Current drive induced crash cycles in W7-X

K. Aleynikova[1]
In collaboration with S. Hudson[2], P. Helander[1], A. Kumar[3], J. Geiger[1],
M. Hirsch[1], J. Loizu[4], C. Nührenberg[1], K. Rahbarnia[1], Z. Qu[3], Y. Gao[1], H. Thomsen[1], Y. Turkin[1], M. Zanini[1]
and W7-X team.

[1] Max-Planck-Institut für Plasmaphysik, Greifswald, Germany
[2] Princeton Plasma Physics Laboratory, Princeton University, Princeton, NJ, USA
[3] Mathematical Sciences Institute, the Australian National University, Canberra ACT 2601, Australia
[4] Ecole Polytechnique Fédérale de Lausanne, Swiss Plasma Center, Lausanne, Switzerland
Acknowledgments:
V. Igochine, A. Bhattacharjee, A. Reiman, A. Zocco, C. Smiet, J. Schilling

- Introduction/motivation: Wendelstein 7-X (W7-X) stellarator and Electron Cyclotron Current Drive (ECCD, EC-wave driven currents) experiments.

- Details of the experimentally observed crashes.

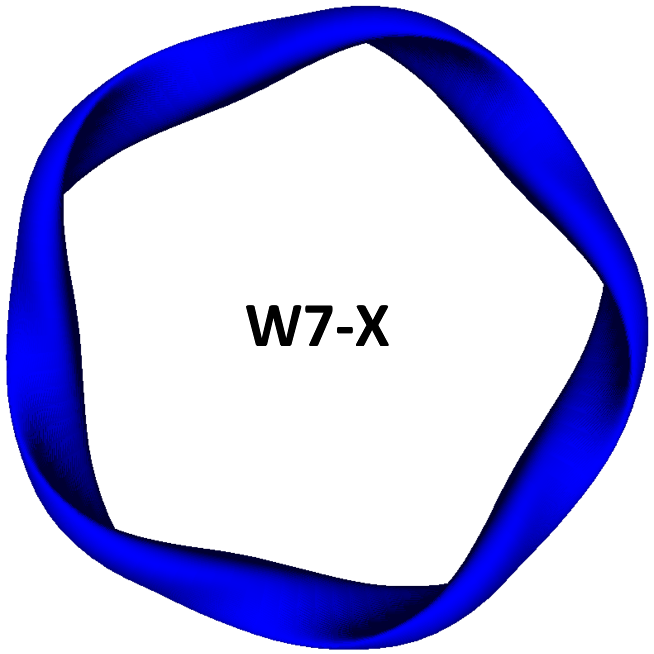
- Flux diffusion model with relaxations → application of the model

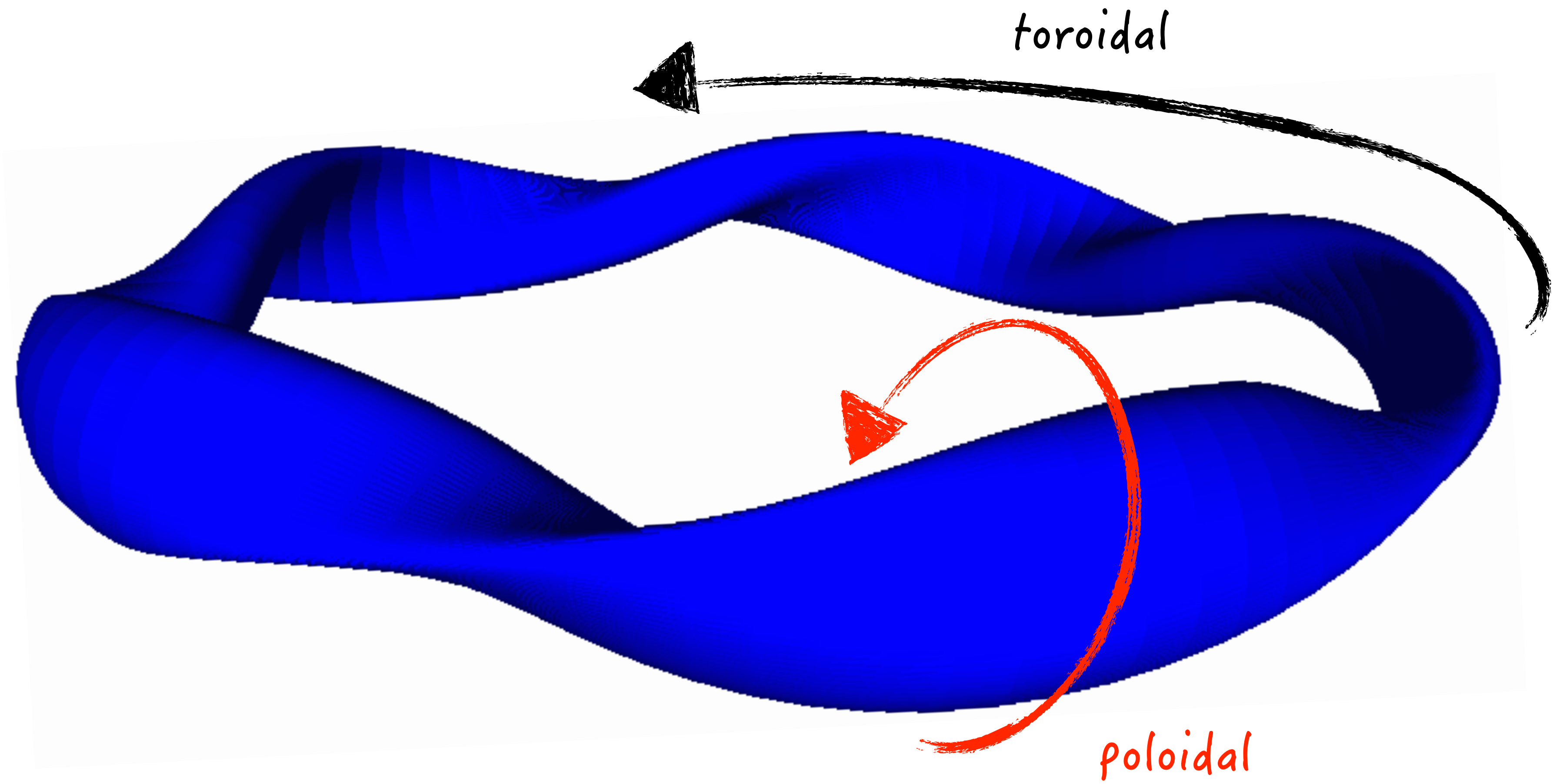
- Large crashes in W7-X / could Taylor model describe them?

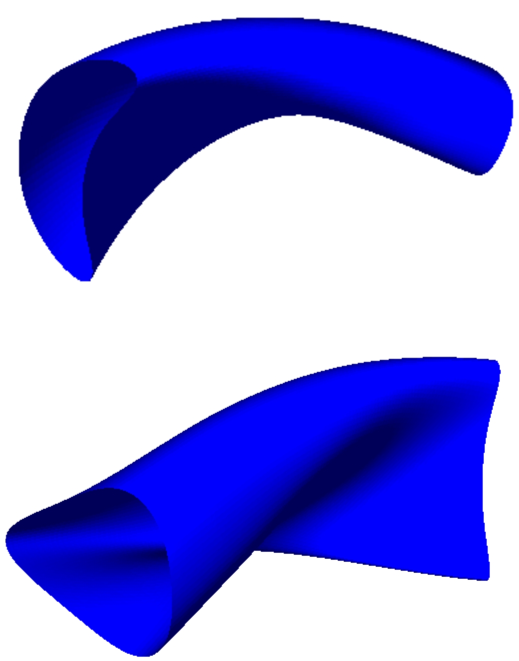
Wendelstein 7-X (W7-X) stellarator

- W7-X is well optimised to avoid MHD activity.
- Electron-cyclotron resonance heating (ECRH, ≈10 MW, largest one in the world).
- 5 field periods, major radius R=5.5 m, minor radius r=0.53 m.
- Normally, no toroidal current (small bootstrap current) except

for ECCD (EC-wave driven currents) experiments.







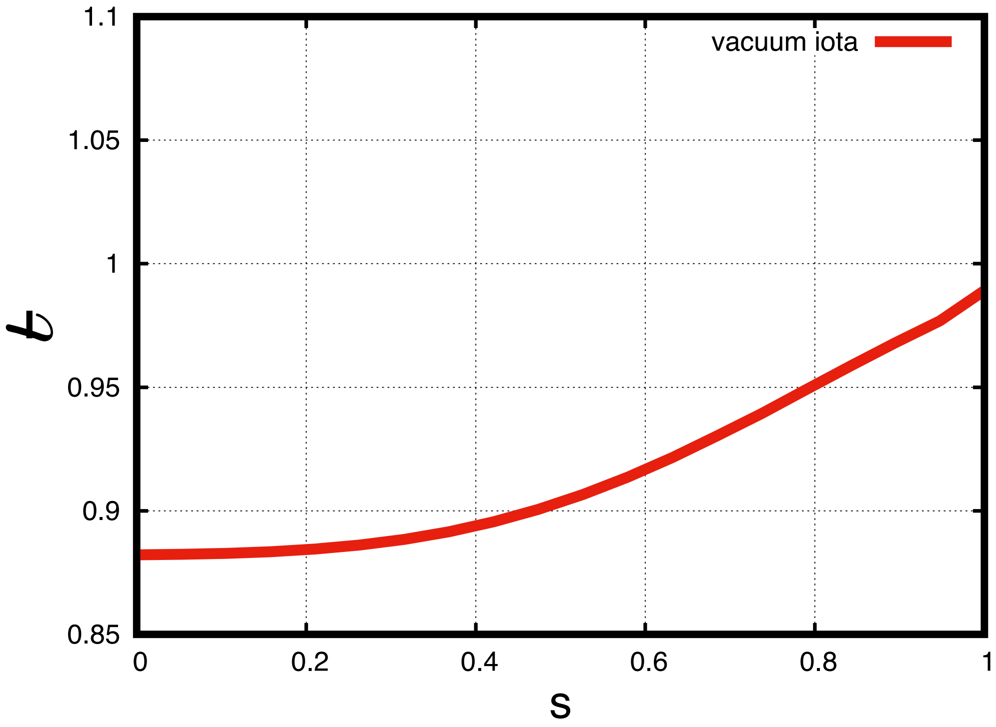
Motivation

- In W7-X, vacuum $\iota\!\!\!-$ has an almost **flat radial profile** and does not cross any major rational resonance.

Rotational transform, $\iota\!\!\!-$ (if nested flux surfaces exist):

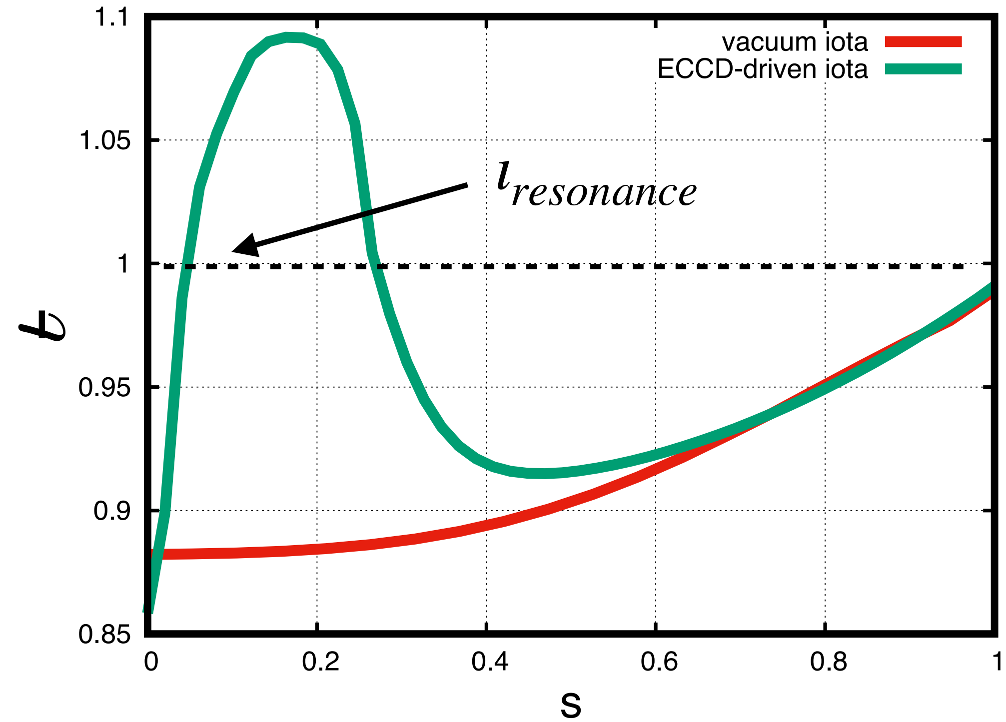
$$\iota\!\!\!- = \frac{d\psi}{d\phi}$$

where ψ is the poloidal magnetic flux, and ϕ the toroidal magnetic flux, $s = \left(\frac{r_{eff}}{a}\right)^2$.



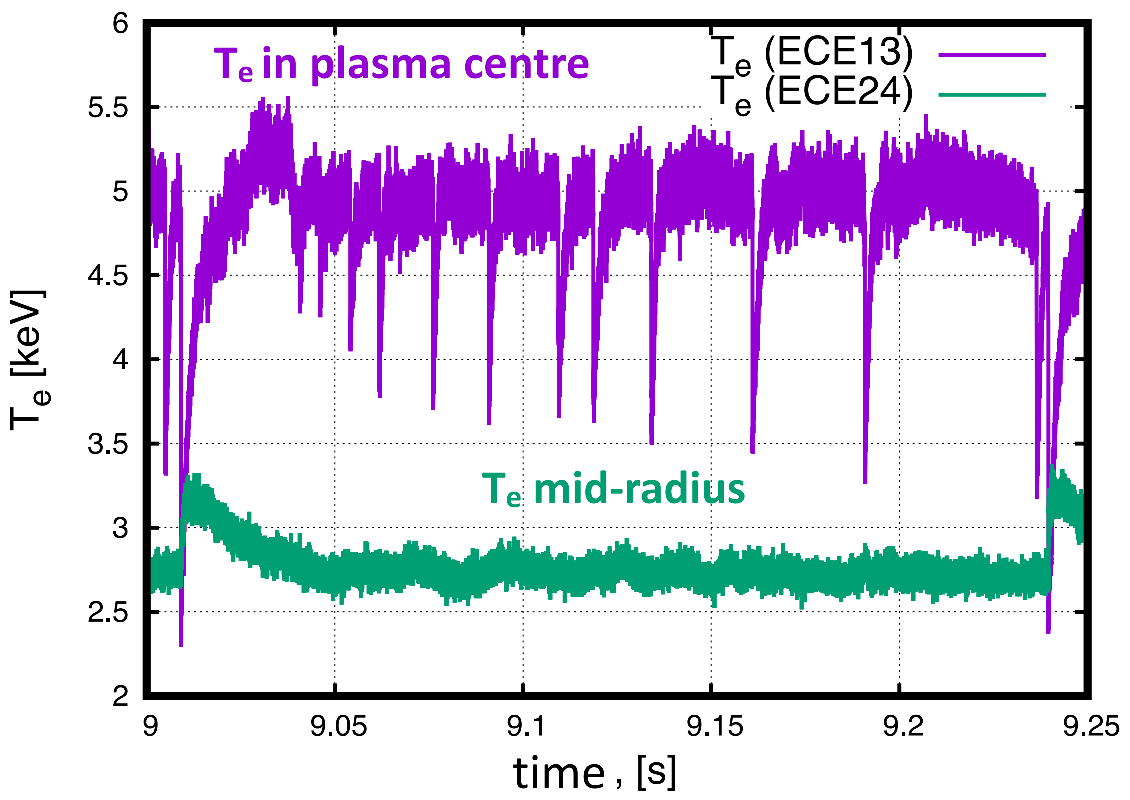
Motivation

- In W7-X, vacuum ι has an almost **flat radial profile** and does not cross any major rational resonance.
- During plasma operation the ι-**profile can be varied** by EC-wave driven currents (ECCD). The resulting current modifies the iota profile, which can lead to **MHD-activity** if passing major rational values.



Motivation

- In W7-X, vacuum ι has an almost **flat radial profile** and does not cross any major rational resonance.
- During plasma operation the ι-**profile can be varied** by EC-wave driven currents (ECCD). The resulting current modifies the iota profile, which can lead to **MHD-activity** if passing major rational values.
- **In W7-X discharges** with ECCD, phenomena reminiscent of tokamak **"sawtooth" instabilities** are observed. There are also examples of discharges where related events lead to **termination** of **the entire plasma**.



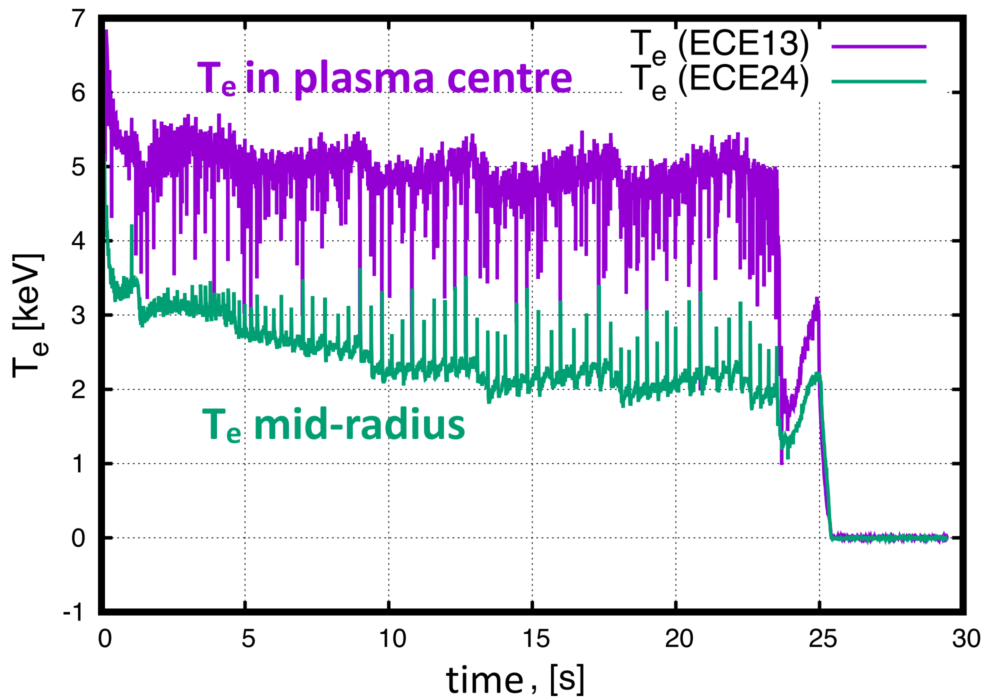
Motivation

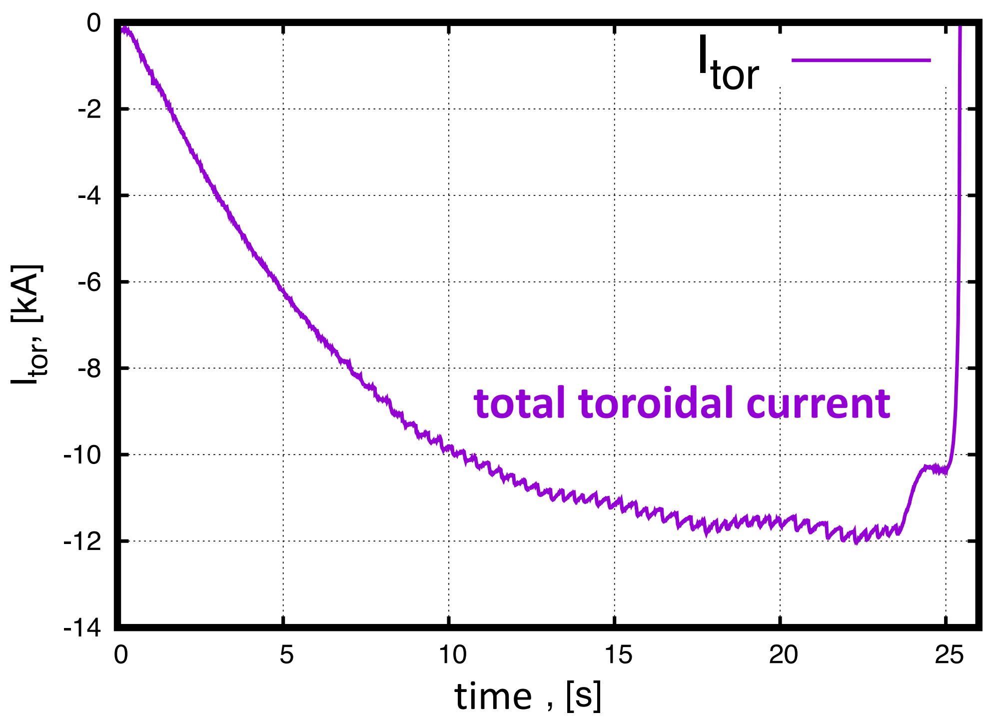
- In W7-X, vacuum $\iota\!\!\!-$ has an almost **flat radial profile** and does not cross any major rational resonance.
- During plasma operation the $\iota\!\!\!-$-**profile can be varied** by EC-wave driven currents (ECCD). The resulting current modifies the iota profile, which can lead to **MHD-activity** if passing major rational values.
- **In W7-X discharges** with ECCD, phenomena reminiscent of tokamak **"sawtooth" instabilities** are observed. There are also examples of discharges where related events lead to **termination** of **the entire plasma**.

The origin of these MHD instabilities is under investigation: [Zocco et al. JPP, 2019];
[Strumberger et al. Nucl. Fusion, 2020];
[Yu et al. Nucl. Fusion, 2020];
[Zocco et al. PPCF, 2020]
[Zocco et al. Nucl. Fusion, 2021]

The question addressed in this work is **what happens to the plasma as a result of these instabilities.**

Experimental Program (XP) 20171206.025





Crashes are observed on the experimental total toroidal current and electron temperature.

In the beginning of the experiment 14 kA ECCD is applied around $r_{eff} \approx 0.08$m.

The temperature crashes appear shortly after the start of the ECCD.

All crashes demonstrate similar trend of central electron temperature decrease with temperature increase in the external regions, the other crash parameters vary (scale, frequency and amplitude).

[Zanini et al, Nuclear Fusion, 2020 & 2021], [Aleynikova et al, Nuclear Fusion, 2021]

Conservation of helical flux in relaxations

Several models for sawtooth crashes:

Taylor (1975), Kadomtsev (1975), Bhattacharjee (1980&1982,) Waelbroeck (1989), Porcelli (1996).

Helical flux, $\chi = \psi/\iota_r - \phi$, reorganisation (a.k.a. Kadomtsev) model: **dominant mode** helical flux is conserved while the flux profile becomes monotonic.

- plasma volume conservation

$$rdr = r_1 dr_1 + r_2 dr_2$$

- reconnected helical flux

$$d\chi_\infty = d\chi_1 = d\chi_2$$

- lower magnetic energy state

- current sheets

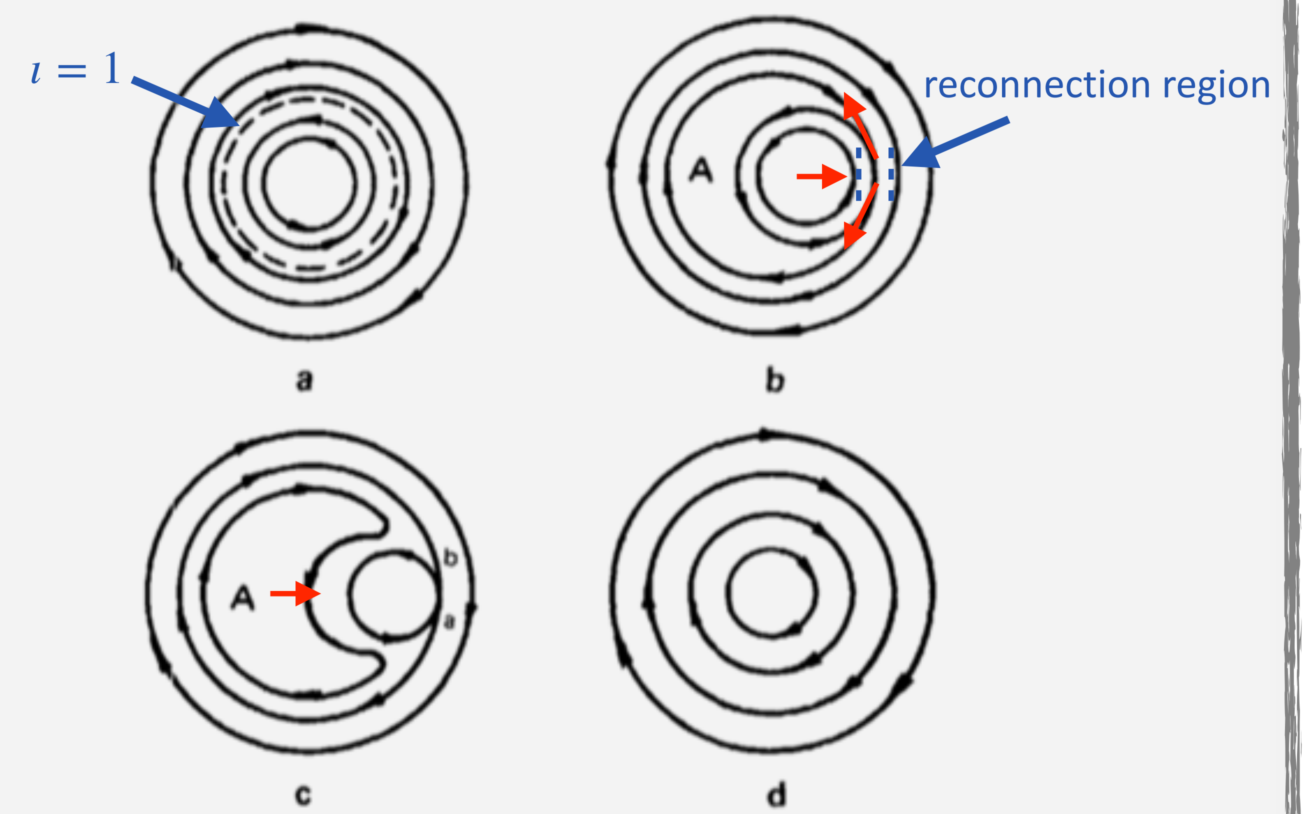


FIG.1. Auxiliary field B_* in a column in the initial state (a), when the inner surface touches the outer surface (b), during reconnection due to finite resistivity (c) and after reconnection (d).

Kadomtsev, B. B. (1975). Disruptive instability in tokamaks. *FizPl*, *1*, 710-715.

Conservation of helical flux in relaxations

Several models for sawtooth crashes:

Taylor (1975), Kadomtsev (1975), Bhattacharjee (1980&1982,) Waelbroeck (1989), Porcelli (1996).

Helical flux, $\chi = \psi/\iota_r - \phi$, reorganisation (a.k.a. Kadomtsev) model: **dominant mode** helical flux is conserved while the flux profil

- plasma volume conservation

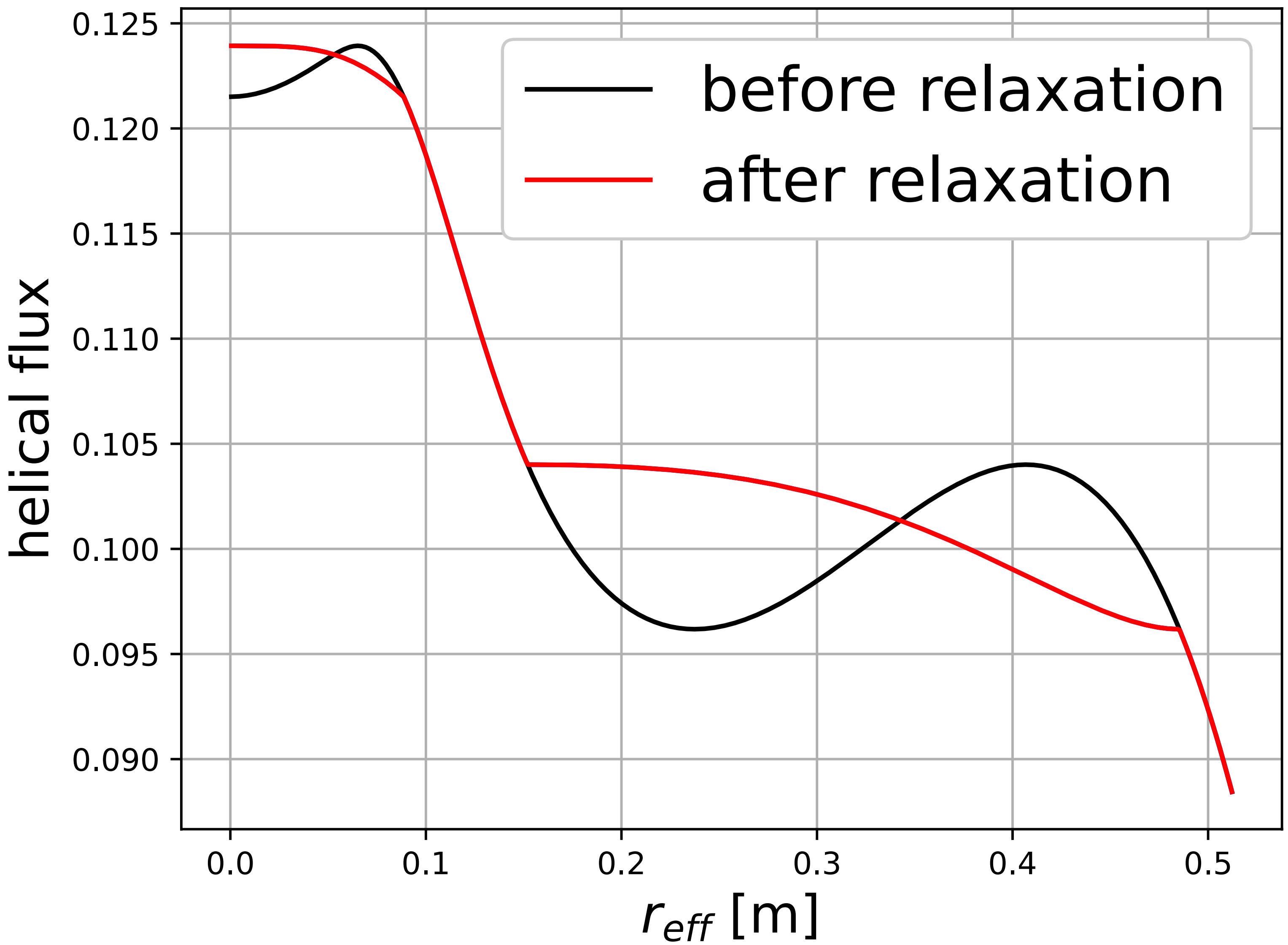
$$rdr = r_1 dr_1 + r_2 dr_2$$

- reconnected helical flux

$$d\chi_\infty = d\chi_1 = d\chi_2$$

- lower magnetic energy state

- current sheets



Conservation of helical flux in relaxations

Several models for sawtooth crashes:

Taylor (1975), Kadomtsev (1975), Bhattacharjee (1980&1982,) Waelbroeck (1989), Porcelli (1996).

Helical flux, $\chi = \psi/\iota_r - \phi$, reorganisation (a.k.a. Kadomtsev) model: **dominant mode** helical flux is conserved while the flux profil

- plasma volume conservation

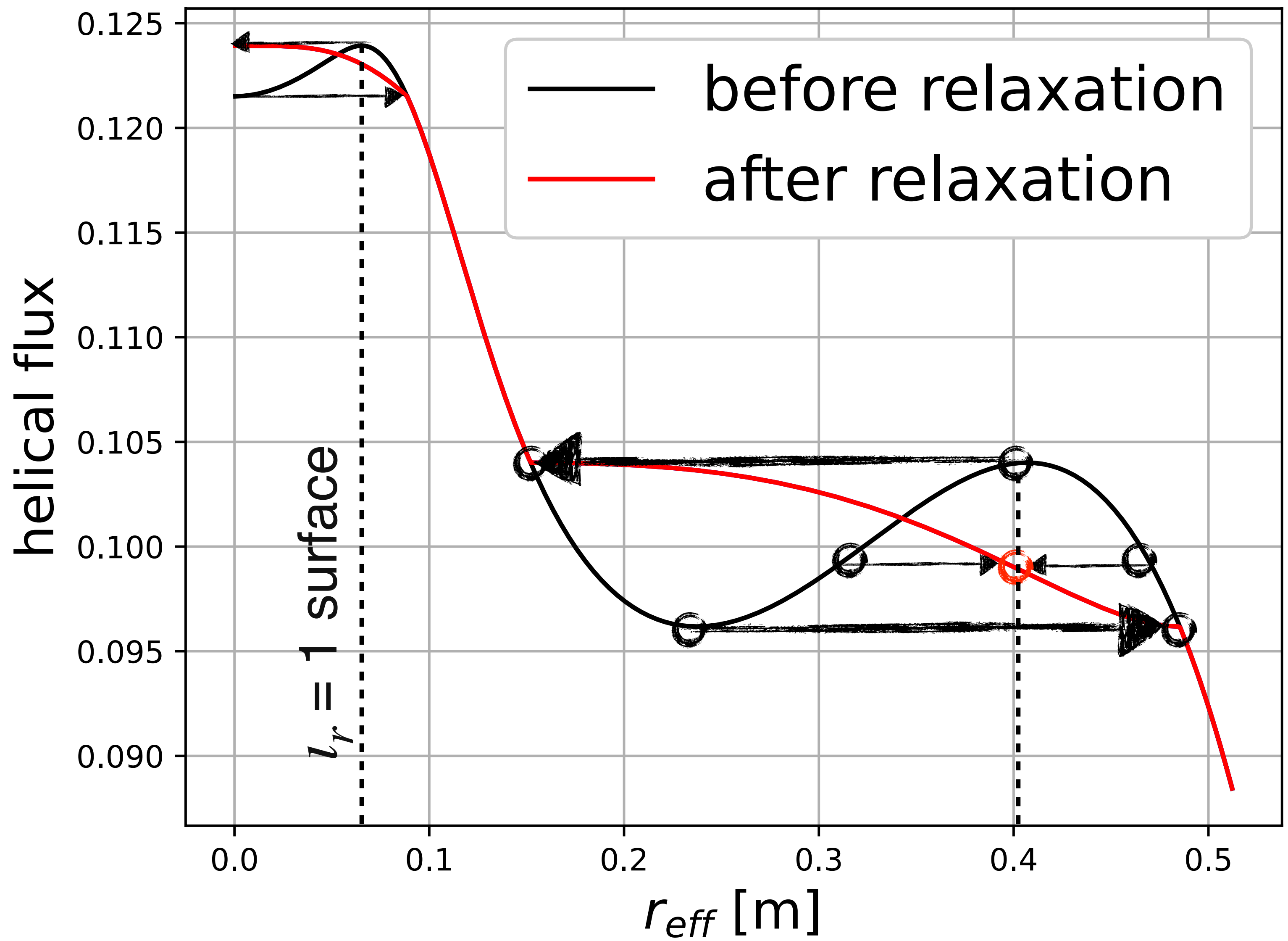
$$rdr = r_1 dr_1 + r_2 dr_2$$

- reconnected helical flux

$$d\chi_\infty = d\chi_1 = d\chi_2$$

- lower magnetic energy state

- current sheets



Conservation of helical flux in relaxations

Several models for sawtooth crashes:

Taylor (1975), Kadomtsev (1975), Bhattacharjee (1980&1982,) Waelbroeck (1989), Porcelli (1996).

Helical flux, $\chi = \psi/\iota_r - \phi$, reorganisation (a.k.a. Kadomtsev) model: **dominant mode** helical flux is conserved while the flux profil

- plasma volume conservation

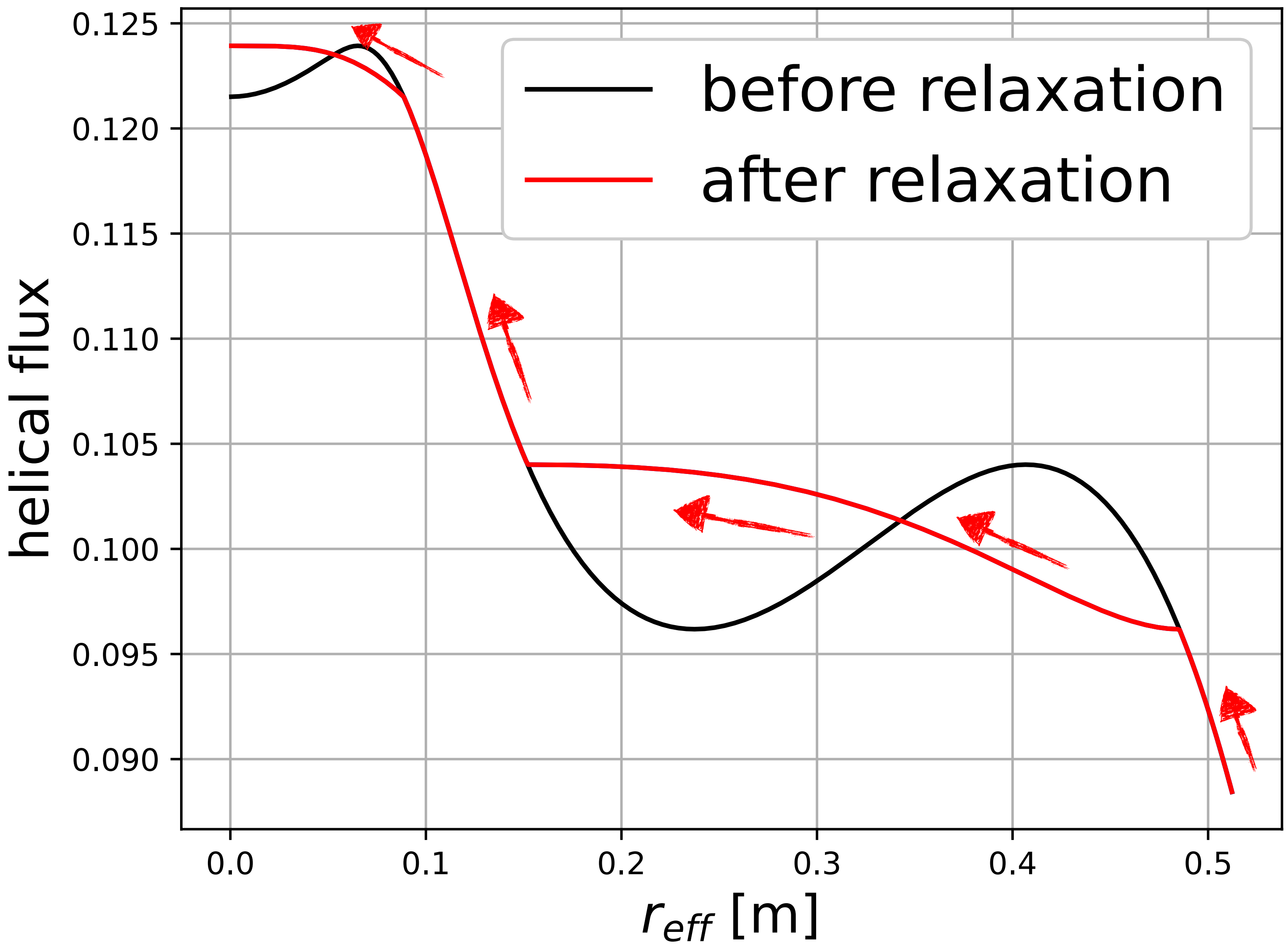
  $$rdr = r_1 dr_1 + r_2 dr_2$$

- reconnected helical flux

  $$d\chi_\infty = d\chi_1 = d\chi_2$$

- lower magnetic energy state

- current sheets



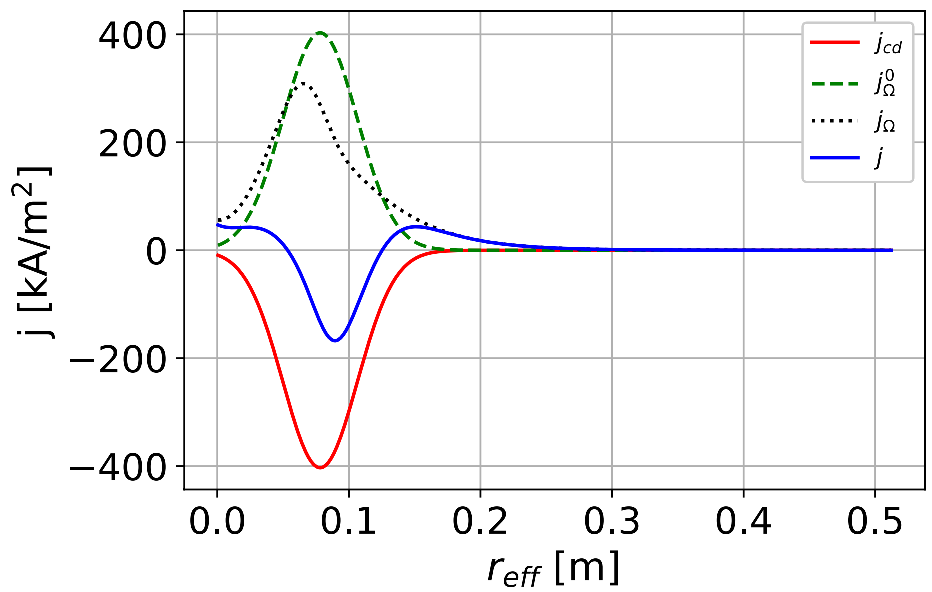
Flux diffusion model with relaxations

Following Strand & Houlberg (2001), we write the evolution equation for the poloidal flux ψ:

$$\sigma_{||}\frac{\partial\psi}{\partial t} = \frac{J^2 R_0}{\mu_0 \rho}\frac{\partial}{\partial\rho}\frac{S_{11}}{J}\frac{\partial\psi}{\partial\rho} - \frac{V'}{2\pi\rho} j_{CD},$$

Ohm's law for the toroidal current density:

$$j(r,t) = \sigma_{||} E(r,t) + j_{CD}$$

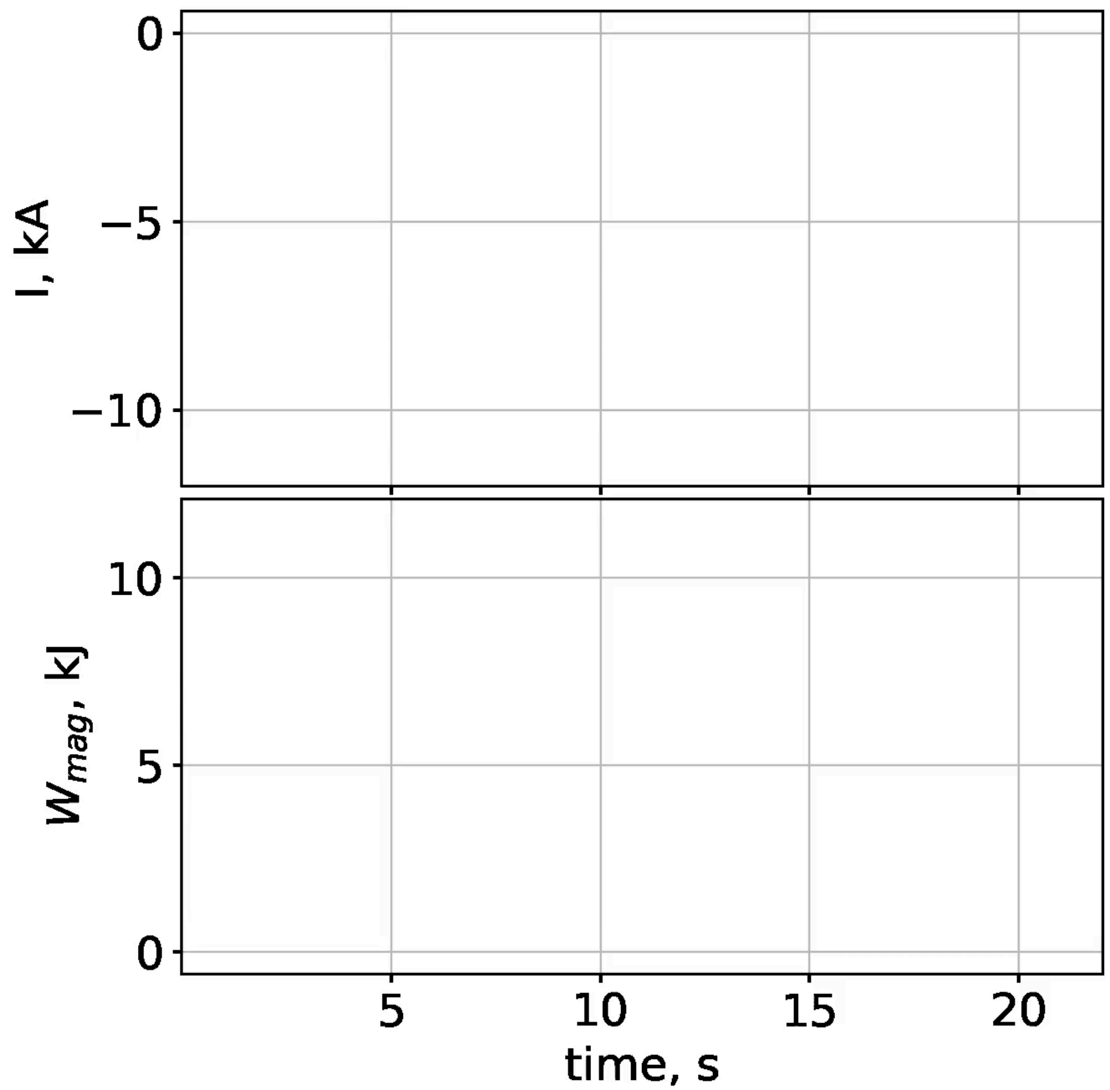


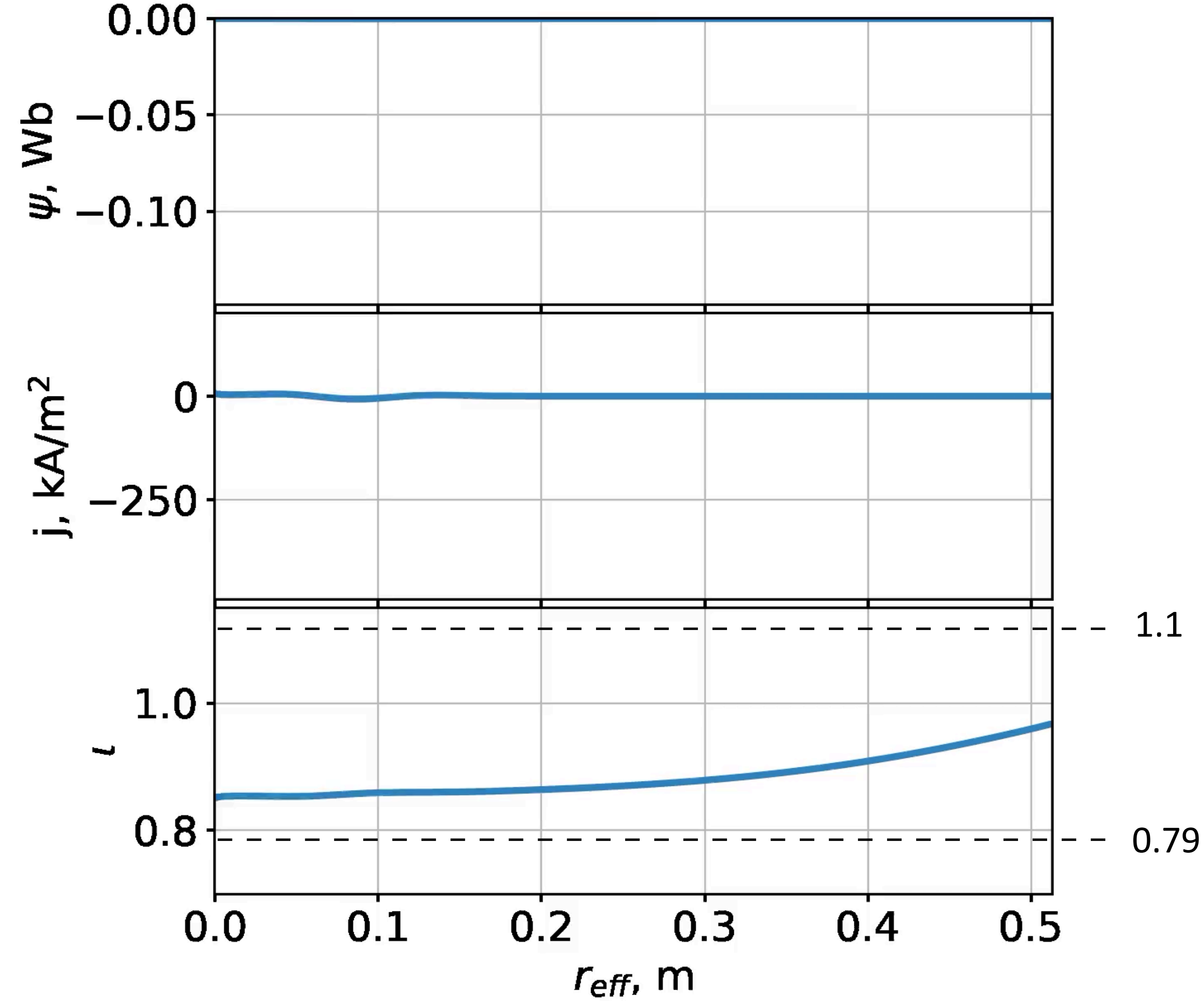
where $\sigma_{||}$ is the parallel conductivity, μ_0 is the permeability constant, r and R_0 are minor and major plasma radius.

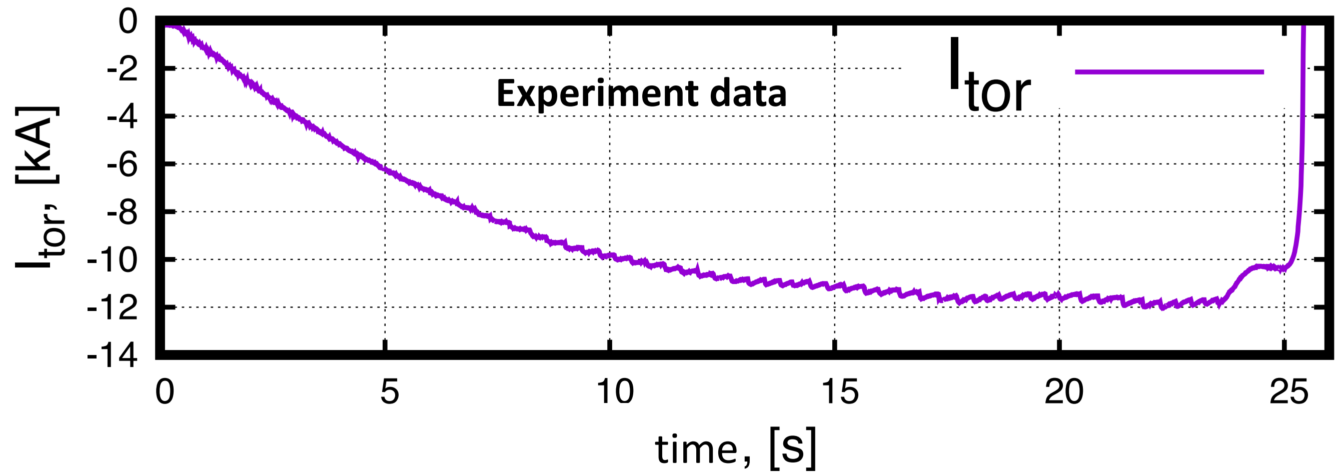
Once ι reaches "instability"-target value ι_{relax} (in this case: $\iota_{relax} > 1$ or $\iota_{relax} < 5/6$), flux reorganisation is triggered. Then diffusive evolution of the post-crash flux profile is calculated until the ι_{relax} is reached again.

Application of the model

XP20171206.025





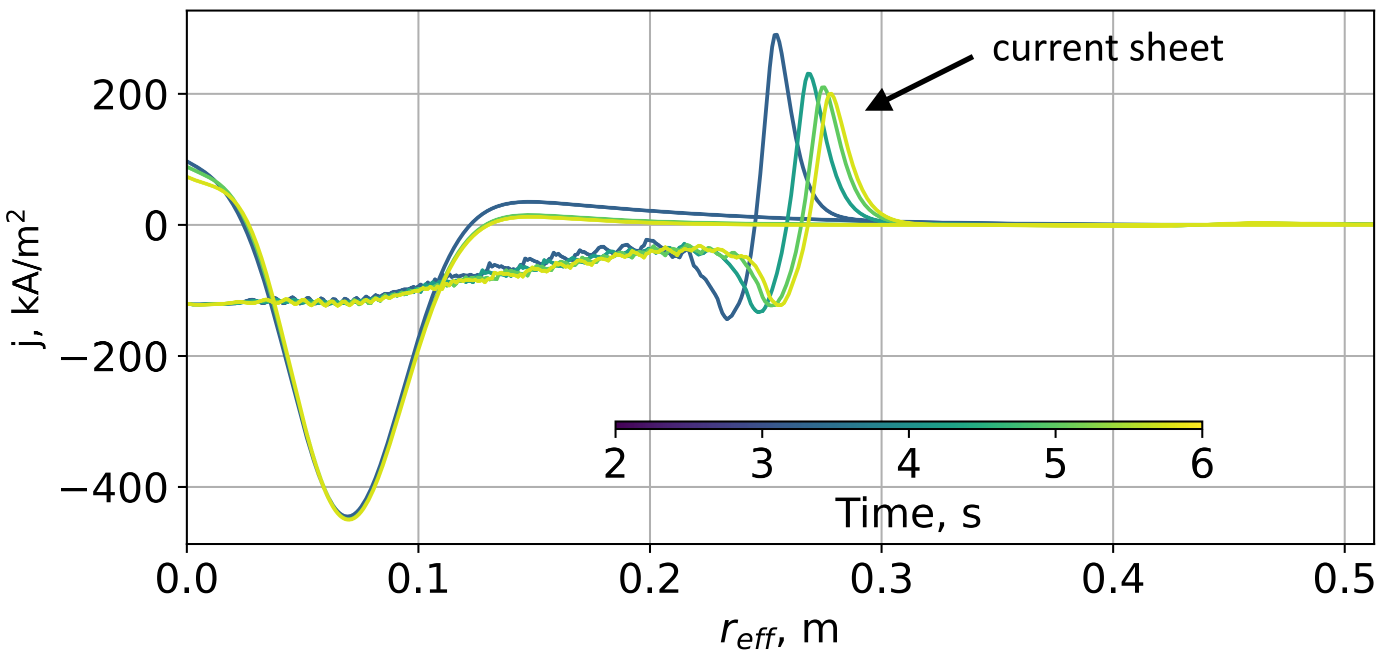


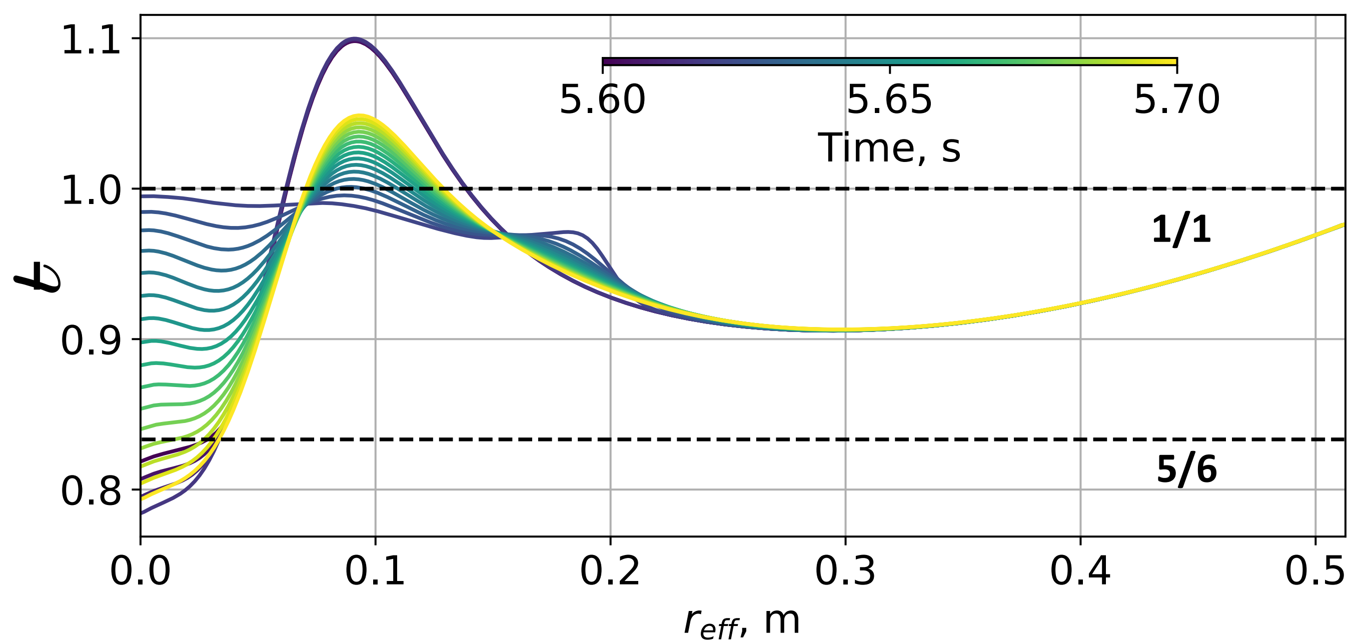
$\iota_{relax\ 1} = 1.1$

$\iota_{relax\ 5/6} = 0.79$

Application of the model

XP20171206.025





The ECCD current density has been calculated with the Travis ray-tracing code [1].

The plasma current and iota evolution is calculated from the flux diffusion equation with relaxations.

Time evolution is color-coded.

$$\iota_{relax\ 1} = 1.1$$
$$\iota_{relax\ 5/6} = 0.79$$

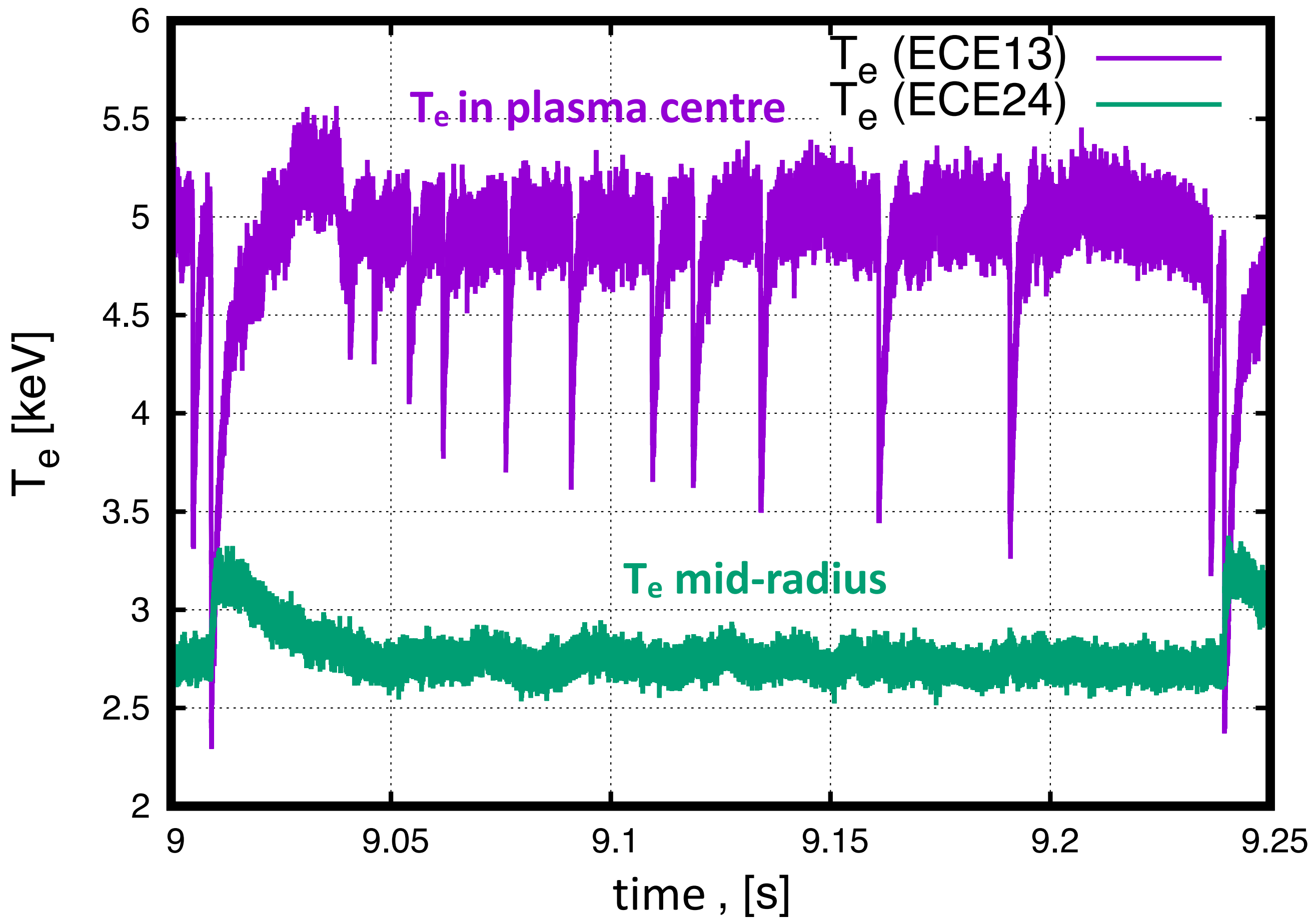
Mixing area is getting larger.

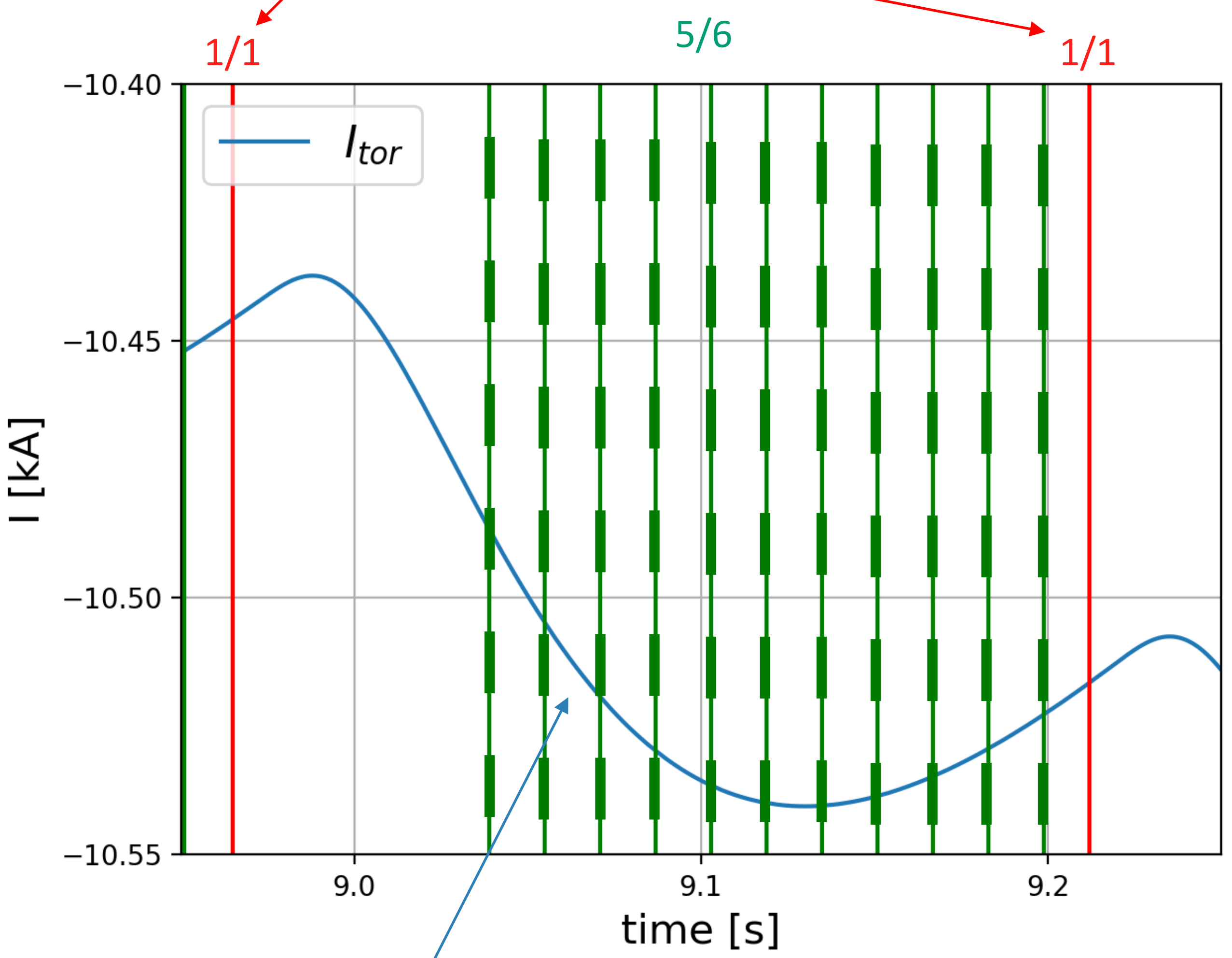
[1] Marushchenko et al, Computer Physics Communications 185/1 (2014).

Application of the model

XP20171206.025

Two type of crashes: associated with $\iota\!\!\!- = 1$ resonant surface and $\iota\!\!\!- = 5/6$.



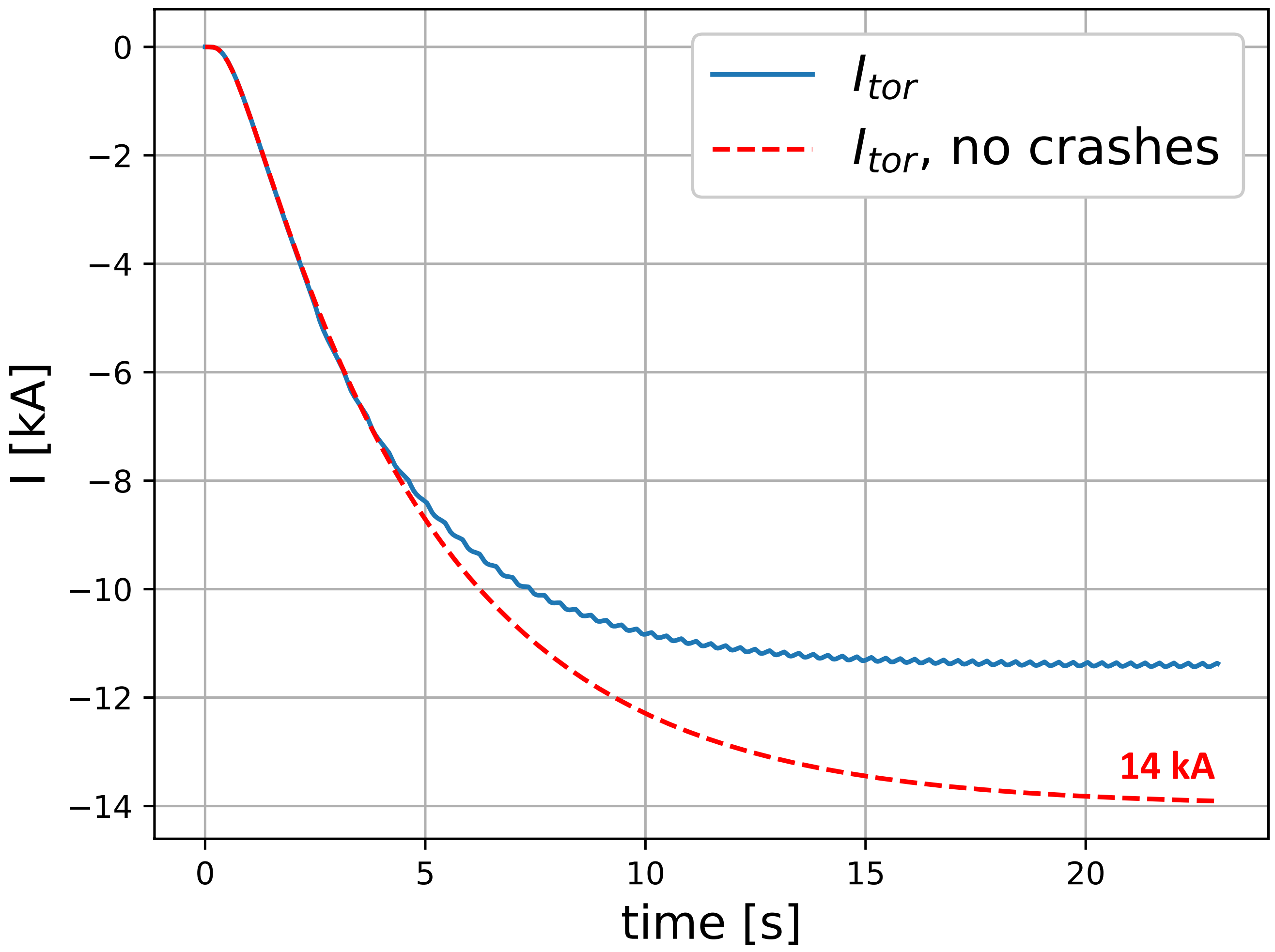


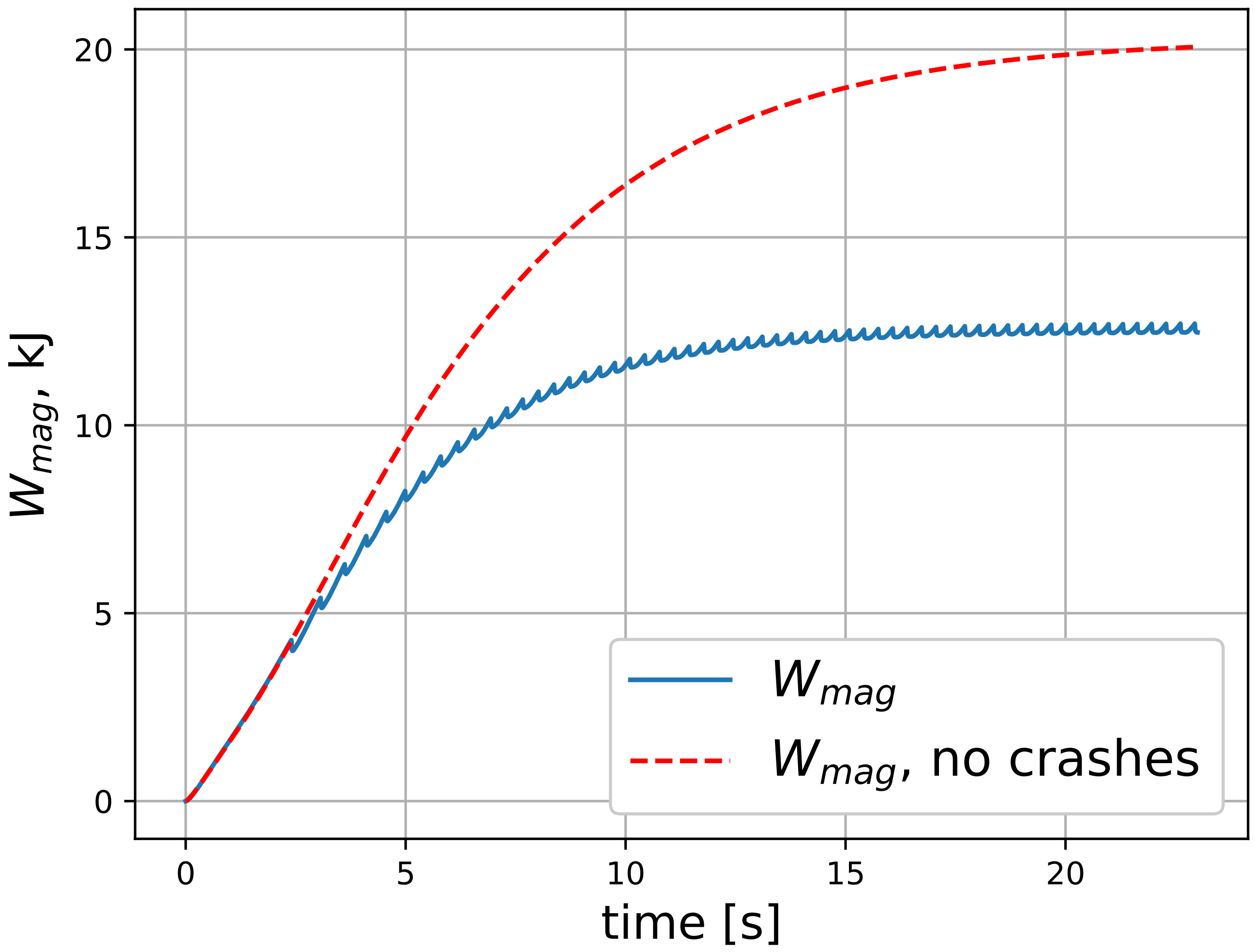
The shape is due to resistive evolution of the current sheet

5/6 resonance (not only 1/1) **is important.**

Current saturation with and without crashes

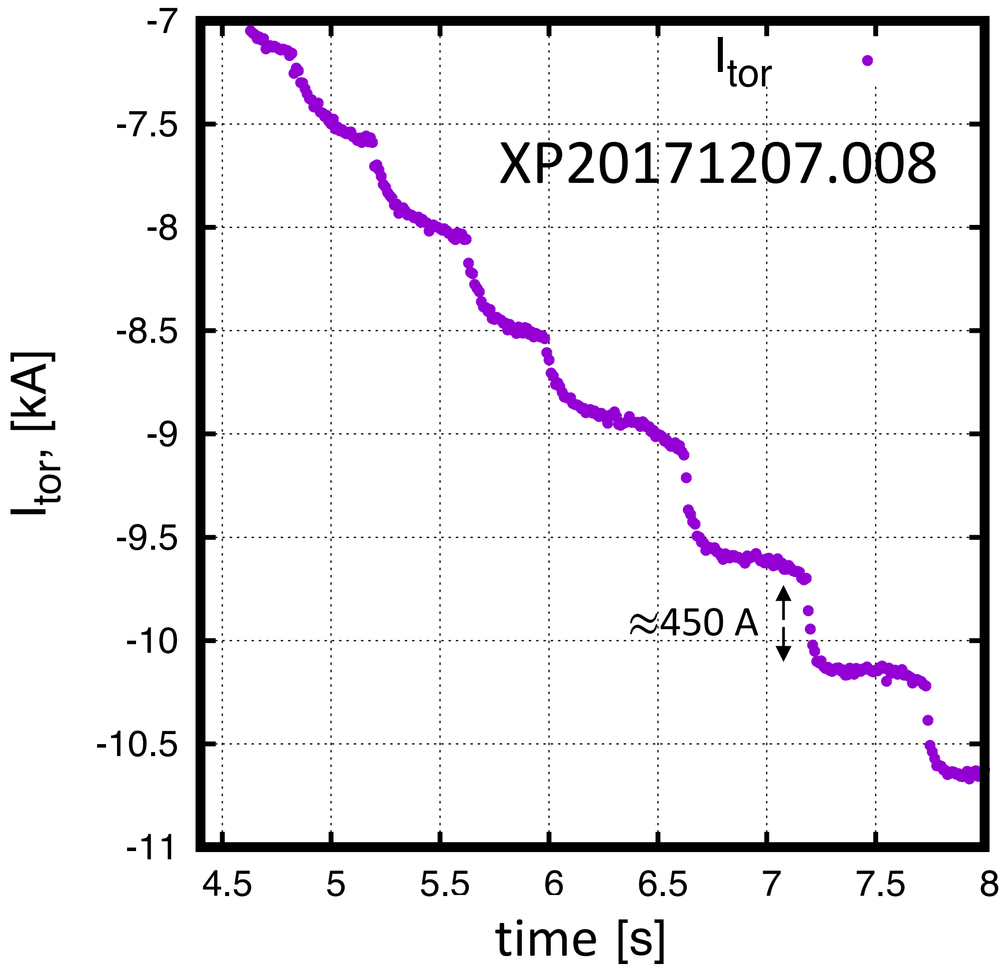
XP20171206.025

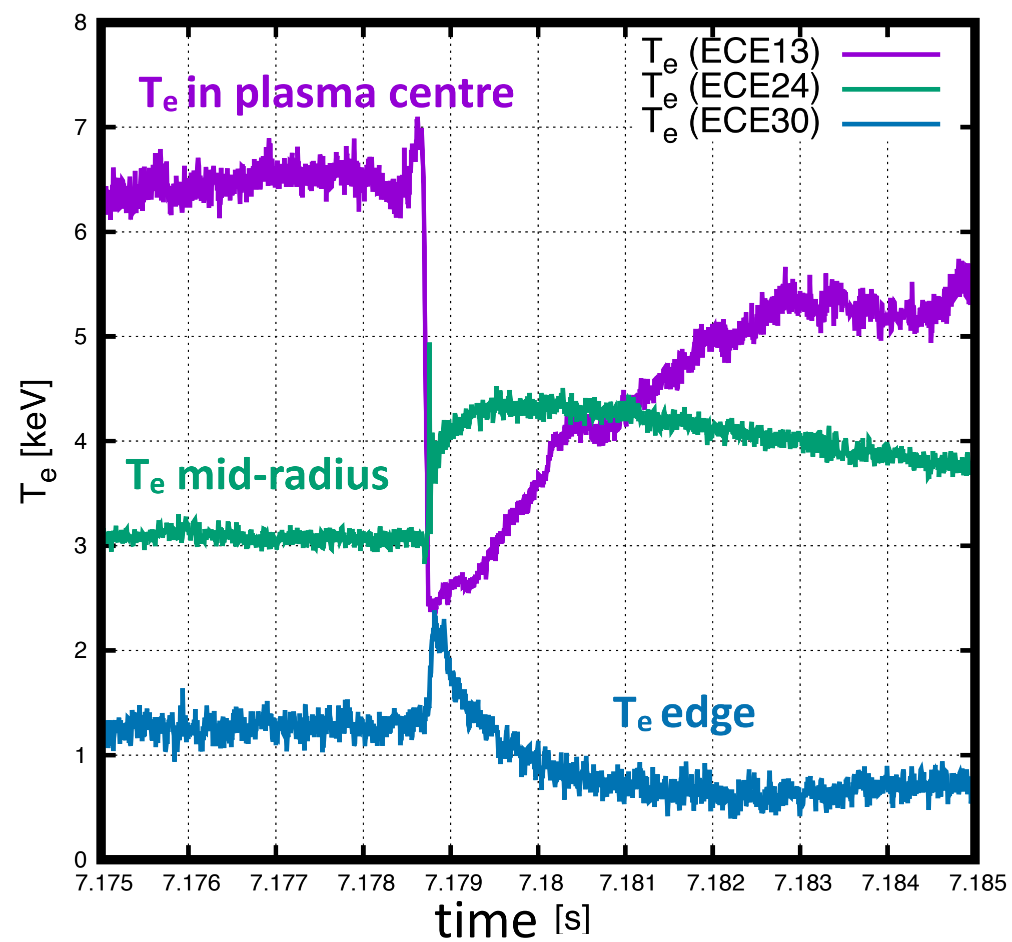




Toroidal current saturates at a lower value due to continuous magnetic energy dissipation via MHD crashes.

Large crashes in W7-X





We note that the global invariant K_0 corresponds to $\alpha = 0$ of the hierarchy

$$K_\alpha = \int_{V_0} d\tau\, \chi^\alpha \frac{\mathbf{A}\cdot\mathbf{B}}{2} .$$

It may be plausibly argued that since K_0 is the only invariant that is independent of q_s, it is the sole member of the intersection of all sets, each of which contains an infinite number of constants of the motion for each assumed helicity. In the presence of at least two modes strongly coupled to one another, it is likely that K_0 is the only surviving invariant.

A. Bhattacharjee and R. L. Dewar, The Physics of Fluids 25, 887 (1982)

Taylor theory

The key assumption in the Taylor theory is that a plasma subject to an instability will seek to **minimize its magnetic energy**,

$$W = \frac{1}{2\mu_0} \int B^2 dV,$$

subject to the constraint of **fixed magnetic helicity,**

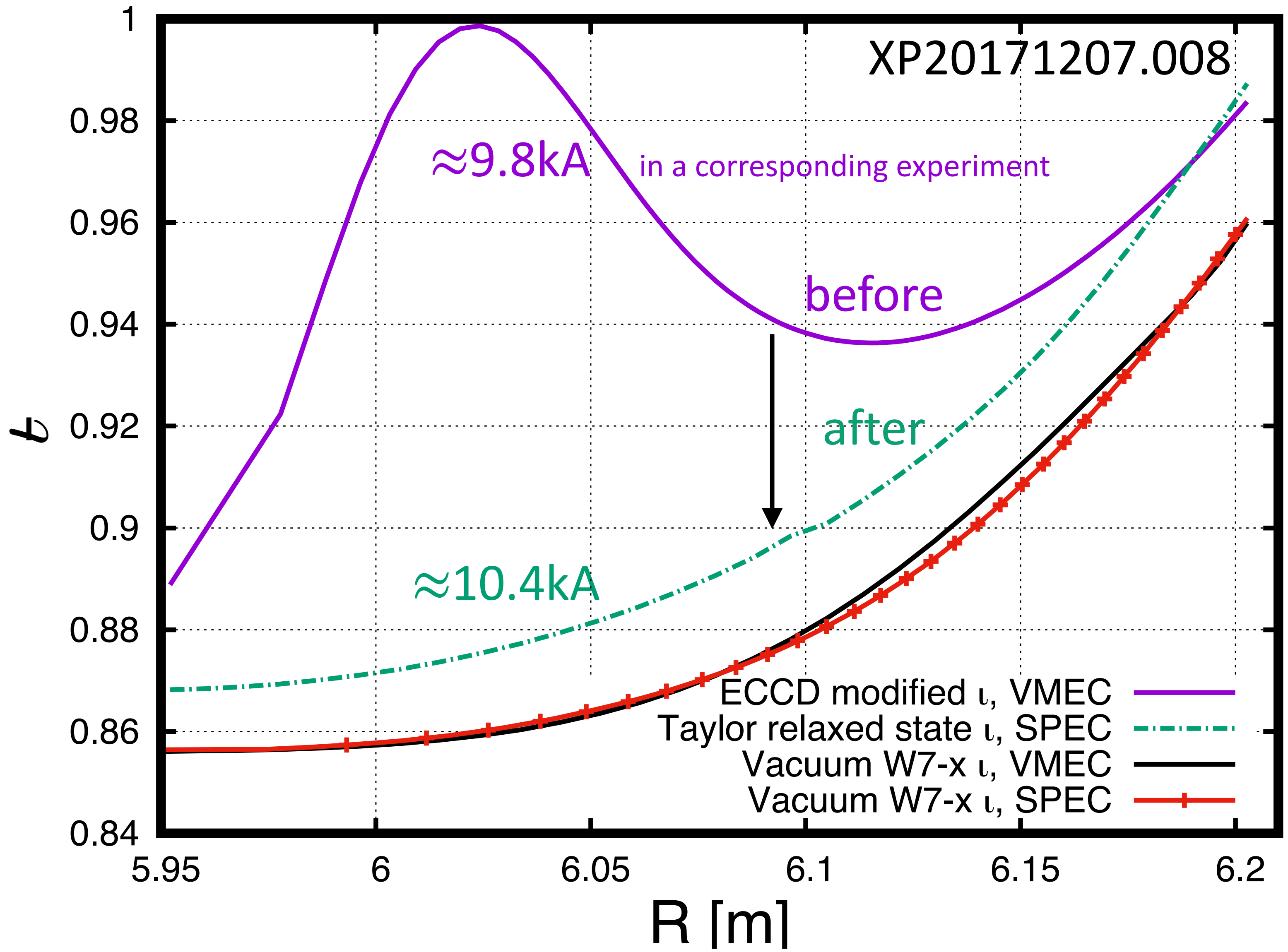
$$K_0 = \int \vec{A} \cdot \vec{B} dV,$$

and toroidal flux on the plasma boundary.
This assumption leads to the prediction of a plasma state, where the current flows in the direction of the magnetic field and the current density is proportional to the field strength, i.e.

$$\nabla \times \vec{B} = \mu \vec{B}$$

with constant μ. We suggest that the nonlinear result of the large crash in W7-X may be such a **Taylor-relaxed state**.

Taylor relaxed state in W7-X



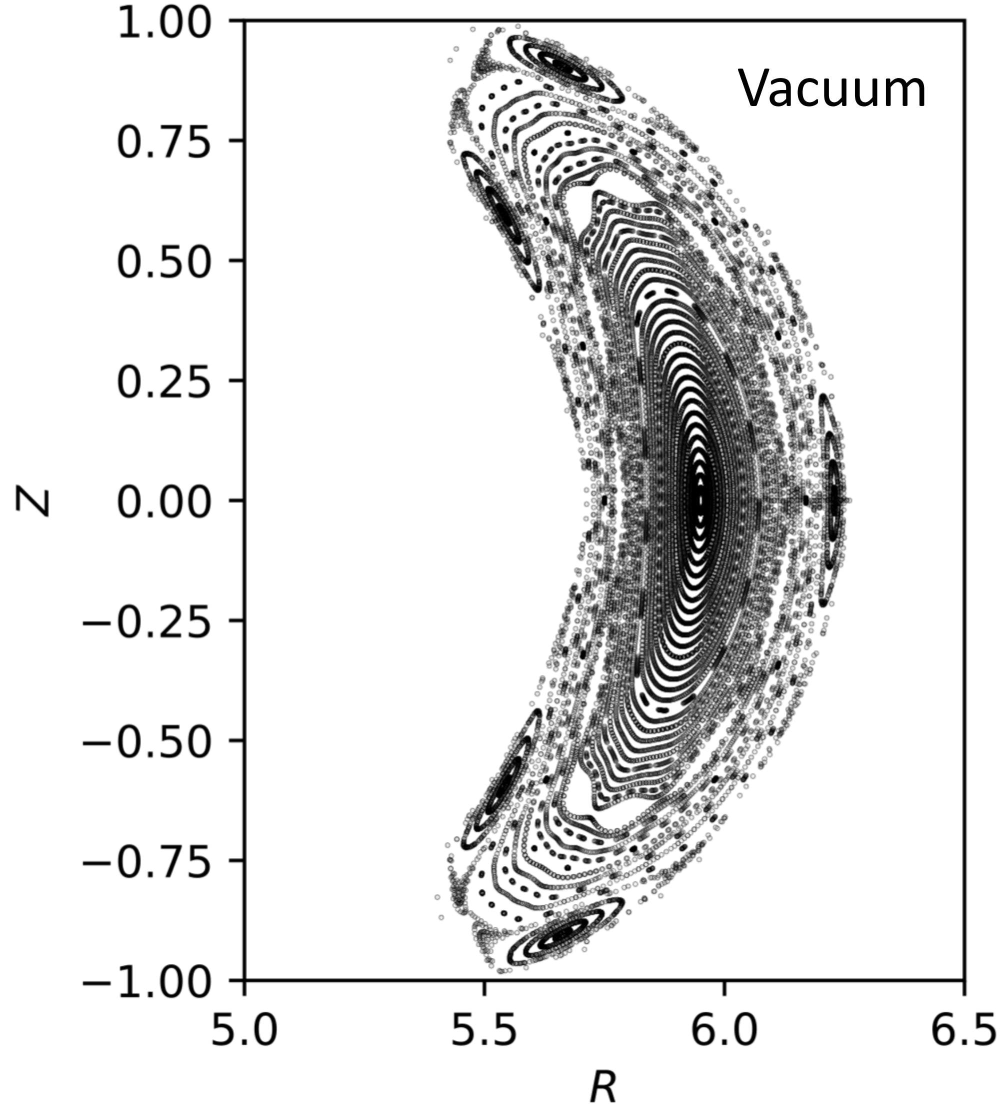
The Stepped-Pressure Equilibrium Code (**SPEC**) [2] is well suited for such calculations since it solves the Beltrami equation $\nabla \times \overrightarrow{B} = \mu \overrightarrow{B}$ in toroidal geometry.

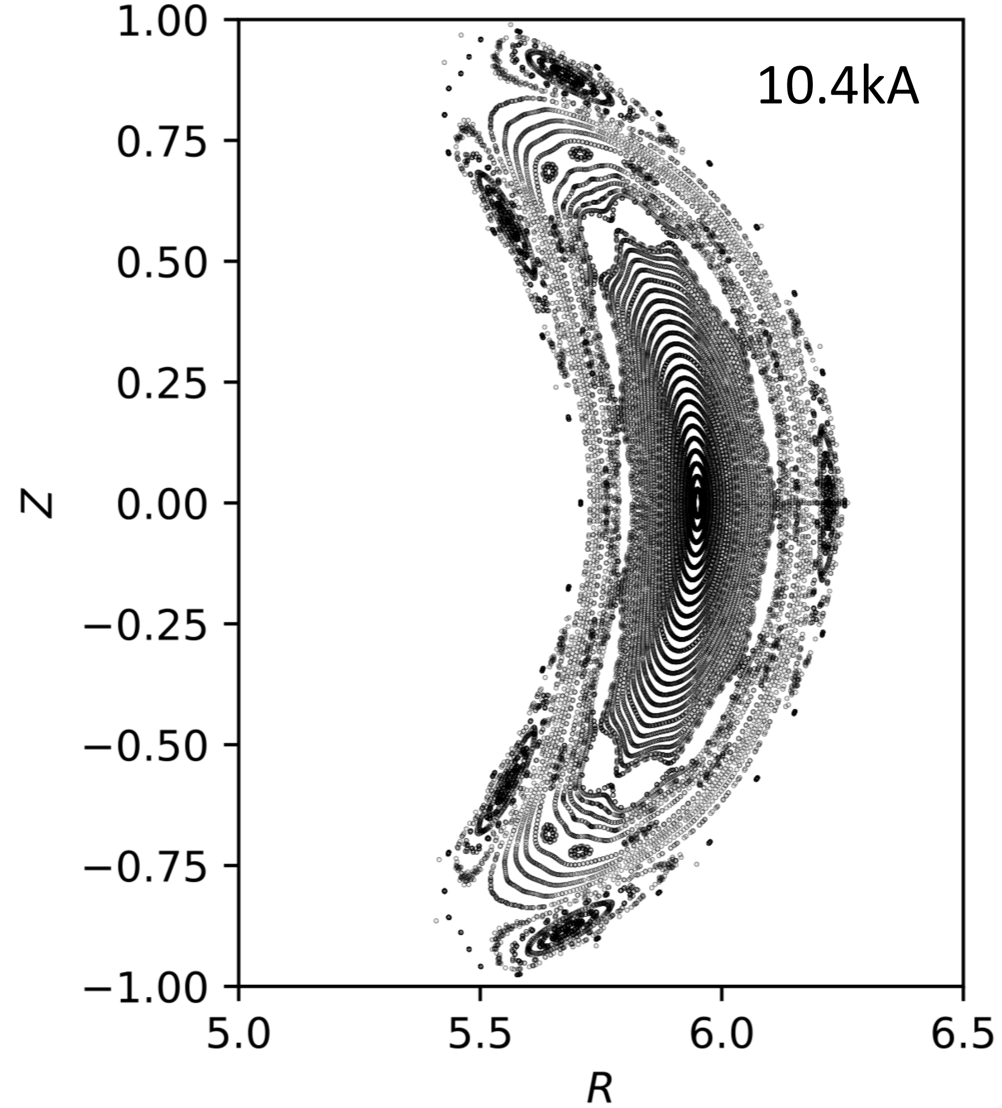
Helicity and total enclosed toroidal magnetic flux are conserved.

Predicted current jump $\delta I \approx$ 550A is in a good agreement with the experiment.

[2] Hudson et al, Physics of Plasmas 19 (11), 112502 (2012).

Taylor relaxed state in W7-X





A positive plasma current, resulting in an increase of ι_{edge}, makes the edge magnetic islands move into plasma.

This result is consistent with the experimental observation [Gao et al, Nuclear Fusion, 2019].

Conclusions

- F**lux diffusion model with relaxations** was demonstrated.
- Application for sawtooth cycles in W7-X:
  - similar (to the experiment) **evolution** of the total **toroidal current**
  - sawtooth crashes force an **earlier saturation of** the total **toroidal current** than it is expected due to ECCD
- At least in case of (effective) off-axis ECCD, we distinguish three types of temperature crashes, according to the temperature profile flattening area: **small, medium** and **large crashes**.
- Plausible **importance of 5/6 mode** was demonstrated.
- **Comparison** of current jumps (for the **largest crashes**) observed in the experiment and obtained from **Taylor relaxed state** was done (good agreement).

More about this work can be found in: [Aleynikova et al, Nuclear Fusion, 2021].

On-going:

- Implementation of the temperature crashes (starting from a simple “toy” model)