EUROfusion

Simulating tokamak edge instabilities: advances and challenges

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What are edge localized modes (ELMs) and why do we study them?

How do we simulate ELMs and what are the challenges?

What can we learn about ELMs and ELM control?

What are edge localized modes (ELMs) and why do we study them?

ITER tokamak

- Constructed in France by international consortium
- Next step towards fusion reactor
- **Large-scale plasma instabilities are a key research topic**

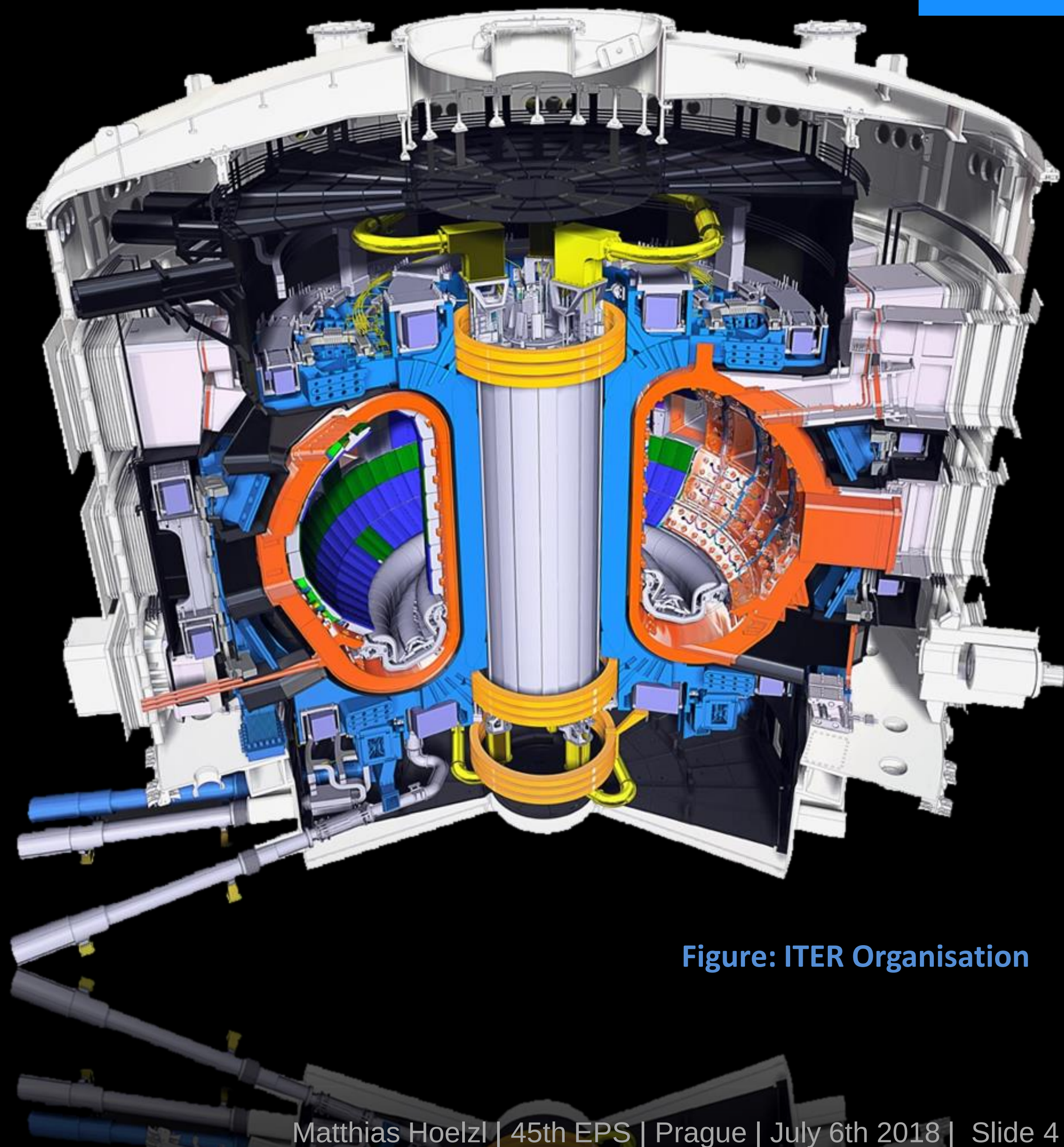
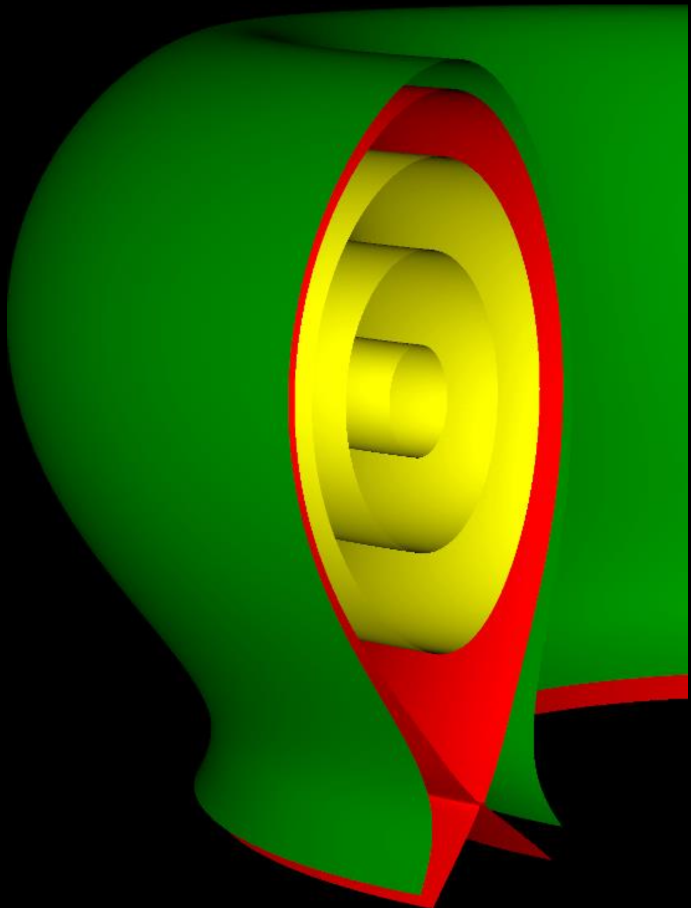
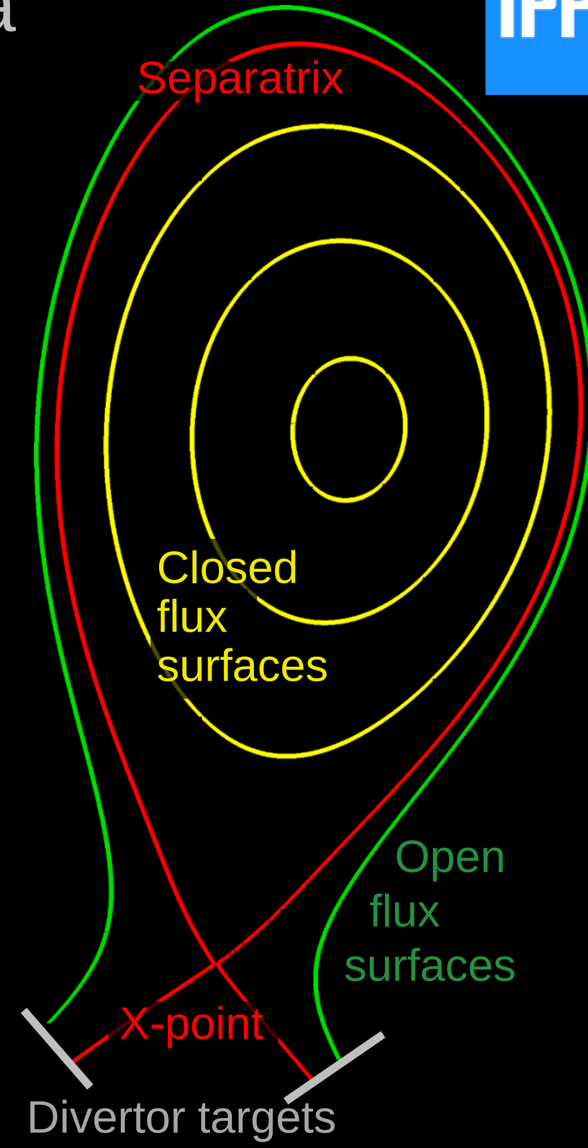


Figure: ITER Organisation

Tokamak X-point plasma



Helical field lines forming nested toroidal flux surfaces



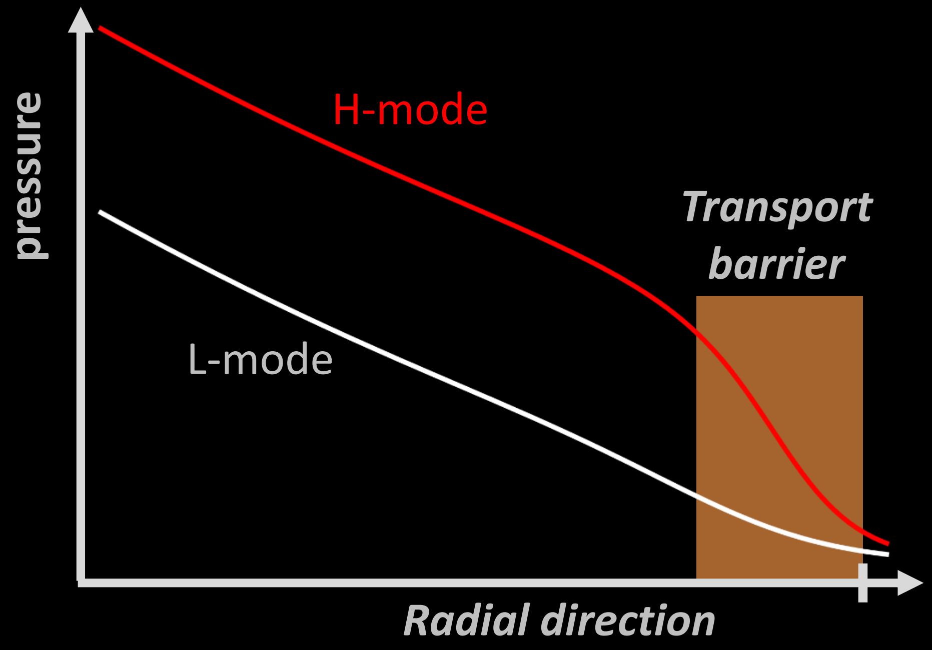
Safety factor q = $\frac{\text{number of toroidal turns}}{\text{number of poloidal turns}}$

"Rational surfaces"

High confinement mode (H-Mode)

- First observed 1982 in ASDEX divertor tokamak
  - Improved confinement
  - Edge transport barrier
  - *„Short bursts which lead to periodic density and temperature reductions in the outer plasma zones.“*

  [F Wagner et al, PRL 49, 1408 (1982)]



- **Large edge pressure gradients and current densities**

Linear Stability Analysis

$$\delta W_F = \frac{1}{2}\int_F \left(\frac{|B_{1\perp}|^2}{2\mu_0} + \frac{B_{0\perp}^2}{2\mu_0}\left|\vec{\nabla}\cdot\vec{\xi}_\perp + 2\vec{\xi}_\perp\cdot\vec{\kappa}\right|^2 + \gamma p_0\left|\vec{\nabla}\cdot\vec{\xi}\right|^2 - 2\left(\vec{\xi}_\perp\cdot\vec{\nabla}p_0\right)\left(\vec{\kappa}\cdot\vec{\xi}_\perp^*\right) - \frac{j_{0\parallel}}{B_0}\left(\vec{\xi}_\perp^*\times\vec{B}_0\right)\cdot\vec{B}_1 \right) dV$$

Linear Stability Analysis

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stabilizing terms

$$\left. - 2\left(\vec{\xi}_\perp\cdot\vec{\nabla}p_0\right)\left(\vec{\kappa}\cdot\vec{\xi}_\perp^*\right) - \frac{j_{0\parallel}}{B_0}\left(\vec{\xi}_\perp^*\times\vec{B}_0\right)\cdot\vec{B}_1 \right) dV$$

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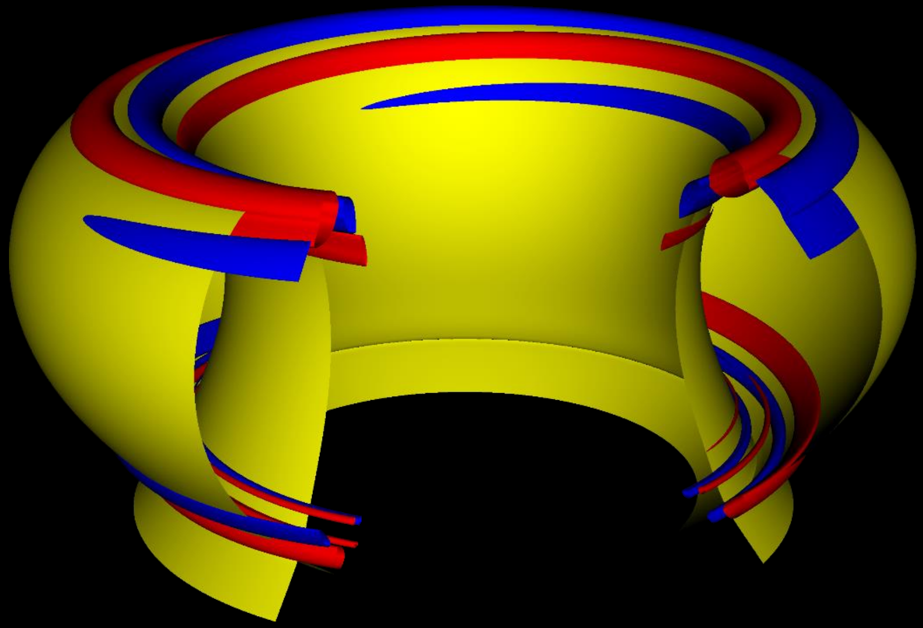
Peeling mode
Low mode number
Current driven



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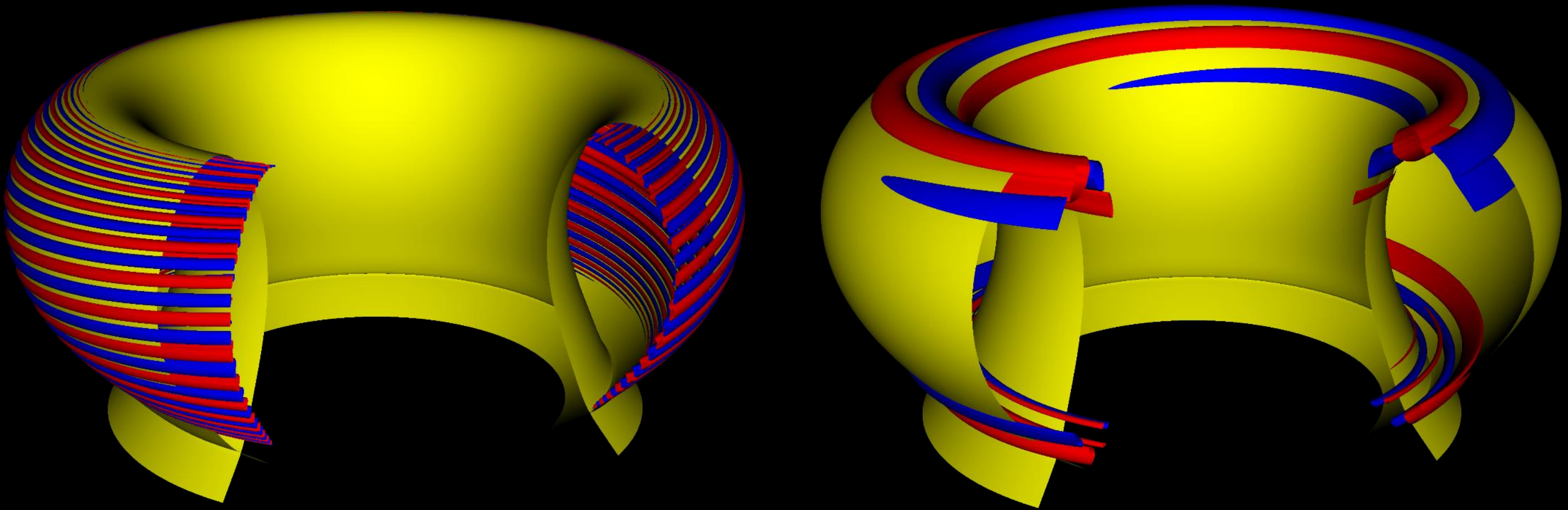
Ballooning mode
High mode number
Pressure gradient driven
Localized to outboard side

Peeling mode
Low mode number
Current driven



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Ballooning mode

High mode number

Pressure gradient driven

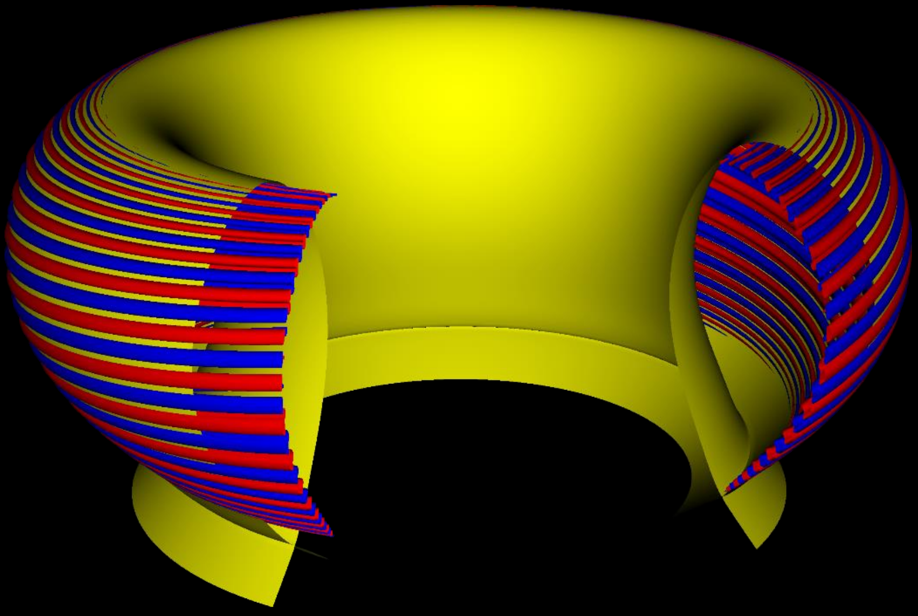
Localized to outboard side

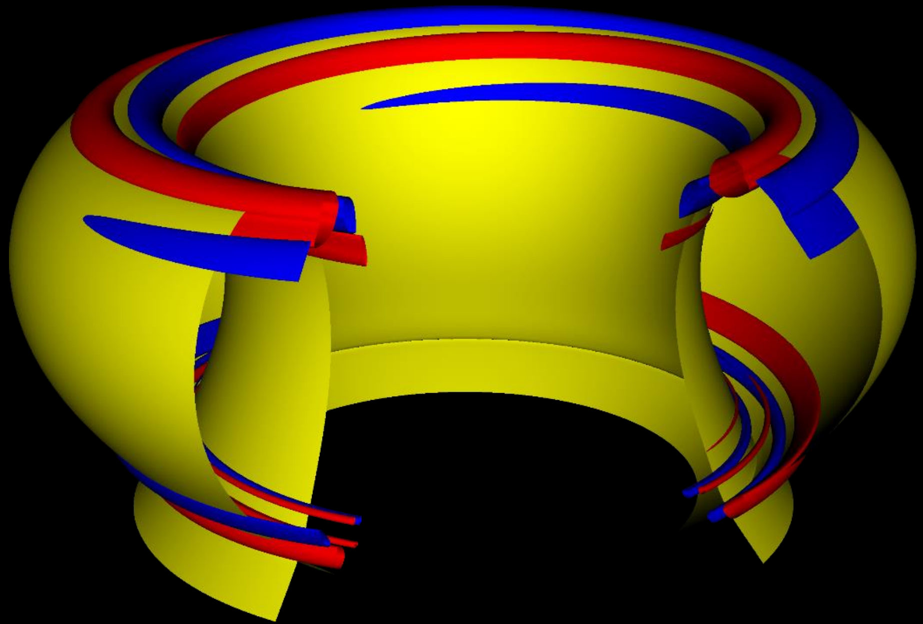
Peeling mode

Low mode number

Current driven

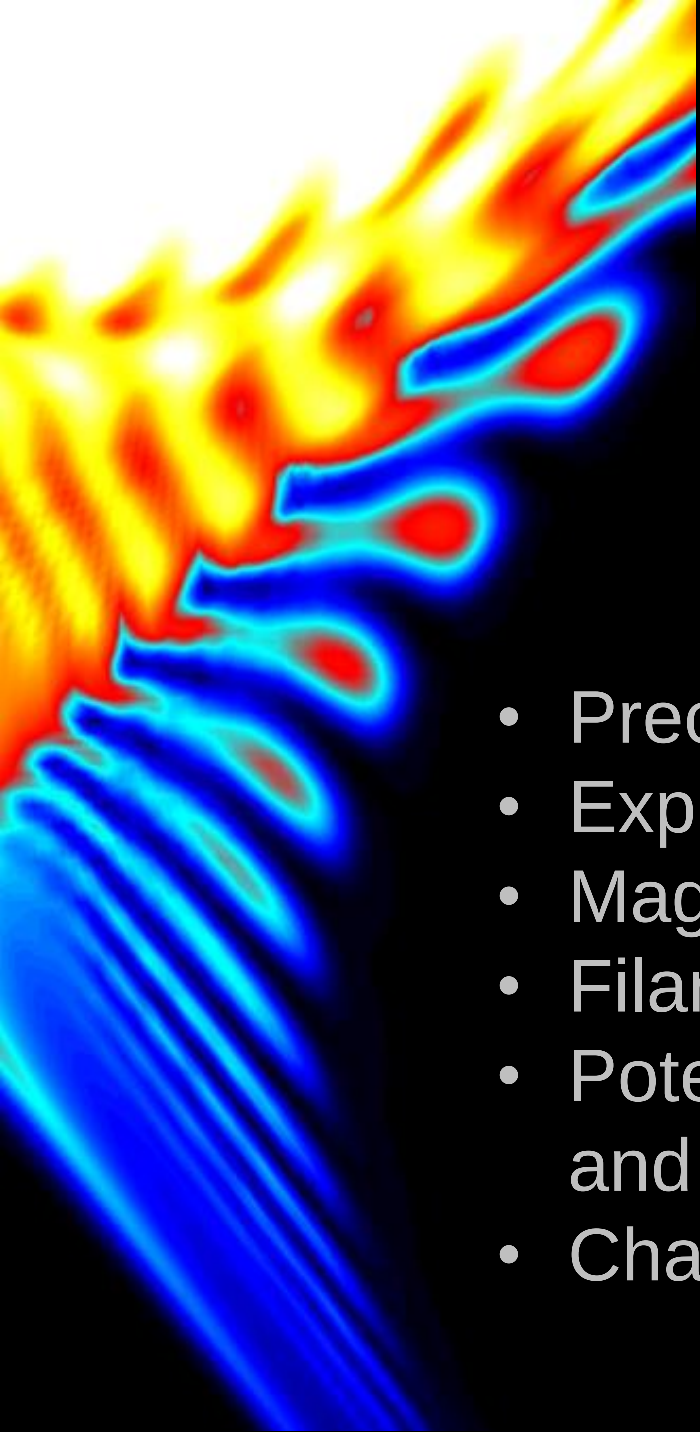
ELMs are the non-linear consequences of peeling-ballooning modes



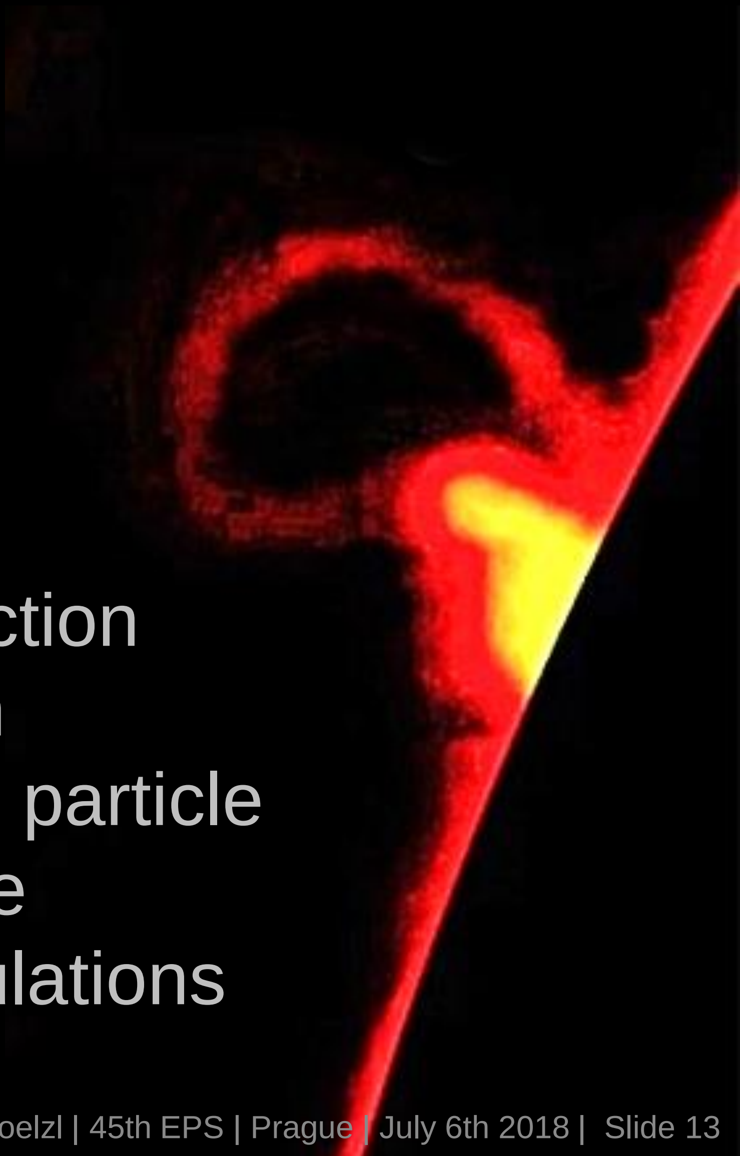


Why do
we study ELMs?

… ELMs are interesting



- Precursors
- Explosive onset
- Magnetic reconnection
- Filament formation
- Potentially harmful particle and energy release
- Challenge for simulations

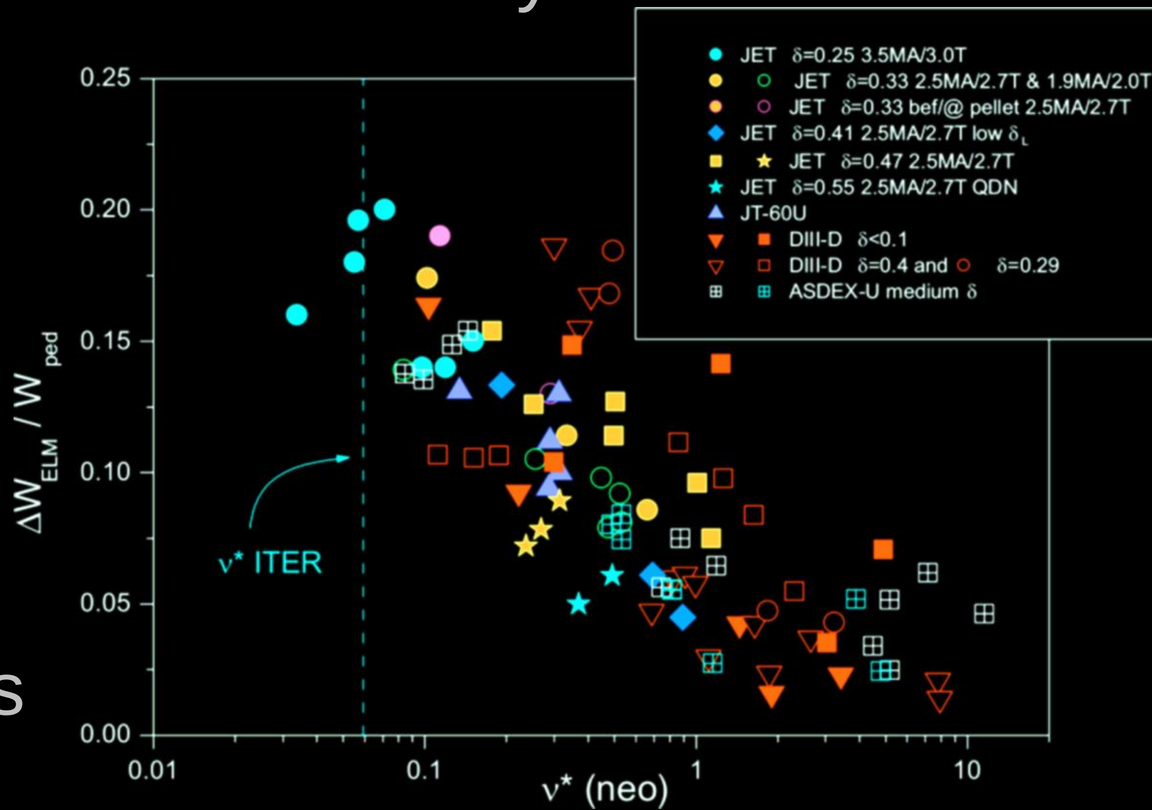


… and ELMs are important

- Fast periodic crash of plasma edge profiles
- Large peak heat fluxes to divertor
- Losses increase at low collisionality

- **Risk of strongly reduced ITER divertor life-time**

- Frequent small ELMs might help to control impurities



[A Loarte et al, PPCF 45, 1549 (2003)]

How do we simulate ELMs and what are the challenges?

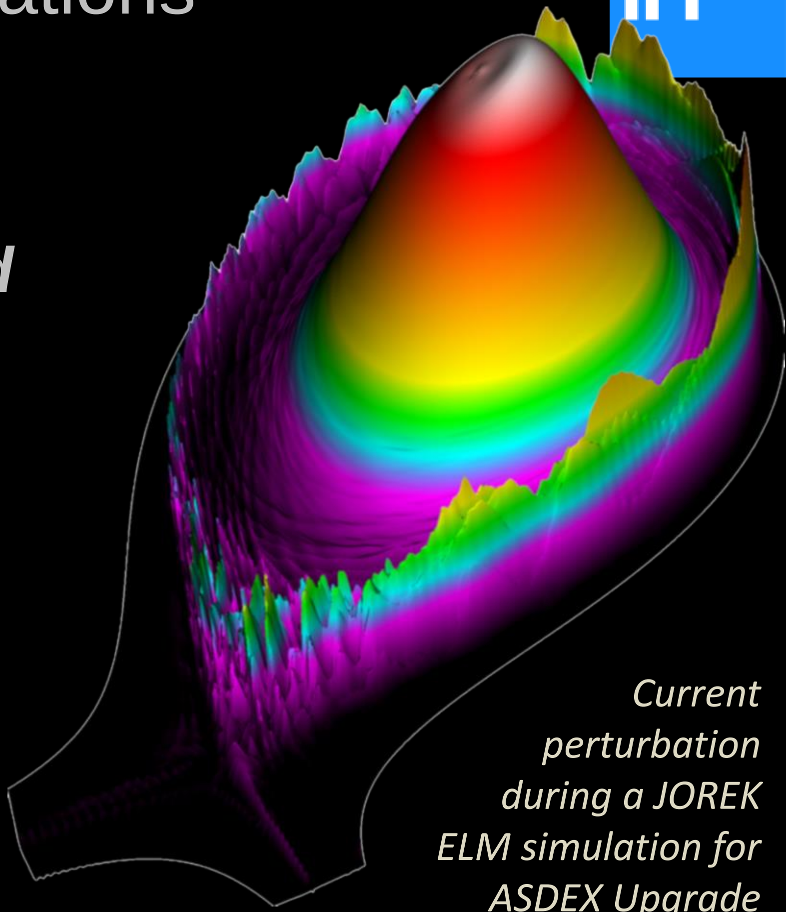
Non-linear simulations

- ***Aim: Extrapolation of ELMs and their control to ITER and beyond***

- **Multi-scale**
  temporal and spatial

- **Multi-physics**
  plasma, impurities, fast particles, scrape off layer, sputtering, electro-magnetic interactions…

- **Magnetic topology and high anisotropy**

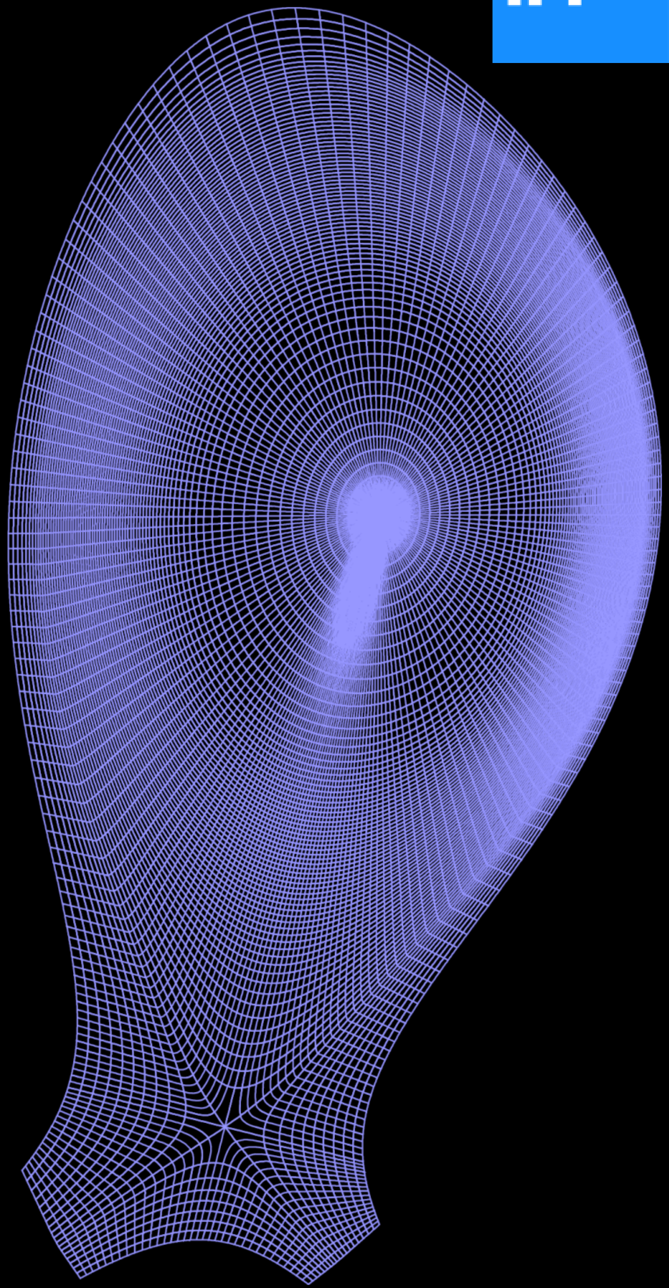


Current perturbation during a JOREK ELM simulation for ASDEX Upgrade

- **Non-linear MHD codes** for studying ELMs in realistic X-point geometry: BOUT++, JOREK, M3D, NIMROD, …
  Review: [GTA Huijsmans et al, PoP 22, 021805 (2015)]

JOREK: Numerics Methods

- 2D Bezier finite elements
- Flux-surface aligned X-point grid
- Toroidal Fourier series
- Fully implicit time stepping
  [O Czarny and G Huysmans, JCP 227, 7423 (2008)]
- Large time steps depending only on physics time scales



JOREK Base Model

$$\vec{B} = \frac{F_0}{R}\vec{e}_\phi + \frac{1}{R}\nabla\psi \times \vec{e}_\phi$$

Toroidal (constant in time) — poloidal

$$\vec{v}_{\text{tot}} = \vec{v}_{||} + \vec{v}_E + \vec{v}_{*i}$$

Parallel — ExB — diamagnetic

[HR Strauss, The Physics of Fluids 19, 134 (1976)]
[GTA Huysmans and O Czarny, NF 47, 659 (2007)]
[F Orain, M Becoulet et al, PoP 20, 102510 (2013)]
[E Franck, M Hoelzl, et al, ESAIM: M2AN 49, 1331 (2015)]

Perpendicular velocity

$$\rho\frac{\mathrm{d}\vec{v}_E}{\mathrm{d}t} = -\rho\vec{v}_{*i}\cdot\nabla\vec{v}_E - \nabla_\perp p + \vec{J}\times\vec{B}$$

Parallel velocity

$$\rho\frac{\mathrm{d}\vec{v}_{||}}{\mathrm{d}t} = -\rho\vec{v}_{||}\cdot\nabla\vec{v}_{||} - \nabla_{||}p + \mu\nabla^2\vec{v}_{||}$$

Poloidal magnetic flux

$$\frac{\partial\psi}{\partial t} = \eta(j - j_A) + R\,[\psi,\Phi] - \frac{\partial\Phi}{\partial\phi} - \frac{\delta^* R}{\rho}[\psi, p_e] + \frac{\delta^*}{\rho}\frac{\partial p_e}{\partial\phi}$$

Density

$$\frac{\partial\rho}{\partial t} = -\nabla\cdot(\rho\vec{v}_{\text{tot}}) + \nabla\cdot(D_\perp\nabla_\perp\rho) + S_\rho$$

+ many extensions

Pressure

$$\frac{\partial p}{\partial t} = -\vec{v}_E\cdot\nabla p - \gamma p\nabla\cdot\vec{v}_E + \nabla\cdot(\kappa_\perp\nabla_\perp T + \kappa_{||}\nabla_{||}T) + S_T$$

JOREK: Applications

- **ELMs and ELM control – this presentation**
  [GTA Huysmans and O Czarny, NF 47, 659 (2007)]
  Disclaimer: *I'm by far not able to show all activities (ITER, JET, AUG, JT60-SA, MAST-U, TCV, WEST,…)*

- **Disruptions**
  - Disruption onset, tearing modes, mode locking and control
    [J Pratt, GTA Huijsmans, E Westerhof, PoP 23, 102507 (2016)]
    [D Meshcheriakov, M Hoelzl, V Igochine et al (in preparation)] + Poster P5.1033 at this conference
  - Disruptions and disruption mitigation
    [A Fil, E Nardon, M Hoelzl, GTA Huijsmans, et al, PoP 22, 062509 (2015)]
    [E Nardon, A Fil, M Hoelzl, GTA Huijsmans et al, PPCF 59, 014006 (2016)]
    [D Hu, E Nardon et al, PoP (submitted)] + Poster P4.1043 at this conference
  - Vertical displacement events and Halo currents
    [M Hoelzl, P Merkel et al, JPCS 561, 012011 (2014)]
    [FJ Artola, GTA Huijsmans, M Hoelzl et al (in preparation)]
  - Runaway electrons
    [C Sommariva, E Nardon et al, NF 58, 016043 (2018)]
    [V Bandaru, M Hoelzl et al (in preparation)]

- **Fast particle physics**
  [A Dvornova, GTA Huijsmans et al, in preparation] + Poster P2.1052 at this conference

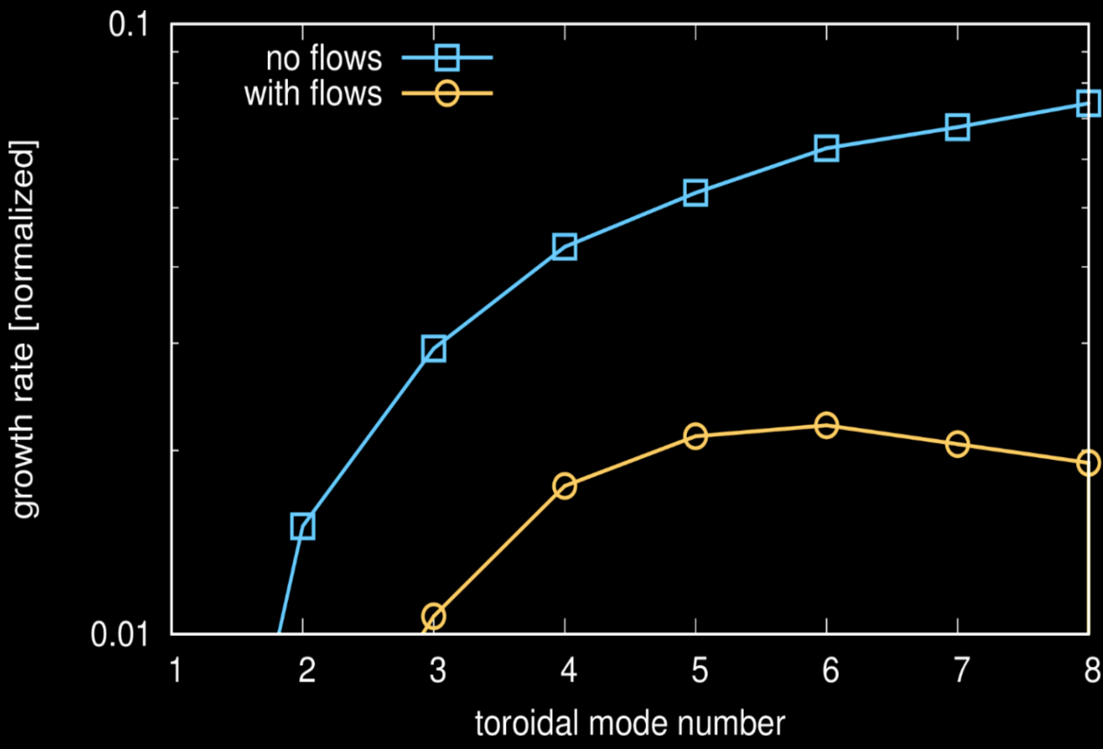
- **ITG turbulence**
  [M Becoulet, GTA Huijsmans, J Zielinski et al, in preparation]

What can we learn about ELMs?

Flow stabilization of high-n modes

- ASDEX Upgrade simulations for discharge #33616 with realistic plasma parameters
  (resistivity ≈ Spitzer predictions + neoclassical corrections)
  [M Hoelzl et al, CPP; doi:10.1002/ctpp.201700142]

- Important influence of ExB, diamagnetic, and toroidal flows



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Linear instability

- Low-n: peeling structure
- High-n: ballooning structure

- n=6 dominant,
  growth rate $(4 \pm 1) \cdot 10^4 s^{-1}$
  (uncertainty from equilibrium reconstruction)
  [M Hoelzl et al, CPP; doi:10.1002/ctpp.201700142]

- ASDEX Upgrade #33616:
  [F Mink, M Hoelzl, E Wolfrum et al, NF 58 026011 (2018)]
  – Growth rate $(5 \pm 2) \cdot 10^4 s^{-1}$
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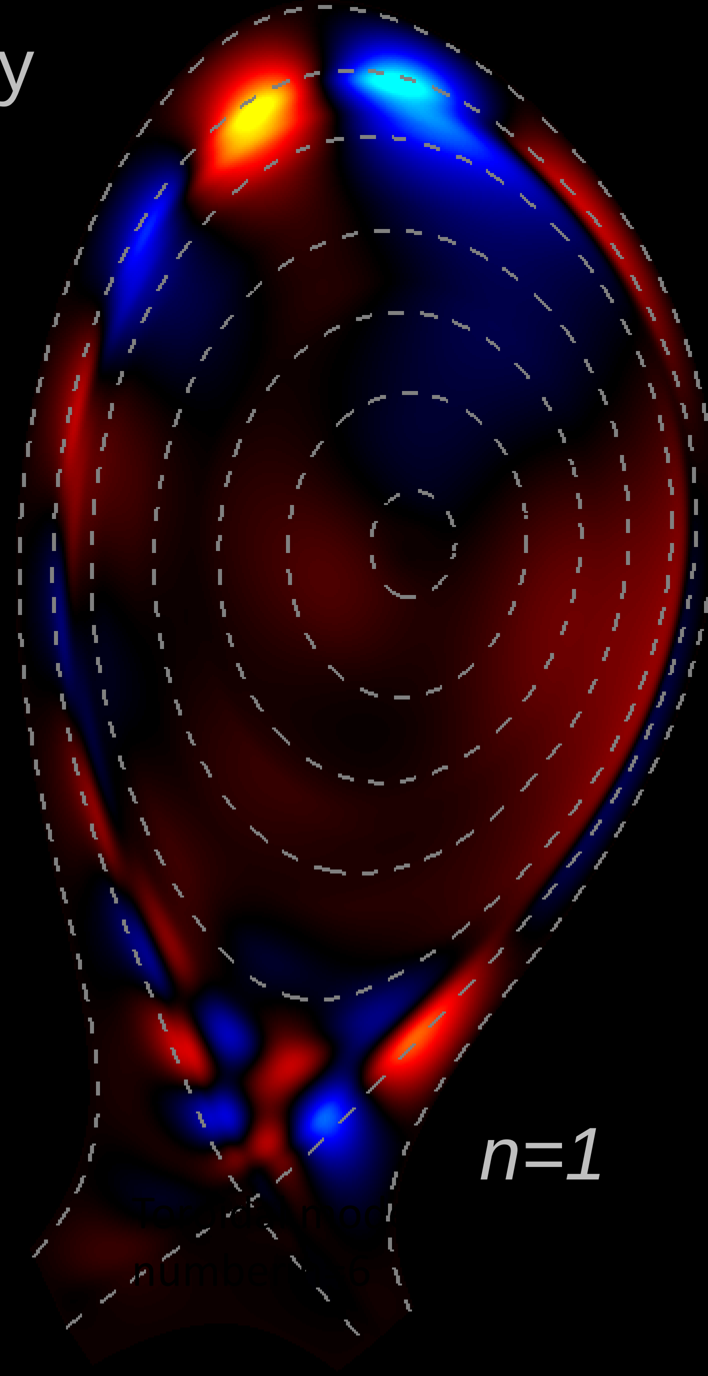

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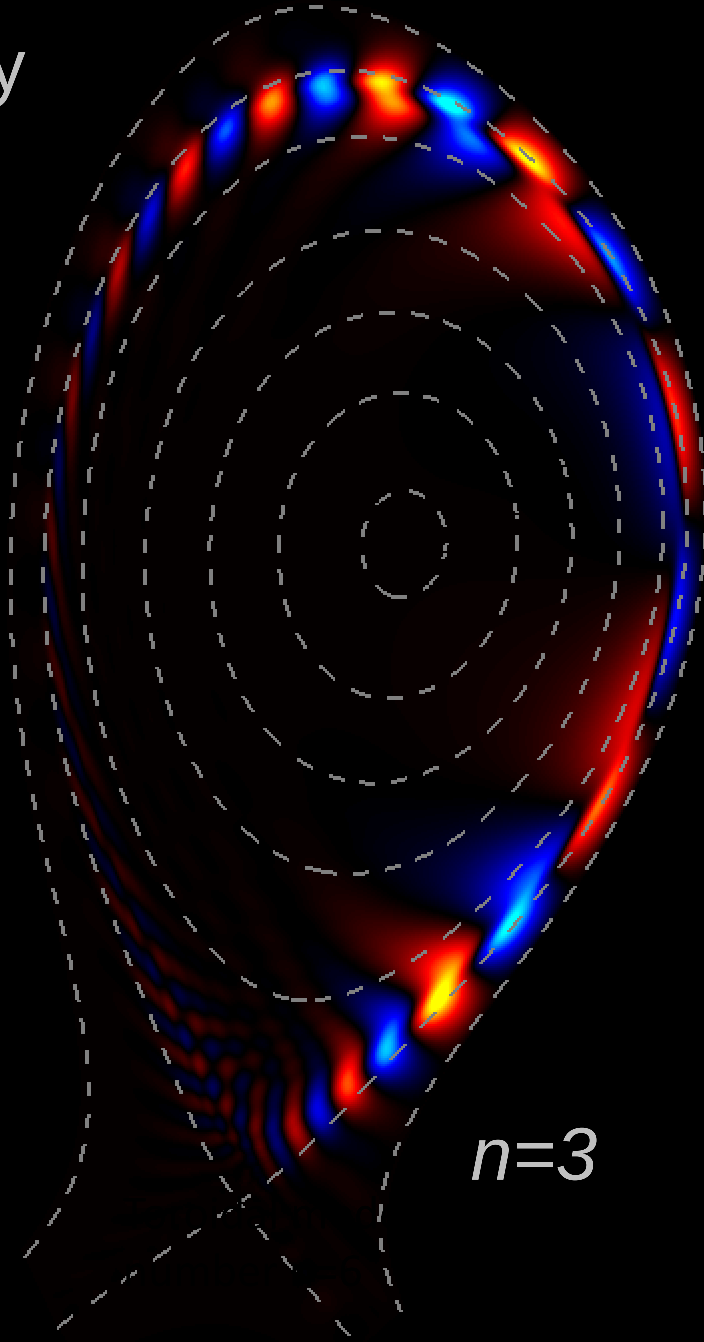

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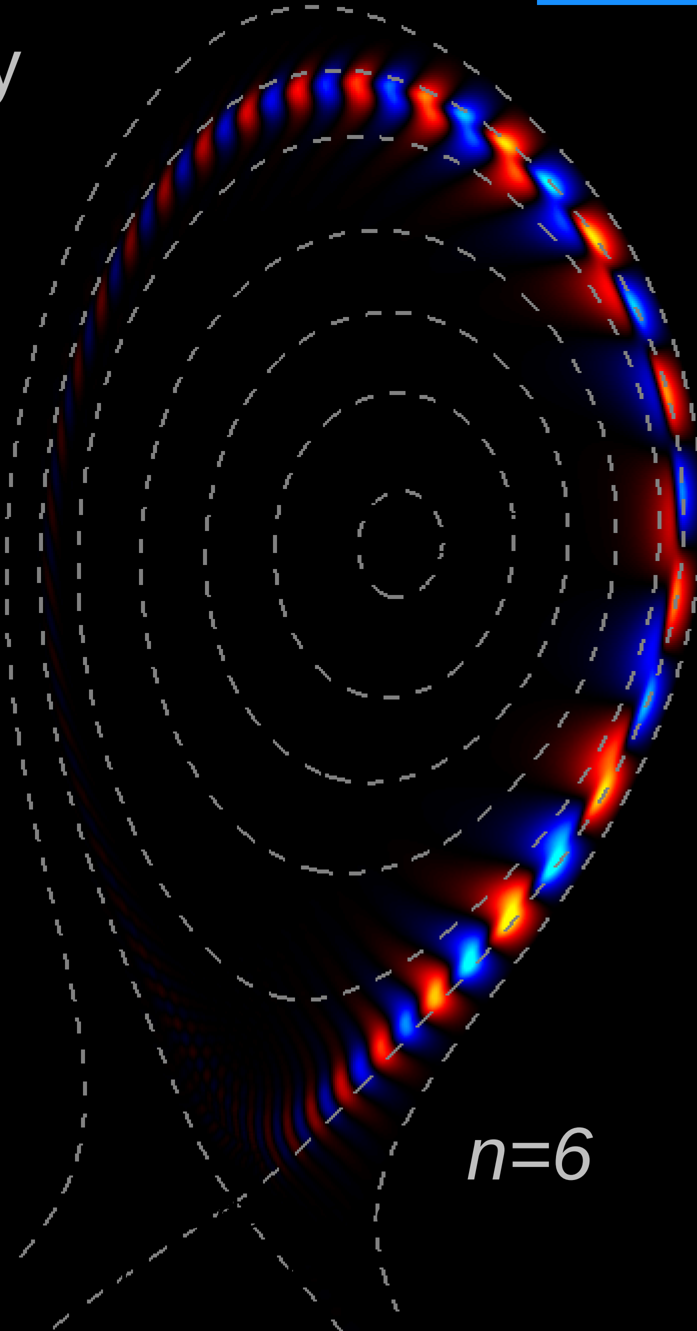

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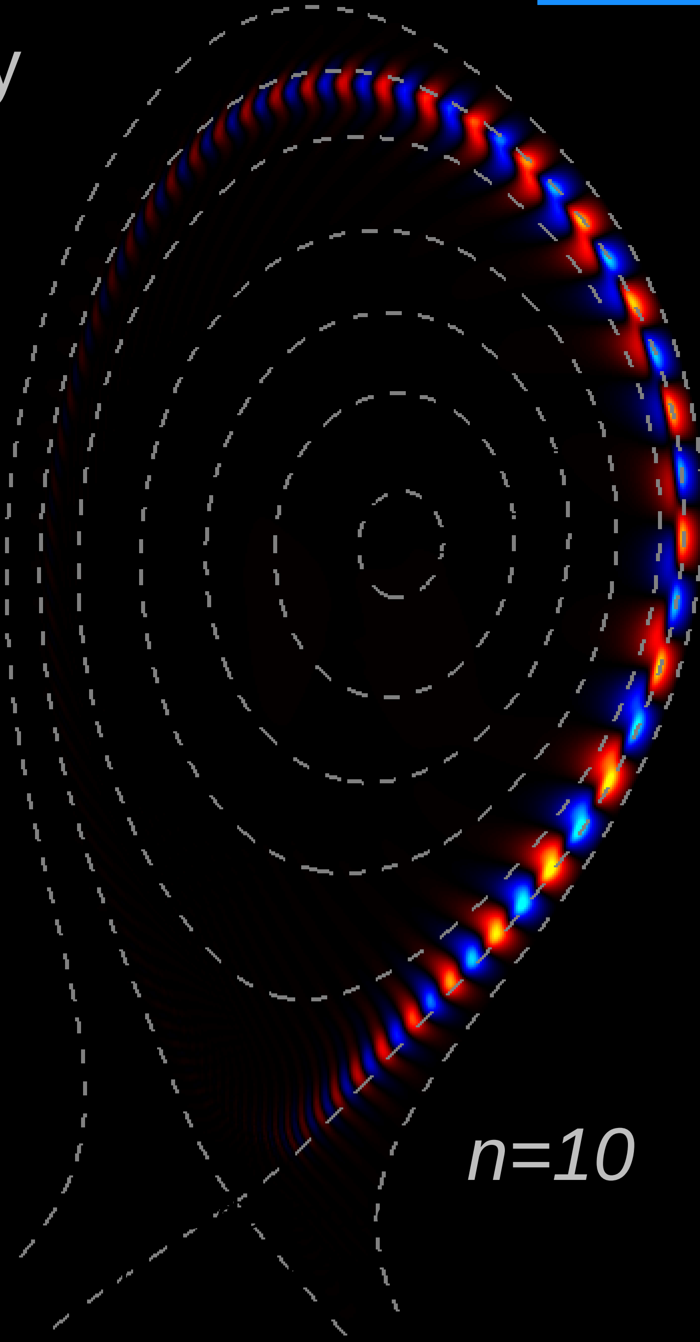
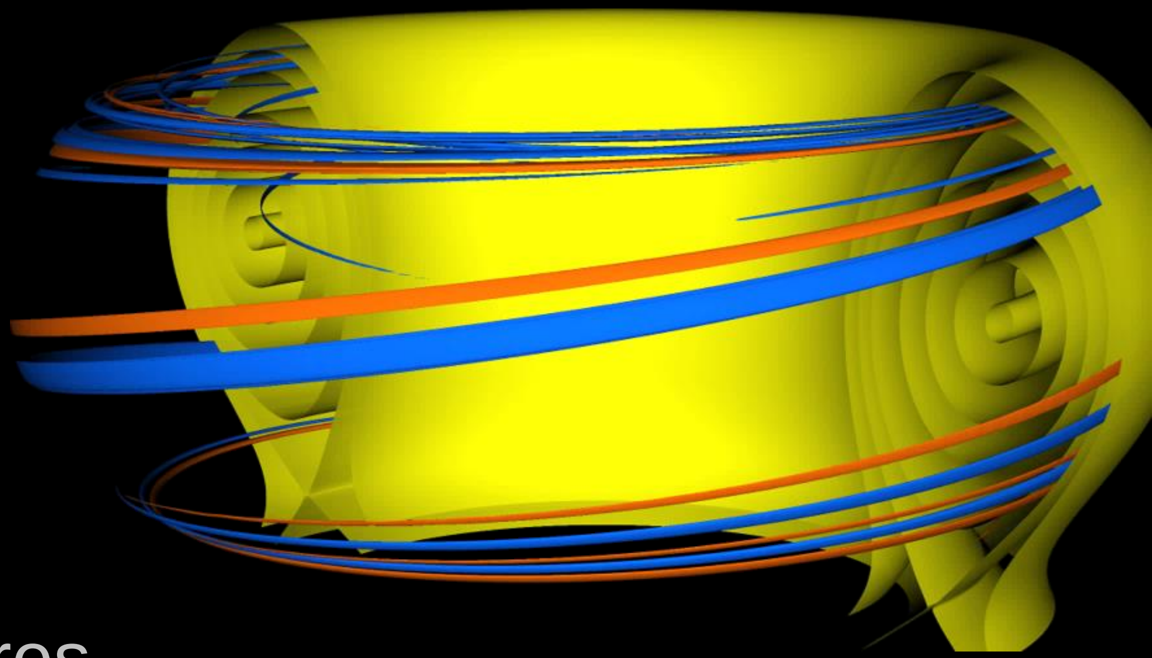


Non-linear mode coupling

- Drives low-n harmonics [I Krebs, M Hoelzl et al, PoP 20, 082506 (2013)]
- Localized ELM structures [M Hoelzl et al, PoP 19, 082505 (2012)]



- Experiment:
  - solitary structures
    [RP Wenninger et al, NF 52, 114025 (2012)]
  - low-n features
    [RP Wenninger et al, NF 53, 113004 (2013)]
  - mode coupling
    [B Vanovac et al, NF (submitted)]

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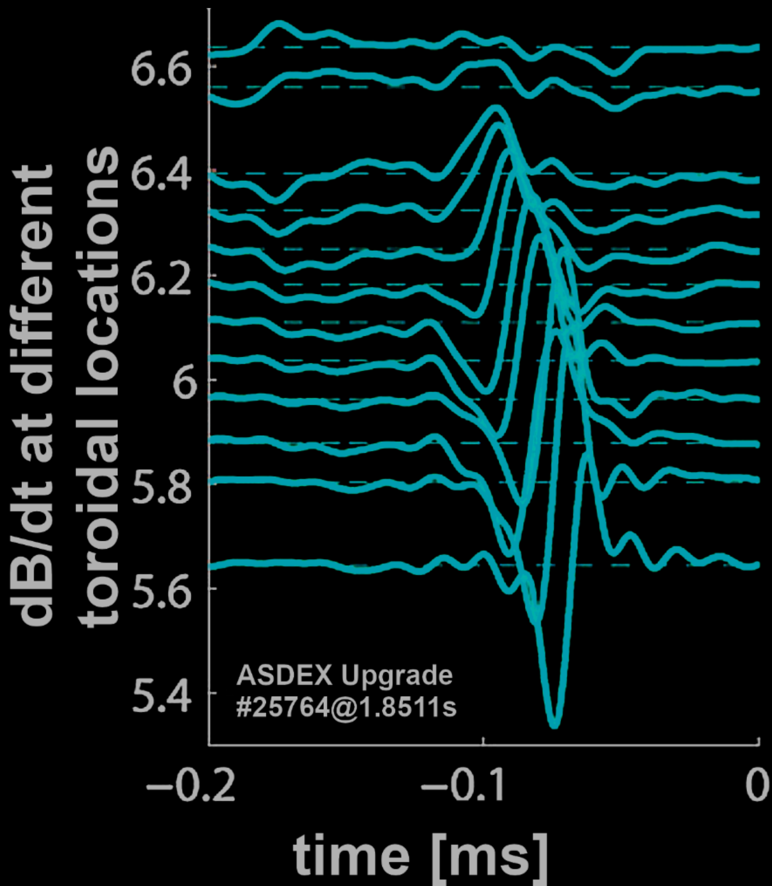

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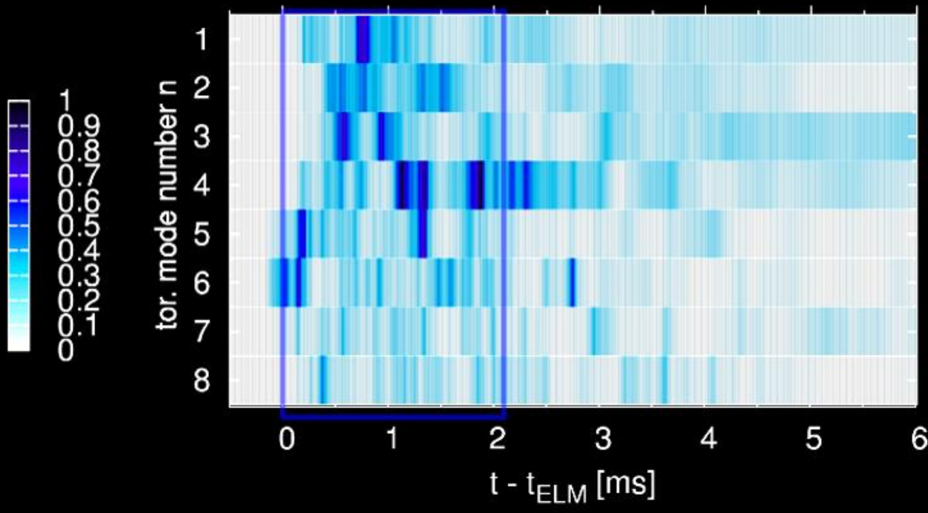
ELM crash in the simulation

- Duration: ~2 ms
  Experiment: ~2 ms

- Dominant n: 4 (1…5 significant)
  Experiment: 3 (2…5 significant)

Simulation result

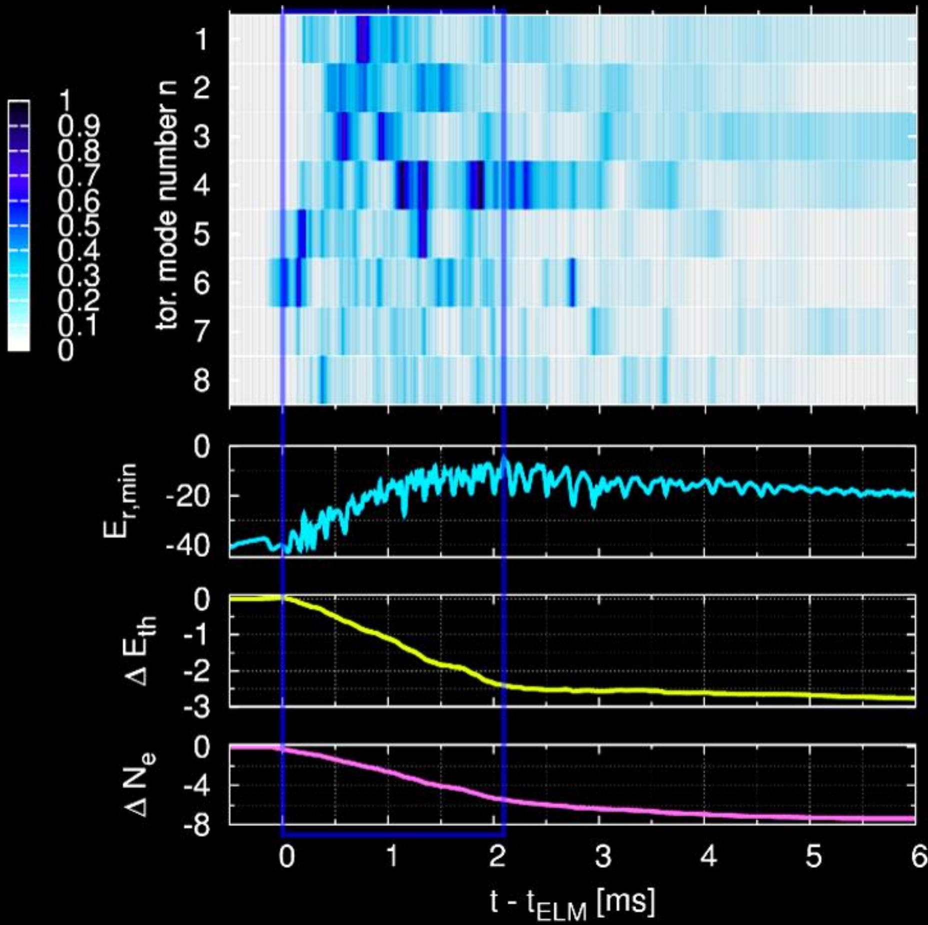


[M Hoelzl et al, CPP; doi:10.1002/ctpp.201700142]
[F Mink, M Hoelzl, E Wolfrum et al, NF 58 026011 (2018)]

ELM crash in the simulation

- Duration: ~2 ms
  Experiment: ~2 ms
- Dominant n: 4 (1…5 significant)
  Experiment: 3 (2…5 significant)
- E_r drop: -35 to -12 kV/m
  Experiment: -40 to -10 kV/m
- Energy losses: 3%
  Experiment: 6%
- Particle losses: 7%
  Experiment: 8%

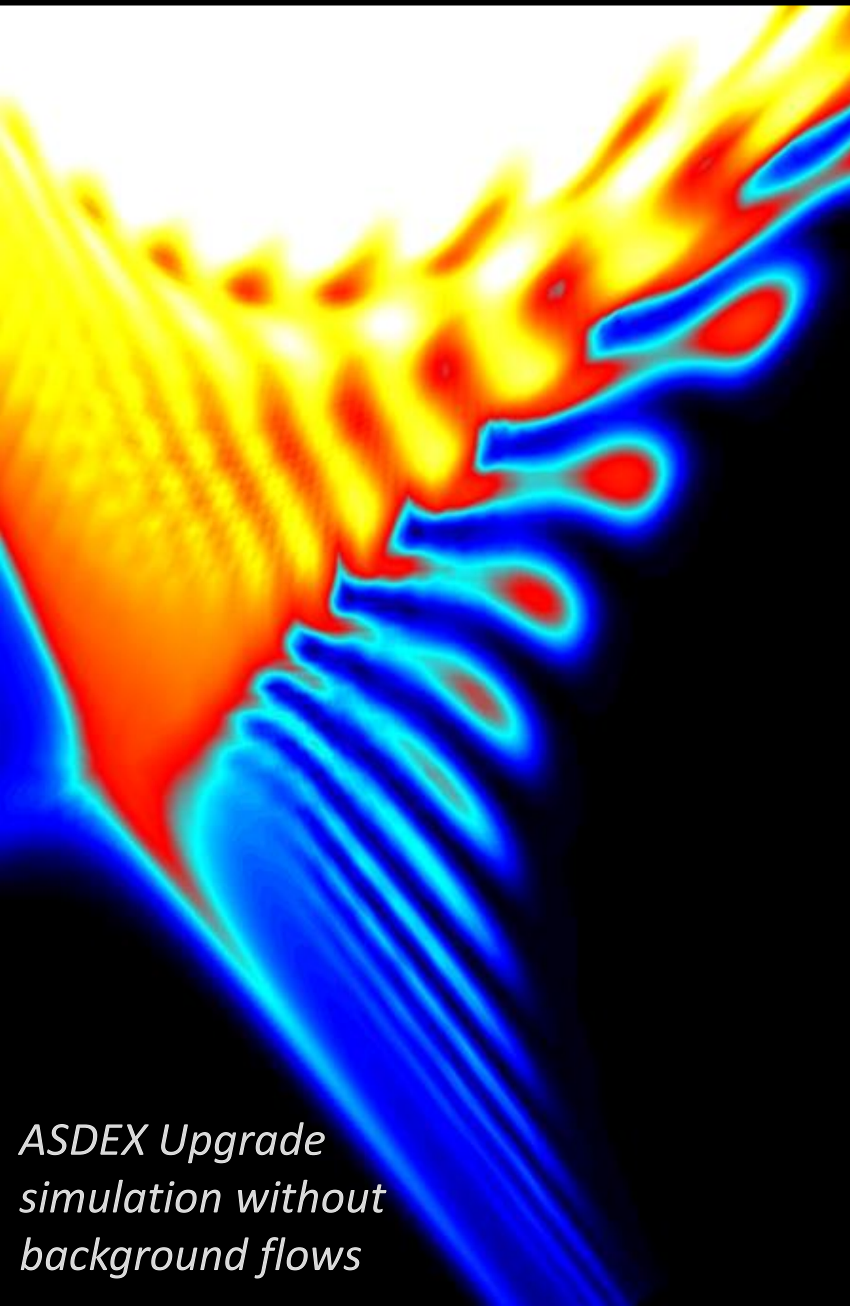
Simulation result



Important role of background flows and non-linear mode coupling

[M Hoelzl et al, CPP; doi:10.1002/ctpp.201700142]
[F Mink, M Hoelzl, E Wolfrum et al, NF 58 026011 (2018)]

Kinetic perturbation



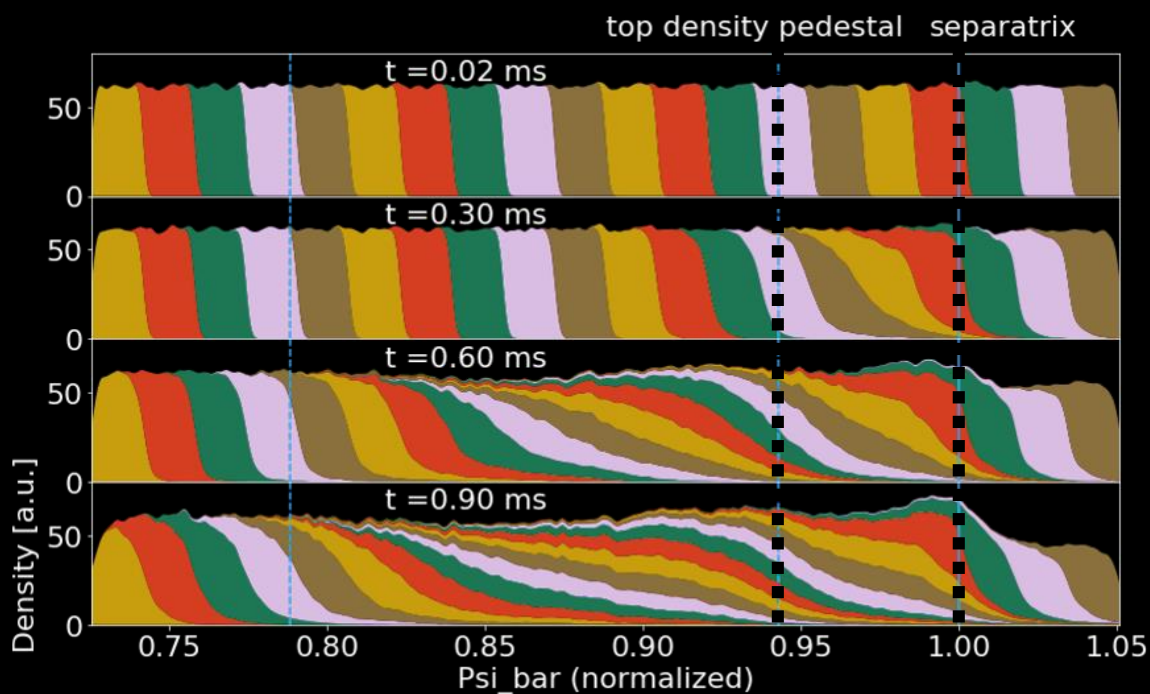
ASDEX Upgrade simulation without background flows

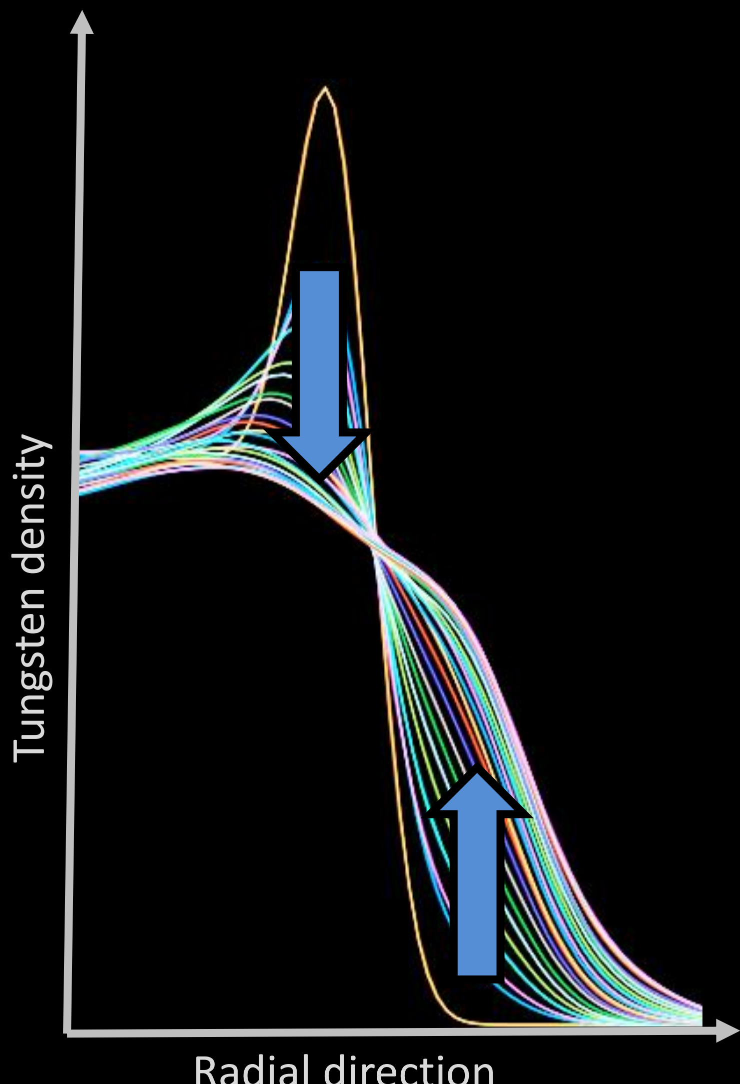
- Ballooning fingers produced by interchange-like ExB inward and outward motion
- Formation of **filaments** due to poloidal shear flows similar to experiment
  - Radial velocity ~1 km/s
    e.g. [A Schmid et al, PPCF 50, 045007 (2008)]
  - Several filament bursts during “long ELMs”
    e.g., [L Frassinetti et al, NF 57, 022004 (2017)]
- **Convective losses**

Tungsten transport

- ExB interchange motion during ELM crash in ASDEX Upgrade
- Now: collisions, sputtering and coupling to MHD being added

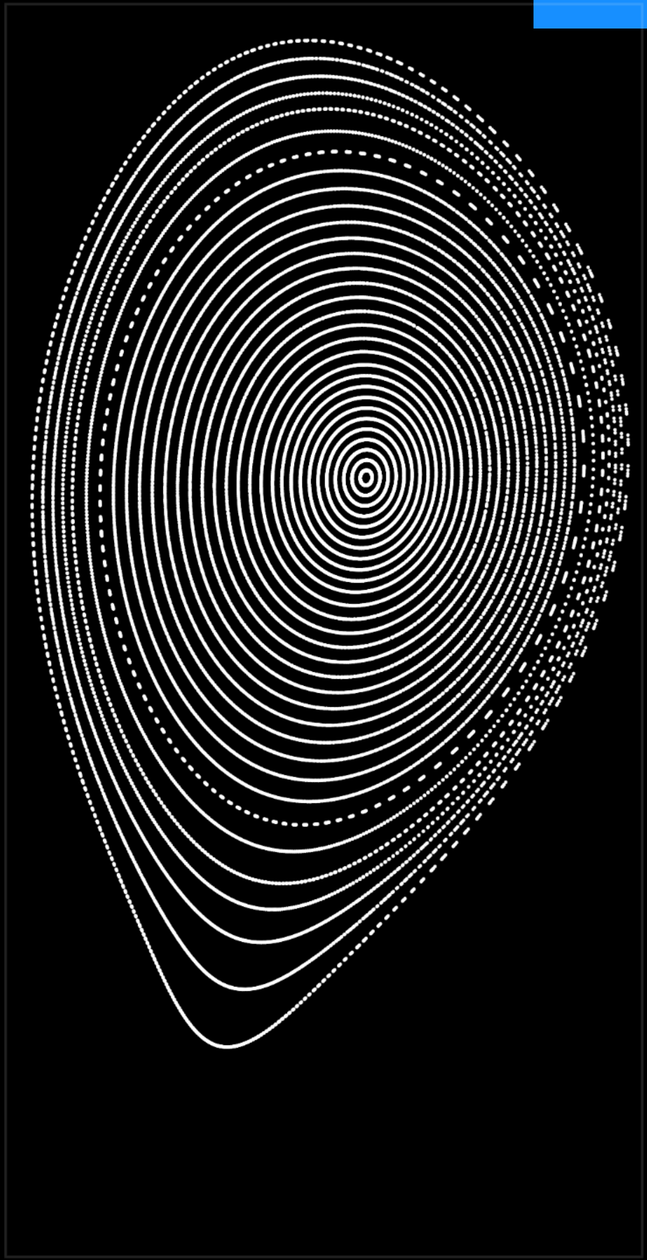
[DC van Vugt, GTA Huysmans, M Hoelzl et al, NF (submitted)]
+ Poster P1.1049 at this conference





Magnetic perturbation

- During the ELM crash, magnetic reconnection causes a **stochastic field** at the plasma boundary



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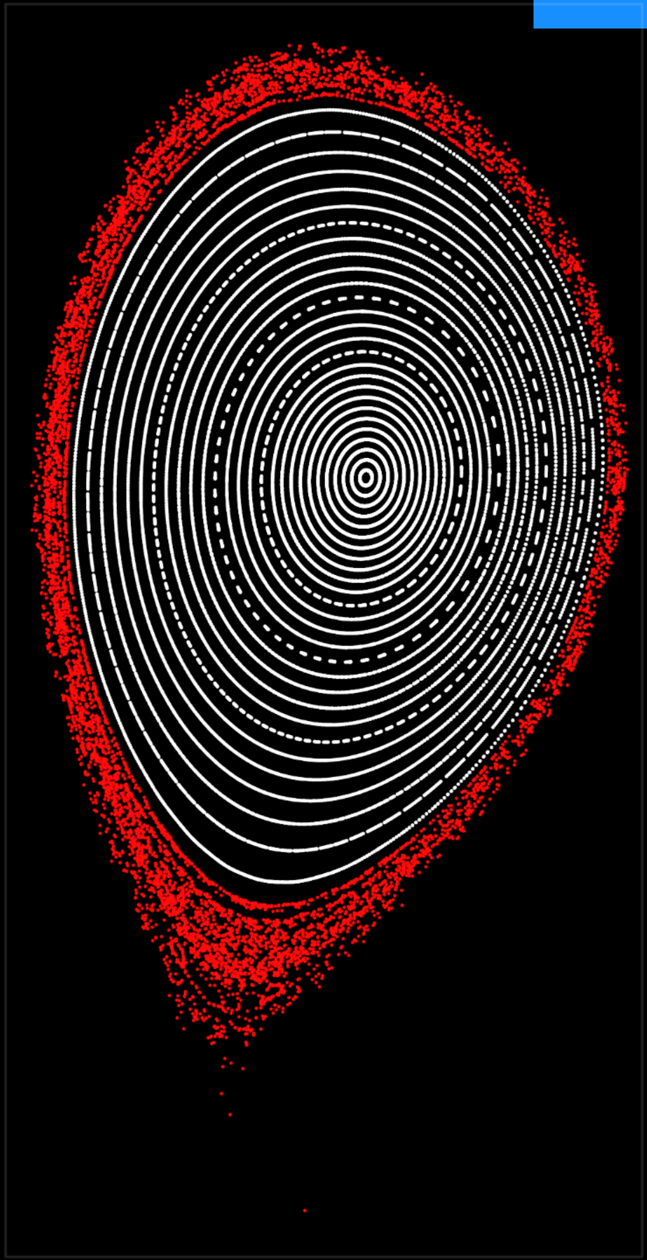
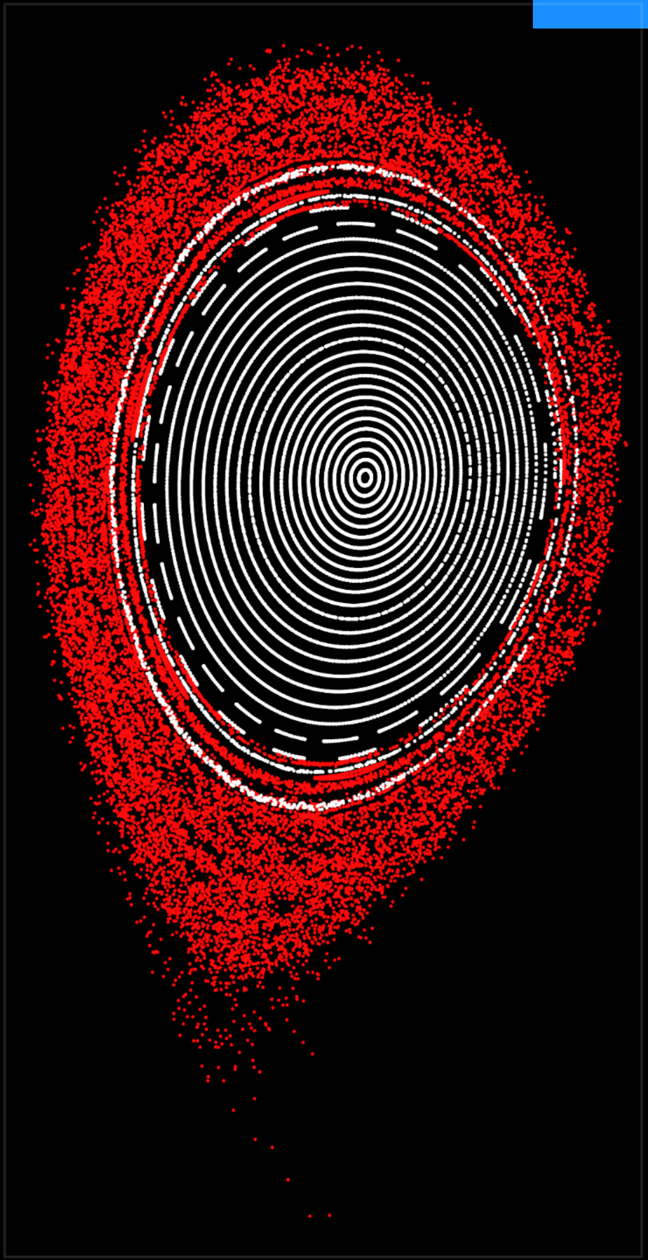


Magnetic perturbation

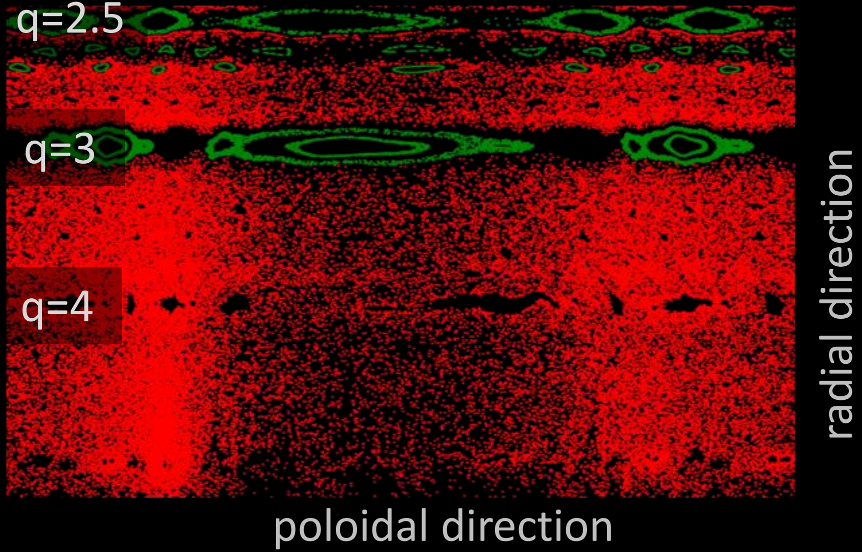
- During the ELM crash, magnetic reconnection causes a **stochastic field** at the plasma boundary

- Direct connection of field lines to the divertor target

- **Conductive losses along magnetic field lines**



Connection length



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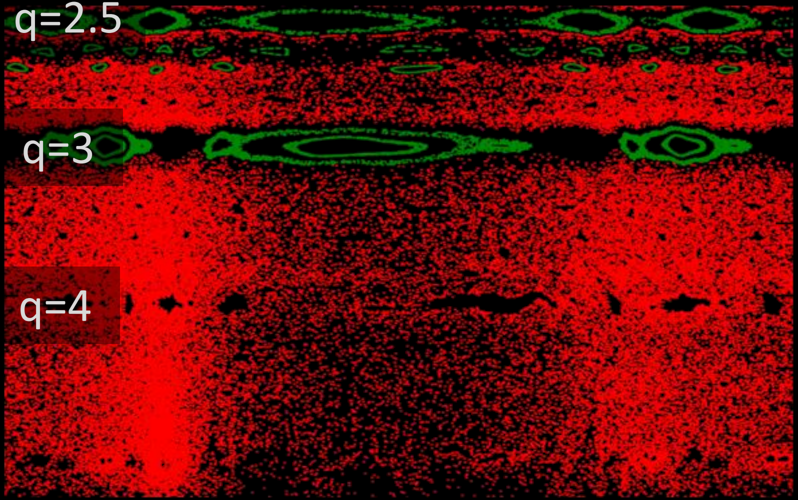
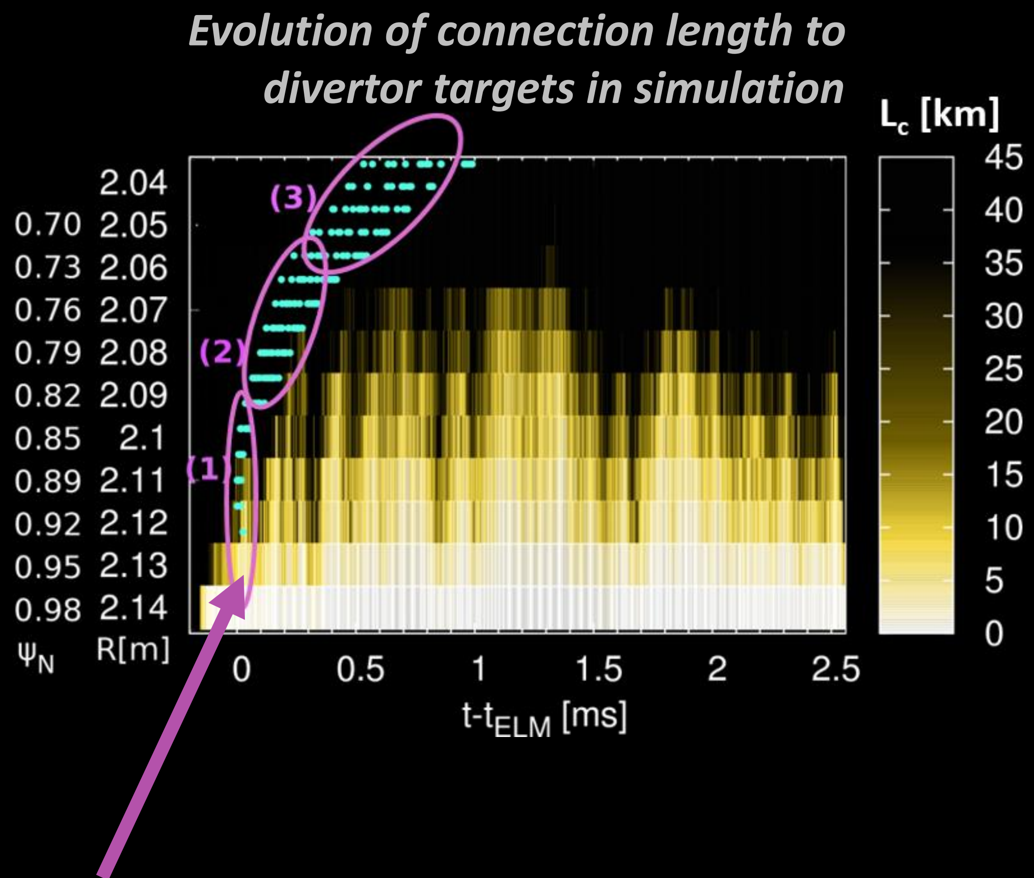


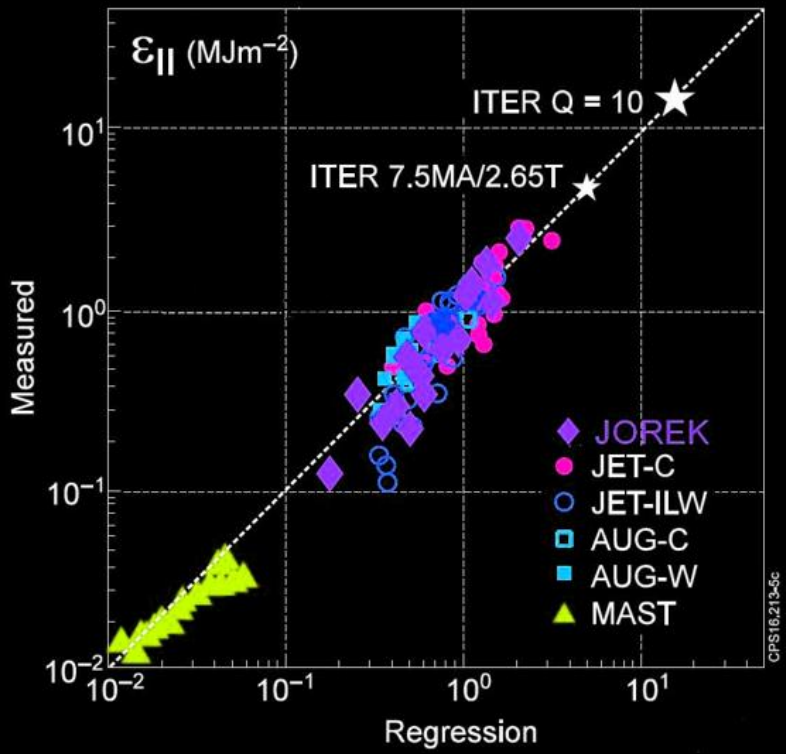


Consistent with "ELM cold front penetration" in the experiment

[E Trier, E Wolfrum et al, PPCF (submitted)]

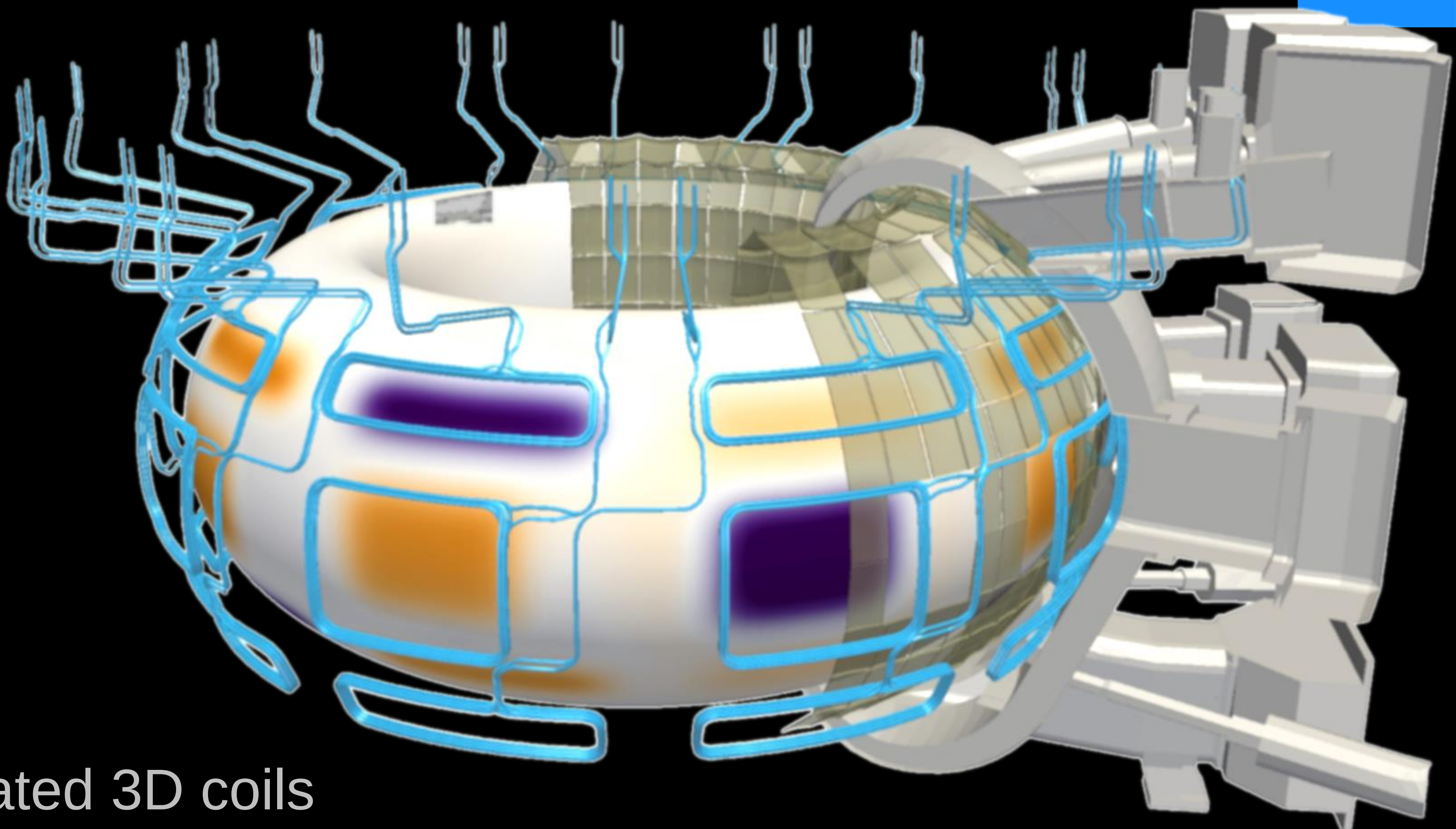
Divertor heat loads

- ELM energy fluence to divertor agrees well between experiment and a series of JET simulations
  (uncertainty regarding the role of flows)
  [T Eich et al, Nucl. Materials and Energy 12, 84 (2017)]
  [S Pamela et al, NF 57, 076006 (2017)]



What can we learn about ELM control?

Mitigation / suppression by coils



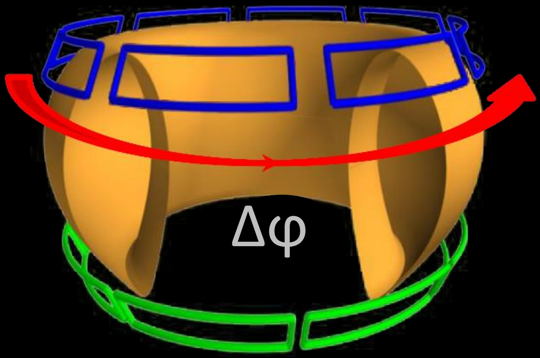
- Dedicated 3D coils
- Main ELM control method for ITER
- Demonstrated in many experiments already

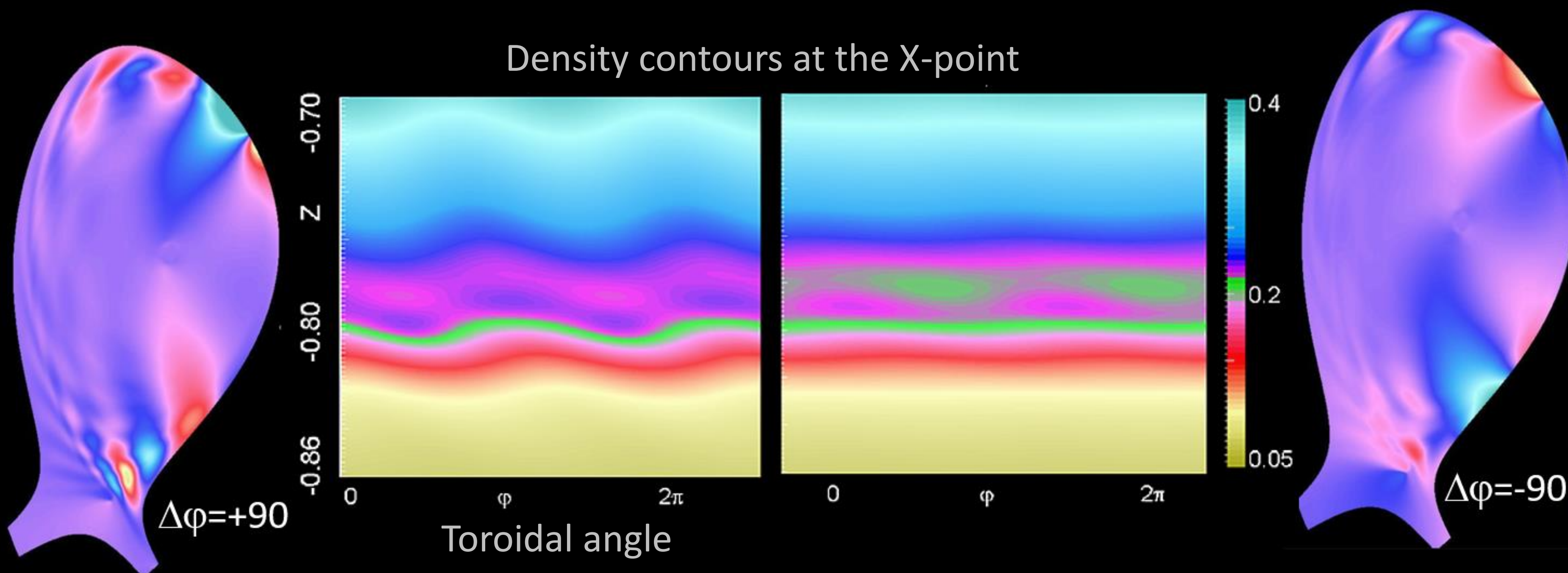
Figure provided by GTA Huijsmans

- But: Low collisionality, high recycling, partially detached, also during ramp-up and ramp-down

Mitigation / suppression by coils

- Large kink/peeling response (left) important for ELM stabilization
- Corresponds to large X-point corrugation

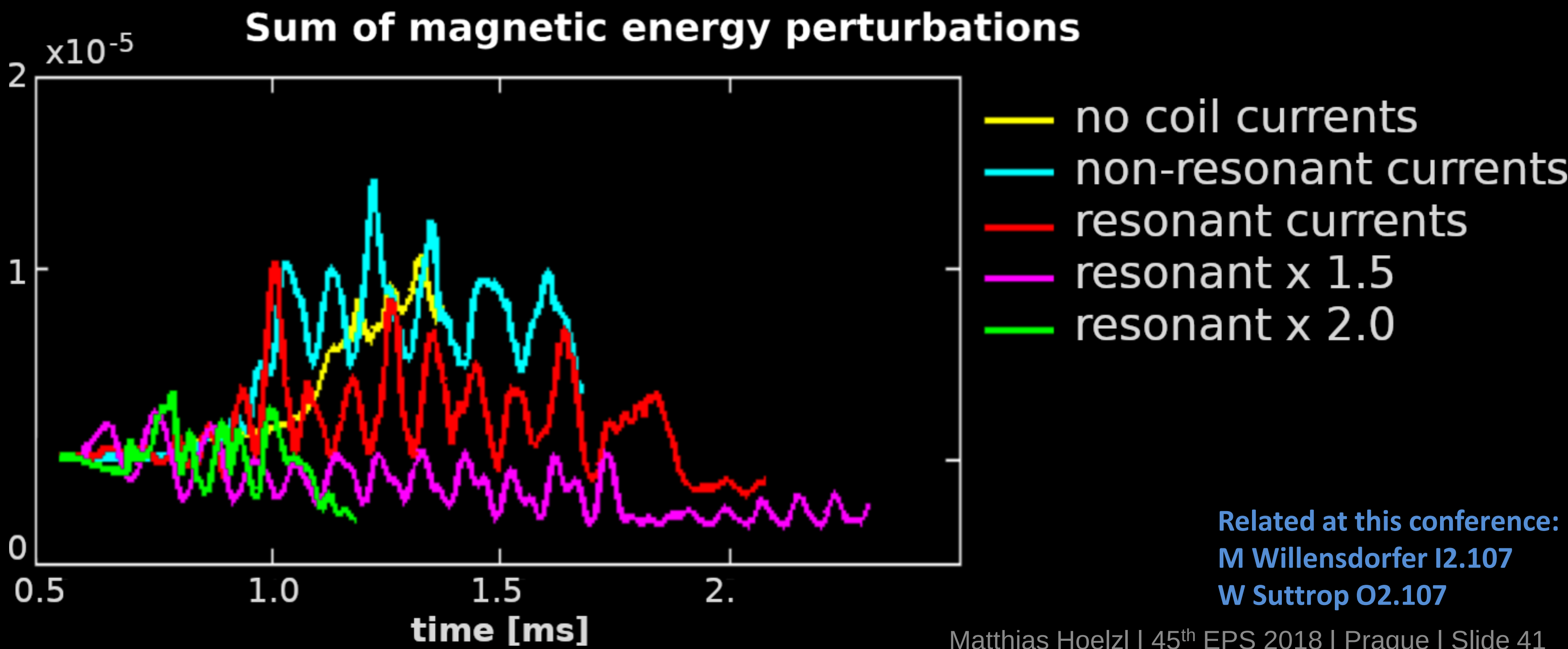




[F Orain, M Hoelzl et al, NF 57, 022013 (2016)]

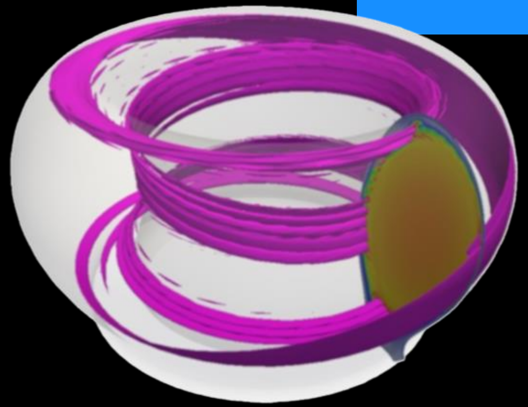
Mitigation / suppression by coils

- **Non-linear coupling of toroidal modes important for ELM mitigation / suppression**
  [M Bécoulet, F Orain et al, PRL 113, 115001 (2014)]
  [F Orain, M Hoelzl et al NF (in preparation)]

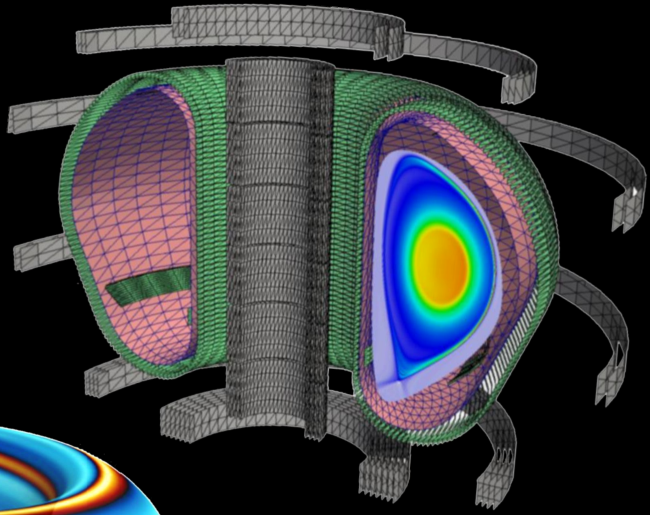


Related at this conference:
M Willensdorfer I2.107
W Suttrop O2.107

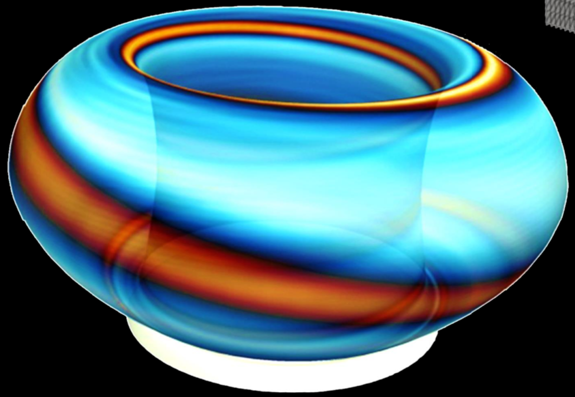
Other methods for ELM control



- ELM pacing by pellet injection
  simulations e.g.:
  [S Futatani, G Huysmans, et al, NF 54, 073008 (2014)]



- ELM pacing by magnetic kicks
  simulations:
  [FJ Artola, GTA Huijsmans, M. Hoelzl et al, NF (accepted)]
  + Presentation I2.109 at this conference



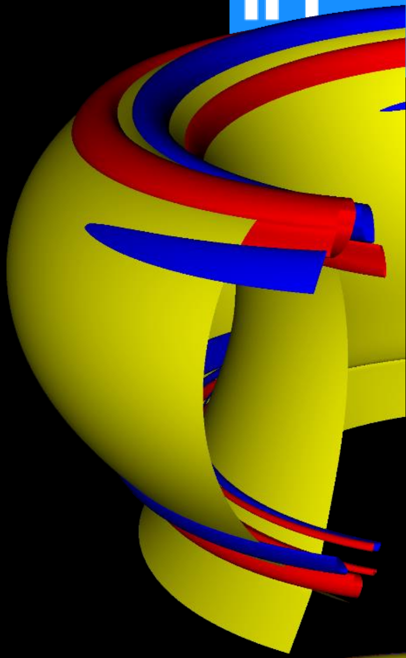
- ELM-free regimes
  simulations e.g.:
  [F Liu et al, PPCF 60, 014039 (2018)]

Conclusions and Outlook

Conclusions

Edge localized modes (ELMs)

- Critical for ITER divertor
- Peeling-ballooning modes
- Important influence of plasma flows and mode coupling
- Filament formation
- Edge ergodization

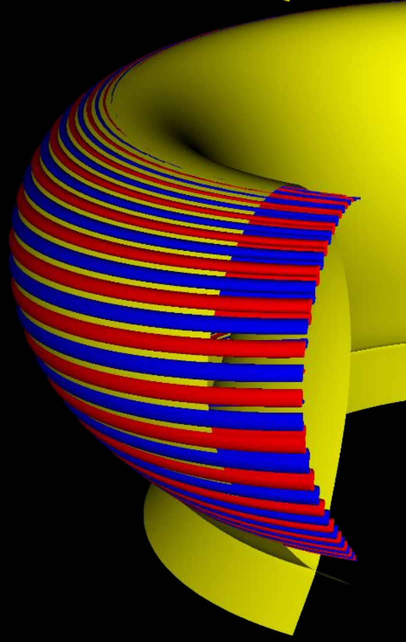


Non-linear MHD code JOREK

- ELM and disruption physics

Simulations of ELMs and ELM control

- Good agreement on many key features
- Not yet fully predictive



Outlook for ELM related questions

- Further physics and numerics developments as well as validation on present experiments

- Full ELM cycles
- Free boundary effects
- Improved scrape-off layer physics
- Transport coefficients from turbulence codes
- Heavy impurity sources and transport

  …

EPS contributions directly related to JOREK

DC van Vugt, GTA Huijsmans, M Hoelzl et al
Coupled nonlinear MHD-particle simulations for ITER with the JOREK + particle-tracking code (P1.1049)

FJ Artola, GTA Huijsmans, M Hoelzl et al
An in depth look into the physics of ELM triggering via vertical kicks through non-linear MHD simulations (I2.109)

A Dvornova, GTA Huijsmans, S Sharapov, M Hoelzl et al
Modelling of TAE mode excitation with an antenna in X-point geometry (P2.1052)

D Hu, E Nardon, GTA Huijsmans et al
JOREK simulations of Shattered Pellet Injection with high Z impurities (P4.1043)

S Smith, S Pamela, et al
Numerical Simulations of Edge Localised Modes in MAST-U Plasmas (P4.1061)

M Hoelzl, GTA Huijsmans et al
Simulating tokamak edge instabilities: advances and challenges (I5.J601)

D Meshcheriakov, M Hoelzl, V Igochine et al
Tearing mode seeding by resonant magnetic perturbations (P5.1033)

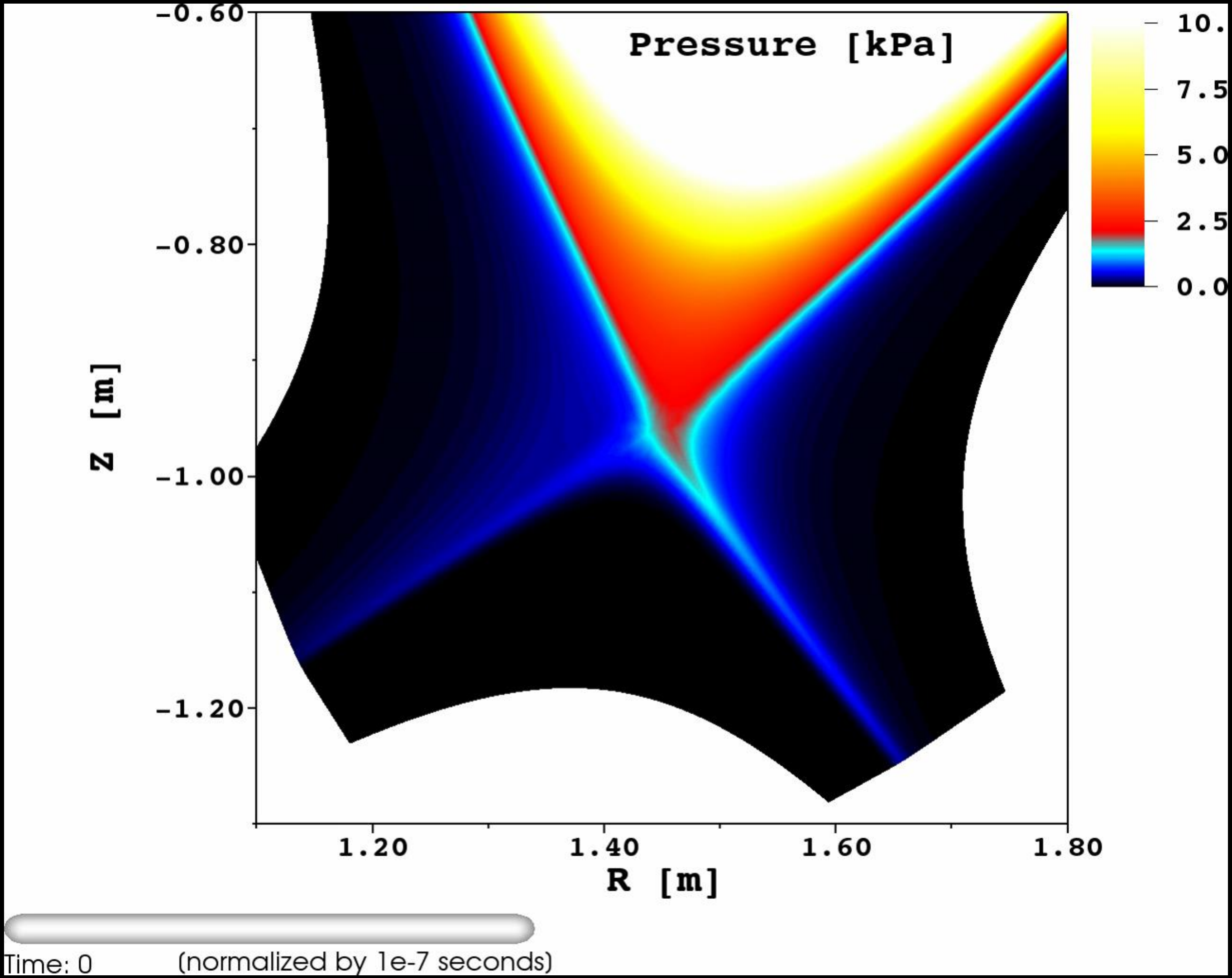
Backup slides

JOREK: Extended MHD Models

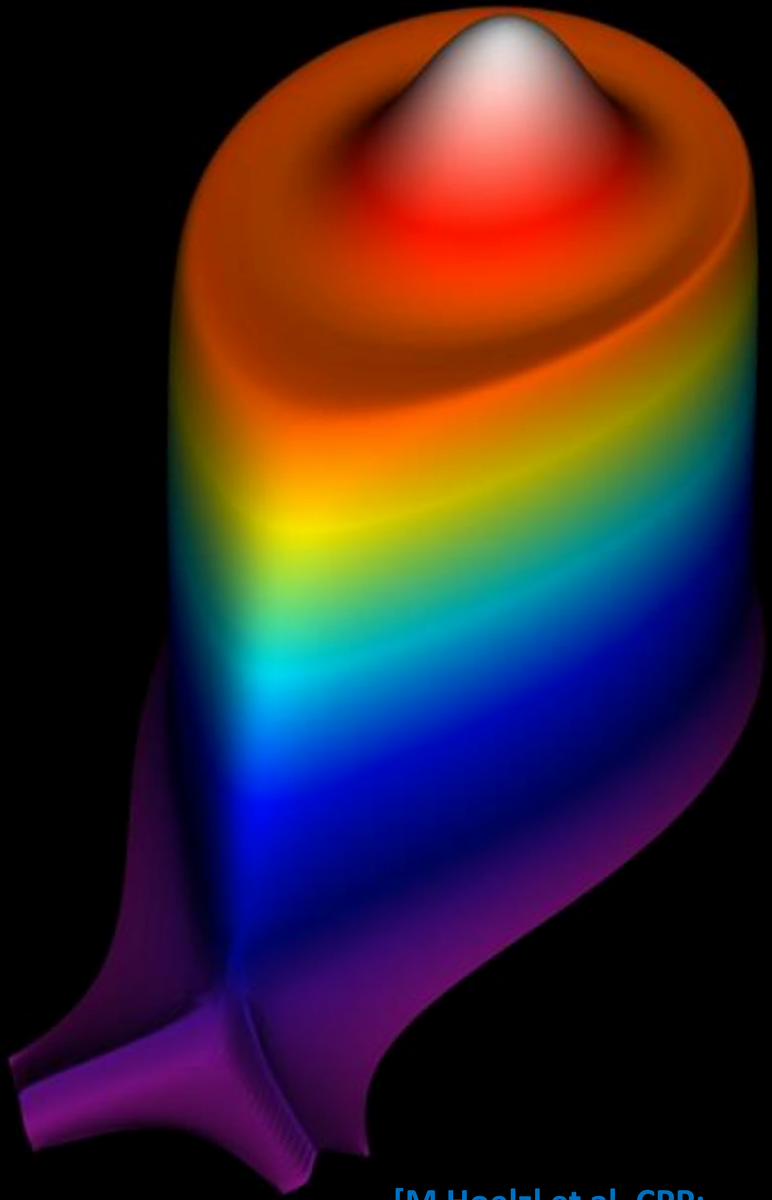
- Reduced MHD, ideal wall and divertor sheath boundary conditions [GTA Huysmans and O Czarny, NF 47, 659 (2007)]
- Two-fluid + neoclassical physics [F Orain et al, PoP 20, 102510 (2013)]

- Free boundary extension [M Hoelzl et al, JPCS 401, 012010 (2012)]
- Pellet ablation model [S Futatani et al, NF 54, 073008 (2014)]
- Full orbit particle model [DC van Vugt, et al, 44th EPS, P2.140 (2017)]
- Relativistic guiding center tracer [C Sommariva et al, NF 58, 016043 (2018)]
- Relativistic electron fluid model [V Bandaru et al (in preparation)]
- Neutrals model [A Fil et al, PoP 22, 062509 (2015)]
- Impurity fluid model [E Nardon et al, PPCF 59, 014006 (2016)]
- Full MHD [JW Haverkort et al, JCP 316, 281 (2016)]
- …

Filament formation



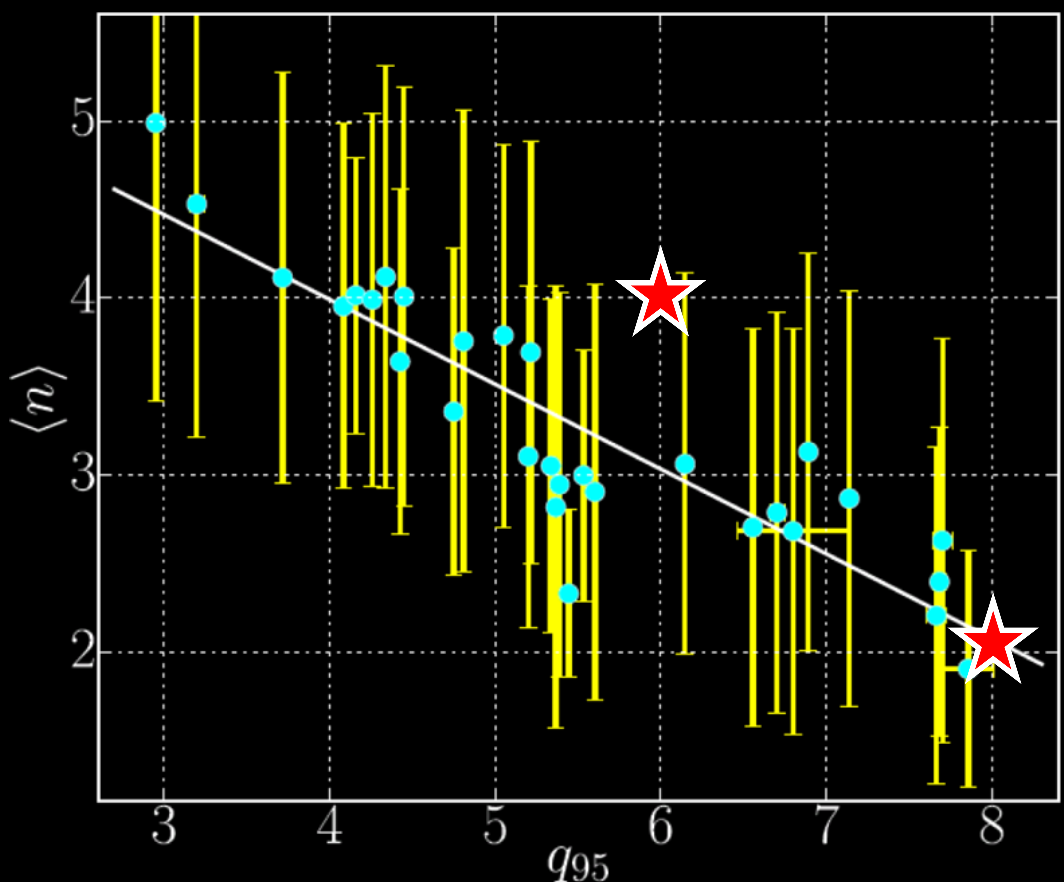
Crash of density pedestal



Evolution of the density distribution during a type-I ELM crash in ASDEX Upgrade

[M Hoelzl et al, CPP; doi:10.1002/ctpp.201700142]

q95 dependency



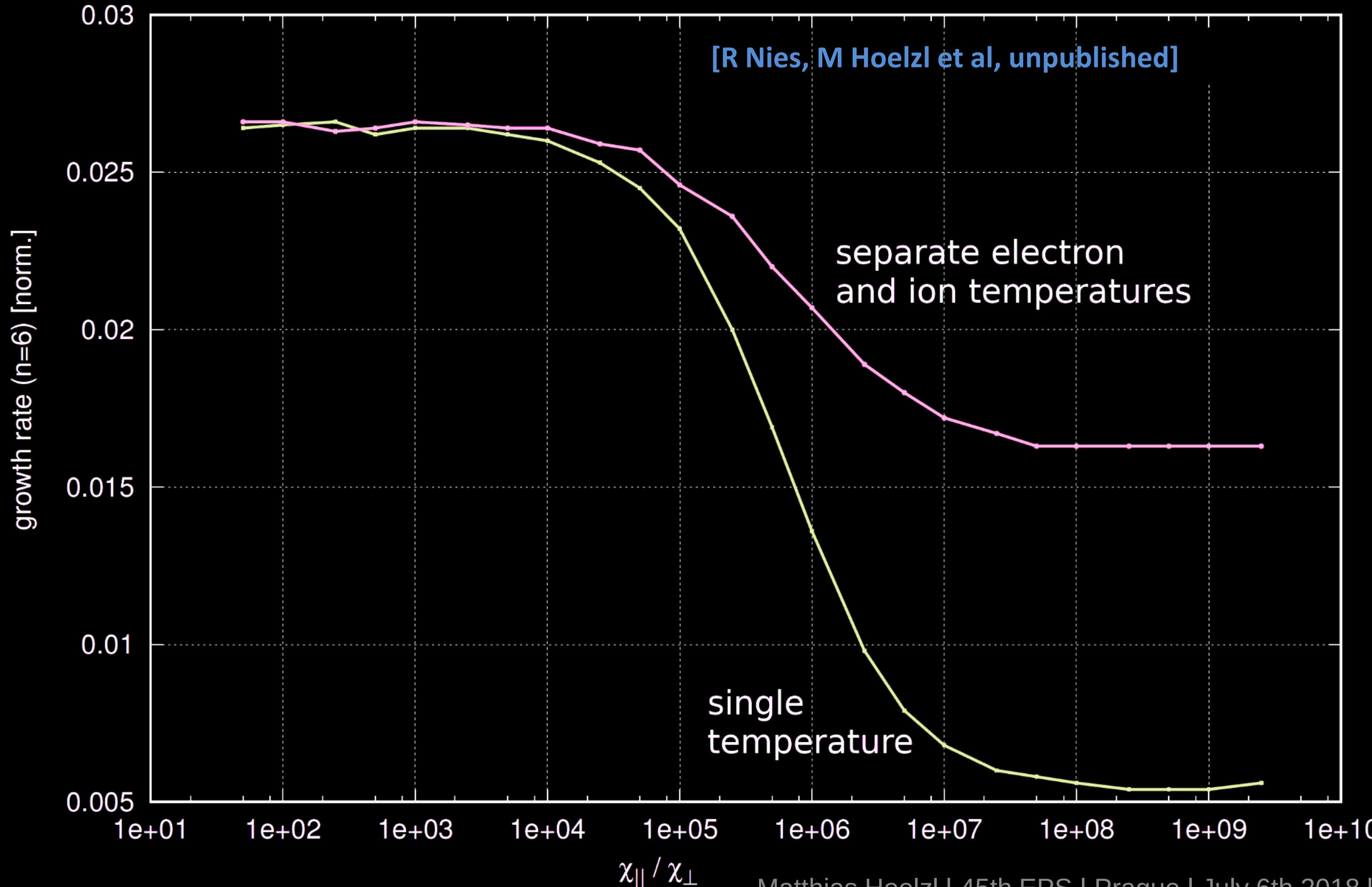
- Strong dependency of dominant mode number on q95 observed
  [Mink A.F., Wolfrum E., Dunne M., Hoelzl M., et al, PPCF (submitted)] + Poster P2.1015 at this conference
- Similar trend in simulations (★)

q95 varied via scan in toroidal field strength in simulations

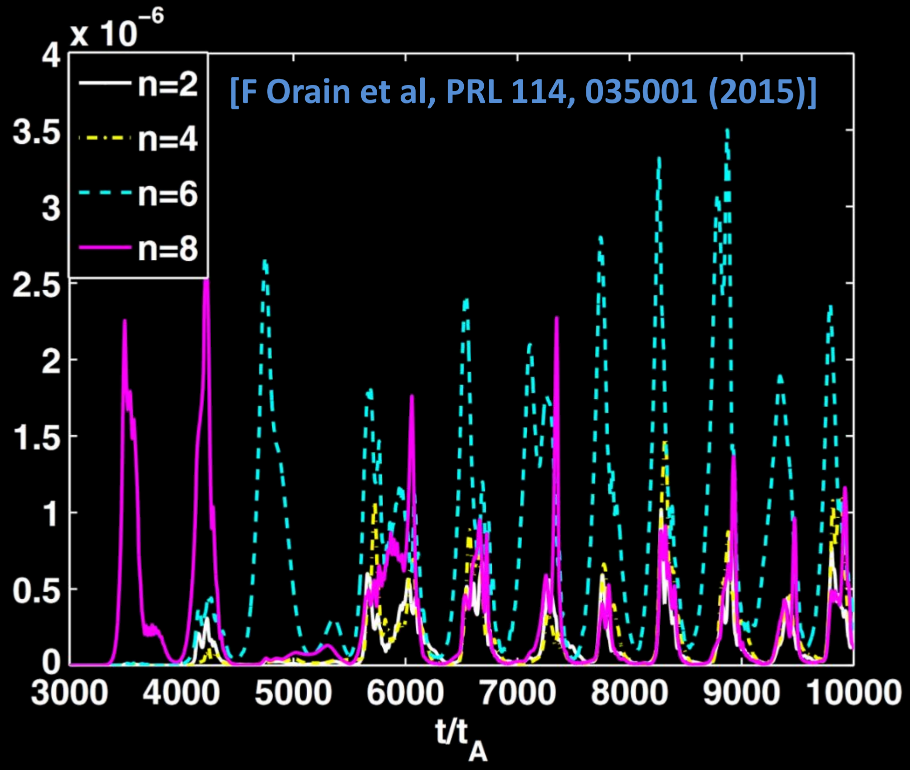
A one to one comparison requires simulations for different discharges due to the cross-correlation of q95 with other parameters and influence of “magnetic shear”

Influence of parallel conductivity

- Linear codes usually do not capture this correctly



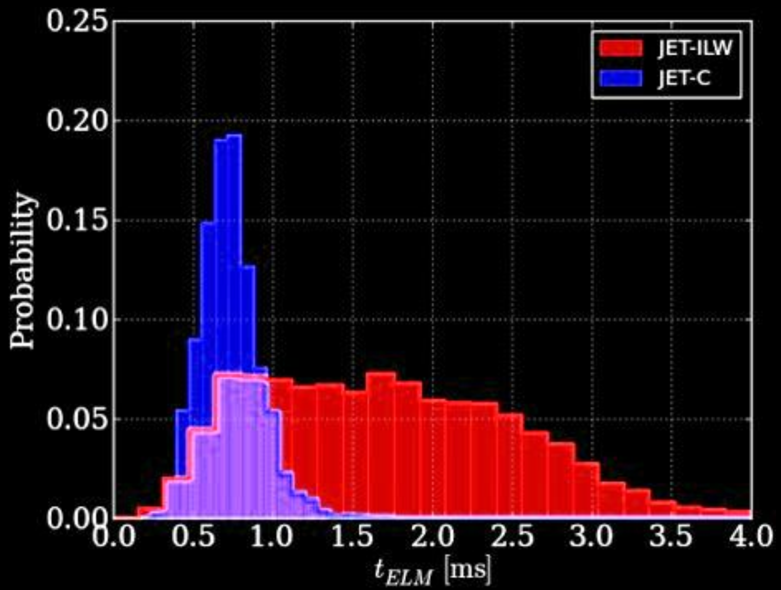
ELM cycles



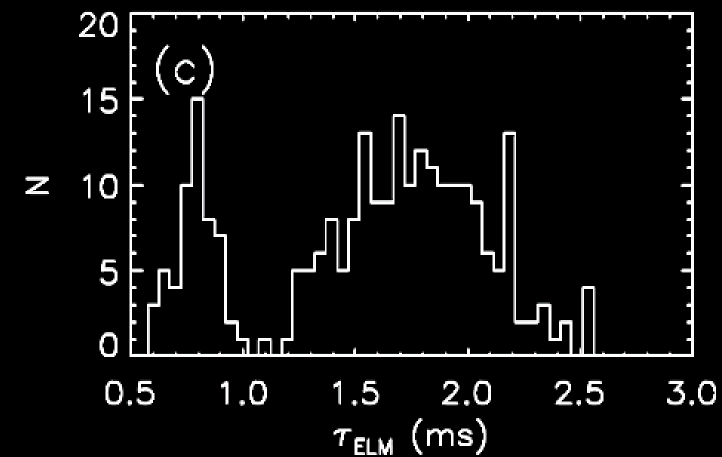
Large number of experimental findings for ELM cycle will allow to validate simulations properly

Decay of the instability

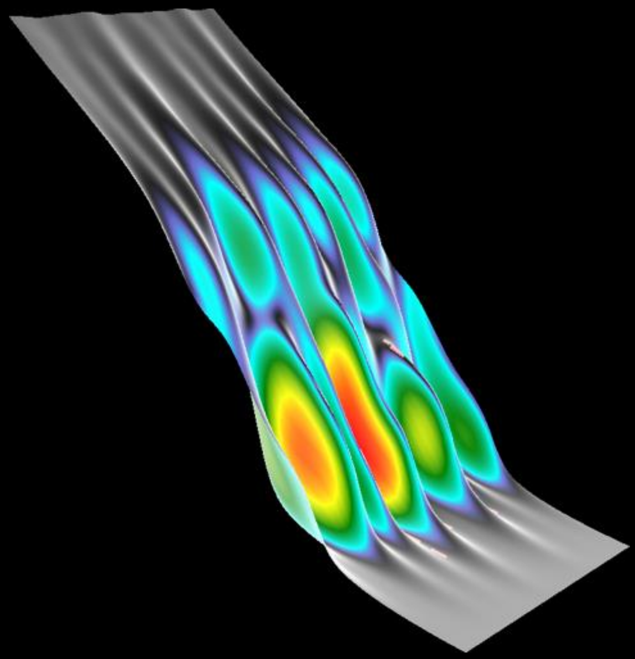
- Decay well below stability threshold
- Short and long ELMs in experiment



[B Sieglin et al, PPCF 55, 124039 (2013)]



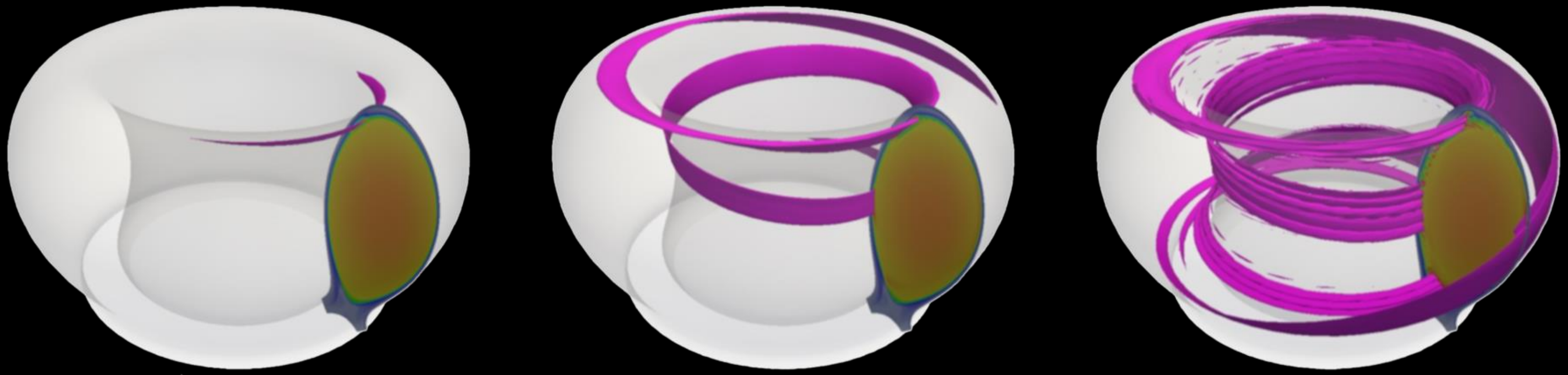
[L Frassinetti et al, NF 57, 022004 (2017)]



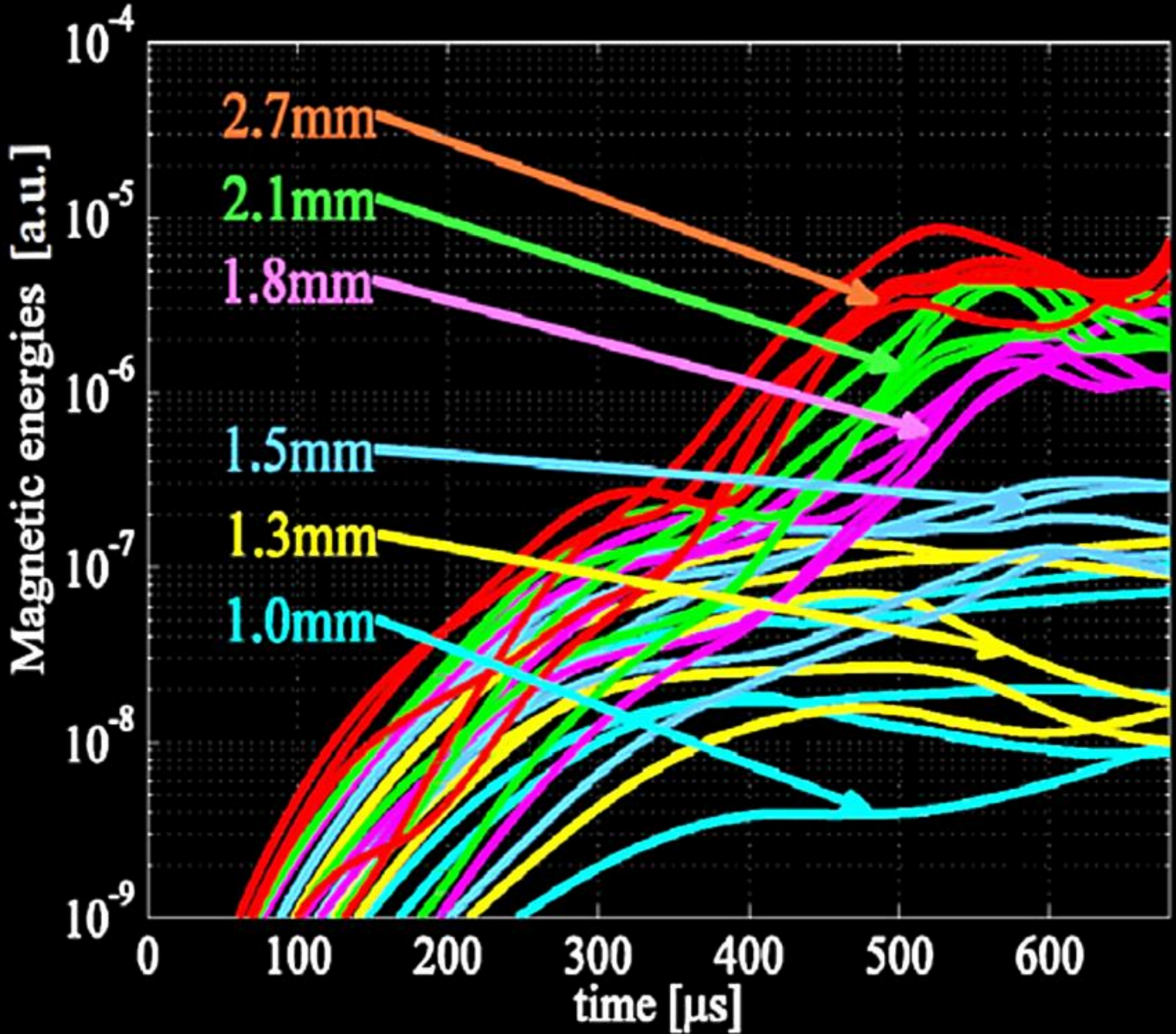
- Stabilizing: Reduced pressure gradients and current densities
- Destabilizing: Reduced plasma flows, large local gradients

ELM pacing by pellets

- Backup method forseen in ITER
- Allows to reduce ELM size [P Lang et al, NF 44, 665 (2004)]
- ELM destabilized by 3D pressure perturbation:
  - Adiabatic ablation in pellet cloud
  - Density increases, temperature drops
  - Local re-heating by parallel transport faster than density spreading [S Futatani, G Huysmans, et al, NF 54, 073008 (2014)]



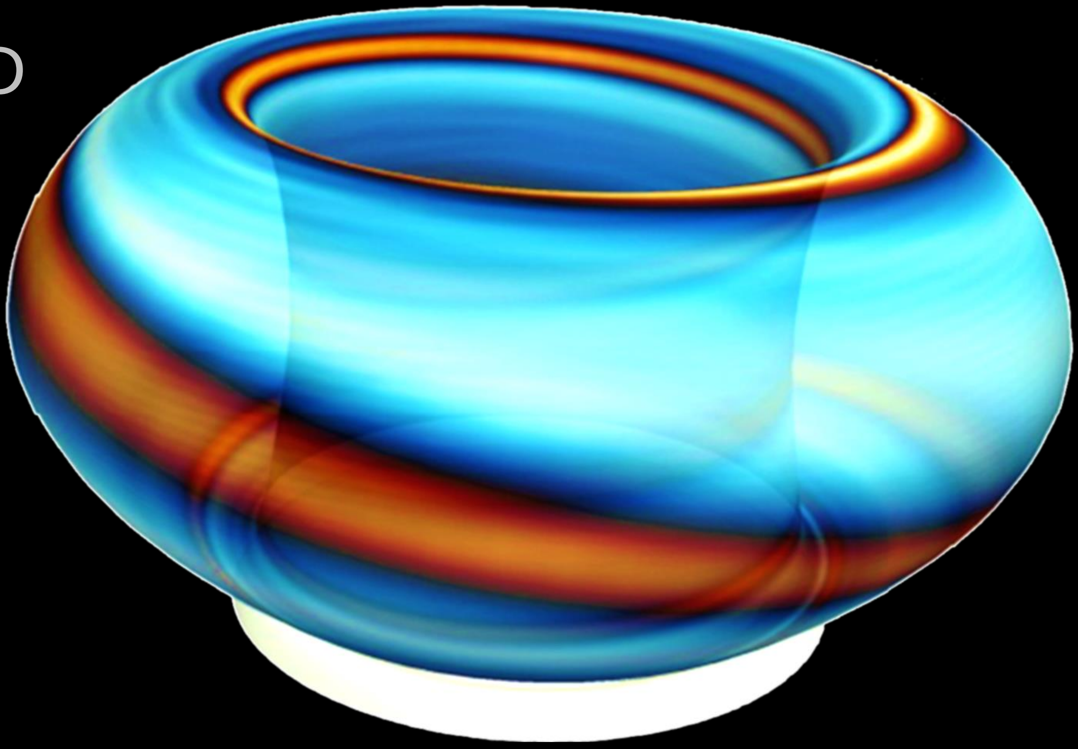
ELM pacing by pellets



[S Futatani, G Huysmans, et al, NF 54, 073008 (2014)]

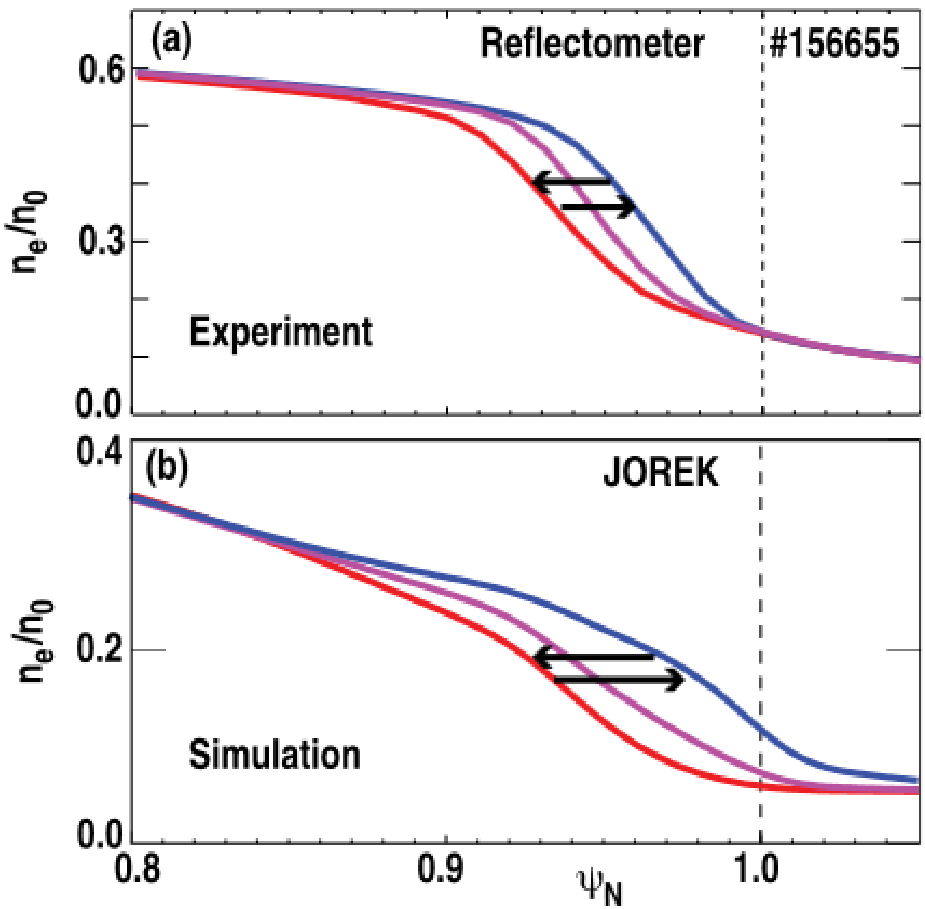
Quiescent H-Mode

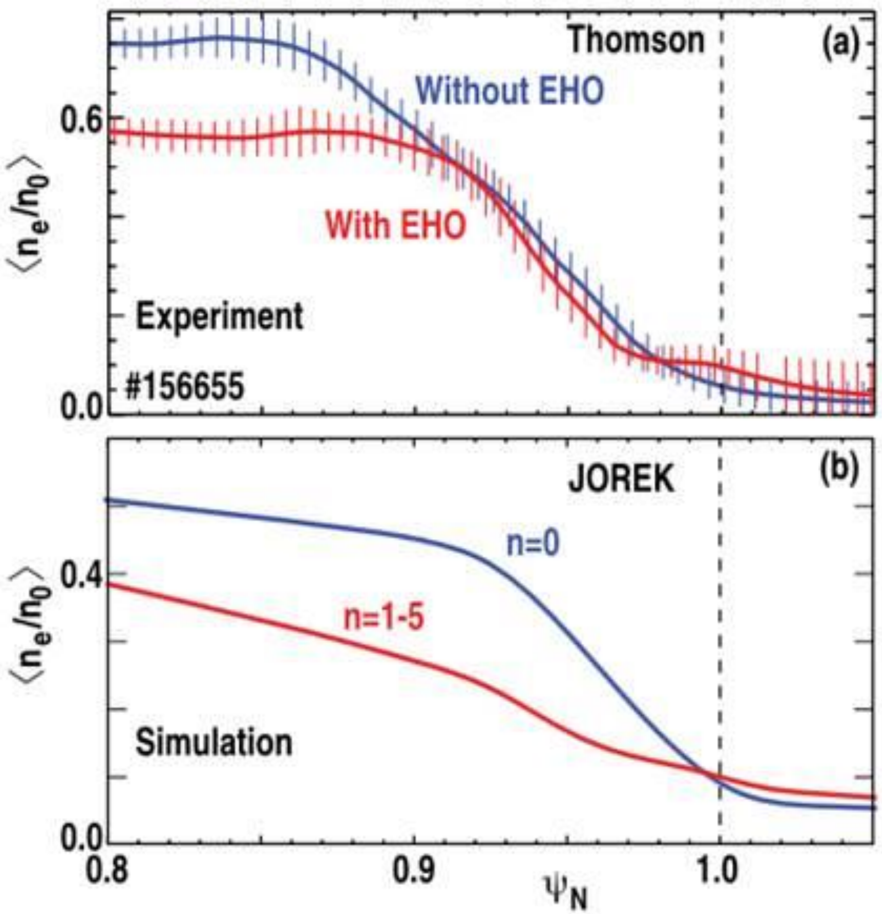
- First observed at DIII-D
  [CM Greenfield et al, PRL 86, 4544 (2001)]
- Key to access:
  Plasma shaping,
  shear flows,
  field direction
- Not excluded for ITER



- Key features reproduced in simulations
- "Edge harmonic oscillation" of density caused by saturated rotating modes
  [F Liu et al, NF 55, 113002 (2015)]
  [F Liu et al, PPCF 60, 014039 (2018)]

QH-Mode

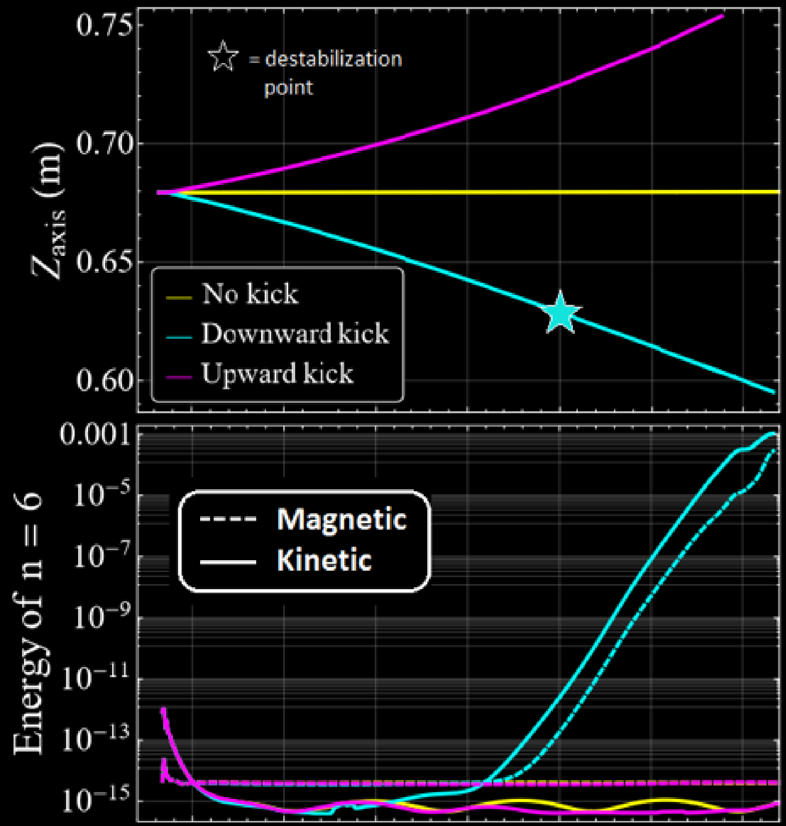


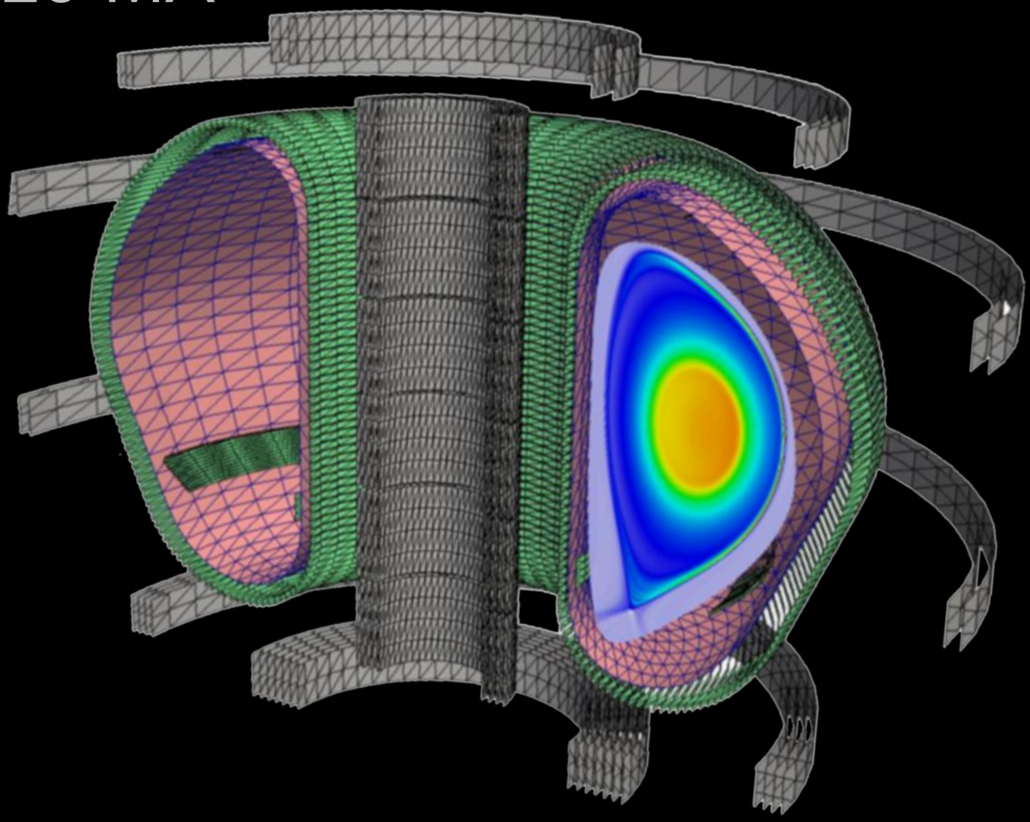


[F Liu et al]

ELM pacing by vertical kicks

- First demonstrated in TCV [AW Degeling, PPCF 45, 1637 (2003)]
- Option for ITER up to 10 MA
- Induced edge current destabilizes ELM

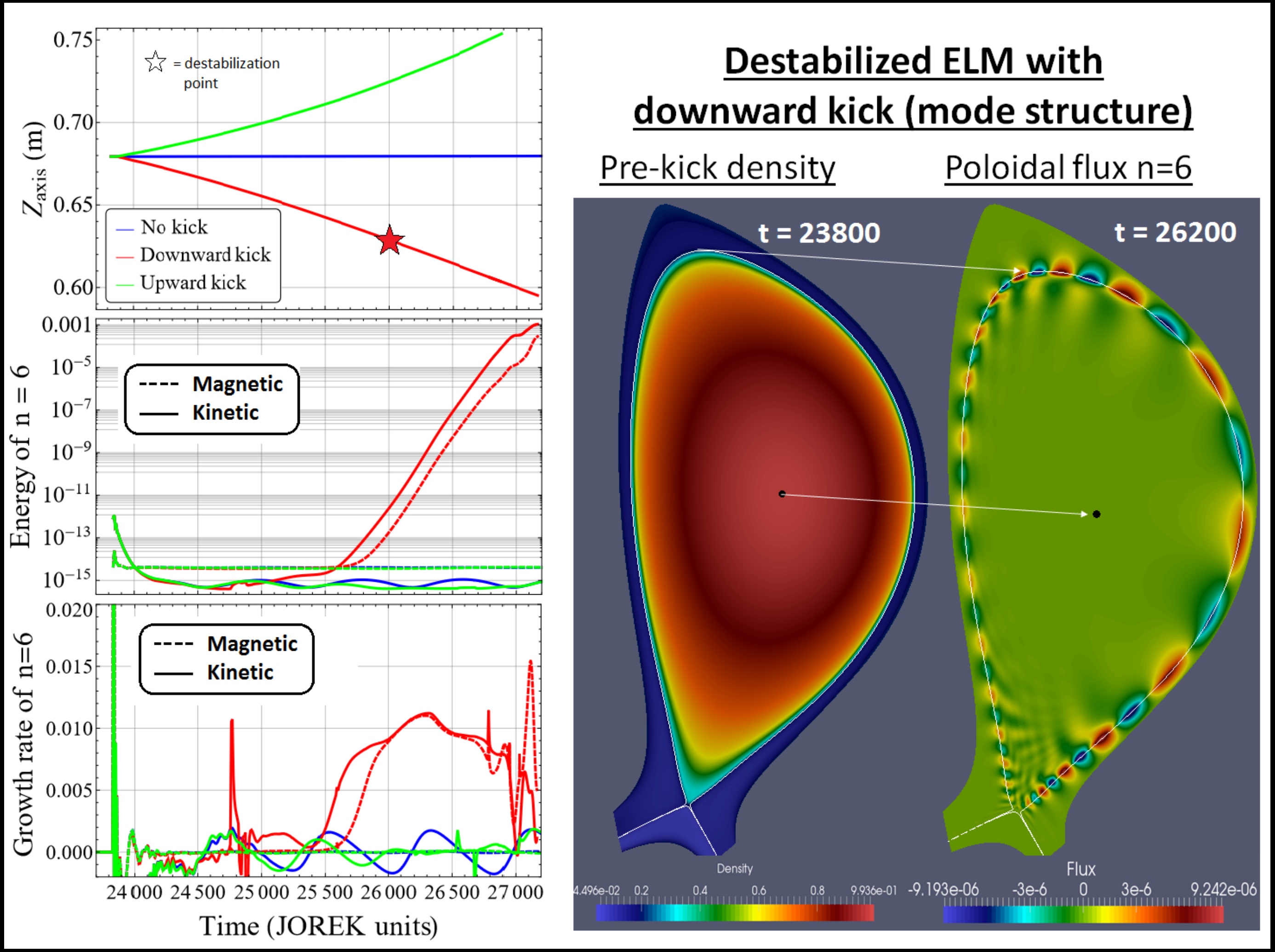




[FJ Artola, GTA Huijsmans, M. Hoelzl et al, NF (accepted)]
+ Presentation I2.109 at this conference

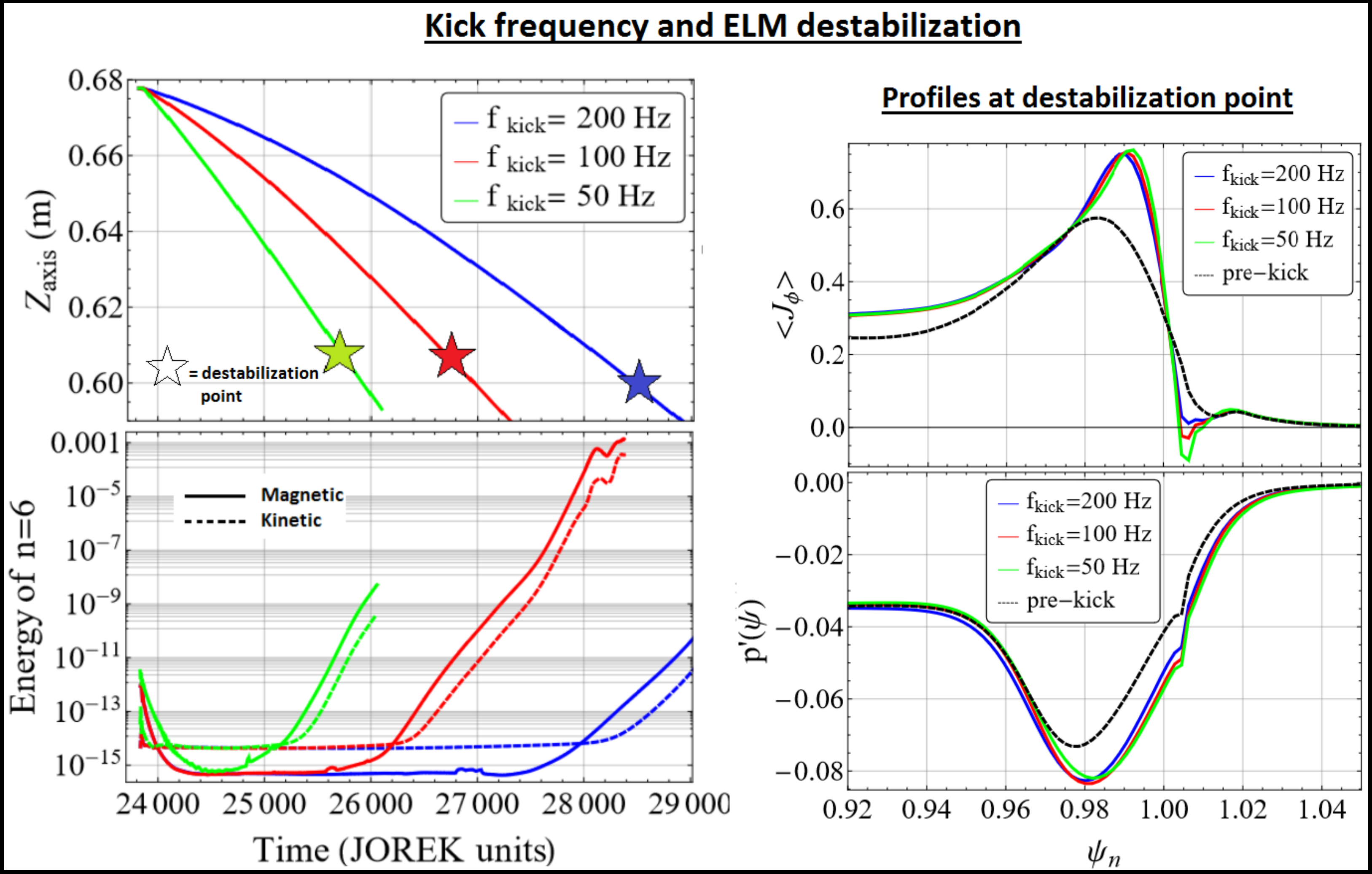
Kick ELM triggering

[FJ Artola et al]



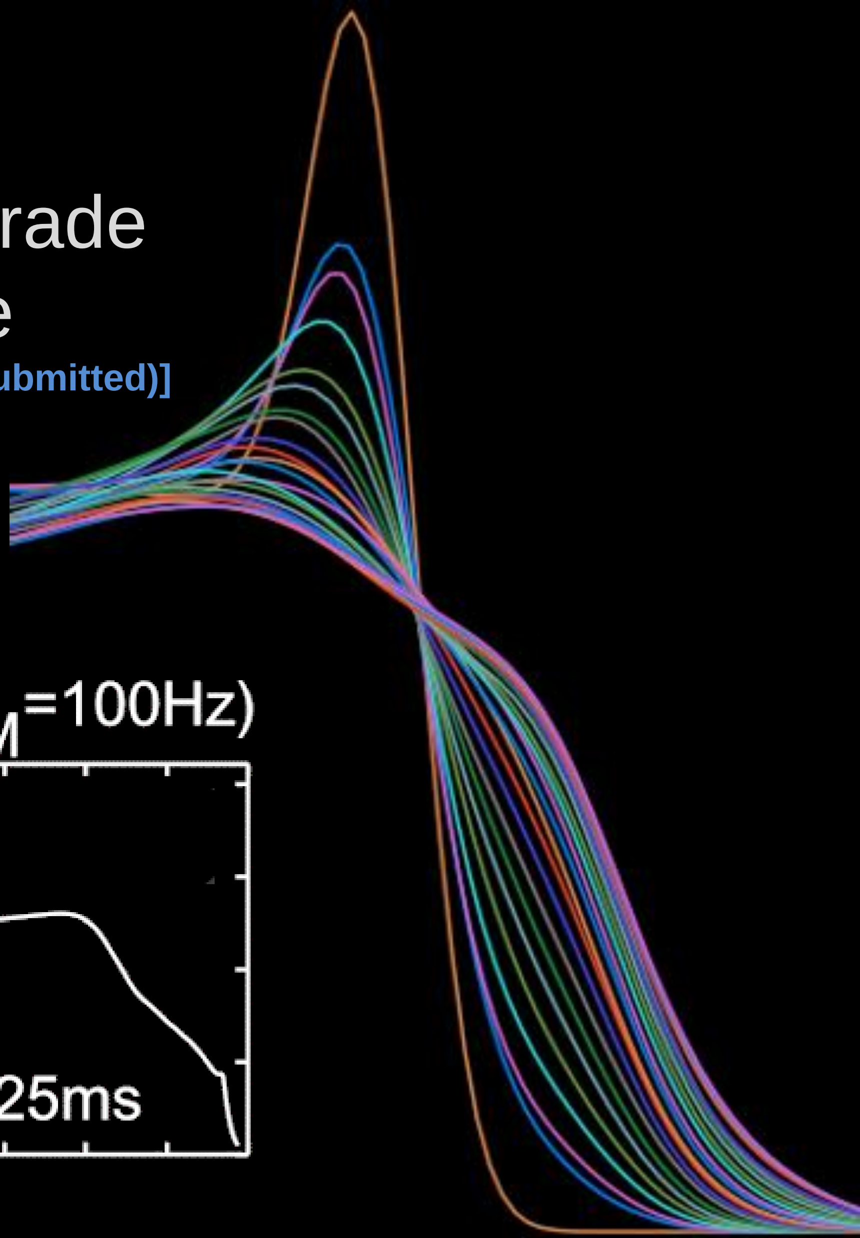
Kick ELM triggering

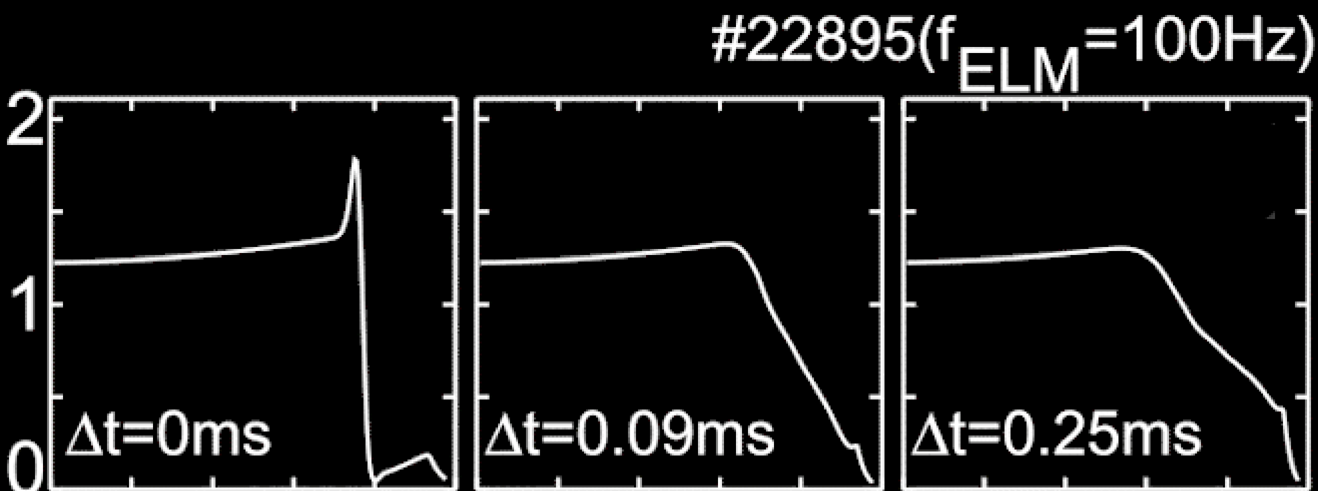
[FJ Artola et al]



Tungsten transport

- Simulation of the Tungsten transport in an ASDEX Upgrade ELM case: ExB interchange
  [DC van Vugt, GTA Huysmans, M Hoelzl et al, NF (submitted)]
  + Poster P1.1049 at this conference





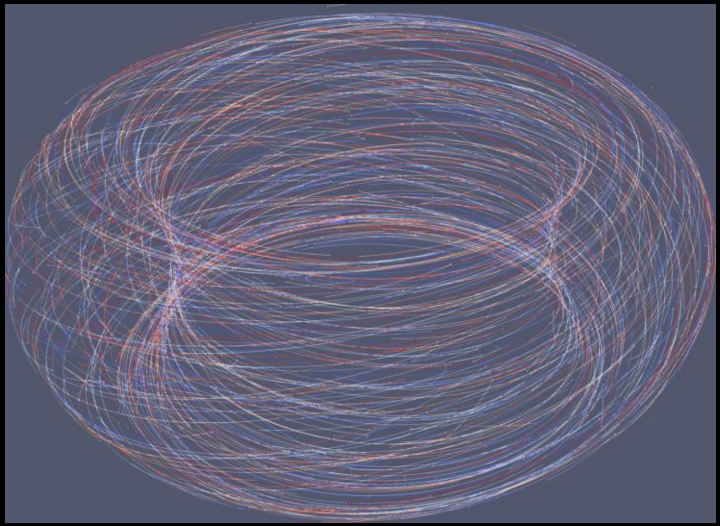
[R Dux et al, NF 51, 053002 (2011)]

EUROfusion

JOREK kinetic particle extension

[D van Vugt et al]

- Couple JOREK MHD solver with particle tracking code
- Follow particles in time-varying electromagnetic fields
  - 6D Full-Kinetic (Boris method)
  - 5D Fieldline tracer (Adams-Bashforth, forward Euler)
- Ionisation/recombination with OPEN-ADAS coefficients
- Particle-background collisions with binary collision model
- Feed-forward now, feedback to MHD underway



Applications:

- W impurity transport (in ELMs)
- W radiation impact on MHD
- Fast ions, impact on MHD (A. Dvornova)
- Runaway electrons (C. Sommariva)

- Delta-f contribution in MHD equations
- Divertor physics

Tungsten transport

[D van Vugt et al]