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Saturation of fishbone instability by self-generated zonal flows in tokamak plasmas

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Abstract

Gyrokinetic simulations of the fishbone instability in DIII-D tokamak plasmas find that self-generated zonal flows can dominate the nonlinear saturation by preventing coherent structures from persisting or drifting in the energetic particle phase space when the mode frequency down-chirps. Results from the simulation with zonal flows agree quantitatively, for the first time, with experimental measurements of the fishbone saturation amplitude and energetic particle transport. Moreover, the fishbone-induced zonal flows are likely responsible for the formation of an internal transport barrier that was observed after fishbone bursts in this DIII-D experiment. Finally, gyrokinetic simulations of a related ITER baseline scenario show that the fishbone induces insignificant energetic particle redistribution and may enable high performance scenarios in ITER burning plasma experiments.

Introduction. - Energetic Particles (EPs) in fusion plasmas can destabilize instabilities at different spatial scales that may lead to their outward transport. This is a critical issue for burning plasmas as in ITER [1], where the core confinement of 3.5 MeV fusion-born alphas and other EPs is essential to maintain a dominantly self-heated plasma with a fusion gain of $Q \geq 10$. This EP transport therefore needs to be predicted for mitigation strategies to be incorporated in plasma scenarios. The macroscopic MHD mode named fishbone [2][3], a helicoidal EP-driven instability of the core plasma in tokamaks, is one such instability that could drive large EP transport in fusion devices. Its amplitude and the associated EP transport depend strongly on nonlinear processes that lead to the mode saturation. The mechanism presumably dominating the fishbone saturation was identified in kinetic-MHD simulations [4][5] to be the resonant wave-particle interaction. However self-generated zonal flows (ZFs), which are axisymmetric flows due to the electrostatic potential averaged over the magnetic flux surfaces, were not included or under-evaluated in these simulations without kinetic thermal ions, which can impact the fishbone saturation [6]. Indeed, zonal flows are known to dominate the saturation of instabilities arising at microscopic and mesoscopic scales such as drift-waves [7] and Alfvén eigenmodes (AEs) [8][9]. The radial electric field shear of zonal flows can suppress turbulent transport [10], resulting in the formation of an internal transport barrier (ITB) that greatly enhances plasma confinement [11]. An outstanding issue is whether zonal flows can play a similar role in saturating macroscopic MHD modes, which may

affect turbulent transport through cross-scale interactions common in fusion [12] and astrophysical plasmas [13]. In this Letter, we report the first self-consistent gyrokinetic simulations finding fishbone saturation by self-generated zonal flows, in a DIII-D tokamak experiment [14] which is chosen for validation purposes to predict the EP transport in a ITER pre-fusion power operation (PFPO) scenario [15]. Global gyrokinetic simulations using the GTC code [7] find that self-generated zonal flows greatly reduce the fishbone saturation amplitude, by preventing the EP phase space zonal structures [16] from persisting or drifting in the nonlinear phase with the mode frequency down-chirping, which reduces the EP resonant drive. Results from the simulation with zonal flows agree quantitatively, for the first time, with experimental measurements of the fishbone saturation amplitude and the neutron emissivity drop due to the associated EP transport. Moreover, the shearing rate of the zonal electric field exceeds the linear growth rate of unstable drift-waves. The associated suppression of the microturbulence by fishbone-induced zonal flows is likely the mechanism for the formation of an internal transport barrier (ITB) that was observed after fishbone bursts in this DIII-D experiment, similar to that in the EAST tokamak experiment [17]. Our simulation results confirm the long suspected role of fishbones in ITB formations [18], where fishbone bursts have been observed to precede ITB formations in ASDEX [19], MAST [20], HL-2A [21] and EAST [22] plasmas. Finally, building on the nonlinear validation using the DIII-D experiment, gyrokinetic simulations find that the fishbone-induced EP transport

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in the ITER baseline scenario is insignificant, with less than 2% of the core EPs being redistributed. The intentional destabilization of fishbone modes in ITER is therefore possibly a way to enhance fusion performances.

Experimental setup. - The selected DIII-D discharge #178631 [14] has a nearly circular oval shape (elongation $\kappa = 1.17$, triangularity $\delta = 0.07$) that is limited on the carbon inner wall. The major radius is $R_0 = 1.74$ m, the minor radius is $a = 0.64$ m, the toroidal field is 2.0 T, the plasma current is 0.88 MA, and the line-average electron density is $\sim 2.0 \times 10^{19} \text{ m}^{-3}$. This discharge was chosen primarily because it has an accurately known, weakly reversed, q profile with $q_0 = 1.2$, $q_{min} = 1.09$, and $q_{95} = 3.8$ values that resembles the profile predicted for the ITER PFPO baseline scenario. The deuterium, L-mode plasma is heated by 3.8 MW of 81 keV deuterium beams that are injected in the midplane in the direction of the plasma current and by 1.0 MW of 2^{nd} harmonic, central electron cyclotron heating.

Numerical setups. - The DIII-D discharge #178631 is studied numerically through gyrokinetic simulations with the GTC code [7], and with kinetic-MHD simulations using the M3D-C1 [23] and XTOR-K [24] codes. The magnetic configuration at $t=1580\text{ms}$ is reproduced from the EFIT code [25]. Plasma profiles are obtained from TRANSP [26] simulations using experimental measurements. To ensure that the sum of pressures of all species from TRANSP equals to the total pressure in EFIT, the EP pressure is constrained as $p_f = p_{tot} - p_i - p_e$, given that the uncertainty on EP profiles is the highest in TRANSP. The experimental NBI distribution is reproduced from the NUBEAM [27] code. Such a distribution is described in our first-principle simulations using an anisotropic slowing-down model [28]. A superposition of three slowing-downs is used to reproduce the injection energies at nominal, half and one-third energies. The critical velocity is adjusted to recover similar gradients in the $(E, v_{||}/v)$ phase space. All nonlinear simulations cover the core region including the magnetic axis, with an edge buffer after $\rho_T = \sqrt{\psi_T/\psi_{T,edge}} = 0.8$ in GTC where equilibrium gradients are removed, with ψ_T the poloidal flux. GTC gyrokinetic simulations retain only the $n=1$ mode, with or without the $n=m=0$ zonal flows, and use gyrokinetic thermal/fast ions and fluid electrons. Electron contribution to zonal density is neglected based on their adiabatic response. M3D-C1 kinetic-MHD simulations incorporate low- n modes $n = 0, 1$ with both thermal and fast ions kinetic effects. XTOR-K kinetic-MHD simulation treats kinetically only the fast ion species in this work. Due to the anisotropic nature of the chosen configuration that has $\beta_f/\beta_{tot} = 54\%$ on axis, where β is the ratio between thermal and magnetic pressures, only the $n=1$ mode is evolved in XTOR-K simulations, since the $n=0$ mode contains both equilibrium and perturbed fields in the code. Convergence studies over spatial grid size, time step and number of particles per cell have been successfully conducted. These three codes have been rigorously verified and validated for simulations of the kink instability in another DIII-D experiment [29].

Fishbone saturation by self-generated zonal flows - Both gyrokinetic and kinetic-MHD simulations find that the internal kink mode is stable in the absence of fast ions, and that the fishbone

is driven unstable by EPs in this DIII-D experiment. The $n=1$ fishbone mode is linearly unstable, with a marginal stability threshold at $p_{f,thres} = 0.8p_f$, a growth rate of $\gamma_{n=1} = 8.5 \times 10^4 \text{ s}^{-1}$ and a mode frequency of $\omega/2\pi = 17\text{kHz}$ in GTC simulations. When the realistic beam is replaced by its equivalent Maxwellian distribution, this mode is fully stabilized, showing the sensitivity of fishbone instabilities to EP distributions. The effects of MHD nonlinearities on the $n=1$ fishbone were previously examined in kinetic-MHD simulations by keeping side-band $n=0-4$ modes, indicating reduction of initial saturation amplitude [4][17] by additional dissipation, and generation of $n=m=0$ zonal flows [5][17]. The specific role played by zonal flows in the fishbone saturation was however not identified, and kinetic thermal ions were not included. The effects of zonal flows on the fishbone instability are studied here self-consistently for the first time with gyrokinetic simulations. A gyrokinetic treatment of thermal ions is essential for a realistic description of zonal flows, to account for their residual level after collisionless damping [30].

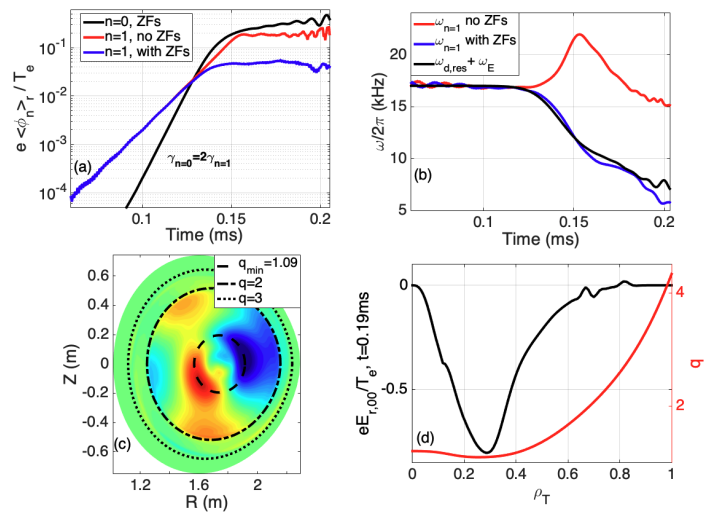


Figure 1: Time evolution of (a) volume-averaged perturbed electrostatic potential $e\phi/T_e$ ($n=0,1$), (b) $n=1$ mode frequency $\omega_{n=1}$ and linearly resonant precessional frequency $\omega_{d,res}$ plus zonal $E \times B$ frequency ω_E at q_{min} , in GTC simulations. (c) $e\phi/T_e$ in poloidal plane and (d) Radial profiles of safety factor q and zonal electric field $eE_{r,00}/T_e$ (a.u.) after saturation at $t=0.19\text{ms}$.

GTC nonlinear simulations are performed with and without the $n=m=0$ zonal flows, as illustrated in Fig.1. The time evolution of the volume-averaged electrostatic potential $e\phi/T_e$ shows that the $n=1$ fishbone mode generates $n=m=0$ zonal flows, with a growth rate twice that of the $n=1$ mode. Similar to that in TAEs [31], the zonal flows are force-driven through the fishbone mode coupling, rather than the modulational instability in the driftwave instability [32]. As the $n=0$ amplitude exceeds the $n=1$ mode at $t=0.13\text{ms}$, the fishbone saturates at $\delta B/B_0 \sim 2 \times 10^{-3}$, which is lower by a factor of 4 compared to the simulation without zonal flows. Zonal flows saturate at an even larger amplitude with a slower growth after $t=0.15\text{ms}$.

Zonal flows also reduce significantly the EP diffusivity at saturation, from 30 to 4 $\text{m}^2.\text{s}^{-1}$. As shown in Figure 1b, the mode frequency down-chirps in the laboratory frame after the $n=1$ mode saturation, which is a typical fishbone signature. In the simulation without zonal flows, the mode frequency chirps up right before the fishbone saturation but chirps down when the mode starts saturating. This initial up-chirping may be attributed to the larger mode amplitude near saturation that induces ideal MHD nonlinear effects [33]. The $n=1$ electrostatic potential and the $n=0$ radial electric field after saturation at $t=0.19\text{ms}$ are displayed on Fig.1c-d. The $n=1$ mode features a dominant $m=1$ harmonic centered around q_{min} , as well as a significant $m=2$ side-band that vanishes outside the $q = 2$ surface. The zonal electric field exhibits a macroscopic structure centered near q_{min} as well, which differs from the usual microscopic/mesoscopic scale observed with drift-waves/AEs-induced zonal flows. This electric field leads to a strongly sheared poloidal rotation in the electron direction, which is opposite to the $n=1$ fishbone propagation direction. This novel mechanism of fishbone saturation by self-generated zonal flows is supported by DIII-D measurements of the fishbone amplitude shown in Fig.2.

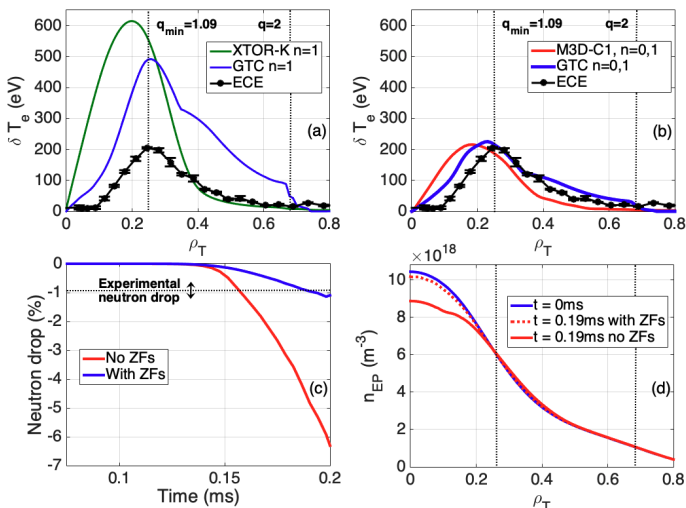


Figure 2: Radial envelope of electron temperature perturbation δT_e after saturation without (a) and with (b) zonal flows in GTC, M3D-C1 and XTOR-K simulations, compared to ECE measurement in DIII-D #178631. (c) Time evolution of neutron drop in GTC. (d) EP density profiles in GTC simulations before and after fishbone burst.

The electron temperature perturbation envelope δT_e obtained from GTC, M3D-C1 and XTOR-K nonlinear simulations at saturation are compared with the ECE measurements [34] on Fig.2 (a-b). The δT_e envelope is defined here as the sum of all poloidal harmonics for the $n = 1$ mode. Without zonal flows, XTOR-K and GTC results have comparable saturation amplitudes with $\delta T_{e,max} \sim 500 - 600$ eV, which are three time larger than the experimental value. When including zonal flows, GTC saturation amplitude at $\delta T_{e,max} \sim 200$ eV matches well with the experimental one. M3D-C1 saturation amplitude also agree reasonably with both GTC and the ECE measurements,

qualitatively supporting the nonlinear gyrokinetic simulation of the fishbone mode. The significant $m=2$ harmonic outside the q_{min} surface in the GTC simulation leads to a quantitative agreement with the ECE measurement, which provides a nonlinear validation for GTC simulations. Nonlinear simulation scans over the radial position and amplitude of q_{min} using GTC all show the same significant saturation by zonal flows. This nonlinear validation is further demonstrated by comparing the simulated and experimental neutron emissivities. In GTC the volume-averaged neutron flux is defined as $\Gamma_N = n_i \sum_k \delta(\mathbf{x} - \mathbf{x}_{f,k}) \delta(\mathbf{v} - \mathbf{v}_{f,k}) \sigma(v_{f,k}) v_{f,k}$ with n_i the thermal ion density profile, x_k and v_k the position and velocity of EPs, and σ the D-D nuclear fusion cross section. As shown on Fig.2c, without zonal flows GTC exhibits a neutron drop of about 6%, much higher than the experimental one at $\delta\Gamma_N = 0.9\% \pm 0.3\%$. When including zonal flows in the simulation however, the neutron drop yields $\delta\Gamma_N \sim 1.1\%$, which agrees with the measurements within the experimental uncertainty. As expected from these neutron drop values, the fishbone-induced EP transport from the simulation with zonal flows is rather weak as shown on Fig. 2d, with about 3% of EPs inside of the q_{min} surface redistributed outward. The redistribution is more significant without zonal flows, as it affects 15% of EPs in the core plasma.

Mechanism for fishbone saturation by zonal flows - The EP phase-space analysis reveals that zonal flows influence the time evolution of coherent phase space zonal structures, thus impacting the $n=1$ fishbone mode saturation. On Fig.3, the instantaneous EP distribution evolution $\partial_t \delta f$ is displayed in the phase space diagram ($P_\zeta, \lambda = \mu B_0 / E$), with P_ζ and λ respectively the toroidal canonical momentum and the pitch angle, at fixed magnetic momentum $\mu B_0 = 45\text{keV}$ before and after the fishbone saturation. The time derivative is chosen rather than the usual perturbed EP distribution δf [5] since the fishbone mode frequency is chirping in the nonlinear phase, which causes phase space zonal structures to drift in time. In the linear phase, the mode is excited by two resonances, the precessional one $\omega = \omega_d$ due to trapped particles, and a drift-transit one due to passing particles $\omega = \omega_c - \omega_b$ with ω_c, ω_b the toroidal and poloidal transit frequencies, similar to [5]. As can be observed on Fig.3 (a-b), a hole and clump structure develops around each resonances in the late linear phase in both cases, indicating a resonant outward EP redistribution. In the nonlinear phase shown in Fig.3(c-d), the dynamical evolution of these phase space zonal structures differ significantly between the simulations with and without zonals flows. Without zonal flows, the hole and clump in the trapped region (around the red dotted line in Fig.3) nonlinearly drift to higher ψ positions due to the mode down-chirping since $\omega_d \propto 1/\sqrt{\psi}$, while the one in the passing part does not move. However with zonal flows, the phase space zonal structure in the trapped region remains static, even though the mode is chirping down. The hole and clump in the passing particle region vanishes. Therefore, zonal flows nonlinearly prevent the resonant interaction of the fishbone with EPs that are not linearly resonant with the mode, which leads to a weaker fishbone saturation due to the absence of additional drive. This novel physics of phase space zonal structures trapping by fishbone-induced zonal flows is reminis-

cent of the trapping of turbulence eddies by zonal flows in microturbulence.

These differences in nonlinear evolution can be explained by the influence of zonal flows on the EP wave-particle resonance.

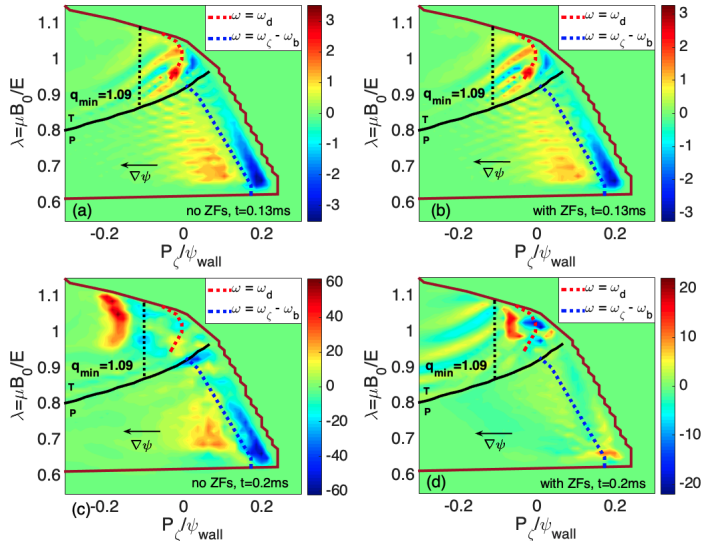


Figure 3: Instantaneous EP distribution $\partial_t \delta f$ in linear (top) and nonlinear (bottom) phases, without (left) and with (right) zonal flows in GTC simulations. Passing (P) and trapped (T) phase space zones are separated by a black line, and envelope of EP distribution at $\mu B_0 = 45$ keV is highlighted by a brown line.

The perturbed radial electric field associated with zonal flows generates a $E \times B$ frequency $\omega_E = \delta \mathbf{v}_E \cdot (mq \nabla \theta - n \nabla \zeta)$ which modifies the precessional resonance condition to $\omega = \omega_d + \omega_E$, as discussed in [5] and [6] (Eq. 4.182). As can be observed on Fig.1b, the time evolution of the precessional frequency of linearly resonant EPs plus the perturbed $E \times B$ frequency at $\rho = \rho_{q_{\text{min}}}$ matches almost exactly the time evolution of the fishbone frequency with zonal flows. Therefore the linear resonance condition is still satisfied despite the mode down-chirping in laboratory frame, which explains why the phase space zonal structure in the trapped region remains static. The $E \times B$ flow shear could also modify the EPs transit frequencies, which may account for the disappearance of the $\omega = \omega_\zeta - \omega_b$ hole and clump through resonance detuning. Zonal flows are therefore able to dominate the fishbone saturation by strongly reducing the resonant wave-particle drive.

Fishbone-induced ITB formation - Besides affecting the fishbone saturation, zonal flows also generate a strong shear within $\rho_T \in [0.1, 0.5]$, with an instantaneous shearing rate of $\gamma_E \sim 3 \times 10^5 \text{ s}^{-1}$. High-n electrostatic GTC simulations with kinetic trapped electrons were performed for this DIII-D configuration, finding that the most unstable drift-wave is a trapped electron mode (TEM) at $\rho = 0.4$, shown on Fig.4a, with a linear growth rate of $\gamma_{\text{TEM}} = 1.38 \times 10^5 \text{ s}^{-1}$. Since the shearing rate generated by the fishbone is larger than the TEM growth rate, the fishbone mode could then lead to turbulence suppression, confirming the speculated role of fishbones

in the formation of ITBs [18]. The evidence of this suppression is obtained experimentally in DIII-D with the ion temperature measurement using the charge exchange recombination spectroscopy (CXRS) diagnostic [35]. The formation of an ion ITB after fishbone bursts occurring at $t = 1581, 1594, 1607$ and 1615 ms can indeed be observed in Fig.4 c. The increase of the core T_i cannot be explained by the heating from the beam, as it was at constant power since $t = 300$ ms, for multiple slowing-down times before the onset of fishbones. Fishbone bursts were also observed to precede ITBs in four other DIII-D discharges with similar heating power, density, current and q_{min} parameters.

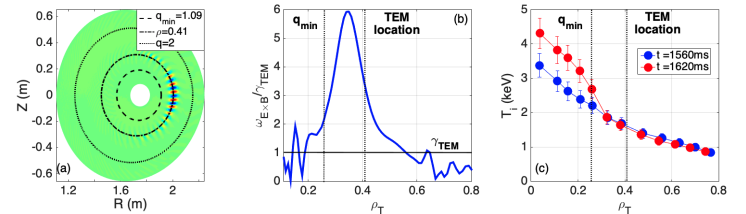


Figure 4: a) Electrostatic potential ϕ of unstable TEM in the poloidal plane in GTC simulation b) Fishbone-induced shearing rate profile after saturation c) T_i profiles before and after fishbone bursts from CXRS measurements in DIII-D shot #178631.

EP transport in ITER PFPO scenario - Building on the nonlinear validation, GTC is now applied to the selected ITER PFPO scenario with a 7.5 MA/2.65 T H-mode plasma heated by 33 MW of NBI and 20 MW of ECH [15], to predict the fishbone-induced EP transport. Similar to the DIII-D simulations, the EP beam is fitted from an analytical anisotropic slowing-down distribution. Linear GTC simulations show that the $n=1$ fishbone is unstable, with a mode growth rate and frequency of $\gamma = 4.4 \times 10^4 \text{ s}^{-1}$ and $\omega/2\pi = 48$ kHz, while simulations with equivalent Maxwellian distributions find a stable $n=1$ mode. Similarly to DIII-D simulations, zonal flows lower the $n=1$ fishbone saturation amplitude. The zonal electric field at the fishbone saturation peaks with negative values close to the q_{min} surface. Electrostatic GTC simulations were also performed for this ITER scenario, finding an unstable TEM at $\rho = 0.71$ with $\gamma_{\text{TEM}} = 3 \times 10^4 \text{ s}^{-1}$. At that location, the fishbone-induced shearing rate is three times larger than the TEM linear growth rate, suggesting that an ITB could also be triggered for this ITER PFPO scenario.

After the end of the fishbone burst in the simulation without zonal flows, the overall redistribution within q_{min} is of order 2% of the initial distribution, which gives an upper-bound for the EP redistribution by the fishbone. Overall, the NBI fishbone should not impact significantly the plasma heating of this ITER PFPO scenario, similar to what was shown for the alpha-fishbone in the ITER 15MA baseline DT scenario [5]. Longer GTC simulation times will be needed for a realistic evaluation of the EP and thermal transport, which will also require cross-scale couplings between microturbulence and MHD modes [12]. *Discussion* - Since fishbone oscillations may not cause significant EP redistribution in ITER plasmas, it can be of great interest to design ITER scenarios triggering them on purpose

rather than avoiding them. As was shown in this Letter, fishbones can generate strongly sheared flows that can damp drift-wave instabilities and hence reduce the turbulent transport. While it was observed here and in several other tokamaks [19][20][21][22] that fishbone oscillations can lead to ITB formations, that was not the case in some others such as JET [36], despite efforts to reproduce the fishbone-induced ITB formations observed in ASDEX plasmas [19]. There may therefore exist a parametric dependency for the fishbone instability that controls the emergence of strongly sheared zonal flows. The computational prediction and experimental observation of such a dependency could enable the creation of high-performance scenarios, of crucial importance for ITER burning plasmas.

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