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14. ABSTRACT
The thrust of this research program was to improve the understanding of physics issues in the operation of the Pasotron, and to exploit this knowledge for improving the Pasotron's performance. Substantial improvement was demonstrated in all aspects of Pasotron performance. It is important to note that the Pasotron does not use guiding magnetic field, magnetic field power supply, filament or modulator that makes this device lightweight and, hence, suitable for airborne applications. The key to high power, high efficiency, pure spectrum operation is a controlled amount of plasma at the right location in the tube.

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PHYSICS AND OPTIMIZATION OF PASOTRON MICROWAVE SOURCES

AFOSR Grant Number F496200210060

Final report for the period ending December 2004

Submitted to

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Summary.

This is the final report for AFOSR Grant #F49620-0210060, entitled "Physics and Optimization of Pasotron Microwave Sources", covering the period to December 2004 (The previous report covered the period from July 2003 to July 2004).

The thrust of this research program was to improve the understanding of physics issues in the operation of the Pasotron, and ***to exploit this knowledge for improving the pasotron's performance.*** Substantial improvement was demonstrated in all aspects of pasotron performance. Some of the ***most significant accomplishments of this research program*** over the past three years were:

1) ***1.5 MW, long pulse (~100μsec)*** plasma-assisted pasotron was demonstrated, without pulse shortening.
2) ***High efficiency (~50%)*** operation was demonstrated, and even higher efficiency may be possible.
3) "Pure", vacuum-like noise characteristics ***(-105dBc)*** was demonstrated.
4) Output microwave energy of ***1kJ/pulse*** & beyond is within reach.
5) In depth theoretical understanding of the physics of plasma-loaded devices was developed.
6) It was shown that 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.

It is important to note that the pasotron do not use guiding magnetic field, magnetic field power supply, filament or modulator that makes this device lightweight and, hence, suitable for airborne applications. The key to high power, high efficiency, pure spectrum operation is a controlled amount of plasma at the right location within the tube.

An example of a long pulse operation of a MW-class pasotron exploiting the knowledge gained under this research program is shown in Fig. 1.

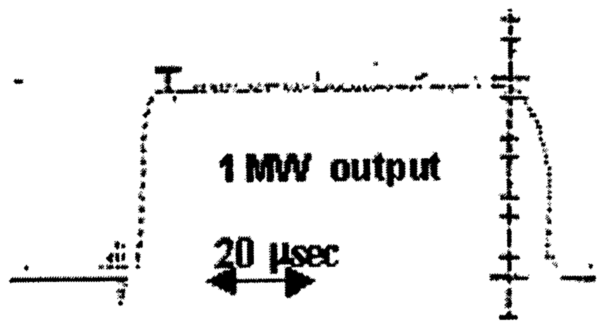

Fig. 1. Pulse shape of a 1.2GHz pasotron radiation

The contribution of this three-year research program to the remarkable improvement in efficiency of plasma-assisted microwave oscillators is demonstrated in Fig. 2. High efficiency (~50%) operation was demonstrated in a MW class pasotron and even higher efficiency may be possible.

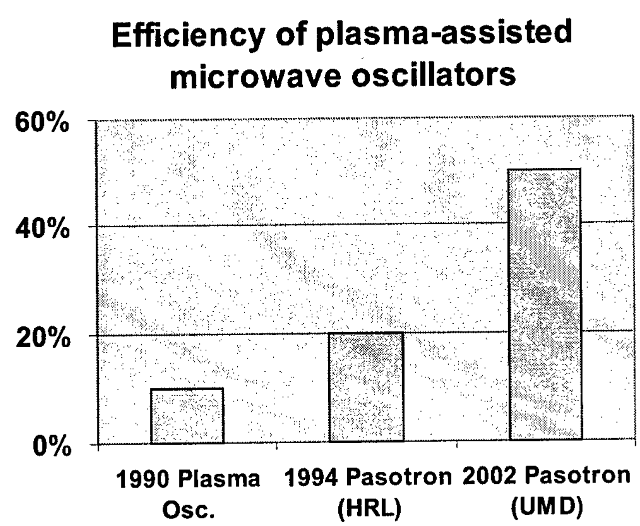

Fig. 2: The remarkable improvement in efficiency of plasma-assisted microwave oscillators over time.

The concept of plasmas inside microwave sources is sometimes treated with skepticism, as plasmas are non-linear, anisotropic, lossy, unstable and inhomogeneous media. Our recent results ***show that those concerns do not apply to the conditions of pasotron operation.*** A remarkably stable output frequency and amplitude were achieved. The measured power spectrum, which is shown in Fig. 3, demonstrates that the pasotron is capable of generating high power with spectral characteristics that compare favorably with vacuum microwave oscillators. Wideband noise is 105 dB below the carrier level at frequency offsets greater than ±30 MHz, and all spurious sidebands including the second harmonic are at least 50 dB below the carrier.

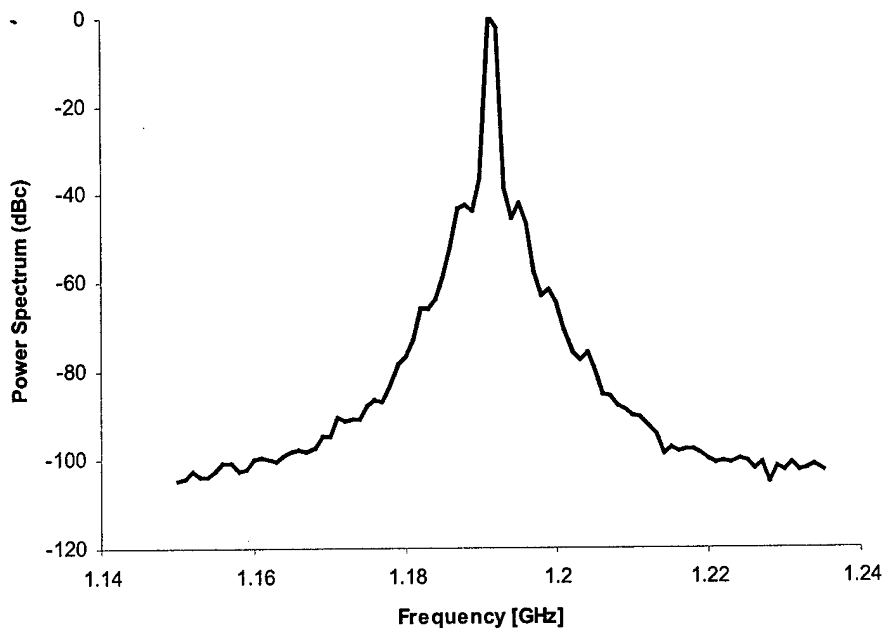

Fig. 3: Measured power (relative to carrier) versus frequency showing that the line width is narrow, wideband noise is more than 105 dB below the carrier, and, since the sideband powers roll off steeply, the carrier amplitude and phase have low noise characteristics.

One of the most important goals of this research program was to investigate the feasibility of achieving 1kJ of output microwave energy per pulse. We can now confidently say that this goal is within reach. The progress in this area over time is demonstrated in Table 1. The projected operating parameters of a 1kJ/ pulse advanced pasotron are given in Table 2. One can see that the projected parameters could be achieved with a modest increase in the already demonstrated operating voltage and beam current, and more substantial increase (X6) in pulse duration (from ~80μsec to 500μsec). While this is a challenging goal, based on our in-depth understanding of the physics of plasma loaded devices we are confident that the goal can be met.

Table 1: The progress towards a 1kJ/pulse pasotron

50 J/pulse in 2002

135 J/pulse in 2003

540J/pulse projected for 2005 (longer pulse power supply)

1080 J/pulse projected for 2006 (redesigned tube & higher voltage power supply)

Table 2: The projected operating parameters of a 1kJ/ pulse advanced pasotron

PARAMETER	VALUE
Power [MW]	2
Efficiency [%]	≥ 35
Beam current [A]	100
Beam voltage [kV]	60
Pulse duration [msec]	0.5
Operating frequency [GHz]	1.2
Repetition rate [Hz]	0.1

The experimental achievements briefly described above were supplemented with intense theoretical studies and PIC-simulations of the pasotron. Theoretical efforts were directed along two major lines: the theory of the electron beam focusing and transport and the theory of interaction between electrons propagating in the ion focused regime and backward electromagnetic waves excited in the backward-wave oscillator configuration of the pasotron.

The theory of the beam focusing and transport showed in the region between the plasma gun and the interaction space the beam changes its configuration from a quasi-laminar one in the vicinity of the gun to the phase-mixed configuration after the first focal plane. The beam focusing, at least, during the initial stage of the beam current pulse, is an inherently a non-stationary process, because at the beginning of the pulse, there is no plasma, but some neutral gas leaking from the gun. Then, the plasma appears due to the beam impact ionization of this gas, and the plasma ions provide the beam transport in a so-called Bennet-pinch regime. This ionization reaches its stationary level in a 10 microsecond scale; thus during this time first the beam focusing exhibits some non-stationary features. It was also shown that the formation of the phase-mixed beam configuration is associated with the appearance of a halo created by some electrons whose betatron oscillations have large amplitude. The use of a small local magnet in the region of the beam focus can greatly reduce and even practically eliminate this halo. The non-stationary features of the beam transport during the first stage of the pulse and the formation of the phase-mixed beam configuration were confirmed by PIC simulations performed by J. Verboncouer of UC, Berkeley.

The interaction between electrons propagating in the ion-focused regime and backward electromagnetic waves of a slow-wave structure was studied in the stationary and non-stationary regimes. It was shown that, since due to the absence of the guiding magnetic fields the beam electrons can exhibit in pasotrons a two-dimensional motion, the pasotron efficiency can greatly exceed the efficiency of conventional backward-wave oscillators, in which the electrons focused by strong solenoidal fields exhibit a one-dimensional motion. For realizing this efficiency enhancement, the beam should be injected into the interaction region near the device axis; from this point of view it is reasonable to position the entrance of the interaction space near the focal plane of the ion-focused beam. Then, the radial component of the electric field of the wave will deflect electrons outwards, hence forwarding them closer to the slow-wave structure where the RF field amplitude is much larger than on the axis. Correspondingly, the electrons initially modulated by a weak electric field on the device axis, then, being gathered into electron bunches can transform their energy into the energy of microwave oscillations efficiently interacting with the fields of large amplitudes. Just these theoretical arguments were successfully used in the experiments where more than 50% efficient pasotron operation has been demonstrated.

In summary, we can now confidently say that an output microwave energy of ***1kJ/pulse*** & beyond is within reach. 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. In addition, it is likely that the pasotron can be configured as a novel, unique ***high-power, wide-band chaotic source for advances EW applications.***

The pasotron research program received recognition in the form of multiple invited talks in national and international conferences, invited journal articles and a book chapter. These aspects, as well as educational aspects and industrial collaboration were described in details in previous progress reports and will not be duplicated here, with one exception. This topic was part of a recent Keynote Talk presented by V. Granatstein on January 23rd, 2005 at the 8th Israeli Conference on Plasma Science and Applications, ICPSA, ***("Symbiosis: Microwave Sources for Application to Plasmas and Plasma-Assisted Microwave Sources"***, V. Granatstein, Y. Carmel, G, Nusinovich).