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Experimental and modelling study of locked mode dynamics prior to disruptions in high performance JET plasmas

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Error fields (EF) locked modes (LM) and initially rotating tearing modes, which finally lock due to the presence of un-intended 3D magnetic fields, can severely affect plasma performance and access to the full operational space in present magnetic fusion devices and in ITER. Identification of EFs and determination of robust methods for LM avoidance is thus of crucial importance, especially when the rotation shielding mechanism is not available, i.e. during the plasma ramp-up and plasma termination phases. An investigation of the LM dynamics during such critical plasma phases has been carried out in JET high performance plasmas, proving the tendency of the mode to lock to the intrinsic EF phase, finally leading to a plasma disruption. The use of EF correction coils is proposed as a promising candidate for LM avoidance, based on the actual LM spin-up obtained during 2006 EF correction studies.

Locked mode dynamics in high performance JET plasmas. Both baseline and hybrid plasma scenarios investigated in JET ITER-like wall tokamak are characterized by the presence of an unstable rotating mode that slows down, due to wall image currents, and then

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[*] See the author list of Joffrin E. et al 2019 NF 59 https://doi.org/10.1088/1741-4326/ab2276, [1] Pucella G. et al *Early disruptions in shear reversal plasmas on JET*, 46th European Physical Society Conference on Plasma Physics, July 8-12, 2019, [2] Brunetti D. et al 2011 Eur. Phys. J. D **64** 405, [3] http://w3/pppl/gov/share/help/tranps.htm, [4] Fitzpatrick R. et al 1993 NF **33** 1049, [5] Fishpool G.M. et al 1994 NF **34** 109, [6] Zanca P. et al 2015 NF **55** 043020, [7] Wesson J., *Tokamaks*, Oxford University Press, [8] Militello F. et al 2006 PoP **13** 112512 [9] Arcis N. et al 2007 PoP **14** 032308

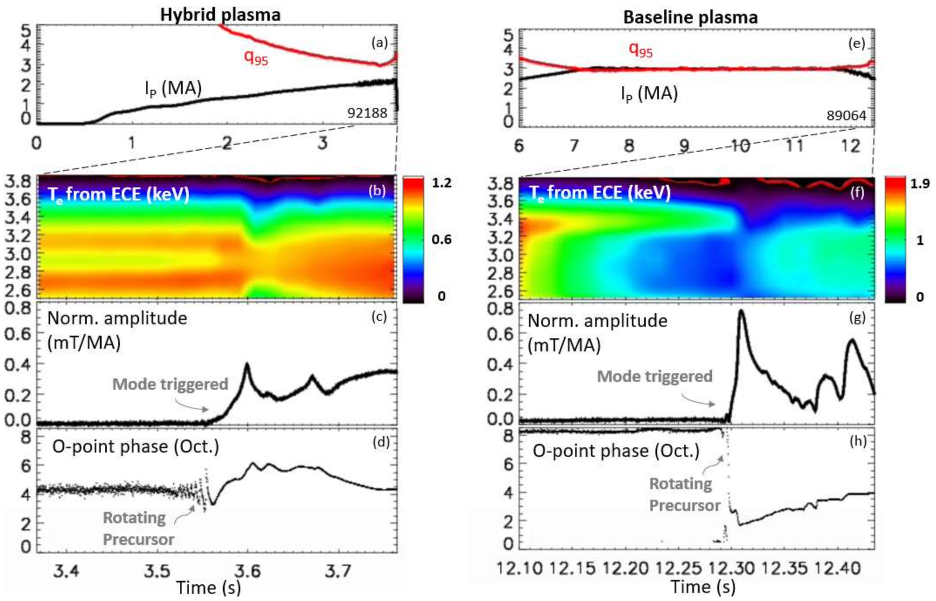

Figure 1: Time evolution of (a-e) plasma current (in black) and q95 (in red), (b-f) T_e profiles from ECE diagnostic, (c-g) n=1 normalized mode amplitude and (d-h) O-point mode phase inferred by saddle loops, located outside JET vacuum vessel. Panels on the left refer to 92188 hybrid discharge, the panels on the right to 89064 baseline discharge.

finally locks causing disruption mitigation valve (DMV) triggering.

The locked mode (LM) is observed when the plasma performance is already compromised. For example, in the discharges reported in figure 1, plasma performance is degraded by core impurity accumulation, which is observed during the plasma ramp-up phase in the hybrid plasma and during the plasma termination phase in the baseline plasma. A core impurity accumulation event causes temperature (T_e) collapse, formation of hollow T_e profiles, as shown in figures 1(b-f), and triggering of an n=1 LM, whose amplitude normalized to plasma current and O-point phase, i.e. the toroidal angle at which the island O-point lies on the outboard mid-plane, are reported in figures 1(c-g), (d-h), for a hybrid and for a baseline plasma, respectively.

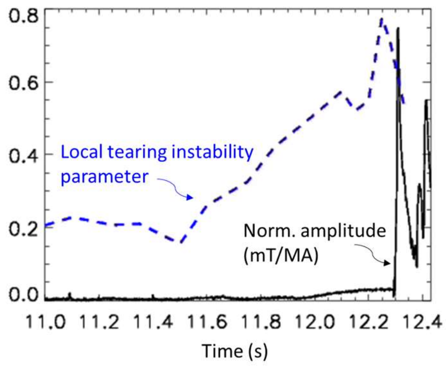

Figure 2: Time evolution of the computed local tearing instability parameter at q=2 (in blue) and the normalized mode amplitude (in black) of the baseline plasma reported in figure 1.

It is thought that the change of current density gradient, ∇j, at q=2, associated with the formation of hollow T_e profiles, is the drive of the instability. Indeed, the local tearing instability parameter, i.e. $\lambda = -0.5\, r_s R\, \mu_0\ \nabla j/n\, s\, B_t$ (where r_s is the resonant

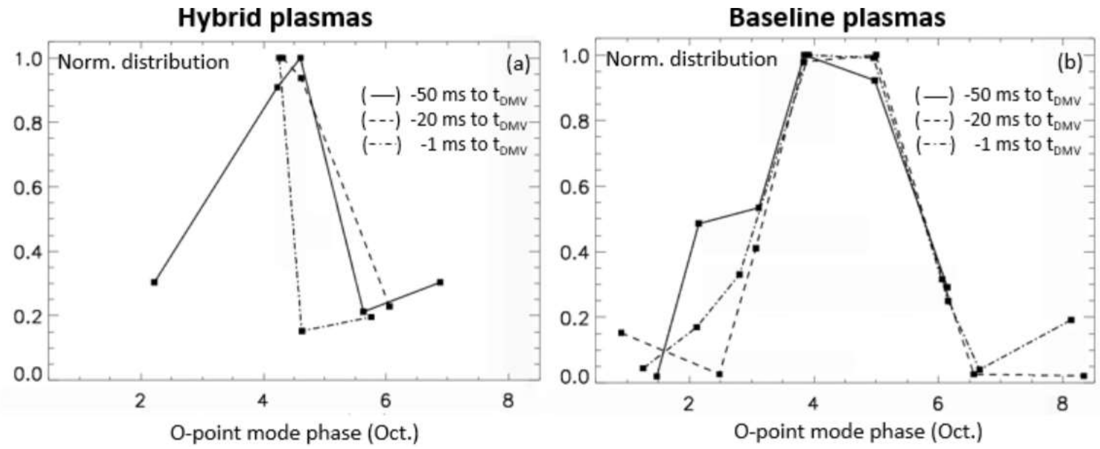

Figure 3: Normalized distribution of O-point mode phase of (a) hybrid plasmas and of (b) baseline plasmas, at various instants of time from DMV triggering (t_{DMV}). The statistics refer to 70 baseline discharges and 12 hybrid discharges with different plasma currents and toroidal magnetic fields.

radius, R the magnetic axis radius, n the toroidal mode number, s the magnetic shear, and B_t the toroidal magnetic field) [2], computed for the baseline plasma reported in figure 1, from EFIT++ and TRANSP [3] outputs neglecting shaping effects, sharply peaks approaching the mode onset, as shown in figure 2. However, maintaining the mode into rotation has a stabilizing effect since in this case the wall acts as a perfect (stabilising) conductor [4]. Identification of control strategies for LM avoidance is thus of crucial importance to reduce disruptivity in JET and ITER scenarios.

To this aim, a systematic characterization of LM dynamics in hybrid plasmas, during plasma ramp-up, and in baselines plasmas, during plasma termination, has been carried out by analysing saddle loops and T_e radial profile signals. Such a study revealed that the mode is more prone to be located at certain toroidal locations, i.e. octants 4-5, as shown in figures 3, which represent the normalized distributions of the O-point mode phase at various instants of time from DMV triggering. This confirms the presence of an intrinsic error field (EF), associated with asymmetries in the poloidal field coils [5]. The electro-magnetic torque exerted by the EF acts to decelerate the mode rotation, causing mode amplitude increase until the DMV triggering.

Use of error field correction coils for mode locking avoidance. The compass scan technique, using JET's 4 EF correction coils (EFCCs) to apply variable phases, has been exploited in the past (2006) to identify the intrinsic EF and deduce the corresponding optimal correction currents for EF compensation. In the I_p = 1.5 MA, B_t = 1.6 T Ohmic discharge with ITER-like configuration reported in figure 4, currents in EFCCs have been ramped up to the

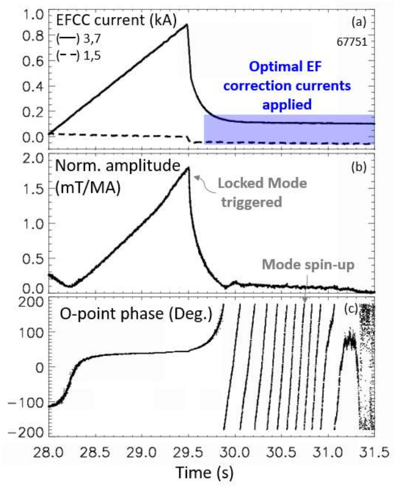

Figure 4: Time behaviour of (a) EFCC currents, (b) n=1 normalized amplitude and (c) O-point phase.

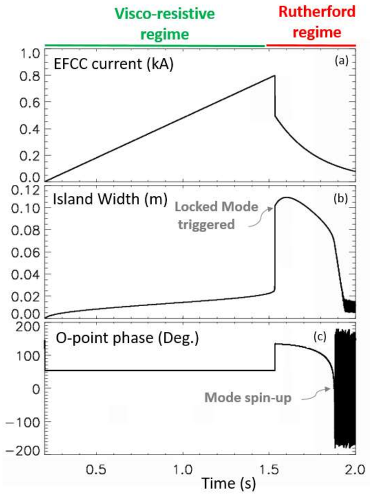

Figure 5: Time evolution of modelled (a) EFCC current, (b) island width and (c) O-point phase. Δ' formula as in [7] has been used.

formation of a LM. Afterward, the optimal correction currents for EF compensation has been applied to test the effectiveness of the EF control strategy. A LM spin-up, with uniformly varying phase, has been observed by compensating the EF, as shown in figure 4(c), proving that the EF control strategy is able to avoid the LM.

To simulate the mode un-locking mechanism, the cylindrical RFXlocking code [6] has been adapted to JET tokamak configuration. The linear-resistive regime [4] has been applied to model the external magnetic field penetration and the LM formation, while the Rutherford regime is used to model the subsequent magnetic island (Δ') evolution. Independently of Δ' formulas used [7,8,9], RFXlocking modelling, reported in figure 5, shows that the LM width decreases by reducing the external magnetic field and the mode eventually starts to rotate below a threshold value of the external field: in the experiment this condition is realized by a proper compensation of the intrinsic EF.

Discussion and outlook. A systematic analysis of LM dynamics before DMV triggering in baseline and hybrid JET plasmas highlights the tendency of the mode to lock at the intrinsic EF position, i.e. octants 4-5. Spin-up of an induced LM observed when correcting the intrinsic EF supports the exploitation of EFCC system to avoid disruptions induced by LMs in future JET campaigns.

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