Plasma Relativistic Microwave Electronics in the A.M. Prokhorov General Physics Institute

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Abstract – A review of experimental studies of plasma relativistic microwave oscillators and amplifier is presented. Elements of the theory are also mentioned which allow to explain the observed facts. Plasma microwave oscillators were created in the range 1.5 to 28 GHz with the power 50 MW and the efficiency 5 to 7%, tunable in a broad range of frequencies. Plasma microwave amplifier was created in the range 9 to 13 GHz with the same power 50 MW and the efficiency 4 to 6%.

Plasma relativistic microwave electronics continues studies of plasma non-relativistic microwave electronics conducted in 1960th and 1970th in the Physical Technical institute, Kharkov, Ukraine, and the Institute of radio technology and electronics, Moscow, Russia. The reviews of these studies are in [1] and [2]. In 1974 (then our team was a part of the Lebedev Physical institute) investigations in the plasma relativistic microwave electronics started and in 1982 the first plasma relativistic microwave oscillator was created [3].

The most important difference in physical conditions of the new experiments due to the utilization of relativistic electron beams is the following. The relativism of electrons facilitates the difficult task of the extraction of microwaves from the plasma waveguide to the vacuum one. It is also substantial that the experiments [1, 2] were conducted with the pulse duration of the electron beam current more that 10 μs or in a continuous regime. The pulse duration of the high-current relativistic electron beams is usually of the order of 100 ns that allow to exclude difficulties due to low frequency plasma instability.

1. The Scheme of the Experiment

Figure 1 presents the scheme of the plasma microwave oscillator. The cylindrical waveguide with the radius R is immersed in a longitudinal, homogeneous magnetic field. A hollow plasma with the radius r_p and the wall thickness Δr_p is produced, $\Delta r_p \ll r_p$. A hollow relativistic electron beam with the radius r_b and the wall thickness $\Delta r_b \ll r_b$ is injected into this plasma waveguide. The length of the waveguide is bounded by the edge of the central conductor of the coaxial radiating unit. Microwaves are generated in the plasma waveguide, propagate along the vacuum coaxial waveguide and are radiated by the horn.

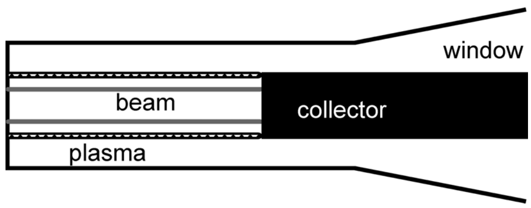

Fig. 1. Scheme of the plasma microwave oscillator

2. Basics of the Theory

The operation principle of the microwave oscillator is the excitation of the slow plasma wave by an electron beam on basis of the effect of Vavilov and Cherenkov [4]. Fig. 2 presents the dispersion of the slow waves of a plasma waveguide for two values of plasma density and the dispersion of the wave of an electron beam space charge in the approach of a little beam current.

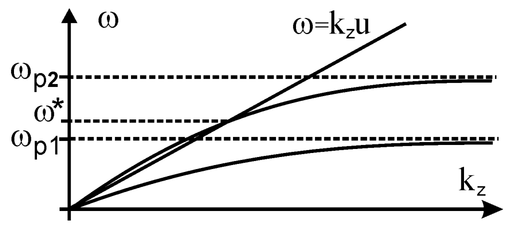

Fig. 2. Dispersion curves

It is seen from Fig. 2 that when the plasma density is little the dispersion curves of the plasma and the beam do not intersect. As the plasma density rises, the intersection point ω* appears when the condition of Vavilov and Cherenkov is fulfilled: the phase velocity of the wave is equal to the beam electrons speed. Hence, the interaction of the beam with plasma takes place only when the plasma density exceeds a threshold value. From Fig. 2 it is also seen that a rise of the plasma density allows to increase the radiation frequency.

Figure 2 shows only the lowest over the radial index axially symmetric plasma mode E_{01}^{pl}. Actually, higher modes exist with the dispersion curves below the curve E_{01}^{pl}. Therefore, a range of the plasma density values exists where only one mode E_{01}^{pl} is excited. With the following rise of the plasma density, an excitation of several transverse modes is possible.

With the values of the beam currents which are used in experiments the system "beam-plasma" is unstable not only at the frequency ω* but also in the whole frequency range. Fig. 3 presents the dependence of the growth rate δk of the plasma wave on the frequency for different values of the plasma density. Note that the maximal value of the growth rate is almost constant in a wide range of plasma densities. It is this fact which permits to realize microwave oscillator with a broad frequency tuning.

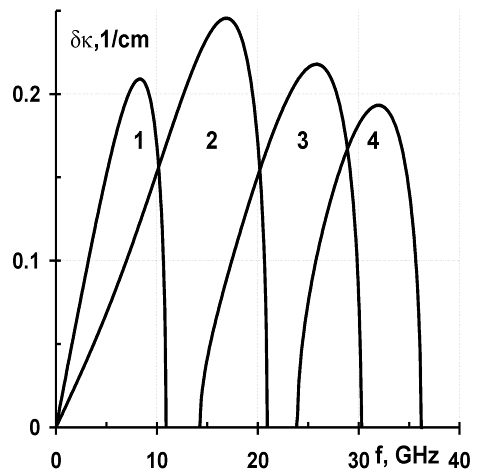

Fig. 3. The dependences of the growth rate δk of the plasma wave on the frequency for different values of the plasma density. The curves 1–4 correspond to $n_p = (0.8, 2.3, 4.4$ and $6) \cdot 10^{13}$ cm^{-3}, respectively

The structure of the electric field of the plasma wave and the wave in the coaxial radiating unit is presented in Fig. 4. It is seen that the structure of the plasma wave field at $r > r_p$ resembles that of the TEM mode of the coaxial vacuum waveguide. This circumstance as well as the closeness of the phase velocity of the plasma wave to the speed of light in vacuum leads to the possibility of effective transformation of the plasma wave into TEM wave of a coaxial waveguide. At the same time the presence of the field in the area $r < r_p$ leads to the reflection of the plasma wave from the edge of the central conductor of the coaxial waveguide. The dependencies of the power reflection coefficient $æ_2^2$ on the frequency for different values of the plasma density are shown in Fig. 5 [5]. If the reflection coefficient of the plasma wave from the left border is $æ_1$ then the condition of switching on the self-oscillations in plasma waveguide with the length L is written as

$$æ_1 \cdot æ_2 \cdot e^{\delta k L} > A.$$

For continuously operating oscillators $A = 1$, for pulsed microwave oscillators $A \geq 1$.

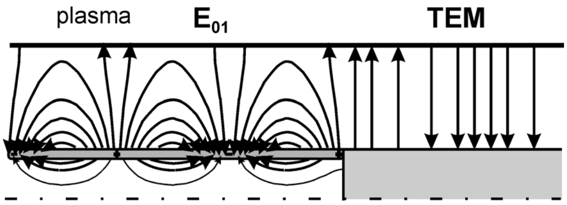

Fig. 4. Structure of the electric field of the plasma wave

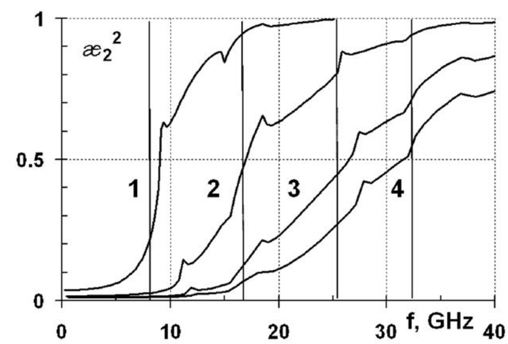

Fig. 5. The curves 1–4 are calculated for the same values of the plasma density as in Fig. 3. Vertical lines correspond to frequencies at which the growth rate δk achieves it maximum according to Fig. 3

3. Experiment

Plasma was created by an additional electron beam with 600 eV of the electron energy, up to 100 A beam current and 30 μs pulse duration. When this beam passed through the gas xenon with the pressure of $5 \cdot 10^{-4}$ Tor in a magnetic field of 1–2 T it created an annular plasma with the density up to $8 \cdot 10^{13}$ cm^{-3} [6]. After this a relativistic electron beam with the electron energy of 500 keV, the current of 1–2 kA and the pulse duration of 30, 100 or 1000 ns was injected into the plasma waveguide.

The following physical values were experimentally measured: the cathode potential (the full beam electrons energy), the beam current, radial distribution of the current density, angle distribution of the beam electrons [7, 8], the plasma density, longitudinal and radial distribution of the plasma density, microwave pulse energy [9], and a waveform of the microwave signal. The importance should be specially noted of using in the measurements of the microwave calorimeter [9] and the calorimetric spectrometer [10] which were created in our Institute. These devices are located out of the vacuum chamber and measure parameters of the whole microwave beam with a diameter up to 50 cm. Their sensitivity is 0.1 J in a broad frequency band from 2 to 30 GHz.

Figure 6 presents the dependence of the microwave oscillator power on plasma density for different lengths of plasma waveguide [11]. It is seen that microwave radiation appears after an excess of a threshold value of the plasma density. The closeness of the threshold values for two lengths of the plasma waveguide 20 and 15 cm means that with $n_p \le 2.5 \cdot 10^{13}$ cm^{-3} the system plasma-beam is stable. This value is close to the calculated threshold value of the plasma density $2 \cdot 10^{13}$ cm^{-3}. At the length $L = 12$ cm and the density values $2.5 < n_p < 5 \cdot 10^{13}$ см$^{-3}$ the system is unstable but apparently, the condition $\text{æ}_1 \cdot \text{æ}_2 \cdot e^{\delta kL} > A$ is not fulfilled and so the radiation energy is not registered. At $n_p > 5 \cdot 10^{13}$ cm^{-3} the radiation appears in spite of the decrease of δk (Fig. 3). This phenomenon could be explained by a rise of æ_2 when the plasma density rises at the excited frequencies (Fig. 5), but this explanation does not fit quantitatively. The point is in a fact that the calculations (Figs. 3 and 5) were performed in an approach of strong magnetic field when the cyclotron frequency is much more than plasma frequency, $\omega_H >> \omega$. This is not valid when the plasma density $n_p > 5 \cdot 10^{13}$ cm^{-3}.

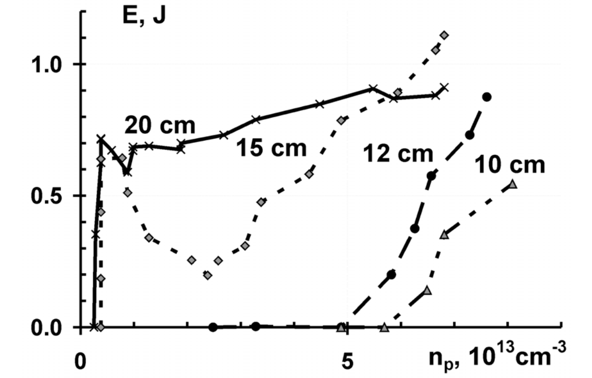

Fig. 6. The dependences of the oscillator microwave power on plasma density for different lengths of plasma waveguide

The radiation spectrum was measured by a calorimetric spectrometer. The calorimeter registered an energy of the total microwave flux in 8 frequency bands from 0 to 32 GHz (Fig. 7). Note that the radiation energy is almost constant whereas the frequency is tuned from 4 to 28 GHz. Fig. 8 proves that the experimental dependence of the radiation frequency on the plasma density coincides with the calculated one.

In the above experiments, the radiation spectrum was measured integrally, without temporal resolution. In the plasma microwave oscillator [12] which was calculated for the frequency band 1.5 to 6 GHz, a possibility appeared to register the dependence of the microwave electric field on time by a fast oscilloscope, i.e. to have the very complete information about the radiation spectrum (Fig. 9). It occurred that at the leading edge of the microwave pulse a broad spectrum is generated due to a variation of the electron energy and the electron beam current at the leading edge of the accelerator pulse. Then the radiation becomes monochromatic since 50 to 230 ns. After then the spectrum becomes broad.

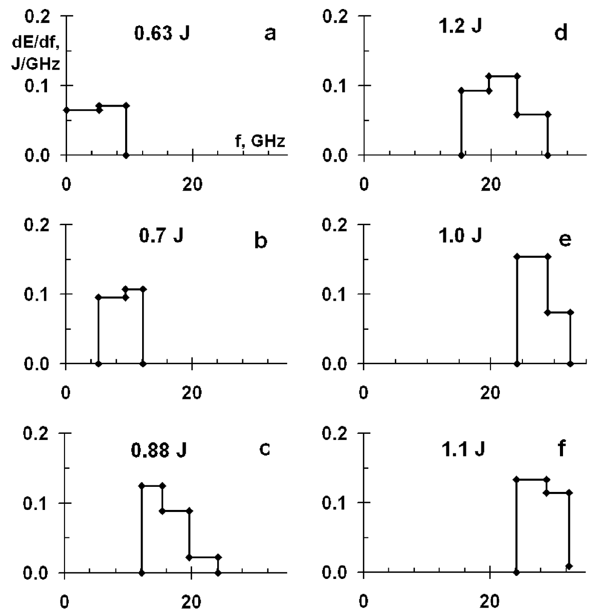

Fig. 7. The spectrum of the microwave energy for different values of plasma density, (a) $n_p = 0.4$; (b) 0.8; (c) 2.3; (d) 4.4; (e) 6; (f) 7 · 1013 см$^{-3}$

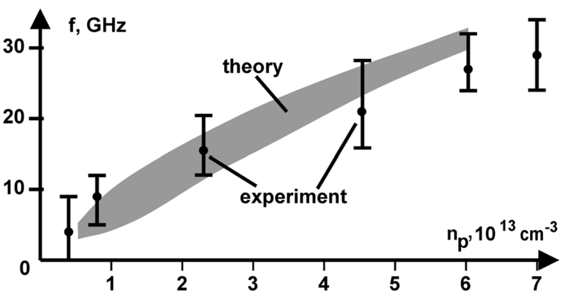

Fig. 8. The experimental and theoretical dependences of the radiation frequency on plasma density

Calculations of the radiation spectrum were conducted using the “Karat” code. The energy of electrons and the beam current changed in time correspondingly to the experiment. In Fig. spectra are presented: the experiment is to the left, the calculation is to the right. It is seen that at first the spectra evolution in the experiment and the calculation coincide, at the leading edge of the beam current the spectrum is broad and then it becomes narrow. But after 120 ns the spectrum in experiments broadens whereas in the calculations it remains narrow. This permits us to think that the spectrum broadening which takes place after 120 ns in experiments is due to non-linear plasma properties, because in calculations the plasma was considered as linear.

Thus, the plasma microwave oscillator allows obtaining monochromatic radiation for ~ 100 to 200 ns while the influence of microwaves on the plasma is little. The frequency of monochromatic radiation was tuned from 1.5 to 2.7 GHz. With the further frequency increase due to a rise of the plasma density, the radiation spectrum was always broad because several longitudinal and transverse modes generated. However the whole energy of the microwave pulse remains constant. Generation of microwaves is obtained with the mean frequency tuning from 1.5 to 6 GHz, pulse energy 20 J and pulse duration up to 800 ns.

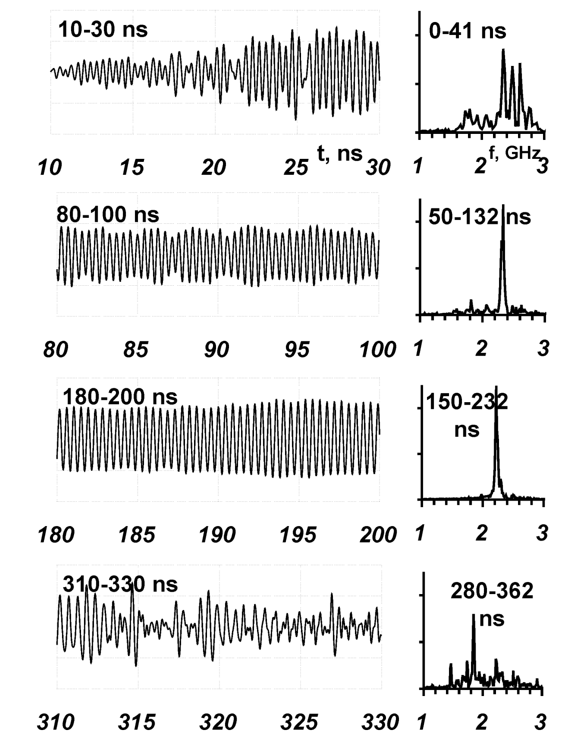

Fig. 9. Experimentally measured dependences of the microwave electric field on time and calculated spectrum

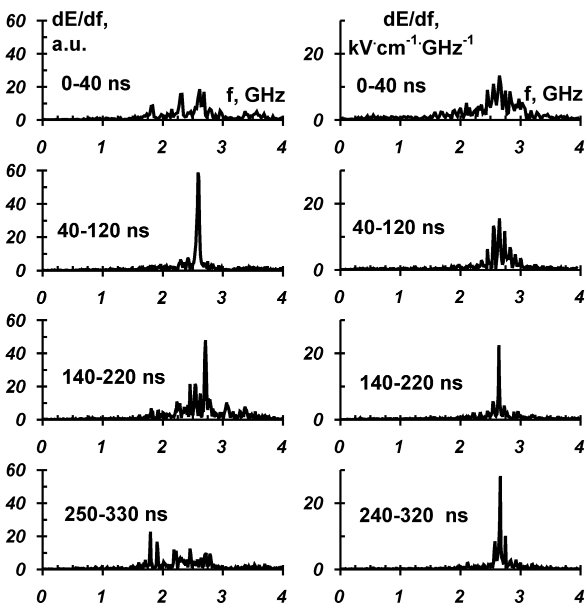

Fig. 10. The microwave electric field spectra for different time intervals. Left – experiment, right – calculations

Experimental studies of plasma relativistic microwave amplifier were conducted [13]. The differences of the amplifier scheme from that of the oscillator are as follows. First, to the entrance of the amplifier a microwave power is brought at a certain frequency. Second, there is a microwave absorber in the middle of the amplifier plasma waveguide. Near the absorber the efficiency of the wave amplification decreases and an effective absorption (~ 10^3 times) of the wave which reflected from the radiating unit takes place. This allowed to exclude the self-oscillating process in presence of a partial reflection of the power from the exit of the plasma waveguide and high amplification coefficient. It was proved that the spectrum of the output radiation coincide with that of the input signal.

An optimization of the plasma amplifier was carried out. Figs. 11 end 12 demonstrate the dependencies of the output power on the plasma waveguide length for two frequencies of the input signal, 9 and 13 GHz, and two values of the electron beam current, 1 and 2 kA.

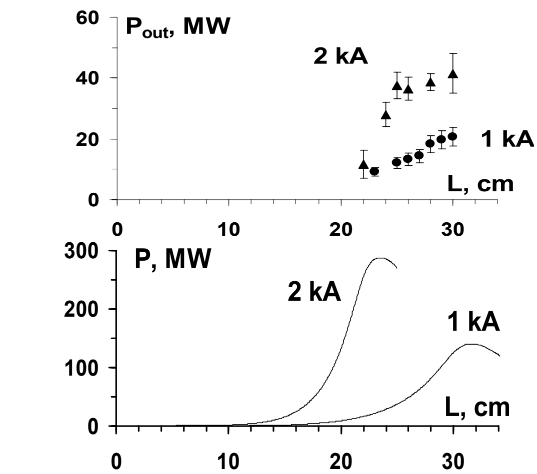

Fig. 11. Dependence of the amplified output power on interaction length for 9.1 GHz frequency of the input signal. Upper – experiment, lower – calculations

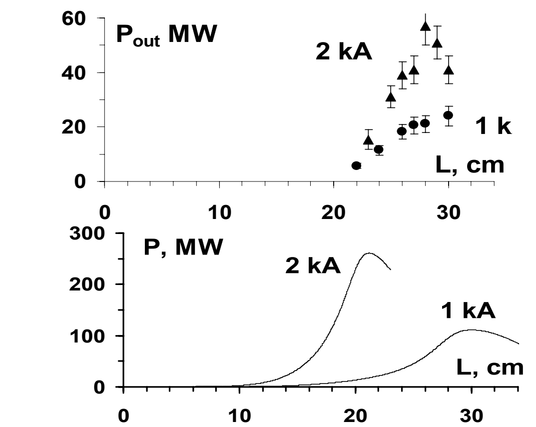

Fig. 12. The same as Fig. 11 for 13 GHz frequency of the input signal

The input microwave power is 50 kW, the electron energy is 500 keV. It is seen that if the plasma waveguide length is 28 cm, the power level of 40 to 60 MW is achieved, i.e. an amplification is of 29 to 30 dB. The difference of the optimal lengths in experiments and calculations is due to the facts that in the calculations, first, there was no absorber and, second, reflections from the output border of the plasma waveguide were neglected (ideal amplifier). Experiments showed that there exist the plasma density $\sim 1.5 \cdot 10^{13}$ cm^{-3} at which the both frequencies, 9 and 13 GHz (40 MW at the output), are amplified effectively. This means that the amplification band is $\approx 40\%$. Tuning the plasma density for each frequency allowed to achieve an output power 40 MW for 9 GHz and 60 MW for 13 GHz.

Thus, the following main experimental results were obtained.

1. Frequency tuning of one microwave oscillator from 4 to 28 GHz at the power level 50 MW was demonstrated. Electron beam parameters were: 500 keV, 2 kA, 30 ns.

2. Frequency tuning of monochromatic radiation from 1.5 to 2.7 GHz was obtained at the power level 50 MW and pulse duration 100 to 200 ns. Electron beam parameters were: 500 keV, 2 kA, 1000 ns.

3. An amplification of 29–30 dB was obtained for two frequencies of the input signal, 9 and 13 GHz, to the output power of $\approx$ 50 MW, microwave pulse duration 80 ns. Electron beam parameters were: 500 keV, 2 kA, 100 ns.

4. Conclusion

At present the entity of experimental results may be explained perfectly enough by the theory of plasma microwave electronics. It was shown that during 100 to 200 ns an electric microwave field $\sim 10^5$ V/cm does not change parameters of plasma and the plasma remains a linear media. Thus, plasma waveguide may be used as a slow wave system in devices of relativistic microwave electronics because the pulse duration of relativistic microwave devices usually does not exceed 100 ns.

The created plasma microwave devices concede in efficiency to vacuum devices. Plasma relativistic microwave devices has an efficiency of 4 to 7% whereas the efficiency of vacuum devices is 20 to 30%. The analysis of results show that only one transverse mode of the plasma waveguide is excited. However, the mode structure of the output radiation of the plasma devices was not studied thoroughly. Thus, in their main parameters the plasma devices do not yield to vacuum ones. Besides, the plasma devices can tune the radiation frequency. The typical time of the tuning is determined by the time which is necessary to change plasma density. In practical experiments it is the time of tens of microseconds. No devices of vacuum relativistic microwave electronics exist with such broad electronic frequency tuning. This explains practical interest to the studies in the field of plasma relativistic microwave electronics.

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