Thomson Scattering spectra of α-particle-heated electrons in ITER

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Abstract

A study of the effects of α-particle heating on the electron distribution function (EDF), and subsequently on the Thomson Scattering (TS) measurements is performed for ITER-relevant plasmas. The electron distribution function is computed using a Fokker-Planck code, including ECE losses, and the results show that the effect of such additional heating on the EDF is remarkable, the average electron kinetic energy being substantially increased with respect to its initial value, taken in the range from 18 to 40 keV. The TS spectrum is computed for the outcoming EDF and the substantial increase of electron temperature when α -particle heating would be present makes that this effect should be taken into account in the design of the proposed TS system for ITER.

1.- Introduction

The ITER plasmas will pose several challenges to TS system when such device be fully operational and fast ions and α-particle heating be available. Evaluating the impact of fast-ions and α-particle heating on the EDF, and on the TS spectrum arising from it, is mandatory. New developmewnts must be used since the customary TS approximations can be doubtful in such plasmas: relativistic effects are not negligible and are taken into account by introducing new techniques in the simulations allowing us to go beyond standard TS approximations, namely, the inclusion of arbitrary EDFs and the computation of scattered spectra from first principles, as well as the inclusion of arbitrary non-Maxwellian EDFs [1]. The ITER TS system is specified to measure electron temperatures of up to 40 keV, with spatial resolution of the order of 6 cm, at 100 Hz repetition rate, which is not enough taking into account the results shown here. In any case, the measurements will be rather challenging due to the high electron temperature involved, which may be well expected to cause both a large blue-shift of the maximum of the scattered emission with respect to the incoming laser wavelength, and a large overall broadening of the spectrum. If, as argued at length in this paper, the electron temperature turns out to be substantially higher than 40 keV due to the combined effect of fast-ions and alpha-particle heating, then this fact will have to be considered on the overall design of the ITER TS system.

2.- Fokker-Planck calculations of the EDF

When fully operational, ITER will produce a substantial amount of α-particles coming from the fusion reactions, which will provide the main contribution to plasma heating, allowing a gain factor Q=10 in 30 min pulses. The α-particles will transfer their energy mainly to

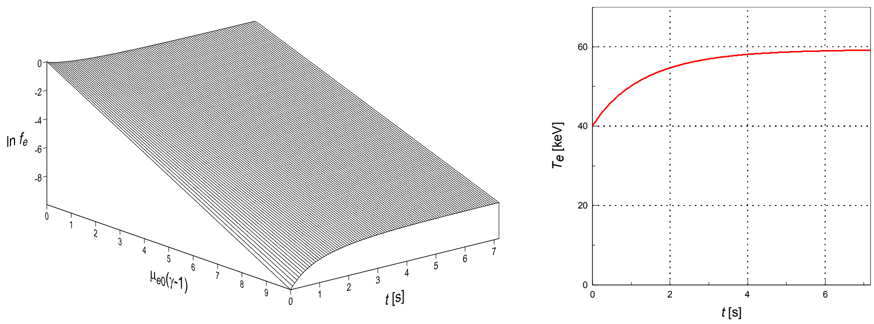

Figure 1: Evolution of EDF and T_e for T_{e0}=40 keV and n_e=1.8 x 10^{18} m^{-3}.

electrons, given the fact that the critical kinetic energy is ≈ 500 keV for the expected plasma parameters in ITER [2]. The TS spectra that can be expected in these D-T plasmas must be obtained using the new developed TS techniques, starting from the EDF. In order to obtain the EDF, a series of FP computations has been performed. As will be seen, the results clearly show that irrespective of the initial temperature of the EDF (assumed to be an isotropic relativistic Maxwellian with temperature in the range from 10 to 40 keV), a final equilibrium is achieved for a substantially higher electron temperature, with significant variation depending on the initial temperature of the Maxwellian distribution.

We perform the calculations assuming homogeneous plasmas and we estimate the distribution function of the electron population in a background plasma formed by the electrons themselves, the ions and the alpha particles, taking into account electron cyclotron emission (ECE) losses. The electron density is considered to be equal to the ion one and equal to n=8 x10^{19} m^{-3}. The ion temperature is assumed constant and equal to the initial electron one, and the α-particles are considered to have a constant kinetic energy of E_α=3.5 MeV and to be distributed isotropically [3]. We solve the FP equation assuming that only the electron distribution function will evolve. Relativistic effects must be considered for this high energy electrons, while ions and α-particles are non-relativistic, although we will consider these particles as relativistic too. The equation to solve is [4]:

$$\frac{\partial f_e}{\partial t} = \frac{\nu_{e0}}{p^2}\frac{\partial}{\partial p}\sum_{j=e,i,\alpha} Z_j^2\left(\frac{m_e}{m_j}A_j(p)f_e + B_j(p)\frac{\partial f_e}{\partial p}\right), \qquad (1)$$

Here, we have introduced the electron collisionality ν_{e0}. The convective term of the equation includes the function:

$$A_j(p) = \gamma^2\int_0^p p'^2\gamma'^{-1}\bar{f}_j(p')\left(3 - p'^2\gamma'^{-2}\right)\mathrm{d}p' + 2p^3\gamma^{-1}\int_p^\infty p'\bar{f}_j(p')\,\mathrm{d}p' \,, \qquad (2)$$

and the diffusion in momentum space is governed by the coefficient:

$$B_j(p) = \frac{\gamma^3}{p}\int_0^p p'^4\gamma'^{-2}\bar{f}_j(p')\,\mathrm{d}p' + p^2\int_p^\infty p'\gamma'\bar{f}_j(p')\,\mathrm{d}p' \ , \qquad (3)$$

In the case of not very high temperature the coefficients B_j ($j = e,i$) can be expressed via the incomplete gamma functions:

$$B_j \approx \frac{3\sqrt{2}}{\mu_{e0}^{3/2}\mu_j}\frac{n_j}{n_e}\left\{\frac{\gamma^3}{p}\int_0^{\mu_j(\gamma-1)}\sqrt{z}\left(1-\frac{5}{12}\frac{z}{\mu_j}\right)e^{-z}\mathrm{d}z + \frac{\sqrt{2\mu_j}}{3}p^2\left(\gamma+\mu_j^{-1}\right)e^{\mu_j(1-\gamma)}\right\} ; \qquad (9)$$

the expression for B_α is

$$B_\alpha = \frac{\sqrt{2\pi}}{\mu_{e0}^{3/2}\mu_\alpha}\frac{n_\alpha}{n_e}\left\{\frac{\gamma^3}{p}U(p-p_\alpha)+\frac{p^2}{p_\alpha^3}U(p_\alpha-p)\right\} . \qquad (10)$$

We have defined $\mu_{e0} = m_e c^2 / T_{e0}$, T_{e0} being the initial electron temperature of the simulation In principle, for high electron temperatures, the electron cyclotron emission (ECE) is a significant loss mechanism. In fact, following the Trubnikov formula [5], the emitted power rises strongly with temperature $P_{ECE} \propto T_e^{5/2}$, but depending on the wall reflection coefficient R_w, a fraction of this power can be reabsorbed by the plasma. So the ECE is a significant loss mechanism for Te > 30 keV [6]. The effect of extra electron cooling can be modelled via an additional heuristic term in the collision operator, which consists of introducing a virtual kind of particles whose coefficient in the collision operator is obtained from the given value of transferred power P_{ECE}. The steady state density of alpha particles for $T_i = T_{e0}$, in the case of a 50% - 50% DT plasma, can be obtained following [7]. Taking $Z_{eff} = 2.3$, $n_e = 8\times10^{19}$ m^{-3}, $T_{e0} = 18$ keV / 30 keV / 40 keV, this calculation gives $n_\alpha = 4.1\times10^{17}$ m^{-3} / 1.2×10^{18} m^{-3} / 1.8 x 10^{18} m^{-3}, respectively. An extra calculation has been done for T_{e0}= 40 keV and $n_\alpha = 4\times10^{18}$ m^{-3} just to show the strong effect on electron temperature of stronger fusion heating. The final results for these four cases are T_e= 28.2, 46.1, 59.5 and 72.6 keV, repectively. Figure 1 shows the evolution of EDF and T_e for the third case. These FP calculations have been validated with JET experimental results [8]. Figure 2 shows the estimated evolution of T_e for JET in the latter experimental conditions, showing an excellent agreemnt with the experiments.

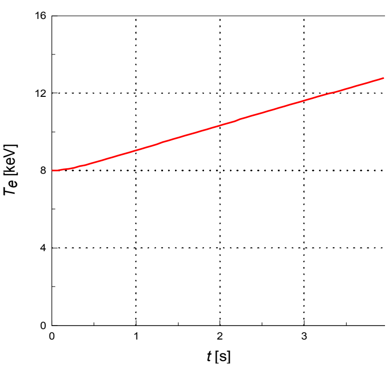

Figure 2: Evolution of T_e in JET DT experiments, due to electron heated by α-particles.

4. TS spectra of alpha-heated plasmas.

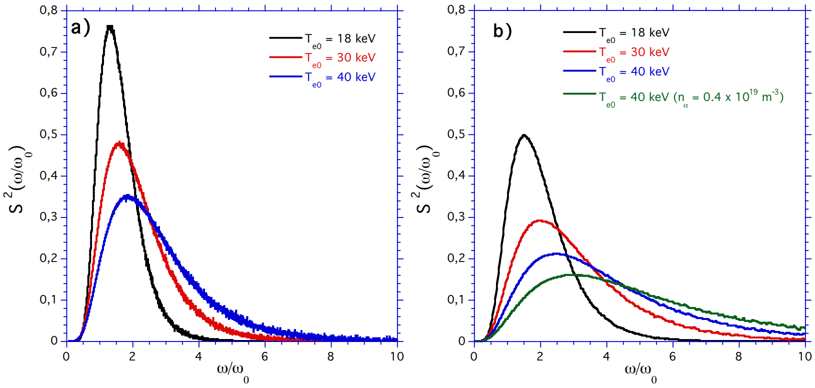

Figure 3: TS spectra for a) the initial temperatures of the three considered cases and b) for the final EDFs of the four cases.

In all the cases the frequency spectra calculations have been done using the formerly developed techniques. It is seen that the calculated spectra are widened and shifted to the blue. Another point of interest is the polarization composition of the scattered spectra. It is well known that as the electron temperature increases, and for linear input polarization of the incoming laser, the scattered radiation acquires a polarization component orthogonal to that polarization, the overall effect being a depolarization of the scattered light. This effect should also be taken into account in analyzing the performance of the ITER TS system. A comparison among the frequency spectra for the four cases appears in Figure 2, showing in Fig. 2a) the spectra for the initial temperatures and in Fig. 2b) for the final FP EDFs. This brings out and makes evident the clear blue shift of the final FP spectra in all cases (mainly for high temperatures), as well as the widening, and the emergence of high frequency tails.

5.- Conclusions

The effects of alpha particle heating on TS measurements in ITER plasmas have been explored in this paper, using improved TS simulation techniques. The results show that the final EDF is compatible with a relativistic Maxwellian, but with a substantially higher electron temperature. The corresponding TS spectra are blue-shifted and widened and these predicted frequency shifts and spectral widenings should have some impact on the designs of the TS system for ITER: the possibility of using several spectrometers should be contemplated (one for Te ≤ 40 keV for H plasmas and another one for Te ≥ 60 keV for D-T plasmas). Alternatively, the inclusion in the system of a second laser whose fundamental wavelength would be ≈ 2 μm to compensate with this longer wavelength the larger blue-shift.

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