

Article

The Pump-Out Effect as a Trigger for the Electron to Ion Root Transition in TJ-II

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Abstract

In this paper, we study electron to ion root confinement transitions triggered by Electron Cyclotron Resonant Heating switch-off when the line-averaged electron density is sufficiently high and while Neutral Beam Injection heating is on. We use a Heavy Ion Beam Probe system to document the transition in considerable detail. The transition occurs in two phases. An initial, fast phase is characterized by a rapid, global decay of the plasma potential and the concomitant establishment of an edge radial electric field shear layer. This phase is induced by the pump-out effect, as documented using simultaneous measurements of the evolution of the plasma potential at different radial locations. This initial, fast phase is followed by a slow phase during which the profiles adjust to the new edge and heating conditions via transport.

Keywords: fusion; stellarator; confinement transition; pump-out effect

1. Introduction

The electron to ion (e-i) root transition is an important phenomenon in stellarators. It is a transition to improved confinement that involves the establishment of a transport barrier, and therefore it is in the same category of transitions as the L–H (low to high confinement) transition and Internal Transport Barriers (ITBs) [1]. A related transition is also observed in the core region, called the Core Electron Root Confinement (CERC) phenomenon, observed in various stellarators [2].

In the TJ-II stellarator, the electron to ion root transition to enhanced confinement, reported initially in [3], has been studied extensively [4]. Recall that the distinction between electron and ion root depends on the sign of the radial electric field, E_r (positive and negative, respectively) [1]. This transition is characterized by several phenomena in TJ-II. It usually occurs when the rising line-averaged electron density crosses the critical value of $\bar{n}_{e,c} \simeq 0.6 \cdot 10^{19} \text{ m}^{-3}$ [5]. At the transition, turbulence amplitudes and the turbulence correlation time increase, whereas above the transition point, they decrease [6]. Moreover, long-range correlations between toroidally separated Langmuir probes increase at and above the transition point [7]. In addition, above the transition, the radial electric field, E_r , becomes negative at the plasma edge, a significant shearing rate in the poloidal velocity is established [8], and the edge density gradient increases [9]. The enhanced particle



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confinement is reflected in a sudden increase of $d\bar{n}_e/dt$, the growth rate of the line-averaged electron density.

Previous work at TJ-II has clarified that the e-i root transition can be achieved through various means, once the plasma is in an appropriate state. One possibility is by simply raising the line-averaged electron density above the critical value $\bar{n}_{e,c}$ using gas puff [3]. This transition can be forced also by applying a (negative) biasing voltage in the plasma edge [5,10,11]. The transition also occurs frequently at the end of the Electron Cyclotron Resonance Heating (ECRH) phase, when the density is sufficiently high: then the transition may occur after switching off or reducing microwave heating [12,13]. A common aspect of these external actions is that they tend to modify the plasma potential (making it more negative). Thus, the plasma potential profile is a key player in this transition.

The evolution of the potential profile at TJ-II as a function of $\bar{n}_e$ has been documented in some detail using a Heavy Ion Beam Probe (HIBP) [14]. The potential profile decreases gradually as the electron density increases, and near the critical density $\bar{n}_{e,c}$ it changes sign. Thus, the edge radial electric field E_r also tends to change sign when $\bar{n}_e$ crosses the critical value. However, one should remember that the transition is more complex than a mere sign change of E_r at the edge, namely, a ‘corrugation’ or shear of E_r in the edge region is important, as E_r shear may produce a transport barrier, changing the confinement quality.

In addition, there is a second parameter that modifies the global plasma potential, namely, the Electron Cyclotron Resonance Heating (ECRH) power. Namely, the plasma potential increases with ECRH power at constant $\bar{n}_e$ [15]. Consequently, as ECRH power is switched off, the overall plasma potential becomes more negative. When $\bar{n}_e$ is sufficiently high (i.e., near but still below $\bar{n}_{e,c}$), the plasma potential is positive and small, and the additional drop in potential induced by switching off ECRH may then push the plasma into the ion root state. This effect is regularly observed in TJ-II discharges [12]. This paper focuses on the transition caused by ECRH switch-off.

In view of the above, documenting the evolution of the plasma potential at the transition seems essential to reach a full understanding of this phenomenon. The Heavy Ion Beam Probe is a very relevant diagnostic for this purpose, as shown in other devices, e.g., the LHD stellarator [16] and the CHS stellarator [17]. TJ-II possesses a dual HIBP system [14] that allows tracking the time evolution of the plasma potential simultaneously at two radial locations, which can be placed upon demand at almost any radial location, as well as Langmuir probe systems in the plasma edge. To obtain insight into the potential evolution across the plasma volume, in the present study we will analyze similar e-i root transition events in a large set of experiments, with measurements made at different locations.

This article is organized as follows: Section 2 discusses the methods we have used. Section 3 presents experimental results. Section 4 provides an interpretation of the results. In Section 5 we draw some conclusions.

2. Methods

The experiments reported here are performed at the TJ-II stellarator [18], with toroidal magnetic field $B_T \simeq 1$ T, major radius $R_0 = 1.5$ m and minor radius $a < 0.22$ m.

2.1. Experiments

The magnetic configuration in vacuum that was used is the one labeled 100_44_64, often referred to as the ‘standard configuration’, which has a rotational transform of $\iota = \iota/2\pi \simeq 1.65$ at the Last Closed Flux Surface (LCFS). Typically, plasma currents are small in TJ-II.

Plasmas are initiated using two Electron Cyclotron Resonance Heating (ECRH) beam lines, operating at 53.2 GHz, delivering up to about 300 kW of power each. One or two

tangential Neutral Beam Injection (NBI) systems, operating in a co/counter configuration, then inject up to ~ 1 MW of through-put power at ≤ 32 keV into the TJ-II vessel for ≤ 120 ms. NBI heating is started before ECRH ends. A typical heating scenario is shown in Figure 1. ECRH is used to start the plasma and maintain it for about 80 ms, after which it is switched off. NBI heating starts about 20 ms prior to ECRH switch-off. When NBI is started, the line-averaged electron density from the interferometer, $\bar{n}_e$, starts to rise slightly due to the fueling implied by NBI. However, when ECRH is switched off, the rate of change $d\bar{n}_e/dt$ increases sharply, while the edge H_α signal drops, reflecting reduced edge outward particle transport. Together, this indicates improved particle confinement in spite of a reduction of heating power.

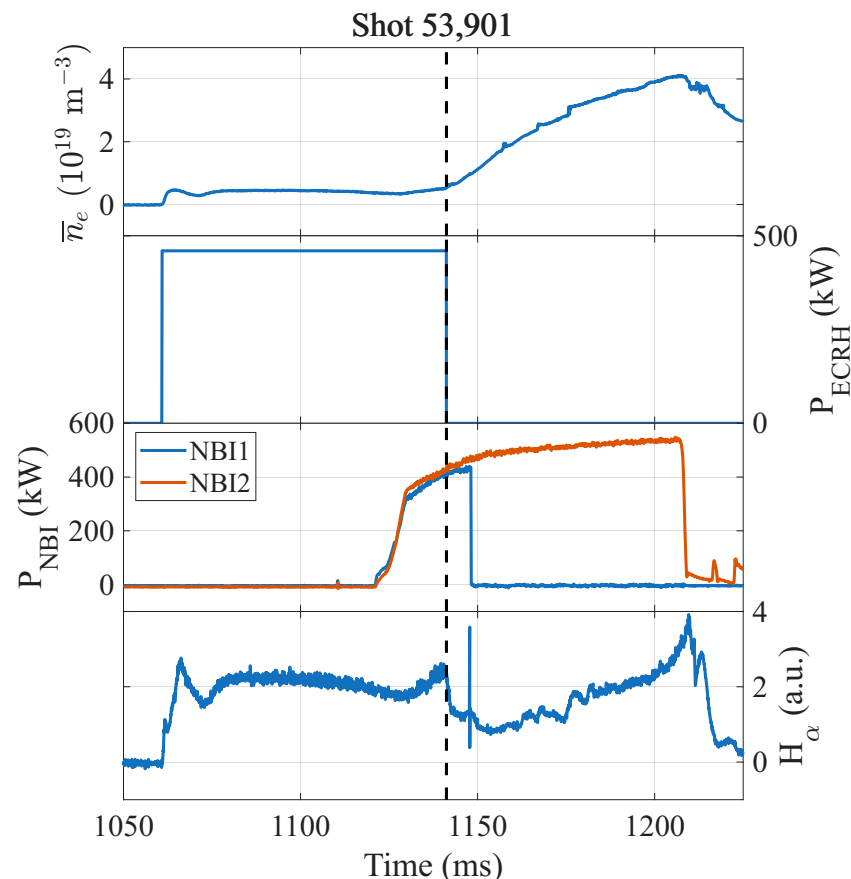


Figure 1. Typical heating scenario in TJ-II. Top to bottom: evolution of the line-averaged electron density, $\bar{n}_e$; nominal ECRH power; nominal power of the two NBI systems; and H_α emission from the Scrape-Off Layer. The time of ECRH switch-off is indicated by a vertical dashed line.

This paper will focus on the time period around the switching off of ECRH. When the line-averaged electron density, $\bar{n}_e$, is sufficiently high but still below the critical density $\bar{n}_{e,c}$, this action often produces an immediate transition from the electron to the ion root. This fact can be verified using the characteristic indicators mentioned in Section 1.

2.2. Diagnostics

In this work, we will make extensive use of the dual Heavy Ion Beam Probe (HIBP) system of TJ-II [14]. The HIBP operates by injecting a narrow, collimated beam of fast Cs^+ ions into the plasma. The ions may be ionized once more, yielding Cs^{++} ions that exit the plasma and are collected in an energy analyzer, providing information on the plasma potential and electron density. The intersection of the orbits of the incoming Cs^+ ions and the collected Cs^{++} ions defines an interaction or ‘sampling’ volume. The sampling

volume is either fixed or can be scanned through the plasma using beam deflection plates. The sampling volume has a resolution better than 1 cm, and the sampling rate is typically 1 MHz. Scans require between 5 to 20 ms to sweep all or part of the plasma diameter. The position of the sampling volume is expressed in terms of the normalized plasma radius $\rho = r/a$, such that $\rho < 0$ on the High Field Side (HFS), and $\rho > 0$ on the Low Field Side (LFS), by definition.

TJ-II also disposes of a dual set of reciprocating Langmuir probes [19]. Among other things, these probes allow for the measurement of the floating potential, V_f , and the ion saturation current, I_{sat} , in the plasma edge region, with high spatial and temporal resolution. The typical sampling rate is 1 MHz.

Another diagnostic of interest is the 12-channel Electron Cyclotron Emission (ECE) system that allows for the measurement of the local electron temperature T_e at up to 12 different radial positions along the midplane, with a radial resolution of about 1 cm [20]. The measurements are cross-calibrated with T_e profiles obtained by the Thomson Scattering diagnostic [21].

3. Experimental Results

Figure 2 shows some e-i transitions at the time of ECRH switch-off (marked by a vertical dashed line). The root transition is marked by the rapid drop of potential, Φ , and the subsequent increase in the growth rate of the line-averaged electron density, $d\bar{n}_e/dt$. H_α emissions from the Scrape-Off Layer (SOL) drop after the transition, reflecting a reduction of edge outward particle transport. The figure also shows the exponential drop of the electron temperature following ECRH switch-off, with a decay time of 1–2 ms. The initial change of slope dT_e/dt occurs simultaneously for all ECE channels, and concurs with the initial drop of the potential Φ . However, the subsequent exponential relaxation is longer for ECE channels located at larger normalized radius, ρ .

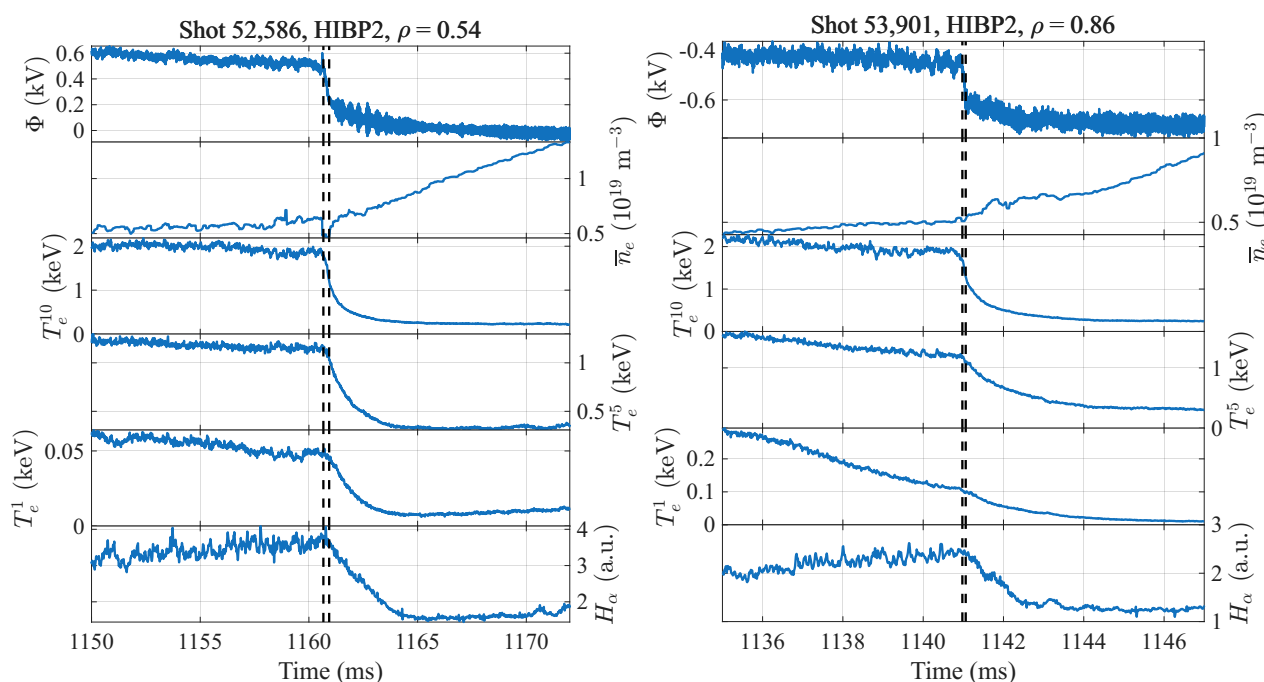


Figure 2. Root transition examples. Top to bottom: plasma potential, Φ , at the radial location indicated in the header; line-averaged electron density, $\bar{n}_e$; electron temperature, T_e^n for various channels ($\rho^{10} \simeq 0$, $\rho^5 \simeq 0.35$, $\rho^1 \simeq 0.75$), and edge H_α emission signal. In each panel, the left vertical dashed line indicates the time of ECRH switch-off (t_0); the right one corresponds to the end of the fast potential drop phase (t_1 , see text).

Figure 3 shows an example of an observation of the e-i root transition using the HIBP diagnostic while in scanning mode. The transition occurs at $t \simeq 1160$ ms and is seen as a sharp drop in the potential. Potential profiles $\Phi(\rho)$ are peaked in the center of the plasma in the ECRH heating phase. As noted in Section 1, the transition occurs when ECRH is switched off. After the transition, Φ profiles are globally negative. The increased electron density due to NBI heating results in a reduced secondary HIBP beam current due to beam attenuation and hence an increased noise level in the Φ signal. Nevertheless, the smoothed Φ signal still provides useful information. The figure also shows an estimate of the radial electric field, calculated as $E_r = -\frac{d\Phi}{dt} / (a \cdot \frac{d|\rho|}{dt})$, where a is the minor plasma radius. This approximation, based on the scanning motion of the sampling volume, is only valid for quasi-static $\Phi(\rho)$ profiles, hence is not valid at the transition where Φ is changing rapidly in time. The formation of a strong E_r shear layer at the plasma edge (near $\rho = 0.8$), after the transition, is clearly visible in the form of a narrow dip in E_r . Such a shear layer implies a zonal flow shear (due to the drift velocity $\vec{v} = \vec{E} \times \vec{B}$) that may lead to turbulence suppression and the formation of an edge transport barrier.

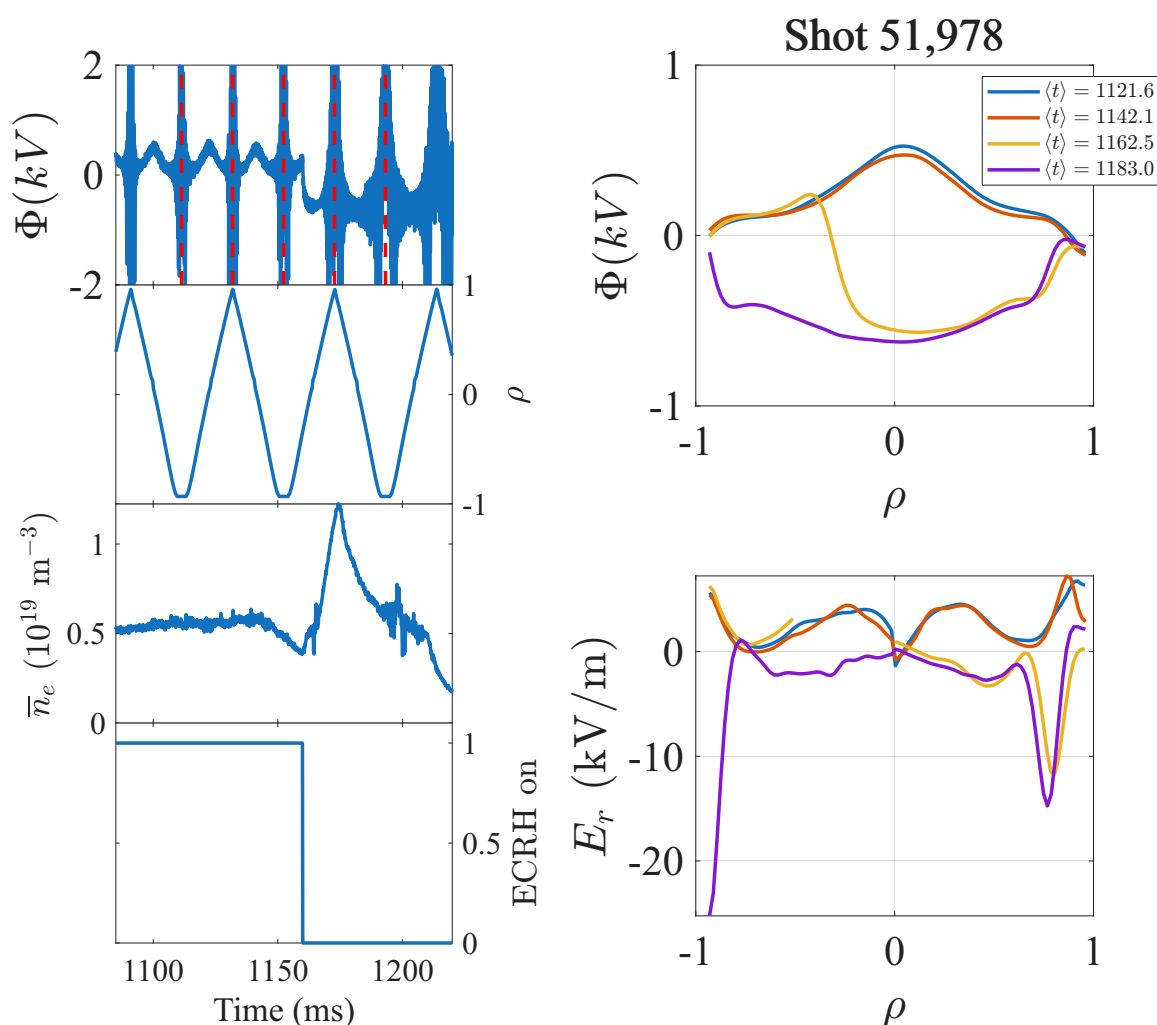


Figure 3. Left, top to bottom: measured potential $\Phi(t)$ (red dashed lines indicate the limites between radial scans); calculated normalized radius of the sampling volume, $\rho(t)$, which results from the scanning motion of the Cs^+ ion beam; line-averaged density; and ECRH on/off. Individual scans are delimited by vertical red dashed lines in the top left plot. Top right: smoothed $\Phi(\rho)$ profiles; the legend indicates the mean time of each radial scan. Bottom right: calculated radial electric field, E_r .

3.1. Transition Phases

Figure 4 shows an example of a measurement $\Phi(\rho(t), t)$ (abbreviated $\Phi(t)$) in a short time window around the time of the e- to i-root transition. The measurement location $\rho(t)$ is varying in time due to the scanning motion of the Cs^+ beam. The curve can be subdivided into three sections: an initial, roughly linear variation associated with the scanning movement of the sampling volume and reflecting the nearly unchanging potential profile $\Phi(\rho)$. Next, one observes a fast drop, on a sub-ms time scale. And finally, an exponential relaxation phase is observed, characterized by a longer time scale (of several ms).

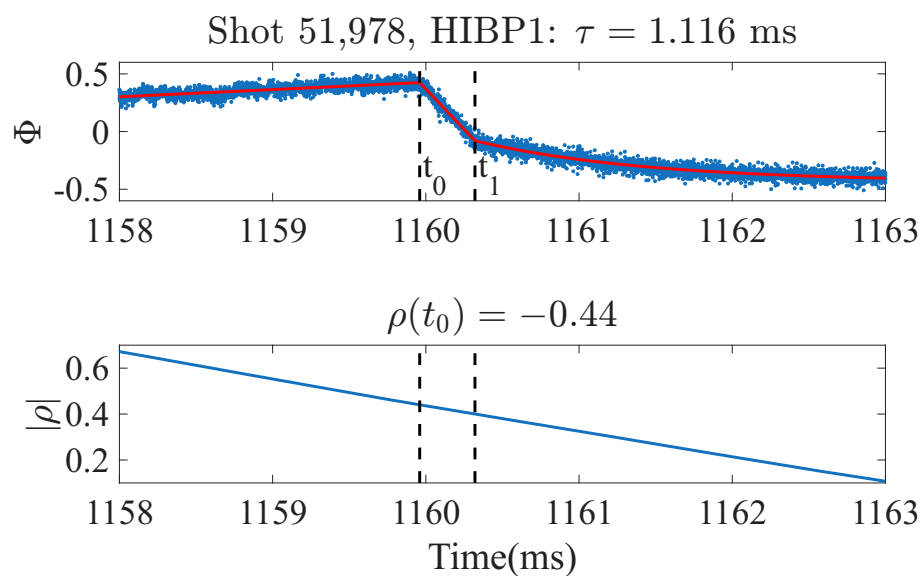


Figure 4. (Top): time trace for $\Phi(t)$ and fit. (Bottom): radial location of the sampling volume. Dashed vertical lines correspond to the times t_0 and t_1 (see text).

To quantify this behavior, we fit the following heuristic function to the trace data:

$$\Phi(t) = \begin{cases} \Phi(t_0) + B(t - t_0) & (t < t_0) \\ \Phi(t_0) + (\Phi(t_1) - \Phi(t_0))(t - t_0)/\Delta t & (t_0 \leq t < t_1) \\ \Phi(\infty) + (\Phi(t_1) - \Phi(\infty)) \exp\left(-\frac{t-t_1}{\tau}\right) & (t \geq t_1) \end{cases} \quad (1)$$

where $\Delta t = t_1 - t_0 > 0$. An example fit is shown in Figure 4. The fit is performed over a 4–5 ms long time window, roughly centered on the transition, as shown in the figure. From this fit one obtains: the transition time interval $[t_0, t_1]$ (vertical dashed lines), the potential at the start of the transition $\Phi(t_0)$, the potential at the end of the transition $\Phi(t_1)$, the duration of the transition Δt , the asymptotic potential for $t \rightarrow \infty$, $\Phi(\infty)$, and the exponential decay rate τ .

3.2. Dependence on ρ

We have performed the fit described in Section 3.1 on time traces corresponding to a database of 94 discharges. The line-averaged electron density at time t_0 is $\bar{n}_e(t_0) = (0.59 \pm 0.11) \cdot 10^{19} \text{ m}^{-3}$. We find that the drop in potential during the fast phase is correlated with the duration of this phase, see Figure 5 (left). While the duration of the fast phase does not vary across the plasma in any single shot (as will be shown in Section 3.3 below), the graph shows that the potential drop is larger in the core than at the edge. This occurs because the size of the potential drop is proportional to the ECRH power deposition profile (see Sections 3.3 and 4). Something similar occurs with the drop in potential during the second phase and the relaxation time, see Figure 5 (right); in this case, however, the

difference between the core ($|\rho| \leq 0.5$) and the edge ($|\rho| > 0.5$) is much more marked, as radial transport also plays a role in the relaxation of profiles.

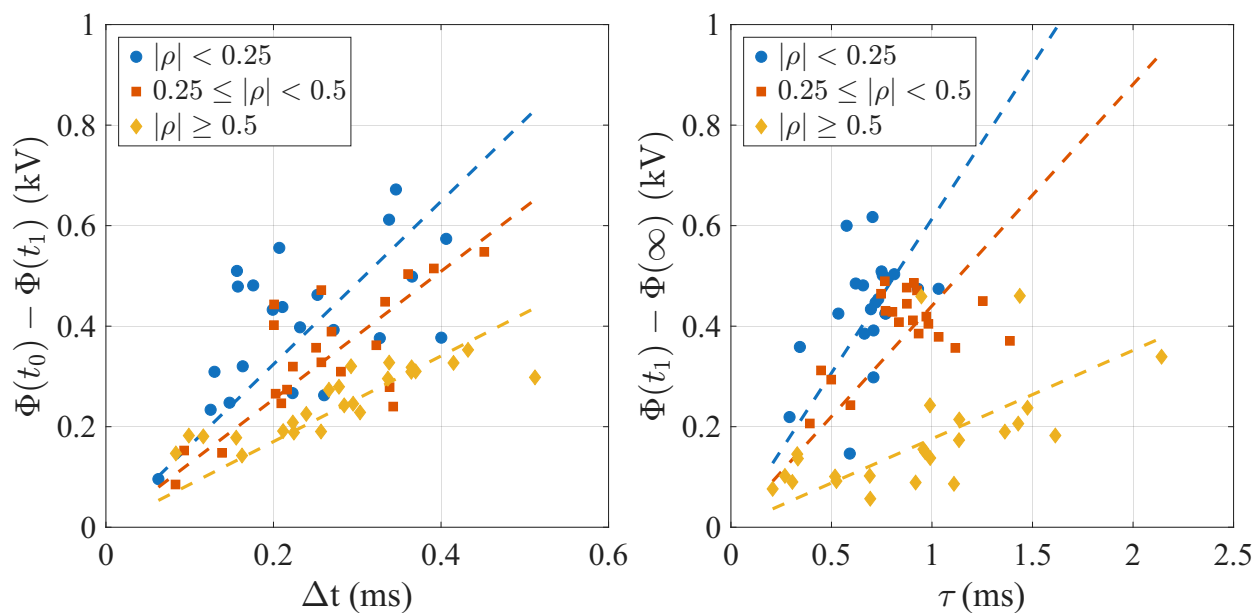


Figure 5. (Left): potential drop versus drop duration for the first, fast phase. (Right): potential drop versus relaxation time for the second phase. Dashed lines are linear fits to the corresponding points.

3.3. Fast Transition Simultaneity

Figure 6 shows potential measurements from the two HIBP systems. System 1 is scanning, and the e-i transition occurs when the sampling volume is in the deep plasma core. System 2 is not scanning and measures at the edge, at $\rho \simeq 0.82$. The fast potential drop associated with the e-i transition occurs simultaneously in the core and the edge. In order to determine the existence of a possible time delay, we have computed the cross correlation between $\Phi_1(t)$ and $\Phi_2(t)$ in a time interval of 3 ms around the time of the transition. From this analysis, the peak of the cross correlation was found to occur at $\Delta t = 0 \pm 1 \mu\text{s}$. The fast drop in the core (~ 0.5 kV) is bigger than the drop at the edge (~ 0.2 kV).

To evaluate how systematic these results are, results from the analysis of a set of nine discharges with e-i transitions following ECRH switch-off, for which measurements from both HIBP systems, are considered. The results are shown in Figure 7. The duration of the fast phase, Δt , as determined using the fit procedure described above, is similar for both HIBP systems (within about 0.05 ms), even when they are measuring at very different radial locations. However, the potential drop in the fast phase, $\Delta\Phi = \Phi(t_0) - \Phi(t_1)$, is clearly peaked in the core. This difference in potential drop according to radius is perhaps clearest for discharges 53,900 and 53,901, which have simultaneous measurements at the edge and in the core. The overall radial shape of the potential drop (indicated by a grey area) roughly matches the ECRH power deposition profile, $\Delta\Phi \propto P_{\text{ECRH}}$ (see [22] and Section 4).

Figure 8 shows examples of transitions in which we have measurements from both HIBP and Langmuir probes. The floating potential change at the edge during the transition is fully synchronized with the fast plasma potential Φ change in the core: so again, the initial fast transition occurs simultaneously in the core and at the edge. Again, the change in slope $d\bar{n}_e/dt$ clearly illustrates the particle confinement enhancement occurring at the transition, as does the change in slope of the HIBP beam current, dI_{tot}/dt (recall that I_{tot} is proportional to the local electron density). These observations extend the preceding results to radial positions very close to the Last Closed Flux Surface, namely, $\rho \simeq 0.94$.

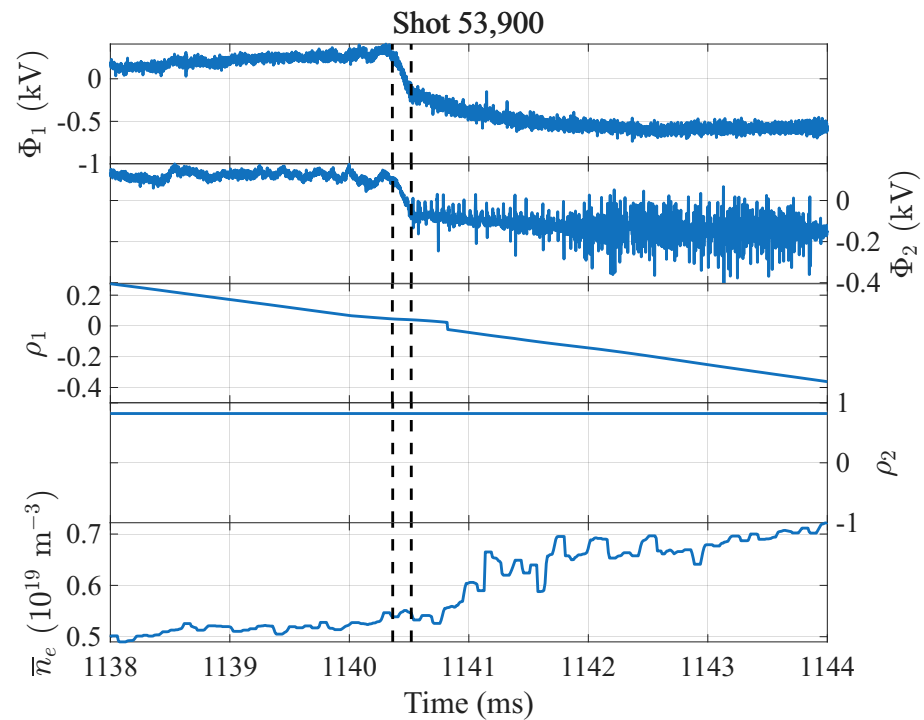


Figure 6. Comparison of potential Φ measured by the 2 HIBP systems, discharge 53,900. Top to bottom: Φ from HIBP 1; Φ from HIBP 2; ρ for HIBP 1 (scanning); ρ for HIBP 2 (fixed at $\rho = 0.82$); and line-averaged electron density. The times t_0 and t_1 are indicated with vertical dashed lines. A similar case is discharge 53,901.

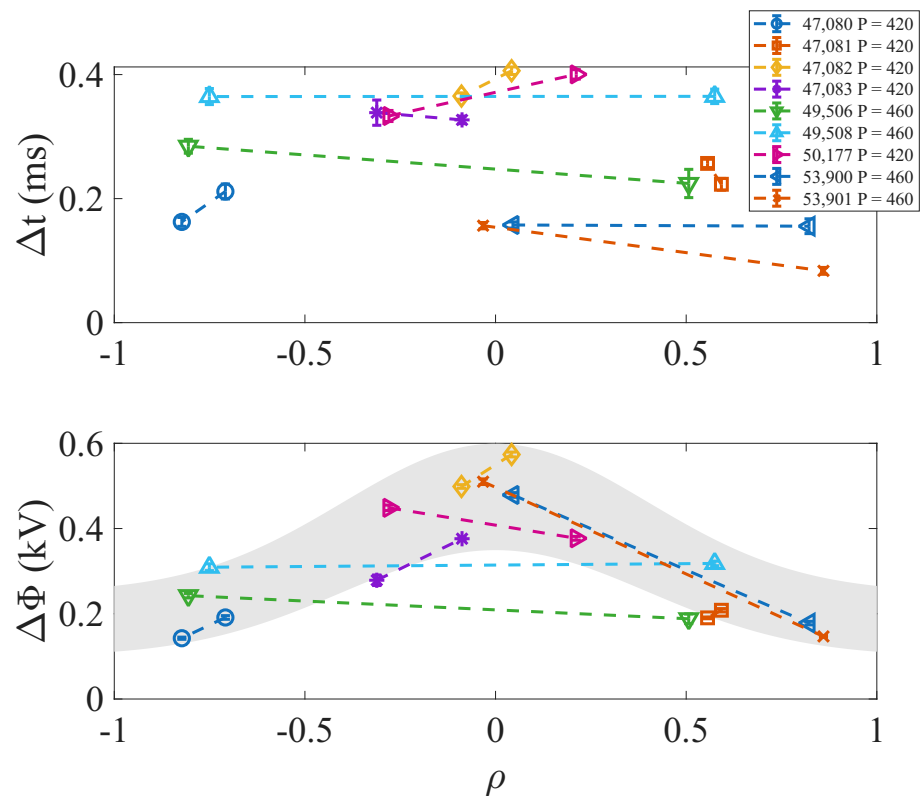


Figure 7. Duration of the fast phase, Δt , and potential drops $\Delta \Phi = \Phi(t_0) - \Phi(t_1)$, detected by the dual HIBP system measuring simultaneously at different radial locations; the two simultaneous measurements are connected by dashed lines. Error bars returned by the fit procedure are shown. The nominal heating power, P_{ECRH} (kW), is indicated in the legend. The grey area is explained in the text.

In all cases, the perfect synchronization of the transition is confirmed (to 1 μs accuracy). One can therefore conclude that the fast potential drop occurs simultaneously across the plasma.

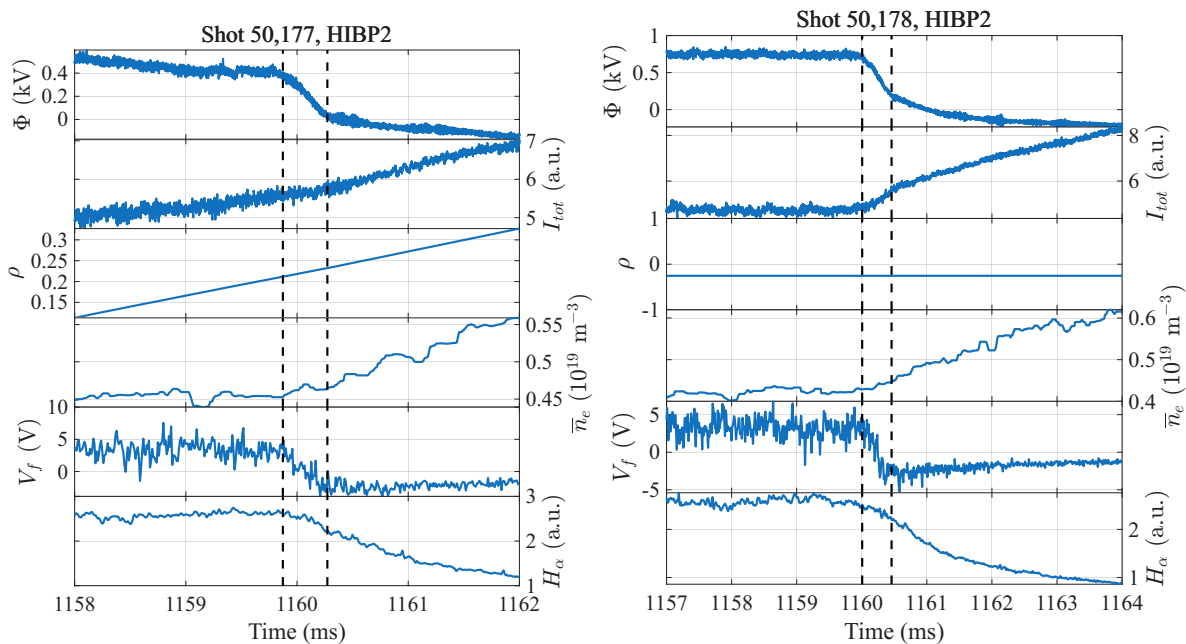


Figure 8. Top to bottom: plasma potential, Φ , in the core; HIBP secondary beam current I_{tot} ; normalized radius of the sampling volume, ρ , line-averaged electron density $\bar{n}_e$; floating potential from the Langmuir probe, V_f , at the edge; and H_α emission from the Scrape-Off Layer. The position of the Langmuir probe is $\rho = 0.94$. Left: discharge 50,177, HIBP scanning; right: discharge 50,178, HIBP not scanning ($|\rho| \simeq 0.25$). Vertical dashed lines indicate the times t_0 and t_1 .

3.4. Density Response

An important issue is how the local electron density (rather than the line-averaged density) responds to the transition. This quantity should reflect the change in particle confinement. The HIBP does not measure the density directly, but the secondary (Cs^{2+}) beam current, I_{tot} , is proportional to the local electron density at the sampling volume, as well as a non-local beam attenuation factor that is expected to vary only slowly [23].

Figure 8 shows the response of I_{tot} to the transition in an experiment with a fixed position of the sampling volume, for discharge 50,178. Prior to the transition, both Φ and I_{tot} are constant. During the fast phase, the Φ drops at a nearly constant rate, while I_{tot} increases. This is due to the local inverse proportionality of Φ and n_e and is not a transport effect. Immediately after the fast phase, I_{tot} increases at a (different) constant rate. This is a transport effect, indicating enhanced confinement. There is no discernible delay between the end of the fast phase and the start of the density rise.

4. Discussion

In this work, we study the electron to ion root transition triggered by the switching off of ECRH heating in some detail at TJ-II. We find that the transition occurs in two phases.

4.1. Fast Transition Phase

This phase is short, occurring on a sub-ms time scale ($\Delta t \simeq 0.1 - 0.5$ ms). In this time, one observes a sharp drop in the potential, $\Delta\Phi_{01} = \Phi(t_0) - \Phi(t_1)$, of the order of 0.3–0.4 kV. The rate of change is $\Delta\Phi_{01}/\Delta t \simeq 1.25$ kV/ms, but it varies with radius (cf. Figure 5).

Comparing simultaneous measurements made at different radial positions, we find that the time lag between the observed fast drop at different locations is $\lesssim 1$ μs , i.e., si-

multaneous within measurement precision, implying that the occurrence of this drop is essentially global. The size of this drop is peaked in the core and does not decrease to zero for $\rho \rightarrow 1$, such that it is roughly proportional to the ECRH power deposition profile [22].

In a previous related study at the LHD stellarator, a similar result for the temporal evolution was obtained in an ECRH switch-on experiment, combined with HIBP measurements of the potential, see Figure 7 of [24]. The cited work interprets the initial, fast phase in terms of direct electron losses or ‘pump-out’ due to electron energy gain from the microwave radiation. In our case, the fast phase we observe is similarly understood to be due to ‘pump-out’, or rather the sudden disappearance of ‘pump-out’ due to the switching off of ECRH, leading to a positive variation of electron density and a negative variation of plasma potential Φ [5,25]. This effect is seen clearly in Figure 8. The ‘pump-out’ hypothesis explains both the short time scale and the fact that it occurs globally (simultaneously over the whole ECRH power deposition region, and in proportion to the power deposition profile). The authors are not aware of any other mechanism to explain both the observed global simultaneity of the potential drop, and the approximate proportionality of the size of the drop to the ECRH power deposition profile.

The potential profile at the end of the fast transition phase, $\Phi(\rho, t_1)$, only exists fleetingly and therefore is difficult to measure directly, in the absence of multiple simultaneous local measurements. A crucial question to understand the mechanism of the formation of the edge transport barrier is whether it is already established at the end of the fast phase. It should be noted that the local electron density response, shown in Figure 8 (especially discharge 50,178), indicates that the rate of increase of $\bar{n}_e$, $d\bar{n}_e/dt$, increases immediately after the end of the fast phase. The immediate decay of the edge H_α emissions following the transition (cf. Figure 2) signals a rapid reduction of outward particle transport in the plasma edge. Thus, it seems likely that a ‘seed’ for a transport barrier is established during the fast phase, which is then reinforced during the second, slower and transport-dominated phase. An actual transport barrier can of course only be established over times of the order of the transport time scales.

4.2. Slow Relaxation Phase

This initial rapid drop is followed by a slow exponential relaxation phase, with a typical time scale of $\tau \simeq 1$ ms (i.e., the transport time scale). Figure 6 shows that the drop in Φ is larger in the core ($\Delta\Phi \simeq 0.5$ kV) than at the edge ($\Delta\Phi \simeq 0.2$ kV). As the plasma is no longer heated in the core by ECRH, the temperature profile flattens, so that the initially peaked electron temperature profile drops more in the core than at the edge. This also means that the potential Φ must drop more in the core than the edge, which is in accordance with observations.

4.3. Interpretation in Terms of the Pump-Out Effect

ECR heating causes an increase of the perpendicular velocity of electrons through microwave absorption. This may cause some electrons to enter the so-called ‘loss cone’ in momentum space, after which they escape the plasma on a very short timescale [25]. In order to model the evolution of the electron density n_e in an ECR heated plasma, including the pump-out effect, consider the continuity equation for electrons:

$$\frac{\partial n_e}{\partial t} + \nabla \cdot \Gamma_e = S_{\text{ion}} - L_{\text{rec}} - L_{\text{pump}},$$

where Γ_e is the radial electron flux, while S_{ion} and L_{rec} are the ionization source and recombination loss, respectively. Ionization is important mostly in the plasma edge region, due to its proportionality to the neutral density, n_0 . Likewise, recombination also occurs

predominantly in the edge region, where the electron temperature, T_e , is relatively low. Of main interest here is the pump-out term, L_{pump} , associated with the radial flux of ripple-trapped suprathermal electrons [26], which can be written as

$$L_{\text{pump}} = \frac{n_e}{\tau_{\text{pump}}},$$

where τ_{pump} is the pumping rate, which is assumed to depend only on P_{ECRH} (more power implying smaller τ_{pump}). This equation expresses that the number of electrons lost is proportional to the number of bulk electrons present.

On a fast timescale (less than the confinement time), a change in P_{ECRH} , implying a change in L_{pump} , will induce a corresponding change in $\partial n_e / \partial t$, and this change would be proportional to the local power deposition dP_{ECRH} / dV . This idea is consistent with the reported observations. On a longer timescale, the profiles will evolve to a new equilibrium state, as a change in P_{ECRH} will change the (diffusive) transport properties [24]; this longer timescale should therefore be of the order of the transport timescale or the (particle) confinement time, again consistent with the observations.

The described evolution of the potential profile is sketched in Figure 9. The pre-transition Φ -profile (at $t = t_0$) is peaked, related to the peaked T_e profile associated with core ECR heating, and the plasma is in the electron root state. The Φ -profile after the fast phase (at $t = t_1$) is reduced in proportion to the ECRH power deposition profile, as suggested above, except near the very edge, where the boundary condition $\Phi(\rho = 1) = 0$ is imposed. Due to this, the Φ profile has a ‘wiggle’ in the edge region, which constitutes the seed of a negative edge radial electric field layer. The final Φ -profile is negative over most of the plasma radius, so that the plasma is in the ion root state, and a strong negative radial electric field layer exists at the plasma edge.

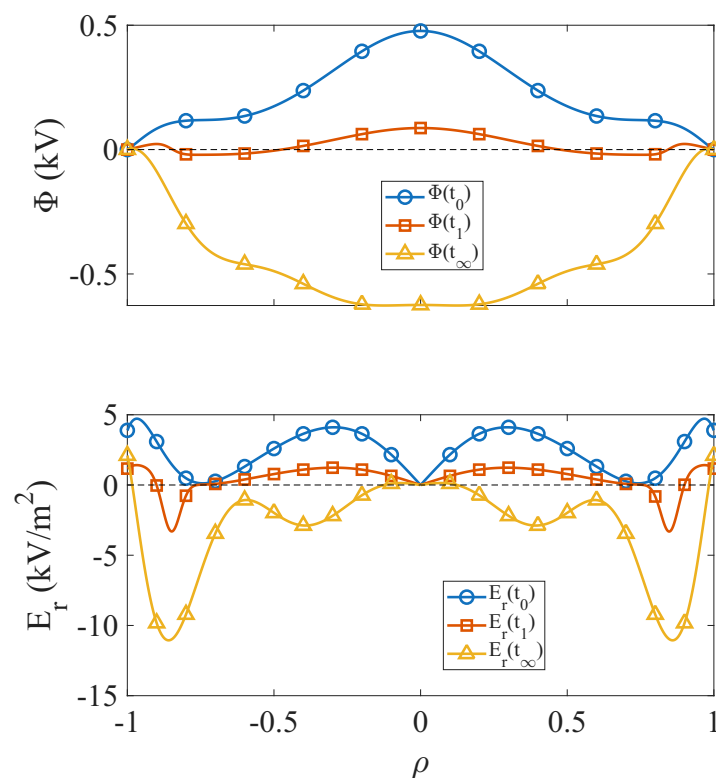


Figure 9. Hypothetical evolution of the plasma potential profile. The profiles at t_0 and t_∞ are closely similar to those of Figure 3. The profile at t_1 is hypothetical.

5. Conclusions

The experimental results clearly show that the e-i transition triggered by ECRH switch-off occurs in two phases. The initial phase is short ($\Delta t \simeq 0.1 - 0.5$ ms) and occurs simultaneously across the whole plasma volume, with any delays being less than the detection threshold of 1 μ s. This study documents this simultaneity for the first time using multiple diagnostic systems measuring the local plasma potential. During this phase, the plasma potential drops roughly in proportion to the ECRH power deposition profile. The most likely explanation for these observations is a sharp reduction of ‘pump-out’ due to ECRH switch-off.

This sharp, fast drop of potential may create a seed edge radial electric field shear layer or transport barrier in the plasma edge region, which may explain why the rate of change of the local and line-averaged densities increases immediately after the fast phase. The remainder of the second phase is a relaxation, on a time scale of 1 ms, toward a new confinement state in which a fully formed edge transport barrier is present. This relaxation involves the modification of profiles due to transport effects.

Consequently, it appears that the formation of the edge radial electric field shear layer induced by the pump-out mechanism following ECRH switch-off initiates the e-i transition in this scenario. This would conveniently explain why the e-i transition often occurs immediately following ECRH switch-off in TJ-II.

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