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

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Abstract

In low magnetic shear experiments in TJ-II, low plasma energy content is found to be related to the presence of low order rational surfaces. Small 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.

Introduction

TJ-II is a helical device with a magnetic field of $B_0 < 1.2$ T, a major radius of 1.5 m and an average minor radius of 0.22 m. A notable property of this device is its considerable flexibility with regard to the magnetic configuration. The rotational transform can be varied over a wide range ($0.9 < \iota < 2.2$) by changing the current fed into the two central coils, helical and circular. The vacuum field of TJ-II has a low and positive magnetic shear ($\Delta\iota/\iota < +6\%$, note that the stellarator approach is used for the definition of magnetic shear). The achievable energy content may depend, as it has been reported in other low magnetic shear devices [1-3], on the rotational transform at low net plasma current.

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 [4] 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 T_e and 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 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 [5] and the n_i profile equal to the n_e profile divided by the effective ion charge, Z_{eff}. Diamagnetic loops, Rogowski and Mirnov coils, installed inside the vacuum vessel of TJ-II, are used to measure the diamagnetic energy content, the plasma current and the magnetic fluctuations [6].

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 $\iota/2\pi$ (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. In these plasmas the line density is about $0.5 - 1\cdot10^{13}$ 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 (the ECH system is set for no EC current drive).

In the magnetic configuration scan with low gas puffing the plasma energy content depends strongly on the edge rotational transform. By increasing the pre-programmed gas puffing the energy content increases and the dependence on ι becomes weaker (see figure 1).
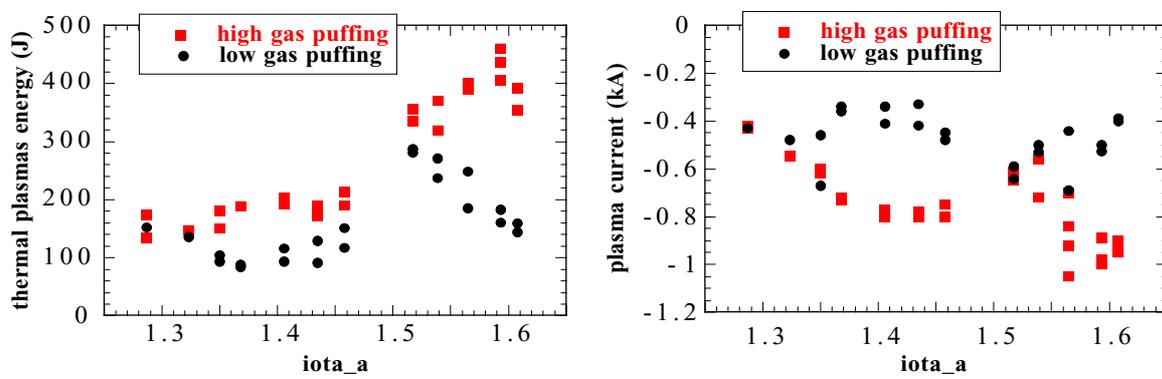

Figure 1: Thermal energy content (left) and net plasma current (right) vs. edge ι in vacuum, for low (black) and high (red) gas puffing conditions.

In the low gas puffing case, the confinement degrades when low order rational values of ι (ι = 4/3 or 3/2) enter the confinement region. In these configurations narrow plasma pressure profiles are measured together with low net plasma currents (up to 0.4 kA). By increasing the pre-programmed gas puffing 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 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) at low
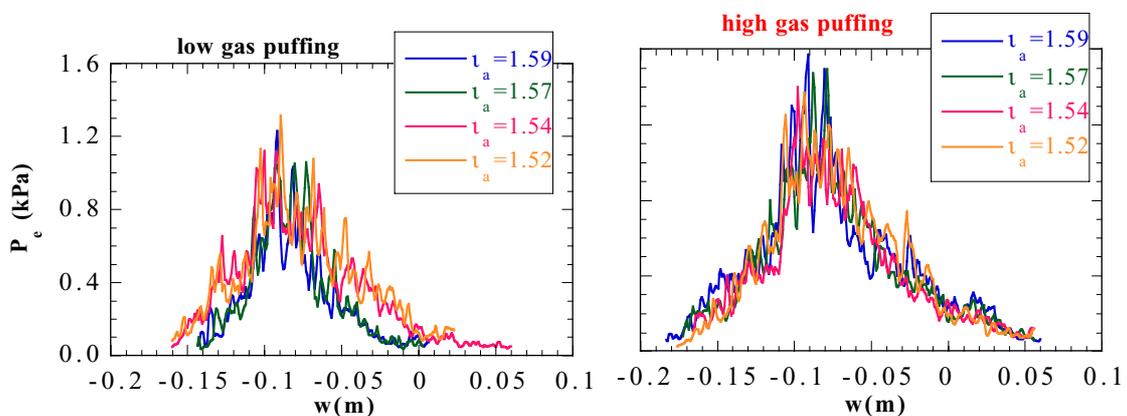

Figure 2: Pressure profiles for different configurations at low (left) and high (right) gas puffing conditions

and high gas puffing conditions. The rotational transform profiles in vacuum for these magnetic configurations are shown in figure 3. 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 gas puffing plasmas. Thus, the presence of low order rational surfaces within the plasma region affects substantially the confinement characteristics. 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 [7].
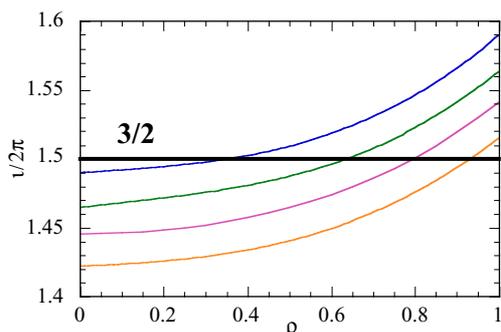

Figure 3: ι profiles calculated in vacuum for the configurations of Fig 2.

The rotational transform profiles in vacuum for these magnetic configurations are shown in figure 3. 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 gas puffing plasmas. Thus, the presence of low order rational surfaces within the plasma region affects substantially the confinement characteristics. 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 [7].

The measured plasma current is negative: 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 leads an increase in the positive magnetic shear. To estimate the modification of the ι profile due to the toroidal current equilibrium calculations have been performed using the VMEC code [8]. The current density profile is considered to be proportional to the gradient in the plasma pressure and the total current is set as the value measured by the Rogowski coils. Figure 4 show the ι profiles calculated for low and high gas puffing experiments: plasma currents of -0.5 and –1 kA respectively, for two magnetic configurations (ι_a = 1.59 and 1.57).
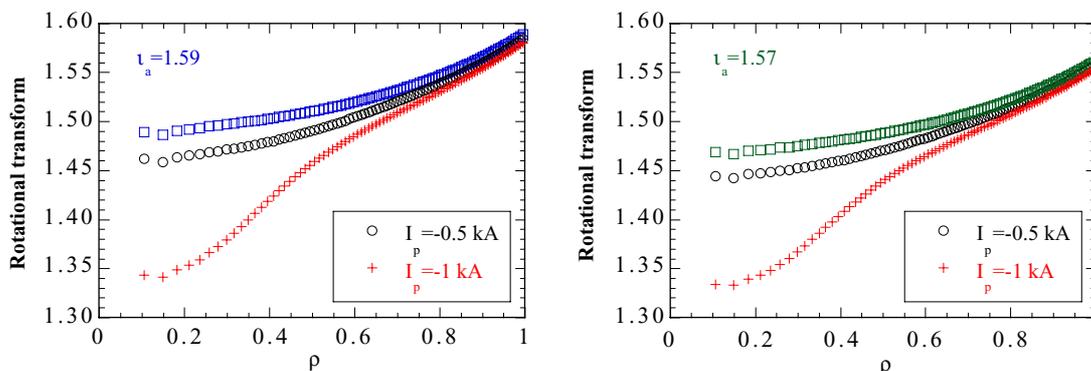

Figure 4: ι profiles calculated for low and high gas puffing discharges with ι_a = 1.59 (left) and ι_a = 1.57 (right).

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 current values are high enough to modify the ι profile increasing the magnetic shear and having a positive influence on the confinement.

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. We have selected magnetic configurations that in vacuum exclude low order rational surfaces. Plasma currents up to +/–10 kA have been induced. Preliminary results show a non-symmetric dependence on the sign of the magnetic shear. A substantial

Figure 5: Pressure profiles in discharges without (blue) and with (red) positive OH induced

improvement of the energy content is observed in the case of negative plasma current (positive magnetic shear), in agreement with previous OH induced current experiments [9]. 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 5 displays the plasma pressure profiles measured in two discharges with 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.
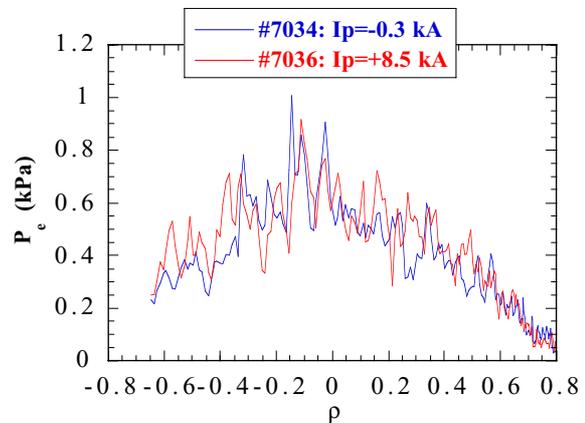
This behaviour could indicate that the anomalous transport in TJ-II is dominated by modes that are stabilised only by positive shear. This characteristic excludes localised interchange modes, since they are stabilised by global shear independently of its sign and the currents considered are not large enough to make them unstable. Also, the instability threshold for resistive balloning modes is still well above the pressure gradients obtained in the experiment [10]. The change in global shear could affect some type of micro-instabilities and be responsible for the improved confinement but presently a definite explanation is yet to be given.

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