TEMPORAL EVOLUTION OF THE MICROWAVE SPECTRUM IN THE COURSE OF A RADIATION PULSE FROM A RELATIVISTIC CHERENKOV PLASMA MASER*

I. L. Bogdankevich, I. E. Ivanov, O. T. Loza, A. A. Rukhadze, P. S. Strelkov, D. K. Ulyanov, V. P. Tarakanov*, E. Garate†

General Physics Institute, Moscow, Russia

Abstract

A new Cherenkov plasma maser driven by a high-current relativistic electron beam (500 kV, 2 kA, 1 μs) was designed. The frequency of microwaves was tuned from 1.5 to 6 GHz with a power output from 50 to 80 MW and pulse duration from 500 to 700 ns. The radiation frequency depends on the plasma density and may be re-established during less than 100 μs. In different operation regimes microwave spectra were obtained with a width from 40 MHz to 1 GHz, and the spectra changed in the course of the pulses. The results of experiments coincide well with that of analytical theory and numerical simulations.

I. INTRODUCTION

This work continues our studies which we have carried out since 1982. The operation of a relativistic Cherenkov plasma maser (CPM) is based on Cherenkov interaction of a relativistic electron beam with plasma [1]. If the speed of electrons coincides with the phase velocity of the wave, an instability arises with a frequency that depends on the Langmuir plasma frequency. The basic maser has not significantly changed during the past 20 years. The system is azimuthally symmetrical and an annular relativistic electron beam from an explosive cathode propagates through a preformed annular plasma to a coaxial collector in a strong magnetic field. Microwaves propagate in the metallic coaxial waveguide to the outlet horn and vacuum-proof dielectric window.

Several years ago we made a plasma maser [2] which operated in the band from 4 to 28 GHz at a power level of 50 MW, and the experimental results coincided with theoretical predictions. Microwave spectra were measured using a calorimetric spectrometer, which consists of a set of cut-off filters, overlapping a significant part of the maser output microwave flux, and calorimeters. After several identical pulses, it was possible to obtain the radiation spectrum of the broad-band source, integrated throughout the pulse duration.

II. EXPERIMENTAL DATA

Presently we discuss a maser which is tunable from 1.5 to 6 GHz. Its frequency was also measured by the calorimetric spectrometer. **Figure 1** presents the dependencies of microwave pulse energy which passed through certain microwave filters to the calorimeter on an external parameter (current from the plasma source cathode), which we can change.

Waveforms in **Figure 2** present the temporal behavior of microwaves in 3 frequency bands. Microwave pulses have a duration of 500 ns with a power output of about 50 MW. Absolute values of microwave power were obtained using total pulse energy measured by the calorimeter.

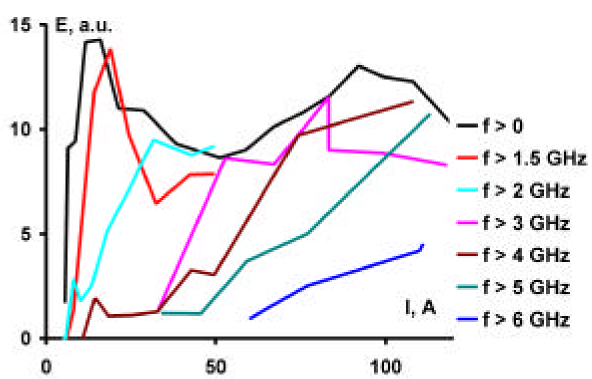

Figure 1. Microwave pulse energy E passed through a certain filter with cut-off frequency f.

* Work supported in part by the **US Civilian Research & Development Foundation**, award # RP1-2269; **Government of Russia**, program of the state support of unique scientific research and experimental installations in Russia, reg. # 01-04; **Russian Academy of Sciences**, Complex program "Generation of powerful pulses of electric energy, corpuscular and electromagnetic radiation", project "Plasma relativistic wide-band microwave oscillator with microsecond pulse duration".

* High-energy density research investigation Center, Moscow, Russia

† University of California, Irvine, CA, USA

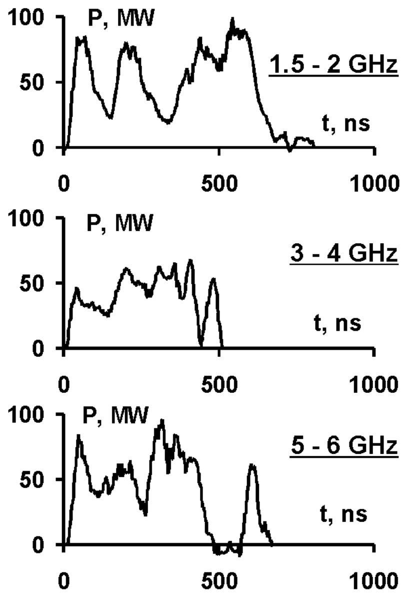

Figure 2. Waveforms of microwave pulses in different frequency ranges.

The study was carried out on an accelerator with a 1 μs pulse duration, a cathode voltage of 500 kV and a beam current of 2kA. The plasma density was varied from $5{\cdot}10^{11}$ to $5{\cdot}10^{12}$ cm^{-3}, and the microwave frequency changed from 1.5 to 6 GHz.

The comparatively low frequency of the radiation permitted another method of determining the microwave spectrum, namely, a dipole antenna and an oscilloscope with sufficient frequency bandwidth. Measurements of the temporal behavior of the microwave radiation in different regimes revealed a typical situation presented in **Figure 3**. At the beginning of the pulse the spectrum is broad and consists of several distinguishable lines, which appear one after the other. Then, for a comparatively long time, the spectrum bandwidth is narrow, although the frequency changes, sometimes discretely. By the end of the pulse the spectrum broadens and finally the radiation terminates, although the electron beam continues its propagation.

If the plasma density is increased the radiation frequencies increase also, but the temporal behavior remains the same: the spectrum narrows down just after the pulse front and broadens after some time. At higher plasma density and for a radiation frequency greater than 3 GHz a narrow spectrum almost does not appear, either in experiment, or in simulations.

Numerical modeling was carried out using the 2-dimensional version of the KARAT code, with the electrons simulated by a PIC-method, and the plasma considered either as a linear medium with constant properties or it was treated by a PIC-method. The numerical results coincide well with experimental data except the effect of microwave pulse shortening. In simulations with a "linear plasma" microwave emission continued for the duration of the electron pulse through the plasma. With the plasma treated as "particles" the microwave pulse shortening did take place, but only at low plasma densities.

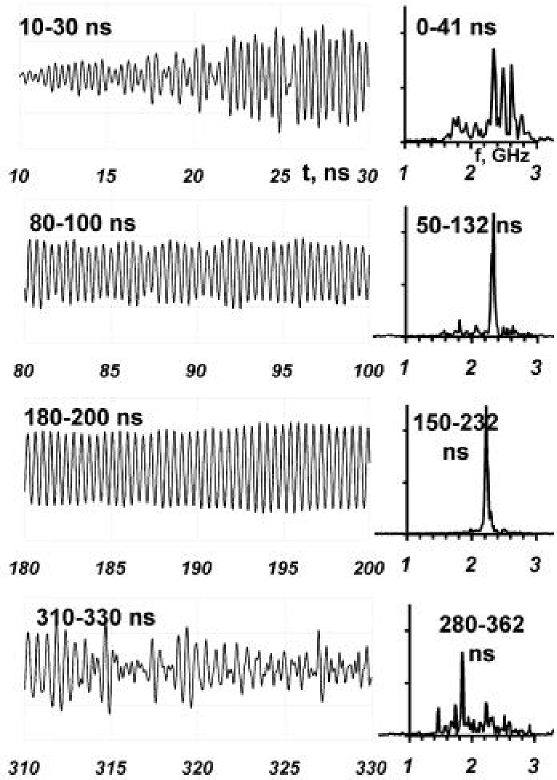

Figure 3. Typical behavior of microwaves.

Hence, there are several peculiarities of the maser operation: both the central frequency and the bandwidth depend on the plasma density, both these parameters change in time, and the broad spectrum is actually a set of narrow lines.

III. DISCUSSION

The *dependence of the radiation frequency on plasma density* is straightforward: with an increase in the plasma Langmuir frequency the Cherenkov interaction takes place at a higher frequency.

The *variation of the radiation frequency on the pulse front* is due to the increase of the electron's energy from about 200 to 500 keV during the rise of the beam current. As this takes place the frequency drops from 2.6 GHz to 2.4 GHz. The Cherenkov interaction of plasma and electrons takes place at a lower frequency for an increase in the electron's energy.

The *broad radiation spectrum is actually a set of equidistant lines*. This is due to the fact that the maser is an amplifier with feedback. Such a device can work if an integer number, N, of wavelengths coincides with the oscillator length, L as: $\frac{L}{\lambda_{dir}} + \frac{L}{\lambda_{ref}} = N = 1, 2, 3, ...$

Since the dispersion of the direct wave which interacts with the electron beam and the backward wave are different, the wavelengths λ_{dir} for the direct and λ_{ref} for the reflected waves are different. Also different are the group velocities v^{gr}_{dir} and v^{gr}_{ref}. In terms of wavenumbers $k_i = 2\pi/\lambda_i$ the above becomes: $\frac{L}{2p}(k_{dir} + k_{ref}) = N$. This integer number N might be interpreted as the longitudinal mode number.

If so, the wavenumbers of the waves may change only by a fixed increment. Hence, the radiation frequencies may also be only of a discrete set with the increment δf inversely proportional to the time of complete feedback in the system: $df = \frac{< v^{gr} >}{2L}$, where the average group velocity $< v^{gr} >= 2\frac{v^{gr}_{dir} \cdot v^{gr}_{ref}}{v^{gr}_{dir} + v^{gr}_{ref}}$. This was calculated using the linear model of the plasma-beam interaction as $< v^{gr} > = 1.8 \cdot 10^{10}$ cm/s. Taking into account that the length L = 70 cm, one may find that the frequency increment has to be 130 MHz which coincides well with the experimental data.

The bandwidth depends on plasma density. As indicated above, the maser is an amplifier with mirrors. The device works if the amplification compensates for the energy losses at the ends of the system: $\kappa_l \cdot \kappa \cdot e^{\delta K \cdot L} > 1$, where $\kappa_l = 1$ and κ are the reflection coefficients at the entrance and exit of the interaction area, correspondingly, and δK is linear growth rate. Calculations of both κ and δK in the framework of linear theory show that the bandwidth is narrow if the Q-factor is low, and vice versa. For a plasma density $5.25 \cdot 10^{11}$ cm^{-3} ($f \approx 1.6$ GHz, see **Figure 4**) $\kappa^2 \approx 0.15$, i.e. $Q \approx 4$, and $\kappa \cdot e^{\delta K \cdot L} \approx 60$, whereas for $1.25 \cdot 10^{12}$ cm^{-3} $\kappa^2 \approx 0.65$, i.e. $Q \approx 20$, and $\kappa \cdot e^{\delta K \cdot L} \approx 1000$.

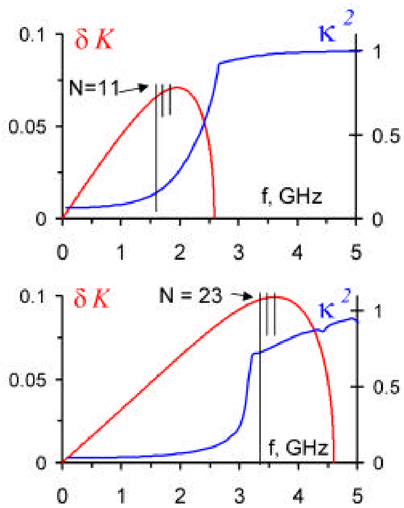

Figure 4. Linear growth rate δK and the squared reflection coefficient κ for two plasma concentrations: *top* — $5.25 \cdot 10^{11}$ cm^{-3}; *bottom* — $1.25 \cdot 10^{12}$ cm^{-3}.

IV. SUMMARY

We designed and operated a relativistic Cherenkov plasma maser which generates microwave pulses with frequency tunable in the band from 1.5 to 6 GHz, and has a pulse duration of 0.5 μs at a power level of 50 MW. In the band between 1.5 and 3 GHz, during the first several hundred nanoseconds the bandwidth is narrow and the frequency corresponds strictly to the energy of the relativistic electrons. Above 3 GHz the spectrum is also tunable, but always broad: see **Figure 5**.

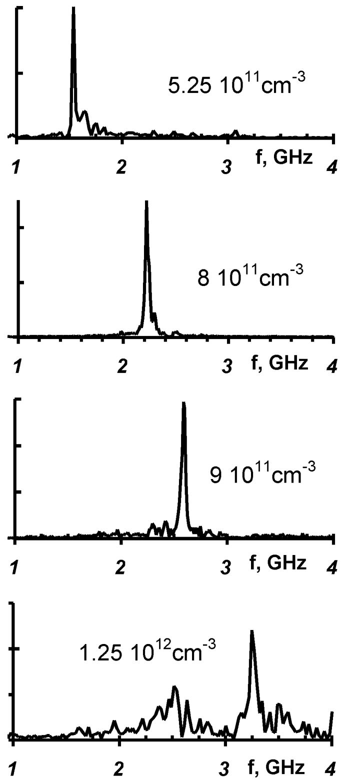

Figure 5. Microwave spectra of the maser with constant energy of driving relativistic electrons for different concentrations of plasma.

The results of numerical simulations generally coincide with the experimental data. The observed effect of "microwave pulse shortening" may be due to non-linear effects in the plasma: it was not obtained in simulations using a "linear plasma", but was obtained with a PIC-method at low plasma densities. For the higher density plasma the microwave pulse shortening is presumably determined by the comparatively high Q-factor (~8 instead of ≈2) and comparatively strong microwave field in the beam-plasma interaction area.

V. REFERENCES

1. Kuzelev, M.V., Loza, O.T., Rukhadze, A.A., et. al. *Plasma Phys. Rep.*, **27**, No. 8, 669–691, (2001).
2. P. S. Strelkov and D. K. Ul'yanov. *Plasma Phys. Rep.*, **26**, No. 4, p. 303–307, (2000).