inequalities permits one to distinguish the adiabatic regime with maximum at $\delta \sim 0$ and the Landau–Zener regime, when $\xi_s v^2/(\alpha_2 - \alpha_1)^2 \lesssim 1$, with narrow maximum at $\delta \sim |\delta_s|$.

1) The linear Stark effect in an alternating field can occur in some cases in systems which are not centrally symmetric,[3] but this possibility is not taken into account here.

2) Nonmonotonicity of the saturation curve in the case of single-photon resonance due to rearrangement of the multiplet structure of the atomic levels in a monochromatic field was considered in Ref. 15.

3) The possibility of a maximum of the dispersion curve at a point other than $\delta = 0$ was noted by Fedorov.[10]

4) To obtain Eq. (1) in the case of instantaneous switching-on of the interaction, it is necessary to use the smallness of $|vI_0/4\Delta|$ already in Eq. (32) and then set $t \gg \gamma_2^{-1}$; this is the usual procedure when one considers decay with instantaneous switching-on of the interaction (cf. Ref. 19).

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Self-focusing of laser beams at various spatial profiles of the incident radiation

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The character of formation of a nonlinear focus was investigated for a media with a Kerr type nonlinearity, under subthreshold conditions as well as in the regime of developed self-focusing at various spatial profiles of the incident radiation. A numerical experiment was used to determine the influence of the profile of the incident radiation and of its intensity on the character of the field distribution in the region of the nonlinear focus and on the power flowing into the first nonlinear focus in the case of beams of the supergaussian type. The dependence of the self-focusing threshold on the initial beam divergence is obtained for both bounded and unbounded media.

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INTRODUCTION

Even though the main laws governing the self-focusing of laser radiation have by now been sufficiently well-investigated, many aspects of this phenomenon remain unclear. Thus, the process investigated in greatest detail was self-focusing of light beams with Gaussian intensity profiles, which were found to have a multi-focus structure.[1] The question of deviation of the incident radiation from gaussian as it affects the main characteristics of wave propagation in a medium with Kerr type of nonlinearity remains open. Thus, for

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certain beams with developed radial intensity profiles it was established in Ref. 2 that the power trapped in the first nonlinear focus is independent of the profile of the incident radiation and is equal to the value cited in Refs. 3 and 4 for gaussian beams. This result, however, was obtained for radial profiles with wings of gaussian type, and only for one value of the incident-radiation power P_0, exceeding the threshold by a of two. At the same time it was found in Ref. 5 that in beams with a plateau-like intensity distribution ($E_0 = \exp(-\alpha r^N)$, where $N > 2$) an increase of P_0 can lead to a considerable increase of the power flowing into the first nonlinear focus. This result, however, was obtained for absorbing media, and since the absorption was not varied in a wide range, it remains unclear whether this conclusion is valid for a problem of this type.

We have therefore undertaken the study, for beams of super-gaussian type, of the influence of the profile and intensity of the incident radiation on the character of the field distribution in the region of the nonlinear focus, in media with cubic nonlinearity. The singularities that arise are determined from the radial distribution of the field and from the power trapped in the nonlinear focus. It must be noted that these quantities can be correctly determined only by solving the problem of self-focusing without absorption.

In addition to determining the character of the singularity that arises in the solution of the problem, we investigate here the influence of the initial beam profile on the self-focusing threshold and length. We find accordingly the dependence of the self-focusing threshold on the initial beam divergence, in both bounded and unbounded media.

The influence of the nonlinearity of the medium on the light-wave propagation is not restricted to a determination of the self-focusing threshold and to the behavior of the field under above-threshold conditions. Thus, the field behavior under subthreshold conditions has not been sufficiently investigated to date even in the case of gaussian beams.[6,7] We study therefore, by means of a numerical experiment, the beam deformation in the initial stage of the self-focusing.

1. INFLUENCE OF THE INCIDENT BEAM SHAPE ON THE CHARACTER OF THE SELF-FOCUSING AT $P_0 > P_{cr}$

Beam propagation in a medium with cubic nonlinearity was analyzed on the basis of a parabolic equation of the type

$$2ik\frac{\partial E}{\partial z}+\Delta_r E+k^2\frac{n_2}{n_0}|E|^2E=0. \qquad (1)$$

The problem was solved for beams of various profiles and intensities by numerical methods, using a computer. Since this problem is characterized by strong oscillations of the complex field amplitude E, we put $E = \exp(A/2 + ikS)$ and integrated numerically the system of nonlinear equations for the "amplitude" A and the phase S of the field.

It should be noted that at input powers $P_0 \geqslant P_{cr}$ (P_{cr} is the critical self-focusing power) our problem is characterized by a highly inhomogeneous distribution of the energy flux and, in the absence of absorption, by the presence of singular points at which the field amplitude increases without limit. Taking this into account, we used a grid of points r_i located on the constant energy flux lines

$$\int_0^{r_i}|E|^2\,r\,dr=P_i=\text{const.} \qquad (2)$$

The chosen numerical-solution method made it possible to consider self-focusing at an arbitrary axisymmetric initial distribution of not only the intensity but also the phase of the field, and to describe the solution with sufficient accuracy as the singular points are approached. Our calculation method permits a highly accurate determination of the power trapped in the first nonlinear focus, since the chosen integration paths provide a picture of the energy flux.

The correctness of the accuracy was monitored against the manner in which the solution converged when the number of points of the radial grid and the size of the interval of integration with respect to z were varied. In addition, satisfaction of the conservation laws for the initial equation (1) was checked for the beam power (2) as well as for the Hamiltonian of the corresponding variational problem:

$$H=\int_0^\infty\left\{\frac{1}{2}\left|\frac{\partial E}{\partial r}\right|^2-\frac{k^2n_2}{4n_0}|E|^4\right\}r\,dr=\text{const.} \qquad (3)$$

As for the total beam power, it was conserved with sufficient accuracy in the entire range of z. Conservation of the second invariant (3), however, calls for a much higher solution accuracy. The reason is that the quantity

$$H(r)=\int_0^r\left\{\frac{1}{2}\left|\frac{\partial E}{\partial r'}\right|^2-\frac{k^2n_2}{4n_0}|E|^4\right\}r'dr'$$

has a maximum that increases rapidly as the singular point is approached ($E\to\infty$). Thus, in our case the change of $H(r)$ reached 10^6-10^7 in units of $H(\infty)$. We regard therefore the invariant (3) and invariants of higher order as inadequate criteria of the correctness of the calculation.

Equation (1) with $P_0 > P_{cr}$ was solved numerically by the described method for gaussian and supergaussian beams

$$|E_0|^2=\exp\{-\alpha(r/a_0)^N\}$$

with $N = 2$, 4, 6, 8, and 10. The coefficient α was chosen such as to normalize the total energy integral $P(r) = \frac{1}{2}$ as $r\to\infty$ ($\alpha = 1$ for gaussian beams). Typical results for collimated beams at $N = 2$ and $N = 8$ are shown in Fig. 1. It is seen that the field distributions differ in character. in the case of supergaussian beams, especially at $P_0 \gg P_{cr}$ and large N, annular zones are formed in the region ahead of the focus. These zones can contain a power greatly exceeding the critical value. With further propagation, these zones are focused on the beam axis to form a multifocus structure. Within a single zone, these foci are much closer to one another than in a Gaussian beam. Thus, at

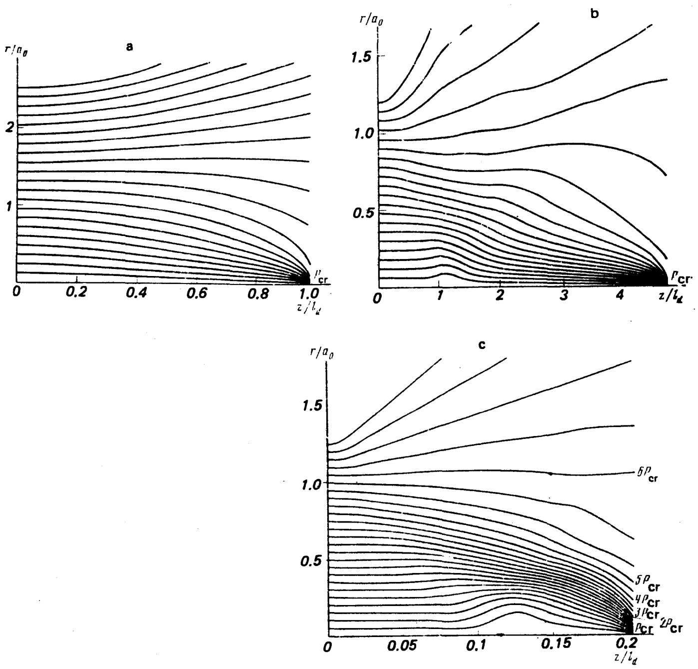

FIG. 1. Energy flux lines for beams with different intensity profiles: a) gaussian beam, $N=2$, $P_0 = 1.5P_{cr}$; b) supergaussian beam $N=8$, $P_0=1.5P_{cr}$; c) $N=8$, $P_0=7P_{cr}$; a_0 and ld are the characteristic radius and diffraction length of the beam. The quantities marked on the figure correspond to the streamlines that limit the indicated power.

$N=8$ and $P_0=7P_{cr}$, the distances between foci is of the order of $10^{-3}ka_0^2$, as against $2\times10^{-2}ka_0^2$ for a gaussian beam of the same power. An essential distinguishing feature of the self-focusing if supergaussian beams, compared with the gaussian ones, is that the multifocus structure can be formed at $P_0 \gg P_{cr}$ in such a way that the new foci appear behind as well as ahead of the first focus (on the z axis). This result is due to collapse of the annular zones. Figure 2 shows a plot of the self-focusing length for the first two annular rings against the input power (case of supergaussian beams with $N=8$). In this case the threshold for formation of a nonlinear focus for the second zone turns out to be $16P_{cr}$. Obviously, introduction of absorption can lower the multifocus-structure intensity contrast, and this apparently took place in Ref. 5.

An analysis of the results obtained by us on the character of the field distribution in the region of the nonlinear focus has shown that, independently of the intensity and phase profiles of the incident beams and of the values of P_0, the power trapped in the first focus is equal to P_{cr}.[8] In analogy with Ref. 2, the limit of the critical region was determined from the maximum slope of the beams relative to the z axis sufficiently close to the singular point z_0. The power trapped in the first nonlinear focus was determined accurate to not more than 5% at $P_0 \gg P_{cr}$ and with a substantially smaller error at $P_0 \approx P_{cr}$.

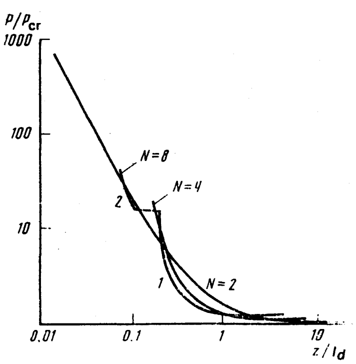

FIG. 2. Dependence of the self-focusing length on the input power for various values of N. The numbers indicate the annular zones for an $N=8$ supergaussian beam.

The calculation yielded also the radical distribution of the beam intensity as the nonlinear focus was approached. It turned out that, regardless of the initial intensity profile, a characteristic radial distribution is formed in the focal region, with the form shown in Fig. 3. It can be seen from the figure that as the nonlinear focus is approached ($\Delta z = z_0 - z$) the paraxial part of the distribution becomes parabolic in the region $P(r) \leq P_{cr}$, and its wings tend asymptotically to the exponential dependence

$$I\sim e^{-\eta r};\quad \eta\sim(z_0-z)^{-1/2}. \tag{4}$$

The behavior of the field near a singular point was investigated by watching the change of the quantity[9]

$$B(z)=I_{zz}''(0,z)I(0,z)/[I_z'(0,z)]^2.$$

The numerical calculations has shown that as the singular point is approached, $z_0 - z \to 0$, the value of $B(z)$ tends to 2 faster the closer P_0 to P_{cr}. An investigation of the variation of $B(z)$ has shown that $I(0, z)$ has an asymptotic form

$$I(0,z)=\frac{f(z_0-z)}{z_0-z},$$

where the function $f(z_0 - z)$ is weaker than $\ln(z_0 - z)$.

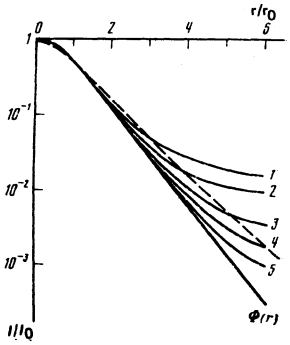

FIG. 3. Radial distribution of the intensity at various distances from the nonlinear focus (gaussian beam, $P_0 = 5P_{cr}$: 1) $\Delta z = 4.5\times10^{-3} l_d$; 2) $\Delta z = 1.1\times10^{-3} l_d$; 3) $\Delta z = 1.5\times10^{-4} l_d$; 4) $\Delta z = 1.3\times10^{-5} l_d$; 5) $\Delta z = 2\times10^{-6} l_d$. I_0 is the intensity on the beam axis, r_0 is the radius at the intensity level $I = I_0/2$, and the dashed line is the Townes intensity profile.

We note that the existence of an asymptotic radial distribution $\Phi(r)$ (see Fig. 2) can be used to determine the critical power with the aid of the relation

$$P_{кр}=\int_0^\infty \Phi(r)rdr.$$

The asymptotic approach of the radial-distribution wings to the form $\Phi(r)$ gives rise to a transition layer called "relaxation layer" in Ref. 2. The energy width of this layer, due to the continuity of the solution in the prefocal region, is determined by the degree of approach to the singular point $\Delta z \to 0$.

The results shown in Fig. 3 were obtained for beams with an initial gaussian intensity profile. The calculations have shown, however, that a perfectly analogous picture of the field distribution in the near-focal region is obtained also for supergaussian beams. It is therefore not presented here.

Neither the distribution of the energy flux, nor its value in the nonlinear focus, is thus dependent on the incident-beam characteristics in a medium with cubic nonlinearity. This result seems to indicate that the characteristics of a nonlinear focus are determined not by the initial distribution of the field at the input but only by the form of the nonlinearity of the medium.

2. BEAM DEFORMATION IN THE INITIAL SELF-FOCUSING STAGE ($P_0 < P_{cr}$)

We now dwell on the behavior of the wave field under subthreshold conditions and on the formation of the first nonlinear focus. We present first the results of the analytic solution of the problem of propagation of a relatively weak Gaussian beam through a semi-infinite medium, when the nonlinearity of the medium need to be taken into account in first order as a perturbation, i.e., under the condition

$$|E/E_L-1|\ll1, \tag{5}$$

where E_L is the field if the medium is linear.

A solution of the initial equation (1) was first obtained for this case by Lugovoĭ[6] in general form for beams with initial profile

$$E|_{z=0}=E_0 \exp[-(1/2a_0^2+ik/2R)r^2]. \tag{6}$$

His expressions, however, are complicated and difficult to use in actual calculations. We have therefore used the integral-transformations method for our problem (1), (5) and (6) and obtained in first-order approximation a simpler analytic expression for the field on the beam axis:

$$E(0,z)=E_L(0,z)\left[1+\frac{k^2a_0^2}{8}\frac{n_2|E_0|^2}{n_0}\ln\frac{1-z/R+3iz/ld}{1-z/R-iz/l_d}\right]. \tag{7}$$

Here R is the curvature radius of the phase front as it enters the medium, $l_d = ka_0^2$ is the diffraction length of the beam, and a_0 is the radius of the gaussian beam.

Analysis of our expression shows that the ratio $|E/E_L|$ always has its maximum at the geometric focus of the beam, $z=R$ in the case of focused beams or $z=\infty$ for beams with a plane wavefront at the entry into the medium. We have therefore for the maximum of this ratio

$$|E/E_L|^2_{max}=1+|E_0/E_1|^2, \tag{8}$$

where $|E_1|^2 = 3.64(ka_0)^{-2}n_0/n_2$.

The result (8) shows that even in the initial self-focusing stage the contraction of the beam follows a law that differs greatly from that given by the zero-aberration-approximation theory,[10] and $|E_1|^2$ itself is very close to the self-focusing threshold.

The stronger contraction of the beam was investigated by numerical methods. The results obtained for collimated beams are shown in Fig. 4 for various values of the incident power referred to the threshold. As seen from Fig. 4, the maximum contraction also takes place at $z=\infty$. The ratio $|E/E_L|^2$ at not too strong a contraction is sufficiently well described by the expression

$$\left|\frac{E}{E_L}\right|^2_{max}=\frac{1}{1-|E_0/E_1|^2}. \tag{9}$$

The coefficient of $|E_1|$ is here the same as in (8). A radial distribution similar to that shown in Fig. 3 is then formed in the region $z \gg l_d$. It is of interest to note that near the self-focusing threshold, on either side, the radial intensity profile differs from the Townes profile[11] which is the exact solution of Eq. (1)

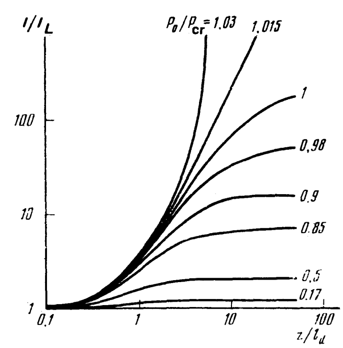

FIG. 4. Field intensity on the beam axis in a nonlinear medium at various P_0/P_{cr}. I_L is the field intensity in the absence of nonlinearity.

in the presence of a plane phase front. The latter carries a total power close to the critical self-focusing power,[1] and the fact that this profile is not realized seems to indicate instability of the profile. In fact, the phase front in the wings of the radial distribution is not planar near the self-focusing threshold. This means in fact that the Townes profile is very sensitive to the planarity of the phase front.

For beams having a nongaussian incident-wave profile [(e. g., $E|_{z=0} = \exp(-\alpha r^4)$] the ratio of the nonlinear and linear solutions is also described by the same relations (8) and (9) and with the same coefficient $|E_1|$. Thus, for the class of considered initial distributions, the behavior of the beam under subthreshold conditions, i.e., the degree of contraction of the beam (relative to the linear solution) does not depend noticeably on the initial distribution profile.

At powers P_0 close to the self-focusing threshold, the nonlinear compression relation (9) ceases to hold. The initial distribution $E_0(r)$ influences in this case the very value of the beam-collapse threshold power. Thus, for Gaussian beams the self-focusing threshold is given by

$$|E_{\text{thr}}|^2=3.77(ka_0)^{-2}n_0/n_2, \quad P_{\text{thr}}=0.942\lambda^2c/8\pi^2n_2;$$

for beams of the form $E_0(r)=\exp(-\alpha r^4)$ the threshold is somewhat different:

$$|E_{\text{thr}}|^2=3.95(ka_0)^{-2}n_0/n_2, \quad P_{\text{thr}}=0.988\lambda^2c/8\pi^2n_2;$$

and at $E_0(r)=\exp(-\alpha r^8)$ we have

$$|E_{\text{thr}}|^2=4.42(ka_0)^{-2}n_0/n_2, \quad P_{\text{thr}}=1.105\lambda^2c/8\pi^2n_2.$$

The critical power, i.e., the power trapped in the nonlinear focus, is the same in the cases indicated and amounts to

$$P_{\text{cr}}=0.932\lambda^2c/8\pi^2n_2.$$

We note that the cited results (8) and (9) are valid for collimated as well as for focused beams, and the results shown in Fig. 4 can be easily recalculated for the case of focused beams by using the lens transformation in the region ahead of the geometric focus.[12]

3. SELF-FOCUSING OF DIVERGING BEAMS

We discuss now the influence of the initial beam divergence on the self-focusing process. The solution of this problem is of practical importance for the assessment of the possibility of self focusing in high-power laser systems. To this end we have determined by numerical calculation, for collimated beams, the dependence of the self-focusing length z_0 on the input power. Figure 2 shows this dependence for gaussian and supergaussian ($N=2, 4, 8$) beams. Using the lens transformation, we plotted for the gaussian beams the self-focusing threshold against the curvature l_d/R of the phase front, for both a semi-infinite medium and a medium of length l ($L=l/l_d$). This dependence is shown in Fig. 5. That these plots are valid for strongly defocused beams was verified by comparing the results obtained with the lens transformation with the direct numerical calculation.

It is seen that a noticeable change of the self-focusing

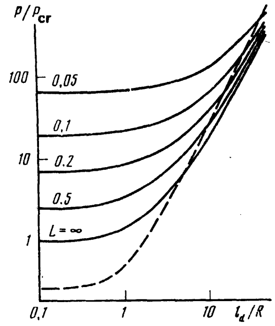

FIG. 5. Dependence of the self-focusing threshold on the divergence of the input beam for different medium nonlinearity lengths L. The dashed line is the plot obtained to the zero aberration approximation, R is the curvature radius of the phase front at the input, and $l_d = ka_0^2$ is the diffraction length of the beam. The quantities marked on the figure correspond to the streamlines that limit the indicated power.

threshold sets in only at a very large initial beam divergence. In real systems this suppression of the self-focusing is apparently impossible to realize, inasmuch as at such high powers ($P_0>10^3 P_{\text{cr}}$) small-scale self-focusing is more likely to set in.[13]

The presented analysis of self-focusing of beams with different intensity and phase profiles, in a wide-range of input powers and for nonabsorbing media with cubic nonlinearity, as shown the following:

1) The power flowing into a nonlinear focus (critical power), as well as the structure of the field in the region of the nonlinear focus, does not depend on the characteristics of the incident beam.

2) An important role in the beam deformation during the initial stage of the self-focusing ($P_0<P_{\text{cr}}$) is played by nonlinear aberrations. The character of the contraction was determined for gaussian beams up to $P_0 \lesssim 0.9P_{\text{cr}}$.

3) In real cases, the defocusing of the incident beam does raise the self-focusing threshold significantly.

[1)] The difference in the wings of the radial distribution (Fig. 3) is inessential, for by choosing the normalization coefficient r_0 we can make $\Phi(r)$ and the Townes profile agree either in the radial-distribution wings or in the paraxial zone.

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Measurement of ionization threshold intensities in helium using ponderomotive force accelerated electrons

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The results of an experimental program to study the ionization of atoms by intense laser beams are presented. New experimental results concerning the distribution of photo-electrons as a function of their energy and the dependence of electron emission on laser beam intensity for values up to 6×10^{16} W/cm^2 have been obtained.

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1. INTRODUCTION

Accurate knowledge of both the electric field intensities and the time at which ionization occurs in any test gas volume is essential to a number of the projects involving the interactions of intense laser beams with matter. These include self-focusing[1] and ionization of dense plasmas by intense laser beams[2] and the ionization and radiation-matter interaction studies in tenuous plasmas[3-5], as well as the study of possible photon fission processes within intense laser beams enveloped by intense Coulomb fields.[6]

In the experiments discussed here the number and integrated energy spectra[3,4] of electrons emitted by the action of ponderomotive force from the focus region of a high intensity neodymium laser beam focused into a tenuous helium plasma were measured as a function of the laser intensity over the range 10^{14} to 6×10^{16} W/cm^2.

The energy spectra were found to be characteristic of electrons accelerated by ponderomotive forces.[3,5] The spectral profiles are independent of laser intensity, but strongly dependent on the degree of ionization of the test gas. Measurement of the intensities at which sepctral shape changes occur provides a means of obtaining the ionization threshold intensities for any test gas. Alternatively these threshold intensities will be obtained more accurately as the asymptotic values of curves of the number of electrons against intensity with electron energy as a parameter. Both types of measurement were carried out and the results compared with values calculated using the general formula for ionization probability as given by Keldysh.[7]

2. APPARATUS

The laser system consisted of a passively mode-locked Nd:YAG oscillator producing trains of individual pulses with a nominal duration equal to 25 psec. Single pulses from the oscillator were isolated using a pair of tandem-connected Pockel's cells with an overall contrast ratio greater than 10^4, and then amplified to a level of about 1 joule using Nd;YAG and Nd:Glass amplifiers. A single-vacuum spatial filter was also included within the amplifier chain to keep the value of the beam break-up integral low and thereby ensure that the beams focusing properties were not adversely affected by refractive index non-linearly within the laser glass.

Measurements have shown a significant fluctuation in the pulse duration from the oscillator[8] with 80% of pulses having durations between 18–36 psec and 60% between 20 and 30 psec. The duration of individual pulses used in the experiments was measured using a two photon fluorescence monitor to an accuracy of better than 10%.

As illustrated in Fig. 1, the beam was focused using a 75 mm aspheric lens inside an evacuated chamber which had subsequently been filled with helium gas to a pressure of 10^{-4} Torr after evacuation to less than 5×10^{-7} Torr. The distribution of power in the focused beam was measured in a separate experiment by ablating an aluminum film off a glass substrate which was placed in the beam.[5]

The electrons emitted from the focal region were collected over a solid angle of 2.7 sr by a multidirectional retarding-field electron energy analyzer. This detector was constructed from four monodirectional retarding-field electron-energy analyzers, one of which is illustrated in Fig. 1. Grids 1 and 3 were grounded and grid 2 acted as a retarding grid which was negatively biased to prevent electrons with energies less than the grid potential from reaching the collector. The collector itself was biased to + 45 volts to prevent secondary electron losses.

The minimum charge which could be detected was ~10^{-15} Coulombs, which is equivalent to a detection

