MAX-PLANCK-INSTITUT
FÜR PLASMAPHYSIK

Transient processes in fusion plasmas – Non-linear MHD modelling with JOREK

Matthias Hoelzl for the JOREK community
(see references on the slides).

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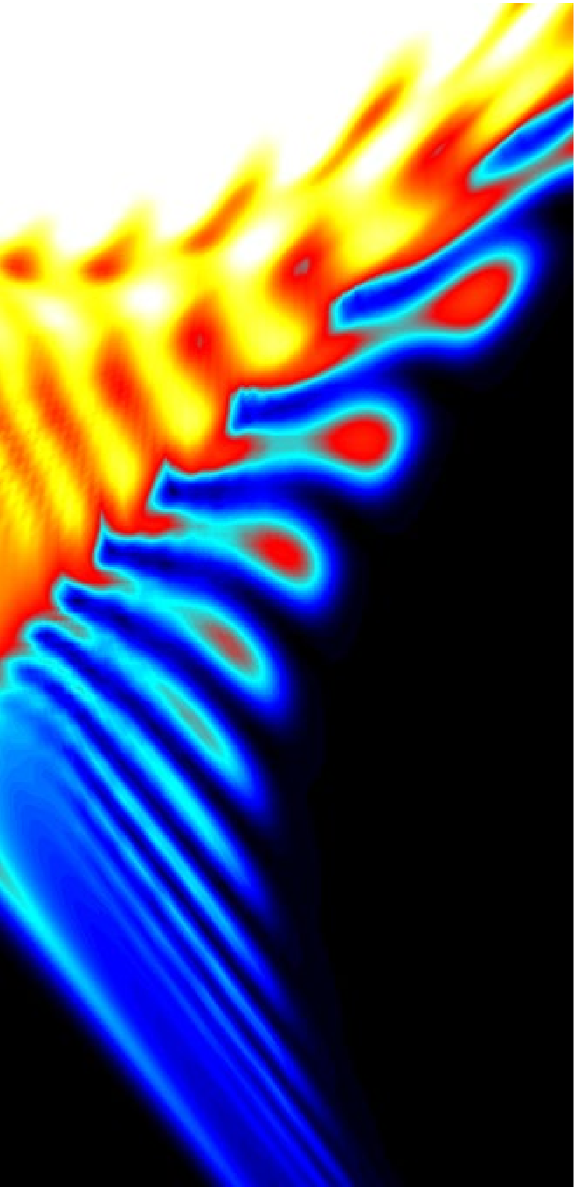
What are MHD transients and why do we study them?

Interesting multi-physics processes



Edge localized modes (ELMs)

Solar eruptions

Precursors

Explosive onset

Filament formation

Magnetic reconnection

Potentially harmful energy release

Described by magneto-hydrodynamics

Challenging multi-scale problem

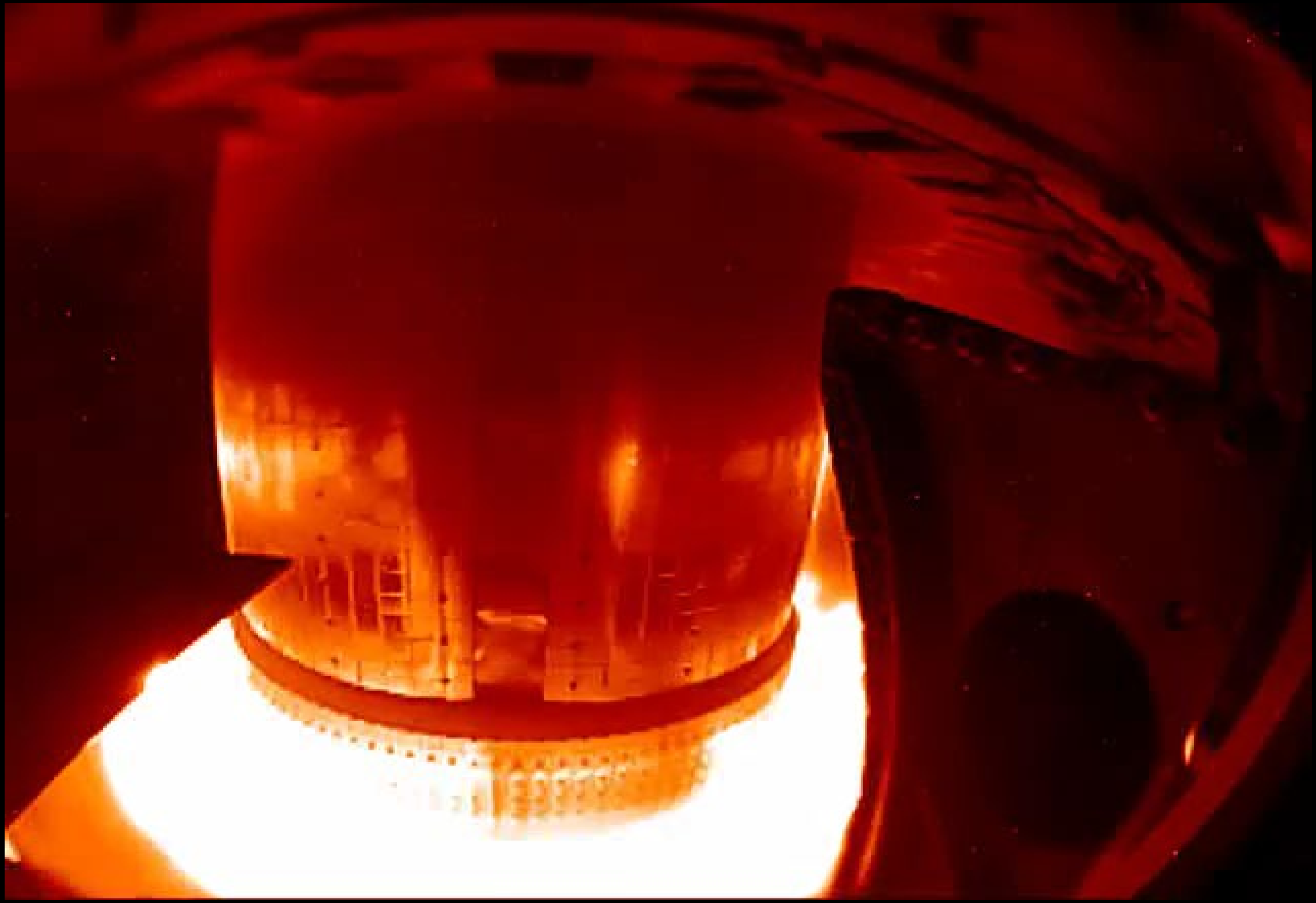
Interaction with turbulence

Critical for a fusion power plant

Large scale violent plasma instabilities constitute a serious risk for large fusion devices

- **Edge localized modes**
  - Periodically expell heat and particles from the boundary of the plasma and can reduce the lifetime of wall components
- **Major disruptions**
  - Complete loss of the plasma confinement causing strong heat loads and mechanical forces onto the machine
- …

Aim to control and mitigate



LOSS OF RELATIVISTIC ELECTRONS TO MATERIAL SURFACES
VIDEO FROM ALCATOR C-MOD; R. GRANETZ, PRIVATE COMMUNICATION

How do we simulate MHD transients and their control?

Extended and hybrid MHD

Magneto-hydrodynamics (MHD) describes the plasma as a fluid

by evolution equations for

- **Density**
- **Temperature**
- **Velocity**
- **Current**
- **Magnetic field**
- **Electric field**

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- **Electric field**

+ Kinetic effects captured by a powerful particle in cell module

Extended and hybrid MHD

Two-fluid effects

Neutral particles

Impurities

Supra-thermal particles

Neoclassical physics

Electrostatic turbulence

Magneto-hydrodynamics (MHD) describes the plasma as a fluid by evolution equations for

- **Density**
- **Temperature**
- **Velocity**
- **Current**
- **Magnetic field**
- **Electric field**

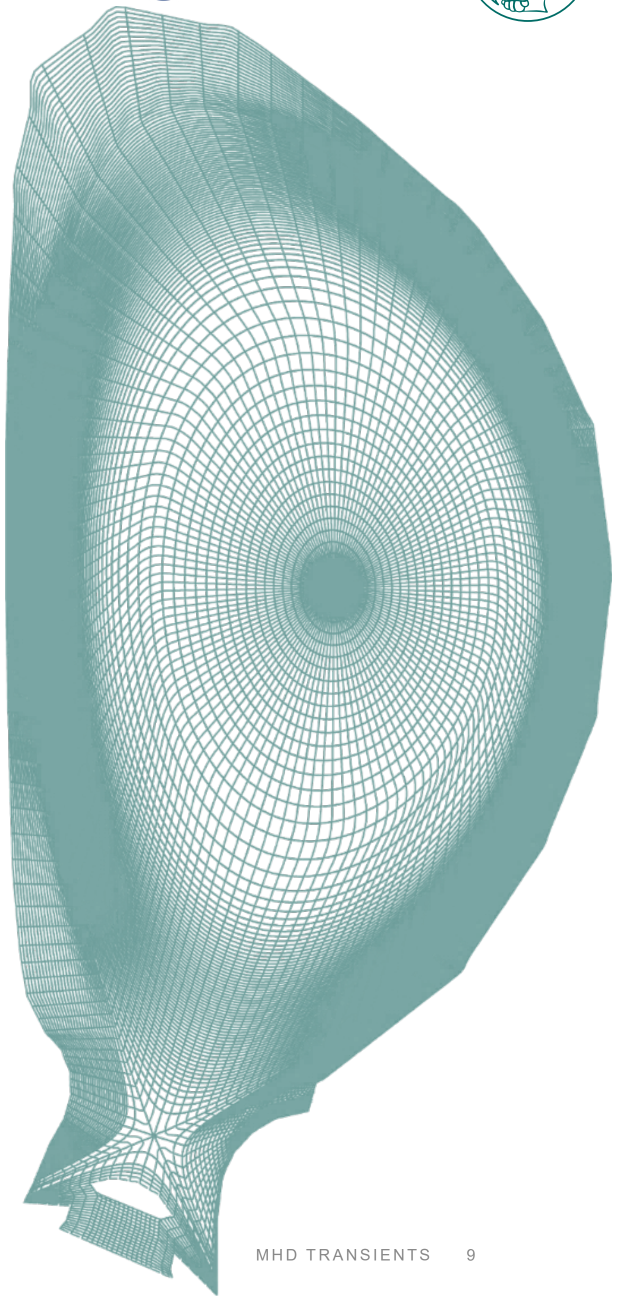
Interaction with material surfaces

Interaction with conducting structures

Ablation of injected pellets

+ Kinetic effects captured by a powerful particle in cell module

The JOREK non-linear MHD code



- 3D non-linear extended MHD
- 2D finite elements, realistic geometry
- Toroidal Fourier expansion
- Implicit time stepping
- Large HPC systems
- Strong international community lead by EUROfusion project TSVV 8 on MHD transients

[https://www.jorek.eu]

[M Hoelzl, GTA Huijsmans, SJP Pamela, M Becoulet, E Nardon E, FJ Artola, B Nkonga, et al. Nuclear Fusion 61, 065001 (2021)]

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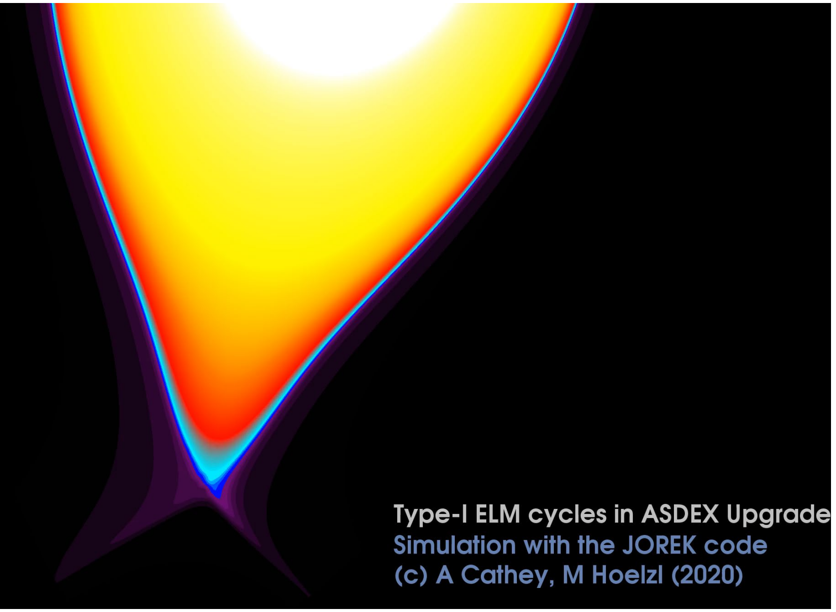
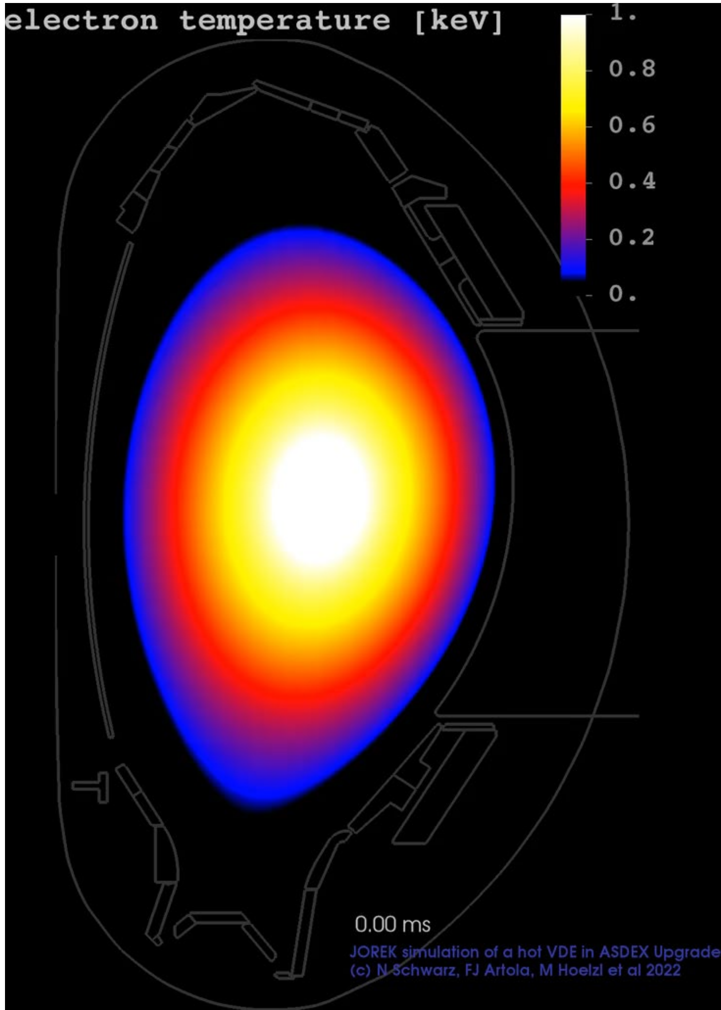
Main fields of research



Type-I ELM cycles in ASDEX Upgrade
Simulation with the JOREK code
(c) A Cathey, M Hoelzl (2020)

Pedestal physics: Type-I ELM cycles, small ELM regimes (QCE, EDA-H-mode), ELM free regimes (QH-mode), ELM control by resonant magnetic perturbations, pellet ELM pacing, vertical kick ELM triggering, advanced SOL/divertor modelling including kinetic neutrals and impurities, plasma-wall interaction, X-point radiator …

Disruptions: Natural and mitigated disruptions, vertical displacement events, runaway electrons, wall forces and loads, massive gas injection, shattered pellet injection, …



JOREK simulation of a hot VDE in ASDEX Upgrade
(c) N Schwarz, FJ Artola, M Hoelzl et al 2022

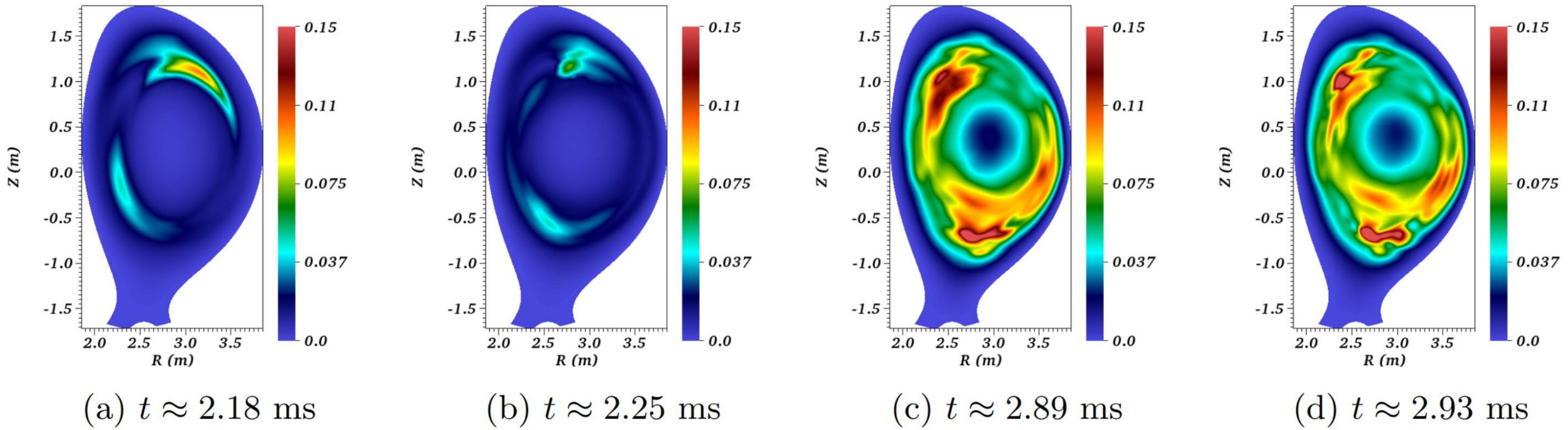
Further fields: Energetic particles, stellarator MHD, ITG and TEM turbulence, …

What were the main developments during the last JFRS-1 cycle?

(performed by EUROfusion project TSVV 8)

Impurity inclusion in full MHD + shock capturing

- JOREK has a set of **reduced and full MHD** models
- For many applications, reduced MHD is sufficient (eliminates fast magneto-sonic waves); validity is, however, limited for 1/1 internal kink modes at finite beta
- The full MHD model now includes a **neutrals fluid model, diamagnetic drift effects, two-temperature effects, an impurity fluid model** (free boundary extension is under development)
- Also a **shock capturing** method was implemented
- First application to impurity shattered pellet injection in the JET tokamak:

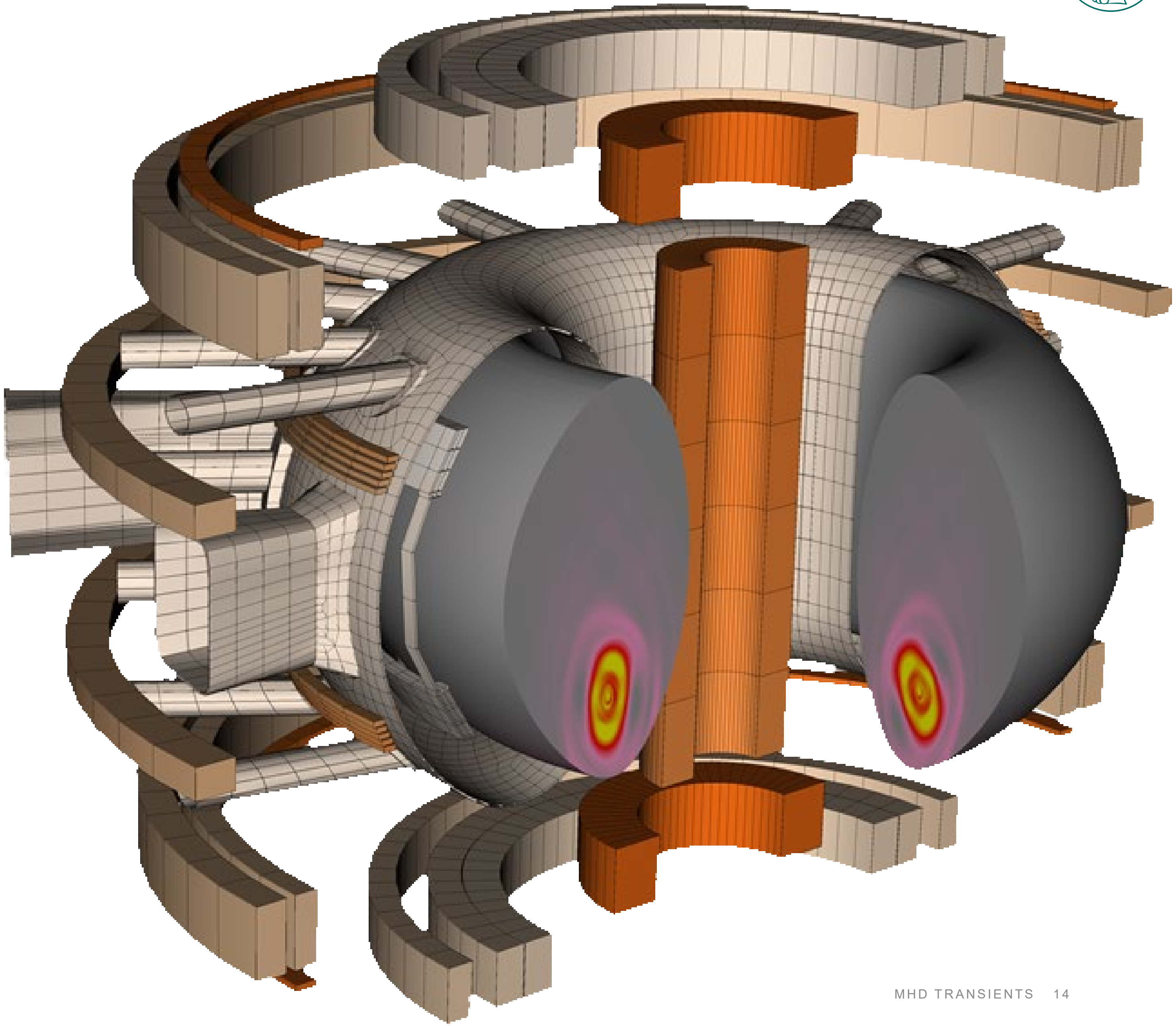


(a) $t \approx 2.18$ ms (b) $t \approx 2.25$ ms (c) $t \approx 2.89$ ms (d) $t \approx 2.93$ ms

[A Bhole et al, Computers & Mathematics with Applications 142, 225 (2023)]

Accurate 3D wall models

- **Eddy current coupling to the CARIDDI code was completed and verified by various benchmarks**
- (Halo current coupling is future work needed for accurate horizontal forces)
- This enables accurate 3D plasma studies taking into account detailed 3D models of conducting structures
- One of the first applications is a 3D vertical displacement event in the ASDEX Upgrade tokamak (figure)



[N Isernia, N Schwarz et al, in preparation]

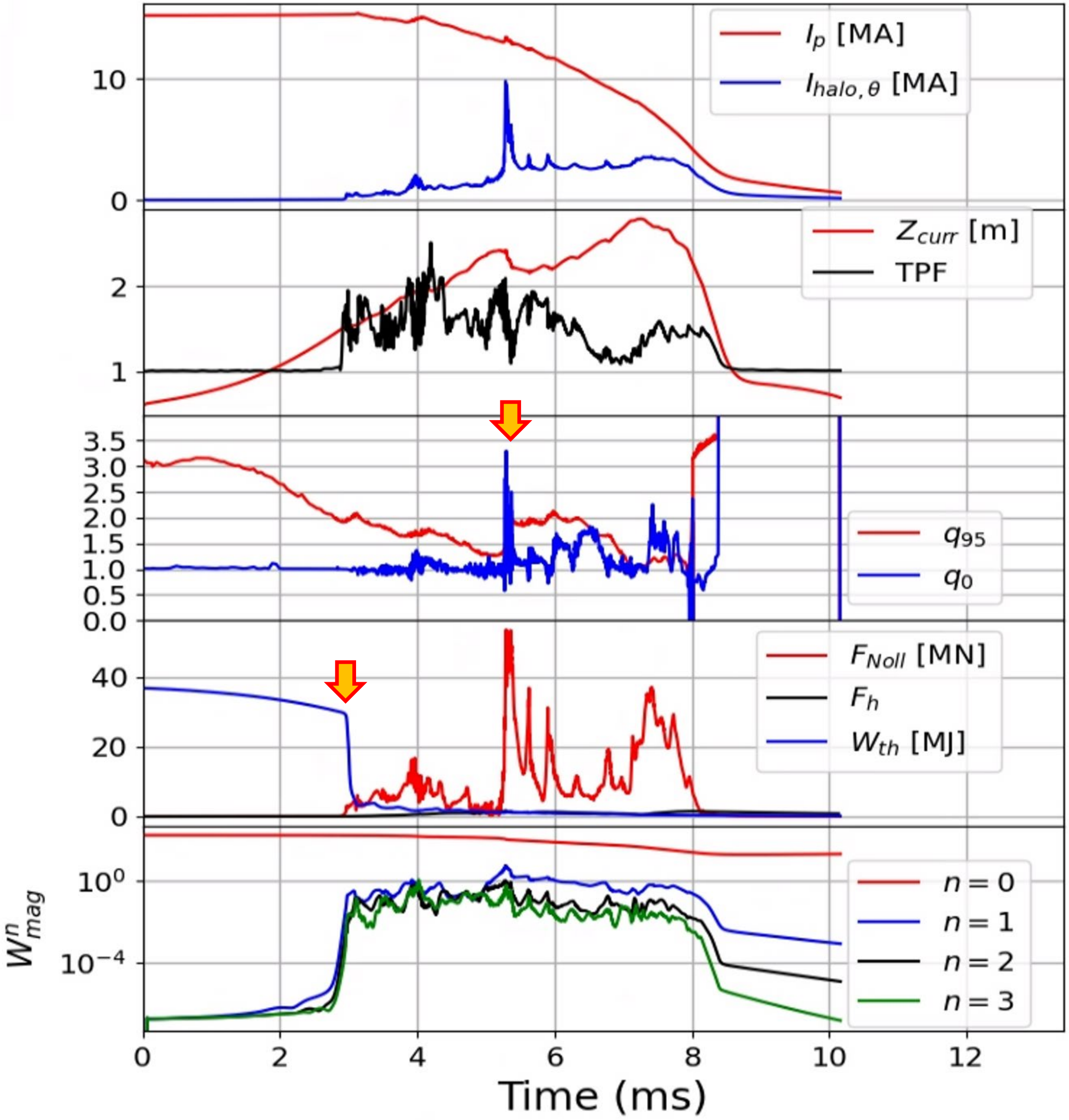
Selected research highlights

- **Predicting the thermal quench in future devices**
- Mechanism of force mitigation by massive material injection
- Electrostatic turbulence: PiC modelling of ITGs and TEMs in perturbed plasmas
- Establishing a stellarator model in JOREK

Predicting the thermal quench in future devices

- Simulation of **natural disruption during a hot VDE**
- Realistic ITER parameters not easily accessible due to computational constraints (~500 ms VDE time scale)
- Rescaling of time, resistivity, diffusivity, etc. keeps the dynamics largely unmodified (tested by scan)

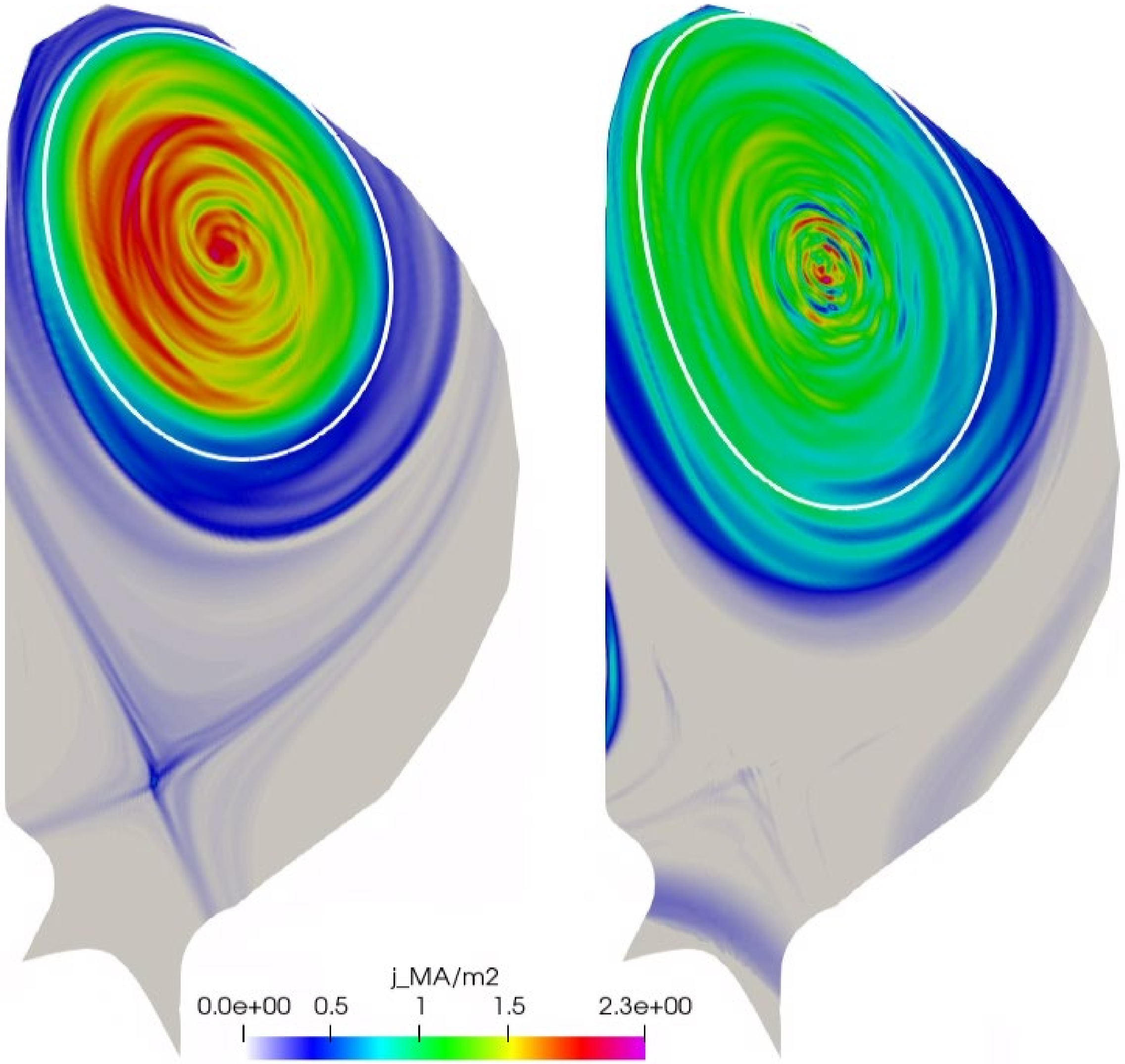
- **ITER simulation with scaling factor 60 – thermal quench triggered when q_{95}~2**
- **Several current spikes during TQ and CQ**
- **MHD burst at q_{95}~1.3 moves q_{95} back to 2**



[FJ Artola, N Schwarz et al, in preparation]

Predicting the thermal quench in future devices

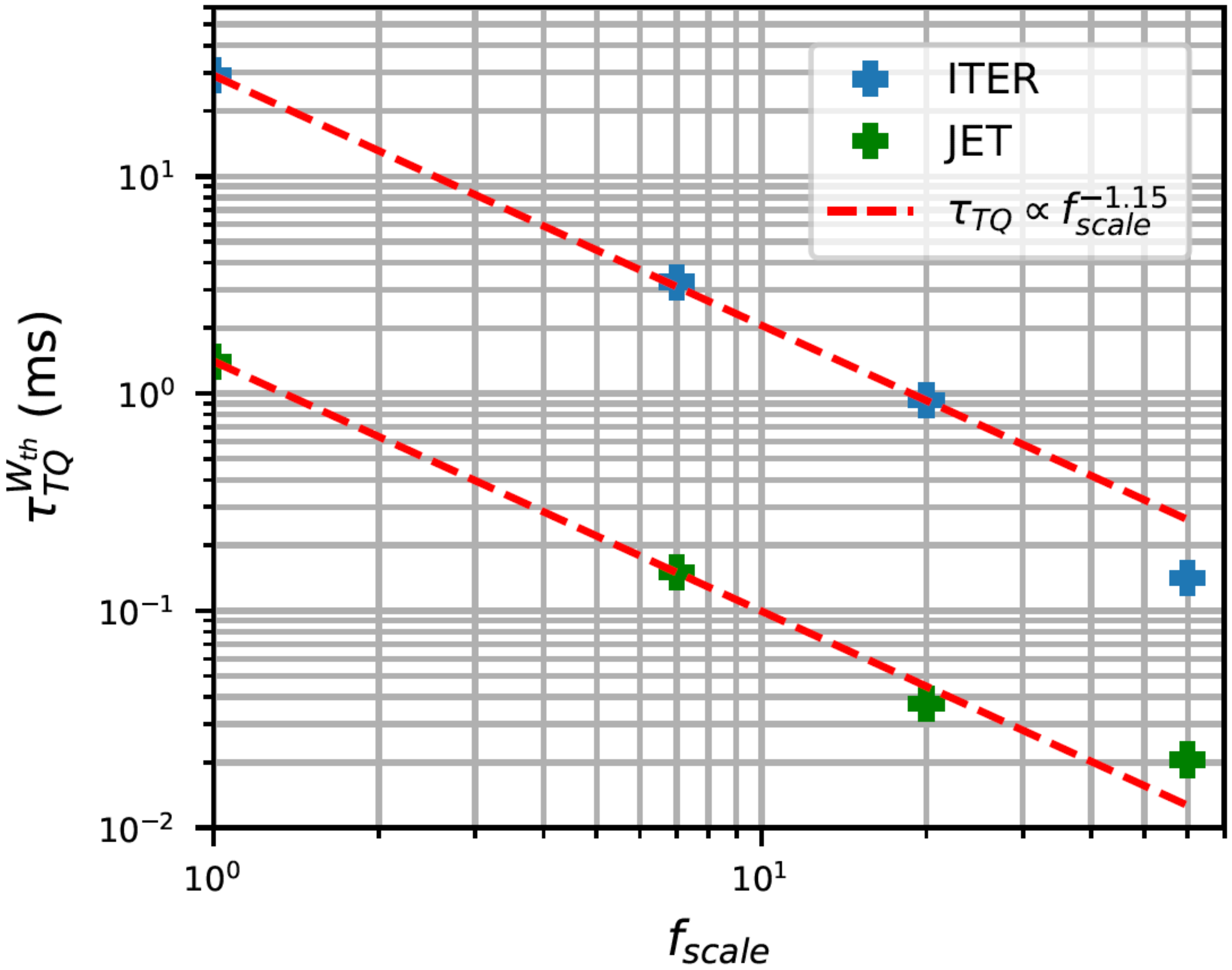
- **MHD burst at q_{95}~1.3 moves q_{95} back to 2 by transferring current into the halo region**



[FJ Artola, N Schwarz et al, in preparation]

Predicting the thermal quench in future devices

- A scan in the scaling factor shows a nearly linear dependency of the thermal quench time on the scaling factor
- **This allows to obtain a prediction of the thermal quench time in ITER in the range of 30 ms**



[FJ Artola, N Schwarz et al, in preparation]

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- **Mechanism of force mitigation by massive material injection**
- Electrostatic turbulence: PiC modelling of ITGs and TEMs in perturbed plasmas
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Mechanism of force mitigation by massive material injection

Previously:

- force reduction explained by reduction of poloidal halo currents

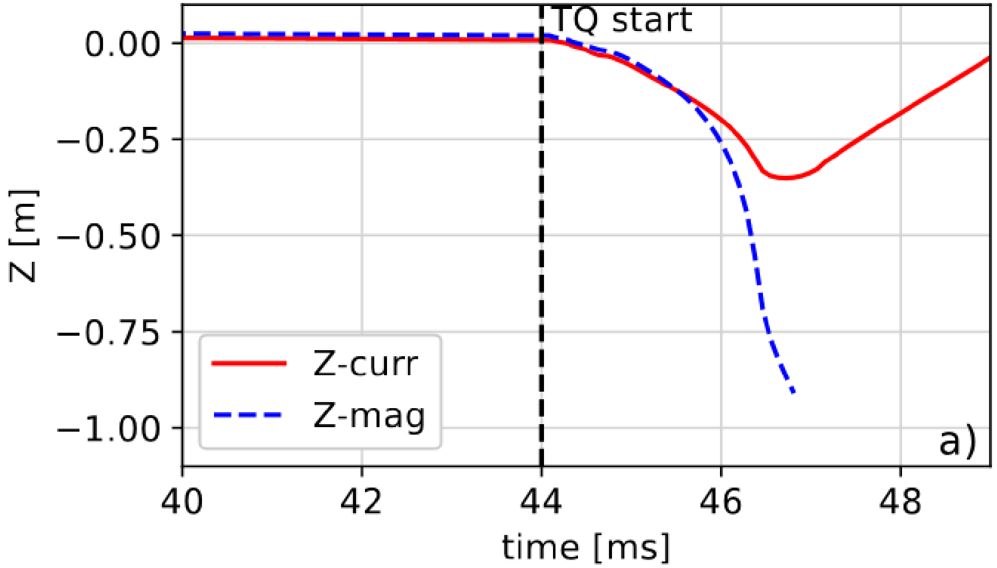
New theory:

- **The vertical force is connected to the current centroid**

$$F_z \propto I_p \Delta z_{curr}$$

- **Impurity injection leads to a flattening of the current profile beyond the separatrix**

→ toroidal currents in the SOL stabilize the centroid motion and reduce forces



The current centroid remains stationary during a mitigated disruption (simulation result)

[N Schwarz, FJ Artola, F Vannini, M Hoelzl et al, Nuclear Fusion (submitted)]

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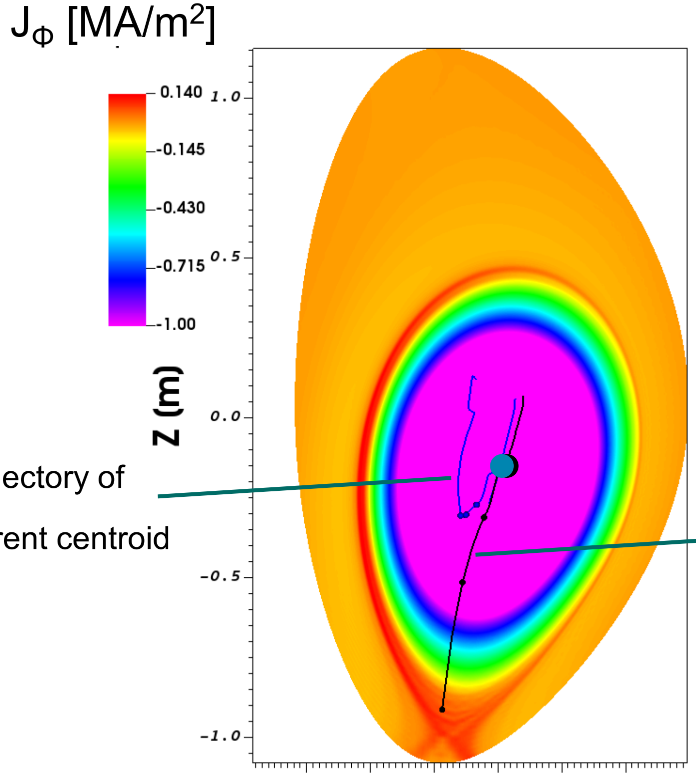

Trajectory of current centroid

Trajectory of magnetic axis

Before disruption:

Axis and centroid move together

[N Schwarz, FJ Artola, F Vannini, M Hoelzl et al, Nuclear Fusion (submitted)]

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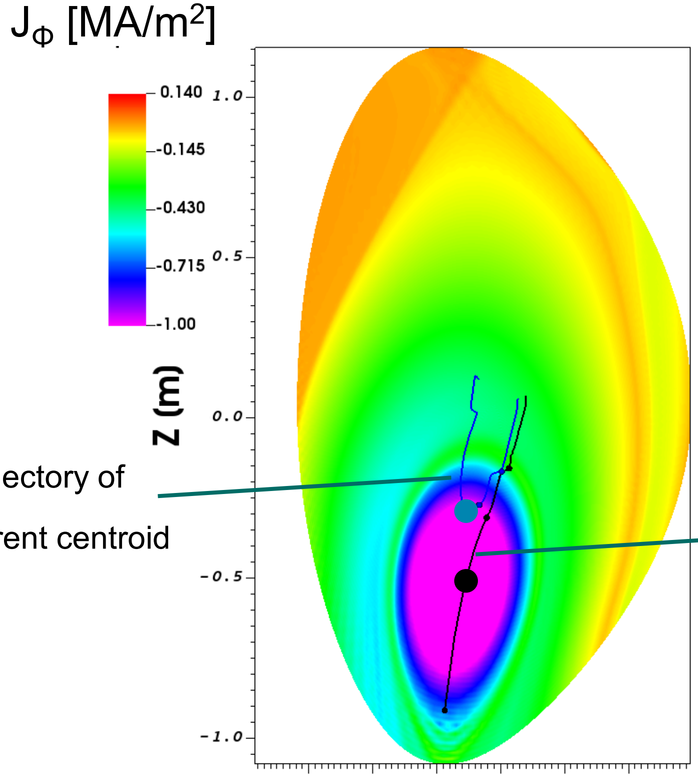

Trajectory of current centroid

Trajectory of magnetic axis

After disruption:

Large toroidal currents outside the separatrix

Axis and centroid motion decouples

[N Schwarz, FJ Artola, F Vannini, M Hoelzl et al, Nuclear Fusion (submitted)]

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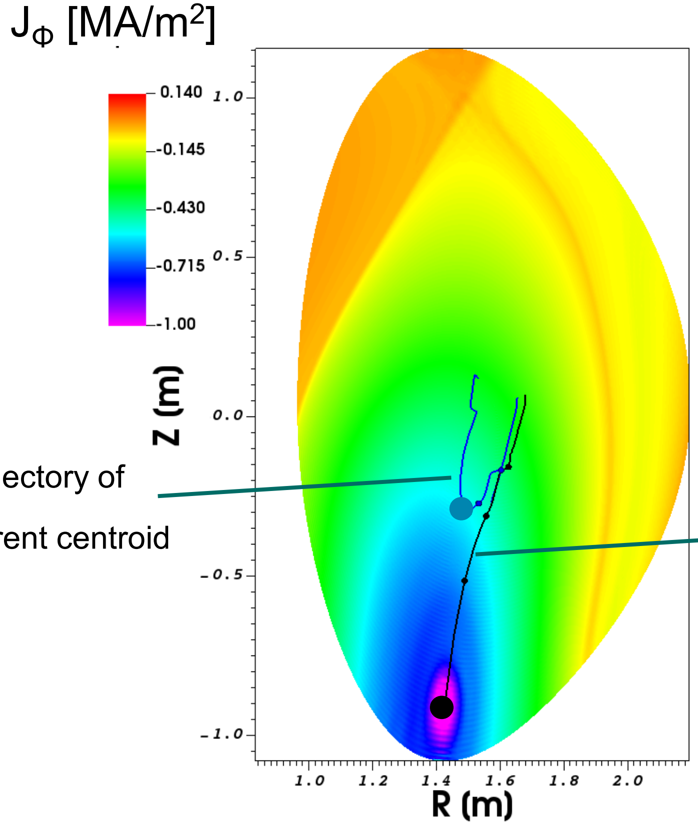


Trajectory of current centroid

Trajectory of magnetic axis

Late during VDE:

Axis reaches the wall, i.e., separatrix vanishes

Current centroid location remains close to the midplane

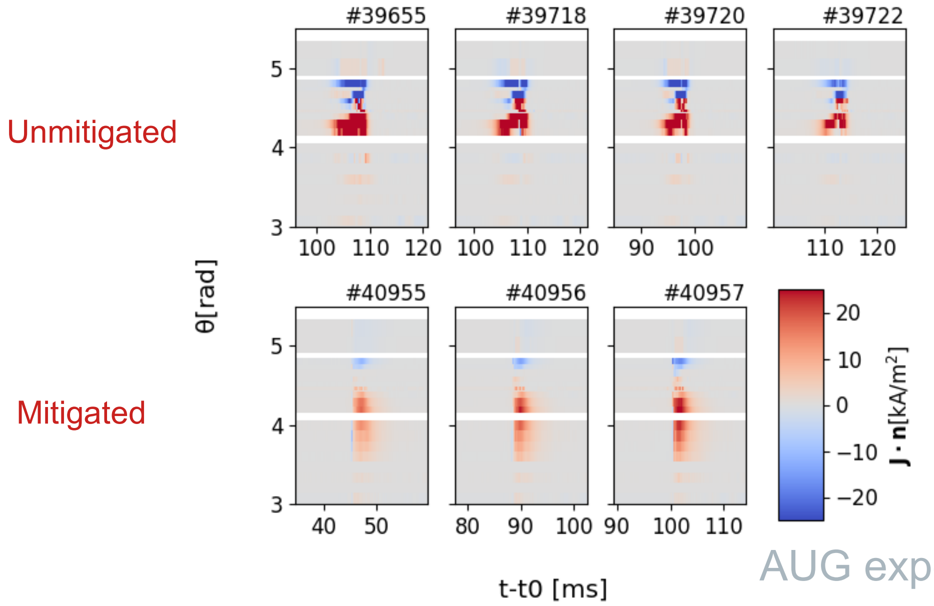
[N Schwarz, FJ Artola, F Vannini, M Hoelzl et al, Nuclear Fusion (submitted)]

Mechanism of force mitigation by massive material injection – Experimental evidence from ASDEX Upgrade and JET

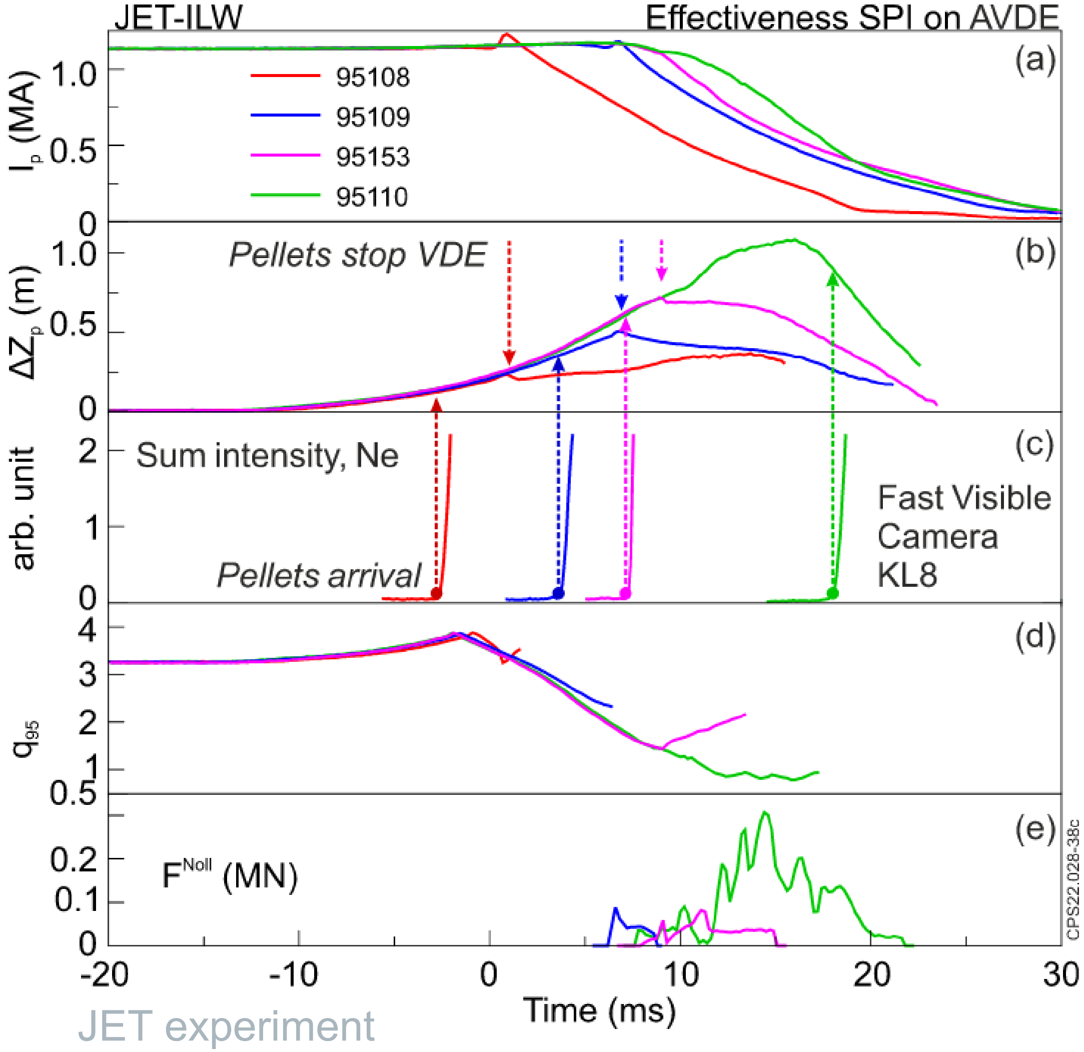
SPI mitigated VDEs

Shattered Pellets injected into moving plasma

- **Current centroid Z_{curr} becomes stationary after injection leading to force reduction**
- **Widening of currents in the SOL confirmed experimentally**



AUG experiment



JET experiment

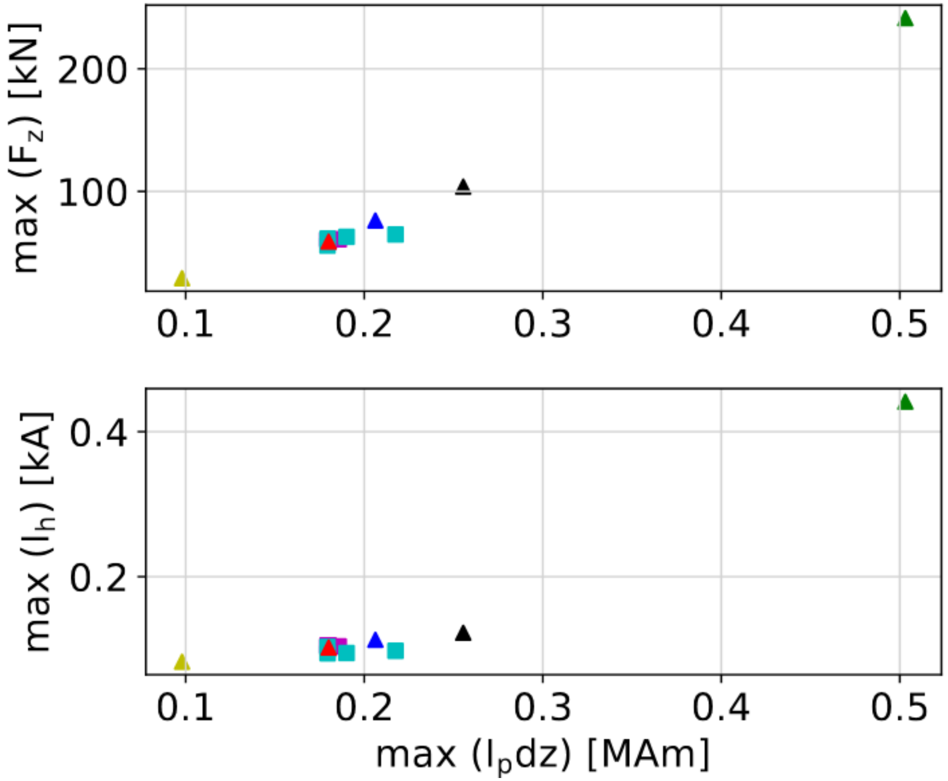
[Gerasimov, EPS 2020, P1.1031]

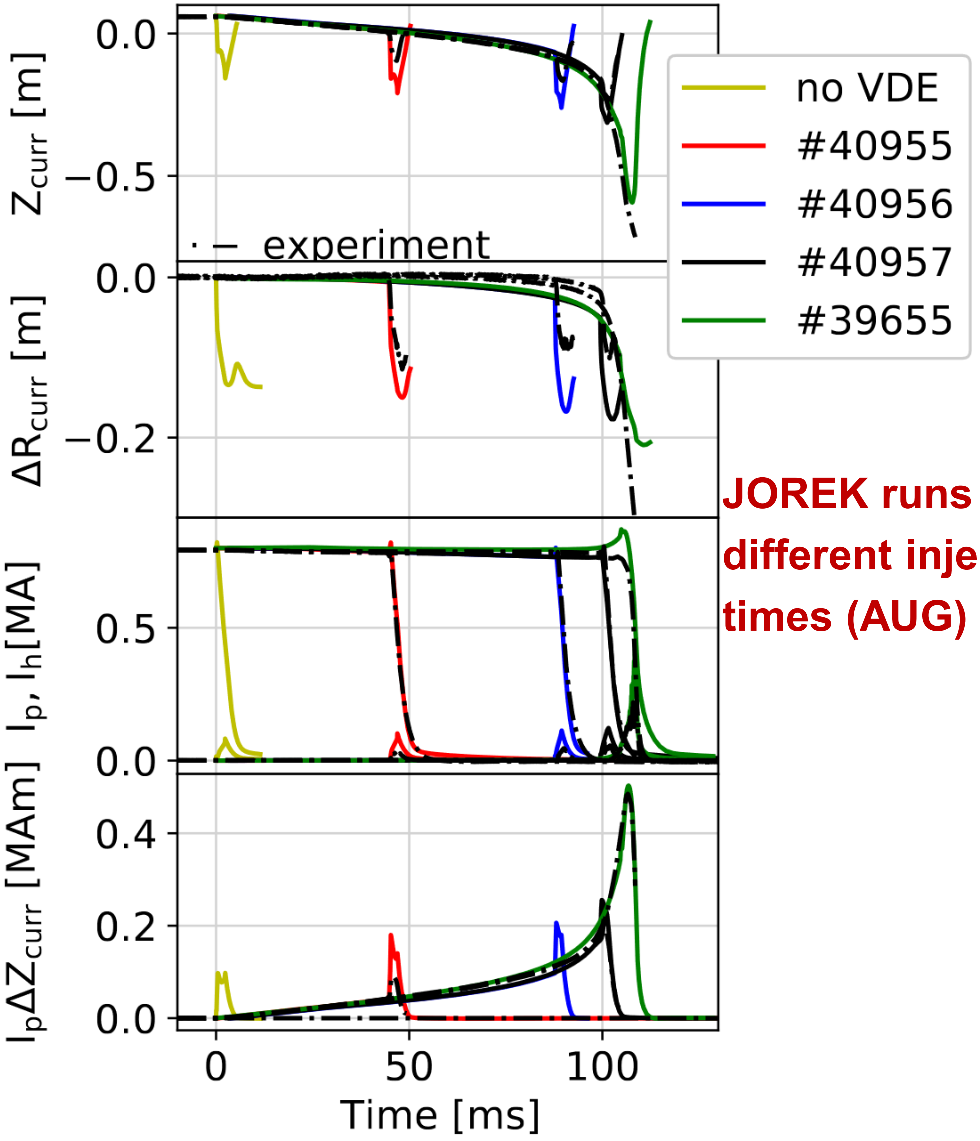
[N Schwarz, FJ Artola, F Vannini, M Hoelzl et al, Nuclear Fusion (submitted)]

Mechanism of force mitigation by massive material injection – JOREK simulation results

Simulations for JET, AUG and ITER

- **Relevant experimental features reproduced** (CQ time, force reduction, Z_{curr} behaviour)
- **Force proportional to $I_p \Delta Z_{curr}$**





JOREK runs for different injection times (AUG)

[N Schwarz, FJ Artola, F Vannini, M Hoelzl et al, Nuclear Fusion (submitted)]

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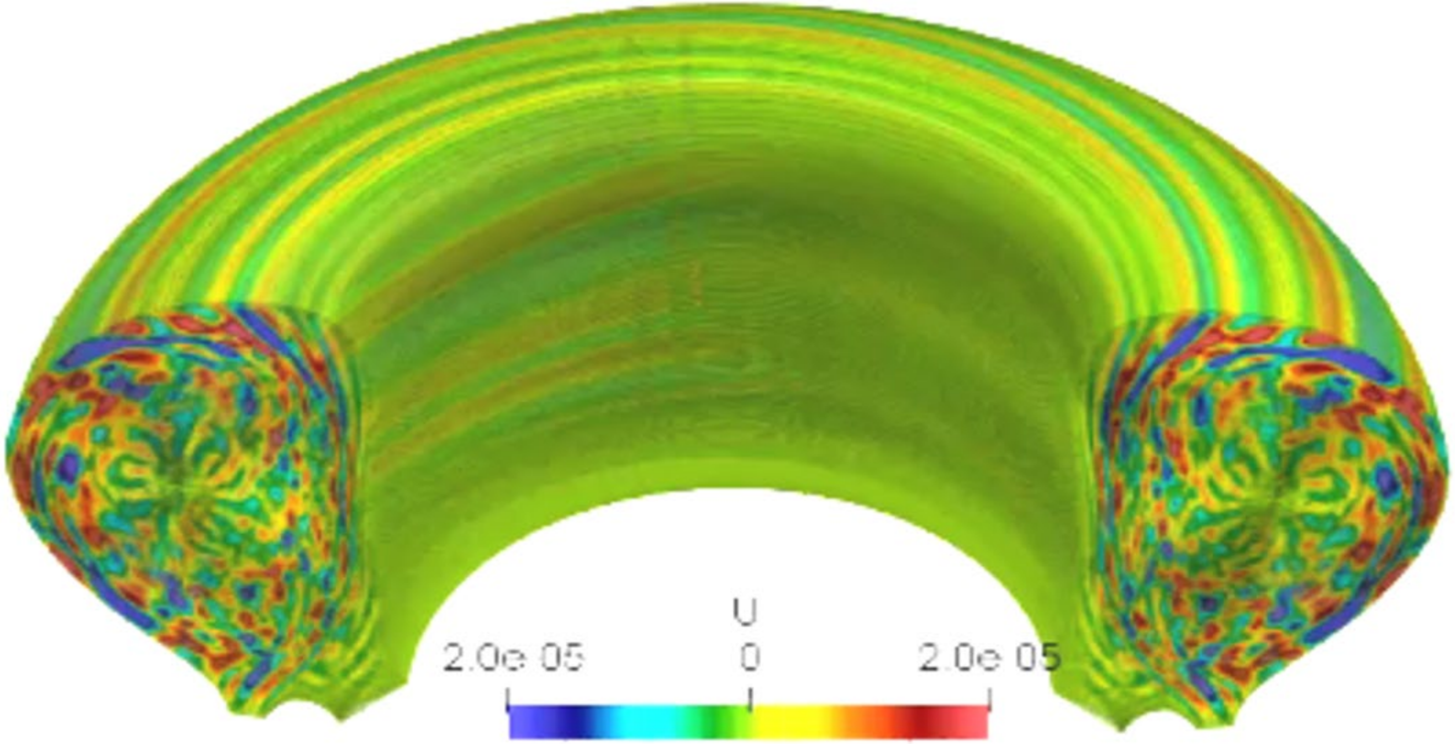
- Predicting the thermal quench in future devices
- Mechanism of force mitigation by massive material injection
- **Electrostatic turbulence: PiC modelling of ITGs and TEMs in perturbed plasmas**
- Establishing a stellarator model in JOREK

Electrostatic turbulence: PiC modelling of ITGs and TEMs in X-point plasmas with applied magnetic perturbations

- Various hybrid and kinetic models have been established in JOREK for neutrals, impurities, energetic particles, runaway electrons
- **The following is about the electrostatic ITG and TEM turbulence model with gyro-kinetic ions and adiabatic or kinetic electrons**
- (electromagnetic model with kinetic thermal ions is on the way)



[M Becoulet, GTA Huijsmans et al, in preparation]

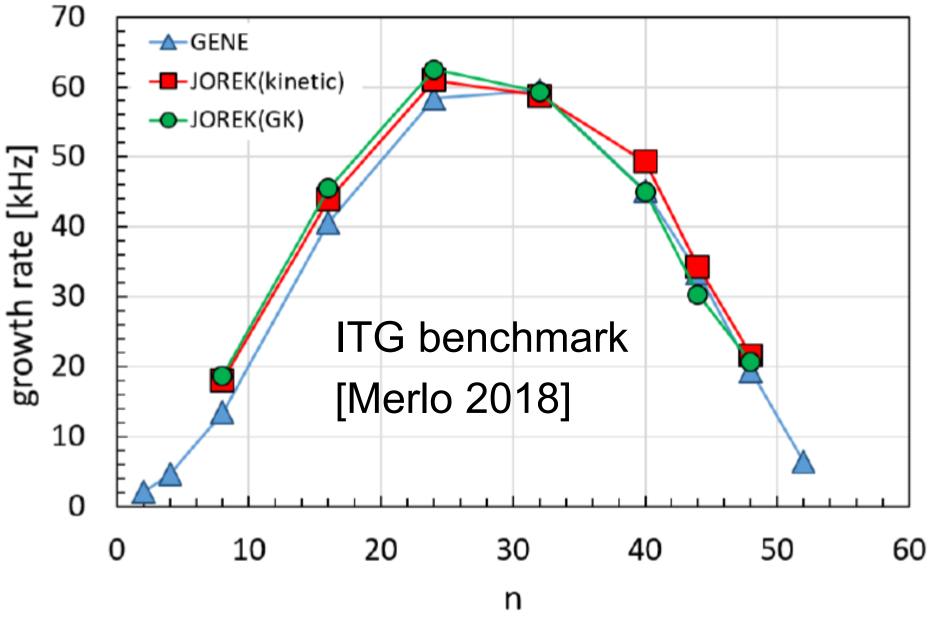
Electrostatic turbulence: PiC modelling of ITGs and TEMs in X-point plasmas with applied magnetic perturbations

$$\frac{d\vec{x}}{dt} = \frac{\vec{B}^*}{B_{\|}^*} u - \frac{\vec{b} \times \vec{E}^*}{\vec{b} \cdot \vec{B}^*} \qquad u = \vec{b} \cdot \frac{d\vec{x}}{dt}$$

$$\frac{du}{dt} = \frac{\vec{B}^* \cdot \vec{E}^*}{B_{\|}^*} \qquad \vec{B}^* = \nabla \times \vec{A}^* = \nabla \times \left(\vec{A} + u\vec{b}\right)$$

$$\vec{E}^* = \langle \vec{E} \rangle - \mu \nabla B$$

Poisson equation: $n_i = n_e$



Adiabatic electrons **=>ITGs only, no zonal in the model**

$$\nabla \cdot \frac{m_i n_0}{q_i B^2} \nabla_\perp \phi - \frac{e n_0}{T_e}(\phi - \langle\phi\rangle) = n_i$$

$$\int -\nabla\left(\frac{T_e}{e n_0} v^*(\vec{x})\right) \cdot \frac{m_i n_0}{q_i B^2} \nabla_\perp \phi - v^*(\phi - \langle\phi\rangle) dV = \int \frac{T_e}{e n_0} v^*(\vec{x}) \sum_{i=1}^{N} w_i \delta(\vec{x} - \vec{x}_i)\, dV$$

Adding kinetic electrons **=>ITGs/TEMs, zonal flows**

(Heavy electrons: m_i/m_e=100)

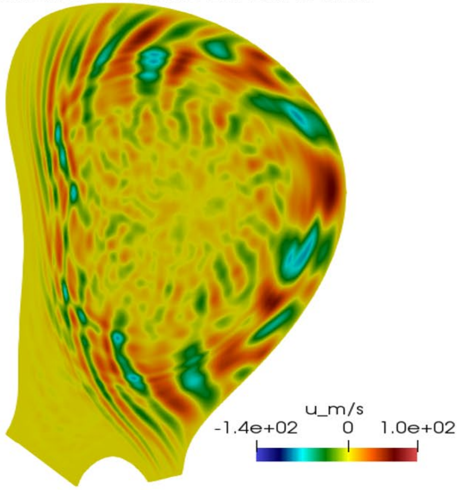
$$\int -\nabla\left(\frac{T_e}{e n_0} v^*(\vec{x})\right) \cdot \frac{m_i n_0}{q_i B^2} \nabla_\perp \phi - v^* \phi dV = \int \frac{T_e}{e n_0} v^*(\vec{x}) \sum_{i=1}^{2N} \frac{q_i}{e} w_i \delta(\vec{x} - \vec{x}_i)\, dV$$

[M Becoulet, GTA Huijsmans et al, in preparation]

Electrostatic turbulence: PiC modelling of ITGs and TEMs in X-point plasmas with applied magnetic perturbations

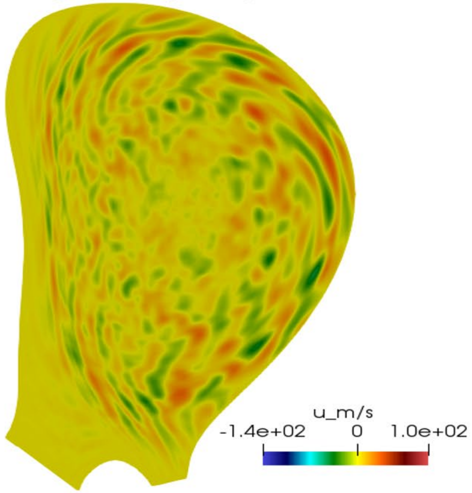
t=1.5ms,ITG+TEM, no zonal,no RMP

ITG+TEM,w/o zonal



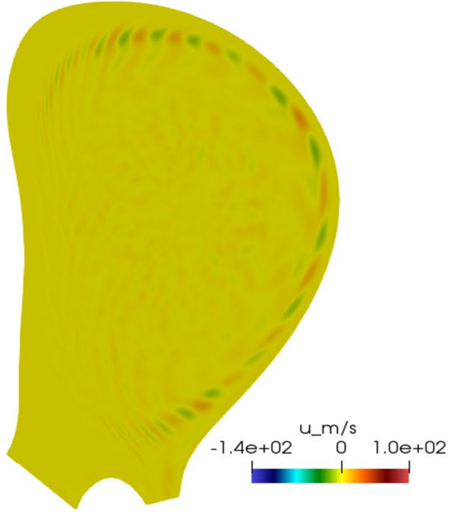
t=1.5ms,ITG+TEM,zonal,no RMP

ITG+TEM,zonal



t=2ms,ITG ad el,no RMP

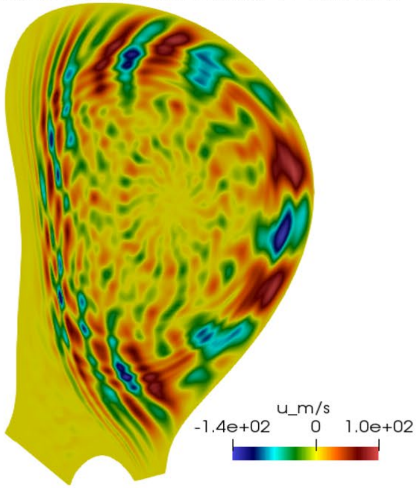
ITG,ad



Without RMP

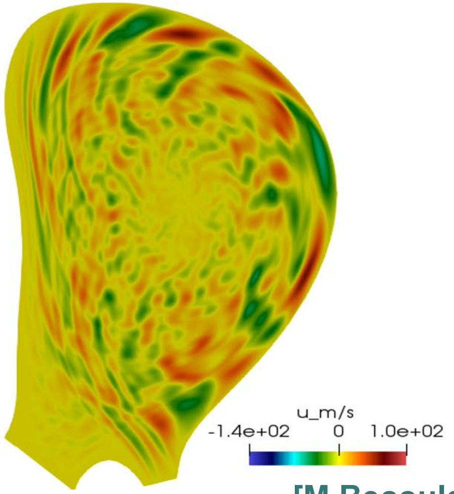
t=1.5ms,ITG+TEM, no zonal,RMP N=2,1.5kAt

ITG+TEM,w/o zonal



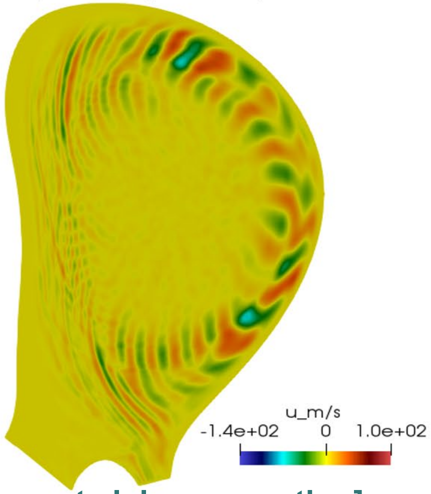
t=1.5ms,ITG+TEM,zonal,RMP N=2,1.5kAt

ITG+TEM,zonal



t=2ms,ITG ad el,RMP N=2,1.5kAt

ITG,ad



With RMP

COMPASS L-mode:

- **Larger turbulence in presence of RMP fields.**
- **TEM+ITG turbulence is stronger than ITG only.**

[M Becoulet, GTA Huijsmans et al, in preparation]

Selected research highlights

- Predicting the thermal quench in future devices
- Mechanism of force mitigation by massive material injection
- Electrostatic turbulence: PiC modelling of ITGs and TEMs in perturbed plasmas
- **Establishing a stellarator model in JOREK**

Stellarator model in JOREK

Starting from the viscoresistive MHD equations, using the ansatz:

$$\mathbf{B} = \nabla\chi + \nabla\psi \times \nabla\chi \qquad (1)$$

$$\mathbf{v} = \frac{\nabla\Phi \times \nabla\chi}{B_v^2} + v_{\parallel}\mathbf{B} \qquad (2)$$

Where $\nabla\chi$ is the vacuum field generated by external coils, and defining the auxiliary equations:

$$j = \Delta^{*}\psi \qquad (3)$$

$$\omega = \Delta^{\perp}\Phi \qquad (4)$$

The following equations are derived:

$$\frac{\partial\rho}{\partial t} = -B_v\left[\frac{\rho}{B_v^2}, \Phi\right] + \nabla\cdot\left(D_{\perp}\nabla_{\perp}\rho + D_{\parallel}\nabla_{\parallel}\rho\right) + S_{\rho} \qquad (5)$$

$$\begin{aligned}\nabla\cdot\left(\frac{\rho}{B_v^2}\nabla^{\perp}\frac{\partial\Phi}{\partial t}\right) =& \frac{B_v}{2}\left[\frac{\rho}{B_v^2}, \frac{(\Phi,\Phi)}{B_v^2}\right] + B_v\left[\frac{\rho\omega}{B_v^4}, \Phi\right] - \nabla\cdot\left(\frac{P}{B_v^2}\nabla^{\perp}\Phi\right)\\ &+ \nabla\cdot(j\mathbf{B}) + B_v\left[\frac{1}{B_v^2}, p\right] + \nabla\cdot\left(\mu_{\perp}\nabla^{\perp}\omega\right) - \Delta^{\perp}\left(\mu_{num}\Delta^{\perp}\omega\right)\end{aligned} \qquad (6)$$

$$\begin{aligned}\rho\frac{\partial T}{\partial t} =& -\frac{1}{B_v}[\rho T, \Phi] - \gamma\rho T B_v\left[\frac{1}{B_v^2}, \Phi\right] + \nabla\cdot\left[\kappa_{\perp}\nabla_{\perp}T + \kappa_{\parallel}\nabla_{\parallel}\nabla_{\parallel}T + \frac{\rho T D_{\perp}}{\rho}\nabla_{\perp}\rho\right.\\ &\left.+ \frac{\rho T D_{\parallel}}{\rho}\nabla_{\parallel}\rho\right] + \left(S_e + \eta_{Ohm}B_v^2 j^2\right) - T\frac{\partial\rho}{\partial t}\end{aligned} \qquad (7)$$

$$\frac{\partial\psi}{\partial t} = \frac{\partial^{\parallel}\Phi - [\psi, \Phi]}{B_v} - \eta\left(j - j_{source}\right) + \nabla\cdot\left(\eta_{num}\nabla^{\perp}j\right) \qquad (8)$$

[Nikulsin N., Ramasamy R., Hoelzl M., et al. Physics of Plasmas 29, 063901 (2022)]

(4, 1) external kink simulation shows the nonlinear triggering of a (7, 2) internal mode in an l=2 stellarator

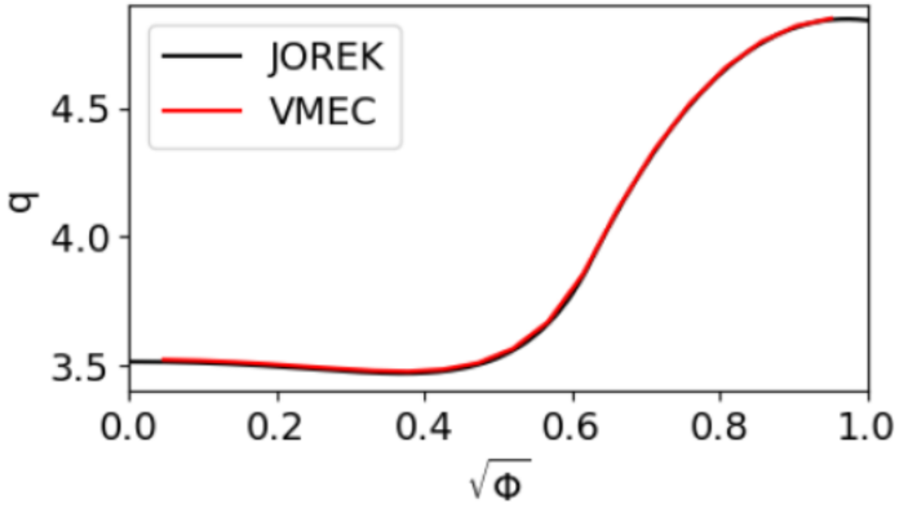


Figure 1: q profile of the simulated $N_p = 5$ case.

The radial extent of the (7, 2) mode is larger than in a tokamak with the same edge safety factor.

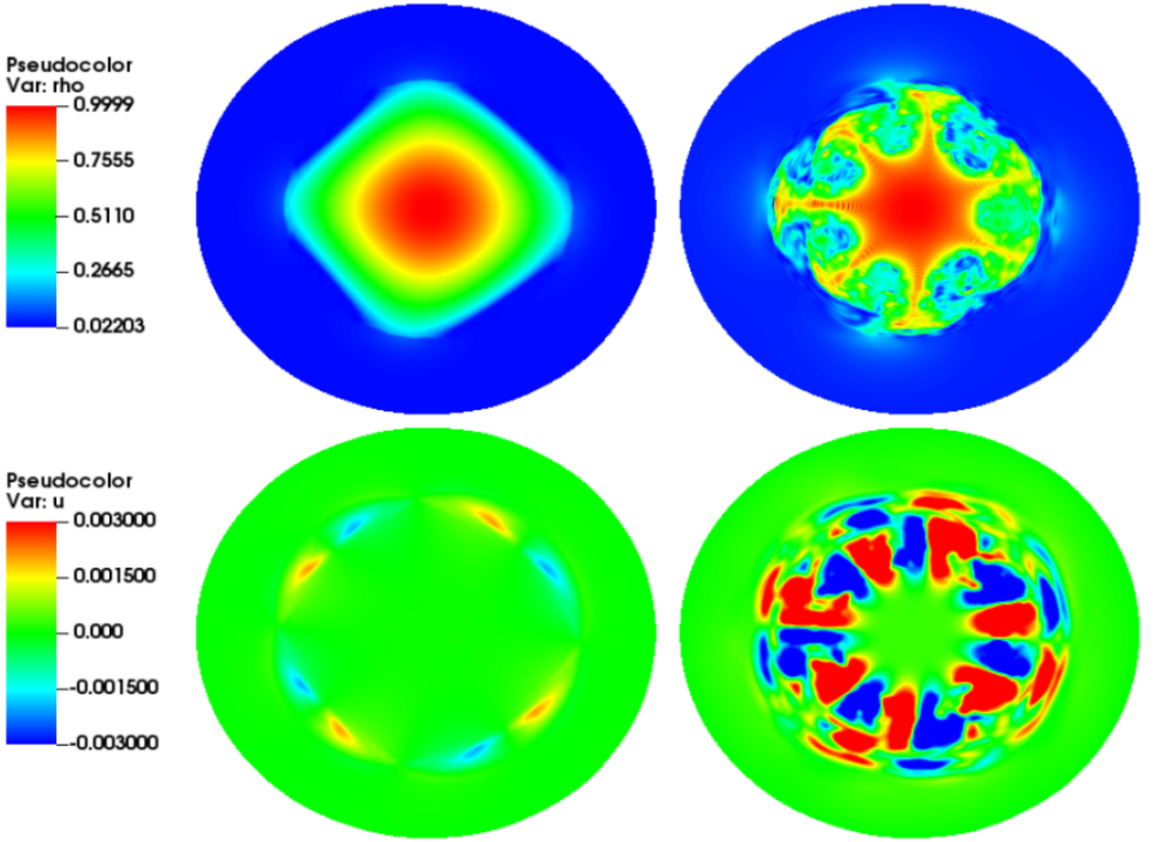


Figure 2: Pseudocolour plots of ρ and u in $\phi = 0$ plane.

[Ramasamy R. et al, Physics of Plasmas (submitted)]

Ongoing verification for optimised stellarator studies

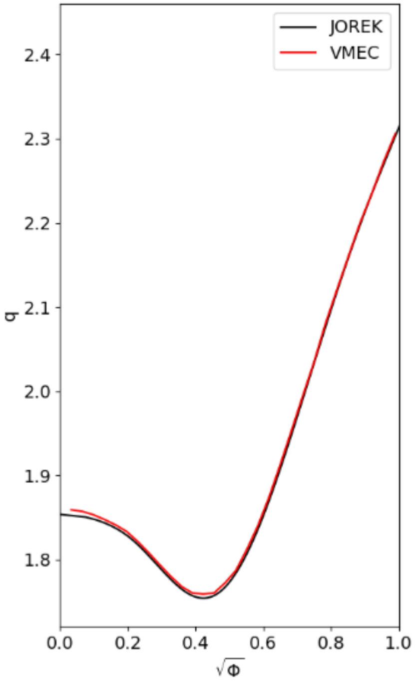


Figure 3: q profile of the W7-AS test case.

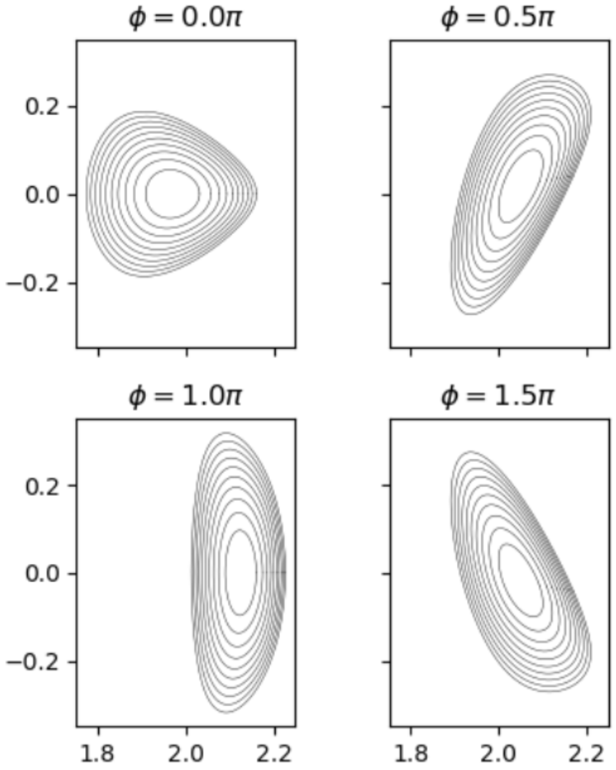


Figure 4: Flux surfaces of W7-AS from initial VMEC equilibrium.

[Ramasamy R. et al, in preparation]

The expected (2, 1) tearing mode is observed, but requires further verification of the linear mode structure.

The MHD JFRS-1 project has enabled high toroidal resolution scans, necessary in the verification of this test case.

(Simulations of double tearing mode instabilities on the way for W7-A and for advanced stellarators **[K Aleynikova et al]**)

Summary

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- **MHD transients like edge localized modes or disruptions** are critical for fusion reactors
- **The non-linear MHD code JOREK** aims to predict physics and control of such phenomena
  - Many fluid and kinetic extensions beyond basic MHD
  - Implicit time stepping, G^1 continuous 2D Bezier FEs + toroidal Fourier
- Major recent extensions
  - **Inclusion of impurities in full MHD and shock capturing**
  - **Coupling to CARIDDI for 3D walls**
- Recent highlights
  - **Disruption mitigation:** Mechanism of force mitigation
  - **Predicting the thermal quench** in future devices
  - **Electrostatic turbulence** in perturbed plasmas
  - **Stellarator MHD** is undergoing validation