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Plasma relativistic microwave amplifier

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Plasma relativistic microwave amplifier is investigated in General Physics Institute during ten years The new results received in 2016 are presented in this report [1,2]. The plasma relativistic microwave amplifier uses an electron beam with electron energy of 500 *keV*, beam current – 2 *kA*, and cathode voltage pulse duration of 500 *ns*. At the input of the amplifier is fed a microwave pulse with a power of about 50 *kW* from one of the three magnetrons with frequencies of 2.4 *GHz*, 2.7 *GHz* and 3.1 *GHz*. The energy of the microwave pulse at the output from the horn was measured by calorimeter with a diameter of 50 cm. The receiving antenna in the form of a conductor piece is installed on the axis of the calorimeter. The microwave signal from antenna by a coaxial cable, attenuated by 63 dB, was fed to the oscilloscope with a bandwidth of up to 4 GHz. Thus, the energy of the microwave pulse and the dependence of the electric field strength of the microwave radiation on time on the microwave beam axis in each pulse were measured. The rotation of the antenna made it possible to determine the degree of the microwave radiation polarization.

If the electric field structure at different points of the microwave beam cross section is constant in a series of microwave pulses, then the quantity $\int U^2\,dt$ and the total energy of the microwave pulse *W* must be proportional to each other. Here *U* is the amplitude of the signal from the antenna. Figure 1 shows the dependence of the quantity $\int U^2\,dt$ and the energy of the microwave pulse *(W)* on the plasma density

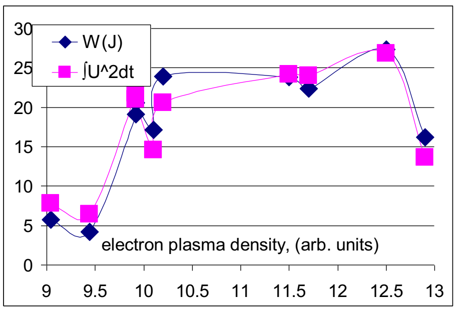

Fig. 1. Dependences of *W* (J) and $\int U^2 dt$ (arb. units) on the plasma density (arb. units) at 2.7 GHz

This graph demonstrates the proportionality of the quantities $\int U^2\,dt$ and *W* when the plasma density varies from 9 to 13 (arb. units). Moreover, the constancy of the structure of the microwave beam was confirmed by measurements [1].

The thin dielectric film with metal microparticles pasted onto it was installed at different distances from the horn. The microwave discharge occurred on this film, Fig. 2. A grid with a 5 cm cell size is superimposed on the film. It can be seen that the size of the glowing spot increases with increasing distance between the horn and the film. The electric field structure of the microwave beam cross section was calculated using the "KARAT" code. On the photos of the glow of the screen, on the left, the glowing threads are visible.

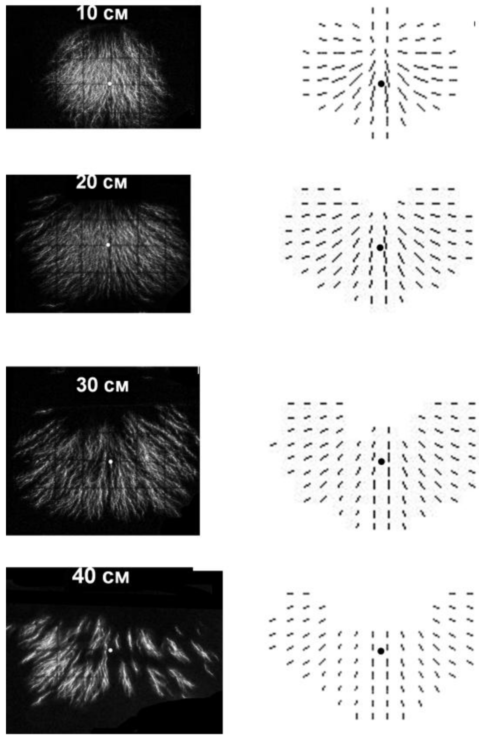

Fig. 2. Photos of the film glow, at different distances from the horn – on the left, the result of computer modeling – on the right. The dots represent the axis of the microwave beam. The length of the segments on the computer image is proportional to the electric field strength at a given point

One can see a good coincidence of the electric field structure in the experiment and in the calculation, and also the coincidence of the divergence of the beams. To measure the total energy of the microwave pulse, it is necessary to arrange the calorimeter close to the emitting horn aperture, as that the horn aperture diameter is smaller than the calorimeter diameter. At a distance of less than 70 cm, breakdown was observed on antenna. Therefore, measurements were made at a distance of 70 cm. At a distance of 70 cm the diameter of the microwave beam exceeded the diameter of the calorimeter. The divergence coefficient of the microwave beam was determined from the results of a numerical experiment. The data on the divergence of the microwave beam and Fig. 1 make it possible to calculate the total microwave radiation power according to the formula

$$P_f(t) = k\,W\,U^2_f(t)/2\int U^2(t)dt \qquad (1)$$

Here $P_f(t)$ and $U^2_f(t)$ the radiation power and the square of the output signal amplitude in the frequency band $f_0 \pm 15$ MHz, where f_0 is the frequency of the input signal.

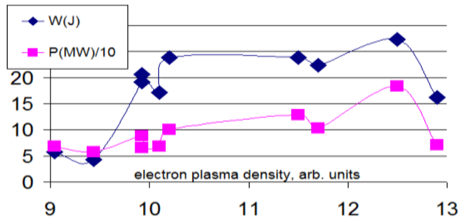

Fig. 3. Dependence of the microwave pulse energy and power on the plasma density, frequency 2.7 GHz

Figure 3 shows the dependence of the power and energy of the microwave pulse on the plasma density. The radiation power exceeds 100 MW.

The following picture were observed. The microwave pulse duration at small plasma density values is small and the maximum power is observed in the microwave pulse beginning. With an increase in the plasma density, the duration of the microwave pulse rises and exceeds the duration of the plateau of the cathode voltage pulse. The maximum microwave power is observed at the end of the microwave pulse.

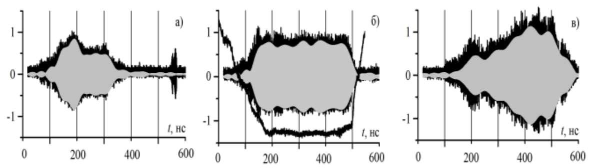

Fig. 4. Shape of microwave pulses. The plasma density increases from left to right. The accelerator voltage pulse on the cathode is shown on the middle figure. Gray color - the signal is passed through the filter 2710 ± 15 MHz from left to right. The frequency is equal to 2.7 GHz

This picture is observed for all three frequencies of the input signal.

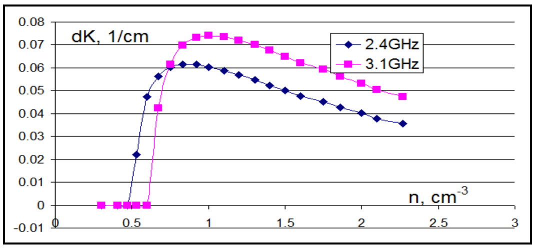

Fig. 5. Dependence of the linear amplification coefficient of the plasma wave electric field dK on the plasma density n at 2.4 and 3.1 GHz

The amplification coefficient decreases sharply when the plasma density decreases from the optimum value and decreases more smoothly when the plasma density exceeds the optimal value. In this way, one can expect different dependence of the microwave pulse amplitude on time for different values of the initial plasma density. If we assume that the initial value of the plasma density is less than the optimum value or slightly exceeds it, then a decrease in the plasma density during the current pulse of the REB should lead to a rapid decreasing of microwave power. For this reason the short microwave pulse is observed. If the initial plasma density value significantly exceeds the optimum value, then its decrease during the current pulse of the REB should lead to an observed increase in microwave pulse duration and increase in amplitude at the end of the microwave pulse. In addition, it was found that the output signal frequency is less than the frequency of the input signal by 10 MHz at a low plasma density and by 3 MHz at high plasma density. This phenomenon can also be explained by the assumption of a decrease in the plasma density during the microwave pulse. As the plasma density decreases, the wave vector of the plasma wave increases, which leads to an additional phase shift of the plasma wave at the plasma length. As a result, the output radiation frequency decreases in comparison with the input signal frequency.

The plasma density change during the mi-crowave pulse was recorded in the numerical simulation of the process of a plasma wave amplification by means of the "KARAT" code. The relativistic electron beam and the plasma were modeled by the particle in cell method.

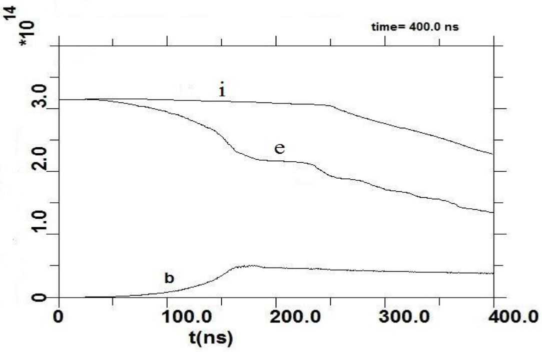

Fig. 6. Dependence of the total particles number on time: i – ions, e – plasma electrons, b – beam electrons

It can be seen that the total number of plasma electrons decreases twofold in 400 ns. Thus, the duration of the microwave pulse is limited by the decay of the plasma, which arises when the electron beam is injected into the plasma.

The microwave pulses parameters are presented in Table 1.

Table 1. Microwave pulses parameters. The percents (%) are power fraction in the frequency band $f_0 \pm 15$ MHz

(GHz)	W (J)	P (MW)	%
2.4	27	110	91
2.7	22	130	85
3.1	20	100	94

References

1 *I.S. Alekseev, I.E. Ivanov, P.S. Strelkov, V.P. Tarakanov, and D.K. Ulyanov*. Visualization of the Microwave Beam Generated by a Plasma Relativistic Microwave Amplifier// Plasma Physics Reports, 2017, Vol. 43, No. 3, pp. 340–345

2. *I.N. Kartashov, M.V. Kuzelev, P.S. Strelkov, V.P. Tarakanov*. Influence of plasma instability on the spectrum and shape of microwave pulses of a plasma relativistic microwave amplifier // article sent to the journal.