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Experimental study of extended operating zone of a 170 GHz/1 MW gyrotron locked by a narrowband external signal

Andrey N. Kuftin, German Yu. Golubiatnikov, Vladimir A. Vilkov, Andrey P. Fokin, Yulia V. Novozhilova, Mikhail Yu. Glyavin, and Grigory G. Denisov

***Abstract*—For a gyrotron with operating frequency of 170 GHz and a megawatt power level, an expansion of the operating zone by 2.4 times compared to a free-running gyrotron was experimentally demonstrated in the frequency locked regime. The locking signal with the power not exceeding 16 kW was provided by a gyrotron-driver (pulse operating mode 100 μs/10 Hz) stabilized by the phase-lock loop. The expansion of the operating zone of the $TE_{28,12}$ mode into the region of lower magnetic field (compared to the free-running regime) was accompanied by an increase of output power by 10% and the improvement of efficiency from 32.1% to 35.2% due to advance to a more optimal cyclotron resonance detuning. The significant expansion of the operating zone in the region of greater magnetic field demonstrated the suppression of excitation of parasitic modes. In the frequency-locked regime the gyrotron radiation spectrum width was reduced to 20 kHz, defined by the locking signal from the stabilized gyrotron-driver, compared to the 2-4 MHz in stand-alone mode.**

***Index Terms*—gyrotron, frequency locking, tuning band, mode selection**

I. Introduction

DEVELOPMENT of powerful gyrotrons is directly tied with the development of controlled fusion plants [1]. The increase of magnetic field and plasma density requires the increase of the Electron Cyclotron Resonance Heating (ECRH) frequency [2], [3]. Combined with the output power requirements, it escalates the importance of mode selection in the gyrotron development. The frequency stability is another feature that is beneficial to the use of gyrotrons for plasma heating and diagnostics by the means of Collective Thomson Scattering (CTS) [4]. Even more applications can benefit from the coherent operation of several gyrotron systems: the electron cyclotron current drive in fusion reactors [5], particle acceleration [6] or wireless power transmission [7], [8]. Although, there are methods that provide mode selection of frequency stabilization, the use of frequency locking by an external narrowband signal can provide both.

The effect is well investigated theoretically [9]–[15], while the experiments are not so numerous [16]–[18]. In earlier works the magnetron was used as the source of the locking signal. The spectrum width of the external signal was comparable with one of the gyrotron radiation, therefore the frequency stability was not improved. The previous experiments mainly focused on investigating the dependency of the frequency locking zone width on the input power at a single operating regime of the powerful gyrotron. The recent experiments with the medium-power gyrotron as a locking source [18] were also performed without the frequency stabilization.

In this paper we investigate the frequency locking of the megawatt-class gyrotron by a narrowband external signal. The experiments were performed with a general scheme similar to one used in [18]. The 170 GHz gyrotron was operating at the $TE_{28,12}$ mode with the output power of 1 MW [19], and for this experiment the frequency of the 20 kW gyrotron-driver [20] was stabilized by the phase-lock loop [21]. The dependence of the width of the locking zone on the parameters of the powerful gyrotron at a fixed power and varying frequency of the external signal is investigated. The operating zone of the powerful gyrotron is extended due to suppression of excitation of parasitic oscillations. The extension to the lower magnetic fields is accompanied by the increase of output power by 10%, and the extension to higher magnetic fields allows to widen the frequency tuning range. The frequency stabilization of the megawatt gyrotron was confirmed by the spectral measurements in the locking regime.

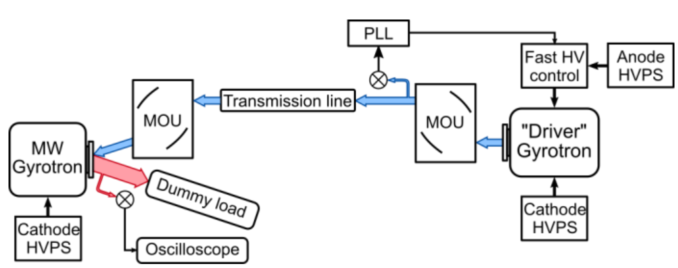

Fig. 1. The scheme of the experiment on the frequency locking of the 170 GHz MW-class gyrotron by a narrowband signal from the 20 kW gyrotron-driver.

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The authors are with the Federal Research Center A.V. Gaponov-Grekhov Institute of Applied Physics of the Russian Academy of Sciences (IAP RAS), 46 Ul'yanov Street, Nizhny Novgorod, 603950, Russia (e-mail: fokin@ipfran.ru).

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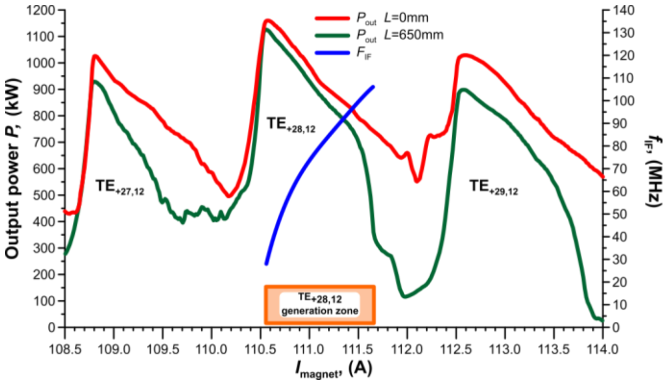

Fig. 2. The experimental dependencies of output power with the calorimeter placed directly on the output window and at the distance of 650 mm as well as the dependence of the generation frequency of $TE_{28,12}$ mode on the current of the main solenoid.

II. Experimental Setup

The scheme of the experiment is presented in Fig. 1 and is similar to the one used in [18]. The megawatt-class gyrotron with operating frequency of 170 GHz [19] had the internal quasi-optical converter designed for the transformation of $TE_{\pm28,12}$ modes of cylindrical waveguide rotating in directions coinciding (+) and opposite (-) to the rotation of electrons to two gaussian beams. The output of the radiation is performed through the same BN window, with the relative angle between beams corresponding to different rotation directions of 21.4 degrees. In the experiment, one of the channels was used to output the radiation of $TE_{+28,12}$ mode, while the other was used in reverse, to input the external signal into the resonator of the gyrotron. Such setup provided the correct rotation direction of the transformed external signal in the gyrotron resonator, coinciding with the rotation of the desired operating mode.

The gyrotron was operating at the accelerating voltage of 100 kV and beam current 35 A in the pulse-periodical regime with pulse duration of 50 µs and repetition rate 5-10 Hz. The beam parameters were fixed during the experiment. The maximum output power in this regime was 1.125 MW (Fig. 2) with the efficiency (ratio of the output power to the beam power) of 32.1% without the recuperation of the remaining electron energy. The width of the $TE_{28,12}$ operating zone on the current of the main superconducting solenoid I_{magnet} (magnetic field can be calculated using coefficient 0.0617 T/A) in the free-running regime was limited by the excitation of parasitic modes $TE_{-25,13}$ at the lower magnetic fields and $TE_{-26,13}$ at the higher fields. The excitation of parasitic modes is indicated both by the frequency measurements, as well as the drop of the measured radiation power at the water calorimeter placed at the distance of 650 mm from the output window compared to power measured at the window (Fig. 2). The parasitic modes have the opposite direction of rotation; therefore, they are radiated at a different angle and only the scattered radiation reaches the calorimeter. The frequency of the radiation for both gyrotrons was measured using the 13^{th} harmonic mixers, with the heterodyne frequency f_{LO} = 13057.4 MHz provided by a Keysight E8257D generators and intermediate frequency f_{IF} signal measured using Keysight DSAZ594A oscilloscope: f_{MW} & f_{driver} = (f_{LO}*N) + f_{IF} = 169746.2 MHz + f_{IF}. The spectrum width of the free-running megawatt gyrotron is about 3 MHz (Fig. 6a)

The locking signal was provided by the 20 kW gyrotron-driver, with the triode-type electron optical system [20]. The beam current was 2.8 A, the accelerating voltage 24 kV and the mean modulating anode voltage was 2.6 kV. The driver was also operating in the pulsed regime with pulse duration 100 µs and repetition rate 5-10 Hz. The frequency of the driver was stabilized by the phase-lock loop controlling the modulation-anode voltage [21], [22], with resulting spectrum width of the locking signal equal to 20 kHz, limited by the pulse duration (Fig. 6b). The frequency of the locking signal f_{driver} was tuned in the range of 115 MHz by varying the temperature of water in the resonator cooling circuit (see Fig. 3) from 5 °C to 50 °C, and within 4 MHz by the PLL system. The radiation from the gyrotron was transported to the MW gyrotron input by a transmission line consisting of corrugated waveguides 63.5 mm in diameter, five miter bends and two matching optics units (MOU). The MOU provided the correct matching of the field distribution and propagation direction between the driver output and transmission line, as well as between the transmission line and input of the MW gyrotron. To limit the coupling loses to less than 2%, the required alignment accuracy was less than 2 mm for the axial offset and less than 10′ of angular deflection [23]. Taking into account the losses in the transmission line and MOU, the power of the external signal at the window of the MW gyrotron was less than 16 kW. The pulse of the MW gyrotron was synchronized with the pulse of the driver signal, with delay of 40 µs from

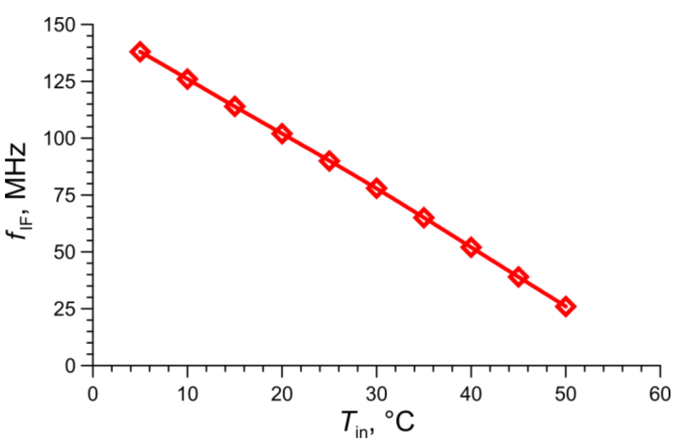

Fig. 3. The experimental dependency of the “driver” gyrotron generation frequency on the temperature of the water in the cooling circuit of the resonator.

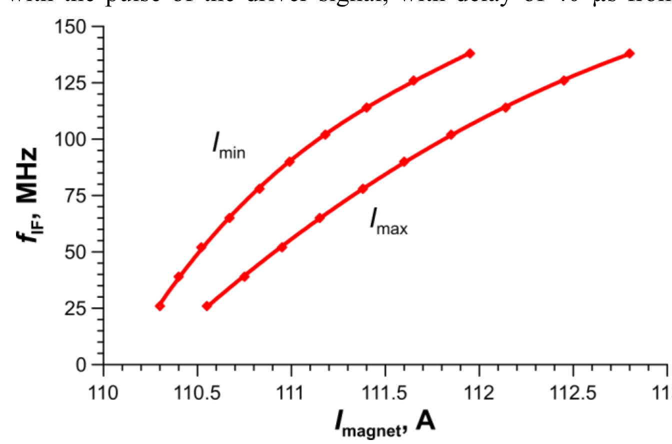

Fig. 4. The dependence of the locking zone boundaries on the current of the main solenoid of the MW gyrotron.

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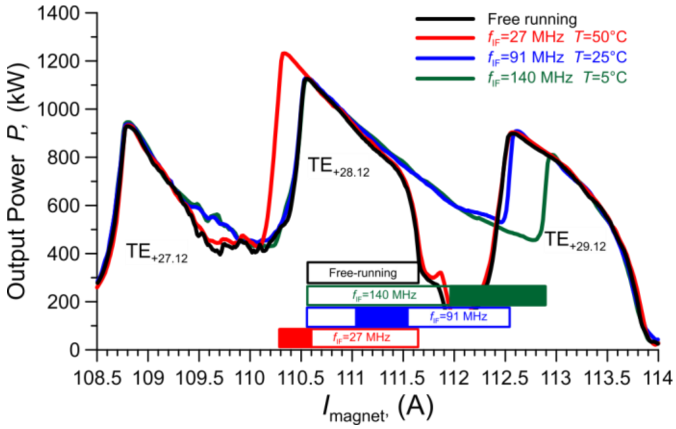

Fig. 5. The experimental dependencies of output power in the free-running regime and under the influence of the external signal with frequency at different frequencies. The shaded area depicts the locking zone.

the driver pulse start to allow the settling of the PLL system to occur.

III. Experimental Results

In the experiment the frequency of the external signal was set at a certain value, and then the current in the cryomagnet of the MW gyrotron was slowly varied to determine the boundaries of the locking zone, and the process was repeated for the full tuning range of the driver. The obtained dependency of the locking zone boundaries on the frequency of the locking signal and the cryomagnet current is presented in Fig. 4. Since the power of the locking signal was constant, and the output power of the MW gyrotron was varied by magnetic field, the measured width of the locking zone increases with the increase of the ratio of external signal amplitude to the amplitude of oscillations, in accordance with the theory of injection locking. Being that the locking zone is smaller than the operation zone of the free-running gyrotron in order to investigate the effect of frequency locking on the generation regimes of the MW gyrotron, the frequency of the external signal was tuned to a number of points. As a result, the position of the locking zone over the gyrotron operating zone was shifted (Fig. 5).

At the intermediate frequency (IF) of the locking signal of f_{IF} = 27 MHz (f_{driver} = 169773.2 MHz), the locking zone was placed at low magnetic fields, at the parameters corresponding to high output power and efficiency. In the locked regime the maximum achieved output power was increased by 107 kW from 1.125 MW to 1.232 MW (an increase of 10%) and the efficiency was improved from 32.1% to 35.2% due to advance to a more optimal cyclotron resonance detuning. The oscillations breakdown point was shifted by 0.25 A down the cryomagnet current, due to suppression of excitation of $TE_{-25,13}$ mode. Since the regime is close to the cutoff, the extension of the frequency tuning range in this regime is minor.

At f_{IF} = 91 MHz (f_{driver} = 169837.2 MHz) the locking zone was placed at the middle of the operating zone. There was no change in the output power or extension of the operating zone to lower magnetic fields. However, the excitation of parasitic $TE_{-26,13}$ mode at higher field was suppressed, even outside the locking zone. The operating zone was extended by 0.95 A into

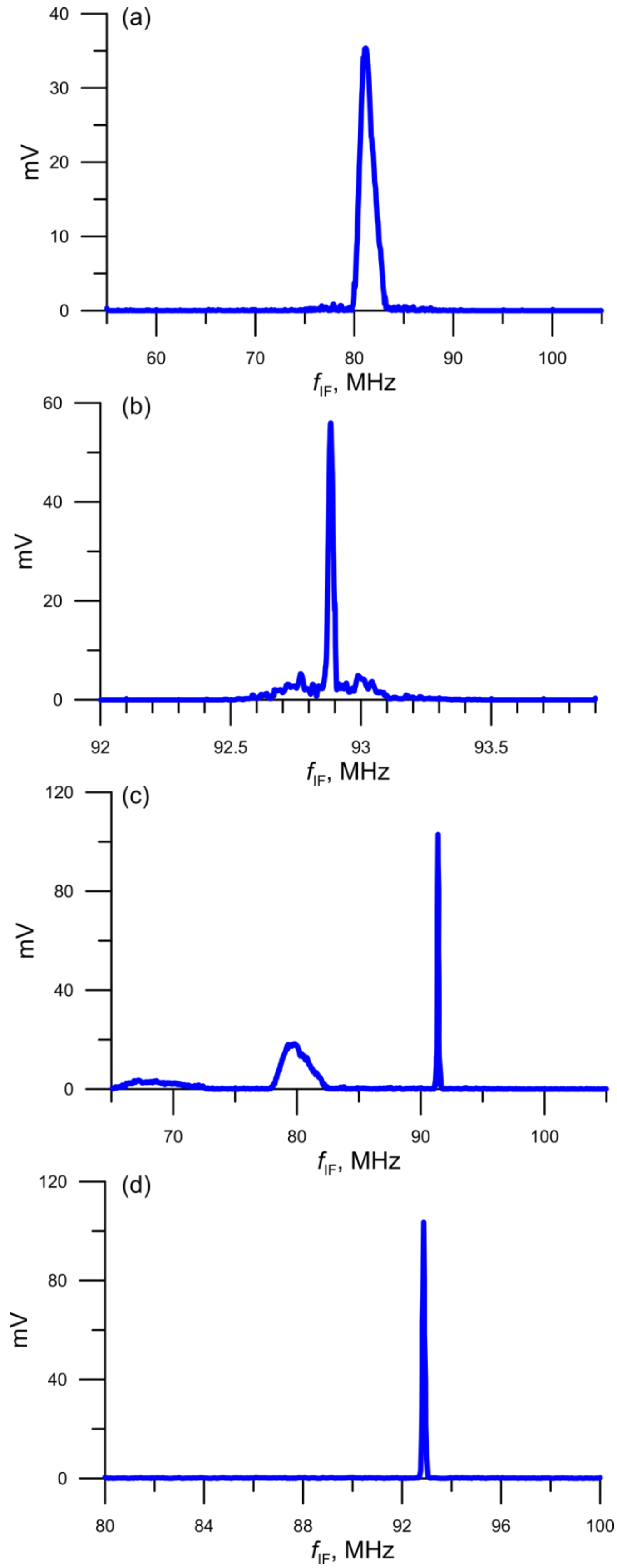

Fig. 6. The spectrums of the radiation: the MW gyrotron in the free-running regime (RBW 75 kHz) (a); the gyrotron-driver with the frequency stabilized by PLL in a 100 µs pulse (RBW 16.3 kHz) (b); the spectrum of the MW gyrotron at the boundary of the locking zone (RBW 75 kHz) (c); the spectrum of the MW gyrotron in the locking zone (RBW 75 kHz) (d);

higher cryomagnet currents.

With the intermediate frequency of the signal at 140 MHz (f_{driver} = 169886.2 MHz) the maximum extension of the operating zone at high magnetic fields was observed (Fig. 5). The operating zone boundary was shifted upward by 1.25 A, providing a significant increase of the frequency tuning range and completely suppressing the excitation of parasitic $TE_{-26,13}$ mode. The excitation of the next parasitic mode $TE_{29,12}$ mode was also noticeably suppressed, with its maximum power reduced from 0.9 to 0.8 MW. Considering the ability to change the frequency of the locking signal depending on the required regime, the total operating zone of the desired $TE_{28,12}$ mode was expanded by 2.4 times compared with the free-running MW gyrotron.

IV. Spectral measurements

The spectrum of the radiation was calculated using a recorded signal at the intermediate frequency f_{IF}. The signal of the driver was analyzed with the gate of 100 µs and resolution bandwidth (RBW) of 16.3 kHz, while the signal from the MW system was investigated with the 20 µs gate and 75 kHz RBW. The results of spectrum measurements are presented in Fig. 6. The spectrum width of the megawatt gyrotron in the free-running regime is 2-4 MHz (Fig. 6a), defined by the stability of the accelerating voltage power supply. The thermal dependence of the radiation frequency on time can be practically neglected for short pulses. The spectrum width of the driver stabilized by PLL is limited by the pulse duration of 100 µs and is close to 20 kHz (Fig. 6b).

At the boundary of the locking zone, the complex spectrum is observed (Fig. 6c): the narrowband (20 kHz) component corresponding to the frequency of the locking signal and a 3 MHz line separated by 8-15 MHz corresponding to the beating regime [24] outside the locking zone.

In the frequency-locking regime the spectrum of the powerful gyrotron and its generation frequency f_{MW} become identical to the spectrum and frequency of the locking signal f_{driver} (Fig. 6d). Thus, it is possible to achieve a narrowband megawatt power radiation within a relatively wide 115 MHz frequency band by simultaneous tuning of the powerful gyrotron parameters and the locking signal frequency.

V. Discussion

The experiment confirms the possibility of frequency stabilization and mode selection by locking with an external narrowband signal. However, the relatively low power of the locking signal and short pulse duration did not allow to achieve the maximum characteristics. The increase of pulse duration up to continuous wave regime should allow further reduction of spectrum width down to 1 Hz (as in [21]). The increase of the locking power should widen the locking zone [15], [24], making it possible to achieve a frequency-locked operation in the whole operating zone.

To further investigate the frequency locking of a gyrotron, the new MW continuous-wave gyrotron prototype with the operating frequency of 230 GHz was designed [25]. It has denser mode spectrum, so the suppression of parasitic modes is required to achieve full power. The design of the prototype has the improved quasi-optical converter which provides the input and output of the radiation through separate windows, which solves the non-symmetrical heating problem. The new 230 GHz 100 kW driver gyrotron was also developed.

VI. Conclusion

The operation of the 170 GHz gyrotron with the megawatt output power under the influence of the external narrowband signal from the 20 kW gyrotron-driver was investigated experimentally.

The possibility of significant expansion (2.4 times) of the operating zone of the desired $TE_{28,12}$ mode in the regime of the frequency locking with simultaneous tuning of the leading magnetic field of the MW gyrotron and the frequency of the gyrotron-driver was demonstrated. Such expansion is possible due to suppression of parasitic modes. Obtained experimental results confirm the possibility to use the frequency locking to provide mode selection in perspective high-frequency megawatt gyrotrons.

In the locked regime, expansion of the operating zone to lower magnetic fields due to suppression of parasitic modes leads to a significant increase in efficiency (by 3 %pt.) and power (by 10%) as a result of moving into the region of parameters optimal for efficiency. This makes it possible to create a system of phased radiation sources with practically unlimited integral power. Such systems are in demand, in particular, for electron-cyclotron plasma heating complexes in controlled thermonuclear fusion installations, since they make it possible to obtain high radiation power while maintaining the technical parameters of high-voltage power supplies.

The frequency locking allowed to improve the spectral characteristics of the 170 GHz/1 MW gyrotron. In the free-running regime, the width of the spectrum was about 2-4 MHz. In the locked regime, the spectrum width becomes equal to the spectrum width of the external signal, provided by the gyrotron-driver. Since the driver frequency is stabilized by phase-locked loop (PLL), the width of the locking signal spectrum is determined by the duration of its pulse duration of 100 µs and is about 20 kHz. The demonstrated improvement in spectrum width and frequency stability is of great importance for the plasma diagnostics by means of Thomson scattering.

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