Impact of the rotational transform and pellets on enhanced confinement and turbulence in the TJ-II stellarator

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This work considers a set of experiments designed to clarify the impact of the rotational transform and pellets on confinement quality at the TJ-II stellarator. For this purpose, the net plasma current, I_p, is controlled using external coils (cf. Fig. 1), resulting in the modification of the rotational transform profile and hence the radial location of specific rational surfaces. This work studies this effect in the configuration labelled '100_48_65'.

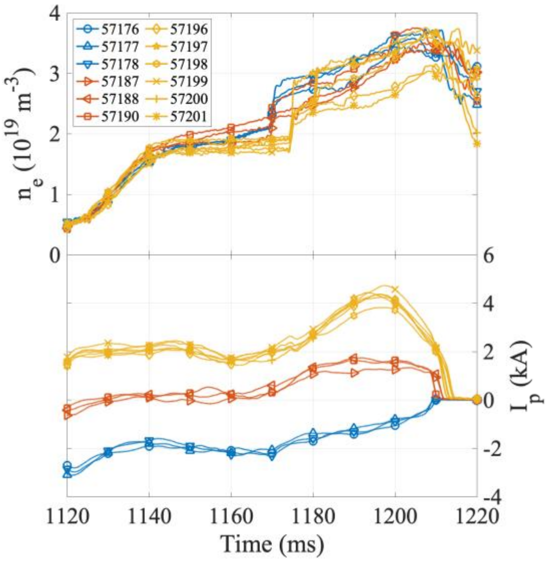

Fig. 1 – Density time traces (top) for shots with pellet injection (1170<t<1175), with different values of the net plasma current (bottom).

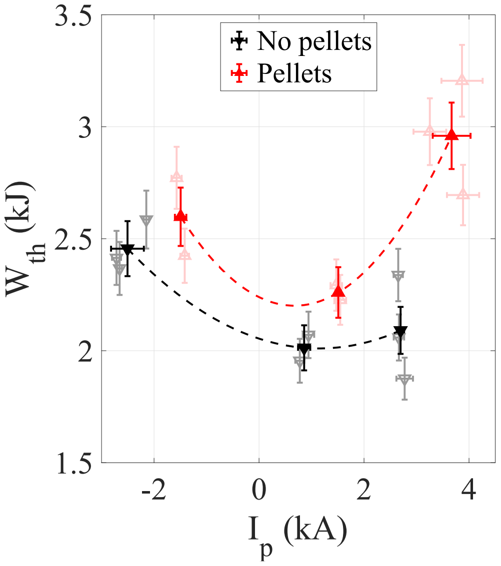

Fig. 2 – Stored energy achieved in shots with and without pellets, according to the plasma current.

Significant and systematic variations of the edge electron density gradients (up to 50%−60%) and the plasma energy content (20%−30%) are achieved, depending on I_p (cf. Fig. 2). The explanation of this remarkable behaviour relies on the precise placement of low-order rational surfaces in relation to the edge gradient region, which affect local turbulence fluctuation levels, facilitating the formation of zonal flows and the concomitant transport barriers. This hypothesis has been confirmed experimentally on the basis of a broad array of diagnostic measurements [1].

In this work, we focus on the case with highest stored energy shown in Fig. 2. As shown in Fig. 3, with sufficiently positive I_p, the rotational transform profile becomes hollow. At $I_p \approx 2$ kA, the 5/3 rational surface occurs twice in the plasma region, both near the edge and at half radius. This also means that the density of rational surfaces (indicated in the top panels of Fig. 3) is very low, implying that there is a radial region (indicated by the

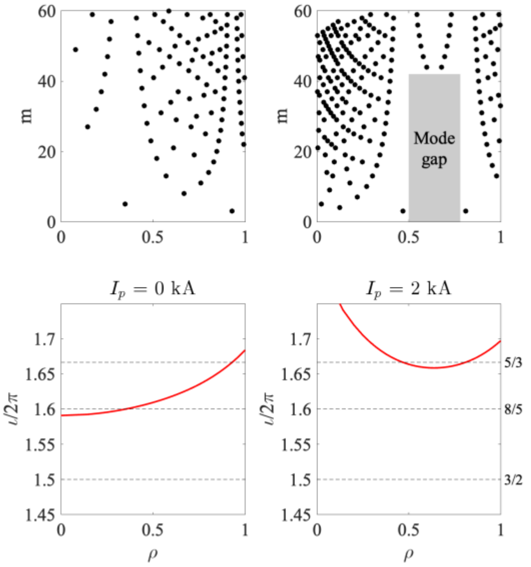

Fig. 3 – Bottom panels: estimated rotational transform profiles according to the value of I_p. Top panels: resonant modes (n/m) according to the rotational transform in the bottom panels.

grey square labelled 'mode gap') where MHD type turbulence will be insignificant due to the absence of low-order modes resonant with the rotational transform profile. If I_p increases a bit further, the 5/3 rational surface will no longer be present, and the 'mode gap' will become even larger. It should be noted that this 'mode gap' essentially coincides with the density gradient region, where turbulence is typically driven strongly.

In some of these shots, measurements from the Heavy Ion Beam Probe (HIBP) system made at the fixed position $|\rho| \simeq 0.6$ were available, i.e., precisely in the 'mode gap' region. In these cases, it is interesting to calculate some relevant fluctuation measures: the intermittence parameter C1, which is a measure of the degree of multifractality, such that C1 = 0 corresponds to a monofractal system, and C1 = 1 is the maximum value [2], and the Jensen-Shannon Complexity that quantifies the existence of correlational structures [3]. In the case of resistive instabilities, it was shown using turbulence modelling calculations that C1 drops near low-order rational surfaces if the corresponding mode is activated [4].

In Fig. 4, a comparison is made between two shots in which the HIBP was measuring at the mentioned radial position. In the first shot (57187), I_p was small, so that the rotational transform profile was similar to the left panel of Fig. 3. In the second shot (57200), I_p was large, and its rotational transform was similar to the right panel of Fig. 3.

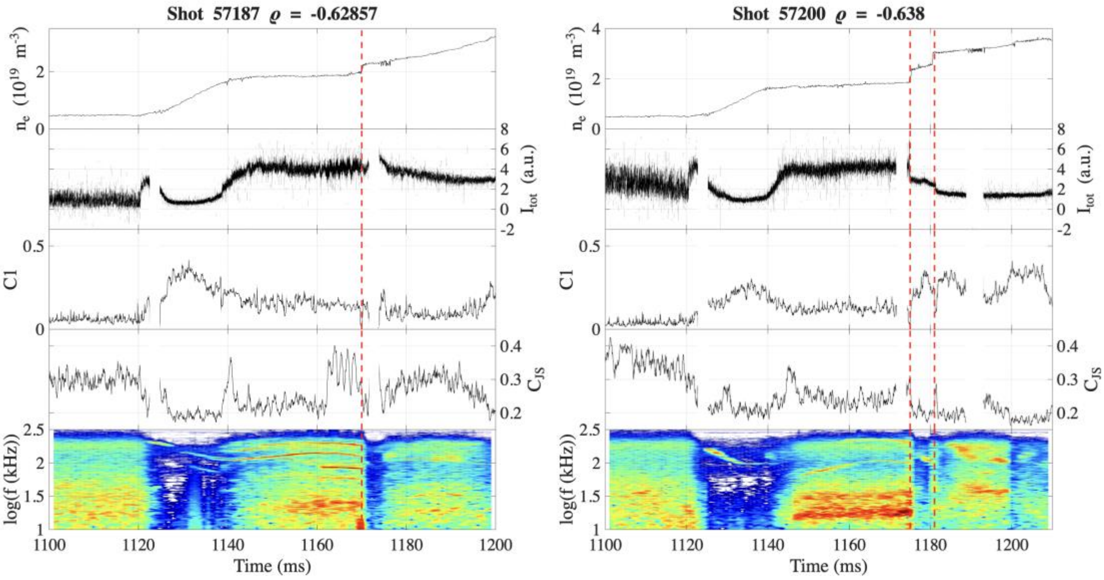

Fig. 4 – Top to bottom: Line integrated electron density, beam current I_{tot} (HIBP), intermittence (of I_{tot}), Jensen-Shannon Complexity (of I_{tot}), spectrum of a Mirnov coil. Red dashed lines indicate pellet times. Left: shot with small I_p. Right: shot with high I_p (cf. Fig. 1).

In both discharges, one has an ECRH phase that ends around $t \approx 1120$ ms. Then, NBI heating takes over and the density rises. Alfvén modes are visible in the spectrum at high frequencies ($f > 50$ kHz). One or two pellets are injected around $1175 < t < 1181$ ms. Note that both ECRH switch-off and pellet injection (cooling events) lead to a strong suppression of MHD turbulence, as reflected in the broadband drop of the Mirnov spectrum.

It is interesting to note that in both discharges, the fluctuation measures behave similarly up to the pellet injection. In both shots, the intermittence is low in the initial ECRH phase, while the complexity is high. This is likely due to the presence of filamentary structures [5]. After ECRH switch-off, MHD turbulence is reduced and the intermittence increases substantially, while the complexity drops. Once the plasma reaches a new steady state (at $t \approx 1140$), MHD turbulence resumes and the intermittence drops a little while the complexity goes up a little, and they remain relatively constant until pellets are injected.

However, after the pellets, the behaviour is opposite in some ways. In the left shot (57187), the intermittence remains low after the pellet, whereas the complexity rises. But in the right shot (57200), the intermittence is significantly increased after the pellets – by a factor of 2 or more – while the complexity drops to very low values. The Mirnov spectrum also shows that the lowest frequencies ($f < 30$ kHz) are not as intense in this case. Referring again to Fig. 3, we interpret that this is mainly caused by the difference in the rotational transform profile: while the profile is near ‘nominal’ in the left shot, in the right shot it is expected to be hollow and even higher than the profile shown in Fig. 3, so that the 5/3 rational surface is not present. Thus, in the second case, a prominent ‘mode gap’ exists where MHD turbulence is strongly suppressed, which explains the high value of C1 and the exceptional confinement of the right shot, also evidenced in Fig. 2.

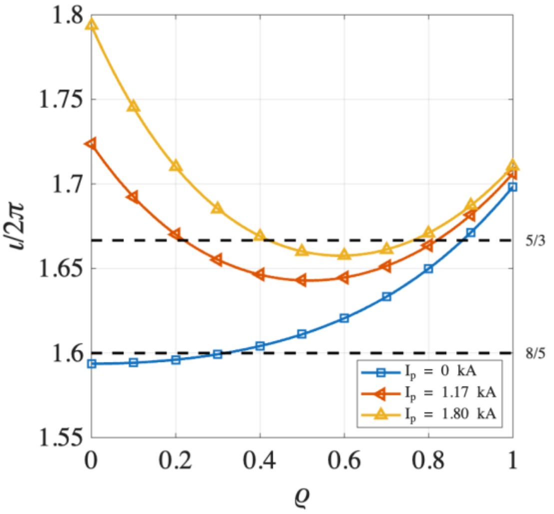

Fig. 5 – Rotational transform profiles used in the model calculations.

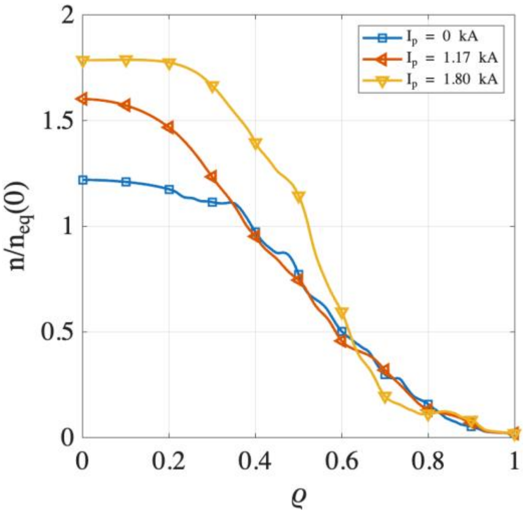

Fig. 6 – Normalized density profiles from turbulence model, corresponding to the rotational transform profiles of Fig. 5

Calculations based on a resistive magnetohydrodynamic turbulence model provide some support for these observations [1]. Figs. 5 and 6 show example profiles. The `nominal’ case ($I_p = 0$) shows a typical density profile. The case with moderate positive current ($I_p = 1.17$ kA) has a mildly hollow iota profile, with a minimum at $\rho = 0.5$. The density profile is unchanged for $\rho > 0.4$, but the 5/3 surface at $\rho = 0.2$ is responsible for better confinement in the core. The case with relatively strong positive current ($I_p = 1.8$ kA) has a strongly hollow iota profile, with a minimum at ρ = 0.6. The steepening of the density profile around ρ = 0.6, indicating locally reduced transport, is clearly visible. This steepening is attributed to the ‘mode gap’ occurring at this position.

This work clarifies the impact on confinement due to (a) the presence of specific rational surfaces and (b) the density of rational surfaces. Together, this highlights the complex nature of magnetically confined fusion plasmas. We note that confinement enhancement based on a ‘mode gap’, i.e., a rarefaction of rational surfaces near a minimum of the rotational transform profile, is similar to the mechanism often invoked to explain Internal Transport Barriers in tokamaks occurring near a safety factor minimum [6]. TJ-II and other stellarators provide an ideal platform for studying this effect in more detail.

Acknowledgements

Research sponsored in part by the Ministerio de Ciencia e Innovación of Spain under project Nos. PID2021-124883NB-I00 and PID2022-137869OB-I00. This work has been carried out within the framework of the EUROfusion Consortium, funded by the European Union via the Euratom Research and Training Programme (Grant Agreement No 101052200 – EUROfusion). Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or the European Commission. Neither the European Union nor the European Commission can be held responsible for them.

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