NONRELATIVISTIC PLASMA HF-ELECTRONICS

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The main physical principles for the elaboration of plasma and hybrid plasma-filled microwave devices based on the beam-plasma interaction are formulated. The theoretical and experimental results of the investigations of electromagnetic oscillations excitation in beam-plasma systems carried out in National Science Center “Kharkov Institute of Physics and Technology” are presented. The electrodynamics of plasma-filled slow wave structures, nonlinear stage of beam-structure interaction, and stochastization mechanism are studied. Some experimental installations elaborated are described and obtained results on power level, efficiency, and spectra are shown.

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1. INTRODUCTION

Prediction of the beam-plasma instability [1,2], discovery of the beam-plasma discharge [3-5], and investigation of plasma waveguide electrodynamics [6] have laid the foundation of the new branch of plasma physics – the plasma electronics. Numerous theoretical and experimental investigations carried out in NSC “KIPT” on this subject brought to the elaboration of the new kind of HF-devices of regular and stochastic electromagnetic oscillations, so called beam-plasma generators and amplifiers [BPG]. The physical principles for the creation of such devices were firstly formulated in NSC “KIPT” in 1965. Only later they were partly published by the researches of NSC “KIPT” [7-9] and by authors from other places [10-11].

The theoretical efforts were undertaken to the investigation of plasma filled conventional slow wave structures [hybrid structures] electrodynamics, stochastization mechanisms, and spectrum evolution in such strong nonlinear and nonequilibrium systems as BPG’s are.

Experiments were performed both for relativistic and nonrelativistic electron beams. The first ones in plasma waveguides [12,13] and in corrugated vacuum waveguides, filled with plasma [14,15] showed the impressive enhancement of the efficiency. “KIPT” experiments on nonrelativistic beams interaction with hybrid plasma structures were firstly represented in [16] demonstrating some merits of beam-plasma devices. The essential advanced elaboration and technological perfection of amplifier type were made in VEI [17]. Some experiments with BPD were fulfilled in MRTI [18].

The idea of using plasma as a slow wave structure concludes to the high gain parameter in beam-plasma interaction reaching to 15 dB/cm [19]. The frequency of excited oscillations can be tuned simply by plasma density changing. As an electromagnetic noise source, the beam-plasma system is a good approach due to the strong nonlinearity and nonstationarity of plasma, needed for dynamic chaos development, and abundance of plasma eigen modes. The problem of extracting of excited plasma oscillations is solved comparatively simply for the relativistic beam as their phase velocity is close to the speed of radiated electromagnetic waves [12-15]. In the nonrelativistic case, more attractive one because of compact electron beam sources, plasma oscillations are trapped in plasma. So, special measures and tools should be used to match the electrodynamics of nonrelativistic beam-plasma system with vacuum waveguide tract or open space. For this goal the conventional slow wave structures filled with plasma were used [20,21]. As it was established in [7] optimal configuration is the partial filling with plasma, i.e. plasma is produced [for example by electron beam collisions with neutral gas] only in beam transit channel. It provides the interaction of the electron beam with vacuum eigen mode modified with plasma in such a way that the wave field in plasma has volumetric topography and, hence, beam-wave coupling is effective and gain parameter is high. Electron beam is efficiently interacting with plasma in transit channel and excited HF-power is being extracted and transported in surrounding vacuum region of waveguide.

The main advantages of the beam-plasma devices using plasma-filled slow wave structures are:

- possibility of power increase by rising of the vacuum limit current due to the compensation of the beam space charge;
- volume character of the excited wave that leads to the considerable increasing of the growing rate and consequently efficiency enhancement in comparison with the vacuum case;
- tuning of the excited frequency by plasma density changing;
- possibility to realize the interaction in a large volume and, hence, to obtain high power output;
- great number of the eigen modes in plasma-filled structures vary and enrich obtained spectra without losing the possibility of their governing.

2. THEORY

2.1 ELECTRODYNAMICS [7, 16, 22, 23]

Theoretical investigations involved the study of the electrodynamics of hybrid plasma structures and stochastization processes. The gain, start current, nonlinear saturation and efficiency, and thresholds of bifurcation should be estimated. Some conventional slow wave structures (SWS) – helix, chain of coupled cavities, corrugated waveguide, ring-bar SWS, sequence of rings, and coaxial grate – were investigated under plasma filling to apply for various frequency bands. The main feature of these devices filled with plasma is the essential modification of dispersion properties and field topography that leads to the efficiency enhancement, activation of dynamic chaos evolution, and enriching of excited spectra. Below we present theoretical investigations of the hybrid SWS consisting of the chain of inductively coupled cavities in which the transit channel for electron beam is filled with plasma. The cross-section of this structure is represented in Fig. 1..

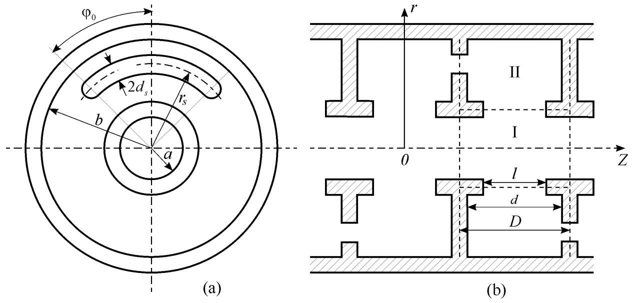

Fig. 1. Cross-section of chain of inductively coupled cavities

Dispersion equation (DE) for such hybrid structure was obtained in (22,23) by the method of partial regions (24) and the theory of the slit antenna (25). Due to the periodicity of the structure and plasma filling a great number of radial plasma waves (Trivelpiece-Gould modes) multiplied by system periodicity (spatial Flouquet modes) cover densely the plane longitudinal wave vector-frequency *(k_z, ω)* in the frequency region *$(0 - \omega_p)$*, where *ω_p* is the plasma frequency. In Fig. 2 the noninteracting dispersion curves corresponding to the mentioned modes are represented on plane *(k_z, ω)* only for four radial modes (to illustrate of the phenomenon). The interaction of electron beam with such structure leads to the excitation of so-called "dense" spectrum (26).

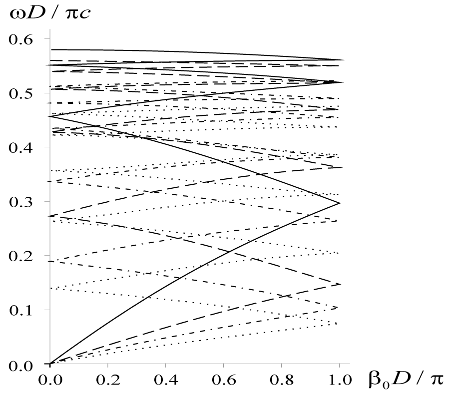

Fig. 2. Eigen radial and spatial modes

The left side of obtained dispersion equation in absence of the beam (cold system) *$F(\omega)=0$* is pictured in Fig. 3 as a function of frequency ω at fixed geometric parameters and plasma frequency *$\omega_p = 0.5\ \pi c/D$* (*c* is speed of light, *D* is structure period). It is seen the abundance of spatial. harmonics of many radial modes of the low frequency plasma wave *$(\omega < \omega_p)$* and clearly expressed principal TE-mode of the vacuum coaxial resonator, modified by plasma assistance. We should note that the eigen frequencies of noninteracting vacuum modes (the roots of *$F(\omega)$*) become the poles with vertical lines-asymptotes, when modes interact and the roots of *$F(\omega)$* displace. It is important that roots displacement is also caused by plasma presence and depends on plasma density. It means that excited frequency can be tuned by plasma density changing. The value of the displacement from vacuum noninteractive case for the principal mode can be seen in Fig. 3 as the most right cross point of the dispersion curve with a small incline.

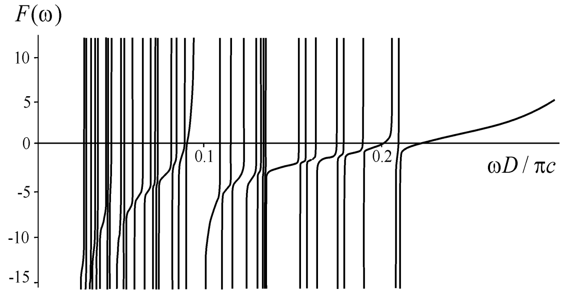

Fig. 3. Dependence of function F of DE upon frequency

The evolution of the radial topography of the longitudinal field ε_z inside transit channel filled with plasma when plasma density grows is shown in Fig. 4. The curves *1,2,3* correspond to the plasma frequencies *$\omega_p = (0;0.5;1.5)\ \pi\ c/D$*. Volume property of the field inside the channel is evident for higher plasma densities.

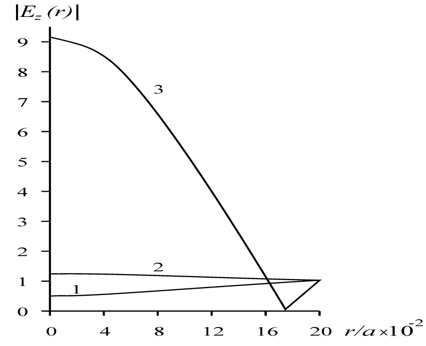

Fig. 4. Radial topography of ε_z

2.2 STOCHASTIZATION [27-30]

The preliminary experimental of beam-plasma HF-generator with the SWS described above have shown the following scenario. With beam current growth the change of generator operation regimes takes place: regular monochromatic generation is being changed by automodulation regime with a lot of satellites and noise component, which makes each spectral component wider. With further increase of beam current "natural" width of spectral lines becomes so wide that satellites overlap. Noise spectrum becomes uniform, its band coincide with the passband of SWS. Such evolution of spectra is typical for the majority of HF-devices (TWT, gyrotron etc.), however such peculiarities as spectral line widening and uniformity of noise spectrum indicate that hybrid SWS possesses new qualities not typical for vacuum devices.

Stochastization mechanism in vacuum devises is based on phenomenological point map, that is treated as amplitude transformation for synchronous wave after one propagation along feed-back circle. Meanwhile the conception of "function of mapping" for amplitude can be introduced exactly only for monochromatic signal as such function depends strongly on signal frequency in amplification band. So for description of noise regime with wide band the new theory (functional map) was required, that would be based on the peculiarities of solutions for nonstationary equations of TWT with delayed feedback. Nonstationary equations of TWT-amplifier have two families of characteristics. Information from the entrance of amplifier of L length transmitted to its exit by beam particles and synchronous wave with velocities v_b and v_g, correspondingly. So the output signal $\varepsilon_{output}(\tau)$ is determined by input signal on the time interval $\Delta t = L(v_b - v_g)/(v_b v_g)$. By other words, output signal $\varepsilon_{output}(\tau)$ is not the function, as it was supposed in point map, but a functional of input signal $\varepsilon_{input}(\tau)$.

The plasma-beam microwave generator is considered as a circular system that consists of non-linear amplifier of HF-oscillations and feedback that maintains the excitation of the whole system. Non-linear amplifier is TWT, in which an electron beam interacts with synchronous wave of the structure. At analytical investigation we use the results, published in (27-30), and treat, in particular, the theory of circular generator with TWT as a non-linear amplifier. We consider also the influence of low-frequency non-stationary processes in plasma on a signal dynamics. The example of spectra of stochastic generation, obtained without and with taking into account the self consistent dynamics of plasma are pictured in Figs 5 and 6, correspondingly.

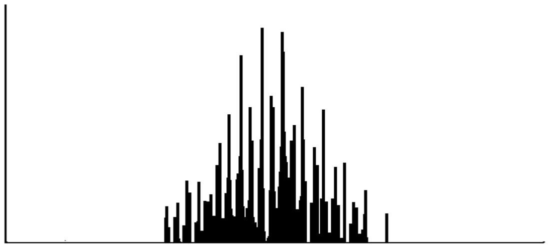

Fig. 5 Spectrum without plasma dynamics

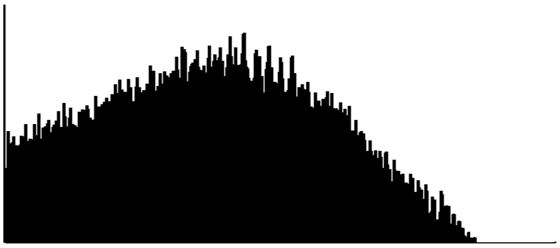

Fig. 6 Spectrum with plasma dynamics

The observation of spectrum enhancement due to low-frequency plasma instabilities may be difficult because this phenomenon is possible in the hybrid plasma-filled slow-wave structure if the microwave power is sufficiently high and generator operates in stochastic automodulation regime. Therefore the investigation of it is easily carried out in the regime in which the monochromatic external signal is applied to the TWT-generator input. In this case the generator may be driven from stochastic regime to monochromatic one without essential power change. The low-frequency instabilities may be identified as low-frequency oscillations of the phase shift $\Delta\alpha(\tau)$. The spectrum of such oscillations determines spectral line form of the plasma-beam microwave generator at high level of the power.

So due to the sufficiently large growing rate in the hybrid structure the threshold of stochastic generation are lower. The stochastization mechanism at high power levels is the alternating turbulence. Besides, the presence of a great number of radial modes and their space harmonics and also low frequency plasma motion (ion. sound, density modulation etc.) leads in the nonlinear regime to more homogeneous spectra of the stochastic automodulation comparatively to the vacuum case.

3. EXPERIMENT

3.1 RESULTS OF CENTIMETER GENERATION

Experimental realization of the generation in centimeter range has been carried out with slow wave structure of chain of coupled cavities (CCP) type with plasma filled transit channel. The scheme of the device is represented in Fig. 7.

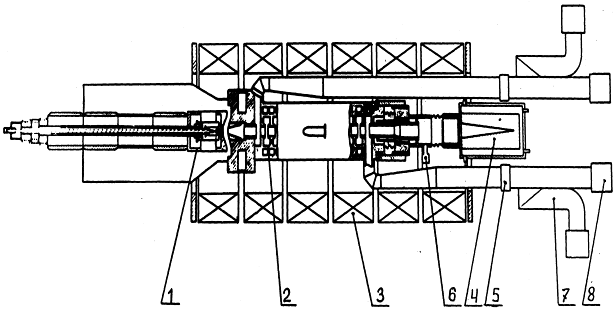

Fig. 7 Scheme of generator with CCP structure

Electron gun (1), injecting beam current 10 A at voltage 40 keV, is matched with compact high efficient ion-getter pump maintaining the pressure 10^{-6} Torr; slow wave structure (2) composed of cupper cavities, inductively coupled with slits of lentil form, and drift tubes was placed in a solenoid (3) producing magnetic field 3 kG; cooled collector (4) was capable to dissipate the power up to 260 kW; the power output was realized by the waveguide of 74×36 mm sizes wideband sapphire window (5); the plasma of density $5\cdot10^{10}-10^{12}$ cm^{-3} was produced by beam-plasma discharge in the transit channel under gas filling. The standing wave coefficient was 1.5 – 2.0 over the frequency band 2.4 – 5 GHz. The electron gun has the protection from the ion bombardment.

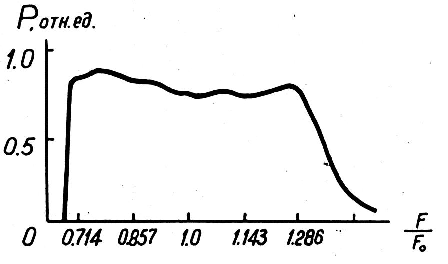

Fig. 8. Power spectrum

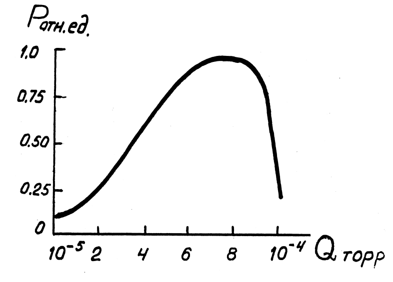

Fig. 9. Dependence of power on pressure

Start current was 100 mA and the stochastization threshold was 1.0 A in a good agreement with calculations.. With current increasing the generated frequency band overlapped the whole passband of the CCP structure.. Frequency spectrum is wide and homogeneous in the band of about a half of octave (Fig.8). The efficiency enhancement under plasma assistance and the existing of optimum of plasma density, that was discussed in theory is demonstrated in Fig.9.

The efficiency reached 40% for the optimum conditions in continuous operations. Varying phase velocity by the corresponding structure geometry the electronic efficiency was obtained 50% and output power 40 kW. For the pulsed operation during 4 ms the power 100 kW was achieved.

3.2 RESULTS OF DECIMETER GENERATION

In decimeter range of wavelength the BPG of stochastic oscillations has been elaborated and created using plasma -helix structure with a single or modified contra-wound helix circuits that are operating in quasi continuous or continuous regimes.

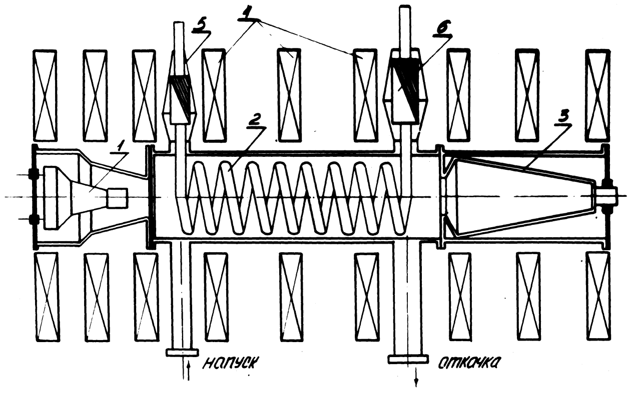

Fig. 10. Scheme of generator with helix structure

The generator (Fig.10) is consist of the following units: 1 — electron gun, 2 — helix structure, matched with beam-plasma interaction region, 3 — collector, 4 — solenoid, 5 — HF-load, 6 — HF power register. The beam current is 13 A, beam energy — 15 keV, magnetic field strength — 1100 G, plasma density — 6-10^{10}cm^{-3}. The total generated power was 80 kW and efficiency was 40%.

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НЕРЕЛЯТИВИСТСКАЯ ПЛАЗМЕННАЯ СВЧ-ЭЛЕКТРОНИКА

И.Н. Онищенко

Сформулированы основные принципы разработки плазменных и гибридных плазмонаполненных СВЧ-приборов, основанных на пучково-плазменном взаимодействии. Представлены результаты теоретических и экспериментальных исследований возбуждения электромагнитных колебаний в пучково-плазменных системах, которые проводились в ННЦ ХФТИ. Исследованы электродинамика плазмонаполненных замедляющих структур, нелинейная стадия взаимодействия с ними пучков и механизмы стохастизации. Описаны некоторые экспериментальные стенды и приведены полученные на них мощность, кпд и спектры.

НЕРЕЛЯТИВІСТСЬКА ПЛАЗМОВА СВЧ-ЕЛЕКТРОНІКА

І.Н. Онищенко

Сформульовані основні принципи розробки плазмових і гібридних плазмонаповнених СВЧ-приладів, заснованих на пучково-плазмовій взаємодії. Представлені результати теоретичних і експериментальних досліджень збудження електромагнітних коливань в пучково-плазмових системах, які проводились в ННЦ ХФТІ. Досліджені електродинаміка плазмонаповнених уповільнюючих структур, нелінійна стадія взаємодії з ними пучків і механізми стохастизації. Описані деякі експериментальні стенди і приведені отримані на них потужність, ккд і спектри.