Long lasting ITB in FTU

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Abstract – Steady electron Internal Transport Barriers (ITBs) are obtained in FTU by the combined injection of Lower Hybrid (LH) up to 1.9 MW, and Electron Cyclotron (EC) up to 1.2 MW, radio frequency waves. ITBs occur during either the current plateau or the ramp up phase, up to peak densities $n_{e0}>1.4\cdot10^{20}$ m^{-3}, relevant to ITER operation, with central electron temperatures $T_{e0}>5.5$ keV are sustained for as long as the heating pulse (>35 confinement times). At $n_{e0}\approx0.8\cdot10^{20}$ m^{-3} T_{e0} can be larger than 11 keV. The ITB extends over an internal region with an almost flat or slightly reversed q profile and $q_{min}\approx1.3$, resembling that of the hybrid regimes, that is fully sustained by off-axis LHCD. This causes also a pretty good alignment of the bootstrap current generated by the ITB large pressure gradients with the externally driven current. Despite the longest ITB is about one ohmic current relaxation time, steadiness is attained much earlier, on times of the order of the energy confinement and of the electron fast tail generation and no evolution is observed thereon. Reflectometry shows a clear change in the turbulence close to the ITB radius consistent with the reduced electron transport. Significant collisional ion heating is also observed, but thermal equilibrium with the electrons cannot be attained since the e^- -i^+ equipartition time is always 4-5 times longer than the energy confinement time. The global ion transport is not degraded, rather the transport analysis must invoke a reduction of χ_i respect to the ohmic phase to account for the 10-fold increase of the neutron rate. The control of the ITB radius can be achieved by varying the LH power deposition profile that is affected mostly by the total current.

1. Introduction

A very important goal of an internal transport barrier (ITB) in order to be considered an attractive alternative to the base scenario for ITER is to attain full current drive (CD) to ensure a very long pulse duration. The elimination of the ohmic (OH) electric field as a CD tool would also help greatly to maintain the correct current profile, whose shape has been proved on most devices to be a primary key for sustaining a barrier. The limits imposed on the ITER additional power imply also to have a large fraction of bootstrap current (>50%) with a radial profile consistent with the desired one. Other crucial questions are whether the collisional coupling to ions (i^+) degrades ITB quality affecting the turbulence stabilisation mechanisms producing electron ITBs, and whether a barrier on ion transport can even be built by electron (e^-) heating methods. Indeed, in ITER the e^--i^+ collisional coupling is much higher than in the present day machines, and α particles that deliver their energy mostly to electrons are by far the most powerful heating source. This issue is particularly important for the impact on ITER operations, because so far ion transport has been improved only with plasma robust

rotation that will be problematic in ITER for the allowed small momentum injection. In addition, the study of the ion transport in an e^-ITB would clarify the role of the many mechanisms candidate to stabilize the long wavelength ion turbulence.
The FTU work [1, 2] contributes to progress in both lines, because steady e^-ITB are produced at ITER relevant high plasma density (central values $n_{e0}>1.4\cdot10^{20}$ m^{-3}) by means of only lower hybrid CD (LHCD) and electron cyclotron heating (ECH) that interact exclusively with electrons. Full CD conditions are attained and considerable power is collisionally transferred to ions, albeit it is still lower than the one foreseen for ITER.

2 . Transport barrier formation and main characteristics

ITBs are formed in FTU in a large range of plasma parameters, namely line averaged density $0.3\leq\bar{n}_e\leq1.1\cdot10^{20}$ m^{-3}, plasma current $0.35\leq I_p\leq0.7$ MA and toroidal magnetic field $5.2\leq B_T\leq7.2$ T [3]. The only request to be satisfied is to drive off-axis enough current to create a safety factor radial profile q(r) with a central value $1<q_0<2$, followed by a shearless or inverted shear region with $q_{min}\approx1.2$-1.3. This avoids harmful MHD activity, as double tearing modes at the q=2 surfaces or sawteeth. Mild m=1 activity is instead often present in ITBs with possible beneficial effect against impurity accumulation. These q profiles are quite similar to those typical of hybrid regimes [4] and are even steadier, essentially because they do not need any mechanisms to prevent the current diffusion, which is mostly fixed by an external drive. No significant difference is observed in the construction of such steady q profiles whether LHCD is applied during the discharge plateau or in the I_p ramp-up phase, mainly because various constraints do not allow injecting LH power in the very beginning of the discharge, when the actual q profile is very far from the relaxed one [5].
The sustainment of proper q profiles by LHCD alone becomes more difficult as density raises, then ECH may offer a twofold valuable assistance. Regardless of its toroidal injection angle it enhances the LHCD efficiency by increasing the plasma temperature. Moreover, it provides a small but centrally very localized counter current drive when launched with the proper toroidal component in the so-called counter-ECCD configuration, leading to a slightly reversed q profile, suited for an ITB, that otherwise would not be reached. Both LHCD and ECH are of course also the heating sources for the bulk plasma. The use of central ctrECCD has been essential to built the so far highest density steady ITB in FTU, whose main features are illustrated in Fig. 1. Without the ECCD contribution a remarkably weaker ITB is obtained if ECH is launched perpendicularly to the toroidal direction, whereas, if coECCD configuration is used, even sawteeth reappear and an ITB is not built at all. Figure 1 shows that an almost full CD ($V_{loop}<0.2$ V, OH current <20% of the total) is sustained for the whole duration of the ECH pulse at central density and e^- temperature exceeding $1.4\cdot10^{20}$ m^{-3} and 5 keV respectively. Fusion neutron rate grows about 10 times respect to the OH phase, for a central ion temperature increment of more than 40%. The strength of the barrier in term of the

normalized inverse temperature scale length $\rho^*_T=\rho_{L,s}/L_T$, where $\rho_{L,s}$ is the Larmor radius of the ions moving at the sound velocity and $L_T=T_e/(dT_e/dr)$, is well above 0.02, against a threshold value of 0.014, and stays constant as all the other ITB relevant features. In particular, no evolution of the q profile is evidenced by variation of the hard X-ray (HXR) perpendicularly emitted via bremsstrahlung by the LH generated fast electrons. The calculated q profiles maintain a mildly reversed shape in the centre with $q_0>1.5$ and $q_{min}\approx1.2$. As shown in Fig. 2, no variation of the e^- temperature profile, and hence of ρ^*_T, is observed. Consequently, the ITB radius, i.e. where $\rho^*_T=0.014$, remains fixed at $r_{ITB}/a\approx0.35$ (a= plasma minor radius), where q_{min} is≈1.5 and the shear is quite small. A weak MHD activity, m=3 n=2, is observed that is consistent with a double tearing mode developing at the two radii where q(r) crosses the value of 1.5. The ITB foot is very often located close to where q has a simple rational value and the magnetic shear is quite low. This latter feature facilitates a good alignment of the bootstrap and the driven currents in the LH generated ITBs, as requested for ITER. Indeed the largest modification of the shear occurs in the proximity of the radial LH deposition peak and just there starts the steep pressure gradient originating the bootstrap current. Figure 3 shows for two discharges the radial profiles of the LH and bootstrap driven current for two quite different radial ITB sizes: in the wider ITB both the LH and the bootstrap current are outward shifted.

3. Transport and confinement in ITBs

The drop of the electron heat conductivity in e^-ITBs is now a well assessed [5] in the energy transport analysis. The shear dependent mixed Bohm-gyroBhom (B-gB) model can interpret the FTU results until the ITB is enough weak. Then a reduction of the gB coefficient must be invoked possibly due to the onset of some turbulence stabilization process [3]. The α (or pressure gradient) mechanism has been proposed as a candidate for the medium-low k_θ (poloidal wave number) range [6]. The first direct evidence of a change in the turbulence nature when an ITB is built has been recently obtained for just the high density discharge of Fig. 1. Measurements are carried out with a 2-channels fixed frequency reflectometer looking along two chords poloidally apart by 5 deg. The fluctuation and coherence power spectra are compared respectively in Figs. 4 and 5 with those obtained from a discharge identical but for the fact that ITB is only marginal, if any, due to the lack of ECH power. The reduction of both the total fluctuation power and of the coherency is evident in case of ITB. It must be pointed out, however, that the reflecting layer is external to the ITB footprint because the rise of density in the additional power phase shifts outwards the cut-off layer for the fixed frequency. This apparently disagrees with DIII-D that claims effects on turbulence only inside the ITB [6]. We are at present examining whether phenomena linked to reduced transport could be actually observable even outside the ITB zone. In the consistent hypothesis that this observation is closely related to the onset of the ITB the results of Fig. 5 can be interpreted as an important drop of the long wavelength components (i.e. low k) of the k_θ turbulence spectrum in the range $k_\theta\rho_i\approx0.2$-0.3, which is a scale length at the boundary between the ITG and TEM modes.

The ion transport, instead, shows no variation between the two mentioned discharges. In both of them it decreases non-negligibly in the CD phase respect to the OH one, to the neoclassical level according to the transport analysis. This would imply a reduction of the ion transport before the full onset of an e^- barrier that however cannot still be verified because consistent reflectometric data are missing. The low ion thermal diffusivity in ITBs confirms the first observations made at lower density and power [7], and it agrees with the global ion behavior inside the ITB. Indeed, the comparison presented in Fig. 6 (derived from Ref [5]) between an ITB and an OH reference discharge, shows that the neutron rate, R_N, and the central ion temperature, T_{i0}, are higher for ITB despite that density and e^--i^+ collisional coupling are very similar. Figure 7, taken from Ref [3], plots on a multi-shot base the energy gained by the ions inside the ITB versus the increment of the power collisionally received by electrons, per unit of volume. The straight line, quite well fitting the data, indicates an incremental energy confinement time ≥24 ms close or even higher than the global confinement time $\tau_E\approx22$ ms.

An ITB displays also an improvement of the global energy confinement, as expected, to an extent that depends on the ITB strength, as shown in Fig. 8, where the confinement enhancement factor H_{97}, defined as the ratio between the actual τ_E and the prediction of ITER97-L scaling, is plotted versus $\rho^*_{T,max}$. The H_{97} values grow with $\rho^*_{T,max}$ reaching a maximum >1.6, and locate stably above 1 when $\rho^*_{T,max}>0.014$, the threshold value. Just inside the ITB the enhancement is made even clearer when ECH power is deposited directly there, whereas no sign of impurity accumulation is observed, as inferred from Fig. 9. Here the temporal evolution of the most relevant parameters is shown for a discharge with central e^- cyclotron resonance (B_T=5.3 T). No change of τ_E occurs between phases with and without ECH, despite in this latter the larger power would imply a decrease more than 20%, as evidenced by the trace of the ITER97-L scaling. Either no significant change in the peaking of the effective ion charge or even in its value is detected.

The studies on the particle transport in full CD conditions [8] are encouraging for producing peaked density profiles in ITER ITBs, where no central particle fueling will be available. As shown in Fig. 10 (same discharge as Fig. 1), the density profile flattens only slightly respect to the OH phase in a high density ITB. The peaking factor $n_{e0}/\langle n_e\rangle$ remains above 1.7, despite only thermal gas is released into the plasma and the Ware pinch mechanism due to the toroidal electric field is very weak in almost full CD conditions. Nevertheless, this value is still higher than that quoted (≈1.3) in other devices as JET [9] or Asdex U [10] for similar values of the adimensional collisionality ($\nu^*_e\approx0.2$ at r_{ITB}). Consequences for density peaking in ITER are being evaluated.

4. Control of the ITBs

A full control of the ITB would require ability to prefix the radius and strength of an ITB. Increasing the spatial extent of the barrier increases fusion performance and MHD stability limits, and results in a favorable bootstrap alignment with the total current profile, while control of gradients is required to avoid instabilities and disruptions. The barrier location can be controlled in FTU only by varying the current profile, since ITBs start where the magnetic shear approaches zero. There are only two active ways in FTU, both involving ECH: to change $T_e(r)$ in order to shift the LHCD absorption profile, or with central ctrECCD to modify locally the current profile. Even if quantitative results are still poor, both methods have been successfully applied in FTU to widen ITBs: the first one especially in the I_p ramp-up phase [5], whereas the ctrECCD method is briefly outlined in Sect. 2. The importance of a central counter current had previously been recognized [3] in cases when excessive non-inductive current (LH+bootstrap) must be balanced by the external coils. However a significant control would require putting the ECH resonance too off-axis and hence would ask for a great amount of power due to the large volume of the external regions. Alternatively, the width of the barrier can be passively determined with a proper choice of the plasma target. The main physical quantities involved have been singled out through a linear regression analysis, whose result is given in Fig. 11. In addition to the fraction of the driven current, obviously, the q of the discharge is crucial: as claimed in a previous work [3] at lower q the LH deposition is expected to shift outwards, whereas density does not play a clear role. The negative exponent of $<T_e>$ (volume e^- temperature) is probably linked to the non-single pass LH absorption that complicates the simple picture of more peripheral absorption at higher T_e. Finally, the mild widening the barrier with the effective ion charge Z_{eff} is consistent with the impurity injection experiment in DIII-D ITBs [6].

The best way, so far found to act on the strength of the barrier and T_{e0} is to heat via ECH inside the barrier, as evidenced by the second frame of Fig. 9.

5 . Conclusions

Stationary electron ITB, lasting >35 τ_E and about one ohmic current relaxation time are obtained in FTU up to $n_{e0}>1.45\ 10^{20}\ m^{-3}$, $B_T \geq 5$ T, indicating that operations close to n_e and B_T of ITER do not prevent ITBs to be achieved. Local $\rho_T^* \geq 0.05$ (threshold =0.014) and $R/L_T \geq 19$ at the barrier footprint, larger than the values quoted for $T_e(r)$ stiffness, are observed. Good relation between r_{ITB} and the weak shear region is found and χ_e for $r<r_{ITB}$ is reduced during main heating. The barrier size grows if q_a is reduced, and with ECH off-axis preheating (outward shift of the LH deposition). The energy confinement time exceeds up to 1.6 times the ITER97-L thermal scaling. Ions are mainly heated from collisions with $\Delta T_{i0}/T_{i0}>40\%$, and 10 times increase of the fusion neutron yield. The still long thermal equipartition time $\tau_{ei} \approx 180$ ms with $\tau_E \approx 22$ ms does not allow T_i to approach T_e. The ion confinement remains good even in presence of partial collisional heating, rather the transport analysis shows that the ion thermal diffusivity is reduced in high density ITBs respect to the OH phase. Consistently, the ion incremental energy confinement time inside the ITB is $\Delta\tau_{E,i}\approx25$ ms, comparable to τ_E. This at least indicates that electron-ion collisions do not prevent electron ITBs to be achieved. A reduction of the amplitude of the fluctuation external but close to the barrier is observed to be well correlated to the onset of the ITB, together with a drop in the coherence between two separate reflectometer channels that is consistent with a reduction of the turbulent spectrum in the medium-low k_θ range.

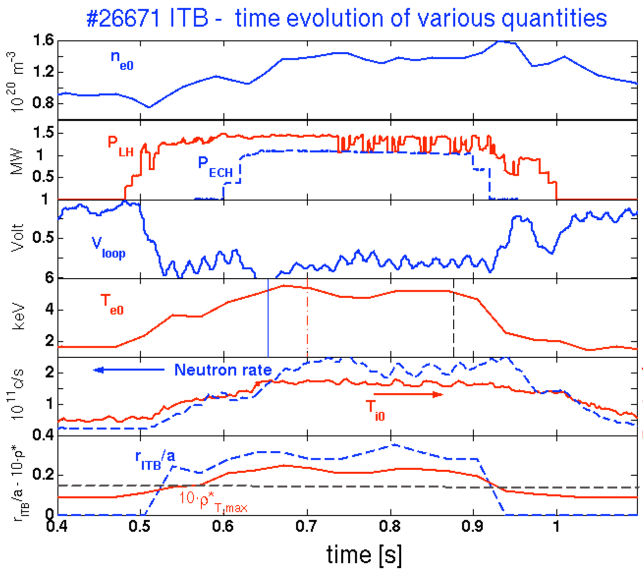

Fig. 1 – Time evolution of the most significant macroscopic plasma parameters for #26671, the steady ITB at the highest density

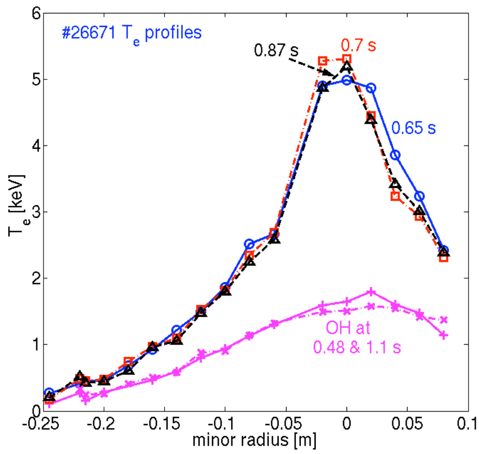

Fig. 2 – Electron temperature profiles in ohmic and in the ITB phase for the discharge of Fig. 1

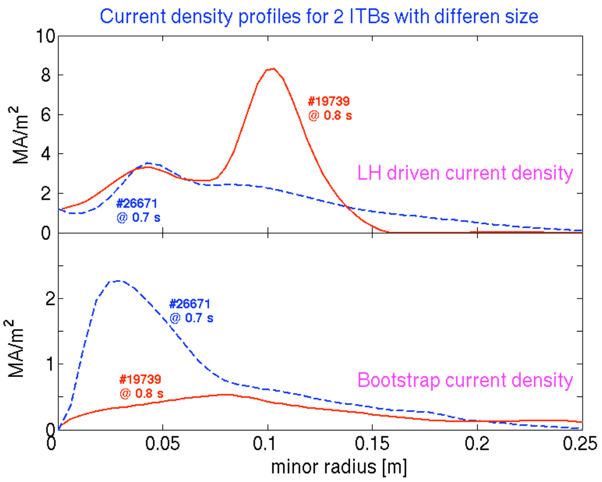

FIG. 3 - Radial profiles of the LH (upper) and bootstrap current (lower) for two ITBs with different radius, showing the good alignment of the two currents in both cases

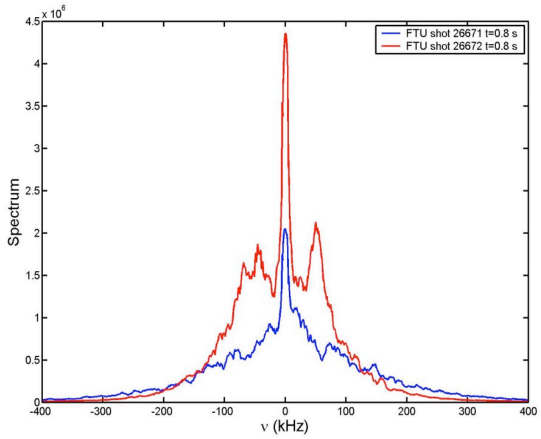

Fig. 4 – Fluctuation power spectra for two discharges with ITB (#26671, blue) and without (#26672, red); $n_e \approx 0.9 \cdot 10^{20}$ m^{-3} for both

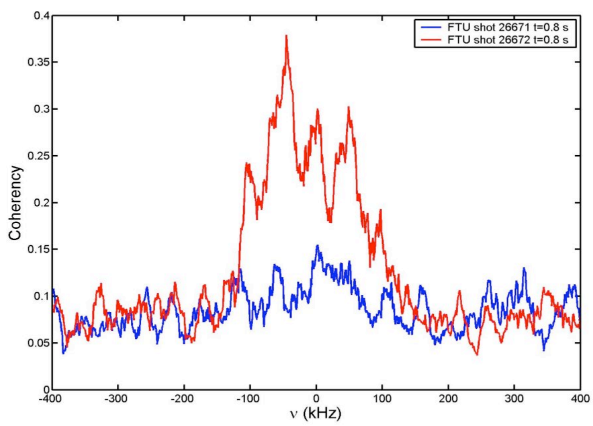

Fig. 5 – Coherence spectra for the same two discharges of Fig. 4

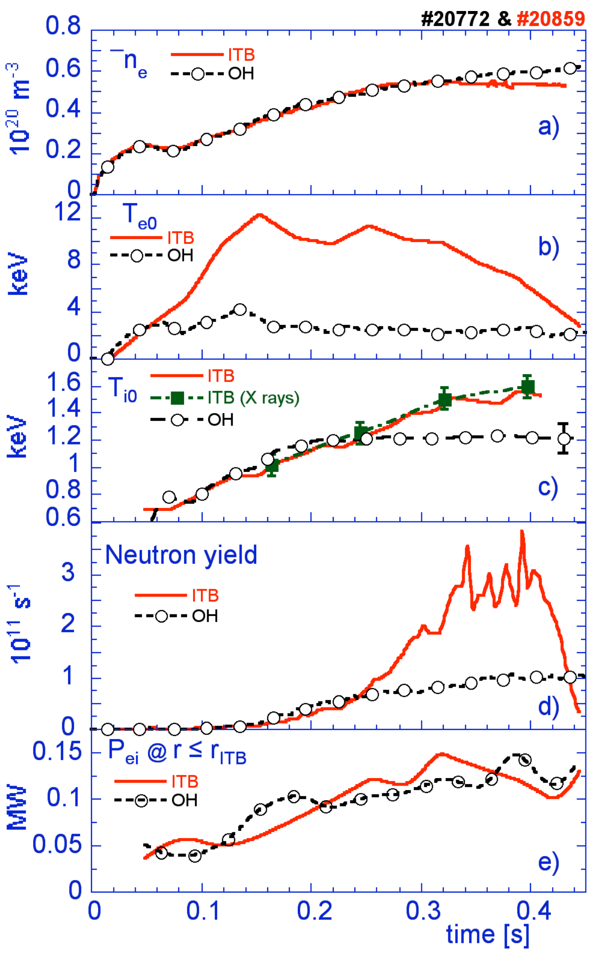

Fig. 6 – Comparison between the ion behavior in an e⁻ITB and in an OH discharge, with same density and same e-i collisional coupling

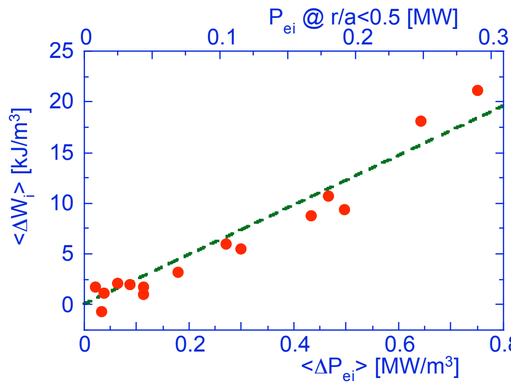

Fig. 7 – Increment of the ion thermal energy versus the increment of the e-i collisional power, averaged over the ITB volume. The incremental confinement time is ≈25 ms and $\tau_E \approx 22$ ms

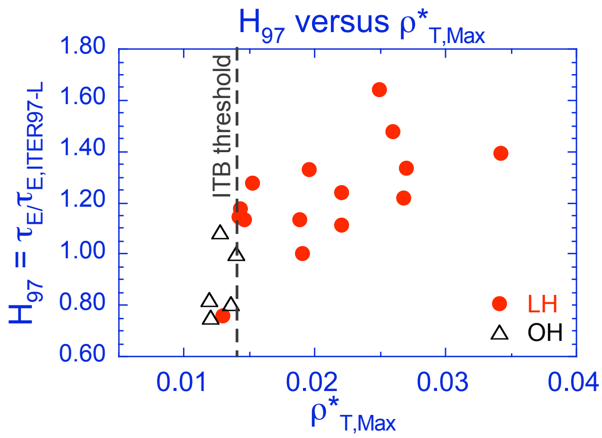

FIG. 8 – Global confinement properties of the ITBs, shown as the enhancement over the ITER97-L scaling versus the barrier strength

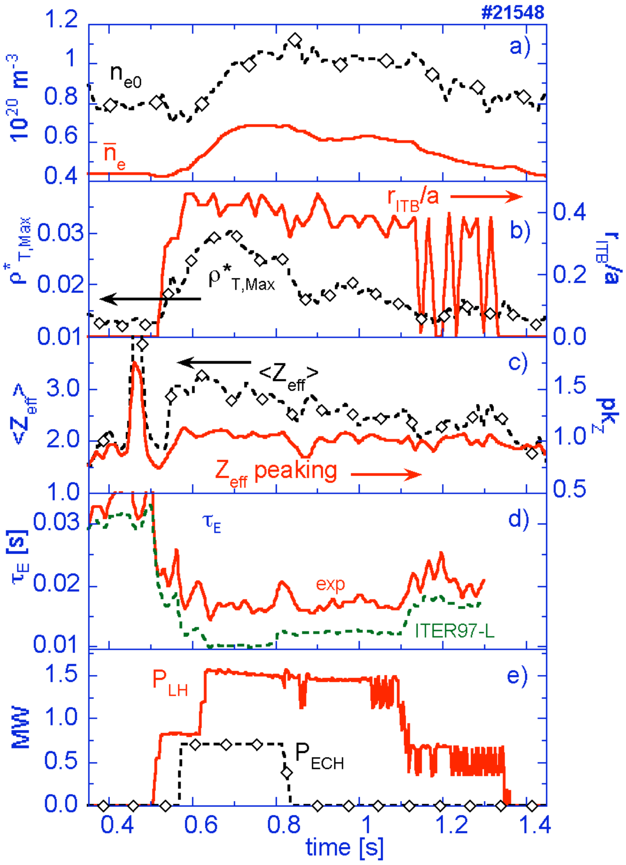

FIG. 9 – Time evolution for #21548 showing the absence of impurity accumulation (frame c) and the good energy confinement inside the ITB (frame d)

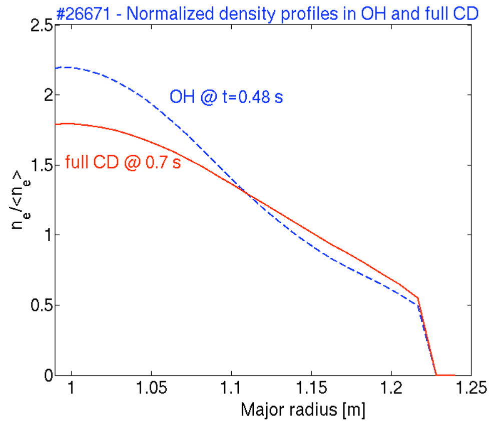

FIG. 10 – Normalized density profiles in OH and almost full CD phase for #26671 (same as Fig. 1) showing that also without the particle ware pinch the profile remains quite peaked

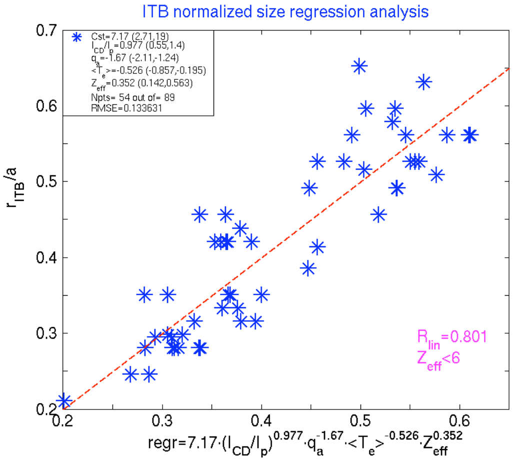

FIG. 11 – Linear regression analysis for the ITB radius versus the most significant quantities for the profile and the amount of the driven current

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