# Model for current drive induced crash cycles in W7-X

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## (Taylor relaxation in Wendelstein 7-X)

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## ABSTRACT


- During plasma operation in W7-X the ɩ-profile can be strongly modified by Electron Cyclotron Current Drive (ECCD) in such a way that the resulting ɩ-profile passes through low-order rational values, and this can trigger magnetohydrodynamic (MHD) events.
- In the present work, we try to shed some light on the nature of different MHD events happening during the course of sawtooth cycles in W7-X by using a model that combines a slow current diffusion with a fast relaxation that conserves the corresponding helical flux (Kadomtsev-like).
- We propose a simple model based on Taylor relaxation to predict the nonlinear redistribution of plasma current caused by the largest of the observed events.

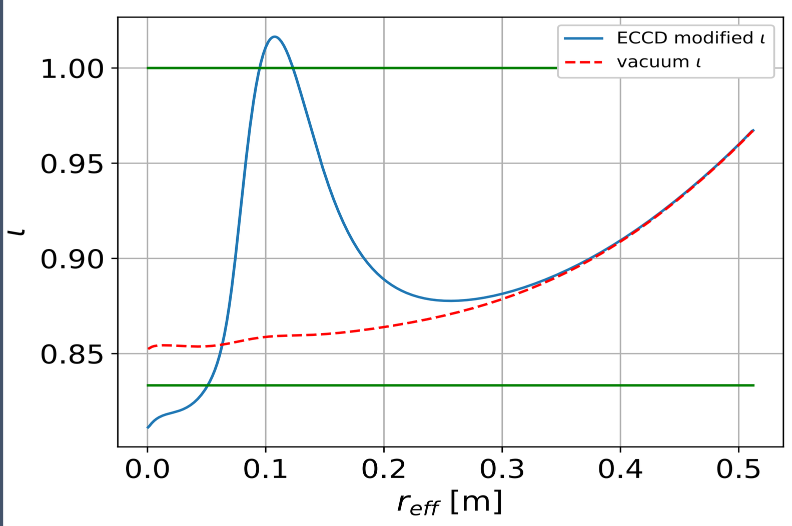




*FIG.1. Vacuum ɩ, red curve. ECCD modified ɩ after 0.2s of drive (plasma β=0). Resonant surfaces ɩ=1 and ɩ=5/6 marked in green.*

## EXPERIMENTAL OBSERVATIONS (DISCHARGE XP20171206.025)

In the beginning of this experiment 14 kA ECCD was applied around $r_{eff}$≈0.08m. Temperature crashes started to appear shortly after the start of the ECCD. Note that the current is negative, because of a reversed field configuration.

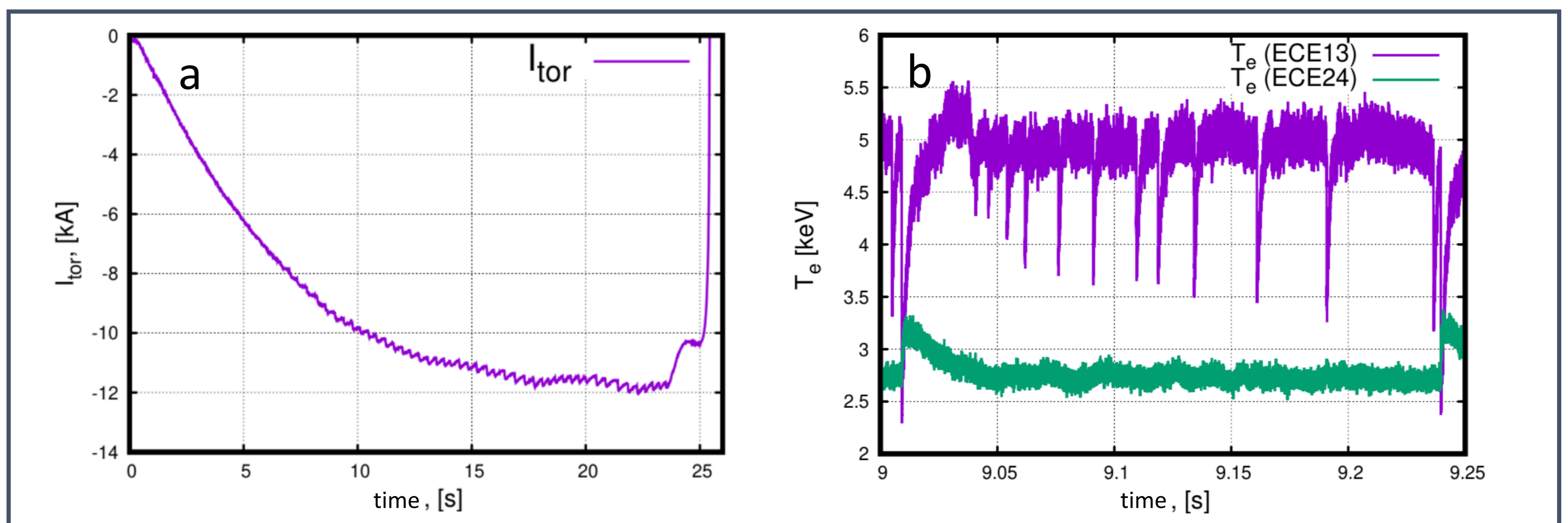



*FIG.2. a: evolution of the total toroidal current measured by the Rogowski coil. b: time traces of the electron temperatures measured by two channels of the ECE diagnostic in W7-X from 9.0s to 9.25s with ECCD. The first channel (which views the plasma centre) is called ECE13, the resonance is located at 0.05 r/a. The second one, looking at mid-radius, is ECE24 located at 0.7 r/a, where r is the effective radius, a is the minor radius. The small crashes are detected only by channel 13 while the medium crashes affect the mid-radius area as well (seen on channel 24 around 9.01s and 9.24s).*

## 1-D FLUX DIFFUSION MODEL WITH RELAXATIONS

The plasma current evolution is governed by the diffusion equation for the poloidal magnetic flux, $\psi$:

$$\frac{\sigma}{2\pi R_0}\frac{\partial\psi}{\partial t}=\frac{1}{2\pi R_0\mu_0}\frac{1}{r}\frac{\partial}{\partial r}r\frac{\partial\psi}{\partial r}+j_{CD}. \quad (1)$$

This equation represents Ohm's law for the net-toroidal current density:

$$j(r,t)=\sigma E+j_{CD}, \quad (2)$$

$$\sigma E=-\frac{\sigma}{2\pi R_0}\frac{\partial\psi}{\partial t}, \quad (3)$$

where $\sigma E=j_{screen}$ denotes the Ohmic current density, $\mu_0$ is the permeability constant, and r and $R_0$ the minor and major plasma radius. The neoclassical conductivity, $\sigma$ is smaller than the Spitzer value and is calculated using the NTSS code. The ECCD current density was calculated with the TRAVIS ray-tracing code.

To account for relaxations we rely on the helical flux reorganisation model discussed in Kadomtsev's work (1975). The features of this model, in which the dominant mode helical flux, $\chi=q\psi+\phi$, is conserved while the flux profile becomes monotonic, result in:

1) plasma volume conservation
2) a lower magnetic energy state

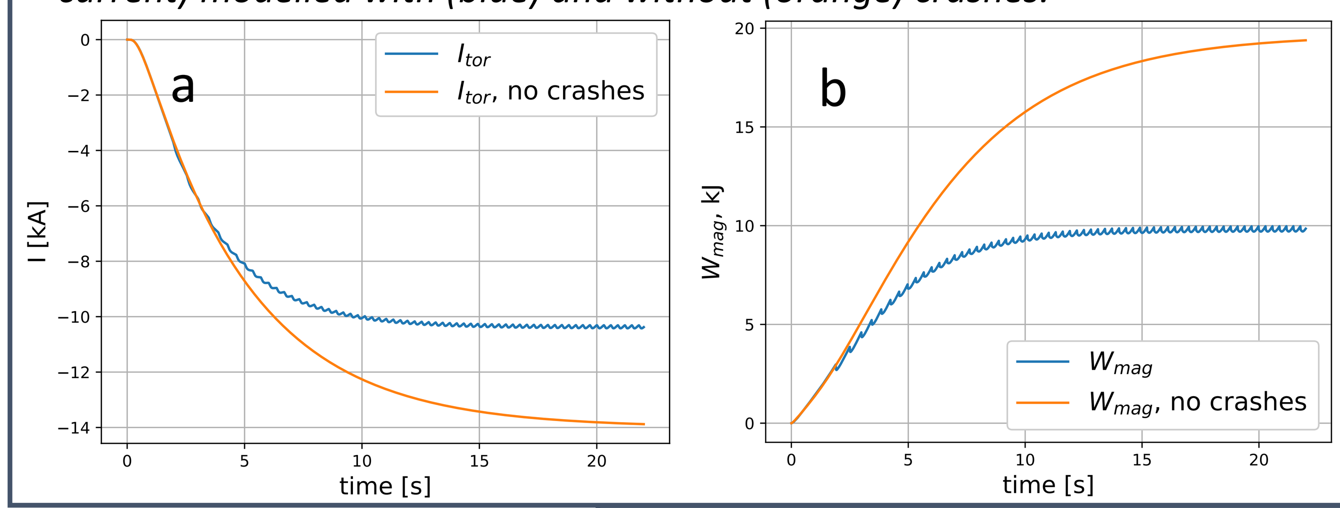
$\psi$ and $\phi$ here are, poloidal and toroidal fluxes, $q=m/n=1/ɩ$.

We assume that the helical flux is suddenly redistributed when the rational transform reaches a certain value (in our case: **$ɩ_{relax}$>1** or **$ɩ_{relax}$<5/6**, see Fig.1, left plot, marked in green).

## SAWTOOTH CYCLES IN W7-X

- Note that the total toroidal current saturates at a lower value due to continuous magnetic energy dissipation via MHD crashes, Fig.3. Such an early saturation is often observed in ECCD experiments in W7-X.
- Even though all the crashes demonstrate a similar trend of electron temperature flattening, the other crash parameters vary (frequency, amplitude), Fig2, b. This important aspect is captured in the proposed simplified model, Fig.4.
- The increase of mixing area for medium crashes, Fig.5, a. This is consistent with the experimentally observed increase of plasma volume where the temperature profiles flatten.

*FIG.3. a: Resistive current evolution modelled with (blue) and without (orange) crashes. b: total magnetic energy (associated with the toroidal current) modelled with (blue) and without (orange) crashes.*



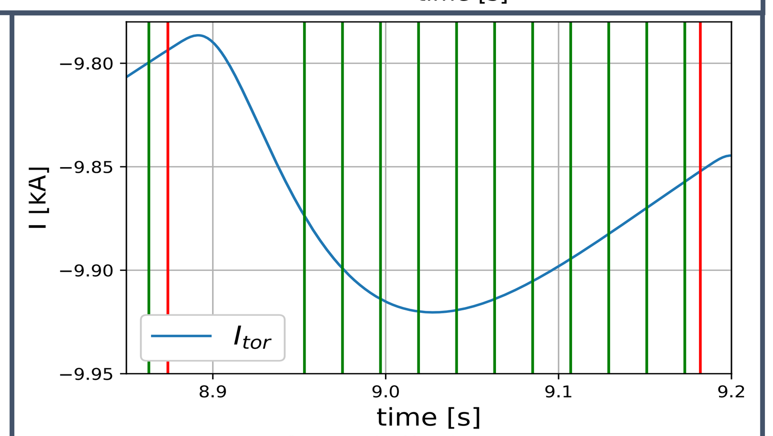




*FIG.4. Zoom of modelled resistive current evolution, shown in Fig.3, b. Times at which the small crashes are triggered marked with green vertical lines. Medium size crashes marked in red.*

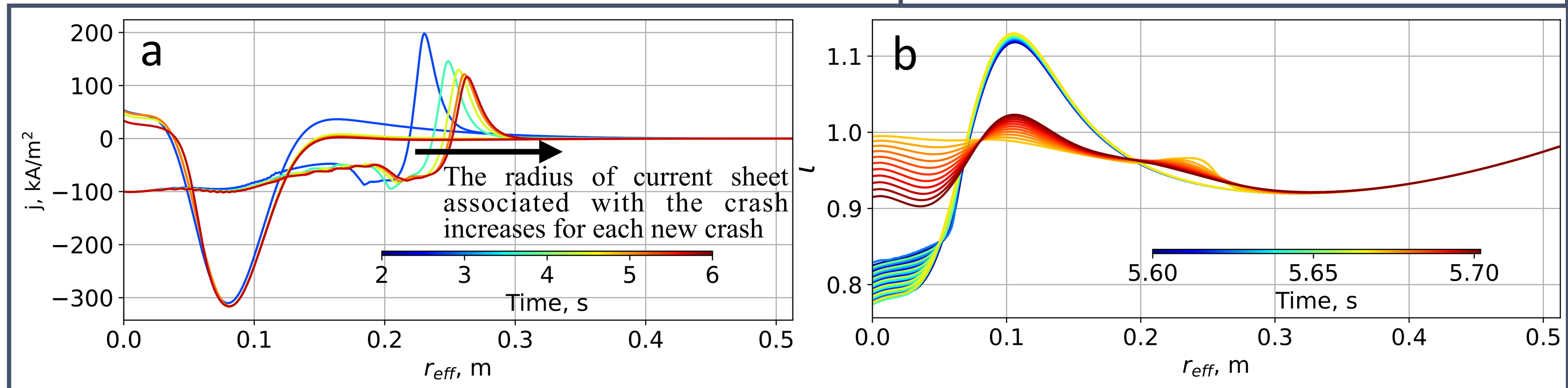



*FIG.5. Current density (a) and ɩ profile (b) time evolution (color-coded) calculated from the flux diffusion equation with relaxations for the XP20171206.025 discharge properties. Left plot presents current density before the medium crash and right after for several events. The rapid change from yellow to orange (around t=5.675 s) is a medium crash.*

## TAYLOR RELAXED STATE IN W7-X (more global events)

- Taylor relaxation principle (1974) postulates that a plasma tends to minimize its magnetic energy subject to the conservation of magnetic helicity and toroidal flux enclosed by the plasma.
- To find the post-relaxation state (using SPEC) corresponding to a particular initial condition (calculated by VMEC), one finds the one with the same helicity.

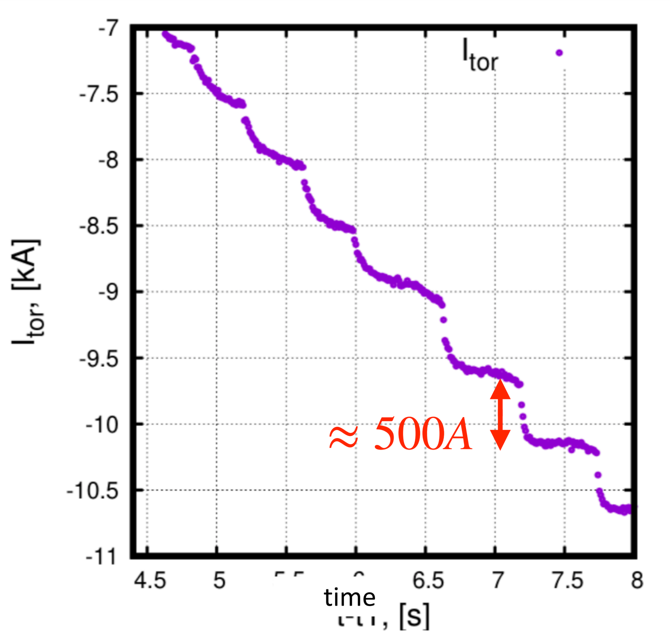



*FIG.6. W7-X discharge with ECCD, XP20171207.008. Evolution of the total toroidal current, measured by the Rogowski coil, noticeable sudden steps in the total current.*

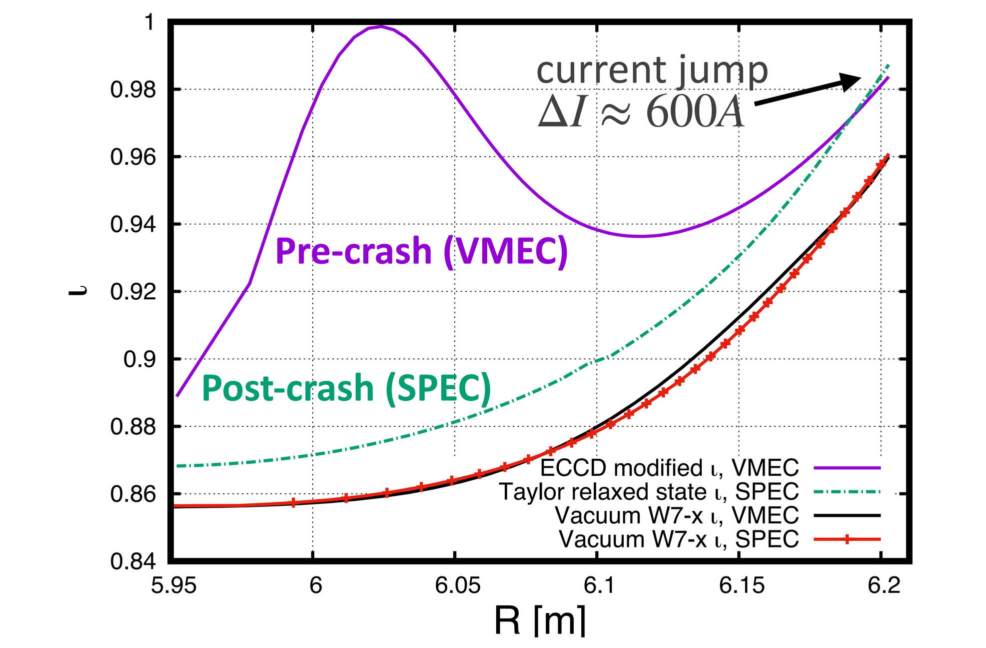



*FIG.7. Vacuum W7-X standard configuration ɩ-profile obtained from VMEC (black line) and SPEC (red curve). ECCD-driven, "pre-crash", ɩ-profile (purple line), obtained from VMEC, and "after-crash", relaxed ɩ-profile from SPEC (green curve) verus major radius R.*

## CONCLUSION

- A **1-D flux diffusion model with relaxations** based on a helical flux conservation of one dominant mode was introduced.
- An application of this model which **predicts toroidal current** evolution **qualitatively similar to the experimental observations** was presented.
- The model shows that the **loss of magnetic energy via the MHD crashes** can have a **significant effect** on the evolution of the total current.
- To model the largest of the crashes, we consider global relaxation events and present **the full-volume Taylor relaxed state for 3D geometry** which we suggest may be the nonlinear result of the large crash happening in W7-X.