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Evidence of Non-Maxwellian Electron Bulk Distributions on JET

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Introduction

The electron temperature is usually determined, with both Electron Cyclotron Emission (ECE) and Thomson Scattering (TS) diagnostics, by measuring the average slope of the electron distribution function over a relatively narrow interval of energies, corresponding to electrons in the bulk of the electron distribution. In order to transform slope measurement into temperature measurement, a nearly Maxwellian bulk is assumed.

Recently, a significant violation of the assumption of Maxwellian bulk was shown to occur on FTU[1,2] in the presence of central electron cyclotron heating on the current ramp.[3,4] The reliance of enhanced confinement regimes on high levels of auxiliary power therefore makes one wonder to what extent that assumption is valid in general.

A puzzling result observed on TFTR during ICRF+NBI heating (injected power up to 7MW+30MW respectively) was that $T_{\mathrm{eTS}} < T_{\mathrm{eECE}}$ (up to 15-20% lower).[5,6] Since the two diagnostics weigh differently the bulk electrons, one may expect this to imply that the bulk was non-Maxwellian in those experiments. A new method of analysis of the ECE spectra examining the cyclotron emission over several harmonics, however, was inconclusive and not able to determine the cause of the temperature discrepancy between TS and ECE.[7]

The present work is motivated by a similar discrepancy between T_{eTS} and T_{eECE} observed on JET during ICRF+NBI heating (with or without the additional presence of lower-hybrid current drive). The analysis is inspired by the main idea of Ref. [7] — ie, the study of the measured ECE spectra over several harmonics of the electron cyclotron frequency — and takes it one step further by using the full frequency range of the spectra measured by the Michelson spectrometer, including also the first harmonic depolarized ordinary mode.[8] Instrumental effects — the Michelson instrumental function, and the effect of the antenna pattern in both poloidal and toroidal directions — are included in the analysis as well. A manageable computation time is obtained by using a parallel code for the computation of the ECE spectra for an arbitrary electron distribution function.[1] Predictions, stemming from the analysis of the ECE spectra and from the non-Maxwellian electron distribution function that is thus determined, are then given for the Thomson scattering temperature profile, by computing the relativistic Thomson scattering spectra[1] for the ECE-determined distribution function.

Determining the bulk distribution from the ECE spectra

On JET, the ECE spectra are measured in the *X*-mode polarization by an absolutely calibrated Michelson spectrometer, viewing the plasma in a plane parallel to the equatorial plane, from the low-field side and normally to the toroidal magnetic field. Figure 1 shows a typical spectrum measured by the spectrometer during ICRF+NBI heating (5MW+15.7MW).

In order to interpret the spectrum, one has to determine the phase-space location of the emitting electrons: for each frequency ν, there is a plasma volume (described by a line-shape function) centered at $x_{\mathrm{rad}}(\nu)$ ($x = \pm r$), that contains the resonant electrons; let $u_{\mathrm{rad}}(\nu)$ be their average momentum. The width of the plasma volume is determined by the optical thickness of the frequency ν: the larger the optical thickness, the narrower the width (and

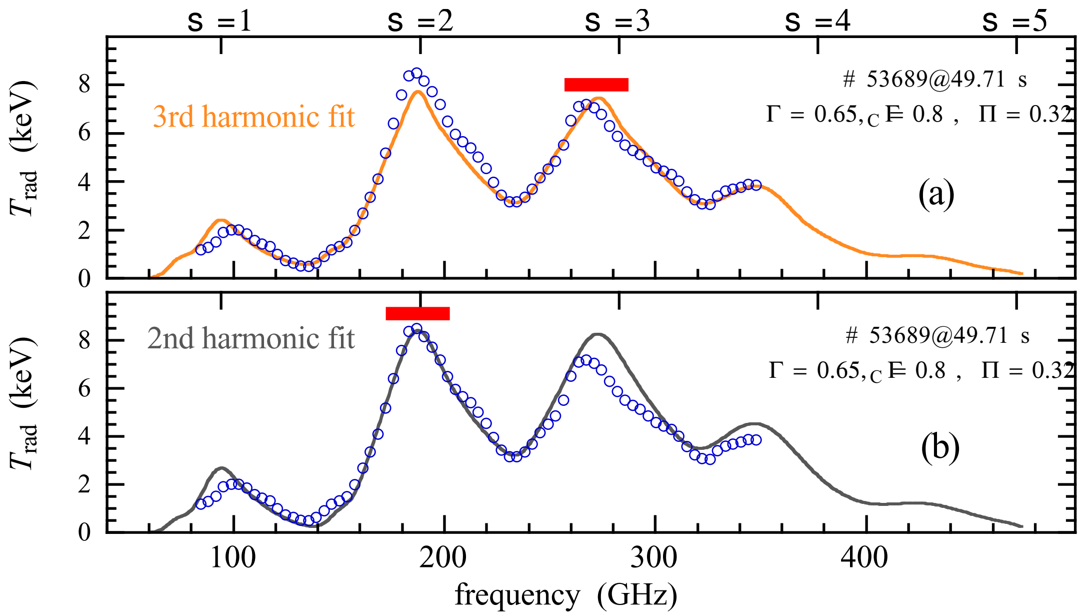
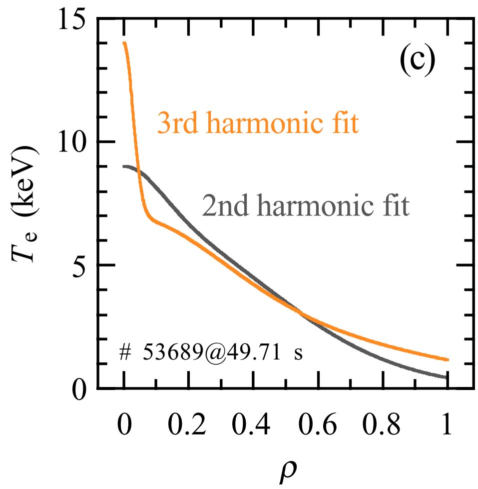


Fig. 1 *Two fits to the measured Michelson spectrum (circles), obtained by fitting either (a) the range of frequencies resonant at the 3rd harmonic, or (b) the one resonant at the 2nd harmonic. The top scale gives the harmonic number, s, for on-axis resonant electrons.*
(c) The two different temperature profiles that are deduced from the previous fits. [Observe that the edge temperatures are different because of the different core temperatures: the measured (nominal) edge temperature is a combination of edge and core temperatures.]



the lower their average momentum). If the electrons can be described by a Maxwellian distribution function, the radiation temperature is the convolution of the local electron temperature with the line-shape function; when the distribution is non-Maxwellian, the averaged quantity is the inverse of the perpendicular slope of the distribution function evaluated at the local resonant momentum $u_{res}(x)$.

The argument supporting the main result of the paper (Figs. 2 and 3a) is that in a multiharmonic spectrum there exist several frequencies for which, on average, the emitting electrons are located at the same position but have different momenta.[8] In the core of hot and dense plasmas, in particular, there exist at least four such groups of frequencies for which the emitting electrons belong to the bulk of the electron distribution. From these frequencies, one can determine whether the bulk distribution function is Maxwellian.

The spectrum shown in Fig. 1 presents an anomaly: both 2nd and 3rd harmonic emission is optically thick, therefore the radiation temperature corresponding to each harmonic should be the convolution of the corresponding line-shape function (the 3rd harmonic one is broader than the 2nd one) with the same electron temperature profile, if the electron distribution function were Maxwellian. This is not the case: two mutually incompatible temperature profiles fit the two harmonics (Fig. 1c).

The anomaly of the spectrum appears to be authentic since the same fitting procedure applied to ohmic spectra works well, and this seems to exclude both calibration problems, and modelling inaccuracy as the cause of the anomaly. Figures 2 and 3a show how a model

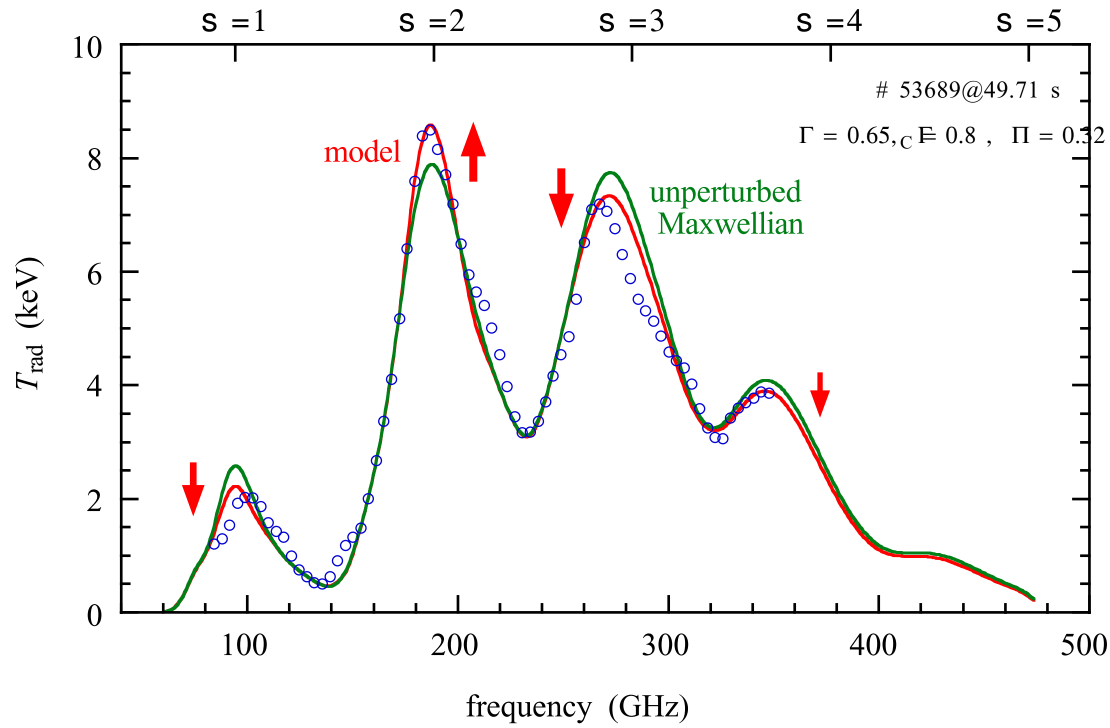


Fig. 2 *Two-step determination of the model distribution function that fits the experimental spectrum: 1) intermediate fit to both 2nd and 3rd harmonic emission peaks, assuming a Maxwellian distribution function. 2) perturbation of the Maxwellian by flattening (steepening) its slope at momenta corresponding to electrons emitting at the 2nd harmonic (at the 1st, 3rd, and 4th harmonics); see also Fig. 3a. The distribution function is assumed to be Maxwellian for ρ > 0.35.*

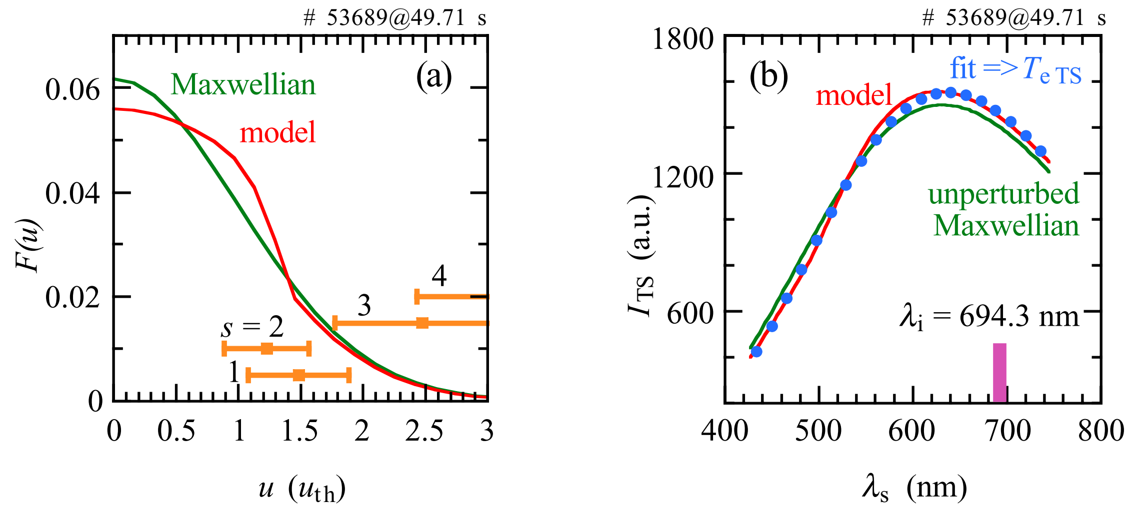


Fig. 3 *(a) Model distribution function and unperturbed Maxwellian used to compute the radiation temperature profiles shown in Fig. 2, for ρ = 0. The horizontal bars give the average momentum of the emitting electrons (±1 standard deviation), at ρ = 0, for each harmonic s. [* $u=p/u_{th}$ *,* $u_{th}=(m_e T_e)^{1/2}$ *]. (b) Computed Thomson scattering spectra for the previous distribution functions; the Maxwellian fit to the model-distribution spectrum (filled circles) mimics the procedure used in practice to determine the value of the TS temperature.*

distribution function is determined to fit the experimental spectrum: the distortion that has to be applied to the Maxwellian distribution is very sharply localized at $u < 1.5$ by the fit to the 1st and 2nd harmonic emission (Fig. 3a). It is worth stressing as well that a single change in the shape of the distribution function has to cause four independent changes in the computed emission spectrum in order to fit the experimental one (Fig. 3a).

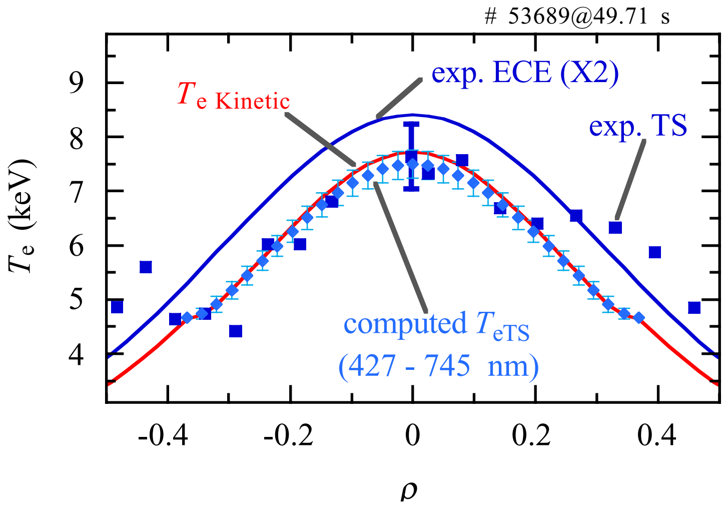


Fig. 4 *Computed Thomson scattering temperature profile (diamonds) from the model distribution function, see Fig. 3b (the error bars are not of statistical nature but due to the non-Maxwellian form of the fitted TS spectra). The profile corresponding to the average kinetic energy of the model distribution, and the measured temperature profiles (exp.) are also shown. [The experimental TS data points are shifted, $\rho \Rightarrow \rho - 0.06\,(1-\rho^2)$, in order to correct the EFIT-determined Shafranov shift with the one obtained from the fit to the ECE spectrum].*

The Thomson scattering temperature profile is computed for the model distribution function and compared to the experimental profiles in Fig. 4. The calculated TS temperature agrees quite well with the measured one near the plasma axis (although this is not a statistically significant results: more TS data should be fitted), and they both are lower than the ECE temperature, which was the one used to determine the model distribution function. The radial dependence used for the model distribution function is crude, and comparison with the experimental profiles at larger radii is not very significant.

The main point is that the observed anomaly in the ECE spectra implies that the TS scattering temperature should be lower than the ECE temperature; there is ample statistical evidence that during ICRF+NBI heating on JET this actually happens.[9] Similar results were also found for ICRF+NBI heating with additional LH current drive.

Conclusions

The JET results presented here (and the FTU ones in Ref. [2]) point to the existence of non-Maxwellian bulks during strong auxiliary heating. In the presence of non-Maxwellian bulks, familiar concepts have to be revisited: eg, nominal temperature gradients can be due to changes in both the average kinetic energy of the particles and the shape of the bulk distribution; the quantitative explanation of ITBs may require us to distinguish between these two effects.

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