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# Electron internal transport barrier formation and dynamics in the plasma core of the TJ-II stellarator

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**Abstract**

The influence of magnetic topology on the formation of electron internal transport barriers (e-ITBs) has been studied experimentally in electron cyclotron heated plasmas in the stellarator TJ-II. e-ITB formation is characterized by an increase in core electron temperature and plasma potential. The positive radial electric field increases by a factor of 3 in the central plasma region when an e-ITB forms. The experiments reported demonstrate that the formation of an e-ITB depends on the magnetic configuration. Calculations of the modification of the rotational transform due to plasma current lead to the interpretation that the formation of an e-ITB can be triggered by positioning a low order rational surface close to the plasma core region. In configurations without any central low order rational, no barrier is formed for any accessible value of heating power. Different mechanisms associated with neoclassical/turbulent bifurcations and kinetic effects are put forward to explain the impact of magnetic topology on radial electric fields and confinement.

## 1. Introduction

Electron internal transport barriers (e-ITBs) are commonly observed in electron cyclotron heated (ECH) plasmas in stellarator devices such as CHS [1], W7-AS [2], LHD [3] and TJ-II [4]. At a high heating power density, electron temperature profiles are centrally peaked and core electron heat confinement is improved [1–4]. In addition, a large radial electric field shear has been measured [1, 2] accompanied by a reduction of fluctuations [1]. These experimental results support the hypothesis that the mechanism for barrier formation is linked to a bifurcation of the radial electric field, while the subsequent reduction of turbulence is due to a sheared $E_r \times B$ flow generated by the $E_r$ shear [1, 2]. A comparative study of these transport barriers has been reported in [5]; a topical review has been published recently [6].

TJ-II is a helical device ($B_0 < 1.2$ T, $R = 1.5$ m, $\langle a \rangle = 0.22$ m) offering the possibility of controlling the presence of low order rationals in the rotational transform profile due to its low magnetic shear and flexibility with regard to its magnetic configuration. These properties permit us to study the role of rational surfaces in plasma confinement. Experiments in which the rotational transform profile was lowered dynamically during the discharge (by inducing a toroidal OH current) have shown that the formation of an e-ITB occurs at a certain value of the plasma current [7]. In addition, the occurrence of transient behaviour, interpreted as the repeated annihilation and creation of e-ITBs, was found to be correlated with the presence of a rational surface in the central region of TJ-II plasmas [8].

This paper presents new experimental studies carried out in the stellarator TJ-II with the purpose of studying the influence of magnetic topology on the formation of e-ITBs. Changes in the plasma potential at the moment of e-ITB formation and during transient events are reported, as measured by the heavy ion beam probe (HIBP) diagnostic [9]. Finally, several mechanisms that might provide an explanation for the experimental results are discussed briefly.

## 2. Experimental results

Previous experiments in which the rotational transform was modified dynamically showed that the formation of an e-ITB occurs at a certain value of the plasma current [7]. In the experiments cited, the rotational transform and the magnetic shear were modified due to the plasma current. The rotational transform was decreased and the strength of the negative magnetic shear was increased as the induced OH current was driven to more negative values. New experiments in which the vacuum magnetic configuration is modified on a shot to shot basis have been performed with the purpose of studying the influence of magnetic topology on e-ITB formation in TJ-II. The experimental results refer to ECH plasmas (2 gyrotrons, 200 kW each at 53.2 GHz, second harmonic, X-mode) with a power density of about 15 W cm$^{-3}$. The study is based on four different magnetic configurations having a slightly different rotational transform profile, characterized by central vacuum $\iota$-values: 1.55, 1.57, 1.59 and 1.61. In each magnetic configuration, the rotational transform profile is lowered dynamically during the discharge. To lower $\iota$, a set of four OH coils is used to induce a negative toroidal current of at most $-3$ kA. We observed the formation of an e-ITB in all these configurations, but the value of the plasma current at which the formation takes place is found to depend on the magnetic configuration. Figures 1(*a*)–(*c*) shows the time evolution of the central electron temperature, measured by ECE [10], and the line-averaged density, in three configurations with vacuum $\iota$-values at the plasma core of 1.55, 1.57 and 1.61, respectively, while figure 1(*d*) shows the evolution of the net plasma current in these three discharges. The e-ITB formation appears as a sudden increase in the central electron temperature, while the line density changes only slightly. In some cases, the line density increases (cf figures 1(*a*) and (*b*)), but in some other discharges it decreases. The value of the plasma current at which the e-ITB is established is plotted as a function of the central vacuum $\iota$-value in figure 2 for several discharges. The plasma current at which the e-ITB forms is seen to depend on the magnetic configuration: when the vacuum rotational transform is higher, the plasma current (in absolute value) needed for the transition is also higher.

Additional experiments have been carried out to study the range of ECH power and density values at which an e-ITB is established in different magnetic configurations. We find that if an e-ITB is established in a given magnetic configuration, it is established for a wide range of line density values. Figure 3 shows the central electron temperature just before the formation of the e-ITB and the increase in the central electron temperature when the e-ITB forms, as a function of the line-averaged density, at fixed heating power. The increase in the core

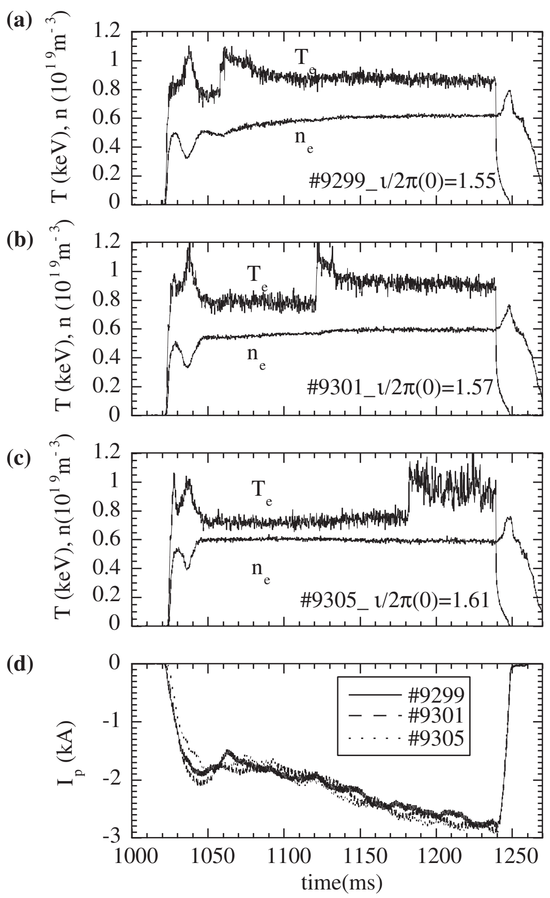


**Figure 1.** Time evolution of central electron temperature and line-averaged density in three magnetic configurations with central rotational transform in vacuum, $\iota/2\pi(0) = 1.55$, 1.57 and 1.61 ((*a*)–(*c*)). Evolution of the net plasma current in these three discharges (*d*).

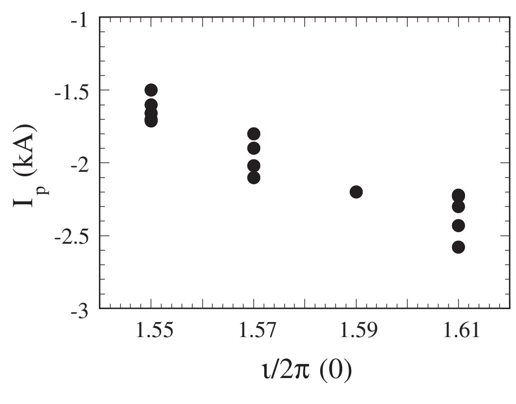


**Figure 2.** Plasma current at which an e-ITB is established as a function of the central rotational transform in vacuum for several discharges.

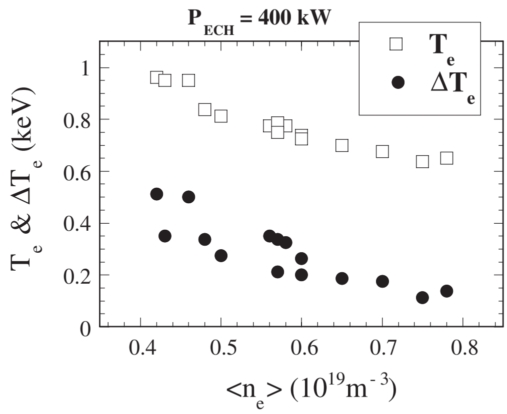


**Figure 3.** Central electron temperature before the formation of an e-ITB (□) and increase in the central temperature when the e-ITB forms (●) as a function of the line-averaged plasma density at fixed ECH input power; $P_{\mathrm{ECH}} = 400$ kW.

electron temperature is more pronounced in the low density plasma. On the other hand, some configurations exist in which no indication of an e-ITB is found within the available range of ECH power.

The plasma potential profile is characterized by means of the HIBP diagnostic. The HIBP diagnostic uses a $Cs^+$ ion beam with a beam energy of 200 keV [9]. A considerable modification of the plasma potential profile is measured across the e-ITB formation, similar to the modification of the electron temperature profile. The plasma potential is found to increase in the plasma core region when the barrier forms, while it remains almost unchanged at outer radii. Since these experiments were performed at low plasma densities, the total beam intensity measured by the HIBP can be considered to be proportional to the local plasma density. Measurements of the total beam intensity profile indicate that at the transition the density profile in the plasma core changes to a slightly more hollow profile. Figure 4 shows a comparison between the profiles before and after e-ITB formation: (*a*) electron temperature measured by ECE, (*b*) plasma potential and (*c*) total beam intensity, the latter two measured by the HIBP. In this experiment, the HIBP profiles are measured by sweeping the primary beam over the plasma in 5 ms. Assuming that during this time interval the plasma potential profile does not change significantly, the profile of the radial electric field can then be estimated from the radial derivative of the measured plasma potential profile. In the central plasma region ($\rho = 0.2$–$0.3$) the radial electric field increases by a factor of 3, from $\approx 5\,\mathrm{kV\,m^{-1}}$ before to the e-ITB to $\approx 15\,\mathrm{kV\,m^{-1}}$ during the e-ITB. While the absolute error in $E_{\mathrm{r}}$ can be large (up to a factor of 2) due to lack of knowledge about the precise spatial localization of the beam, the relative increase in $E_{\mathrm{r}}$ is robust since this uncertainty affects both profiles in the same way. However, the large uncertainty in the estimation of the absolute value of the radial electric field only allows a rough estimation of the shearing rate (between $10^5$ and $10^6\,\mathrm{s^{-1}}$).

The reported HIBP measurements are similar to the results obtained in CHS [11], where a bifurcation in the radial electric field is observed when either the line density is decreased or the input ECH power is increased. In addition, a reduction in the turbulence level is measured at the barrier location. Decreasing the line density further ($n_{\mathrm{e}} < 0.3 \times 10^{19}\,\mathrm{m^{-3}}$), a second bifurcation appears at an outer radial position ($\rho = 0.5$). So far, turbulence measurements are not available for this kind of experiment at TJ-II, and no indication of such a second bifurcation has been observed.

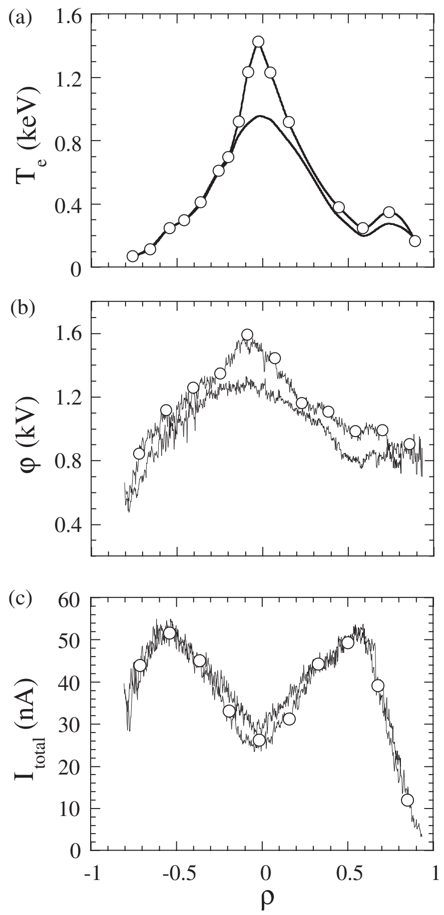


**Figure 4.** Plasma profiles before (no symbols) and during (○) the e-ITB: (*a*) electron temperature, (*b*) plasma potential and (*c*) total beam intensity.

A particular type of transient behaviour characterized by fast drops in the core electron temperature has been observed in ECH TJ-II plasmas [8]. This behaviour was interpreted as the annihilation and creation of e-ITBs. It resembles the electric pulsation phenomenon discovered at CHS [12] and the appearance of the 'electron root' with fast transitions in ECE signals observed at W7-AS [2, 13]. At TJ-II, this behaviour is correlated with the presence of a rational surface close to the plasma core [8]. In recent experiments, it has been found that some sudden modifications in the core plasma potential are coupled dynamically to modifications of the central electron temperature. During the transient events, the drops in the core plasma potential and electron temperature take place on a timescale of about 50–100 $\mu$s and recover to the initial state in about 300–500 $\mu$s. These timescales are shorter than the energy confinement time ($\tau_E \approx 2.5$–3 ms). The total beam intensity is correlated with the plasma potential on a similar timescale. Figure 5 shows the time evolution of the ECE and HIBP signals at the plasma core during the transients. The core potential and electron temperature drop as the core density increases and vice versa. In the example shown in figure 5, the nominal ECH power is 300 kW, the plasma density is low ($n_e \approx 0.4 \times 10^{19}\,\mathrm{m}^{-3}$) and the electron temperature drops from $T_e \approx 1.2$ to 0.8 keV during the transients. The vacuum rotational transform changes

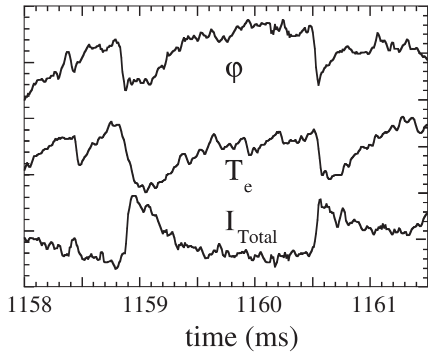


**Figure 5.** Time evolution of the plasma potential, electron temperature and total beam intensity in the plasma core during the transient events.

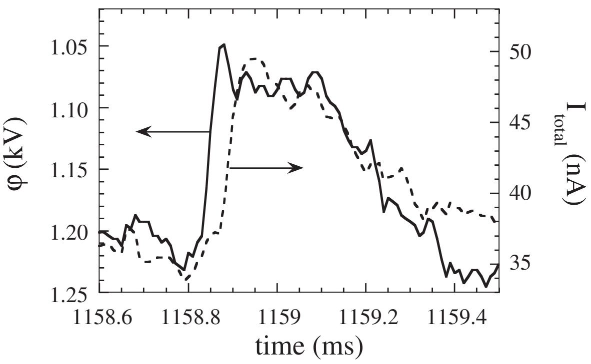


**Figure 6.** Delay between the plasma potential and total beam intensity. The plasma potential signal has been inverted for a clearer comparison.

from 1.49 at the plasma centre to 1.59 at the plasma edge. The net plasma current (mainly due to bootstrap) is very low, $I_p \approx -0.1$ kA, because in this experiment there is no OH current induction and the ECH system is set for no current drive. Therefore the location of the rational surface, $\iota/2\pi = 3/2$, can be taken to be close to $\rho = 0.3$ (its vacuum location). The detailed analysis of the transients dynamics shows that the modification in the plasma potential occurs about 30–50 $\mu$s before any change in the core density. Figure 6 illustrates this time delay. In this figure, the plasma potential signal has been inverted for a clearer comparison. This result points to a leading role of the plasma potential in e-ITB dynamics.

## 3. Discussion

To interpret the experimental findings reported in the previous section, it is important to know the modification of the rotational transform profile due to the plasma current. To calculate this, one needs to know the radial profile of the toroidal current. In TJ-II, as in many other devices, no direct measurement of the current profile is available; therefore, the relevant contributions to the current should be calculated separately. In these experiments, we consider that the only contribution to the current profile is the induced Ohmic current. This assumption is supported by the following facts: the ECH system is set for no EC current drive, and therefore its contribution to the total current is very small. The second possible source of plasma current,

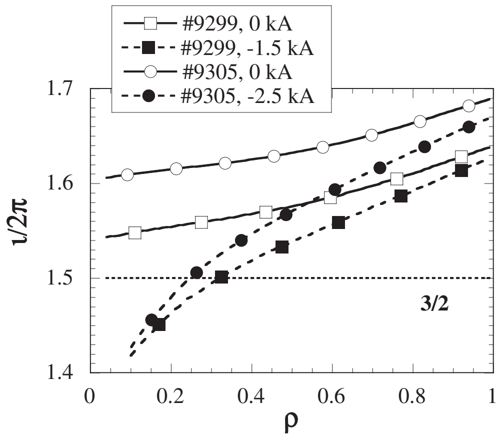


**Figure 7.** Rotational transform profiles in vacuum (—— and ○, □) and just before the e-ITB formation (– – – and ●, ■) for two of the discharges of figure 1.

namely bootstrap current, is very small compared with the OH-driven current. This assertion is based on an experimental fact: although the complex geometry of TJ-II has prevented us—so far—from estimating accurately the bootstrap current, the total plasma current is always measured. We find that discharges similar to those described here but without OH-inducted current are characterized by a measured net plasma current of about $-0.2$ kA, i.e. almost one order of magnitude less than the current in the experiments discussed in this work. The modification of the rotational transform profile due to the Ohmic current is calculated assuming Spitzer resistivity; i.e. we assume that the current density profile is proportional to $T_e^{3/2}$, scaled to match the experimental value of the total plasma current. Figure 7 shows the rotational transform profiles in vacuum and just before the e-ITB formation for two of the discharges of figure 1. The modification of $\iota$ due to the OH current is more pronounced in the inner plasma region than near the edge, such that the negative magnetic shear increases in proportion to the negative plasma current.

Within the values explored in our experiments, the strength of the negative magnetic shear does not seem to be a key ingredient in the e-ITB formation, for otherwise, the plasma current at which the e-ITB forms should be independent of the magnetic configuration (in contradiction with the dependence shown in figure 2). Rather, it seems that the configuration is the key element.

Experimental results obtained in tokamaks [15] show that not only the sign of the magnetic shear but also the strength of the negative magnetic shear is important in the formation of e-ITBs. The negative magnetic shear acts by decreasing the anomalous electron heat transport due to electron temperature gradient (ETG) and trapped electron modes (TEMs). For a review of ITBs in tokamaks, see [16]. By contrast, in stellarators the effect of the sign of the magnetic shear on these modes is unknown. In TJ-II, ongoing experimental and theoretical work is in progress to explore the effects of the plasma current and the magnetic shear on plasma confinement [17]. Future experiments are planned to induce a positive OH current in order to investigate e-ITB formation in configurations with positive magnetic shear.

From the calculated rotational transform profiles (figure 7), one may conclude that in the reported experiments the rational surface 3/2 has to be positioned near the plasma core for an e-ITB to appear. Taking into account the assumptions made in the calculation of the rotational transform profiles, it is difficult to determine the precise radial position of the rational surface at e-ITB formation. Nevertheless, calculations performed varying the total plasma current show that the position of the rational surface moves no more than $\Delta\rho \leqslant 0.05$ when the current is changed by 200 A. The calculated rotational transform profiles show that the location of the rational surface ($\rho \approx 0.2$–$0.3$) coincides with the foot of the transport barrier, within the error bars. The presence of a rational surface within the ECH power deposition zone seems to be the key element in e-ITB formation. Once the barrier is formed, its position does not change even if the rational surface moves outwards, up to $\rho \approx 0.5$. The barrier is lost when the rational surface moves closer to the plasma edge.

It is worth mentioning that the induced OH current is not essential for barrier formation. In these experiments, we used the OH current only as a tool to control e-ITB formation, but with a vacuum configuration naturally possessing a low order rational surface at the plasma core, an e-ITB is also observed without the need for OH current induction.

Thus, the presence of the 3/2 rational surface as the trigger for e-ITB formation appears to be the most likely explanation for the dependence found between e-ITB formation and the magnetic configuration in TJ-II.

In other stellarator devices, so far no specific experiments have been reported in which the influence of low order $\iota$-values on e-ITB formation have been studied. However, the CHS results point to a possible relation between the location of the rational surfaces $\iota/2\pi = 1/3$ and $1/2$, and the foot points of the barriers [5]. More recently, LHD results also suggest a possible link between the foot point of the e-ITB and the location of the $\iota/2\pi = 1/2$ rational surface [14]. The TJ-II results confirm the influence of rational surfaces on the formation of e-ITBs.

Indeed, in some tokamaks [15, 16] the formation of e-ITBs is also affected by the presence of rational surfaces in the $q$-profile, especially for input powers close to the threshold power. At higher powers, e-ITB formation is less sensitive to rational surfaces in the $q$-profile. This result suggests that rational surfaces modify the power threshold for barrier formation. From the TJ-II results, we cannot elucidate whether the low order rational surface in the $\iota$-profile is essential for e-ITB formation or whether it simply modifies the power density threshold.

The current understanding of the formation of e-ITBs in stellarators is as follows [2, 5]: first, a strong radial electric field is generated by neoclassical mechanisms; as a consequence, a reduction in the neoclassical transport ensues [13, 18], and due to the $E_r \times B$ shear flow, the turbulent transport is also reduced. Furthermore, the dynamics of the e-ITB can possibly be explained by the characteristics of the neoclassical $E_r$-bifurcation [5, 6]. However, for TJ-II, neoclassical calculations indicate that only a single solution (root) for the radial electric field is accessible [18]; so, while in steady state plasmas $E_r$ may be generated by neoclassical mechanisms, the observed changes in the electric potential at e-ITB formation and during these transient events are so rapid that other mechanisms must be invoked. Moreover, in the experiments performed in TJ-II, the low order rational surfaces appear as an important ingredient in the formation of e-ITBs, modifying radial electric fields and electron heat transport.

From this perspective, a key open question is the following: Why do rational surfaces play a role in transport barrier formation?

Recently, the effect of a rational surface on the (neoclassical) radial transport fluxes in tokamaks has been reported [19, 20]. After applying the ambipolar condition, the resultant equation for the radial electric field may possess bifurcated solutions in the vicinity of the magnetic island with higher values of the radial electric field. In TJ-II the situation is more complex due to its geometry. Nevertheless, a qualitative discussion is possible by taking into account the fact that the diffusion coefficient in ergodic layers or magnetic islands can be expressed as [21]

$$D = D_{\mathrm{M}}|v_{\parallel}|\Psi(v_{\parallel}), \qquad (1)$$

where $v_{\parallel}$ is the parallel velocity, $D_{\mathrm{M}}$ is a topological coefficient and $\Psi(v_{\parallel})$ is an orbit averaging factor. While the peculiarities of the geometry and the magnetic configuration of the device are represented by the quantities $D_{\mathrm{M}}$ and $\Psi$, the explicit dependence on the parallel velocity is common to all cases. Therefore, the presence of the island will enhance the electron flux more than the ion flux, and as a consequence, the equilibrium ambipolar radial electric field will be modified by the presence of the island. This mechanism could explain the reported increase in $E_{\mathrm{r}}$ and the subsequent enhancement of electron heat confinement. In addition, the radial electric field could have bifurcated solutions, explaining the transient behaviour.

Near rational surfaces, sheared poloidal flow can be established due to the coupling of flow generation and turbulence [22]. The competition between fluctuation driven transport and sheared poloidal flow generation may determine the confinement properties near rational surfaces. This mechanism is consistent with the shearing rates observed close to rational surfaces at the plasma edge of TJ-II [23] and could also be consistent with the shearing rates estimated in the plasma core.

On the other hand, in the absence of sheared poloidal flows, fluctuations are expected to be high at rational surfaces. Close to each low order rational, there is a region free of high order rationals where an enhanced electron energy confinement might be expected as a consequence of the reduction in anomalous transport. It has been argued that this mechanism may explain the $\iota$-dependence of energy confinement observed in low magnetic shear stellarators [24]. This mechanism may also facilitate the formation of an e-ITB close to a low order rational surface, although other ingredients are needed to explain the modification of the radial electric field.

Finally, kinetic effects should also be considered as a possible mechanism for the generation of radial electric fields [13]. The hollow density profiles of TJ-II may be the manifestation of an outward particle flux induced by ECH (i.e. the pump-out effect). Precise calculations of the modification of suprathermal electron fluxes due to rational surfaces are difficult. However, the dependence of the diffusion coefficient on the energy [21] indicates that the rational surfaces can indeed modify these fluxes. In fact, there are experimental indications that soft x-ray spectra are modified in harmony with changes in magnetic topology in TJ-II [25]. The timescale of the variation of the ECE-electron temperature and the density as measured by the HIBP system seems to be consistent with such ECH-based mechanisms.

A more systematic investigation of the structure of the plasma potential profile near low order rational surfaces in different plasma regimes is needed to quantify the relative importance of neoclassical, turbulent and kinetic effects as driving mechanisms of radial electric fields.

## 4. Conclusions

The influence of magnetic topology on the formation of e-ITBs has been studied experimentally in ECH plasmas in the stellarator TJ-II. The main conclusions can be summarized as follows:

- e-ITB formation is characterized by an increase in core electron temperature and plasma potential. The positive radial electric field increases by a factor of 3 in the central plasma region when an e-ITB is established.
- Magnetic configuration scan experiments have shown that there exists an interplay between the magnetic topology and the formation of e-ITBs.
- The calculation of the modification of the rotational transform due to plasma current leads to the following interpretation: the formation of the e-ITB can be triggered by positioning

a low order rational surface at the plasma core region. In configurations without any central low order rational surface, there are no indications of barrier formation within the available range of heating power.
- Different mechanisms, based on neoclassical/turbulent bifurcations and kinetic effects, are candidates for explaining the impact of magnetic topology on radial electric fields and confinement.

## Acknowledgment

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