

## PLASMA OSCILLATIONS AND WAVES

# Emission Spectra of a Cherenkov Plasma Relativistic Maser

P. S. Strelkov and D. K. Ul'yanov

*Institute of General Physics, Russian Academy of Sciences, ul. Vavilova 38, Moscow, 117942 Russia*

Received June 24, 1999

**Abstract**—The spectra of a plasma relativistic maser are measured. It is shown that the microwave frequency can be varied from 4 to 28 GHz by varying the plasma density from  $4 \times 10^{12}$  to  $7 \times 10^{13}$  cm<sup>-3</sup> at a power of 30–50 MW. The relative width of the emission spectrum is within 50–80% for low plasma densities and 15–30% for high densities. Experimental results are compared with calculations. © 2000 MAIK “Nauka/Interperiodica”.

A Cherenkov plasma relativistic maser (PRM) is based on the Cherenkov mechanism for the excitation of a slow eigenmode of a plasma waveguide by a high-current relativistic electron beam (REB). The phase velocity of the excited wave is approximately equal to the electron velocity and the frequency range of the generated microwaves is determined by the plasma density and diameter and the diameter of a metal waveguide surrounding the plasma.

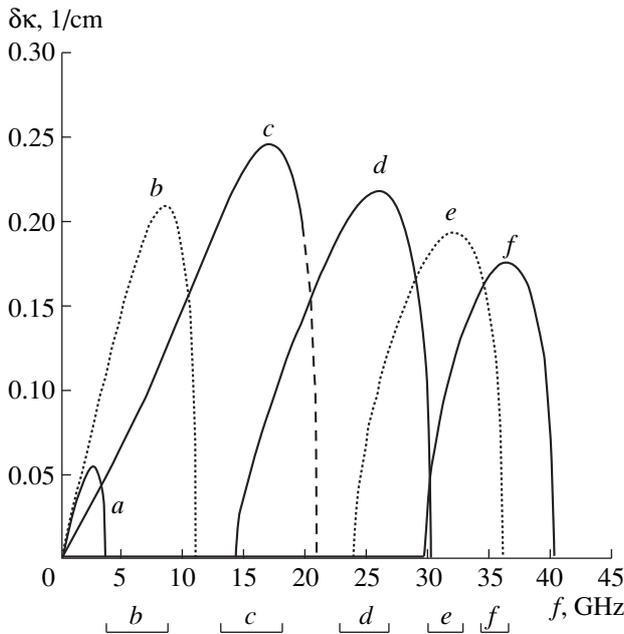
The first experimental study of a PRM [1] showed that, as the plasma density increases eightfold, the microwave emission frequency nearly doubles. In [2], attempts were made to measure the shape of the PRM spectrum and, finally, in [3], absolute measurements of the PRM spectrum (in units of MW/GHz) were carried out with the help of a specially designed calorimetric spectrometer. By this time, both the linear and nonlinear theories of the Cherenkov PRM were well developed [4]. The problem of an amplifier was solved in the following way. A noisy signal in a wide frequency band was taken as an input signal, and the longitudinal profile of the emission power along the plasma waveguide was calculated. The length at which the microwave power reached its maximum was determined. The emission spectrum and the efficiency of the amplifier were studied. The bandwidth of the input signal was chosen as follows: it was increased from one calculation to another until the output emission spectrum became narrower than the input-signal spectrum. In calculations, the plasma, REB, and waveguide diameters coincided with those of the existing experimental devices. The REB and the plasma were assumed to be in a homogeneous infinitely strong longitudinal external magnetic field; i.e., it was assumed that  $\Omega_e \gg \omega_p$ , where  $\Omega_e$  is the electron cyclotron frequency and  $\omega_p$  is the plasma frequency.

It is known that the onset of a beam–plasma instability in a bounded plasma occurs if the plasma density exceeds the threshold value [5]. In the linear stage of the instability, the amplitude  $E$  of the electric field oscillations at the frequency  $f$  increases along the beam

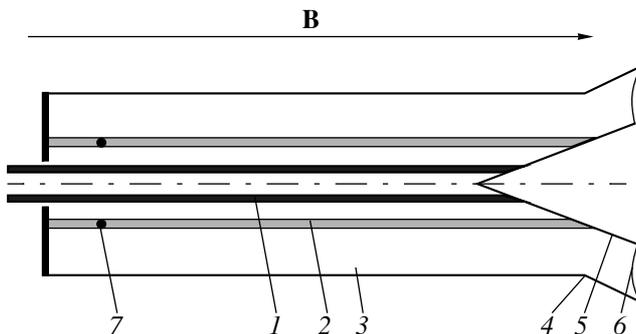
(along the  $z$ -axis) according to the law  $E = E_0 e^{\delta k z}$ , where  $E_0$  is the electric field amplitude at the amplifier input and  $\delta k$  is the spatial growth rate. Figure 1 shows the calculated frequency dependence of the spatial growth rate  $\delta k$  for different values of the plasma density.<sup>1</sup> It is seen that, according to linear theory, the mean emission frequency increases with increasing the plasma density; the frequency band in which the amplification occurs can be very broad. In contrast, in the nonlinear stage of amplification, the emission spectrum is markedly narrower. In Fig. 1, the spectrum width is represented by line segments  $b$ – $f$  showing the frequency ranges in which the spectral density of emission power  $dP/df$  exceeds a level of 0.3 of its maximum value.

A comparison of the experimental spectra of a PRM with the calculated spectrum of a microwave amplifier showed that they differed markedly [3]. According to calculations, the amplifier spectrum had one maximum; however, in the experiment with an oscillator, two maxima were observed. One of these maxima was observed at low frequencies. The mean frequency of this spectral component was lower than the calculated value of the mean amplifier frequency. The high-frequency component of the oscillator emission was observed near the relativistic electron cyclotron frequency  $\Omega_e/\gamma$ , where  $\gamma$  is the relativistic factor. The energies of these two spectral components differed insignificantly (no more than twice). As the plasma density  $n_p$  increased from  $1.5 \times 10^{13}$  to  $3.8 \times 10^{13}$  cm<sup>-3</sup>, the mean frequency of the low-frequency spectral component increased from 5 to 12 GHz, whereas the mean frequency of the high-frequency spectral component remained almost unchanged and was equal to 26–28 GHz ( $\Omega_e/2\pi\gamma = 24$  GHz). According to calculations, the mean amplifier frequency should vary from 10 to 22 GHz and the 26-GHz component should be absent for  $n_p = 1.5 \times 10^{13}$  cm<sup>-3</sup>. There was a significant discrepancy in the spectral width  $\Delta f$ ; e.g., the calculation

<sup>1</sup> Figure 1 and the calculated curve in Fig. 5 were presented by the authors of [4].



**Fig. 1.** Dependence of the spatial growth rate  $\delta\kappa$  on the frequency  $f$  for plasma densities of (a) 0.3, (b) 0.8, (c) 2.3, (d) 4.4, (e) 6.0, and (f)  $7.0 \times 10^{13} \text{ cm}^{-3}$ . The curves represent the results of calculation by linear theory, and the horizontal line segments on bottom show the results of calculations of the spectrum width by nonlinear theory.



**Fig. 2.** Schematic of the PRM: (1) REB, (2) plasma, (3) metal waveguide, (4) coaxial conical emitting horn, (5) collector, (6) dielectric window, and (7) hot ring cathode of the plasma source.

yielded  $\Delta f/f \approx 0.3$ , whereas the experimental value was  $\Delta f/f \sim 1$ .

As was mentioned above, the amplifier was calculated assuming the external magnetic field to be infinitely strong. In the experiment, we had  $\Omega_e = (1.4-0.85)\omega_p$ . Nevertheless, the generation of gyrotron emission at the frequency  $\Omega_e/\gamma$  by an electron beam in which electrons entering the waveguide only had the longitudinal velocity component was an unexpected result.

All these discrepancies were discussed in [3], in which it was noted that “the main discrepancies—a wide experimental spectrum and the presence of a low-frequency emission simultaneously with a high-frequency emission—require further theoretical and experimental investigations.”

In [3], we compared the spectra of the microwave oscillator with the calculated spectra of an amplifier. The subsequent theoretical study was aimed at the development of numerical methods for calculating the microwave oscillator. The beam instability is convective in nature; for this reason, generation can occur in a plasma waveguide of a limited length  $L$  if the reflection coefficient  $\kappa$  of the wave reflecting from the end of the plasma waveguide is high enough to satisfy the condition  $\kappa e^{\delta\kappa L} > 1$ . On the other hand, if  $\kappa = 1$  in the generation frequency range, then no emission leaves the microwave oscillator. Therefore, there exists an optimum  $\kappa$  value for which the oscillator emission power is maximum. In the linear stage of the instability, a high-current REB generates a broad frequency spectrum (Fig. 1). If the reflection coefficient  $\kappa$  in the generation frequency range depends substantially on the frequency, then the spectrum of the microwave oscillator can differ markedly from that of the microwave amplifier. In the papers on the plasma microwave oscillator [6, 7], an approximate formula is used to describe the dependence of  $\kappa$  on the frequency and the dimensions of a device. Thus, the development of the numerical model of the microwave oscillator is still far from completion even for  $\Omega_e \gg \omega_p$ .

This paper is devoted to the experimental study of a PRM in which, as compared to [3], we changed the geometry of the transition of a plasma waveguide to a coaxial emitting horn in order for the coefficient  $\kappa$  to be independent of the frequency. As a result, the measured PRM spectrum became close to the calculated spectrum of the microwave amplifier [4].

Figure 2 shows the schematic of the experiment. The Terek-2 accelerator produces a high-current REB with an electron energy of 500 keV, a beam current of 2 or 3 kA, and a current-pulse duration of 30 ns. An annular electron beam (1) with a mean radius of  $r_b = 6$  mm and thickness  $\Delta r_b = 1$  mm passes inside a hollow plasma column (2) with a mean radius of  $r_p = 9$  mm and thickness  $\Delta r_p = 1$  mm. A coaxial plasma waveguide consisting of a hollow plasma and a metal waveguide (3) with a radius of  $R = 18$  mm ends in a conical horn with metal outer (4) and inner (5) cones. Microwaves are generated in the plasma waveguide, enter the metal coaxial horn, and then are output into free space through a dielectric window (6).

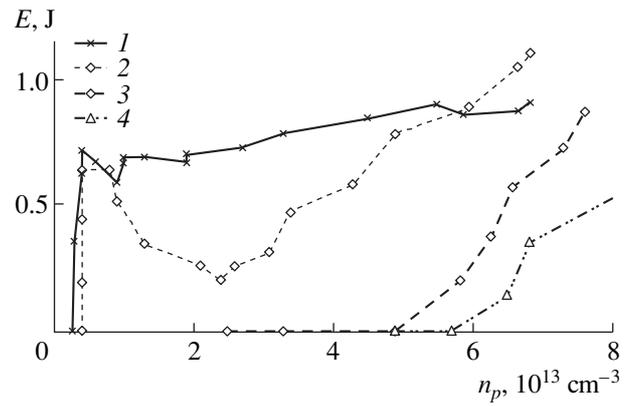
The REB and the plasma are in a homogeneous longitudinal quasistatic magnetic field ( $B = 1.3-2.2$  T and the current pulse duration is 5.5 ms). As in the previous experiments [3, 8], the plasma is created in a discharge with a hot ring cathode (Fig. 2, position 7). The plasma source has the following parameters: the cathode volt-

age is 500 V, the discharge current is up to 90 A, the working gas is xenon, and the gas pressure is  $4.5 \times 10^{-4}$  torr. At first, the voltage is applied to the plasma-source cathode and the plasma is created over 30  $\mu$ s. Then, the REB is injected into the plasma. The discharge current is controlled by changing the cathode temperature, which allows us to change the plasma density from shot to shot.

To solve the main problem of this study (to carry out measurements of the PRM spectrum), we used a calorimetric spectrometer described in [3]. The total energy of the radiation flux from the PRM was measured in eight frequency bands: 5.1–9.3, 9.3–12.1, 12.1–15.3, 15.3–19.5, 19.5–24.1, 24.1–28.9, 28.9–32.4, and 32.4–38.8 GHz. The energy spectrum was measured in units of J/GHz. The measurements of the microwave-pulse shape allowed us to calculate the power spectrum in units of MW/GHz. Typical values of the spectral power density were 2–4 MW/GHz to within a measurement accuracy of  $\pm 0.25$  MW/GHz.

Figure 3 shows the dependence of the total emission energy on the plasma density for several values of the plasma-waveguide length  $L = 10, 12.5, 15,$  and  $20$  cm. The total REB energy per one pulse is  $\approx 30$  J (at an electron energy of 500 keV, a current of 2 kA, and pulse duration of 30 ns). Hence, it follows from Fig. 3 that the PRM energy efficiency is  $\approx 3\%$ . The microwave-pulse duration is 20 ns; therefore, the emission power attains  $\sim 50$  MW and the power efficiency is  $\approx 5\%$ . For  $L = 20$  cm (curve 1), emission arises when the plasma density exceeds a threshold level of  $2.5 \times 10^{12}$  cm $^{-3}$ . This value is close to the calculated value of the plasma density at which, under our conditions, the spatial growth rate is  $\delta k > 0$ . Since, for low plasma densities, the maximum value of the spatial growth rate  $\delta k_{\max}$  increases with increasing the plasma density (Fig. 1), a PRM with  $L = 15$  cm operates at a higher plasma density,  $n_p = 4 \times 10^{12}$  cm $^{-3}$  (Fig. 3), according to the formula  $k\epsilon^{\delta k L} > 1$ . The fact that the threshold plasma density increases as the plasma-waveguide length further decreases ( $L = 12.5, 10$  cm) cannot be explained by this simple model because the value of  $\delta k_{\max}$  for  $n_p = 5\text{--}6 \times 10^{13}$  cm $^{-3}$  (Fig. 1, curves *e, f*) is lower than the maximum value, which is attained at  $n_p = 2 \times 10^{13}$  cm $^{-3}$  (Fig. 1, curves *c, d*).

Figure 4 shows the PRM spectra for the length of the plasma waveguide  $L = 20$  cm and different plasma densities. The total microwave-pulse energy expressed in J is shown in each of the six plots. It is evident that the mean emission frequency increases from 4 to 28 GHz as the plasma density varies from  $4 \times 10^{12}$  to  $7 \times 10^{13}$  cm $^{-3}$ . The accuracy of the measurements of the spectral width is rather low. It follows from the measurements that the spectral width exceeds the width of the spectrometer bands; i.e.,  $\Delta f > 3$  GHz. This can be inferred from the fact that the microwave frequency is a continuous function of the plasma density and, for any value of the plasma density, the measured spectrum

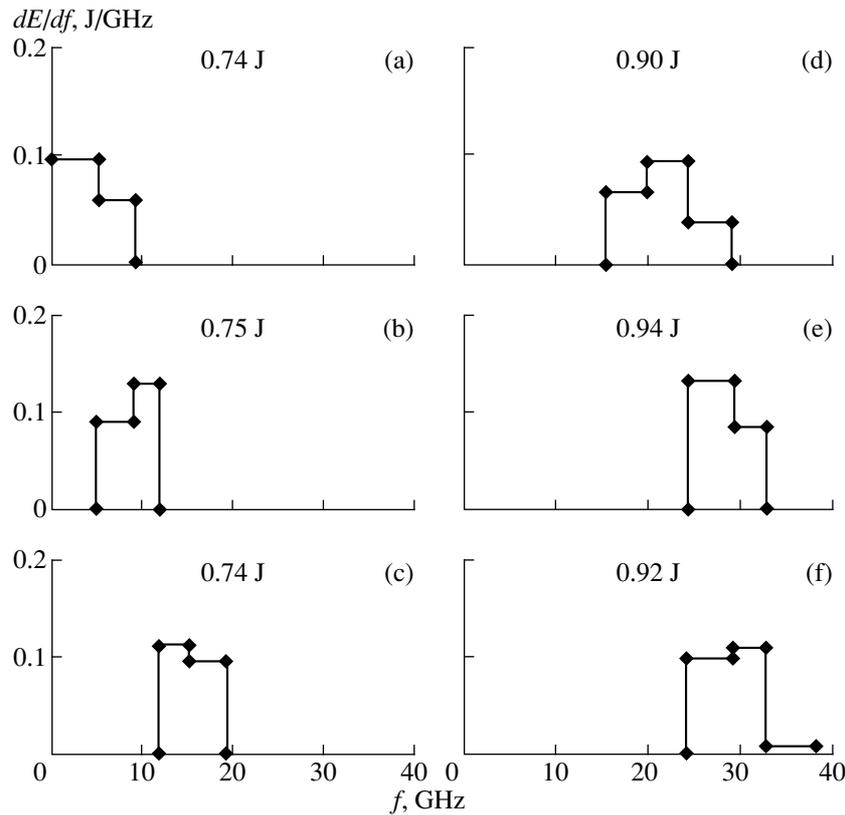


**Fig. 3.** Microwave-pulse energy as a function of the plasma density for different values of the interaction length: (1) 20, (2) 15, (3) 12.5, and (4) 10 cm at  $B = 2.2$  T,  $r_p = 0.9$  cm,  $r_b = 0.6$  cm, and  $p = 4.5 \times 10^{-4}$  torr; the working gas is xenon.

never falls into one spectrometer band. The maximum spectral width is determined by the boundaries shown in Fig. 4; i.e., this width comprises two or three spectrometer bands. In Fig. 5, the calculated dependence of the mean emission frequency of the microwave amplifier on the plasma density (assuming  $B \rightarrow \infty$ ) is compared with the experimental dependences for PRM for two values of the magnetic field  $B = 1.3$  and  $2.2$  T. The shaded area is the domain in which the calculation gives  $dP/df > 0.3 (dP/df)_{\max}$ . It is seen that, for low plasma densities (low emission frequencies), the experimental results agree with the calculations. For higher plasma densities, there is a discrepancy between the experiment and calculation. For example, the experiment shows that, for  $n_p = 6 \times 10^{13}$  cm $^{-3}$  and  $\Omega_e = 0.5\omega_p$ , the emission frequency  $f$  is equal to 21 GHz and, as the electron cyclotron frequency increases to  $\Omega_e = 0.9\omega_p$ , the emission frequency increases to  $f = 27$  GHz. The calculation for  $n_p = 6 \times 10^{13}$  cm $^{-3}$  and  $\Omega_e \gg \omega_p$  yields the frequency  $f = 32$  GHz. Hence, the discrepancy between the calculation and experiment can be attributed to the fact that, in the experiment, the condition  $\Omega_e \gg \omega_p$  is not satisfied at high plasma densities.

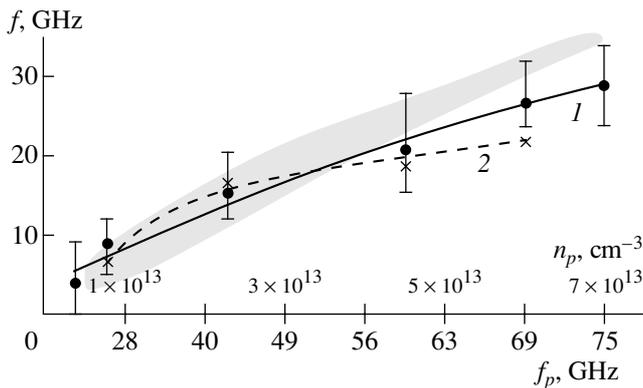
The maximum widths of the experimental spectra are shown in Fig. 5 by vertical line segments. As was mentioned above, the spectral width is measured rather roughly. Nevertheless, we can conclude that, for low plasma densities, the experimental spectral width is approximately equal to the calculated value; for high plasma densities, the experimental spectral width exceeds the calculated values.

The coincidence of the experimental results with the calculated dependence of the emission frequency on the plasma density  $f(n_p)$  is the most reliable argument in favor that the generated mode is the azimuthally symmetric lowest radial mode of the slow plasma wave. In our previous papers, we suggested that the generated mode was precisely this mode, but the dependence  $f(n_p)$



**Fig. 4.** Spectra of the plasma microwave oscillator for plasma densities of (a) 0.4, (b) 0.8, (c) 2.3, (d) 4.4, (e) 6.0, and (f)  $7.0 \times 10^{13} \text{ cm}^{-3}$  at  $B = 2.2 \text{ T}$ ,  $L = 20 \text{ cm}$ ,  $r_p = 0.9 \text{ cm}$ ,  $r_b = 0.6 \text{ cm}$ , and  $p = 4.5 \times 10^{-4} \text{ torr}$ .

did not confirm this suggestion. Our suggestion was based on the fact that emission was observed in the frequency range  $\omega < \omega_p$  and the threshold value of the plasma density (for long plasma waveguides) coincided with the calculated one.



**Fig. 5.** Mean emission frequency as a function of the plasma frequency  $f_p = \omega_p/2\pi$ . Experimental curves 1 and 2 correspond to  $B = 1.3$  and  $2.2 \text{ T}$ , respectively. The shaded domain shows the results of calculations by nonlinear theory. The vertical line segments indicate the maximum measured spectral width.

It is seen from Fig. 3 (curve 1) that the measured emission power remains almost constant as the plasma density varies. This is due to the fact that the maximum value of the spatial growth rate  $\delta k$  remains at nearly the same level for different values of the plasma density (Fig. 1). Furthermore, this means that the coefficient of reflection from the transition of the plasma waveguide to the vacuum coaxial waveguide remains nearly constant when the plasma density and the generation frequency change simultaneously.

As is known, filling a waveguide with a plasma makes it possible to transport currents exceeding the limiting vacuum current [9]. Therefore, it is interesting to examine how the microwave power depends on the current. All of the above results were obtained at a current of 2 kA, whereas the limiting vacuum current was equal to 3.5 kA. The increase in the beam current to 3 kA did not lead to an increase in the microwave power. This result agrees with the theoretical prediction [10] that the amplifier efficiency decreases as the beam current approaches the limiting vacuum current.

Thus, it is experimentally shown that, in a Cherenkov PRM, the azimuthally symmetric lowest radial mode of a slow plasma wave can be generated over a wide range of plasma densities. For the first time, a sevenfold frequency change (from 4 to 28 GHz) was

obtained at a power of 30–50 MW by changing only the plasma density. From a practical standpoint, it is important that such a frequency change can be performed during a time of about 30  $\mu$ s, which is determined by the rate of the plasma density variation.

Further progress in PRM studies requires the development of a numerical model of a plasma microwave oscillator, which will make it possible to increase the PRM efficiency to 15–20% as is predicted by the calculations of the amplifier. These calculations show that the width of the emission spectrum can be varied by changing the gap between the beam and the hollow plasma. However, to date, we have failed to implement such control of the spectral width at a constant microwave-oscillator power. These two problems form the basis for future PRM studies.

#### ACKNOWLEDGMENTS

We thank A.A. Rukhadze, M.A. Krasil'nikov, M.V. Kuzelev, and O.T. Loza for fruitful discussions. This work was performed with the Plasma Relativistic Maser device (registration no. 01-04) under the financial support of the Ministry of Science and Technology of the Russian Federation and the Russian Foundation for Basic Research (project no. 97-02-16948 and the grant "Controlled Fusion and Plasma Processes").

#### REFERENCES

1. M. V. Kuzelev, F. Kh. Mukhametzyanov, M. S. Rabinovich, *et al.*, Zh. Éksp. Teor. Fiz. **83**, 1358 (1982) [Sov. Phys. JETP **56**, 780 (1982)].
2. A. A. Rukhadze, P. S. Strelkov, and A. G. Shkvarunets, Fiz. Plazmy **20**, 686 (1994) [Plasma Phys. Rep. **20**, 617 (1994)].
3. M. V. Kuzelev, O. T. Loza, A. V. Ponomarev, *et al.*, Zh. Éksp. Teor. Fiz. **109**, 2048 (1996) [Sov. Phys. JETP **82**, 1102 (1996)].
4. M. Biro, M. A. Krasil'nikov, M. V. Kuzelev, and A. A. Rukhadze, Usp. Fiz. Nauk **167**, 1025 (1997) [Sov. Phys. Uspekhi **40**, 159 (1997)].
5. L. S. Bogdankevich, M. D. Raizer, A. A. Rukhadze, and P. S. Strelkov, Zh. Éksp. Teor. Fiz. **58**, 1219 (1970) [Sov. Phys. JETP **31**, 655 (1970)].
6. M. A. Krasil'nikov, M. V. Kuzelev, and A. A. Rukhadze, Zh. Éksp. Teor. Fiz. **108**, 521 (1995) [Sov. Phys. JETP **81**, 280 (1995)].
7. M. Biro, M. A. Krasil'nikov, M. V. Kuzelev, and A. A. Rukhadze, Zh. Éksp. Teor. Fiz. **111**, 1258 (1997) [Sov. Phys. JETP **84**, 694 (1997)].
8. O. T. Loza, A. V. Ponomarev, P. S. Strelkov, *et al.*, Fiz. Plazmy **23**, 222 (1997) [Plasma Phys. Rep. **23**, 201 (1997)].
9. V. I. Kremontsov, P. S. Strelkov, and A. G. Shkvarunets, Fiz. Plazmy **2**, 936 (1976) [Sov. J. Plasma Phys. **2**, 519 (1976)].
10. M. V. Kuzelev, A. A. Rukhadze, and D. S. Fillipychev, Fiz. Plazmy **8**, 537 (1982) [Sov. J. Plasma Phys. **8**, 302 (1982)].

*Translated by N. F. Larionova*