PASOTRON™ HIGH-ENERGY MICROWAVE SOURCE*

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Abstract- We describe the operation and performance of a new high-energy microwave source called the PASOTRON, for Plasma-Assisted, Slow-wave Oscillator. Recently developed at Hughes Research Laboratories, the PASOTRON is a unique combination of a novel electron-gun and plasma-filled slow-wave structure which creates a source capable of generating 100 µsec-long rf pulses maintained at power levels of a few MW without the use of any magnetic focusing fields. A Hughes' hollow-cathode-plasma electron-gun is used to produce long, high-power beam pulses from which energy is efficiently extracted and converted into electromagnetic radiation. We present results which show rf output power is in the 1-to-5 MW range, for rf pulse lengths up to 120 µsec from a PASOTRON tube designed to operate in the C-band frequency range. The integrated rf energy per pulse is up to 500 J, and the electron-beam to microwave-radiation power-conversion efficiency is ~20%. Instantaneous bandwidth measurements confirm that for the long rf pulse duration, the PASOTRON's oscillation center frequency is maintained in a narrow line < 3 MHz.

I. INTRODUCTION

In recent years, a resurgence of interest in microwave tube technology has occurred in response to new requirements imposed on sources used for applications such as communication, radar, simulation of enhanced-electromagnetic pulse/interference effects, and directed-energy weapons. Efforts to fulfill these requirements, along with advances in electron beam generation has led to the development of new High-Power Microwave (HPM) versions of traditional microwave tubes. Recently, Hughes Research Laboratories reported[1] on the development of a unique HPM tube based on the operation of a Backward-Wave Oscillator (BWO). Called PASOTRON[2], for Plasma-Assisted, Slow-wave Oscillator, it integrates a novel electron gun and plasma-filled Slow-Wave Structure (SWS) as shown in the cut-away drawing of the Fig. 1, to generate and propagate long-duration, high-power beam pulses which require no magnetic focusing fields. These long, high-power beam pulses generate long (>100-µsec), high-power (>1 MW) rf pulses as energy from the electron beam is extracted and efficiently converted into electromagnetic radiation during the beam's transit through the SWS. Through the use of plasma-assisted beam production and transport, a simple, compact and lightweight source has demonstrated the ability to generate high-energy, rf-pulses.

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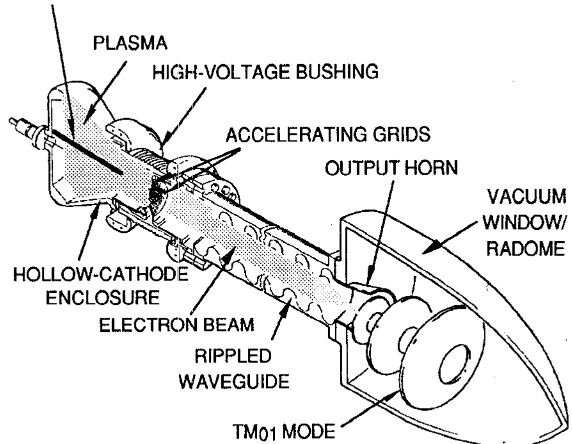

Fig. 1. Plasma-Assisted Slow-Wave Oscillator (PASOTRON) Apparatus.

In the following paper we describe the components of an experimental PASOTRON system and its fundamental operation. Results are reported from a series of experiments which employed a 150-to-250-A, 60-to-100-kV electron beam to drive a SWS designed for C-band operation. Spontaneously-generated rf power is shown to be 1-to-5 MW, for rf pulsewidths up to 120 µsecs achieved at a 0.2-Hz repetition rate. Calculations show that the total integrated energy per pulse was 300-to-500-J, and the electron beam to microwave-radiation conversion efficiency was ~20%. The fundamental mode of operation was found to be a TM_{01} mode, however, under certain beam voltage and current conditions, TE mode radiation was also observed. Frequency spectrum measurements show that for either mode the center frequency of the generated electromagnetic radiation is maintained in a narrow line of < 3 MHz.

II. EXPERIMENTAL APPARATUS

The PASOTRON experimental apparatus shown in Fig. 2. Long, high-power electron-beam pulses are obtained from a Hollow-Cathode-Plasma Electron-gun (HCP E-gun). The HCP E-gun overcomes the limitations of most HPM tubes which employ either thermionic cathodes that produce limited current-density beams, or field emission cathodes that offer high-current density but provide only short pulsewidths (<< 1 µsec) because of plasma closure of the accelerating gap. The

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HCP E-gun provides both high-current density (>50 A/cm^2) and long-pulse operation without gap closure by generating a controlled-plasma discharge which serves as the electron source. A low-pressure glow discharge generated inside the hollow cathode, produces a uniform and stable plasma front from which a high-current density beam is extracted. The anode of the discharge is the first grid of a high-perveance, multi-aperture electron accelerator. The plasma density in the hollow cathode and subsequently the beam current density, is controlled by a low-voltage (< 5 kV), discharge pulser. A dc high-voltage power supply accelerates electrons across the gap while the low-voltage discharge pulser modulates the beam current to generate arbitrary pulse waveforms. Bursts of multiple pulses and high pulse-repetition rates (up to 500 Hz) have been achieved with HCP E-guns.

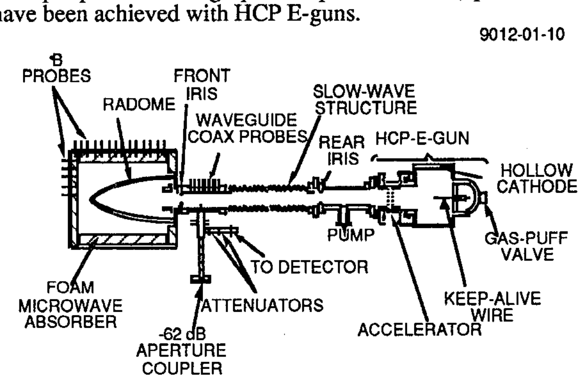

Fig. 2. Overview of experimental PASOTRON apparatus.

Electrons accelerated across the high-voltage gap are focused electrostatically by shaping electrodes and injected into a gas-filled waveguide. In most high-power, O-type microwave sources axially-directed magnetic fields are required to transport the high-current beams because electrostatic space-charge forces can lead to the rapid radial expansion of the beam diameter. In the PASOTRON, however radial space-charge forces responsible for beam expansion are eliminated by allowing the beam to ionize a low-pressure gas which typically consists of xenon at a pressure of 0.01 mTorr. In the absence of space-charge forces and an external-magnetic field, the beam's self-magnetic field causes the beam radius to compress. This process, graphically represented in Fig. 3, is commonly known as the Bennett Pinch Effect[3], and occurs when the beam self-generated azimuthal magnetic field pressure exceeds the beam thermal pressure.

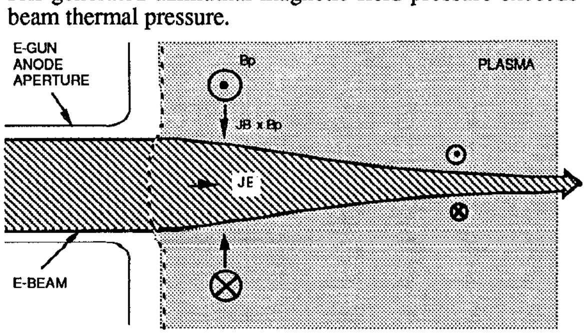

Fig. 3. Graphical representation of the Bennett Pinch effect.

The pinched, high-current-density electron beam travels through the plasma-filled drift section and enters the SWS. The SWS is composed of a hollow-cylindrical waveguide with a sinusoidally-varying wall radius. It provides a set of periodically-dispersive, electromagnetic-wave modes having regions in which the phase velocity is less than the speed of light. The plasma filling the SWS can influence the dispersive properties of these modes similar to the effect found in smooth-walled waveguides[4]. However, in the PASOTRON the background-plasma density did not significantly influence the dispersive characteristics of the waveguide modes. When an electron beam is introduced into the slow-wave structure, an energy source is provided that can drive an unstable interaction. This instability occurs when a normal mode of the structure, having positive energy, merges with the negative-energy, slow space-charge wave of the electron beam to form a resonant interaction that can be described with complex-conjugate solutions. This interaction can be seen in the numerically-generated dispersion curve[5] of Fig. 4 for a structure having average wall radius of 3.25 cm, a ripple depth of 0.715 cm and a period of 2.4 cm and driven by a 225-A, 90-kV electron beam. The linear growth rate of the instability, ω_i, is shown in the figure with the dashed line. It is in this narrow band of frequencies and wavenumbers that microwave generation is possible.

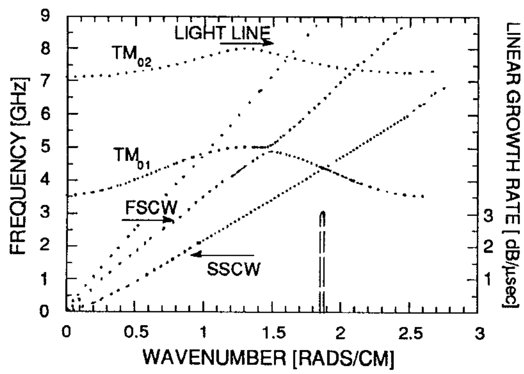

Fig. 4. Dispersion diagram of a beam-structure system where r_o= 3.25 cm, r_1=0.715 cm, z_o=2.4 cm, I_b=250 A, and V_b=90 kV. Represented are the electron beam's Fast Space-Charge Wave (FSCW), Slow Space-Charge Wave (SSCW), and the structure's TM_{01} and TM_{02} modes. The linear growth rate of the instability is shown with the dashed line.

In the dispersion diagram of Fig. 4, the intersection of the slow space-charge wave with the structure's TM_{01} mode occurs where the mode has a negative group velocity dw/dk<0. This results in a transfer of beam energy to the electromagnetic-wave field in a direction which is backward or anti-parallel to the beam velocity. Physically, if you were an observer viewing the structure's wave amplitude at any point along the device you would see it increasing exponentially in time. This is commonly called an absolute instability. In this system, no input rf signal is required for the instability to develop since it can grow out of electron beam noise and internal structure feedback. Slow-wave structures which generate microwave radiation in this manner are commonly called backward-wave oscillator.

The rf output of the PASOTRON is extracted from the downstream end of the device. By positioning a reflective iris upstream of the SWS, the reverse power of the wave generated by the oscillator is reflected and passes back through the structure to the output horn which is a slightly diverging section of cut-off C-band waveguide. Since the coupling between the pencil electron beam and the large diameter C-band SWS is weak, a second iris positioned downstream of the SWS was found to be useful for feedback enhancement which reduces the instability's development time. The microwave radiation is coupled out of the system through the radome and absorbed in a microwave load.

The rf signal exiting the SWS is monitored with a hole coupler having an average coupling coefficient of -62 dB in the frequency range of interest. The sampled signal from the coupler is further attenuated and either sent to a calibrated detector with its output viewed on an oscilloscope for peak power and pulsewidth measurements, or sent to a spectrum analyzer operated as a tuned receiver with its vertical output sent to an oscilloscope for frequency and bandwidth analysis. A set of E_r probes positioned downstream of the hole coupler are used for correlative power measurements and for determining the VSWR of the system. Since the presence of plasma in the system might influence the coupling coefficients of the rf probes, measurements were also taken outside of vacuum by radiating the rf signal into a small anechoic chamber. Twenty-four dB/dt loop probes are placed along the length of the microwave load to measure the pattern of the radiation.

III. EXPERIMENTAL RESULTS

Typical operation of the PASOTRON is characterized in Fig. 5 where the upper and lower traces represent respectively the voltage response of an electron-beam current monitor and a calibrated microwave detector monitoring the downstream hole coupler. In this example a 91-kV, 225-A electron beam having a 40-μsec pulsewidth was used to generate a 12-μsec- long rf pulse. The average rf power was 2 MW which gave an energy per rf pulse of 20 Joules. The frequency of the observed radiation was maintained within a 3 MHz line centered about 4.38 GHz. The long time delay between the injection of the electron beam and the observation of rf is due to the weak coupling between the small diameter electron beam and the large diameter C-band SWS. In this case no downstream iris was used to provide additional system feedback, thus a long-growth period is observed as the beam- structure instability slow develops to detectable rf levels. The fact that the rf pulsewidth is much shorter than the beam pulsewidth should not be confused with "pulse-shortening" characteristically found in HPM generators[6,7] and plasma-filled BWOs[8]. "Pulse-shortening" is used to describe the premature termination of an rf pulse in relation to the driving electron-beam pulse which continues to propagate. In the PASOTRON, once the rf signal is observed it remains at measurable levels until the end of the beam pulse. Thus the PASOTRON sincurrs some pulse-delay, but not pulse-shortening.

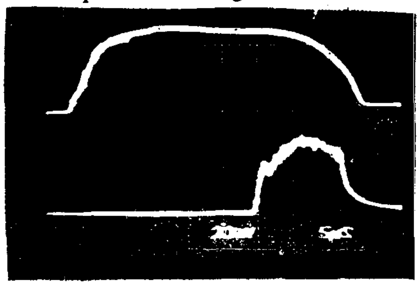

Fig.5. TM_{01} mode operation of PASOTRON.

Long-pulse operation of the PASOTRON is shown in Fig. 6 where the upper and lower traces represent respectively the voltage response of an electron-beam current monitor and a calibrated microwave detector monitoring an anechoic chamber probe. For this shot, a 130- μsec-long beam pulse was used to generate a 120-μsec-long rf pulse. The rf-power level varied from 3-to-5 MW over the course of the pulse, which gives an integrated power of 500 J/pulse, and the E-beam to microwave-radiation power conversion efficiency of about 20%. In this case a delay is still observed between the injection of the electron beam and the observation of rf, however the delay time was reduced through the addition of a partially-reflective downstream iris. We again observe that the duration of the rf pulse terminates with the beam pulse. The microwave power produced by the PASOTRON has a duration of about three orders-of-magnitude longer than conventional high-power BWO[9].

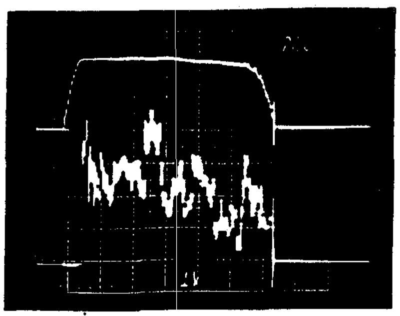

Fig. 6. Long pulse (120 μsec) output from the PASOTRON.

An interesting result, discovered during experimental investigations of the PASOTRON, is the device's ability to operate in either a TM or TE mode. The microwave power detected in Fig. 6 shows a highly-modulated amplitude suggesting the presence of multiple-frequency components. However, close examination of the frequency spectrum revealed that the center frequency was in fact maintained in a narrow band, typically less than 3 MHz, centered at a frequency of 5.42 GHz for the entire duration of the microwave pulse. This is shown in Fig. 7 where the upper trace is the beam current, the middle trace is the sidewall hole-coupler output, and the lower trace the narrow-band receiver output. This behavior is presently correlated with the generation of a TE mode in the SWS. As the polarization of the TE mode rotates in the system, the localized sidewall probe detects varying electric-field amplitudes thus the output signal appears highly modulated even through a single-frequency component is present. In this example the operation frequency of the PASOTRON was consistent with the excitation of a TE_{21} mode as shown in dispersion diagram of Fig. 8.

The excitation of TE mode radiation has previously been observed in magnetically confined BWO experiments[10,11], however its generation has always been attributed to excitation of beam-cyclotron waves. In the PASOTRON, no magnetic field is employed; thus the existence of cyclotron waves is not possible. It is postulated that the existence of this mode is attributed to a hydrodynamic beam-plasma instability associated with beam propagation in the ion-focused regime. Further investigations studying the motion of the electron beam and its stability during TE mode radiation are underway to understand the existence of this mode.

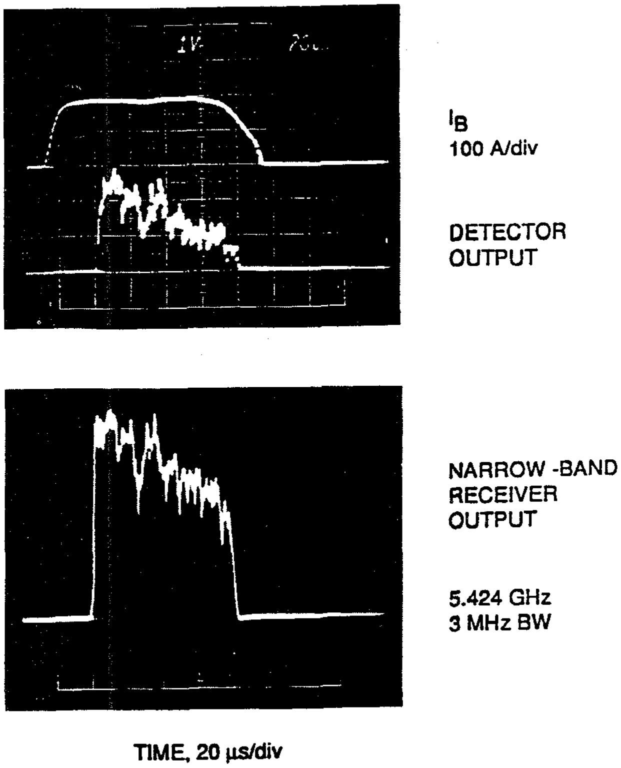

Fig. 7. Stable output frequency of 5.42 GHz with a 3 MHz bandwidth.

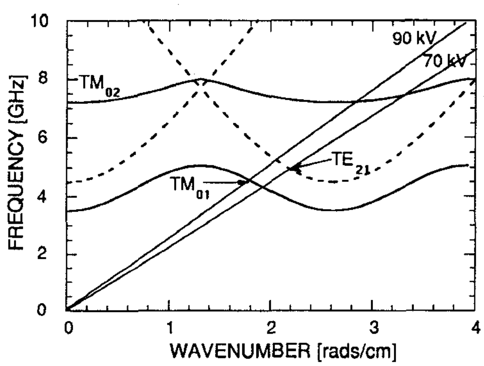

Fig. 8. Dispersion diagram estimating TM_{01} and TE_{21} mode resonances.

IV. CONCLUSION

The PASOTRON is a unique device which integrates a novel electron gun and plasma-filled SWS, to generate and propagate long, high-power beam pulses which require no magnetic focusing fields. These long, high-power electron-beam pulses generate long (100-µsec), high-power (1-to-5 MW) rf pulses as energy from the electron beam is extracted and efficiently (20%) converted into electromagnetic radiation during the beam's transit through the SWS. Through the use of plasma-assisted beam production and transport, a simple, compact and lightweight source has demonstrated the ability to generate high-energy, rf-pulses of 500 J/pulse.

V. REFERENCES

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