 (-5)	196.3	88.4	0.023	
8	10	0.24	7.5	0	62.5	---	---	Constant Images
9	10	0.24	5	1.44(-4)	130.9	58.9	0.085	
10	10	0.24	5	0	41.7	---	---	Constant Images
11	4	0.216	2	7.29(-4)	58.2	26.2	0.076	
12	4	0.216	2	0	18.5	---	---	Constant Images

TABLE II
FOLDED NEAR CONCENTRIC PARAMETER STUDY
(1.5-J coherent beam, 10.6- μ m wavelength)

Number	Focused Spot Radius ω_0 (cm)	Average Focused Spot Fluence I_0 (J/cm ²)	Aspect Ratio A/d	Chamber Length d (cm)	Mirror Effective Curved Width A (cm)	Initial Beam Radius ω (cm)	Length Line of Foci $\omega+2\omega_0$ (cm)	Average Initial Beam Fluence I (J/cm ²)	Total Number of Focused Passes n
1	2(-2)	1 194	$\pi/2$	883.	1387.	7.45	7.49	0.0086	585.
2	2(-2)	1 194	$\pi/4$	442.	347.	3.72	3.76	0.034	293.
3	2(-2)	1 194	1/3	187.	62.5	1.58	1.62	0.19	124.
4	2(-2)	1 194	1/4	141.	35.1	1.19	1.23	0.34	93.
5	2(-2)	1 194	1/10	56.2	5.62	0.47	0.51	2.12	37.2
6	1(-2)	4 775	$\pi/2$	110.	173.	1.86	1.88	0.14	293.
7	1(-2)	4 775	$\pi/4$	55.1	43.3	0.93	0.95	0.55	146.
8	1(-2)	4 775	1/3	23.4	7.81	0.40	0.42	3.06	62.1
9	1(-2)	4 775	1/4	17.6	4.39	0.30	0.32	5.44	46.6
10	1(-2)	4 775	1/10	7.03	0.70	0.12	0.14	34.	18.6
11	5(-3)	19 099	$\pi/2$	13.8	21.7	0.47	0.48	2.2	146.
12	5(-3)	19 099	$\pi/4$	6.9	5.42	0.23	0.24	8.8	73.1
13	5(-3)	19 099	1/3	2.93	0.98	0.099	0.11	49.	31.
14	5(-3)	19 099	1/4	2.2	0.55	0.074	0.084	87.	23.2
15	5(-3)	19 099	1/10	0.88	0.09	0.03	0.04	544.	9.3
16	2(-3)	119 366	$\pi/2$	0.88	1.39	0.074	0.077	86.	58.5
17	2(-3)	119 366	$\pi/4$	0.44	0.35	0.037	0.041	344.	29.3
18	2(-3)	119 366	1/3	0.19	0.06	0.016	0.02	1911.	12.4

$$A = \omega/2b = \omega^2/2\omega_0, \delta \ll d. \quad (51)$$

Equation (47) then gives

$$d = 2\pi a/\lambda = 2\pi\omega_0\omega/\lambda, \quad (52)$$

so that

$$A/d = (\lambda/4\pi)(\omega/\omega_0^2). \quad (53)$$

For normal use the aspect ratio might reasonably be $A/d \lesssim 1/3$, see Fig. 2. As we've noted, A/d can approach total enclosure, i.e., $A/d \rightarrow \pi/2$; the line of foci is then surrounded by the mirrors. Much smaller aspect ratios than, say, $1/3$ or so give needlessly ineffective absorption because of long path lengths, d , per pass.

Equation (29) gives the total possible number of passes before exit:

$$\bar{n} = \pi/2b = \pi\omega/2\omega_0. \quad (54)$$

Equation (30) gives the extent of the line of foci, $\omega + 2\omega_0$. Starting, therefore, with ω_0 , λ , and A/d , Eq. (53) gives ω , whence Eq. (52) gives d , Eq. (54) gives $\bar{n}$, and

$$I = E/\pi\omega^2 \quad (55)$$

gives the original average beam fluence at the aperture (diameter 2ω) for beam energy E .

In Table II we give a study over a very limited range of parameters for a coherent 10.6- μm beam of 1.5 J. For poor-quality beams other parameters are possible; see, for example, Table I. Note that Table II can be used as a basis for estimates as well as used literally. Thus, for example, an intensity I of 544 J/cm² (Row 15) on the mirrors is far in excess of present day tolerances. As a second example one might use the parameters of Row 11 to get $\sim 20\,000$ J/cm² per repeated focus from a 1-cm-diameter beam, but in a chamber of mirror length L less than the full $A = 21.7$ cm at the sacrifice of a high pass number (147). For $L < A$ the pass number immediately drops to one-half or less because there is no return of the beam to the entrance.

In Table II we have chosen four focused spot sizes of radius ω_0 , and five chamber dimensions of

differing aspect ratio A/d , from which, given the beam energy and frequency, we have a completely determined problem for a coherent beam, and from which we can calculate the beam entrance aperture radius, the chamber length d , and the mirror length for full turnaround A , the intensities at beam waist and at the mirrors, and the total number of possible passes $\bar{n}$. Mirror fluences of the order of 100 J/cm² for short (< 1 μs) pulses exceed tolerances at this time; such intensities are included for scaling purposes.

Advantages and Disadvantages of the Folded Concentric and Near-Concentric Resonators

Advantages

1. Refocuses a beam to the same size, image or waist, if desired.
2. Refocuses on a line, on two points, or in general along any Lissajous figure, so that either distributed or concentrated foci are available.
3. Refocuses on each pass.
4. Leaves a very small, useless reaction volume in the medium.
5. Uses an external beam, so that laser and reaction chamber can be worked on separately.
6. Beam repetition can be made disparate and can thus be counted and if need be "dumped" or reinserted.
7. Images can be made disparate.
8. A high number of refocusing passes are possible, many hundreds if desired.
9. Adaptable to beams of any quality.
10. Very high light intensities are possible.

Disadvantages

1. For coherent beams the resonator and beam sizes are interdependent (Table II), limiting flexibility.
2. Again for coherent beams, high spot intensity implies high mirror intensities or low pass number.
3. For poor-quality beams higher pass numbers imply quadratic growth of image size.
4. Not as tightly coupled to the laser as the common cavity so that effective beam power on target is therefore lower.
5. Needs matching or insertion optics.

IV. ASYMMETRIC CONFOCAL RESONATOR

Because the asymmetric confocal resonator³ (Fig. 5) has the property of trapping, compressing, and focusing a beam for a time, it has merit, perhaps superior merit, for high-intensity reaction chamber design. Indeed it usually gives the highest absorption in weakly absorbing distributed media.³

However, compression and trapping of the beam are directly limited by mirror tolerances and the (strong) focusing, which is not so limited, occurs only on every other pass so that ab initio the confocal resonator is not as suitable as the foregoing designs for very high intensity chambers. In the notation of Ref. 3., we define the width of the cavity between mirrors W , the radius of the mirrors $\ell + 2c$, the beam radius c , the insertion radius $\ell + C$, and the effective total loss per pass $1 - \Lambda$; and calculate thereby the parameters of Table III for an energy $E_0 = 1.5$ J at a wavelength of $10.6 \mu\text{m}$ for a coherent or diffraction-limited beam. The resonator will do less well for poorer beams. We take the far-field spread of the beam to be $\lambda/\pi c$ (Ref. 4, p. 309) so that,

$$e/d_0 = \lambda/\pi c. \quad (56)$$

The ratio of focal lengths s , Column 7, Table III, is determined from Ref. 3, Eq. (42):

$$(\lambda/\pi c)Ws(s^3 + s^2 + s + 1) - \ell s^2 + (\ell + 2c) = 0. \quad (57)$$

The radius of the first focal spot, ω_0 , Column 8, from Ref. 3 [Eqs. (47) and (2)] is:

$$\omega_0 = Ws\lambda/\pi c(1 + s). \quad (58)$$

The average fluence at first focus, I_{fo} , Column 9, is:

$$I_{fo} = E_0/\pi\omega_0^2. \quad (59)$$

The summed average fluence, I , at focus, Column 10, is [Ref. 3, Eq. (50c)]:

$$I \approx I_{fo}/[1 - (\Lambda^2/s^2)]. \quad (60)$$

The pass number, $2n'$, at which the beam edge just reaches the center is given by Ref. 3, Eqs. (51b)

Fig. 5. Asymmetric confocal resonator reaction chamber.

and (56), to:

$$2n' = \ell n(\ell/\omega_0)/\ell n s = \bar{n}, \quad (61)$$

where $2\bar{n}$ (Column 13) is the pass number at which the beam just begins to leak back out the entrance aperture. The total fluence at the mirror centers I_c , Column 11, was obtained from Eq. (54) of Ref. 3:

$$I_c \approx I(\Lambda/s)^{2n'}. \quad (62)$$

The time for the beam to complete a round trip in the chamber, τ , Column 12, is given by

$$\tau = 2W/v_c, \quad (63)$$

where v_c is the velocity of light. Last, the initial beam fluence, I_0 , Column 6, is:

$$I_0 = E_0/\pi c^2. \quad (64)$$

One figure of merit of the confocal cavity is the ratio of the summed focus fluence, I , to the central mirror fluence, I_c , i.e., the maximum chamber fluence to the maximum mirror fluence. Note that I_c is only the maximum mirror fluence when s/Λ is not too different from unity. From Eq. (62) and using Eqs. (61) and (58):

$$I/I_c = (s/\Lambda)^{\bar{n}} = \ell\pi c(1 + s)/(Ws\lambda \Lambda^{\bar{n}}), \quad (65)$$

so that to maximize this ratio we want a large mirror radius ℓ , a large beam radius c , minimum focal length ratio $s > 1$, minimum cross-chamber path, W , and maximum number of paths, $2\bar{n}$, within the chamber [leading again to minimum s , maximum ℓ , etc. from Eq. (61)]. We do not want minimum Λ , in spite of Eq. (65), because $1 - \Lambda$ is the beam absorption

TABLE III
ASYMMETRIC, CONFOCAL RESONATOR PARAMETER STUDY
(1.5-J coherent beam, 10.6- μ m wavelength)

Run Num- ber	Chamber Length W (cm)	Chamber Mirror Minimum Radius ℓ (cm)	Beam Radius C (cm)	Initial Beam Fluence, I_0 (J/cm ²)	Total Fractional Loss per Pass $1 - A$	Ratio of Mirror Focal Lengths S	First Focus Spot Radius ω_0 (cm)	First Focus Fluence, I_{f0} (J/cm ²)	Summed Focus Fluence, I (J/cm ²)	Central Fluence, I_c (J/cm ²)	Round- Trip Time (2 Passes) (nsec)	Pass Number at Beginning of Leak- out, $2n$
1	2.	0.5	0.5	1.91	0.005	1.736	8.56(-4)	651 080	969 582	1567.	0.13	23.
2	2.	0.5	0.5	1.91	0.10	1.736	8.56(-4)	651 080	890 380	452.	0.13	23.
2A	2.	0.5	0.5	1.91	0.20	1.736	8.56(-4)	651 080	826 616	108.	0.13	23.
3	2.	0.5	0.2	11.94	0.005	1.345	1.94(-3)	127 496	281 661	992.	0.13	37.4
4	2.	0.5	0.2	11.94	0.10	1.345	1.94(-3)	127 496	230 893	124.	0.13	37.4
4A	2.	0.5	0.2	11.94	0.20	1.345	1.94(-3)	127 496	197 309	11.7	0.13	37.4
5	2.	0.5	0.1	47.7	0.005	1.186	3.66(-3)	35 614	120 136	762.	0.13	57.6
6	2.	0.5	0.1	47.7	0.10	1.186	3.66(-3)	35 614	83 920	29.6	0.13	57.6
7	2.	0.5	0.1	47.7	0.20	1.186	3.66(-3)	35 614	65 324	0.8	0.13	57.6
8	10.	0.5	0.5	1.91	0.005	1.753	4.30(-3)	25 861	38 155	314.	0.67	17.
8A	10.	0.5	0.5	1.91	0.10	1.753	4.30(-3)	25 861	35 119	123.6	0.67	17.
9	10.	2.	0.5	1.91	0.005	1.226	3.72(-3)	34 573	101 384	161.	0.67	61.8
9A	10.	2.	0.5	1.91	0.10	1.226	3.72(-3)	34 573	75 021	5.4	0.67	61.8
10	10.	2.	1.	0.48	0.005	1.415	1.98(-3)	122 147	241 530	216.	0.67	39.8
10A	10.	2.	1.	0.48	0.10	1.415	1.98(-3)	122 147	205 082	24.9	0.67	39.8
11	10.	2.	2.	0.12	0.005	1.733	1.07(-3)	417 175	622 219	311.	0.67	27.4
12	10.	2.	2.	0.12	0.10	1.733	1.07(-3)	417 175	571 170	72.2	0.67	27.4
13	10.	2.	2.	0.12	0.20	1.733	1.07(-3)	417 175	530 102	13.3	0.67	27.4
14	10.	2.	0.2	11.94	0.005	1.096	8.82(-3)	6 134	34 786	114.2	0.67	118.
15	10.	2.	0.2	11.94	0.10	1.096	8.82(-3)	6 134	18 809	0.2	0.67	118.
16	10.	2.	0.2	11.94	0.20	1.096	8.82(-3)	6 134	13 119	1.1(-4)	0.67	118.
17	50.	10.	0.5	1.91	0.005	1.049	1.73(-2)	1 600	15 958	14.2	3.33	266.
18	50.	10.	0.5	1.91	0.10	1.049	1.73(-2)	1 600	6 064	8.6(-6)	3.33	266.
19	50.	10.	1.	0.48	0.005	1.096	8.82(-3)	6 137	35 022	21.	3.33	154.
20	50.	10.	1.	0.48	0.10	1.096	8.82(-3)	6 137	18 872	5. (-3)	3.33	154.
21	50.	10.	1.	0.48	0.20	1.096	8.82(-3)	6 137	13 147	4. (-7)	3.33	154.
22	50.	10.	2.	0.12	0.005	1.183	4.57(-3)	22 843	77 947	28.3	3.33	91.4
23	50.	10.	2.	0.12	0.10	1.183	4.57(-3)	22 843	54 180	0.2	3.33	91.4
24	50.	10.	2.	0.12	0.20	1.183	4.57(-3)	22 843	42 068	7. (-4)	3.33	91.4
25	50.	10.	5.	0.02	0.005	1.414	1.98(-3)	122 209	241 942	42.3	3.33	49.2
26	50.	10.	5.	0.02	0.10	1.414	1.98(-3)	122 209	205 357	3.	3.33	49.2
27	50.	10.	5.	0.02	0.20	1.414	1.98(-3)	122 209	179 697	0.2	3.33	49.2

per pass and clearly we do not want to increase useless absorption. Equation (65) is only an appropriate figure of merit when the loss $(1 - \Lambda)$ is small enough to make the central fluence the maximum on the mirrors. For small Λ , the ratio I/I_0 is a more relevant figure of merit.

It is to be noted that the asymmetric confocal resonator gains high fluence by trapping the beam for a relatively long time ($t = \infty$ for rays passing through the confocal point) so that time-dependent reactions will behave differently in this chamber. Also, the image size grows proportional to s^{2n} (Ref. 3) where n is the number of passes.

Advantages of the Asymmetric Confocal Resonator

1. Gives high volumetric, intensity-independent irradiation efficiency, indeed generally the highest of external beam designs.
2. Provides concentrated central illumination.
3. Has a small useless reaction volume in the medium.
4. Compresses and overlaps as well as focuses beam.
5. Uses an external beam.
6. Yields a very high number of passes (∞ for rays through the confocal point).

Disadvantages

1. Requires high-quality beam.
2. Useless volume is the highest of the cases discussed.
3. The summed focused intensity is mirror-damage limited to a greater degree than the other designs.
4. Using an external beam means lower power compared to the common cavity.
5. Needs insertion optics.
6. Refocuses beam every other pass.
7. Image size, beam size and position are continually varying. Has a single maximum integrated fluence region.

V. FINAL REMARKS

It is not possible to a priori recommend one cavity over another for very high intensity illumination. Nor are the lists of advantages and disadvantages really sufficient for more than a first assessment. The parameters of each circumstance should be inserted into the appropriate formulae in order to select the best cavity. Not fully represented here is the important factor of convenience to the operator or experimentalist, which to a large extent must be individually determined.

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