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Ion temperature and toroidal rotation measurements in low torque plasmas[a)]

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Over the years a database for intrinsic rotation has been collected at the Joint European Torus (JET). Much effort has been put to obtain intrinsic rotation measurements in which the use of one CX PINI, required for the diagnostic analysis, combined with low impurity content lead to low active CXRS signal and low rotation. This paper reports on the procedure developed as the best method to provide an accurate and reliable estimation of T_i and v_ϕ, along with the description on how the absolute calibration and the ELMs are dealt to minimize error propagation to quantities of interest.

I. INTRODUCTION

In present tokamaks plasma rotation is largely driven by Neutral Beam Injection (NBI). However, the NBI torque in ITER will be small, due to the increased plasma inertia when compared with current devices, and this has led to an enhanced interest in measuring plasma rotation observed in the absence of torque, known as intrinsic rotation, along with renewed efforts to develop the underlying theory. Accurate and reliable measurements of both rotation and temperature are thus of crucial importance. At JET these measurements are obtained by Charge eXchange Recombination Spectroscopy (CXRS) of the CVI emission line. The use of one PINI, for diagnostic purposes, results on low active CXRS signal with respect to the passive component, thus turning the analysis sensitive to photon statistics and small disturbances. This paper is intended to discuss the issues encountered at JET in obtaining reliable rotation measurements in plasmas with low external torque, alongside with the procedures and assumptions necessary to overcome these difficulties.

II. JET CORE CXRS

JET has two CXRS systems, the core and edge CXRS diagnostic. The core CXRS diagnostic[1-2], used in this paper, consists of two periscopes, in octant 1 and 7, which define toroidal views aligned with the Neutral Beam Injector (NBI) located in octant 8. The NBI is constituted of Positive Ion Neutral Injectors (PINIs) divided in two banks, a tangential and normal bank. The diagnostic views are mainly aligned on PINI 8.6 from the normal bank and PINI 8.7 from the tangential bank, but all see PINIs 8.1 and 8.4. The PINIs are identified by two numbers, the first indicates that the injector is located in Octant 8 while the second, a number from 1-8, is the PINI number in the beam box. The system has twelve Lines-Of-Sight (LOS) located in the equatorial plane, tangentially to the flux surfaces. Each of the 12 fibres transmits the collected light to one of the five available wave tuneable spectrometers. The spatial resolution[2] is typically ~8 cm, depending on the cross-section area of the NBI with the LOS, whereas the temporal resolution is of 10 ms.

III. INTRINSIC ROTATION

The aim of the JET intrinsic rotation database is to provide ion temperature (T_i) and toroidal velocity (v_ϕ) measurements collected in absence of deliberate momentum input. The difficulty in analysing the intrinsic rotation database arises from the facts that CXRS signal is low, due to the use of 1 CX PINI only and low carbon content, and that rotation is low. Although these conditions are outside the standard operations for the JET CXRS diagnostic, they mimic what is expected in ITER, where the high-density plasma will lead to substantial beam attenuation. The discharges that constitute the database are with Ohmic heating, Lower Hybrid Current Drive (LHCD) or Ion Cyclotron Resonance Heating (ICRH), and were performed with JET's carbon wall[3]. This allows to use the CVI n=8-7 transition, with natural wavelength of 529.059 nm, for the CXRS diagnostic. To provide the least possible disturbance to the plasma (i.e. limit the momentum input), intrinsic rotation measurements are taken with a short blip from one PINI, at reduced voltage. The PINI most used for intrinsic rotation measurements is the PINI 8.6. This choice is due to the fact that this PINI has a nearly normal angle with respect to the magnetic axis and that the intersection between the CXRS LOS and the beam is optimised when compared with other available PINI (i.e. PINI 8.4). The main advantage of the CXRS diagnostic arises from the fact that neutral density is small along the LOS except in two regions. The first region is close to the plasma edge where background neutrals are able to penetrate, contributing therefore to a passive charge-exchange emission before ionization. The second region is located at the intersection between the NBI and the LOS, which defines the volume of active charge-exchange. The total emission during neutral beam injection is the sum of these active and passive contributions. The intensity of the active CX signal depends on the beam density at the radial intersection point, which depends on the beam operating conditions and beam attenuation. Therefore, in these conditions when the ratio

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between passive to active signal approaches unity, as it can be inferred from Fig. 1, the analysis method to provide ion rotation and temperature is more sensitive to photon statistics, Magneto-HydroDynamics (MHD) activity, or even to the use of an intrinsic impurity to define the reference for the zero angular frequency. Fitting the full spectrum with multiple Gaussian would confer too much liberty whilst the beam modulation method, described below, can improve results by a perfect suppression of background line-emissions in short time scales or in stationary conditions.

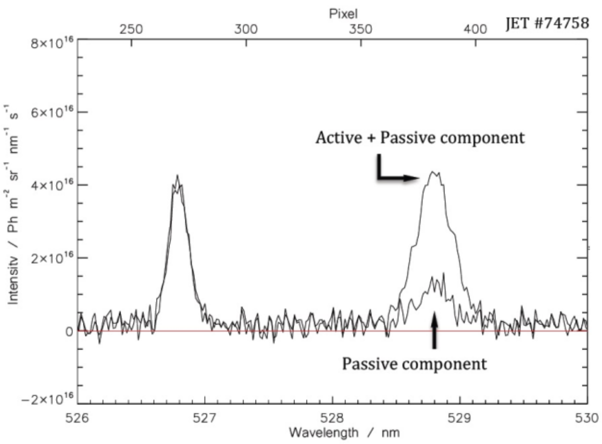

FIG. 1. Passive spectrum (before NBI) and full spectrum (during NBI) for JET discharges #74758, with 1.4 MW of NBI from PINI 8.6.

A. Beam Modulation at JET

The beam modulation method uses the passive component acquired prior to the injection of neutrals to be subtracted to the full spectrum, acquired during NBI. The remaining spectrum, which now only accounts for the active charge-exchange emission, is then analysed with a single Gaussian fit, allowing to retrieve the impurity T_i and v_ϕ from the Doppler broadening and Doppler shift respectively.

The results obtained during this study have shown discrepancies when using a single or multiple passive frames for the subtraction, mostly in the plasma core region. The weaker signal in the core is due to beam attenuation and causes the ratio between the passive and the full spectrum to increase when traveling towards the plasma center, making the method more sensitive to errors. Therefore, to reduce statistical noise, 10-20 passive CX measurements, acquired prior the NBI, are averaged and used for the subtraction.

B. Absolute calibration

During standard operations torque contribution from the NBI is dominant and consequently rotation is high. In the cases considered here, to decrease the uncertainty of the method used to treat intrinsic rotation measurements, the absolute calibration has to be consistently calculated in the ohmic phases of the discharges.

Although the presence of other impurities spectral lines can complicate the analysis, due to the possible overlap of emissions, it can also be beneficial for the analysis of a complex spectrum. For example the case of Be^{1+}, peaking at λ = 527.063 nm, originated mostly from the plasma edge is often assumed as stationary ($v_{Be} << v_C$), allowing this emission line to be used as a reference for the zero angular frequency[4]. In this case, the calibration line is fitted and the wavelength grid is re-calculated based on this line being at its specific theoretical wavelength, while wavelengths of the other lines are adjusted accordingly. However, the absolute calibration can be calculated using the BeII line in different phases of the discharge, either in an ohmic or in heated phase. The results that arise from the analysis with the Be taken in different heating phases, and hence plasma conditions, are shown in Fig. 2, for a plasma with ICRH. Here, the D_α emission from the outer divertor is depicted in a), the additional heating from RF and the NBI for diagnostic purposes in b) while c) shows the maximum electron temperature (T_e). The angular frequency (ω_ϕ) in the plasma core (R = 3.1 m) is shown in d) whereas edge angular frequency edge rotation (R = 3.8 m) is depicted in e).

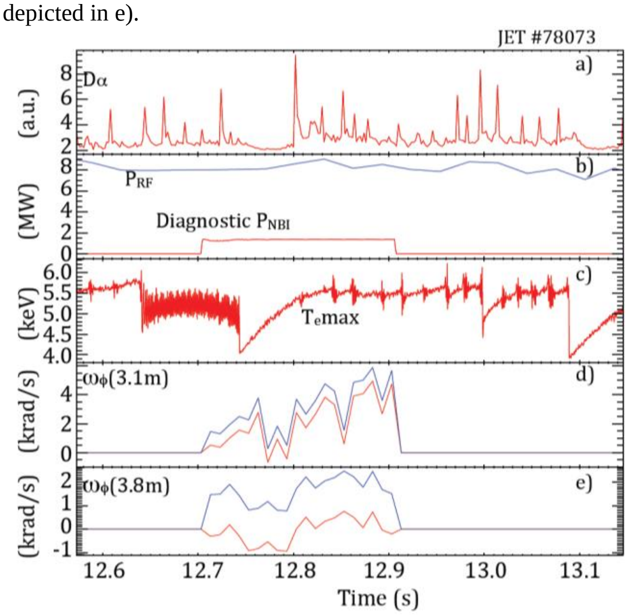

FIG. 2. Time evolution of a) D_α, b) P_{ICRF} and diagnostic P_{NBI}, c) maximum value of T_e, and angular frequency for d) R = 3.1 m and e) R = 3.8 m. For the angular frequency, calculation was made assuming the absolute calibration from ohmic (red) and ICRH phase (blue).

Results clearly indicate that for intrinsic rotation studies, in which the Doppler shift of the carbon line is small, the absolute calibration has a significant impact. The time evolution of the angular frequency in red is obtained when the reference is taken in the ohmic phase, whereas the blue line is obtained when the absolute calibration is fitted during the ICRH phase. In both core and edge, the angular frequency is enhanced in the co-current direction when the reference line is fitted during the ICRH phase. The explanation for this effect is that the Be reference line has shifted in the counter-current direction to justify the increase of the apparent shift of carbon in the co-direction, intriguingly this means that beryllium is rotating in the opposite direction with respect to the carbon during the ICRH phase. The core CXRS in standard operation do not suffer greatly from this, but in these cases, in which rotation is low, measurements would benefit from a system for wavelength calibration as in the edge CXRS system at JET[5].

The ion temperature is derived from the Doppler broadening of the active spectrum. Therefore, although not presented here, it is clear that the selection of the Be line does not have any impact on the results for T_i since this reference line only define the zero angular frequency and do not alter the spectrum to be analysed.

C. MHD Impact on Passive Emission

Since the method relies on subtracting the passive emission to the full spectrum, it is important to verify whether MHD events could affect the passive emission. For an H-mode discharge with 8 MW of RF power, it was found that the Edge Localised Modes (ELMs) have a strong effect on the analysis whereas no clear effect could be linked to sawtooth activity.

For the influence of ELMs, the passive charge-exchange component has been acquired at two instants to subsequently infer the impact on the results for both T_i and ω_ϕ. For those two instants shown here, the 10 ms integration time of the diagnostic allowed to acquire a passive frame with and a frame without an ELM. For each case the active component is obtained by subtraction of the passive component to the full spectrum. The results are shown in Fig. 3, indicating that both T_i, represented in a), and ω_ϕ, shown b), are drastically different depending in passive component used for the analysis. T_i presents a maximum difference close to 60% with substantial discrepancies across the entire profile, which are well outside the error-bars shown by dashed lines.

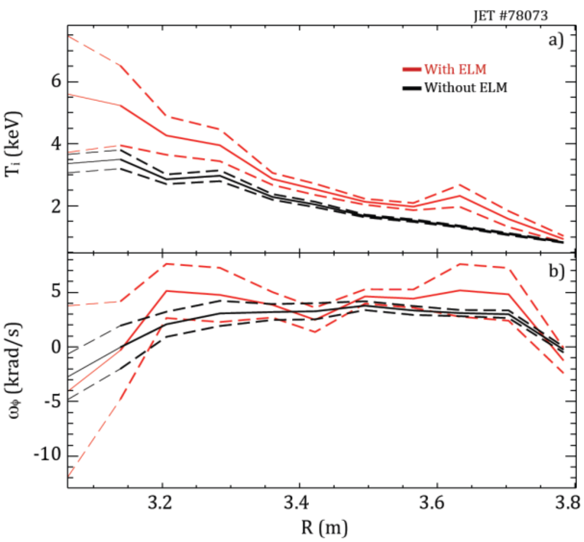

FIG. 3. Radial profile of a) T_i and b) ω_ϕ obtained with a single Gaussian fit of CVI line after subtracting the passive CX component, obtained with a single frame integrated over an ELM (red) or without an ELM (black), to the full spectrum during NBI. Dashed lines are the error-bars.

In the case of subtracting the passive CX acquired during an ELM it is clear that the final results are overestimated. The ELMs periodically expel plasma energy and particles[6]. The enhanced particle content in the plasma edge following an ELM increases the intensity of the spectrum, since the magnitude of C^{5+} passive emission is proportional to the carbon density along the LOS. This spectrum subtracted to the full spectrum result in a less intense active CX component and a broader half-width of the remaining spectral lines and therefore larger error-bars due to low signal-to-noise ratio.

To assess the possible impact of the sawtooth, the obtention of the remaining active CX has been performed subtracting to the full spectrum the passive component at three distinct instants. Those were selected to compare the subtraction of the passive component acquired prior, just after a sawtooth crash and 100 ms into the sawtooth ramp-up phase and for which no ELM occurred during the acquisition of the spectrum. Fig. 4 shows the results for T_i (a) and ω_ϕ (b) profiles. The red line is obtained by subtracting the passive spectrum acquired prior to sawtooth, black line from passive just after while the green line corresponds to 100 ms after the sawtooth. It is clear that sawteeth do not have a significant impact. The largest observed difference is ~15% in the plasma core for T_i although the measurements are within the error-bars. In terms of angular frequency the same conclusion can be drawn since the profiles are in reasonable agreement.

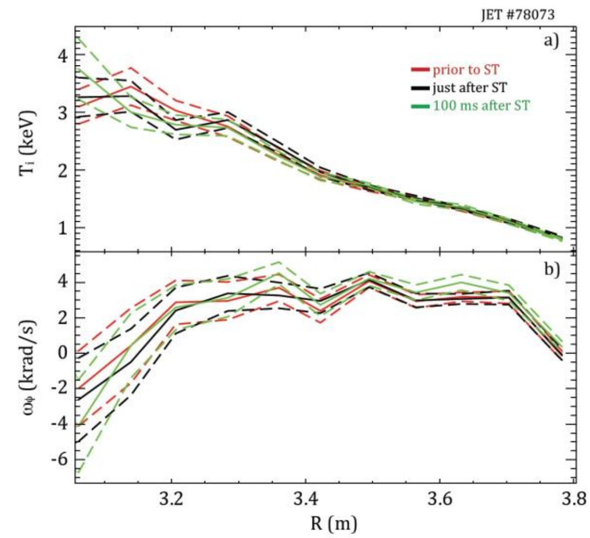

FIG. 4. Radial profile of a) T_i and b) ω_ϕ obtained with a single Gaussian fit of CVI line after subtracting the passive CX component obtained prior a sawtooth (red), just after a sawtooth (black) or 100 ms after a sawtooth (green). Dashed lines are the errors associated to the measurements.

In order to take into account all the above mentioned subjects, CXSFIT software[7] has been modified to perform JET intrinsic rotation analysis. CXSFIT has now a subroutine which, when selected, can detect the instants where ELMs event occurs and select a fixed number of passive frames prior the NBI and subtract the averaged passive emission to the full spectrum acquired. The number of passive frames used is chosen by the user, the program only deals with passive frames which do not include an ELM, disregarding the frame(s) with ELM and selecting the adjacent one(s).

IV. ACKNOWLEDGMENTS

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