Inductive Current Density Perturbations to Probe Electron Internal Transport Barriers in Tokamaks

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Improved electron energy confinement in tokamak plasmas, related to internal transport barriers, has been linked to nonmonotonic current density profiles. This is difficult to prove experimentally since usually the current profiles evolve continuously and current injection generally requires significant input power. New experiments are presented, in which the inductive current is used to generate positive and negative current density perturbations in the plasma center, with negligible input power. These results demonstrate unambiguously for the first time that the electron confinement can be modified significantly solely by perturbing the current density profile.

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Improving the energy confinement time in scenarios compatible with steady-state operation is one of the main goals of present tokamak research. Electron internal transport barriers (EITB) are characterized by an improved core thermal electron energy confinement and are bounded by large electron temperature gradients, stronger than obtained in the usual low (L-) and high (H-) confinement scenarios. This significant steepening of the temperature gradient is related to a local reduction of turbulence [1] and therefore of the electron heat diffusivity. EITBs have been observed in many tokamaks [1,2] and have been obtained in most cases with a fast ramp-up of the inductive current in order to create a flat or nonmonotonic current density profile. The latter is then sustained mainly by the self-generated bootstrap current [3] and also by auxiliary current drive sources such as electron cyclotron current drive (ECCD), lower-hybrid waves, or neutral beams. In some cases it is argued that negative magnetic shear, resulting from a nonmonotonic current profile, is required to obtain the improved electron confinement, while in other cases momentum input and rotational shear are believed to be the primary cause [2]. Even in the first case, it is not yet clear whether the improved electron confinement in the core is due to the existence of a radial position with zero magnetic shear, to the proximity of the minimum value of the safety factor, $q_{\min}$, to a rational value, or to the magnetic shear being negative inside $\rho(q_{\min})$.

In order to answer some of these key questions, we present a new experimental technique, which is used to provide direct experimental insight into the physics of electron internal transport barriers. In usual tokamak operation, including common EITBs scenarios, the plasma current is dominated by an inductive component, generated by a time-varying current in the primary Ohmic transformer coils. By contrast, recent TCV (Tokamak à Configuration Variable) experiments have built on well-established fully noninductive scenarios [4]. The possibility of generating EITBs without inductive current has been demonstrated. In these experiments, the current density profile was sustained solely with ECCD and bootstrap current [5]. Up to now, the current profile had been modified by changing the poloidal location and the toroidal angle of the microwave launchers. Early experiments had demonstrated that by adding counter-current drive in the center, the electron energy confinement time was improved [6,7]. However, in these experiments, the ECCD beams also provided the main heating source in the center. Therefore it was not possible to discriminate, beyond any doubts, the effects of changing the current profile, the pressure profile, the power deposition profile, and even the rotation profile. To achieve this, we had to design a new set of experiments.

In these new experiments, we take advantage of two important characteristics of TCV EITB scenarios: (a) the gyrotron pulse length (2 s) is long compared to the current redistribution time, $\tau_{\mathrm{crt}} \sim 0.15$–$0.25$ s; (b) the plasma current is fully sustained by noninductive currents: ECCD and bootstrap. Thus the inductive current can now be used as an auxiliary source by inducing either a positive or a negative parallel electric field depending on the sign of the surface loop voltage, i.e., on the sign of the time derivative of the current in the primary "Ohmic transformer" circuit. To induce such a current, the feedback on the Ohmic transformer current has been modified to allow for a given waveform, typically of zero or finite constant slope. This is a "new" current source in the sense that it is used in a novel way for probing and modifying the current density profile, and presents three main advantages: (i) The current generation is very efficient and therefore inductive current can be driven essentially with no input power, a few kW compared to the main heating source of about 1.5 MW. (ii) The physics of this inductive current is well known and its radial profile (j_{ind}), once in steady state, is given by the neoclassical conductivity which is readily evaluated from the electron temperature profile and equilibrium quantities [8]. (iii) The amplitude of j_{ind} is linearly dependent on the applied loop voltage (V_{loop}), which can be finely tuned to as low a value as $V_{loop} \approx \pm 10$ mV, in order to induce a small local perturbation.

The first property in particular offers the uncommon opportunity of fine tuning a single physical parameter, i.e., the current profile, with minimal perturbation to the other main plasma parameters. By allowing one to test the evolution of the electron confinement time and of the EITBs with only a current perturbation at constant input power, this technique yields key new insights into the physics mechanisms at play in EITBs.

This new method of modifying the current density profile has two main potential limitations: (a) the current penetrates relatively slowly inside the plasma, in about 2–3τ_{crt}; (b) the spatial distribution of the perturbation cannot be controlled since it is essentially proportional to $T_e(\rho)^{3/2}$ and thus peaks on axis. The first point causes no difficulties on TCV since $\tau_{crt} \sim 0.2$ s and the gyrotron pulse length, during which the current is fully noninductively sustained, is 2 s. The second point is actually beneficial for probing EITBs, as the aim is precisely to perturb the current density on axis, j_0, and to reduce or increase the reverse shear with positive or negative $j_{0,ind}$, respectively.

We show in Fig. 1 the typical EITB scenarios used to study the effect of current perturbation on EITB performances. First an Ohmic L-mode plasma is formed with a small plasma current. Once a stationary phase is reached, two co-CD off-axis beams, of 0.45 MW each, are launched at 0.4 s [beams A in Fig. 1(e)]. At about the same time, the feedback control of the plasma current is switched to impose a constant current in the Ohmic transformer [Fig. 1(b)]. Typically at 0.6 s the barrier is formed and

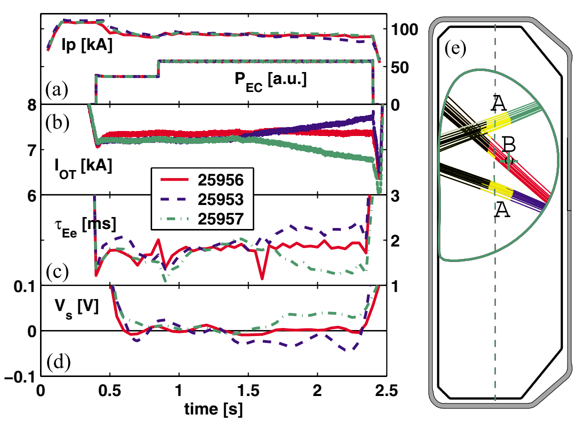

FIG. 1 (color online). Time traces of the (a) plasma current and EC power, (b) Ohmic transformer current, (c) electron thermal confinement time, and (d) loop voltage for typical scenarios. We show cases with no perturbation at 1.4 s (#25 956), +30 mV (#25 957), and −30 mV (#25 953). (e) TCV poloidal cross section with the plasma boundary and the rays representing the gyrotrons beams. The beams A drive co-CD off axis, while B is in the poloidal plane, ECH on axis.

we add a central beam, at 0.8 s, to heat inside the good confinement region to enhance the EITB as seen in Fig. 2 from the electron pressure profile p_e averaged over the period [1.1 s, 1.4 s] (star symbols). The p_e profile just before the central heating is turned on is also shown (circles). This target plasma is purposely not the best performance scenario in order to leave an operational margin to observe either an increase or a decrease of the central confinement properties. Then, at 1.4 s, we change the waveform of the current in the Ohmic transformer to impose a constant small positive or negative slope [I_{OT}, Fig. 1(b)]. The slope is about 15–30 times smaller than in the Ohmic L-mode phase. We have performed a shot-to-shot scan of the slope such as to vary V_{loop} from about −90 mV to +60 mV [9]. Two examples are shown in Fig. 1 with +30 mV (#25 957) and −30 mV (#25 953), demonstrating that the electron energy confinement time is significantly modified even though only less than 3 kW of Ohmic power is used in a discharge which is heated with 1.35 MW of EC power. The case #25 956 is the reference case with no perturbation, $V_{loop} \equiv 0$, and therefore has the same T_e profile for $t > 1.4$ s as the star symbols shown in Fig. 2. After 0.2–0.4 s, most of the inductive current has penetrated and we show p_e profiles averaged in the latter steady-state phase [1.9 s, 2.35 s] for the two cases with +30 mV (triangles) and −30 mV (squares). The barrier is clearly reduced for shot #25 957 which has a $j_{0,ind} > 0$ perturbation and increased in the opposite case, #25 953. Remarkably, the confinement is so degraded in #25 957 that the central temperature is close to the value at [0.6 s, 0.8 s] (circles in Fig. 2). Thus the effect of this current source with negligible input power is almost as significant as removing 0.45 MW of central heating, since it can annihilate its effect. This also shows that the requirements for sustaining EITBs are not related to a question of power threshold but effectively of current profile.

As mentioned above, a fine scan of V_{loop} perturbations has been produced in order to test also if any significant nonlinearities or discontinuities (e.g., bifurcation effects) could be observed. In Fig. 3 we show discharges with

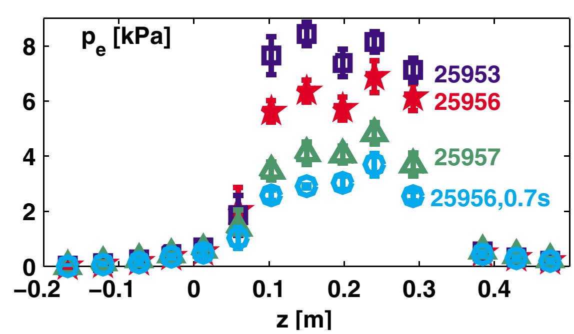

FIG. 2 (color online). Pressure profile before any perturbation, averaged on [1 s, 1.4 s] (star symbols), with +30 mV, [1.8 s, 2.4 s] #25 957 (triangles), −30 mV, [1.8 s, 2.4 s] #25 953 (squares). The profile before the central heating beam is added is also shown [0.6 s, 0.8 s] (circles).

dI_{OH}/dt varying between -1 kA/s and $+1$ kA/s in steps of 0.5 kA/s. This corresponds to V_{loop} varying between +60 mV (#25 958) and −60 mV (#25 952) in steps of about 30 mV, respectively. Figure 3(a) shows that H_{IT98L}, τ_{Ee} normalized to the ITER-98 L-mode scaling [10], varies steadily following the current perturbations. The lowest values are obtained with the maximum current on axis, leading to a monotonic q profile as discussed below, and the best performance with the largest negative current perturbation on axis, yielding a significant reverse shear q profile. An additional case not shown here with −90 mV, #25 954, leads to such an improved confinement and steep gradients that it becomes MHD unstable to the $n = 1$ ideal mode and disrupts [9]. On the other hand, the cases with $j_{0,ind} > 0$, leading to monotonic q profiles, yield similar pressure profiles in steady state, confirming that in fact the improved confinement is removed.

The pressure profiles, Fig. 3(b), show that only the strength of the barrier is modified, that is, the maximum gradient around $z = 0.08$ and 0.35. The position of the barrier [$\rho_V \approx 0.4$, where $\rho_V = \sqrt{(V/V_a)}$] is not modified but the degree of confinement improvement clearly varies. This is consistent with a change in the confinement properties occurring either everywhere inside $\rho_V = 0.4$ or only in the region [0.35, 0.4]. One cannot discriminate between these two hypotheses because the central beam deposition profile was not sufficiently central and the profiles are expected to be flat inside $\rho_V \approx 0.3$ in either case [11].

In order to compare the results with the expected modification of the current profile and to check that the observed time scales for the EITB evolution are consistent with an external current perturbation, we have performed transport

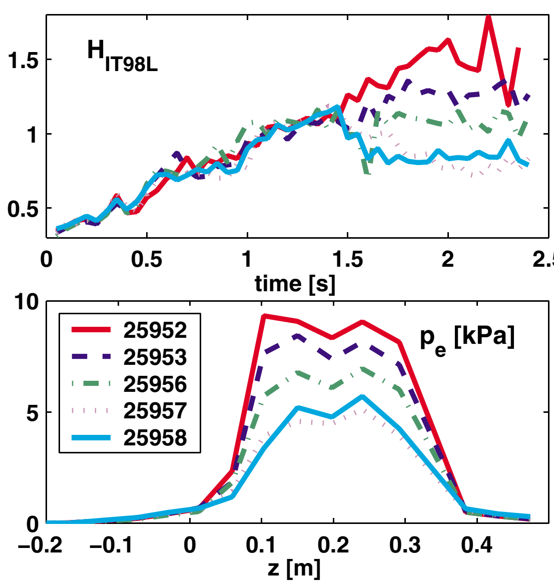

FIG. 3 (color online). (a) $H_{IT98L} = \tau_{Ee}/\tau_{IT98L}$ for a series of discharges with different constant slopes in the Ohmic transformer current imposed at 1.4 s. (b) Electron pressure profiles for the discharges shown in (a) averaged over the time interval [1.8 s, 2.4 s].

simulations with the code ASTRA [12], which calculates the self-consistent evolution of the current profile with density and temperature profiles and 2D equilibrium modifications. We start from the experimental conditions at 1.4 s, which are the same for all discharges, with the electron heat diffusivity and bootstrap current density profiles obtained from experimental measurements, and the driven current from Fokker-Planck CQL3D simulations [13]. The conditions are such that $V_{loop} = 0$ across the minor radius [9]. Then we impose $V_{loop}(\rho_V = 1) = +30$ mV or −30 mV to obtain the correct current density profile time evolution assuming constant transport properties and EC power input. The initial q profile, corresponding to #25 956, is shown in Fig. 4 (solid line) along with the profiles obtained with +30 mV and −30 mV inductive current perturbation. The initial q profile is slightly reversed with $q_{min} = 1.7$ and $q_0 = 2.0$. With positive $j_{0,ind}$, the q profile becomes flat ($q_0 = q_{min} = 1.3$), while it is clearly reversed with a negative inductive current perturbation ($q_0 = 4$, $q_{min} = 2.3$) [14]. With the larger V_{loop} perturbations, these modifications are of course enhanced. Therefore the scan shown in Fig. 3 spans q profiles from very reversed to monotonic, and a continuous, albeit rapid, change in the confinement properties is observed experimentally. Linear gyrokinetic calculations have confirmed that these discharges are dominated by trapped electron modes and that the growth rates of these modes are significantly reduced with an increasingly reverse shear q profile [15]. In the interpretative ASTRA simulations, the effective charge profile Z_{eff} is assumed constant. SXR tomography suggests in fact that Z_{eff} is typically hollow, which would tend to further favor Ohmic current penetration and peaking, but the uncertainties in the reconstruction are too great for a quantitative assessment. It should also be mentioned that there is no indication from the various scans that a rational q_{min} value is necessary for the EITB, since the q_{min} value does evolve significantly, as indicated by Fig. 4(a), while the barrier location hardly moves. However, more experiments varying the number of co-

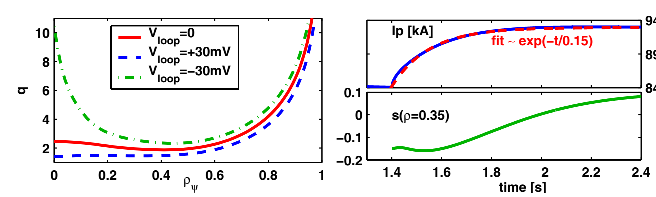

FIG. 4 (color online). (a) q profile corresponding to the case #25 956, solid line, as calculated with ASTRA using only experimental inputs for profiles, P_{EC}, j_{cd}, and χ_e. The q profiles obtained by imposing $V_{loop} = +30$ mV (dashed line, #25 957) and −30 mV are also shown (dash-dotted line, #25 953). (b) Time evolution of I_p and magnetic shear near q_{min} when a $V_{loop} = +30$ mV perturbation is imposed at $t = 1.4$ s, as calculated with ASTRA and corresponding to the evolution from the solid line shown in (a), #25 956, to the dashed line, #25 957. $I_p(t)$ can be fitted with $\exp(-t/0.15)$ yielding $\tau_{crt} = 0.15$ s.

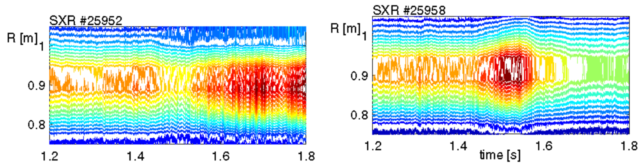

FIG. 5 (color online). Contour of the soft x-ray signals for the cases with +60 mV (#25 958) and −60 mV (#25 952) perturbations. In the first case, the barrier improves when the positive inductive current enhances the nonmonotonic j profile and then it degrades the barrier when the central j_0 increases. The opposite happens with a negative current induced from the plasma edge, #25 952.

CD beams in particular are required to assess this question. It also cannot be excluded that a rational q_{min} is necessary for the EITB formation but not for its subsequent persistence. Note that the $s = 0$ position does not move significantly, but it cannot be the only key to EITBs since the ITB can be improved by forming a more reversed q profile [solid and dash-dotted lines in Fig. 4(a)]. The time evolution of the total plasma current is shown in Fig. 4(b) for the +30 mV case, and it defines the characteristic current redistribution time to be about $\tau_{\mathrm{crt}} = 0.15$ s with $T_{e0} \approx 5$ keV and to scale essentially as $T_{e0}^{3/2}$ [14]. The time evolution of the magnetic shear just inside q_{min} is also shown. After 2–3 τ_{crt} most of the current has penetrated and the q profile is essentially in steady state. This is consistent with the main modifications of the EITB which occur between 1.5 s and 1.8 s (Fig. 3) that is 0.1–0.3 s after the change in the slope of the Ohmic transformer current at 1.4 s.

In the first 0.2 s, ASTRA predicts a transiently opposite change in the central shear, as seen in Fig. 4(b): as the positive V_{loop} perturbation propagates inward from the edge, the central shear becomes momentarily more negative before evolving towards positive values. The opposite behavior is seen with negative V_{loop}. To observe this subtle transient effect, we need a slightly larger perturbation. In Fig. 5 we show the contour plot of the time evolution of the soft x ray just after applying a positive (#25 958, +60 mV) and a negative (#25 952, −60 mV) loop voltage. As shown earlier, the first case leads to confinement degradation and the second to a further increase in barrier strength. Figure 5 shows that first the opposite is observed, the barrier initially improves between 1.5 s and 1.6 s in the case #25 958, and then degrades, and vice versa for the −60 mV perturbation. Therefore the experimental results are consistent not only with the asymptotic but also with the transient time evolution of the q profile obtained in the simulations.

In conclusion, we have shown that electron internal transport barriers can be significantly modified by only modifying the current profile at constant input power and without momentum input. The imposed current perturbation is known to be peaked on axis since it is induced by a finite loop voltage and the duration of the perturbation is much longer, about 1 s, than the current penetration time of about 0.15 s. Introducing either a positive or a negative current density on axis can either remove the barrier or double the electron confinement time. Moreover, we have observed a continuous modification of the electron confinement with the change in the q profile through a shot-to-shot scan in edge perturbations. A finer scan is required to assess how rapidly local transport properties are modified with small changes in the perturbations, and periodic perturbations will also be used to further study these effects. Recent studies have shown that the barrier formation around 0.6 s is fast—less than 1 ms [16]. The simulation of the current evolution due to the current perturbations imposed experimentally clearly shows that the time scales and positions of maximum change in confinement and magnetic shear are consistent with electron transport depending principally on the local current profile.

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