Magnetic reconnection rate during sawtooth crashes in ASDEX Upgrade

O. Samoylov[1], V. Igochine[1], Q. Yu[1], H. Zohm[1], and the ASDEX Upgrade Team[1]

[1]Max Planck Institute for Plasma Physics, Boltzmannstr. 2, 85748 Garching, Germany

Introduction Sawtooth oscillations are internal relaxation events in a tokamak, in which the heat and current in the core of the plasma are redistributed at regular intervals in time. A better understanding of sawtooth physics is beneficial to (i) the fusion research (in tokamaks, sawteeth may trigger neoclassical tearing modes, which deteriorate the plasma confinement and may lead to disruption [1]); and (ii) the magnetic reconnection research (as the reconnection has similar nature in space and laboratory plasmas [2]).

In this paper, we analyze the dynamics of sawtooth crashes in ASDEX Upgrade. Namely, we measure the radial velocity of the plasma core with the electron cyclotron emission imaging (ECEI) diagnostic [3]. The experimental results are compared with nonlinear two-fluid simulations using the TM1 code [4]. To our knowledge, the described approach of obtaining the radial velocity and comparing it directly with the simulation is novel.

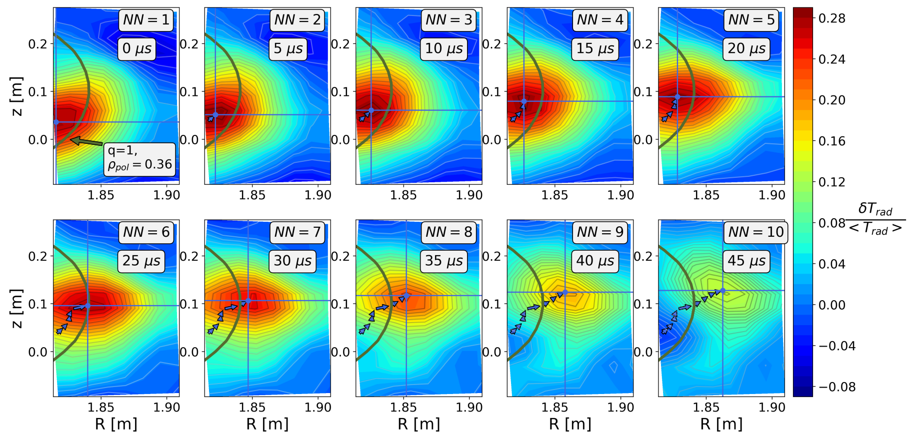
Description of the experimental measurement and the simulation An example of a sawtooth crash measured by the ECEI is shown in figure 1a. The blue arrows indicate the plasma core movement during the crash phase. Namely, the point with the maximum electron temperature is traced. In this work, the radial velocity V_{rad} of the plasma core during the crash is studied. For the $m/n = 1/1$ non-ideal internal kink mode, the radial motion of the plasma core corresponds to the growth of the magnetic island on the opposite side, as shown by the Kadomtsev model [5] and the numerical simulation results [4]. This island grows due to the magnetic reconnection as no other physical mechanisms can explain heat redistribution perpendicular to the magnetic equilibrium flux surfaces at such a fast time scale. Thus, the radial velocity V_{rad} of the plasma core during the crash can be used as a characteristic rate of the magnetic reconnection. This study consists of 6 well-diagnosed crashes from 3 discharges. For the plasma parameters of these discharges, the reader refers to [6].

The radial velocity V_{rad} is calculated as follows. In each time frame, the position of the plasma core is detected: (R_i, Z_i). The corresponding normalized poloidal flux ρ and poloidal angle θ^* are received from the magnetic equilibrium: $(R_i, Z_i) \rightarrow \rho_i, \theta_i^*$. The radial velocity in the flux coordinate system is:

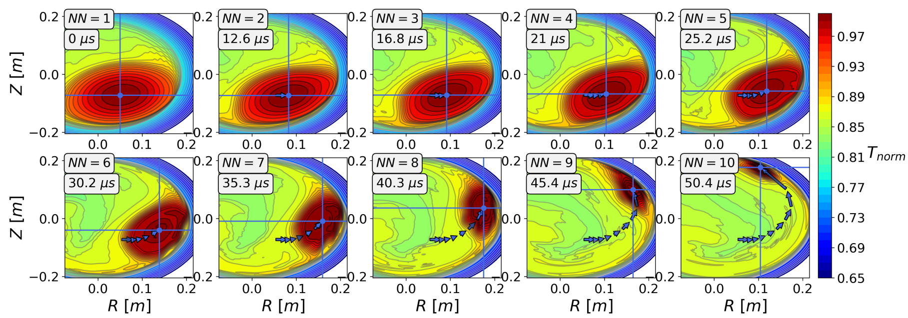
$$V_{rad} = \frac{(R_{Sep} - R_{Ax})(\rho_{i+1} - \rho_i)}{t_{i+1} - t_i} \quad (1)$$

where R_{Sep} and R_{Ax} are radial coordinates of the separatrix and the central axis, respectively; t_i is the time.

The nonlinear MHD code TM1 [4] is capable to simulate the sawtooth crash phase with realistic plasma parameters: Lundquist number S in the order of 10^8 (based on the total magnetic field); the ratio between the parallel and perpendicular heat conductivities $\chi_{\parallel}/\chi_{\perp} = 10^9$; plasma resistivity, electron pressure gradient and electron inertia terms are included in the generalized Ohm's law. The input parameters for the code are taken from the experimental data, more details in [6]. The simulation result and its plasma core velocimetry tracing are shown in figure 1b.



(a) ECEI data, #25775 $t = 2.064$ s, $T_e^{core} = 2.1$ keV



(b) nonlinear two-fluid simulation, $T_e^{core} = 2.1$ keV

Figure 1: *Tracing of plasma core movement during sawtooth crashes is shown for: (a) crash in ASDEX Upgrade measured with ECEI diagnostic and (b) nonlinear two-fluid simulation. Normalized fluctuation of electron radiation temperature* $\delta T_{rad}/ < T_{rad} >$ *is used in the ECEI plot. Normalized absolute electron temperature is used in the nonlinear simulation. R and Z correspond to the major radius and the vertical axis of the tokamak, respectively. The blue arrows trace the movement of the plasma core.*

Comparison of the experimental data with the simulation The size of the ECEI window can cover only part of the $q = 1$ surface as one can observe from the experimental measurements in figure 1a. Since only part of the sawtooth crash phase is observed, thus only part of the numerical simulation should be used. The plasma core displacement is used as the criterion for the correct comparison between the experimental data and the simulation. Namely, the simulation data with the displacement smaller than the experimental displacement have not been used (the very first time point in figure 1b: NN=1 corresponds to the minimal displacement observed in the experiment).

The comparison of the analyzed radial velocities during the sawtooth crashes is shown in figure 2. The average radial velocity lays in the range $1.5-6\ km/s$ in the experimental data, and in the range $2.3-3.8\ km/s$ in the numerical simulation. From this comparison, we conclude that the simulation gives realistic values of the outward movement.

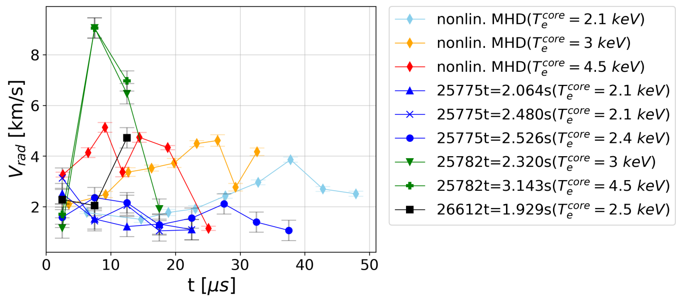
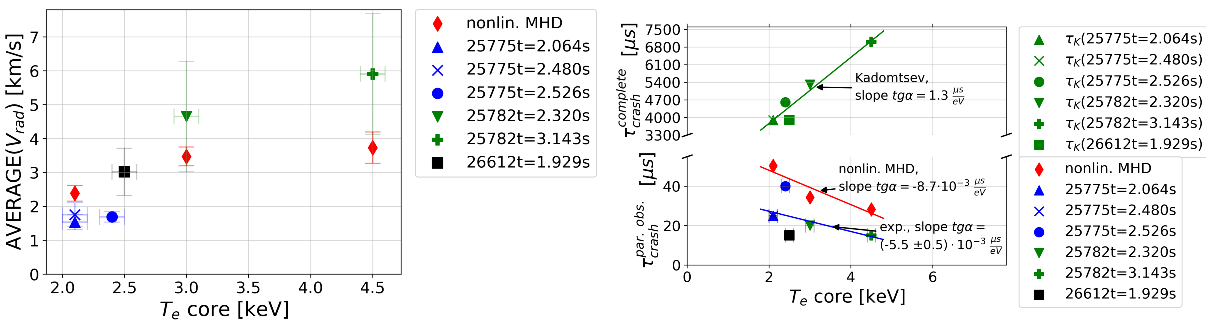


Figure 2: *Radial velocity plot during the sawtooth crash phase for 6 crashes in ASDEX Upgrade and three two-fluid simulations is shown.*

In general, the reconnection rate increases with the ion sound Larmor radius $\rho_s = \sqrt{\frac{k_B T_e}{m_i}}\frac{1}{\omega_{ci}}$ [7, 8, 9], where T_e is the electron temperature, m_i is the ion mass, ω_{ci} is the ion Larmor frequency. Since $\rho_s \sim \sqrt{T_e}$, we investigate a possible dependency of the average radial velocity $AVG(V_{rad})$ (which characterizes the magnetic reconnection rate) on the core electron temperature T_e^{core} in figure 3a. From this figure, one can conclude that the simulation matches with the experiment in terms of behavior ($AVG(V_{rad})$ grows with the increase of T_e^{core}) and quantity (the absolute values of $AVG(V_{rad})$).



(a) (b)

Figure 3: *The dependence of the averaged radial velocity $AVG(V_{rad})$ on the plasma core electron temperature T_e^{core} during sawtooth crashes is shown in (a). The dependence of the duration of partially observed sawtooth crashes $\tau_{crash}^{part.obs.}$ on the plasma core electron temperature T_e^{core} is shown in (b). Kadomtsev times of complete crash τ_K are calculated using the experimental parameters from the six crashes and are shown in (b). Straight lines represent a linear fit to the data.*

Finally, in figure 3b, the experimental and simulation crash times are compared between each other and with the Kadomstsev crash time τ_K [5]. τ_K is calculated using the experimental data (plasma densities, temperatures, displacements, poloidal magnetic fields, radii of $q = 1$ magnetic surface). The simulation points match the experimental data qualitatively and quantitatively. The prediction based on the Kadomtsev model gives wrong dependencies and its crash time values differ by two orders of magnitude compared to the experiment. This means that single-fluid Sweet-Parker type reconnection [10, 11] (which the Kadomtsev crash is based on) is not observed in the experiment. On the other hand, nonlinear simulations agree well with the experimental results. Thus, the physical model used in the simulation includes the necessary physics for a correct description of magnetic reconnection during a sawtooth crash.

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