Magnetic configuration and transport interplay in TJ-II flexible heliac

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Abstract: This paper presents an overview of experimental results and progress in the investigation of the role of the magnetic configuration on stability and transport in the TJ-II stellarator. Significant improvement in the characterization of confinement and stability properties of TJ-II stellarator plasmas has been recently achieved. Global confinement studies have shown a positive dependence of energy confinement on rotational transform, reinforcing the dependence found with the ISS95 database. Spontaneous transitions in particle and energy confinement have been observed which resemble some characteristics of previously reported H-mode regimes in other stellarator devices. Magnetic configuration scan experiments have shown the interplay between magnetic topology (e.g. rationals), transport and electric fields. Cold pulse as well as the transport events provoked by decreasing magnetic well generates non-diffusive propagation. First measurements of radial electric fields and plasma potential show values that are comparable with those expected from neoclassical calculations. Active biasing experiments have shown an impact both in edge and global plasma parameters. In low magnetic well configurations sheared edge poloidal and parallel flows are linked near marginal stability.

1. Introduction

Stellarators are inherently flexible devices very well suited for the investigation of the complex phenomenology that interrelates electric field, instabilities, magnetic configuration and transport [1,2]. Among them, the TJ-II heliac ($B \leq 1.2$ T, $R = 1.5$ m, $\langle a \rangle \leq 0.22$ m, $P_{ECH} \leq 600$ kW, $P_{NBI} \leq 2$ MW) presents some peculiarities that place it as a very suitable tool for this type of studies [3]. It has a very wide range of achievable magnetic configurations ($0.9 \leq \iota/2\pi \leq 2.2$) and low magnetic shear, which allow an accurate control of the low order rationals present in the $\iota/2\pi$-profile. Magnetic well is the main stabilising mechanism in TJ-II [4]. The

magnetic well depth (up to 6%) can be almost suppressed in the edge region keeping essentially constant the rotational transform profile. This fact allows locating TJ-II plasmas close to instability thresholds and studying the onset of fluctuations and related phenomena.
TJ-II is equipped with advanced diagnostics for plasma profile measurements, including a Heavy Ion Beam Probe (HIBP) diagnostic [5] that can measure plasma potential profiles in all the TJ-II configurations and a high resolution Thomson Scattering (TS) system used to determine the radial profiles of the electron temperature and density [6]. The results presented in this paper have been obtained in plasmas produced and heated with ECRH (2 gyrotrons, 300 kW each, 53.2 GHz, 2nd harmonic, X-mode polarisation).

This paper is organised as follows: Section 2 presents results on global confinement in TJ-II and its dependence on plasma parameters. A series of experimental results linking the presence of low order rationals in the plasma with several transport-related phenomena are reported as well. In section 3 some improved confinement regimes are reviewed. Section 4 deals with the measurement of radial electric field and plasma flows including first limiter biasing results. MHD stability and transport are discussed in section 5.

2. Confinement and magnetic topology

Global energy confinement. Both Lackner-Gottardi (LG) [7] and International Stellarator (ISS95) [8] scaling laws predict a positive dependence (exponent factor 0.4) of confinement time on rotational transform. The TJ-II dataset exhibits also a positive $\iota/2\pi$-dependence of the energy confinement time, with an exponent value of 0.5, as shown in table I. Provided the wide TJ-II rotational transform range, this result reinforces the positive $\iota/2\pi$-dependence found in ISS95 database, in which, with the exception of W7-AS, the devices have a fixed $\iota/2\pi$-value [9].

	α^x	α^a	$\boldsymbol{\alpha^\iota}$	α^P	α^n	α^R	α^B
TJ-II	*-1.63±0.08*	*1.93±0.10*	***0.51±0.10***	*-0.74±0.03*	*0.61±0.04*	*0.65*	*0.83*
ISS95	*-1.10±0.06*	*2.21±0.05*	***0.4±0.05***	*-0.59±0.02*	*0.51±0.01*	*0.65±0.04*	*0.83±0.02*

TABLE 1: Regression results of TJ-II energy confinement time compared to the exponents deduced from the ISS95 database. From left to right exponents of the pre-factor, minor radius, rotational transform, absorbed power and plasma density. The last two columns correspond to major radius and magnetic field, which are fixed in TJ-II; their exponents are taken as the corresponding ISS95 ones.

Transient behaviour and magnetic topology. The operational flexibility and the control of the magnetic topology in stellarator devices make them useful tools to investigate the role of rational surfaces on transport. The presence of natural resonances has clearly been observed as a flattening in the edge plasma profiles in TJ-II and other stellarators. Structures in plasma profiles have been observed in the case of low-order rational surfaces with significant variation in plasma potential just outside the flattening region. These results have been interpreted as an increase of the shear in ExB flow linked to the radial location of rational surfaces. These experimental results illustrate the impact of rational surfaces in the generation of ExB sheared flows, pointing them out as a potential trigger for transport barriers. There are experimental indications in TJ-II suggesting that the presence of low order rationals close to the central plasma region might increase even further the pressure gradient (e.g. improving confinement) [10].
A transient behaviour has been observed in the plasma core of TJ-II with fast drops in the electron temperature [11]. Changes in the line-averaged density occur synchronised with temperature drops (see figure 1). The transient behaviour resembles both, the electric pulsation discovered in CHS [12] and the "electron root" feature reported by the W7-AS team

[13,14]. In TJ-II, the fast spontaneous transitions appear related to the magnetic topology in conditions of fixed plasma density and ECH power. The flexibility and low magnetic shear of TJ-II have allowed the identification of the plasma current as the control parameter for the appearance of this phenomenon. The results obtained during the magnetic configuration scans carried out in TJ-II point to the hypothesis that the transient behaviour is connected with the presence of a rational surface close to the plasma centre. Although the connection between rational and transport events is still not fully understood, it is sensible to consider that the rational surface is affecting the radial electric field in its vicinity [15].

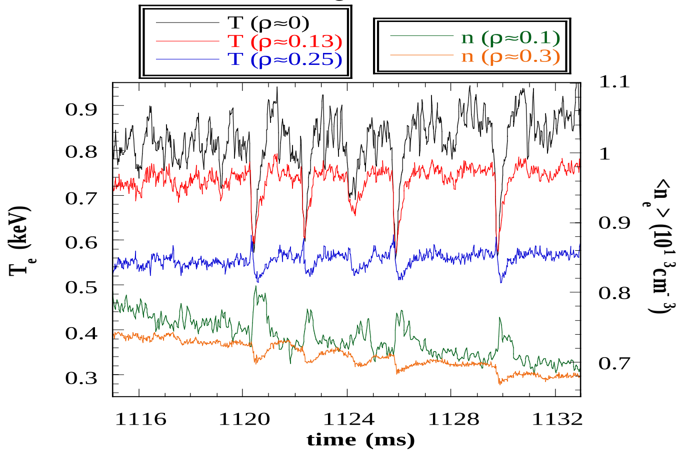

Figure 1: Time evolution of the electron temperature (three top traces) and line-averaged density (bottom traces) in a plasma with $\iota/2\pi$ (0) = 1.51 in vacuum.

In some cases these transients are accompanied by sudden changes in the convective flux of ripple-trapped suprathermal electrons generated by the ECRH. These changes are detected from variations in the wall desorption near the gyrotron port. The associated changes in radial profiles of density and emissivity suggest that the magnetic structure (e.g. resonant surfaces) may play a relevant role in moderating the ripple losses [16].

3. Enhanced confinement modes

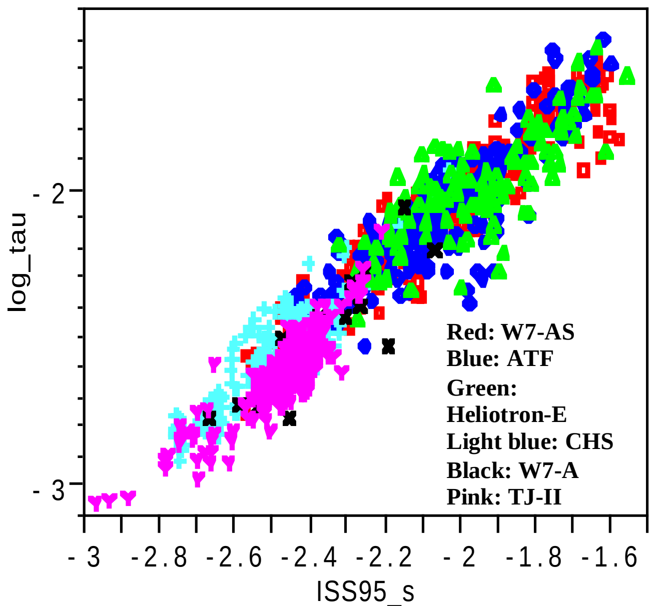

Figure 2: Actual values of the log τ_E vs ISS95 predictions for TJ-II and the stellarators included in the ISS95 database.

Spontaneous transitions. TJ-II global energy confinement time and plasma parameter dependencies are consistent with ISS95 predictions as shown in figure 2 [17]. However, spontaneous transitions to improved confinement regimes have already been observed. An enhanced particle confinement regime (EPC) has been found for TJ-II plasmas in all metal scenario [18]. It consists of a spontaneous transition to a highly peaked density profile mode that leads to a decay of the electron density in the edge region and to an increase of the total particle content. This mode produces an increase in the global particle confinement time by a factor larger than 3. The conditions to achieve the transition to this mode, under metal wall, include a critical trimming of the gas puffing waveform and a critical density, $\langle n_e \rangle_{crit}$ ~6.10^{18} m^{-3}. For boronised wall the transition was obtained under different recycling/gas puffing conditions [19]. The comparison between both wall scenarios points to the energy balance at the edge region as the key parameter for achieving the transition, rather than the neutral concentration.

Boronisation of the first wall has lead to an increase in edge electron temperature and gas fuelling rate for a given electron density. Under these conditions, enhancement of energy content and ion temperature has also been observed during the EPC regime.

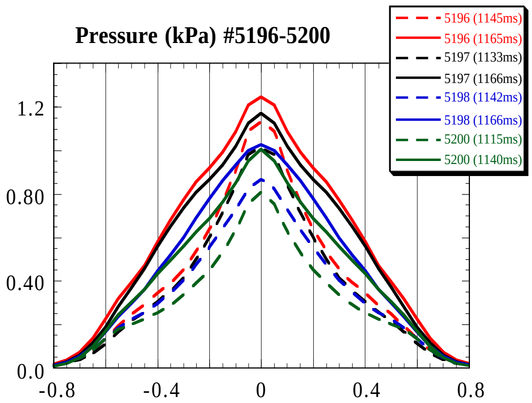

Figure 3: Electron pressure profiles for a series of discharges with transition. The gas-puff is reduced shot by shot. Broken lines: before transition; solid lines: after transition.

Another type of spontaneous improvement in particle and, also, in energy confinement has been observed in some TJ-II plasmas, again triggered by the fuelling rate as the only external knob [20]. Density and temperature profiles broaden (see figure 3) giving rise to energy content enhancement up to a factor 1.4. The time evolution of the plasma parameters (see figure 4) shows a reduction of the H_α signal and magnetic fluctuations (ELM-like events) and an increase in the plasma density, stored energy and electron temperature after the transition. The transport analysis for the discharge of figure 4 describes the evolution of the profiles via a sudden reduction (~50%) of the thermal and particle diffusivities inside the main plasma.

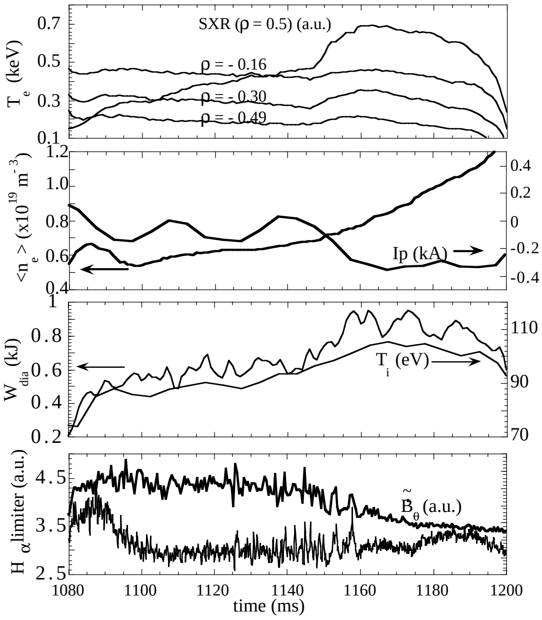

Figure 4: Time evolution of different plasma parameters across the transition in the discharge #5196. Transition time ≈ 1147 ms.

Effect of transformer induced toroidal current in confinement. A set of coils designed to induce positive or negative toroidal net plasma currents, $I_p \leq \pm 10$kA, can be used to sweep ι profiles during a discharge. Two global magnitudes can change sign under toroidal electric field induction: E_ϕ itself and, being TJ-II vacuum configurations almost shearless, the magnetic shear defined as $\hat{s} = -(\rho/\iota)(d\iota/d\rho)$, where ρ is a flux surface radial coordinate. A movable mirror in the ECH line allows for non-inductive electron cyclotron current drive (ECCD) up to $I_p \approx \pm 1$ kA. Comparing discharges without and with positive and negative ECCD, for the same transformer action, $\hat{s}$ and E_ϕ effects can be discriminated in time. Changing the sign of ECCD shifts the temporal plasma response with respect to the transformer switch-on time back and forth, correspondingly. This observation clearly points to shear effects as the responsible of plasma confinement changes. The OH system has been used to study the dependence of plasma confinement on the magnitude and sign of $\hat{s}$. Within the range of achievable induced plasma currents, an improvement of the energy content as the net plasma current becomes more negative is found [21]. In figure 5 the plasma pressure profiles measured in two discharges without and with negative OH current are displayed. A remarkable broadening of the pressure profile can be observed in the case of negative plasma current, enhancing the confinement about 50%. On the contrary, the energy content decreases with moderate (up to 6 kA) positive I_p and then recovers at higher values of I_p. This fact is illustrated in figure 6 where the evolution of line density is plotted versus the plasma current for three discharges with different line densities. The diamagnetic energy temporal trace is perturbed by the induced OH current, therefore the line density is used to monitor the confinement, after cheking that it follows the same tendency as the energy one. The apparent dependence of the density on I_p is stronger at higher $<n_e>$. When the induced current is negative (not shown) the density increases monotonically with the magnitude of the current.

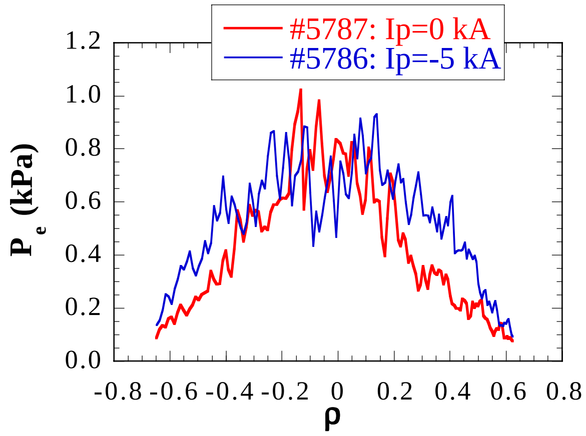

Figure 5: Plasma profiles measured in a reference discharge without OH (red) and in another one with negative OH current (blue).

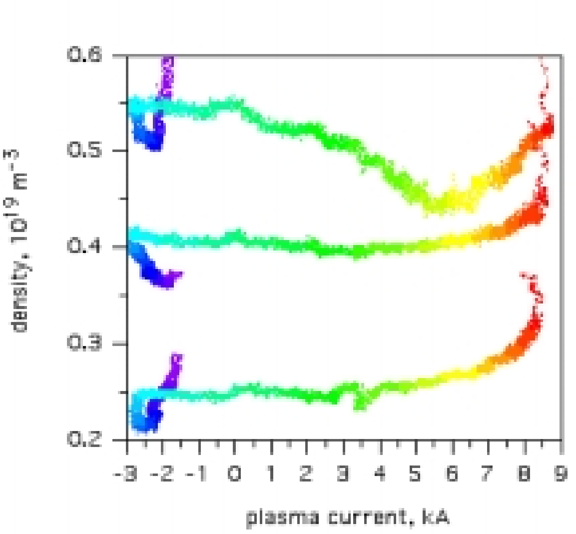

Figure 6: Relation between line density and plasma current in three discharges with different density. The discharges begin with net negative current.

If, as we suggest, the *global* magnetic shear is a true knob in these experiments via plasma current, then not only its magnitude, but also its sign, plays a role in the confinement. Several mechanism can be acting on plasma transport: i) Dissipative trapped electron modes: These are expected to be relevant for $T_e >> T_i$, low collisionality and large fraction of trapped particles (The estimated fraction of trapped particles is about 35% in these experiments [22]). DTEM are sensitive also to global magnetic shear [23]. ii) Electron temperature gradient modes, whose corresponding growth rates may be affected by both the sign and the magnitude of the magnetic shear. iii) The modification of particle orbits due to changes in the magnetic topology cannot be excluded, since this may affect considerably the fraction of direct particle losses in TJ-II, as shown by three-dimensional calculations [24]. iv) Numerical calculations of drift wave growth rates in stellarator geometry point to the *local* magnetic shear as an important magnitude to consider [25]. However, the very low values of plasma β in these experiments should exclude any changes in this parameter.

Impurity transport. Impurity confinement is being studied by injecting impurities using the laser ablation method. The main goal of these experiments is to explore the possible existence of non-exponential relaxation in TJ-II plasmas. First results suggest that this perturbation can be analyzed by a stretched exponential. Impurity confinement times of up to 100 ms have been obtained (see figure 7), almost an order of magnitude higher than particle confinement times [26].

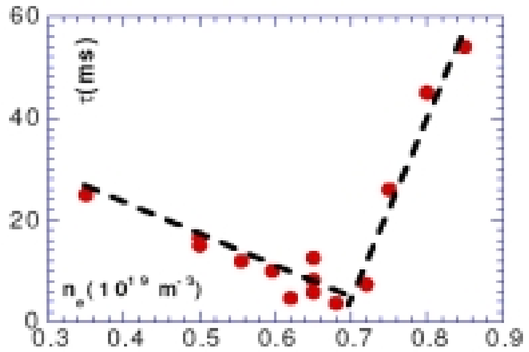

Figure 7: Decay time parameter vs. <n_e>.

4. Radial electric fields and confinement

Understanding the driving mechanisms of radial electric fields and sheared flows is a key issue to explain the transition to improved confinement regimes in fusion plasmas. For this reason an intense and coordinated research programme is in progress in the TJ-II stellarator and other devices to improve our understanding of the driving and damping mechanisms of radial electric fields and flows in fusion plasmas.

Measurements of radial electric fields by Heavy Ion Beam Probe diagnostic. First radial profiles of plasma potential have been obtained by the HIBP diagnostic [5]. Plasma potential profiles have been investigated in a sequence of different configurations and at different densities in ECRH plasmas, <n_e> = 0.5 – 1.1 x 10^{19} m^{-3}. HIBP measurements were done with a 125 – 140 kV Cs^+ beam.

Measured radial profiles of plasma potential show that the potential increases up to 1 kV near the magnetic axis (i.e. positive radial electric fields) in low density plasmas (<n_e> < 8 x 10^{18} m^{-3}) (see figure 8, right). The secondary (Cs^{++}) ion current profiles are hollow (figure 8, left) in good agreement with density profiles measured by the Thomson scattering system. In addition, plasma potential shows a strong dependence with plasma density. Whereas positive radial electric fields have been observed for <n_e> < 10^{19} m^{-3}, at higher densities negative radial electric fields have been measured at ρ-values ranging from 0.2 to 0.8 (see figure 9).

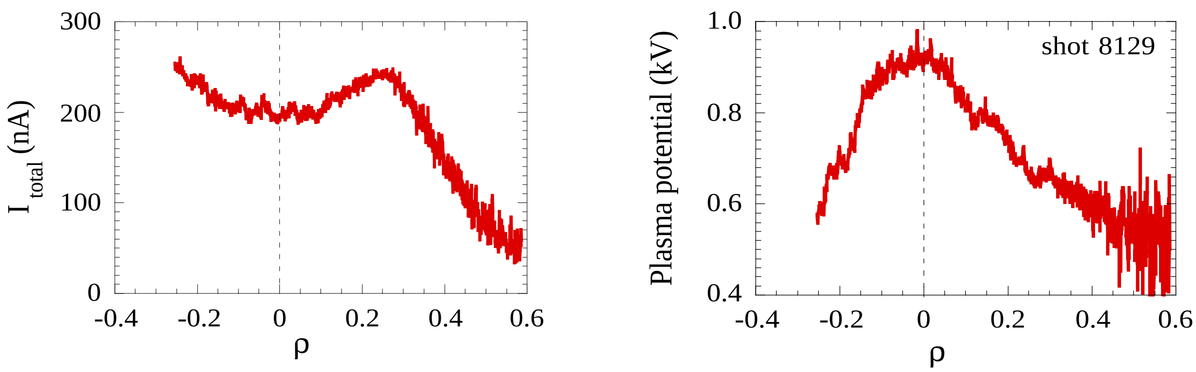

Figure 8: Measured plasma profiles reaching beyond the magnetic axis for a plasma configuration with $\iota/2\pi(a) = 1.46$ and <n> = 0.6 x 10^{19} m^{-3}.

Neoclassical transport estimations performed for low collisionality ECRH plasmas show that, because of the different ion and electron temperatures, the electron particle fluxes usually exceed their ion counterparts, thus driving a relatively large radial electric field to maintain ambipolarity [27]. This electric field partially compensates the quite different diffusions of electrons and ions. In simulations carried out in low density plasmas the resulting radial electric field is positive (about 100 V/cm), thus reducing mainly the electron particle and energy fluxes. The positive values of radial electric field (50 V/ cm) measured by the HIBP system at low density plasmas are of the order of the neoclassical estimations as shown in figure 10.

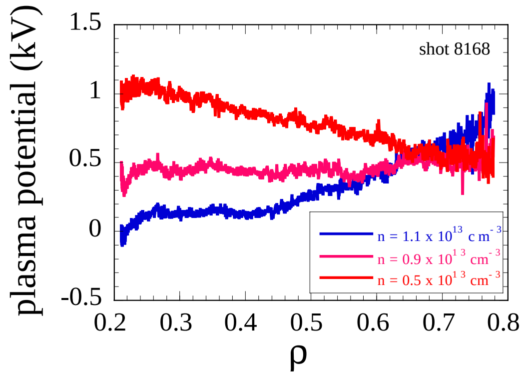

Figure 9: Influence of plasma density in plasma potential profiles (configuration with ι/2π(a) = 1.59).

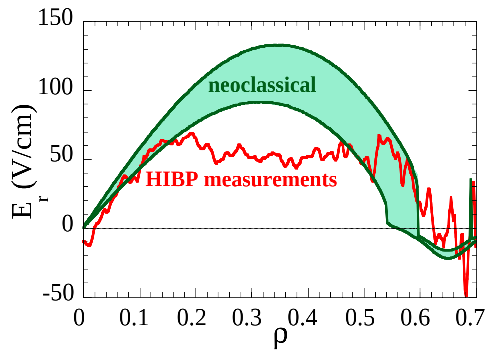

Figure 10: Comparison between neoclassical estimation and HIBP measurement of the radial electric field profile.

An important improvement in the signal to noise ratio allows measuring plasma potential fluctuations in the TJ-II stellarator. Radially localized bursts in plasma potential fluctuations have been observed with frequencies in the range 10 – 40 kHz. In particular, correlation between HIBP and Mirnov coil signals has been found at some radial locations and frequencies (10 - 20 kHz). The rms value of HIBP fluctuations increases in the proximity of the radial location where the correlation HIBP-Mirnov is high. Furthermore, the radial location where HIBP and Mirnov signals show the maximum correlation depends on the magnetic configuration. An example is shown in figure 11. These findings can be explained on the basis of MHD fluctuations linked to low order rational surfaces. The characterization of the radial structure of plasma potential in the proximity of rational surfaces is currently under investigation.

The TJ-II HIBP system is expected to play a key role in clarifying the importance of low-order rationals in the generation of radial electric fields and transport barriers in fusion plasmas.

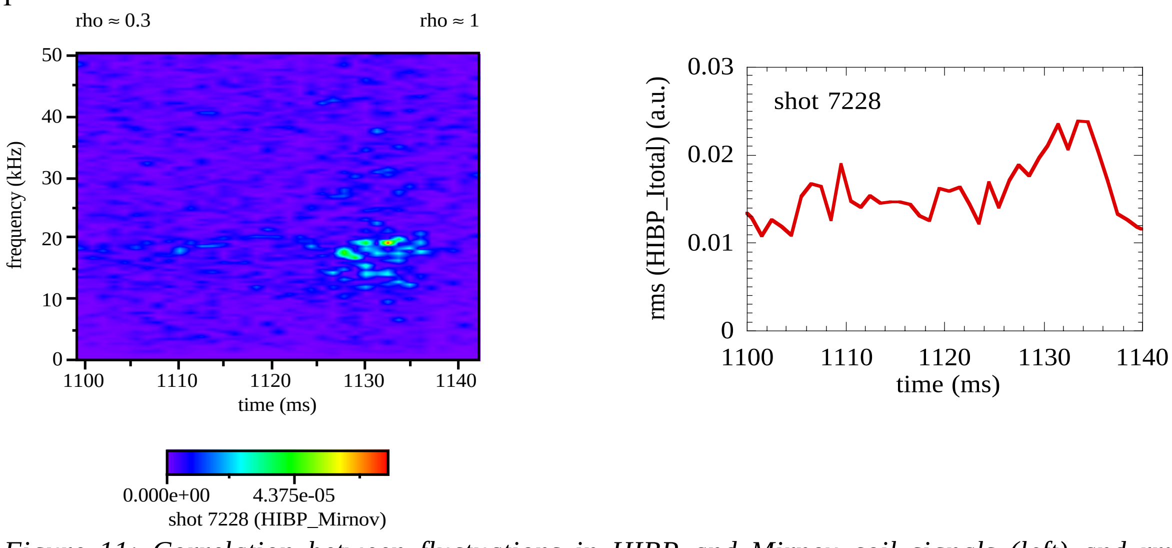

Figure 11: Correlation between fluctuations in HIBP and Mirnov coil signals (left) and rms of fluctuations (right) vs. time. Note that time and radius are equivalent in the sense that the sample volume is swept from ρ = 0.3 to 1 in the time interval 1100-1140 ms. Configuration with ι/2π(a) = 2.31.

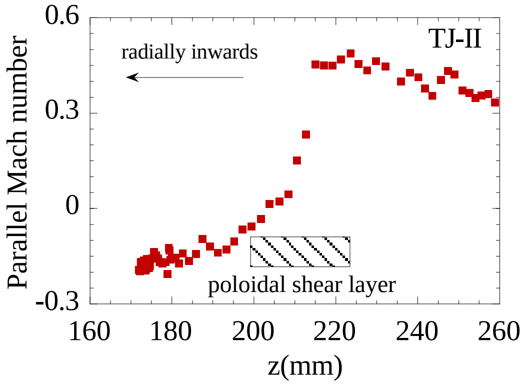

Figure 12: Radial profile of the parallel Mach number in the proximity of the LCFS.

Interplay between parallel and poloidal sheared flows and fluctuations in the plasma boundary region. Radial profiles of the poloidal velocity of fluctuations and parallel flows have been simultaneously measured in the proximity of the TJ-II last closed flux surface (see figure 12). It has been observed that sheared poloidal and parallel flows are linked in stellarator plasmas, as previously reported for tokamaks [28]. The shear in the poloidal flow is close to the inverse time of the correlation of fluctuations and the level of low frequency fluctuations is reduced at the shear location, suggesting that sheared poloidal flows and fluctuations self-organize near marginal stability in TJ-II [29]. Parallel flows are affected by the degree of instability in the plasma edge of the TJ-II suggesting that both neoclassical and anomalous mechanisms play a role in their generation. Interestingly, the shear in the parallel flow is close to the ratio between the ion sound velocity and the density scale length, suggesting that these flows are near the threshold of Kelvin-Helmholtz instability.

An experimental programme is in progress to clarify the mechanisms that provide a link between parallel and poloidal sheared flows and the possible role of parallel flows to drive edge instabilities (like harmonic oscillations or/and ELM like events).

Biasing experiments in tokamak and stellarator plasmas. The evolution of plasma flows and electric fields after the application of external plasma biasing is under investigation in tokamak and stellarator devices, including TJ-II, to clarify the underlying damping (neoclassical/anomalous) mechanisms of radial electric fields and plasma flows. In the TJ-II experimental set-up a limiter, radially localized 3 cm inside the LCFS, has been biased up to 400 V with respect to a second limiter located in the SOL region. First results show that it is possible to induce plasma flows and modify global as well as edge plasma parameters as displayed in figure 13.

In this context it is worth mentioning the recent results on plasma flows and plasma profiles decay times -after electrode biasing- recently carried out in the plasma boundary of tokamak devices [30]. Poloidal flow and potential profiles show a transient behaviour with a time scale smaller than the expected damping time based on neoclassical parallel viscosity. These findings suggest the existence of anomalous damping rate mechanisms for radial electric fields and poloidal flows in the plasma boundary of fusion plasmas. This result might have a direct impact in understanding the L-H transition physics in tokamak and stellarator plasmas.

5. MHD stability and transport

Magnetic well scan. As already mentioned before, TJ-II is mainly stabilized via magnetic well. Taking advantage of the TJ-II configuration flexibility, magnetic well depth may be modified over a broad range of values, i.e. from 0% to 6 %, while the radial extent of the magnetic well can also be strongly modified. A configuration having magnetic well in the plasma bulk can also have magnetic hill in the outer region. These properties make TJ-II an ideal device to study the onset of fluctuations and related phenomena in a controlled way [31]. Recent experiments show that, as expected from the theoretical point of view, the level of edge fluctuations and the degree of intermittency increase significantly as magnetic well is reduced, as shown in figure 14.

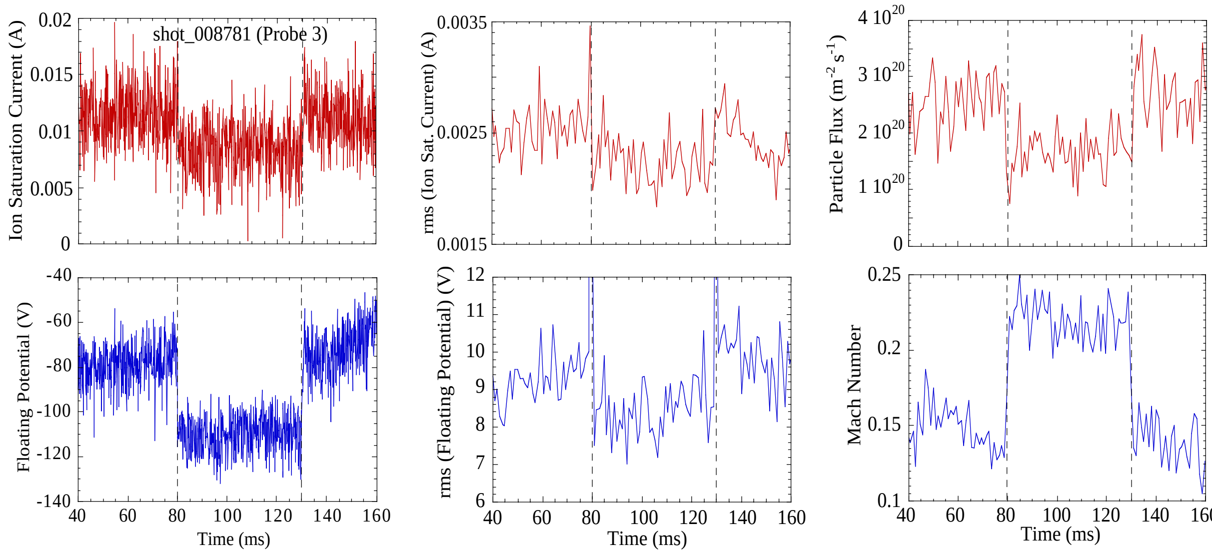

Figure 13: Modification of edge parameters (ion saturation current, floating potential, particle flux and Mach number) in response to an external biasing applied to the TJ-II plasma edge.

TJ-II results also prove that the turbulent ExB particle flux increases as the well is decreased. A significant fraction of the total ExB turbulent flux can be assigned to large and sporadic transport bursts whose amplitude increase as well depth is decreased. This bursty behaviour of turbulent transport is strongly coupled with fluctuations in density gradients. As the density gradient increases above the most probable value, the ExB turbulent driven transport increases until the system relaxes back to the initial marginally stable situation. Similar results have been recently observed in the plasma boundary region of the JET tokamak [32].

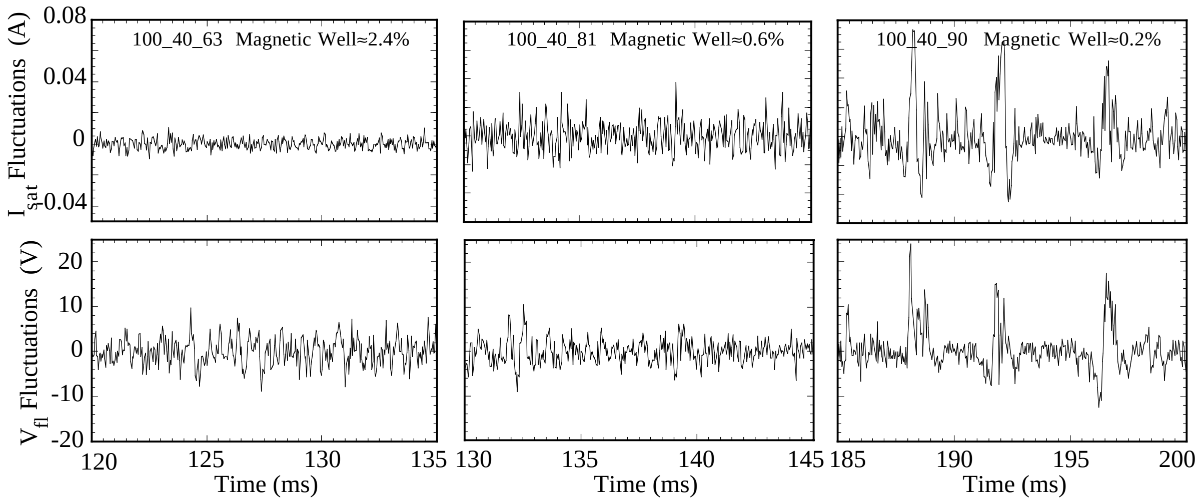

Figure 14. Fluctuations of the ion saturation current and floating potential for three configurations with different magnetic well in the plasma edge: 2.4% (left), 0.6 % (centre) and 0.2% (right).

The probability density function (PDF) of the local ExB transport can also be significantly modified as plasma conditions are changed via magnetic well. The PDF´s of transport in TJ-II have an interesting property: they can be rescaled assuming a functional form, $PDF(\Gamma_{ExB}) = L^{-1}g(\Gamma_{ExB}/L)$, where L is a scaling factor. Similar results have been found in the JET tokamak. The empirical similarity in turbulent transport suggests that edge plasma turbulence evolves into a state in which the PDF´s of transport exhibit the same behaviour over the entire amplitude range of transport events [33]. However, it should be noted that the local ExB transport can be strongly affected by the presence of rational surfaces. In particular, the ExB transport reverses from outwards to inwards in the proximity of the n=4/m=2 resonance [34].

ELM-like transport events. MHD instabilities coupled together to ELM-like transport events have been observed in TJ-II [35]. Some specific experiments have been carried out in order to investigate the influence of the presence of low order resonances in the confined plasma region, on the occurrence of ELM-like events. The ι profile has been modified in discharges with similar pressure profiles by two different methods: configuration scan by fine tuning of the coil currents and ECCD in co and counter directions. It has been concluded that the appearance of ELM-like transport events requires the presence of a low order resonance in the confinement region.

The propagation velocity of strong edge transport events generated as magnetic well is reduced is in the range 500 – 1000 m/s, a value comparable to the radial propagation of ELMs in the JET plasma boundary region. These results emphasize the importance of the statistical description of transport processes in fusion plasmas suggesting the existence of different transport mechanisms for small and large transport events (diffusive versus non-diffusive) in the plasma boundary region.

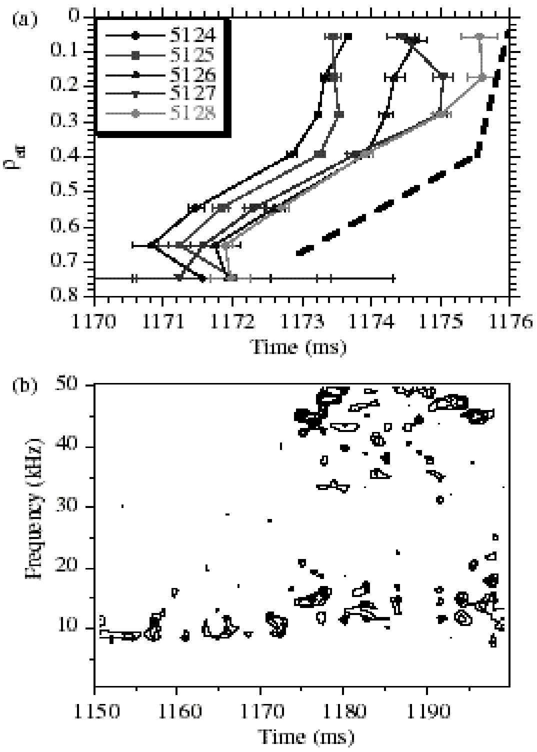

Figure 15: (a) Time of arrival of the cold pulse front at various radial locations in several discharges. Dash line: propagation at 10 m/s for ρ > 0.4 and at 80 m/s for ρ < 0.4.
(b) Contour plot of the frequency spectrum of a Mirnov coil signal in discharge 5127.

Non-diffusive transport phenomena and MHD instabilities. Cold pulse propagation has been studied in TJ-II using nitrogen injection by means of a fast injection system with the goal of elucidate transport mechanisms [36]. The results show that the propagation speed is of the order of v = 10-20 m/s in the outer half of the plasma, whereas it speeds up to around v = 50-80 m/s in the central part as shown in figure 15(a), while the pulse front remains sharp. This behaviour is not at all in accordance with diffusive propagation, which would slow down as it propagates (travelled distance $\propto \sqrt{t}$). As it is shown in figure 15(b), an MHD mode with frequency of about 40 kHz is triggered at the time the cold pulse reaches the plasma region where the $\iota/2\pi = 3/2$ rational surface is located according to VMEC calculations. Also, a turbulent burst was observed by the 2mm scattering diagnostic at the time the cold pulse pertubation crossed the measurement position (ρ = 0.6).

Qualitatively, the pulse propagation behaviour is very similar to the pulse propagation seen in a simulation of resistive pressure-gradient driven turbulence in cylindrical geometry. Thus, it is suggested that a possible explanation for the observed propagation of the cold pulse front is the sequential triggering of pressure-gradient driven modes, in an avalanche-like fashion.

Conclusions

Significant improving in the characterization of confinement and stability properties of TJ-II stellarator plasmas has been recently achieved. The main conclusions can be summarized as follows:

1) Global confinement studies have shown a positive dependence of energy confinement on rotational transform, pointing out a parameter dependence consistent with ISS95 predictions.
2) Spontaneous transitions in particle and energy confinement have been observed that resemble some characteristics of previously reported H-mode regimes in other stellarator devices.
3) Magnetic configuration scan experiments have shown the interplay between magnetic topology (e.g. rationals), transport and electric fields. Cold pulse as well as the transport events provoked by decreasing magnetic well generates non-diffusive propagation.
4) First measurements of radial electric fields and plasma potential show values that are comparable with those expected from neoclassical calculations. Active biasing experiments have shown an impact in both edge and global plasma parameters. In low magnetic well configurations sheared edge poloidal and parallel flows are linked near marginal stability.

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