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Short-pulse frequency stabilization of a MW-class ECRH gyrotron at W7-X for CTS diagnostic

L. Krier[a,*], K.A. Avramidis[a], H. Braune[b], G. Gantenbein[a], S. Illy[a], J. Jelonnek[a,c], H.P. Laqua[b], S. Marsen[b], D. Moseev[b], F. Noke[b], T. Ruess[a,c], T. Stange[b], M. Thumm[a,c], R.C. Wolf[b], W7-X Team[1]

[a] IHM, Karlsruhe Institute of Technology, Kaiserstr 12, 76131 Karlsruhe, Germany
[b] IPP, Max-Planck-Institute for Plasma Physics, Wendelsteinstr. 1, D-17491 Greifswald, Germany
[c] IHE, Karlsruhe Institute of Technology, Kaiserstr. 12, 76131 Karlsruhe, Germany

ABSTRACT

At the Wendelstein 7-X stellarator, a 174 GHz Collective Thomson Scattering (CTS) diagnostic will be implemented. One of the 140 GHz Electron Cyclotron Resonance Heating (ECRH) gyrotrons will be operated at around 174 GHz in a higher cavity mode, using it as source for the CTS mm-wave probing beam. To prevent any damage to the CTS receiver, a notch filter cuts out the high-power gyrotron signal at the entrance of the receiver. The bandwidth of the gyrotron signal determines the notch filter bandwidth. First proof-of-principle experiments on frequency stabilization were conducted on W7-X ECRH gyrotrons employing Phase-Locked Loop techniques. The gyrotron output frequency was controlled with the accelerating voltage, which is applied between the anode and cathode of the gyrotron diode-type Magnetron Injection Gun. Frequency stabilization experiments with 10 ms pulses were conducted at the gyrotron nominal frequency of 140 GHz as well as at 174 GHz. It is concluded that the gyrotron frequency could be stabilized for at least 3 ms at 140 GHz and 8 ms at 174 GHz. In the frequency spectrum, a clear main peak of the gyrotron frequency at 140 GHz with a full -15 dB linewidth of below 500 Hz was achieved.

1. Introduction

For successful controlled fusion power plants, it is important to understand the behavior of the plasma in magnetic confinement fusion reactors. For this purpose, a variety of different diagnostic systems are employed in experimental fusion reactors. Collective Thomson Scattering (CTS) allows to measure several plasma parameters such as bulk ion temperature, fast ion velocity distribution function, isotope ratio, plasma rotation, etc. [1,2]. The CTS diagnostic is an active measurement method and injects a beam of electromagnetic waves into the plasma, which is called the probing beam. Information about the different plasma parameters is obtained from the frequency spectrum of the scattered signal at the receiver. In magnetic fusion reactors, millimeter waves (mm-waves) are often used as probing radiation, since they allow a large flexibility in choosing scattering geometries.

A crucial part of the CTS diagnostic is the source of the mm-wave probing beam, which needs high power and narrow bandwidth in the frequency spectrum. Gyrotron oscillators are electron vacuum tubes that can generate mm-waves in the megawatt range [3]. Furthermore, MW-class gyrotrons are used in experimental nuclear fusion reactors to heat up the plasma through Electron Cyclotron Resonance Heating (ECRH).

The CTS receiver needs to be highly sensitive to capture the signal of the scattered wave from the collective electrons. To prevent any damage to the receiver, the stray radiation from the high-power probing beam that enters the receiver needs to be filtered out with a notch filter. Currently, the frequency chirp of the gyrotron at the beginning of a pulse defines the stop bandwidth of the notch filter, which is how much in the received spectrum is cut out. In the future, when the frequency chirp will be stabilized, the bandwidth of the gyrotron radiation will be the decisive factor for choosing the stop bandwidth of the notch filter. The larger the gyrotron bandwidth, the more information is cut out of the received spectrum. For the CTS diagnostic, reducing the bandwidth of the gyrotron output spectrum results in better measurement accuracy. In recent experimental fusion reactors, CTS receiver notch filters have a bandwidth of a few hundred MHz [2,4,5].

Gyrotrons are oscillators and operate at a single frequency. However, due to varying conditions during operation, the output frequency of gyrotrons changes and is not stable over time. These frequency variations are in an acceptable range for ECRH. At the Wendelstein 7-X (W7-

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* Corresponding author.
E-mail address: laurent.krier@kit.edu (L. Krier).

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X) stellarator [6] in Greifswald, Germany, the megawatt-class ECRH gyrotrons are operated free-running, i.e., without any kind of external frequency stabilization. Since one of the ECRH gyrotrons is also used for CTS diagnostic, the CTS system at W7-X would highly benefit from a more stable frequency output of this high-power gyrotron. This would allow to reduce the notch filter bandwidth at the CTS receiver. A notch filter bandwidth of below 100 MHz results in a significant increase in precision of the bulk ion and fast ion measurements. A notch filter bandwidth of below 50 MHz allows accurate measurements of ion Bernstein waves (IBW) of the main plasma species (Hydrogen, Deuterium and Helium). Further reducing the notch filter bandwidth to below 10 MHz with a gyrotron linewidth narrower than 0.5 MHz allows IBW measurements of impurities. Finally, a notch filter bandwidth of below 1 MHz and gyrotron linewidth below 100 kHz makes plasma turbulence measurements possible [7].

In recent years, several investigations have been conducted to stabilize the output frequency and phase of gyrotrons. The excellent potential to stabilize the frequency of a low- to medium-power gyrotron via the modulation anode voltage of a triode-type Magnetron Injection Gun (MIG) using a Phase-Locked Loop (PLL) [8] was demonstrated in [9] and [10] already. The output frequency was stabilized to a bandwidth below 1 Hz and below 2 Hz, respectively. In the present work, a PLL system is implemented for MW-class gyrotrons [11] with a diode-type MIG used for ECRH system [12,13] at W7-X. First proof-of-principle frequency stabilization experiments at 140 GHz were conducted that are relevant for the CTS diagnostic system. Furthermore, frequency stabilization experiments at 174 GHz are presented.

This work is organized as follows. After the introduction in Section 1, Section 2 explains the CTS diagnostic at W7-X and its requirements for the gyrotron probing beam. In Section 3, it is investigated on which parameters the output frequency of the gyrotron depends and how the frequency can be stabilized. Section 4 shows the experimental setup for the frequency stabilization experiments at W7-X and in Section 5, the results of the experiments are presented. Finally, a conclusion and outlook are given in Section 6.

2. Collective Thomson Scattering diagnostic at W7-X

A CTS diagnostic was installed at W7-X for ion temperature measurements in the plasma core [4]. The CTS diagnostic operates at 140 GHz and uses one of the ECRH gyrotrons to generate the high-power probing beam. A diagram of CTS diagnostic at W7-X is shown in Fig. 1. Since one of the ECRH gyrotrons is used for the generation of the CTS probing beam, the multibeam ECRH transmission line is used to transfer the probing beam into the plasma vessel of the stellarator. The CTS receiver is located at one of the ECRH gyrotron sites. Therefore, the ECRH transmission line is also used to transfer the receiver beam from the plasma vessel to the CTS receiver.

First results of ion temperature measurements from the CTS diagnostics operating at 140 GHz showed good agreement with the X-ray spectroscopy [4]. However, the operation at 140 GHz limits the range of the CTS diagnostic, because the second harmonic of the electron cyclotron resonance is also at 140 GHz. On the one hand, measurements in the electron cyclotron resonance layer of the plasma are not possible since the electromagnetic (EM) waves are absorbed at 140 GHz. On the other hand, the electron cyclotron emission (ECE) is high in this frequency range, which deteriorates the signal-to-noise ratio of the CTS diagnostic.

Therefore, changing the frequency of the CTS diagnostic improves its measurement results. In the spectrum of the ECE radiation during a nominal W7-X operation, a minimum is present between 170 GHz to 180 GHz [14]. Moving to higher frequency is also beneficial, because the refraction of the probing beam in the plasma reduces with higher frequency – allowing for much better beam alignments in the plasma. It was also shown in [15] theoretically, that it is possible to operate one of the ECRH gyrotrons at approximately 174 GHz. With these considerations, the CTS diagnostic at W7-X will be changed to 174 GHz for the next operational campaign. The 174 GHz operation of a W7-X gyrotron requires a gyrotron magnetic field strength of 7 T inside the cavity for which the current magnets are not capable. Therefore, a new magnet was procured that satisfies the requirements for the 174 GHz operation.

Changing the operating frequency of the CTS diagnostic from 140 GHz to 174 GHz adds another requirement on the probing beam. Opposed to the 140 GHz operation, where the probing beam is absorbed by the plasma in the electron cyclotron resonance layer, the probing beam at 174 GHz passes mostly through the plasma and directly hits the plasma vessel wall. Since the probing beam needs power in the hundreds of kW range, the pulse duration needs to be limited to prevent any damage of the plasma vessel wall. Therefore, the gyrotron for the probing beam will be operated with short pulses in the ms range. The duty cycle is selected so that the total energy deposition on the plasma vessel wall does not damage it. The exact requirements will be determined when the 7 T new magnet is installed on the W7-X gyrotron and the operation of the gyrotron at 174 GHz is fully characterized.

The short-pulse operation of the gyrotron complicates the frequency stabilization due to the frequency drop at the beginning of a pulse from cavity expansion and beam space charge neutralization, which will be explained at the end of the following Section 3.

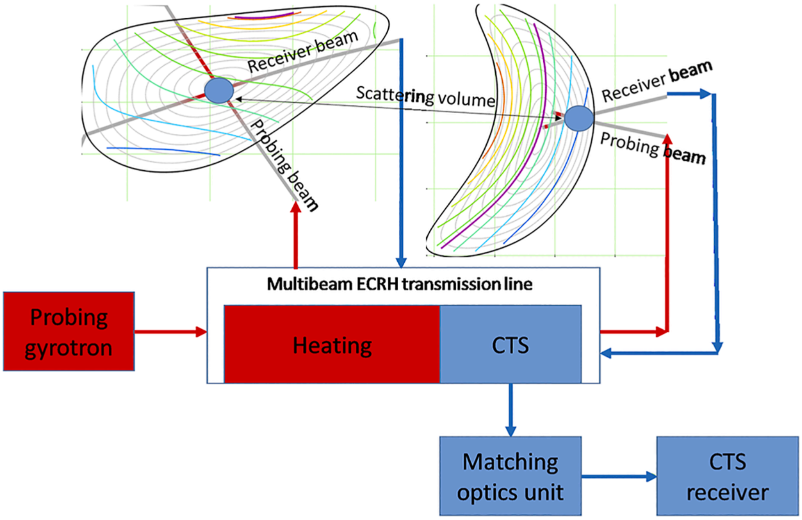

Fig. 1. Principle of CTS diagnostic at W7-X (Fig. from [4]).

3. Frequency dependence of gyrotrons

The gyrotron is an electron vacuum tube, where the electrons transfer parts of their perpendicular kinetic energy to the electromagnetic wave. The electrons are guided by an external static magnetic field and move in helical trajectory with the relativistic electron cyclotron angular frequency

$$\Omega_c = \frac{eB}{\gamma m_e} \tag{1}$$

where B is the magnetic field strength, e the elementary charge, m_e the electron mass. γ is the relativistic Lorentz factor:

$$\gamma = 1 + \frac{e\left(U_{\mathrm{acc}} - U_{\mathrm{dep}}\right)}{m_e c^2} \tag{2}$$

where c is the speed of light in vacuum. U_{acc} is the accelerating voltage, which is applied between the cathode and anode of the gyrotron MIG. U_{dep} is the depression voltage due to the electron beam space charge.

To excite an EM-wave at angular frequency ω inside the gyrotron, the synchronization condition needs to be fulfilled [16]:

$$\omega - k_{\|} v_{\|} \approx s\Omega_c \tag{3}$$

where $k_{\|}$ and $v_{\|}$ are, respectively, the component of the wave vector and of the electron velocity parallel to the external static magnetic field. s is a positive natural number, denoting the harmonics of the electron cyclotron frequency.

From Equation (3), the excited frequency depends on the electron cyclotron frequency. During the gyrotron operation, the electron cyclotron frequency is manipulated by either the magnetic field strength, which follows directly from (1), or by the accelerating voltage, which changes the Lorentz factor.

The frequency of a gyrotron can be stabilized by two methods: injection locking or by an external control circuit. With injection locking, an external highly stable signal with the desired frequency is injected into the gyrotron. If the frequency difference between the free-running excited frequency and the injected frequency is not too large, the gyrotron frequency locks on the injected frequency. The stabilization of high-power gyrotrons with injection locking is studied in [17,18]. In contrast to injection locking, the frequency stabilization with a control circuit measures the output frequency of the gyrotron and changes the operating parameters of the gyrotron accordingly to counter any unwanted frequency changes. An advantage of an external control circuit is that the design of the gyrotron does not need to be changed and that it can be used with existing gyrotron such as the W7-X gyrotrons. In this work, the output frequency of a gyrotron with diode-type MIG is stabilized by a PLL, which is a well-known external control circuit for frequency and phase stabilization of free-running oscillators.

To control the gyrotron frequency, either the magnetic field strength or the accelerating voltage can be used. The magnetic field strength of the superconducting gyrotron magnet can only be changed slowly and thus, is not suitable for a fast frequency control system. On the other hand, the power supplies, which are used for the accelerating voltage, can be controlled faster. Thus, for gyrotrons with a diode-type electron gun, the accelerating voltage can be used for a fast control of the frequency.

If the accelerating voltage is not changed too drastically, the frequency dependence of the gyrotron can be linearized and for a zero-order approximation, the gyrotron can be viewed as a voltage-controlled oscillator. This facilitates the considerations for the whole PLL control system and the standard PLL techniques can be used to design the control system.

The most noticeable frequency change during the gyrotron operation happens at the beginning of a pulse. The frequency drops due to electron beam space charge neutralization and thermal expansion of the cavity, due to heating of the cavity wall from power dissipation. The electron beam space charge neutralization [19] results in a smaller depression voltage and thus, increases the Lorentz factor and decreases the excited frequency. Typically, the final neutralization for W7-X gyrotrons is around 60 % [20]. Furthermore, due to cavity wall losses, the cavity wall heats up, leading to an expansion of the cavity radius. The cavity cooling system needs some time (hundreds of ms) to cool down the cavity wall and to stop the cavity expansion. With both effects, the gyrotron frequency drops hundreds of MHz during the first half second of a pulse. Afterwards, small variations of the gyrotron frequency still arise due to smaller variations of the operating parameters from noise; however, they are in the MHz range. The free-running frequency of a W7-X gyrotron from manufacturer CPI [21] with the frequency drop at the beginning of the pulse is shown in Fig. 2.

To determine the optimal PLL control parameters, the frequency sensitivity on the accelerating voltage should be known. For the W7-X gyrotron, this was determined experimentally for the main operating point. The accelerating voltage of the gyrotron was changed during a pulse and the gyrotron output frequency was measured. For the CPI gyrotron, a frequency dependence on the accelerating voltage of 3 MHz/kV was determined.

It should be noted that in a frequency stabilization system for gyrotrons with a diode-type MIG, the change in accelerating voltage to counter unwanted frequency deviations also changes the gyrotron output power. While these power changes are not significant if the unwanted frequency changes are small, additional care needs to be taken if the frequency is stabilized at the beginning of the pulse. There, the frequency drop is significant and the corresponding accelerating voltage change to counter it is so large that the gyrotron output power decreases strongly and the gyrotron could even lose its nominal operating mode. It is therefore not possible to counter the entire frequency drop of hundreds of MHz only with the accelerating voltage.

However, since a pulse length in the ms range is required for the CTS diagnostic, the full frequency drop does not need to be countered; only a small part of it directly at the beginning of the pulse.

4. Experimental setup

As described in the previous Section 3, the gyrotron can be viewed simplified as a Voltage Controlled Oscillator (VCO) for which the well-known PLL techniques can be used to stabilize its output frequency. The general principle of a PLL is shown in Fig. 3.

The main components of a PLL are the VCO, the Phase Frequency Detector (PFD) and the loop filter. The VCO outputs a frequency that is proportional to the input voltage. Afterwards at the PFD, the output signal of the VCO is compared to a reference signal. The reference signal needs to come from a highly frequency and phase stable source. With a PLL, the VCO is phase-locked on to the reference signal. The PFD outputs

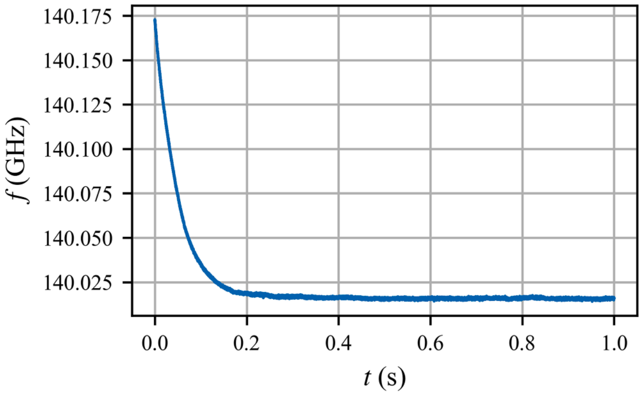

Fig. 2. Frequency over time of W7-X CPI gyrotron at the beginning of a pulse

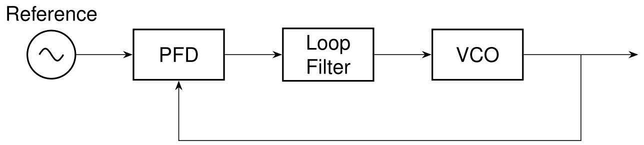

Fig. 3. General principle of a PLL

an error voltage if any difference of phase and frequency between the VCO and reference signal is present. The error signal then passes through a loop filter, which determines the dynamic and stability of the whole control system. The resulting voltage is then applied to the VCO and any unwanted frequency changes are countered.

For high-power gyrotrons operating at mm-wave frequencies, two additional items need to be considered. First, the mm-wave frequencies are too high for any conventional PFDs. Therefore, a frequency down conversion needs to be added to the PLL system. The frequency down conversion translates the gyrotron output frequency to the MHz range, which is suitable for conventional PFDs. Second, the dynamics of the high voltage power supplies, which are used for the operation of high-power gyrotrons, needs to be considered in the whole control system. In fact, the high voltage power supply is the slowest component in the PLL system and limits the dynamic and stability of the whole PLL system.

The gyrotrons at W7-X are operated with an elevated body (anode) and have a diode-type MIG. The potential of the collector is at earth potential. The anode, beam tunnel, cavity and mirror box are on positive body potential and the cathode is on negative cathode potential. Two power supplies are used to provide the cathode voltage U_{cathode} and body voltage U_{body}. The accelerating voltage U_{acc} for the electron beam is calculated with

$$U_{\text{acc}} = U_{\text{cathode}} - U_{\text{body}}. \tag{4}$$

For the PLL control system, the body power supply was used to control the accelerating voltage and with it the gyrotron frequency. The body power supply at W7-X can be modulated with arbitrary signals and the maximal modulation frequency is 20 kHz [22], which makes it suitable for the PLL control system.

With these considerations, a PLL system was designed and implemented for the W7-X gyrotrons. A diagram of the PLL system, which was used for the experiments, is shown in Fig. 4. The gyrotrons are located in the gyrotron hall and one floor above are the body power supplies. A small portion of the gyrotron mm-wave beam is coupled out and transmitted via a waveguide system to the control room. There, the frequency down conversion and the PLL control circuit are located. For the down conversion, a local oscillator (LO), which operates up to 20 GHz, is multiplied by 9 to achieve the required frequency around 140 GHz. The gyrotron signal is down converted to an Intermediate Frequency (IF) of 45 MHz. The LO for the down conversion is set such that the desired frequency of the gyrotron corresponds to 45 MHz at the IF frequency. The PLL system employs an Integer-N PLL and divides the IF gyrotron signal by 45. This signal is then compared with a reference signal at 1 MHz. After the PFD and consecutive Proportional Integral (PI) loop filter, the value for the body voltage is sent through fiber optics to the body power supply.

For the experiments, the gyrotron from manufacturer CPI was used [21]. A nominal operating of the gyrotron was chosen and with the PLL system, the body voltage was changed during the pulse. The experiments were conducted for short pulses, where the frequency drop at the beginning of the pulse needs to be countered. Since a decrease in body voltage results in an increase of the gyrotron frequency, the body voltage should be variably decreased during the pulse by the PLL system to counter the frequency drop. The accelerating voltage could be modulated between 77 kV and 82 kV, resulting in a maximum deviation of 5 kV.

To analyze the frequency over time behavior and the spectrum of the gyrotron, two measurements were taken. A Frequency Time Analyzer (FTA) directly measured the gyrotron mm-wave signal. Furthermore, an oscilloscope captured the gyrotron IF signal at 45 MHz. With this, the spectrum of the gyrotron IF signal was calculated. The accelerating voltage and gyrotron output power were also measured.

5. Experimental results

To stabilize the frequency at the beginning of the pulse as fast as possible, the set frequency of the PLL system needs to be as close as possible to the free-running frequency of gyrotron. In Fig. 5, the orange curves show a closer look at the accelerating voltage, frequency and power during the first 10 ms of a free-running gyrotron pulse. Since the PLL system is not active, the accelerating voltage stays constant at 80.5 kV. At the start of the pulse, the gyrotron is excited at a frequency of 140.165 GHz. The total frequency drop over 10 ms is 35 MHz, which results in a rate of 3.5 MHz/ms. For the frequency stabilization, the

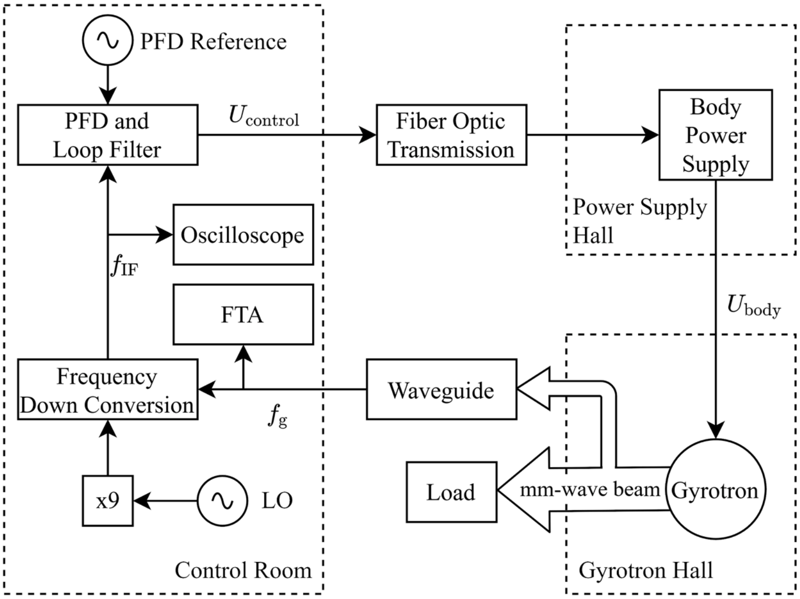

Fig. 4. PLL system for W7-X gyrotrons

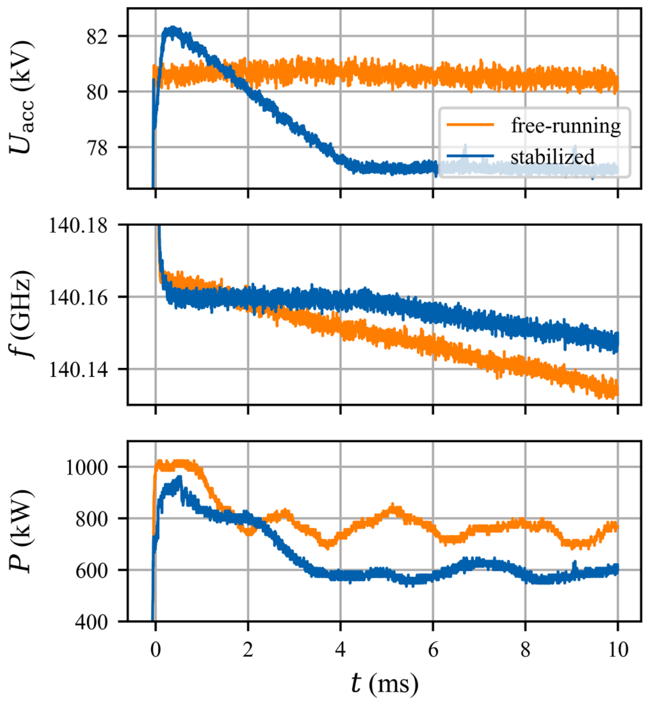

Fig. 5. Accelerating voltage, frequency and output power over time of W7-X CPI gyrotron in free-running (orange) and stabilized (blue) operation for a 10 ms pulse.

desired frequency needs to be slightly lower than the excited gyrotron frequency at the start of a pulse. Then, due to the frequency drop, the gyrotron frequency reaches the set PLL frequency and the PLL system starts locking the gyrotron frequency onto the set frequency.

In Fig. 5, the blue curves show the frequency stabilized gyrotron operation over time. The PLL system is conFig.d such that the gyrotron frequency shall be 140.160 GHz. Now, the PLL system controls the accelerating voltage. At the first half millisecond of the pulse, the gyrotron frequency is higher than 140.160 GHz. Therefore, the PLL system increases the accelerating voltage to decrease the gyrotron frequency. Combined with the cavity expansion and electron beam space charge neutralization, the gyrotron frequency decreases until the desired 140.160 GHz is reached. Afterwards, the gyrotron frequency would still drop in the free-running case. However, the PLL system realizes that the gyrotron frequency is lower than 140.160 GHz. Therefore, it lowers the accelerating voltage to increase the gyrotron frequency, which exactly counters the frequency drop and stabilizes the gyrotron frequency to the desired 140.160 GHz. This process happens until the minimum accelerating voltage of 77 kV is reached and the PLL system was not allowed to further reduce the accelerating voltage. Afterwards, the effects of cavity heating and electron beam space charge neutralization still result in a frequency drop. The total time during which a stable frequency is achieved is 3 ms.

Since with the frequency stabilization the accelerating voltage is decreased by 5 kV, the gyrotron output power necessarily also decreases. However, as can be seen in Fig. 5, the gyrotron power stays for the stabilized frequency duration at 140.160 GHz above 600 kW. The difference in power between the free-running and stabilized operation during the first is not significant for the CTS diagnostic.

For the CTS diagnostic, the gyrotron shall emit repetitive multiple pulses. The cavity heats up with each pulse and – depending on the duty cycle – will not fully cool down when a new pulse starts. Thus, the cavity radius – and with it the initial gyrotron frequency – is not the same for each pulse. Eventually after several pulses, if the duty cycle is kept constant, a stable point will be reached at which the cavity radius is the same at the beginning of each pulse. This needs to be considered for choosing the correct stabilization frequency for the gyrotron.

In Fig. 6, the measurements of four consecutive gyrotron pulses are shown for the free-running and frequency stabilized operation. Each pulse has a duration of 10 ms and the pulses were repeated after 50 ms. In the frequency stabilized operation, the PLL system was set such that the gyrotron frequency stabilizes to 140.150 GHz. For the first pulse, the cavity is cold and thus the free-running frequency at the start of the pulse is – as in the single shot in Fig. 5 – at 140.165 GHz. It takes longer for the free-running frequency to reach the set frequency of 140.150 GHz, which is reached after 2.5 ms, and is stabilized for 3 ms. At the second pulse, the cavity did not have enough time to fully cool down during the 40 ms without a pulse. The free-running frequency at the start of the pulse is therefore lower than for the first pulse and the set frequency is reached after 0.4 ms. For the third pulse, the cavity is heated up even more and the free-running frequency is again lower than the pulse before. The set frequency of 140.150 is already reached at the start of the pulse, which is also the case for the fourth pulse. To stabilize the gyrotron frequency at the start of each pulse for multiple consecutive pulses, the set PLL frequency depends on the duty cycle. After the first pulse, the frequency is much more stable during the first 3 ms with the PLL system compared to the free-running operation. Although less output power is achieved with the frequency stabilization due to the lower overall accelerating voltage, the output power levels is still in an acceptable level for the CTS diagnostic during the frequency stabilization.

The output spectrum of the gyrotron signal during the stabilized period is important for the CTS diagnostic, since it determines the width of the stopband from the notch filter at the CTS receiver. To fully characterize the frequency spectrum of the gyrotron, the frequency was stabilized for a pulse length of 5 s and the gyrotron IF signal was captured during the last 34 ms. In Fig. 7, the resulting spectrum of the frequency stabilized gyrotron pulse is shown and compared with the free-running operation. The spectrum is taken from the Fourier Transform of the gyrotron IF signal. In Fig. 7, a clear main peak is present. The spectrum from the frequency stabilized operation is normalized such

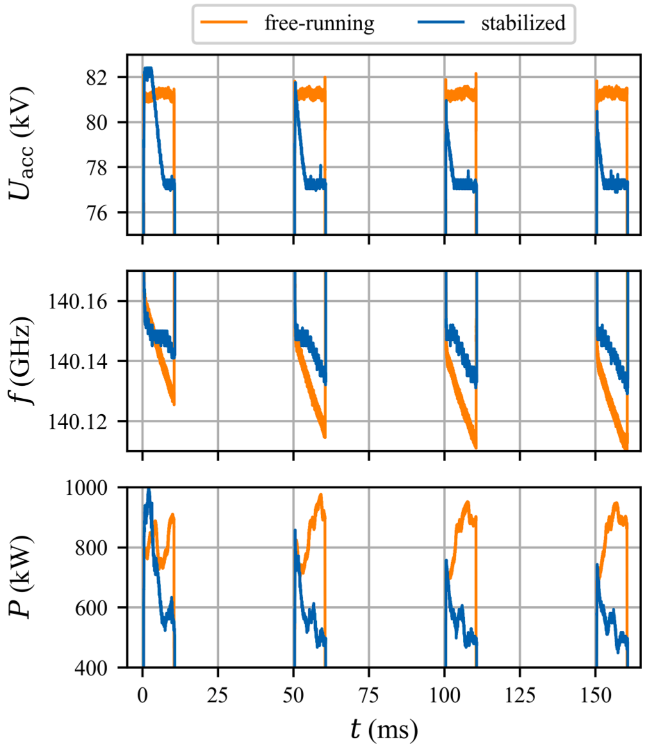

Fig. 6. Accelerating voltage, frequency and output power over time of W7-X CPI gyrotron for 4 pulses with 10 ms duration and 50 ms repetition time. Orange: free-running, blue: frequency stabilized.

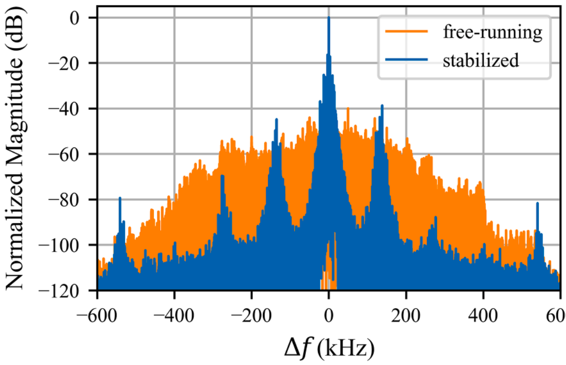

Fig. 7. Spectrum of the gyrotron IF signal. The spectrum is centered on the main peak of the spectrum, which corresponds to a gyrotron mm-wave frequency of 140.000 GHz.

that the main peak is at 0 dB. The free-running spectrum is normalized such that the noise floors of the free-running and of the frequency stabilized operation are the same. For the frequency stabilized operation one clear main peak is visible. The main peak is located at the set IF frequency of 45 MHz, which corresponds to a mm-wave frequency of 140.000 GHz. Without the stabilization, the spectrum does not have a clear main peak at a specific frequency and a much wider band of frequencies is present.

However, for the frequency stabilized operation, other side peaks appear in the spectrum. The most noticeable side peaks appear 135 kHz from the main peak and are -40 dB lower than the main peak. Other side peaks appear at 3.3 kHz from the main peak and are -16 dB lower than the main peak. The gyrotron main peak has a full -15 dB linewidth lower than 500 Hz. This shows the potential of such a frequency stabilization for the CTS diagnostic. With it, a much narrower notch filter can be used at the CTS receiver – increasing the accuracy of the ion temperature measurements and enabling other measurements such as IBW measurements of the main plasma species and impurities.

Investigations of the noise in the power supplies were conducted to determine the source of the side peaks. In the spectrum of the cathode power supply, frequency peaks at 3.3 kHz and 135 kHz were present. It is concluded that the PLL system with the body power supply could not fully counter the noise of the cathode power supply.

To conclude the investigations, frequency stabilization experiments with a gyrotron from manufacturer Thales [11] were conducted at 174 GHz with a new 7 T magnet. The oscillating mode for the 174 GHz operation is the $\mathrm{TE}_{34,10}$ mode, as described in [15]. The results are shown in Fig. 8. As for the 140 GHz operation, the frequency can be stabilized. Since the output power at 174 GHz is lower (300 kW), the cavity does not expand as fast as for the 140 GHz operation (> 600 kW). Therefore, less accelerating voltage is needed to counter the frequency drop and the frequency can be stabilized for the full 10 ms with only changing the accelerating voltage by 2.5 kV.

6. Conclusion and outlook

First proof-of-principle experiments were conducted at W7-X to demonstrate a PLL frequency stabilization system with gyrotrons in short-pulse operation for the CTS diagnostic. To stabilize the gyrotron frequency, the body voltage was modulated within a range of 5 kV. The first experiments at 140 GHz show that the gyrotron frequency could be stabilized at the beginning of the pulse for a duration of 3 ms. Analyzing the frequency spectrum of the gyrotron, a clear main peak with a full -15 dB linewidth 500 Hz could be achieved at the set PLL frequency. Furthermore, experiments with a new 7 T magnet were conducted at 174 GHz for the CTS diagnostic. The frequency could be stabilized for longer than 8 ms. The experiments show the potential to reduce the notch filter width of the CTS receiver and to improve the CTS diagnostic.

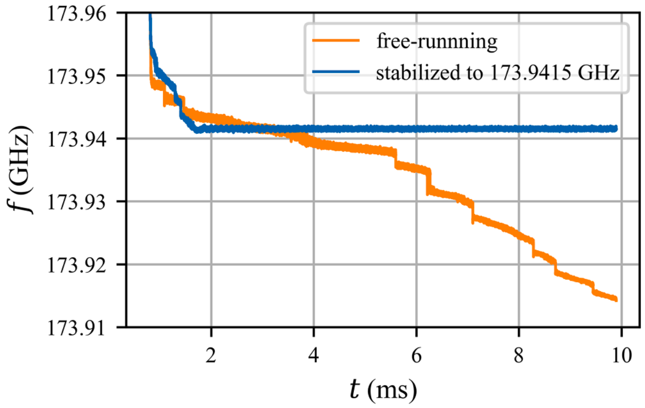

Fig. 8. Frequency over time for free-running (orange) and frequency-stabilized (blue) operation at 174 GHz.

To protect the CTS receiver when the gyrotron frequency is outside the stopband of the notch filter, a PIN-diode switch at the receiver entrance is closed.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

Data availability

Data will be made available on request.

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