Studying Incomplete Sawtooth Reconnection in ASDEX Upgrade with the Non-linear Two-fluid 3D MHD Code M3D-C^1

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First observed by von Goeler et al. in 1974 [1], the sawtooth instability has not yet been entirely understood. Sawteeth are macroscopic relaxation-oscillations affecting the core of tokamak plasmas. A sawtooth cycle starts with a ramp phase where the plasma core density and electron temperature increase slowly, which later is accompanied by the rise of a (m=1, n=1) helical perturbation and then is suddenly terminated by a fast drop of the core density and electron temperature. A detailed overview of this topic can be found, for example, in [2] and [3].

One attempt to explain the sudden temperature crash and the subsequent stabilization is B.B. Kadomtsev's model of complete sawtooth reconnection [4]. According to this model, the rising core temperature causes the safety factor (q) on axis to drop below unity which destabilizes the (1,1) internal kink leading to a (1,1) magnetic island. Surfaces of equal helical magnetic flux reconnect until the island has replaced the core yielding a stable configuration where the island O-point has become the new magnetic axis. The central temperature drop is explained by the hot core being expelled.

The complete reconnection model thus predicts the central safety factor to be unity after the sawtooth crash, which has been contradicted by measurement results in several tokamaks [5, 6, 7]. The observation of the (1,1) magnetic island surviving the crash while maintaining its radial position [8, 9] suggests that the temperature crash does not coincide with the island entirely replacing and expelling the hot core. The island seems to saturate before reconnection is complete.

A model explaining incomplete sawtooth reconnection would need to account for a reason for the saturation of the island as well as a mechanism that allows the fast heat flow out of the core during the crash. One possible explanation could be that mode coupling causes the magnetic field lines to ergodize on the q=1 surface starting at the island X-point. The enhanced perpendicular heat transport would allow a temperature exchange between the hot core and the colder surrounding plasma. The resulting flattening of the temperature profile at the resonant surface would then stabilize the pressure-driven contribution to the instability leading to a saturation of the island.

Our aim is to investigate the mechanisms underlying the phenomenon of incomplete sawtooth reconnection by means of 3D non-linear two-fluid magnetohydrodynamic simulations based on an ASDEX Upgrade tokamak [10] discharge. Typical sawtooth crashes in ASDEX Upgrade are followed by a (1,1) postcursor and the radial position of the q=1 surface is approximately the same before and after the crash. Our simulations are based on a typical example of such a sawtoothing ASDEX Upgrade discharge (#25854) which has been analyzed in [9].

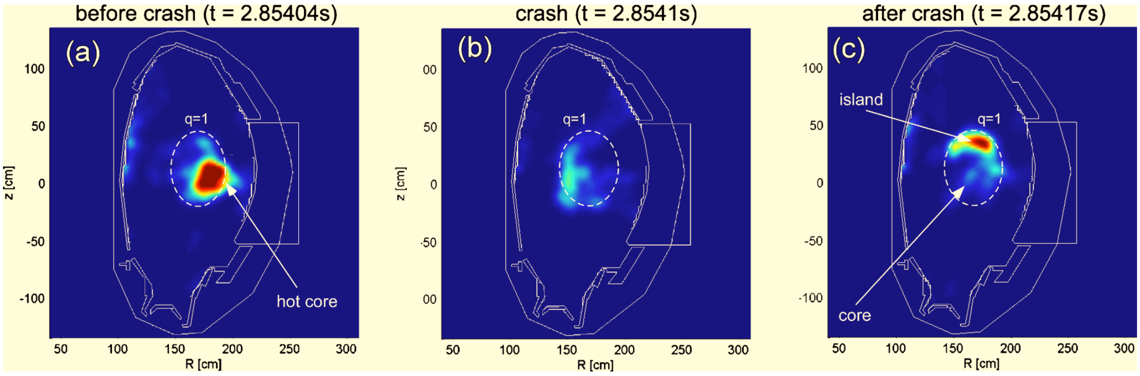

Figure 1: *Soft X-ray tomography before, during and after a sawtooth crash in ASDEX Upgrade discharge #25854. The color scheme is different for each figure. Reproduced with permission from [9]. Copyright 2010, AIP Publishing LLC.*

The soft X-ray system [12], consisting of 8 cameras providing about 200 lines of sight, and the 2D ECE Imaging system [13], covering a 12x40 cm area with 128 channels, give information about the evolution of the sawteeth in this discharge. Fig. 1 shows the soft X-ray emission before, during and after a sawtooth crash. Note that a different color scheme has been used for each time slice. Before the crash, the displaced plasma core shows as a rotating hot spot. The (1,1) perturbation which is seen in the soft X-ray tomography after the crash can be explained by a (1,1) magnetic island whose emission is slightly stronger than that of the core as the island contains plasma from inside the inversion radius. It can be seen that the q=1 surface does not significantly move radially during the crash.

While the soft X-ray diagnostic cannot resolve the time evolution of the crash, 2D ECE Imaging shows how the electron temperature evolves in the covered area during the crash. As can be seen in Fig. 2, the heat leaves the core through a narrow poloidally localized region. This localized heat flow out of the core and a (1,1) magnetic island surviving the crash and maintaining its radial position are the two key features that our simulations should qualitatively reproduce.

For the simulations the 3D non-linear two-fluid MHD code M3D-C^1 [11] is applied. M3D-C^1 uses high-order finite elements and a fully implicit time stepping scheme. Its unstructured mesh

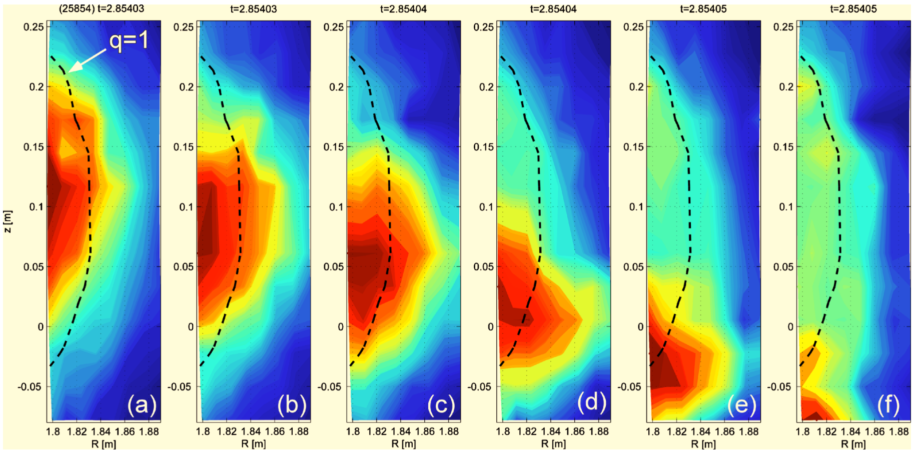

Figure 2: *2D ECE Images of a sawtooth crash in ASDEX Upgrade discharge #25854. Reproduced with permission from [9]. Copyright 2010, AIP Publishing LLC.*

in the poloidal plane can be refined locally and allows for complex geometries such as realistic vessel walls. An example of a grid that has been refined in the vicinity of a magnetic surface is shown in Fig. 3. M3D-C[1] is highly versatile providing options for 3D linear and 2D as well as 3D non-linear simulations. The code can either be run in cylindrical or in toroidal geometry and offers a choice of various MHD models ranging from reduced resistive MHD (two variables) to full two-fluid MHD (eight variables). The two-fluid model includes i.a. the Hall term and the diamagnetic term.

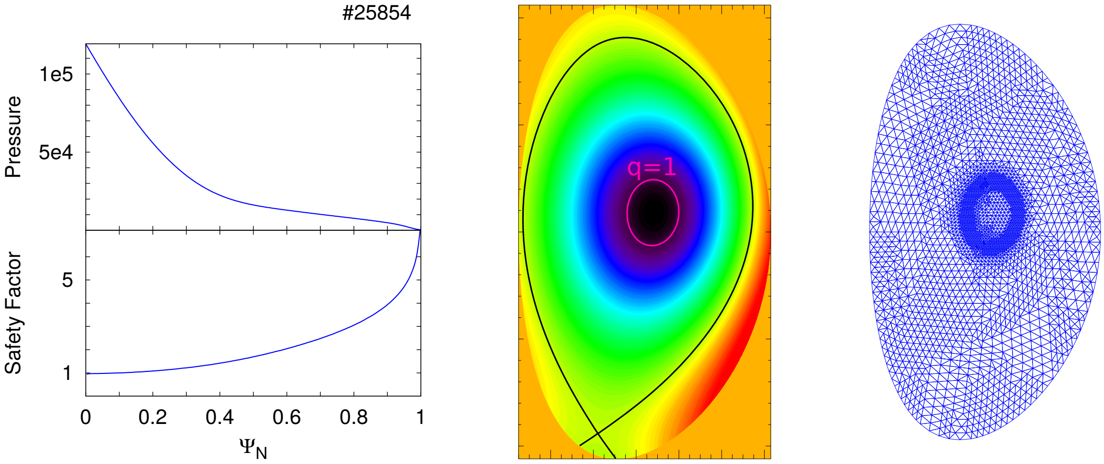

Figure 3: *Left: Equilibrium profiles and poloidal magnetic flux used for the simulations. Right: Unstructured mesh that has been refined around the resonant surface.*

In our case, the full two-fluid model in 3D toroidal geometry is used. The parameters are based on the presented ASDEX Upgrade discharge, except for the resistivity which has to be enhanced due to computational restrictions. The equilibrium has been set up from an equilibrium reconstruction of the discharge which has been generated using the CLISTE equilibrium code [14]. The corresponding equilibrium profiles and the poloidal magnetic flux are shown in Fig. 3. The transport coefficients have been calculated with the transport code ASTRA [15] and are adjusted by means of two-dimensional M3D-C^1 simulations.

If incomplete sawtooth reconnection is reproduced in the ongoing simulations, this will enable investigations on several interesting questions such as if stochastization is the mechanism that allows the fast heat release and what causes the island to saturate.

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