Massive Deuterium injection into an MHD active ASDEX Upgrade plasma

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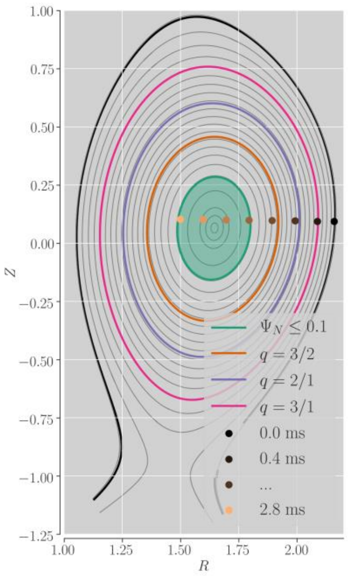
1. INTRODUCTION

Major disruptions are considered a serious threat for the successful operation of ITER, as they lead to mechanical and thermal heat loads, the generation of runaway electron beams, and vertical displacement events. This makes robust and thoroughly validated disruption mitigation scheme as the last line of defense necessary. Shattered pellet injection (SPI) is the main strategy for disruption mitigation. One scheme that targets the termination of runaway seeding, proposes to dilute the plasma by deuterium SPI prior to the TQ. Numerical studies have shown that fast dilution is possible without immediately triggering strong MHD activity that would lead to an early thermal quench (TQ).[1, 2] A late TQ or even no TQ (or, in other words: a long cooling time) here is favourable. In these simulations, SPI has only been applied to "healthy plasmas" that do not exhibit any prior MHD activity. However, in a real situation of disruption mitigation, the mitigation system might be triggered when the plasma is already MHD active, often exhibiting an m/n=2/1 (neoclassical) tearing mode (NTM) forming a pre-existing island structure.

In this study, we present the first set of global MHD simulations of Deuterium (shattered) pellet injection into an MHD active plasma. The focus of the work is to assess the possible implications for the strategy of plasma dilution prior to the TQ. Of interest are in particular injection parameters that are marginal for triggering a TQ shortly after plasma dilution has happened, as a possible detrimental effect of pre-existing islands is expected to be most relevant in this scenario. The physical mechanisms are investigated here while detailed experimental comparisons are left for future work.

2. SIMULATION SETUP

Simulations are performed with the non-linear extended MHD code JOREK[3]. Here a reduced MHD model with fixed boundary conditions is applied, that includes extensions for a neutral deuterium fluid and (shattered) pellet ablation. The toroidal direction is Fourier



decomposed and the toroidal modes n=0,…,7 are included. Radiative cooling by background impurities or stabilizing background rotation are not taken into account for simplicity. Simulations are based on a typical ASDEX Upgrade L-Mode equilibrium. The initial safety factor in the core, q_0=1.4, is well above 1, guaranteeing no intrinsic core instabilities.

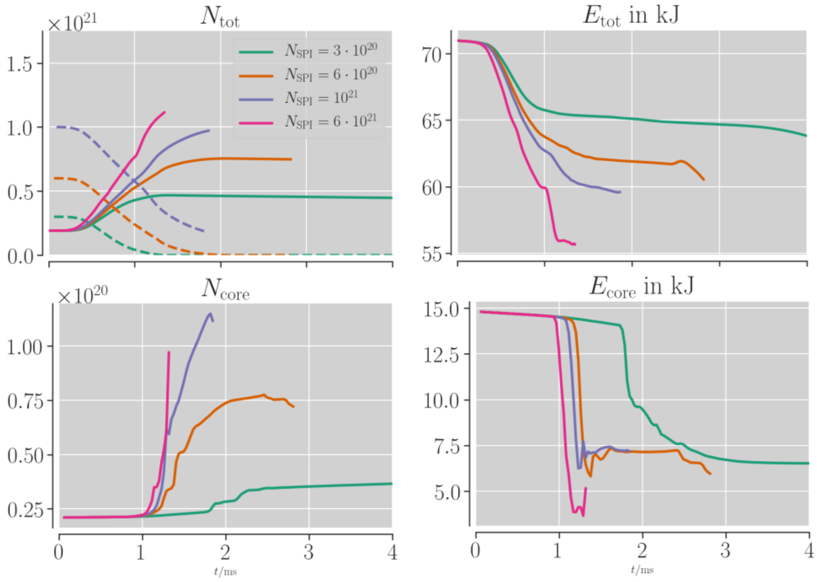
To initialize pre-existing magnetic islands of different sizes, a separate simulation is performed with an increased current gradient around the q=2 rational surface, that constitutes a configuration in which the 2/1 TM is classically unstable. The obtained locked magnetic island is imported from different time points into the original equilibrium and evolved self-consistently then to obtain different initial island sizes w_i=1cm,…,6 cm. A pellet broken into ten shards of equal size only is simulated to simplify deep penetration of the material. The pellet nozzle is positioned on the outer midplane and activated shortly after importing the magnetic island perturbation into the simulation. For the amount of injected atoms different values $N_{SPI}=3\cdot10^{20},\dots,6\cdot10^{21}$ are considered. The toroidal phase of the injection relative to the O-point is varied, where $\varphi_O=0°$ refers to injection into the O-point and $\varphi_O=180°$ into the X-point. Altogether, including simulations without pre-existing island (w_i=0 cm), more than 30 non-linear simulations are performed and analysed. Simulations are stopped at the time of full stochastization, i.e. at the onset of the TQ to save computing time. We investigate the local dynamics within the core region, which is defined as the volume inside the Ψ_N=0.1 surface of the initial equilibrium, by the core particle content N_{core} end thermal energy content E_{core} and compare them with the regarding total quantities N_{tot} and E_{tot}.

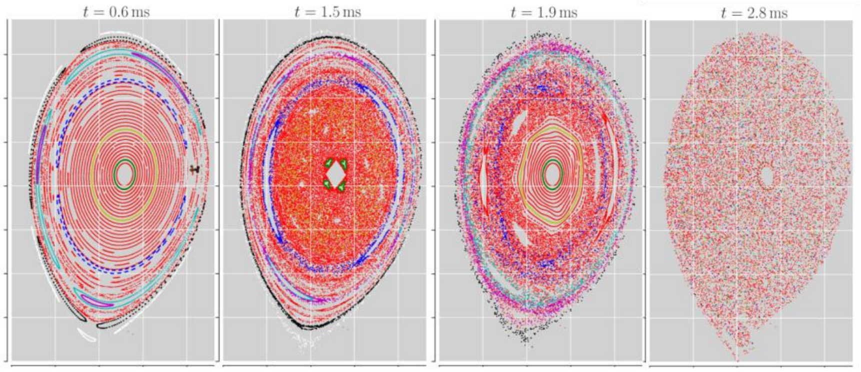
3. INJECTION INTO UNPERTRUBED PLASMA

To determine the effect of the injection itself, we first compare cases with w_i= 0cm and varying N_{SPI}. They can be categorized according to the observed dynamics:

- $N_{SPI}=3\cdot10^{20}$: we see a temporary degradation of the confinement. However, the MHD activity is not sufficient to trigger a true TQ.
- $N_{SPI}=6\cdot10^{20}$: The first impact onto N_{core} starts around t=1.2 ms followed by a partial crash. The plasma stabilizes after that and a full TQ only occurs with some delay at t=2.5 ms, when the shards are already fully ablated.

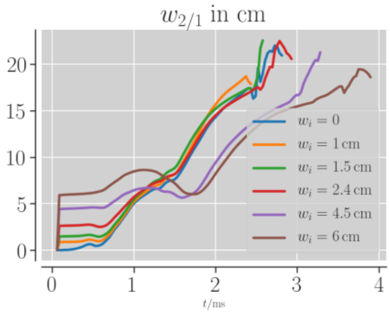
- $N_{SPI}=6\cdot10^{21}$: A full TQ is triggered at an early stage of the injection (t=1.1 ms), when the shards are still far outside the plasma core and only a fraction has been ablated.





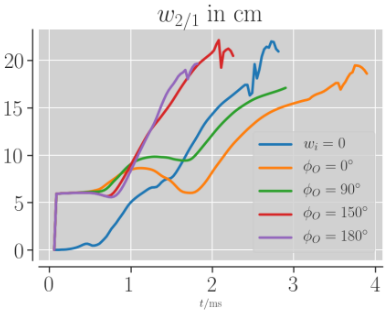
The case with delayed TQ after plasma dilution ($N_{SPI}=6\cdot10^{20}$) is the most relevant for this study and can be expected to be particularly sensitive to pre-existing MHD modes. Noteworthy, the 2/1 perturbation has dominant kink parity and the small associated island has the X-point in phase with the injection location when shards are outside the q=2 (t=0.4,…,0.7 ms). This is associated with a large pressure bump produced by the shards. After t=0.8 ms, the 2/1 NTM, driven by helical cooling, dominates and n=2,3 core modes are excited, leading to a first crash (t=1.2,...,1.5 ms). Due to the crash, the ablation cloud located around q=1.5 re-heats and hence produces a hollow pressure profile. Flux surfaces reform (t=1.9 ms) and the core continuously dilutes, while n=1 modes are successively growing. This ends up with full stochastisation (t>2.5ms) and the TQ.

4. INJECTION INTO THE O-POINT LOCATION FOR MHD ACTIVE PLASMA



For the case with $N_{SPI}=6\cdot10^{20}$, large island with w_i=6 cm delays the onset of full stochastisation by around 1 ms. Prior the first crash, which still happens around t=1.2 in all cases, the island grows due to helical cooling. For large islands, the island size then drops significantly in the following, leading to the delay of the further plasma dynamics. The reason for the decrease lies in a change in sign of the axisymmetric current density gradient at q=2 from the early phase already, which leads to a classical stabilisation of the mode up to t=1.9 ms. The effect of smaller islands than ~3cm onto the overall dynamics is negligible.

5. INJECTION INTO DIFFERENT PHASES WITH RESPECT TO THE ISLAND



A strong dependency of the dynamics onto the injection location is observed for $N_{SPI}=6\cdot10^{20}$. For X-point injection with a large island, the first crash directly leads into the TQ around t=1.6 ms, where n=1,2,3 modes are excited simultaneously. The axisymmetric current density gradient remains negative at q=2 explaining continuous 2/1 mode destabilization. In contrast, for O-point injection, where the TQ is delayed, the gradient gets transiently positive during and after the first crash. The origin of the different current profile evolutions requires further studies. In case of $N_{SPI}=3\cdot10^{20}$, a TQ is not triggered even with w_i=6 cm independently of the phase.

6. CONCLUSIONS

Results indicate that pre-existing islands do not render the dilution strategy ineffective. In case of large initial island sizes, the TQ might be delayed, for injection into the O-point, which is in favour for a long cooling time. However, the injection into the X-point may trigger the TQ earlier. Prior to the TQ, dilution is hardly affected by the pre-existing island. Simulations so far indicate that the TQ triggering threshold in the amount of injected deuterium is not strongly affected. Further studies are required to confirm this for ITER, where some of the involved time scales differ strongly. The role of background impurities, that might enhance island growth by radiative, helical cooling, is a subject of future studies.

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