Theoretical Investigation on Injection Locking of the EU 170 GHz 2 MW $TE_{34,19}$-Mode Coaxial-Cavity Gyrotron

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***Abstract*—Injection locking of gyrotron oscillators offers an improved mode stability and the precise phase and frequency control of the generated millimeter-wave signal. It might offer completely new possibilities for applications related to nuclear fusion plasma, spectroscopy, and radar. In this presentation it is shown that the theory of Kurokawa can be applied to understand the injection locking of gyrotrons and that it provides accurate prediction of the locking behavior. Based on that, the investigation on injection locking of the EU 170 GHz 2 MW $TE_{34,19}$-mode coaxial-cavity gyrotron using self-consistent single and multi-mode simulations is presented. Detailed studies on injection signals containing competing modes to account either for signal impurities or for deliberate injection of competing modes are presented.**

I. INTRODUCTION

PHASE locking of gyrotron oscillators by external signal injection [1] was studied in the past [2,3] showing a fundamental agreement with Adler's theory [4]. However, the use of this locking technique at megawatt power levels was prevented by the missing possibility for injection of the required power in the correct mode. In [5], a novel quasi-optical converter geometry was presented, enabling injection of external signals through the vacuum window of the gyrotron. Since then, outstanding theoretical progress has been made in injection locking of hollow-cavity gyrotrons, e.g. [6]. For the first time, here, the concept is applied in self-consistent, single and multi-mode, time-domain simulations to the EU 170 GHz 2 MW coaxial-cavity gyrotron [7] using the code-package EURIDICE [8].

II. RESULTS

Fig. 1 shows the output frequency of the gyrotron at a beam current I_B of 75 A as a function of time in free-running (dashed) and locking scenarios resulting from single-mode simulations assuming an ideal electron beam. As indicated by the second x-axis, the beam voltage V_B is linearly swept over time. An external signal of the correctly rotating $TE_{34,19}$ mode is injected at various power levels and at a frequency of 169.972 GHz, which is the free-running frequency close to mode loss. Due to the injected signal, the coaxial-cavity gyrotron is locked securely and a stable output frequency in a wide range of operating voltages is achieved. Thus, in contrast to the free-running gyrotron, locking enables precise control of the output frequency even for not completely stable supply voltage. As it becomes evident from Fig. 1, oscillation can be maintained at higher detuning regimes compared to free-running operation due to locking. It is clearly visible, that the locking bandwidth can be extended by increasing the injection signal power. At low voltages, where the free-running frequency becomes too high, the gyrotron is outside of the locking regime and several peaks appear in the frequency spectrum as predicted by fundamental theory [9]. The shown frequency in this area represents an instantaneous value calculated as the time derivative of the phase of the RF field and, therefore, a beating behavior is apparent. By this visualization, unlocked and locked operating regimes can be clearly distinguished.

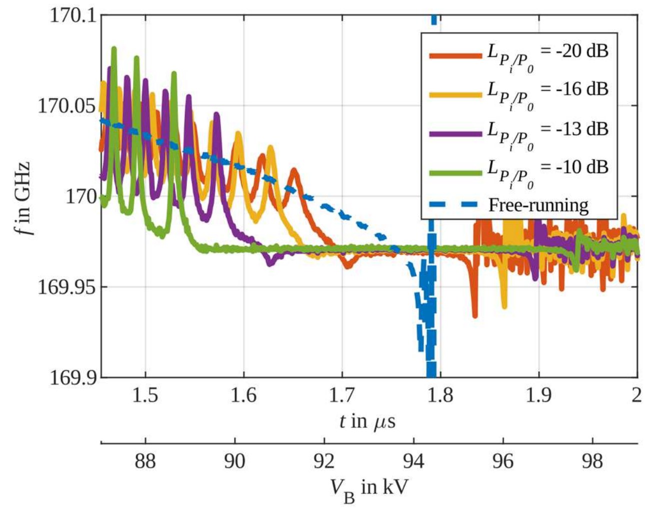

Fig. 1. Instantaneous frequency of the free-running and driven gyrotron for constant injection frequency of 169.972 GHz and various external signal powers as a function of time. The beam voltage is swept linearly with time.

The contours of electronic efficiency are presented in Fig. 2 for the free-running gyrotron (black lines) and the gyrotron driven by an external source (colors) in the plane of operating voltage V_B and current I_B, as predicted by single-mode calculations with ideal electron beam. As has been the case with Fig. 1, unlocked and locked operating regimes can be clearly distinguished if the appearance of beating with decreasing voltage is observed. The area of stable oscillations in the high-efficiency regime is extended by approximately 1.5 kV. In the additional operational area, the electronic efficiency is increased by 2 percentage points compared to the maximum efficiency achieved in autonomous operation.

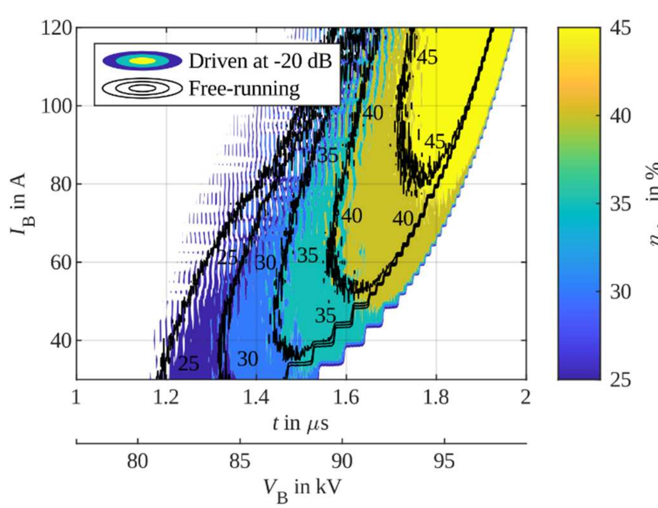

Fig. 2. Contours of electronic efficiency in beam voltage-current plane.

Advanced multi-mode simulations accounting for 42 modes are performed, considering also realistic beam spread values, i.e., a root-mean-square (rms) spread in velocity ratio of 6 %, a kinetic energy of 0.01 % rms, and a guiding center spread of twice the Larmor radius. The output power of the operating $TE_{34,19}$ mode is presented in Fig. 3. Small fluctuations in free-running operation (blue line) indicate mode competition appearing at high beam voltages. By injection of an external signal (green line) of the operating mode at -20 dB referred to the free-running output power and at the free-running frequency close to mode loss, the mode competition becomes more severe in that region. This is indicated by the significant reduction in output power. On the other hand, in the additional operating regime, enabled due to injection locking, the maximum output power does not show fluctuations anymore (indicating an absence of mode competition), and can be increased by 10 %.

Considering a higher rms spread in velocity ratio of 30 %, mode competition can be prevented in free-running operation as visible in Fig. 3 (red line). In this case, injection of an external signal (yellow line) does not lead to regimes of reduced power as before. Thus, for gyrotrons suffering from mode competition in autonomous operation, injection of external signals can intensify the competition in some operating points. However, in the studied cases at least, the external signal injection does not introduce mode competition by itself if mode competition is not present in free-running operation.

The influence of non-ideal mode conversion by the quasi-optical input system, i.e., competing modes contained in the injected signal are studied in detailed multi-mode simulations accounting for 16 modes. The total external signal power corresponding to -20 dB referred to free-running output power is distributed as follows: 92.5 % $TE_{34,19}$ (operating mode) and 0.5 % each other mode which is considered in the simulation. As evident from Fig. 4, the fractional power in the competing modes leads to a locking of their frequencies to the injection signal frequency. This can be explained as their free-running powers at low voltages are at the noise level and hence, small power (-43 dB referred to free-running power) is sufficient to cause locking. As these modes are shifted to frequencies far from their respective cutoff frequencies, gyrotron interaction with the electron beam is effectively prevented. Thus, mode impurities of the injection signal or even specific injection of competing modes may provide an alternative method of selective mode suppression.

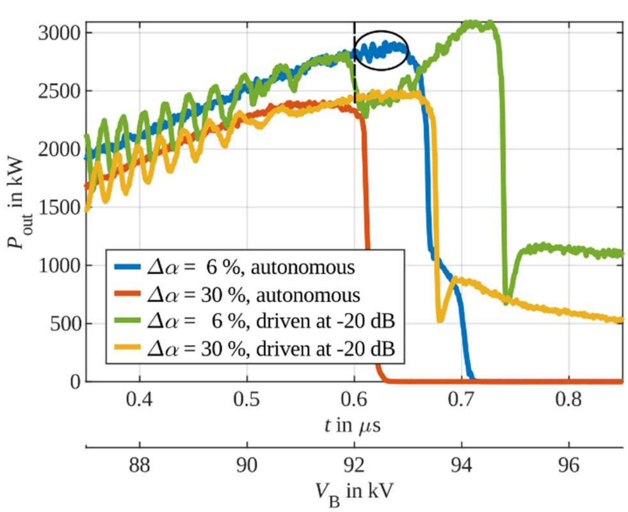

Fig. 3. Output power of the operating $TE_{34,19}$ mode in free-running and driven operation at 6 % and 30 % of rms spread in velocity ratio.

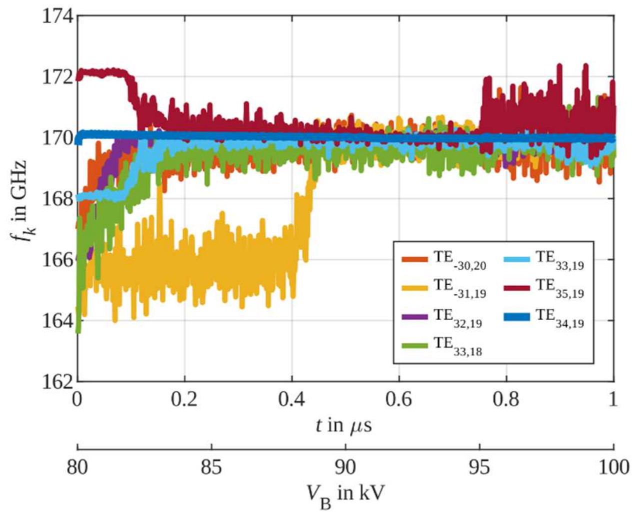

Fig. 4. Frequencies of main competitors and operating mode with injected signal containing 92.5 % of the total injected power in the $TE_{34,19}$ mode and 0.5 % in each other considered mode.

III. SUMMARY

Detailed studies on injection locking of the EU 170 GHz 2 MW coaxial-cavity gyrotron have been carried out. It is shown that the locking bandwidth is correctly predicted by the model of Kurokawa. Considering interaction efficiency of the high-power coaxial-cavity gyrotron, it is found that injection locking does not lead to significant improvements. By advanced multi-mode models, an injection signal containing competing modes is studied and it is concluded that these modes can be effectively locked, which prevents them from being excited and reduces mode competition.

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