Non-linear MHD simulations for ITER

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Non-linear MHD modelling of ELMs and their interaction with RMPs in rotating plasmas

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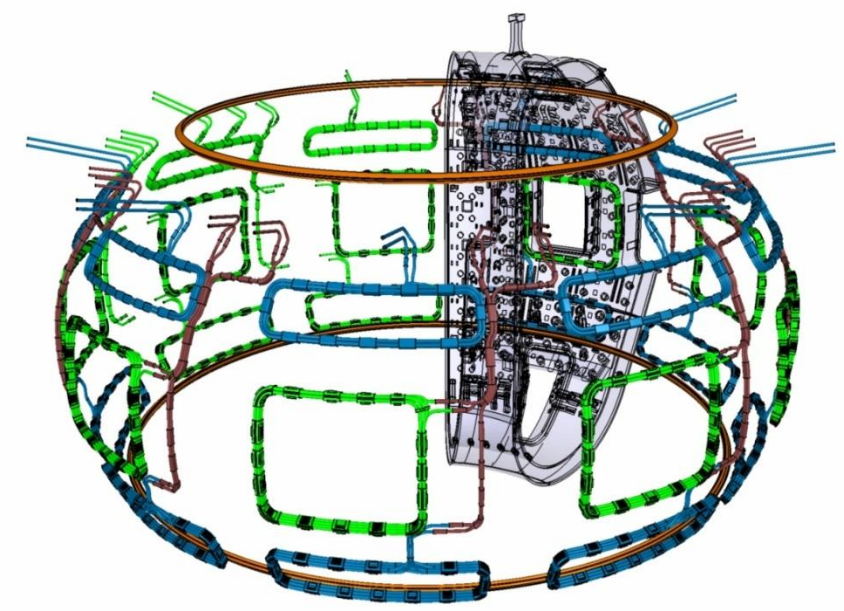
ELM Control in ITER


ITER ELM coils

- Natural ELMs in ITER
  - Exp. collisionality scaling: $\Delta W=20$ MJ
  - Mitigation to 0.7MJ required
- ITER ELM control methods
  - **Magnetic perturbation coils (RMP)**
  - **Pellet injection**
- Alternatives?
  - Vertical kicks (Y. Gribov, PPC/P3-21)
  - **QH-mode**
- Physics basis for ITER
  - Prediction natural ELM size requires simulations of multiple ELM cycles
  - Physics of RMP ELM mitigation
  - Minimum pellet size for ELM trigger, pellet triggered ELM size
  - Conditions for QH-mode in ITER

Outline

- Introduction
  - ITER ELM control
- Non-linear MHD code JOREK
  - MHD model, flows
- ELMs, multiple cycles
  - Diamagnetic flow

TH/6-1Rb
Becoulet et al.

- ELM control:
  - RMPs, ELM mitigation
  - Pellet pacing in JET
  - QH-mode in DIII-D

TH/6-1Ra
Huijsmans et al.

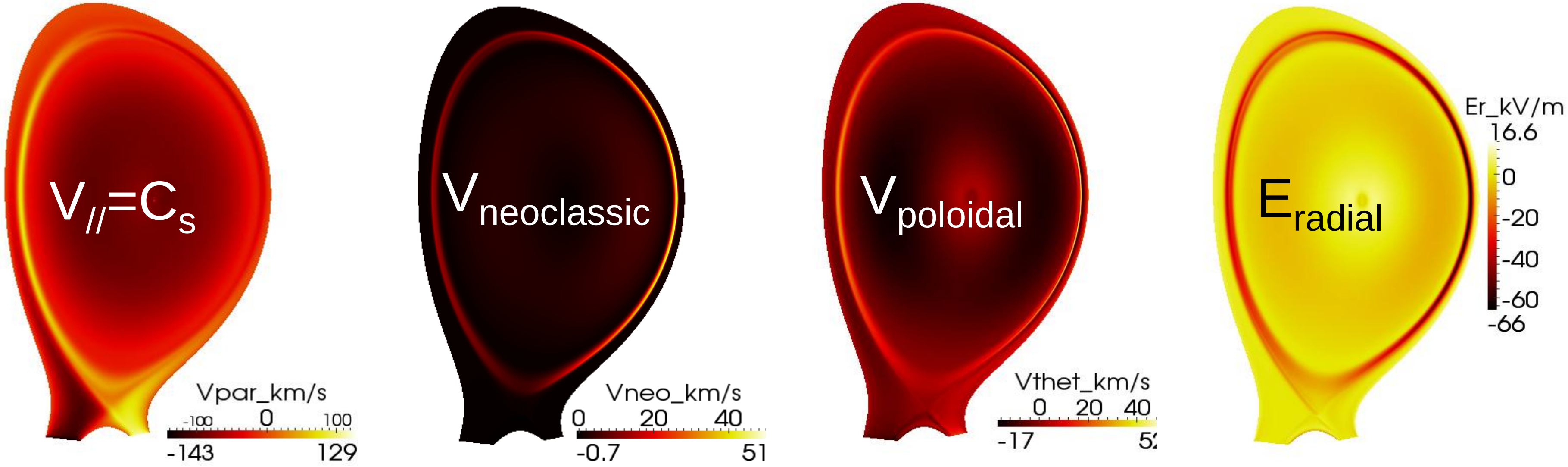
- Narrow Scrape-off Layer MHD Stability in ITER
- Conclusions

Non-Linear MHD code JOREK

- 3D toroidal geometry (reduced) MHD code
  - full domain, open-closed field lines, resistive wall, vacuum, PF coils
  - developed within (mostly) European collaboration
- including flows: ion and electron diamagnetic flows, source of toroidal rotation, neoclassical poloidal viscosity
  - divertor sheath boundary conditions

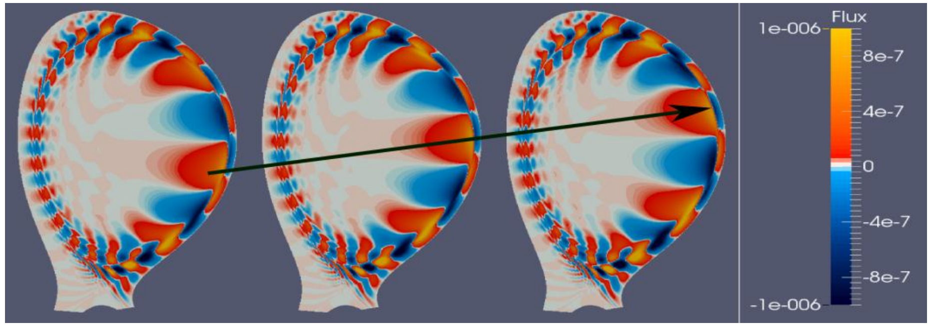
Stationary equilibrium flows

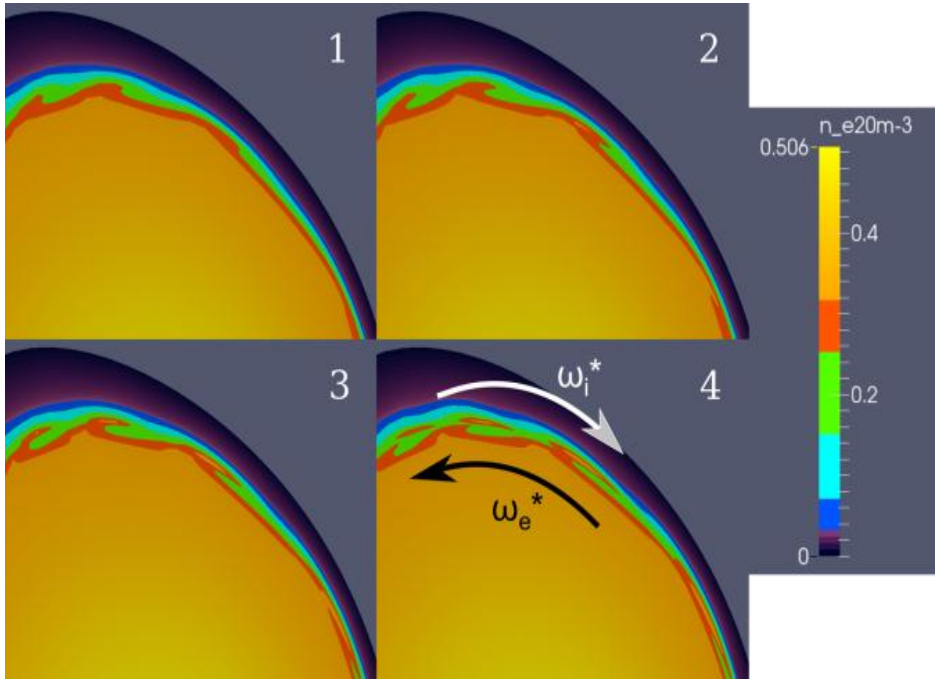
JET #77329



ELM Simulation: Mode Rotation

- Observations in MAST, AUG, KSTAR: ELM precursor rotating poloidally mainly in the electron diamagnetic (=ExB) direction
- ELM simulations with consistent poloidal, diamagnetic and parallel flows show linear ballooning mode (~precursor) moving in electron diamagnetic direction (~0.5ω_e*, in the lab frame, Vpol~20-40 km/s)
  - mode rotation in ion diamagnetic direction in plasma frame (~0.5ω_i*)



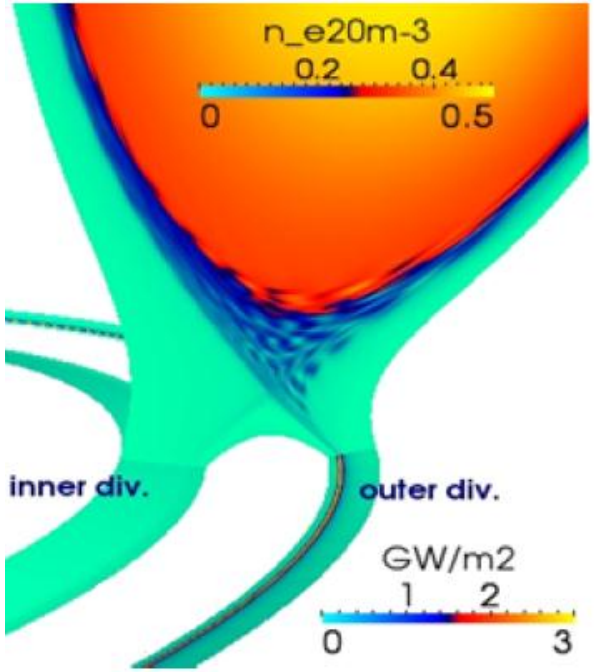


- In the **non-linear phase**:
  - Reduction of flows
  - Filaments are sheared off in the opposite (ion) direction due to non-linear driven n=0 poloidal flow

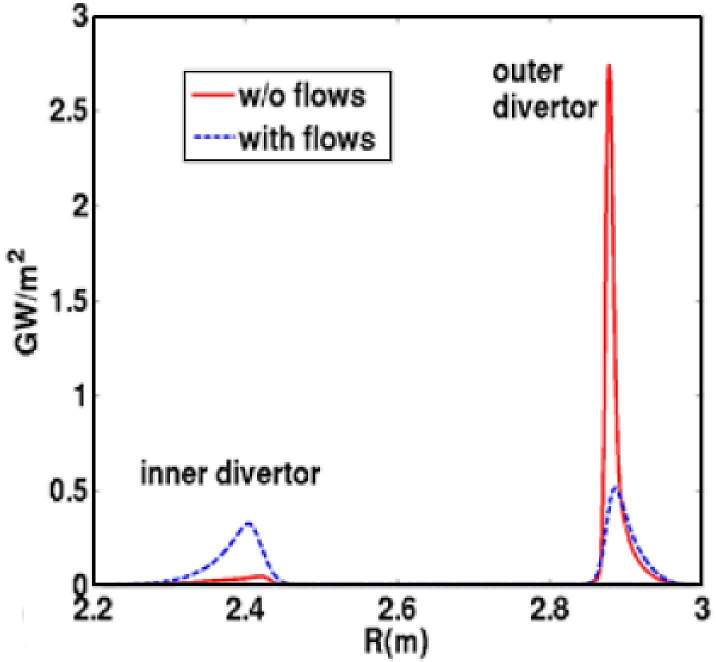
ELM Simulations with Diamagnetic Flows

- Experimentally, ELM energy losses are predominantly (2:1) towards the inner divertor
- Previously, ELM MHD simulations (not including diamagnetic flow) yielded larger heat load asymmetry towards the outer divertor
- Including diamagnetic flows leads to a **symmetric distribution (1:1)** of ELM divertor heat loads

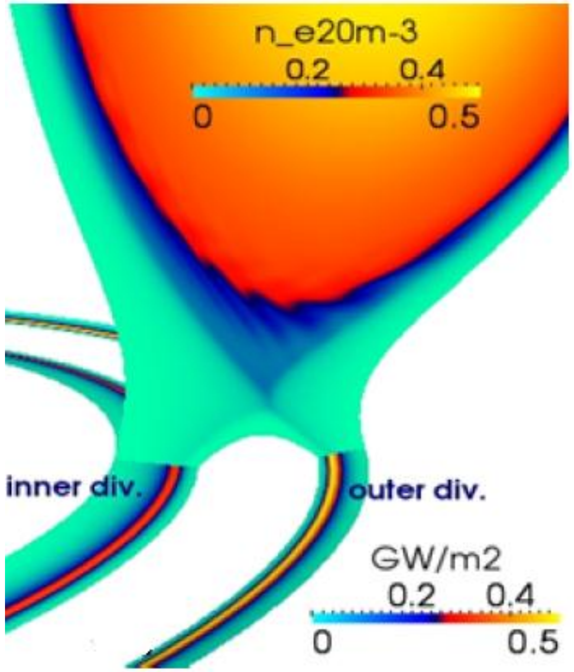
ω^*=0 (no diamagnetic flows)



Divertor Power

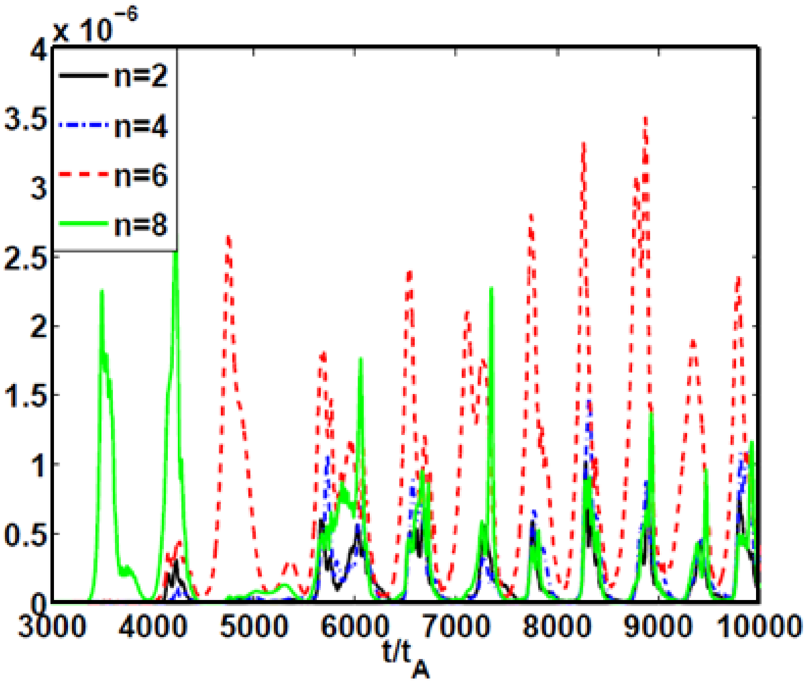


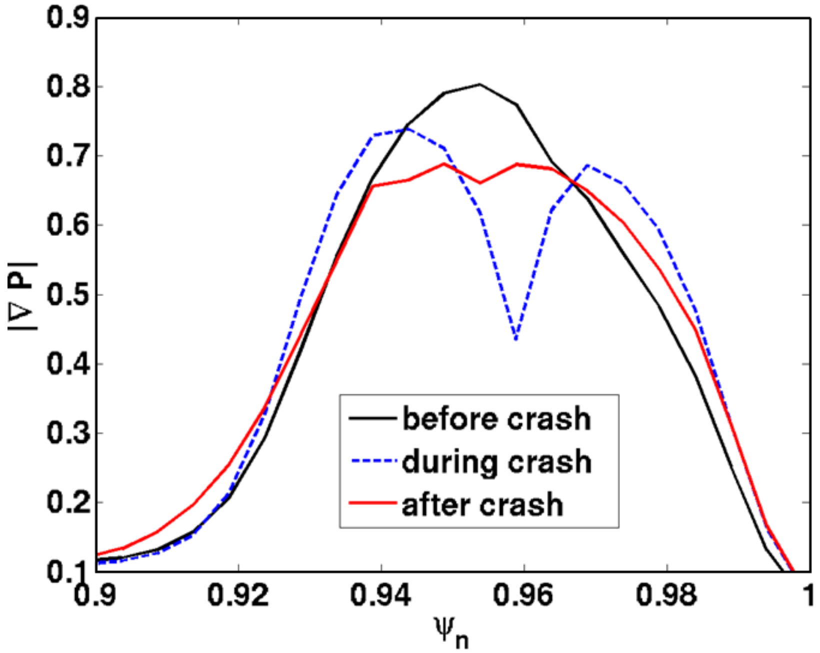
including ω^*, V_{neo}, V_{tor}



MHD Simulation of Multiple ELM Cycles

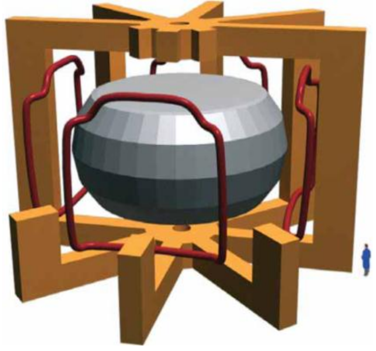
- Without diamagnetic flow:
  - residual MHD after ELM crash prevents pedestal rebuild **=> single ELM**
  - ELM size depends on initial conditions (no reliable ELM size predictions)
- Including diamagnetic flows: **regular ELMy regime**
  - Stabilisation of residual MHD by diamagnetic flows allows pedestal rebuild
  - Small high frequency ELMs (~500-2000 Hz)



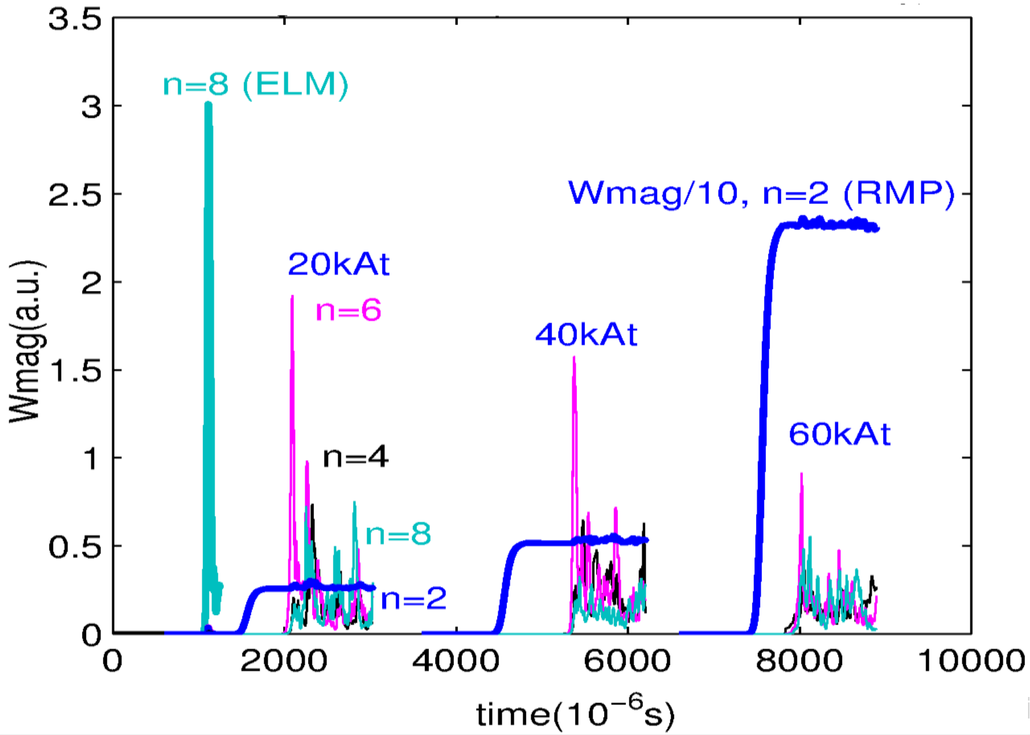


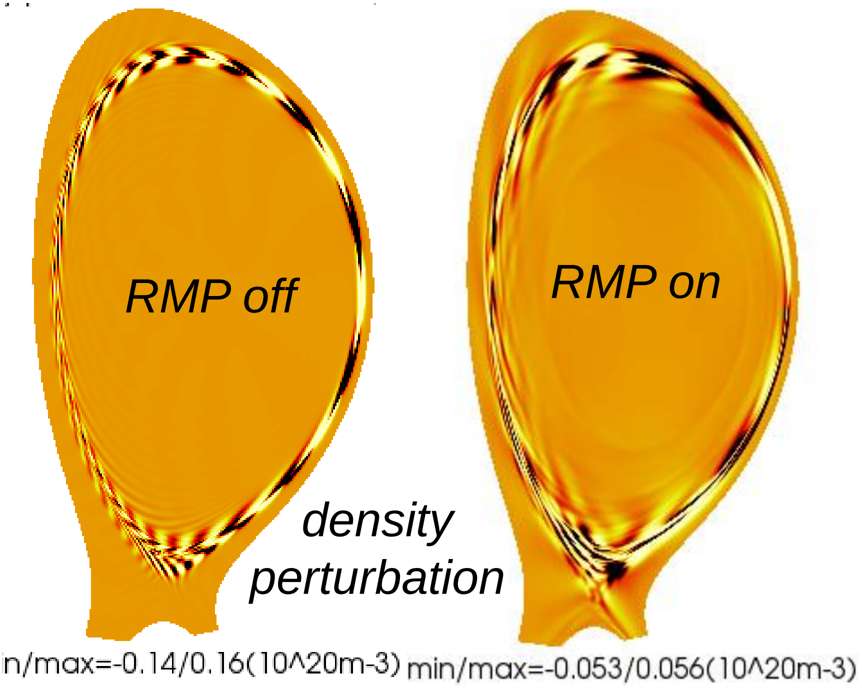
RMP ELM Mitigation

- JET #77329, Error Field Correction Coils (EFCC), n=2
- Large discrete ELMs are replaced by small bursty events-continuous MHD
  - Due to non-linear coupling of toroidal harmonics by low-n RMP
  - Threshold in RMP coil current
- Divertor peak heat flux reduced up to factor ~10



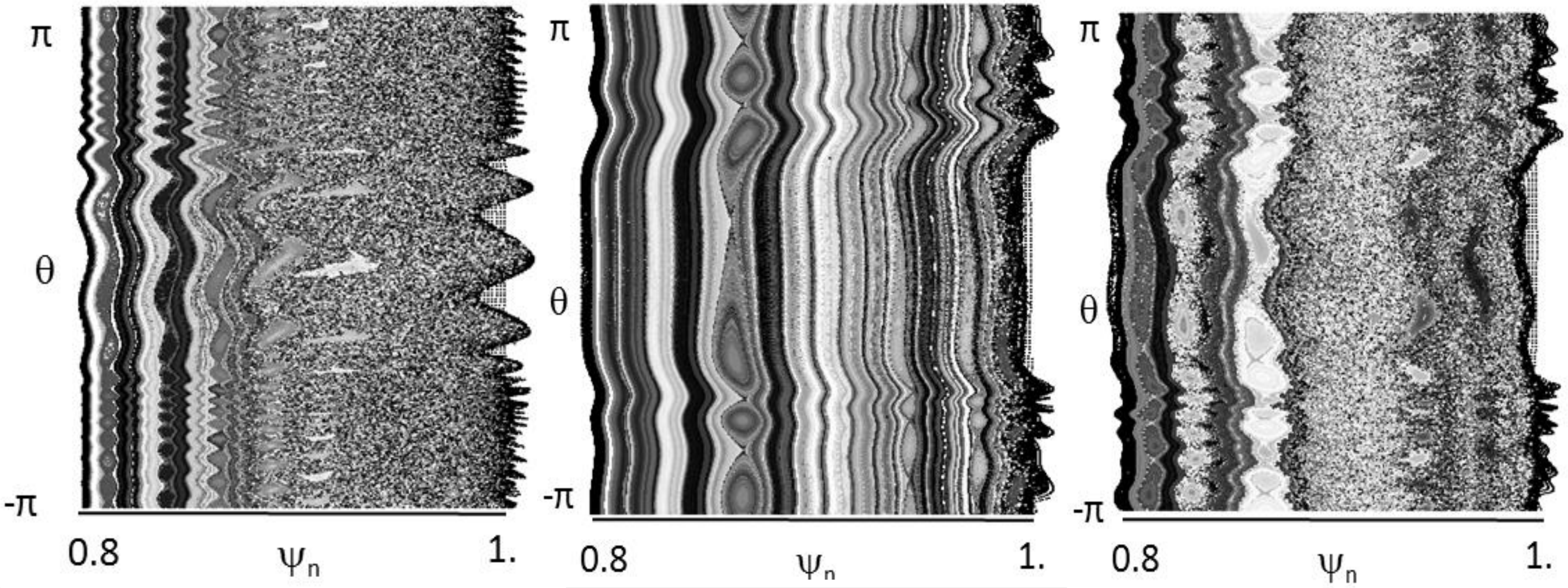
[Becoulet, PRL2014]





ELM Mitigation by RMPs

- Ballooning mode structure of natural ELM changes to modes with tearing parity
  - Island chains form at q = $m/n = 9/4$, $14/6$ and $15/6$
  - Modes non-linearly driven through coupling with n=2 RMP fields


no RMP, n=0-8

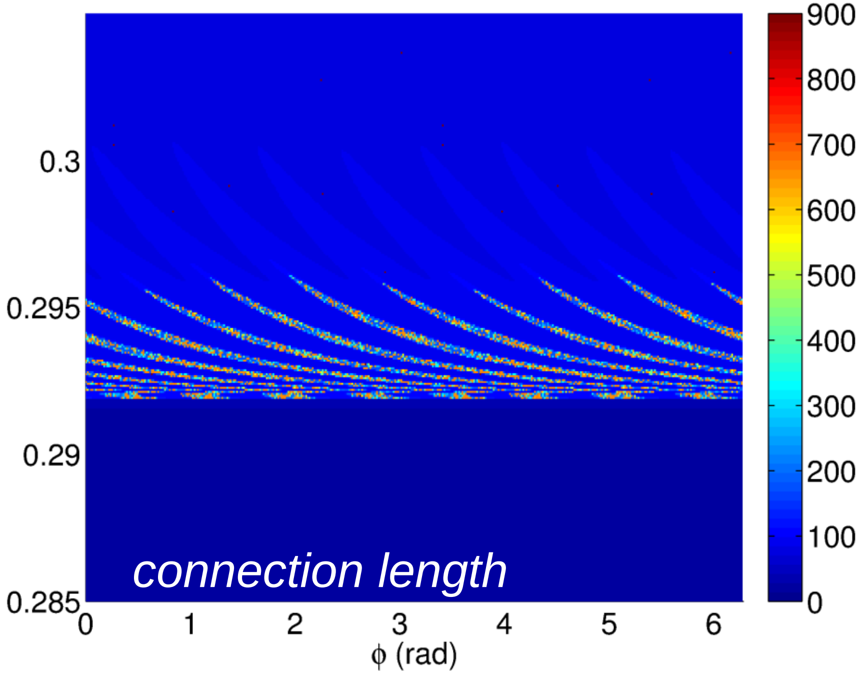
n=2 RMP

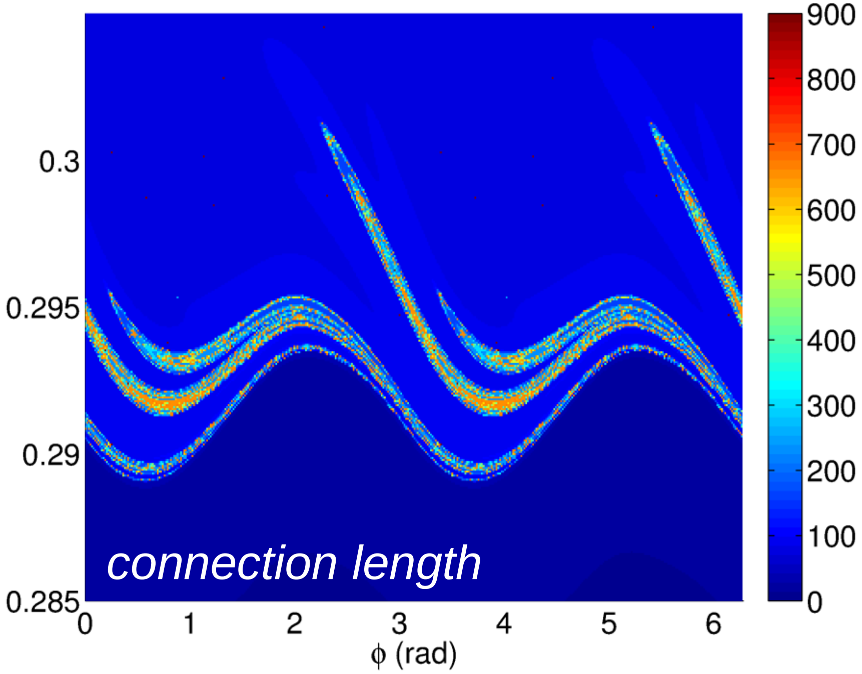
n=2 RMP, n=0-8

RMP Mitigated ELM Divertor Foot Prints

[Cahyna, TH/P6-1]

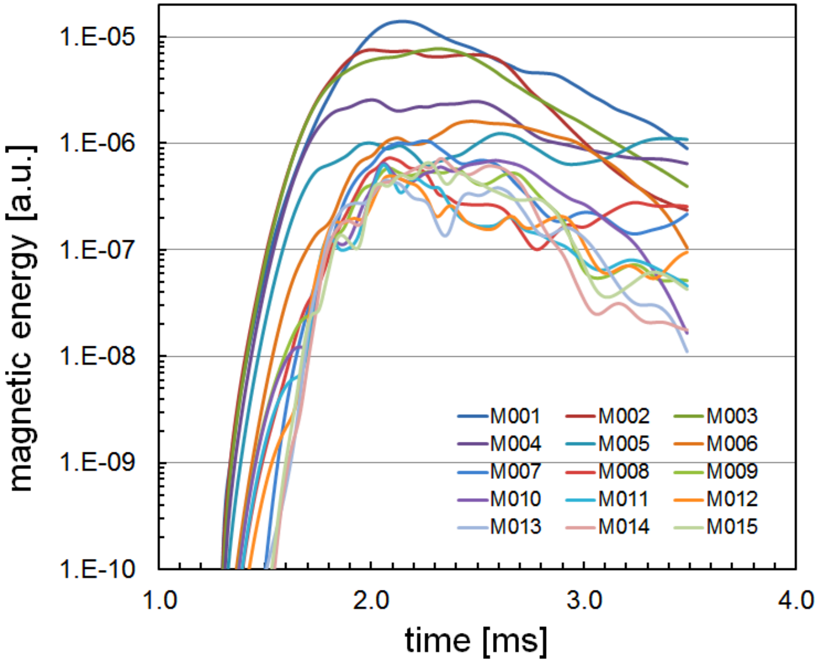
- The divertor footprints of the simulated mitigated ELMs mainly exhibit structures created by RMPs (here n=2), modulated by other toroidal harmonics of mitigated ELMs (n=4,6,8)
  - Mitigated ELM perturbation not locked to RMP

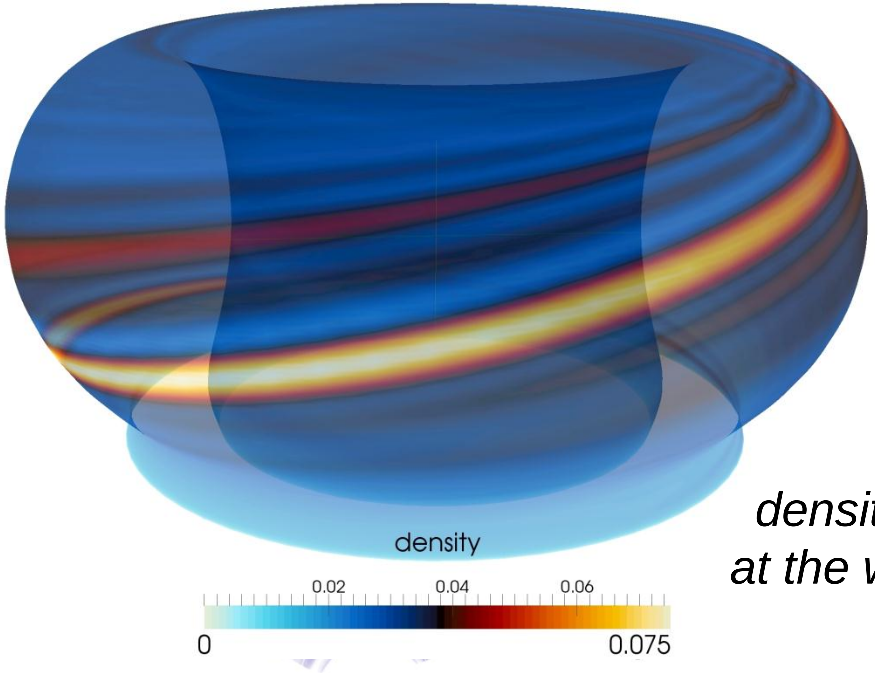

RMP off: rotating footprints with main mode structure n=8 ELM


RMP(n=2)+ELMs: n=2,4,6,8

Pellet Triggered ELMs in JET

- Previous: pellet triggered ELM simulations in DIII-D
  - ELMs (ballooning modes) are triggered by local 3D pressure perturbation created by the pellet
    - Density perturbation moving with sound speed, faster parallel conduction
    - Reasonable agreement on minimum pellet size required for ELM trigger
- Here: complete cycle pellet triggered ELM in JET (#82885)
  - Pellets simulated as adiabatic moving density source using NGS ablation model
    - Pellet size $3.2\text{x}10^{20}$, speed 78 m/s , LFS-mid plane, I_p = 2.0 MA, B_0 = 2.1T, W = 2.9 MJ

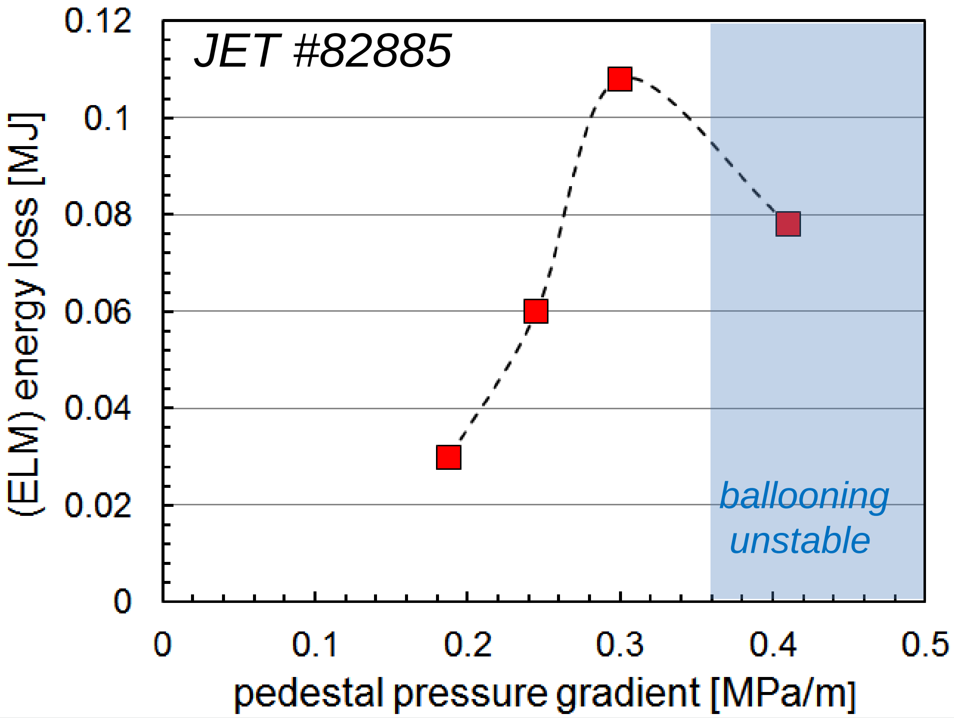




density at the wall

Pedestal Dependence Pellet Triggered ELMs Size

- “Predicted” ELM size 108kJ ($\Delta W/W=4\%$) compares to 100-250kJ in JET #82885
- Experimentally, pellet triggered ELM size increases with time since previous ELM
- Non-linear MHD simulations show strong dependence of pellet triggered ELM energy loss on pedestal pressure gradient
  - No sharp transition from stable to unstable
  - This dependence (and imposed pellet frequency) determines the maximum sustainable pedestal gradient and possible performance penalty due to pellet pacing.

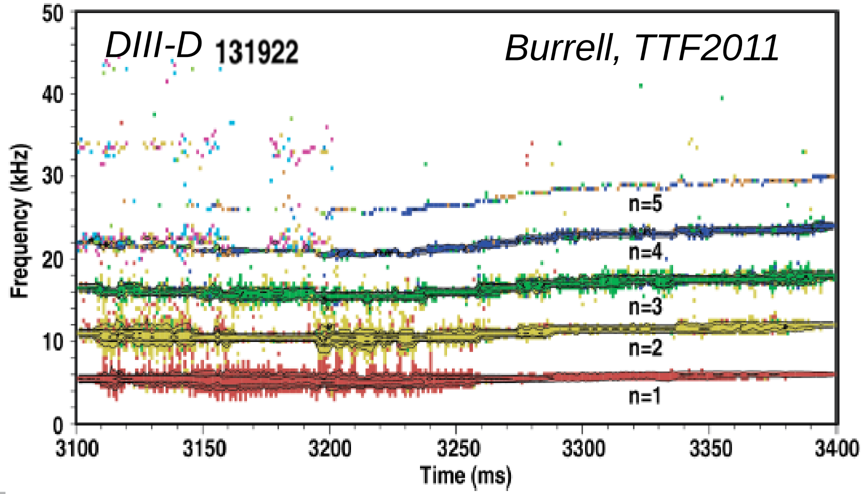


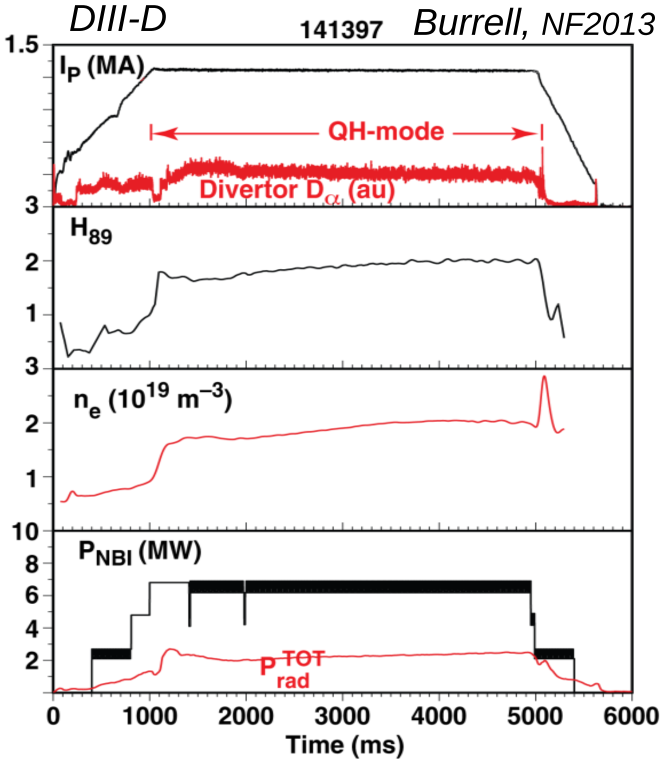
MHD Simulations of DIII-D QH-mode Plasmas

- Quiescent H-mode regime characterised by good confinement without ELMs
  - discovered in DIII-D, reproduced in AUG, JET, JT60-U
- Edge Harmonic Oscillation (EHO) induces density losses and allows a steady state H-mode
  - EHO assumed to be a saturated kink-peeling MHD mode
- DIII-D QH-modes approaching ITER-relevant conditions

Can QH-mode be an option for ITER?

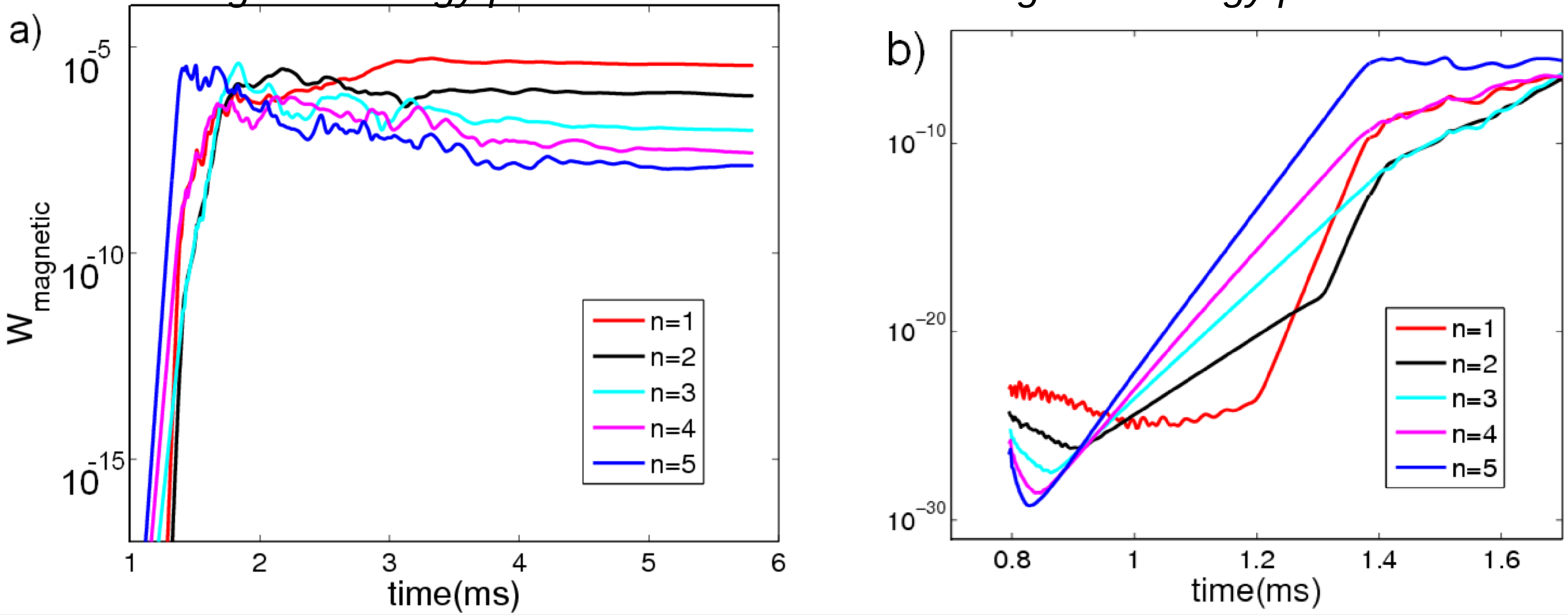
- Towards validation of non-linear MHD simulations on DIII-D QH-mode plasmas
- Extrapolation to ITER





MHD Simulation of DIII-D QH-mode #145117

- DIII-D #145117 pedestal close (below) to kink-peeling ideal MHD stability limit
- JOREK simulations (ideal wall, no rotation) show **saturated kink-peeling mode** with dominant n=1 structure (3D stationary state)
  - n=5 mode most unstable mode, n=1 strong growth due to non-linear coupling
  - Bursting behavior found in some cases at high resistivity

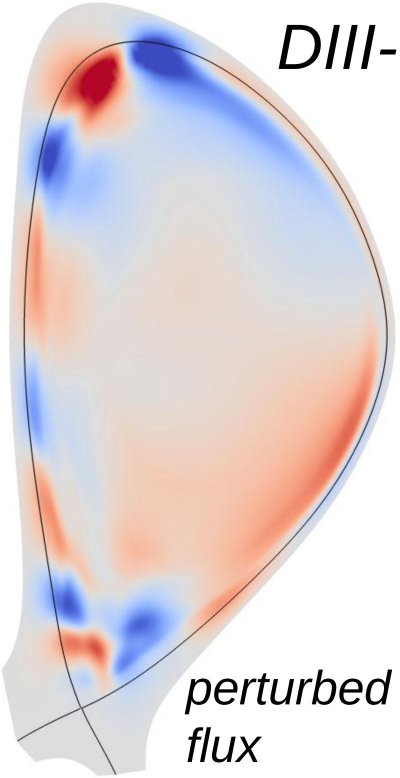

magnetic energy perturbation

magnetic energy perturbation

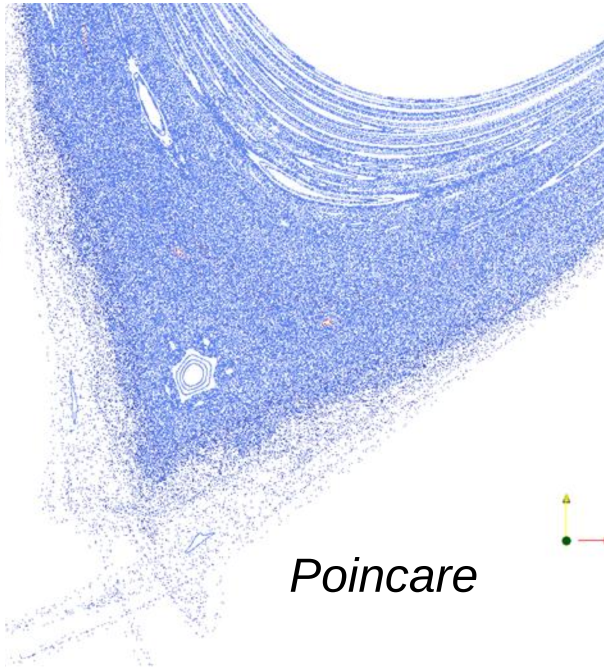
EHO: Saturated Low-n Kink-peeling Mode

- Toroidal localisation, n=1-5 toroidal harmonics in phase
  - Localised density perturbation at the separatrix
  - Consistent with EHO observations
- Ergodic region (~5cm width in mid-plane)
  - Contributes to mode saturation?

DIII-D #145117

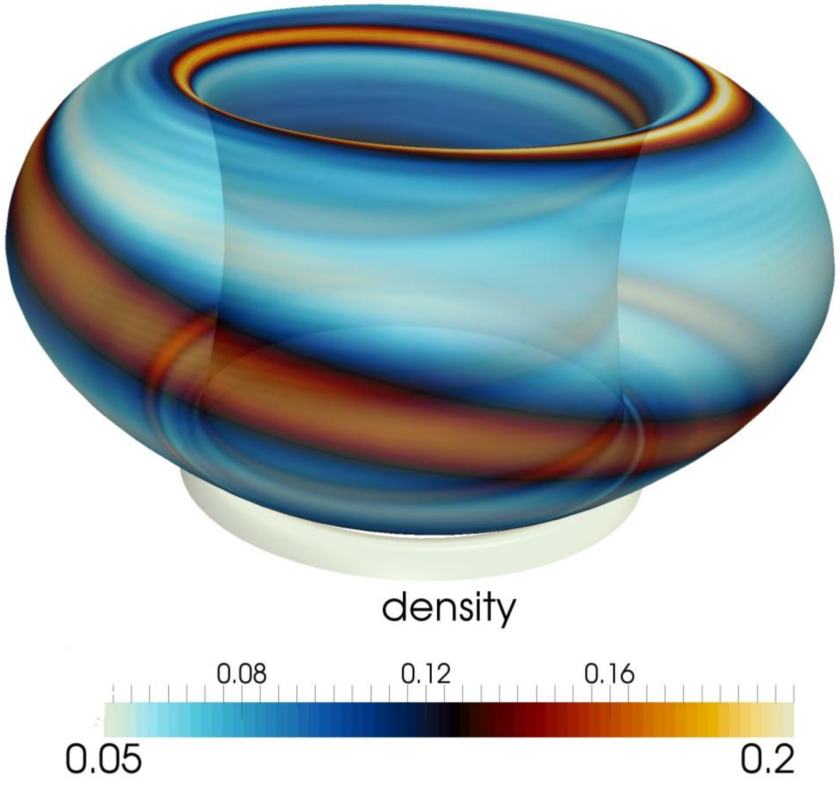


perturbed flux



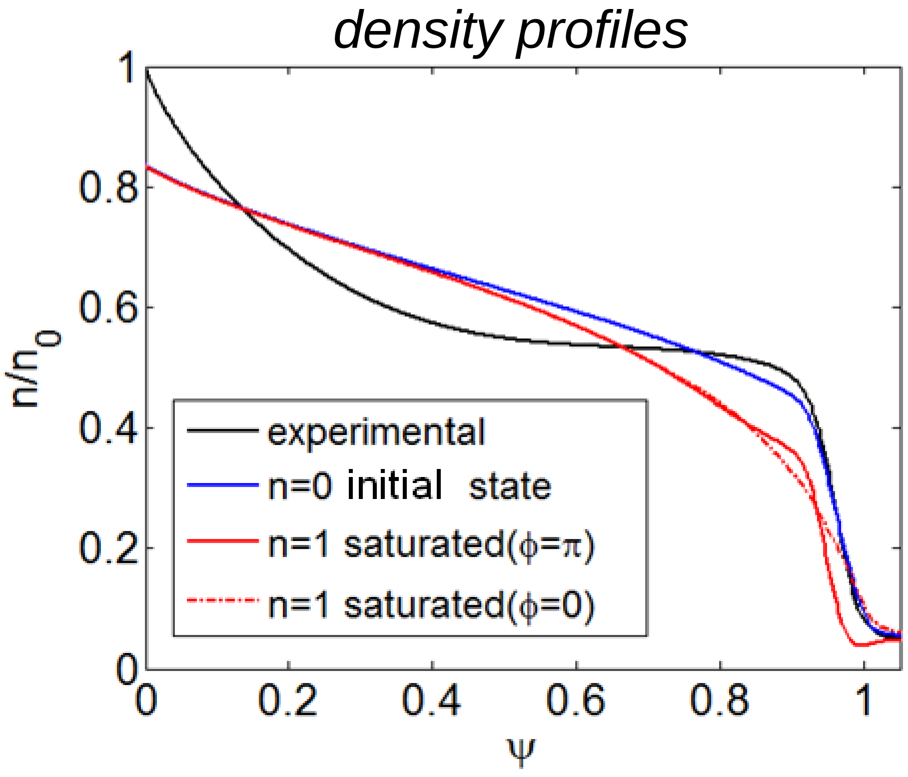
Poincare

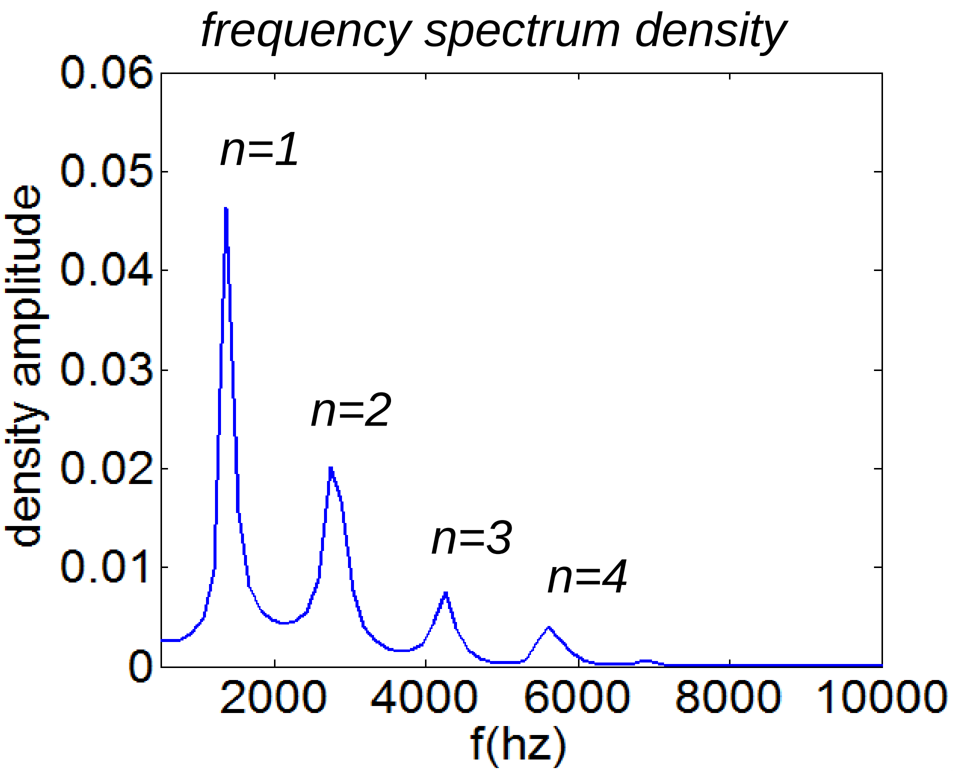
density at separatrix



QH-mode Density Perturbation

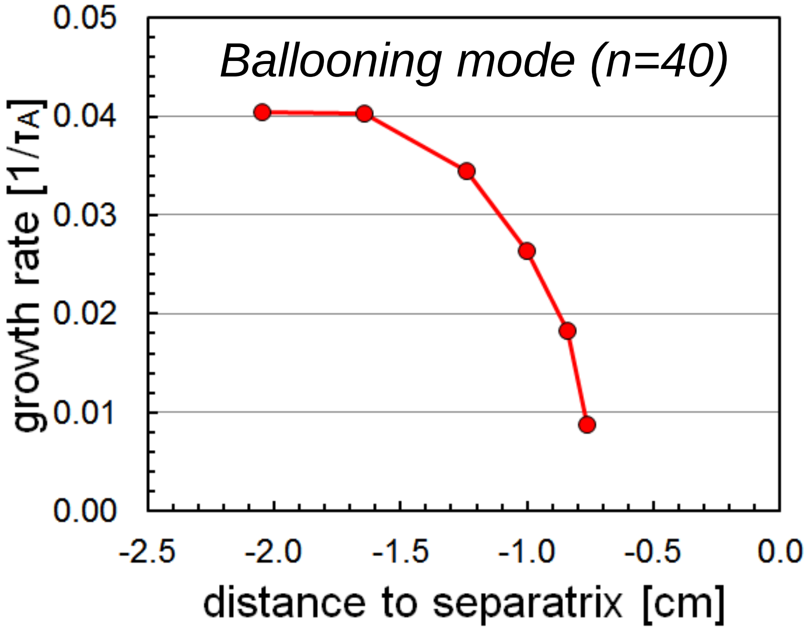
- ExB flows from external kink/peeling mode leading to a significant outflow of density
  - Reduction of pedestal density by ~25%
  - Provides density/energy loss channel necessary for stationary ELM free H-mode

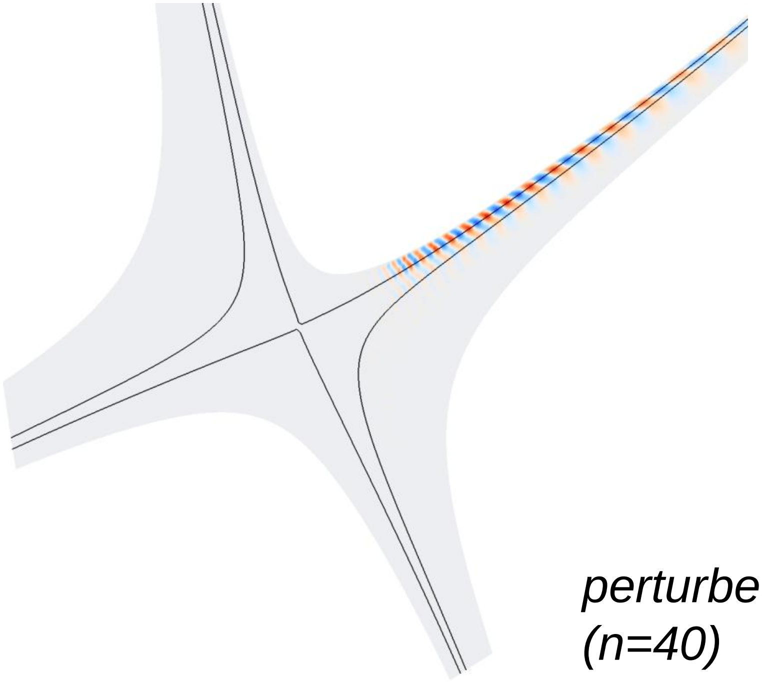




MHD Stability of Narrow SOL in ITER

- Scaling laws for the SOL width (in low-recycling regime) predict narrow SOL widths in ITER attached divertor conditions
  - Is there an MHD limit to the narrow SOL widths in ITER?
- MHD stability analysis shows ITER plasmas with a narrow 1.2mm SOL are MHD stable
  - Pressure gradient is below infinite-n ballooning limit at separatrix
  - Integrated pedestal/SOL MHD stability using JOREK code finds no local SOL MHD limit (n<50)





perturbed flux (n=40)

Conclusions

- Nonlinear MHD simulations of ELMs
  - Regular ELMy regime (diamagnetic effects)
  - ELM precursor rotates in electron diamagnetic direction, filaments mostly in opposite direction
- RMP ELM mitigation
  - non-linearly driven by RMP modes with “tearing” like structure, providing reconnections with open field lines before large ELMs have time to develop
- Pellet triggered ELMs
  - reasonable agreement on ELM amplitude
  - pellet triggered ELM amplitude depends on phase in ELM cycle
- QH-mode
  - Simulation of DIII-D QH-mode plasmas show low-n saturated kink-peeling mode, with EHO-like features (density loss, toroidal localisation)
- SOL Stability
  - No MHD stability limit found for SOL widths down to 1.2mm in ITER
  - MHD not likely to limit ITER SOL width

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