Relativistic X-band plasma maser with 7-fold frequency tuning at 50 MW power level.

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A Cherenkov plasma relativistic maser (CPM) 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 the diameters of a plasma tube and a metal waveguide surrounding the plasma.

The main advantage of the CPM comparing to vacuum relativistic oscillators is the possibility to tune frequency. This possibility was qualitatively demonstrated in our first work [1] in 1982. But only in 1996 [2] the method of measurements of the pulse energy spectrum was invented. It permits to know what microwave energy (in Jouls) is emitted in a certain frequency band. The spectrometer accuracy is about 3 GHz inside the frequency band from 3 GHz to 30 GHz.

In numerical simulations the CPM was studied using the model of plasma microwave amplifier. e.g., the CPM was considered without the feedback which is provided by microwave reflectors at the inlet and the outlet cross sections of the device. The experimental spectrum of the CPM differed from the calculated spectrum of an amplifier very strongly. This fact can be explained by the dependence of the reflection coefficient of the plasma wave from the plasma waveguide end. Indeed, if for the frequency of the generated wave this coefficient is equal to one, this frequency will not be emitted by the oscillator.

This paper is devoted to the experimental study of a CPM; the difference from our previous paper [2] is the following. We changed the geometry of the transition of a plasma waveguide to a coaxial emitting horn in order to diminish the reflection. As the result, the measured CPM spectrum became close to the calculated spectrum of the microwave amplifier [3].

Fig. 1 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 Δr_b = 1 mm passes inside a hollow plasma column 2 with a mean radius of r_p = 9 mm and thickness Δr_p = 1 mm. A coaxial plasma waveguide consisting of a hollow plasma and a

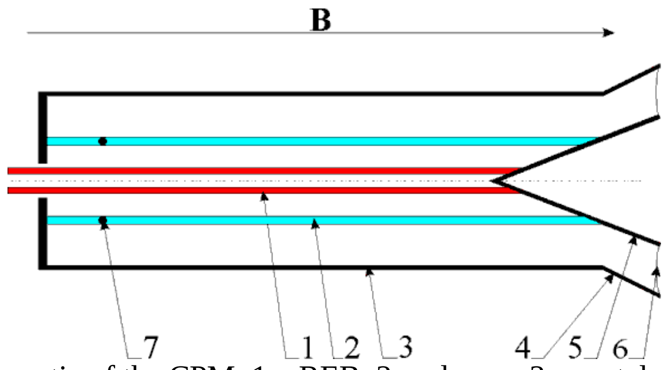

Fig. 1. Schematic of the CPM: 1 – REB, 2 – plasma, 3 – metal waveguide, 4 – coaxial conical emitting horn, 5 – collector, 6 – dielectric window, and 7 – hot ring cathode of the plasma source.

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 pulse duration is 5.5 ms. As in the previous experiments [1, 2], the plasma is created in a discharge with a hot ring cathode (Fig.1, position 7). The plasma source has the following parameters: the cathode voltage is 500 V, the discharge current is up to 90 A, the working gas is xenon, and the gas pressure is $4.5\cdot10^{-4}$ Torr. At first, the voltage is applied to the plasma source cathode and the plasma is created over 30 μs. 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 pulse to pulse.

To solve the main problem of this study (to carry out measurements of the CPM spectrum), we used a calorimetric spectrometer described in [2]. The total energy of the radiation flux from the CPM 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 with the measurement accuracy of ±0.25 MW/GHz.

Fig.2 shows the CPM 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

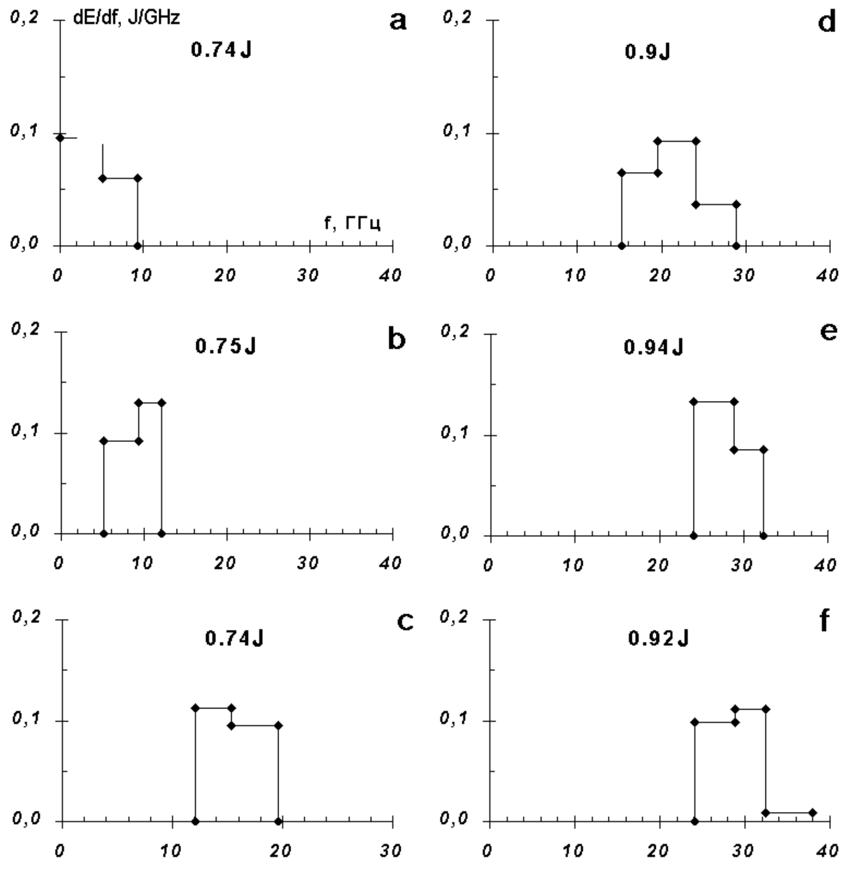

Fig. 2. Spectra of the plasma microwave oscillator for plasma densities of (a) 0.4, (b) 0.8, (c) 2.3, (d) 4.4, (e) 6.0, and (f) $7.0\cdot10^{13}$ cm^{-3} at B = 2.2 T, L = 20 cm, r_p = 0.9 cm, r_b = 0.6 cm, and p = $4.5\cdot10^{-4}$ Torr.

density varies from $4\cdot10^{12}$ to $7\cdot10^{13}$ 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 never falls into one spectrometer band. The maximum spectral width is determined by the boundaries shown in Fig.2; i.e., this width comprises two or three spectrometer bands.

In Fig.3, the calculated dependence of the mean emission frequency of the microwave amplifier on the plasma density (assuming $B \to \infty$) is compared with the experimental dependencies for CPM for two values of the magnetic field B = 1.3 T 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 n_p, there is a discrepancy between the experiment and calculation. For example, the experiment shows that, for $n_p = 6\cdot10^{13}$ cm^{-3} and plasma gyro-frequency $\Omega_e = 0.5\omega_p$, the emission frequency f = 21 GHz. When $\Omega_e = 0.9\omega_p$, the emission frequency increases to f = 27 GHz. The calculation for $n_p = 6\cdot10^{13}$ cm^{-3} and $\Omega_e >> \omega_p$ 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 $\Omega_e >> \omega_p$ is not satisfied at high plasma densities.

The maximum widths of the experimental spectra are shown in Fig.3 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 $f(n_p)$ 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

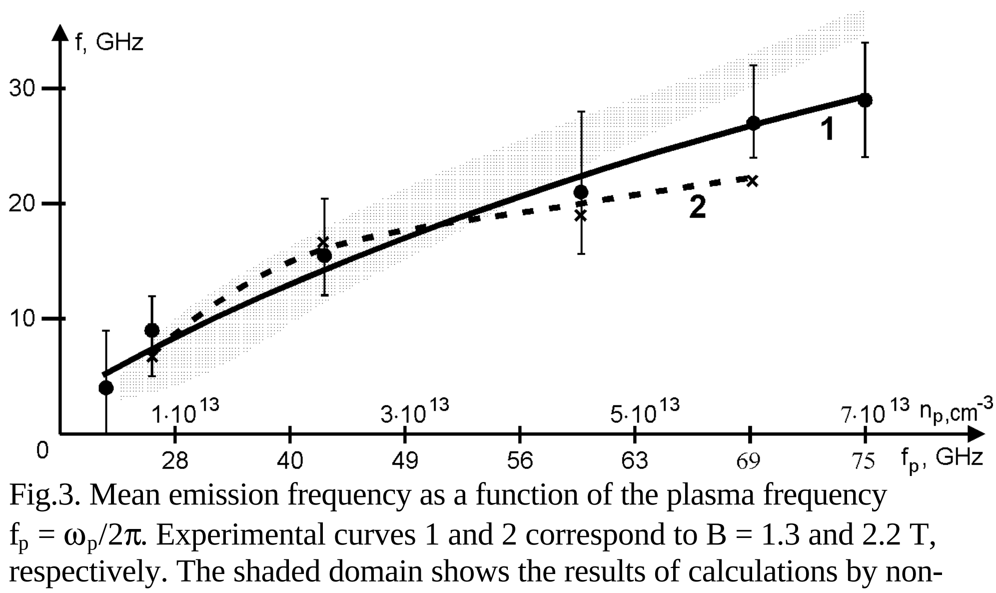

Fig.3. Mean emission frequency as a function of the plasma frequency $f_p = \omega_p/2\pi$. Experimental curves 1 and 2 correspond to B = 1.3 and 2.2 T, respectively. The shaded domain shows the results of calculations by non-linear theory. The vertical line segments indicate the maximum measured spectral width.

density (for long plasma waveguides) coincided with the calculated one.

Thus, it is experimentally shown that, in the Cherenkov plasma maser, 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 μs, which is determined by the rate of the plasma density variation.

Further progress in CPM studies requires the development of a numerical model of a plasma microwave oscillator, which will make it possible to increase the CPM 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 CPM studies.

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