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Analysis of ECCD scenarios for the W7-X Stellarator by high-field-side ECE measurements

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From the earliest stages of W7-X operation, standard heating scenarios will be used, i.e. electron cyclotron resonance heating (ECRH) with perpendicular and oblique launch at the 2nd harmonic X-mode. The ECRH system is designed for continuous operation with total injected microwave power up to 10 MW at the frequency 140 GHz. W7-X is based on the concept of optimised confinement with low shear of the rotational transform, ι, and reduced bootstrap current. Because W7-X lacks an ohmic transformer, electron cyclotron current drive (ECCD) will be used for feedback control of the total plasma current to maintain the confinement properties. The possibility to perform this control is already being investigated with the help of a newly developed predictive transport code [1].

The scenario we analyse is a high power ECCD case with the deposition profile highly peaked near the axis [1] within $\Delta \approx 5$ cm. Plasma parameters correspond to expected values for the initial stage of W7-X operation: $n_e \simeq 3 \cdot 10^{19}$ m^{-3} with an almost flat profile, $T_e \simeq 4$ keV with a Gaussian profile, and B = 2.54 T on axis. The ratio of the absorbed power density P_{RF} and of the thermalisation rate, $\kappa = P_{RF}/n_e T_e \nu_{ee} \simeq 5 \cdot 10^{-4} P_{RF} \sqrt{T_e}/n_{20}^2$, where T_e is in keV and $n_{20} = n_e/10^{20}$, is a natural indicator of suprathermal population existance (in this case $\kappa \sim 1$). For $P_{RF} \lesssim$ 30 MW/m^3 we obtain $\kappa \simeq 0.35$, which is large enough to expect a significant disturbance of the electron distribution function. Fokker-Planck (FP) simulations with the neoclassical (stellarator-specific) loss model [2-3] also demonstrate a significant deviation of the distribution function from the Maxwellian in the heated region.

The tools for electron temperature diagnostic for W7-X are now under development, and apart from the standard ones, i.e. low-field-side (*lfs*) ECE measurements and Thomson scattering, the applicability and informativity of the high-field-side (*hfs*) ECE measurements needs to be checked. The *hfs* observations provide general information about the tails of the distribution function (see, e.g. [4-5]), but their interpretation is not trivial and requests special attention.

The ECE diagnostic system will be installed at the “bean-shaped” plane, where $\partial B/\partial R$ is largest. In this plane with the maximum of B no trapped particles exist, and only passing electrons populate the suprathermal fraction. For simulations of the ECE spectrum the bounce averaged distribution function was mapped along the axis to the maximum of B. Similar to [4], the ECE spectrum is obtained by integration of the radiative transport equation for both *lfs* and *hfs* cases with absorption coefficient and emissivity defined from the results of FP simulations.

We check the frequency range 115 GHz to 160 GHz, which more than covers the standard range of X2 observation for B = 2.5 T, i.e. 135 GHz to 160 GHz. From the point of view of analysing suprathermal effects, the low frequencies, which correspond to the cold resonances situated outside of the plasma, are most interesting for *hfs* ECE measurements. At the same frequencies, the *lfs* observation, in principle, also contains the suprathermal contribution, but it is strongly depressed by reabsorption.

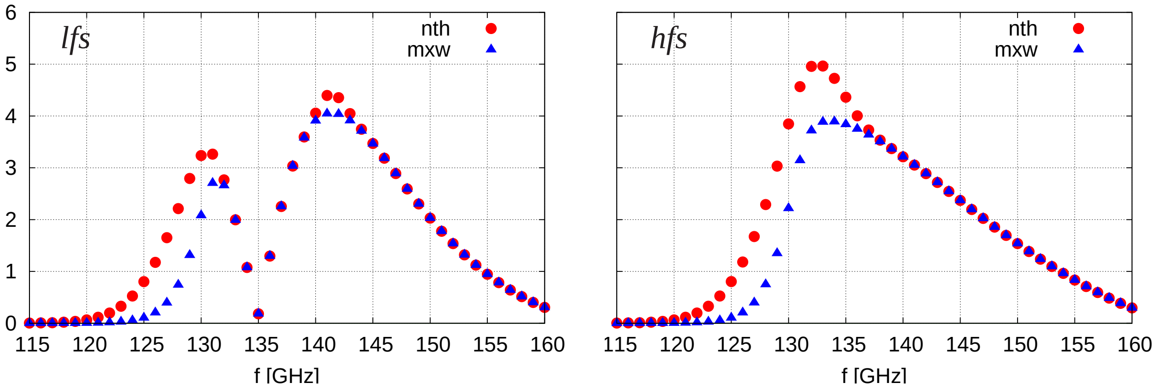

Figure 1: ECE spectrum for *lfs* (left) and the same for *hfs* (right) observations. Note, that the frequencies of less than 135 GHz correspond to the resonance points situated outside of the plasma.

Simulations of *lfs* observations usually give a spectrum with the big “hump” at the low frequencies. An example of this is shown in Fig.1, where the feature below 135 GHz corresponds to the (relativistically) down-shifted emission. One can also see that the existance of suprathermal populations produces a very small effect in the frequency range above 135 GHz for both *lfs* and *hfs* observations. At the frequencies under 130 GHz both the *lfs* and the *hfs* spectrum are almost identical. This is a consequence of the extremely poor reabsorption, and a transfer of the emission becomes, in fact, symmetrical for both the *lfs* and the *hfs*. Most informative for us should be the frequency range 130 - 135 GHz. Important is that the *hfs* and the *lfs* observations at the same frequency are related to quite different radial positions. This is illustrated by Fig.2, where the profiles of emissivity with and without reabsorption are shown. The main contribution in emission for the *hfs* observation at these frequencies comes from the plasma center, where the suprathermal population is largest. Observe, that for *lfs* the “center” of emission at the same frequency is much more peripheral ($R_* \approx 6.1$ m, that is about half the plasma radius) in comparison with *hfs* case ($R_* \approx 6.02$ m, that is near the axis).

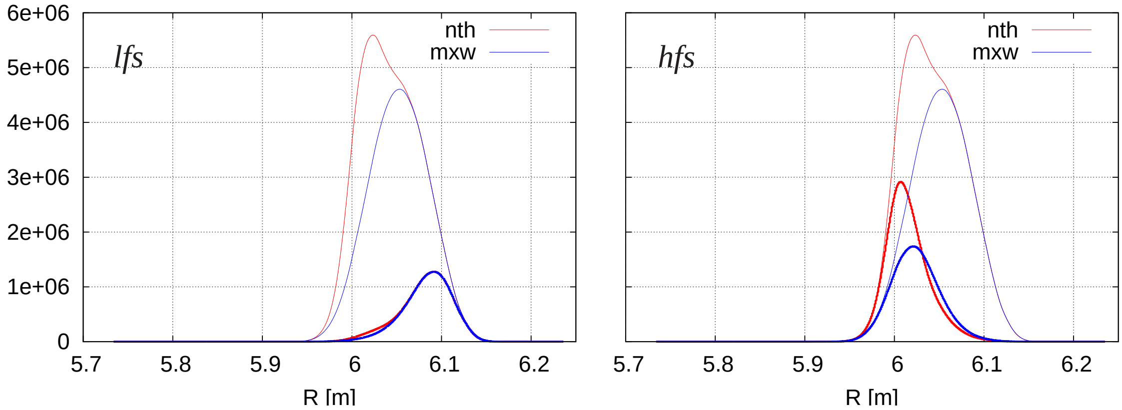

Figure 2: Frequency 132 GHz: emissivity with (thick lines) and without (thin lines) reabsorption for both Maxwellian (blue) and non-Maxwellian (red) distribution functions, obtained from FP simulations. The cold resonance point is located outside of the plasma ($R_{cy} \simeq 6.3$ m).

Estimated from the relativistic resonance condition the energy ranges of electrons, which contribute to the emission, are 25 - 45 keV for *hfs*, i.e. $E \sim (6-12) \cdot T_{e0}$, and 15 - 30 keV for *lfs*, i.e. $E \sim (15-30) \cdot T_{e,\rm per}$, respectively. FP simulations show that the main disturbance of the distribution function is also located at energies of 25 - 45 keV. However, the weight of this disturbance is quite different: being maximal on axis, from where the *hfs* emission is originates, it is almost nothing on the periphery (*lfs* case). It is clearly seen in Fig.2, where both Maxwellian and non-Maxwellian distribution functions produce quite different effects for *lfs* (small difference) and *hfs* cases (significant difference).

So far, the *hfs* observation can be used as an appropriate tool for diagnostic of the suprathermal effects. Note, that despite poor localisation of the emission, the *hfs* diagnostic can be used for a rough estimation of the deposition profile. In this case the standard measurements of the T_e profile have to be used to obtain the “non-disturbed” spectrum, and then the estimation of the deposition width can be obtained by comparing the measured and the simulated (for Maxwellian) spectra (see Fig.1). Another interesting possibility is to analyse the time behaviour of the selected low frequency channels during power modulation experiments and switching off the power. Comparison of the time scales for the *lfs* and the *hfs* can also give information about the weight of the suprathermal populations in the different regions, with and without heating.

For the *lfs* measurements the big low frequency “hump” of the ECE spectrum was observed during ECRH experiments at W7-AS [4]. It was also found that after switching off the ECRH power the low frequency emission decayed on a very short time scale, much shorter than the

T_e-decay times. The main conclusion was that these results cannot be simply interpreted as the emission by suprathermal electrons located within the narrow deposition profile. The power modulation experiments confirmed the assumption about the fast convective broadening of the distribution function disturbance.

Interesting, that during experiments the low frequency channels do not show so big spectral “hump” as predicted by theory for the *lfs* observation, if an existance of the suprathermal populations is not expected. The real distribution function cannot be Maxwellian up to extremely high energies, because of the natural limitations coming from the particle transport rate. Indeed, the simplest scaling of the time scale for the neoclassical transport in the $1/\nu$-regime is $\tau_{tr} \propto T_e^{5/2}/n_e$, and the ratio $\tau_{tr}/\tau_{ee} \propto T_e$ shows that on the periphery with low temperatures only bulk electrons should be Maxwellian (the electrons, which belong to the tails, are lost before any thermalisation). The tails on the periphery appear only due to the fast convection from the heated region. For example, if the main heating does not create any suprathermal populations of electrons (NBI, ICRH), the periphery distribution function can be expected to have “lost” its tails. If, on the other hand, during ECRH/ECCD scenario suprathermal electrons appear in the center of the plasma, the fast convective transport creates tails on the periphery.

Application of the *hfs* ECE diagnostic for the W7-X stellarator can have important advantages. The standard *lfs* diagnostic gives only the bulk electron temperature. Even the “hump” at low frequencies of the *lfs* spectrum is expected to be supressed due to the optimised confinement (the rate of the convective transfer of the distribution function disturbance from the center to the periphery is strongly reduced). At the same time, the *hfs* measurements always contain the information about the suprathermal population in the heated region. Due to of this possibility of observing the heated region directly from the *hfs*, the power modulation experiments should also be more informative in comparison with the *lfs*.

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