Recent Progress in Understanding the Physics of Plasma-Filled, High-Power Microwave Sources

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Abstract. The use of plasmas for generating high-power microwaves is studied for more than 50 years. During the 1990's Plasma-Assisted Slow-wave Oscillators (PASOTRONs) were invented and actively developed at Hughes Research Lab (HRL). These devices have a number of unique and attractive features. However, the experiments at HRL showed that to explore these features a better understanding of the physics is necessary. The present paper is focused on the recent studies of various physical issues, which are important for the pasotron operation. This theoretical and experimental activity resulted in more than doubling the pasotron efficiency (from about 20\% to more than 50\%) in the experiments carried out at the University of Maryland.

INTRODUCTION

Here we will not attempt to describe a long history of the development of plasma-filled microwave sources, which was recently overviewed in Ref. 1. Let us mention only that during the 1990's two new promising concepts of plasma-filled microwave devices were suggested and successfully realized. The first concept is based on the use of hybrid modes [2], which can be formed in plasma-filled slow-wave structures (SWS) by superposition of the plasma waves and slow waves of the SWS. These two sorts of waves become coupled when their phase velocities are synchronized and also their transverse structures overlap. The use of this concept has led to substantial increase in the gain and bandwidth of coupled-cavity traveling-wave tubes [3].

The second concept was suggested and pursued at Hughes Research Lab, where the devices named PASOTRONs (this acronym stands for Plasma-Assisted Slow-wave Oscillators) were invented [4] and successfully developed [5]. Pasotrons are unique devices, in which the electron beam propagation through the interaction space is provided not by solenoids or magnets, as in conventional microwave tubes, but by ions, which compensate for the radial beam space charge force, and thus, cause the effect known as a Bennett pinch [6]. The absence of the guiding magnetic field makes a number of interesting effects possible in PASOTRONs. Just these effects, which were studied recently at the University of Maryland, will be considered below.
Initially, an electron beam propagates in a neutral gas, where it diverges radially due to a non-compensated electric space charge field. The beam impact ionization creates a plasma in this gas. Then, the beam expels plasma electrons while the ions neutralize the beam space charge field, thus causing the beam pinching. Clearly, this process, at least in its initial stage, is an inherently non-stationary process. Moreover, this process is a self-consistent process, because the gas ionization depends on the radial profile of the beam, while, in turn, the beam profile depends on the presence of ions.

In principle, the ions oscillate in both the radial and axial directions in the potential well formed by the beam space charge field, when this field is not fully compensated. The estimates show that for typical parameters of PASOTRON’s the frequency of ion transverse oscillations is on the order of 1 MHz (we assume that the volume is filled with the helium only), while the frequency of ion axial oscillations is much lower and also the gas ionization proceeds in a much slower time scale (on the order of 10 sec). Therefore, one can treat ion transverse oscillations as relatively fast, and therefore, consider a slow evolution of the beam envelope in the presence of ions with the stationary transverse profile of the density. This evolution, in turn, depends on the relation between the ionization time and the period of ion axial oscillations.

A. Fast Ionization

When the ionization time is much smaller than the period of ion axial oscillations the ion axial motion can be neglected. (Indeed, in such a case the accumulation of ions destroys the potential well faster than the ions pass from one of its walls to another.) In this case the ion density in a given cross-section of the device is determined by the local ionization rate, which is important when the initial gas density distribution along the device axis is nonuniform. As a result, the beam envelope equation can be written as

\[
\frac{d^2 \rho}{d \xi^2} = \frac{F(k\tau)}{\rho} [1 - \gamma^2 (k + C) \tau] + \frac{T}{\rho^3} \tag{1}
\]

Here a number of normalized parameters is introduced: \( \rho = a(z)/a(0) \) is the beam envelope radius \( a(z) \) normalized to its value at the entrance, \( \xi = \sqrt{2 I_e/I_A} (1/\gamma \beta) [z/a(0)] \) is the normalized axial coordinate, \( I_e/I_A \) is the ratio of the beam current to the Alfvén current, \( I_A = (mc^2/e) \gamma \beta \), \( \gamma \) is the electron Lorentz factor, \( \gamma = 1/\sqrt{1 - \beta^2} \) and \( \beta \) is the initial axial velocity of electrons normalized to the speed of light. Also, in Eq. (1) the function \( \eta = n_z(\xi)/n_z(0) \) describes the initial axial profile of the gas density for the gas (He) leaking from the gas-filled, plasma electron gun and \( C = (\sigma_h/\sigma_{He}) [n_{0,h}/n_{0,He}(0)] \) is the coefficient, which takes into account the presence of an additional background gas (Ar or Xe), (here \( \sigma \)’s are corresponding
ionization cross-sections and the index "b" designates the background gas). The function $F(kr)$ models the beam current ramp-up during the time $t_{\text{rise}}$, $I_b = F(t)I_b$, with $F(t) = t/t_{\text{rise}}$ for $t < t_{\text{rise}}$ and $F(t) = 1$ otherwise. Here $\tau = t/t_{\text{ion}}(0)$ is the time normalized to the ionization time for the gas density at the entrance, $t_{\text{ion}}(0) = 1/\sigma_{\perp}n_0(0)$, and correspondingly, $k = t_{\text{ion}}(0)/t_{\text{rise}}$. Finally, the last term in the right-hand side of Eq. (1) describes the effect of a spread in transverse velocities. Here, parameter $T = \gamma^2 \beta^2 (I_a/2I_b) < \alpha_0^2 >$, where $\alpha_0 = \beta_{\perp}/\beta_{\parallel}$, is the transverse-to-axial velocity ratio at the entrance, is proportional to $\varepsilon^2$, where $\varepsilon$ is the beam emittance.

This equation was studied for the exponentially decaying gas density profile, $n(\xi) = \exp(-\xi/L)$, in the presence or absence of the background gas and in the presence or absence of the initial transverse velocities of electrons. In a beam with a finite emittance, the stationary profile of the envelope, as is shown in Fig. 1, exhibits axial pulsations. The beam reaches this stationary state in a time scale on the order of the ionization time for the gas density near the entrance. Note that the position of the first focal plane shown in Fig. 1 agrees well with the results of the analysis of the stationary beam envelope equation presented in Ref. 8.

**B. Slow Ionization**

In the limiting case of a slow ionization $t_{\text{ion}} >> t_f$, the ions make a large number of axial oscillations during the ionization time. So, not only transverse but also axial profiles of the ion density become stationary during the ionization processes. When the gas density profile is practically constant, the ion axial motion does not play a big role in the beam pinching, as is shown in Fig. 2a, where the "fast" and "slow" ionization results are shown by the solid and dashed lines, respectively, for $L = 50$.

Here (a), (b), (c) and (d) show the temporal beam radius evolution at different cross-sections of $\xi = 2, 4, 6$ and 8, respectively. On the contrary, in the case of gas localiza-

![FIGURE 1. Onset of a stationary profile of the beam with a finite "temperature," T=0.05, in the absence of an additional background gas.](https://example.com/figure1.png)
FIGURE 2. Beam pinching in the cases of fast (solid lines) and slow (dashed lines) ionizations: (a) $L=50$, (b) $L=1.0$. The cases a, b, c and d in each figure correspond to the cross-sections located in $\xi = 2, 4, 6$ and 8, respectively.

Axial ion motion near the entrance, which is shown in Fig. 2b for $L=1.0$, this axial ion motion is important, because it results in much faster beam pinching.

Also an intermediate case, $t_{\text{ion}} \sim t_{\text{in}}$, when the ions are described by kinetic equation for the ion distribution function $F = F(v_1)$,

$$\frac{\partial F}{\partial t} + \frac{\partial}{\partial z} (Fv_1) - \frac{e}{M} \frac{\partial \phi_0}{\partial z} \frac{\partial F}{\partial v_1} = S(z,t),$$

has been studied. Here $\phi_0$ is the potential describing the profile of the potential well responsible for ion axial oscillations and $S$ is the ion source term, which is associated with the beam impact ionization, i.e., it depends on the electron beam parameters. Of course, the beam potential, in turn, depends on the ion density. Some results of the study of such a self-consistent problem are shown in Fig. 3, where the ion density per unit length, $N_i = \int_{-\infty}^{\infty} Fdv_1$, is shown as the function of the normalized axial coordinate, $\xi$, and time, $t$. The filaments shown in Fig. 3 can be interpreted as the axial acceleration of ions.
ELECTRON 3-D MOTION IN THE INTERACTION SPACE

The ion focusing of an electron beam, which was discussed above, takes place in the absence of RF generation. However, since there is no strong guiding external magnetic field, in the presence of RF, the radial electric field of the wave may initiate the radial motion of electrons. This radial motion may enhance the wave excitation, because in the source term $\langle j\vec{E} \rangle$ describing the wave excitation (here angular brackets denote the averaging over the cross-section of the device), in addition to the term $j_z E_z^*$, which is the standard source term for the case of 1D-motion of electrons, also the term $j_y E_y^*$ appears. In particular, this term, as it was mentioned in Ref. 9, can be responsible for experimentally observed excitation of TE-waves [10].

The dispersion equation for such TWTs and BWOs, in which electrons can exhibit a 3-D motion, was derived a long time ago by Pierce [11]. In the variables normalized to the Pierce gain parameter $C$ this equation can be written as

$$\gamma^2 (\gamma - \delta) + 1 + q = 0,$$

(3)

where $\gamma$ is the wave propagation constant, $\delta$ is the detuning between the wave phase velocity and initial electron velocity and $q$ is in additional term responsible for the transverse interaction. It is obvious from Eq. (3), that this term increases the wave growth rate, and hence, can either increase the total gain in the device of a given length, or, alternatively, allows one to shorten the interaction length while realizing the same gain. This is the result of the small-signal analysis.
The large-signal theory was developed, in general, in Ref. 9, where it was shown that the radial motion of electrons at some detunings $\delta$ leads to the beam interception by a slow wave structure just at the instant when the field amplitude reaches its maximum. At the same time, at larger detunings the interception occurs later, which makes it possible to realize a high-efficiency operation without beam interception.

The efficiency enhancement was studied later in more detail in two subsequent papers [12,13]. In Ref. 12 the effect of the additional weak external magnetic field was analyzed. The theoretical analysis showed that an addition of a weak external magnetic field allows one to simultaneously enhance the interaction efficiency and avoid the beam interception by a slow-wave structure. For the parameters of the experimental PASOTRON-BWO which is currently under study at the University of Maryland, a corresponding magnetic field should not exceed 100G. This theoretical prediction was checked in the experiment [12], where it was shown that adding a 50G magnetic field causes the efficiency enhancement from 30% (at zero magnetic field) to 37%.

A more detailed analysis of the Helix PASOTRON-BWO efficiency was carried out in Ref. 13. The emphasis of this study was made on the role of the radial motion for electron coupling to the wave. Before presenting the results of this study, recall that the beam-wave interaction can be efficient when electrons are initially modulated by a weak RF field, and then electron bunches are decelerated by a strong field. In the BWO with a 1-D electron motion and a well-matched output, the situation is quite opposite: the RF field has the maximum at the beam entrance and equals zero at the beam exit. Therefore, a typical interaction efficiency in BWOs ranges from 10% to 20%.

The radial motion of electrons can drastically change this situation, if electrons are initially injected near the axis of a tube. Recall that the field of any slow wave is localized near the SWS and exponentially decays with the departure from it. So, when electrons are initially injected near the device axis, they start interacting with the weak field. Then, moving radially under the action of the radial component of the electric field of the wave, they start experiencing the strong RF field, which causes their deceleration. So, the effective amplitude of the RF field acting upon electrons moving both axially and radially may have an axial profile much more favorable for efficient interaction than in the case of a 1-D motion.

These simple arguments have been confirmed in the simulations presented in Ref. 13. Some results of these simulations are shown in Fig. 4. Here trajectories of two groups of electrons are shown: those injected near the axis are well bunched and move radially without substantial radial spread. On the contrary, the electrons having a large initial radius (1.5 cm) experience a large spread of trajectories. Another example is shown in Fig. 5 where the efficiency of electrons initially injected inside and outside of the helix are shown. As one can see, the efficiency of the first group exceeds the efficiency of the second group by more than two times. These preliminary steps resulted in simulations of the efficiency at the 55% level for the helix PASOTRON-BWO with an initially small beam radius. A corresponding dependence of the efficiency on the axial coordinate is shown in Fig. 6.
FIGURE 4. The radial trajectories of electrons with the different rays corresponding to different entrance phases for some selected beamlets. The operating frequency is \( f = 1.26 \) GHz, beam current \( I_b = 21 \) Amp, beam voltage is 40 kV, and initial beam radius is 1.5 cm. The power in the backward direction at the beam entrance is about 1.5 MW. Electron beamlet entered close to the axis experiences small radial spread, while that entered away from the axis experiences large spread.

FIGURE 5. Electrons efficiency depends on their initial radial position in the beam. Electrons inside the helix have higher efficiency than those outside the helix.
FIGURE 6. Electron efficiency of a beam with a small initial radius ($R_{0} = 1.5$ cm). Parameters are the same as in Fig. 4.

In accordance with these theoretical predictions some modifications in the PASOTRON tube were made. First, the plasma gun grid diameter was reduced from 8 cm to 4 cm, thus reducing the initial beam radius. Also, an adjustable upstream reflector was added to the waveguide arm leading to a matching load for controlling the $Q$-factors of competing axial modes. (Note that some issues in the competition of these modes were analyzed in Ref. 14.) So, the $Q$-factor of the desired mode was optimized for efficiency operation, while $Q$-factors of parasitic modes were simultaneously reduced.

These two modifications resulted in more than 50% efficiency operation at the 0.5 MW power level. This result is illustrated by Fig. 7, where the efficiency and power are shown as the functions of the cathode current. This experiment is described in more detail in Ref. 15.
FIGURE 7. Pasotron power and efficiency as functions of the cathode current.

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REFERENCES