New ECE diagnostics for the TEXTOR-94 tokamak

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To aid the scientific research program on the Toroidal Experiment for Technology Oriented Research (TEXTOR)-94 tokamak, the existing electron cyclotron emission (ECE) diagnostics for the electron temperature studies are being extended with new systems that feature a good temporal and radial resolution. Using the possibility of obtaining the data on a fast time scale, ECE systems allow one to study fast phenomena like the dynamics of small-scale structures such as magnetic islands and transport barriers and microscopic temperature fluctuations throughout the plasma. The quantitative information about nonthermal electron populations can be obtained from the comparison of the second and third harmonic emission. A new 16-channel frequency tunable radiometer and a four-channel second harmonic system were recently installed at TEXTOR-94. The detailed description of the new TEXTOR-94 ECE systems and the recent results will be given and discussed in this article. © *2001 American Institute of Physics.* [DOI: 10.1063/1.1309001]

I. INTRODUCTION

A large part of the future TEXTOR (Toroidal Experiment for Technology Oriented Research) research program will be concentrated around the observation of localized structures [e.g., transport barriers, filaments, magnetohydrodynamic (MHD) islands] in the plasma. Therefore, the number of electron cyclotron emission (ECE) diagnostics has recently been extended to open the way for new physics.[1] Although the spatial resolution of the ECE diagnostics (typically 1–4 cm) is not as good as that of Thomson scattering ($\approx$8 mm), the temporal resolution is up to several hundreds of kilohertz. This makes ECE systems perfectly suited for fast measurements of the electron temperature profile.[2,3]

An 11-channel heterodyne radiometer, three separate six-channel spectrometers and a four-channel third harmonic radiometer are already available (see Table I). The 11-channel X-mode radiometer with a spectral range between 105 and 145 GHz and an intermediate frequency (IF) bandwidth of 200 MHz is used to routinely measure the electron temperature profile.[4] It is absolutely calibrated by means of a hot-cold source, positioned in the tokamak vessel during machine venting. Three six-channel spectrometer systems are covering three separate frequency bands. Under standard plasma conditions the radial locations of the six-channel spectrometers are in the vicinity of the rational q surfaces. The main aim of the spectrometers is to perform high-resolution localized measurements of MHD phenomena.[4] The four-channel third harmonic radiometer is used for temperature observations in plasmas with a density that is so high that the second harmonic channels are in cutoff.[5]

In particular new systems are being developed by the

FOM-Institute for Plasma Physics ''Rijnhuizen:'' a 16-channel ECE imaging system (in collaboration with UC-Davis), a 16-channel frequency tunable heterodyne radiometer, and four-channel second harmonic radiometer, to be combined with the existing third harmonic system. The ECE-imaging system is described elsewhere in these proceedings.[6] This article will focus on the other two systems.

As can be seen in Table I, the ECE diagnostics on TEXTOR-94 tokamak ($R_0 = 1.75$ m, $a = 0.46$ m, $B < 2.9$ T) cover the frequency range of 98–180 GHz.

This article is organized as follows. The combined second/third harmonic radiometer is presented in Sec. II and the 16-channel frequency tunable radiometer in Sec. III. First results with the second-third harmonic radiometer are presented in Sec. IV. The 16-channel radiometer is being installed exactly at the moment of writing this article, therefore, first results are not yet available. A conclusion is given in Sec. V.

II. THE COMBINED SECOND-THIRD HARMONIC RADIOMETER

The main ECE diagnostic tool for the fast electron measurements on TEXTOR-94 is a new combined second (110.7, 113.3, 116.7, and 120 GHz) and third (166, 170, 175, and 180 GHz) harmonic system. This allows simultaneous measurement of second and third harmonic radiation from four radial positions in the plasma. The spectral bandwidth of each channel is 200 MHz. Quantitative information about the velocity distribution of nonthermal electrons can be obtained from a comparison of the optically thick second and optically thin third harmonic spectra.

The plasma millimeter-wave emission is received by a parabolic antenna located in the equatorial plane at the low field side (LFS) of the vacuum vessel. To avoid reflections

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TABLE I. ECE diagnostics on TEXTOR-94.

	T_e-profile radiometer	Spectrometers	Second/third harmonic radiometer	16-channel tunable radiometer	ECE imaging
No. of channels	11	3×6	4/4	16	16
Frequency	105,107,	104–114	111–120	98–146	113–145
	109,112	125–130	166–180		
Range	115(5)	133–148			
(GHz)	145				
IF bandwidth	200	200	200	400–3000	550
(MHz)		400			
Sampling	25	2000	25	100–2000	100–2000
Rate (kHz)		25			

from the opposite wall, graphite beam dumps are used. A notch filter at 110 GHz is installed to protect the mixers from gyrotron radiation used for electron cyclotron resonance heating (Fig. 1). A 10 dB directional coupler with an insertion loss of less than 1.3 dB is used to divide the radio frequency (rf) power between the second harmonic from the third harmonic branch. A 10 dB coupler, rather than a 3 dB coupler, is applied to ensure that still enough signal of the much weaker third harmonic emission reaches the detector. Since both systems view the plasma through the same antenna, and because the frequencies of the second harmonic systems are exactly 2/3 of those of the third harmonic system, they observe the same electron population.

The power coupled to the second harmonic section is passed through an image rejection (high pass) filter (106 GHz) to suppress the lower sideband. Then it is fed to a double-balanced mixer, where it is down converted by means of a 104 GHz Gunn oscillator (10 mW output) to an IF band of 6–18 GHz. Two cascaded IF amplifiers provide a total IF gain of about 65 dB. The intermediate signals are split in four branches using a power divider (insertion loss is about 7 dB), then it is bandpass filtered to IF frequencies of 6.7, 9.3, 12.7, and 16 GHz with a bandwidth of 200 MHz. After that, the signals are fed to Schottky diodes for detection. The resulting signal is conditioned by video amplifiers with a gain of 400 and a bandwidth of 10 kHz.

The receiver noise temperature was measured to be about 1.5 eV, in agreement with the calculations[7]

$$T_r = \frac{T_{\text{hot}} - Y T_{\text{cold}}}{Y-1} \approx 18\,000\text{ K} \approx 1.5\text{ eV},$$

where $T_{\text{hot}}=300$ K, $T_{\text{cold}}=77$ K (Li N$_2$), $Y=P_{\text{hot}}/P_{\text{cold}}=1.012$.

Although a crosscalibration is made with respect to the absolutely calibrated 11-channel heterodyne radiometer for every discharge, the minimum detectable electron temperature with the four-channel second harmonic system is typically several tens of electron volts. The reason for this is that the noise temperature of the total system increases by the losses in the front end, which was not included in the measurements of the noise temperature.

III. THE 16-CHANNEL FREQUENCY TUNABLE HETERODYNE RADIOMETER

The main part of this diagnostic is derived from the 20-channel radiometer that was used on the late Rijnhuizen Tokamak Project.[3] The scheme of the new 16-channel frequency-tunable heterodyne system is given in Fig. 2. The system is installed at the same toroidal position as the three existing high-resolution six-channel spectrometers.
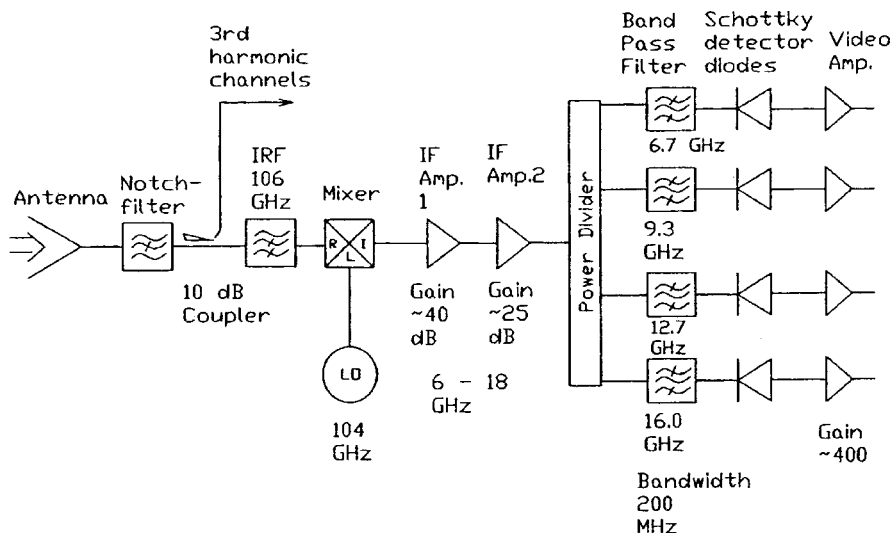

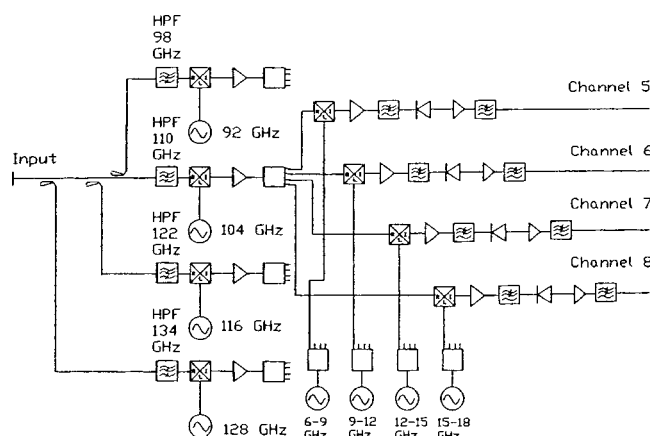FIG. 1. Second harmonic branch of the four-channel heterodyne ECE radiometer.

FIG. 2. Schematic view of the 16-channel tunable heterodyne radiometer. The second down-conversion stage is only shown for channel 5–8 for reasons of clarity.

The overall spectral range of the radiometer is 48 GHz, from 98 to 146 GHz, divided over 16 channels with a bandwidth of 3 GHz each. The rf signal from the antenna is split into four branches by directional couplers. Each branch transmits the signal to a front end for down conversion of the rf signal to an IF range of 6–18 GHz. By using different local oscillators (LO) with frequencies of 92, 104, 116, and 128 GHz the IF ranges for each branch correspond to different parts of the input radiation spectrum. High pass filters are used at the input of the mixers to suppress the lower sideband (similar as in the combined second-third harmonic four-channel system). In the IF stage, after the first down conversion, the signals are amplified and split into four branches by coaxial power dividers, followed by a second down conversion step to shift the frequency further down to a frequency band of 0–1.6 GHz for each channel by double sideband mixing. To do this, four LOs are required with different frequencies, to cover the input frequency band of 6–18 GHz. The result is a total amount of four times four is 16 signals. The yttrium iron garnet-tuned oscillators allow tuning of the central frequency over 3 GHz. The tuning bandwidth allows for neighboring channels to overlap each other, to make it possible to measure electron temperature fluctuations and their correlation lengths. The signals are amplified, low-pass filtered, and detected by zero-bias Schottky detectors after the second down-conversion stage. The cutoff frequency of the low-pass filters (LPF) can be selected from 1.5 GHz to 200 MHz in five steps. The radial resolution depends on the selected value of the LPF, the Doppler, and relativistic broadening, and is typically in the range of 1–2 cm. The output voltage of the detector is amplified with a programmable video amplifier (0–36 dB). Then, the signals are filtered with a 300, 500 kHz, or 1 MHz LPF and sampled with a maximum sampling rate of 2 Msa/s.

The total gain of the radiometer, from waveguide input to detector input is about 45 dB. The sensitivity of the radiometer is approximately 2.2×10^7 V/W, with a detector sensitivity of 700 V/W. The noise equivalent temperature T_{noise}, referred to the input of the receiver is about 2 eV. However, since the 16-channel radiometer is using the same antenna as

the three six-channel spectrometers, additional losses of about 10 dB have to be taken into account, due to waveguide losses and the directional couplers to redirect part of the rf signal to the spectrometers. The receiver noise temperature, referred to the antenna input, is 20 eV. The error ΔT on the temperature measurement, due to receiver noise, can be estimated from the equation[7]

$$\Delta T = T_{\text{noise}} \sqrt{\left(\frac{2B_V}{B_{\text{IF}}}\right)},$$

where B_V is the video bandwidth, and B_{IF} the IF bandwidth. For $B_V = 1$ MHz, $B_{\text{IF}} = 3$ GHz, and $T_{\text{noise}} = 20$ eV, one finds an error in the temperature measurement of $\Delta T = 0.52$ eV.

The possibility to tune the central frequency of the channels makes it possible to study the level of electron temperature fluctuations in TEXTOR-94 plasmas. Correlation lengths can be deduced by varying the different frequencies, and thus the distance between two neighboring channels. It is also possible to determine cross correlations between the 18 fixed channels of the spectrometers and the 16 tunable channels of the new system.

IV. FIRST MEASUREMENTS AND DISCUSSION

A unique feature of the combined second-third harmonic radiometer is that direct measurements and calculations of the reflection coefficient of the vessel are possible. This can be done for ohmic plasmas with a central density of $1.5-2.0 \times 10^{19}$ m^{-3}, where the plasma is optically thick for the second harmonic ($\tau_2 \sim 10-15$) but optically thin for the third harmonic ($\tau_3 \lesssim 1$, typically 0.4–0.8). Furthermore, one should take care that no nonthermal populations are present, which can be verified by looking to ECE emission at a frequency that corresponds to a radial location outside the plasma. The third harmonic signal depends on the electron temperature (measured at the same location by the second harmonic), the electron density (measured by a nine-channel interferometer) and on the unknown reflection coefficient. The measured reflection coefficient is 0.67 ± 0.12.

The density dependence of nonthermal electron population is investigated during ohmic shots. ECE time traces in Fig. 3 show that low energetic nonthermal electrons are very sensitive to small density changes. For $n_e \lesssim 0.76 \times 10^{19}$ m^{-3} a large generation of nonthermal electrons is observed. ECE time traces [Figs. 3(a) and 3(b)] indicate that a small density increase from 0.76×10^{19} m^{-3} up to 0.8×10^{19} m^{-3} at time 1.6 s causes a decay of the emission. The third harmonic signals (170 and 175 GHz) fall more rapidly than second harmonic (113 and 117 GHz) with the typical ECE intensity relaxation time 0.3 and 0.5 s, respectively, which is attributed to a reduction of the low energetic nonthermal electron population. From the maximum intensity of the third harmonic signal, corrected for relativistic downshift, it is concluded that the nonthermal population is located in the plasma center. A significant runaway population with energy of about 20 MeV is detected with a delay of about 1 s with respect to the low energetic nonthermal electron presence. From the neutron signal it is seen that highly energetic electrons are not directly responsive to small density changes.
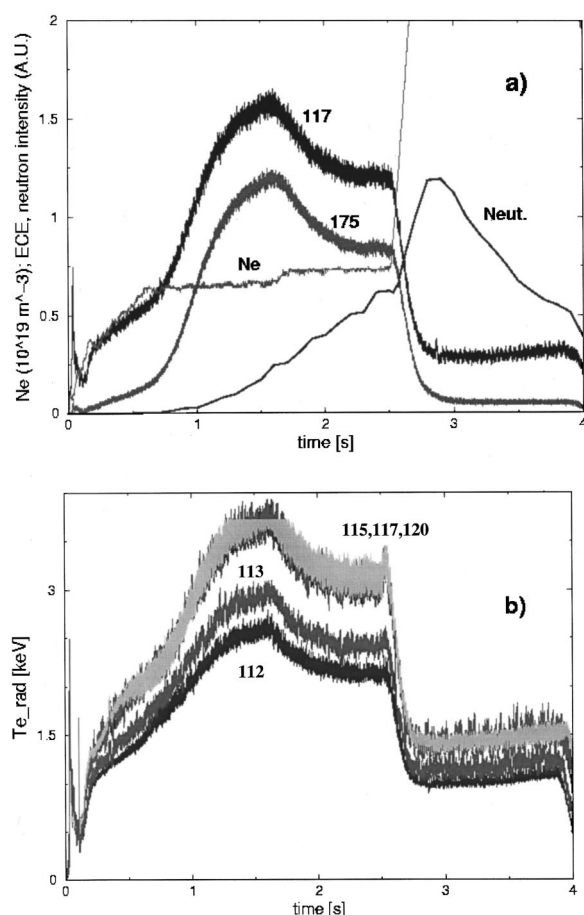
FIG. 3. ECE time traces, density, and neutron signals during a TEXTOR-94 low density discharge: (a) noncalibrated ECE signals (second harmonic 117 and third harmonic 175 GHz) and neutron (Neut.) time trace, calibrated density signal (Ne); (b) result of the crosscalibration with channels of 11-channel radiometer for the same shot. The new second harmonic ECE channels are 113 and 117 GHz. The 112, 115, and 120 GHz time traces are signals from the 111-channel radiometer. The signal from 111 GHz channel cannot be used now because of the broad bandwidth (1 GHz) of the notch filter to shield for the gyrotron frequency of 110 GHz.

However, they are affected by the substantial density ramp up due to a gas puff (Ne) at time ~2.6 s [Fig. 3(a)]. At this moment the low energetic electrons are lost immediately while high energetic runaways are still existing for more than 0.5 s after the gas puff has been started.

The three-dimensional NOTEC code,[8] simulating ECE spectra, has been adapted for TEXTOR-94 plasma conditions. A good agreement between experimental data and simulated spectra is obtained. Comparison of the measured and simulated for LFS ECE spectra indicates the presence of a nonthermal population with a density n_{nth} which is 0.08%– 0.2% of the full electron density $n_e = 0.8 \times 10^{19}$ m^{-3} and with a temperature $T_{nth} = 60$–100 keV. Figure 4 shows the full radiation temperature spectra for the second-third harmonic frequencies for the same TEXTOR-94 shot as in Fig. 3 at time 2 s. Due to saturation of a few high field side (HFS) heterodyne radiometer channels not all second harmonic experimental points (from 130 to 145 GHz) are indicated. The antenna specification in NOTEC is fully adapted to the present combined second-third harmonic system antenna.
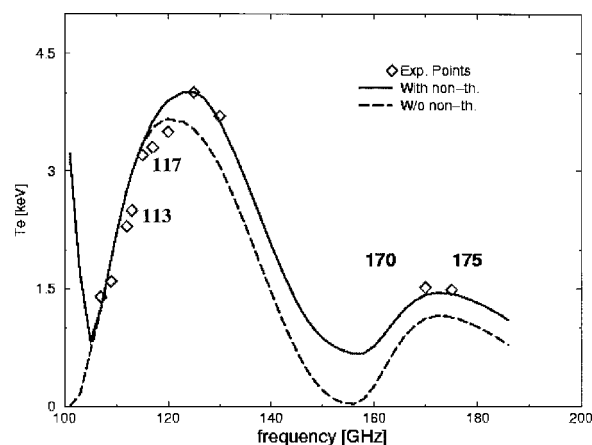

FIG. 4. Simulations with the NOTEC code of X-mode ECE spectra of a plasma ($T_e = 3.5$ keV, $n_e = 0.8 \times 10^{19}$ m^{-3}) observed from the LFS. The parameters are similar to those for the shot in Fig. 3. A significant nonthermal population ($T_{nth} = 80$ keV, $n_{nth} = 0.1\%$ from n_e) is detected. Two data points at the third harmonic (170 and 175 GHz) show the emission by the optically thin plasma ($\tau_3 \approx 0.35$). Also the simulations for the same plasma, but without nonthermal population are given for comparison. The experimental data are calibrated ECE signals. The measured reflection coefficient of 0.67 for the wall at the hfs was used in the simulations.

The total current carried by these low energetic nonthermal electrons is less than 1 kA compared to the full current of 240 kA.

V. CONCLUSION

Two new high-resolution ECE diagnostics have been installed at TEXTOR-94: a 16-channel frequency tunable radiometer to study small-scale structures and fast fluctuations in the electron temperature profile throughout the plasma, and a combined second-third harmonic radiometer to diagnose nonthermal electron populations. The latter system has already yielded physics results in the sense that nonthermal electrons in the plasma core have been observed.

ACKNOWLEDGMENTS

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