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To cite this article: K. J. McCarthy *et al* 2003 *EPL* **63** 49

EUROPHYSICS LETTERS 1 July 2003
Europhys. Lett., **63** (1), pp. 49–55 (2003)

Results of an experiment relating apparent Doppler ion temperatures with non-thermal velocities in hot-fusion plasmas

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(received 3 April 2003; accepted 5 May 2003)

PACS. 52.25.Vy – Impurities in plasmas.
PACS. 52.35.Ra – Plasma turbulence.
PACS. 52.55.Hc – Stellarators, torsatrons, heliacs, bumpy tori, and other toroidal confinement devices.

Abstract. – We present the results of an experiment carried out in the core of a hot magnetically confined plasma to substantiate a claimed relationship between apparent ion temperatures and non-thermal velocities. For this, the heaviest ions were injected into the plasma by laser ablation and localised ion temperatures were obtained from Doppler line-widths and energy spectra of escaped charge-exchange neutrals. Strong collisional coupling between majority (H^+) and impurity ions ensures that these should be well thermalised. However, the linear dependence found between apparent ion temperature and mass (H, O, Si, Fe) permits one to relate apparent Doppler ion temperatures to non-thermal velocities. The implications for the physics and diagnosis of thermonuclear plasmas are addressed.

Introduction. – Doppler spectroscopy of emission lines is one of the most powerful methods to estimate ion temperatures in hot-fusion and astrophysical plasmas [1]. In hot 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, measured impurity temperatures deduced from line-width measurements have been found to be significantly higher than local proton temperatures in several fusion devices [2,3]. Now, it has been long recognized in astrophysics that the superimposed effect of micro- and macro-turbulence on thermal motion could affect such measurements [4,5]. 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 electrons and ions should have the same temperature because of the long particle confinement times inherent to gravitational confinement [6]. Moreover, the non-thermal velocity strength deduced in this way is of paramount interest for supporting, or ruling out, any model capable of explaining anomalous coronal heating mechanisms [7].

In contrast, in most magnetically confined plasma devices the ion temperature is well below that of the electrons, an exception being for very high plasma densities in high-performance machines. Also, in fusion plasmas, alternative methods to Doppler line-width measurements exist for deducing ion temperatures. These include energy analysis of charge-exchange neutrals, neutron spectroscopy, high-resolution X-ray spectroscopy, or charge-exchange recombination spectroscopy (CXRS) of ion species. However, in practice it is difficult to have all these operating and measuring simultaneously at the same plasma radius. Even when two of these are available, it can still be difficult to verify the effect due to large temperature ranges. Nonetheless, in recent years, simultaneous measurements of spatially resolved proton and low-mass impurity temperatures have been performed in high-temperature plasmas using CXRS [3]. Even under such unfavourable conditions where the smallness of the effect is obvious, it can nonetheless be observed [2, 3, 8, 9]. 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.

The theory of non-thermal velocities, as introduced in astrophysics, is a measure of the excess broadening of spectral lines and is justified as being caused by the presence of velocities associated with plasma fluctuations. If non-thermal velocities are assumed to produce a Gaussian contribution to line-width, then the full-width at half-maximum (FWHM), after deconvolution with the instrumental function, is given by $\Delta\lambda = 1.665(\lambda/c)(2kT_\mathrm{i}/M_\mathrm{i} + \xi^2)^{1/2}$, where λ is the spectral line wavelength, c is the velocity of light, k is the Boltzmann constant, T_i and M_i are the temperature and mass of the ion under study, and ξ is the dispersion of the Gaussian micro-turbulence velocity distribution. As ξ is independent of ion charge and mass, its manifestation for bulk plasma ions and impurity ions with long ionisation times will be different and can be unambiguously identified. Thus expressing it in terms of temperature, one obtains $T_\mathrm{obs} = T_\mathrm{i} + (M_\mathrm{i}/M_\mathrm{p})T_\mathrm{NT}$, where T_obs is the apparent Doppler temperature, T_NT is the temperature associated with the velocity field of the plasma fluctuations, and M_p is the mass of the bulk plasma ion mass [10]. Hence, if non-thermal velocities are irrelevant, then the ions should exhibit temperatures similar to those of the bulk plasma ions due to the strong collisional coupling between them. These simple formulae allow one to estimate the effect of the plasma turbulence level on the apparent temperature 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 is to measure the apparent temperature of two of more ions with different masses and sufficient times of residence so as to be thermalised. In this way, thermal and non-thermal contributions can be separated and one can check for the claimed linear dependence on mass. In this paper, we describe an experiment performed on the TJ-II stellarator device, employing both Doppler spectroscopy and the energy analysis of charge-exchange neutrals to measure ion temperatures, in order to check for this dependence.

Experiment. – The TJ-II is 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 [11]. It is an ideal device for testing such a hypothesis as the bulk ion (proton) temperature profile, which closely represents the kinetic ion temperature, is practically flat across its minor radius. This precludes that ions peaking at slightly different radii exhibit different temperatures. For this experiment, plasmas were created in hydrogen with standard TJ-II configurations and heated (≤ 250 ms) using a single gyrotron operated at 53.2 GHz, *i.e.*, the 2nd harmonic of the electron cyclotron resonance frequency. This gyrotron is coupled to the plasma by means of a quasi-optical transmission line and up to 300 kW of power can be injected in X-mode at densities up to 25 W/cm^3. No auxiliary heating was provided. As a result, central electron densities and temperatures up to $n_\mathrm{e}(0) \approx 0.7 \times 10^{19}\,\mathrm{m}^{-3}$ and $T_\mathrm{e}(0) \approx 0.6$ keV, respectively, were obtained

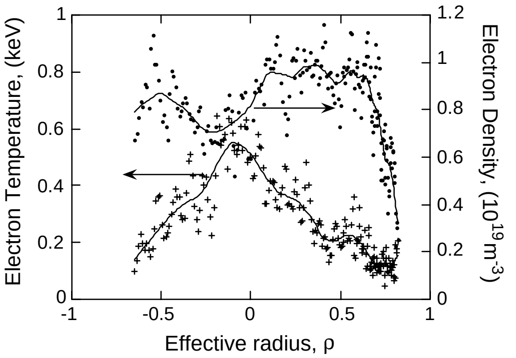

Fig. 1

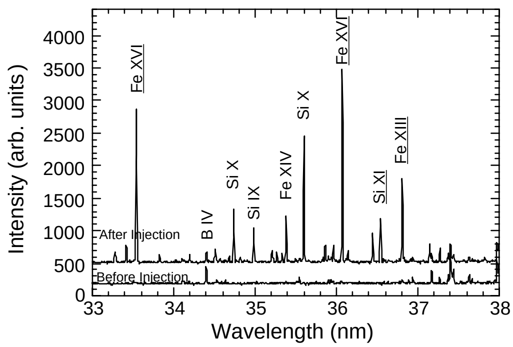

Fig. 2

Fig. 1 – Electron temperature and density profile across the TJ-II minor radius. These profiles, which are representative of this experiment, were obtained with the Thomson Scattering diagnostic [12]. The profiles have been smoothed (thick continuous lines) to aid the reader.

Fig. 2 – Line emission spectra (centred near 36 nm) collected before and after laser ablation was performed. The isolated and intense silicon and iron lines used for the analysis are highlighted.

for these experiments, see fig. 1. Note: the majority ion temperature (H^+) remains low in this low-density regime, thus making the effect easier to observe [13]. Also, Stark and Zeeman effects are negligible, while strong collisional coupling between ions assures thermalisation of the different species.

Spectral line information was collected with a $f/10.4$ 1 m normal-incidence vacuum spectrometer equipped with 1200 and 3600 lines/mm gratings and a CCD camera with 400×1340 pixels ($20 \times 20\,\mu\text{m}^2$). The instrument, whose entrance slits were ~ 1.4 m from the plasma centre, was mounted so that its wavelength dispersion plane was parallel to the plasma poloidal cross-section plane and its line-of-sight axis traversed the central magnetic axis for standard magnetic configurations. With its entrance slits height and width fixed at $30\,\mu$m and 5 mm, respectively, the instrument was restricted by stops to view the central 10 cm of the plasma poloidal cross-section and a few centimetres along the toroidal direction. 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 $1\,\mu$m Fe film deposited on a pyrex plate by a 30 ns long pulse from a 2 J Q-switched ruby laser. This target was located in an auxiliary chamber located on the TJ-II equatorial plane at a distance of ~ 70 cm from the plasma edge [14]. Finally, 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 set perpendicular to the magnetic field. These analysers scanned the poloidal cross-section along a narrow strip through the plasma. In this set-up, the analysers mainly measured the energy distribution of trapped particles as the temperature is relatively low and collisions ensured that particles were well thermalised, *i.e.* of particles in the range from 2 to 10 times the predicted thermal range in order to ensure that central ion temperatures for standard TJ-II plasmas were obtained.

Results and discussion. – In fig. 2, spectral lines before and after impurity injection are identified in the wavelength region about 36 nm [15]. Silicon was also injected, its most likely source being ablation of the sample plate. Apparent temperatures were determined from iso-

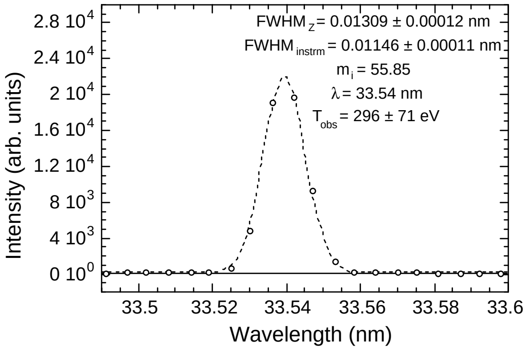

Fig. 3

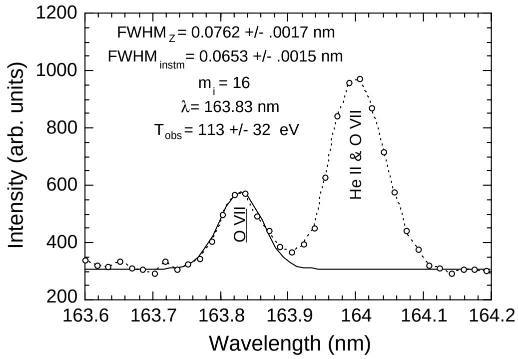

Fig. 4

Fig. 3 – The best-fit Gaussian profile (dashed line) to the measured Fe XVI line at 33.54 nm (open circles). The background prior to iron injection is shown (continuous line). T_{obs} has been corrected for Doppler shift.

Fig. 4 – A measured spectrum about 163.9 nm showing O VII lines at 163.83 nm and 163.988 nm (open circles). The O VII line at 163.998 nm is contaminated by lines from He II. The slit height was increased to 40 μm to improve light collection. The continuous line is the best-fit Gaussian profile to the O VII 163.83 nm line. T_{obs} has been corrected for Doppler shift.

lated, uncontaminated, Si and Fe lines where the line-widths associated with temperature were obtained by deconvolving the recorded emission line-widths with the instrumental function, where this was determined using nearby plasma-edge ion emission lines, *e.g.* the C III line at 38.6 nm and the O III line at 32.098 nm. Note: lines emitted by plasma-edge ions provide good, although slightly overdetermined, estimates of the instrumental function as they have almost negligible Doppler broadening. Also, lines from low ionisation stages do not have sufficient time to achieve thermalisation with either protons or the turbulent field. Furthermore, the most important electrostatic turbulence at the edge appears to be that producing poloidal velocity fluctuations and its influence on these radial observations would thus be negligible. See ref. [8] and references therein.

Next, fig. 3 shows the spectral region about 33.5 nm before and after injection. Here the Fe XVI line at 33.54 nm is well fitted by a Gaussian distribution and exhibits significant excess broadening. Good fits were also obtained for nearby uncontaminated, strong, single transition lines, *i.e.*, the Fe XVI line at 36.07 nm, the Fe XIII line at 36.81 nm, and the Si XI line at 36.54 nm. These emission lines also exhibited excess Doppler broadening. Oxygen is a main impurity in TJ-II and the spectrum in fig. 4 is centred about the O VII lines at 162.36, 163.83 and 163.98 nm. Only the line at 163.83 nm was free from contamination. The instrumental function was determined from nearby Ar III lines around 167 nm that appeared in spectra near the end of discharges when an argon gas puff was performed.

Recorded spectral lines from both low- and high-Z ions are well fitted by a Gaussian distribution. Indeed both the central peak and the wings of the lines investigated are well accommodated by a 30-point Gaussian fit with a resultant $\leq 5\%$ random error in the FWHM of both the instrument function and plasma core lines. In particular, the instrumental function is notably free of wings. Such wings, if present, can lead to a significant overestimation of the ion temperature unless they are adequately dealt with [16]. Furthermore, a simple simulation was performed to determine the contribution to line broadening from ion poloidal Doppler shifts (the radiation collected is chord integrated). For this the ion mass was assumed to rotate

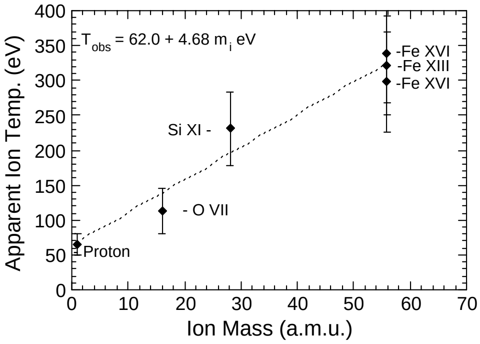

Fig. 5

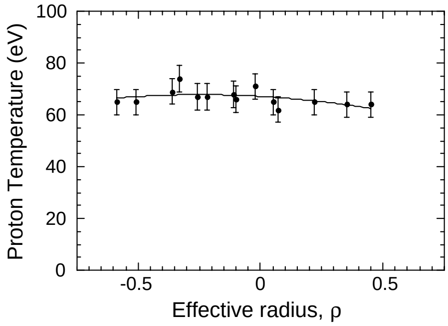

Fig. 6

Fig. 5 – Apparent Doppler ion temperatures as a function of emitting-ion atomic mass.

Fig. 6 – Measured proton temperature profile ($\rho \leq 0.5$) for this experiment. A fit has been made to the measured data (points).

about the plasma centre as a cylindrical rigid body. In the case of iron, this body rotated with an angular velocity of $2.2 \times 10^5\,\mathrm{rad\,s^{-1}}$ (for $T_\mathrm{i} = 70\,\mathrm{eV}$, 5 cm radius) and the resultant line-width increase was equivalent to 36 eV of Doppler broadening. Similar values were found for oxygen and silicon ions. Hence, when determining apparent ion temperatures, corrections based on these simulations were made to the measured values for Doppler shift contributions.

The apparent Doppler temperatures determined for the ions under study are plotted in fig. 5 as a function of atomic mass together with the measured central proton temperature (the central proton temperature profile, as shown in fig. 6, is flat with a mean value of $66.5 \pm 3\,\mathrm{eV}$). Note that the effect of an overestimated instrumental function is to underestimate the apparent temperatures. Also, random errors in measured instrumental and ion line FWHMs can work through to create not insignificant errors in the Doppler temperature [16]. For this reason, only well-isolated and intense impurity ion lines were considered and analysed. Also, all the ions plotted here have ionisation potentials above 390 eV and emit from a highly localized region near the core of the TJ-II plasmas, *i.e.* in a narrow confined region at $\rho \leq 0.5$. That

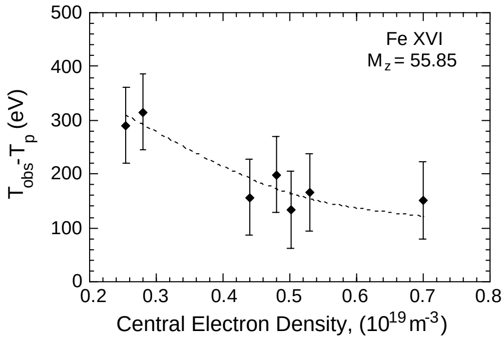

Fig. 7 – $T_\mathrm{obs} - T_\mathrm{p}$ as determined from Fe XVI spectral lines as a function of TJ-II central electron density. The dashed line is intended to guide the eye.

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 earlier, a linear dependence on atomic mass is apparent. The best-fit slope of this linear dependence, that is the temperature T_{NT} associated with the velocity field of the micro-turbulence, is $4.68 \pm 0.597\,\mathrm{eV}$. This corresponds to an equivalent turbulence level of the order $T_{\mathrm{NT}}/T_{\mathrm{i}} = 7.2\%$. This value is of the same magnitude as values reported in other machines where non-thermal velocity fluctuations were considered as a possible cause for anomalous ion impurity temperatures [2, 3, 13].

Next, we investigate the dependence of T_{NT} on electron density. For this, the ion temperature associated with non-thermal velocities for a single ion is plotted in fig. 7 for a range of central electron densities obtained during these experiments. In this plot T_{p} is the proton temperature measured by the multi-channel neutral-particle analysers during iron injection. It is observed that the magnitude of T_{NT} is greatest at low central electron densities and that it tends to diminish with increasing electron density. Similar behaviour was also reported in refs. [2, 3, 8]. Experimental limitations in the TJ-II did not permit higher electron densities to be explored.

Conclusions. – To date excess broadening of spectral ion lines has been reported for several magnetically confined plasma devices. In all cases the measurements reported where for single light impurities or for a single heavy impurity [2, 3, 13], thereby making it difficult to establish whether such observations could be attributed to non-thermal fluctuations. Indeed, in some cases alternative explanations were sought, for instance a $Z_{\mathrm{i}}^2/M_{\mathrm{i}}$ scaling of the heating power per ion of a neutral beam [3]. This cannot be so in TJ-II, where neutral beam heating was not available for these experiments. In contrast, the range of atomic masses in the present experiment is broad and the linear mass dependence predicted by the model was observed. In consequence, since TJ-II plasma conditions are similar to those existing in the outer-radii regions of large devices, this may have some consequences for fusion relevant plasmas. In particular, non-thermal fluctuations should be now considered as a possible source of excess ion temperatures determined from Doppler-broadened line-widths in other machines. Finally, the cause of such fluctuations in TJ-II and in other devices still needs to be identified. The flexibility of the TJ-II enables experiments to be performed for a wide range of plasma conditions and configurations, which may lead to a better understanding of the source of our observations.

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This work was partially funded by the Spanish Ministry of Science and Technology under Project No. FTN 2000-0922. The assistance of the TJ-II team is kindly appreciated.

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