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Influence of Rotational Transform and Magnetic Shear on the Energy Content of TJ-II Plasmas

Estrada, T.; Ascasíbar, E.; Castejón, F.; Jiménez, J.A.; López-Bruna, D.; Pastor, I.

13 pp. 6 figs. 12 refs.

Abstract

In the magnetic configuration scans performed in TJ-II stellarator, low plasma energy content is found to be related to the presence of low order rational surfaces within the confinement region in low plasma density experiments. Plasma currents of about -1 kA (mainly bootstrap driven) can substantially increase the magnetic shear in TJ-II and under these conditions the confinement is no longer deteriorated by low order rational surfaces.

Experiments with higher plasma currents (OH induced currents up to +/- 10 kA) show a non-symmetric dependence on the sign of the magnetic shear. Preliminary results show a substantial improvement of the confinement in the case of negative plasma current, while minor changes are observed in the plasma energy content when positive current is induced in magnetic configurations that in vacuum exclude low order rational surfaces.

Influencia de la Transformada Rotacional y la Cizalladura Magnética en el Contenido de Energía de los Plasmas de TJ-II

Estrada, T.; Ascasíbar, E.; Castejón, F.; Jiménez, J.A.; López-Bruna, D.; Pastor, I.

13 pp. 6 figs. 12 refs.

Resumen

En los experimentos de barrido en configuración magnética llevados a cabo en el stellarator TJ-II, se observa un menor contenido de energía asociado a la presencia de superficies racionales de bajo orden en la región de confinamiento, en plasmas de baja densidad. Corrientes en el plasma del orden de -1 kA (principalmente corriente de bootstrap) pueden aumentar considerablemente la cizalladura magnética en TJ-II y en estas condiciones el confinamiento no se ve tan afectado por la presencia de superficies racionales de bajo orden. Experimentos llevados a cabo con corrientes de plasmas más altas (corrientes inducidas OH de hasta +/- 10 kA) muestran una dependencia no simétrica con el signo de la cizalladura magnética. Resultados preliminares muestran una mejora considerable del confinamiento en los casos de corriente de plasma negativa, mientras que el contenido de energía apenas se modifica cuando se induce corriente positiva en configuraciones magnéticas en la que en vacío no hay racionales de bajo orden en el perfil de transformada rotacional.

II. Experimental results

The experimental results have been obtained in plasmas heated by 300 kW of ECRH (at a frequency of f = 53.2 GHz, 2nd harmonic, extraordinary mode of polarisation), coupled to the plasma by a quasi-optical transmission line with a high power density of about 15 W/cm^3.

A Thomson scattering system [5] is used to determine the radial profiles of the electron temperature and density with a high spatial resolution. A single profile is obtained per discharge. The electron contribution to the thermal plasma energy is evaluated from measured electron temperature T_e and density n_e profiles. In the plasma edge region, where the error in the Thomson scattering measurement is large, T_e and n_e profiles are fitted up to the last closed magnetic surface with a parabolic dependence. The ion contribution to the plasma energy is obtained as follows. The shape of the ion temperature T_i profile is assumed to be equal to that of the n_e profile with a central value equal to the value obtained experimentally by charge exchange spectroscopy [6] and the ion density n_i profile equal to the n_e profile divided by the effective ion charge, Z_{eff}. Diamagnetic loops and Rogowski coils, installed inside the vacuum vessel of TJ-II, are used to measure the diamagnetic energy content and the plasma current [7].

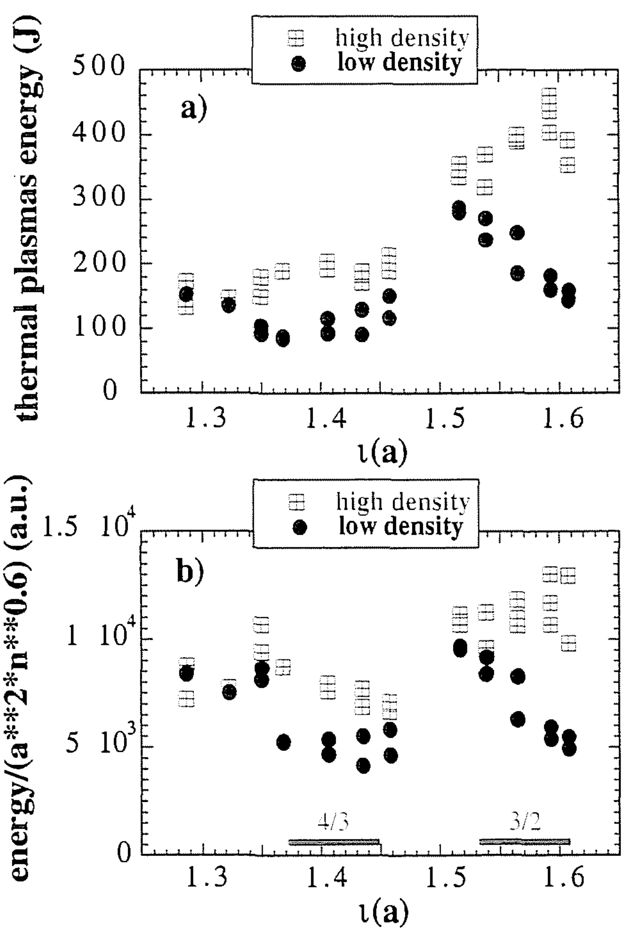

Figure 1: Thermal energy content (a) and normalised energy (b) as a function of the edge ι in vacuum, for low (black) and high (red) density conditions.

II.a. Low magnetic shear experiments

To study the dependence of the confinement on the rotational transform, a magnetic configuration scan has been performed changing ι on a shot to shot basis, from ι/2π (a) = 1.28 to 1.61 (vacuum values at the plasma edge). In each magnetic configuration discharges with different pre-programmed waveform of the gas puffing are performed, namely low and high gas puffing conditions, i.e. low and high density plasmas. In these plasmas the line density is about 0.5 and $1\cdot10^{13}$ cm^{-3}, the central T_e is high (close to 1 keV) as compared with central T_i (about 0.1 keV) and plasma current is principally bootstrap driven (in these experiments the launching parameters of the ECH system are set for no EC current drive).

Figure 1.a displays the thermal plasma energy for the low and high density plasmas, as a function of the edge rotational transform. In the magnetic configuration scan with low density, the plasma energy content depends strongly on the edge rotational transform. By increasing the pre-programmed gas puffing the energy content increases and the sensitivity to the edge rotational transform becomes weaker. To isolate the dependence of the energy content on the rotational transform from the dependence on the plasma density and plasma radius, the energy has been normalised using the parametric scaling obtained for the TJ-II plasmas [8, 9]. The result is shown in figure 1.b (the blue lines mark the configurations that have the rational surface 4/3 or 3/2 within the confinement region). In the low density case, the confinement degrades when low order rational values of ι (ι = 4/3 or 3/2) enter the confinement region (see figure 1.b). In these configurations narrow plasma pressure profiles are measured together with low net plasma currents (up to -0.4 kA, mainly bootstrap driven current). The plasma current measured by the Rogowski coils is displayed in figure 2. By increasing the pre-programmed gas puffing, the density increases and the confinement improves: the plasma pressure profile broadens and the plasma current and the plasma energy increase up to a factor of two.

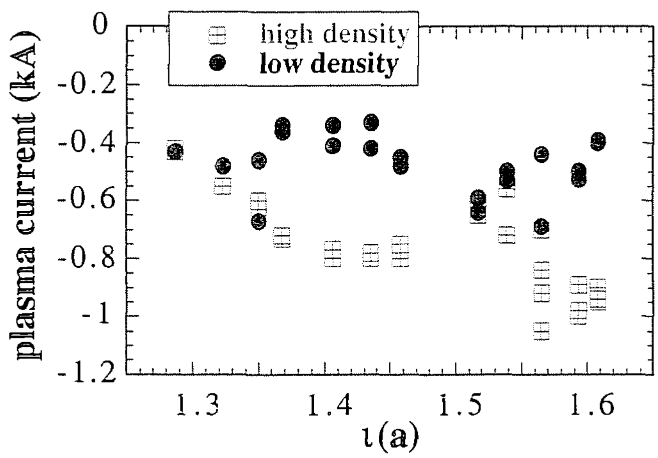

Figure 2: Net plasma current as a function of the edge ι in vacuum, for low (black) and high (red) density conditions.

Figure 3 shows the pressure profiles in configurations having the rational surface ι=3/2 within the confinement region (blue and green profiles), and close to the plasma edge (pink and yellow profiles) for low and high density plasmas (left and right figures, respectively). The rotational transform profiles in vacuum for these magnetic configurations are shown in figure 4. In magnetic configurations with low order rational values of ι located within the confinement region, there is a notable difference in the plasma pressure profiles between low and high density plasmas. Therefore, the presence of low order rational surfaces within the plasma region affects substantially the confinement characteristics, particularly in the low density plasmas. However, in configurations without low order rational values or with them located close to the plasma edge, the dependence of the confinement on the density follows the general parametric scaling [8, 9].

In these experiments, the measured plasma current is negative (see figure 2). It flows in opposite direction to the currents in the circular and helical coils, resulting in a decrease of the rotational transform with respect to the vacuum case and therefore leading to an increase in the

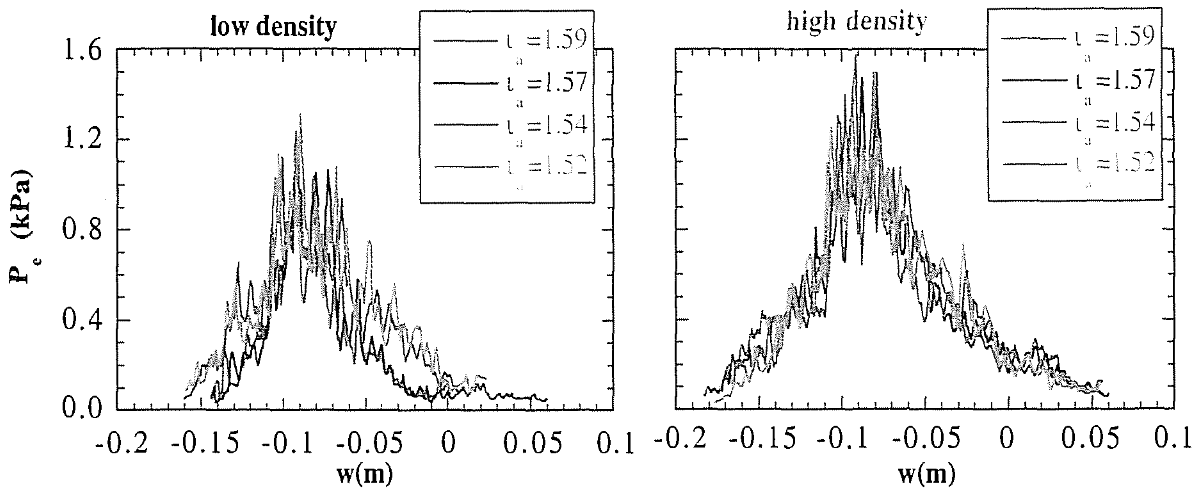

Figure 3: Pressure profiles for different magnetic configurations at low (left) and high (right) density conditions

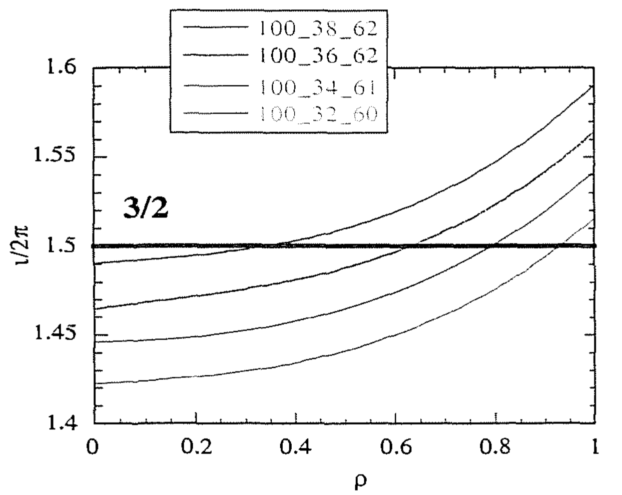

Figure 4: ι profiles calculated in vacuum for the configurations of Fig 3.

negative magnetic shear. To estimate the modification of the ι profile due to the toroidal current equilibrium calculations have been performed using the VMEC code [10]. The complexity of TJ-II has not allowed us a good assessment of the bootstrap current so far. Therefore, in the calculation of the ι profile, the total current is set as the value measured by the Rogowski coils and the current density profile is considered to be proportional to the gradient in the plasma pressure. Several reasons supporting this assumption are discussed in ref. [11]. Figure 5 shows the rotational transform profiles calculated for low and high density conditions, with plasma currents of -0.5 and –1 kA respectively, and for two magnetic configurations with ι_a = 1.59 (figure 5 left) and ι_a = 1.57 (figure 5 right).

Small plasma currents (of about -1 kA) can substantially increase the magnetic shear in TJ-II, and confinement is no longer deteriorated by low order rational surfaces. These values of the plasmas current are high enough to modify the ι profile increasing the magnetic shear and having a positive influence on the confinement, which leads to broadening of the plasma pressure profile and a further increase of the bootstrap current. A similar mechanism has been reported in ref. [2] to explain the non-linear increase of the energy content with the ECR heating power found in certain magnetic configurations of W7-AS plasmas. In those experiments an OH current (negative) is induced to compensate the bootstrap current (positive) resulting in a negative magnetic shear within the confinement region that increases as the energy content increases.

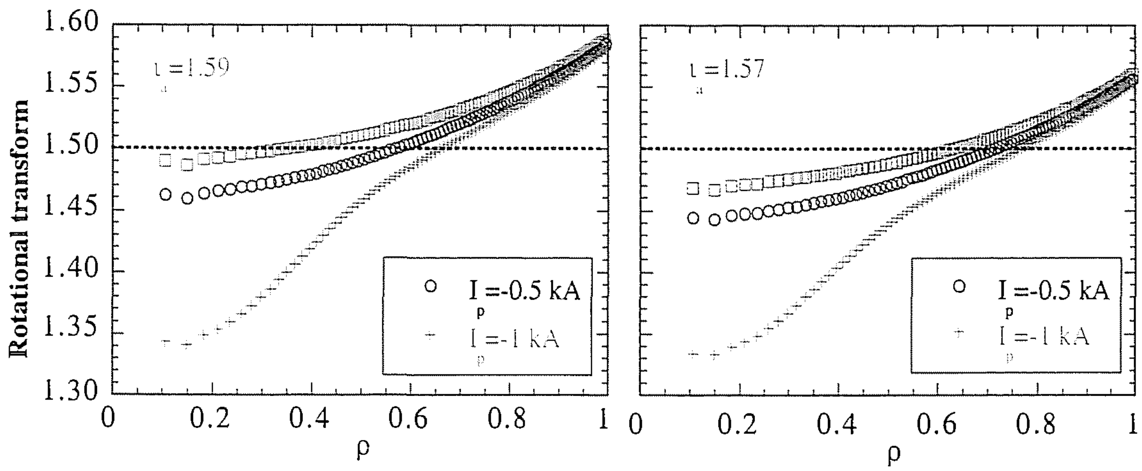

Figure 5: ι profiles calculated for low and high density discharges, low and high plasma current, with ι_a = 1.59 (left) and ι_a = 1.57 (right). The ι profiles in vacuum are displayed in blue and green.

II.b. Moderate magnetic shear experiments

Recently, OH induced current experiments have been carried out to study the dependence of the confinement on the sign of the magnetic shear. For these studies, we have selected magnetic configurations that in vacuum exclude low order rational surfaces. Plasma currents up to +/–10 kA have been induced. In the positive current experiments the magnitude of the induced current is high enough to reverse the negative magnetic shear of TJ-II configurations. Preliminary results show a non-symmetric dependence on the sign of the magnetic shear. A substantial improvement of the energy content is observed in the case of negative plasma current (negative magnetic shear), in agreement with previous OH induced current experiments in which an increase in stored energy of 40% was found [12]. On the contrary, in plasmas with induced positive current minor changes are observed in the plasma energy content as compared with the non-induced current plasmas. As an example, figure 6 displays the plasma pressure profiles measured in two discharges with

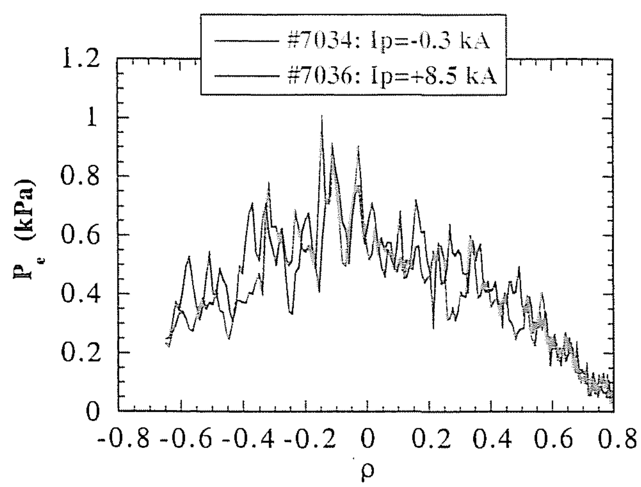

Figure 6: Pressure profiles in discharges without (blue) and with (red) positive OH induced current.

equal ι in vacuum (1.55 at the plasma centre and 1.66 at the edge), equal line-averaged density 0.75 10^{13} cm^{-3}, and different plasma current, -0.3 and +8.5 kA. The plasma pressure profile and therefore the energy content is very similar in both discharges. This behaviour could indicate that the anomalous transport in TJ-II is dominated by modes that are stabilised only by negative shear. The change in global shear could affect some type of micro-instabilities and be responsible for the improved confinement but, so far, there is not a definite explanation for this behaviour. Plasma current scans performed in W7-AS and reported in refs. [3, 4] indicate that the confinement scales with the plasma current independently of its sign. To clarify this discrepancy further studies are needed.

III. Conclusions

In the magnetic configuration scans carried out in TJ-II at low plasma density, low plasma energy content is found to be related to the presence of low order rational surfaces within the confinement region. Increasing the plasma density, the confinement is no longer deteriorated by low order rational surfaces, becoming weaker the sensitivity to the edge rotational transform. The influence of the magnetic shear on the confinement could explain these experimental results. In TJ-II, bootstrap driven currents can substantially modify the rotational transform profile, increasing the negative magnetic shear and having a positive influence on the confinement, which leads to broadening of the plasma pressure profile and a further increase of the bootstrap current.

Experiments with higher plasma currents (OH induced currents up to +/- 10 kA) show a non-symmetric dependence on the sign of the magnetic shear. Preliminary results, carried out in magnetic configurations that in vacuum exclude low order rational surfaces, show a substantial improvement of the confinement in the case of negative plasma current, while minor changes are observed in the plasma energy content when positive current is induced. A definite explanation is yet to be given.

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