Two-dimensional Langmuir solitons and discreteness of the spectrum of the microwave radiation from a plasma at $\omega_{pe} < \omega_{ce}$

V. I. Petviashvili, N. F. Perepelkin, V. A. Suprunenko, M. P. Vasil'ev, and A. E. Kulaga

I. V. Kurchatov Institute of Atomic Energy
(Submitted 5 December 1979)
Zh. Eksp. Teor. Fiz. **79**, 828–835 (September 1980)

We investigate the radiation of electromagnetic waves at Langmuir frequencies from a plasma in a strong magnetic field, as well as the Langmuir and ion-sound noise in such a plasma. Experiments with the "Uragan-2" stellarator have shown that in an electric field weaker than the Dreicer field the Langmuir noise is localized relative to the radius and angle of the plasma column. The frequency spectrum of this noise, just as in the case of electromagnetic radiation, is discrete. These phenomena are attributed to formation of traveling Langmuir solitons localized on a magnetic surface or around a force line, and enhanced by accelerated electrons produced on a resonant magnetic surface during the development of magnetodydrodynamic (MHD) helical instability. A solution of the plasma equations in the form of such a soliton is obtained. The energy density in the soliton can be comparable with the plasma pressure. Modulation instability of the soliton is eliminated by a resonant Doppler damping.

PACS numbers: 52.35.Hr

1. INTRODUCTION

Reconnection of magnetic force lines from neighboring magnetic surfaces can be initiated in closed magnetic traps under conditions of instability with respect to buildup of helical magnetohydrodynamic (MHD) modes along some resonant force lines.[1] The process accelerates strongly in the presence of an anomalous magnetic-field dissipation mechanism. Such a mechanism can be the buildup of Langmuir waves by electrons accelerated in the enhanced electric field that is produced in the reconnection region. Since the growth rate of the buildup is small and is localized in a small region, it is important, to maintain the anomalous resistance, that the Langmuir waves built up in this region not spread over the entire plasma.

In this paper we point out the possibility of self-localization of Langmuir waves around a magnetic-field force line or on a magnetic surface, accompanied by narrowing of the frequency spectrum of the turbulent noise. These two effects were observed experimentally in the "Uragan-2" stellarator. A feature of these strongly nonlinear effects is the absence of a plasma-density well. The oscillation become phased-in via the higher harmonics of their natural modes. The modulation instability is suppressed by Doppler-resonance damping.

2. EXPERIMENT

We investigated superthermal microwave radiation of the plasma in the stellarator "Uragan-2" in a regime typical of most tokamaks. The cyclotron electron frequency ω_{ce} exceeded the plasma frequency ω_{pe}, and the longitudinal electric field E was weaker than the Dreicer field E_{Dr}. For the sake of completeness, we present also the results obtained at $E > E_{\mathrm{Dr}}$.[2]

The spatial distributions of the microwave and high-frequency fields, as well as of the flux of the accelerated electrons in the plasma, were obtained using a combined probe. The x-ray measurements were made with a molybdenum bead (2 mm diameter) and with an organic scintillator crystal with good screening and collimation. The minimum energy of the registered quanta was 10 keV. The fields of the microfluctuations were measured in the plasma with a coaxial electric probe. The spatial resolution of the combined probe along the plasma radius was not worse than 3 mm. The plasma perturbations introduced by the probe were monitored with a standard diagnostic assembly. The principal relations and spectra were obtained at a plasma density $n_0 = 2\times 10^{12}$ cm^{-3} and at a ratio $\omega_{ce}/\omega_{pe} = 1.6$.

Figure 1 shows plots of the discharge current and of the power $P_{\omega_{pe}}$ of the superthermal microwave radiation observed outside the plasma in the vicinities of the plasma frequency, of the power P_γ of the hard x-radiation of energy up to 100 keV from a target in the plasma, as well as of the intensity of the fluctuations of the potential fields inside the plasma, at frequencies close to the electron, ion, and double the ion plasma frequencies ($E^2_{\omega_{pe}}, E_{\omega_{pi}}{}^2, E^2_{2\omega_{pi}}$) as functions of the electric field intensity E in the loop of the stellarator discharge chamber. It is seen that near the threshold $E = E_{\mathrm{Dr}} = 1.6\times 10^{-2}$ V/cm, and when the discharge current J increases linearly, a qualitative change of the character of the turbulent spectrum takes place in the plasma. Whereas in a weak field ($E < E_{\mathrm{Dr}}$) the runaway electrons excite intense Langmuir oscillations and the energy of the registered quanta from the walls of the discharge chamber and from the target reaches 100 keV, in a strong field the fast electrons are effectively decelerated and intense ion-plasma noise appears in the plasma. The growth of the turbulent fluctuations at the ion frequencies is accompanied by a decrease in the power $P_{\omega_{pe}}$ of the superthermal microwave radiation from the plasma, and the intensity of the Langmuir noise inside the plasma is simultaneously decreased.

Thus, the measurements show that high-power Langmuir noise in a stellarator is produced at $\omega_{pe} < \omega_{ce}$ in

 0038-5646/80/090421-05$02.40

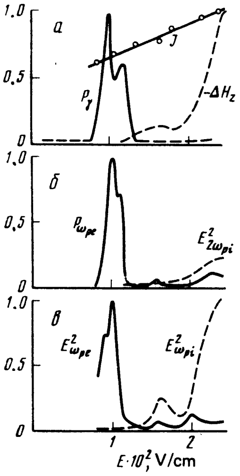

FIG. 1. Relations obtained in the stellarator "Uragan-2" at a constant plasma density in a strong magnetic field ($n=2\times 10^{12}$ cm^{-3}, $\omega_{ce}/\omega_{pe}=1.6$) with increasing electric field intensity on the torus loop: a) J—discharge current, $J_{max}=2.5$ kA, P_γ—intensity of the hard x rays from the target in the plasma (the horizontal dashed line marks the threshold sensitivity of the recorder at 6 keV level), $-\Delta H_z$—local diamagnetic perturbations; b, c) $P_{\omega_{pe}}$—power of the superthermal microwave radiation outside the plasma, $E^2_{\omega_{pe}}$, $E^2_{\omega_{pi}}$, $E^2_{2\omega_{pi}}$—intensities of field fluctuations at the Langmuir, ion, and double ion plasma frequencies. The quantities are in relative units.

the regime of weak electric fields $E < E_{\rm Dr}$, when an appreciable number of the runaway electrons can be produced only on individual magnetic surfaces, probably as a result of MHD instability on these surfaces, which leads to a reconnection of the force lines.

The absence of a strong increase of the electric current J when the Dreicer field is increased was first observed in Refs. 3, 4, and elsewhere. Figure 1 shows that when $E_{\rm Dr}$ is exceeded the drastic changes occur not in the current but in the character of the fluctuation and radiation from the plasma. We note that owing to the strong deviation from a Maxwellian electron distribution, it is possible that our measurements are not accurate in the sense that the noted critical value of the

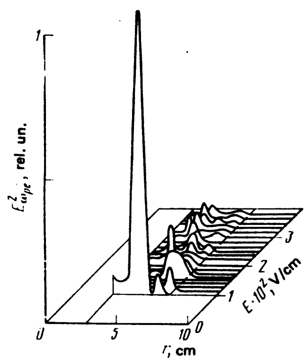

FIG. 2. Redistribution of the intensity $E^2_{\omega_{pe}}$ of the Langmuir oscillations in a plasma for different values of electric field intensities on the torus loop in the region of the minimum discharge-parameter perturbations introduced by the combined probe. (The dashed line designates the outer-most unperturbed magnetic surface in the "Uragan-2" stellarator; the plasma density distribution is uniform enough within the limits of the separatrix).

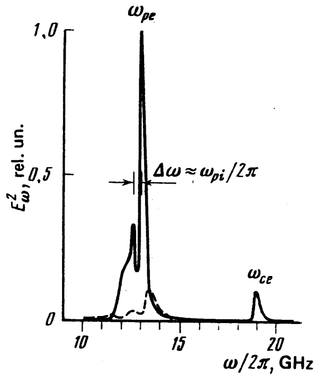

FIG. 3. Intensity spectrum of the microwave fluctuations in a magnetized hydrogen plasma of the "Uragan-2" stellarator in a weak ($E=10^{-2}$ V/cm—solid line) and in a strong electric field ($E=2.5\times 10^{-2}$ V/cm—dashed).

electric field $E_{\rm Dr}$ can differ somewhat from the real Dreicer field. Another shortcoming is that the oscillation-frequency measurement at the probe is not simultaneous with the measurements of the plasma density.

At $E < E_{\rm Dr}$, a characteristic of the observed specific feature of the Langmuir oscillations and of the flux of accelerated electrons is their two-dimensional localization in space in the pinch cross section, both in radius and in angle. In addition, the Langmuir spectrum excited in the plasma is of strongly pronounced discrete character.

The distribution of the microwave field intensity $E^2_{\omega_{pe}}$ of the Langmuir oscillations over the radius of the pinch is shown in Fig. 2 for different electric field intensities. The frequency spectrum of $E^2_{\omega_{pe}}$, registered by an electric probe inside the plasma, is shown in Fig. 3. These figures demonstrate both the localization with respect to the plasma radius and the narrow-band character of the Langmuir spectrum. Another characteristic feature is the appearance of satellites in the spectra, spaced ω_{pi} apart.

At $E > E_{\rm Dr}$ the number of runaway electrons decreases sharply,[5,6] as is seen also from the decrease of the intensity P_γ of the x radiation (Fig. 1). Simultaneously, the intensities of the ion-plasma noise at the first and second harmonics of the ion-plasma frequency ω_{pi} increase sharply.

3. LANGMUIR SOLITON WITHOUT A DENSITY WELL

Some of the effects described above at $E < E_{\rm Dr}$ can be attributed to the strongly nonlinear properties of the Langmuir waves. One of us[7] had derived a simplified nonlinear equation for Langmuir waves in a magnetic field. In analogy with Zakharov's paper,[8] where the analysis was carried out without the magnetic field, the nonlinearity mechanism was the formation of density wells in the plasma under the influence of the high-frequency pressure. In this equation, at $\omega_{pe} < \omega_{ce}$, the dispersion correction transverse to the magnetic field reverses sign, so that the one-dimensional soliton solutions become stable.

Such solitons were observed in Ref. 9. They were the result of instability of an electron beam with a small scatter in velocity space. In the experiment considered by us, there are clearly no such solitons. Instead of localization of the oscillations along the magnetic field, localization across the field is observed (Figs. 2 and 4), and no density well is observable in the localization region. The explanation is that in place of a narrow beam we have here an elongated tail of runaway electrons in the electron-velocity distribution function f, which has only one maximum. Such a distribution function is unstable to enhancement of potential waves with frequencies $\omega < \omega_{ce}$.[10,11] The enhanced waves are those traveling towards the tail, at the "anomalous" Doppler resonance with electrons whose velocity along the magnetic field is

$$v_z=\left(1+\frac{\omega_{ce}}{|\omega|}\right)\frac{\omega}{k_z}.$$

It is necessary in this case that the buildup at the Cerenkov resonance $v_z = \omega/k_z$ be small, as is the case when the derivative $\partial f/\partial v_z$ at this point is small.

The waves traveling in a direction opposite to the tail are attenuated at the "normal" Doppler resonance

$$v_z=\left(1-\frac{\omega_{ce}}{|\omega|}\right)\frac{\omega}{k_z}.$$

The growth or decay rates at these Doppler resonances are of the order of $\alpha\omega(\omega_{pe}/\omega_{ce})^2$, where α is the ratio of the densities of the tail particles and the thermal particles. Therefore, in the presence of a tail on the distribution function of the electrons there are only waves traveling along the tail. The one-dimensional solitons observed in Ref. 9 contain a standing Langmuir wave in the density well. The standing-wave component traveling in the direction opposite to the electron tail is attenuated by the normal Doppler effect, as a result of which no density wells are produced in our case. If, however, we have a beam bounded in velocity space instead of a tail, solitons of the type of those in Ref. 9 can build up at the Cerenkov resonance or at the anomalous Doppler resonance. There will be no damping at the normal Doppler resonance because there are no beam particles in the region of this resonance.

This explanation is confirmed by a circumstance noted in Ref. 9: in the presence of a beam of electrons with large velocity scatter, i.e., when damping at the normal Doppler resonance becomes possible, the density wells are registered much less frequently than in the case of a beam with a small velocity scatter, although the difference in the Langmuir-noise level is negligible.

We shall show that at $\omega_{pe} < \omega_{ce}$ a traveling Langmuir soliton without a density well is possible and is localized on a magnetic surface or around a force line. Such a soliton is easily excited by a tail on the electron distribution function, and if a component traveling in the opposite direction appears, then this component is damped, so that the density well that accompanies this component is not formed in the presence of a tail of accelerated electrons.

Assuming ω_{ce} to be sufficiently large, we can regard the electron motion in the hydrodynamic approximation as one-dimensional. We then have

$$\frac{\partial v}{\partial t}+v\frac{\partial v}{\partial z}=-\frac{v_{Te}^2}{n}\frac{\partial n}{\partial z}+\frac{e}{m}\frac{\partial\varphi}{\partial z}, \tag{1}$$

$$\frac{\partial n}{\partial t}+\frac{\partial}{\partial z}nv=0, \quad \omega\ll\omega_{ce}, \tag{2}$$

$$\Delta\varphi=4\pi e(n-n_0). \tag{3}$$

In these equations v is the velocity of the electrons along the z direction of the magnetic field.

We seek a stationary solution that travels along z with constant velocity u, so that all the quantities depend on $\zeta = z - ut$ and $\mathbf{r}_\perp$. The velocity u is much higher than the thermal velocity v_{Te}, therefore the pressure in (1) can be neglected. We then obtain from (1) and (2)

$$v=u[1-(1+\psi)^{1/2}]; \quad \psi\equiv 2e\varphi/mu^2, \tag{4}$$

and

$$n=n_0[1+N(\mathbf{r}_\perp)](1+\psi)^{-1/2}; \quad n_0=\text{const.} \tag{5}$$

Here N is an integration constant, which differs from zero only in the region of the localization wave, and is chosen to satisfy the condition imposed on the z-averaged electron density: since they are frozen-in, the thermal electrons do not move across the magnetic field, so that their average density is unperturbed. For the same reason the average potential electric field in the wave is equal to zero, but on the other hand the average electron flux inside the wave differs from zero relative to the electron flux outside the wave: the wave drags the particles. We have thus

$$\langle n\rangle=n_0, \quad \langle\psi\rangle=0, \quad \langle nv\rangle=-n_0uN(\mathbf{r}_\perp). \tag{6}$$

The angle brackets denote averaging with respect to z.

Substituting (5) in the Poisson equation (3), we obtain the equation for the soliton

$$\begin{gathered}\Delta\psi=2k_0^2[(1+N)(1+\psi)^{-1/2}-1]; \quad k_0\equiv\omega_{pe}/u;\\ N(\mathbf{r}_\perp)=\langle(1+\psi)^{-1/2}\rangle^{-1}-1.\end{gathered} \tag{7}$$

We investigate (7) at a small amplitude $|\psi| \ll 1$. We assume that the soliton is localized on a magnetic surface that coincides with the plane $x = 0$, and decreases rapidly and exponentially with increasing distance from this surface.

We represent ψ in the form of a series

$$\psi=\sum_{m=1}^{\infty}\psi_m(x)\cos m(k_z\zeta+k_yy); \quad \zeta\equiv z-ut, \tag{8}$$

and at small amplitudes we represent (7) in the form

$$\begin{gathered}\Delta\psi\approx k_0^2[2N-(1+N)\psi+{}^3/_4\psi^2-{}^5/_8\psi^3],\\ N(x)=-{}^3/_8\langle\psi^2\rangle.\end{gathered} \tag{9}$$

We assume that $0 < k - k_0 \ll k_0$, where $k = (k_z^2 + k_y^2)^{1/2}$. Substituting (8) in (9) we obtain for the fundamental harmonic theory, after eliminating ψ_2 by perturbation theory,

$$\begin{gathered}k_0^{-2}\partial^2\psi_1/\partial x^2=A^2\psi_1-{}^3/_8\psi_1^3,\\ A^2\equiv(k^2-k_0^2)k_0^{-2}\ll 1.\end{gathered} \tag{10}$$

The amplitudes of the higher harmonics are much smaller than that of the first and are of the order of $\psi_m \sim A^m$. Equation (9) has a soliton solution localized near the plane $x = 0$:

$$\psi_1=2.3A/\mathrm{ch}\,(Ak_0x).$$

At high amplitudes (of the order of unity) this solution is unstable with respect to modulation in y. It is then necessary to consider cylindrically symmetrical soliton solutions (7) which are periodic in z: $\psi=\psi(\zeta, r)$, where the principal quantum number k_z satisfies the relation $0<k_z-k_0\le k_0$, and $N=N(r)$. We cannot use perturbation theory, and the solution can be obtained numerically by the stabilizing-factor method.[12] Since the magnetic pressure is high, it can be assumed that the plasma density averaged over the oscillations does not depend on the coordinates even in the case of high-frequency pressure comparable with the plasma pressure.

A two-dimensional soliton elongated along the z axis, oscillating with wave number k_z, traveling with velocity u such that the fundamental frequency is $\omega=k_z u>\omega_{pe}$, and having an amplitude A of the oscillation of the dimensionless potential ψ such that $A\le 1$, and with a transverse wave number of the order of Ak_z. The soliton radius is of the order of $1/Ak_z$.

4. DISCUSSION

According to quasilinear or weakly turbulent theory, waves with different wave vectors have different frequencies, owing to the spatial dispersion, therefore the turbulence spectrum in this theory is broad, and a wave packet always spreads out. A quasilinear theory for the buildup of Langmuir waves by a tail of fast particles was developed by Parail and Pogutse.[13] This approach is justified for a small noise level. When a certain energy-density threshold is exceeded, nonlinear self-consistent phasing-in of the waves sets in, a fact usually manifest in a narrowing of the frequency spectrum and self-localization of the wave packets. Whereas in the weakly turbulent case, according to theory, the width of the spectrum is of the order of the fundamental frequency itself, and the strongly nonlinear case this width is much smaller (Fig. 3). Therefore the effects observed in "Uragan-2" cannot be explained by the weakly turbulent theory.

When the applied electric field in this stellarator is less than E_{Dr}, a considerable number of accelerated electrons is produced only on individual resonant magnetic surfaces or force lines, where the electrons are accelerated on account of the development of MHD helical instability.[1] These electrons, owing to the anomalous Doppler effect, cause buildup of Langmuir waves, and the latter would spread out over the entire plasma were it not for the self-localization effect, which leads to formation of solitons localized in the instability region. The energy density in such solitons can be compared with the plasma pressure, and this contributes to effective transfer of the longitudinal energy of the runaway electrons to the transverse electrons. At such a high energy density, the number of trapped electrons in the soliton is high. This points to the need for development of a nonlinear theory of instability on the anomalous Doppler resonance. Such a theory can be developed in analogy with the theory of electrons captured in a monochromatic Langmuir wave. With the aid of this theory it will become possible to estimate the anomalous resistance and to obtain a more complete picture of the reconnection of the force lines.

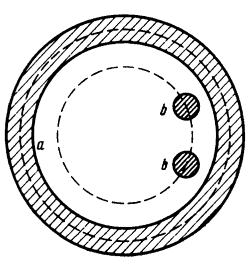

FIG. 4. Schematic representation of the localization of the traveling Langmuir solitons in the plasma-pinch cross section. Dashed circles—resonant magnetic surfaces. The small-amplitude solitons are localized over the entire magnetic surface (a). At high amplitude they are localized around individual force lines (b).

The emission of electromagnetic waves in the $E<E_{Dr}$ regime is particularly large, despite the low level of the ion noise needed to transform the Langmuir waves into electromagnetic waves. On the other hand, when the electric field in the entire plasma becomes larger than E_{Dr}, the ion-noise level increases drastically, probably in the form of ion-sound solitons. This, as seen from the decrease of the intensity of the x-rays (Fig. 1), coincides with the vanishing of the runaway electrons. The ion-sound solitons can be maintained, by the current of electrons at the Cerenkov resonance and by the runaway electrons at the anomalous Doppler resonance, as ordinary ion-sound waves.[11] Their formation is apparently hindered by the fact that they are one-dimensional and therefore lose energy on the edges because the plasma bounded and also as a result of the nonlinear formation of a plateau at the Cerenkov resonance. If they travel at an angle to the magnetic field, then in the view of the large range with respect to k_z they can draw energy from runaway electrons with arbitrarily high velocity at the anomalous Doppler resonance ($v_z=u_s+\omega_{ce}/|k_z|$, where u_s is the velocity of the soliton along the magnetic field), and this slows down the runaway. The $E>E_{Dr}$ regime was experimentally investigated in a preceding study.[14]

Thus, the representation of Langmuir waves in the form of monochromatic solitons produced in a strongly magnetized plasma on resonant magnetic surfaces agrees qualitatively with the experimental data obtained with the "Uragan-2" at $E<E_{Dr}$.

We must emphasize the universal character of the phenomenon connected with the radiation of a discrete superthermal spectrum near the frequency ω_{pe} in closed magnetic traps. Narrow-band radiation at the Langmuir frequency, the band width of which is much less than the Langmuir frequency, was observed in a number of tokamaks[15,16] together with the emission of cyclotron harmonics. The strong monochromaticity of the spectrum over a long time interval $t\approx 100-130$ msec occurred near ω_{pe} in the TFR tokamak.[17]

An important feature of the superthermal microwave radiation is connected with the mechanism of transformation of the Langmuir waves. The radiation-spectrum fine structure obtained with the "Uragan-2" stellarator points to the most probable process: transformation of a Langmuir wave into an electromagnetic wave upon scattering by ion-plasma noise. Special notice should be taken of the Raman type of the radiated superthermal spectrum, in which the width of the individual satellites is $\ll \omega_{pi}$.[6] Such a discrete character of the spectrum can be possessed only by solitons.

We note in conclusion that the tail on the particle distribution function in a magnetized plasma is a phenomenon that is much more natural and therefore more frequently encountered than a beam, which usually must be produced by a special device. Usually the tail carries an appreciable fraction of the electric current with anomalously low resistance, and thereby strongly influences the hydrodynamic properties of the plasma. Therefore the interaction of the runaway electrons of the tail with the considered solitons, which in addition to the aforementioned resonance takes place also at resonances with multiple cyclotron frequencies, calls for further study.

[1]B. B. Kadomtsev, in: Nelineĭnye volny (Nonlinear Waves), Nauka, 1979, p. 131.
[2]A. V. Longinov, N. F. Perepelkin, and V. A. Suprunenko, Fizika plazmy 2, 636 (1976) [Sov. J. Plasma Phys. 2, 344 (1976)].
[3]A. V. Stefanovskiĭ, Nuclear Fusion 5, 215 (1965).
[4]S. D. Fanchenko, B. A. Demidov, N. I. Elagin, and N. F. Perepelkin, Dokl. Akad. Nauk SSSR 183, 77 (1968) [Sov. Phys. Doklady 13, 1128 (1969)].
[5]A. G. Dikiĭ, O. S. Pavlichenko, N. F. Perepelkin, and V. A. Suprunenko, in: Voprosy atomnoĭ nauki i tekhniki (Problems of Atomic Science and Engineering), No. 1, Khar'kov, Khar-kov Physicotech. Inst. Ukr. Acad. Sci., 1974, p. 22.
[6]A. G. Dikiĭ, Yu. K. Kuznetsov, O. S. Pavlichenko, V. K. Pashnev, N. F. Perepelkin, V. A. Suprunenko, and V. T. Tolok, Research into Plasma Physics and Controlled Thermonuclear Fusion, IAEA, Vienna, 1975, p. 45.
[7]V. I. Petviashvili, Fizika plazmy 1, 28 (1975) [Sov. J. Plasma Phys. 1, 15 (1975)].
[8]V. E. Zakharov, Zh. Eksp. Teor. Fiz. 62, 1745 (1972) [Sov. Phys. JETP 35, 908 (1972)].
[9]S. V. Antipov, M. V. Nezlin, E. I. Snezhkin, A. S. Trubnikov, *ibid*. 76, 1571 (1979) [49, 797 (1979)].
[10]B. B. Kadomtsev and O. P. Pogutse, *ibid*. 53, 2025 (1967) [26, 1145 (1968)].
[11]A. B. Mikhaĭlovskiĭ, Teoriya plazmennykh neustoichivosteĭ (Theory of Plasma Instabilities), Vol. 1, Atomizdat, 1975, p. 158.
[12]V. I. Petviashvili, Fizika Plazmy 2, 469 (1976) [Sov. J. Plasma Phys. 2, 257 (1976)].
[13]V. V. Parail and O. P. Pogutse, Nuclear Fusion 18, 202 (1978).
[14]N. F. Perepelkin, V. A. Suprunenko, V. I. Petviashvili, and M. P. Vasil'ev Eighth European Conf. on Controlled Thermonucl. Fusion and Plasma Phys., No. 2, Prague, 1977, p. 144.
[15]J. H. Hutchinson and D. S. Komm, Nuclear Fusion 17, 1077 (1977).
[16]P. Brossier, *ibid*. 18, 8 (1978).
[17]P. Brossier, M. Churet, J. Gratadeur, and Y. Tosolini, EUR-CEA-FC-995, Dec. 1978, p. 107.

Translated by J. G. Adashko

Theoretical study of the hydrodynamics of spherical targets taking the refraction of the laser radiation into account

Yu. V. Afanas'ev, E. G. Gamaliĭ, N. N. Demchenko, O. N. Krokhin, and V. B. Rozanov

P.N. Lebedev Physical Institute, Academy of Sciences of the USSR
(Submitted 10 December 1979; resubmitted 29 April 1980)
Zh. Eksp. Teor. Fiz. 79, 837–849 (September 1980)

We consider the problem of the refraction and absorption of laser light in a dispersing spherically symmetric plasma. The process of the interaction of the radiation with the medium is described by the Maxwell equations for heating radiation and the hydrodynamical equations with electron thermal conductivity. The proposed model takes into account absorption mechanisms: inverse bremsstrahlung, and anomalous and resonance absorption. We give a numerical solution of these equations for glass shells of diameter of about $100\,\mu$m and laser pulse power of about 5×10^{10}W with a length of about 2 ns. We pay our main attention to a study of the absorption of the laser light in the target. We compare the results of our calculations with experimental data.

PACS numbers: 52.25.Ps

1. STATEMENT OF THE PROBLEM

One of the problems arising when one irradiates spherical targets with laser light is the determination of the fraction of energy of the laser pulse which is spent on heating and compressing the target. In a previous paper[1] we considered such a problem for the case of a plane target and normal incidence of the light. In the present paper we use a similar approach for the case of spherical targets. We note that experimentally in spherical heating it is impossible to establish an absolutely symmetrical spherical irradiation of the target. This follows, for example, from the fact that the solid angle filled by the focusing optics must be less than 4π.

Under such conditions an important effect which may strongly increase the loss of laser energy is the refrac-

 0038-5646/80/090425-07$02.40