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# Observation and Study of Low-Frequency Oscillations in a 1.5-MW 110-GHz Gyrotron

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**Abstract**—We report the observation of low-frequency oscillations (LFOs) in the range 165–180 MHz in a 1.5-MW 110-GHz gyrotron operating in 3- $\mu$ s pulses. The oscillations have been measured by a capacitive probe located just before the entrance to the cavity. The LFOs are observed only in a narrow region of beam parameter space, at voltages between 45 and 60 kV, where no microwave emission occurs. When the gyrotron operates near 96 kV, with high output power, they are not seen. The variation of the frequency of the oscillations with electron beam voltage and magnetic compression was measured, and the results are reported. Time-domain analysis of the probe signal shows the influence of the beam current and cathode voltage on the time of onset of the oscillations. The amplitude of the time-domain signal indicates that the trapped electron current associated with the LFOs represents a few percent of the total electron current.

**Index Terms**—Fusion, gyrotron, high-power microwave source, low-frequency oscillations (LFOs), trapped electrons.

## I. INTRODUCTION

ELECTRON cyclotron heating and electron cyclotron current drive using high-power gyrotrons are among the most promising methods for plasma heating, current drive, and instability control for thermonuclear fusion research [1], [2]. The requirements on fusion reactors to be sustainable and profitable energy sources lead to demands on gyrotrons for high-efficiency continuous wave (CW) operation. Thus, research on fusion gyrotrons has been focused on achieving high-power levels, in long pulse or CW operation with the highest possible efficiency. Operation at 170 GHz for 800 s, with a power level of 1 MW, and with an efficiency of 55% after energy recovery has recently been demonstrated [3].

Any parasitic instability on the electron beam such as the low-frequency oscillations (LFOs), the subject of this paper, can deteriorate the beam quality by increasing the velocity and energy spreads thus reducing the efficiency of the gyrotron [4]–[6]. Strong LFOs in the 100-MHz range can interfere with the diagnostic and control system of the gyrotron as was

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observed in General Atomics [7]. Similar problems have been reported in a coaxial gyrotron [8].

LFOs have been the focus of recent experiments on moderate-power pulsed gyrotrons [4], [9]. The obtained results have highlighted the role of emission nonuniformity in the formation of the trapped electron population, identified the role of the reflected electrons in the onset and growth of the LFOs, and allowed to investigate ways for suppressing the oscillations. However, understanding of the LFOs remains incomplete. Particle-in-cell simulations model the development of oscillations of the space charge in the adiabatic trap [10], but the physics of the electron dynamics in the adiabatic trap is only partially understood. The processes of escape of the trapped electrons have not clearly been identified, and the size of the trapped electron population has not been previously reported. Additional experimental studies of LFOs in gyrotrons therefore aim at answering these questions.

In this paper, new observations of LFOs in a 1.5-MW 110-GHz gyrotron are reported and discussed. The gyrotron has an internal mode converter and a depressed collector. These new results complement the previous results, obtained on the same gyrotron operating without an internal mode converter, in an axial output configuration, reported in [11]. The LFO signal is measured with a capacitive probe installed just prior to the resonant cavity. The probe is very broadband, but the observed LFOs have frequencies in the range 165 to 180 MHz. The influence of the beam parameters on the characteristics of the oscillations is studied extensively. It is shown that the LFOs only appear in a region of parameter space which does not overlap with the region of high-power operation of the gyrotron. Analysis of the time-domain capacitive probe signal gives an estimate of the trapped electron population when oscillations are observed.

## II. EXPERIMENTAL SETUP

The experiments have been performed on the 1.5-MW 110-GHz gyrotron at Massachusetts Institute of Technology (MIT) [12], [13], a pulsed device with 3- $\mu$ s pulse duration. The electron beam is generated by a diode magnetron injection gun which is designed to operate at 40 A and 96 kV, with a velocity ratio  $\alpha = V_{\perp}/V_{\parallel} = 1.4$  in the cavity, where  $V_{\perp}$  and  $V_{\parallel}$  are the transverse and axial velocity of the electrons, respectively, for a compression ratio  $R = B_0/B_c = 25$ , where  $B_0$  is the magnetic field at the cavity, and  $B_c$  the gun magnetic field. Whereas in the previously reported experiment [11] the gyrotron was in the axial configuration, all the results presented here have been

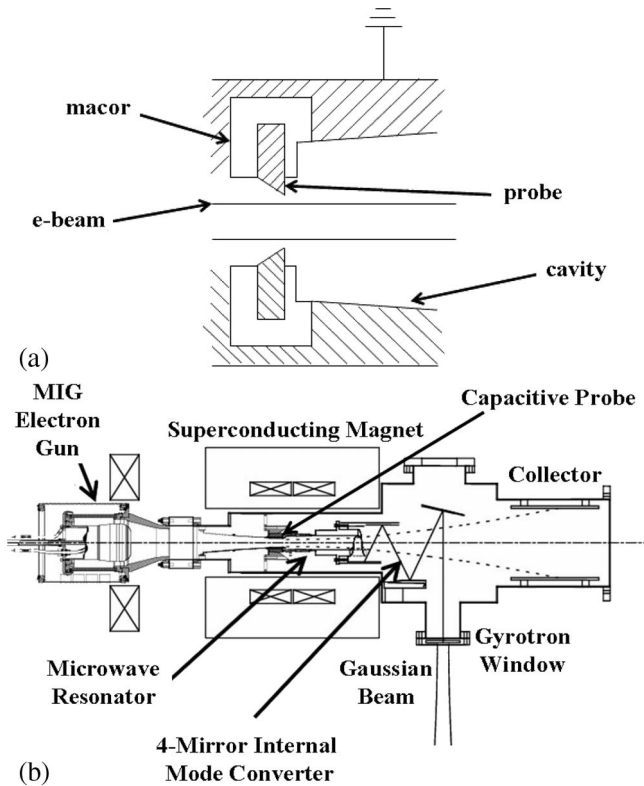


Fig. 1. Side-cut schematics of (a) the capacitive probe and of (b) the 1.5-MW MIT gyrotron.

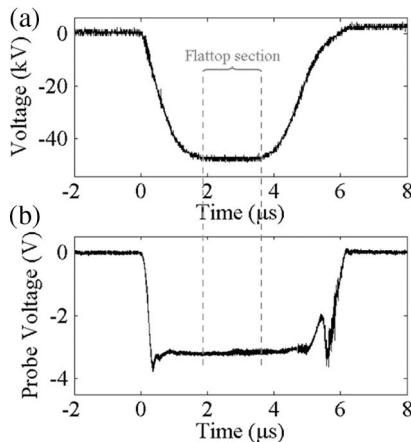


Fig. 2. Time-domain signals of (a) the cathode voltage and of (b) the capacitive probe, with the indication of the beginning and of the end of (dashed lines) the flat-topped section of the pulse.

obtained with the gyrotron operating with a mode converter, consisting of a launcher and four mirrors, as shown in Fig. 1.

The LFOs in the gyrotron are observed by analyzing the signal of a capacitive probe on a 350-MHz 1-Gs/s LeCroy Waverunner LT264 oscilloscope. The probe is located at the end of the beam tunnel, just before the cavity entrance, as shown in Fig. 1(a) and (b). It was originally installed for velocity ratio measurements, based on the technique described in [14].

A typical capacitive probe signal is shown in Fig. 2(b), along with the cathode voltage signal corresponding to the same pulse [Fig. 2(a)]. In this paper, the focus has been on the study of the flat-topped section of the pulse, shown in Fig. 2, thereby ignoring

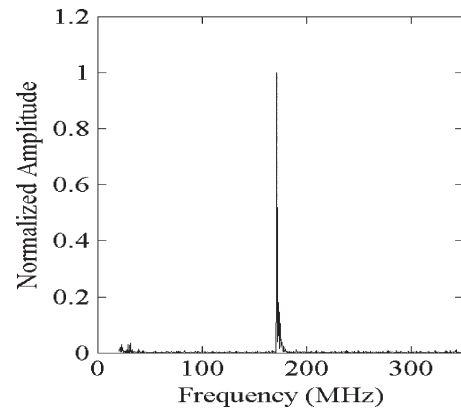


Fig. 3. Capacitive probe frequency spectrum, for frequencies above 30 MHz, in the case of an LFO observation.

the oscillations associated with the charging and discharging phases of the capacitive probe which follow the ramp up and down of the voltage pulse in our pulsed experiments.

### III. EXPERIMENTAL RESULTS

#### A. Observation of the LFOs

Capacitive probe signals have been recorded and analyzed over a wide range of voltages (between 25 and 96 kV), beam currents (between 15 and 46 A), compression ratios ( $R$  between 22.9 and 26.5), and cavity magnetic fields ( $B_0$  between 4.2 and 4.6 T). The frequency content of the LFOs was obtained by taking the fast Fourier transform of the flat-topped section of the time-domain probe signal. For the beam parameters for which the LFOs were observed, typical frequency spectra above 30 MHz are as shown in Fig. 3, indicating the presence of a very strong, isolated component around 170 MHz. This component has a full-width at half-maximum between 0.5 and 1.5 MHz.

LFOs are observed only in a narrow region of the accessible beam parameter space. At a fixed compression ratio, there exists both a lower voltage threshold, in the range 46–48 kV, and an upper voltage threshold, in the range 58–60 kV, below which and above which oscillations are not observed. Moreover, for voltages between these two thresholds, LFOs only occur if the beam current is above a certain threshold current, which depends on the cathode voltage. These results are summarized with the collector current–cathode voltage map ( $I$ – $V$  map) in Fig. 4, for a compression ratio  $R = 23.8$ . This map has been obtained by analyzing a very large number of shots in the whole accessible  $I$ – $V$  space, and by recording those which corresponded to the observation of LFOs and those which did not.

The same operation has been realized for several different values of  $R$ . The qualitative features of this map do not change with changes in value of magnetic compression ( $R$ ); however, the region where LFOs are observed either expands or shrinks. It has been found that for too high compression ratios (above 25.1), the beam parameters become very noisy due to the strong presence of trapped electrons, and the LFO oscillations cannot be observed in any region of  $I$ – $V$  space, because they are below the noise level. As the compression ratio is decreased from this value, the area of the region of occurrence of the LFOs increases. For compression ratios between 24 and 22,

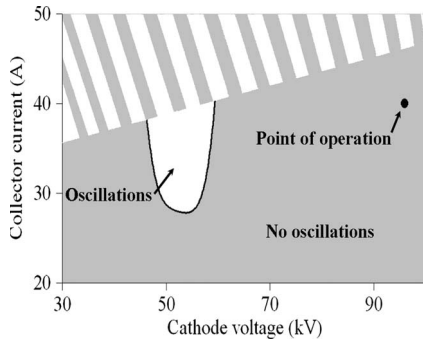


Fig. 4.  $I$ - $V$  map of the region of observation of the LFOs, at a compression ratio  $R = 23.8$ . The gray region corresponds to voltages and currents for which LFOs are not observed, the white region to voltages and currents for which LFOs are observed, and the stripes to a region not accessed experimentally to avoid cathode overheating. A dot labeled “point of operation” indicates the nominal voltage (96 kV) and current (40 A) for high-power microwave generation.

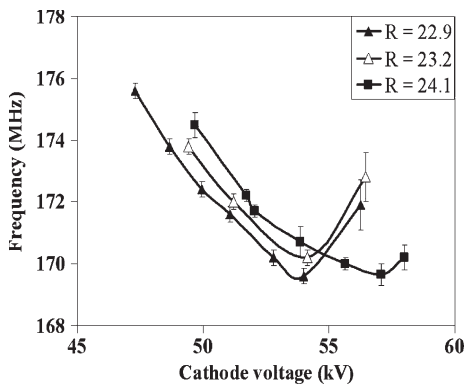


Fig. 5. Frequency as a function of cathode voltage, for a beam current of 32 A, and for three different compression ratios: (black triangles) 22.9, (open triangles) 23.2, and (black squares) 24.1.

the extension of this area is maximal and remains approximately constant, independent of  $R$ . The effect of even lower compression ratios on the size of the area where LFOs are observed could however not be investigated, due to experimental limitations on the maximum current that can flow in the gun coil. As mentioned, at  $R = 22$ , the lowest value that could be investigated experimentally, LFOs were still observed.

It should also be mentioned that for the beam parameters for which LFOs were measured by the capacitive probe, the same oscillations could be detected at an open port of an oscilloscope located at 1 m from the gyrotron. This result indicates that the oscillations of the space-charge in the adiabatic trap not only lead to a perturbation of the electron current, but are also the source of electromagnetic radiation which can be seen outside of the gyrotron. This radiation can potentially disturb measurement and control signals for the gyrotron, as was observed in [7].

### B. Frequency-Domain Results

Varying the beam parameters, it was possible to tune the observed frequencies in the range 165–180 MHz. The influence of cathode voltage on the oscillation frequency, with all the other parameters fixed, is shown in Fig. 5, for three different values of  $R$ , and for a beam current of 32 A.

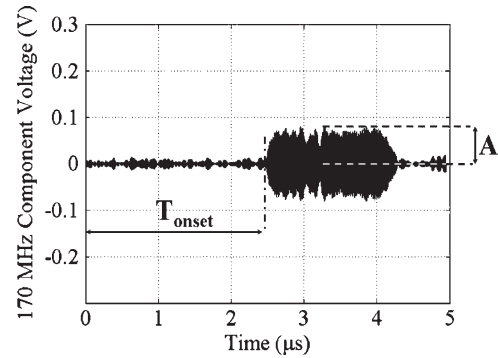


Fig. 6. Time domain trace of the  $\sim 170$ -MHz component of the capacitive probe signal. Two parameters discussed in this paper,  $A$  and  $T_{\text{onset}}$  are defined in the figure.

The measurement of an initial decrease of the frequency with increasing cathode voltage is in disagreement with other experiments, and some theoretical predictions involving electron time-of-flight calculations in an adiabatic trap, as in [9] and [15]. Previous studies report only an increase in frequency with voltage [9] and a single particle time of flight theory has been developed [15] to explain this phenomenon. In that analysis, the increasing voltage leads to higher velocity electrons that can pass through the trap more quickly, thus increasing the frequency with voltage. Our results show first a decrease in frequency with voltage and then an increase in frequency with voltage. In Section IV, it will be suggested that this apparent disagreement with a simple single-particle theory is due to the particular space charge and beam optics characteristics of the gyrotron under study, and that a single particle time of flight explanation might still apply to the results presented in this paper.

### C. Time-Domain Results

Information on the time-domain properties of the low-frequency oscillations under observation was obtained by isolating for study the  $\sim 170$ -MHz component of the capacitive probe time-domain signal, using a numerical bandpass Butterworth filter. A typical observation of the time-domain features of the  $\sim 170$ -MHz oscillations is shown in Fig. 6. The time scale used on this figure is the same as the one used in Fig. 2. The three phases of the oscillation, namely, growth, saturation, and decay, are clearly visible in Fig. 6. Two characteristics of the oscillation which have been studied in this paper: the maximum amplitude  $A$  at saturation and the time  $T_{\text{onset}}$  from the start of the pulse at which the instability starts to grow, have been defined in the figure.

$T_{\text{onset}}$  has been seen to depend on the beam current and on the cathode voltage. These dependences are shown in Figs. 7 and 8, respectively.

Higher values of beam current lead to shorter times  $T_{\text{onset}}$  for the start of the oscillations. The influence is more subtle in the case of the cathode voltage because the instability starts earlier in the pulse for intermediate voltages, between 51 and 54 kV. As the cathode voltage is further decreased from 51 kV, the onset of oscillations takes a longer time. Similarly, at voltages above 54 kV, the onset of oscillations takes a longer time.

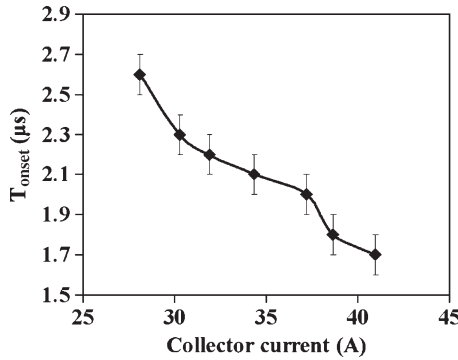


Fig. 7.  $T_{\text{onset}}$  as a function of the collector current, for a cathode voltage of 54 kV and a compression ratio  $R = 23.4$ .

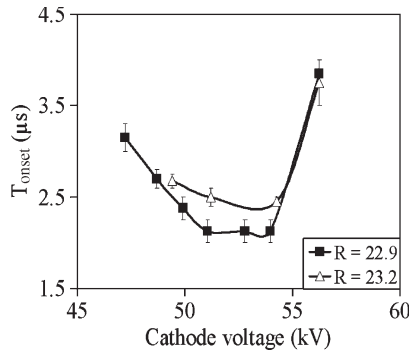


Fig. 8.  $T_{\text{onset}}$  as a function of the cathode voltage, for a beam current of 32 A, and for the compression ratios (black squares)  $R = 22.9$  and (open triangles)  $R = 23.2$ .

These results, combined with the fact that the gyrotron is operated in short pulses, may explain in part the shape of the region where oscillations are observed in Fig. 4. Indeed, for  $T_{\text{onset}}$  larger than 4  $\mu\text{s}$ , the oscillations cannot appear during the flattop part of the pulse, and are therefore not observed. Conversely, operation in longer pulses could lead to an extension of the white region in Fig. 4, both to lower and higher voltages.

The study of the maximum amplitude at saturation ( $A$  in Fig. 6) gives an estimate of the size of the trapped electron population contributing to the oscillations. For the beam parameters for which  $A$  is found to be maximum, the current due to the 170-MHz component leads to a capacitive probe voltage of 0.15 V, and the total current to a capacitive probe voltage of 3.7 V. The ratio of these two values is a measure of the proportion of trapped electrons involved in the instability in the total population. With  $0.15/3.7 \approx 4\%$ , one concludes that the trapped electron population contributing to the observed LFO is of the order of a few percent of the total electron population.

#### IV. DISCUSSION

##### A. Frequency Dependence on Voltage

It is suggested in this section that the dependence of the oscillation frequency on the cathode voltage (Fig. 5) might be due to the particular characteristics of the electron beam produced by the MIT 1.5-MW gyrotron. Some of these characteristics are analyzed here, using the code EGUN.

For any cathode voltage, EGUN calculates the average parallel velocity of the electron beam, and the parallel velocity

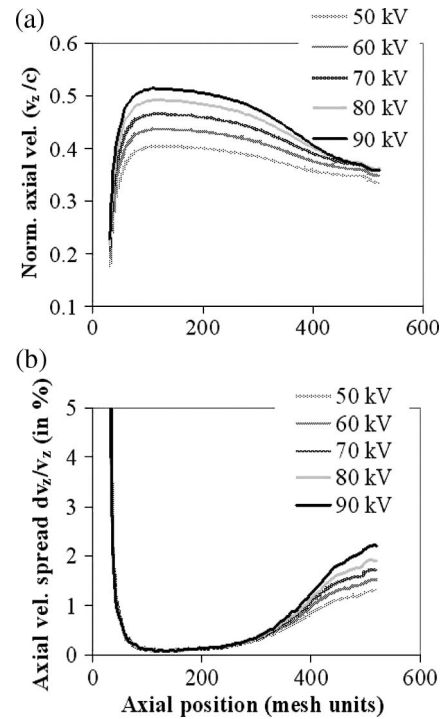


Fig. 9. EGUN simulations, for a beam current of 32 A, a compression ratio  $R = 22.9$ , and for five voltages (50, 60, 70, 80, and 90 kV) of (a) the normalized axial velocity as a function of the axial position and (b) the axial velocity spread in percent, as a function of the axial position.

spread due to space charge and beam optics, at any position between the gun and the cavity. We have carried out EGUN simulations for five different voltages (50, 60, 70, 80, and 90 kV), for a compression ratio of 22.9 and a beam current of 32 A, as shown in Fig. 9. In this figure, the cathode is located at zero (0) mesh units and the cavity is at 520 mesh units.

The interesting features in Fig. 9 are seen in the mixing region, a zone corresponding to positions between 420 and 520 mesh units. There, one can observe that as the cathode voltage increases, the axial velocity spread also increases, approximately linearly with voltage. The dependence of the axial velocity on voltage is more complicated. At low voltages, the axial energy of the electron beam increases with increasing voltage. However, at intermediate voltages, one observes the saturation of this effect, with the axial velocity virtually independent of the cathode voltage. In addition, at high voltages, one even notices the opposite effect, i.e., a decrease of the velocity with increasing voltage.

In the frame of a single particle time of flight explanation, the phenomenon seen in Fig. 5 could then result from a tradeoff between the increase of the spread with increasing voltage and the saturation of the axial velocity as voltage is increased. For low voltages, the spread of the electron population increases as voltage increases, but so does the axial energy. Therefore, the electrons travel farther before being reflected, and the bounce frequency will decrease. For intermediate to high voltages, however, the axial energy of the electron population saturates and even decreases with increasing voltage, whereas the spread keeps increasing. The electron population will therefore be reflected farther and farther from the resonant cavity, hence the

saturation and the reincrease of the frequency with increasing voltage shown in Fig. 5.

A single particle theory of the transit time, which predicts the oscillation frequency, could be developed using the results of Fig. 9 after adding a correction for velocity spread due to surface roughness and work function variation. Our analysis shows that uncertainties in the magnitude of these corrections lead to significant uncertainty in the results, and we have therefore not pursued such a theory for quantitative comparison with experiment.

### B. Excitation of Different LFO Modes

In our previous publication on LFOs observed in our 1.5-MW 110-GHz gyrotron, we reported LFOs in the 120- to 140-MHz range [11]. That gyrotron was set up in the axial configuration, with output power coming directly out of the gyrotron in a waveguide oriented along the axis of the magnetic field. In addition to the results at 120–140 MHz, we also had data showing LFOs with a frequency near 170 MHz. The characteristics of the LFOs around 170 MHz are exactly the same as the ones indicated in this paper, which reports results on the gyrotron in the internal mode converter configuration. The LFO results are the same both in the frequency domain and in the time domain. They were moreover observed in the same range of cathode voltages, 46 to 60 kV, and beam currents, 28 to 40 A. As in this paper, these oscillations were never observed in the vicinity of the point of high-power operation, at 96 kV and 40 A. Our results thus suggest that depending on the regime in which the gyrotron is operated and depending on the beam parameters, one or two LFO modes may be excited, in our case around 120–140 MHz and around 170 MHz. Recent theoretical work [16] seems to lead to the same conclusion. This fact will be investigated further in future work.

## V. CONCLUSION

The obtained results show that LFOs do not appear in the regime of high-power operation in the 1.5-MW 110-GHz MIT gyrotron. However, the observation of these oscillations in a narrow region of parameter space, where no microwave production is found, and the measurement by a capacitive probe located in the vicinity of the cavity, has allowed the study of the characteristics of this parasitic phenomenon often seen in high average power gyrotrons. The trapped electron population contributing to the oscillation has been measured to be of the order of a few percent of the total electron population. The frequency of the oscillations is seen to depend on the beam parameters, such as the cathode voltage and the compression ratio. The time of onset of the LFOs is also found to depend on the cathode voltage, as well as the beam current. In particular, at higher voltages the oscillations are observed at a later time. This result suggests that the region of parameter space where the LFOs occur could be larger if the pulse duration of our experiment were not limited to 3  $\mu$ s.

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