Effects of After Cavity Interaction in a 1.5 MW, 110 GHz Gyrotron with a Depressed Collector

Yoshiteru Hidaka[a], E. M. Choi, I. Mastovsky, M. A. Shapiro, J. R. Sirigiri, and R. J. Temkin
[a]MIT Plasma Science and Fusion Center, Cambridge, MA 02139 USA

***Abstract*—We report experimental results on a 1.5 MW, 110 GHz gyrotron operating in 3 microsecond pulses with a single-stage depressed collector. Our research is focused on the observation of the after cavity interaction (ACI), and its effect on re-absorption of microwave power by the electron beam and, more importantly, broadening of the spent beam energy distribution in the launcher, i.e., the region after the cavity. The second effect limits the efficiency of a depressed collector considerably. Simulations indicate that this reduced depressed collector capability deteriorates with higher initial velocity spread of the electron beam. Efforts to design a cavity or magnetic field profile that minimizes the ACI effects are under way. While ACI affects the depressed collector operation as mentioned above, we recently found experimental evidence of collector depression affecting the cavity interaction itself. The minimum amount of current required to sustain the design mode, $TE_{22,6}$ in the hard self excitation regime decreased by as much as 6 A as the collector was depressed by up to 30 kV. This has implications in being able to reach further into the high efficiency hard self excitation regime. The microwave frequency also increased by as much as 15 MHz.**

I. Introduction

Efficiency of high-power gyrotrons has been significantly improved over the years. Recently, a 1-MW, 170-GHz, CW gyrotron has achieved over 55% efficiency with a single-stage depressed collector by tuning the magnetic field rapidly to reach the hard excitation region [1]. Generally, without either altering the accelerating voltage or the magnetic field during the pulse, the efficiency of a MW-class gyrotron is usually below 50%, which is much lower than the theoretically predicted value. Our recent experimental study found a possible cause for this underperformance, namely, the after cavity interaction (ACI) [2, 3]. In this paper, we describe this phenomenon and its effects on the performance of a gyrotron using MAGY simulations [4].

Also equally important for efficiency increase is to understand how the collector depression modifies the beam-wave interaction inside the cavity. We report here two effects discovered experimentally upon the application of retarding potential on the collector: a decrease in the minimum required current to excite the main $TE_{22,6}$ mode; and a frequency increase of the main mode.

II. After Cavity Interaction

By including the region after the cavity, i.e., the launcher section, in simulations, we verified that the microwave power extracted from the electron beam in the cavity region is transferred back into the beam power in the after cavity region, indicated as a dip in the power trace in Fig. 1(a). This second interaction occurs because the tapering magnetic field satisfies the synchronism condition at some location in the launcher whose radius is larger than the cavity radius. As Fig. 1(a) shows, the coupling coefficient in the ACI region is comparable to that in the cavity. This compensates the shorter interaction length in the ACI region and can still cause a huge impact on the gyrotron performance.

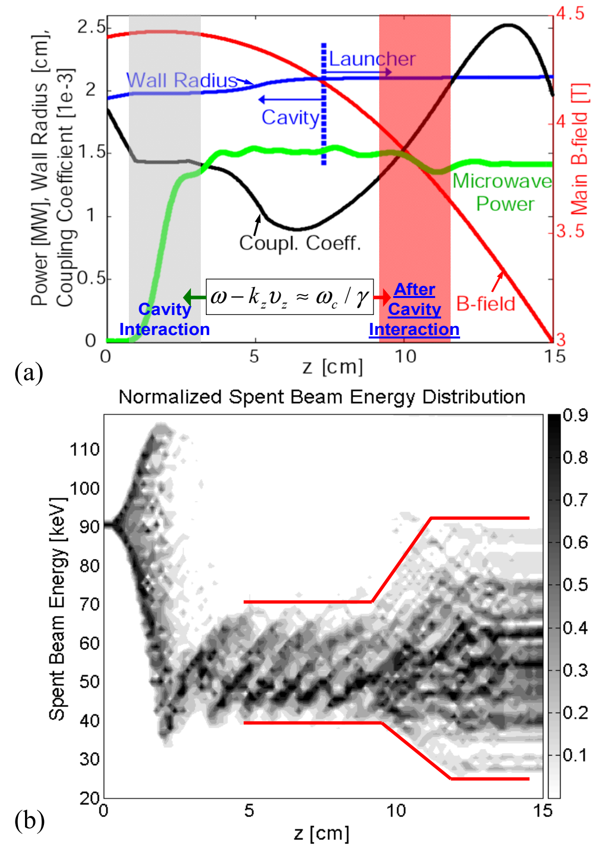

Fig. 1: (a) Cavity and magnetic field profile including after cavity region. Microwave power in (a) and spent beam energy distribution in (b) is a result of a single-mode ($TE_{22,6}$) MAGY simulation with 96 kV beam voltage, 42 A beam current, α (=$v_\perp/v_{||}$) of 1.3, and perpendicular velocity spread of 7%.

There is another hidden side effect of the ACI. As demonstrated by Fig. 1(b), the ACI broadens the spent beam energy distribution. This reduces the minimum spent beam energy, which limits how much the collector can be depressed without reflecting back the electron beam. Our previous experimental study with a single-stage depressed collector achieved 50% efficiency with 25 kV depression voltage. However, the simulation predicts the collector can be

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depressed up to 38 kV without reflection, if the ACI were absent, which would raise the total efficiency to ~60%.

Furthermore, we have found that having a small initial perpendicular velocity spread is very crucial to achieve high efficiency with a depressed collector because of the ACI effect. Simulations were performed with the initial spread changed from 0.5% to 7%; with the ACI included, the efficiency drops only from 37% to 35% if the collector depression is not considered. However, with a maximum collector depression, the total efficiency drops from 59% to 49%. Ways to suppress the ACI even with a high velocity spread are also currently being investigated, by modifying cavity/magnetic field profiles.

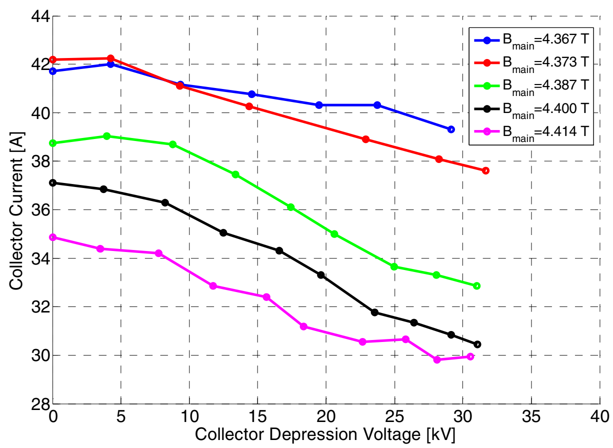

Fig. 2: Experimentally measured value of the threshold beam current to sustain the $TE_{22,6}$ mode in the hard self excitation regime vs. collector depression voltage.

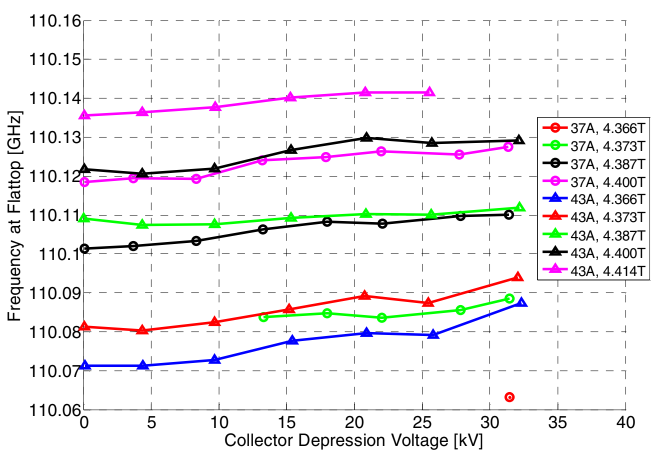

Fig. 3: Experimentally measured Gyrotron output frequency at pulse flattop vs. collector depression.

III. Effects of Collector Depression on Cavity Interaction

The detailed experimental setup for the results reported in this section is provided in [3]. Figure 2 shows the relationship between the beam current required to excite the $TE_{22,6}$ mode and the collector depression voltage, with the cathode-anode voltage and the beam compression ratio fixed at 96 kV and 23.6, respectively. For all the cavity magnetic fields investigated, the minimum current dropped significantly with the depression, by up to 6 A. This implies that the mode map can change with collector depression. For example, if we were to operate at the beam current of 41 A, we would think that the lowest field at which the main mode can be excited is 4.387 T. With enough depression, however, the lower fields are accessible and hence the optimal magnetic field parameters may as well change with depression. Thus, it appears essential to re-optimize the magnetic field for a given collector depression voltage in order to discover the highest achievable power.

Another influence of collector depression on the cavity interaction is the frequency up-shifting with increasing collector depression, as shown in Fig. 3. The data were obtained in the same conditions as the data shown in Fig. 2. The rising trend of the frequency is consistent even with very different beam currents, though the higher currents result in higher frequencies. This up-shifting could be explained by the increased space charge in the cavity due to the reflected electrons, which decrease the effective beam voltage.

There is a link between the lower minimum required current and the frequency up-shifting. The minimum current appears to be determined by how much the cavity can be detuned, since the $TE_{22,6}$ mode disappears when the frequency reaches around 110.06-07 GHz. By increasing the retarding potential, the frequency increases so that the current can be reduced further until the frequency decrease by the current cancels out the frequency increase obtained by the retarding potential. Hence, the minimum current to excite the main mode decreases with the collector depression voltage.

The present results indicate that it is worth investigating further the impact of the collector depression on the beam dynamics in the cavity now that we have found these noticeable effects.

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