Effect of sawteeth on fast ions in MAST

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This work presents a study of the effect of sawteeth on the fast ion confinement and on the neutron emission in MAST [1] using the Kadomstev [2] and Porcelli [3] models as implemented in TRANSP [4] and NUBEAM [5]. MAST is a medium-size spherical tokamak with a low aspect ratio $R/a \approx 1.3$ ($R \approx 0.85$ m and $a \approx 0.65$ m), high elongation ($1.5 \leq \kappa \leq 2.5$) and triangularity ($\delta \leq 0.5$), with plasma current I_p up to 1.5 MA in toroidal fields ($B_T \approx 0.6$ T at $R \approx 0.75$ m). Additional heating (and source of fast ions) is provided by two horizontal mid-plane deuterium NBIs with tangency radius of 0.7 m, each delivering a maximum of 2.5 MW with full energy up to $E_b \approx 75$ keV. The electron density n_e is in the range $0.1 - 1.0 \times 10^{20}$ m^{-3} and the electron temperature is $T_e \leq 2$ keV. Observations of the redistribution and losses of fast ions due to sawteeth were carried out in L-mode plasmas in double-null divertor configuration with $P_{NBI} = 1.5$ MW ($E_b = 50$ keV), $I_P = 0.6$ MA, a high density n_e and a monotonic q-profile with $q(0) \leq 1$. More details on the sawteeth plasma scenarios can be found in [6]. Initial findings, where only the standard Kadomstev model was employed (hereafter called *Reference* model), indicated that, following a sawtooth crash, fast ions were redistributed from the core to the plasma region outside the mixing radius with a reduction in the passing ion population and an increase in the trapped one [6]. The redistribution of fast ions due to sawteeth resulted in a large drop in the neutron emissivity across the entire plasma profile. Since on MAST the neutron emission is dominated by the beam-target component (typically around 90 % of the total neutron emission), neutrons are considered a good proxy for the fast ions. Neutron emission on MAST is measured globally by a Fission Chamber (FC) and by a Neutron emission profile monitor Camera (NC) [7].

Kadomtsev and Porcelli sawtooth model comparison

The default sawtooth model in NUBEAM is based on the Kadomtsev mixing where regions of equal helical flux on both sides of the $q = 1$ surface reconnect resulting in $q(0) = 1$ and $q(r) > 1$, all the fast (and thermal) ions participate in the mixing and the total ion energy density is conserved. Reducing the level of plasma current mixing resulted in a very large discrepancy between the predicted and measured neutron rates Y_n: for this reason, in the rest of this work, full current mixing is always assumed. The fraction of fast ions participating in sawtooth mixing resulting in a good match between measured and predicted Y_n is approximately 60 %.

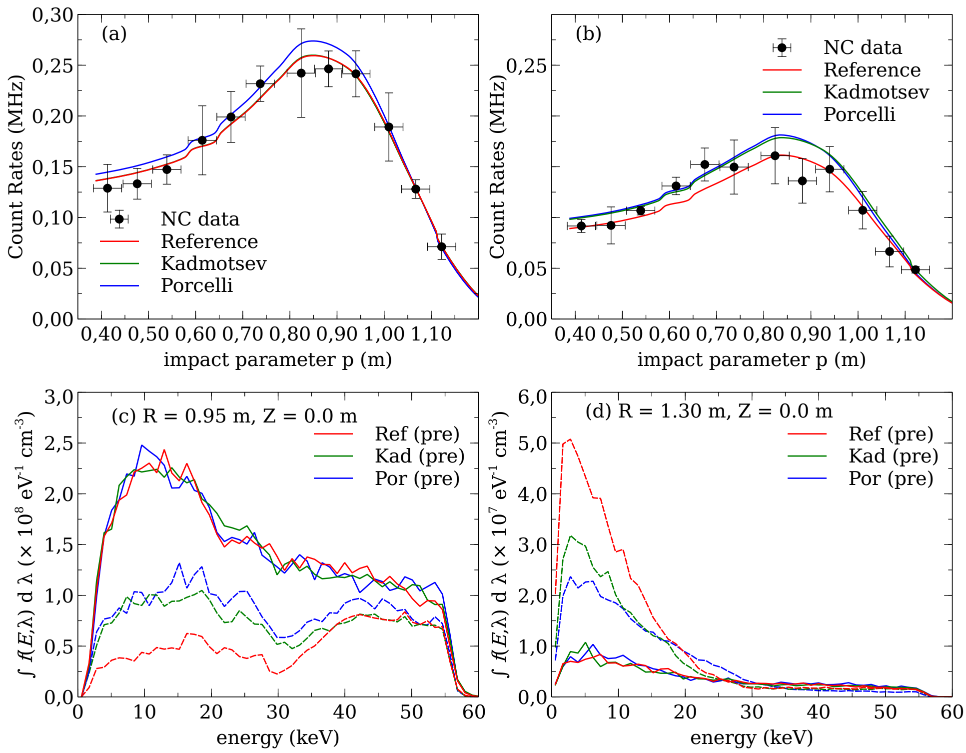

Figure 1: *Top panels: neutron count rate profile as a function of the impact parameter p before (a) and after (b) a sawtooth crash: three different models (continuous curves) are compared with experimental observations (black solid circles). Bottom panels: fast ion distribution integrated over all pitch angles in the core (c) and near the last close flux surface (d) before (continuous) and after (dashed) the sawtooth crash for the three different sawtooth mixing models.*

Good agreement is found between the predicted (red curve) and measured (black solid circles) NC count rates using this reference simulation as shown in figure 1. Figure 1 also shows the predicted NC rates when using Kadomtsev's full particle mixing rather than the reference helical flux matching (green curve) by setting `NMIX_KDAW` = 2. In this case, NUBEAM slightly over-estimates the NC measured count rates. Finally, Porcelli's method with ergodic mixing (`NMIX_KDAW` = 4) with different fractional widths of the magnetic island around $q = 1$ were tested and the best match with the NC observations was obtained by setting the parameter `FPORCELLI` to 50 % (blue curve). Also in this case, the predicted NC count rate after the sawtooth rate is slightly higher than the experimental one. However, given the large experimental uncertainties in the experimental NC count rates, all three mixing models are compatible with the experimental observations. It is interesting however to observe that the fast ion distribution $f(R,Z,E,\lambda,t)$ predicted by the three models are quite different in the (E,λ) space for energies below 40 keV with the reference model indicating a much larger redistribution (roughly by a factor of 2) of fast ions from the core to the edge region while conserving the total fast ion density. This can be understood observing that most of the neutron emission comes from the core plasma regions and that the NC is mostly sensitive to fast ion with energies close to the injection energy. The NC is therefore not very sensitive to the differences in the fast ion distribution obtained from the different models suggesting that comparison with other fast ion diagnostics (such as FIDA) might possibly resolve this ambiguity.

Effect of sawteeth on passing and trapping fast ions

A preliminary FIDA analysis of the effect of sawteeth crash on the fast ions suggested a small redistribution of mainly passing fast ions with $E \geq 48$ keV for $R \geq 1.15$ m but little or no effect near the magnetic axis (≈ 0.95 m) and that some trapped fast ions with $E \geq 6$ keV are redistributed for 0.95 m $\leq R \leq$ 1.10 m [6]. All three TRANSP simulations in the previous section results in a similar global increase of the trapped ion fraction at each sawtooth crash increasing from ≈ 22 % to ≈ 35 % while the trapped fast ion population is increased, indicating increased pitch angle scattering. This is not consistent with FIDA observations which reveal that sawteeth also affect trapped fast ions. This analysis was based on a simplified model of the passing/trapped fast ion boundary. In order to determine more accurately this boundary, a FulL Orbit Code (FLOCk) has been developed to calculate the orbits of charged particles in axis-symmetric equilibria (i.e. toroidal field ripples are not modeled). Full orbits, and derived guiding-centre orbits, have been calculated for pre- and post-sawtooth MHD equilibria scanning the (λ, E) space with initial zero gyro-angle for $R \in [0.9; 1.4]$ m and for $Z = 0.0$ m. The full orbits have been calculated using the 2nd order backward differentiation method as implemented in the LSODE package [8]. An example of the orbit topology boundaries are shown in figure 2 together with the NUBEAM predicted fast ion distribution using the reference Kadomtsev's mixing model at $R = 1.1$ m and $Z = 0$ m (the equilibrium does not change significantly before and after a sawtooth). Integration of $f(\lambda, E)$ within each different orbit topology region provides the passing and trapped fast ion densities (fast ion densities characterized by stagnation and potato orbits are not discussed here). The results indicated that along the major radius, strong redistribution of both passing and trapped fast ions occurs. For example, at $R = 0.9$ m the passing/trapped ion population is reduced at a sawtooth crash by approximately -74 % and -70 % respectively, while at $R = 1.1$ m the reduction is approximately -67 % and -75 %. These preliminary results indicate that, in the region where both FIDA and the NC are most sensitive, redistributions of both trapped and fast ions of similar amplitude are expected. This is in contradiction with the initial FIDA observations and a more detailed analysis is ongoing to investigate this. It is worth mentioning that the boundaries between different orbit topologies are very sensitive to the initial gyro-angle and a more systematic study is on-going to address the impact this has on the evaluation of the trapped and passing fast ion densities. Finally, calculations of the critical energies [9] for sawtooth redistribution of trapped and passing particle for the distributions shown in figure 2 give 12 and 2 keV respectively. According to standard Kadomtsev's mixing, mostly trapped fast ions with energies below the critical energy are expected to be redistributed unless a strong diamagnetic component to the precession motion is included as it seems to be the case here. In the case of passing fast ions, we can preliminary conclude that redistribution is mainly due to resonance effects between the passing fast ions and the sawtooth instability. Further analysis is required to confirm these initial findings.

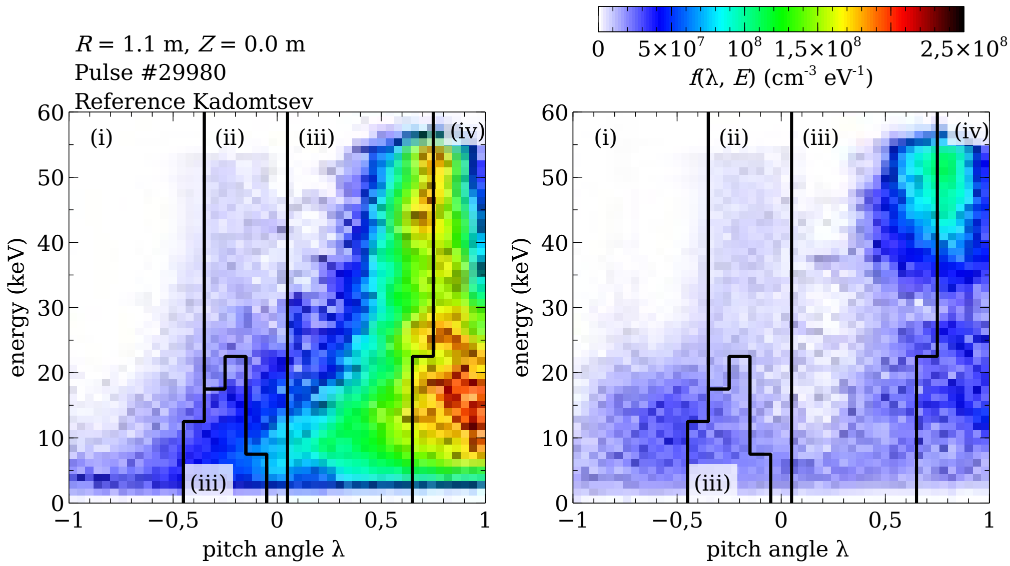

Figure 2: *Fast ion distribution from NUBEAM before (left panel) and after (right panel) the sawtooth crash at* $t \approx 0.260$ *s for pulse 29880. Orbit topology:* (i) *counter-passing,* (ii) *stagnation,* (iii) *trapped and* (iv) *co-passing.*

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