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Structure of incomplete sawtooth crashes in ASDEX Upgrade

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Introduction

Investigation of sawtooth crashes in ASDEX Upgrade shows that in many cases the magnetic reconnection is not complete [1], which means that all complete reconnection models are in contradiction with experimental observations. It is shown that also some partial reconnection models are in contradiction with experimental observations in ASDEX Upgrade. In this situation, the stochastic model becomes a possible candidate for explanation of the sawtooth crash [2, 3].

Comparison of the q=1 positions before and after the sawtooth crash

Incomplete sawtooth reconnection is not only demonstrated the presence of the (1,1) mode after the crash, but it also allows one to determine the position of the q=1 surface after the crash. Three typical cases of incomplete sawtooth reconnection are shown in figure 1 where the FFT amplitude of the line integrated Soft X-ray signals is plotted versus the Soft X-ray line angle.

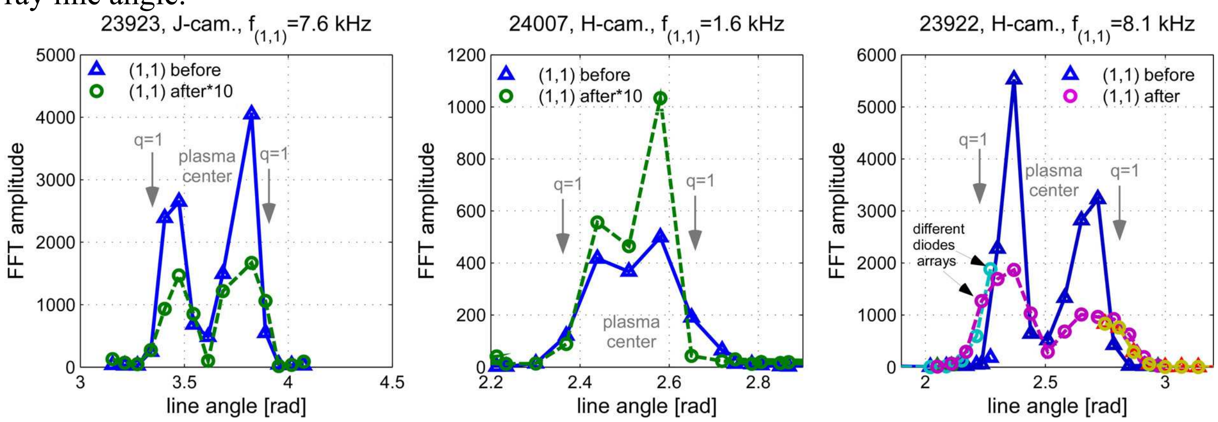

Figure 1. FFT amplitude of the (1,1) mode depending on the line of sight for three cases of incomplete sawtooth crash (#23923, t_{before}=2.1672704-2.1691394s,t_{after}=2.1724201-2.1738035s; #24007, t_{before}=2.9667013-2.9692684s, t_{after}= 2.9832781-2.9918858 s; #23922, t_{before}=2.6116926-2.6124464s,t_{after}=2.6130237-2.6136350 s). The frequencies of the (1,1) mode are different due to different heating power. One can see that pre-cursor (1,1) mode and post-cursor (1,1) mode give the same position for q=1 surface. In some cases, even a small increase of q=1 radius can be seen after the crash (#23922). No cases with reduction of the q=1 radius after the crash were observed. One global minimum in the plasma centre gives clear m=1 structure of the pre-cursor and post-cursor.

The sawtooth pre-cursor and sawtooth post-cursor correspond to the same position of the q=1 surface and the same m=1 structure (one minimum in the plasma centre). Moreover, in spite of the search for opposite behaviour, <u>no cases with pronounced reduction of q=1 radius were found</u>. This result is in clear contradiction with the Kadomtsev model which suggests q=1 after the crash only at the magnetic axis (see figure 2).

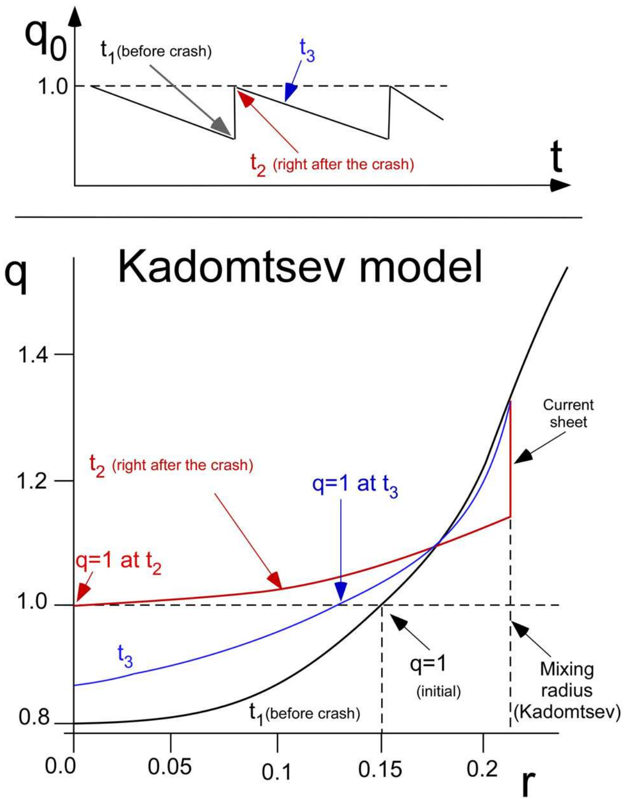

Figure 2. Kadomtsev model of the sawtooth crash. Evolution of the safety factor profile is shown. In the Kadomtsev model, the safety factor profile has q=1 at the magnetic axis after the crash (t_2). Thus, relaxation is accompanied by shift of the q=1 point from plasma centre to the original q=1 position (t_3). The jump in the safety factor profile provides a negative current sheet which is indicated on the plot. This model eliminates the (1,1) structure after the crash which is in contradiction with experimental observations of incomplete reconnection.

The subsequent relaxation of the current profile moves the q=1 surface to its original position in this model. The partial reconnection models are generally based on Kadomtsev model and assume that reconnection is stopped at a particular radius (for example in the Porcelli model [4]). Such an assumption adds one free parameter to the model (the inner radius r_{inner} at which reconnection is stopped). Thus, partial reconnection models also suggest a reduction of the q=1 radius after the crash and eliminate the (1,1) mode. These predictions are in clear contradiction with experimental observations during incomplete sawtooth reconnection in ASDEX Upgrade. At the same time, experimental results are consistent with the stochastic picture of the sawtooth crash where q=1 remains at the original position after the crash. It should be noted that partial reconnection models allow one to make good predictions for the sawtooth period in transport calculations [5]. The reason for this good agreement is that these calculations are sensitive to the amount of the reconnected flux, which is defined by, for example, r_{inner} , but are not sensitive to the exact mechanism of the crash and can not be used to verify/falsify the models.

Changes of the safety factor profile in a stochastic region

It was shown by means of the mapping technique that amplitudes of the primary (1,1) mode together with its harmonics are sufficient to stochastize the region if the central q is smaller than 0.85-0.9 [2]. This is in good agreement with measurements of the central safety factor profile (Refs.[6-8]) and allows one to explain the existence of the mode after the sawtooth collapse. In the following, we investigate the local behavior of the safety factor for the same case as in Ref.[2] (figures 9 (a,b,c)). The safety factor profiles in the figures 9 (a,b,c) are equilibrium profiles. In equilibrium situation by definition the safety factor value is a constant on a particular flux surface, i.e. each field line has the same q-value. The situation is different in a stochastic region. The flux surfaces no longer exist and two neighbouring field lines would be shifted to completely different positions on a Poincare plot after several rotations of the field line. In spite of this difficulty it is still possible to define an average safety factor value for each field line. The standard definition of the safety factor is the ratio of the poloidal and toroidal paths of the magnetic field line: $q = \Delta\phi/2\pi$, where $\Delta\phi$ is variation of the toroidal angle after one full rotation in the poloidal plane. This definition reflects the topological property of the magnetic field line (the strength of winding of the line) and does not require existence of flux surfaces. Thus, a similar definition can also be used in a stochastic region. The basic difference to the ordinary case is the fact that the *q-value is no longer a flux surface constant but a field line constant*. This allows one to define the average safety factor of a magnetic field line as follows:

$$q = \lim_{\Delta\phi \to \infty} \frac{\sum \Delta\phi}{\sum \Delta\theta} \approx \frac{2\pi \cdot (N-1)}{\sum_{i=1}^{N-1} (\theta_{i+1} - \theta_i)}, \qquad (1)$$

where N is the number of toroidal rotations of the magnetic field lines and θ_i is a poloidal position of the field line at i th iteration. This is just a reformulated definition of the safety factor averaged over a large number of toroidal rotations. The field line follows a helical path around the torus even in the presence of stochasticity (but this path is not lying on a magnetic surface). In the following we take a set of 50 trajectories with random initial positions and follow them 5000 times around the torus. Each of these 50 trajectories has a corresponding value of the safety factor defined by equation 1. The result is shown in figure 3, which corresponds to the most stochastic case (figure 9a in Ref.[2]).

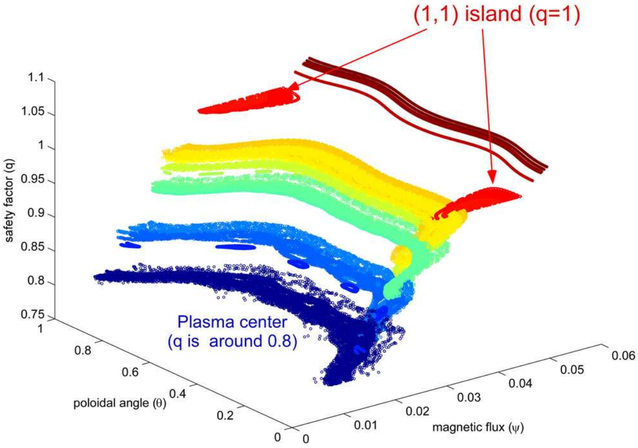

Figure 3. Safety factor values for the same case as shown in figure 9a in Ref.[2].

One can see that field lines in the island have safety factor values equal to unity which is an expectable result. The more surprising result is the value of safety factor in the stochastic region. In spite of the strong stochasticity and overlap of the regions with different safety factor values, the general features of the safety factor profile remains the same. The safety factor is smaller in the core and higher close to the island. This can be seen more clearly in figure 4b, where the result is presented as a contour plot.

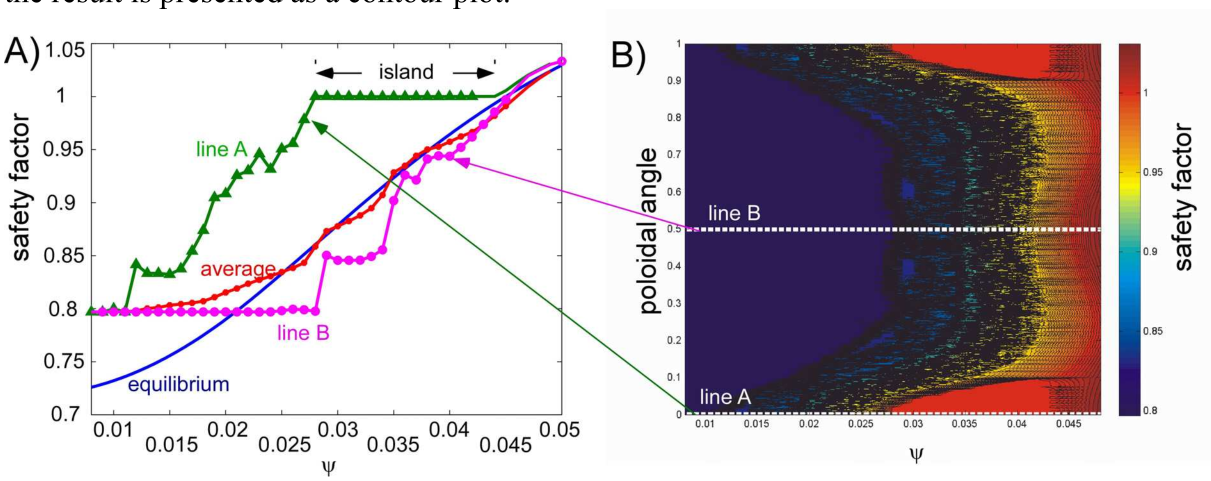

Figure 4. Contour plot of the average safety factor values for the same case as in figure 2a. The changes of the safety factor values are shown across the O-point of the island (line A) and across the X-point (line B). Equilibrium q-profile is also shown (solid line) together with poloidaly averaged safety factor profile in stochastic case. It is clearly seen that even in the

case of large stochasticity the average values of safety factor remain almost unchanged. Thus, strong field line mixing does not affect their helicity. The central safety factor lies well below unity.

This is an averaged contour plot for the same case as in figure 9a (Ref.[2]) and figure 3. The changes of the averaged safety factor values are shown across the O-point of the island (line A) and across the X-point (line B) in figure 4a. The initial equilibrium profile is also shown (solid line). It is possible to introduce additional averaging along the poloidal angle and compare resulting profiles with the equilibrium case. Here even in case of large stochasticity the average values of safety factor remain almost unchanged in presence of perturbations (the central value has slightly increased from 0.7 to 0.8). Thus, strong field line mixing has small effect on the field line helicity. This example demonstrates that the stochastic model can resolve one of the main problems of the sawtooth crash. The stochastic model provides simultaneously:

- strong and fast equalization of temperature as shown for the experimental perturbations in Ref.[9]. This is a natural and general feature of stochastic regions in the plasma, due to high parallel heat conductivity along the magnetic field.
- small changes in the safety factor profile (as it is shown here for the most stochastic case). Thus, this agrees with observations which suggested small changes of the safety factor value in the core after the crash.

After the crash, the mixing of field lines is relaxed on the resistive time scales. During this relaxation, the (1,1) structure also decays and vanishes after 5-20 rotations around the torus because there is no further drive any more. For less stochastic case (see figure 9b in ref.[2]) the average value changes less because perturbations are very small as shown in figure 5.

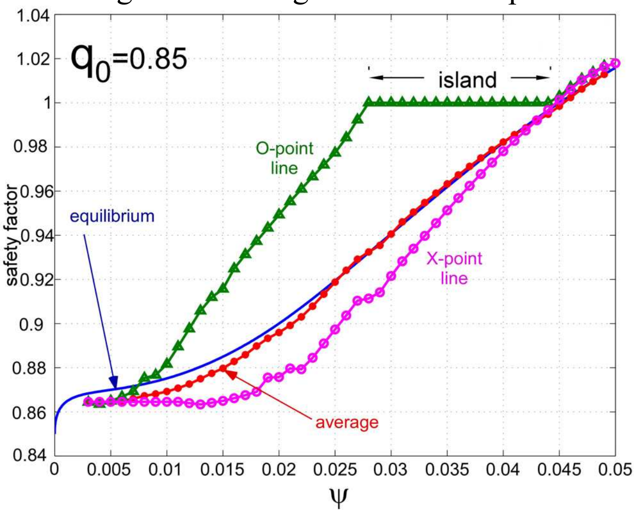

Figure 5. Changes of the safety factor profile due to perturbations for the same case as in figure 3b. One can see that initial equilibrium safety factor profile is almost identical to average value in the presence of perturbations.

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