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Influence of magnetic topology on transport and stability in stellarators

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Abstract

The influence of the magnetic topology on transport and stability has been investigated in four stellarators: an almost shearless medium size flexible heliac (TJ-II), a medium size and a large heliotron (CHS and LHD) with shear, and a quasihelically symmetric device (HSX) with moderate shear. All of these have variable rotational transform profiles and magnetic ripples. Using these capabilities, bifurcated states can appear and plasma can jump from one to another with subsequent changes in the transport properties. Low rational values of $\iota/2\pi$ can create transport barriers in LHD and TJ-II when they are located close to the plasma core or at the edge. The key ingredient for transport barriers is a positive and sheared electric field. Internal transport barriers also appear in CHS, but the role of rationals is not clear yet in this device. The time evolution of the electric field shows the onset of a bifurcation triggered either by the rational or by the presence of the ion and electron roots. The electric potential inside ITBs follows the ECE-temperature profile in a fast time scale. The plasma stability properties and its effect on the viscosity are also studied in the HSX, and the influence of the dynamics of rational surface is studied in the LHD and TJ-II stellarators.

(Some figures in this article are in colour only in the electronic version)

1. Introduction and description of the problem

The magnetic topology is a very important ingredient of plasma confinement in magnetic traps, having a greater influence than the magnetic configuration on the transport in the several collisionality regimes. The presence of rational surfaces that can break the magnetic topology

of nested flux surfaces does affect the particle and heat fluxes as well as the turbulence and electric fields [1]. In fact, transport barriers close to rational magnetic surfaces have been found in tokamak plasmas in the confinement region (internal transport barriers, ITBs) and in the plasma edge (ETBs) (see e.g. [2] for a report on ITBs in RTP and [3] for a review of ITBs in tokamaks). Stellarator plasmas also have transport barriers close to rational surfaces, as shown in [4] and [5] for ETBs and in [6] and [7] for ITBs (a review of ITBs in stellarators can be found in [8]).

Two different explanations for the appearance of ITBs have been considered up to now. One of them attributes the formation of ITBs to a rarefaction of resonant surfaces in the proximity of low order rationals, which is expected to decrease turbulent transport [9, 10]. This idea has been used to explain several tokamak [2, 11] and stellarator [12] experimental results. The other explanation relies on the fact that the electric field profile is strongly modified close to the rational surface, sometimes giving a sheared flow. These fields can also trigger the so called neoclassical transport barriers [13] or give rise to $\mathbf{E} \times \mathbf{B}$ sheared flows that appear in the proximity of rational surfaces and can decorrelate turbulent structures and, hence, diminish anomalous transport [14].

Nevertheless, the effect of rational surfaces in stellarators has been the subject of a controversy. It has been claimed that its presence inside the plasma column is prejudicial because it always tends to degrade the confinement [12] in low shear devices. On the other hand, locating the rotational transform profile close to a rational value should improve the confinement in a shearless device, due to the same mechanism of rarefaction explained above. A feasible explanation for this discrepancy can be found in this work.

The onset of electron heat ITBs (that will be called eITBs in this work) in stellarators is accompanied by the appearance of positive sheared radial electric fields that can be driven in several ways: by the turbulence itself [15] via Reynolds stress and shear generation in the mean flow; by neoclassical mechanisms due to the difference between the ion and electron fluxes [16]; and by kinetic effects induced by electron cyclotron resonance heating (ECRH) through enhancement of the outward electron flux [17, 18]. These mechanisms can act cooperatively. The plasma viscosity should also be reduced so that it cannot hinder plasma rotation.

The influence of the magnetic topology on transport and stability has been studied in four different stellarators: an almost shearless medium size flexible heliac (TJ-II) [19], a medium size heliotron (CHS) [20] and a large heliotron (LHD) [21], both of them with shear, and a quasisymmetrically symmetric device (HSX) [22], with moderate shear. All these have rotational transform profiles that may be varied by driving currents in the plasma or by changing their magnetic configurations, especially TJ-II, that can scan magnetic configurations with a rotational transform from 0.9 to 2.2. The confinement properties of LHD and HSX can be changed by modifying their respective magnetic ripples, which changes the neoclassical transport. Studies of bifurcated transport states between electron and ion roots in CHS have shown that the electric field can jump between them. Experiments in these stellarators have allowed us to determine how the transport and stability are modified when the magnetic topology is changed and to understand better the mechanisms that act in the different devices. In all the cases the modification of the electric field structure plays a dominant role.

Transport barriers have appeared close to low rational values of $\iota/2\pi$ in the edge or in the plasma core of TJ-II. Low order rational values of rotational transform have been positioned either by scanning the rotational transform, driving currents using ECCD, or inducing OH currents. LHD is characterized by having an $n = 1, m = 1$ island close to the edge, which is created by an error field and can be reinforced using an auxiliary coil. As will be shown,

transport is reduced in the vicinity of the island. Both cases demonstrate that low order rationals are not always deleterious for confinement but can be beneficial, depending on the plasma conditions. The key reason for this fact is the appearance of a positive and sheared electric field, which can be created by the additional non-ambipolar fluxes that appear due to the presence of the rationals or the onset of a sheared flow in the vicinity of low order rational surface.

LHD [23] and TJ-II [18] experiments indicate that it is possible to create eITBs in the plasma through neoclassical mechanisms, without the presence of low order rationals. This occurs when the electron root appears in the plasma core, as has been observed also in other stellarators [24, 25]. The role of rationals is not clear yet in CHS, but they could be having some effect on the confinement, as will be shown below. The electron temperature profile is very similar in the case with low order rationals to the case in which an ITB is triggered by neoclassical mechanisms, and so both states are called eITBs.

The time evolution of the electric field has been studied and fast transitions have been found between high and low confinement regimes. The electric potential inside eITBs follows roughly the temperature profile, and the electric field is developed on a fast time scale (hundreds of microseconds). The viscosity and the influence of the magnetic configuration on the time scale of the rise of the electric field were studied in HSX. The influence of the plasma stability and island dynamics on ITBs is discussed using the results of TJ-II and LHD.

This paper is organized as follows: section 2 is devoted to a study of the role of low order rationals in transport barriers; section 3 deals with kinetic effects and transport; section 4 deals with the appearance of bifurcations; the time scales of the onset of electric fields and the neoclassical effects are dealt in section 5; section 6 is devoted to the effect of island dynamics on transport barriers and, finally, the conclusions are presented in section 7.

2. The role of low order rationals

We have positioned low order rational surfaces close to the plasma core in TJ-II ECRH plasmas using two methods: performing a magnetic configuration scan and inducing current in order to modify the rotational transform profile. Electron internal heat transport barriers (eITBs) appear in both cases when the low order rational surface is close to the plasma core region (effective radius $\rho \approx 0.2$ – 0.3), while they disappear when the rational surface is positioned at outer positions [7]. No barriers are observed either in particle transport or in the ion channel for the moment.

An important difference between these two methods is that the OH-induced current introduces a magnetic shear, especially in the bulk plasma, while in the configuration scan the vacuum rotational transform profile is only modified by the bootstrap current (less than 1 kA in absolute value), whose profile is not well known in TJ-II. Thus, the effect of low order rationals is studied in low and moderate shear environments.

We have performed a magnetic configuration scan where the vacuum position of the ($n = 3/m = 2$) rational is changed. The shots performed in a configuration with a rotational transform above $3/2$ ($\iota(0)/2\pi \approx 1.508$) does not present an eITB, the one with $3/2$ at $\rho \approx 0.35$ ($\iota(0)/2\pi \approx 1.464$) is an intermediate case, and the eITB appears during the shot, depending on the bootstrap current value, while the shot performed in a configuration with the rational at an effective radius $\rho \approx 0.6$ ($\iota(0)/2\pi \approx 1.490$) presents a steep temperature gradient during the whole discharge. In these three cases, as in that presented in the following, on-axis heating is applied to the plasma.

The latter paragraph deals with shots without an inductive current, while we are discussing now the effect of introducing the rational surface by driving OH-current. The formation of

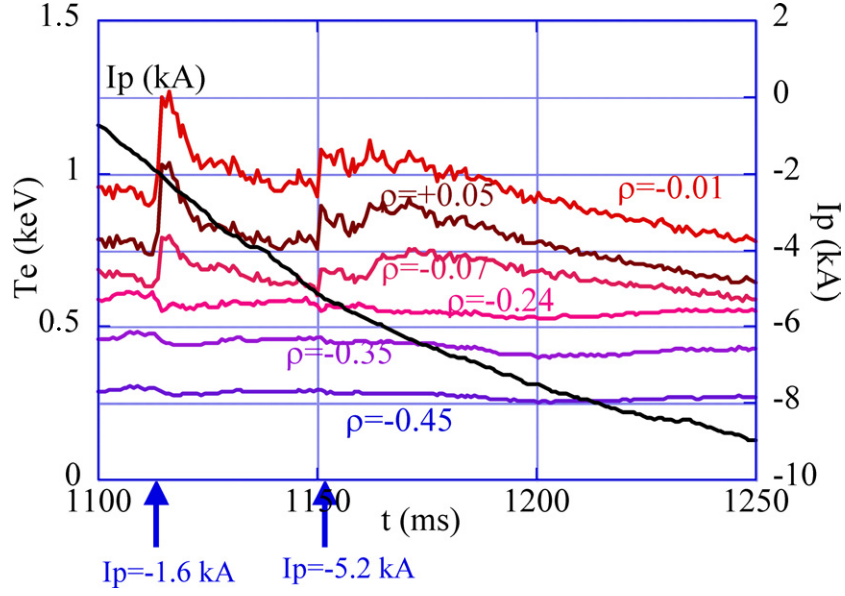


Figure 1. Time evolution of ECE measured temperatures and plasma current. The arrows point to the times when the main jumps in central temperature take place.

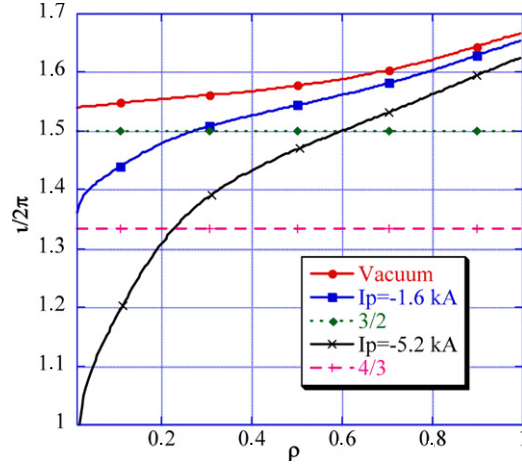


Figure 2. Vacuum rotational transform profile and estimated ones profiles the currents that provoke the jumps in central temperature. The 2/3 and 4/3 resonances appear at similar positions.

eITBs when the rational surface position is moved in a single shot by inducing plasma current by OH-coils is characterized by a sudden increase in the core electron temperature and in the core plasma potential [6]. eITBs triggered by a configuration scan have the same properties as those created by an induced current. Figure 1 shows the evolution of the ECE measured electron temperature, with jumps in the central channels showing that an eITB is being created. Figure 2 shows the estimated rotational transform profiles in the discharge of figure 1 just at the two times when the jump in temperature happens. It is shown that the $n/m = 3/2$ and $4/3$

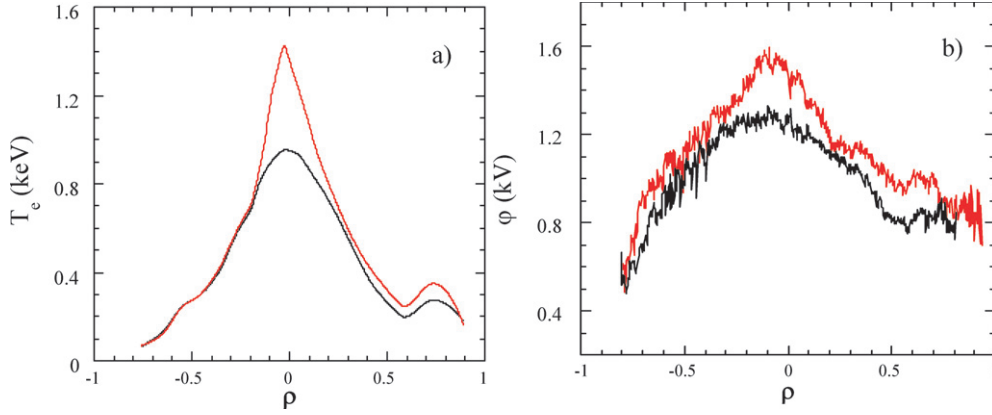


Figure 3. (a) Temperature profiles in plasmas with and without a barrier. (b) The potential profile measured using HIBP for the same cases as before, demonstrating that a stronger positive radial electric field appears in the core.

resonances are close to the plasma core at those times. This kind of transition has also been observed for the $5/3$ rational, although these transitions appear to be weaker.

The estimation of the rotational transform profile is based upon calculation of the current profile considering that the plasma resistivity is described by the Spitzer formula corrected by the fraction of trapped particles. The bootstrap current is neglected in comparison with driven OH-currents for this estimate. After careful calculations with the appropriate geometry, we can be sure that the measured loop voltage in TJ-II (along the central conductor) can be considered as a diagnostic of the plasma loop voltage or the circulation of the parallel electric field induced with current ramps in the OH-coils, under conditions of steady state plasma currents. This has been proven to be very valuable in obtaining information on the plasma conductivity: it is found that the evolution of the plasma current density yields loop voltages in fair agreement with the diagnostic, imposing the experimental net plasma current as a boundary condition, when the resistivity is described with the Spitzer formula corrected by the magnetic ripple of the device.

The measured radial electric field, E_r , in TJ-II plasmas with an eITB is in the range of $10\text{--}15\text{ kV m}^{-1}$, three times the value without the barrier, which is in the range of $4\text{--}5\text{ kV m}^{-1}$. The rotation velocity in the plasma core is three times faster in the case with an eITB, in agreement with the ion-momentum balance equation [7].

The former experiments show that the eITB only appears for low order rational surfaces and disappears when the rational surface is positioned outside the plasma core. This last result can be due to the fact that the ECRH-induced pump-out is smaller for outer radii, due to the lower absorbed power density and the higher collisionality.

We show in figure 3(a) the temperature profiles in plasmas with and without a barrier; and (b) the potential profile measured by HIBP for the same cases as before, demonstrating that a stronger positive radial electric field appears in the core. Transport analysis performed with the modified predictive transport code Proctr shows a reduction of the core heat diffusivity by a factor 2 [7]. A reduction in the turbulent transport due to the sheared $\mathbf{E} \times \mathbf{B}$ flow is claimed to be the cause in [26] and [13], and modification of the neoclassical transport is postulated in [25]. In the first case the important magnitude is the sheared flow, i.e. the quantity dE_r/dr , being the value of the electric field in the second one. In TJ-II, the mechanism for heat transport reduction must be compatible with no particle confinement enhancement.

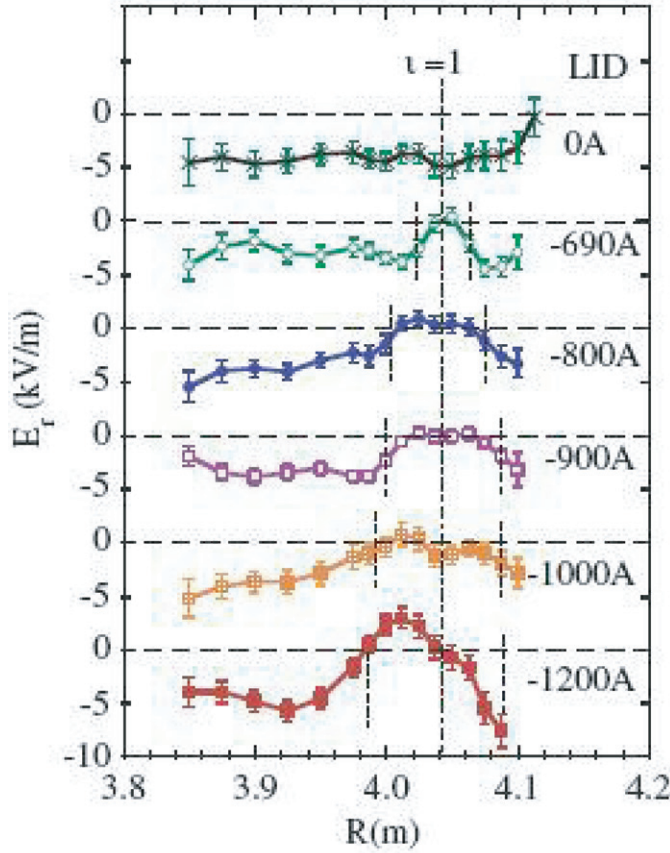


Figure 4. Radial profiles of radial electric field for different island widths in LHD. The currents that are driven in the external coil to reinforce the island are indicated in the picture.

Low order rationals have been positioned close to the edge of TJ-II also and the measured electric field presents a sheared flow that is able to reduce the turbulence level [4] and to create a small transport barrier. It is also seen that the edge sheared flows and fluctuations are close to a marginal stability equilibrium, since the $\mathbf{E} \times \mathbf{B}$ shearing rate takes a value of 10^{-5} s^{-1} , close to the value needed to overcome the turbulence growth rate [27].

A close relation between the rationals, confinement, and transport was also found in Wendelstein 7-AS, where the value of the rotational transform in the edge was varied both by current drive and a configuration scan [28, 29], these two methods being equivalent. The modes $m/n = 3/9$ and $3/10$ were located inside the plasma and, depending on their phases and positions, a transition from a bad to a good confinement regime, accompanied by a decrease in the of fluctuations, was observed.

The LHD configuration has the $n = 1, m = 1$ rational surface at the edge of the device that is able to create a magnetic island. The width of the island can be varied using an external coil: the higher the current, the wider the vacuum island. The electric field is measured inside the island for different widths and is shown in figure 4. A sheared flow has been observed in the vicinity of the island and, moreover, it also appears inside the island, provided it is wider than a given size, clearly demonstrating that magnetic islands are able to generate a shear flow [30]. The effect of this island on transport will be shown in the next section.

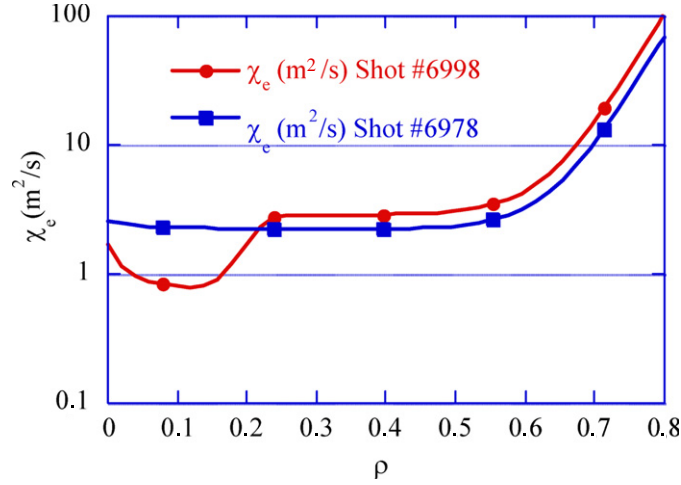


Figure 5. Heat diffusivity in TJ-II estimated using the Proctr code with and without an eITB. The central heat diffusivity is reduced by a factor of 2 with an eITB.

3. Kinetic effects and transport

A large body of experimental evidence shows the onset of an extra electron flux when the low order rational is positioned close to the plasma core in TJ-II. The density profile is more hollow and SXR has an increase in direct losses, detected by fast changes in the emissivity profiles [17]. These changes are correlated with modifications of the electron distribution function, as deduced from SXR spectra, and the increased outward particle flux leads to an enhancement of the H_α line emission. All these facts and the ones outlined in the previous sections point to kinetic effects induced by ECRH and the presence of rational surfaces as the ingredients necessary for explaining the observed heat transport modification in the plasma core. The heat diffusivity is reduced by a factor of 2 in the case with an eITB, as can be seen in figure 5.

The perturbed electron flux, which is much larger than the ion one during the transient phase, is given by $\Gamma_e(E_r) = \Gamma_e^{\text{NC}}(E_r) + \Gamma_e^{\text{TURB}}(E_r) + \Gamma_e^{\text{ECH}}(E_r) + \Gamma_e^{\text{RS}}(E_r)$. The neoclassical flux, the $\mathbf{E} \times \mathbf{B}$ turbulent flux, the ECH-induced flux and the flux induced by the rational surface are considered in this expression. The experimental results from TJ-II show that the cooperation of the third and fourth terms is necessary to create the radial electric necessary for reducing the heat transport.

The estimation of the flux through the magnetic surface needs a detailed knowledge of the magnetic topology. A recent calculation for tokamak plasmas shows a strong modification of the electron and ion fluxes and, hence, of the ambipolar electric field [16]. The viscosity is expected to increase when the nested surfaces are broken but; on the other hand, the electric field increases the poloidal rotation drive.

An approximate estimation can be done if the modification of the ion flux due to the presence of the rational surface is negligible in comparison with the electron one. In this case, the electric field will be given by $E_r \approx (T/e)(n'/n - T'/2T)$ [7]. If we neglect the density gradient in comparison with the temperature gradient, we obtain $E_r \approx -T'/2e$. This means that the shape of the plasma potential is the same as that of the temperature profile, as far as the former assumptions hold. In fact, the oscillations of the plasma potential observed during

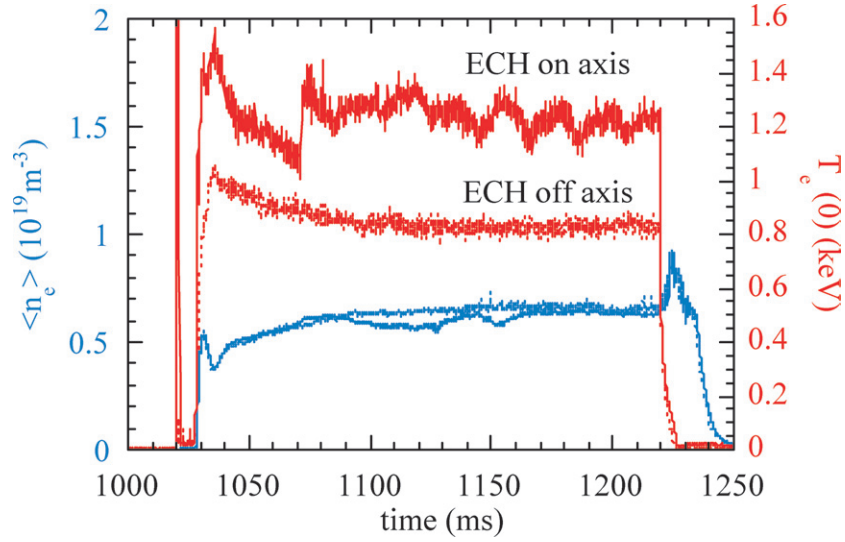


Figure 6. Time evolution of density and central electron temperature for two discharges, one with on-axis heating and the other one with off-axis heating. The transition to the eITB only happens in the case with on-axis heating.

the transient behaviour previously observed in eITB [31] are in phase with the temperature oscillations and in counter-phase with the HIBP beam current.

The ECRH-induced flux roughly estimated using the Langevin equations [32] is, not surprisingly, directed outwards. This extra flux causes the onset of an electric field that increases the heat confinement and keeps $\Gamma_e = \Gamma_i$, therefore stopping the electron flux. Moreover, accordingly to the former calculations, the outward ECRH-induced flux is proportional to the absorbed power density. The experimental data show a clear dependence on that magnitude, as can be seen in figure 6, where two TJ-II discharges with the same magnetic configuration and the same plasma density are displayed. One of them has on-axis power deposition profile, while the other is off-axis heated. It is seen that the eITB appears in the shot with on-axis heating, in which the absorbed power density is larger (about 5 W cm^{-3}) rather than in the case with off-axis heating (about 1 W cm^{-3}). The pump-out will be stronger in the first case and so will be the outward flux. This flux, together with the presence of the $3/2$ rational is enough to trigger the eITB. The total plasma current in these two discharges is the same when the eITB is triggered; therefore, the displacement of the rational must be very small and cannot be the cause of the different behaviours.

Modulation experiments also show the same evolution of the plasma potential and temperature. We kept a gyrotron with about 200 kW and another one with other 200 kW 100% modulated. It is seen that the eITB appears at the phase of maximum injected power and disappears when the modulated gyrotron is off. The evolution of the line density is clearly in counter phase with the temperature, showing again the appearance of ECRH pump-out.

In the case of low order rationals positioned close to the plasma core, the mechanism for heat transport reduction is compatible with particle orbit modification due to the electric field. Hot electrons that suffer rare collisions are better confined with a positive electric field, which would imply an improvement of heat confinement, despite the enhanced particle flux.

The sheared flow observed inside and close the magnetic island at the edge of LHD also has beneficial effects on the transport. A pellet is injected by TESPEL, and the subsequent

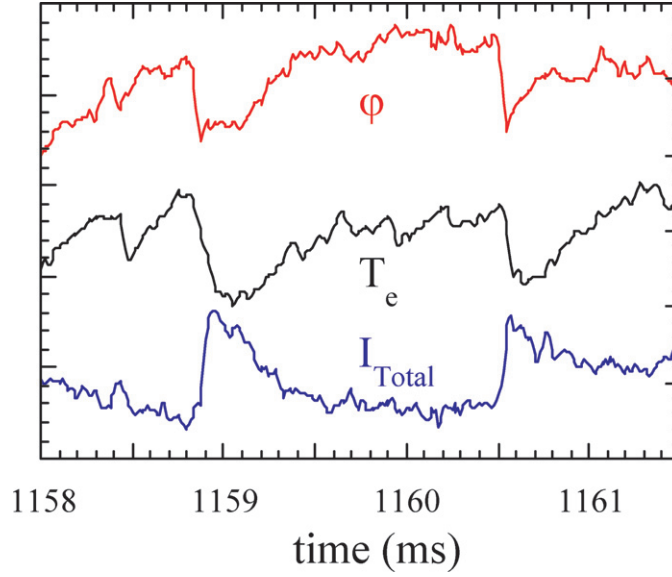


Figure 7. Time evolution of beam intensity and central plasma potential measured using HIBP in TJ-II and of evolution of the central temperature, showing that the potential and temperature are in phase and the beam intensity, proportional to the plasma density, is in counter phase.

cold pulse propagation is studied outside and inside the magnetic island. The result of the simulation is that the cold pulse propagation outside the zones without sheared flow is well simulated with a heat diffusivity of $\chi = 5 \text{ m}^2 \text{ s}^{-1}$, while the propagation inside and in the vicinity of the island is one order of magnitude smaller: $\chi = 0.3 \text{ m}^2 \text{ s}^{-1}$. The reduction in heat transport due to the appearance of shear flow agrees with the former theoretical studies that predict such behaviour [14] and with previous experimental results [4].

4. Bifurcation and eITBs

The appearance of eITBs in the plasma core of stellarators is always accompanied by a positive electric field. Sometimes a transient behaviour is observed and the eITB appears and disappears (see e.g. [31]) and the onset of eITBs usually happens on a fast time scale. Figure 7 shows the time evolution of the potential and HIBP beam intensity during eITB formation in TJ-II. All these results suggest that a bifurcation of the equation of the electric field appears and gives the possibility of fast transitions from one confinement regime to the other. This transition is similar to the one observed from the neoclassical ion to the electron root. The properties of the fluxes and fields are drastically modified by the presence of the rational surface, and, in particular, new roots of the ambipolar condition can appear [16].

Experiments in CHS have shown this kind of transient behaviour. The collapse of an eITB in the electron temperature profile is accompanied by a collapse of the plasma potential, as illustrated in figure 8, which shows the evolution of the plasma potential at different radial positions: it can be seen that the central potential value undergoes a strong change during the phase of EC + NBI heating: the eITB disappears for $t = 54.5 \text{ ms}$ and is restored for $t = 57 \text{ ms}$. The radial current, which is proportional to the enhanced electron flux, is given by

$$j_r = \varepsilon_{\perp} \varepsilon_0 = \frac{\partial E_r}{\partial t}.$$

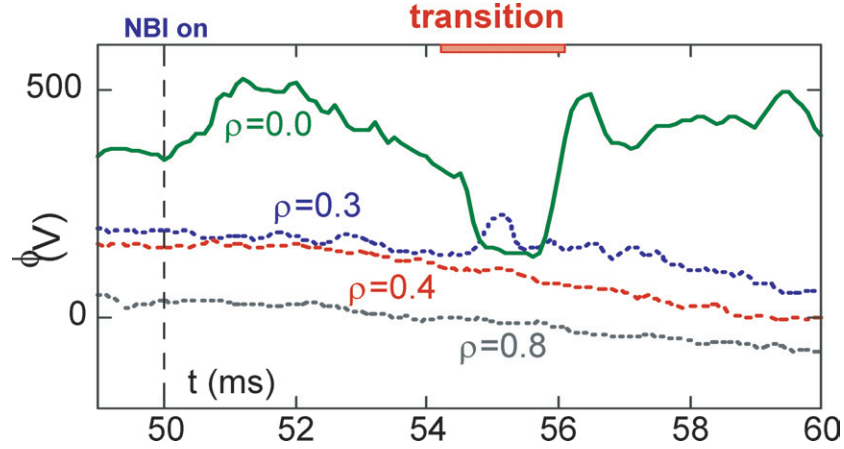


Figure 8. Time evolution of the plasma potential measured using HIBP in several radial positions in CHS, showing a clear transition after NBI switch-on.

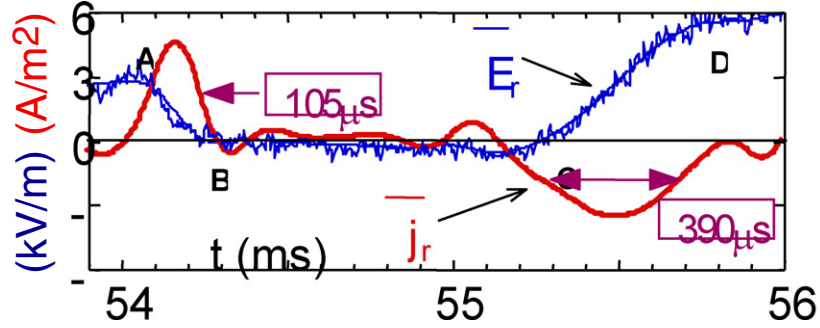


Figure 9. Time evolution of the electric field and radial current in CHS during the transition described in figure 8.

The evolution of the electric field and current, estimated from the latter expression, is plotted in figure 9, where it is seen that the radial current is directed inwards when the electric field is reduced and outwards when it increases. These changes happen on a time scale of hundreds of microseconds, in agreement with the time scale of TJ-II transitions, and are consistent with the kinetic effects observed in TJ-II and commented on above.

The dependence of the radial current, calculated using the former expression, on the radial electric field, measured by HIBP, is plotted in figure 10 and is seen to be non-linear.

The plasma potential profiles at the different plasma regimes are plotted in figure 11, together with the rotational transform profile. It is worth noting that the plasma potential changes strongly from a pure ECRH regime to a pure NBI one, the most positive (bell shape) corresponding to ECH plasmas and to the best electron heat confinement, i.e. the electron root, and the most negative (Mexican hat shape) corresponding to NBI heating phase with the plasma in the ion root.

The rotational transform profile shows that two low order rational values are present: $\iota/2\pi = 0.33$, located close to the plasma core, and $\iota/2\pi = 0.5$, closer to the edge. The latter appears just on the foot of a steep potential and temperature gradient in the ECRH phase.

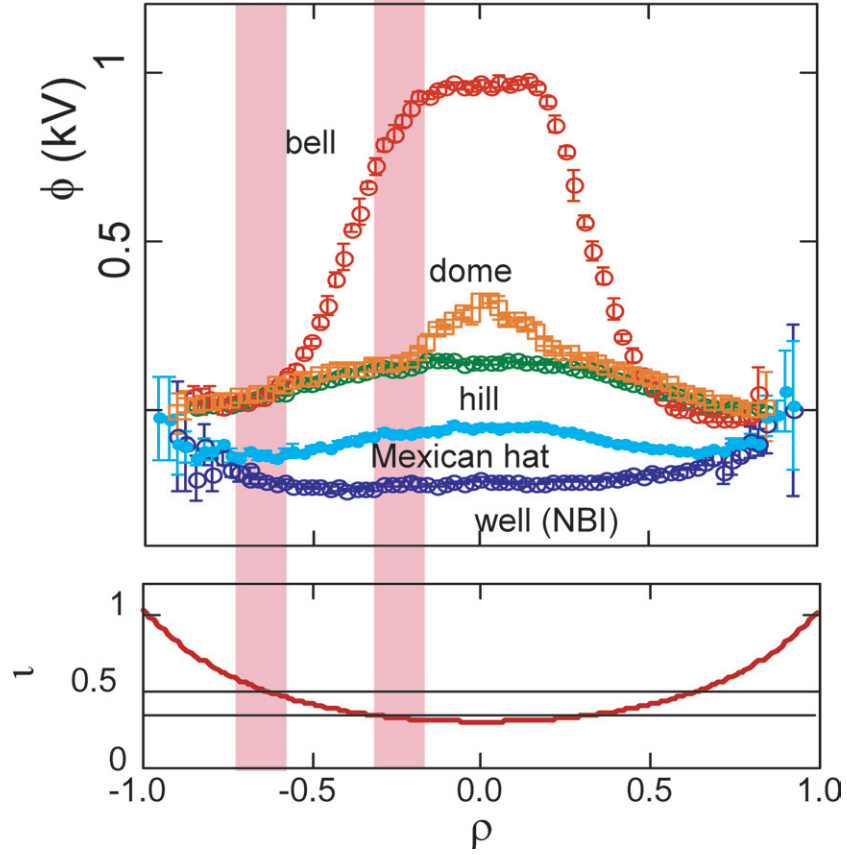


Figure 10. Plasma potential and rotational transform profile in CHS.

During the NBI+ECRH phase the injectors are driving a positive current that moves the rational inwards. A feasible explanation for the observed transition is that rational disappears and the eITB is destroyed, but one has to take into account the changes in plasma characteristics like the collisionality.

It is also observed in this picture that eITBs are better developed close to the low order rationals when ECRH is present. In particular, an eITB is observed in the bell case for $\iota/2\pi = 0.5$ and another one is developed for $\iota/2\pi = 0.33$ in the dome case. Nevertheless, the modified rotational transform profile under plasma current must be calculated, and more investigations are needed to find out why the eITBs are developed for different rationals in these cases and what the actual radial positions of the rationals are.

5. Time scales and neoclassical effects

The time scale in which the radial electric field is created is of the order of hundreds of microseconds in TJ-II and CHS. The HSX team has conducted electrode polarization experiments to investigate the dynamics of the electric field and plasma rotation in two magnetic configurations: the quasihelical symmetry (QHS) case, which is optimized from the neoclassical point of view, and the mirror one, that has a strong magnetic ripple. Neoclassical

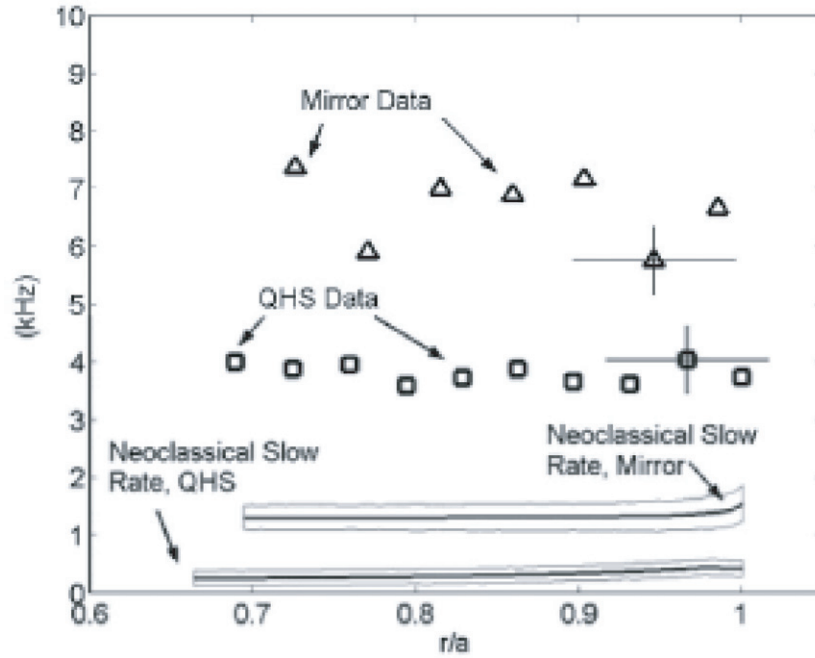


Figure 11. Damping rates estimated from electrode polarization experiments in HSX, compared with the neoclassical estimates.

calculations predict that the mirror magnetic configuration should have a larger viscosity than the quasihelical symmetric one [33]. Two time scales and damping rates must be considered in all the configurations: the toroidal one is the slower and is of the order of milliseconds, and the perpendicular one is of the order of hundreds of microseconds.

Electrode biasing experiments have been performed in HSX [34] that show that the flow induced by the electrode biasing in the mirror is smaller than the one in the QHS configurations. Therefore, the QHS configuration has a lower viscosity than does the mirror one, but both viscosities appear to be greater than that predicted by neoclassical calculations, as can be seen in figure 11. The explanation that has been given to these anomalous viscosities is that the turbulence is governing the plasma response. The fact that the viscosity in the mirror configuration is greater than the QHS one shows that neoclassical effects are still playing some role and, somehow, must be taken into account. The concrete values of viscosity obtained in HSX cannot be applied or extrapolated to plasma dynamics in the other devices since their magnetic configurations are very different, but these results show a general fact: despite the fact that the viscosity is anomalous, neoclassical effects cannot be forgotten, since the viscosity is always lower in the configuration that displays better neoclassical properties.

6. Island healing, stability and eITBs

The dynamics of the island is a key element in understanding the behaviour of transport barriers and bifurcations. It has been shown that the development of a sheared flow depends on the island width, but kinetic effects must also be taken into account to explain the onset of transport barriers. Moreover, the existence of the barrier, which changes the electron flux, may also have

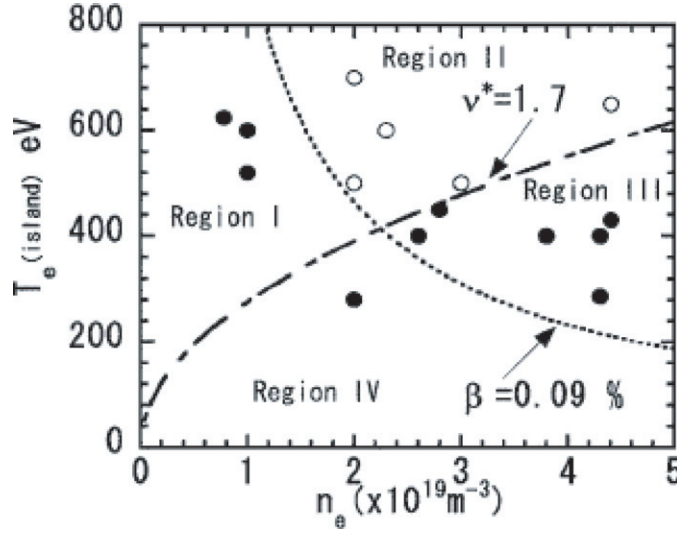


Figure 12. Island width dependence on electron temperature and density in LHD. It is observed that the island is present in regions I, III and IV (●) and disappears in region II (○), corresponding to high β and low collisionality.

an influence on the rational surface dynamics. All these elements must be taken into account together to explain the behaviour of transport barriers.

The experiments performed on LHD have shown that plasma parameters do modify the island characteristics, even when the shaping is by external coils. The evolution of magnetic islands has been studied through measuring temperature profiles using a Thomson scattering system and the density profile and performing a tomographic reconstruction of the interferometer signals [35], and it is seen that the island width depends on β and the collisionality, ν^* . The island width is reduced for high β values and low collisionality values [36]. In fact, the plasma conditions for which an island is present or absent have been identified, as can be seen in figure 12: the island disappears in region II, where β is high enough and the collisionality is low enough. Regions I, III and IV are defined by the boundary curves for island appearance. The experiments of [36] show that the island needs the conditions of $\beta < 0.09$, $\nu^* > 1.7$ to be present. The position of the X and O points of the island are also changed by the plasma with respect to vacuum.

The results of these experiments, combined with the reduction in transport that appears when a sheared flow is present inside or close to the island, could explain why low order rational surfaces are sometimes deleterious and sometimes beneficial for confinement. For given plasma parameters (low pump-out, high collisionality, island not wide enough, or low β), the island cannot create either a shear flow or a positive electric field, and therefore no transport barrier is generated.

As has been mentioned, transient eITB behaviour was found in TJ-II when the rational surface was located close to the plasma core, showing that when the plasma is close to a bifurcation regime it is possible to jump from one state to another, as can be seen in figure 13, where the time evolution of ECE signals is plotted. Recently, it has been found that when transient behaviour appears a quasi-coherent mode is detected through HIBP and ECE signals [37] in an intermittent fashion. This mode has a frequency of about 20 kHz and when it appears is located close to $\rho \approx 0.3$, as the ECE and HIBP signals have shown. Figure 14 shows a Fourier analysis of the beam intensity measured using HIBP, which shows

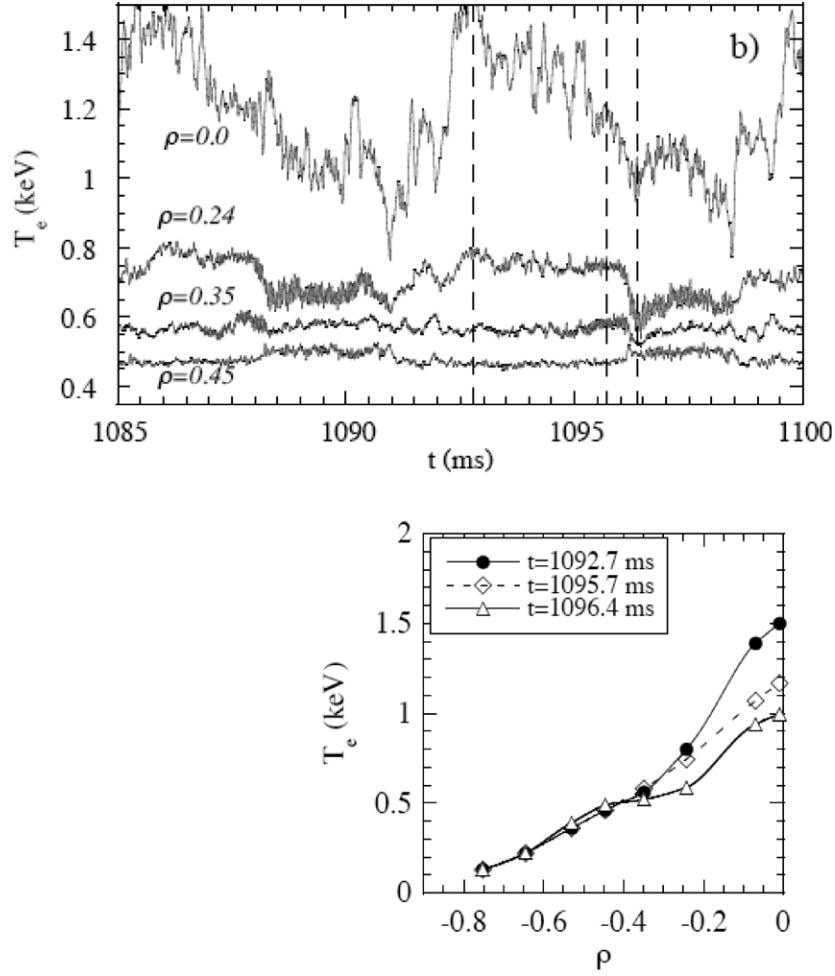


Figure 13. Transient behaviour of ECE-measured temperatures in TJ-II. The top panel shows the time evolution of electron temperature at several radial positions with strong variation of central temperature and the bottom panel shows the three temperature profiles corresponding to the three times marked with dashed lines in the top panel. The first profile (closed circles) correspond to the phase with eITB, while the others correspond to two times of the crash of the barrier.

a high coherence with ECE measurements [37]. The important fact is that the mode disappears when the eITB is restored and is destabilized when the eITB suffers a crash. The reason for this intermittent behaviour is under investigation, but a relationship between the onset of the eITB and mode stabilization must exist.

7. Conclusions

The effect of introducing low order rational surfaces in the plasma column is studied in the present work. The results of four working stellarators with very different magnetic configurations and properties are considered: TJ-II, which is a medium size shearless flexible heliac; LHD, a large superconductor heliotron and CHS, a medium size heliotron, both with shear; and HSX, a small size stellarator in which the magnetic configuration can be changed

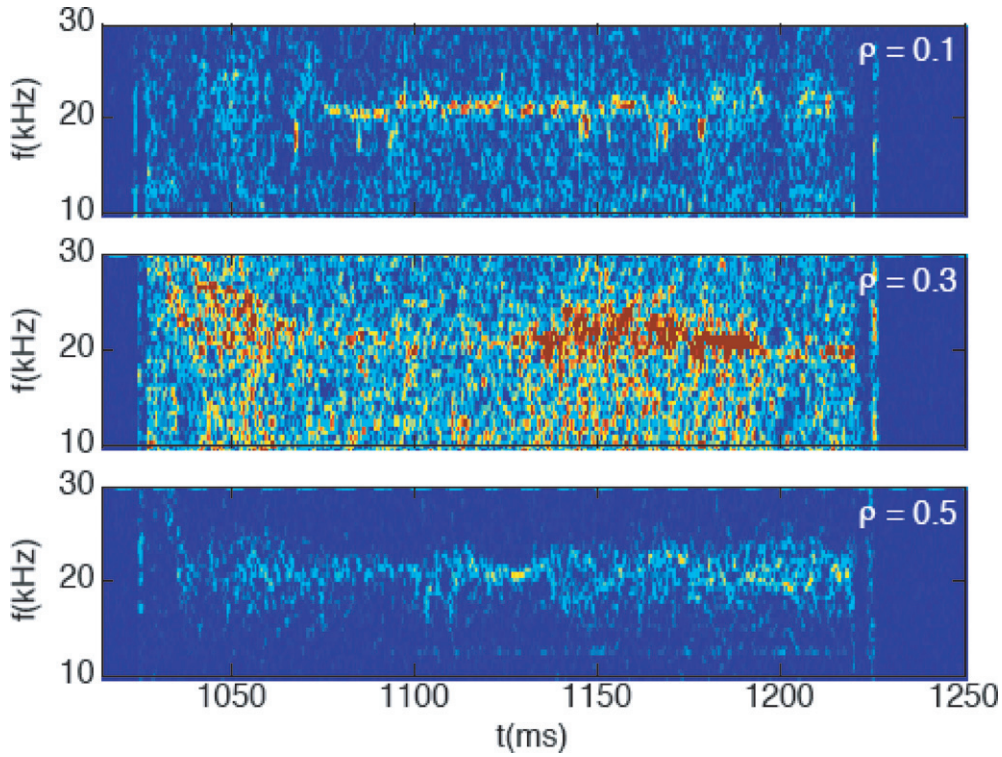


Figure 14. Fourier transform of beam intensity of HIBP in TJ-II at three different radial positions. A quasiscoherent mode appears at $\rho \approx 0.3$ with a frequency of around 20 kHz.

from a QHS to a mirror configuration. The results obtained from these devices provide valuable information on the influence of rational surfaces on the transport, stability, turbulence, and electric fields.

It is seen that, under certain plasma conditions, low order rational surfaces are beneficial for confinement, since they are able to create transport barriers. In such cases it is seen that transport barriers are accompanied by a positive and/or a sheared electric field that is able to reduce transport. In fact, the heat transport is reduced by a factor of 2 in the core of TJ-II and one order of magnitude at the edge of LHD. The sheared flow is seen to reduce the level of turbulence, and the positive electric field reduces the heat transport. The mechanisms that are acting in the transport reduction can be different in the plasma core and in the edge. The transport is reduced at the edge by the shear flow, but it is not clear that this mechanism is the one responsible for the appearance of eITBs. The results of CHS show a reduction in the turbulence at the centre, but no effect can be detected in the electron density profile. Possibly the convective flux is strong enough to overcome such an effect. The reduction in heat transport at the centre can be attributed to the shear flow or to the presence of such a positive electric field. More studies are necessary to elucidate this point.

The possible triggers of this electric field are diverse, depending on the position of the rational surface and on the plasma properties. A redistribution of the plasma momentum by the broken topology, the onset of a vortex velocity inside the island, and the creation of a non-ambipolar flux are mechanisms that are acting close to the island.

Kinetic effects play a key role in establishing the conditions for creating the barrier in the plasma core. An extra outward electron flux is needed to generate the electric field that will

reduce heat transport, as has been observed in TJ-II and CHS during the transient behaviour of the eITB. In fact, an inward (outward) radial current appears when the electric field becomes more negative (positive) in CHS. The response of the current to the field is seen to be non-linear. The role of rational surfaces is not clear in the dynamics of CHS eITBs, but the presence of the 0.3 rational surface is close to the position where the eITB appears and is modified by the plasma current induced by NBI.

The time scales of electric field modification and eITB formation depends on the viscosity. The time scale for eITB onset is of the order of hundreds of microseconds in CHS and TJ-II. The experiments in HSX show that the toroidal and poloidal viscosities are much greater than those predicted by neoclassical calculations, which means that they have an anomalous origin. On the other hand, it is seen that both are greater in the mirror configuration than in the QHS configuration that is optimized from the neoclassical point of view. This suggests that neoclassical effects are still playing a role.

Finally, it has also been shown that the dynamics of the island is a key element to understanding the behaviour of transport barriers and bifurcations. The capability of creating a sheared flow depends on the island width. And the kinetic effects and, therefore, collisionality, must be taken into account to explain the onset of transport barriers. Moreover, transport barriers change the plasma characteristics that will themselves modify the dynamics of the island. In fact, it is shown in LHD that the radial electric field profile and hence the appearance of a shear flow able to trigger a transport barrier depend on the island characteristics, which depend on plasma pressure and collisionality. Similarly, the quasi-coherent mode is stabilized in TJ-II when the eITB appears. The results presented in this paper could explain why rational surfaces are sometimes deleterious and sometimes beneficial for confinement. As has been shown, for given plasma parameters the island cannot create either a shear flow or a positive electric field, and therefore no transport barrier is generated.

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