Non-thermal electrons in TEXTOR-94 tokamak plasmas.

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1. Introduction

Observation of non-thermal electrons in magnetically confined plasmas can be used to study the confinement of collisionless electrons and thus, it can improve our understanding of anomalous transport in tokamak plasmas. Measurements of 30 MeV runaway electrons on TEXTOR-94, diagnosed by infrared synchrotron radiation, showed an energy dependence of the runaway confinement. From these results, estimates about the scale length of the magnetic turbulence could be made [1]. Lacking in the interpretation was the experimental information about the lower energetic part of the fast electron distribution function. For that purpose a new Electron Cyclotron Emission (ECE) diagnostic has been developed to measure simultaneously the 2nd and 3rd harmonic X-mode emission at four radial locations.

2. Experimental set-up

The main ECE diagnostic tool for fast electron measurements on TEXTOR-94 (R_0 = 1.75 m, a = 0.46 m, B < 2.9 T) is a new combined 2nd (111, 113, 117 and 120 GHz) and 3rd (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. Quantitative information about the velocity distribution of non-thermal 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 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 (ECRH). A 10 dB directional coupler is used to separate the 2nd from the 3rd harmonic system. Since both systems view the plasma through the same antenna, they observe the same electron population. The power coupled to the 2nd harmonic section (see Fig.1) is passed through an image rejection filter to suppress the lower side band. Then it is fed in to a mixer where it is down converted, by means of a 104 GHz Gunn oscillator, to an IF frequency of 6 - 18 GHz. Two cascaded IF amplifiers provide a total IF gain of about 65 dB. The power is split in four branches using a power divider, then it is band-pass filtered to reduce the bandwidth to 200 MHz and 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.

Measurements with the method of ref. [2] showed that the receiver noise temperature is about 1.5 eV, in agreement with the calculations.

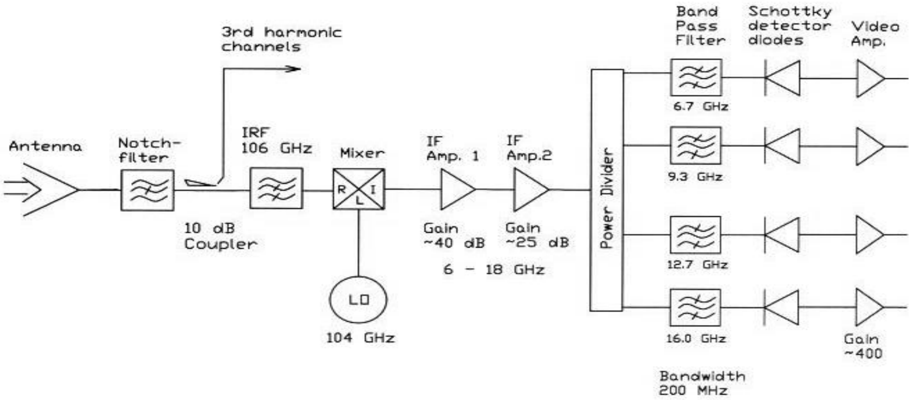

Figure 1. Four channels heterodyne radiometer (2nd harmonic branch).

An 11-channel heterodyne radiometer with a spectral range of 105 – 145 GHz and an IF-bandwidth of 200 MHz is also used for non-thermal electron studies and for cross-calibration with the combined 2nd–3rd harmonic system. This system uses a LFS horn antenna for the frequencies 105 – 125 GHz and a HFS parabolic one for the frequencies 130 – 145 GHz. Both antennas are located in the equatorial plane at a toroidal angle of 90° with respect to the 2nd-3rd harmonic radiometer. The 11-channel radiometer is absolutely calibrated by means of a hot-cold source, positioned in the tokamak vessel during machine venting. The cross-calibration of the signals from the combined 2nd-3rd harmonic system and 11-channel heterodyne radiometer has been made for each shot.

For higher energetic runaway electrons the ECE-systems are not suitable. The loss of runaways with energy of more than 10 MeV can be seen on the neutron diagnostics [1]. The threshold energy of about 10 MeV is determined by the TEXTOR-94 limiter material that is carbon. Confined runaway electrons can be detected by an infrared camera that observed the synchrotron radiation emitted in the forward direction. The sensitivity of the detector is limited by the optics [1], and is in the wavelength range of 3 – 8 μm.

3. Results and discussions

a) Reflection coefficient

A unique feature of the combined 2nd-3rd 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•10^{19} m^{-3}, where the plasma is optically thick for the 2nd harmonic ($\tau_2 \sim 10 – 15$) but optically thin for the 3rd harmonic ($\tau_3 \leq 1$, typically 0.4 – 0.8). Furthermore, one should take care that no non-thermal 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 3rd harmonic signal depends on the electron temperature (measured at the same location by the 2nd harmonic), the electron density (measured by a 9-channel interferometer) and on the unknown reflection coefficient. The measured reflection coefficient is 0.67 ±0.12.

b) Non-thermal electron studies under the density scan and ECRH

The density dependence of non-thermal electron population is investigated during Ohmic shots. ECE time traces in Fig. 2 show that low energetic non-thermal electrons are very sensitive to small density changes. For n_e = 0.8•10^{19} m^{-3} a large generation of non-thermal electrons is observed. ECE time traces (Fig. 2, a) indicate that a density increase from $0.8 \bullet 10^{19}$ m^{-3} up to $0.85 \bullet 10^{19}$ m^{-3} at time 2.5 s causes a decay of the emission. The 3rd harmonic signals (170 and 175 GHz) fall more rapidly than 2nd harmonic (113 and 117 GHz) with the typical ECE intensity relaxation time 0.3 s and 0.5 s respectively, which is attributed to a reduction of the low energetic non-thermal electron population. From the maximum intensity of the 3rd harmonic signal, corrected for relativistic downshift, it is concluded that the non-thermal 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 non-thermal electron presence. However, the neutron signal shows that highly energetic electrons are not directly responsive to such small density changes but affected by the substantial density ramp up. Soon after a gas puff (Ne) (Fig. 2, b) the low energetic electrons are lost immediately while high energetic runaways are still existing more than 0.5 s after the gas puff has been started [3].

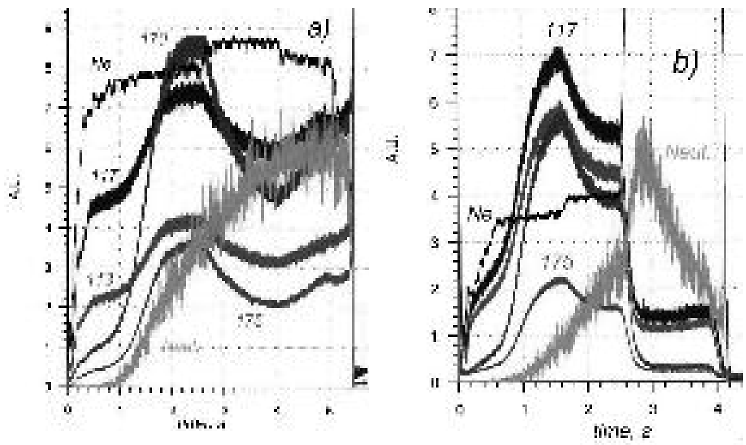

Figure 2. ECE time traces (113, 117, 170 and 175 GHz) show very high sensitivity of low energetic non-thermals for small (less than 5 %) density changes (Ne). Neutron signal (Neut.) indicates that runaway electrons are seemly unaffected to small density perturbations (a, b). A Ne gas puff has been started at 2.6 s (b). ECE signals are not calibrated on both figures.

Figure 3 shows a drop in ECE emission of about 20% during ECRH at 1.5 s (duration 80 ms, injected power 300 kW). This indicates a loss of non-thermal electrons due to a drop in the parallel electric field, which is seen as a decrease in the loop voltage. Another possible mechanism that can also take place is a degradation of the confinement of non-thermal electrons as a result of enhanced magnetic turbulence in the presence of ECRH. The synchrotron radiation and neutron time traces illustrate that the injected ECRH power has no direct influence to the high-energy runaway electrons.

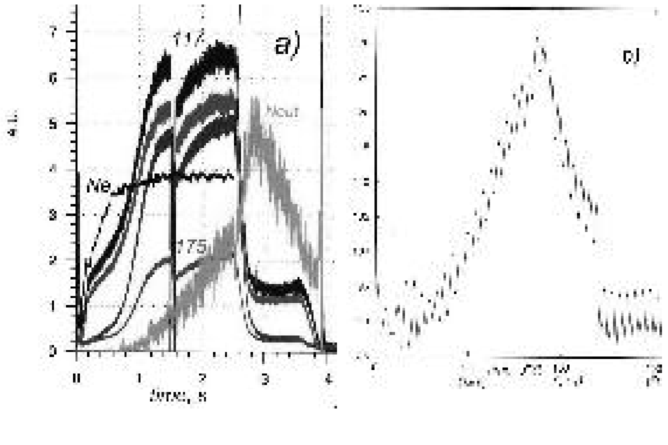

Figure 3. Low and high energetic electrons behave differently during ECRH (300 kW, pulse duration 80 ms) at 1.5 s. A loss of non-thermal electrons can clearly be seen on both 2nd – 3rd harmonic ECE signals (a). The neutrons signal (a, Neut.) and synchrotron radiation (b) indicates that runaways with energies up to 20 MeV are not directly sensitive to ECRH during this shot. Plasma density is $0.75 \bullet 10^{19}$ m^{-3}.

c) Simulations

The 3D NOTEC code [4], 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 non-thermal population with a density n_{nth} which is 0.08 – 0.2 % of the full electron density $n_e = 0.8 \cdot 10^{19}$ m^{-3} and with a temperature T_{nth} = 60 – 100 keV. Figure 4 shows the full radiation temperature spectra for the 2nd – 3rd harmonic frequencies for the same TEXTOR-94 shot as on the Fig. 2 b at time 2 s. Due to saturation of a few HFS heterodyne radiometer channels not all 2nd harmonic experimental points (from 130 to 145 GHz) are indicated. The antenna specification in the NOTEC is fully adapted for the present combined 2nd-3rd harmonic system antenna. The total current carried by these low energetic non-thermal electrons is less than 1 kA compare to the full current of 240 kA.

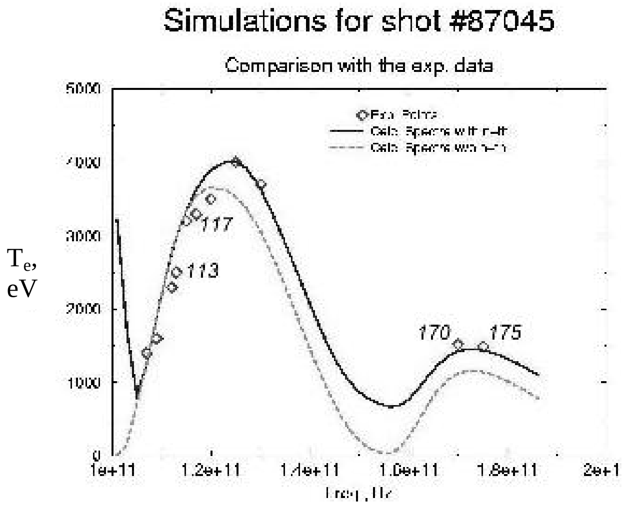

Figure 4. Simulations for LFS with the NOTEC code of X-mode ECE spectra of a plasma (T_e=3.5 keV, n_e= $0.8 \cdot 10^{19}$ m^{-3}) for the same shot as on the Figure 2,b. The significant non-thermal population (T_{nth} = 80 keV, n_{nt} = 0.1% from n_e) is detected. Two data points of 3rd harmonic (170 and 175 GHz) show the emission from optical thin plasma ($\tau_3 \approx 0.35$). The comparison with the simulations for the same plasma without non-thermal population is given. ECE signals are calibrated. Reflection coefficient is 0.67.

4. Conclusion.

Non-thermal electron population studies at TEXTOR-94 revealed a different behavior for low and high energetic electrons. Low energetic non-thermals are quite sensitive to small (less than 5 %) density changes and ECRH. The density changes and the ECRH power do not directly affect runaway electrons with energy of about 20 MeV. Simulations with the NOTEC for low-density TEXTOR-94 discharges (T_e=3.5 keV, n_e= 0.75-0.85$\cdot 10^{19}$ m^{-3}) show the presence of non-thermal populations with the temperature T_{nth} = 60 – 100 keV and density n_{nth} = 0.08 – 0.2 % from total electron density. These non-thermal populations are likely located in the plasma center.

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5. References.

[1] I. Entrop et al., Phys. Rev. Lett. 84 (2000) 3606.
[2] H.J.Hartfuss, T.Geist and M.Hirsch, Plasma Phys. Control. Fusion 39 (1997) 1693-1769.
[3] I.M.Pankratov et al**.,** Proc. 26th EPS Conf. Contr. Fusion and Plasma Phys., Maastricht 1999, Vol. 1, 96-99.
[4] R.M.J. Sillen et al., Rijnhuizen Report 86-165 (1986).