Experimental Investigations of Cherenkov Plasma Amplifier

Anatoly V. Ponomarev, Pavel S. Strelkov

Prokhorov Institute of General Physics, Russian Academy of Sciences,
38 Vavilova str., Moscow, 119991, Russia

Abstract. Experimental investigations of Cherenkov plasma amplifier have been carried out. The dependencies of output microwave power on plasma density, interaction length, input microwave power, relativistic electron beam current, and input signal frequency were measured. A pure amplification regime (without accompanying generation) at two frequencies of 9.1 and 13 GHz is achieved. It is shown experimentally that there is a range of plasma densities where the only azimuthally-symmetric plasma waveguide mode with the lowest radial index is excited. The relative bandwidth of the amplifier, according to the experiment, is no less than 40%. It is experimentally shown that, by changing only one parameter, namely, the plasma density, is possible to achieve maximum output microwave power at any of two frequencies – 9.1 and 13 GHz. At a frequency of 9.1 GHz, the maximum output power amounts to P = 40 MW, the efficiency is η = 4%, and the power gain is K_p = 800 (29 dB). At a frequency of 13 GHz, these parameters are P = 60 MW, η = 6%, and K_p = 1000 (30 dB).

INTRODUCTION

Microwave devices that allow to obtain pulse microwave radiation with power of tens and hundreds megawatts and tunable in a broad frequency band are of great interest at present. In General Physics Institute plasma relativistic microwave oscillator with frequency tuning from 4 to 28 GHz and output microwave power of 30-50 MW have been created [1]. Frequency tuning was achieved by means of plasma density changing. However spectrum width of the output radiation was considerable. The problem of narrowing of the radiation frequency band leads to necessity of Cherenkov plasma amplifier (**CPA**) creation. In this case the radiation frequency is governed by the frequency of the input signal and output radiation spectrum can be narrow.

The first successful experiment on CPA [2] demonstrated the possibility of amplifying the input signal in a narrow interval of plasma densities, but the amplification regime was unstable. The use of a broadband absorber improved the amplifier parameters [3]. In that experiment, the possibility of amplifying the input signal at both 9.1 and 12.9 GHz was demonstrated for the first time. At the same time, there was generation at some plasma densities, which resulted in the broadening of the output spectrum. A further modification of the experimental device made it possible to suppress generation over a wide range of plasma densities [4]. As a result the main characteristics of the amplifier have been measured. The results of this study are presented in this report.

It should be noted that studies on high-power microwave amplifiers based on the effect of slowing-down of waves in a vacuum corrugated waveguide are being carried out. Thus, in [5], an output power of 1 GW at a frequency of 9 GHz was achieved; however, the amplification bandwidth was lower than 1%. In [6], the amplification bandwidth was 20% (8.4–10.4 GHz), but the output power was as low as 1 MW. A microwave amplifier described here has an output power of 50 MW and amplification bandwidth 40% (9–13 GHz); i.e., it possesses a unique combination of parameters.

EXPERIMENTAL SETUP

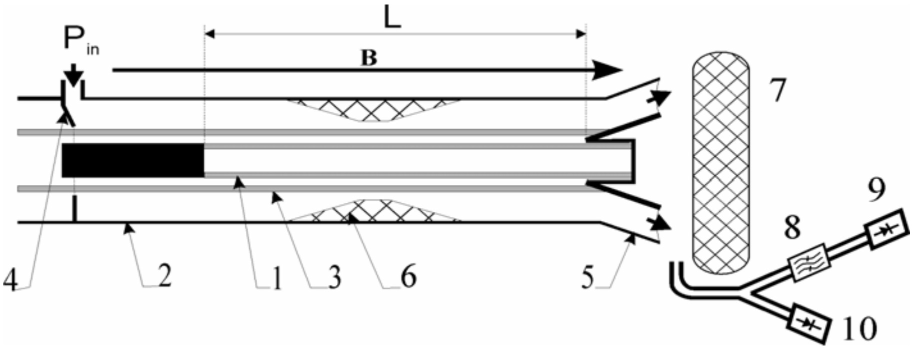

FIGURE 1. Schematic of the experimental setup: 1 – plasma, 2 – metal waveguide, 3 – REB, 4 – amplifier input, 5 – coaxial emitting horn, 6 – microwave absorber, 7 – microwave calorimeter, 8 – narrowband filter ($\Delta f/f$ = 5%), 9 and 10 – detectors.

A schematic of the device is shown in Fig. 1. Annular plasma 1 was created in smooth cylindrical waveguide 2 by an annular electron beam in xenon. The system was placed in a strong uniform longitudinal magnetic field **B**. Annular relativistic electron beam (**REB**) 3 with an electron energy of 500 keV and time duration 100 ns was injected into the system from a diode located on the left (not shown in the figure). The REB current could be varied. These experiments were carried out at currents of 1 and 2 kA. At the entrance to the system, microwave converter 4 was placed which converted the TE_{01} mode of a rectangular waveguide into the slow wave of the plasma waveguide. It was then amplified by the REB, and emitted by coaxial horn 5. To suppress microwave generation in the system, we used ceramic microwave absorber 6 of length 14 cm. The interaction length *L* could be varied in the range 22–30 cm.

The input microwave signal was generated by one of the two pulsed magnetrons operating at frequencies of 9.1 and 13.0 GHz. The output magnetron power could be varied within the range 20–60 kW by varying the magnetron anode voltage.

In order to estimate the spectral width of the output radiation, we used a receiving transmission line consisting of two detectors 9, 10 and a narrowband filter 8, tuned to the frequency of the input signal. The total energy of the output microwave pulse was measured by a broadband large-area (30 cm in diameter) microwave calorimeter 7. Knowing the energy of the microwave pulse and its envelope, we could calculate the power of the output microwave radiation.

EXPERIMENTAL RESULTS

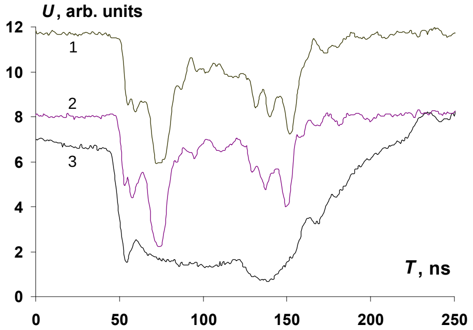

FIGURE 2. Waveforms of the broadband (1) and narrowband (2) receivers signals and the diode voltage pulse (3); f = 9.1 GHz, I = 2 kA, P_{in} = 60 kW, P_{out} = 47 MW.

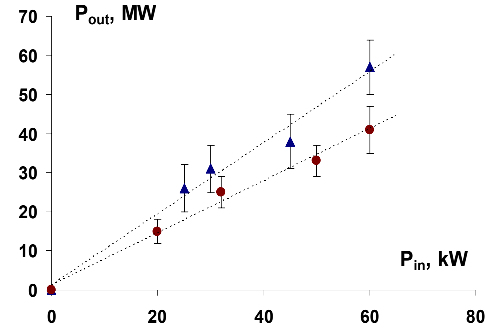

FIGURE 3. Output amplifier power vs. input power at input frequencies of 9.1 (circles) and 13 GHz (triangles). I = 2 kA. The dashed lines show the straight-line fits.

A typical waveform is shown in Fig. 2. The curves 1 and 2 show the same behavior what means that the output radiation spectrum is narrower than 5% throughout the entire pulse. We call that the pure amplification regime (without accompanying generation). It is important that this regime was achieved for all parameters of the system used in experiment. This result differs radically from the result described in [3].

Figure 3 shows the amplifier output power as a function of the input power for two input frequencies: 9.1 GHz and 13 GHz. For both frequencies, a decrease in the input power results in a proportional decrease in the output power. It confirms that the system operates as an amplifier rather than a frequency-locked oscillator. The power gain is 29 dB for a frequency of 9.1 GHz, and 30 dB for 13 GHz.

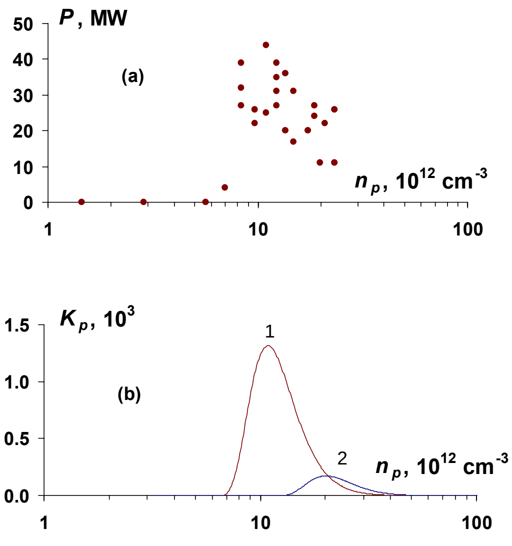

FIGURE 4. Output microwave power (a) and the gain factor (b) vs. plasma density; f = 9.1 GHz. 1 – E_{01} mode, 2 – E_{11} mode.

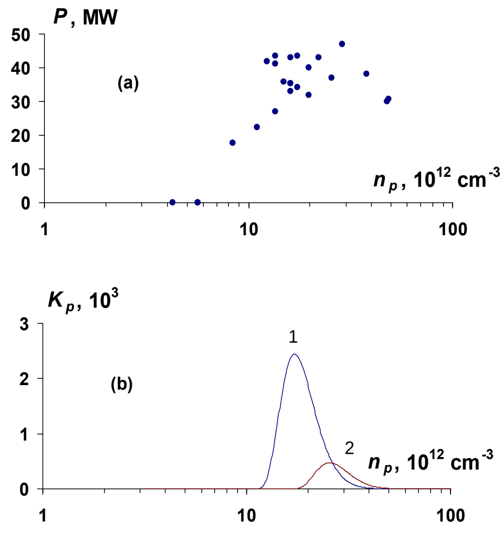

FIGURE 5. The same as in Fig. 4, but for an input frequency of 13 GHz.

Figures 4 and 5 show the measured output microwave power and the gain factor as functions of the plasma density. It can be seen that at both input frequencies the plasma density range in which the amplification is observed agrees well with the calculated plasma density range for the E_{01} mode. For an input frequency of 13 GHz, the operating plasma density range shifts toward higher densities, which also agrees well with calculations. Moreover, comparison of Figs. 4 and 5 shows that, at a plasma density of $1.5{\cdot}10^{13}$ cm^{-3}, amplification is observed at both frequencies of 9.1 and13 GHz with a substantial output power. It means that the amplification band is no less than 40%.

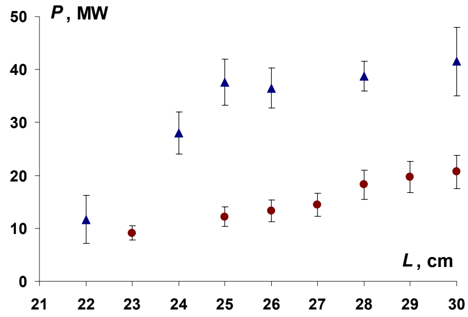

FIGURE 6. Output microwave power vs. interaction length. I = 1 kA (circles) and 2 kA (triangles). f = 9.1 GHz, $n_p = 1.2{\cdot}10^{13}$ cm^{-3}.

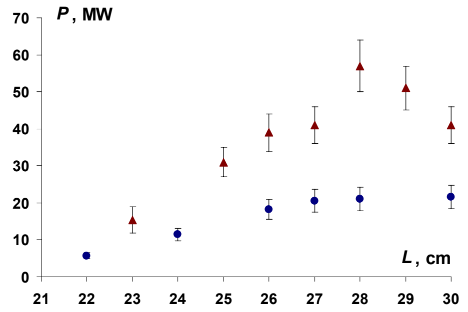

FIGURE 7. The same as in Fig. 6, but for f = 13 GHz, $n_p = 1.8{\cdot}10^{13}$ cm^{-3}.

Experimental dependencies of output microwave power on interaction length are presented in Figs. 6 and 7. It is seen that for REB current of 1 kA there is no saturation in the range 22–30 cm. According to theory, REB current rising should lead to shortening of the saturation length. The experiment confirms it. For a current of 2 kA this length is 25 cm for a frequency 9.1 GHz and 28 cm for a frequency 13 GHz. A remarkable result is that there is a configuration in which the maximum output power is achieved at both frequencies. For the length of 28 cm and REB current of 2 kA the output power is equal to 40 MW at 9.1 GHz and 60 MW at 13 GHz. The only parameter that should be changed to this end is the plasma density.

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