Time-frequency analysis of modulation of high-power microwaves by electron-beam voltage fluctuations

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This paper applies a time-frequency analysis to the output signal from a coaxial gyrotron oscillator. It is shown that the voltage fluctuations on the diode can be directly correlated to the frequency modulation on the rf output. A simple analytic theory is constructed to explain this correlation. This technique, properly extended, is expected to open up a new way to investigate pulse shortening, mode competition, noise and unwanted frequencies in rf generation. [S1063-651X(98)11211-4]

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The most pressing issue in the generation of high-power microwaves (HPM) is pulse shortening, that is, the rf output pulse length is significantly less than the duration of the voltage pulse on the diode [1–3]. Depending on the HPM source, variations in the diode conditions due, for example, to an evolving plasma within the diode may lead to departure from the design values. Generation of HPM then ceases. While there are many scenarios being proposed for pulse shortening, most of which are drawn from speculations, few, if any, have been substantiated by a direct correlation between the diode voltage fluctuations and the rf output. Faced with the paucity of such a correlation, we initiated a time-frequency analysis of the output rf from a coaxial gyrotron [4]. The rf modulations were explicitly linked to the diode voltage fluctuations.

As is well known, from the (time-integrated) spectrum alone, it is virtually impossible to correlate the output signal with diode voltage fluctuations. Recently developed analyses, which permit the display of joint time-frequency spectra, naturally provide such a direct correlation [5–7]. Being essentially a ''real-time'' diagnostic, this powerful technique can also be applied to study noise, unwanted frequencies, and mode hopping in various rf sources. One simply takes a time-frequency analysis of the output signal, and correlates it with whatever factor (e.g., beam voltage or current fluctuation) that is suspected of being the contributing cause, as is done in this work.

To directly show the evolution of the rf in the presence of diode voltage fluctuations, we consider the rf output that is extracted from a coaxial gyrotron. The time-frequency analysis of this output signal shows that the frequency chirp in fact tracks the diode voltage. We provide a simple analytic theory, based on the beam-cyclotron mode, to explain this correlation.

The experimental configuration is depicted in Fig. 1. The electron beam is generated by MELBA (Michigan Electron Beam Accelerator [8]) at the following parameters: energy $=0.75$ MeV, $I(\text{tube})=100–300$ A, and pulse length from 0.5 to 1 μs. Cathode voltage is measured by a resistive divider across the insulating stack. The annular electron beam is generated from plasma flashover on a bare aluminum cathode; nonemitting regions are coated with insulating enamel (Glyptal). This electron beam is extracted through an annular aperture in a graphite anode; the anode-cathode gap is 11 cm.

The electron beam is run through a magnetic-cusp field reversal that occurs over 10 cm (-1.1 kG at diode up to $+3$ kG in the interaction cavity) to generate a large-orbit, axis-encircling electron beam [Fig. 1(a)]. The e-beam's perpendicular-to-parallel velocity ratio (α) is approximately unity [9]. The gyrotron's inner coaxial rod (6 mm diam) runs the full tube length from anode to output window. The microwave cavity (outer coaxial tube) has an inside diameter of 7.4 cm and a length of 26 cm. The gyrotron is operated in the TE_{11} coaxial mode. Microwave emission is directed into a large chamber lined with microwave absorber. An open-ended S-band waveguide collects microwave power, which is passed through a directional coupler into a coaxial cable.

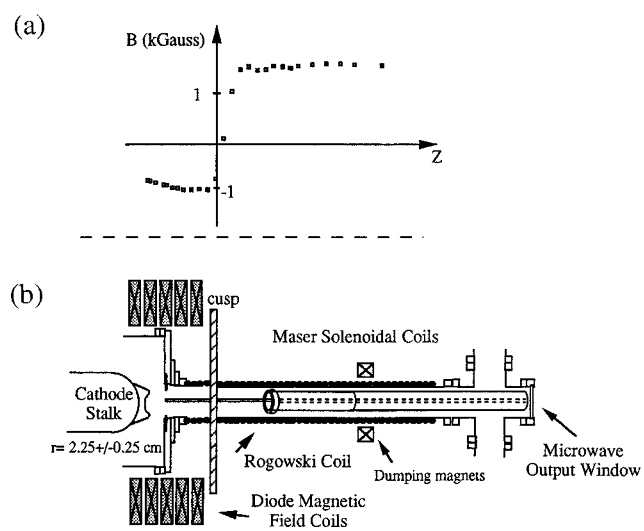

FIG. 1. Configuration of a coaxial, large-orbit gyrotron. (a) Typical axial magnetic-field profile as a function of axial distance z; (b) experimental schematic drawing.

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The coaxial cable transmits microwave signal to attenuators and a heterodyne mixer driven by a local oscillator located in a Faraday cage. The intermediate (beat) frequency signal from the mixer is input to a 2-GSa/s digital signal analyzer (Tektronix DSA602); for time synchronization, the cathode voltage signal is measured on the same signal analyzer.

The digitally stored intermediate frequency from the mixer is subjected to a time-frequency analysis [5,6]. Traditionally, joint time-frequency analyses have utilized the spectrogram. The spectrogram is derived from the magnitude-squared Fourier transform of a windowed portion of the signal being analyzed. The spectrogram has been a useful tool, but it suffers from a time-frequency uncertainty effect because of the analysis window [5]. More recently, joint time-frequency distributions, which avoid the spectrogram windowing effect, have been developed [5]. Reduced interference distributions (RID's) have been developed over a period of more than ten years at the University of Michigan [6,7]. The Wigner distribution, as known in quantum mechanics [5] provides a methodology for deriving effective joint time-frequency distributions, but suffers from cross terms or interference terms between time-frequency components. RID's retain the numerous desirable properties of Wigner distributions, but considerably reduce the troublesome cross terms [6,7]. Proper representation of group delay and instantaneous frequency along with high-resolution time-frequency representation are among the valuable RID properties that are particularly important to this study. The binomial time-frequency distribution [6] is an effective discrete form of RID for computational purposes, and for this reason it was used in the time-frequency analysis presented in this paper. These techniques are particularly effective in the analysis of nonstationary signals and have been applied to biological signals, radar, sonar, and other areas. We note that RID's do not theoretically require windowing to produce their results. Practically, however, finite-length data segments much longer than those commonly used in spectrograms are utilized, greatly reducing the time-frequency uncertainty effects observed with spectrograms.

The signal used for analysis is the heterodyne signal. Heterodyne detectors generate a signal in which the frequency is either an upshifted or a downshifted beat frequency between the incoming microwave and a local oscillator. The local oscillator is set at the frequency of 2.3 GHz. This frequency corresponds to the cutoff frequency of the TE_{11}mode in the coaxial waveguide, so the microwave frequency equals 2.3 GHz plus the upshifted beat frequency. Figure 2(a) is the actual output of a heterodyne signal. The time-frequency analysis of this signal is shown in Fig. 2(b). This figure clearly shows that there is significant frequency chirp from, for instance, 2.39 GHz (2.3 GHz+90 MHz) at $t=920$ ns to 2.51 GHz (2.3 GHz+210 MHz) at $t=960$ ns. To correlate this frequency chirp, we display in Fig. 2(c) the evolution of the diode voltage. A comparison of Figs. 2(b) and 2(c) shows that there is a definite correlation between the frequency modulation and the diode voltage variation—the microwave frequency drops when the diode voltage increases [i.e., becomes more negative in Fig. 2(c)]. This direct modulation of the frequency by the diode voltage fluctuations is readily interpreted [see below and Eq. (2)]. We have run many shots and similar correlations are unmistakable. We should add that the time axes in the microwave signals shown in Fig. 2 have taken into account the finite-group propagation time that is required for the rf to transport through the output waveguides and the transmission system. Typically, the time-frequency analysis of the heterodyne signal, such as that shown in Fig. 2(b), shows a shorter interval of HPM generation than the diode voltage pulse. Low-level rf signals (not shown) have been detected under certain conditions for almost the entire duration of the voltage pulse, however.

The color intensity shown in Fig. 2(b) is indicative of the power of the signal (red: higher power, yellow: lower power). By taking the maximum intensity at each time in Fig. 2(b), we obtain Fig. 2(d), which displays the power fluctuations. To verify these power fluctuations, we show in Fig. 2(e) an independent diode detector measurement of the microwave power generated by the coaxial gyrotron. Both Figs. 2(d) and 2(e) show three humps in the microwave power. The differences between these two figures are due to differences in the frequency response of the detectors and

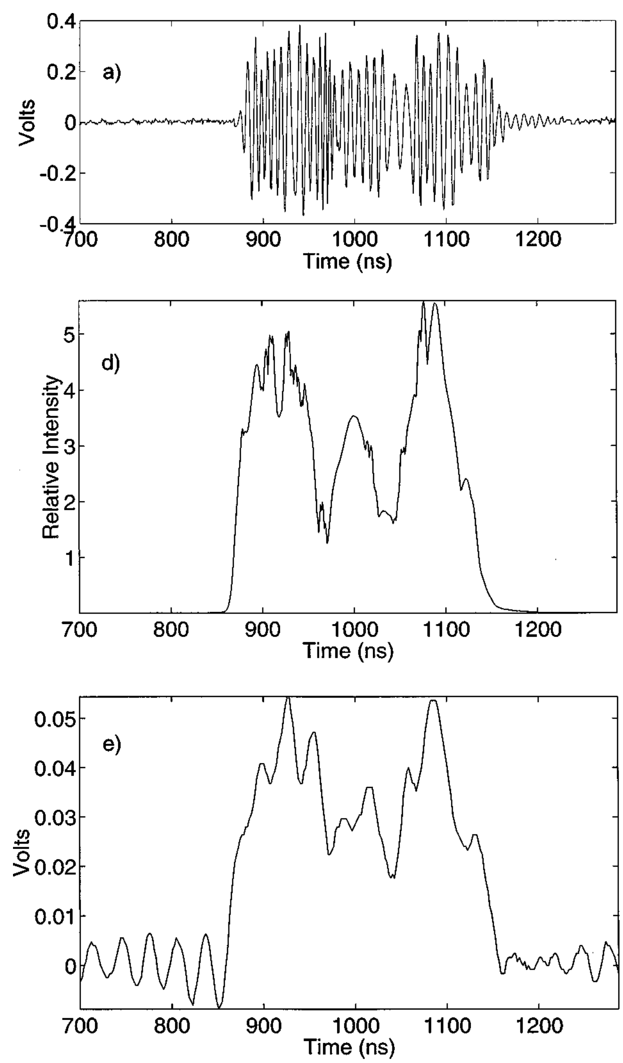
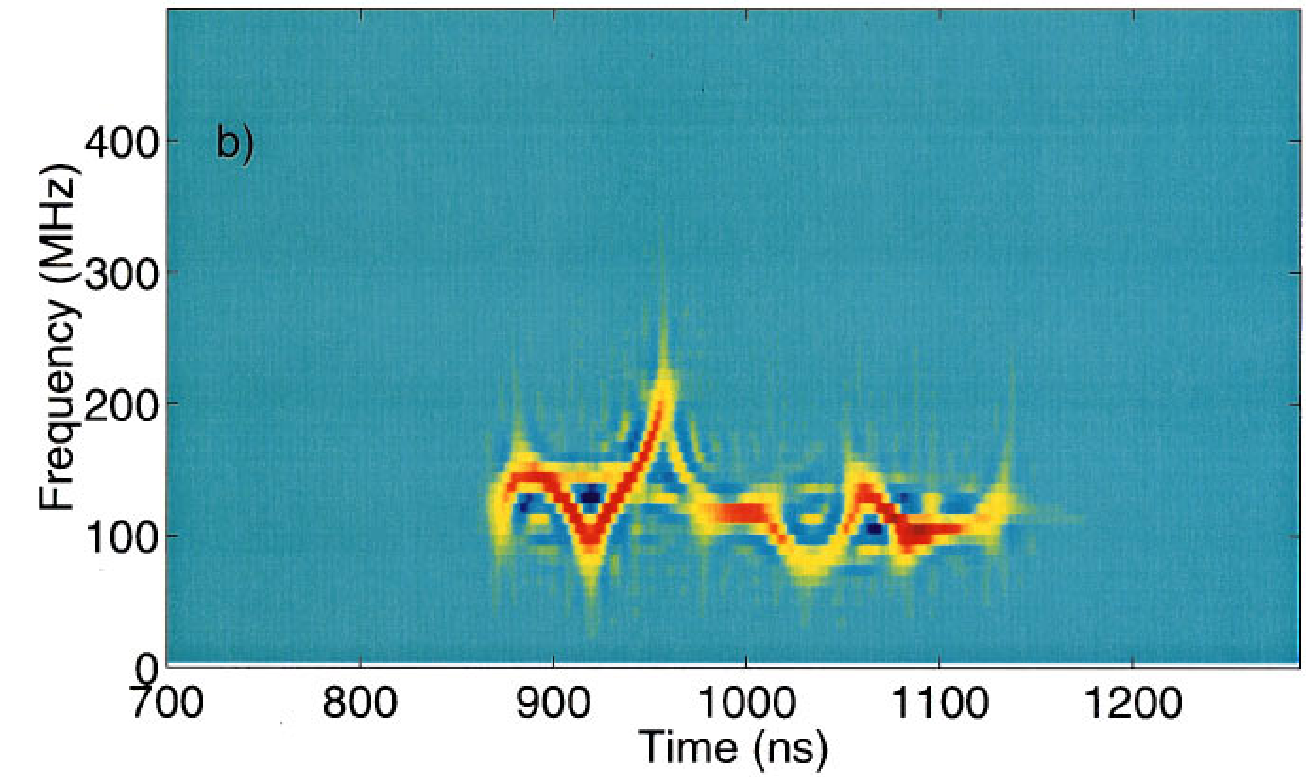


FIG. 2. Analysis of output microwaves from a coaxial gyrotron. (a) Heterodyne detector signal with the local oscillator set at 2.3 GHz. (b) (color) Joint time-frequency spectra from reduced interference distributions (RID) analysis: red is higher power, yellow is lower power. (c) (color) Cathode voltage signal. (d) Intensity from RID program. (e) Microwave diode detector signal; peak corresponds to 1.2 MW; smoothed by a 20-MHz low-pass filter.



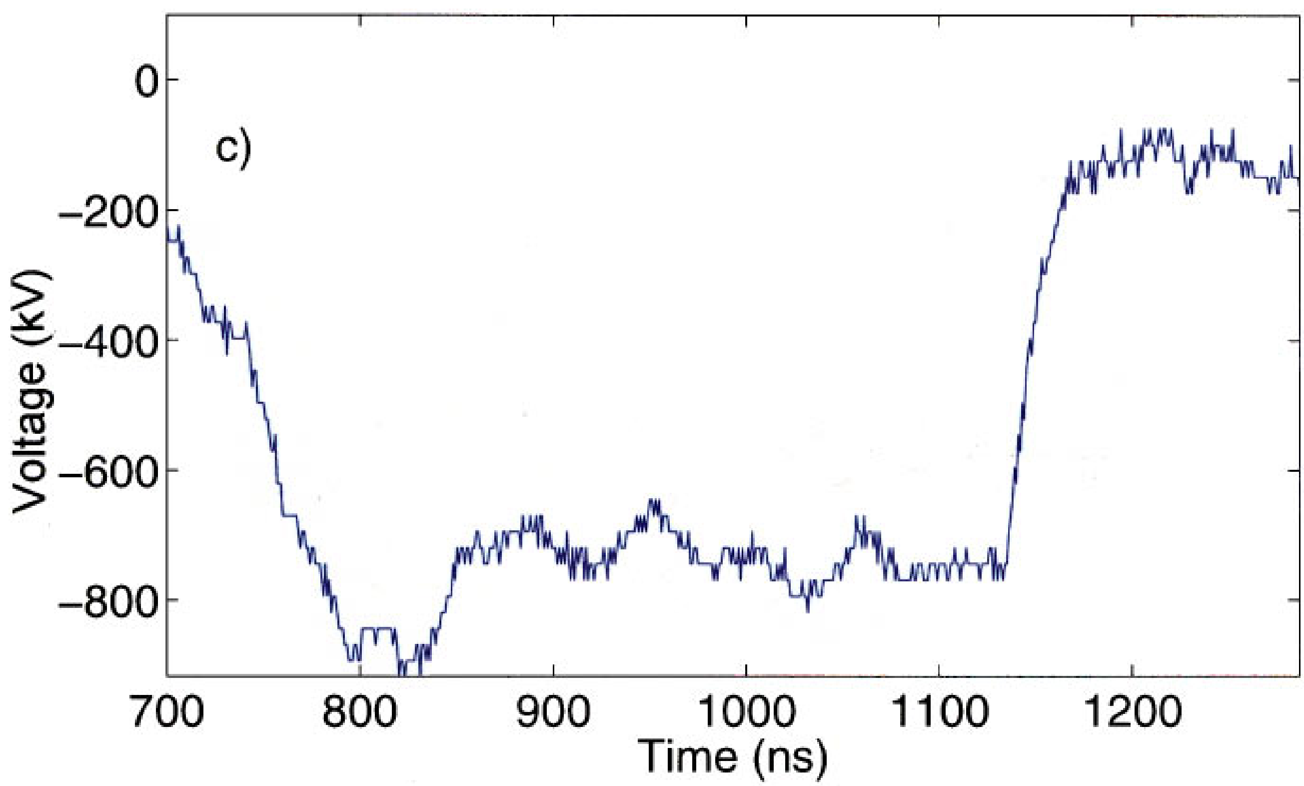


FIG. 2. (*Continued*).

filtering in the signal analyzers. Thus, Figs. 2(b)–2(e) strongly suggest this causal sequence of events: fluctuations in the diode voltage lead to fluctuations in the interaction frequencies, which in turn leads to large fluctuations in the output rf power.

The frequency modulation by the diode voltage shown in

Figs. 2(b) and 2(c) may be explained as follows. In cyclotron masers, the frequency ω is related to the electron orbit through the beam-cyclotron mode [10]

$$\omega = k v_z + \Omega/\gamma, \tag{1}$$

where k is the axial wave number, Ω is the nonrelativistic cyclotron frequency of an electron, v_z is the axial velocity of an electron, and γ is the relativistic mass factor. Small variations in the diode voltage δV leads to small variations in γ and in v_z, and hence in ω according to Eq. (1). Assuming that the last term in Eq. (1) gives the dominant contribution, we obtain the fractional change in ω in terms of the fractional change in the beam energy (diode voltage):

$$\frac{\delta\omega}{\omega} = -\left(\frac{\delta\gamma}{\gamma}\right)\left(1 - \frac{\gamma}{\beta^2}\frac{k v_z}{\Omega}\right) \approx -0.48\left(\frac{\delta V}{V}\right). \tag{2}$$

In deriving the middle term in Eq. (2), we have used $\beta^2 \equiv v_z^2(1+\alpha^2)/c^2 = 1-\gamma^{-2}$ and assumed that α, the ratio of the perpendicular velocity to the parallel velocity of an electron, is a constant. The numerical value given in the last term of Eq. (2) is obtained by taking a dc magnetic field of 2 kG, $\beta = 0.914$, $\alpha = 1$, corresponding to a diode voltage $V = (\gamma - 1)511$ kV$=750$ kV, and $k = \pi/26$ cm$^{-1} = 12$ m^{-1}. Note the direct proportionality of diode voltage fluctuations and frequency chirp as shown in Eq. (2) and Figs. 2(b) and 2(c). The numerical value on the right-hand side of Eq. (2) only gives a qualitative indication because (a) there are uncertainties in k and in α, and (b) more importantly, Eq. (2) does not give the frequency dependence in the power distribution in the chirped rf output, so the range of $\delta\omega/\omega$ predicted by Eq. (2) is only an estimate. Using the values of $\delta\omega/\omega$ and $\delta V/V$ inferred from Figs. 2(b) and 2(c) we find that Eq. (2) is satisfied to within 20%.

While this paper provides direct evidence of the consequences of diode voltage fluctuations, namely, frequency chirp and the large fluctuations in the output power in a coaxial gyrotron, it exemplifies the tremendous opportunities opened up for a critical examination of pulse shortening, mode competition, and interference, noise, and beam loading, etc., most of which are yet to be fully understood. Causal effects can be identified in a real-time analysis, which may also be conveniently adopted in particle simulations. For example, one may apply a time-frequency analysis of the voltages at the various gaps of a relativistic klystron [11] to determine if the loading of the gap(s) by the intense beam, or simply the diode voltage fluctuations as studied in this paper, could lead to pulse shortening. Such an examination may also be applied to computer simulations, and to other high-power microwave sources.

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