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Publication Date
1976-07-01

Submitted to Physical Review Letters

LBL-5182
Preprint c. /

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July 1976

Prepared for the U. S. Energy Research and
Development Administration under Contract W-7405-ENG-48

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Submitted to Physical Review Letters LBL-5182

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ABSTRACT

We have made quantitative measurements on the characteristics of self-focusing varying from transient to quasi-steady-state. The results agree well with a simple unified physical description of self-focusing and with known theoretical predictions. Stimulated Brillouin scattering is identified as the mechanism responsible for the limiting diameter of the self-focused beam in our experiment.

Self-focusing of light has long been a subject of great interest in nonlinear optics.[1] While many aspects of the phenomenon are now well understood, a number of important questions still remain to be answered. In particular, it is not clear how self-focusing behaves differently if the laser half-power pulsewidth t_p is varied with respect to the relaxation time τ of the field-induced refractive index in the medium. Earlier experiments have supported the moving focus model for self-focusing in the quasi-steady-state case ($t_p/\tau >> 1$)[2,3] and the dynamic trapping model in the transient case ($t_p/\tau \lesssim 1$).[4] The physical pictures of these two models are seemingly very different; one may therefore ask how the self-focusing picture would change from moving focus to dynamic trapping as t_p/τ varies from one limit to the other. In this paper, we first present a unified physical description of self-focusing for all cases. We then show that by using a liquid crystalline material as the nonlinear medium, we can make quantitative measurements on self-focusing varying from the transient to the quasi-steady-state limit. Our experimental results strongly support the unified description. We have also been able to identify the mechanism limiting the focal diameter in our case.

The main difference between various cases of self-focusing is the way consecutive sections of a laser pulse self-focus and diffract. This forms the basis of our unified physical description. In the quasi-steady-state limit, the field-induced refractive index Δn responds almost instantaneously to the laser intensity variation, causing rather abrupt self-focusing followed by strong diffraction. In the transient case, Δn depends on the past history of the local field intensity and varies more slowly than the laser intensity. Self-focusing and diffraction then become more gradual in the more transient case. Following this description, we can construct an overall picture of how a laser pulse changes its spatial profile in the process of self-focusing as shown in Fig. 1.

Figure 1(a) describes the quasi-steady-state case. Each consecutive section (a - a, b - b, ---, etc.) of the pulse with an instantaneous power $P(\xi)$ self-focuses abruptly at the focal distance[5,6]

$$z_f(t) = K/\left[\sqrt{P(\xi)} - 0.858\sqrt{P_{cr}}\right] \qquad (1)$$

where $\xi = t - z_f n/c$, and K and P_{cr} are constants. The subsequent diffraction is also very abrupt, so each section forms a sharp focal spot. Thus in general, for $z > (z_f)_{min}$, an instantaneous snap shot of the laser pulse in the medium would show that two sections of the pulse have shrunk into two sharp focal spots. The relative positions of these spots within the pulse vary with time. This is just another way of describing the moving foci. (In practice, the first focal spot induces backward stimulated Raman and Brillouin scattering[7] which effectively eliminates the lagging section after the first focal spot in the snap shot.) As t_p/τ becomes smaller, the transient response of Δn gradually sets in so that self-focusing and diffraction become less abrupt as shown in Fig. 1(b). Self-focusing of a later section of the pulse now depends to some extent on the self-focusing dynamics of the earlier sections of the pulse. As a result, even the end part of the pulse now weakly self-focuses. The focus appears more like a line than a spot although its relative position within the pulse still varies with time. Finally, Fig. 1(c) describes the extreme transient case.[4] The end part of the pulse now self-focuses gradually but strongly into a limiting diameter. Because of the large Δn induced in the focal region by the earlier part of the pulse, the divergence after focusing is very weak. The result is that the input pulse should first deform into a horn shape and then propagate on without much further change.[4] As we shall see, Fig. 1 does give a good qualitative description of the variation of self-focusing from the quasi-steady-state to the transient limit.

Experimental investigation of self-focusing has so far been limited to either the quasi-steady-state case or the extreme transient case. The difficulty lies in the fact that neither the laser pulsewidth t_p nor the relaxation time τ for an ordinary medium can be easily adjusted. We have recently found that Δn and τ for a nematic liquid crystalline medium in the isotropic phase are both strong functions of temperature T and can be written as[8]

$$\Delta n(t) = \frac{A}{\tau(T-T^*)}\int_{-\infty}^{t} I(t')e^{-(t-t')/\tau}\, dt'$$

$$\tau = [B/(T-T^*)] \exp(W/kT) \qquad (2)$$

where A, B, and W are constants independent of temperature, T^* is a ficticious second-order transition temperature only slightly below the real isotropic-nematic transition temperature, and I(t) is the time-varying laser intensity. By adjusting T, we can vary τ continuously from a few nsec to a few hundred nsec.[8] Then, if $t_p \sim 10$

nsec, we can have t_p/τ vary from $t_p/\tau >> 1$ to $t_p/\tau << 1$. In the quasi-steady-state limit, $\Delta n(t) = AI(t)/(T-T^*)$, while in the extreme transient limit, $\Delta n(t) = (A/Be^{W/kt})\int_{-\infty}^{t} I(t')dt'$. In all cases, $\Delta n(t)$ induced by a Q-switched laser pulse in such a medium can be sufficiently strong to cause self-focusing.

We used in our experimental investigation a single- mode Q-switched ruby laser pulse with a pulsewidth of 15 nsec, a diameter of 260 μm, and a maximum peak power of 20 kW. The self-focusing medium was p-ethoxybenzylidine-p-butylaniline (EBBA) in a 10-cm cell enclosed by a thermal-controlled oven. By varying the temperature from 79°C to 131°C, τ of EBBA was varied from 70 nsec to 1.3 nsec.[8] To study the self-focusing dynamics, we measured the time-varying on-axis intensity at the end of the cell with respect to the total laser power.[4] Then, assuming that the transverse profile of the focused beam was always a Gaussian, we could deduce the beam radius as a function of time at the end of the cell. We checked the results by simultaneously imaging the self-focused beam at the end of the cell onto a streak camera with a time resolution of about 1 nsec. The pictures thus obtained with different input laser powers were qualitatively the same as those snap shot pictures along z in Fig. 1. We also took time-integrated photographs of the self-focused beam at the end of the cell and monitored the possible appearance of stimulated Raman and Brillonin scattering.

We made a series of measurements with different input laser powers for each of the following values of t_p/τ: 11.3, 5.2, 2.07, 0.47, and 0.21. In Fig. 2, we present a typical set of results at a certain input power showing clear self-focusing for three cases: (I) near quasi-steady-state limit, $t_p/\tau = 11.3$; (II) intermediate case, $t_p/\tau = 5.2$; (III) near transient limit, $t_p/\tau = 0.21$. Figures 2(a) and 2(b) show respectively the laser pulses and the on -axis intensity pulses of the self-focused beam, from which we deduced the temporal variation of the self-focused beam radius shown in Fig. 2(c). From Figs. 2(a) and 2(b), we could also calculate the intensity contour map of the self-focused beam as shown in Fig. 2(d). The contour map could then be directly compared with the streak picture in Fig. 2(e). The agreement in all cases was excellent.

The radial profiles of the self-focused laser pulse in Fig. 2(c) should now be compared with those in Fig. 1 at the end of the medium for the three cases. They clearly have the same qualitative features. (Note that because of backward stimulated Brillouin scattering, only the leading part of the pulse up to the first focal spot in the snap shot of Fig. 1(a) can be seen in the experiment.) We actually found that with increasing input power, the self-focused laser pulse did indeed have its transverse profile gradually deformed in the way described in Fig. 1, for the three cases. This shows that our unified description of self-focusing in Fig. 1, though qualitative, is a valid description. Towards the transient limit, the on-axis intensity pulse and the corresponding radial profile of the self-focused beam (see, for example, Figs. 2(b) and 2(c))developed weak oscillations in the focal region. These have been predicted by theory[9] and are believed to be due to interference of different parts of the focused beam in the focal region. In the quasi-steady-state limit, the on-axis intensity pulse showed a pulsewidth of the order of τ. This was also in agreement with the theoretical prediction.[10] When t_p/τ decreased towards the transient limit, the on-axis intensity pulse increased in length as one would expect from the physical description in Fig. 1.

Another qualitative aspect of self-focusing one can deduce from Fig. 1 is that near the self-focusing threshold, the peak of the on-axis intensity pulse should be delayed from the peak of the input laser pulse because of the transient effect. For the more transient case, the self-focusing threshold is higher and the delay is longer. As the input power increases, the peak of the on-axis intensity pulse should move forward in time, but it will first move backward until the self-focused beam reaches its limiting diameter. These features are actually what we observed in our experiment as shown in Fig. 3. The results in Fig. 3 indicate that even with $t_p/\tau = 11.3$, the transient effect on self-focusing is still quite appreciable. For the more transient case, the variation of the self-focusing characteristics with input power appeared to be slower as one would expect.

We finally show in Fig. 4 the observed minimum radius of the self-focused beam at the end of the cell as a function of the normalized input peak power P/P_{cr}. for the various cases. The theoretical curve (a) for the quasi-steady-state limit is also plotted there for comparison.[6] Curve (b) shows again that with $t_p/\tau = 11.3$, self-focusing still appears to be somewhat transient. It is seen that for the more transient cases, the minimum radius R_{min} of the self-focused beam shrank more gradually with increasing input power. Towards the transient limit, curve (f), R_{min} varied almost exponentially with P/P_{cr}. These results are in good agreement with theoretical predictions.[9] In all cases, R_{min} approached a limiting value at high P. Such a behavior is a well-known characteristic of self-focusing and is believed to be due to other highly nonlinear effects occuring in the focal region,[1] but the particular nonlinear mechanism has never been clearly identified. In our present case, we observed that backward stimulated Brillouin scattering always appeared (marked by arrows in Fig. 4) before R_{min} reached the limiting value, while no other nonlinear effects such as stimulated Raman scattering or multi-photon absorption could be detected. We can therefore conclude that stimulated Brillouin scattering must be responsible for the limiting focal diameter in our case. In fact, in the more steady-state case, stimulated Brillouin scattering set in more suddenly as it should, and hence stopped more abruptly the shrinking beam radius at the limiting value as shown in Fig. 4.

In conclusion, we have shown that our quantitative measurements strongly support the unified qualitative description of self-focusing in Fig. 1 from transient to quasi-steady-state, and are in good qualitative agreement with the available theoretical predictions. Unfortunately, because numerical calculations of self-focusing for our cases do not exist at present, we have not yet been able to make quantitative comparison between theory and experiment.

We would like to thank Drs. S.A. Thomas, H. Lowdermilk, and D. Grischkowsky for helping us on the streak camera, and the Materials and Molecular Research Division of Lawrence Berkeley Laboratory for use of facilities. One of us (YRS) acknowledges a research professorship from the Miller Institute of University of California.

FIGURE CAPTIONS

Fig. 1. Schematic drawing showing how an input pulse gets deformed through self-focusing (a) in the quasi-steady-state limit, (b) in an intermediate case, and (c) in the transient limit.

Fig. 2. Typical sets of results showing (a) input laser pulses, (b) on-axis intensity pulses, (c) radial profiles of the self-focused pulses, (d) intensity contours of the self-focused pulses, and (e) streak photographs. In each case the horizontal axis is the local time ξ. The intensity contour map shows the intensity as a function of transverse coordinate and time. Contours shown are $I = 0.30\ I_{max}$ and $I = 0.03\ I_{max}$. For $t_p/\tau = 11.3$, the input peak power is $P = 11.6$ kW, $P/P_{cr} = 8.1$, and the on-axis peak intensity is $I_{max} = 1.13\ GW/cm^2$. For $t_p/\tau = 5.2$: $P = 7.6$ kW, $P/P_{cr} = 8.2$, and $I_{max} = 1.10\ GW/cm^2$. For $t_p/\tau = 0.21$: $P = 6.4$ kW, $P/P_{cr} = 89$, and $I_{max} = 0.80\ GW/cm^2$. Here, P_{cr} is a critical power proportional to $(T-T^*)/A$.

Fig. 3. Peak position of the on -axis intensity pulse of the self-focused beam as a function of normalized input peak power in different cases: (a) $t_p/\tau \to \infty$, (a theoretical curve), (b) $t_p/\tau = 11.3$, (c) $t_p/\tau = 5.2$, (d) $t_p/\tau = 2.07$, and (e) $t_p/\tau = 0.47$. Curve (a) is calculated from Eq. (1), which gives $z_f = 10$ cm for $P = 4.36\ P_{cr}$.

Fig. 4. Reduced minimum radius of the self-focused beam at the end of the cell as a function of normalized input peak power in various cases: (a) $t_p/\tau \rightarrow \infty$ (a theoretical curve from Ref. 6), (b) $t_p/\tau = 11.3$, (c) $t_p/\tau = 5.2$, (d) $t_p/\tau = 2.07$, (e) $t_p/\tau = 0.47$, and (f) $t_p/\tau = 0.21$. The reduced radius is normalized to the radius of the incoming beam. The threshold power for stimulated Brillouin scattering in each case is marked by an arrow.

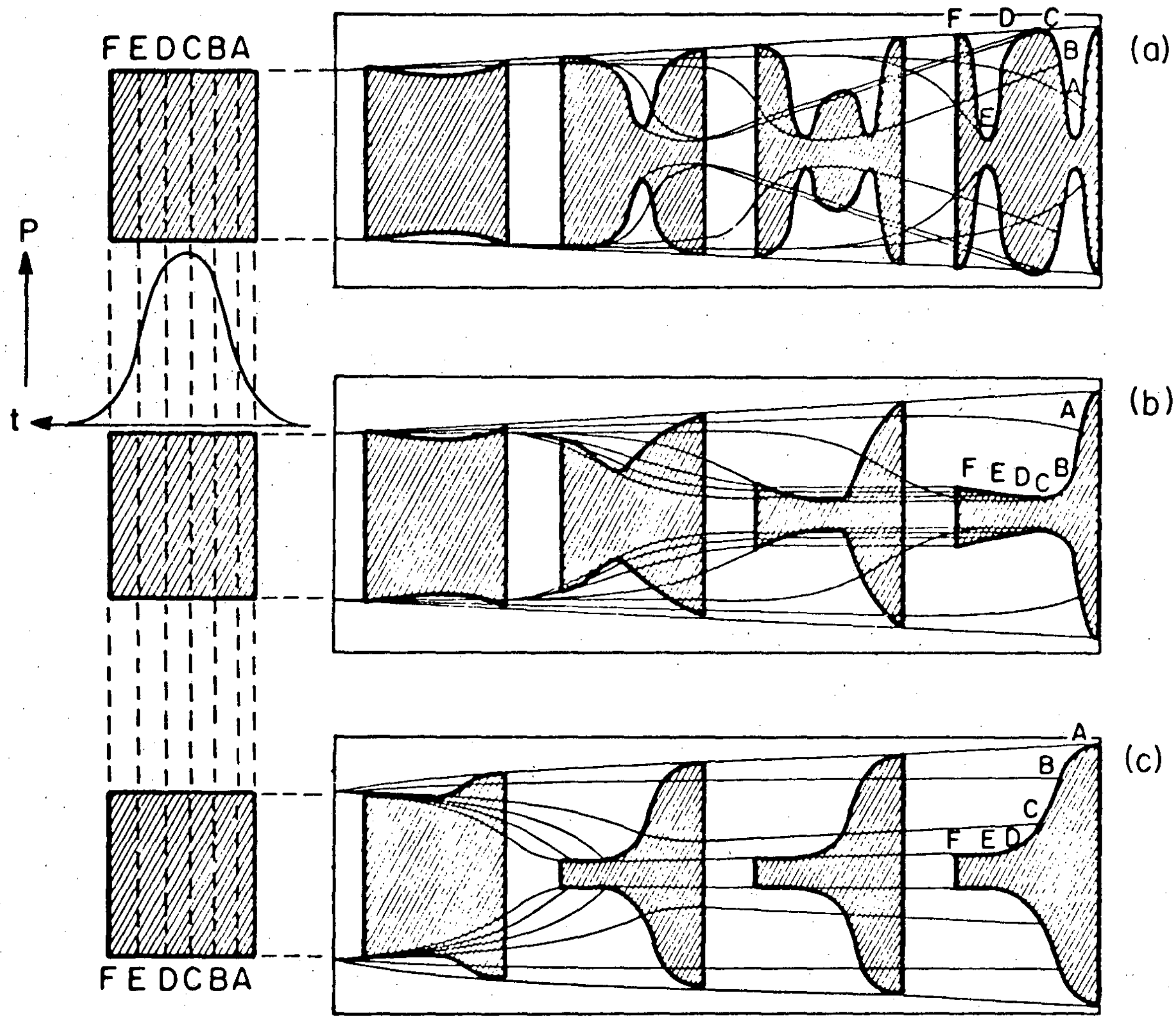

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Fig. 1

0 0 3 0 4 5 0 6 5 4 7

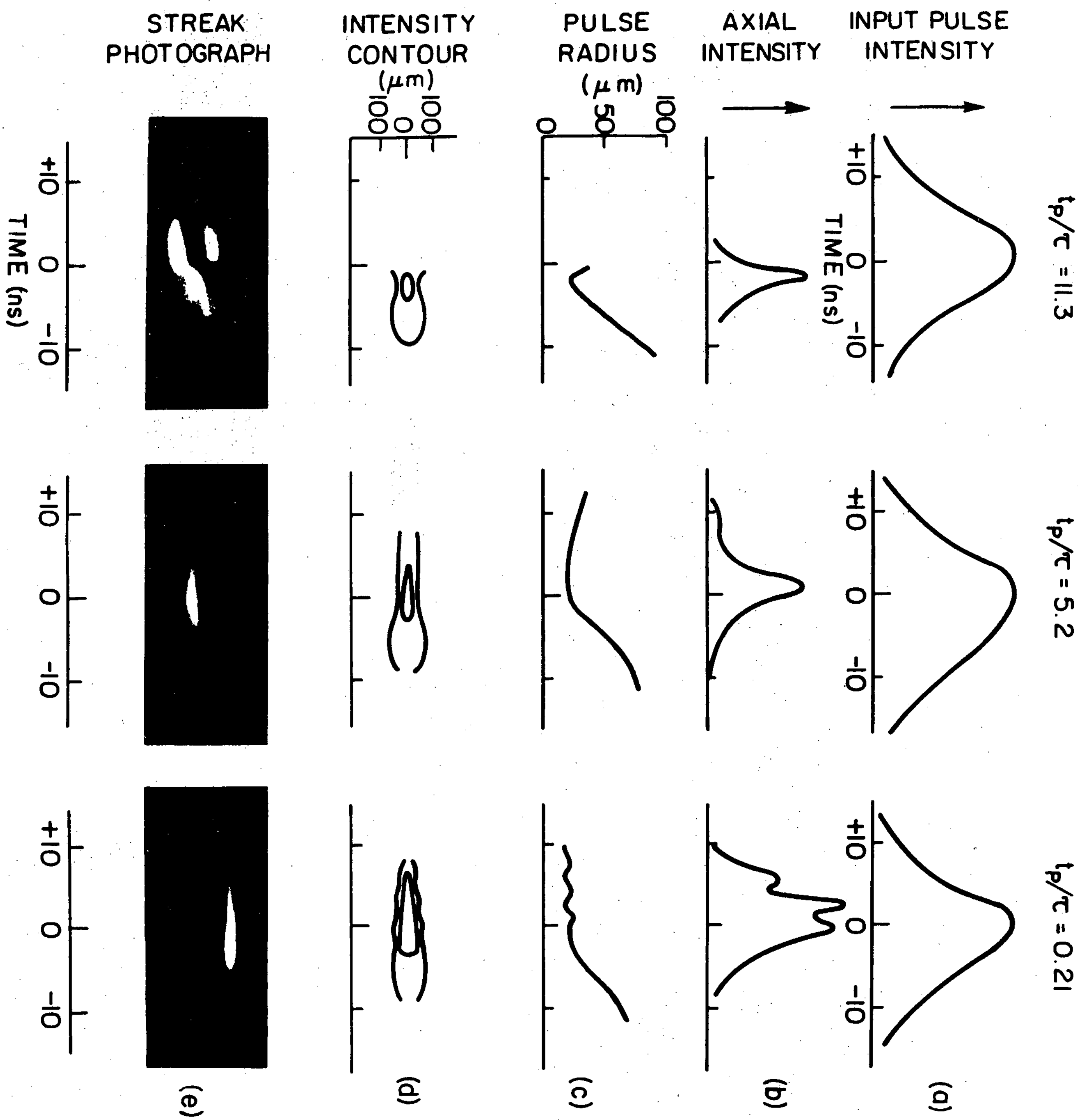

Fig. 2

0 0 J 0 4 5 0 6 5 4 8

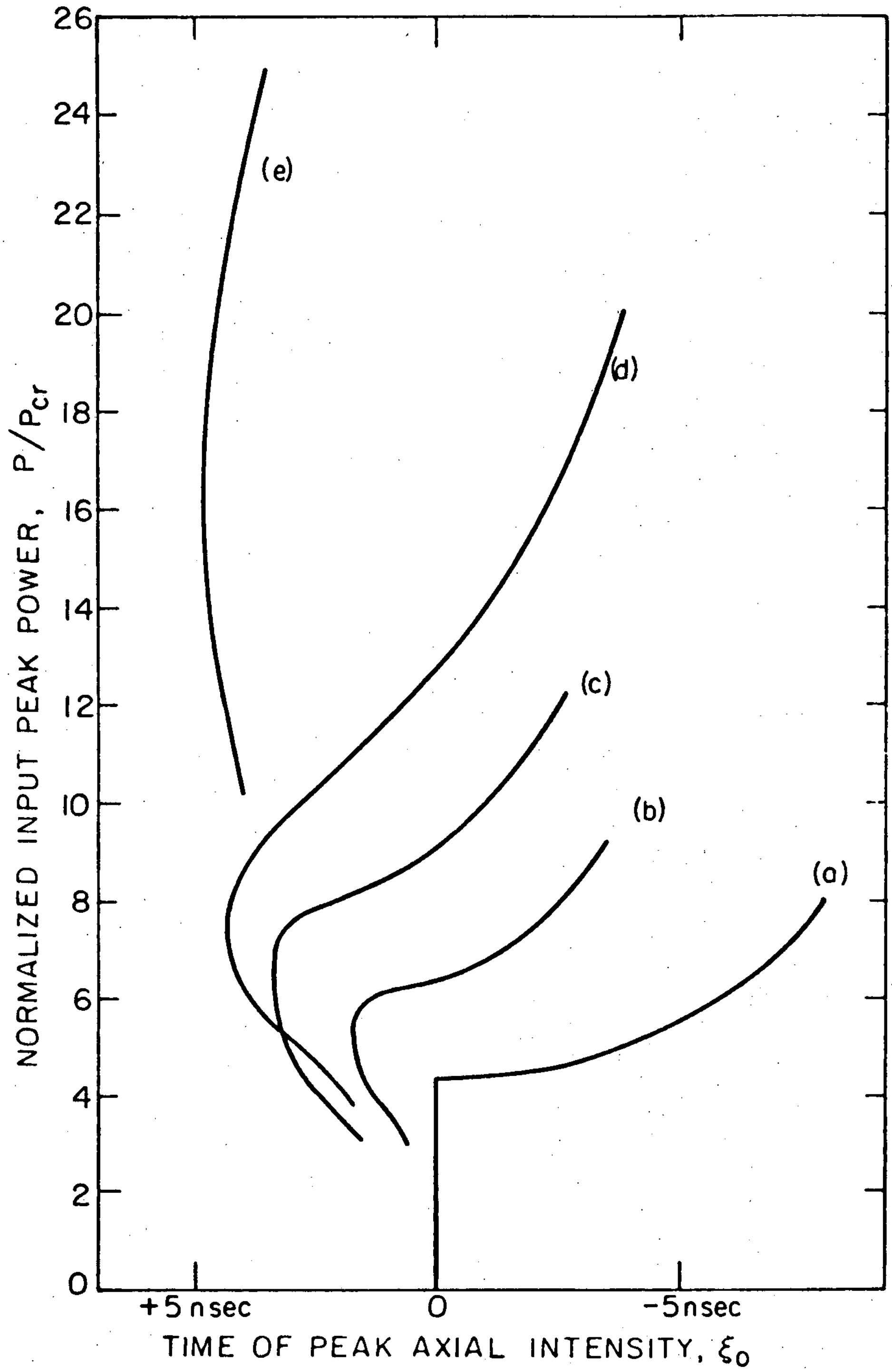

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Fig 3

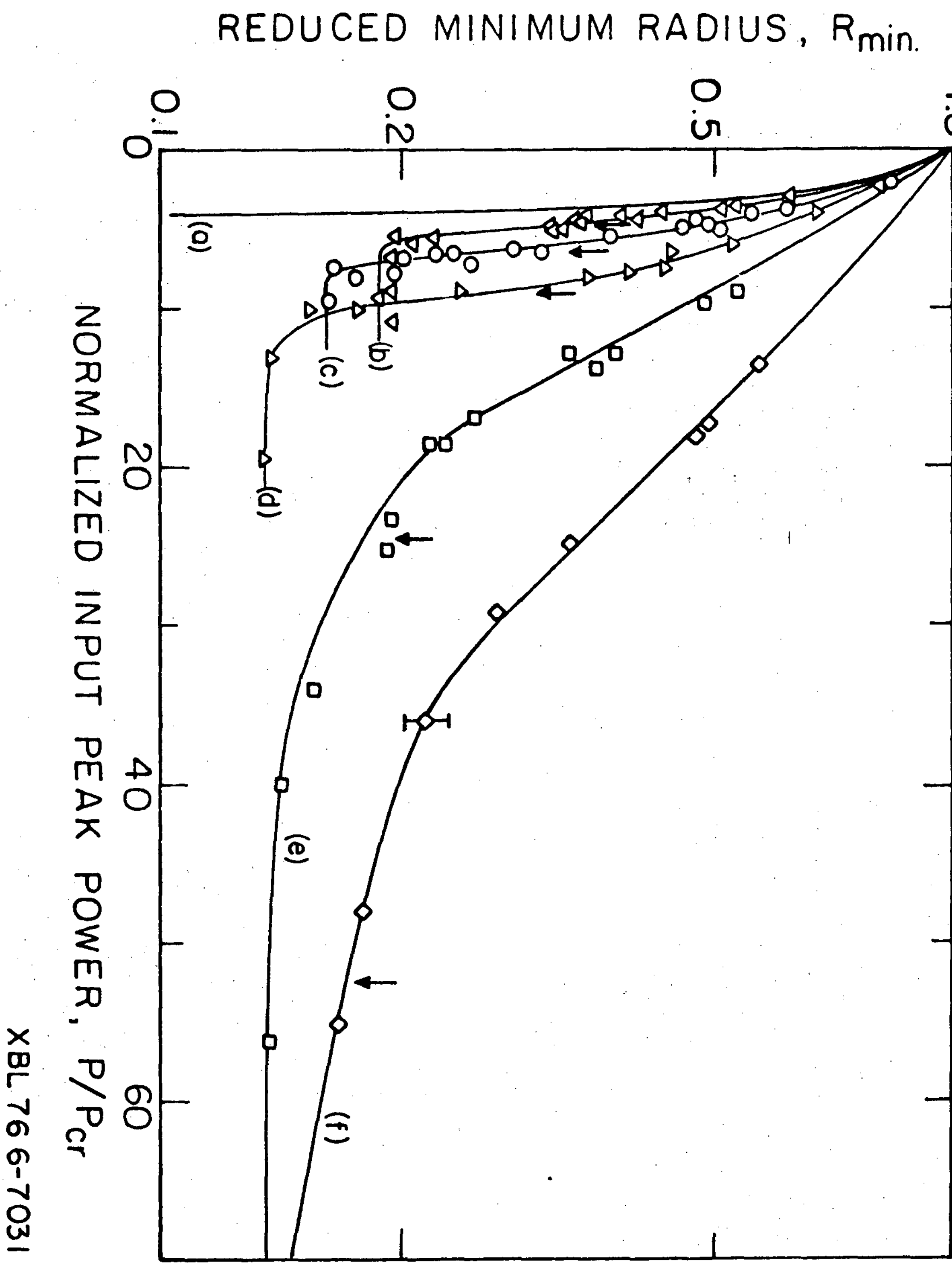
REDUCED MINIMUM RADIUS, $R_{min.}$
0.1
0.2
0.5
1.0
0
20
40
60
(a)
(b)
(c)
(d)
(e)
(f)
NORMALIZED INPUT PEAK POWER, P/P_{cr}
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Fig. 4

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