EXPERIMENTAL RESULTS OF CUSPTRON MICROWAVE TUBE STUDY+

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Summary

A cusptron microwave tube generates microwave radiation at high harmonics of the electron cyclotron frequency. This device utilizes the negative mass instability for the resonant interaction of an axis rotating electron beam and the modes in a conducting boundary with a multivane structure. A 17 kV, 3 μsec and 60 pps electron beam passed through a cusped magnetic field, produces radiation at the sixth and twelfth harmonic frequencies with the six and twelve vane structures, respectively. In the sixth harmonic case, the grazing condition is obtained at B = 250 G and approximately 500 W radiation is produced at 4.36 GHz. In the twelfth harmonic case, however, it is operated in a continuously tunable frequency range of 7.4 - 8.2 GHz in B = 210 - 220 G. The radiation power level is substantially reduced to few watts without the grazing condition satisfied. Since it is operated at high harmonic frequencies it holds promise as an efficient, compact, and tunable microwave tube suitable for many practical applications.

1. Introduction

Powerful microwave radiation has been observed, in the past, from axis rotating relativistic electron beams (E layer) in Astrons [1] for fusion plasma confinements and in Electron Ring Accelerators [2] for collective ion accelerations. The interacting mechanism between E layers and the modes of the conducting boundaries has been identified as the negative mass instability [3-5]. It induces uniform E layers to be azimuthally bunched, and the beam energy is thereby transferred to the wave energy. In most experiments with smooth conducting walls, the radiation spectra have shown many harmonic frequencies simultaneously, e.g., the harmonic numbers up to 40. Recently, the mode competition has been controlled by introducing a resonant circuit with multivanes similar to anode blocks in magnetrons [6].

In order to be a practical microwave device, however, it is necessary that the device can be operated at a lower beam energy in contrast to those previous experiments. A cusptron [7,8] uses a magnetic cusp field to produce a low energy rotating E layer and a multivane conductor to control mode competitions. Since it produces radiation at a high harmonic of the electron cyclotron frequency, it uses very low applied magnetic fields.

2. Description of Experimental Apparatus

The experimental setup and the magnetic field distribution at the beam radius are shown schematically in Fig. 1. The magnetic cusp field is produced by two independently controlled coils on the diode side and by a long solenoid on the downstream side. The cusp transition width is narrowed substantially by a soft iron plate placed between the coils. The transition length has been measured as 0.5 cm, which is determined by the FWHM of the radial magnetic field at the beam radius. The system vacuum is maintained by ion pumps at 2 - 5 x 10^{-7} Torr.

A hollow electron beam is produced from an annular thermionic cathode of 1.5 cm radius and 0.2 cm radial width with a Pierce-type focusing electrode.

+Work supported by the IR Fund at NSWC and by AFOSR at the University of Maryland.

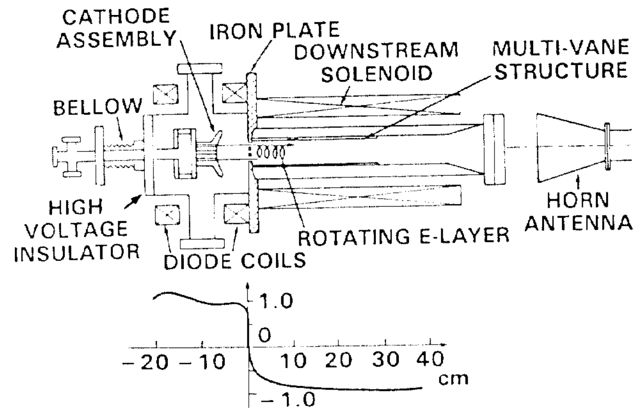

Fig. 1. Schematic of the cusptron experiment and the axial magnetic field distribution at r = 1.5 cm.

The cathode assembly is mounted on a bellows coupled pipe for its alignment and the cathode-anode gap can be adjusted without breaking system vacuum. An anode with an annular slit supported by three bridges is attached to the iron plate. A 0.2 cm wide annular slit allows the cylindrical beam to pass through the magnetic cusp transition region, where the (V_z x B_r) force converts effectively the beam axial velocity into the azimuthal velocity on the downstream side of the cusp transition.

Even though details of electron dynamics in a cusped magnetic field may be found in reference 9, it is worthwhile noting several important features of the electron orbits in order to understand the experiments:

i) There is a threshold energy level over which electrons pass through the cusp transition region and the beam radius is independent of beam energy in an ideal case.

ii) In a non-ideal cusp magnetic field, there is always a shift of the electron gyrocenter, called a coherent off centering. This results in an oscillation of the downstream beam envelope.

iii) The gyroradius is either compressed or expanded depending on the ratio of the magnetic field strength both sides.

iv) The canonical angular momentum spread, due to the finite cathode radial thickness, results in the axial momentum spread and the beam envelope broadening downstream.

These features have been experimentally confirmed prior to the radiation experiments.

The multivane conductor for the beam-wave interaction is placed immediately after the iron plate. The structure design is based on theoretical studies [8,10,11] for the resonant interaction between an E layer of 17 keV energy and the fundamental mode, 2π-mode, of the resonator. The dispersion relation of the 2π mode propagating in the z direction can be described as

$$\frac{\omega^2}{c^2} - k^2 - \frac{\eta^2}{R_a^2} = 0, \qquad (1)$$

where ω is the angular frequency, c is the speed of light, k is the axial wave number, η is a constant, and R_a is the inner radius of the vane structure.

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The cutoff frequency of the circuit $\omega_c = \eta C/R_a$ is a complicated function of the circuit geometry. However, one may expect that the dispersion relation in Eq. (1) would recover that of hollow cylindrical modes in the limit where the outer radius R_c approaches to the inner radius R_a. The physical parameters of the circuits are listed in Table I.

Table I. Circuit Parameters for the 2π Mode.

Harmonic Number	N = 6	N = 12
Inner Radius, cm	1.84	2.35
Outer Radius, cm	3.68	2.82
Circuit Length, cm	30.0	15.0
η	1.656	3.388
Cutoff Frequency, GHz	4.3	6.9
Beam Radius, cm	1.6	2.0

3. Sixth Harmonic Frequency Generation

The diode is operated at 17 kV, 3 μsec, 60 pps and the diode current is typically 1 ampere with the anode-cathode gap of 5.5 cm. The magnetic field near the cathode is fixed at 220 G and the downstream magnetic field is then continuously varied. Radiation is detected by a C-band (3.95 - 5.95 GHz) horn antenna located beyond the downstream viewport. The radiation power signal responds sharply only in a narrow region of the downstream magnetic field. Fig. 2 shows typical oscilloscope traces of the beam voltage, diode current, and detector signal. The radiation power is approximately 500 W as the maximum downstream field, shown in Fig. 1, is 400 G. The radiation frequency is 4.36 GHz from a nonstorage spectrum analyzer.

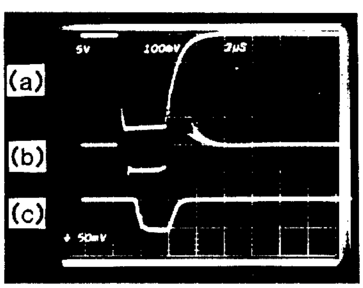

Fig. 2. Oscilloscope traces of (a) beam voltage (5 kV/div), (b) diode current (1 A/div), and (c) detector signal (100 mV/div).

Since the magnetic field distribution and the circuit dispersion relations are known, one can find the interaction location by analyzing the beam condition locally. Due to the slowly rising magnetic field distribution, there exists only one location where the waveguide mode and the beam mode intersect each other. Fig. 3 shows this analysis at z = 2.3 cm where the axial magnetic field is 250 G. It also shows that the grazing condition has been satisfied at the observed frequency.

4. Twelfth Harmonic Frequency Generation

The diode is also operated at 17 kV due to the limitation of the available high voltage modulator. In the circuit design, however, the beam radius is taken as 2.0 cm compared to 1.6 cm in the N = 6 experiment. An X-band (8.2 - 10.4 GHz, 6.5 GHz cut-off) horn antenna is located far beyond the viewport, typically, 86 cm. A storage spectrum analyzer has been used for the frequency detection. A typical trace of the spectrum analyzer is shown in Fig. 4 where the radiation frequency is 8.2 GHz.

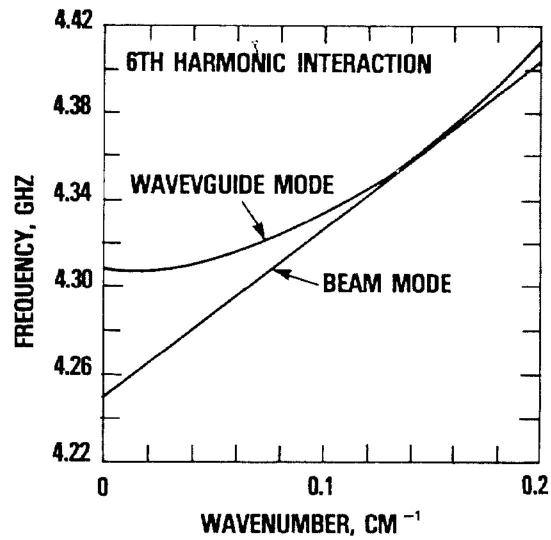

Fig. 3. Dispersion curves for the beam-wave interaction in the sixth harmonic frequency generation.

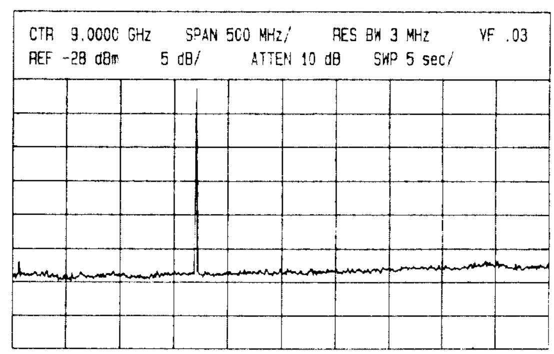

Fig. 4. A typical spectrum analyzer trace.

In contrast to the N = 6 case, the radiation signal is detected in a wide range of the magnetic fields both sides. The field compression ratio K, the maximum downstream value versus the upstream value, is between 1.02 and 1.32 as shown in Fig. 5. The lower limit is due to the envelope expansion of the coherent off centering and the upper limit is due to the fact that the envelope is too much compressed away from the resonator structure. One may note that the parameter $\alpha = V_\perp/V_\parallel$ is around 2.0. Fig. 6 shows that the tunable frequency range is 7.4 - 8.2 GHz and the microwave frequency depends only on the downstream magnetic field. The radiation power level is substantially reduced to about a few watts level. It can be understood from the analysis of the dispersion relation shown in Fig. 7 where the grazing condition is not satisfied and the magnetic field at the interaction location is 210-220 G.

The far field radiation pattern is also investigated by the x-band horn antenna. Radiation is circularly polarized and shows distinctive lobes. The radiation pattern is in good agreement with theory shown in the solid curve which is the radiation pattern of the TE_{01} circular mode from a pipe with radius 7.5 cm and frequency 7.6 GHz.

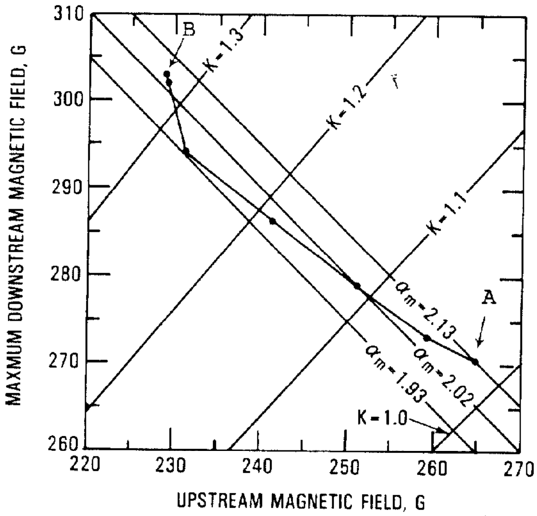

Fig. 5. Microwave radiation in magnetic fields both sides.

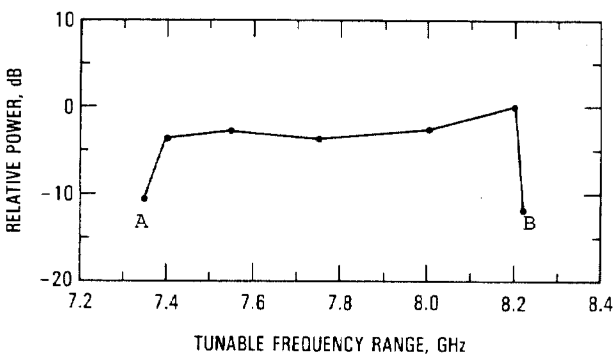

Fig. 6. Relative power of radiation in the tunable frequency range.

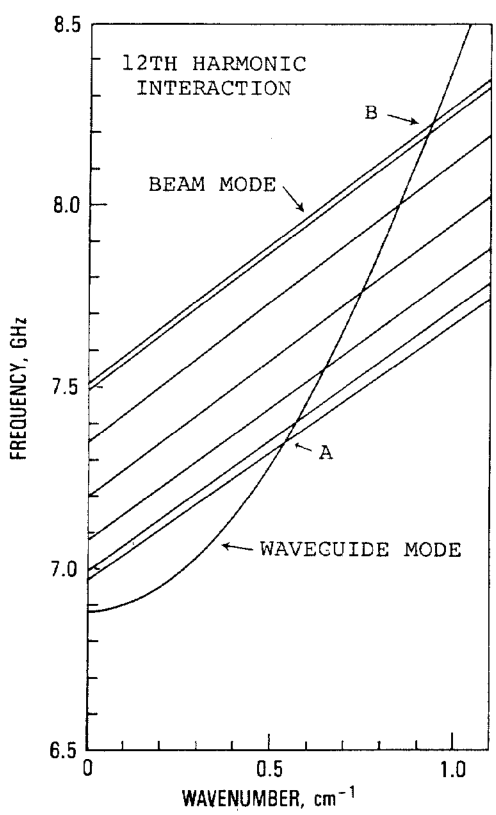

Fig. 7. Dispersion curves for the beam-wave interaction in the twelfth harmonic frequency generation.

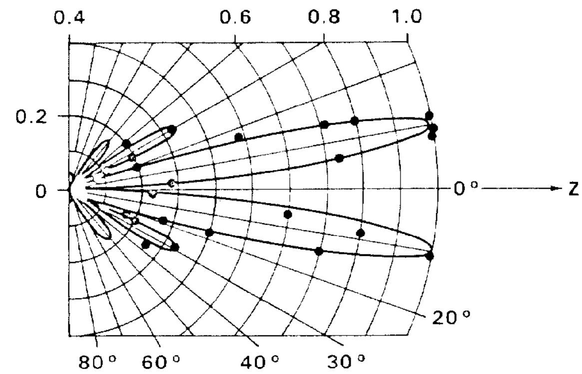

Fig. 8. Far field radiation pattern.

Acknowledgements

We are grateful for useful discussions with Drs. H. S. Uhm, M. J. Rhee, W. W. Destler, and W. Lawson.

5. Conclusions

About 500 W of microwave radiation at 4.36 GHz has been generated by the interaction of a rotating E layer with an N = 6 magnetron type conducting boundary. It is also shown that a tunable frequency range of 7.4 - 8.2 GHz in the N = 12 case. The diode is operated at 17 kV, 1.0 A, and 3 μsec, but the downstream current is measured as 0.2 - 0.4 A. This experiment has successfully demonstrated that high harmonic microwave can be generated from a cusptron device. This device holds promise as an efficient, compact, and also tunable microwave tube suitable for many applications.

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