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P. Woskov
MIT Plasma Science and Fusion Center, Cambridge, Massachusetts 02139

H. Bindslev, F. Leipold, F. Meo, S. K. Nielsen, and E. L. Tsakadze
Risø National Laboratory, Association EURATOM, DK-4000 Roskilde, Denmark

S. B. Korsholm
MIT Plasma Science and Fusion Center, Cambridge, Massachusetts 02139
and Risø National Laboratory, Association EURATOM, DK-4000 Roskilde, Denmark

J. Scholten, C. Tito, and E. Westerhof
FOM-Institute for Plasma Physics Rijnhuizen, Association EURATOM-FOM, Trilateral Euregio Cluster, NL-3430 BE Nieuwegein, The Netherlands

J. W. Oosterbeek
Forschungszentrum Jülich GmbH, Institut für Plasmaphysik, Association EURATOM, D-52428 Jülich, Germany

F. Leuterer, F. Monaco, M. Muenich, and D. Wagner
Max-Planck-Institut für Plasmaphysik, EURATOM Association, D-85748 Garching, Germany

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High resolution frequency measurements of the 110 GHz gyrotron at TEXTOR and the 105 GHz mode of the two-frequency gyrotron (Odissey-1) at ASDEX Upgrade (AUG) have been made in support of fast ion collective Thomson scattering diagnostics. Measurements were done by harmonic heterodyne methods using both fast Fourier transform spectroscopy with digital oscilloscopes and fast scanning spectrum analyzers. Accurate frequencies were obtained with a frequency counter. At TEXTOR, at 180 kW forward power the starting frequency was 109.970±0.005 GHz and chirped down as much as 27 MHz depending on the duty factor. At AUG, at 500 kW forward power the frequency started at 104.786 GHz and chirped down 104 MHz, with 90% of the chirp occurring in the first 100 ms. Plasma perturbation of the TEXTOR gyrotron was observed when both ion cyclotron resonance heating antennas and neutral beam injection were operating, producing modulation at 29 and 58 MHz in the gyrotron output. Each gyrotron was observed to have an instrumental measurement limited linewidth of 120 kHz full width at half maximum. © *2006 American Institute of Physics.* [DOI: 10.1063/1.2347694]

INTRODUCTION

The application of gyrotron radiation to fast ion collective Thomson scattering (CTS) diagnostics[1,2] requires precise knowledge and control of the gyrotron frequency and spectrum. The gyrotron frequency must be accurately known and reproducible to tune narrow receiver notch filters to reject stray background signal, and the gyrotron linewidth including spurious modes must be less than 100 MHz over a large dynamic range (>100 dB) out to bandwidths of ±6 GHz around the center frequency to provide enough resolution and bandwidth for fast ion measurements. Even more precise knowledge of the frequency to <1 MHz is required for plasma rotation measurements.

Many factors determine the gyrotron frequency and spectrum. The gyrotron frequency and spurious mode content are affected by the dimensions of the resonator cavity and through the control of the operating parameters including the magnetic field, beam voltage, and current.[3] Plasma backreflection[4] and external interference in the environment of a major tokamak experimental facility from other high power electrical systems can also perturb the gyrotron. Previous gyrotron frequency measurements have been limited to laboratory environments and to low average power[3,5] or low power high cavity q devices,[6] or to peak frequency measurements.[7] This article summarizes precise, high resolution spectrum measurements of the high power 110 GHz gyrotron at TEXTOR (Ref. 8) and the 105 GHz mode of the two-frequency gyrotron (Odissey-1) at ASDEX upgrade[9] (AUG) being used for fast ion CTS diagnostics. The TEXTOR measurements were made during plasma diagnostic operation and resulted in the first observation of a gyrotron spectrum being perturbed by auxiliary heating in a tokamak.

EXPERIMENTAL SETUP

The TEXTOR and AUG gyrotron spectra were each monitored by two heterodyne systems, as shown in Fig. 1, sharing the signal from a single pickoff horn near the gyrotron output. One heterodyne system was a commercial spec-

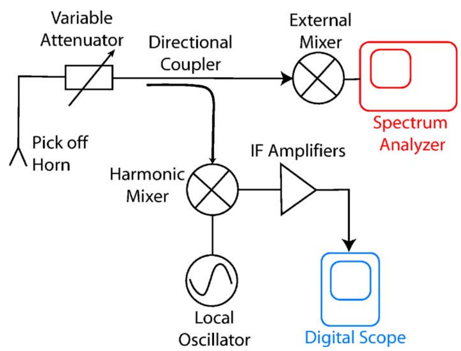

FIG. 1. Experimental setup for gyrotron frequency measurements.

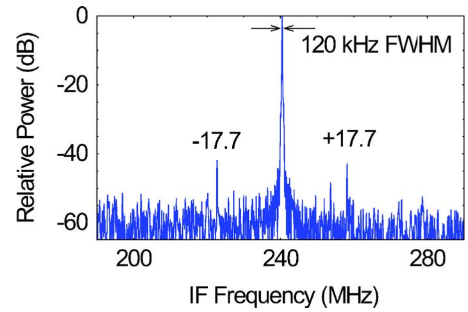

FIG. 3. TEXTOR 110 GHz gyrotron FFT spectrum downshifted to an intermediate frequency showing spurious ±17.7 MHz components that are sometimes present.

trum analyzer with an external mixer, which was an Agilent E4407B at TEXTOR and a Tektronix 492P at AUG. These spectrum analyzers were used to take repetitive frequency sweeps on about a 2 ms time scale over typically a 200 MHz bandwidth with a resolution bandwidth of 1 MHz. The second heterodyne system used a Pacific Millimeter Products MOD WM harmonic mixer operated at the tenth harmonic with an OMIYIG model YOM2228D yttrium iron garnet (YIG) tuned Gunn local oscillator (LO) to downshift the gyrotron spectrum for fast Fourier transform (FFT) spectroscopy by a digital oscilloscope. At TEXTOR the scope was a Tektronix TDS3032B and at AUG it was a LeCroy LC334AM. The digital scopes were operated at a 1 Gsample/s sampling rate to obtain one 10 000 point data set per gyrotron trigger, which resulted in a 10 μs long measurement sample with a maximum bandwidth of 500 MHz and a resolution bandwidth of about 120 kHz. The gyrotron frequency as a function of time during a pulse was studied on a shot to shot basis, by varying the trigger delay. Accurate frequency measurements were obtained by using the frequency counter option of the Agilent spectrum analyzer at TEXTOR or an EIP model 548 frequency counter at AUG to measure LO frequency of the harmonic mixer.

MEASUREMENTS AT TEXTOR

The frequency of the TEXTOR 110 GHz gyrotron chirped downward every pulse by a rate and a magnitude dependent on the average power output of the gyrotron, as would be expected by thermal expansion of the resonant cavity. Figure 2 shows this behavior for a peak output power of about 180 kW for three different duty factors. The starting frequency at this peak power setting occurs at 109.970±0.005 GHz as determined by many measurements over different days. The downshift was 27 MHz for a continuous 40 ms pulse, 23 MHz for a 50% duty factor pulse with 2 ms on and 2 ms off for 400 ms, and 20 MHz for a 20% duty factor pulse with 2 ms on and 8 ms off for 1 s. Typical operation for fast ion CTS diagnostics requires on/off modulation to be able to subtract the background noise from the weak scattered signal.

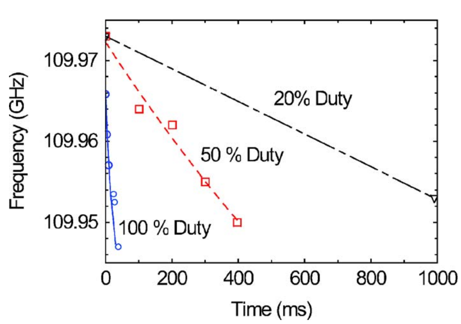

FIG. 2. TEXTOR 110 GHz gyrotron frequency dependence on pulse length and duty factor for approximately 180 kW output power. The gyrotron frequency was 109.960 GHz as measured with the spectrum analyzer.

The frequency spectrum of the gyrotron was found to be generally clean during most tokamak operations over the observed bandwidth and a dynamic range of up to 50 dB, except for weak 17.5±0.3 MHz satellites <-30 dB relative to the main peak, as shown in Fig. 3, and during combined ion cyclotron resonance heating (ICRH) and neutral beam injection (NBI) heating when ICRH (29 MHz) and harmonic satellites (58 MHz) were present in the gyrotron spectrum under some conditions. The 17.5 MHz satellites are not always present in the gyrotron spectrum and can appear whether TEXTOR is operating or not. Their origin is not yet understood.

The effect of combined ICRH and NBI heating on the gyrotron spectrum is shown in the top graph of Fig. 4 for plasma shot 100472. This spectrum is representative of several plasma shots under similar conditions. The gyrotron beam launch angle was −5°, that is 5° to the left from the low field side (LFS) midplane as viewed from the LFS to the high field side (HFS) (see Ref. 8 for a description of the launch antenna). The FFT spectrum was obtained 201 ms into a 2 ms on, 2 ms off gyrotron pulse triggered 2.45 s into the TEXTOR shot when 300 kW was launched from each of two ICRH antennas and with 0.5 MW NBI in the cocurrent torodial direction. The lower graph shows the spectrum for the next identical plasma shot 100473 except that the gyrotron beam was diverted to a beam dump. The 29 MHz component present in both these spectra is direct pickup by the measurement electronics and verifies that the measurement conditions were the same for obtaining both spectra. The interpretation of these spectra suggests that the gyrotron was perturbed by feedback through the gyrotron transmission line by a plasma ICRH modulated reflection. The insert figures show that when the gyrotron spectrum was perturbed, lower frequency amplitude fluctuations also increased in the forward power signal from a pickoff horn near the gyrotron output.

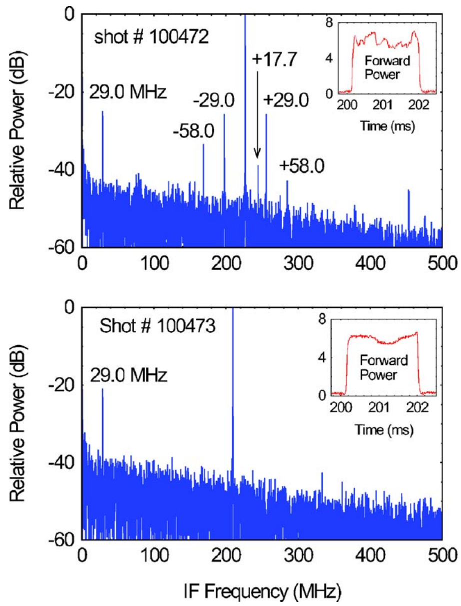

FIG. 4. Fast Fourier transform spectra of the heterodyne frequency downshifted TEXTOR 110 GHz gyrotron. Top spectrum for plasma shot 100472 obtained with both ICRH antennas (2×300 kW) and NBI (1 MW). Bottom spectrum for the next plasma shot 100473 with same conditions, but the gyrotron beam diverted to a beam dump. Inserts show forward power signal. Spectra were obtained at 201 ms and the peak gyrotron frequency was measured to be 109.951 GHz for these conditions on a previous shot.

In these initial measurements the gyrotron was not observed to be perturbed by the ICRH under different auxiliary heating combinations. With the gyrotron in the same $-5°$ launch direction there was no perturbation when both ICRH antennas were on without NBI even when the ICRH power was higher at 2×500 kW, or when only one ICRH antenna was on with NBI. In another measurement the gyrotron launch direction was changed to $-30°$ and no perturbation was observed with when both ICRH antennas where on with 1.2 MW NBI in the countercurrent direction. The polarization of the gyrotron was also adjusted during some of the measurements to optimize coupling to the characteristic propagation mode, which may not have been always achieved. More study will be needed to pinpoint the conditions and mechanism that cause this feedback, which seems be due to a driven plasma fluctuation under a very specific combination of auxiliary heating and gyrotron launch parameters.

MEASUREMENTS AT ASDEX-UPGRADE

The 105 GHz mode of the Odissey-1 gyrotron was found to start at about 0.4 ms after the gyrotron trigger at a frequency of 104.786 GHz. For approximately 500 kW output power and a 2 s pulse, it chirped downward 104 MHz, as plotted in Fig. 5, on a logarithmic time scale. Most of the frequency downshift occurs in the first 100 ms. At lower output power the frequency downshift has the same behavior, but the magnitude of the total downshift is reduced as indicated. For 335 kW the downshift was about 80 MHz and for 180 kW it was about 60 MHz.

When the gyrotron was modulated at 20 ms on and 20 ms off the frequency varied, as shown in Fig. 6, for

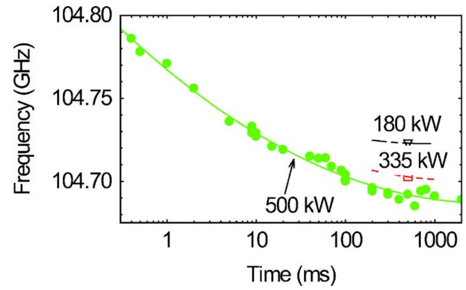

FIG. 5. Frequency dependence on pulse length and power of the 105 GHz mode of the ASDEX Upgrade Odissey-1 gyrotron.

500 kW peak power. The overall frequency downshift is the same as in the continuous pulse case except that it substantially recovers for each 20 ms pulse. This plot was obtained by a free running spectrum analyzer triggered with the gyrotron so the start instant of each 20 ms pulse was not always captured causing the ragged display of the peak frequency. The quick frequency recovery is due in part to millimeter wave turn on before the beam voltage stabilizes at the flat top and to efficient gyrotron cavity cooling. The importance of the latter effect was observed when the off time between pulses was reduced to less than 5 ms and the frequency recovery was seen to be much less.

The AUG gyrotron spectrum was also found to be relatively clean in the vicinity of the main peak and looked similar to the TEXTOR spectrum shown in Fig. 3 except without the spurious peaks. The observed linewidth of both the AUG and TEXTOR gyrotrons was found to be 120 kHz full width at half maximum (FWHM), corresponding to the instrumental measurement limit.

DISCUSSION

The frequency characteristics of gyrotrons are important to understand when applying them to CTS diagnostics. In the case of the TEXTOR 110 GHz gyrotron, the observed frequency downshift of about 20 MHz during a pulse and spurious spectral components of about ±17.5 MHz around the main peak are small relative to the minimum receiver channel bandwidth of 80 MHz and the notch filter bandwidth of about 300 MHz. These spectral characteristics of the 110 GHz gyrotron are therefore not a significant issue for fast ion or for bulk ion CTS diagnostics, but would need to be taken into account for plasma rotation measurements be-

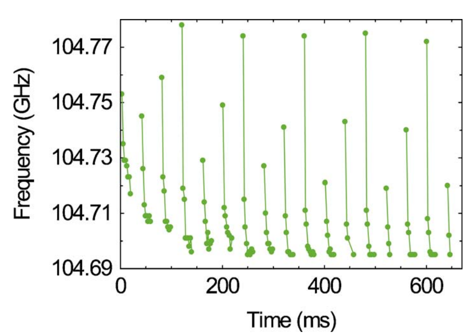

FIG. 6. Frequency dependence of the 105 GHz Odissey-1 gyrotron when modulated 20 ms on and 20 ms off at 500 kW.

cause the maximum Doppler shift due to plasma rotation would be of the same order as the gyrotron frequency chirp. Of more concern for ion diagnostics is the observation of the spectral broadening by the ICRH frequency and its harmonics. The observed second harmonic peaks of ±58 MHz around the main peak combined with the frequency downshift make a much more challenging background spectrum to notch out. Also there may be even higher harmonics present beyond the 50 dB dynamic range of the present measurements but above the thermal CTS cross section of less than −100 dB. The observation that the gyrotron can be perturbed through a long optical transmission line by combined ICRH and NBI heating in a tokamak of itself is a phenomenon that warrants future study.

At AUG the observed larger frequency downshifts of the gyrotron of up to 100 MHz are the same as the minimum 100 MHz CTS receiver channel bandwidths and could be an issue for CTS diagnostics. However, the largest part of the frequency shift occurs in the first 0–0.5 ms of each pulse depending on the off time before (i.e., amount of cooling time of the cavity) and the voltage rise after turn on. This early portion of large frequency drift can be blocked by a millimeter wave switch in the receiver front end to limit signal acquisition to the main part of each pulse where the frequency is not changing significantly, typically less than 20 MHz. Therefore, with its narrow clean spectrum of over 500 kW, the AUG two step gyrotron should be a good source for fast ion CTS diagnostics.

ACKNOWLEDGMENTS

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