*29th EPS Conference on Plasma Phys. and Contr. Fusion Montreux, 17-21 June 2002 ECA Vol. **26B**, P-5.023 (2002)*

A Study of Anomalous Impurity Temperatures in the TJ-II Stellarator

K. J. McCarthy, B. Zurro, A. Baciero, and R. Balbín

Laboratorio Nacional de Fusión, Asociación Euratom-CIEMAT, E-28040 Madrid, Spain

Introduction

Doppler spectroscopy of lines emitted by ions that exist in small quantities is one of the most powerful methods to estimate ion temperatures in hot astrophysical and fusion plasmas. The implicit assumption made is that all ions at the same position and time have the same kinetic temperature so by measuring it for one ion the correct temperature can be obtained. Other possible effects affecting line-width can be separated or are assumed to be negligible. However, it has been long recognised in astrophysics that the superimposed effect of micro- and macro-turbulence on thermal motion could affect such measurements [1]. Indeed, this has been used as a unique method to quantify the level of turbulence, since in space plasmas one can take advantage of the fact that electron and ions should have the same temperature. Moreover, the non-thermal velocity strength deduced by this method is of paramount interest for supporting, or ruling out, any model capable of explaining anomalous coronal heating mechanisms. However, due to the obvious difficulties of measuring this parameter with adequate spatial resolution and with a sufficient number of different ions, it has not yet been substantiated.

The theory of non-thermal velocities, as introduced in astrophysics, is a measure of excess broadening of spectral emission lines. If the spectral line-shape is the result of the convolution of a thermal and a turbulent Gaussian distribution, the latter producing a gross mass motion, the FWHM of the resulting line is $\Delta\lambda = 1.665(\lambda/c)(2kT_i/m_i+\upsilon_{NT}^2)^{1/2}$. Here T_i and m_i are the temperature and mass of the ion under study, $\upsilon_{NT}^2 = 2k(T_Z - T_i)/ m$ is the dispersion of the isotropic Gaussian micro-turbulence velocity distribution and T_Z is the apparent Doppler temperature derived from the resulting line-width. The term micro-turbulence is used as the spatial scale for this velocity field is small compared to the unit optical length [1]. The underlying idea is that because of the long particle confinement times inherent to gravitational confinement, electrons and ions have sufficient time to thermalize their velocity distributions so that both species can be considered to have the same temperature. In contrast, in most magnetically confined plasma devices where this could be tested, the ion temperature is well below that of the electrons, an exception being for very high plasma densities in high performance machines. Indeed, impurity ion temperatures substantially higher than ion temperatures, even under conditions where collisional coupling predicts that such temperatures should be equal, have been reported for several magnetic confinement devices [2]. However it is difficult to judge if the effects observed were due to anomalous ion heating resulting from non-Coulombic processes, or to gross mass motion, as the experiments were carried out either on a single impurity ion or with non spatially resolved measurements.

Now, in a magnetically confined plasma, if non-thermal velocities due to plasma micro-turbulence produce a Gaussian contribution to line-width, then a recorded spectral line-width, after deconvolution with the instrumental function, can be given by $\Delta\lambda^2 = \Delta\lambda^2_T + \Delta\lambda^2_{NT}$ where *T* and *NT* represent thermal and non-thermal. As the non-thermal width is independent of the ion charge and mass, its manifestation for protons (in hydrogen plasmas) and impurity ions with long ionisation times will be different and can be unambiguously identified. Thus expressing it in terms of temperature, one obtains $T_Z = T_i + (m_i/m_p)T_T$ where T_T is the temperature associated with the velocity field of the plasma micro-turbulence, and m_p is proton mass [3]. Similarly, if non-thermal velocities are irrelevant then the ions should exhibit temperatures similar to those of the protons. These simple formulae allow one to estimate the effect of the plasma turbulence level on the T_z deduced from Doppler broadening. The equation has been worked out under the implicit assumption of steady state conditions, and therefore, should be considered as being approximately valid for highly ionised ions that have stayed sufficiently long inside the plasma. An obvious test for this model is to measure the apparent temperature of two of more ions with different masses and sufficient times of residence so as to be thermalized. In this way, thermal and non-thermal contributions can be separated and one can check for the linear mass dependence claimed by the model.

Experimental Approach

The TJ-II, a low magnetic shear stellarator of the heliac type with an average major radius of 1.5 m and an average minor radius of ≤0.22 m, is an ideal device for testing such a hypothesis as the proton temperature profile, which closely represents the kinetic ion temperature, is almost flat across its minor radius [4]. For this experiment, plasmas were created in hydrogen with standard TJ-II configurations and heated (t ≤ 250 ms) with 300 kW using a gyrotron operated at 53.2 GHz. No auxiliary heating was provided. As a result, $n_e(0)$ and $T_e(0)$ were $<1.4 \times 10^{19}$ m^{-3} and 800 eV respectively. Note; the ion temperature remains low because of this low-density regime, thus making the effect easier to observe. Also, Stark and Zeeman effects are negligible due to the magnetic field regimes while strong collisional coupling assures thermalization of the different species. Reduced metallic species, due to wall conditioning with boron, made it necessary to inject high Z ions into the plasmas by the laser ablation technique. For this, material was ablated from a 1 μm Fe film deposited on a pyrex plate by a 30 ns long pulse from a 2 J Q-switched ruby laser [5]. Spectral line information was collected with an f/10.4 1 m normal-incidence vacuum spectrometer equipped with 1200 and 3600 lines/mm gratings and a back-illuminated CCD camera. The entrance slits height and width were fixed at 40 μm and 10 mm respectively. Radial proton temperature profiles were obtained by analysing the slopes of energy spectra of escaped charge-exchange neutral particles. These particles were detected by two multi-channel neutral-particle analysers (charge-exchange spectrometers) with variable lines-of-sight. Note that their lines-of-sight are perpendicular to the magnetic field. These analysers scan the poloidal cross-section along a narrow strip through the plasma. In this set-up, the analysers mainly measure the energy distribution of trapped particles as the temperature is relatively low and collisions ensure that particles are well thermalized.

Results

In Fig. 1a, spectral lines before and after impurity injection are unambiguously identified. Silicon was also injected, its most likely source being ablation of the sample plate. Apparent temperatures were determined from uncontaminated Si and Fe lines. Line-widths were obtained by de-convolving the instrumental function, as determined from the C III line at 38.6 nm, with recorded line-widths. Note; lines from edge ions provide a good, although slightly over-estimated, value of instrumental function as they have almost negligible Doppler broadening. Fig. 1b shows a spectrum with O VII lines at 162.36, 163.83 and 163.98 nm for a discharge of the same series. Only the line at 163.83 nm is free from contamination. The instrumental function was determined from neighbouring Ar III lines. In both cases small corrections were made for variations across the focal plane. Also, lines from both low and high Z ions were well fitted by a Gaussian profile. Indeed both the central peak and the wings of the lines investigated are well accommodated by a 30 point Gaussian fit with a resultant 2 to 3 % random error in the FWHM´s of both the instrument and ion lines. See Fig. 2. In particular, the instrumental function is notably free of wings. Such wings if present can lead to a significant overestimation of the ion temperature, by >30 %, unless properly they are adequately dealt with. Finally contributions to line broadening from Doppler shifts (the radiation collected is chord integrated) are estimated to be negligible.

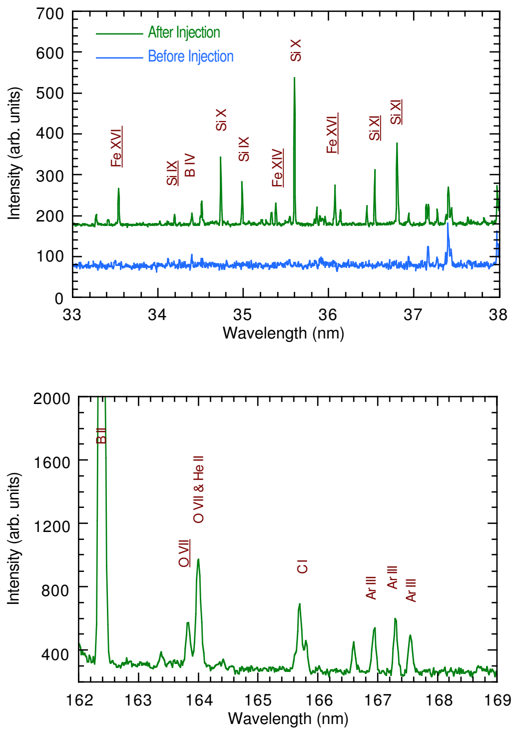

Fig. 1. TJ-II spectra of a) emission before and after laser ablation was performed. (The Si and Fe lines considered for determining Doppler temperatures are underlined), and b) the O V II emission line (also underlined).

Next, the proton temperature was obtained by analysis of the energy distribution of escaped charge-exchange neutral particles. This was performed on particles over a range from 2 to 10 times the predicted thermal range in order to ensure that central ion temperatures could be reached for standard TJ-II plasmas. In the analysed profiles only a single slope was observed and the resultant central proton temperature was flat and 65 ± 10 eV.

In Fig. 3, apparent Doppler temperatures determined for the heavy ions are plotted as a function of atomic mass together with the measured central proton temperature. Note; the effect of an over-estimated instrumental function is to underestimate the apparent temperatures. Also, moderate random errors in the measured instrumental and ion line FWHM´s can work through to create significant errors in the Doppler temperatures [6]. Hence, only well isolated and intense impurity ion lines were considered and analysed here. Also, all the ions plotted here have ionisation potentials above 390 eV and so emit from highly localised regions in the core of the TJ-II plasmas, *i.e.* from $\rho < 0.5$. That is to say, the measurements can be considered as being spatially resolved, a point critical for distinguishing anomalous ion heating effects from other processes. Indeed, as predicted by the model described earlier, a linear dependence with atomic mass is also apparent in Fig. 3. From this data fit, the most probable velocity is estimated to be $\upsilon_{NT} = 3.1 \times 10^6$ cm s^{-1}. This is 1.414 times larger than the *rms* value. If the turbulent velocity is assumed to be due to $\boldsymbol{E}\times\boldsymbol{B}$ drifts and $\upsilon_r \approx E_p/B$, then the equivalent electric field is estimated to be 220 V cm^{-1}, a value similar to that measured previously in TJ-I for a similar electron density [2:1].

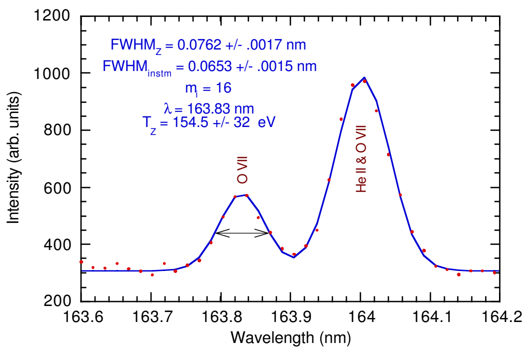

Fig. 2. Gaussian fit to O VII lines

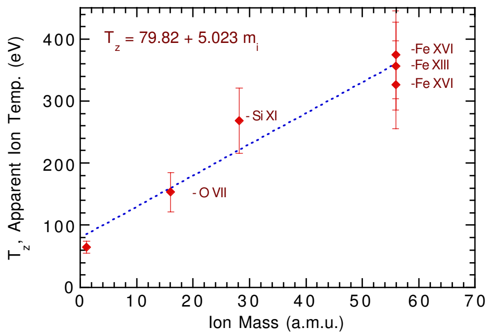

Fig. 3: Apparent Doppler ion temperatures as a function of emitting ion atomic mass.

Conclusions

Ion impurity temperatures in the centre of the TJ-II are shown to be higher than proton temperatures. This difference is attributed to the presence of isotopic non-thermal velocities. A linear fit to a plot of apparent Doppler temperature versus emitting ion atomic mass provides an estimate of the equivalent electric field associated with this process.

This work was supported by the Spanish Ministry of Science and Technology and was partially funded by Project No. FTN 2000-0922.

[1] D.F. Gray, Lectures on Spectral-Line Analysis: F, G and K Stars (Aylmer Express Ltd., Aylmer, Ontario, 1998).
[2] B. Zurro *et al.*, Phys. Rev. Lett. **69**, 2919-2922, (1992), A. Fujisawa *et al.*, Nucl. Fusion **31**, 1443 (1991) and J. M. McChesney *et al.*, Phys. Fluids B **3**, 3363 (1991).
[3] G. Fussman, Report No. JET-R12 (1987).
[4] C. Alejaldre *et al.*, Plasma Phys. Control. Fusion **41**, B109-118 (1999), E. Ascasíbar rt al. Fusion Engin. & Design **56-57**, 145 (2001).
[5] B. Zurro *et al.*, Proc. 13th Stellarator Workshop, Canberra (2002).
[6] K. D. Lawson and N. J. Peacock, Report No. JET-R12 (1988).