Core impurity rotation in TJ-II plasma scenarios in which combined ECRH and NBI heating is used to mitigate impurity accumulation

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Introduction. In both stellarators and tokamaks, long impurity confinement times, or impurity accumulation, are observed in some operational regimes [1-3]. The avoidance of this deleterious effect is critical for these current magnetically confined plasma devices and for future fusion reactors. Electron Cyclotron Resonance Heating, ECRH, has been demonstrated as an effective tool to mitigate this problem, as its application has the capability to reduce impurity accumulation [1].

In the particular case of TJ-II stellarator plasmas, two markedly distinct regimes for impurity confinement exist [4]: pure ECRH plasmas from which impurities, injected by laser blow-off, are expelled within a short time and pure Neutral Beam Injection, NBI, heated regimes where injected impurities exhibit long confinement times, *i.e.*, impurity accumulation. These two distinct regimes correlate quite well with plasma rotation or radial electric field, E_r, the latter being positive for the ECRH case and negative for the NBI case [5].

Due to the suspected relationship between the sign of E_r and particle/impurity confinement, we study here the behaviour of poloidal plasma rotation, as determined by using emission lines from core impurity ions, in mixed regimes where ECRH is applied to NBI plasmas in order to empirically understand how ECRH can contribute to particle and impurity mitigation. First, we present typical TJ-II discharges where this effect is investigated. The details of the passive spectral technique used to determine the rigid core rotation in TJ-II, and how it changes under different conditions of ECRH applied to NBI plasmas, are also explained. Finally, we quantify, in a simple manner, how the relative confinement of selected discharges changes under this operational regime as a key parameter to mitigate impurity confinement in this combined heating scenario.

Experimental. The observations were performed in the TJ-II, a four-period, low magnetic shear stellarator with major and average minor radii of 1.5 m and ≤ 0.22 m, respectively [6]. Plasmas are generated with hydrogen as working gas by ECRH operated at the second harmonic (f = 53.2 GHz, P_{ECRH}< 500 kW), combined with a neutral beam injector providing up to 500 MW of additional heating. Central electron and ion temperatures are in the ranges from 0.25 to 1.5 keV and 70 to 80 eV, respectively, depending on heating power and plasma density. A sketch of the TJ-II operational mode is depicted in Fig. 1(a), which shows the line-averaged electron density evolution for different ECRH and NBI scenarios. Impurity emission lines, obtained by passive spectroscopy, are modeled as Gaussian curves. Rotation velocities are determined from Doppler shifts of C^{4+} (227.1 nm in 3rd diffraction order) and C^{5+} (529 nm in 1st order) spectral lines, assuming that they correspond to core impurity rotation. For this, the rotation diagnostic is a high spectral resolution spectrometer [7]. It was upgraded to allow plasma light collection using direct optics. This approach improves sensitivity for UV radiation, compared to a fiber bundle. Also, it allows more flexibility when defining the number of spatial channels since rather than by software grouping of CCD pixels. The relative response of the entire system is obtained by placing a large commercial diffuser (Spectralon, LABSPHERE) with a flat response over the entire spectral range of interest. This is placed on the vacuum side a fused silica window through which the plasma is viewed.

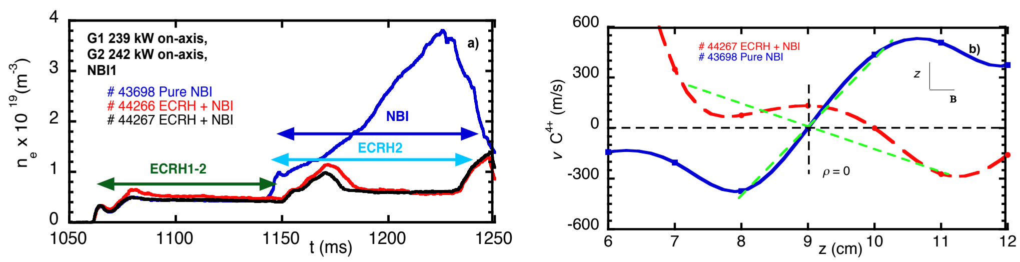

Fig. 1. Plots of electron density and ion rotation for paradigmatic cases with different heating scenarios: a) Electron density evolution for 3 discharges where ECRH is superimposed on NBI; when the mitigation effect is properly programmed (#44266 and #44267), the effect is dramatically reflected in the density evolution, otherwise a discharge similar to a pure NBI regime is obtained (#43698). b) Doppler spectroscopic data corresponding to central core rotation are fitted (dashed green), being the *z* direccion is perpendicular to the magnetic field, B. The integration time chosen for line integrated impurity radiances was 60 ms in order to cope with weak impurity emissions. The figure highlights the impurity ion rotation inversion produced by the aplication of an ECRH pulse to an NBI heated plasma (#43698), where ω sign change is observed compared with a pure NBI plasma (#44267).

In Fig. 1(b), C^{5+} Doppler spectroscopy data are fitted with a straight line. The data correspond to core emissions, *i.e.* where intensity is maximum. It presents raw rotation velocities for C^{5+} for two discharges (#44267 & #43698) with similar densities ($\approx 0.8\times10^{19}$ m^{-3}) where #44267 corresponds to a mixed regime and #43698 to a pure NBI discharge. A rotation inversion occurs here as a consequence of the mixed heating regime operation for these otherwise similar discharges.

Results and discussion. The rotation of C^{4+} and C^{5+} ions is reported for a power scan of ECRH+NBI and pure NBI plasmas. Core rotation (ω in rad/s) vs. line-averaged density, for C^{5+} emission, shown in Fig. 2(a) for mixed, pure ECRH (positive) and pure NBI regimes (negative) regimes. We highlight the contrast observed in the mixed regime where, with different ECRH conditions, we can move along different densities and rotation, or ω signs, for the same density when ECRH is overlapped on NBI heating.

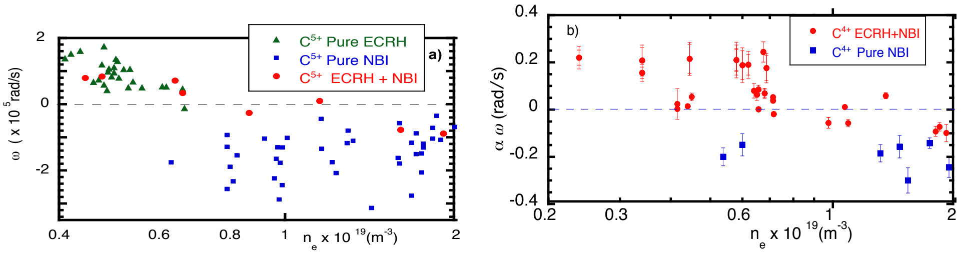

Fig. 2. Plots of rigid-core poloidal angular rotation versus line-averaged electron density: a) for C^{5+}, showing data for the mixed heating regime & for pure ECRH or NBI heating regimes. b) Linear fitting slope ($\propto\omega$) of the Gaussian shift for C^{4+} line emission, showing data for the mixed and pure NBI regimes.

A more complete data set is obtained by measuring core poloidal rotation with C^{4+} ions. See Fig. 2(b) where a comparison is made between the core angular rotation results obtained exclusively in the mixed regime and those for pure NBI heating. We must highlight the broad range of rotation conditions and plasma densities that can be covered, going from ECRH-like positive values at low density to negative values at high densities, less negative than in which pure NBI is applied. Also, some interesting cases are those with similar densities but with ion rotation in opposing directions: see Fig. 2(b). We will investigate more deeply these singular cases. Complementarily, but different, plots of solid-angular ω versus plasma electron density are shown in Fig. 3.

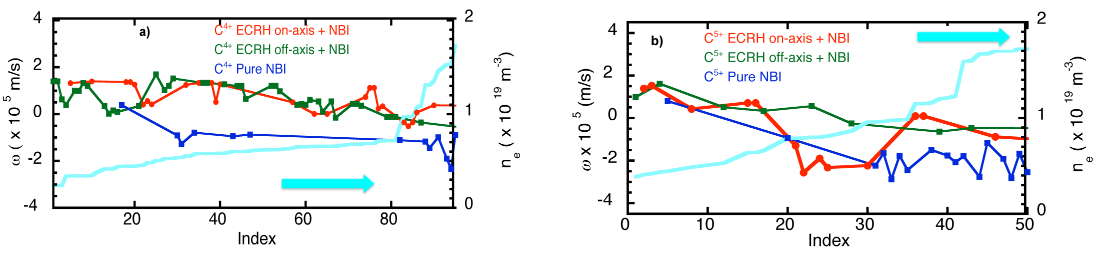

Fig. 3. Plots of ω and n_e in increasing order of density (an index order is assigned) to highlight the influence of ECRH focusing position (on-axis, $\rho = 0$, vs. off-axis $\rho \neq 0$) and a comparison of mixing regime with pure NBI regime, a) C^{4+} ion at 227.1 nm; b) C^{5+} ion at 529 nm emission lines.

The more dense data grid obtained with this element for the mixed heating regime is shown. The selected discharges that compose this plot are ordered in sequentially increasing line-averaged density (index): those with higher density values and negative ω are comparable to pure NBI discharge but with moderated density and rotation, whilst lower density and positive ω are more similar to pure ECRH discharges. Small differences are found at some densities with a different gyrotron focusing radius (on/off) used to moderate the confinement.

In order to understand the influence of the deposition of heating power in Fig. 4, we plot the density variation in the same time window and its changes for a few cases where the ECRH power and focus were varied when it was overlapped with the NBI pulse. These results could highlight that the mitigation operational method could have an effect on particle confinement and confirm the idea that additional ECRH could play a role in changing the ω under this experimental conditions. For this reason it is necessary to complete the study with HIBP measurements of E_r, future works will point in this direction.

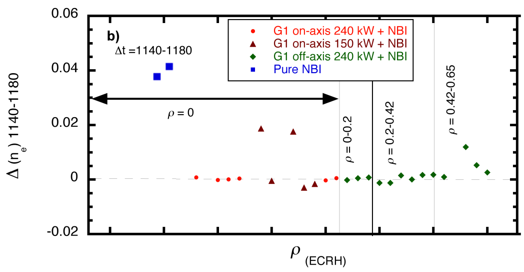

Fig. 4. The effect of particle confinement reduction showing the density variation in the time window where the ECRH is overlapped with NBI: this slope and its dependence with the on-axis/off-axis deposition of heating power.

The obvious questions emerging from those results are: i) are density profiles and rotation inextricably linked? and ii) is there no means to decouple both plasma parameters in a predectable and controllable manner? If this is so, then the only option would be to understand empirically the fine tuning of this potential mitigation mechanism in order to have a control knob to aid with impurity mitigation that does not change dramatically the electron plasma density. Nowadays, combined heating regimes in TJ-II plasmas are being studied not only in order to understand impurity confinement and mitigation but also to investigate the impact of Electron Cyclotrone Current Drive on Alfvén Eigenmodes [8]. A multidisciplinary approach is required to unravel the potential double possitive role of the combined heating method.

Acknowledgements. This work was partially funded by the Spanish “Ministerio de Economía y Competitividad” under Grant No. ENE2014-56517-R. One of the authors (BLM) would like to thank for her scholarship under Grant No. BES-2015-075704.

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