Response of EXTRAP T2R plasma velocity and ion temperature profiles to varying plasma conditions

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EXTRAP T2R [1] has a reversed field pinch configuration with a strong capability for magnetic field control achieved through a comprehensive system of feedback connected sensor and active coils designed to suppress resistive wall modes and error fields [2]. The system also enables external magnetic perturbations to be applied.

The toroidal rotation velocity (v_i) and ion temperature (T_i) of the principle impurity ions are studied in a series of plasma equilibria, varying primarily the plasma current (I_p) and the pinch θ ($\theta = B_\Theta(a)/<B_\phi>$) and reversal F parameters whilst otherwise endeavouring to keep the plasma conditions similar. Studying the effect of plasma equilibrium gives us a clearer picture of the rotation and heating and of the correspondence between the plasma flow and MHD dynamics. Passive spectroscopic measurements are exploited to determine T_i and v_i through the Doppler broadening of the spectral lines and their Doppler shift (with correction for the angle between the line-of-sight and the rotation). Visible wavelength emission lines from the intrinsic oxygen impurities (OII to OV ionisation stages) and from FeI (from the metallic walls) are examined.

Heating of the ions in a plasma through collisions with the Ohmically heated electrons cannot always account for the high T_i observed in several experiments. Various mechanisms have been proposed as additional sources, including activity (fluctuations) of the MHD modes associated with the RFP dynamo with transference through energy cascade and ion viscosity [3]. The rotation around the vessel of the impurity ions intrinsically present in the plasma is assumed be representative of the flow of the plasma. There is an intrinsic toroidal rotation in the EXTRAP T2R plasma both of the impurity ions and of the tearing modes [4].

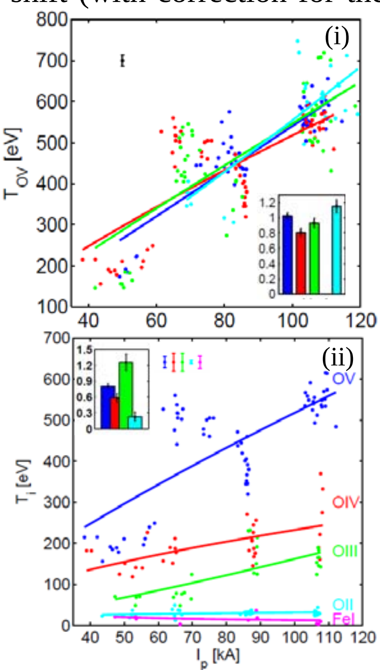


Figure 1 (i) for $1.61 \le \theta \le 1.63$, $1.64 \le \theta \le 1.66$, $1.67 \le \theta \le 1.69$ and $1.72 \le \theta \le 1.74$, T_{OV} (•) and $T_i = a*(I_p)^b$ fit (–) with (inset) b; (ii) for $1.64 \le \theta \le 1.66$ the OV-OII and FeI T_i (•), fit and b (inset).

Ion Temperature From *figure 1(i)* we see that the OV ion temperature increases with plasma current and if we fit the points with $T_i=a*(I_p)^b$ an approximately linear dependence is indicated for all groups of θ *(inset)*. A clear scaling with I_p is also seen in *figure 1(ii)* for OIV and OIII. For the lower ionisation stages – i.e. where the ion becomes more concentrated towards the edge of the plasma – the trend of T_i vs I_p (generally) becomes weaker, with little clear trend seen by OII *(inset)*. The change in plasma equilibrium indicated (driven) by the increasing plasma current seems to have more effect on the ion heating towards the core of the plasma than at the edge. This suggests that the profile of the heating source is changed or that it is more effective in the core.

The picture with respect to θ is not as clear. T_{OV} in *figure 2(i)* appears to increase slightly with θ at the highest plasma current *(blue)* however, at lower I_p there is a quite strong cooling trend. If a power dependence like in *figure 1* was assumed, the mid-I_p *(green)* points for example would give ~θ^{-5}. For the other ions, there is a decrease of T_i with θ even at the highest current, *figure 2(ii)*, although the spread in the data points and relatively narrow θ range, especially for the lower ions, makes it hard to obtain a definitive picture. Some of the scatter may be due to (in many cases) the different θ also representing the evolution during a discharge, however, as there is not a direct correspondence between time and θ this should not override any underlying dependence.

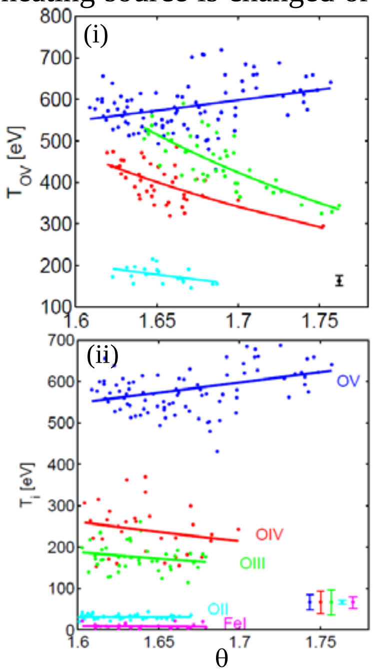
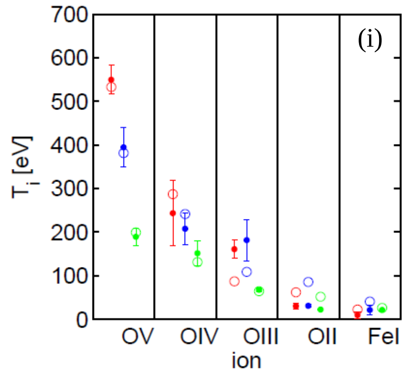


Figure 2: (i) T_{OV} (•) at $105\le I_p\le 112$, $83\le I_p\le 90$, $62\le I_p\le 70$ and $40\le I_p\le 50kA$; (ii) T_i (•) of OV-OII, FeI at $105\le I_p\le 112$. In both (–) is a $T_i=a*(\theta)^b$ fit, typical uncertainties on (•) are indicated.

The approximately linear dependence on I_p that we see for OV is, for example, not as strong as the I_p^2 relation seen in [5] for CV. In [5] they also had a strong positive scaling θ which directly contrasts with the cooling trend with θ that is indicated for our data at all but the highest I_p. However, the picture we have gained for θ is not complete and further work is required to exclude additional influencing factors which may be enfolded into the apparent dependencies.

That the ions close to the edge are less affected by the plasma equilibrium suggests a change in the radial profile of the ion temperature; a steeper gradient and higher core value for higher I_p. A profile of the form $T_i(r)=T_i(0)*(1-(r/a)^2)^b$ is assumed (where a is the minor radius) and the line-of-sight average, weighted by each ion emissivity profile [6] is calculated. These model values for each ion (o in *figure 3(i)*) are fitted to the average experimental points (• in *figure 3(i)*) to determine the free parameters. *Figure 3(ii-iv)* shows that the peaking factor b and core temperature $T_i(0)$ of the ion temperature profile both increase with I_p.



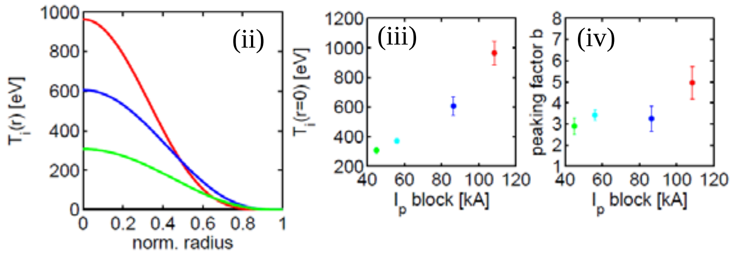


Figure 3: for blocks 107, 86 and 50kA at $1.64 \leq \theta \leq 1.66$, (i) the average experimental T_i (• with errors) and T_i (o) from the model profile (ii) with parameters (iii-iv).

This assumes that the emissivity profiles are constant but as they depend on n_e and T_e they may be affected if these change. For example, shifting the emission inwards, $T_i(r)$ for the low I_p can match well the high I_p experimental values for OIII and OIV but is insufficient to describe the OV. Unfortunately, we do not currently have information on the $n_e(r)$ and $T_e(r)$ in EXTRAP T2R or measurements of the emissivity profiles in the different equilibria.

Toroidal ion rotation The OV velocity is dependent on the plasma current, *figure 4(i)*, although the relation $\sim I_p^{0.5}$ is not as strong as for the temperature. The scaling factor b *(inset)* is a bit stronger at lower θ (shallower reversal F). For each of the lower oxygen ionisations and FeI, progressively closer to the edge, the ion toroidal rotation is slower, *figure 4(ii)*. However, the OIV and OIII velocities, like the OV, are also greater at higher I_p (with b<1). For higher θ v_{ov} seems to decrease, *figure 4(iii)*, although the trend is not always clear due to the degree of scatter and short θ range. For the highest plasma current the OIV and OIII velocities also slow with θ but at lower I_p little dependence is clear.

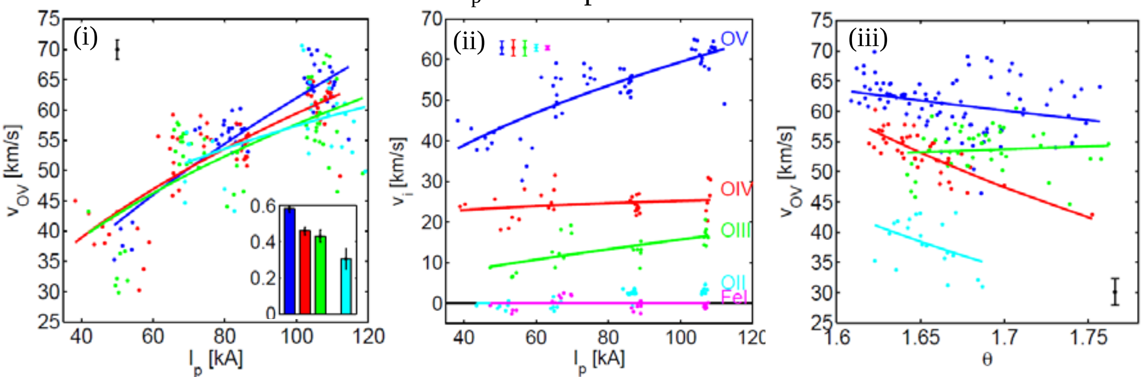


Figure 4: (i) for $1.61 \leq \theta \leq 1.63$, $1.64 \leq \theta \leq 1.66$, $1.67 \leq \theta \leq 1.69$ and $1.72 \leq \theta \leq 1.74$, v_{ov} (•) and $v_i = a*(I_p)^b$ fit (–) with (inset) b; (ii) for $1.64 \leq \theta \leq 1.66$ the v_i (•) and fit of the different ions; (iii) v_{ov} (•) and $v_{ov} = a*(\theta)^b$ fit for $105 \leq I_p \leq 112$, $83 \leq I_p \leq 90$, $62 \leq I_p \leq 70$ and $40 \leq I_p \leq 50kA$. Typical uncertainties on (•) are indicated.

It is apparent that the OV and OIV and OIII rotation – furthest from the edge – are again most sensitive to the changes in plasma equilibrium, both in terms of I_p and θ. This may be that the equilibrium is changed more in the core region or that it has more effect there as the edgier velocities are low, OII for example is usually close to stationary. We investigate this core sensitivity by assuming $v_i(r)=d*(1-(r/a)^2)^b+c$ for the toroidal rotation, allowing for an edge reversal. The line-of-sight average of the velocity component along the line-of-sight, weighted by the emissivity profile, is calculated for each ion and then corrected as for the experimental points to give a toroidal velocity. The parameters (b,c,d) are obtained by fitting these model velocities (o in *figure 5*) to the experimental averages (•) and imply that the core velocity increases at higher I_p. The profile may also become slightly more peaked (higher b).

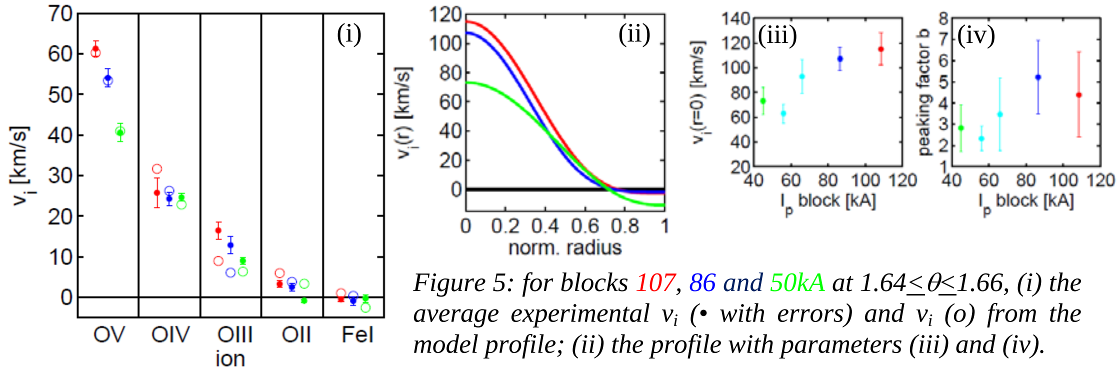


Figure 5: for blocks 107, 86 and 50kA at $1.64 \leq \theta \leq 1.66$, (i) the average experimental v_i (• with errors) and v_i (o) from the model profile; (ii) the profile with parameters (iii) and (iv).

The main limitations of the v_i and T_i profile inversions are the restricted number of data points; that of the five ions only OV and to a lesser extent OIV feel the influence of the central half of the plasma; and the assumption that the emission profiles are not changed.

Conclusions Varying the EXTRAP T2R plasma equilibrium we see that the impurity ion temperature and toroidal rotation are affected; the temperature of OV scales approximately linearly with I_p and its toroidal velocity as the square root of I_p. The θ dependence is not as clear, generally increased θ leads to a cooling and slowing of the ions but the trend is not always clear and some other hidden effect may be enfolded into the experimental data. The changes to the plasma equilibrium are most effective on the OV and OIV ions, which are found further into the plasma with contributions to the emission from the core. Inverting simple radial profiles and fitting to experiment, the $v_i(r)$ and $T_i(r)$ become more peaked and have higher core values for higher I_p, if we assume that the emission profiles are not changed significantly. Further work is required to clarify the role of electron density on the ion heating and rotation and to investigate the response of the ion emission profiles to the equilibrium changes.

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