Computer Simulation of the High-Power Relativistic Plasma Microwave Amplifier[1]

V.P. Tarakanov, I.L. Bogdankevich*, and A.A. Rukhadze*

High Energy Density Research Investigation Center RAS, Moscow, Russia, karat@tarak.msk.su
** Prokhorov's General Physics Institute RAS, Moscow, Russia, bira@fpl.gpi.ru*

Abstract – Computer simulation of the relativistic plasma microwave amplifier was made using the code KARAT. A pure amplification regime (without accompanying generation) was achieved in such amplifier in the experiment [1]. The simulation system was made nearly the same experimental setup. The main feature of this model is a microwave absorber.

1. Statement of the Simulation Problem

Realignment from the amplifier regime to the generation one is a serious task both to the computer simulation and to the experimental study of the plasma relativistic microwave amplifier. The reason is the big value of the gain coefficient, even though there is a small positive reciprocal connection, transfers the system to the generation regime. The microwave absorber is loaded into the system to suppress this effect. Experimental device and study of the microwave amplifier was described in the paper [1]. In [1] the regime of pure amplification (without accompanying generation) of monochromatic microwave signal in a plasma relativistic microwave amplifier was achieved for the first time in experiment at frequencies of both 9.1 and 13 GHz. Some results of the experiment (plasma density ranges, optimum length of the amplifier and other) correlate qualitative well with linear and nonlinear theory of the microwave amplifier [2]. But as previously noted in [1] the presence of the microwave absorber, reflections from the waveguide ends, and the pulsed character of the process lead to an appreciable discrepancy between the experimental and calculated results. This means that is necessary to carry out calculations using a more complicated model. Reflection of electromagnetic waves from the junction between a waveguide filled with tubular plasma and a vacuum coaxial waveguide was considered in [3]. But in this work was not taken into account beam electrons and thereby was not analyzed the operation of the plasma microwave amplifier. In this paper was used two-dimensional axisymmetric version of the KARAT particle-in-cell electromagnetic code [4]. Earlier, we used this code simulating relativistic Cherenkov plasma maser [5].

The computer simulation schematic is shown in Fig. 1. The code solved a set of Maxwell's equations and the relativistic equations of motion for electrons with boundary conditions on metal and a boundary, that does not reflect an electromagnetic wave. The electron beam was simulated by the particle-in-cell method.

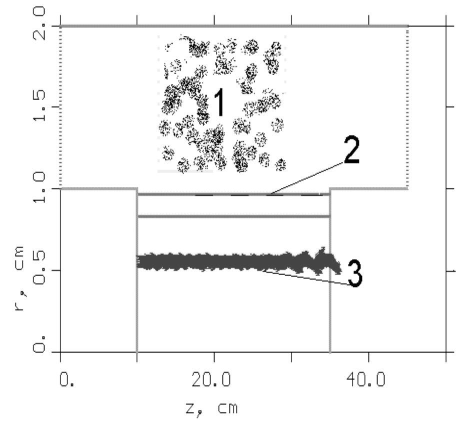

Fig. 1. A computer simulation schematic. 1 – absorbing layer , 2 – plasma, 3 – beam

The particles were injected from the left boundary. The geometry of the collector and output waveguide (right) is near the same experiment setup [1]. The coaxial in the left part of the system, makes possible injecting into a drift tube a TEM-wave with fixed frequency f_0 and power (frequency range from 5 to 15 GHz, average power 25 kWT). Metallic waveguide radius is $R = 2$ cm, annular plasma $R_{pl} = 0.8$–1 cm, beam $R_b = 0.5$–0.6 cm and $R_b = 0.7$–0.8 cm. Length of the plasma-beam interaction area was chosen ($L = 36$ cm) as a result of the computer simulation so to suppress generation at Cherenkov resonance frequencies. In this case was used microwave absorber, located in area 1, in Fig. 1. In this paper was applied a media as an absorber, where were realized absorbing boundary conditions according to Berenger's Perfect Matched Layer [6]. This absorber may be considered as an anisotropic active material. Properly chosen parameters of this media (sizes, gradients, conductivity) provides a fallen wave absorption near the same to real experiment [1].

2. Simulation Results

The amplifier output power dependence of the input wave at difference plasma density values is shown

---

[1] The work was supported by the Russian Foundation for Basic Research (No. 01-02-17265).

on Fig. 2. Two figurers corresponds two cases of the beam location. Up – the gap between beam and plasma is 2 mm, down – the gap is zero. This geometric factor affects on the parameters value of the plasma-beam waves connection [2]. The enhancement of connection is not essential for plasma density values near the threshold density (see triangles on Fig. 2), the gain efficiency is low, and does not depend from geometry features. The gain efficiency increases considerable according to the enhancement of the connection parameter in relative big plasma density range. There is a relative narrow gain frequency band for maximum gain efficiency (see grey squares on down graphic of Fig. 2).

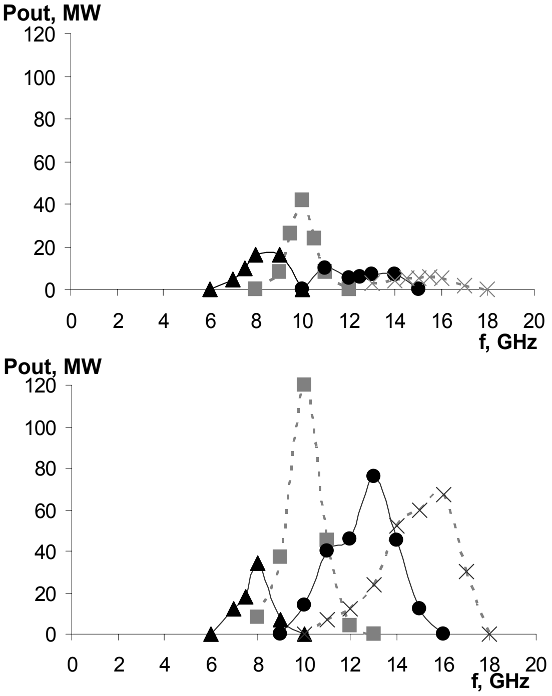

Fig. 2. Amplifier output power dependence of the input wave at difference plasma density values. Triangles – $5 \cdot 10^{12}$, grey squares – $7 \cdot 10^{12}$, circles – $1.1 \cdot 10^{13}$, crosses – $1.3 \cdot 10^{13}$

The maximum efficiency decreases at the magnification of plasma density, but gain frequency band expands. Two gain regimes are in keeping with two graphics on the Fig. 2. Linear regime (up graphic) is in line with the weak connection, nonlinear regime (down) is in line with the strong connection. Two phase portraits for mentioned regimes are shown on Fig. 3. Two values of the input wave (9 and 13 GHz) were used in experiment [1]. The gain efficiency dependence on the plasma density was calculated for these two frequencies. These calculations were made for two cases of the beam location. The value of the magnetic induction was changed too. Graphics for two values of the connection parameter are shown on the Fig. 4. Curves are presented on the Fig. 4 for the magnetic induction $B = 3$ T. From these graphics we notice that there is no area of plasma density values, where the same gain efficiency for both fixed frequencies may be detected.

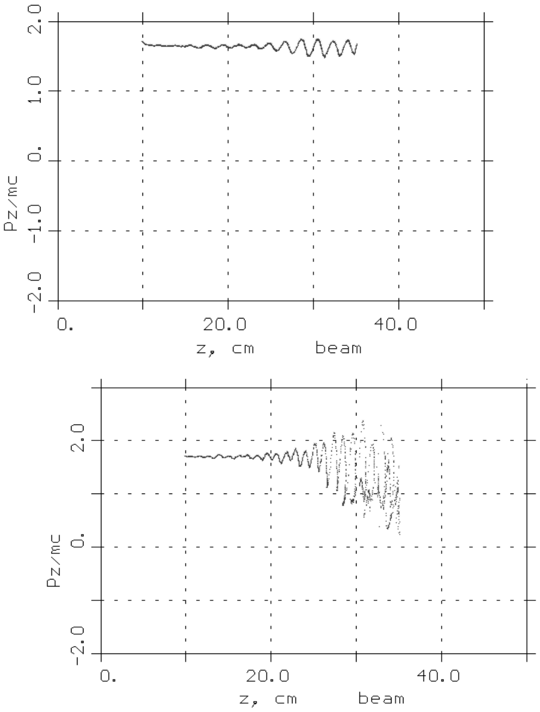

Fig. 3. Electron beam phase portraits (P_z, z) for weak connection (up) and strong one (down)

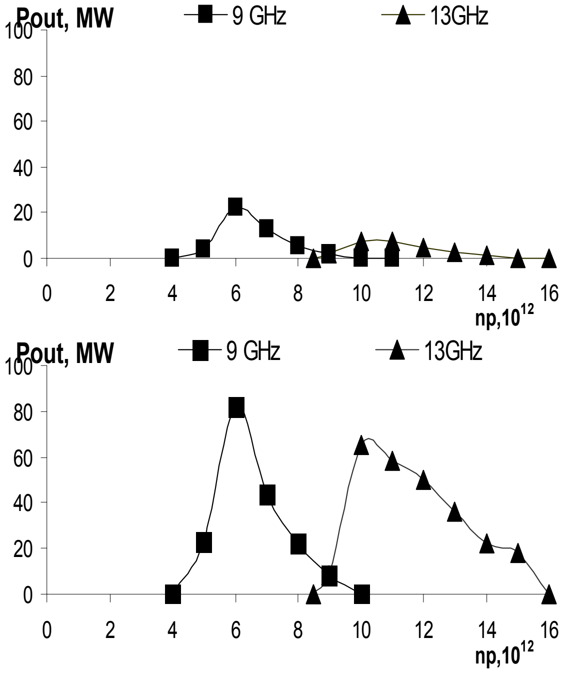

Fig. 4. Amplifier output power dependence on the plasma density for two fixed frequencies of the input wave. Upper graph – weak connection, lower graph – the strong one

The impact of the magnetic induction value upon the plasma microwave amplifier functioning was considered in this work. The computer simulation was made for four values of the magnetic induction $B = 3$ T, 1.5, 1 and 0.6 T, where $f_{h/\gamma} = 42$, 21, 14, 8.5 GHz accordingly. The impact of the magnetic induction value upon the plasma microwave amplifier functioning was not observed for weak connection between beam and plasma. For strong connection, simulation results are presented on Figs. 5a, b, c for $B = 1.5$, 1, and 0.6 T accordingly.

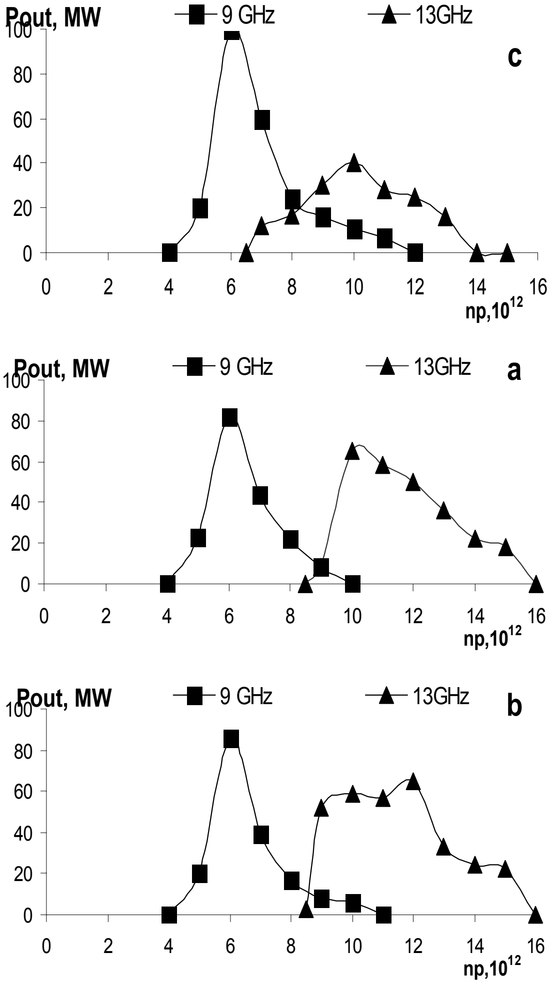

Fig. 5. Functioning efficiency dependence of the amplifier on the magnetic induction value; a – 1.5 T, b – 1 T, c – 0.6 T

From graphics b and c we notice that there is an area of plasma densities, where the same gain efficiency for both fixed frequencies (9 and 13 GHz) may be detected quite well. This fact has a good agreement with experimental results [1]. Gain efficiency decreases as the magnetic induction value is reduced. It is particularly clear noticed for frequency 13 GHz.

Conclusions

A special type of the anisotropic active media was used for the first time to simulate numerically the relativistic plasma microwave amplifier with absorber. The following conclusions are made from above mentioned results.

1. In the course of computer simulation parameters of the absorber were sorted out well to ensure a stable gain regime in a broad frequency range by the variation of the plasma density value.
2. A relatively big gain at frequencies 9 and 13 GHz was observed in a case of the strong plasma-beam connection. It takes place when the gap between electron beam and annular plasma is small. The gain achieved the level 30 dB.
3. Gain efficiency slowly decreases as the magnetic induction value is reduced. It is particularly clear at frequency 13 GHz and the magnetic induction $B \leq 1$ T.

References

[1] A.V. Ponomarev and P.S. Srelkov, Plasma Physics Reports **30,** 1, 62 (2004).
[2] M.V. Kuzelev, O.T. Loza, A.A. Rukhadze et al., Plasma Physics Reports **27**, 8, 710 (2001).
[3] I.N. Kartashov, M.A. Krasil'nikov and M.V. Kuzelev, Journal of Communications Technology and Electronics **44,** 12, 1502 (1999).
[4] V.P. Tarakanov, *User's Manual for Code KARAT*, Springfield, VA: Berkley Research Associates, Inc., 1992.
[5] I.L. Bogdankevich, I.E. Ivanov, O.T. Loza et al., Plasma Physics Reports **28,** 8, 690 (2002).
[6] J.-P. Berenger, J. Comput. Phys. **114,** 2, 185 (1994).