Ion confinement studies in NBI heated TJ-II plasmas using CX-NPA diagnostics

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1.- Introduction

Central ion temperature is obtained routinely in the TJ-II stellarator [1] from two Acord-12 charge exchange neutral particle analyzers (CX-NPA)[2]. This data, along with those of Thomson Scattering, ECE and interferometer, permits a zero dimensional ion power balance analysis and the determination of the ion confinement.

For standard 2nd harmonic X-mode ECR heating operation density is limited to $n_e < 1.7 \cdot 10^{19}$ m^{-3} and the weak collisional electron-ion coupling results in low ion temperatures strongly depending on the radial electric field through the electron dynamics [3].

The continuous improvement of the TJ-II neutral beam injection (NBI) system, both in energy (up to 33 keV) and power (500 kW in each of the two injectors) [4], has greatly extend the operation regime to much higher densities (up to $<n_e> \sim 6 \cdot 10^{19}$ m^{-3}) thereby increasing the ion contribution to the total plasma energy content significantly.

Here we present a systematic study of the ion power balance analysis performed during recent experimental campaigns at TJ-II under quite different heating conditions, i.e. from low power ECRH (just one gyrotron with 200 kW) up to full power NBI (both injectors) for a total 900 kW.

2.- Transport analysis

In TJ-II, ion confinement is routinely estimated from zero dimensional ion power balance analysis taking into account as sources the electron-ion collisional coupling ($\nu_{ie} \propto n_e T_e^{-3/2}$) and the NBI heating (when used) and as sinks the charge exchange and transport losses. Formally assuming constant density, the equation for the time evolution of the ion temperature can be written as:

$$\frac{dT_i}{dt} = \nu_{ie}(T_e - T_i) - \frac{T_i}{\tau_i} + P_{NBI} - P_{CX}$$

Where ν_{ie} is the collision frequency between electrons and ions, transport losses are modelled simply through an ion confinement time, τ_i, P_{NBI} is the NBI heating power

fraction that heats ions and P_{CX} is the charge-exchange losses. The aim of this study is to gain information on the ion energy confinement time through measurements and estimations of the other terms in this equation.

3.- Experimental data

In order to perform the analysis we have chosen discharges from the last 4 experimental campaigns. All the discharges correspond to the standard configuration which has an average minor radius of 20 cm, a plasma volume of ≈ 1 m^3 and a rotational transform $\iota(a) = 1.46$. The plasma heating conditions varies from low power ECRH to high power NBI heating.
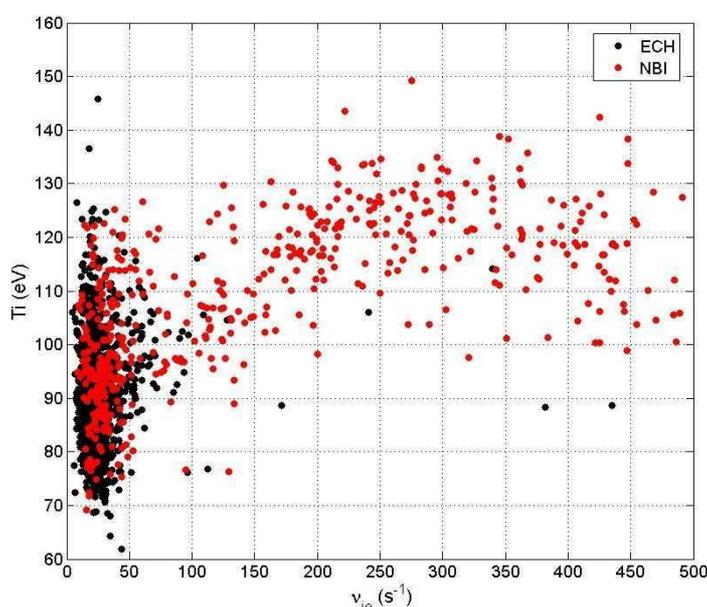

Fig. 1 Ion temperature versus electron-ion collisionality for ECR (black) and NBI (red) heating.

Ion temperature is measured from two identical Acord-12 neutral particle analyzers with lines of sight crossing around $r/a \approx 0.1$ [5]. The average electron density is obtained from microwave interferometry and the central electron temperature is determined from ECE, below the density cut-off, and Thomson scattering. ECR heated plasmas present flat density profiles below the cut-off ($\approx 1.7 \cdot 10^{19}$ m^{-3}) and peaked electron temperatures profiles with central temperature around 1 keV are measured, thus low collisionality plasmas. Oppositely, NBI plasmas have much higher collisionalities because of the density increase, reaching up to $4.5 \cdot 10^{19}$ m^{-3} with less flat profiles, and decreasing electron temperature to 300 eV with much flatter profiles.

Since the NBI injectors at TJ-II work at 33 keV and the central electron temperature is usually below 1 keV in NBI operation, more than 70% of the power is coupled to the electrons. Part of this power is later transferred to the ions through collisions.

In figure 1 the behaviour of the ion temperature versus the collisionality is shown for the whole range of heating of TJ-II plasmas. At very low collisionalities the ion electron coupling is so bad that despite the positive radial electric field the ion temperature is very low $\approx$ 70 eV[3]. The temperature increases with collisionality up to Ti $\approx$ 125 eV and is later followed by a sudden drop with the change from positive to negative electric field (electron to ion root). A further increase of the collisionality results in a better coupling and a larger negative radial electric field, translating in an increased ion temperature. Around $\nu_{ie} \approx$ 300 the ion temperature reaches a maximum.

4.- Analysis

To finally obtain the ion energy confinement time the last two terms of Eq. 1 have to be determined. The fraction of the NBI power coupled to the ions has been modelled, through FAFNER and EIRENE simulations, with a functional which only depends on line density and injector (co or counter). This functional is valid for densities ranging from 0.5 to $5 \cdot 10^{19}$ m^{-3} with an error of less than 10 %. This modelling provides 'shine through' losses, power absorption, the fraction going to ions and electrons and beam CX losses.

The power losses by CX have been estimated averaging the expression $P_{cx}=n_0 \cdot n_i \cdot <\sigma v>_{cx} T_i \cdot V$ over the whole volume. The neutral density, n_0, is calculated through EIRENE code, and has a maximum of $1.2 \cdot 10^{15}$ m^{-3}. With these values, and for ion temperatures in the range of about 100 eV and $<\sigma v>_{cx} = 5 \cdot 10^{-14}$ m^{3}s^{-1}, charge exchange losses are found to be less than 10 kW.

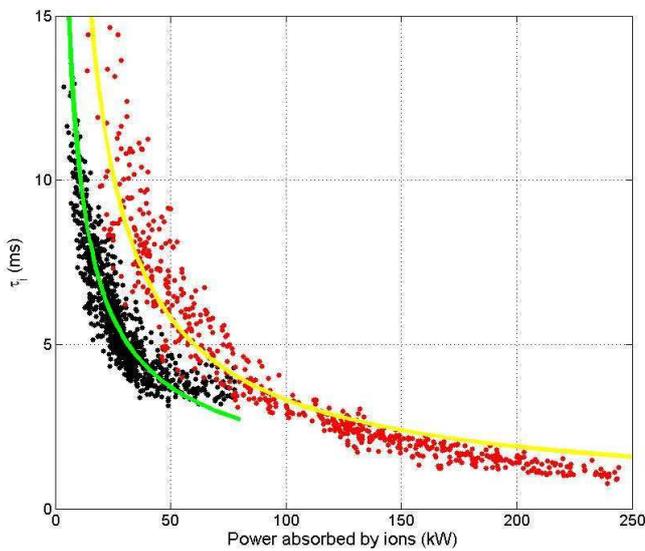**Fig. 2** Ion confinement time versus power absorbed by the ions for ECRH (black) and NBI (red) heated discharges and the shots of Fig. 1.

On Figure 2 the ion confinement time, obtained from equation 1, is plotted versus the power absorbed by the ions and the same shots of Figure 1. The ion

confinement degradation with absorbed power is apparent. Two different scenarios are clearly identified: one with just ECR heating and another above the density cut-off with just NBI (above 75 kW). When both heating systems overlap, the interpretation is not straight forward.

The only parameters that change in the analyzed discharges are the average line density and the power injected, so a fitting following the spirit of the scaling laws, i.e. $\tau_i \propto n_e^{\alpha} P^{\beta}$, was done. The results give a different fitting for pure ECH and pure NBI heating: $\tau_i^{ECH} \propto n_e^{1.6 \pm 0.1} P^{-1.3 \pm 0.05}$ and $\tau_i^{NBI} \propto n_e^{1.2 \pm 0.1} P^{-2.7 \pm 0.1}$. This indicates somehow similar density dependences but a much stronger degradation with power for NBI. Please notice that in ECR ions are only heated through collisions, a thermal effect, whereas in pure NBI there is also a direct ion heating which is localized in phase space at high energies.

As a comparison the ISS04 [6] scaling law dependences are $\tau_i^{ISS04} \propto n_e^{0.54} \cdot P^{-0.61}$. Disagreement on the values is not surprising since here only ion confinement is taken into account whereas in the ISS04 scaling law both electrons and ions are used for the calculations.

5.- Conclusions

In this work a systematic study of ion confinement time using data of ~1500 shots from different experimental campaigns has been done. To do this study experimental data and results from EIRENE-FAFNER codes to model ion power heating and neutral density have been used.

The results show that ion confinement time depends on power, density and heating method, i.e. ECR or NBI. Better statistics in the next experimental campaigns would help us to improve the dependence of ion confinement degradation on power, density as well as TJ-II configuration.

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