1. Introduction. The main motivation in obtaining poloidal rotation measurements in fusion devices is to obtain information about the radial electric field, $E_r$. The prominent role of $E_r$ on transport is due to the reduction of anomalous transport by large ExB shear and in stellarators, due to their lack of symmetry, to the reduction of neoclassical transport [1]. Poloidal rotation measurements in stellarators have been reported for several electron cyclotron resonance (ECR) heated plasmas. For example, in the Heliotron-E device, measurements made using passive emission spectroscopy of C V emitting at 227.1 nm show that the radial electric field is positive (the electron root) in low density plasmas ($n_e(0) < 1 \times 10^{19} \text{ m}^{-3}$) and negative (the ion root) in high density plasmas ($n_e(0) > 2 \times 10^{19} \text{ m}^{-3}$) for $r \approx 0.7 - 0.9 <a> \ [2]$. In electron cyclotron heated (ECH) plasmas of the Wendelstein VII-A stellarator ($n_e(0) \approx 5 \times 10^{19} \text{ m}^{-3}$), the observed negative electric field is consistent with theoretical predictions [3]. Finally, in the Advanced Toroidal Facility, a positive electric field was observed in ECH low density plasmas ($n_e(0) \approx 5 \times 10^{18} \text{ m}^{-3}$), when using a heavy-ion beam probe technique [4]. Detailed reports on the poloidal rotation and deduced radial electric field in stellarators with additional neutral beam injection (NBI) can be found in the review article [5] and in other references [6-8]; some of which are directed towards the goal of understanding the L-H transitions in stellarators. However, despite the extensive work already done and the work carried out on the matter [6], the problem of how to attain the 'electron root' in a controlled manner still remains. Here, we report measurements on the poloidal rotation of C V ions across the TJ-II in ECRH and NBI plasmas, and we use them to estimate the sign and magnitude of the radial electric field. In addition, we describe the upgrades made in the experimental set-up, and outline the results obtained in ECR and NBI TJ-II plasmas.
2. Experimental. The TJ-II flexible stellarator is a four-period medium-sized heliac device with an average major radius of \(<R> = 1.5\) m and an average minor radius of \(<a> \leq 0.25\) m. It can explore a wide rotational transform range \((0.9 \leq \iota(0)/2\pi \leq 2.2)\) in low, negative shear configurations. The \(\text{mod}(B)\) ripple is not negligible, its varies depending on the magnetic configuration, \(i.e.\) from 18 % to 41 % at the edge and from 1.5 % to 3 % at the centre [9]. During the experimental campaign of this work, the injected ECRH power, \(P_{\text{ECRH}}\), was \(\leq 400\) kW while injected NBI power, \(P_{\text{NBI}}\), was \(\leq 250\) kW. The neutral hydrogen, \(E_{H} = 30+35\) keV, was injected in the co-magnetic field direction for \(t=100+150\) ms pulse length. Notice that if looking down from above, the toroidal field and plasma current in an equivalent tokamak, giving rise to a poloidal field in the same direction as that generated by the TJ-II external coils, are in the counter-clockwise direction. In all discharges, the plasma target and the NBI have hydrogen as their working gas. Also, prior to beginning each experimental campaign the vacuum chamber wall is boronized which results in a decrease in the concentration of carbon, oxygen and other impurities (N, F, Fe, Cr, \(etc\)). In addition, helium is used daily, prior to operation, to perform glow discharge conditioning while, in addition, a strong helium puff is injected into the machine after the main plasma discharge in order to calibrate the heavy ion beam probe diagnostic. The spectral system used to perform this experiment, the plasma observation geometry and the data reduction procedure have been explained in detail in a former publication [10]. Therefore, herein we will include exclusively the main changes introduced in the system. We have coped, with the lowering in the C V spectral signal level produced by an efficient vacuum wall boronization, by shortening the fiber bundle length from 10 to 3 meters and by using 9 fibers with a core diameter of 1 mm instead of 200 \(\mu\)m. The sensitivity of the system has shown an improvement in more than a factor 10. In addition, the previous front illuminated CCD detector has been substituted by a back illuminated detector with the longer dimension aligned along the vertical axis. Regarding to the sign criteria chosen in this work, we define the sign of the line shift and therefore velocity by \(v = c \Delta \lambda / \lambda_{0}\) with \(\Delta \lambda = \lambda_{0} - \lambda_{m}\), \(c\) the speed of light and \(\lambda_{0}, \lambda_{m}\) the wavelengths at rest and in the rotating plasma, respectively. Positive rotation of the upper plasma half means: blue shift of the line, rotation in the electron diamagnetic direction and negative radial electric field.
3. Results and discussion. The plasma density seems to be one the main key parameters that set the sign and value of the C V poloidal rotation in TJ-II, although we believed that the own ion temperature might play a minor role, as well as the profile shape. We will emphasized also that it is the plasma density achieved in the discharge and not the type of heating either ECRH or NBI used to achieve it, even if the overlapping of density ranges is very narrow from the operational point of view.

In Fig. 1, we present results of C V poloidal rotation (left) and ion temperature (right) for two ECRH reference discharges \((n_e=0.63 \text{ and } 0.67 \times 10^{19} \text{ m}^{-3})\) and two ECRH+NBI discharges with increasing line-averaged-density \((0.94 \text{ and } 1.72 \times 10^{19} \text{ m}^{-3}, \text{ in red and blue, respectively})\); the spectral line shapes used to deduce line shifts and widths were integrated for 30 ms starting at 1150 ms (plasma starts at 1020 ms). A change in the sign of rotation and the full evolution of the nine points of cord-integrated profiles either of poloidal rotation and C V temperature is evident from these two plots. On the right vertical axis of rotation plot we have depicted the radial electric field values corresponding to that poloidal rotation under the reasonable assumption that the change of this parameter is the main cause of the observed effect.

![Fig. 3. Plots of cord-averaged data for C V ion of poloidal rotation (left) and ion temperature (right) for discharges with increasing electron densities. Blue and red discharges correspond to ECRH + NBI. The Thomson scattering profiles corresponding to a single time in these discharges are depicted in Fig. 2, following a colour code that allows to identify the data corresponding to the same discharge. Here you can observe the typical behaviour observed in TJ-II and other](image-url)
stellarator; when the density increases either by puffing gas or by NBI, the electron temperature decreases from 1 keV to around 250 eV. Because of collisional coupling the electron and ion temperatures tend to equalize as the density increases. A typical correction factor of 1.5 should be applied to peak cord-averaged values of C V temperatures to be converted in local ones.

![Graph](image)

**Fig. 2.** Thomson scattering profiles corresponding to the same four discharges of figure 1.

A more complete view of the role of plasma density on poloidal rotation and therefore radial electric field can be seen by means of the data plotted in Fig. 3 (left) where the peak rotation and temperature of C V, corresponding to the upper plasma half, have been depicted as a function of the line-averaged electron density. Typically in ECRH plasmas at densities below $1 \times 10^{19}$ m$^{-3}$, the radial electric field is positive.

A more fine view of the transition is shown by the experimental sequence depicted in Fig. 3 (right) in a narrower density range. We must emphasize that the highest density discharges achieved with only ECRH heating also exhibits that change in plasma rotation or radial electric field depicted in Fig. 1.
Fig. 3. Plots of C V maximum temperature (open squares) and rotation (full points) versus line-averaged-density for a standard sequence (left). Plot on the right side shows a different sequence where the transition is seen in more detail.

These measurements are in agreement with neoclassical theory calculations [11], that predict a change in the sign of $E_r$ mainly because of a change in the ratio of the electron to ion temperatures. When operated under wall-boronised, TJ-II stellarator plasmas are characterized by peaked electron temperature profiles and rather flat, or even hollow, density profiles. The density is relatively low, because of the 2nd harmonic X-mode cut-off density ($n_e \approx 1.7 \times 10^{19} \text{ m}^{-3}$), and due to the inefficient collisional coupling disparate electron and ion temperatures are observed. For the central plasma column $\Gamma_{e_{\text{neo}}} >> \Gamma_{i_{\text{neo}}}$ and thus the radial electric field is positive, $E_r > 0$. On the other hand, in the NBI heating phase the density is much higher; the electron temperature is lower, it’s profile flatter and the gap between electron and ion temperature shortens, so $\Gamma_{e_{\text{neo}}} << \Gamma_{i_{\text{neo}}}$ and $E_r < 0$.

**Iota dependence.** Since one of the TJ-II features is its flexibility to confine plasmas under a wide range of rotational transform, one of the reasonable questions to raise is for its role in poloidal plasma rotation. In order to answer that point we have plotted in Fig. 3 (left) the dependence of the peak C V poloidal rotation as a function of the edge iota values for a set of ECRH discharges. There exists a small and systematic effect when you go from iota values of 1.6 to 2.2 as can be seen in the former figure. However, when the detailed cord averaged poloidal rotation profiles are compared for two extreme iota values of the former plot, shown in Fig. 3 (right), no significant differences at other cords are observed except...
for the aforementioned one. The plasma center, defined internally from rotation measurements as the symmetry center of the rotation, seems slightly different in these two rotation profiles.

Fig. 4. Influence of iota on poloidal plasma rotation: on the left is depicted maximum rotation versus iota and on the right two rotation profiles are compared.

In conclusion, rotation measurements using a core impurity like C V have allowed to study the changes in plasma rotation and consequently in radial electric field as a function of density and iota for ECRH and NBI discharges of the TJ-II stellarator.

References