The self-focusing effect

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A critical review is presented of the theoretical and experimental research on self-focusing, and its main purposes and development trends are noted. It is indicated that the most complete definition of self-focusing, from which all its variants follow, is a decrease of the divergence (or, equivalently, an increase of the convergence) of high-power radiation in a medium. It is noted that the spatial distribution of the focusing action makes the waveguide description most complete, since it is universally known that waveguides come in a variety of cross sections, lengths, and dielectric-constant distributions, while an arbitrary radiation flux (a beam of rays) can be subdivided into self-focusing beams. The main purpose of self-focusing, namely, directed transmission of concentrated radiation and focusing the radiation into a single focus, is noted. It is shown that in practice the multifocus regime is not suitable for this purpose. It is indicated that the multifocus structure is a particular case of a previously described subdivision of a beam into beams of near-threshold power. Practical applications of self-focusing for radiation energetics, high-temperature heating of matter, control of destruction processes, acceleration of particles by a traveling focus, and others, are indicated.

> *"When the heavens are covered with darkness, ropes seem to be snakes."*[1]
>
> (from the Buddhist book Tanjoor, Vol. 49)

CONTENTS

1. INTRODUCTION

The self-focusing of powerful beams in media has recently been studied intensively. In the abundant flow of studies, the fundamental goals of studying self-focusing became unclear for a time. In our opinion, this involved the unjustified exaggeration by various authors of special results. For example, the non-linear caustic (subdivision of a bem into parts) has been called a "new concept," and has been contrasted with waveguide-type non-linear refraction. The aim of this article is to emphasize the main trends of development of self-focusing to arrange the obtained results on a scale of significance, and to review the possible applications and lines of development of self-focusing.

2. THE SELF-FOCUSING EFFECT

In its most general definition, self-focusing is a decrease in divergence (or equivalently, an increase in convergence) of powerful radiation, owing to various non-linear effects that are caused by the beam itself. The change in divergence is precisely what leads to change in cross-section of the beam, formation of filaments, caustics, condensations, foci, etc. That is, the different special manifestations of self-focusing are consequences of change in divergence of radiation.

The spatial distribution of self-focusing action makes it analogous to the appearance of a dielectric waveguide created by a non-linear change in the dielectric constant. Here we should take the term waveguide in the usually adopted broad sense (see, e.g., the Physical Encyclopedic Dictionary[1]). That is, it can have an arbitrary, variable cross-section and dielectric-constant distribution, and have any length (rather than taking a waveguide to mean a guiding element of constant radius and infinite length, as some authors take it). In particular, people have known for a long time and often used waveguides having cross-sectional constrictions in order to intensify the field, which are analogous to the constriction of the beam in self-focusing. Again we emphasize: the justification of the waveguide description of self-focusing is the extended spatial distribution of the focusing action while the beam cross-section is comparable with the cross-section of the profile of altered refractive index that it creates.

The possibility of a change in divergence of a free powerful beam in a medium arising from non-linear effects was first discussed in[2], where the waveguide description of self-focusing was also noted.2) According to the Formula of Certificate of Discovery dated Dec. 22, 1961,[3] "A previously unknown phenomenon has been established of self-focusing of electromagnetic and sound waves that consists in a decrease in divergence (or increase in convergence) of beams owing to appearance of a transverse gradiant of the non-linear refractive index and appearance of a non-linear waveguide that decreases the cross-section of the beam." Since any flux can be subdivided into beams of rays (ray tubes), the abovesaid can refer either to the entire flux or to its individual parts. Two major practical applications of self-focusing–transport of concentrated radiant energy to great distances, and getting high radiation densities by self-constriction of a beam–involve precisely the simple waveguide constriction of the beam.

Two factors hinder concentration and localization of the beam energy. The first is a change in the non-linear increment of the refractive index arising from the change in time of the field of the beam or the time development of non-linear processes (inertia of onset, relaxation, or secondary processes) that alter the focusing action or cause movement of the focal points. The second factor is the so-called caustic of the focusing action, or focusing of different parts of the beam at different regions of the axis. This caustic can be very strong because the profile of the intensity distribution that determines the non-linear refraction can be so unsuitable as to cause aberration or onset of subdivision of the beam.

This is just why searches have been undertaken from the very onset for a self-consistent intensity distribution of the beam in the non-linear medium that will not vary for great enough distances. Such solutions for electromagnetic waves in a plasma have been given by Talanov[3] and for a medium having a non-linearity of the n_2E^2 type by Townes and his associates.[4] The latter study found an essential characteristic of self-focusing: the so-called threshold power4) $P_{\text{thr}} \sim \bar{\lambda}^2 c/n_2$, i.e., the power at which the non-linear refraction ($\theta_{\text{nl}} \sim \sqrt{n_2}\,E$) is comparable with the diffractional divergence ($\theta_{\text{d}} \sim \bar{\lambda}/a$) and can compensate it. Another essential characteristic of self-focusing is the so-called "Kelley length"[5], or the distance at which the intensity of a beam of small initial divergence varies substantially:

$$L \sim \frac{a}{\theta_{\text{nl}} - \theta_{\text{d}}} \approx \frac{a}{2\sqrt{n_2}\,(E - E_{\text{thr}})} \approx \frac{a}{2\sqrt{n_2}\,E}$$

when

$$E \gg E_{\text{thr}} \approx a^{-1}\sqrt{4P_{\text{thr}}/c}.$$

These two characteristics of self-focusing are manifested in many of its varieties, and in particular, they govern the processes of subdivision of a beam.

Townes et al.[4] also noted that "a beam whose power is considerably above the threshold will probably subdivide into several beams of threshold power." Bespalov and Talanov[6] showed that a powerful plane wave in a non-linear medium is unstable, and it subdivides into portions having powers of the order of the threshold. Any deviations of the intensity distribution from the specially chosen distribution that ensures self-similarity or good focusing lead to this same result. For example, a beam having a Gaussian profile gives a substantial aberration at powers of the order of the threshold or greater. The expression for the Kelley length directly implies that the focus will move as the power is changed.

MacWane[7] first mentioned moving foci, application of them, and the caustic of self-focusing. Beam subdivision at powers above the threshold was treated later in studies on multifocus structure and moving foci,[8,9] in which a machine calculation was given of the subdivision of a Gaussian beam in a medium having an n_2E^2 non-linearity and absorption at the foci. These studies showed that such a beam subdivides into regions, each of which focuses a power close to the threshold, which is a special case of subdivision of a wave.[6] We point out that these studies were carried out in the quasi-optical approximation by solving the well-known parabolic equation.[5] It was shown in the geometrical-optics case that intensity distribution profiles close to parabolic give good focusing. The choice of distribution profile of the beam can affect the self-focusing process very strongly. Thus, it has even been shown that a decrease in intensity near the axis of the beam can cause focusing of most of the beam in a medium in which ordinary beams are defocused (the so-called "banana" self-focusing).[10–12] The self-focusing of a beam having a broken intensity distribution can differ substantially from that of a beam having a smooth profile. In particular, the Kelley lengths of the "hot" regions can prove to be much smaller. After this brief introduction, let us proceed to presenting the fundamental concrete problems: under what conditions will radiation transport by spontaneous waveguide occur, and what position will single- and multifocus structures take in the overall problem?

3. SPONTANEOUS WAVEGUIDE PROPAGATION OF RADIATION

Waveguide restriction of diffractional divergence occurs at powers $P < P_{\text{collapse}}$, and here there are no foci at all. One gets the most extended constriction of the beam when $P \geq P_{\text{thr}}$. This corresponds to a remote focal point when $P \geq P_{\text{thr}}$. Such a mode exists even for a Gaussian initial profile, which, as we know, is not the best approximation to the self-consistent solution[3,4] that makes it possible to maintain the concentration of the entire beam.

In practice, one is always dealing with a limited region of a non-linear medium having the length L. Hence the condition for absence of foci in the medium is considerably expanded: $L < L_{\text{cri}}$, where L_{cri} is the distance to the first focus at which the power of part of the beam is concentrated. We note that an arbitrary (e.g., Gaussian) initial profile of the beam may not permit complete concentration of the power into the constriction.

Restricted divergence of a beam has been observed in many experiments. Thus, Townes and his associates[13] also observed a decrease in the cross-section of a beam emerging from a cell containing a non-linear medium, even in a power range that did not give foci within the cell.

Recently Askar'yan, Diyanov, and Mukhamadzhanov[14] have undertaken the first direct experimental studies on the efficiency of spontaneous-waveguide propagation of radiation in a medium.

Figure 1 shows the experimental setup and the path of the beams. A Q-switched neodymium laser operating in a longitudinal mode gave a pulse of half-width 20 nsec. The beam passed through the diaphragm D_1 having an aperture of diameter 4×10^{-2} cm lying at a distance $L_1 = 8$ cm ahead of the entrance into the non-linear med-

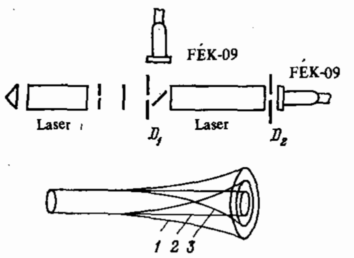

FIG. 1

ium. (This distance ensured a smooth transverse intensity distribution of the beam as it entered the medium). We used nitrobenzene as the non-linear medium in a cuvette of length L = 50 cm in which the linear absorption did not exceed 20%. The diaphragm D_2 having an aperture of diameter $d_2 = 5 \times 10^{-2}$ cm was placed at the exit face of the cuvette. This made it possible to select the concentrated radiation from the overall flux of the expanded transmitted beam, which was measured when the diaphragm D_2 was removed. The diffractional spreading of a low-power beam increased the cross-sectional area of the beam tenfold at the exit from the cell.

The incident, concentrated transmitted, or total transmitted light was detected by two FÉK-09's with subsequent recording on two scans of a many-beam 6LOR-2-M oscillograph. The linearity of response of the FÉK was specially checked. The FÉK pulses at the exit, with and without the diaphragm D_2, could correspond to different entrance flashes. Hence the entrance pulses were monitored. The diaphragm D_2 was positioned exactly so that the maximum fraction of the incident beam fell within the aperture. During the series of flashes, neither the size nor the shape of the pulses from the light transmitted through the diaphragm D_2 varied when the pulses of incident light were identical. This showed good reproducibility of incidence, even without taking special measures of thermostating the liquid.

The light power beyond the diaphragm D_1 at the pulse peak was varied over the range 50–180 kW. This made it possible to study separately subthreshold, threshold, and superthreshold systems (in the latter case, the focal point entered the interior of the non-linear medium). The power at which the cuvette length was equal to the so-called Kelley length was $P_{crL} \approx 120$ kW, which was close to the threshold power $P_{thr} \approx 100$ kW. Fig. 1 shows the path of the beams in the cuvette (1: – $P < P_{thr}$; (2: – $P < P_{thr}$).

The pulses from the coaxial photocells when the diaphragm D_2 was present characterized the concentrated power P_d incident within the aperture of the diaphragm, which was comparable with the beam dimensions at the entrance into the medium (the portion of the power that did not decrease the initial energy concentration), while without the diaphragm D_2, all the power transmitted through the non-linear medium was recorded. Figure 2 shows characteristic pulses. The second trace of the lower half gives the pulse of the incident laser power P, which is the same for both the upper pulses, which are taken with and without the diaphragm D_2. (In order to permit comparing P_d with P_{tr}, only those pairs of pulses were selected from a large number of flashes whose initial laser pulses coincided in shape and size).

Figure 2a is given for a power P at which the focus has not yet entered the medium ($P_{max} \lesssim P_{crL} \approx 120$ kW). Figure 2b shows the case where the power exceeds the threshold ($P_{max} \approx 1.4\ P_{crL}$). Here we see that the increase in P_d is restricted by scattering and absorption of the radiation when the focus enters the non-linear medium.

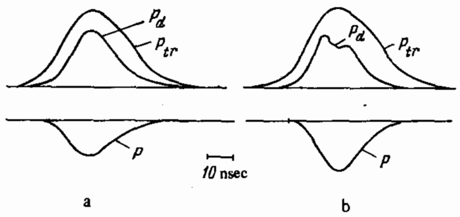

FIG. 2

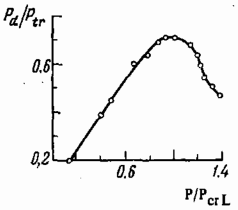

FIG. 3

Figure 3 gives a typical relation between the fraction of concentrated energy $\alpha = P_d/P_{tr}$ and the ratio of the incident energy to the critical energy P/P_{crL}. We see that when $P > P_{crL}$ (here $L > L_{cr}$), the efficiency of concentrated transport declines sharply. The small deviation of α_{max} from unity can involve the fact that the initial diffraction profile does not permit complete collection of the radiation. Here the maximum fraction of concentrated radiation was close to the fraction of the radiation in the main diffraction peak. This showed good collection of the radiation for the simple initial beam profile that was used.

The experimental results show the extreme inefficiency of a multifocus mode for radiation transport, owing to the great scattering and absorption of radiation at the foci that have arisen ahead of the detector. The latter receives only a power close to the threshold, even when a power much greater than the threshold is emitted.

The same group of authors have conducted studies of the so-called multiple waveguide mode of propagation of radiation.[15] A beam having a power that exceeds the threshold manyfold was subdivided into many beams before it entered the non-linear medium by a grid in which the power incident within each aperture was close to the threshold. It turned out that this makes it possible to control the position of the foci in the non-linear medium, and in particular, to draw them outside the non-linear medium. The foci were observed from the glowing breakdown points that arise at the peak of the pulse, i.e., at the instant when the foci are stationary[29,30] (hence the results pertained to the maximum pulse power). The distance of the grid from the entrance to the non-linear medium was revealed to play an essential role in determining the position of the foci. As the distance was increased, first they left the non-linear medium, and then entered it again, although the total beam power was not changed here. These changes were ascribed to the change in contrast of the image of the grid on the entrance plane of the non-linear medium, and the problem was posed of studying the propagation of the diffraction image of the net in the non-linear medium. We note that a waveguide mode of self-focusing is also observed in media that show strong saturation processes. Thus, recently Litvak and his associates[16,17] and Batanov and his associates[18] have observed restricted divergence of a powerful electromagnetic beam in a plasma and the formation of a channel.

Apparently the waveguide mode is of greatest interest in radiation energetics, since it involves minimal losses, On the higher waveguide modes having superthreshold powers, see[45].

All of the abovesaid has pertained to a beam having a plane initial phase front. If we impose an initial divergence that exceeds the diffractional divergence, we can greatly shift the power range at which foci appear, and transmit a much greater power in the waveguide. We can see this even from the fact that the condition for counteracting an angle of divergence $\theta \approx \sqrt{n_2}E$ requires that $E \gg E_{thr}$ when $\theta \gg \theta_{diff}$. The aberration-free theory also implies an increase in the distances to focus when there is an intrinsic divergence

$$L \approx \frac{a}{\theta_0 - \sqrt{n_2}\,E}\,.$$

However, no computer solution has yet been obtained for the parabolic equation of self-focusing with a convex initial phase front, nor has an analysis been made of the optimum choice of phase.

4. THE WAVEGUIDE FOR ABOVE-THRESHOLD POWERS

At high powers, waveguide action is manifested not only in the constriction of individual parts or of the entire wave beam and in drawing down of the wave beyond the focus, but also in the existence of modes of higher types of the non-linear waveguide,[45] which can carry a power that exceeds the threshold many times (the higher the mode, the greater the power: $P_2 \approx 6.5\ P_1$, $P_3 \approx 15.6 \times P_1$, etc.). The profile of these waveguide modes does not vary along the length. All of this confirms that the subdivision of a beam of certain very simple smooth profiles arises from unpreparedness and unsuitability of these profiles for transporting large superthreshold powers in the non-linear medium, rather than being the reason for a new conception or new treatment of the phenomenon.

5. THE WAVEGUIDE MODE UPON FOCUSING OR COLLAPSE OF A BEAM

One of the possible special means of creating a waveguide is to produce it by focusing or collapsing a beam, and this entails the possibility of getting very large channelized flux densities, in spite of the fact that here, apparently, a small part of the initial energy passes into the waveguide.

Pilipetskiĭ and his associates[19] performed the first experimental study to detect concentrated, directed propagation of radiation away from a focal point of a beam in a liquid. They observed filaments and interpreted them as waveguides. These experiments were later carried out in greater detail,[20] and it was shown that the divergence in the filaments was an order of magnitude smaller than the diffractional divergence, while closeness of the lens focus to the surface of the liquid greatly facilitates filament formation and increases their length. The diameter of the filaments was 100 μm for a length of more than 10 cm. With similar beam dimensions and the same initial powers, Korobkin et al.[21] obtained a distance from the entrance to the focus of the order of tens of centimeters upon collapsing a parallel beam. In our case the filament began at a distance at least about a millimeter from the lens focus (close distances cannot be distinguished, owing to fogging), while the power in the filament was much smaller than the initial power.

Thus, the hypothesis that the filament is formed by a moving focus would contradict the estimates of the minimum attainable Kelley length. The hypothesis remained that the filament arises from a waveguide that starts at the lens focus. We note that even if such a filament should end at the focus, it would be a waveguide with a constriction at the end, owing to the colossal preponderance of the length over the radius ($L/a \sim 10^3$).

Much experimental material on filament formation in glasses is given in[22], and here the great length of the filaments rules out interpreting them as resulting from movement of a focus.

A new development of the problem of collapse of a beam into a filament has arisen from the work of Zakharov and his associates.[23] They showed that a waveguide of small radius can be produced from an unfocused beam of Gaussian profile having a large radius in a medium having a linearity departing slightly from the n_2E^2 type. Here a power passes into the waveguide that is close to the threshold, while the rest of the energy is discarded in scattering before the entrance of the waveguide. The same authors[24] have shown the possible existence of a so-called pulsating waveguide, whose cross-section can vary strongly and non-monotonically along the direction of the axis. Two studies have recently appeared by Steinberg[25] and Kerr[26], in which they studied self-focusing filaments in glasses, and they interpreted them from the standpoint of pulsating waveguides.

We note that if the power varies in time, the start of the waveguide and its constrictions make a track, just like the foci. This complicates distinguishing them in the observed manifestations.

6. THE FOCI OF SELF-FOCUSING

Collapse of a beam or formation of a constriction involves the sharp, ever-increasing intensification of the non-linear refraction with decreasing cross-section owing to increase in the flux gradients and densities. A number of theoretical studies[5,8,23] have treated the different cases of focus formation in a conservative non-linear medium and in the presence of many-photon absorption.

The sharp field maxima at the axis of the beam can involve both constrictions of the waveguide and the focusing of different parts of the beam at different points of the axis (the caustic of self-focusing). It was shown in[8,9] that a multifocus caustic is formed in the case of strong many-photon absorption. Here a power close to the threshold is incident on (and is absorbed at) each focus. However, we cannot estimate the degree of applicability of this theory to reality and to describing the fields beyond the foci, because the type of solution depends substantially on the type of non-linearity (as has been shown by Zakharov and his associates[23,24]), and the authors of[8,9] have made a number of errors in their calculation.

For example, they adopt a non-linearity of the type n_2E^2, and absorption of the type $m_{cr} = E^{2k}$, whereas absorption necessarily alters also the type of refractive index (we must account for the higher powers in the expansion of the refractive index arising from absorption).

The very likely contribution of Raman scattering to dissipation of radiation at the foci gives a quite different aspect to the non-linearity. Actually, the change in refractive index caused by formation of excited molecules that have a different polarizability is very large (we must assume a very high concentration of excited molecules to explain the strong absorption of light at the foci). Thus, for small radii of the focal spot ($r_f \approx 3\ \mu m$[21]) and a velocity of the focus $v_f \approx 3 \times 10^9$ cm/sec.[19], we get from the condition of strong absorption of the threshold power at each focus $P_{thr} \approx \pi r_f^2 v_f n^* \epsilon^*$ such a high density n^* of excited molecules (up to energies $\epsilon^* \sim 0.1$ eV) that they will make the fundamental contribution to the change in refractive index, which cannot be written in the simple form n_2E^2, but has a complicated integral nature with high relaxation.

Moreover, the dynamic nature of the process does not allow one to estimate either the absorption or the type of non-linearity near the foci. In fact, if the longitudinal dimensions of the focal regions are $l_f \sim r_f/\theta_f \sim 3 \times 10^{-2}$ cm and the velocity of movement of the focus is $v_f \approx 3 \times 10^9$ cm/sec, we get a time of action of the field on the material $t \approx l_f/v_f \approx 10^{-11}$ sec. This value is comparable with the relaxation time of the Kerr effect. Is it not also clear how to account for absorption under such conditions, determine whether it is realized, and find its dynamics? Perhaps the conditions are fulfilled for multifocus structure at low velocities of movement, but during the movement of the foci, relaxation and saturation substantially change the form of the solution, and the foci leave behind them a waveguide extension.

We also cannot call the experiments on multifocus structure decisive. Thus, the experiments of Korobkin et al.,[21] Lipatov et al.,[27] and Loy and Shen[28] contain no cogent proof of just what is observed: a sequence of foci or constrictions of a modulated waveguide, since the patterns of the phenomena are the same in the two cases: both when detected at the exit face and when detected from the laterally scattered radiation (the scattering depends on the radiation density) and from damage tracks, which are highly critical toward increased radiation density near the critical intensities close to the damage thresholds.

Thus, e.g., to prove the existence of a "focus," Loy et al.[28] cite an experiment in which the lens-screen system was shifted so as to give identical images for the positions of the lens: focused on the exit face of the cuvette and into the interior of the cell containing the non-linear liquid. However, here they did not analyze whether the waveguide reached the exit face of the cell or its end receded into the interior of the liquid as the start of the waveguide was shifted (when such existed). Neither did they consider the fact that the angle of divergence of the radiation transmitted through the focus in the liquid and the angle of divergence of the radiation from a focus at the exit face differed, and they would give different images when foci existed. Also they did not consider the fact that, when a waveguide of not too small a radius existed, a shift of the lens should not give different images, since the light in both positions is collected near the focus of the lens. It is also possible that in both cases radiation is focused that is scattered before the moving entrance to the waveguide. All these uncertainties do not allow us to consider such experiments to be reliable or decisive.

The experiments of Lipatov et al.[27] (besides lacking any decisive distinction between a pulsating waveguide or a system of foci) gave no quantitative data on what the distance to the foci should be according to the multifocus theory, with account taken of the small value of the fast Kerr non-linearity $n_2 \sim 10^{-13}-10^{-14}$ cgs esu, which is hundreds of times smaller than n_2 for Kerr liquids (this is just why most of the studies on glasses[25,26] note the substantial role of striction and sound waves in self-focusing in them, whereas these processes do not give such a simple non-linearity as is used in the multifocus theory[8,9]).

In general, the nature of the subdivision of the beam at the pulse maximum (more exactly, when the light power P(t) has $P \approx 0$) can change in comparison with the dynamics, owing to the change in absorption mode and non-linearity. Precisely, when $P \approx 0$, the foci stand still, and absorption increases sharply. This leads to breakdown,[29,30], damage,[27] and such easily observed phenomena.

The fact that a relaxation track of perturbed refractive index remains in the wake of the moving focus, which channelizes the radiation within itself and is a waveguide (even the ardent proponents of the multifocus structure[5] have come to this conclusion), also simplifies the situation. In our opinion, it removes the "focus or waveguide" dichotomy. Apparently, all of this renders correct Kelley's hypothesis that a waveguide begins after the point of collapse.

7. CONCLUSIONS

1) The cases of greatest interest in self-focusing are the waveguide and single-focus cases, in which the beam energy is not wasted.

2) Waveguide restriction of spreading occurs at powers $P \lesssim P_{collapse}$. Waveguides having very large length-to-diameter ratios are obtained as $P \to P_{thr}$. In this range ($P < P_{collapse}$), foci do not exist at all. Higher waveguide modes exist when $P \gg P_{thr}$.[45]

3) The power that is forced into the waveguide or focus can be varied over a wide range by increasing the initial divergence of by decreasing the non-linearity of the medium. (When $\theta > \theta_D$, we get $P_{collapse} > P_{thr}$).

4) The subdivision of a beam having $P \gg P_{collapse}$ into beams of near-threshold power, as predicted by Townes and calculated by Bespalov and Talanov, and by Lugovoĭ et al., can occur, but this process is harmful and must be suppressed by increasing P_{thr} or selecting the beam profile.

5) There are no experimental and theoretical grounds for assuming that the theory of Lugovoĭ et al. correctly describes the field beyond and near the moving foci. Moreover, there are a number of factors that indicate that a waveguide extension can appear even after a moving focus, owing to relaxation, saturation, and sound. That is, breakdown occurs not at the foci, but in segments of the waveguides, i.e., the foci are entrances to the waveguides. This special problem is under debate, but in no way does it bear on the overall problem of the waveguide nature of self-focusing (see[1,2]).

8. FUNDAMENTAL PATHS OF DEVELOPMENT OF SELF-FOCUSING

In addition to unclearness of the calculations of multifocus structure, the theory of self-focusing contains a number of unsolved cardinal problems.

Within the framework of the parabolic equation with averaged non-linearity, self-focusing of a beam having an initial divergence that would permit increasing the power before collapse has not been studied. Also, the search has not been concluded for an exact solution of the cyclindrically-symmetric parabolic equation.

It would be of great interest to search for a beam profile and for types of non-linearity that would permit collapse of an entire beam into a single point at large powers. A vector treatment of the near-focus field would also be expedient.

It is not superfluous to recall that we have treated only slow non-linearity (as compared with the period of the field), while we have not treated non-linearity that varies with the frequency of the field (this is precisely what electronic non-linearity is, which is highly interesting for superpowerful pulses).

Now we shall take up some applied problems.

At present the self-focusing of various types of radiation has been examined and studied: light in non-linear dielectrics, radio waves in a plasma,[14-16] sound, ultra- and hypersound[31-33] in liquid and solid media, and also combination focusing[34] of one beam by another. The mechanisms of non-linearity that give rise to self-focusing can be the most varied. Decrease in the speed of propagation of radiation can involve: striction ([2], etc.), orientation,[4] excitation,[35-36] or deformation[37] of atoms and molecules, electronic non-linearity, hydrodynamic effects,[38] phase transitions,[33] ionization of the medium,[35] etc. The abundance of possible mechanisms of non-linearity allows us to hope for realization and use of self-focusing in such media of practical interest as air, water, the ionosphere, and artificial media (glasses and other dielectrics).

One of the fundamental practical problems is to learn how to shape the most suitable profile of the initial distribution and get an intensity and divergence of the radiation such as to give the required self-focusing. Another very important problem is to study the features of focusing in air and water involved with non-steady-state sound effects.[38] Apparently the latter cause the radiation itself to become modulated so as to amplify these sonic processes or so as to avoid defocusing stages.

We note that the Kerr effect for natural media is usually small, and the most salient processes are either striction-sonic or thermosonic (for not too short pulses), or electronic non-linearity and pre-breakdown phenomena (for short pulses).

In addition to problems of radiation energetics, the problem is of great practical importance of controlling damage to media in a laser beam. This problem is involved with increasing the transmission of the optical elements, getting high light fluxes without damaging the laser rods (in this case we must avoid collapse of the beam) or, conversely, with the problem of enhancing the damaging action of the beam in order to improve working of materials. In line with this problem, it is of interest to study in detail the initial divergence of the beam on collapse, and the effect of inhomogeneities on the development of real self-focusing.[39] In general, the problem of preventing collapse of the beam is one of the most important when one must avoid not only damage to the medium, but also absorption and scattering of the radiation.

Getting high concentrations of energy by collapsing a beam can raise the temperature of a plasma upon acting on a target, and raise the yield of hard and neutron radiation. Such prethermonuclear experiments can facilitate use of self-focusing to attain thermonuclear synthesis.[40] The choice of type of target, beam distribution, and pulse shape can enhance the self-focusing process.

A moving focus is a rather interesting object because of its high speed of movement (it can be either relativistic or faster than the speek of light). This speed can be well controlled, e.g., by a simple choice of pulse shape or of the divergence of the beam.

By using such a focus, one can study Čerenkov or transition radiation from the averaged rapidly-moving polarization,[41,42] inertia of breakdown, synchronous amplification of light by light, and other optical effects. The breakdown track from moving foci can be used as guiding elements, as antennas or waveguides, and also as lines directing the development of streamers and accelerating their motion.

The high field concentration of a moving focus can be used for synchronous acceleration of particles.[43] For example, by using the gradient force, one can get an equivalent field intensity

$$E_{\mathrm{eq}} \approx \frac{e}{2m\omega^2}\nabla(E_j^2) \approx 1-100\,\mathrm{MV/cm},$$

That is, one can get energies of the order of a mega-electron-volt on a path of movement of a focus of ~ 1 cm. Such migrations or movements of foci or hot spots can be the reason for appearance of groups of accelerated particles and hard radiation upon focusing on a target.

We note that the sharp field inhomogeneity near the focus can lead to appearance of a longitudinal component of the light field, which can give much higher accelerating fields E ~ 10^9–10^{10} V/cm. However, the difficulties of applying this variant have not yet been studied.

We see even from the brief listing of problems that self-focusing opens up an entire spectrum of new scientific and applied possibilities that can facilitate the growth of physics and technology.

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[1] The author beseeches astrophysicists not to interpret the proverb in their behalf, since here the proverb is being used for completely different purposes.

[2] The article of Dyshko, Lugovoi, and Prokhorov [8b] states erroneously that self-focusing had been described by Volkov. [44] He treated the longitudinal distribution of a field and a plasma in plane waves, but he did not pose nor discuss the problem of change in divergence owing to appearance of transverse gradients.

[3] It is interesting to note that U. S. Patent No. 3556634 was issued in 1971 to Townes and his associates on self-focusing waveguides, although the date of submission of the claim was Oct. 11, 1965, or several years after the date of publication of the Soviet studies.

[4] We note that he name "threshold power" is very unfortunate, since self-focusing begins long before the "threshold power", and it is manifested in a decrease in the divergence and cross-section of the beam.

[5] See, e.g., the article by Loy and Shen. [28b].

[1] Fizicheskiĭ éntsiklopedicheskiĭ slovar' (Physical Encyclopedic Dictionary), Vol. 1, Article, "Volnovody" (Waveguides), "Sov. éntsiklopediya", M., 1960.
[2] G. A. Askar'yan, Zh. Éksp. Teor. Fiz. 42, 1568 (1962) [Sov. Phys.-JETP 15, 1088 (1962)]; Certificate of Discovery No. 67 dated Dec. 22, 1961.
[3] V. I. Talanov, Izv. vuzov (Radiofizika) 7, 564 (1964).
[4] R. Y. Chiao, E. Garmire, and C. H. Townes, Phys. Rev. Lett. 13, 479 (1964) (Russ. Transl. in Deĭstvie lazernogo izlucheniya (Action of Laser Radiation), Ed. Yu. P. Raĭzer, Mir, M., 1968, p. 187).
[5] P. L. Kelley, Phys. Rev. Lett. 15, 1005 (1965) (Russ. Transl., see Ref. 4, p. 195).
[6] V. M. Bespalov and V. I. Talanov, ZhÉTF Pis. Red. 3, 471 (1966) [JETP Lett. 6, 307 (1966)].
[7] P. D. McWane, Nature 211, 1081 (1966) (Russ. Transl., see Ref. 4, p. 257).
[8] A. L. Dyshko, V. N. Lugovoĭ, and A. M. Prokhorav, ZhÉTF Pis. Red. 6, 655 (1967) [JETP Lett. 6, 146 (1967)]; Zh. Éksp. Teor. Fiz. 61, 2305 (1971) [Sov. Phys.-JETP 34, 1235 (1972)].
[9] V. N. Lugovoĭ and A. M. Prokhorov, ZhÉTF Pis. Red. 7, 153 (1968) [JETP Lett. 7, 117 (1968)].
[10] G. A. Askar'yan and V. B. Studenov, ibid. 10, 113 (1969) [JETP Lett. 10, 71 (1969)].
[11] G. A. Askar'yan and I. L. Chistyĭ, Zh. Eksp. Teor. Fiz. 58, 133 (1970) [Sov. Phys.-JETP 31, 76 (1970)].
[12] G. A. Askar'yan, V. G. Mikhalevich, V. B. Studenov, and G. P. Shipulo, ibid. 59, 1917 (1971) [Sov. Phys.-JETP 32, 1036 (1971)].
[13] E. Garmire, R. Y. Chiao, and C. H. Townes, Phys. Rev. Lett. 16, 347 (1966) (Russ. Transl., see Ref. 4, p. 216).
[14] G. A. Askar'yan, Kh. A. Diyanov, and M. Mukhamadzhanov, ZhÉTF Pis. Red. 17, 504 (1973) [JETP Lett. 17, 363 (1973)].
[15] G. A. Askar'yan, Kh. A. Diyanov, and M. Mukhamadzhanov, ibid. 16, 211 (1972) [JETP Lett. 16, 149 (1972)].
[16] Yu. Ya. Brodskiĭ, B. G. Eremin, A. G. Litvak, and Yu. A. Sakhonchik, ibid. 13, 136 (1971) [JETP Lett. 13, 95 (1971)].
[17] B. G. Eremin and A. G. Litvak, ZhÉTF Pis. Red. 13, 603 (1971) [JETP Lett. 13, 430 (1971)].
[18] G. M. Batanov and V. A. Silin, ZhÉTF Pis. Red. 14, 445 (1971) [JETP Lett. 14, 303 (1971)].
[19] N. F. Pilipetskiĭ and A. R. Rustamov, ibid. 2, 88 (1965) [JETP Lett. 2, 55 (1965)].
[20] G. A. Askar'yan, Kh. A. Diyanov, and M. Mukhamadzhanov, ibid. 14, 452 (1971) [JETP Lett. 14, 308 (1971)].
[21] V. V. Korobkin, A. M. Prokhorov, R. V. Serov, and M. Ya. Shchelev, ibid. 11, 153 (1970) [JETP Lett. 11, 94 (1970)].
[22] Yu. I. Kyzylasov, V. S. Starunov, and I. L. Fabelinskiĭ, Fiz. Tverd. Tela 12, 233 (1970) [Sov. Phys.-Solid State 12, 186 (1970)].
[23] V. E. Zakharov, V. V. Sobolev, and V. S. Synakh, Zh. Eksp. Teor. Fiz. 60, 136 (1971) [Sov. Phys.-JETP 33, 77 (1971)].
[24] V. E. Zakharov, V. V. Sobolev, and V. S. Synakh, ZhÉTF Pis. Red. 14, 564 (1971) [JETP Lett. 14, 390 (1971)].
[25] G. N. Steinberg, Phys. Rev. A4, 1182 (1971).
[26] E. L. Kerr, Phys. Rev. A4, 1195 (1971).
[27] N. I. Lipatov, A. M. Manenkov, and A. M. Prokhorov, ZhÉTF Pis. Red. 11, 444 (1970) [JETP Lett. 11, 300 (1970)].
[28] a)M. M. T. Loy and Y. R. Shen, Phys. Rev. Lett. 22, 994 (1969); Y. R. Shen and M. M. T. Loy, Phys. Rev. A3, 2099 (1971).
[29] T. Bergqvist, B. Kleman, and P. Wahren, Ark. Fys. B34, 81 (1967).
[30] V. V. Korobkin and R. V. Serov, ZhÉTF Pis. Red. 6, 642 (1967) [JETP Lett. 6, 135 (1967)].
[31] G. A. Askar'yan, ibid. 4, 144 (1966) [JETP Lett. 4, 99 (1966)].
[32] G. A. Askar'yan and V. I. Pustovoĭt, Zh. Eksp. Teor. Fiz. 58, 647 (1970) [Sov. Phys.-JETP 31, 346 (1970)].
[33] G. A. Askar'yan, ZhÉTF Pis. Red. 13, 395 (1971) [JETP Lett. 13, 283 (1971)].
[34] G. A. Askar'yan, Zh. Eksp. Teor. Fiz. 55, 1400 (1968) [Sov. Phys.-JETP 28, 732 (1969)].
[35] G. A. Askar'yan, ZhÉTF Pis. Red. 4, 400 (1966) [JETP Lett. 4, 270 (1966)].
[36] R. Y. Chiao, M. A. Krinsky, H. A. Smith, C. H. Townes, and E. Garmire, IEEE J. Quantum Electronics QE-2, 467 (1966).
[37] G. A. Askar'yan, ZhÉTF Pis. Red. 6, 672 (1967) [JETP Lett. 6, 157 (1967)].
[38] Yu. P. Raĭzer, ibid. 4, 124 (1966) [JETP Lett. 4, 85 (1966)].
[39] G. A. Askar'yan, V. G. Mikhalevich and G. P. Shipulo, Zh. Eksp. Teor. Fiz. 60, 1270 (1971) [Sov. Phys.-JETP 33, 686 (1970)].
[40] W. Engelhardt, Appl. Phys. Lett. 15, 216 (1969).
[41] G. A. Askar'yan, Zh. Eksp. Teor. Fiz. 42, 1360 (1962) [Sov. Phys.-JETP 15, 943 (1962)].
[42] G. G. Bondarenko, I. V. Eremina, and V. I. Talanov, ZhÉTF Pis. Red. 12, 125 (1970) [JETP Lett. 12, 85 (1970)].
[43] G. A. Askar'yan and S. D. Manuk'yan, Zh. Eksp. Teor. Fiz. 62, 2156 (1972) [Sov. Phys.-JETP 35, 1127 (1972)].
[44] T. F. Volkov, in Fizika plazmy i problema upravlyaemkh termoyadernykh reaktsiĭ (Plasma Physics and the Problem of Controlled Thermonuclear Reactions), Vol. III, Atomizdat, M., 1958, p. 336.
[45] É. K. Yankauskas, Izv. vuzov (Radiofizika) 9, 412 (1966); ZhÉTF Pis. Red. 5, 335 (1967) [JETP Lett. 5, 275 (1967)].

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