Frequency Stabilization of Megawatt-Class 140 GHz Gyrotrons at W7-X Using an Off-the-Shelf PLL System

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***Abstract*— An off-the-shelf Phase-Locked Loop (PLL) system is used to stabilize the free-running oscillation frequencies of the 140 GHz, 1 MW CW gyrotrons of the companies Thales, France, and CPI, USA, that both operate at the ECRH system of the Wendelstein 7-X (W7-X) stellarator at IPP Greifswald, Germany. Both tubes are equipped with diode-type Magnetron Injection Guns (MIGs). Considering each of both type of gyrotrons as a Voltage Controlled Oscillator (VCO), each individual gyrotron is controlled by the variation of the body voltage. The results of the experiments demonstrate the capability of the developed and implemented inexpensive off-the-shelf PLL system. It is possible to stabilize the oscillation frequency within a full -20 dB bandwidth of < 100 kHz. Applications such as Collective Thomson Scattering (CTS) systems to accurately diagnose the ions in fusion plasmas could benefit from this development in future.**

I. INTRODUCTION

PHASE-Locked Loops (PLLs) using Phase Frequency Detectors (PFDs) to compare the frequency of a Voltage Controlled Oscillator (VCO) with the stable frequency of a given reference are well-known circuits for frequency control. The excellent potential to stabilize the frequency of a low-power gyrotron via the modulation anode voltage of a triode-type Magnetron Injection Gun (MIG) using a PLL was demonstrated in [1] already. The output frequency was stabilized to a linewidth below 1 Hz. In the present work, an off-the-shelf PLL system [2] was implemented for MW-class industrial gyrotrons with single-stage depressed collector used for Electron Cyclotron Resonance Heating (ECRH) at the Wendelstein 7-X (W7-X) stellarator in Greifswald, Germany [3][4]. Frequency stabilization experiments were conducted with gyrotrons of two different manufacturers, namely Thales (TH1507 SN2i) [5] and CPI (VGT-8141A S/N 3) [6]. Each of both gyrotrons is equipped with a diode-type MIG and the frequency is adjusted through a variation of the acceleration voltage via the body voltage [7]. Since the W7-X gyrotrons operate at 140 GHz, their frequency is too high for conventional PFDs. To overcome this issue, the operating frequency is down-converted to an intermediate frequency (IF) of 45 MHz, which is suitable for the off-the-shelf PFD chip ADF4001 [8]. The gyrotron signal is converted to 45 MHz with a Local Oscillator (LO) at 15.5539 GHz and a 9th harmonic frequency multiplier.

II. EXPERIMENTAL SETUP

In Fig. 1, the experimental setup for the frequency stabilization experiments is shown. A small portion of the gyrotron output mm-wave beam is coupled out and transmitted via a waveguide system to the control room. This signal with frequency f_g is down-converted to the required IF frequency f_{IF}. Then it is fed into the PFD chip. An external reference signal is also fed into the PFD chip to compare the phase and frequency of the gyrotron with this reference. After filtering of the PFD output signal, the control voltage $U_{control}$, which corrects any frequency deviation of the gyrotron, is transmitted via fiber optic transmission to the body power supply. The body power supply is capable to modulate the body voltage U_{body} of the gyrotron with a maximum frequency of 20 kHz. The dynamic limitations of the body power supply are considered for the calculation of the PLL loop filter parameters.

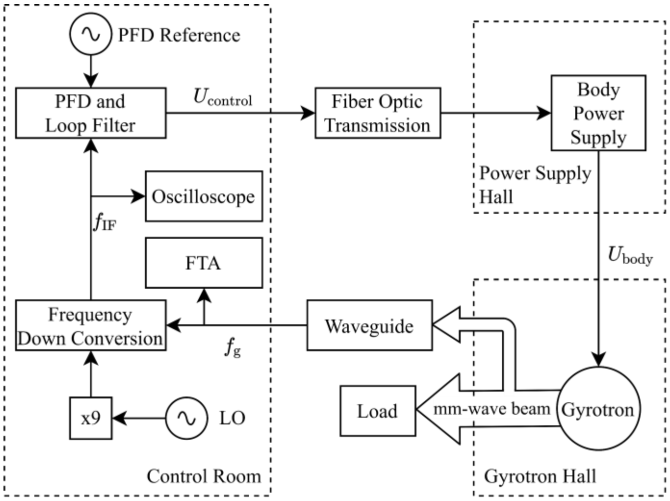

Figure 1: Experimental setup

One of two systems used to measure the output frequency of the gyrotron is a Frequency-Time Analyzer (FTA), which directly evaluates the gyrotron signal after the waveguide transmission in the control room. The frequency data of the FTA is available during the whole pulse duration. The other system is an oscilloscope that captures the IF signal with a sampling rate of 500 MS/s. Due to the high amount of data, only the last 40 ms of a pulse are analyzed. A Fast Fourier Transform of the registered data provides the spectrum of the IF signal.

III. RESULTS

During the experiments, the gyrotrons were operated with a pulse length of 5 s. In Fig. 2, a comparison of the FTA measurements between the free-running and stabilized CPI gyrotron shows the potential of the PLL circuit to stabilize the gyrotron frequency for long pulse durations. In both cases, the frequency dropped due to the cavity expansion at the beginning of the pulse. In the free-running shot, the final frequency was around 139.985 GHz after the expansion of the cavity had stopped. However, the frequency did not remain stable during the whole shot and had visible variations. In the stabilized shot, the PLL was configured to keep the gyrotron frequency at 140.03 GHz, which is shown in Fig. 2. As soon as the frequency of the gyrotron reached 140.03 GHz, the gyrotron frequency stayed continuously at the desired 140.03 GHz. The output power of both, free-running and stabilized, shots was 650 kW.

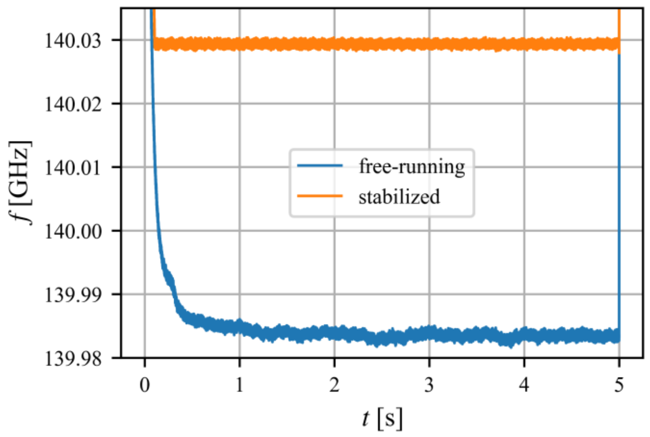

Figure 2: Comparison of the FTA measurement between a free-running and a frequency stabilized shot of the CPI gyrotron

In Figs. 3 and 4, the IF spectra of the free-running and stabilized CPI gyrotron are shown. In contrast to the spectrum of the free-running gyrotron, which is spread out among several frequencies, the stabilized down-converted spectrum has a high peak at 45 MHz, corresponding to 140.03 GHz. The frequency modulation sidebands in the stabilized spectrum arise from the acceleration power supply circuits. The spectrum of the stabilized Thales gyrotron has a similar shape as that of the CPI gyrotron and the same frequency modulation sidebands are present. The full -20 dB bandwidth of the stabilized spectrum is for both, CPI and Thales, gyrotrons below 100 kHz, compared to 1.1 MHz of the free-running gyrotron.

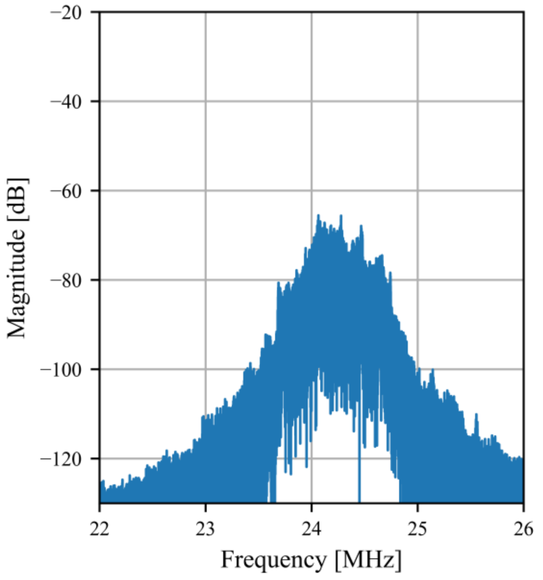

Figure 3: Spectrum of the free-running CPI gyrotron

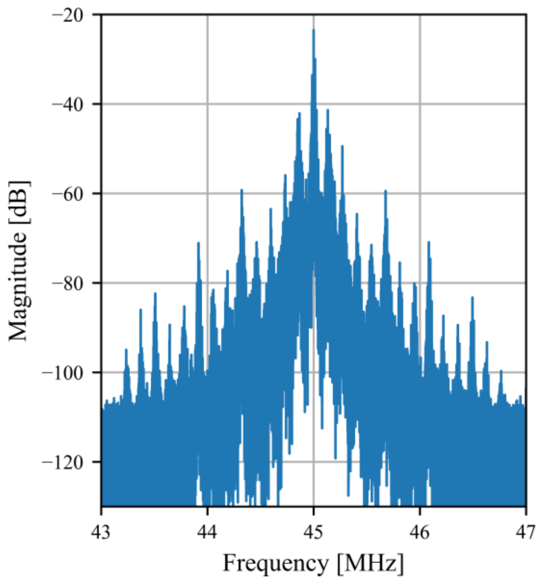

Figure 4: Spectrum of the PLL-stabilized CPI gyrotron

IV. CONCLUSION

In conclusion, the experiments show the excellent potential of stabilizing megawatt-class gyrotrons using an inexpensive off-the-shelf PLL system. Applications, which need a smaller emission bandwidth of high power gyrotrons, such as Collective Thomson Scattering diagnostic [9] or fast directional switch [10] could benefit from this frequency stabilization.

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