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ABSTRACT.
It is shown that the relaxation oscillations associated with repetitive Internal-Transport-Barrier (ITB) buildup and collapse in high-performance tokamak plasmas, with Ion-Cyclotron Resonance Heating (ICRH), Neutral-Beam-Injection (NBI), and Lower-Hybrid Current Drive (LHCD), and with a dominant fraction of bootstrap current, can be overcome if the LHCD power is sufficiently high. This result has been obtained using a benchmarked, fully predictive transport model self-consistently iterated with ICRH, NBI, and LHCD modules, the stabilizing role of E×B flow shear being combined with that of reversed magnetic shear in the simulation of ITB dynamics.

While tokamaks remain the front runners for the first generation of thermonuclear fusion power-plants, the need to provide continuous electrical power makes Steady-State (SS) operation of future tokamak reactors more attractive than the pulsed mode associated with purely Ohmic, inductive drive which, on top of the cyclic thermal and mechanical stresses it implies, must rely on some energy-storage system to feed the electrical grid during transformer recharge [1, 2]. Internal Transport Barriers (ITBs) have hence become a milestone in the route to SS economically viable fusion reactors: besides improving core confinement, their steep pressure gradient induces very large fractions of the self-generated BootStrap (BS) current, enabling the plasma current to be fully driven noninductively with only a small amount of power recirculated to the external Current-Drive (CD) sources, in the so-called Advanced Tokamak (AT) scenarios that have attracted increasing interest [3–15]. According to present-day theoretical understanding and experimental evidence, two key ingredients for ITB formation and sustainment are the shears in the magnetic field and in the E×B drift velocity, s and $\omega_{E\times B}$ respectively, the emerging picture being that ITB dynamics is mainly governed by some synergistic combination of the stabilizing effects due to reversed, non-positive s and high $\omega_{E\times B}$, the latter shearing rate being compared with the linear growth rate of Ion-Temperature-Gradient (ITG) modes or of some other type of drift-wave plasma instabilities [3–5, 16]. Indeed, sheared E×B flows can reduce the amplitude of turbulent fluctuations, or can even suppress them, and can break the turbulent eddies by a decrease in the radial correlation lengths, whereas negative magnetic shear opposes the growth of drift-wave instabilities, eventually stabilizing them, and are also able to reduce their radial extent [3, 5, 16].

Notwithstanding its advantages, SS operation with ITBs and dominant BS current, which generally demands localized, off-axis external CD for Magnetic-Shear Reversal (MSR), often depicts in plasma parameters, and thus also in plasma performance and confinement, an oscillatory behavior linked to repetitive ITB growth and collapse that, although not inevitable [6], has appeared in DIII-D experiments [4, 8], as well as in numerical simulations of AT scenarios [11, 12]. Basically, these relaxation oscillations come from the misalignment between the BS and the externally driven noninductive current densities when the effects of $\omega_{E\times B}$ are neglected, or negligible, and only those of s are contemplated, or effective, in the mechanism for ITB formation because, in such a case, the BS maximum, governed by the location of the steepest pressure gradient [1], is slightly shifted inside the outer edge, or foot, of the ITB, which then coincides with the MSR layer, where $s \approx 0$, and is initially controlled by the external CD source, usually rf waves [8, 11, 12]. Introduce the tokamak major radial coordinate R, along with the toroidal and poloidal components of the equilibrium magnetic field, respectively B_ϕ and B_θ, and their corresponding fluxes Φ and Ψ lying within a given flux surface, and recall that magnetic shear is defined as $s = (\rho/q)(dq/d\rho)$ [1–5, 11, 12], with ρ a normalized flux-surface label taken here to be $\rho = \sqrt{\Phi / \Phi_b}$ where Φ_b is the value of Φ at the boundary [14–16], and with $q = d\Phi/d\Psi$ the so-called safety factor where $d\Phi /dr = \int H\, B_\phi ds$ and $d\Psi /dr = 2\pi R B_\theta$, d/dr designating the gradient component perpendicular to the flux surfaces and the integral over the distance ds moved in the poloidal direction being carried out for a single poloidal circuit [1]. Then, being B_θ linked to the toroidal current density j according to Ampére's law, it is easy to understand how a strong peak in j due to some off-axis rf CD j_{rf} can lead to a significant increase in B_θ and an accompanying decrease in q, whence to a local MSR configuration that subsequently induces an ITB. Existing a positive feedback loop between the plasma pressure P and the BS current density j_{BS} [3–6, 8], since the latter is pulled up by the steeping in dP/dr during ITB buildup and so simultaneously causes MSR strengthening, further reducing transport, at one point the peak in j_{BS} becomes as large as the maximum of j_{rf} and, being the two current peaks mismatched, it is j_{BS} that takes the lead in controlling the ITB foot. Now, because dP/dr is strongest at a somewhat inner value than the one verifying $s \approx 0$, the first location determining the maximum in j_{BS} while the second is determined by it, a process is engendered which displaces j_{BS} further and further inside the plasma, until its peak is eventually lost in the bulk current, this being accompanied by the re-establishment of a monotonic q profile and the concomitant loss of the ITB, which is subsequently restored by j_{rf}, and a new, similar cycle restarts [11, 12]. Note that a similar ITB cyclic behavior has also been observed in noninductive, LHCD-sustained tokamak discharges with dominant LHdriven current and small BS fraction, the oscillations between a lower and a higher core confinement state being linked to the nonlinear coupling of the temperature to the current-density profile that comes into place when the transport coefficients depend locally on magnetic shear, hence on the current density, while the noninductive current profiles are functions of temperature [17–19].

In view of AT operation with ITBs and high fractions of BS current, say $I_{BS}/I_P \gtrsim 65\%$ [3, 4, 6–9], where IBS and IP designate, respectively, the BS and total plasma currents, it is desirable that such ITB oscillations be overcome, not only for the sake of a fully SS fusion reactor, but also because they impose a limit on the attainable values of plasma pressure, BS current, and confinement, thus hindering tokamak performance [4, 8, 11, 12]. A way to go beyond these successive cycles of ITB growth and relaxation, thus ensuring the stationary sustainment of a configuration with a high ratio IBS/IP, is to break the link between the ITB foot and the MSR radius by moving the former slightly outwards, so the region with the largest value of dP/dr, whence also j_{BS}, firmly overlaps jrf. Precisely, remark the high-confinement, high-boostrap discharges that have been reported to be stationary in JT-60U, where the shrinkage of the MSR radius has been suppressed, have the ITB foot shifted towards the outside of the MSR layer [6]. This can be accomplished if, as suggested [12], the naturally stabilizing role of the E×B flow shear, which has not always been accounted for in transport simulations of SS scenarios with significant BS fractions [11, 12], is included to allow the ITB to form in a region of higher s when $\omega_{E\times B}$ is large enough. The velocity shearing rate reading $\omega_{E\times B} = |(RB_\theta/B_\phi)(d/dr)(E_r/RB_\theta)|$, where $E_r = (Z_i e n_i)^{-1} d(n_i T_i)/dr - v_\theta B_\phi + v_\phi B_\theta$ is the "radial", or normal, component of the electric field, with v_ϕ and v the toroidal and poloidal flow velocities, respectively, e the elementary charge, and Z_i the atomic number of the main plasma ion [1, 3, 5, 13, 14, 16], and existing evidence v_ϕ plays an important role in ITB dynamics [3, 4, 14–16], the increase in $\omega_{E\times B}$ can come via a strong increment in the toroidal rotation velocity. So, choosing Lower-Hybrid (LH) waves as the rf CD source, the purpose of this Letter, while stressing the importance of integrating the shear in the E×B drift in time-dependent simulations of ITB physics, is to show that going up in LHCD power leads to stronger ITBs and, therefore, to a greater reduction in momentum transport and a simultaneous increase in plasma toroidal rotation, sufficient to induce a value of $\omega_{E\times B}$ large enough to enable a SS high-performance ITB plasma. This has been done using a well-known and thoroughly tested transport modeling tool [14, 15, 20–22], which has yielded a plasma where j_{BS} remains firmly anchored to the LHCD current density j_{LH} and I_{BS} is overwhelmingly dominant, typically $I_{BS}/I_P \approx$ 80%, as envisaged for operation of fusion reactors based on AT scenarios [3, 4, 6–9].

In spite of their completeness, first-principles, physicsbased models, besides failing often to correctly reproduce ITB dynamics in time-dependent simulations, translate into extremely demanding computations that are still prohibitive for systematic exploitation, so simpler, semiempirical models have been very much relied upon to provide the robust, quantitatively benchmarked numerical tools necessary for transport simulations of ITBs in realistic tokamak plasmas [3–5, 13–15]. In fact, there is an ever greater demand for such tools, not only to interpret actual experiments, but also to predict AT scenarios in support of campaigns and upgrades in existing devices, as well as to extrapolate to reactor-grade fusion machines such as ITER. The analysis has thus been carried out using the JETTO code [14, 15], in which a mixed Bohm–gyro-Bohm transport formulation has been complemented with an empirical scaling that captures the underlying ITB physics outlined above by giving a threshold for the onset of ITBs and the concomitant transport reduction in the form $C_1 + C_2 s - C_3\omega_{E\times B}/\gamma_{ITG} < 0$ [3, 5, 13–15]. Here $\gamma_{ITG} = v_{i,th}/R$ estimates the linear growth rate for ITG-driven turbulence, with vi,th the ion thermal velocity, and C_1, C_2, and C_3 are empirically fitted constants, a good set that stems from simulating several tokamak discharges being $C_1 = 0.1$ and $C_2 = C_3 = 1$ [15], whence $s < -0.1 + \omega_{E\times B}/\gamma_{ITG}$ has been taken as the condition for ITB formation [23, 24]. JETTO takes as input a realistic D-shaped toroidal equilibrium and, after averaging the particle, heat, momentum, and current transport equations over the magnetic flux surfaces, making JETTO a so-called 1.5 dimensional (1.5-D) code, evolves in a fully predictive manner the profiles for the electron and ion temperatures, the plasma and current densities, and the toroidal rotation [14, 15, 25], the transport calculation being self-consistently iterated with modules for ion-cyclotron resonance heating (ICRH) [20], neutral-beam injection (NBI) [21], and LHCD [22].

To derive results with real implications for fusion experiments, the analysis is carried out for configurations typical of the Joint European Torus (JET) [10], taking as target a JET-like AT high-performance deuterium plasma with an ion effective charge $Z_{eff} = 3$ and an equilibrium with $I_P = 2.3MA$, a magnetic field on axis $B_0 = 3.45T$, and a high triangularity $\delta = 0.46$ to make it similar to the ITER SS configuration [2, 10, 26]. The ion density, electron and ion temperatures, and toroidal rotation at the boundary are ramped up to $n_{ib} = 1.0 \times 10^{19}$ m^{-3}, $T_{eb} = 1.6keV$, $T_{ib} = 1.9keV$, and $v_{\phi b} = 5.0 \times 10^4$ ms^{-1}, respectively, these values, taken at the top of the H-mode pedestal [15, 27], ensuring the confinement enhancement factor H basically remains unity when switching off the ITB model [2, 28], the temperatures further obeying the appropriate pedestal scaling $T_{ib}/T_{eb} \approx 1.2$ [29]. The flat-top ICRH and NBI powers read $P_{ICRH} = 10MW$ and $P_{NBI} = 32MW$, while the LHCD power is scanned according to $P_{LH} = 3$, 4, 5, and 6MW, which implies for the total injected power $P_{tot} \geq 45MW$ [30], the LH launched spectrum being peaked at a parallel wave index $n|| = 1.8$ and having a directivity of 80%. So, with μ_0 the vacuum permeability and measuring the volumeaveraged plasma pressure $\langle P \rangle$ using the so-called toroidal beta $\beta_t = 2\mu_0 \langle P \rangle /B_0^2$ [1, 4], time traces for some parameters relevant for plasma performance are depicted in Fig.1, where it is clear the ITB relaxation oscillations become stabilized by increasing the LHCD power, as one goes from a situation with no ITB sustainement at all for $P_{LH} = 3MW$ to a full AT high-performance state when $P_{LH} = 6MW$, passing through an intermediate regime of successive cycles of ITB growth and collapse, or weakening. Worthy of note is the crucial role played by the E × B flow shear for a full account of ITB dynamics since its absence, imposed by putting $C_3 = 0$ in the ITB criterion given above, leads to a totally differ-ent result for $P_{LH} = 6MW$, namely to the impossibility of overcoming the ITB cycling behavior. As shown in Fig.2, a high-performance AT configuration with a wide ITB is obtained for $P_{LH} = 6$ MW, the computed values for the NBI-, LH-, and BS-driven currents being $I_{NBI} \approx 0.2MA$, $I_{LH} \approx 0.7MA$, and $I_{BS} \approx 3.8MA$, respectively, which combine to yield an overdriven plasma where the loop voltage is $V_{loop} \approx 0.1V$ and the Ohmic current is $I_{OH} \approx -2.4MA$. The periodic process of ITB formation and relaxation observed when the foot of the ITB is roughly coincident with the MSR radius is illustated in Fig.3 for $P_{LH} = 4MW$, in which case $\omega_{E\times B}$ effects are negligible [31], so one can confirm that j_{BS} does grow to replace jLH in defining the ITB location, and then continuously drifts towards the plasma core until the ITB is eventually lost, being subsequently reinstated by a local MSR caused by j_{LH} [11, 12].

In summary, an analysis of ITB dynamics with JET parameters has been conducted using an extensively benchmarked 1.5-D transport code where not only the profile for the toroidal rotation velocity is followed in time simultaneously with the profiles for the plasma and current densities and for the electron and ion temperatures, but also where the ICRH, NBI, and LHCD sources are self-consistently integrated in the modeling, making this a considerably more complete study than previous ones on SS regimes with large fractions of BS current [11, 12]. As its main conclusion, it has been predicted that, for JET AT plasma configurations, with 10MW of ICRH and 30MW of NBI [30], 6 MW of LHCD power suffice to sustain a wide stationary ITB whose foot is outside $\rho \approx 0.7$, in an overdriven plasma with a total current of 2.3MA, the BS fraction slightly exceeding 80% of the 4.7MA flowing in the co-direction. These results not only clearly point towards the possibility of SS, predominantly BS-sustained tokamak operation, as projected for an AT fusion reactor, but they also indicate that transformer recharge is possible, which may always be useful in a future reactor [8]. Moreover, they show that the ITB itself can sustain enough toroidal rotation in the plasma core to ensure the stabilizing benefits of E×B flow shear, which may be good news considering the expectation of low torque injection by high-energy NBI at the large plasma densities foreseen for ITER and nextstep devices [4]. The identification of LHCD as an actuator for stationary ITBs in AT high-performance, BSdominated plasmas, which has been possible by combining in the time-dependent ITB modeling the effects of E×B flow shear with those of magnetic shear in the formation and sustainment of ITBs, can be checked in present-day tokamaks by scanning the LHCD power and seeing if, above a certain threshold in PLH, the ITB oscillations are no longer observed. Finally, the need to have the ITB foot moved slightly outwards of the MSR layer, where s   0, in order to have SS ITBs, may explain the differences observed between the JT-60U and DIII-D AT experiments with dominant BS current [6, 8].

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[23] As for the conclusions in this work, a finer tuning of C_1, C_2, and C_3 is superfluous, particularly since they have been further benchmarked by a fully predictive transport simulation of ITB JET Pulse No: 6498.
[24] As explained in Ref. [14], the ratio $\omega_{E\times B}/\gamma_{ITG}$,which is not a flux function [3, 14, 16], is flux-surface averaged before entering the ITB-formation criterion.
[25] The v_ϕ profile comes from the momentum balance equation using the NBI torque as source [14, 15], and assuming the angular-momentum and ion-thermal diffusivities are linked via $\chi = 0.3_{\chi_i}$.
[26]. The reference for the magnetic equilibrium taken here is JET Pulse No: 64323, at instant t = 6s.
[27]. Note that the detailed modeling of the edge pedestal is beyond the scope of this work.
[28]. More precisely, H gives the thermal energy confinement time normalized by the so-called ELMy H-mode scaling, whose expression is given in Eq. (3) of Ref. [2].
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[30]. Note these power levels do not represent the actual JET capability, the values retained for PICRH and PNBI being those foreseen in the JET enhancement project (JET-EP2), while only the lowest value in the P_{LH} scan is achievable in JET.
[31]. As a check, a run with $C_3 = 0$ has also been performed for P_{LH} = 4MW and no significant difference in plasma response has been detected at this level of LHCD power.

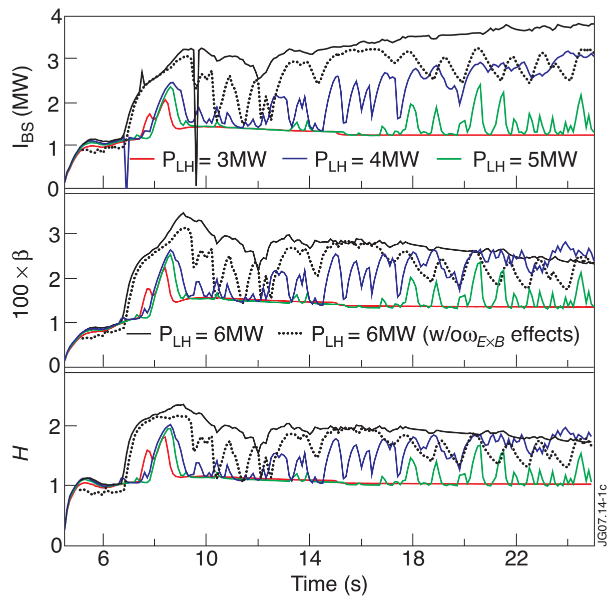

Figure 1: Evolution of plasma performance for P_{LH} = 3, 4, 5, and 6MW. Also shown, for P_{LH} = 6MW, is a simulation without $\omega_{E\times B}$ effects in the ITB model.

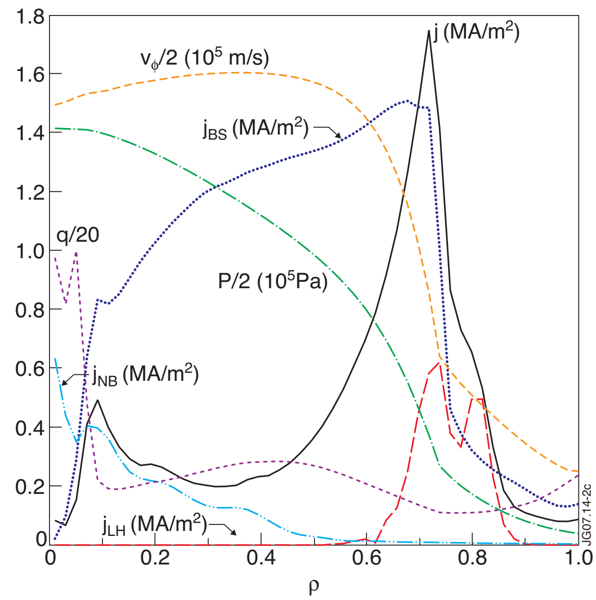

Figure 2: Plasma profiles, at t = 25 s, for P_{LH} = 6MW.

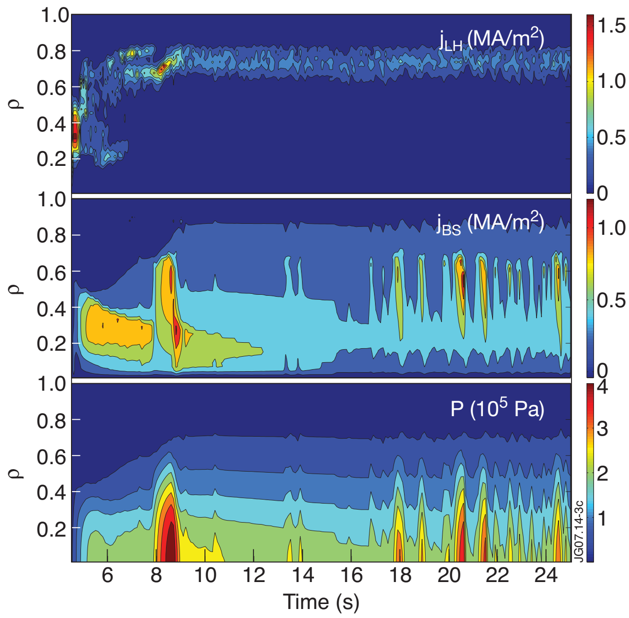

Figure 3: Evolution of plasma profiles for P_{LH} = 4MW.