Optimization of Megawatt 77-GHz Gyrotron Operation for Collective Thomson Scattering in LHD*)

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(Received 13 December 2012 / Accepted 21 February 2013)

To establish a method for suppressing the spurious radiation that interferes with collective Thomson scattering measurements with less degradation of the main mode output power, the frequency evolution, and the output power of the megawatt 77-GHz gyrotron were measured during operation under optimized parameters. According to a mode competition calculation, the main mode output power may be increased by setting a lower gyrotron anode voltage at a higher magnetic field strength in the gyrotron resonator. Although the output power increased from 300 kW to 530 kW without any spurious radiation when the optimized operational parameters were used, the output power was about 50% of that at a lower magnetic field strength, and thus the output pulse width was limited to 60 ms. When an approach using the optimized operational parameters and a PIN switch was applied, the output power increased to 800 kW without any harmful spurious radiation effect and the pulse width was expanded to 2 s.

Keywords: collective Thomson scattering, gyrotron, ECRH, LHD, ECE, mode competition

DOI: 10.1585/pfr.8.2402069

1. Introduction

For bulk and tail ion temperature measurements, collective Thomson scattering (CTS) measurement has been conducted using the existing electron cyclotron resonance heating system [1]. In the Large Helical Device (LHD), CTS measurement with high-power megawatt gyrotrons at a frequency of 77 GHz has been made to clarify the issues and develop the method [2].

CTS measurements have been made by modulating the gyrotron output power to subtract the background electron cyclotron emission (ECE) from fusion plasmas because the signal intensity of the ECE is non-negligible compared with the scattered signal intensity. The CTS receiver is composed of a narrowband notch filter for blocking the intense main radiation and a highly sensitive heterodyne radiometer. Spurious radiation outside of the notch filter frequency band is often observed by the CTS receiver during modulated gyrotron operation. Such spurious radiation interferes with the CTS diagnostic, even though its power is at least 50 dB below that of the main mode. In the present situation, such radiation saturates some receiver channels, blanks scattered signals, and renders those receiver channels unable to detect net scattered signals because of severe gain compression of the intermediate frequency (IF) amplifiers connected above them. Therefore, it is important to identify these spurious radiation modes and suppress or reduce them by optimizing the operational parameters of the 77-GHz gyrotron with less degradation of the main mode power. In addition, to explore the receiving beam in practical CTS measurement, a change in the CTS signal intensity depending on the scattering volume must be measured by scanning the receiving antenna angle. This requires a modulated output pulse width of longer than 1 s.

To date, spurious radiation at a frequency of 74.7 GHz has been observed in the transition phase of the anode voltage of the gyrotron, V_a. The observed spurious radiation mode was identified as $TE_{17,6}$ from calculations of the resonance condition of the resonator and a mode competition calculation. The latter also showed that in a certain range of the magnetic field at the gyrotron's resonator, B_c, the spurious $TE_{17,6}$ mode is hard to start, and the pure main $TE_{18,6}$ oscillation is possible during modulation [3]. As a

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*) This article is based on the presentation at the 22nd International Toki Conference (ITC22).

result, the spurious radiation at 74.7 GHz is suppressed by increasing B_c. However, the main mode output power significantly decreased [4]. As the output power increases, the signal-to-noise ratio of the CTS measurement improves, making the measurement possible. In this study, the radiation characteristics of the other 77-GHz gyrotron for practical application to CTS were measured, and another spurious radiation mode was observed, identified, and suppressed. Finally, a method for increasing the output power of the gyrotron without any spurious radiation signals and without sacrificing the output pulse width is discussed.

The characteristics of the spurious radiation in the 77-GHz gyrotron for practical CTS use are described in section 2. The experimental setup for the gyrotron frequency and output power measurements are discussed in section 3. The results of optimization of the gyrotron's operational parameters are presented in section 4. In section 5, the results of a method using the optimized parameters and a PIN switch are described. The conclusion and future plans are discussed in section 6.

2. Characteristics of Spurious Radiation in 77-GHz Gyrotron for Practical CTS Measurement

Figure 1 (a) shows an example of the RF monitor signal of the 77-GHz gyrotron for practical CTS use. Figures 1 (b) and (c) show the time evolution of the frequency spectrogram around the spurious mode of the 77-GHz gyrotron operating at $B_c = 3.025$ T, which is a setting value containing a ±1% error. The frequency measurement method is described elsewhere [3], and the setup is shown in Fig. 3. Spurious radiation appears at frequencies of 74.7 GHz and 79.3 GHz. The spurious radiation modes are identified as the $TE_{17,6}$ and $TE_{19,6}$ modes from calculations of the resonance condition of the resonator and a mode competition calculation. The latter estimates the oscillation amplitude of the excited RF field as the output power in the gyrotron resonator by alternately solving the equation of motion for electrons and the formula for the RF field. The details of these theoretical formulas and computations are described elsewhere ([5] and [4], respectively). The results of a mode competition recalculation considering the electric field profile of the $TE_{19,6}$ mode are shown in Fig. 2. The stable output power of each mode is plotted as a function of B_c. The result indicates that the radiation modes are dominated by the main $TE_{18,6}$ mode at 77.0 GHz, the spurious $TE_{17,6}$ mode at 74.7 GHz, and the spurious $TE_{19,6}$ mode at 79.3 GHz. In particular, around $B_c = 3.025$ T in region (I), the $TE_{17,6}$ mode is excited in the transition phases of V_a, as shown in Figs. 2 (a) and (b); furthermore, the main radiation mode $TE_{18,6}$ and spurious mode $TE_{19,6}$ are also excited during the settled phase, as shown in Fig. 2 (c). It is found that it is easy to suppress the spurious radiation during the settled phase by slightly increasing B_c, in contrast to the spurious $TE_{17,6}$ mode in the transition phase.

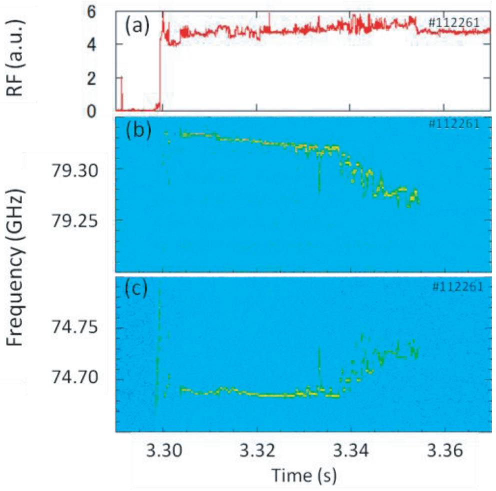

Fig. 1 Time evolution of (a) RF monitor signal, and (b), (c) frequency spectrogram around spurious radiation mode of 77-GHz gyrotron operated at $B_c = 3.025$ T.

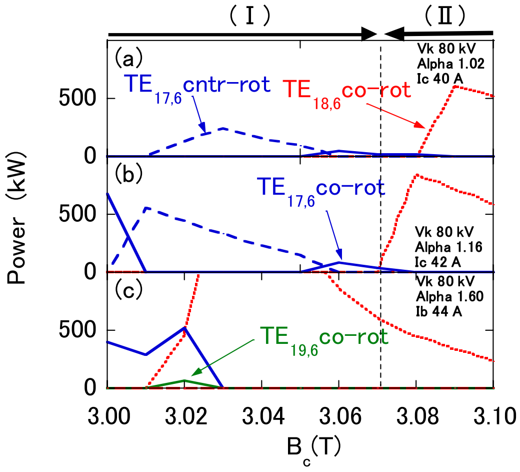

Fig. 2 B_c dependence of calculated output power of the gyrotron according to mode competition calculation.

3. Experimental Setup for Gyrotron Frequency and Output Power Measurement

The temporal evolution of the frequency of the oscillations in the output of the 77-GHz gyrotron was measured using a heterodyne receiver and a fast sampling digitizer connected directly to the IF outputs of the receiver. A block diagram of the heterodyne receiver system is shown in Fig. 3. The details of the heterodyne receiver and fast sampling digitizer are described elsewhere [3]. A PIN switch whose isolation is 70 dB was inserted after the low-noise IF amplifier to block the receiving signal at arbitrary times. In the CTS measurements and the experiment described in section 4, the PIN switch is used to block the receiving signal containing spurious radiation in the transition phase of V_a. Furthermore, during the measurements, calorimetric output power measurements were made with a

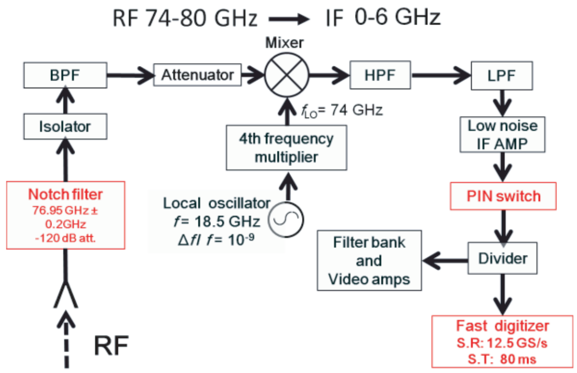

Fig. 3 Block diagram of heterodyne receiver system for frequency measurement.

water dummy load for each combination of the parameters of the gyrotron described in sections 4 and 5.

4. Optimization of Operational Parameters to Eliminate Spurious Radiation

To increase the output power and eliminate spurious radiation, the operational parameters were optimized, specifically B_c, the magnetic field strength at the magnetron injection gun (B_g), and V_a. The output power of the gyrotrons depends on B_c and B_g. Furthermore, the mode competition calculation shows that V_a also dominates the output power. The result of the mode competition calculation shown in region (II) in Fig. 2 indicates that the main mode output power in Fig. 2 (b) is higher than that in Fig. 2 (c). Therefore, the main mode output power may be increased by setting a lower V_a even at a higher B_c.

B_c, B_g, and V_a were optimized on the basis of the mode competition calculation described above. The results are shown in Figs. 4 and 5. Figure 4 shows the results of optimization of B_c and B_g. An open circle indicates an optimized combination of B_c and B_g at which spurious radiation is suppressed and the output power is maximum. Filled circles indicate combinations at which spurious radiation appears. Moreover, V_a was also optimized for the optimized combination of B_c = 105.2 A and B_g = 68.9 A. Figure 5 shows the result of optimization of V_a. The output power without any spurious radiation increases from 370 kW at V_a = 47.0 kV to 530 kW at V_a = 44.2 kV. Although the output power without any spurious radiation is increased by optimizing the operational parameters of the gyrotron, the output power is still about 50% of that at a lower B_c with spurious radiation, and the output pulse width is limited to 60 ms by the thermal load limit of the gyrotron's collector. In practical CTS measurement, the output pulse width must be longer than 1 s in order to explore the receiving beam. Therefore, a larger pulse width is required for scanning the receiving antenna angles. To resolve these issues, we applied a method using both the optimized operational parameters and the PIN switch.

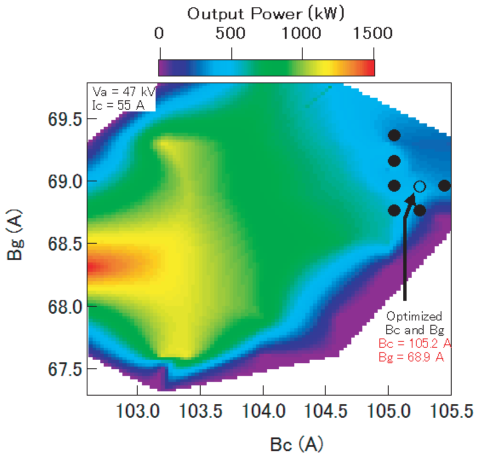

Fig. 4 B_c and B_g dependence of the main mode output power. Open circle indicates an optimized combination of B_c and B_g at which spurious radiation is suppressed and the output power is maximum. Filled circles indicate combinations at which spurious radiation appears.

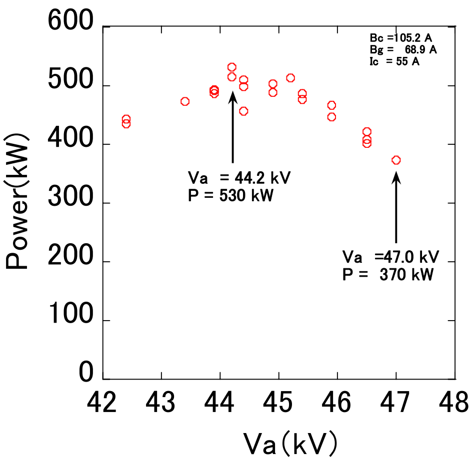

Fig. 5 V_a dependence of the main mode output power without any spurious radiation.

5. Optimized Operation for Scanning the Receiving Antenna Angles during CTS Measurement

To resolve the issues of low output power and short pulse width, as discussed in section 4, we applied a method using the optimized operational parameters and the PIN switch described in section 4. To date, it is found that the spurious radiation in the transition phase of V_a is hard to suppress without sacrificing power, as implied by the mode competition calculation shown in Fig. 2. To completely suppress the spurious radiation in the transition phase of V_a, even higher B_c operation is required than that in the settled phase. Therefore, the output power significantly decreases, and the output pulse width is limited because

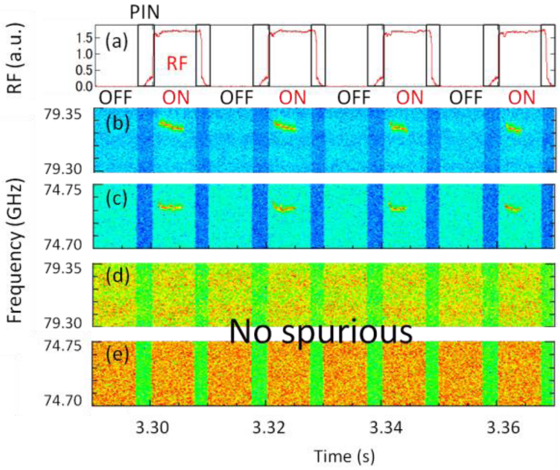

Fig. 6 Time evolution of (a) RF monitor signal (red solid line) and PIN switch gate timing (black squares); frequency spectrogram around spurious radiation modes of 77-GHz gyrotron operated at (b), (c) B_c = 3.025 T, and (d), (e) B_c = 3.033 T.

of the increasing thermal load on the collector. To avoid this problem, the spurious radiation in the transition phase of V_a was blocked by the PIN switch described in section 4, and the residual spurious mode that appears in the settled phase was suppressed by a slight increase in B_c that has little effect on the output power. The results are shown in Fig. 6. Figure 6 (a) shows the time evolution of the RF monitor signal and PIN switch gate timing. Figures 6 (b) and (c) show the frequency spectrograms around the spurious radiation mode of the 77-GHz gyrotron operated at B_c = 3.025 T, and Figs. 6 (d) and (e) show those at B_c = 3.033 T. We achieved operation in which the output power is 800 kW with the spurious mode blocked in the V_a transition phase and suppressed in the V_a settled phase. The increment in B_c is so small that the output power remains almost the same; thus, the output pulse width can be expanded to longer than 2 s, as in output power optimized operation.

6. Conclusion

To apply the 77-GHz gyrotron to CTS measurement in the LHD, the operational parameters were optimized according to a mode competition calculation. The optimized output power and output pulse width were 530 kW and 60 ms, respectively, with complete suppression of spurious radiation. When gyrotron output with higher power and longer pulses is required, it is demonstrated that a PIN switch is effective for blocking the spurious mode in the V_a transition phase and that a slight increase in B_c can suppress spurious modes in the V_a settled phase without degrading the output power and long pulse capability. Consequently, an output power of 800 kW and an output pulse width of 2 s are achieved without any spurious signals in an effective scattering measurement time span.

Now CTS measurement can be conducted using the optimized operational parameters without any harmful spurious signals and with less degradation of the output power and pulse width. Indeed, a receiving beam scan was conducted, and we confirmed an expected change in the CTS signal intensity depending on the scattering volume during a receiving antenna angle scan, which will be reported separately. Furthermore, optimized operational parameters for higher beam current operation of the gyrotron will be applied on the basis of the knowledge described in this study in order to improve the signal-to-noise ratio of CTS measurement.

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