Spatial distortions of laser pulses in coherent on-resonance propagation: Small-scale self-focusing

J. de Lamare
COGEMA and Commissariat à l'Energie Atomique, Centre d'Etudes Nucléaires de Saclay DCC/DPE/SPEA, 91-191 Gif-sur-Yvette, France

Ph. Kupecek
Université Pierre et Marie Curie and Commissariat à l'Energie Atomique, Centre d'Etudes Nucléaires de Saclay DCC/DPE/SPEA, 91-191 Gif-sur-Yvette, France

M. Comte
Commissariat à l'Energie Atomique, Centre d'Etudes Nucléaires de Saclay DCC/DPE/SPEA 91 191 Gif-sur-Yvette, France
(Received 23 August 1994)

We present a quantitative model for coherent on-resonance small-scale self-focusing of laser pulses in atomic media. A vapor-induced diaphragm effect at the edge of the pulse generates a pattern of diffraction rings that modulates the initial transverse profile of the pulse. Practically, because of the spatial asymmetry of the original pulse, this diffraction pattern is perturbed and dots appear superimposed upon the rings. A large-scale self-focusing phenomenon is then initiated from each individual dot and the global transverse energy profile of the pulse evolves in a hot-spot pattern. This final pattern is characteristic of what is usually called small-scale self-focusing. Our theoretical predictions are compared with both the results of an experiment on a ^{169}Tm vapor and the predictions of existing models.

PACS number(s): 42.65.Jx, 42.25.Bs, 42.50.Md, 32.80.−t

I. INTRODUCTION

It is well known that nonlinear self-focusing can cause the degradation and breakup of high power laser beams by amplifying small-scale beam imperfections. This problem is of practical importance because it can limit the useful power of a solid-state laser. A one-dimensional linearized theory of beam instability with respect to transverse perturbations, first derived by Bespalov and Talanov [1], was qualitatively verified experimentally [2,3]. This theory was later extended by other workers to include different physical mechanisms [4–6]. Growth of Gaussian instabilities in Gaussian beams had also been studied [7]. In the common case of nonlinear nonresonant interaction, the main point is that large-scale self-focusing (LSSF) that is to say, focusing of the beam as a whole, is replaced by small-scale self-focusing (SSSF) for high power input pulses [8,9].

In the coherent regime, when the pulse duration τ_p is shorter than all the relaxation times of the two-level atomic system, on-resonance propagation may also lead to SSSF. This phenomenon was reported by Gibbs *et al.* [10]. Resonant pulses of duration 2 ns were propagated through a sodium cell, giving rise to SSSF for large values of the input pulse diameter. Kupecek *et al.* later investigated the case of 12-ns pulses propagating through an oven containing a thulium vapor [11]. This results appeared to be in qualitative concordance with the theoretical predictions of Bol'shov, Likhanskii, and Napartovich [12], whose model is based on a perturbational treatment of the full set of Maxwell-Bloch equations. This one-dimensional model predicts that 2π-sech pulses are unstable with respect to transverse perturbations characterized by a wavelength proportional to $\sqrt{\lambda V \tau_p}$, in which λ is the optical wavelength and V is the velocity of the pulse in the medium (V can be estimated from the self-induced transparency theory of McCall and Hahn [13] and is a function of τ_p). These perturbations can develop over distances of the order of magnitude of $V\tau_p$. Bol'shov and Likhanskii also investigated the influence of detuning from resonance on SSSF [14].

As far as numerical simulations are concerned, a complete treatment of SSSF phenomena in the coherent resonant regime will at least require us to take into account a two-dimensional transverse structure in a time-dependent description, involving a huge memory cost. The validity of the paraxial approximation [15], though it had been questioned in the case of self-focusing in nonlinear media [16], will not correspond to a significant limitation on the reliability of numerical simulations in the coherent resonant regime. In this case, indeed, the characteristic transverse sizes of the filamentary structures are typically in a ratio of two orders of magnitude with the optical wavelength, and focusing phenomena are relatively smooth compared with the nonlinear case. However, the complexity of the full Maxwell-Bloch problem explains why there have been up to now no complete numerical simulations of coherent on-resonance SSSF phenomena.

In a recent paper, we presented a theoretical quantitative model for LSSF in the coherent resonant regime [17]. We derived the parametric dependences on the interaction's parameters, respectively, for the focusing distance L_{foc} and the ratios of on-axis energy densities and pulse transverse sizes between the focus and input

1050-2947/95/51(5)/4289(4)/$06.00

planes, H_{max}/H_0 and r_{foc}/r_p. We pointed out that these ratios appear to depend on whether the medium is degenerate or not. We showed that LSSF can be viewed as a consequence of an inwards energy flow associated with transverse perturbations generated from the edge of the pulse. The central mode transverse wavelength λ_T had been found to be proportional to $\sqrt{\lambda/\alpha}$, in which α is the "low intensity" gain of the medium. A dimensionless formulation of the full set of Maxwell-Bloch equations revealed that the self-focusing problem in cylindrical symmetry depends only on the input pulse optical area and on two parameters, $F=\lambda/(4\pi r_p^2\alpha)$ and $D=\tau_p\Delta\omega_{\rm Dop}$ (we put $\Delta\omega_{\rm Dop}$ as the full width at half maximum of the inhomogeneous spectral distribution of the absorbers). F is an inverse of a Fresnel number and D characterizes the ratio of the inhomogeneous linewidth on the pulse spectral width. We limited our study to cases in which $D>1$. This means that all the photons of the incident pulse can interact with resonant absorbers and accordingly that global absorption of the beam may play an important part. We also noted that the respective predominance of either temporal reshaping and self-focusing phenomena is determined by the parameter $\sqrt{F}$.

In the present paper, we show that a simple extension of the LSSF model (Sec. II) leads to an interpretation of coherent resonant SSSF in good qualitative concordance with the results of an experiment in a ^{169}Tm vapor (Sec. III). Finally, Sec. IV is a summary in which our main results are compared with those of Bol'shov, Likhanskii, and Napartovich [12].

II. THEORETICAL MODEL

In the case of nonlinear nonresonant interaction, as said in the previous paragraph, LSSF is progressively replaced by SSSF when the energy of the input pulse is increased. In the coherent resonant regime, on the contrary, this transition occurs progressively when the transverse size of the input pulse is increased [10,17]. This can be readily explained by the interpretation of SSSF that we shall present now. First we know that transverse perturbations are generated at the edge of the pulse by a vapor-induced diaphragm effect (whose characteristics can be deduced from typical self-induced transparency considerations) [17]. If the transverse size of the input pulse is larger than the mean wavelength of these perturbations, its transverse profile is modulated by a pattern of diffraction rings. Because of the experimental asymmetry of the pulse, this pattern is perturbed, exhibiting dots superimposed upon the rings (let us note that this effect can be readily observed by placing a material quasicircular diaphragm on a He-Ne laser beam, as illustrated in Fig. 1, and that this interpretation agrees substantially, in its theory, with the works of Feit and Fleck [16]). Then comes the second step of our model: each individual dot, whose transverse initial size is of the same order as the width of the rings, λ_T, initiates a LSSF phenomenon. This leads finally to a hot-spot pattern that characterizes the SSSF phenomenon.

According to this model, it is obvious that a necessary condition for SSSF to occur is that the transverse size of the input pulse is sufficiently large to be modulated by at least one ring. The corresponding SSSF criterion is that λ_T/r_p (which is nothing else than $\sqrt{F}$) is "small." This theoretical criterion perfectly corroborates experimental data [10,17]. The dependences of SSSF characteristics—the focusing distance L_{foc}, the filament mean transverse size r_{foc}, and the maximum energy density in each filament H_{max}—on the interaction's parameters can readily be derived from this interpretation. Indeed we know from Ref. [17] [see Eqs. (25), (27), and (29)] the dependences of L_{foc}, H_{max}/H_0, and r_{foc}/r_p in the case of LSSF in a nondegenerate medium. Then one only has to replace r_p by λ_T in these results to obtain the theoretical predictions corresponding to SSSF. As far as L_{foc} and r_{foc} are concerned, this gives clearly

$$L_{foc}\propto\frac{1}{\alpha}\,, \tag{1}$$

$$r_{foc}\propto\left[\frac{\lambda}{\alpha}\right]^{1/2}, \tag{2}$$

but the most striking result is that H_{max}/H_0 is predicted to be independent of r_p, λ, and α. Let us remark that the meaning of H_0 here is the initial energy density corresponding to the transverse position of the filament under consideration. These theoretical predictions, as well as the criterion for the transition between LSSF and SSSF, are compared with the results of an experiment on a ^{169}Tm vapor in the following section.

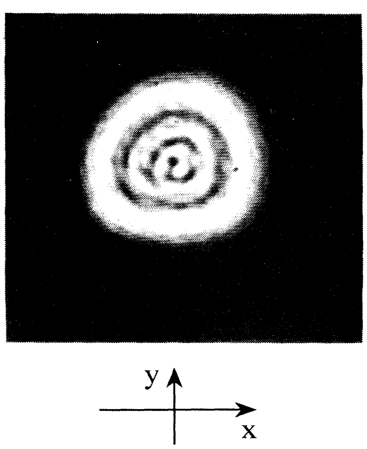

FIG. 1. Fresnel diffraction pattern of a plane wave: because of the experimental slight asymmetry of the aperture, a hot-spot pattern appears superimposed upon the rings.

III. EXPERIMENTAL RESULTS

The experimental study we present now is an extension of the experiment described in Ref. [17], in which it appeared that LSSF was replaced by SSSF when the transverse size of the input pulse was increased. Here the beam radius was given five different values from nearly 0.9 to 3.6 mm.

First, let us note that the observed transition between LSSF and SSSF for increasing transverse sizes of the in-

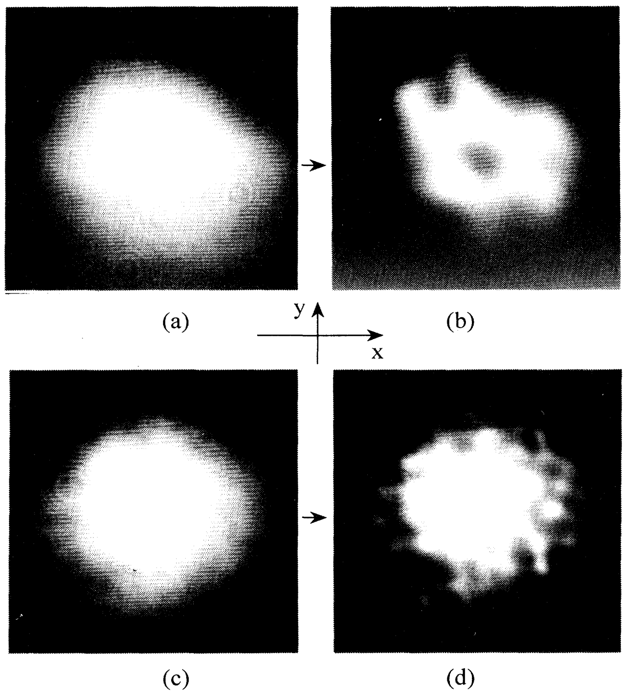

FIG. 2. Dependence of the SSSF effect on the ratio λ_T/r_p: video camera outputs. (a) Input pulse with $r_p=1.1$ mm; (b) output focused pulse corresponding to (a); (c) input pulse with $r_p=2.4$ mm; (d) output focused pulse corresponding to (c); λ_T was constant.

put pulses corresponds closely to the theoretical criterion ($\lambda_T/r_p<1$ that is, $\sqrt{F}<1$) that we presented in the preceding section. We compare in Fig. 2 the input and focused output beams corresponding, respectively, to $r_p=1.1$ and 2.4 mm. In the first case, one can see that the energy cross section of the focused beam (b) exhibited a ringlike shape. With L_{foc} having been defined as fixed and equal to the oven length (1 m), the "threshold" value of r_p corresponding to the transition between LSSF and SSSF was nearly 1 mm. For $r_p=2.4$ mm, one can see that the focused beam (d) exhibited a hot-spot pattern, characteristic of SSSF. The ringlike structure was not evident in this case. For the sake of example, input and output focused beams are compared in Fig. 3, for $r_p=1.7$ mm. In this case, the ringlike structure of the energy cross section of the focused beam (b) could clearly be distinguished. As far as the predominance of either temporal reshaping or the self-focusing effect is concerned, we showed theoretically in Ref. [17] that it was also characterized by $\sqrt{F}$. For large values of this parameter, that is, when LSSF occurs, the simple one-dimensional predictions about temporal reshaping (see the self-induced transparency theory [13]) were predicted to be greatly altered by self-focusing. We showed that it corresponds closely to the experimental data. For small values of $\sqrt{F}$, when SSSF occurs, temporal reshaping could be expected to occur in a close form to those predicted by the one-dimensional theory. More precisely, self-focusing and classical temporal reshaping were predicted to coexist. This has been obviously confirmed by the experimen-

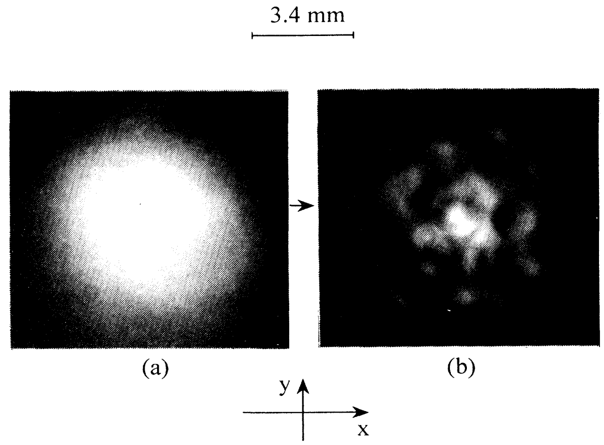

FIG. 3. Experimental evidence of an underlying ringlike modulation when a spatially Gaussian input pulse undergoes SSSF. (Video camera outputs.) (a) Input pulse with $r_p=1.7$ mm; (b) output focused pulse.

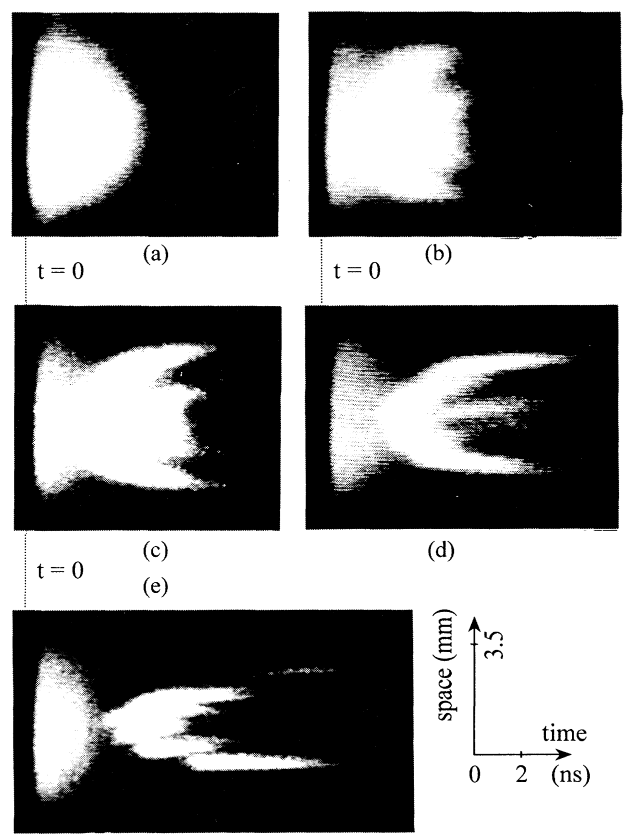

FIG. 4. Experimental evidence of the successive steps of a classical one-dimensional temporal reshaping effect and spatial reshaping when SSSF occurs. Propagation through an increasingly thick medium is simulated by decreasing the detuning between the laser and the atomic resonance frequencies. Output pulses are analyzed by a streak camera. (a) corresponds to the nonresonant pulse "$\Delta\omega_a=\infty$." Then from (b)–(e), we have $\Delta\omega_a>\Delta\omega_b>\Delta\omega_c>\Delta\omega_d>\Delta\omega_e=0$ (resonant pulse).

tal results, as shown in Fig. 4. Streak camera outputs representing the spatiotemporal profile of the intensity of the output pulse are compared for decreasing detunings between the laser frequency and the atomic resonance frequency. The temporal reshaping effect undergone by the input pulse (a) appeared clearly on (b) and (c), until the diffraction effects leading to a filamentary structure became predominant on (d) and at the exact resonance on (e). The appearance of a precursor, that is, a quasi-non-delayed part at the front of the pulse, is obvious in this figure. This was due to the particular shape of the initial pulse, with a very sharp front [18].

We could not verify the full theoretical predictions concerning the dependences of $L_{\rm foc}$, $H_{\rm max}/H_0$, and $r_{\rm foc}$ on the interaction's parameters. Indeed the position of the focus plane depended on the value of α (that is, on the value of the atomic concentration N), according to the prediction (1). The focus plane might be either in or out of the oven, depending on whether N was greater or smaller than the particular value corresponding to $L_{\rm foc}=1$ m. This made it uneasy to interpret the dependences of the SSSF characteristics on α. We still observed a slight decreasing of $r_{\rm foc}$ while α was increased, in qualitative accordance with the prediction (2). However, $L_{\rm foc}$ and $r_{\rm foc}$ appeared to be independent of r_p, confirming our theoretical predictions. As far as $H_{\rm max}/H_0$ is concerned, we did not observe any dependence on the interaction's parameters, in accordance with theoretical predictions. Let us point out that the energy transverse profile of the focused pulse is greatly dependent on those of the input pulse. For the sake of example, it is obvious that the filamentary pattern that develops from a pure Gaussian pulse is radically different from those obtained from an arbitrary apertured pulse. Nevertheless, our theoretical predictions can be applied in any case. Let us note finally that the relative importance of the SSSF effects clearly depends on the ratio of the input pulse optical area on the optical thickness of the medium αL (in which L is the length of the atomic medium). When this ratio is too large, when the major part of the incident photons can cross the atomic medium without being absorbed, the consequences of SSSF effects on the output pulse may be quite small.

IV. SUMMARY

We now have a quantitative theoretical model for coherent on-resonance SSSF. Experimental measurements provided a significant confirmation of our theoretical predictions, concerning the parametric dependences of the focusing distance, the mean transverse size of the filament, and the ratio of the energy densities between the focus and the input planes. A more complete comparison between theory and experiment would have at least required us to use two ovens of radically different lengths, thus providing an alternative choice for the focusing distance (and accordingly for the atomic concentration). Neither of the above-mentioned SSSF characteristics depends on the transverse size of the input pulse. We saw that the predominance of either temporal reshaping or the self-focusing effect, as well as the occurrence of either LSSF or SSSF phenomenon, are characterized by $\sqrt{F}$. Let us note finally that our model provides a unified interpretation of both the LSSF and SSSF phenomena for pulses of arbitrary areas and temporal shapes. The study of Bol'shov, Likhanskii, and Napartovich was limited to the SSSF of 2π-sech pulses [12]. In this case and concerning the focusing distance and the filament mean transverse size, our predictions are in partial agreement (indeed the 2π-sech pulse stationary length $V\tau_p$, in a medium whose gain is α, is proportional to first order to α^{-1}). Consequently there is no fundamental contradiction between our interpretation and those of Bol'shov, Likhanskii, and Napartovich in which SSSF phenomena were explained by the amplification of small-scale defects.

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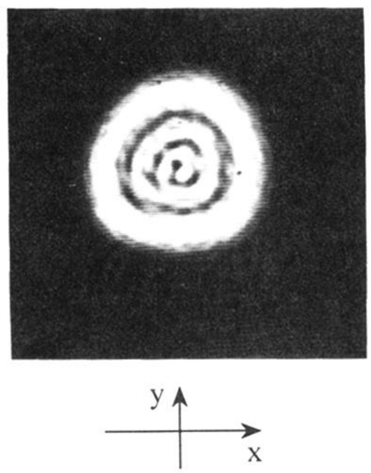

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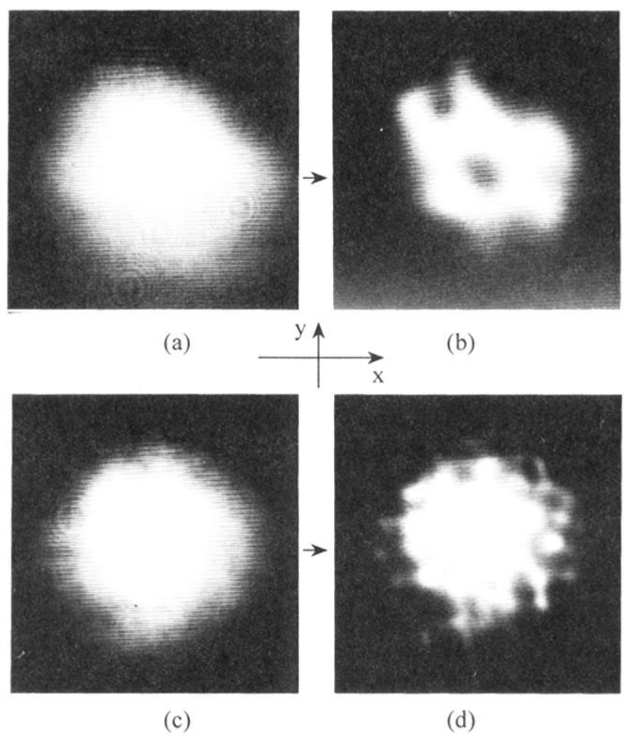

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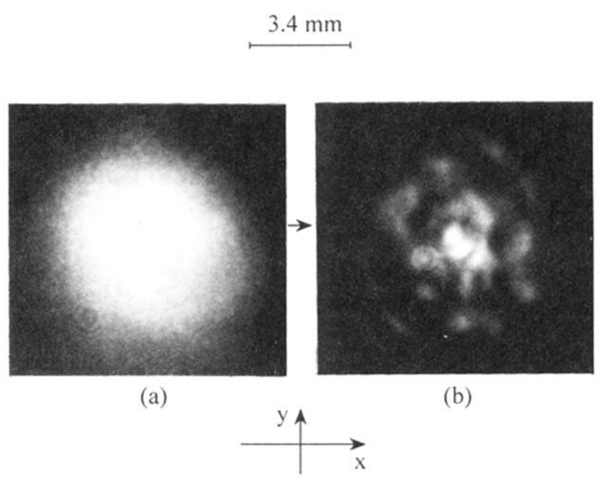

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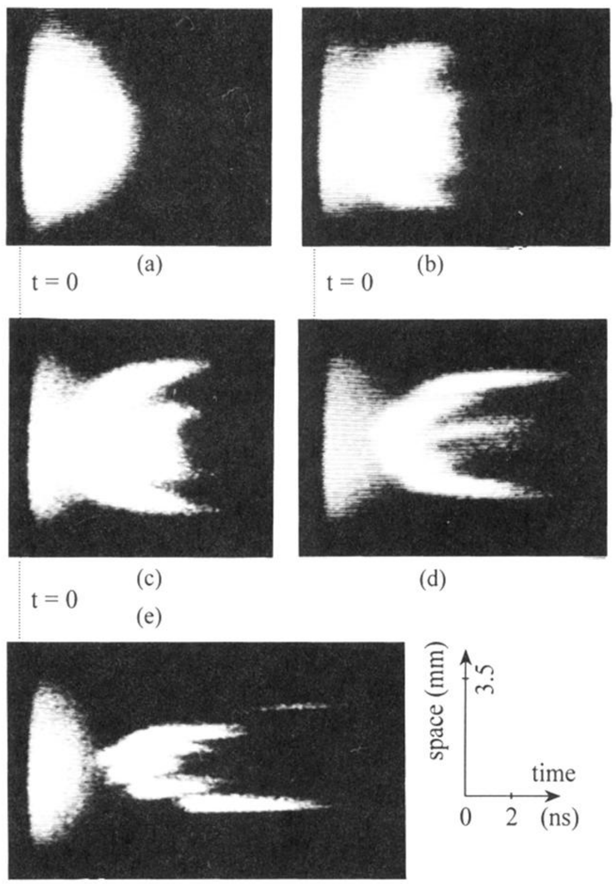

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