Non-linear MagnetoHydroDynamic simulations of Edge Localised Mode triggering via Vertical Kicks with JOREK-STARWALL

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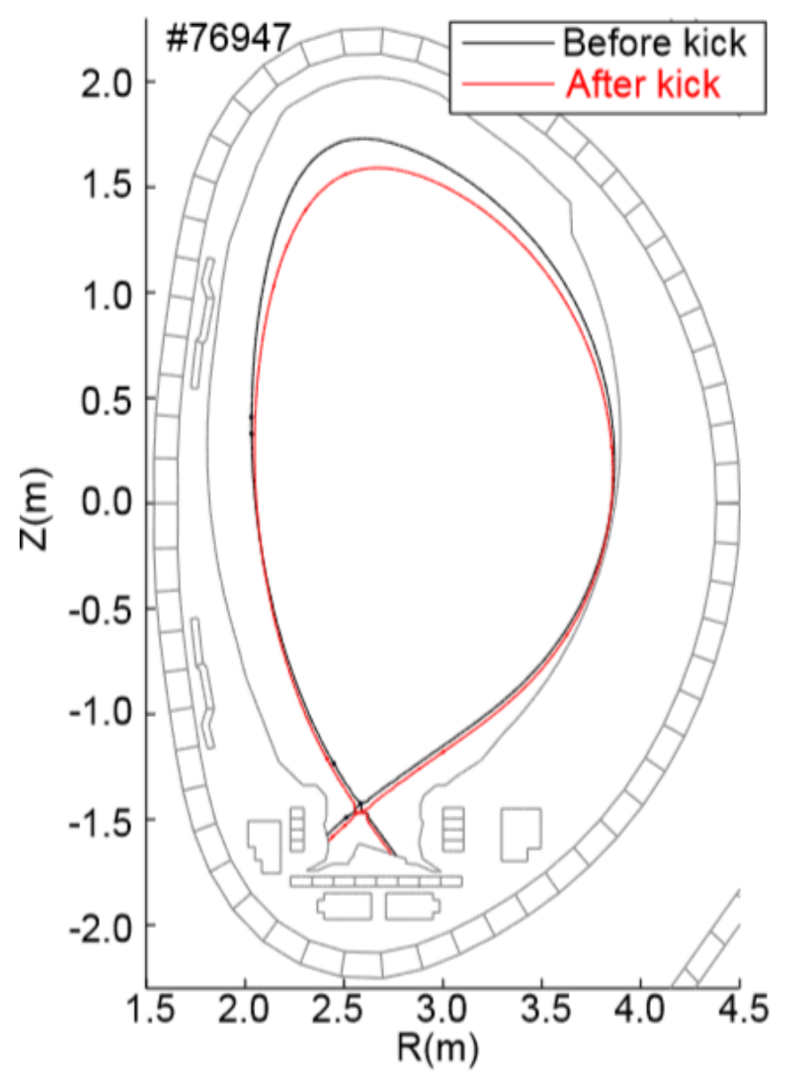
1. Introduction

Magnetic triggering of Edge Localized Modes (ELMs) in ohmic plasmas was first reported in the TCV tokamak [1]. The experiments showed that imposing a vertical plasma oscillation using poloidal field coils (PF coils), leads to a reliable locking of the ELM frequency to the vertical oscillation frequency. These vertical oscillations often called "vertical kicks" were also used for ELM frequency control in the ITER-relevant type-I ELM regime in ASDEX Upgrade [2] and JET [3] tokamaks. This technique can play a crucial role to maintain the ELM frequency so that the ensuing ELM power fluxes remain within the operational limits of Plasma Facing Components and that ELMs provide the required impurity outflux from the confined plasma.



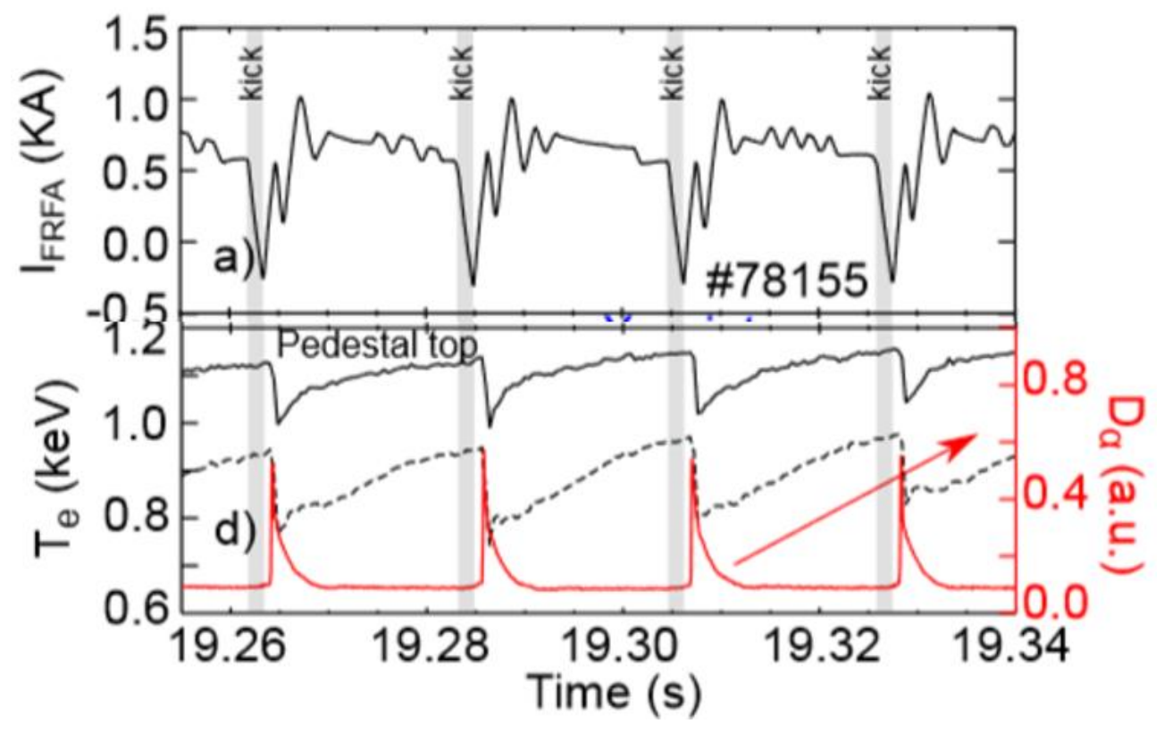


Figure 1. Experimental data from the JET shot #76947 showing the locking of the ELM frequency to the kick frequency [3]. (Left) Plasma shape before and after the kick. (Top) Induced current oscillations in the vertical position control system, pedestal temperature and alpha emission measurements with time.

2. Motivation

- **Clarify the underlying physics of ELM triggering via vertical kicks**
- **The coupled [4] JOREK [8] and STARWALL [10] codes allows 3D MHD non-linear simulations with free-boundary conditions and resistive walls**
- **Simulate for the first time vertical kicks and ELM triggering simulations in a single consistent scheme**
- **Vertical kicks are also considered as a back-up ELM control technique in ITER [5] at low current H-mode operation.**

3. Physics model and numerics

Physics Model: Reduced MHD in toroidal geometry

Poloidal flux	$\frac{1}{R^2}\frac{\partial\psi}{\partial t}=+\eta\nabla\cdot\left(\frac{1}{R^2}\nabla_\perp\psi\right)-\frac{1}{R}[u,\psi]-\frac{F_0}{R^2}\partial_\varphi u$
Parallel momentum	$\vec{B}\cdot\left(\rho\frac{\partial\vec{v}}{\partial t}=-\rho(\vec{v}\cdot\vec{\nabla})\vec{v}-\vec{\nabla}(\rho T)+\vec{J}\times\vec{B}+\mu\Delta\vec{v}\right)$
Poloidal momentum	$\vec{e}_\varphi\cdot\nabla\times\left(\rho\frac{\partial\vec{v}}{\partial t}=-\rho(\vec{v}\cdot\vec{\nabla})\vec{v}-\vec{\nabla}(\rho T)+\vec{J}\times\vec{B}+\mu\Delta\vec{v}\right)$
Temperature	$\rho\frac{\partial T}{\partial t}=-\rho v\cdot\nabla T-(\gamma-1)\rho T\nabla\cdot v+\nabla\cdot(\mathrm{K}_\perp\nabla_\perp T+\mathrm{K}_\parallel\nabla_\parallel T)+S_T$
Density	$\frac{\partial\rho}{\partial t}=-\nabla\cdot(\rho\vec{v})+\nabla\cdot(D_\perp\nabla_\perp\rho)+S$

$$\vec{v}=-R\vec{\nabla}u(t)\times\vec{e}_\varphi+v_\parallel(t)\vec{B}$$

$$\vec{B}=\frac{F_0}{R}\vec{e}_\varphi+\frac{1}{R}\vec{\nabla}\psi(t)\times\vec{e}_\varphi$$

Numerical code: **JOREK-STARWALL** presents the following features

- 3D toroidal geometry
- Non-linear
- **C1 Finite Element Method** in the poloidal plane (Bezier Elements) [9]
- **Fourier decomposition** in the toroidal direction
- **Fully implicit time discretization** (Crank-Nicolson/ Gear scheme)
- **Free-boundary extension:** including 3D coils and passive structures and its mutual interactions implicitly.

4. Benchmarking JOREK-STARWALL

- Benchmark of a vertical kick on an **ITER 7.5MA/2.65T scenario** with DINA [6]
- **Time varying coil currents and passive structures were implemented**
- Mutual interaction between coils and walls were necessary for good agreement

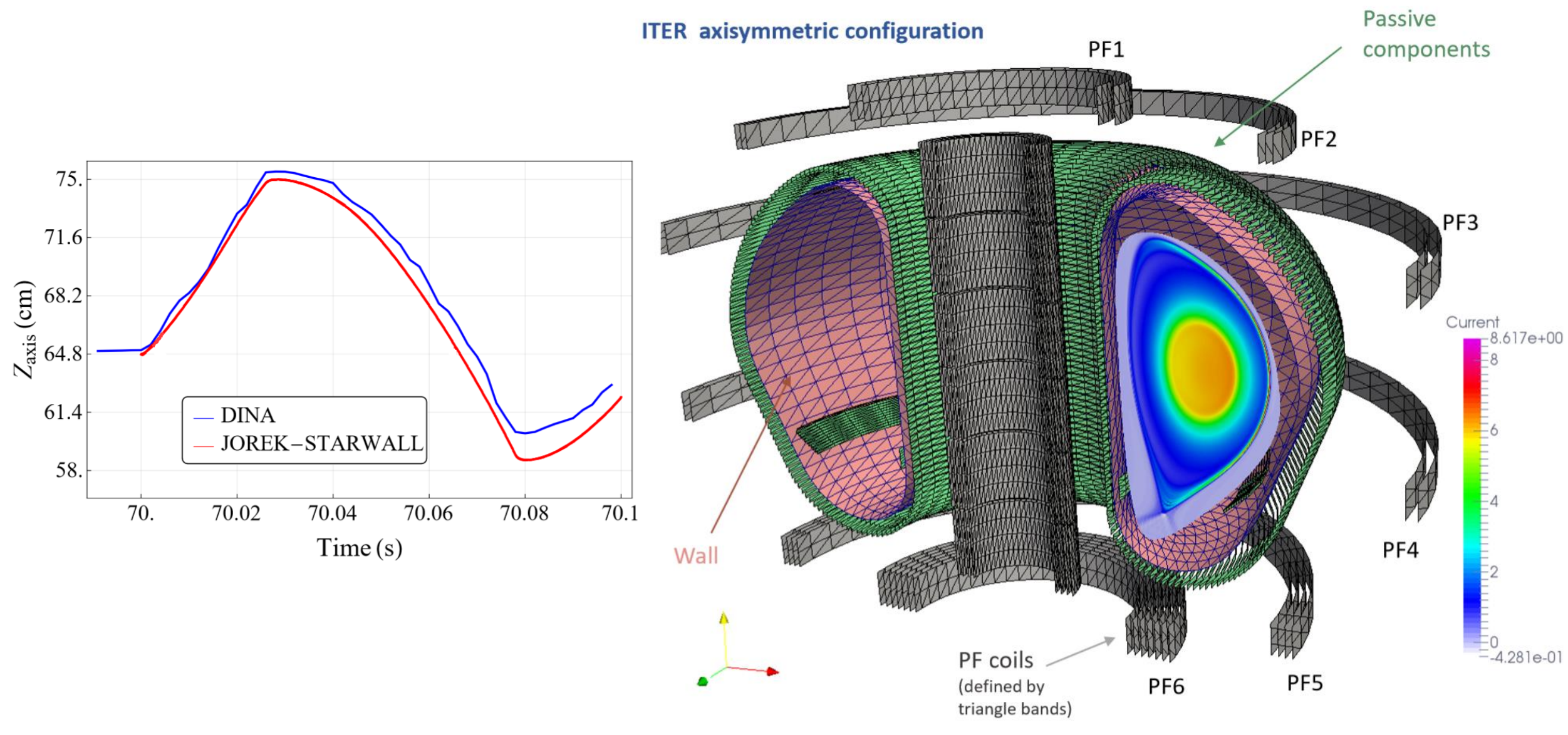


Figure 2. (Left) Plasma position during a vertical kick in the JOREK and DINA codes. (Right) Geometry of the implemented ITER coils, walls and conducting structures for the benchmark with DINA.

5. Understanding edge current induction during kicks

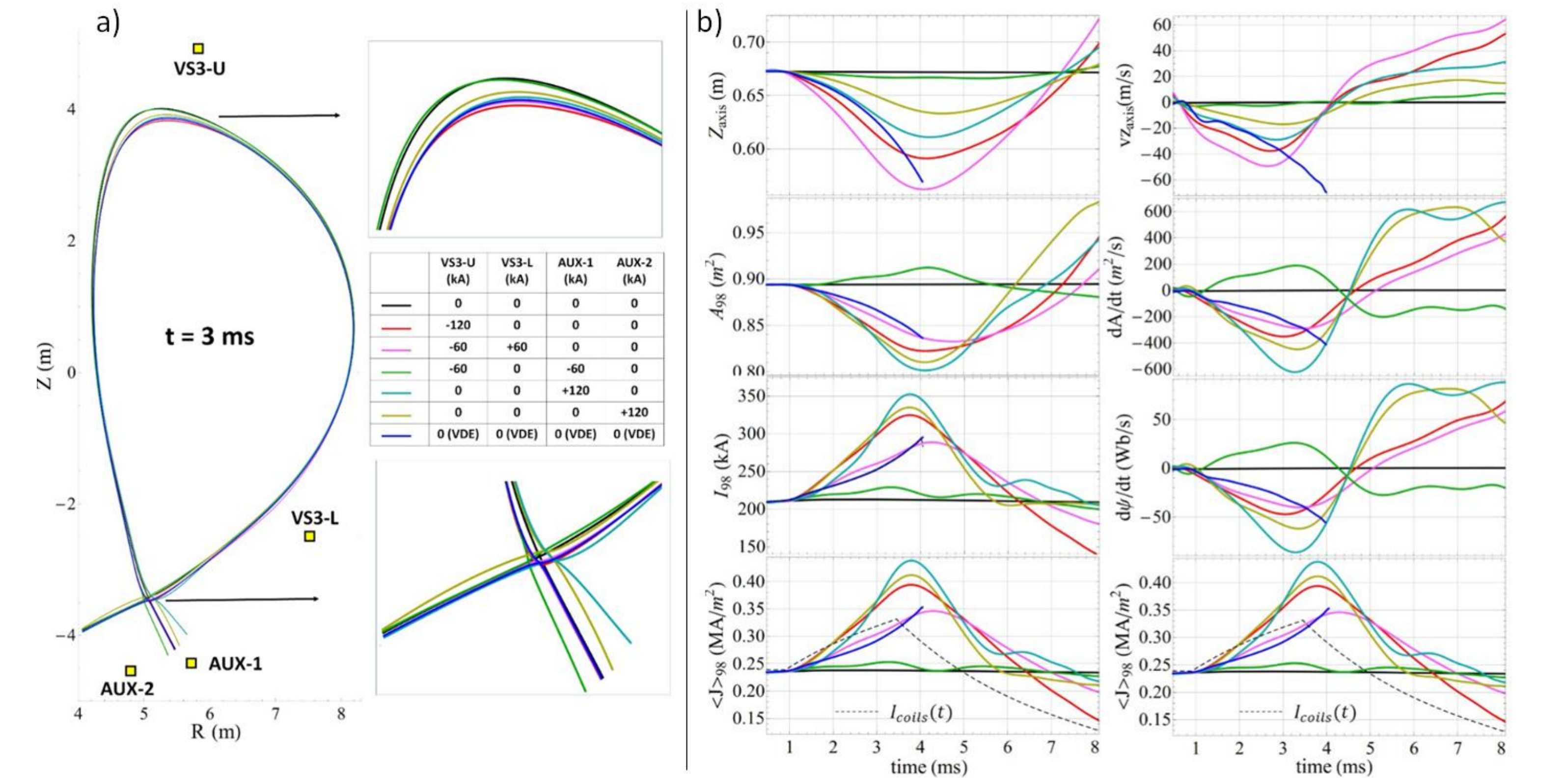
- **The induced edge current during the vertical motion was proposed as mechanism for ELM triggering [3,6]**
- **A simple cylindrical model reveals that the induced edge current $\Delta\mathrm{I}_\phi$ is due to**

1. A change in the boundary external flux $\Delta\psi_{ext}(a)$
2. Edge plasma compression $\Delta\delta_r$

$$\Delta I_\phi^{\delta_r}=\frac{4\pi}{\mu_0 R_0}\left[\Delta\psi_{ext}(a)-B_\theta(r_0)R_0\Delta\delta_r-\eta J_\phi\Delta t\right]$$

- **Dependence on velocity (Δt) only in the resistive decay term**
- **Realistic ITER kick simulations reveal**

1. Maximum induced current is related to maximum plasma compression
2. Compression is due to the plasma motion through the inhomogeneous magnetic field of the PF coils
3. Optimization of the current waveforms of the coils used to oscillate plasma position can be used to enhance compression.



	VS3-U (kA)	VS3-L (kA)	AUX-1 (kA)	AUX-2 (kA)
―	0	0	0	0
―	-120	0	0	0
―	-60	+60	0	0
―	-60	0	-60	0
―	0	0	+120	0
―	0	0	0	+120
―	0 (VDE)	0 (VDE)	0 (VDE)	0 (VDE)

Figure 3. Current induction study of an ITER 7.5MA/2.65T kick using different PF coil configurations. (a) Geometry of the coils moving the plasma, table indicating the different current choices in those coils and separatrix at t=3 ms. (b) Time traces for the chosen configurations. The quantities are identified as, vertical position and velocity (Z_{axis} and $v_{Z_{axis}}$), plasma cross-sectional area (A), total toroidal current (I), poloidal flux (ψ) and averaged toroidal current density ($<J>_{98}$). For (A) and (I) the subscript 98 indicates that the quantity has been integrated over the plasma edge $\psi_N\in[0.98-1.00]$. The dark blue line corresponds to the special case of a natural VDE where no coils where used to move the plasma (just the wall resistivity was increased).

6. Simulations of ELM destabilization

Figure 4. Downward kicks are able to destabilize the n = 6 mode with a (peeling)-ballooning structure

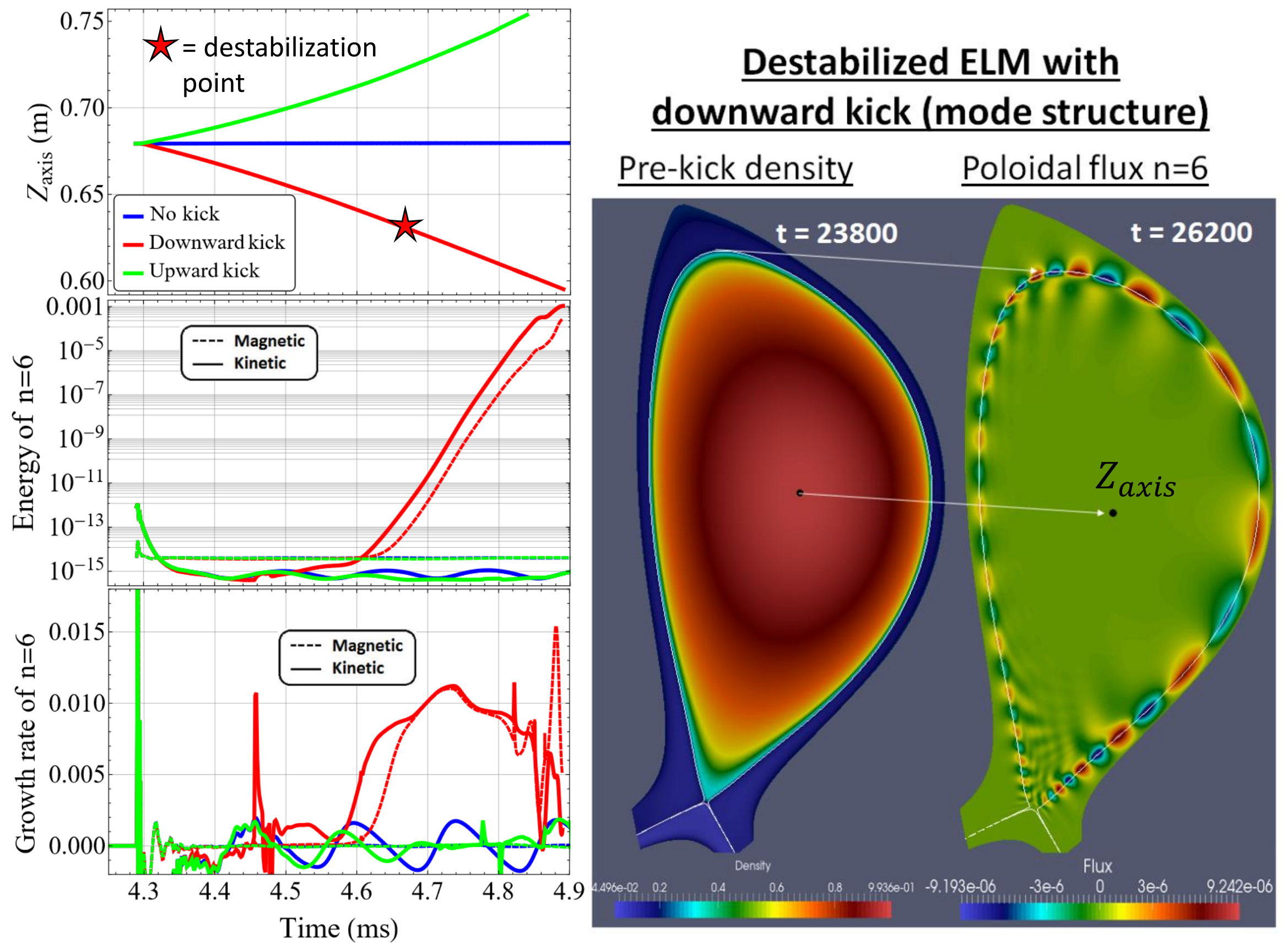


Figure 6. As in experiments [3], ELMs are destabilized with the same vertical displacement ΔZ_{axis} regardless of the plasma velocity

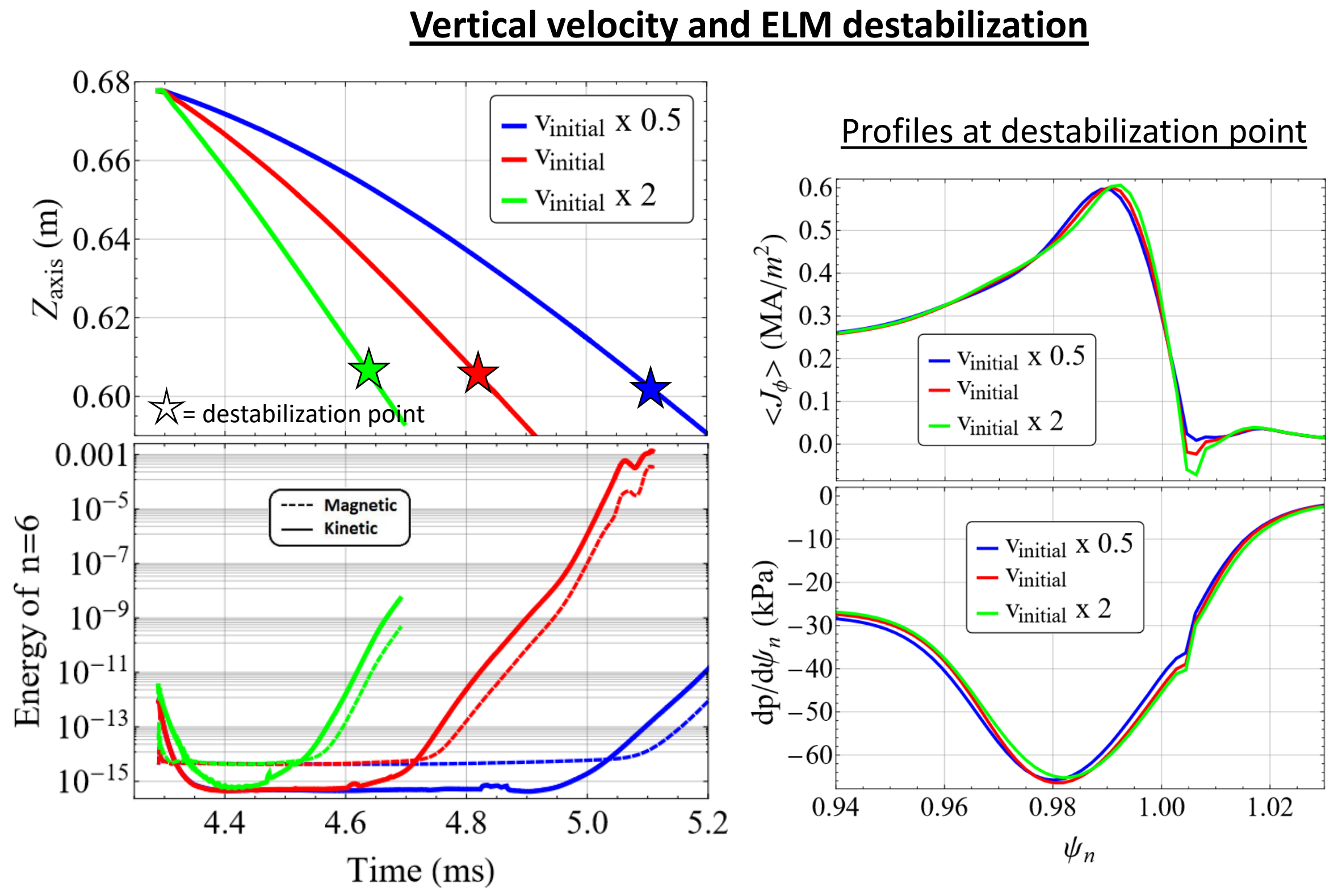


Figure 5. Initially unstable plasmas can be further destabilized by a downward kick and stabilized by an upward one

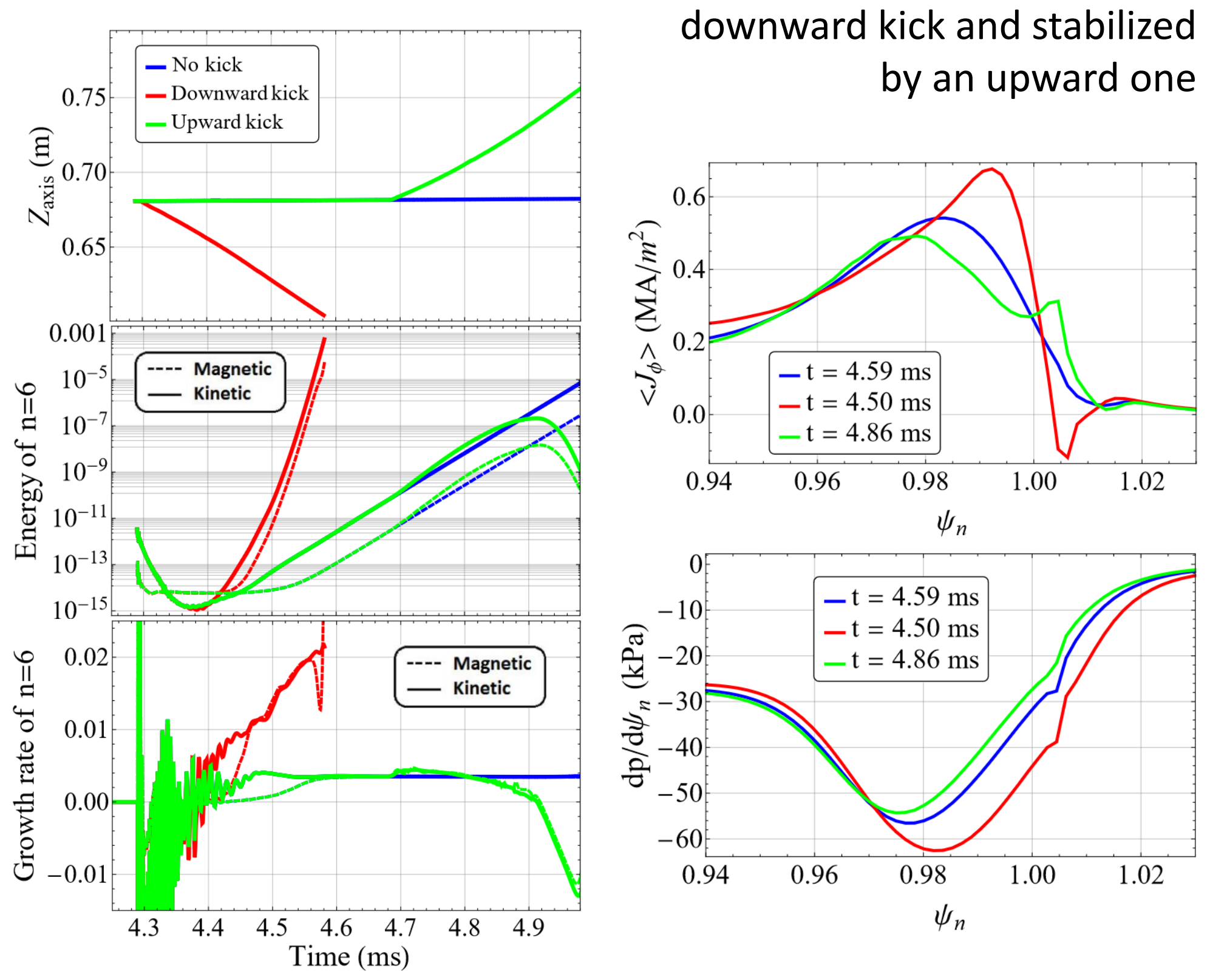
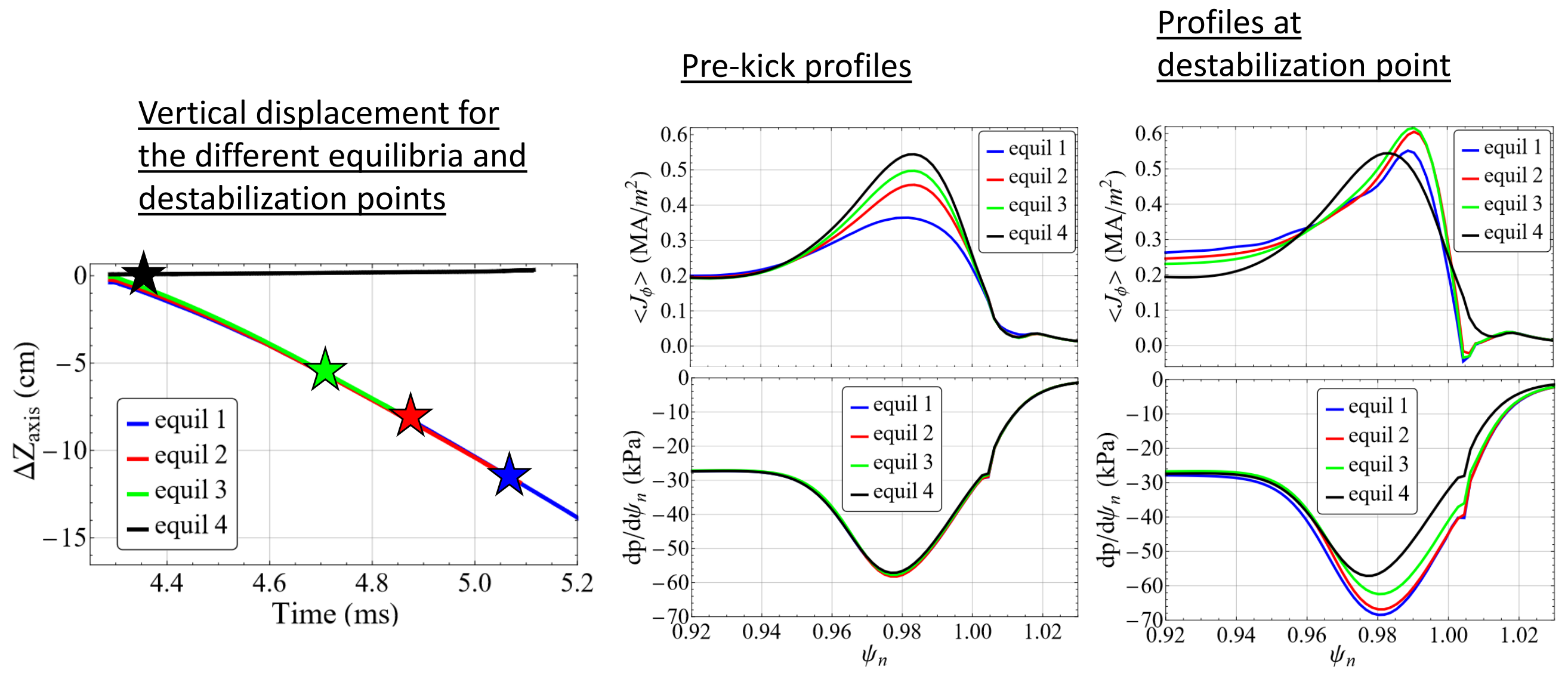


Figure 7. Higher initial edge current levels require smaller ΔZ_{axis}. Typical ΔZ_{axis} for ELM triggering in these plasmas is 0.01-0.15 m



* For all ELM simulations: kick and resistive time scales are a factor 10 smaller than in [6]

7. Conclusions

- **JOREK-STARWALL was benchmarked with the code DINA for a realistic ITER 7.52MA/2.65T scenario with a vertical kick**
- **The induced edge current during a kick is due to the plasma motion through an inhomogeneous magnetic field. The induction of current can be further improved by enhancing the plasma compression with different configurations for the coils used for the plasma vertical oscillation.**
- **ELM-like modes were destabilized with downward kicks and stabilized with upward kicks**
- **As in experiments, ELMs are destabilized at the same vertical displacement ΔZ_{axis} regardless of the plasma velocity**
- **The required ΔZ_{axis} to destabilize an ELM strongly depends on the initial current profile. This suggests that the induced current during the kick is the main factor for ELM destabilization**

8. References

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