NOVEL PLASMA RELATIVISTIC BROADBAND SOURCE OF HIGH-POWER MICROWAVES

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Numerical model of plasma-assisted microwave noise amplifier with 10% of energy efficiency on 150-MW power level is described. Pulse duration of 2 ns prevents the feedback in a 50-cm long device and provides generation of microwave pulses with continuous frequency control from 4 to 17 GHz and ≈ 2 GHz of a pulse bandwidth. Parameters of available electron beam sources are considered.

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INTRODUCTION

Plasma relativistic microwave oscillators (PRMO) and amplifiers are known also as Cherenkov plasma masers, in experimental operation they are since 1982 [1]. These masers are based on Cherenkov interaction of relativistic electron beams (REB) with preformed plasma which mainly determines their oscillation frequency. Plasma concentration range may be very broad, hence, the plasma masers possess uniquely wide bandwidth of emission frequency control. Plasma maser which changed the frequency from 4 to 28 GHz from one pulse to the next one was demonstrated in [2]. Since the plasma is prepared individually before each pulse ~ 100 μs in advance, plasma masers demonstrated broad frequency control with the pulse repetition rate up to 50 Hz [3, 4].

Plasma maser is a travelling wave tube, i.e., an amplifier with frequency domain growth rate governed by plasma concentration. Reflections from inlet and outlet borders may transform the amplifier into a self-oscillator with inherent set of longitudinal modes and related discrete frequencies. Therefore, the radiation spectra of relativistic plasma oscillators consist mainly of separate frequencies [5] although plasma-beam interaction provides continuous range of frequencies.

In order to irradiate all frequencies within the band of amplification, the feedback in the device must be eliminated. One of possible ways is to make the REB pulse shorter than the period of plasma wave propagation back and forth between the borders. As a result, a noise may be amplified in all frequency range which the growth rate provides, but the non-linear theory of plasma maser [6] describes the bandwidth of concurrent irradiation as noticeably less than in linear case.

The authors of experiments [7] with a Cherenkov BWO and that short-term REB called the regime of their microwave device as "superluminescence" by analogy with the well-known quantum effect. Here we will refer to the plasma maser without inlet signal and no feedback as "plasma relativistic noise amplifier" (PRNA). The same plasma maser with longer REB pulse and the feedback is the above mentioned self-oscillator: PRMO.

In this paper we present results of numerical simulations of PRMO and PRNA with almost identical parameters. The PRMO was experimentally and numerically investigated for a long time, and it is possible to compare computer models with known experiments. On the contrary, the short-pulse PRNA was never studied, neither in experiments, nor even in simulations. Comparison of the two devices with mostly similar parameters reveals differences in their operation. Besides, special modeling of PRNA with short pulse REB source [7] was conducted to estimate results of possible experimental implementation of the novel plasma maser.

1. MODEL

Numerical simulations were carried out using fully electromagnetic code Karat [8]. So called 2.5-dimensional version of the code in use considers all three components of all fields and particle velocities but presumes their axial symmetry. Particle-in-cell (PIC) method was applied to model electrons of the REB and plasma particles. The scheme of the maser is presented in Fig. 1.

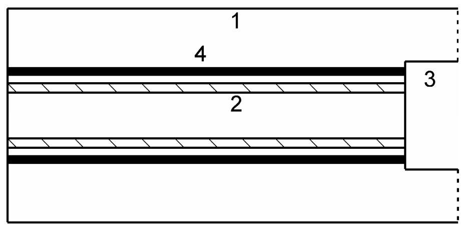

Fig. 1. Model of plasma maser: waveguide 1; REB 2; collector 3 and plasma 4

The area of modeling has axial symmetry, magnetic field of 2 T along the symmetry axis is homogeneous. Circular waveguide 1 with conductive walls is restricted by two borders. The left border is transparent for relativistic electrons, and the right border denoted by dashed line is transparent for microwaves. Hollow REB 2 is injected through the left border and terminates at the collector 3. Hollow plasma 4 exists between the left border and the collector also. Microwaves produced by the beam-plasma interaction are emitted through the right border.

The parameters of the maser are similar to that of experimental devices [2 - 4]. The REB and plasma cylinders have mean radii of 0.75 cm and 1.05 cm, respectively, with the equal thicknesses of 0.1 cm. The collector radius is 1.2 cm, and that of the outer waveguide is 1.8 cm. The 500-keV relativistic electrons and the REB current of 2 kA also correspond to the parameters of PRMO [4].

An important task of modeling PRNA was to find the current pulse duration and shape. Several values of pulse duration were tested with different leading and trailing edges of the pulses. The leading edge was under special study because the initial noise spectrum might greatly affect the amplified wave. It occurred that there is no significant influence of particular pulse shape on the results. Thus, the leading edge, the plateau and the trailing edge of electron current pulses in PRNA were chosen as 0.5 ns, 1 ns and 0.5 ns, respectively.

The Karat code comprises the possibility to calculate the beam current and electron energy accordingly to the Fedosov law for relativistic electron diode. Nevertheless, in the course of current pulse in PRNA with the above parameters the electron energy was presumed to be constant. The reason is that in experiments cold explosive cathodes are used, whereas an explosive electron emission has a delay ~ 1 ns in respect to electric field.

Modeling of comparatively long-pulse PRMO by Karat code has been carried out many times before, including application of PIC-method for studying the reasons for the effect of microwave pulse shortening [9]. To exclude this effect from consideration here the pulse duration of PRMO was set equal to 20 ns with the leading edge of 2.5 ns.

Hence, the two plasma masers here have the most of parameters correspondingly equal. They differ only in the REB pulse shape and the length between the left border and the collector.

2. RESULTS OF CALCULATIONS

Optimal lengths for PRMO and PRNA were calculated first of all for impartial comparison of the devices. The calculations were conducted in the range of plasma concentration $(0.4 \text{ to } 1.7)\cdot 10^{13}$ cm^{-3}. For the PRMO, the results correspond to that obtained in experiments [2], and the optimal length was found to be 23 cm like in [7].

The optimal length of PRNA should be obviously more. As a criterion, energy efficiency was calculated as

$$\eta = \frac{W_{RF}}{W_{REB}}. \quad (1)$$

Here W_{RF} is the total energy in a pulse calculated as Pointing vector flux at the right border. $W_{REB} = 0.5\ \text{MV}\cdot 2\ \text{kA}\cdot 1.5\ \text{ns} = 1.5\ \text{J}$ is the REB pulse energy.

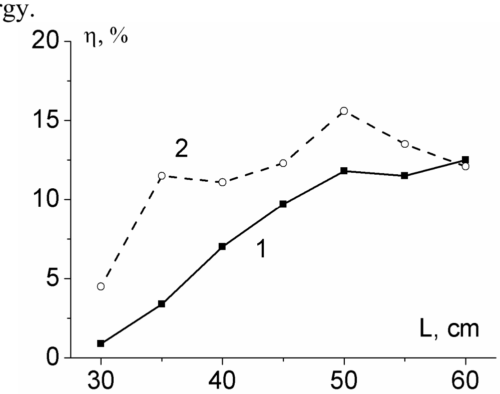

Fig. 2. PRNA efficiency η vs length L. Plasma concentrations $0.7\cdot 10^{13}$ cm^{-3} (1) and $1.4\cdot 10^{13}$ cm^{-3} (2)

Fig. 2 presents dependencies of the PRNA efficiency on the length for two plasma concentrations. A few more curves for other concentrations were obtained which did not differ significantly. At L = 50 cm the curves reach saturation, hence, this length was set as the optimum for further PRNA modeling.

Typical "waveform" of radiation power at the right border of PRNA and the spectrum are presented in Fig. 3. The power averaged through one period exceeds 200 MW, the total pulse duration being about 2 ns. Note that the spectrum consists of two separate fractions. The first fraction is always below 1 GHz, it relates to the short-term pulse of the REB. In absence of plasma the device could operate as well-known ultra wide band (UWB) source with the spectrum depending on high-voltage pulse duration. The second fraction in the spectrum relates to the beam-plasma interaction and will be considered further as high-power microwaves (HPM).

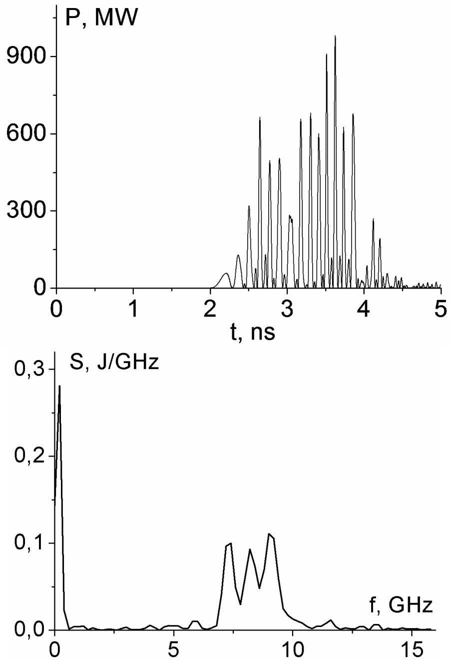

Fig. 3. Time domain RF power (top) and spectrum (bottom) of PRNA

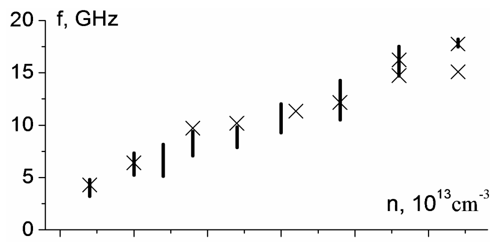

Fig. 4. HPM frequency f vs plasma concentration n of PRNA (vertical lines) and PRMO (crosses)

The main feature and advantage of plasma masers in respect to vacuum analogues is their ability to change emission frequency in broad band in accordance with plasma density variation. Fig. 4 shows that both PRNA and PRMO change emission frequency approximately from 4 to 17 GHz if the plasma rises from 0.4 to $3.2\cdot 10^{13}$ cm^{-3}. What is different is the spectrum width: for the PRMO it consists of separate frequencies denoted by crosses, and the PRNA spectrum is 1…3 GHz wide.

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The most distinctive feature of PRNA is comparatively high efficiency of 15 in respect to 10% of PRMO in the range 4 to 10 GHz. Note that here only HPM with frequencies of >1 GHz are considered, the total energy efficiency exceeds 15%. In terms of energy 15% corresponds to 0.225 J in HPM pulse or average power 150 MW during 1.5 ns.

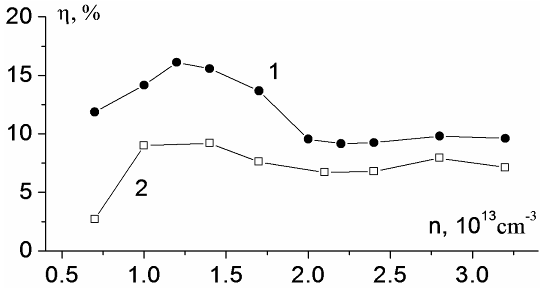

Fig. 5. Efficiency η vs plasma concentration n of PRNA (1) and PRMO (2)

The REB current in the PRNA may be increased if the accelerator in use permits to. The efficiency diminishes a little until the current rises twice from 2 to 4 kA but the HPM energy rises, the mean power reaches 0,4 J / 1.5 ns ≈ 250 MW. After 4 kA there is no sense to increase the current because the energy does not rise.

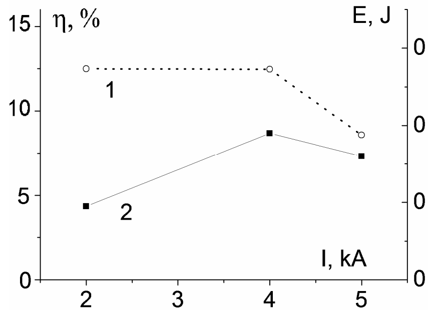

Fig. 6. Efficiency η (1) and HPM pulse energy E (2) vs REB current I of PRNA

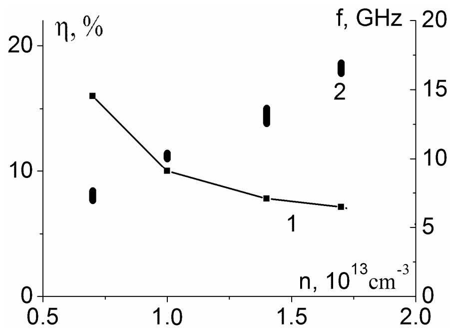

Fig. 7. Efficiency η (1) and HPM frequency (2) of PRNA driven by accelerator [7]

The question which arises is that about practical implementation of the proposed PRNA. Fig. 7 illustrates operation of the above described PRNA if it were "reinstalled" without any modification to the accelerator which was used in [7]. The voltage pulse of this device had sharp leading edge, a plateau at 270 kV level during 0.9 ns and a 2-ns long trailing edge. The peak current was 2 kA. In our model the electron beam current changed with voltage according to the relativistic diode law (Fedosov law). The REB pulse energy may be estimated as 1.1 J.

In the range of plasma concentrations (0.4 to 1.7)·10^{13} cm^{-3} the HPM frequency rises from 7 to 17 GHz, the width of a single pulse spectrum being 1 to 2 GHz. Comparatively to the above described case of 500 kV and 2 kA pulse the frequencies rose for appropriate plasma concentrations. The result is obvious because the velocities of REB electrons which excite slow plasma wave diminished [6]. With the above rise of the frequency, efficiency diminishes from 16 to 7%. Note that 10% of the energy efficiency and 2-ns long pulse correspond to 55 MW in microwaves. Comparatively to PRNA with higher REB energy, see Fig. 5, the dependence of the efficiency on plasma density is different. The reason is that the length L of the described PRNA was optimized for other parameters of REB: higher energy of 500 keV and much less trailing edge.

CONCLUSIONS

Numerical simulations of plasma maser with short pulse named as PRNA and well-known PRMO were carried out. To estimate the simulations accuracy, the results of PRMO modeling may be compared with experimental data, i.e., 7% of the calculated PRMO efficiency and 5% obtained in experiments [3]: 50 MW in HPM with 500 keV, 2 kA in REB. The frequency band in calculations (4 to 17 GHz) and in experiments (5 to 20 GHz) almost coincide, the parameters in calculations and experiment are identical, so the comparison is valid. As a consequence, the efficiency of 10% within two-fold band of frequencies 4 to 8 GHz is likely to preview in experiments with PRNA.

Application of available sources of high-current electron beams (e.g., used in [7]) as a driver for the PRNA is of interest. A plasma maser works with preformed plasma which is prepared ~ 10^{-4} s before a pulse, plasma decay is an order more long. Therefore, the pulse rep-rate as high as 10^3 Hz is quite suitable for PRNA. Prospective efficiency in experiments for PRNA driven by the accelerator [7] may be admitted as 5%, spectrum width of a pulse exceeds 1 GHz. This means that during 10 ms the frequency band 7 to 17 GHz may be confidently overlapped by microwaves with peak power of 30 MW and uniform spectrum density. The total energy spectrum uniformity is easily attainable because in a plasma maser each pulse in a train may be generated with individual frequency within the band.

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НОВЫЙ ПЛАЗМЕННЫЙ РЕЛЯТИВИСТСКИЙ ШИРОКОПОЛОСНЫЙ ИСТОЧНИК МИКРОВОЛН ВЫСОКОЙ МОЩНОСТИ

С.Е. Ернылева, В.О. Литвин, О.Т. Лоза, И.Л. Богданкевич

Описана численная модель плазменного усилителя шума с эффективностью по энергии 10% на уровне мощности 150 МВт. Длительность импульса 2 нс предотвращает обратную связь в генераторе с длиной 50 см и обеспечивает генерацию СВЧ-импульсов с возможностью непрерывной перестройки частоты СВЧ-импульсов от 4 до 17 ГГц и шириной спектра каждого импульса ≈ 2 ГГц. Рассматриваются параметры существующих источников электронных пучков.

НОВЕ ПЛАЗМОВЕ РЕЛЯТИВІСТСЬКЕ ШИРОКОСМУГОВЕ ДЖЕРЕЛО МІКРОХВИЛЬ ВИСОКОЇ ПОТУЖНОСТІ

С.Є. Єрнилева, В.О. Литвин, О.Т. Лоза, І.Л. Богданкевич

Описана чисельна модель плазмового підсилювача шуму з ефективністю по енергії 10% на рівні потужності 150 МВт. Тривалість імпульсу 2 нс запобігає зворотний зв'язок в генераторі з довжиною 50 см і забезпечує генерацію СВЧ-імпульсів з можливістю безперервної перебудови частоти НВЧ-імпульсів від 4 до 17 ГГц і шириною спектру кожного імпульсу ≈ 2 ГГц. Розглядаються параметри існуючих джерел електронних пучків.