Saturated internal instabilities in advanced tokamak plasmas

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'Advanced tokamak' (AT) scenarios were developed with the aim of reaching tokamak steady-state operation. They are designed to optimise the self-generated current, whilst also reaching sufficiently high plasma pressure to achieve optimal fusion reaction rates. AT scenarios exhibit non-monotonic to flat safety factor profiles (q, a measure of the magnetic field line pitch), with the minimum q (q_{min}) slightly above an integer value (q_s). This has the additional benefit of avoiding deleterious magnetohydrodynamic (MHD) instabilities. Nonetheless, it has been predicted that these q profiles are unstable to ideal MHD instabilities as q_{min} approaches q_s. These ideal instabilities, observed and diagnosed as such for the first time in MAST plasmas with AT-like q profiles, have far-reaching consequences like confinement degradation, flattening of the toroidal core rotation or enhanced fast ion losses. These observations motivate the analysis of the stability of advanced tokamak plasmas, with a view to provide guidance for stability thresholds in AT scenarios. Additionally, the measured rotation damping is compared to the self-consistently calculated predictions from Neoclassical Toroidal Viscosity theory.

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A potential tokamak power plant would greatly benefit from steady-state operation and a high ratio of plasma stored energy to magnetic energy. This ratio can be defined as $\beta = 2\mu_0 \langle p \rangle / B_0^2$, with $\langle p \rangle$ the volume average pressure and B_0 the central toroidal magnetic field. In baseline tokamak scenarios, the main contribution to the internal toroidal plasma current is inductively driven, meaning that the poloidal magnetic field can only be maintained for a limited duration. Reaching steady-state operation therefore requires exploiting non-inductive current drive. Consequently, the objective of 'advanced tokamak' (AT) scenarios [1, 2] is twofold: optimising the non-inductive, self-generated 'bootstrap' current and sustaining high plasma β. The bootstrap current is predominantly driven off-axis, hence significantly altering the magnetic field pitch angle, expressed in terms of the safety factor (q, the inverse average pitch angle). In advanced tokamak plasmas, it provides more than half of the total current, producing q profiles with shear ranging from weakly reversed (with off-axis minimum), to broad and low in the core. Here, the magnetic shear is defined as $rq^{-1}dq/dr$, with r the minor radius. These profiles, together with the high β characteristic of AT scenarios, render the plasma prone to the deleterious resistive wall mode instability [3]. Fortunately, it was shown that AT plasmas can be sustained above this 'no-wall' β stability threshold with the help of sufficiently high toroidal rotation [4], feedback control [5] or the interaction with energetic particles [6]. The relatively low fraction of core current helps to maintain the minimum value of q profile (q_{min}) above an integer value q_s, meaning $\Delta q = q_{min} - q_s > 0$, for example preventing the sawtooth instability from occurring at $q = 1$ [2]. Similarly, neoclassical tearing modes (NTM) occurring at low order rational q surfaces are avoided [2]. It has however been predicted that AT plasmas can become unstable to ideal MHD modes when Δq approaches zero [7, 8]. For the first time, such instabilities have been observed as long-lived saturated modes in MAST plasmas with reversed shear q profiles and positive Δq close to zero. These modes significantly deteriorate the confinement, damp the core rotation and enhance fast ion losses. This letter details the analysis of these saturated instabilities and their consequences from a theoretical, modelling and experimental point of view. Such consistent understanding provides guidance for stability thresholds of AT scenarios and may shed light on saturated long-lasting modes in other tokamaks.

In MAST, AT-like q profiles are obtained in low density discharges heated by neutral beam injection (NBI). In these plasmas, high core temperatures result in a decreased resistivity, delaying the penetration of the inductively-driven current into the core and thus creating a weakly reversed q profile (figure 1). The latter is obtained from an EFIT equilibrium reconstruction [9], constrained to pressure profiles deduced from Thomson Scattering (TS), Charge eXchange Recombination Spectroscopy (CXRS) and Z_{eff} measurements, and the magnetic pitch angle profile from the newly installed Motional Stark Effect diagnostic (MSE), with a spatial resolution ≤ 2.5cm ($< 5\%$ of the minor radius). In these plasmas, Δq decreases slowly to become close to zero for most of the discharge. Despite the uncertainty inherent in the EFIT reconstruction, there is great confidence that Δq stays positive, ie the q profile is above 1, since otherwise the sawtooth instability is predicted to be unstable. The early phase of the shot often exhibits frequency chirping fast ion driven instabilities, also known as 'fishbones', of toroidal periodicity $n = 1$. As Δq evolves towards zero, a saturated long-lived mode (LLM) is ob-

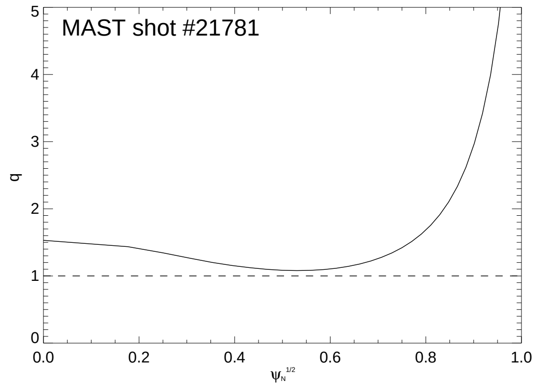

FIG. 1: An AT-like q profile obtained on MAST, prone to a long-lived saturated MHD instability.

served on outboard mid-plane magnetic probe measurements, and persists until the termination of the plasma, ie for several confinement times or $\sim 10^6$ Alfvén times (figure 2). Simultaneously, a degradation of energy confinement occurs, together with a flattening of the rotation profile measured by CXRS, and enhanced fast-ion losses, as indicated by counter-viewing bolometer data. It is also worth noting that the LLM is not observed for low β plasmas.

Although saturated modes are most often resistive (ie associated with tearing of magnetic surfaces and reconnection to form magnetic islands [10]), experimental data give no evidence of magnetic reconnection. No local flattening is detected on high resolution TS profiles. Additionally, the Soft X-Ray (SXR) emissivity is predominantly dependent on electron temperature, the perturbation of which changes sign across a magnetic island. In the presence of an island and without impurity accumulation in it, the SXR channels viewing either side of it would therefore exhibit a π phase inversion, as is indeed observed in the presence of NTMs in MAST. This is however not the case in discharges with the LLM. It can therefore be asserted with some confidence, that the LLM is an ideal mode. Simulation of the fluctuations of SXR data induced by the mode show that the eigenstructure of the LLM is consistent with that of an $(m, n) = (1, 1)$ internal kink mode. The value of the toroidal field was experimentally scanned in order to modify the evolution of the safety factor, although this also changed other parameters, for example β. In low toroidal field discharges, the entire q profile was lower and Δq approached zero earlier than in high field discharges. The onset of the LLM was consistently observed earlier despite lower β, which corroborates the existence of a Δq threshold for the triggering of the mode.

AT-like q profiles are predicted to be ideally MHD-unstable. Theory analysing the reversed shear q profile indicates that it is prone to the $(m, n) = (1, 1)$ internal kink mode [7]. The mode is unstable, even at zero β, for Δq under a critical value Δq_{crit} calculated analytically for low inverse aspect ratio plasmas in [7]. This mode saturates non-linearly if the q profile remains above 1 [11]. The mode being ideal, the saturation occurs when the stabilising field line bending term balances the mode's fluid drive. Theory focusing on flatter core q profiles predicts such plasmas to be unstable to low (m, n) internal kink-ballooning instabilities, called infernal modes [8, 12], the most unstable modes having $m = n$ when $\Delta q \sim 1$. These modes also feature a critical value of Δq under which they are destabilised [7, 8]. This critical value decreases with the n number, whereas the mode's growth rate increases with it at $\Delta q \sim 0$. Infernal modes in AT plasmas have been the subject of much theoretical research [12, 13] and found to disrupt plasmas in several tokamaks [14–16].

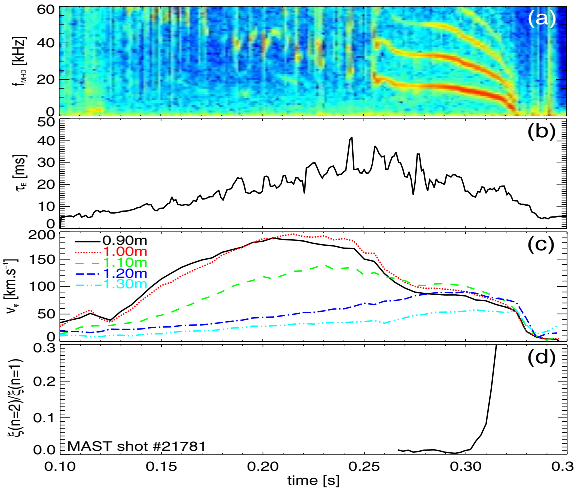

FIG. 2: (a) The spectrogram of outboard magnetic probes measurements for a MAST plasma featuring the LLM. (b) The energy confinement time as calculated by TRANSP. (c) Plasma velocity at different major radius positions (magnetic axis at $R = 0.95$m). (d) The amplitude ratio of the $n = 2$ component to the $n = 1$ component for the LLM.

Both the internal kink and infernal modes are very similar in their drive, structure and threshold, differing only in the core magnetic shear assumed to derive their respective theories. Since the q profile in LLM plasmas evolves from reversed to flat shear, it seems unnecessary to distinguish between these modes in the following discussion. These modes are more unstable in tight aspect ratio geometries, making MAST ideally-suited to study them. Their predicted triggering below a certain Δq and their structures are in excellent agreement with experimental manifestations of the LLM. Assuming that the $n = 1$ and $n = 2$ components of the experimentally observed LLM both resonate at the q_{min} surface, the relative amplitude of these components can be inferred from the peaks in the SXR spectrogram. These show that the $n = 2$ component is not detected at LLM onset, whereas

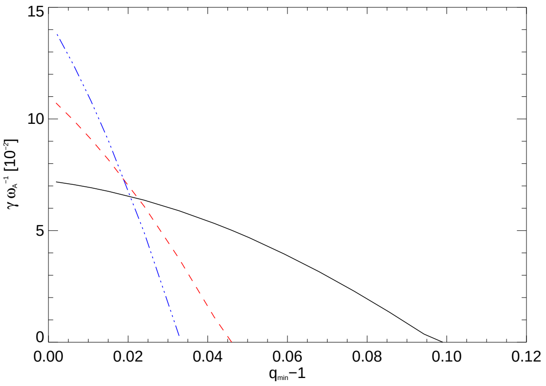

FIG. 3: The growth rates of the $n = 1$ (plain), $n = 2$ (dashed), and $n = 3$ (dashed-dotted) modes as a function of q_{min} for shot 21781 at mode onset. The profile is varied by scanning the toroidal field given as input to the MISHKA-1 MHD code.

it appears and grows in amplitude as Δq decreases (figure 2). Whilst the $n > 1$ modes arise as a nonlinear consequence of the $n = 1$ mode, the change in their relative amplitude is likely to occur because of a resonant field amplification effect [17] in the higher n harmonics as they become marginally unstable. Once their respective Δq_{crit} is reached, the $n > 1$ modes are destabilised and grow. Since theory suggests that the $n = 1$ mode is unstable at larger Δq than instabilities with $n > 1$, but that the latter dominate as Δq approaches zero, this gives increased confidence in the interpretation of the LLM as an ideal mode.

The linear stability of MAST plasmas with AT-like q profiles was analysed with the MISHKA-1 MHD code [18] for different toroidal mode numbers. For each n, the most unstable mode predicted by MISHKA-1 has a kink-ballooning mode structure with dominant $m = n$, a structure similar to that observed and those predicted by theory. In order to investigate the stability of equilibria with different Δq, the toroidal field given as input to MISHKA-1 was scaled accordingly. Figure 3 shows the growth rate of the $n = 1, 2, 3$ modes as a function of Δq. It is evident in this figure that Δq_{crit}, the critical stability threshold, decreases with n, whereas the mode's growth rate increases with it at $\Delta q \sim 0$, consistent with the theoretical features of the ideal internal modes presented above, and experimental observations. Furthermore, analysis also indicates that at low β, AT equilibria are linearly stabilised by toroidal plasma rotation. Since rotation in MAST can be a significant fraction of the ion sound speed, this helps to explain why low β AT-like plasmas do not exhibit the LLM. Similarly, other factors were also found to affect the stability of the ideal modes such as ion diamagnetic effects [19] or the presence of fast ions [20].

AT scenarios have also been found to be more unstable to fast-ion driven fishbone instabilities, with serious consequences for fusion performance in future fusion devices, as these instabilities could expel energetic α particles before they heat the plasma. AT-like MAST plasmas often feature bursts of fishbone instabilities, which cease at the onset of the saturated mode. For reversed shear plasmas with $\Delta q > 0$, the reduced Alfvén continuum damping at the q_{min} surface makes fishbones unstable at lower fast ion pressures. This increased susceptibility to fast ion-driven fishbones could be important in ITER where fusion-born α particles will provide a strong drive for the mode. Additionally, fishbones are found to be unstable at much higher Δq than the ideal mode. This is in good agreement with the experimental observation of an early fishbone phase followed by LLM onset, after which the fishbone activity stops due to the suppression of its drive by enhanced fast ion losses.

Following the onset of the LLM, the mode's rotation frequency remains constant while that of the plasma core is rapidly damped (figure 2). After this phase, both rotation frequencies gradually decrease, probably due to mode locking [21]. Electromagnetic torques can appear even in the absence of magnetic reconnection [22]. They are however localised around integer q positions, which, in discharges featuring the LLM, are located outside the region of rotation damping, and beyond mid-radius. While these torques may account for the slight edge rotation acceleration, they cannot explain the core damping, as MAST momentum confinement times ($\sim$ 50ms) do not allow such localised slowing down to diffuse into the core on the observed timescales ($\sim$ 5ms). In contrast, the distributed, fast damping mechanism by Neoclassical Toroidal Viscosity (NTV) theory [23], arising from the non-axisymmetry of the magnetic field, seems best suited to account for the observed braking. The saturated amplitude is estimated by comparing experimental SXR data to simulations for different eigenstructure amplitudes, enabling the calculation of the braking torque according to the NTV theory. Except at the inertial and rational surfaces, the results show strong similarities with the measured braking (figure 4). Here, the changes to the mode's eigenstructure as it saturates, likely to be small [11, 24], and the effect of enhanced fast ion losses are neglected. While previous work used NTV theory in plasmas with static external magnetic perturbations [25], calculating rotation damping due to saturated internal modes is a somewhat novel application for this theory, in which the response of the plasma to the magnetic perturbation is determined self-consistently. The equivalence to the static case is found by going to the frame co-rotating with the mode, the angular frequency of which is determined using the SXR data.

This letter reports the first analysed observation of a saturated long-lived mode (LLM) occurring in plasmas with advanced tokamak weakly reversed shear q profiles. Experimental data from MAST consistently indicate that

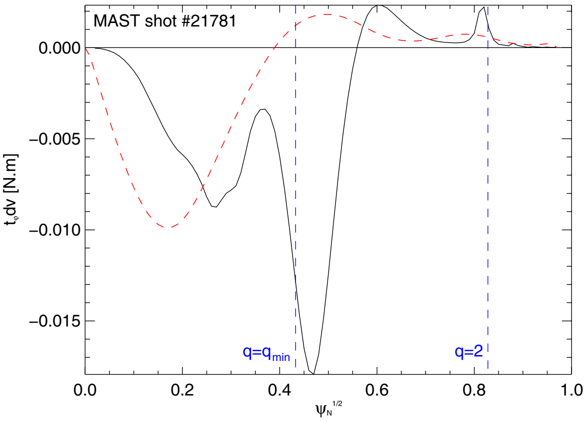

FIG. 4: The torque profile predicted by NTV theory (plain line) and the measured rate of change of angular momentum density (dashed line) for shot 21781 at mode onset.

this mode is of ideal-MHD nature. The LLM entails a significant confinement degradation together with the damping of core rotation and enhanced fast ion losses. These AT reversed shear plasmas also exhibit increased susceptibility to fast ion driven instabilities. All experimental observations, as well as linear stability analyses of MAST advanced tokamak equilibria, indicate that the LLM has the ideally saturated structure of the internal kink mode or the infernal modes analytically studied in [7, 8, 12]. In particular, the LLM is destabilised as q_{min} approaches an integer value, meaning $\Delta q \sim 0$, a characteristic feature of these ideal MHD instabilities. In the absence of rational surfaces to allow magnetic reconnection, the mode saturates when the field line bending stabilisation compensates the fluid drive. While Δq_{crit} at which these ideal internal modes are driven unstable is larger in tight aspect ratio geometries, making MAST a well suited device to study it, the present study could help improve the understanding of other performance-limiting long-lived saturated instabilities observed in various conventional aspect ratio machines. Such modes include the ‘continuous mode’ present in broad low shear $q_{min} \sim 1$ plasmas and reversed shear $q_{min} \sim 2$ plasmas in JET [26]. Similar MHD instabilities were also reported in FTU [27], NSTX [28, 29], JT-60U [30] and DIII-D [31], which emphasises the potential importance of the LLM, and of its improved understanding presented here.

The advanced scenarios deliberately avoid the introduction of low order q-rational surfaces, with the aim of prohibiting deleterious resistive MHD instabilities, such as sawteeth or neoclassical tearing modes, to occur. In the light of this study however, it also seems necessary for these scenarios to operate with a Δq large enough to avoid non-disruptive, performance degrading, saturated ideal MHD instabilities. This applies to ITER’s hybrid scenario especially, as it is designed to have a broad low shear region with $q_{min} \sim 1$. Due to uncertainties inherent in predicting the rotation or fast ion distribution in this future device, AT scenarios cannot confidently rely on the corresponding stabilising effects.

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