USING PIC-PLASMA MODEL IN THE NUMERICAL SIMULATION OF A RELATIVISTIC CHERENKOV PLASMA MASER

I.L.Bogdankevich, A.A.Rukhadze, P.S.Strelkov, V.P.Tarakanov*[*]

General Physics Institute, Moscow, Russia, bira@fpl.gpi.ru;
[*]High-energy density research investigation Center, Moscow, Russia

Relativistic Cherenkov plasma maser experiments in General Physics Institute are supported by the well-developed theory of the plasma-beam interaction. Direct numerical schemes for simulation specific experimental conditions are used alongside with common theoretical ideas. Numerical simulation in this work was done trough the using code KARAT with non-linear PIC-method (particle-in-cell) for plasma electrons as well as for beam electrons.
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This work is directly concerned with experiments, which are carried out in Plasma Electronics Laboratory of General Physics Institute (Moscow, Russia). The operation of a relativistic Cherenkov plasma maser is based on Cherenkov interaction of a relativistic electron beam (REB) with plasma [1]. If the speed of electron coincides with phase velocity of the wave, instability arises with a frequency that depends on the Langmuir plasma frequency. The system is azimuthally symmetrical and an annular relativistic electron beam from a cathode propagates through preformed annular plasma in a strong magnetic field. The end of the central conductor metallic coaxial waveguide limits the electron beam and the plasma. Microwaves generate in the plasma waveguide, propagate through the metallic coaxial waveguide and emit into atmosphere through a dielectric window.

Presently we discuss a maser, which is tunable from 1.5 to 6 GHz. The comparatively low frequency allows using an oscilloscope to obtain the time-dependence radiated microwave electric field (then corresponding spectrum). Microwave radiation from the horn excites a wave in the antenna, and the oscilloscope registers the signal.

Earlier we used numerical modeling with electrons simulated as particles and the plasma considered as a linear medium with invariable properties [2]. 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. The broad spectrum is a set of narrow lines. On this point experiments data closely agree with results of linear simulation. But we can see some discrepancies between the experiment and the linear simulation. On fig.1 is presented the comparison: experiments data and simulation result for the linear model. Here for minimum plasma density (at $n_p < 5\cdot 10^{11}$cm^{-3} the MW-generation does not exist) the spectrum is broad at first and narrows down. In experiment it broads again, but in simulation it does not. Besides, we have in experiment so-called "microwave pulse shortening": termination of microwave before the end of the REB current pulse. In linear simulation the output power of MW-emission does not decrease with time. Possible reason for the differences may be that the linear model of plasma in simulations is not adequate to strongly non-linear plasma in reality.

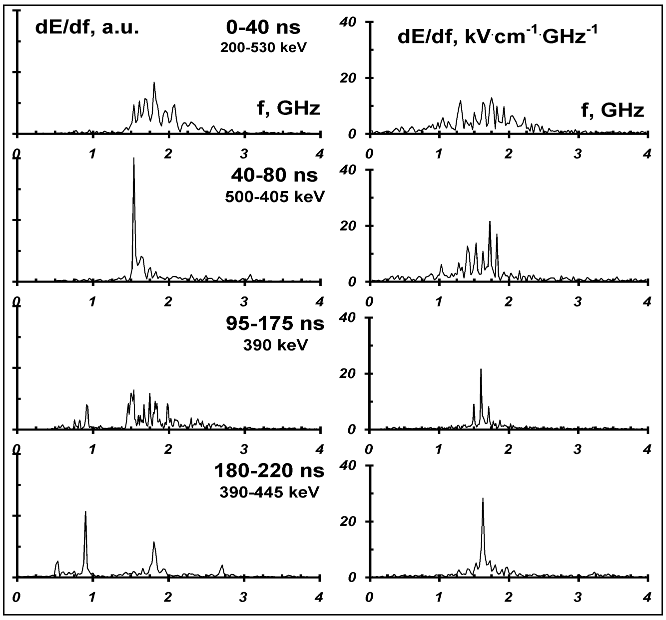

Fig.1. Experimental spectra (left) and results of the linear simulation (right) for plasma density $n_p = 5.5\cdot 10^{11}$cm^{-3}

Among the all possible causes which leaded to microwave pulse shortening, we take into account in this work only one – how so named "temperature" of plasma electrons affects on Cherenkov resonance mechanism. It is suggested, that plasma electrons absorb energy of the wave exiting by REB. For the simple qualitative analyze let consider a dispersion equation for one-dimension infinite plasma medium and beam [3]:

$$\varepsilon^{l} = 1 - \frac{\omega_p^2}{\omega^2}\left(1 + 3\frac{k^2 v_{Te}^2}{\omega^2}\right) + i\sqrt{\frac{\pi}{2}}\frac{\omega\,\omega_p^2}{k^3 v_{Te}^3} e^{-\frac{\omega^2}{2k^2 v_{Te}^2}} - \frac{\omega_b^2}{\gamma^3(\omega - ku)^2} = 0 \quad (1)$$

where ω_p and ω_b – Langmuir plasma and beam frequencies, u – beam electron velocity, $\gamma = \left(1 - u^2/c^2\right)^{-1/2}$ – relativistic factor, $v_{Te} = \sqrt{T_e/m}$, v_{Te} – thermal velocity, T_e – temperature of plasma electrons, ω, k – frequency and wavenumber of MW-radiation. Under conditions of existing Cherenkov resonance there is a known expression for the growth rate δ_1 [4]:

$$\delta_1 = \frac{-1 + i\sqrt{3}}{2}\left(\frac{n_b}{2n_p}\right)^{1/3}\frac{\omega_p}{\gamma}, \quad (2)$$

n_b, n_p – density of beam and plasma electrons.

If $kv_{Te} << \omega$ we obtain from eq.(1), inequality for arising of the nondissipative instability in the plasma-beam system

$$\frac{\sqrt{3}}{2\gamma}\left(\frac{n_b}{n_p}\right)^{1/3} >> \sqrt{\frac{\pi}{8}}\,\frac{u^3}{v_{Te}^3}\,e^{-\frac{u^2}{2v_{Te}^2}}. \qquad (3)$$

In the opposite limit there is a possibility to exist a dissipative instability and the growth rate δ_2 is

$$\delta_2 = \omega_p\left(\frac{n_b}{2n_p\gamma^3}\right)^{1/2}\frac{1}{\left(\frac{\pi}{2}\right)^{1/2}\frac{u^3}{v_{Te}^3}\exp\left(-\frac{u^2}{4v_{Te}^2}\right)} \qquad (4)$$

The transformation efficiency of beam energy into energy of wave field – η is equal [4]

$$\eta = \frac{2\gamma^2\delta}{\omega}\quad. \qquad (5)$$

Since $\delta_1 >> \delta_2$ η_2 is less than η_1

$$\eta_2 \approx \eta_1\frac{1}{\sqrt{\gamma}}\left(\frac{n_b}{2n_p}\right)^{1/6} \le \eta_1 \qquad (6)$$

It is conceivable that two regimes of the MW-radiation exist in Cherenkov plasma maser. The above-mentioned expressions offer only as qualitative estimates to explain the change of the instability mechanism. Numerical model was simulated using 2,5-dimensional version of the code KARAT, where the beam and plasma electrons were simulated by the same PIC-method (particle-in-cell) [5].

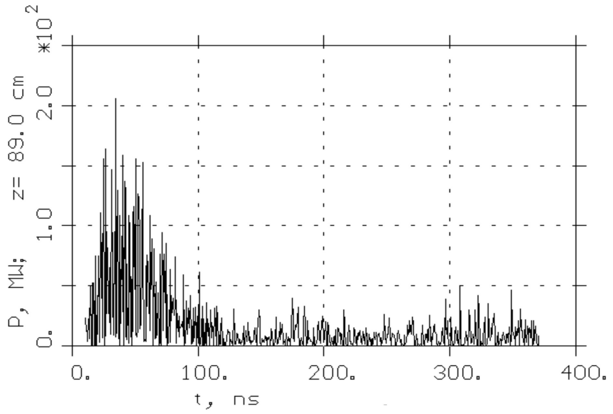

Fig. 2.A time dependence output power of MW radiation (n_p=5.5·$10^{11}$$cm^{-3}$).

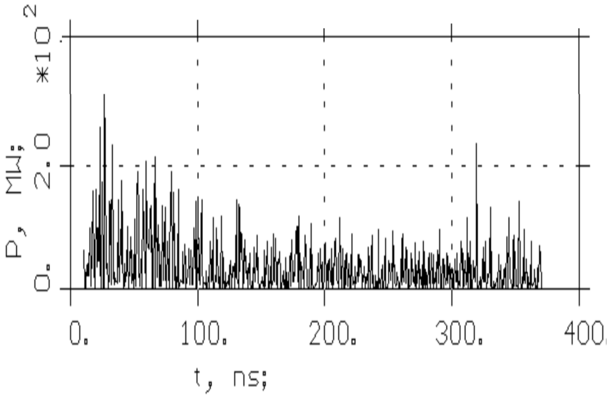

Fig. 3. A time dependence output power of MW radiation (n_p=1.5·$10^{12}$$cm^{-3}$)

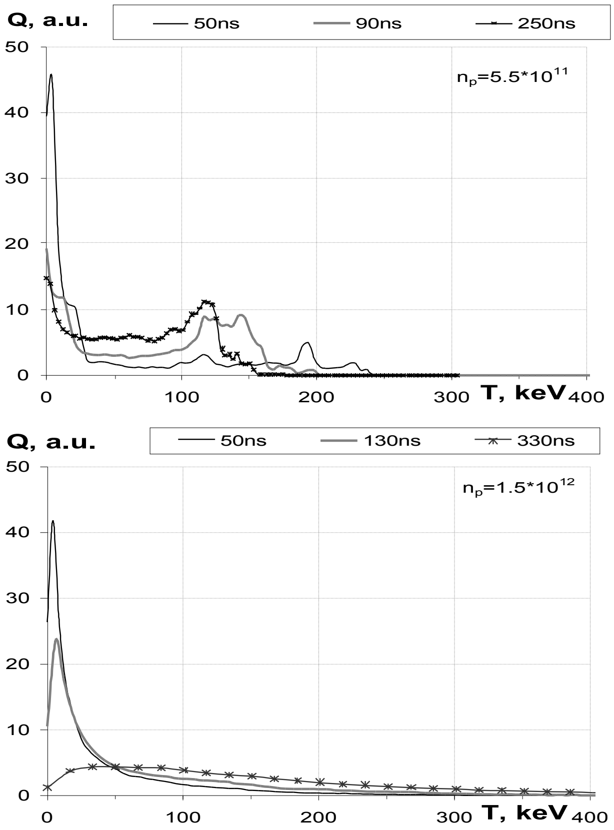

Fig. 4. Distribution functions of plasma electrons with energy in various points of time

On the fig.2 is presented a calculated time dependence output power of MW radiation. At small value of plasma density (n_p/n_b =5) the MW-radiation power decreases with time. The average power at first zone is 50 MW and then 10 MW.

At comparatively high density (fig.3.) there is not a greatly difference between values of MW-power in according time intervals. Average values of power in this case are 90 MW and 50 MW.

On fig.4 are presented distribution functions of plasma electrons with energy in various points of time. At the low plasma density the distribution becomes broad and far from the Maxwell type. The substantial proportion of high energy (till 150 keV) particles appearances in the plasma media. We can connect the MW-radiation power decreasing (fig.2) with the transformation from nondissipative to dissipative instability. On the contrary, at the comparatively high plasma density the distribution holds narrow form and almost Maxwell one.

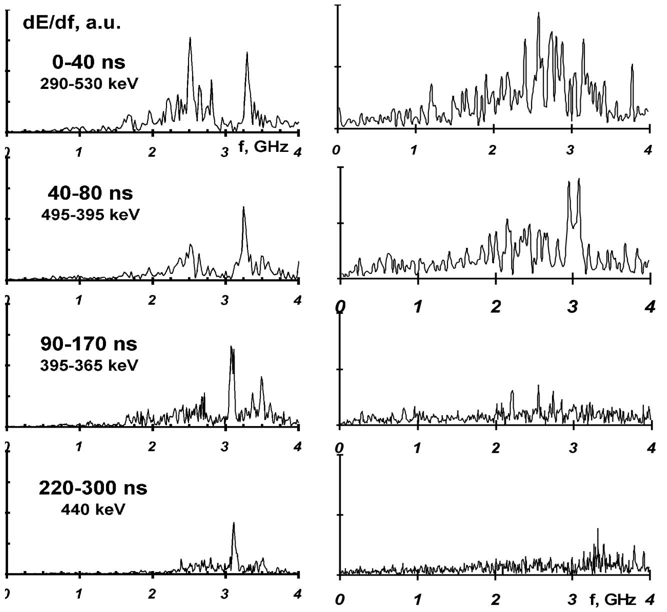

Fig. 6. Experimental spectra (left) and results of the non-linear simulation (right) $n_p=1.5\cdot10^{12}$ *cm*$^{-3}$

Now compare spectra in experiment and results of the non-linear simulation for two values of plasma density. The narrow line in simulation spectrum ($n_p=5.5\cdot10^{11}$ cm^{-3}) is observed in the same interval of time as we see in experiment (fig.5). The MW-radiation power decreasing is attended by the spectrum broadening. With maximum plasma density and the central frequency more than 3 GHz a narrow line does not appear clearly in simulation (fig.6). But there is a qualitative agreement between experiment data and simulation results in the temporal evolution of the MW-spectra.

CONCLUSIONS

Results of the non-linear simulation at difference plasma density have a qualitative agreement with the experiment data better than in the case of linear plasma model. At low plasma density we have also an agreement with analytic view (the connecting between the "heating" plasma electrons and the MW-radiation power decreasing). The situation with another plasma densities is more complicated and demands a detailed analysis.

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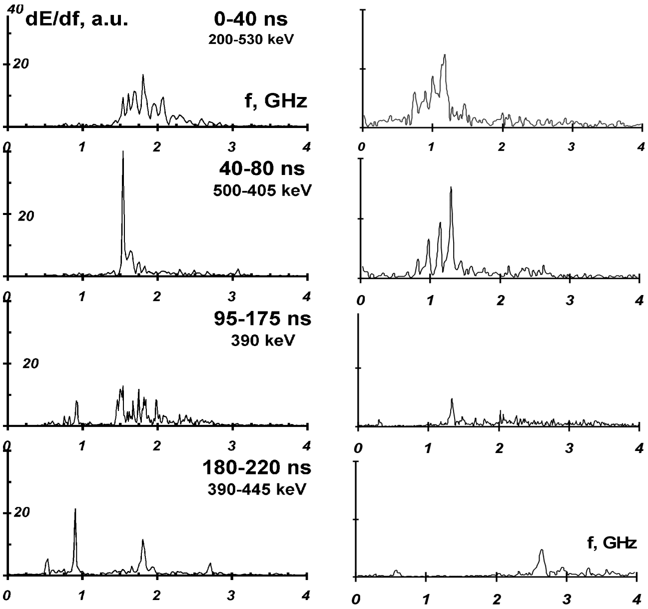

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ВИКОРИСТАННЯ МЕТОДУ ВЕЛИКИХ ЧАСТОК В У ОПИСІ ПЛАЗМИ ПРИ ЧИСЕЛЬНОМУ МОДЕЛЮВАННІ РЕЛЯТИВИСТСЬКОГО ПЛАЗМОВОГО СВЧ-ГЕНЕРАТОРА

І.Л. Богданкевич, А.А. Рухадзе, П.С. Стрєлков, В.П. Тараканов

Експерименти, що проводжуються у тривалий час в лабораторії ІЗФАН, підтримані розвинутою теорією плазмово-пучкової взаємодії. Наряду з загальними теоретичними розглядами для моделювання конкретних умов експерименту

вживаються прямі чисельні схеми. Чисельне моделювання в даній роботі було здійснене за допомогою коду КАРАТ, тобто рівняння Максвела були розв’язані чисельно за допомогою явної кінцево-різницевої схеми. Щільність струму J в законі Ампера обчислюється для пучка методом великих часток (PIC - particle in cell- методом), а для плазми або також, або за допомогою розв’язання рівняння холодної одно рідинної МГД у лінійному наближенні.

ИСПОЛЬЗОВАНИЕ МЕТОДА КРУПНЫХ ЧАСТИЦ В ОПИСАНИИ ПЛАЗМЫ ПРИ ЧИСЛЕННОМ МОДЕЛИРОВАНИИ РЕЛЯТИВИСТСКОГО ПЛАЗМЕННОГО СВЧ-ГЕНЕРАТОРА

И.Л. Богданкевич, А.А. Рухадзе, П.С. Стрелков, В.П. Тараканов

Эксперименты, проводимые в течении длительного времени в лаборатории ИОФАН, поддержаны хорошо развитой теорией плазменно-пучкового взаимодействия. Наряду с общими теоретическими рассмотрениями для моделирования конкретных условий эксперимента применяются прямые численные схемы. Численное моделирование в данной работе было выполнено посредством кода КАРАТ, т.е. уравнения Максвелла решались численно с помощью явной конечно-разностной схемы. Плотность тока J в законе Ампера вычисляется для пучка методом крупных частиц (PIC- particle in cell- методом), а для плазмы либо также, либо в линейной приближении путем решения уравнения холодной одножидкостной МГД.