Identification of Spurious Modes of High-Power 77-GHz Gyrotron for Collective Thomson Scattering in LHD*)

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(Received 9 December 2011 / Accepted 22 March 2012)

Frequency measurements at 74-80 GHz were conducted for the identification and suppression of spurious modes from the 77-GHz gyrotron, which was originally introduced as a power source for electron cyclotron resonance heating and is now also used as a probe beam for the collective Thomson scattering (CTS) diagnostic. The spurious modes are excited as the gyrotron output power is turned on and off by controlling the anode voltage. These modes are harmful for the CTS diagnostic, even though their power is less than approximately 50 dB below than that of the main mode. The measured frequency of one of the spurious modes is approximately 74.7 GHz. The cavity structure, starting current calculation, and mode competition calculation suggest that the spurious mode is the $TE_{17,6}$ mode. The result is important for optimizing the gyrotron operation as a CTS probe beam and suppressing or minimizing the spurious mode excitation.

Keywords: collective Thomson scattering, gyrotron, ECRH, LHD, ECE, transverse electric (TE) mode

DOI: 10.1585/pfr.7.2405061

1. Introduction

The collective Thomson scattering (CTS) diagnostic in the Large Helical Device (LHD) has been developed as a technique for measuring bulk and fast ion velocity distribution functions in high-density and high-temperature plasmas. The recent development of high-power radiation sources such as megawatt-class gyrotrons and the associated transmission/antenna system make it possible to detect the scattered electromagnetic waves by electron density fluctuations associated with the thermal ion motion in plasmas [1].

For bulk and tail ion temperature measurements in the LHD, the CTS diagnostic has been applied using the existing electron cyclotron resonance heating (ECRH) system with high-power megawatt gyrotrons at a frequency of 77 GHz [2, 3]. The CTS measurement has been conducted by modulating the gyrotron power to subtract the background electron cyclotron emission (ECE). When the gyrotron power is turned on and off, intense spurious radiation is often received by the highly sensitive CTS receiver. This spurious radiation negatively affects the CTS diagnostics, even though its power is less than 50 dB below that of the probing beam mode. In the present situation, this spurious radiation causes gain compression in intermediate frequency (IF) amplifiers or damages the mixer in the CTS receiver. Therefore, it is important to identify the spurious mode radiation and suppress or reduce it by optimizing the operational parameters of the 77-GHz gyrotron.

In section 2, we discuss the harmful effects of the spurious radiation on the CTS diagnostic and the necessity of its suppression. The experimental setup for the gyrotron frequency measurements is described in section 3. The results of the frequency measurements for the 77-GHz gyrotron are shown in section 4. Finally, the identification of the spurious radiation mode and a method of suppressing it are discussed in section 5.

2. Harmful Effect of Spurious Radiation on CTS Diagnostic

The power of the CTS probe beam is modulated to subtract the background ECE from the measured radiation. Figure 1 shows (a) an example of the RF monitor signal of the 77-GHz gyrotron and (b) an output of the CTS receiver. The receiver is composed of a narrowband notch filter and a highly sensitive heterodyne radiometer. The details of

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*) This article is based on the presentation at the 21st International Toki Conference (ITC21).

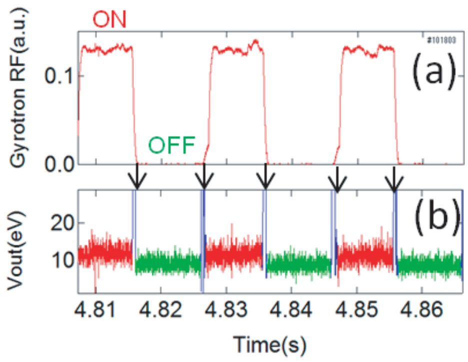

Fig. 1 Time evolution of (a) RF monitor signal of 77-GHz gyrotron and (b) CTS signals obtained by high-sensitivity heterodyne radiometer system [4]. Arrows in Fig. 1 (b) indicate spikes due to spurious mode radiation.

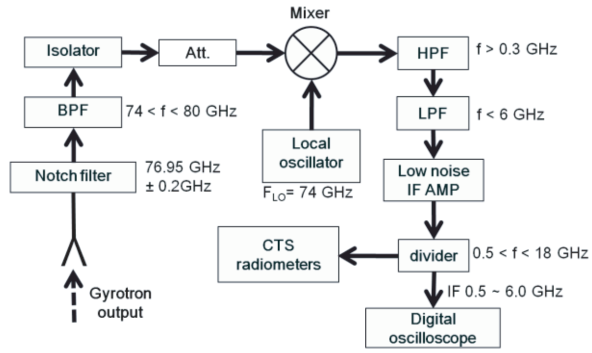

Fig. 2 Block diagram of the heterodyne receiver system for frequency measurement.

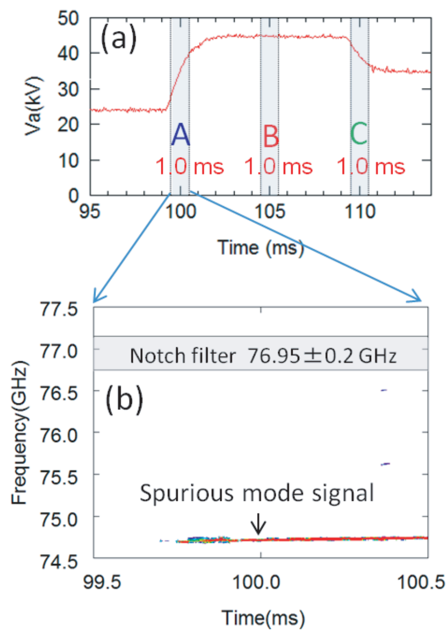

Fig. 3 Time evolution of (a) V_a and (b) the spectrogram of the output frequency of the 77-GHz gyrotron in the V_a range of 24 kV to 40 kV.

the CTS receiver are described elsewhere [4, 5]. As the power modulation is turned on or off, spikes due to spurious mode radiations are superimposed on the measured signal, which is the sum of the CTS component and background ECE. For precise estimation of the CTS spectrum, the received background ECE must be precisely subtracted from the received signal. Therefore, for precise CTS measurement, it is essential to develop a gyrotron operation method that suppresses or minimizes such spurious mode oscillation without degrading the main mode power.

3. Experimental Setup for Gyrotron Frequency Measurements

As the first step for suppressing the excitation of the spurious mode, 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 oscilloscope connected directly to the IF outputs of the receiver. A block diagram of the heterodyne receiver system is shown in Fig. 2. At the front end, two multi-stage notch filters with a bandwidth of 400 MHz and an attenuation of −120 dB at a central frequency of 76.95 GHz are placed to suppress stray highlevel radiation which can damage the mixer or produce a ghost signal at the mixer and saturate the IF amplifier. A bandpass filter rejects the lower side band of the mixer (74-8 GHz). IF signal at the upper side band of the mixer (0.3-6 GHz) is amplified by the lownoise IF amplifier. A mixer with a 74-GHz Gunn local oscillator is used to down-convert the gyrotron frequency spectrum for fast Fourier transform spectroscopy by a digital oscilloscope. The digital oscilloscope is operated at a rate of 20 G sample per second for 1 ms with a maximum bandwidth of 6 GHz.

4. Frequency Measurement of the 77-GHz Gyrotron

The output of the gyrotron is modulated by controlling its anode voltage V_a. Specifically, V_a relative to the cathode is optimized to provide stable, efficient gyrotron oscillation under a given beam current and magnetic field. The time evolution of V_a at the startup phase and half-modulation period is shown in Fig. 3 (a). The optimum V_a = 45 kV is settled at 3 ms after startup. It is subsequently modulated between 45 kV and 35 kV at 50 Hz. The radiation frequencies were measured during the (A) rising, (B) settled, and (C) falling phases of V_a. The spurious mode frequency was observed at approximately 74.7 GHz when V_a transited the rising and falling phases. Figure 3 (b) shows the time evolution of the spectrogram of the output frequency during the rising phase of V_a [indicated by hatched region (A) in Fig. 3 (a)]. Relatively strong oscillation at 74.7 GHz appeared at a V_a range of approximately 27-40 kV. The powerful main output $TE_{18,6}$ mode at 77.0 GHz was observed after V_a settled at approximately 45 kV [indicated by hatched region (B) in Fig. 3 (a)]. The spurious mode is considered to oscillate during the transition phases of V_a and the electron beam current of the gyrotron. The main powerful $TE_{18,6}$mode started to oscillate after V_a settled at 45 kV.

5. Identification of the Spurious Radiation Mode

The TE modes excited at the cavity can be identified by comparing the observed and calculated frequencies. The spurious mode frequency at 74.7 GHz observed by the measurements shown in section 4 is close to the calculated frequency of the $TE_{17,6}$ mode for the given cavity. However, to estimate the actual RF excitation and oscillation efficiency, it is important to consider electron beam matching with the cavity. Therefore, the results of the starting current and the mode competition calculation [6] for the actual RF power output must be considered. The starting current calculation shows that the $TE_{17,6}$ mode as well as the main $TE_{18,6}$ mode begin to oscillate relatively easily compared with the other modes under the measured conditions, as shown in Fig. 4. Here the starting current I_{start} is plotted as a function of the magnetic field strength at the cavity B_c for the $TE_{18,6}$ and $TE_{17,6}$ modes, which have a minimum I_{start} among several possible nearby modes in the scanned B_c range. Furthermore, the mode competition calculations show that the output power is dominated by the $TE_{18,6}$ or $TE_{17,6}$ mode under the measured conditions. In the mode competition calculation, V_a and the beam current I_c in Figs. 5 (a)-(e) are given as one of the input parameters. Table 1 shows the combinations of the parameters V_a, I_c, and the pitch factor α. These parameters, listed as (a)-(d) and (e) in Table 1, correspond to the transition phases and the almost settled phase shown in Fig. 5, respectively. Here α is the design value for V_a according to the magnetron injection gun calculations [7]. The mode competition cal-

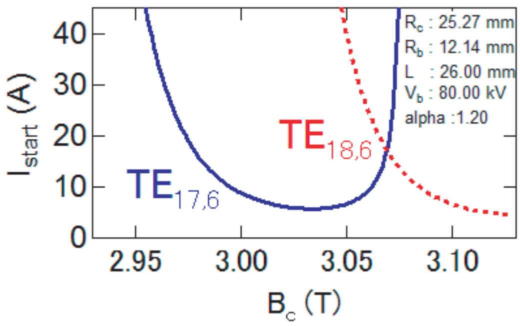

Fig. 4 Starting current calculation for the magnetic field in the cavity B_c. Designed cavity radius R_c = 25.27 mm, beam radius at the cavity R_b = 12.14 mm, cathode voltage V_b = 80 kV, and pitch factor α = 1.2 are used for calculation. $TE_{17,6}$ and $TE_{18,6}$ modes can oscillate above solid and dotted curves, respectively.

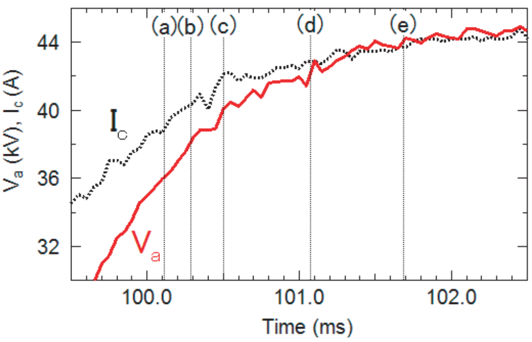

Fig. 5 Time evolution of V_a and I_c of the gyrotron. In the mode competition calculation, obtained values of V_a and I_c at (a)-(e) are used as calculation parameters. V_a and I_c are indicated by solid and dotted curves, respectively.

Table 1 Input parameters in mode competition calculation.

	Anode voltage V_a (kV)	Beam current I_c (A)	Pitch factor α
(a)	36	39	0.92
(b)	38	40	1.02
(c)	40	42	1.16
(d)	42	43	1.35
(e)	44	44	1.60

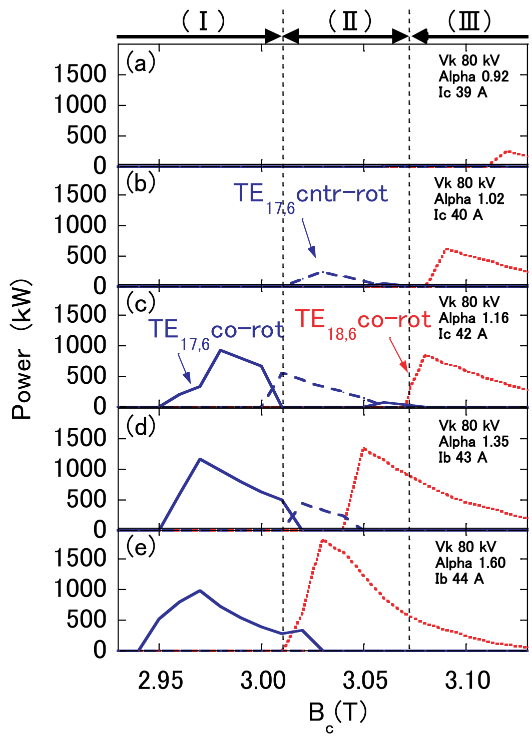

Fig. 6 B_c dependences of the calculated output power of the gyrotron according to mode competition calculation. $TE_{17,6}$ co-rotating mode, $TE_{17,6}$ counter-rotating mode, and $TE_{18,6}$ co-rotating mode are indicated by solid, chain, and dotted curves, respectively.

culation follows the transient evolution of the oscillation modes. The output power stabilizes at a certain level after a few hundreds of nanoseconds. The stable output power of each mode was plotted as a function of B_c. The results of the mode competition calculation with the input parameters given in Table 1 are shown in Figs. 6 (a)-(e), respectively. Three different magnetic field regions are identified, as shown in Figs. 6 (I), (II), and (III). In magnetic field region (I), only the $TE_{17,6}$ mode is excited throughout (a)-(e) in Fig. 6. The $TE_{17,6}$ mode is excited during the transition phase (a)-(d), and $TE_{18,6}$ is excited after the settled phase (e) in region (II). Only the $TE_{18,6}$ mode is excited throughout (a)-(e) in region (III). The magnetic field strength at the cavity in the frequency measurements was considered to be in magnetic field region (II). The spurious $TE_{17,6}$ mode was excited during the transition phase of V_a, and the main output mode $TE_{18,6}$ started to oscillate after V_a settled as a result of mode competition. It is expected that the spurious mode radiation can be suppressed by increasing B_c according to the mode competition calculation, as shown in region (III) in Fig. 6.

6. Conclusion

The frequency evolution of the 77-GHz gyrotron's output power for a modulated pulse has been measured in order to suppress the spurious radiation. The spurious mode frequency was approximately 74.7 GHz at the transition of the anode voltage. A calculation of the resonance condition of the cavity, the starting current, and the mode competition suggests that the observed spurious radiation mode is the $TE_{17,6}$ mode. The mode competition calculation also showed that a magnetic field range exists in which it is difficult for oscillation of the spurious $TE_{17,6}$ mode to start, and only the main $TE_{18,6}$ oscillation is possible. An experimental demonstration of spurious mode suppression under minimized main mode degradation is left as future work.

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