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Summary

Computer modeling of the 32-GHz traveling-wave tube (TWT) for the Cassini Mission was conducted to explain the anomaly observed in the spectrum analysis of one of the flight-model tubes. The analysis indicated that the effect, manifested as a weak signal in the neighborhood of 35 GHz, was an intermodulation product of the 32-GHz drive signal with a 66.9-GHz oscillation induced by coupling to the second harmonic signal. The oscillation occurred only at low-radiofrequency (RF) drive power levels that are not expected during the Cassini Mission. The conclusion was that the anomaly was caused by a generic defect inadvertently incorporated in the geometric design of the slow-wave circuit and that it would not change as the TWT aged. The most probable effect of aging on tube performance would be a reduction in the electron beam current. The computer modeling indicated that although not likely to occur within the mission lifetime, a reduction in beam current would reduce or eliminate the anomaly but would do so at the cost of reduced RF output power.

Introduction

The development of the major components for Cassini involved the NASA Lewis Research Center, the Jet Propulsion Laboratory (JPL), and contractors Varian Associates and Hughes Electron Dynamics Division (HEDD). In January 1990, the TWT development began at Varian as a technology demonstration of Lewis advancements in computer-aided design with potential application to the Cassini Mission. In the fall of 1990, Lewis designed the slow-wave circuit and in early 1991, the multistage collector (ref. 1). Lewis also textured the copper collector electrodes to reduce secondary electron emission (ref. 2). The contract for the 32-GHz TWT (designated 955H) was novated to Hughes when it acquired the Varian space tube business in January 1991. In March 1992, the Jet Propulsion Laboratory requested that Lewis expand the goals of the technology program to deliver two flight-model TWT's and an engineering-qualification-model traveling-wave tube amplifier (TWTA) for the Cassini Mission. The two flight-model tubes, S/N 14 and S/N 16R, were completed in early 1994 and were delivered to bonded storage at HEDD in June 1994. The 955H production was terminated after the construction of S/N 16R; TWT S/N 14 was mated with a flight-model electronic power conditioner (EPC) and designated TWTA 1640H, S/N 101; TWT S/N 16R was installed in TWTA S/N 102.

In early summer 1995, JPL observed anomalies in the RF output power spectrum of TWTA S/N 102 (TWT S/N 16R) when it was operated in the range approximately 10 to 15 dB below saturated drive. (It should be emphasized that this operating point is well outside the mission operational envelope.) This anomaly is a spurious signal produced by S/N 16R at 34.87 GHz, which is 15.3 dB below carrier when driven at 32.03 GHz (B. Titlebaum, 1995, Jet Propulsion Laboratory, Pasadena, CA, private communication). A second spurious signal at 29.20 GHz is apparently a second-order intermodulation product; however, at 25 dB below carrier it is not a concern. As the drive frequency is increased, the separation between the two signals is reduced until they coincide at approximately 33.5 GHz. The spurious signal therefore appears to be an intermodulation product of the drive signal and an oscillation at 66.9 GHz (the sum of 32.03 and 34.87 GHz), which only manifests itself when the tube is driven between 10 and 15 dB below saturated drive. One final observation regarding this anomaly is that as the drive frequency is reduced below 32 GHz, the spurious signal at first increases in frequency and then vanishes abruptly.

The purpose of this report is to explain the cause of the spectrum anomaly at 34.87 GHz, to estimate how it would change as the TWT aged, and to determine whether the Ka-band flight experiments scheduled for Cassini would be in jeopardy. Computer modeling was used for the analysis because S/N 16R had been packaged for flight and only limited experimentation was possible.

Traveling-Wave Tube Design

The major design guideline for the 32-GHz TWT was to maximize single-carrier saturated efficiency within the mission power budget. The state of the art at the beginning of development was the 30-GHz TWTA manufactured by Watkins Johnson for the European Space Agency Olympus project. The Olympus TWTA had an RF output of 5 W and an overall efficiency of 14.7 percent (S. Feltham, Dec. 6, 1988, ESA/ESTEC, Noordwijk, The Netherlands, private communication). The original goal for the Cassini TWTA was 7 W of RF output power with a spacecraft power budget of 30 W. A breakthrough in computer modeling of the slow-wave circuit in the fall of 1990 enabled the Lewis designers to increase the predicted RF output power to 10 W, staying well within the 30-W power budget. In January 1991, the new slow-wave circuit was demonstrated experimentally at Varian in TWT S/N 04R.

As early as 1990, a nonlinearity in the power transfer curve for the 10-W slow-wave circuit was observed in computer predictions and in figure 1 is manifested as a change in the slope of the power transfer curve at approximately 10 dB below saturated drive. The computation presented in this figure was performed using the Detweiler TWT Code (ref. 3). All the TWT's after S/N 04R were manufactured by Hughes using the same 10-W slow-wave circuit design, and all exhibited to some extent the power transfer curve nonlinearity shown in figure 1. The additional 3 W of output power afforded by the new design was a welcomed development, and the nonlinearity in the power transfer curve did not at that time appear to have any relevance to the intended application as a single-carrier amplifier typically used in planetary programs.

The winding schedule of the helical slow-wave circuit for the 955H TWT is shown in figure 2. The circuit consists of input and output sections of helical tape separated by a physical break, called a sever, intended to prevent the TWT from oscillating. The center of the output section features a dynamic velocity taper (DVT) in which the pitch of the helix is reduced exponentially to improve the synchronism between the electromagnetic wave and the electron beam as it is slowed by the extraction of kinetic energy. The output section ends in a 0.3-in. run of untapered helix. This portion of the slow-wave circuit, named "the back porch" by designers, boosts the saturated RF output power of the 955H to 10 W.

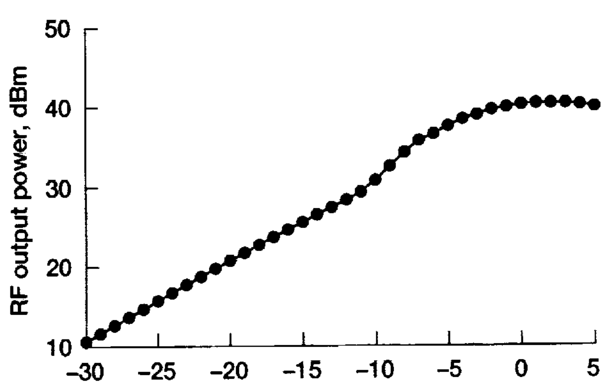

Figure 1.—Computed RF power transfer curve for 32-GHz Cassini TWT. (dBm is absolute power in decibels relative to 1 mW.)

The nonlinearity in figure 1 coincides with the upper end of the range of RF drive power that produces the spectrum anomaly; therefore, additional attention was given to the performance of the TWT in this regime. In figure 3, a computation of the RF output power developed at the end of the DVT is superimposed on the RF output power at the end of the back porch as shown previously in figure 1. The back porch actually reduces the RF output at lower levels of the RF drive, but it acts as a strong amplifier once the RF drive approaches the saturation level, resulting in the observed nonlinearity in the power transfer curve.

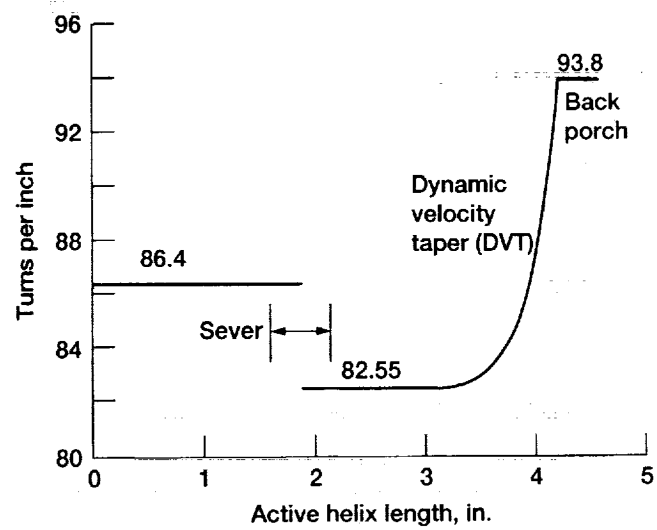

Figure 2.—Winding schedule of helical slow-wave circuit.

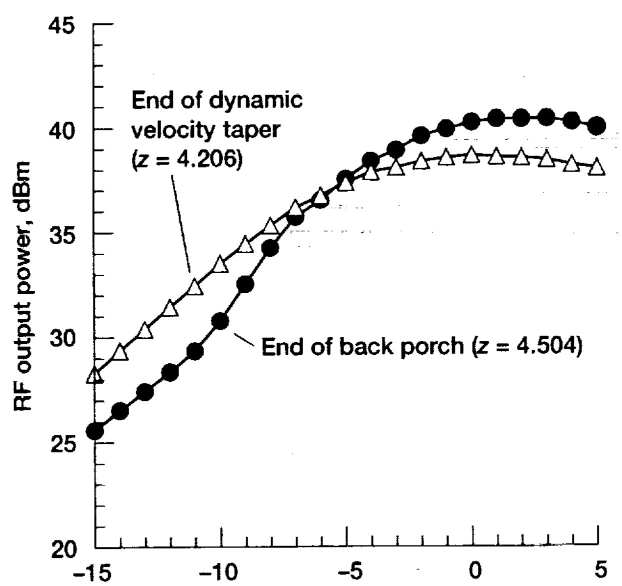

Figure 3.—Computed RF power transfer curves at end of dynamic velocity taper (DVT) and at end of back porch. (z designates position in inches on circuit of fig. 2.)

Second Harmonic Beam Current

Using the Detweiler Code, the peak fundamental and second harmonic currents on the electron beam were computed over a range of drive powers with the result shown in figure 4. When the ratio of the second harmonic current to the fundamental current is plotted, the ratio peaks sharply in the range of drive power between 10 and 15 dB below saturated drive, as shown in figure 5, coinciding with the range of drive power that induces the intermodulation effect. This computation was repeated at 31 GHz with the result that a pronounced peak in the ratio of the second harmonic current to the fundamental current was observed again as seen in figure 5. From these results, we surmised that the strong relative harmonic content of the electron beam in the relevant range of drive power may induce some second harmonic electromagnetic radiation on the slow-wave circuit. This second harmonic radiation may not be directly observable external to the tube, depending on the transmission properties of the output window.

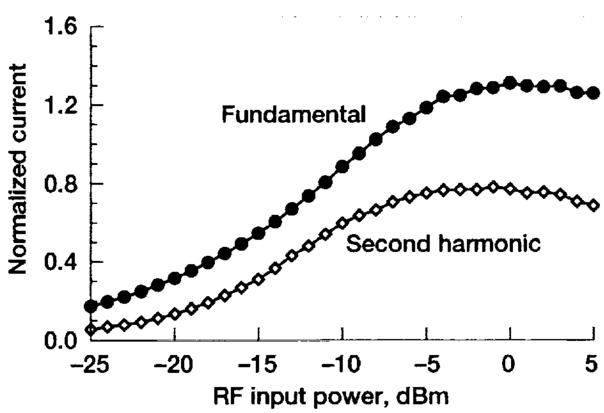

Figure 4.—Computed peak fundamental current and second harmonic current normalized to initial beam current.

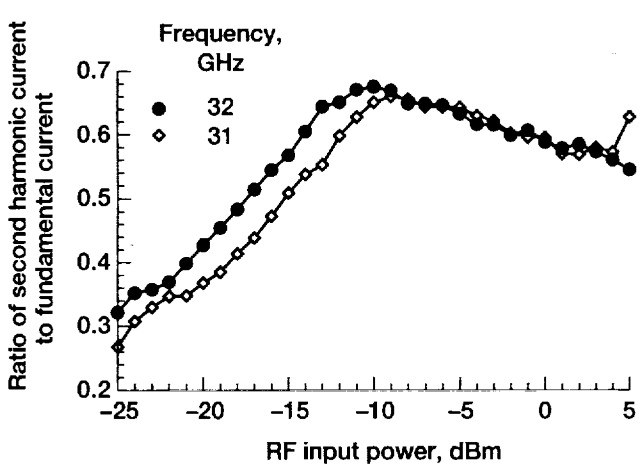

Figure 5.—Ratio of second harmonic current to fundamental current at 31 and 32 GHz.

Mode Diagram of 955H

The helical TWT has been the primary amplifier for high-frequency, high-power signals for over 50 years. However, until recent work at Lewis (refs. 4 to 6), it has been impossible to analyze a helical TWT using its exact dimensions because of its complex geometrical structure. The first accurately computed presentation of the dispersion relations of the fundamental amplifying ($n = 0$) and backward oscillating ($n = -1$) wave modes of a helical TWT ever produced is shown in figure 6 for the back porch section of the 955H. This computation was accomplished using the MAFIA code (the solution of MAxwell's equations by the Finite Integration Algorithm, ref. 7). The accuracy introduced by the MAFIA analysis can be illustrated by the crossing point of the fundamental and backward modes where the phase shift per helical turn equals 180°, which is defined as the "pi" point. The classical theory of the helical TWT predicts that the pi point will occur at 72 GHz, but the exact analysis shown in figure 6 indicates that the pi point is at 62 GHz. Also superimposed on the mode diagram is the phase velocity line for the operating voltage of S/N 16R, 5.076 kV. It can be seen from the expanded dispersion relations in figure 7 that the electron beam phase velocity line intersects the backward wave mode at 69.5 GHz.

If a backward wave oscillation (BWO) were to occur in the 955H, it would have to be in the back porch section of the tube because the tapered portion of the output circuit would disrupt the BWO and prevent it from propagating effectively. Indeed, this analysis indicates that if a BWO were to occur in the back porch, it would be at the approximate frequency observed. However, the oscillation was not observed to occur spontaneously, only under the conditions of reduced drive power described above.

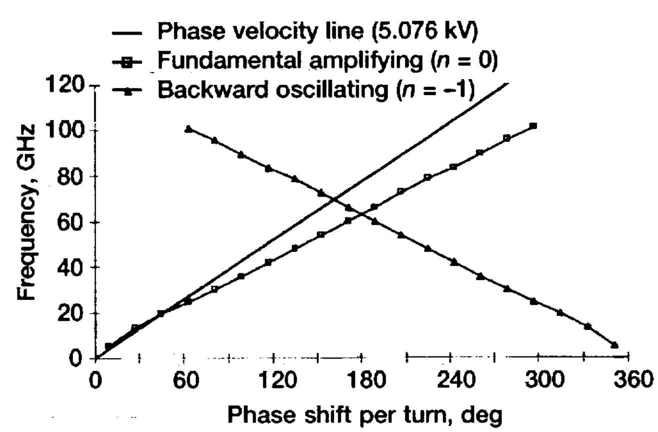

Figure 6.—Computed dispersion relations of fundamental amplifying ($n = 0$) and backward oscillating ($n = -1$) wave modes. Phase velocity line for operating voltage of 5.076 kV is superimposed.

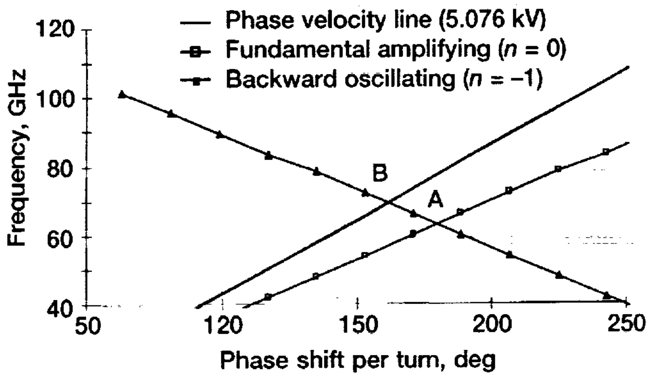

Figure 7.—Expanded computed dispersion relations.

Sympathetic Oscillations

The experimental observations of spurious intermodulation products described in the Introduction suggest the existence of a weak oscillation in the TWT at 66.9 GHz. The computer analysis of the mode diagram shown in figure 6 clearly shows that when the TWT is operated at rated voltage, the frequency of oscillation for the backward wave is in the vicinity of 66.9 GHz. However, the same analysis determined that the interaction with the electron beam is too weak to start an oscillation.

The 66.9-GHz signal is in evidence only under conditions in which a strong second harmonic current is present on the electron beam. The explanation that appears to fit all the experimental observations and computational results is that the 66.9-GHz signal is a sympathetic oscillation in the backward wave mode induced by the strong second harmonic current produced in the highly bunched electron beam created by the TWT at the drive levels 10 to 15 dB below saturated drive (fig. 5).

To illustrate the probable mechanism for the onset of the sympathetic oscillation, the region of interest in figure 6 was expanded as shown in figure 7. As power is extracted from the electron beam, some electrons slow down and are represented by load lines that fall to the right of the nominal 5.076-kV line. For example, for the nominal drive frequency of 32.5 GHz, the locus of second harmonic fields corresponding to these reduced-voltage load lines would fall along the 65-GHz line that intersects the backward mode line at point A (fig. 7). Second harmonic waves would induce an unstable backward wave oscillation that would lock into the nearby stable BWO operating point at B. The resulting 67-GHz signal mixes with the drive frequency to produce intermodulation products, one of which, the difference frequency, is the spurious signal near 35 GHz.

This explanation for the mechanism is supported by the fact that as the drive frequency is reduced, the spurious signals disappear abruptly. As seen in figure 5, the second harmonic current is still quite strong at 31 GHz, but it no longer excites the backward wave oscillation. In figure 7, note that when the drive frequency falls below 31 GHz, the locus of the 62-GHz second harmonic wave no longer intersects the backward wave line and no oscillation is therefore induced. Were this a typical backward wave oscillation, it would not be dependent on the drive frequency.

Impact on Cassini Mission

The spectrum anomaly described herein does not occur within the parameters of operation planned for the Cassini Mission. The question is whether the phenomenon will change during the life of the mission. The frequency of oscillation is determined by the TWT geometry, which cannot change, and by the cathode voltage, which can vary by 17 V according to the worst-case analysis (ref. 8). The intersection of the voltage phase velocity line and the mode line $n = -1$ varies by 0.55 GHz for a change of plus to minus 100 V in cathode voltage. Therefore, the frequency of the oscillation is expected to vary no more than 47 MHz during the mission.

Changes in the TWT current will affect the ratio of the second harmonic current to the fundamental current (fig. 8). Increasing the cathode current from 14 to 15 mA only slightly increases the computed peak value of this ratio while decreasing the current to 13 mA significantly decreases the peak value. It should be noted that an increase in current is practically

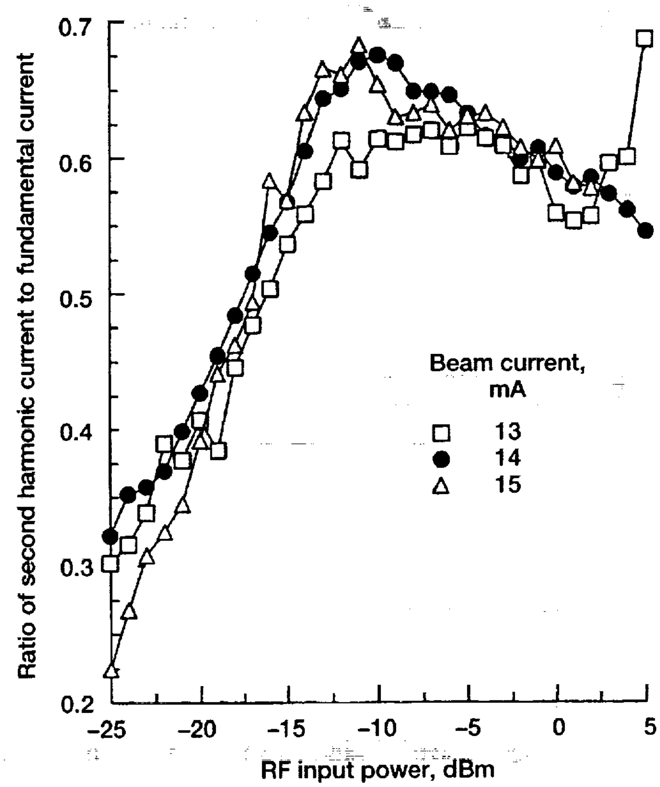

Figure 8.—Computed ratios of second harmonic current to fundamental current with beam currents of 13, 14, and 15 mA. Beam voltage, 5.255 kV.

inconceivable. A decrease in current may occur as the TWT nears the end of life, but the 955H has a design life of 12 yr and this condition is not expected during the mission either. The power transfer curves for the three cases of a 13-, 14-, and 15-mA beam current are shown in figure 9. Operation at 13 mA would result in the loss of about 2 dB in output power at saturation.

Changes in the cathode voltage will have a similar effect on the ratio of the second harmonic current to the fundamental current, as seen in figure 10. Increasing the cathode voltage by 100 V from 5.255 to 5.355 kV slightly increases the computed peak value of this ratio, while decreasing the voltage by 100 V significantly decreases the peak value. Voltage changes of this magnitude are outside the mission expectations, but a change of only 17 V would have a negligible effect.

Why S/N 16R?

The question that naturally arises is, Why should TWT S/N 16R, the TWT selected for flight on the Cassini Mission, be the only 955H exhibiting this spectrum anomaly? First, most of the 955H TWT's were not tested with the spectrum analyzer, so it is not known how many would produce this effect. Second, this effect is very weak and would not occur in routine measurements as would a typical BWO. The nonlinearity in the power transfer characteristic of the 955H was demonstrated (fig. 3) to be a function of the operation of the back porch at the fundamental frequency and cannot be construed as evidence of the existence of a 66.9-GHz oscillation. In fact, the Detweiler Code that was used to produce the power transfer curves presented in this report does not include a provision for the backward wave or for harmonic electromagnetic waves. However, it would appear from the computer analysis that any 955H might exhibit this effect.

If S/N 16R is the only TWT that produces the spectrum anomaly, it may be the result of the fabrication process, some variation in manufacturing tolerance, or its operational characteristics. All 955H TWT's produced after S/N 04R were virtually identical except for the attenuation applied to the dielectric support rods on either side of the sever (see fig. 2). This was changed from tube to tube in an attempt to adjust the gain and to make use of a fabrication process that was more familiar to the manufacturer. One of the functions of the attenuation is to suppress backward wave oscillations; therefore, the tubes in the series have varying stability margins. It must be pointed out that S/N 16R exhibits distinctly different operational characteristics from those of other 955H TWT's. The tube operates at a cathode current of 16.27 mA, 16 percent above nominal, and at a cathode voltage of 5.076 kV, 3.3 percent below nominal.

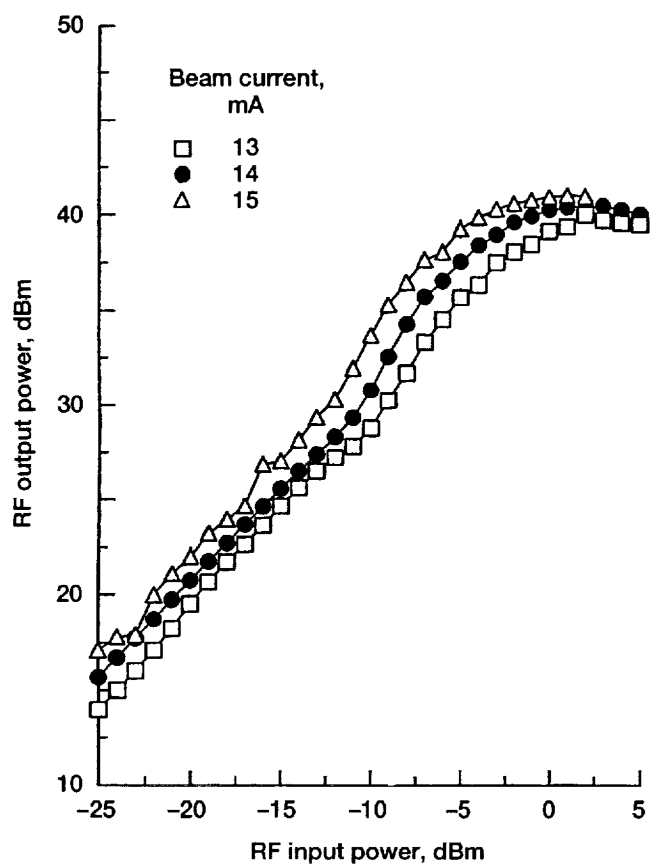

Figure 9.—Computed RF power transfer curves with beam currents of 13, 14, and 15 mA. Beam voltage, 5.255 kV.

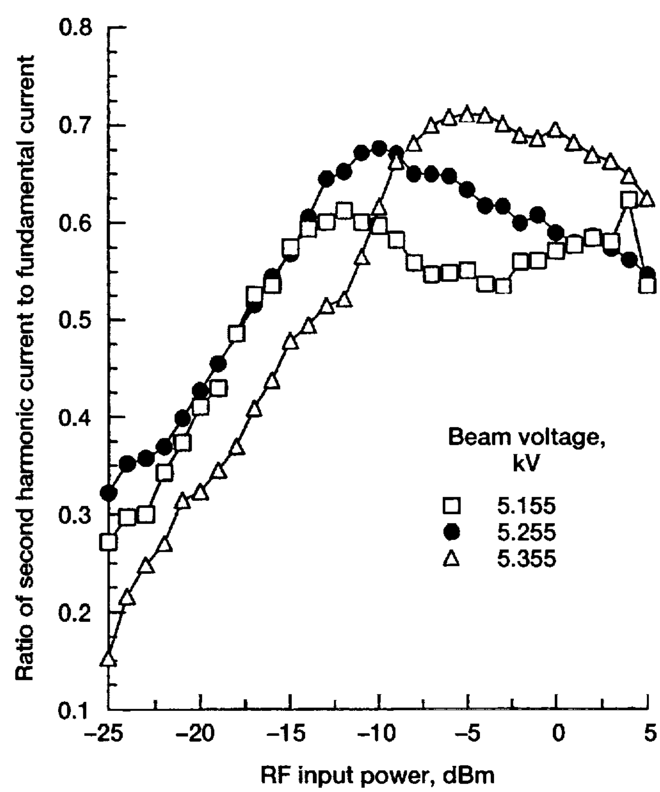

Figure 10.—Computed ratios of second harmonic current to fundamental current with beam voltages of 5.155, 5.255, and 5.355 kV. Beam current, 14 mA.

Conclusions

A spectrum anomaly was observed in one of the flight-model traveling-wave tubes (TWT) for the Cassini Mission. Because the two flight-model and the engineering-qualification-model 32-GHz TWT's had been mated with electronic power conditioners and packaged for flight before the anomaly was observed, it was virtually impossible to experiment with them to investigate the parameters of the anomaly. Fortunately, the problem could be studied by computer modeling. An explanation of the oscillation mechanism is presented in addition to predictions of the changes to be expected during the Cassini Mission. Note that some of the computer modeling techniques employed in this study were developed at the NASA Lewis Research Center beginning in 1996 and were not available for application to this problem when the tube was being designed in 1990 or when the anomaly was first discovered in 1995.

The results of this study indicated that the spectrum anomaly is the result of a weak sympathetic oscillation induced in the backward wave mode of operation by the strong second harmonic electron beam currents generated by the highly efficient slow-wave circuit when driven below saturation. The effect is not now observed within the range of parameters planned for use on the Cassini Mission, and the computer analysis indicates that it is not likely to change significantly during the mission. A worst-case analysis indicates that the frequency of the sympathetic backward wave oscillation will change by no more than 47 MHz during the mission. As the TWT beam current declines near the end of life, the spectrum anomaly may be expected to disappear; however, the TWT lifetime is expected to exceed the duration of the mission.

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13. ABSTRACT *(Maximum 200 words)*

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