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A Plasma Assisted MegaWatt Class Microwave Source with an Output of 1kJ per Pulse

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14. ABSTRACT

The Air Force requires lightweight, compact sources of high-power high-frequency radiation for numerous applications in communications, radar, ECM, and directed-energy weapons (DEW). This effort will be a satellite effort under the "Microwave Power Research Initiative (MiPRI)" program that addresses important research issues that impact directly on both the high-power microwave (HPM) and microwave vacuum electronics (MVE) R&D thrusts within the DOD. The goal of the proposed basic research is to study and understand the physics of the "Plasma Assisted Slow-wave Oscillator (PASOtron). That HPM device concept, originally proposed by Schumacher at the Hughes Research Labs in the late 1980s, holds exceptional promise for a future high efficiency, low cost HPM system of the future. Before progress toward prototype development can move forward, however, the fundamental physics of the device concept must be thoroughly mastered.

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Objectives

Plasma-loaded microwave devices have the potential to advance the technological and scientific base of microwave sources for Air Force applications, and also to have an impact on commercial and industrial applications through the development of transferable, commercially viable technologies. The thrust of this research program is to improve the understanding of physics issues in the operation of the Pasotron, and to exploit this knowledge for improving the Pasotron's performance. The Pasotron is a Megawatt-class microwave source capable of simultaneously producing high power (Megawatts), high efficiency, very low noise and good frequency stability.

The scientific efforts during this reporting period, July 2007 to April 2008, were focused on:

(a) Experimental studies of spectral control
(b) Theoretical studies- phase locking & ion noise

Status of effort and accomplishments

(a) Experimental studies of spectral control

This effort is focused on experimental studies of the spectral broadening in the pasotron operating in various regimes:

1) High power (~1MW), high Q operation: Single mode (90% of power is radiated in one mode- see Fig 1), as well as mode hopping (90% of power is split about equally between 2 modes - see Fig 2) were demonstrated

2) Medium power (~0.25MW), low Q operation: Spectral broadening (~10%) was demonstrated in the regime of large voltage droop (see Fig. 3)

These results can be beneficial for ECM and other applications requiring spectral control.

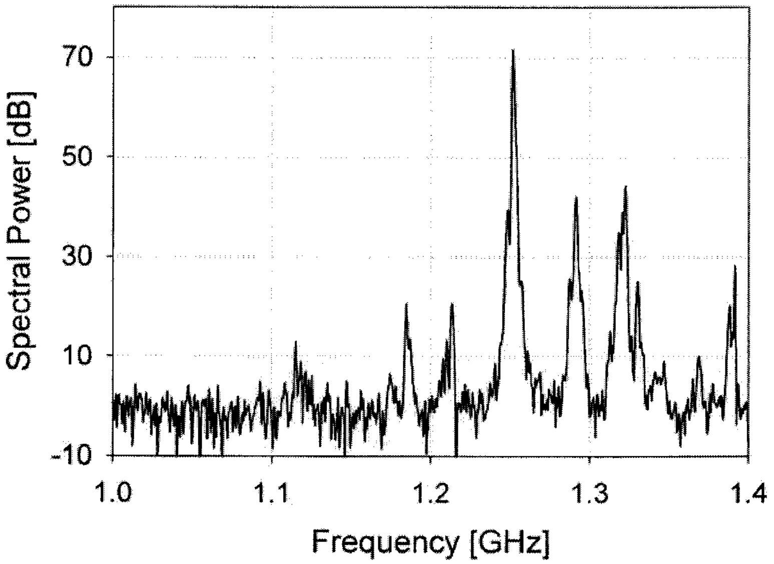

Figure 1: Single mode operation (18 Turns Shorted Helix, 4cm plasma gun, 3cm aperture, V=50kV, J=40A, Reflector position = 17cm)

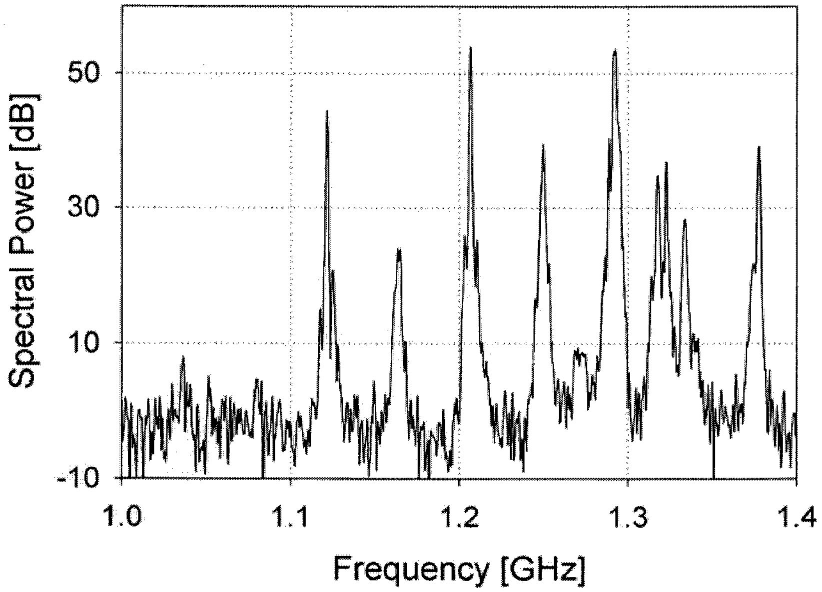

Figure 2: Mode Hopping (18 Turns Shorted Helix, 4cm plasma gun, 3cm aperture, V=50kV, J=40A, #4 Reflector position = 15cm)

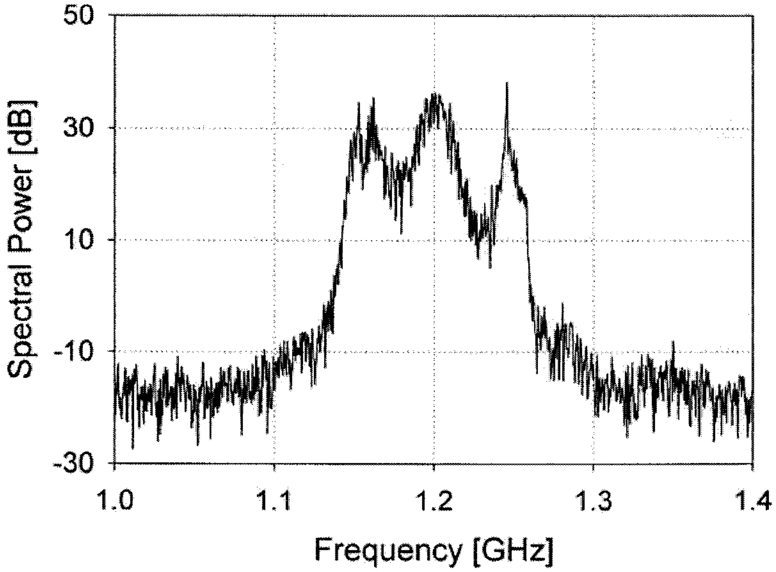

Figure 3: Spectral broadening (~10%) by using voltage droop. (Matched 18 turns helix. 1 capacitor, discharge resistor =78 Ohm #2, p = $1 \cdot 10^{-6}$ Torr, J=125 - 140A, U=46 – 29kV, Uo=57kV)

<u>(b) Theoretical studies</u>

These studies were done along two lines:

1) Phase-locking phenomena in the pasotron oscillator. Such phenomena are important for the phase control of pasotron outgoing radiation. To analyze the pasotron operation in the phase-locked regime it was assumed that for stable operation the main cavity of the pasotron has large end reflections providing rather high Q-factor. It was also assumed that there is an input cavity separated from the main cavity by the drift tube, and in this input cavity an electron beam is modulated by the drive signal. Then, prebunched beam excites oscillations in the main cavity. The locking bandwidth of such oscillations was calculated. Typical results are shown in Figure 4 where the locking bandwidth (normalized to the signal frequency) is shown (the locking region is designated by (b) in the figure) as the function of the bunching parameter proportional to the amplitude of the drive signal.

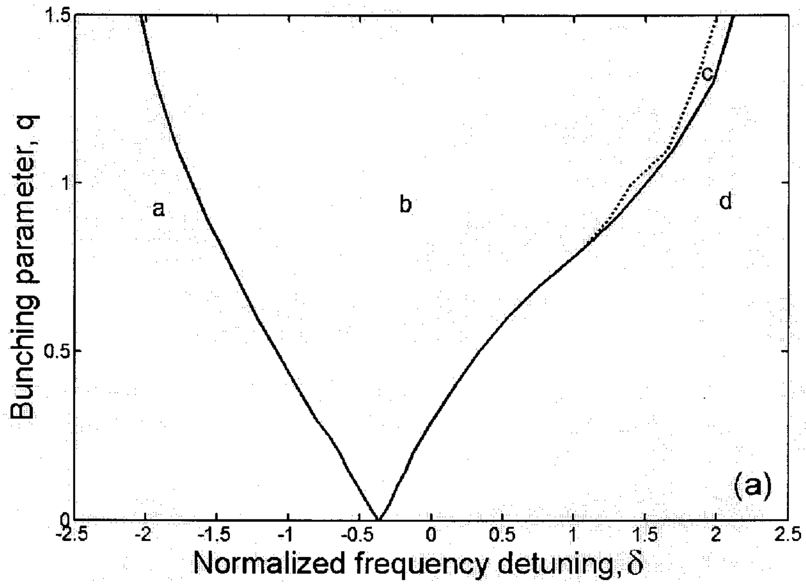

Fig. 4. Locking bandwidth of the pasotron oscillator having a cavity with strong end reflections.

Also some hysteresis phenomena were studied as well as non-stationary processes outside of the locking bandwidth. Typical non-stationary processes in the parameter region (designated by 'c' in Fig. 4) close to the locking bandwidth but outside of it are illustrated by Fig. 5 where each row corresponds to slightly different frequencies. These data show that the pasotron spectrum can be controlled by the drive frequency tuning.

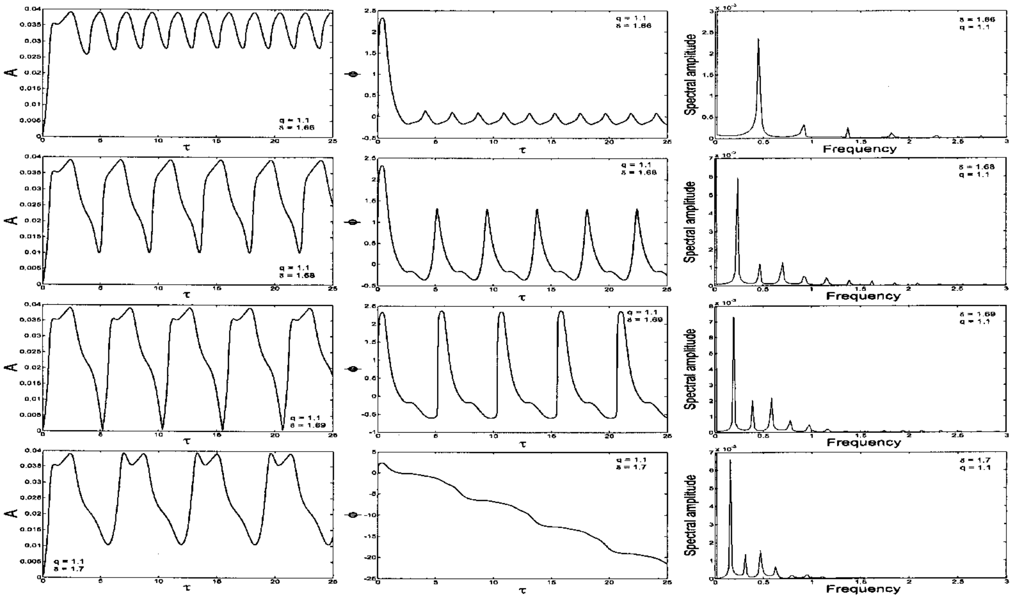

Fig. 5. Amplitudes, phases and spectra of oscillations.

2) Ion noise is an issue critical for performance of many plasma-assisted sources of microwaves. For a long time, it is recognized that ion oscillations play a negative role by widening the spectrum of outgoing radiation; more exactly, such oscillations with typical frequencies on the order of tens MHz cause appearance of sidebands about the wave carrier frequency. Therefore there was a feeling that the ion sidebands in pasotrons should be extremely intense and, hence, these devices should not be suitable for applications requiring a clean spectrum.

Experimental results (A. G. Shkvarunets et al., ICOPS-04, Baltimore, MD, Conf. Proc., p. 218), however, had showed that the level of such sidebands in pasotrons can be on the same order as in vacuum microwave tubes, viz., at -40-50 dBc level. A typical spectrum of pasotron radiation studied in these experiments is shown in Fig. 6 reproduced from A. Shkvarunets et al. One can see there ion sidebands at about -50 dBc level located at about +/-4 MHz on both sides from the carrier.

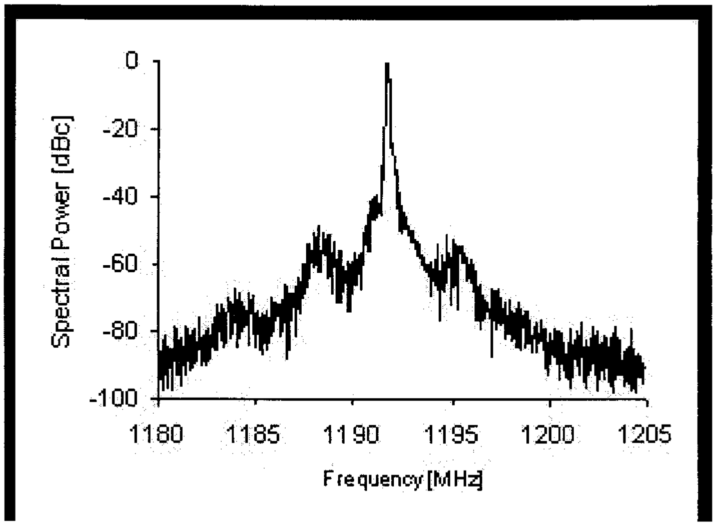

Fig. 6. Experimentally measured spectrum of the pasotron.

The theory explaining why the ions play such a small role in the pasotron radiation spectrum had been developed. This theory is based on a two-dimensional model of electron motion in the pasotron. Briefly, it was shown that the most important for the radiation spectrum are the variations of ion density in the space between the plasma gun and a narrow aperture installed at the entrance to the interaction space. These fluctuations cause fluctuations in the beam focusing by ions in the interaction space resulting in radial oscillations of beam electrons there. The radial oscillations, in turn, vary the beam coupling to slow waves localized in the vicinity of a slow-wave structure elements and, hence, in the power of electromagnetic radiation by electrons (also electrons can be intercepted by the walls when the amplitude of radial oscillations of electrons is large enough). A typical example of oscillations in the wave amplitude and a corresponding spectral intensity of ion noise is shown in Fig. 7 reproduced from Bliokh, Nusinovich et al (see Ref. 2 in the list of references below). The spectrum shown in Fig. 7b should be superimposed with the radiation linewidth determined by other sources of noise, which, in the region of 10-100 kHz off the carrier, falls as inverse frequency due to the flicker noise and then comes to the floor level at frequencies higher than 10-20 off the carrier. Such superposition results in the spectrum shown in Fig. 6. The theory also allows us to determine parameter space where the level of ion sidebands can be reduced.

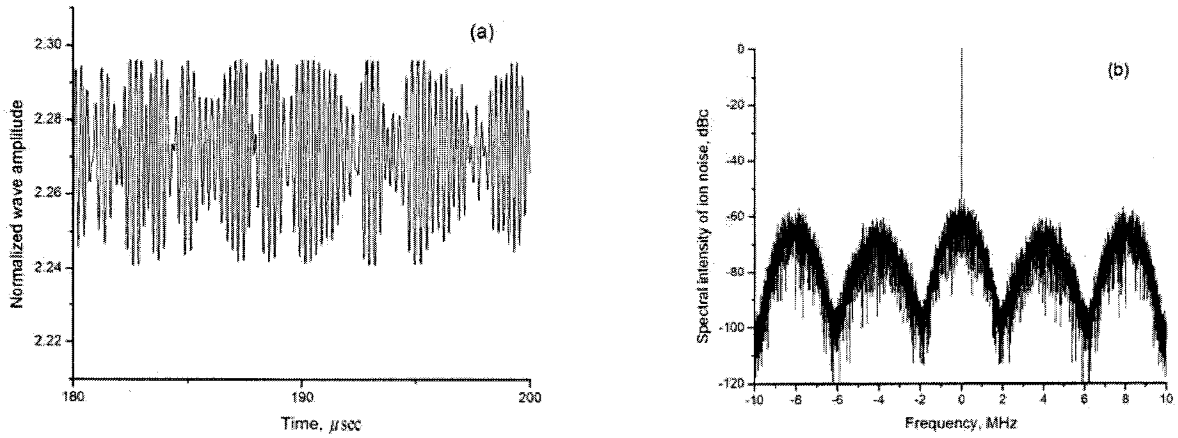

Fig. 7. (a) Sample of realization showing oscillations in the wave amplitude due to the ion noise; (b) corresponding spectrum.

3) Personnel supported

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Collaborators: Yu. P. Bliokh-Technion Israel Inst. of Technology, D. Goebel-JPL.

Journal publications

1) G. S. Nusinovich, O. V. Sinitsyn, J. Rodgers, A. G. Shkvarunets, and Y. Carmel, "Phase locking in backward-wave oscillators with strong end reflections", Physics of Plasmas, vol. 14, 053109, May 2007.

2) Y. P. Bliokh, G. S. Nusinovich, J. C. Rodgers, A. G. Shkvarunets, Y. Carmel and J. Felsteiner, "Ion noise in the plasma-assisted slow-wave oscillators", Special Issue of the IEEE Transactions on Plasma Science on High-Power Microwave Generation, vol. 36, pp. 701-709, June 2008.

Conference publications/interactions

1) G. S. Nusinovich, O. V. Sinitsyn, J. Rodgers, A. G. Shkvarunets, and Y. Carmel, "Phase locking in backward-wave oscillators with strong end reflections", 2007 IEEE Pulsed Power and Plasma Science Conference, Albuquerque, New Mexico, June 17-22, 2007, paper 6B5.

2) (Invited) J. Rodgers, A. Shkvarunets, Y. Carmel and G. S. Nusinovich, "Generation of kilojoule microwave pulses in a plasma assisted slow-wave oscillator," *Proc. IEEE Pulsed Power Plasma Sci., 2007*, Albuquerque, NM, 17-22 June 2007, pp. 1021, DOI 10.1109/PPPS.2007.4346327.

3) (Invited) J. Rodgers, M. Holloway, T. Firestone and V. L. Granatstein, "HPM Effects in Advanced Electronics," *Proc. 10th Annual 2007 Directed Energy Symposium*, Huntsville, AL, 5-8 November, 2007.

4) G. Nusinovich, J. Rodgers -advisors to NRL.

New patents disclosures: None