Non-Linear MHD Simulation with JOREK on HELIOS-CSC

S. Pamela
G.Huijsmans, M.Hoelzl, M.Becoulet, F.Orain, F.Liu,
A.Fil, E.Nardon, J.Morales, A.Lessig, I.Krebs ...

HELIOS-CSC Review Meeting, 15 March 2016

Outline

- **Presentation of the JOREK code**
  - www.jorek.eu
  - The JOREK team
  - Eurofusion ENR project
  - Numerical details
  - The reduced-MHD model
  - Running JOREK on HELIOS-CSC

- **Physics Results 2015**
  - ELMs
  - RMP
  - Pellets
  - QH-mode
  - MGI disruptions

- **Conclusion**
  - Summary
  - Future work

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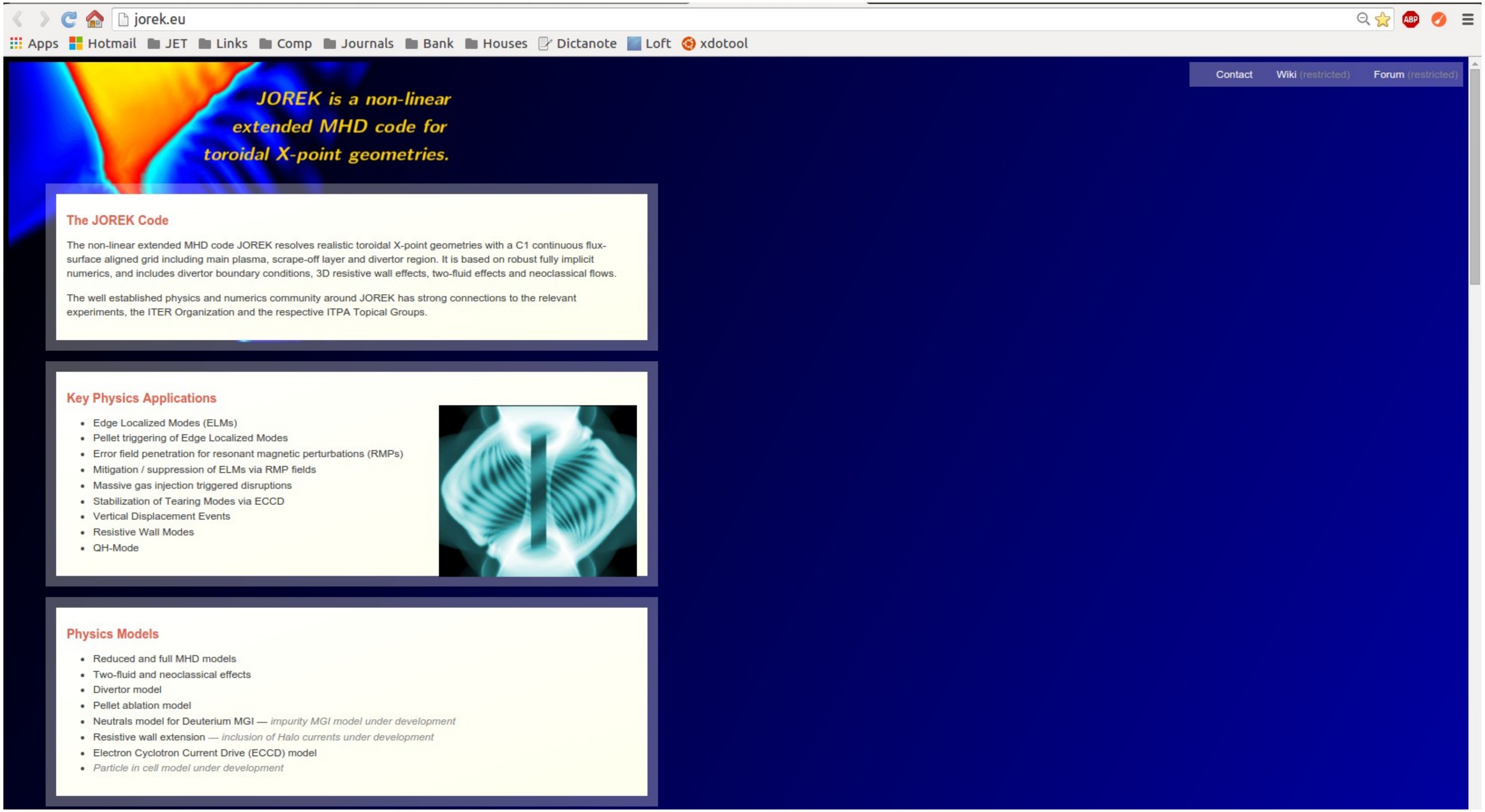
Summary
Future work

www.jorek.eu

JOREK website, including

- References
- Team members
- wiki (restricted)
- Forum (restricted)



The JOREK Team

> 30 members
> 10 international institutions
Includes physicists and mathematicians
Strong collaboration with PaStiX team (direct solver) [ref]

The Present JOREK Team (alphabetical)

- Calin Atanasiu
- Marina Bécoulet
- Pavel Cahyna (website)
- Celine Caldini-Queiros (website)
- Jose Costa
- Guilhem Dif-Pradalier
- Elise Estibals
- Alexandre Fil (website)
- Emmanuel Franck (website)
- Shimpei Futatani
- Virginie Grandgirard
- Herve Guillard
- Florian Hindenlang
- Matthias Hoelzl (website)
- Guido Huijsmans (website)
- Xavier Lacoste
- Guillaume Latu (website)
- Alexander Lessig
- Feng Liu
- Jorge Morales
- Eric Nardon
- Boniface Nkonga
- Francois Orain
- Stanislas Pamela
- Chantal Passeron
- Jane Pratt (website)
- Ahmed Ratnani (website)
- Afeintou Sangam
- Cristian Sommariva
- Eric Sonnendrücker (website)
- Erika Strumberger
- Daan van Vugt
- Egbert Westerhof

Eurofusion ENR Project

PI: M.Hoelzl
over 10 *ppy* ~ 450 *k€* / year
Progress is on schedule

2. Project deliverables

Deliverables planned for 2015	Achieved?	Evidence // Reason for partial or non-achievement
Status report after one year	Fully	at hand
First JOREK simulation of non-deuterium massive gas injection (MGI)	Partly	Model has been derived but implementation was delayed by ~3-6 months. Reason: the following new deliverable.
Investigation of gas penetration with the IMAGINE code **(New deliverable)**	Fully	Refereed article submitted [5]; *This turned out to be important to improve and validate the JOREK MGI model*
First JOREK simulation of a complete thermal quench **(Originally planned for 6/2016)**	Fully	Presentations [23,24]; Publication in preparation
First JOREK simulation of an ELM cycle with a realistic boostrap current model	Fully	First successful non-linear simulations have been carried out; publication in preparation (will take time)
First JOREK simulation of an ELM crash with high recycling divertor conditions	Partly	Model successfully implemented and tested; application to ELM simulations has been started
Analytical and numerical study of ELM precursors and filaments in rotating plasmas	Fully	Refereed article submitted [10]
Implementation of Newton iterations for the time stepping	Fully	Refereed article [8]
Study of stability and theoretical properties of reduced MHD with two-fluid effects	Fully	Report in preparation
Report on the implementation of new development workflows	Fully	Documented in jorek.eu wiki; updated through user's feedback

Numerical Details

Full domain with core, SOL and X-point :

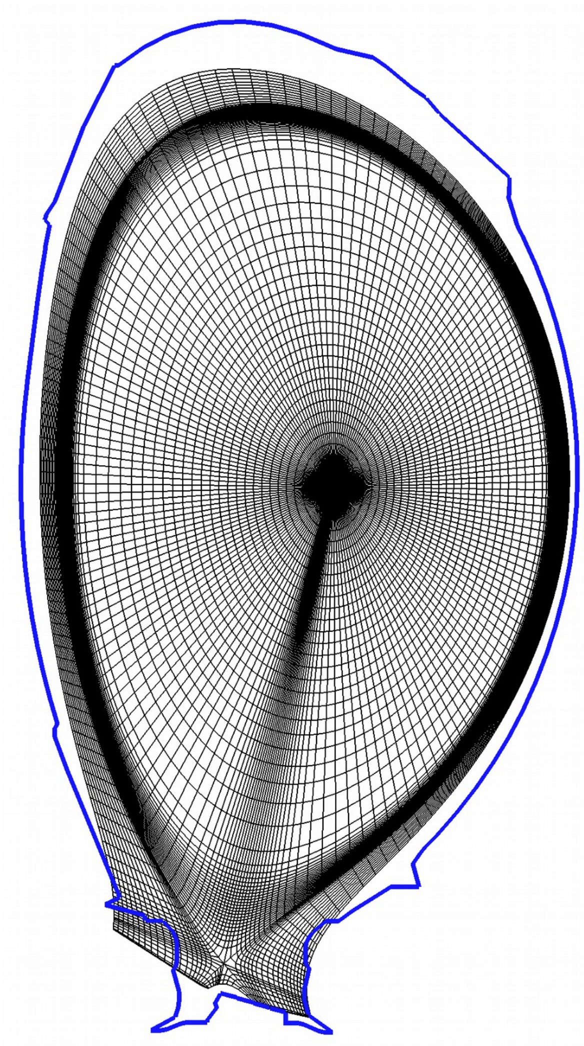
- **Cubic finite-elements**
- **Flux-aligned poloidal grid**
- **Fourier series in toroidal direction**

[*G.Huysmans, Nuc.Fus. 2007*]
[*O.Czarny, Journ. Comp. Phys. 2008*]

Implicit time-stepping :

- **Crank-Nicolson & Gears schemes**
- **Time step depends on MHD activity only**
- **GMRES iterative solver**
- **Physical preconditioner using sub-matrices solved With Sparse-matrix solver PastiX**

[*P.Henon, Parallel Comput. 34 (2008)*]



JET grid

Reduced MHD Model

[H. Strauss, Phys. Fluids 19 134 (1976)]

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

$$\vec{v}_{tot} = \vec{v}_\parallel + \vec{v}_\perp = \vec{v}_\parallel + \vec{v}_E + \vec{v}_{*i}$$
$$= v_\parallel \vec{B} + R\vec{e}_\phi \times \nabla\Phi + \frac{\delta^* R}{\rho}\vec{e}_\phi \times \nabla p_i,$$

perp. momentum

$$\rho\frac{\partial \vec{v}_E}{\partial t} = -\rho\vec{v}_{*i}\cdot\nabla\vec{v}_E - \nabla_\perp p + \vec{J}\times\vec{B} + \mu\nabla^2\left(\vec{v}_E + \vec{v}_{*i}\right)$$

par. momentum

$$\rho\frac{\partial \vec{v}_\parallel}{\partial t} = -\rho\vec{v}_\parallel\cdot\nabla\vec{v}_\parallel - \nabla_\parallel p + \mu\nabla^2\left(\vec{v}_\parallel - \vec{v}_{NBI}\right)$$

Ohm's law

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

Continuity

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

$$j = -R^2\nabla\phi\cdot\boldsymbol{J} = \frac{1}{\mu_0}\Delta^*\psi$$
$$p = \rho T$$

Energy

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

JOREK on HELIOS

Typical job size:	**20,000 poloidal elements** **5 harmonics** **50 nodes** **~240 hours → ~12,000 node.hours**
Large job size:	**30,000 poloidal elements** **15 harmonics** **150 nodes** **~200 hours → 30,000 node.hours**
XL job size:	**20,000 poloidal elements** **20 harmonics** **~300 nodes** **(short tests)**

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  - **RMP**
  - **Pellets**
  - **QH-mode**
  - **MGI disruptions**

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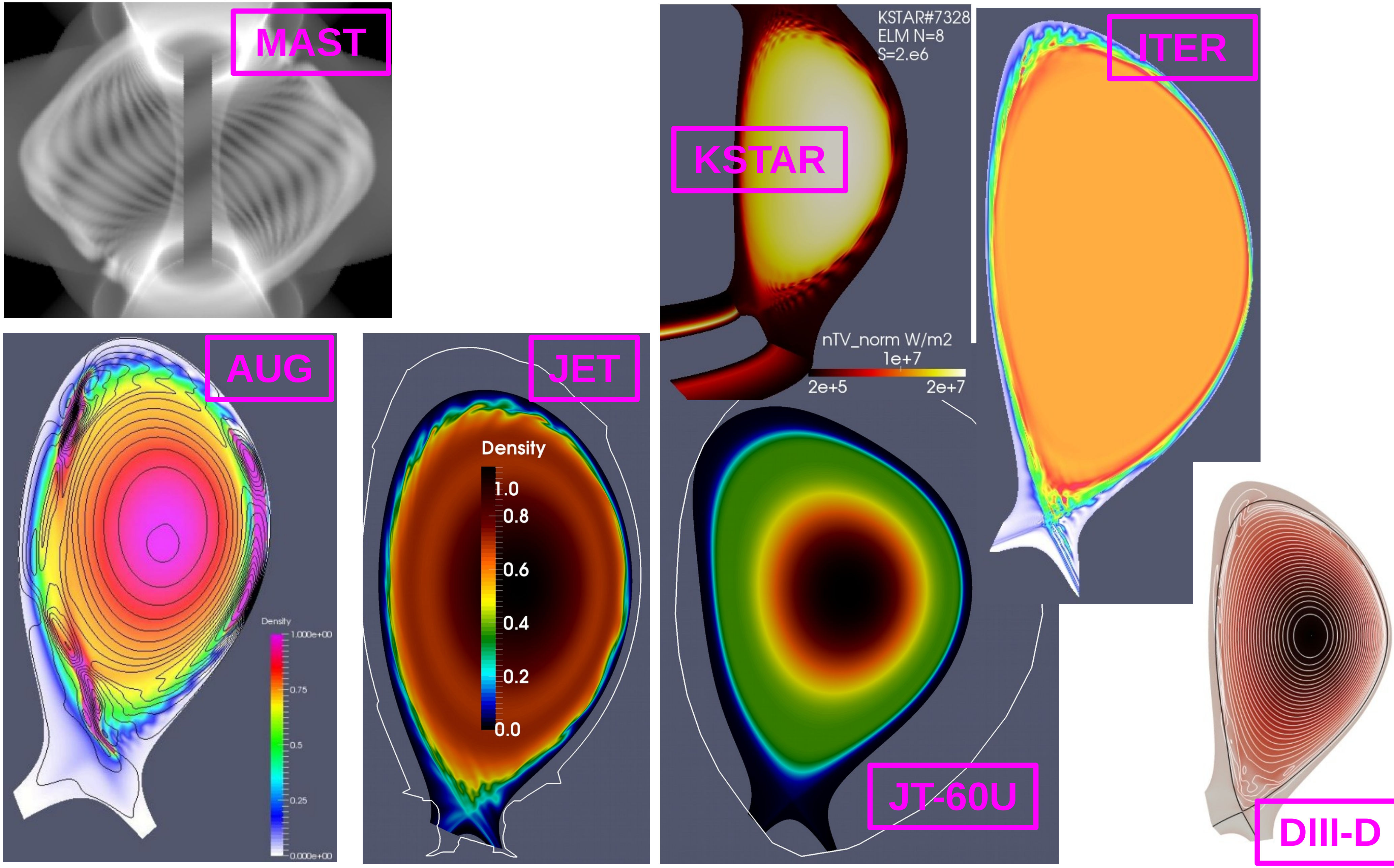
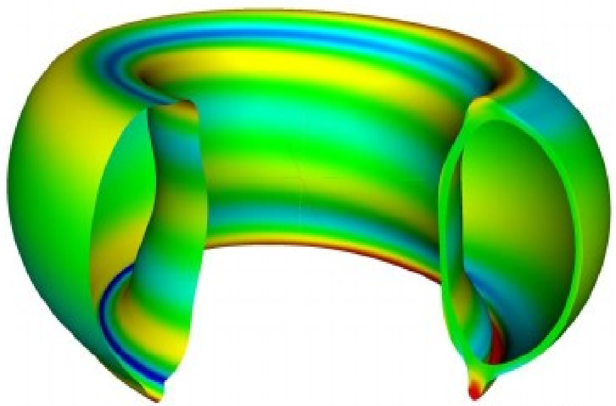
Devices Simulated



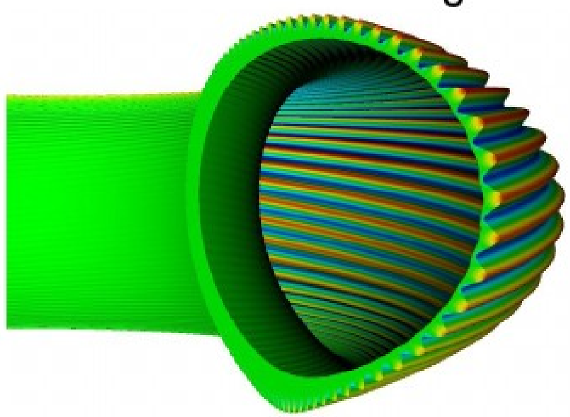
Edge-Localised-Modes

ELMs are necessary for impurity flush-out
But they also need to be controlled due to large divertor heat-fluxes
→ Strong need to understand ELMs

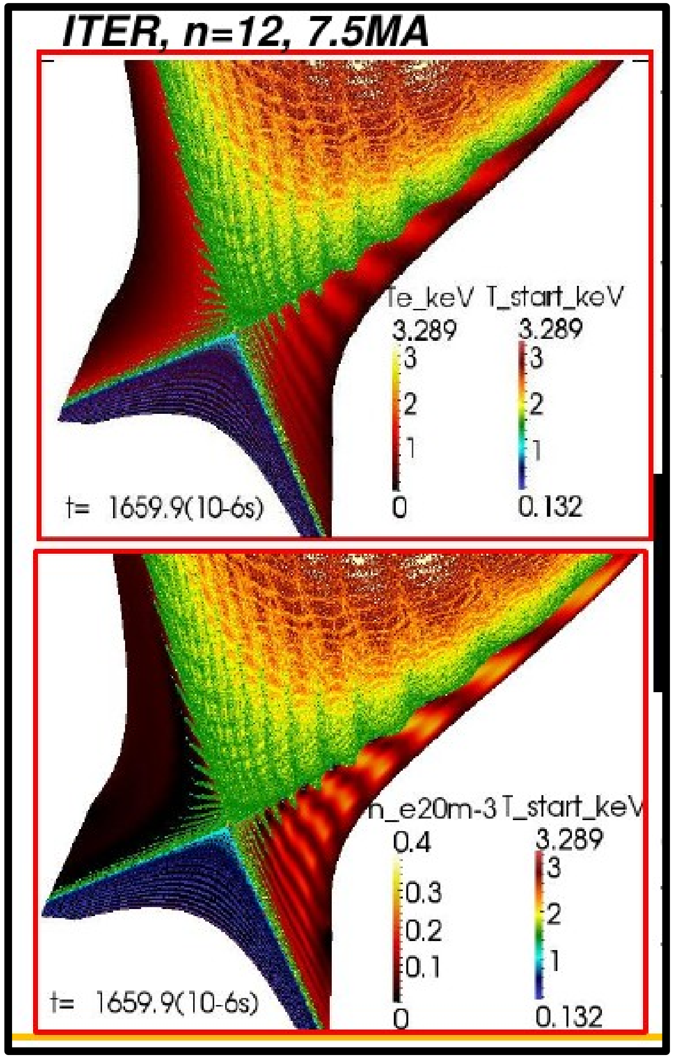
Large edge current (bootstrap): drives peeling/kink modes



Large edge pressure gradient in H-mode drives ballooning modes



[Huysmans PPCF 2005]



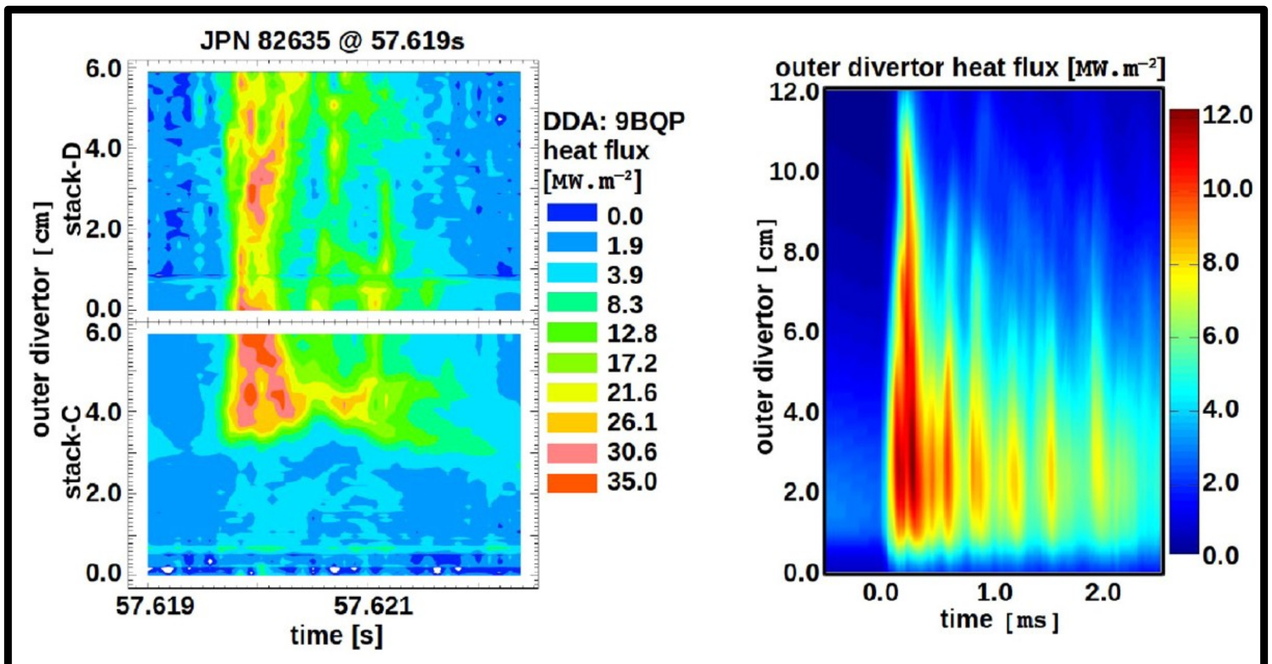
Validation: Comparison Against Experimental Data

In order to predict ELMs in future devices, simulations must be validated
→ Quantitative comparison against experimental data

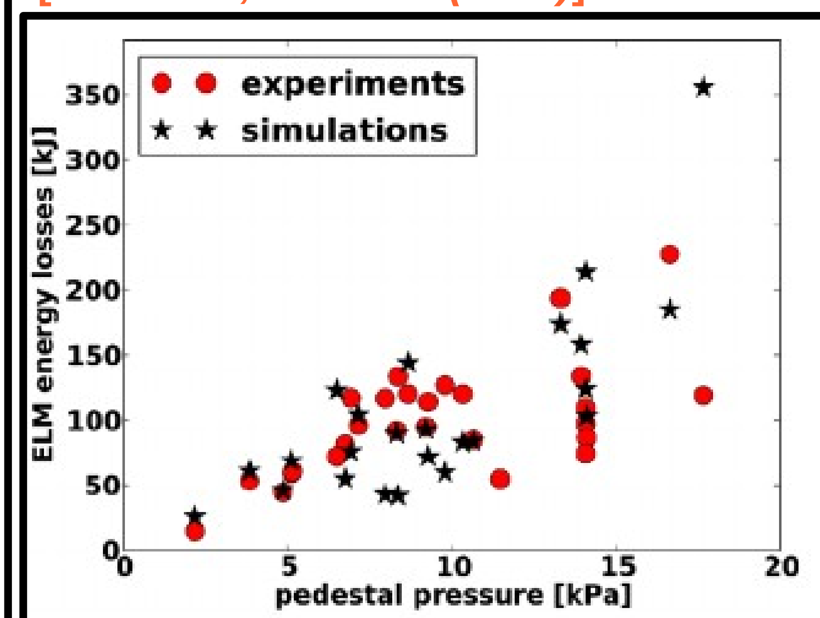
Main comparisons of interest:

- **ELM energy losses**
- **ELM duration**
- **Divertor heat-fluxes**

Quantitative validation started on JET, to be extended to multi-machines



[S.Pamela, *PPCF 58 (2015)*]

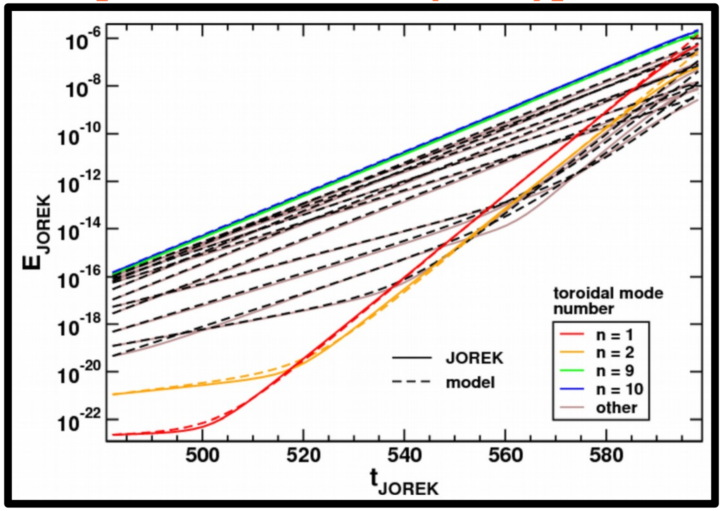


Toroidal Resolution Required for ELMs

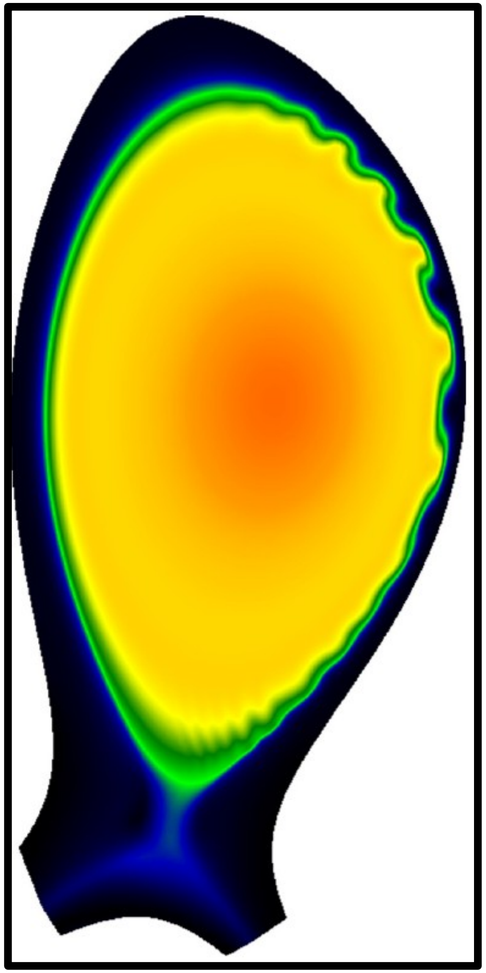
- **Large number of toroidal harmonics is important for good ELM representation**
- **Low mode numbers are linearly sub-dominant, but non-linearly excited**

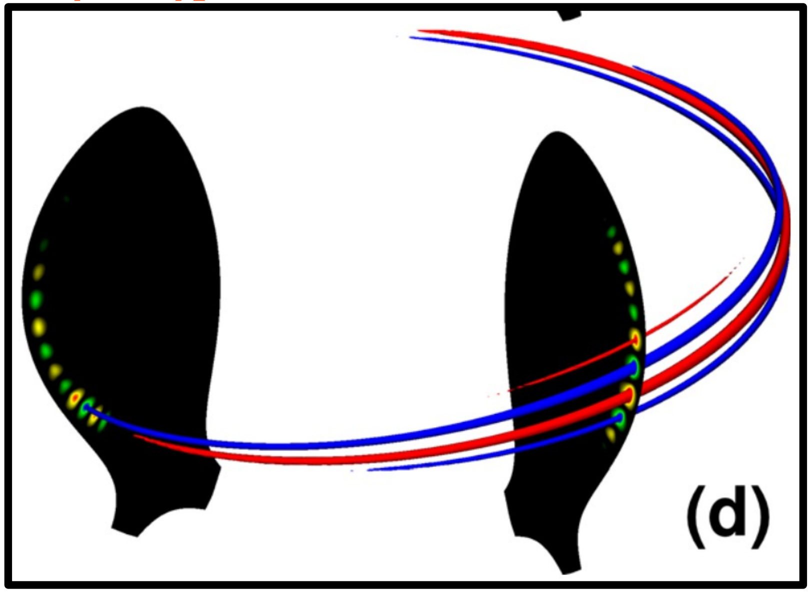
→ poloidally and toroidally localised filaments

[*I.Krebs, PoP 20 (2013)*]

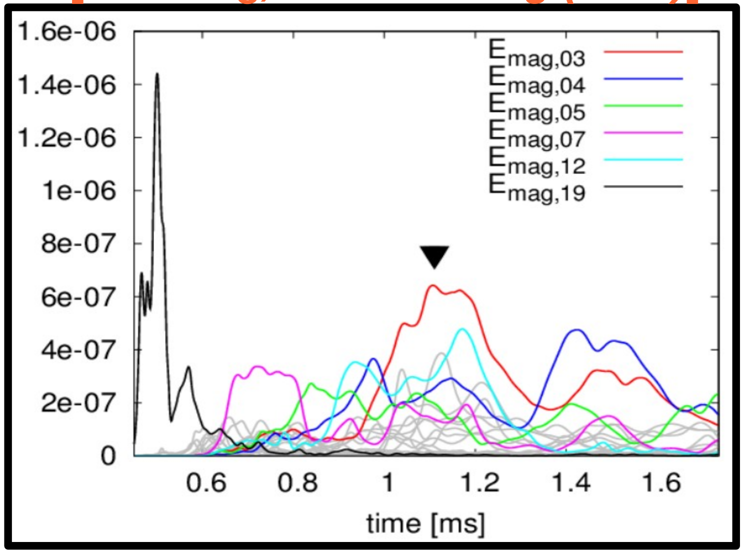


[*M.Hoelzl, PoP 19 (2012)*]





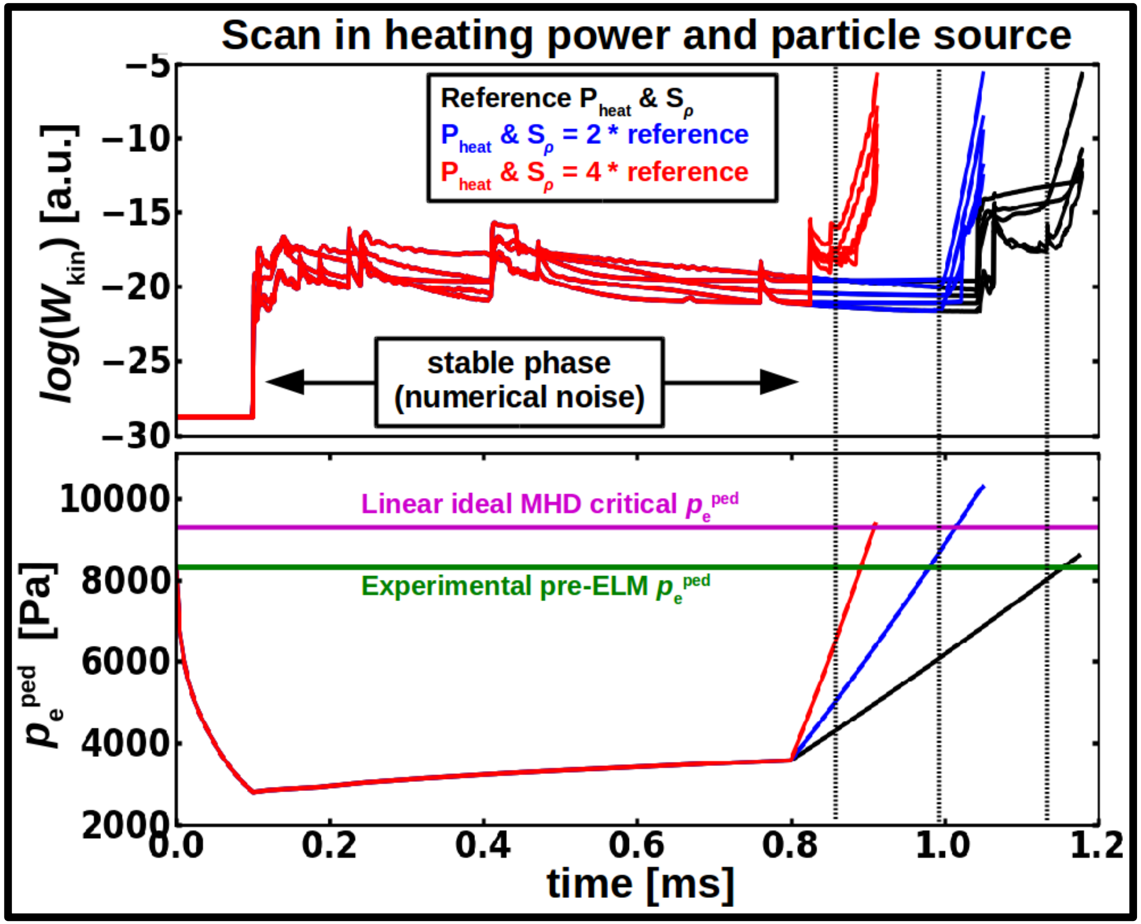
[A.Lessig, *DPG meeting (2016)*]



From Validation To Prediction

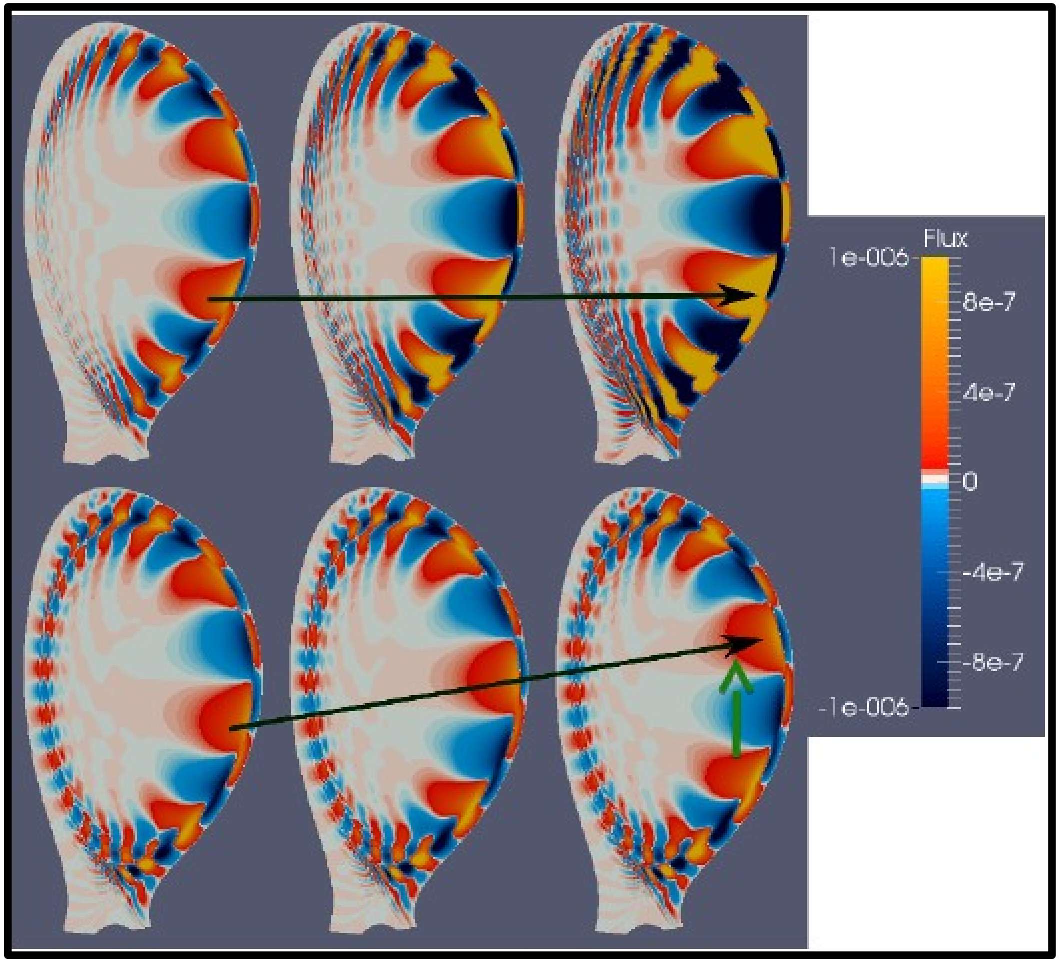
Predictions should include divertor heat-fluxes and ELM energy losses

But also ELM onset information, relevant to pedestal confinement



The Importance of Diamagnetic Terms

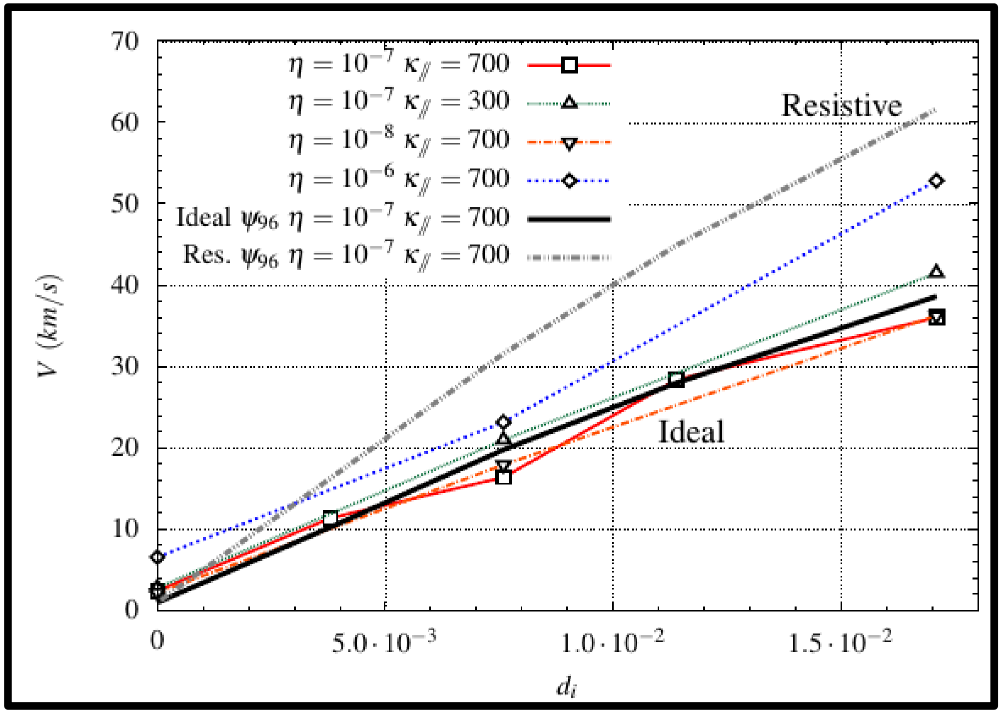
Diamagnetic effects stabilise high-n mode numbers
They induce filament rotation
They enable multiple ELM-cycle simulations



[J.Morales, *subm. PoP (2015)*]

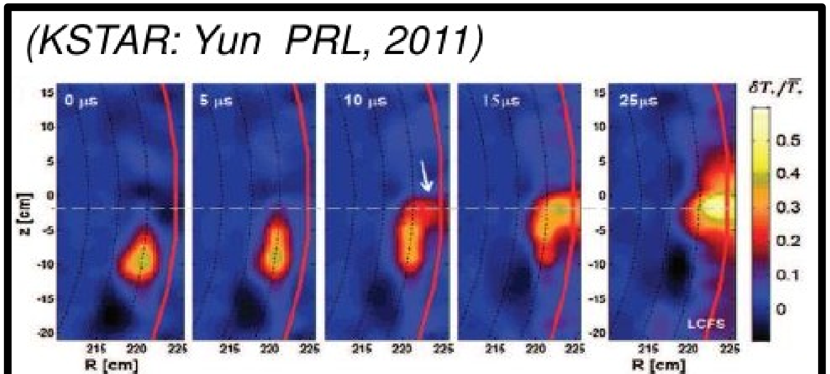
Resistive: $V_{\mathbf{mode}} = V_{\boldsymbol{E}\times\boldsymbol{B}} + V_{/\!/} \cdot b_\theta$

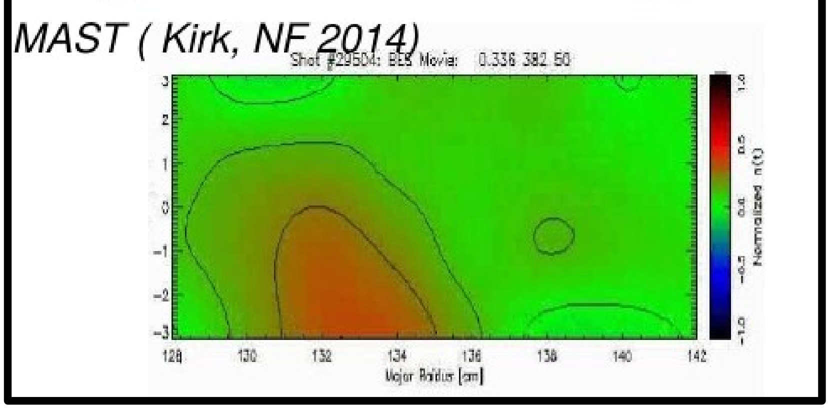
Ideal: $V_{\mathbf{mode}} = V_{\boldsymbol{E}\times\boldsymbol{B}} + V_{/\!/} \cdot b_\theta + V_i^*/2.$



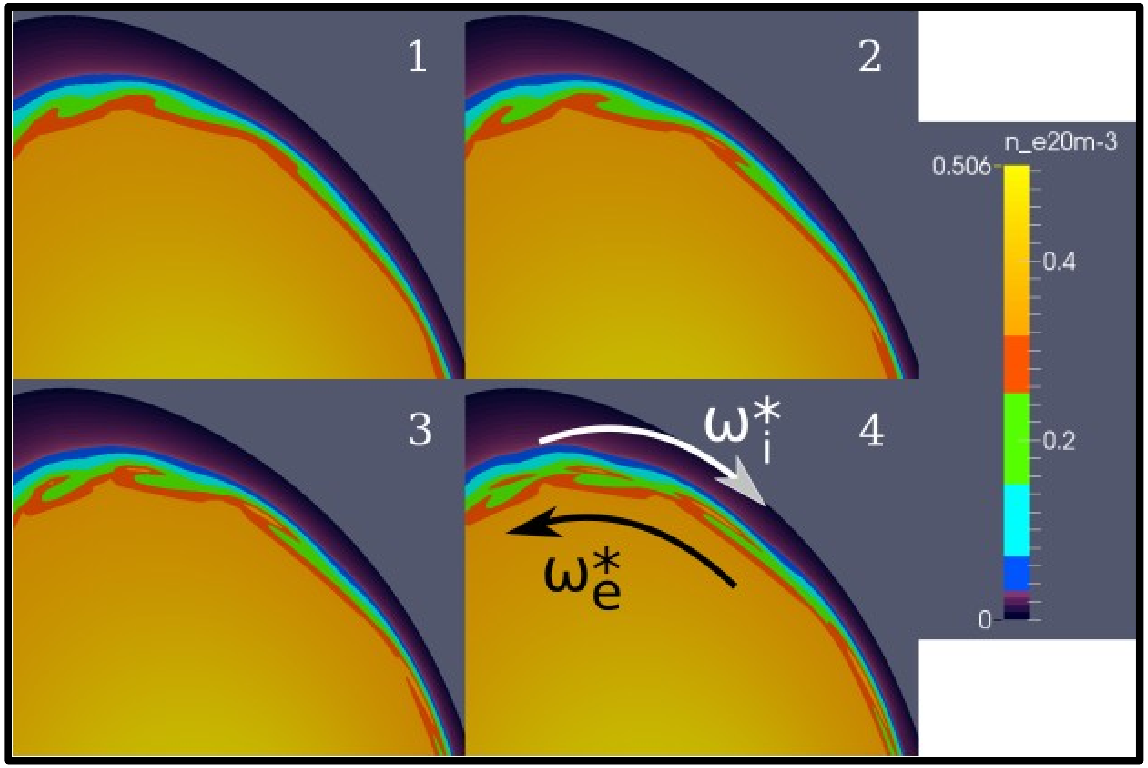
Filament Rotation

Filament rotation observed experimentally
Reproduced by simulations when diamagnetic terms are included
Filament rotation spreads heat-flux on divertor





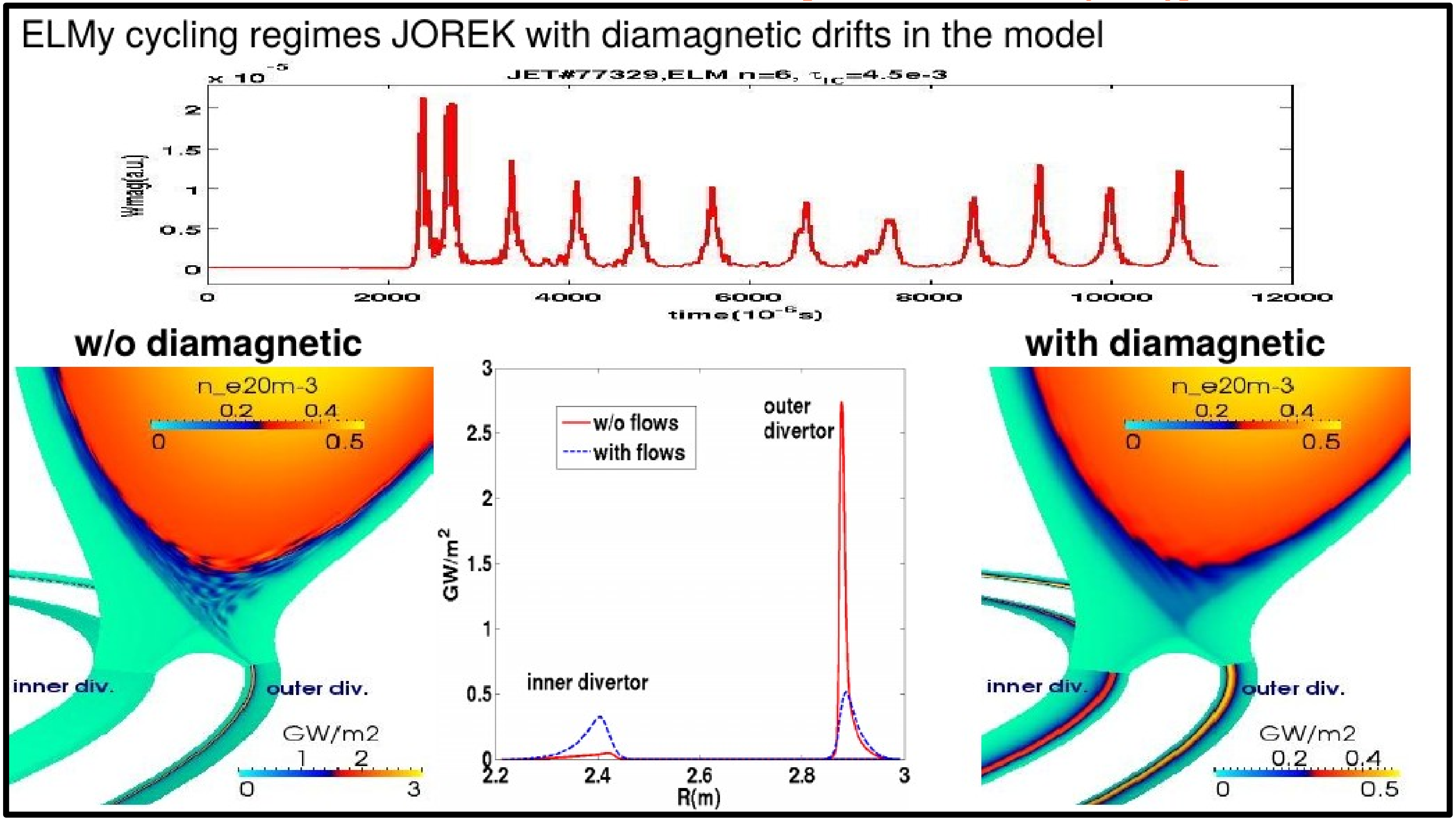
[J.Morales, *subm. PoP (2015)*]



Diamagnetic Terms & Multiple ELM Cycles

Diamagnetic terms necessary to reproduce multiple ELM cycles
Necessary to reproduce inner/outer balance of divertor heat fluxes

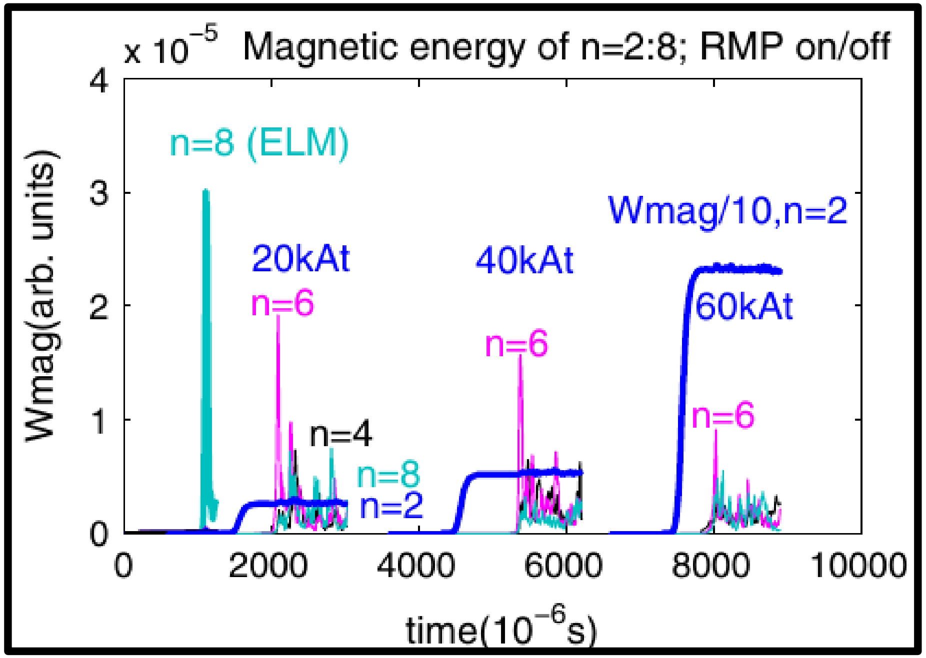
[F.Orain, *PRL 114 (2015)*]



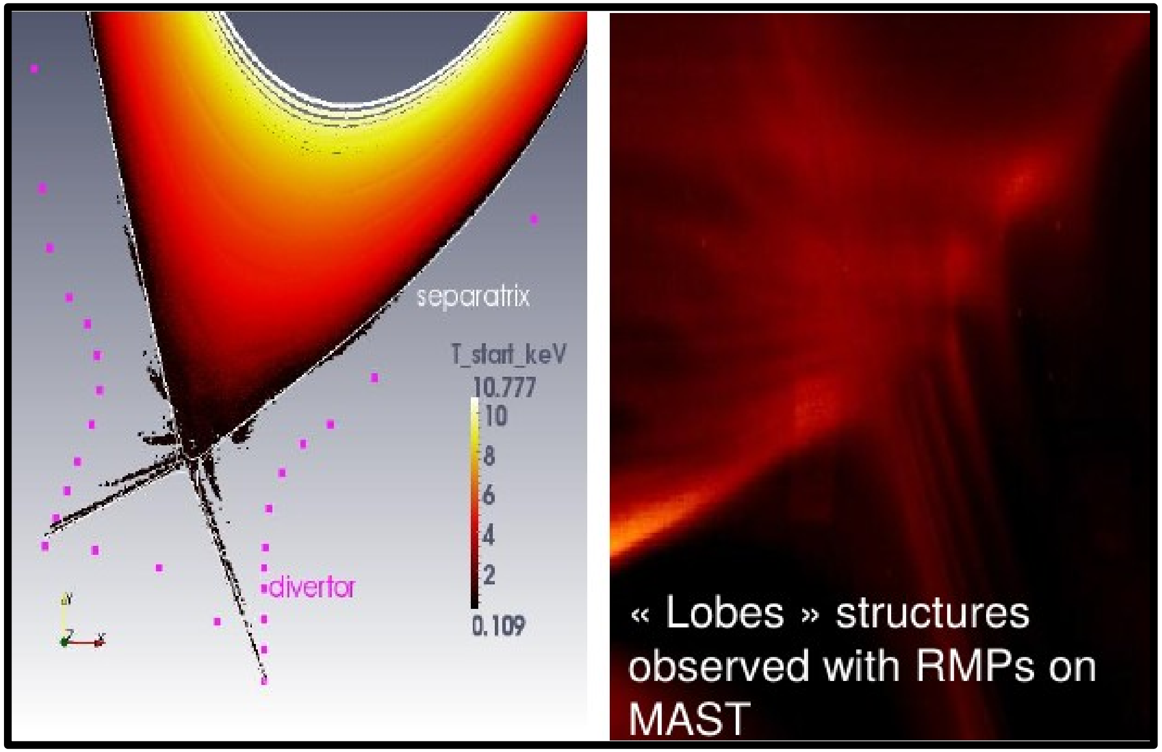
CCFE
CULHAM CENTRE FOR FUSION ENERGY

Mitigation of ELMs by RMPs

RMP simulations reproduce the mitigation of ELMs
Lobes observed near the X-point, like in MAST experiments

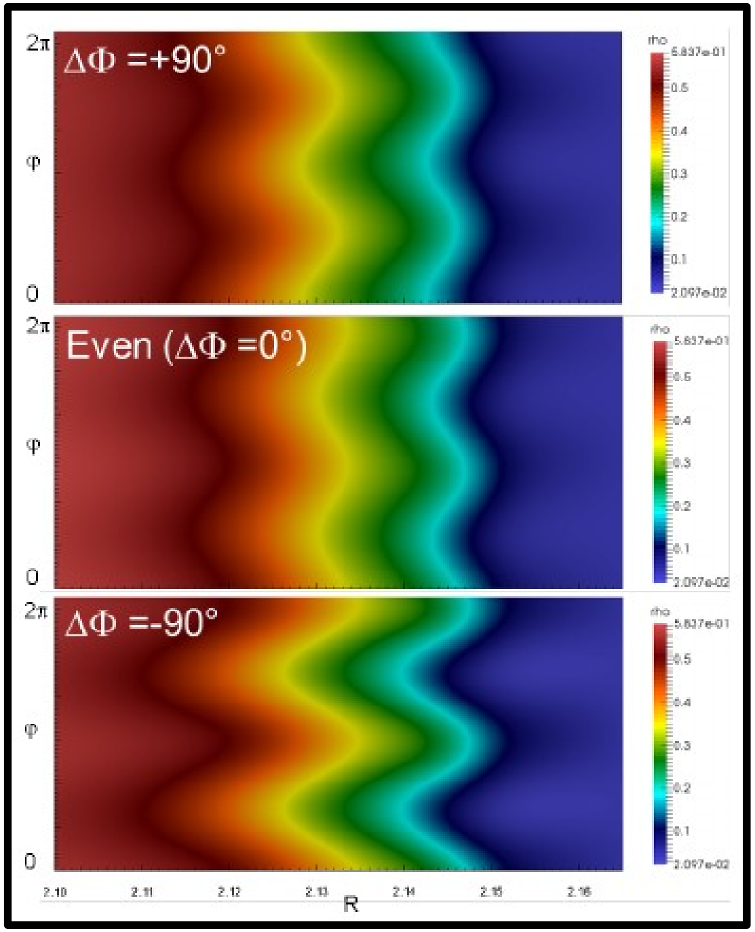


[M.Becoulet, *PRL 113 (2014)*]

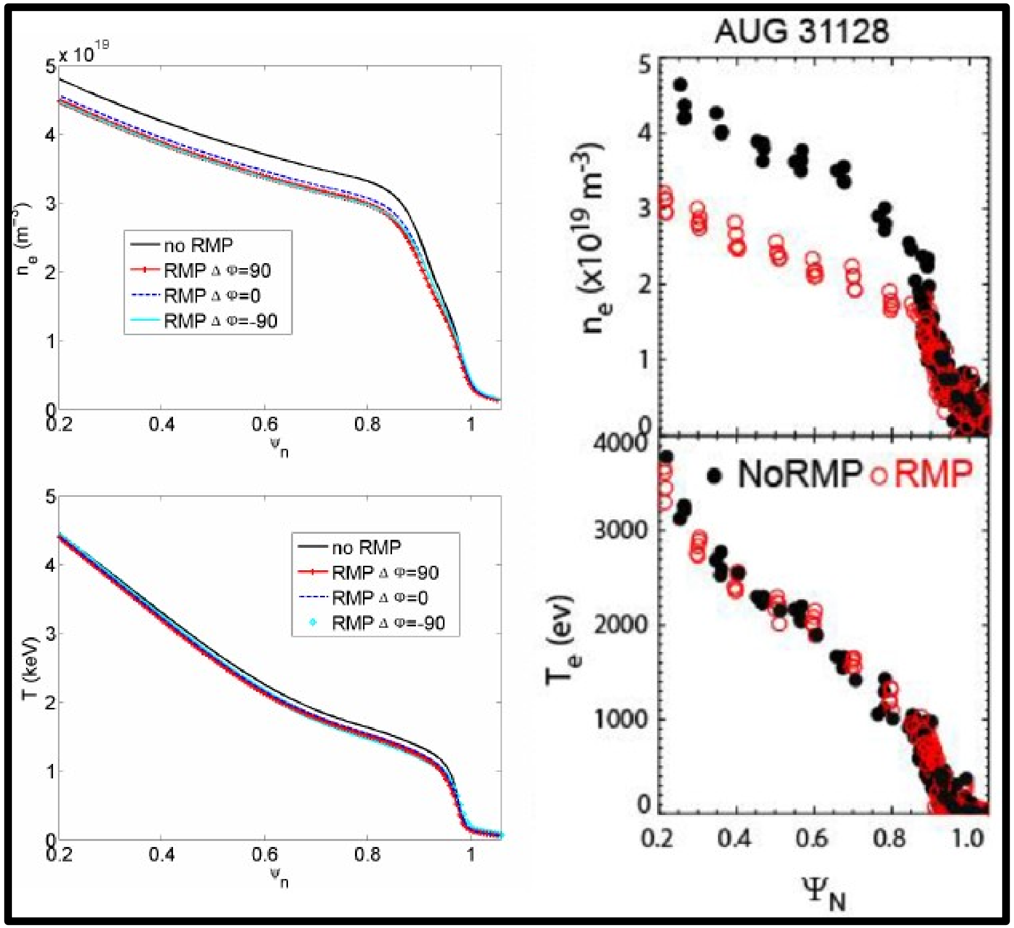


Mitigation of ELMs by RMPs

- Simulation of density pump-out are progressing
- Mitigation more efficient if applied perturbation is amplified by excitation of modes at plasma edge
  - → larger corrugation at X-point
  - → larger lobes
  - → larger pump-out



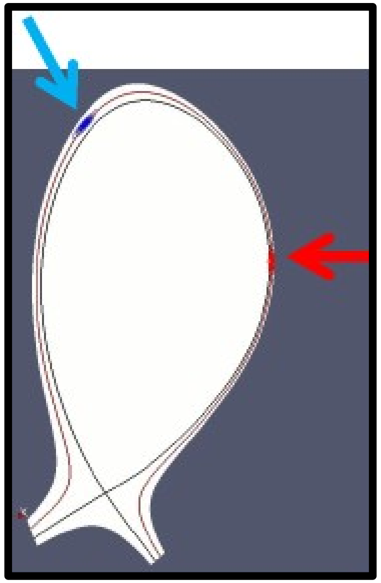
[F.Orain, *subm. Nucl.Fus. (2016)*]

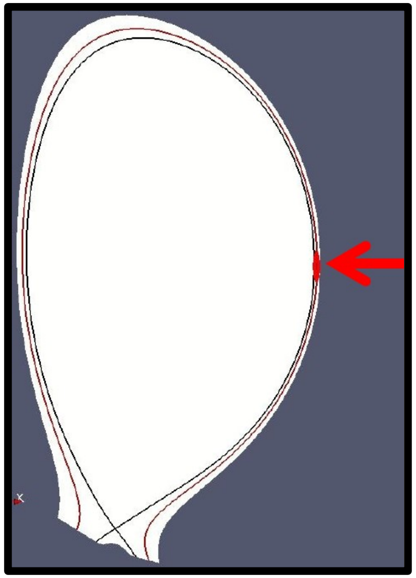


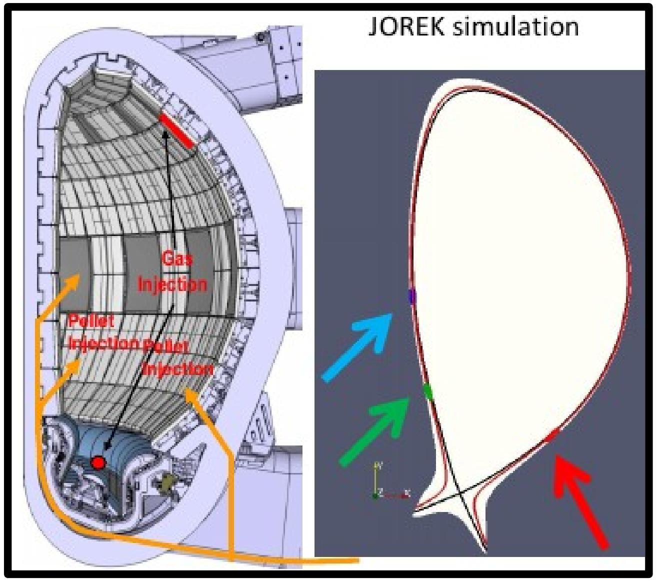
Pellet-Triggered ELMs

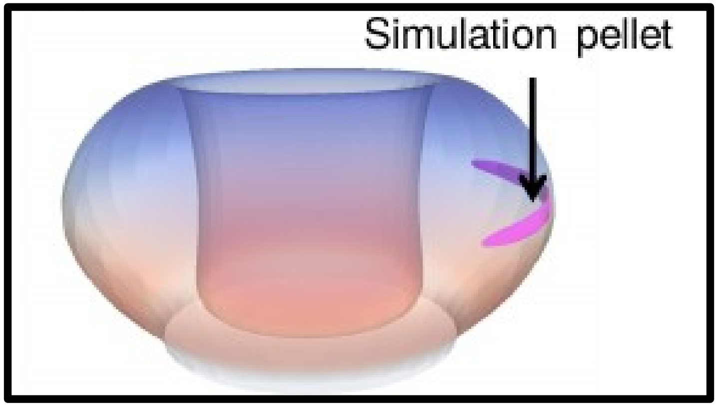
Simulations done on several devices, using various pellet injection locations
Pellet ablates as it enters the plasma, density cloud propagates along flux tube
Ballooning modes are excited, and ELM is triggered

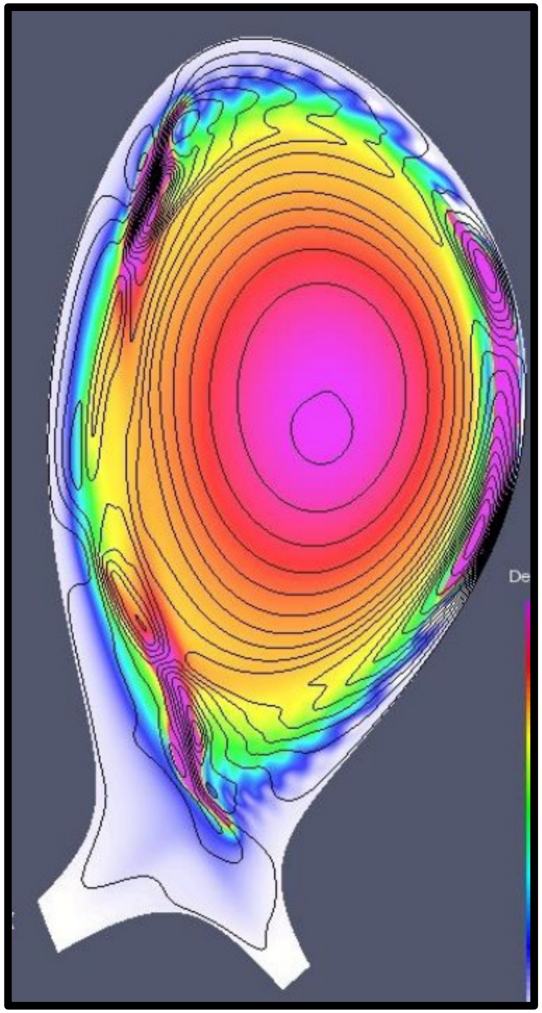
[S.Futatani, *Nuc.Fus. 54 (2014)*]







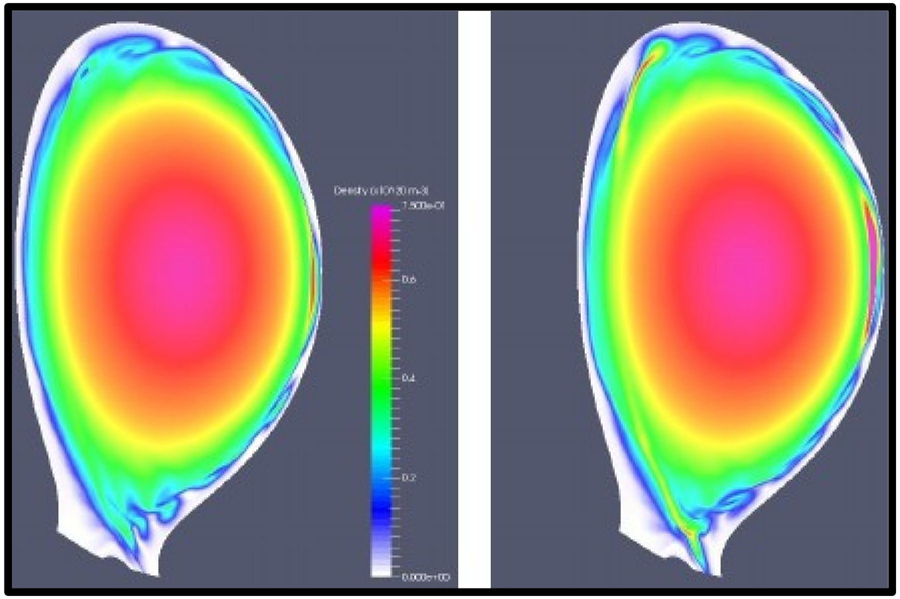


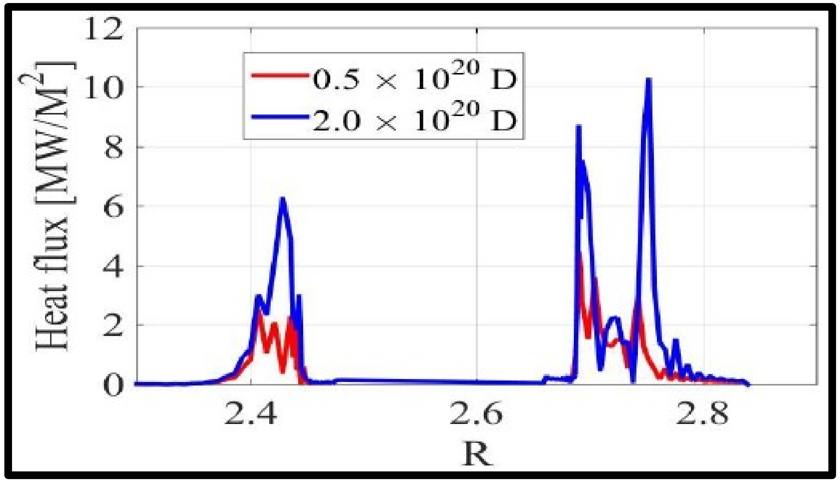


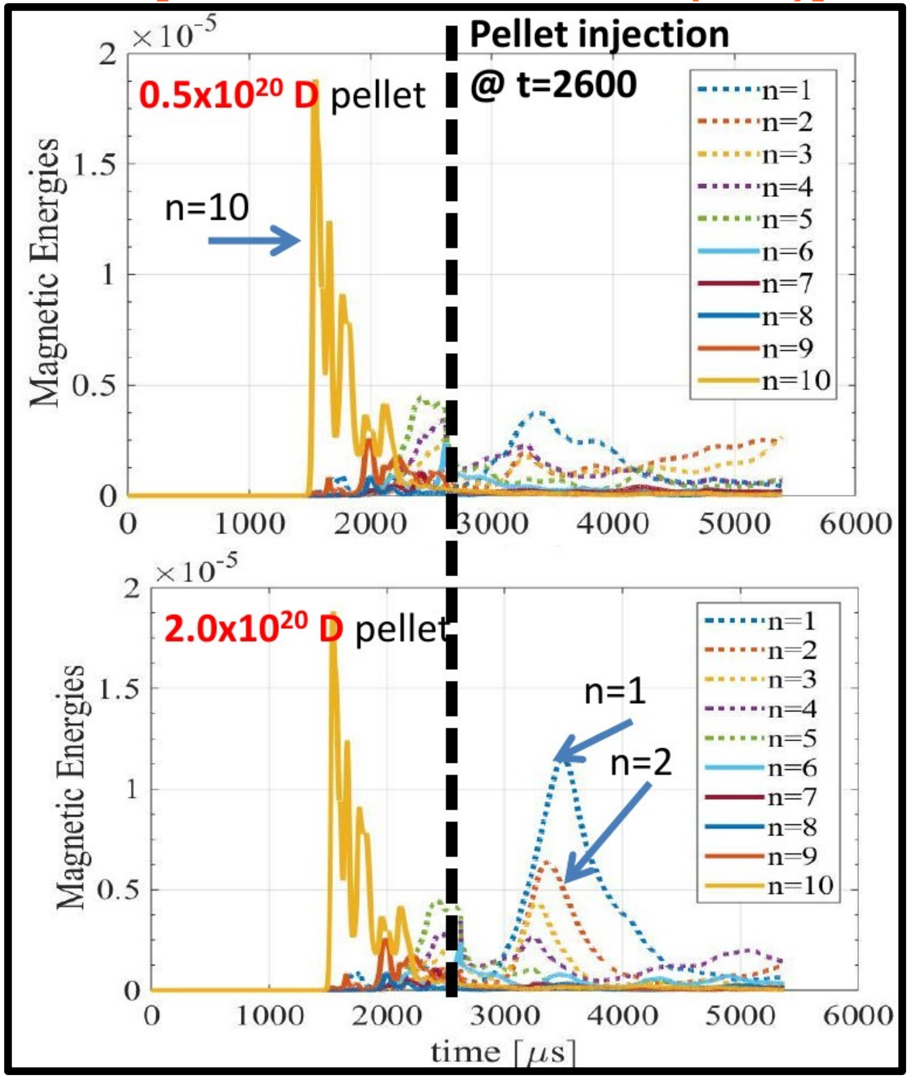
Pellets (2)

Simulations for small and large pellets on JET
ELM clearly triggered by large pellet.
Divertor heat flux is split (also observed experimentally)

[S.Futatani, *recent results (2016)*]



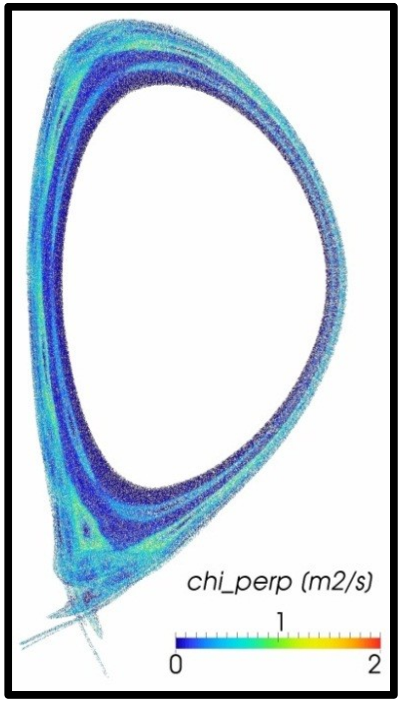


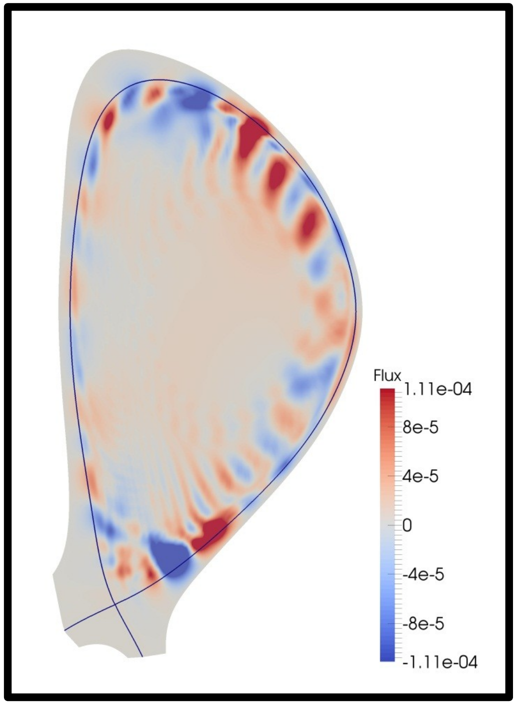


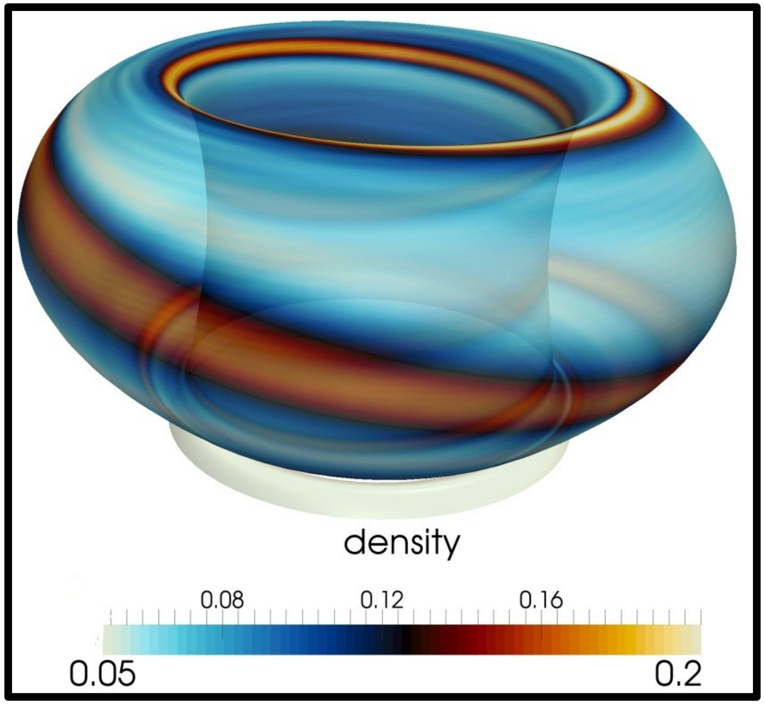
QH-mode Simulations

- QH-mode simulations for DIIID
- Saturated kink-peeling mode at the plasma edge
- Edge Harmonic Oscillation (EHO) causes density losses
- Rotation frequency agrees with experiments
- n=1 dominant mode

[F.Liu, *Nuc.Fus 55 (2015)*]







Mitigation of Disruptions with MGI

Energy: $$\frac{\partial(\rho T)}{\partial t} = -\boldsymbol{v}\cdot\boldsymbol{\nabla}(\rho T) - \gamma\rho T(\boldsymbol{\nabla}\cdot\boldsymbol{v}) + \boldsymbol{\nabla}\cdot(\kappa_\perp\boldsymbol{\nabla}_\perp T + \kappa_\parallel\boldsymbol{\nabla}_\parallel T) + \frac{2}{3R^2}\eta_{Spitzer}j^2 - \xi_{ion}\rho\rho_n R_{ion}(T) - \rho\rho_n L_{rays}(T) - \rho^2 L_{brem}(T)$$

Neutral density: $$\frac{\partial\rho_n}{\partial t} = \boldsymbol{\nabla}\cdot(\boldsymbol{D}_n : \boldsymbol{\nabla}\rho_n) - \rho\rho_n R_{ion}(T) + \rho^2 R_{rec}(T) + S_n$$

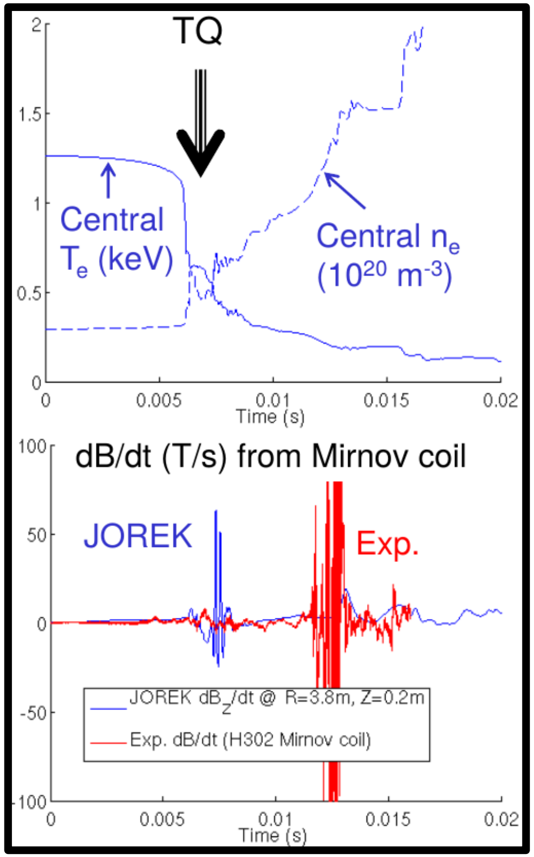
- Neutrals are deposited via a volumetric source term
- Neutral transport is diffusive
- Ionization, recombination and radiation (line and bremsstrahlung) with coefficients from the ADAS database
- Ohmic heating (with Spitzer resistivity)

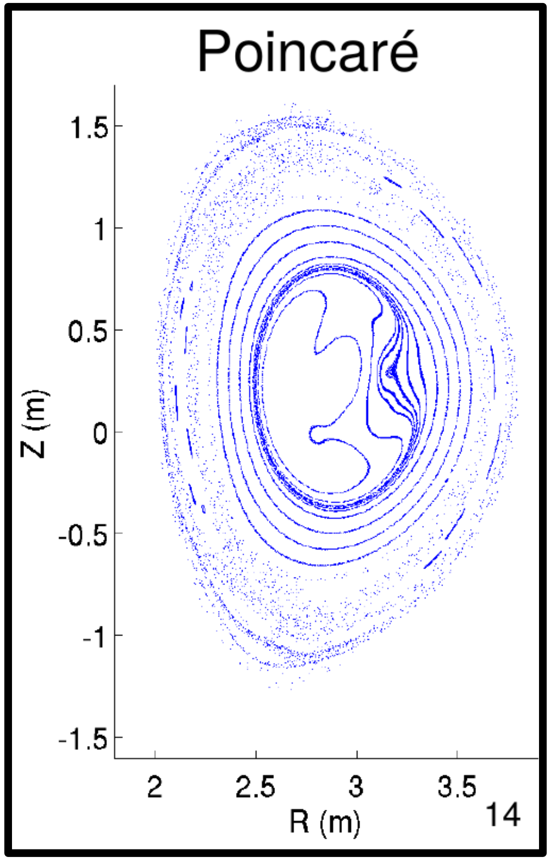
[A.Fil, *PoP 22 (2015)*]

- MGI using neutral density model

- Tearing modes and internal kink leads to thermal quench

- Cooling by parallel conduction along ergodic field lines





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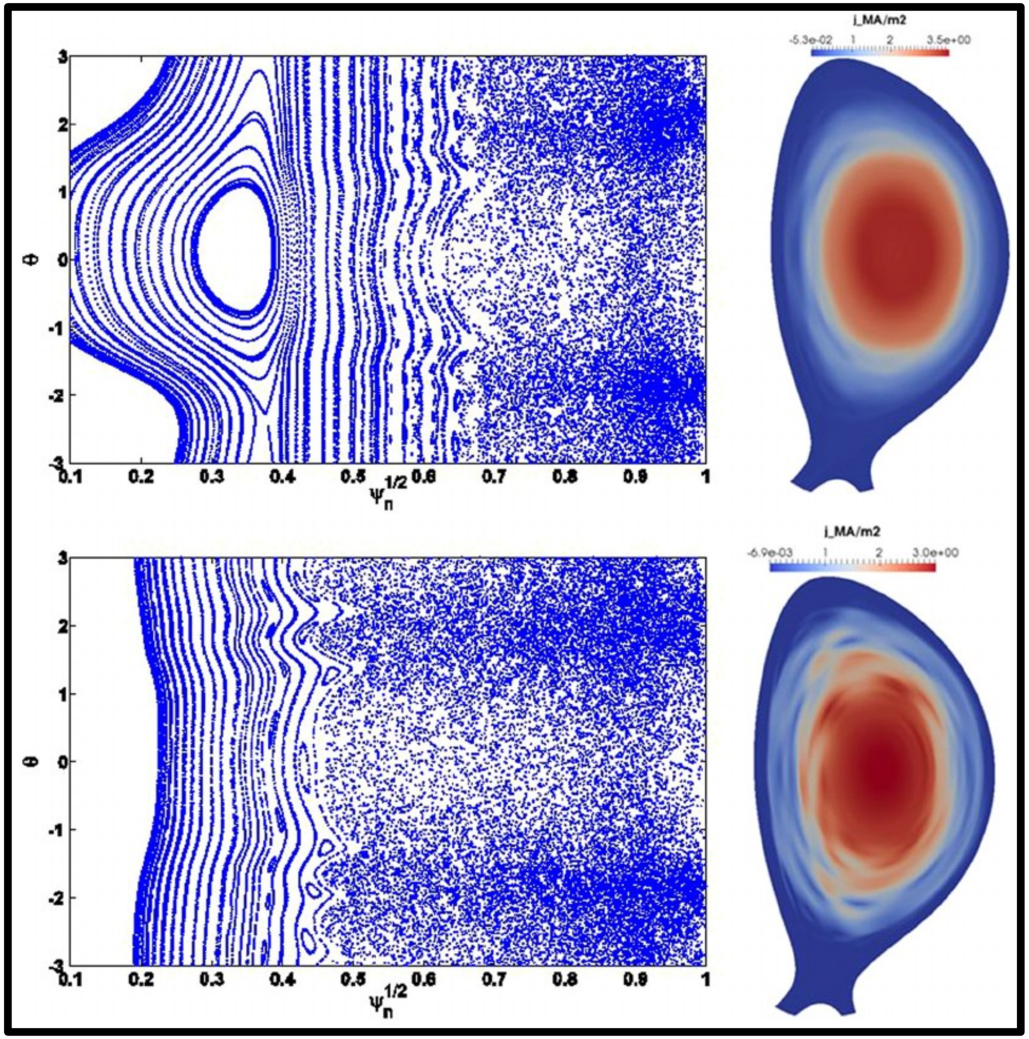
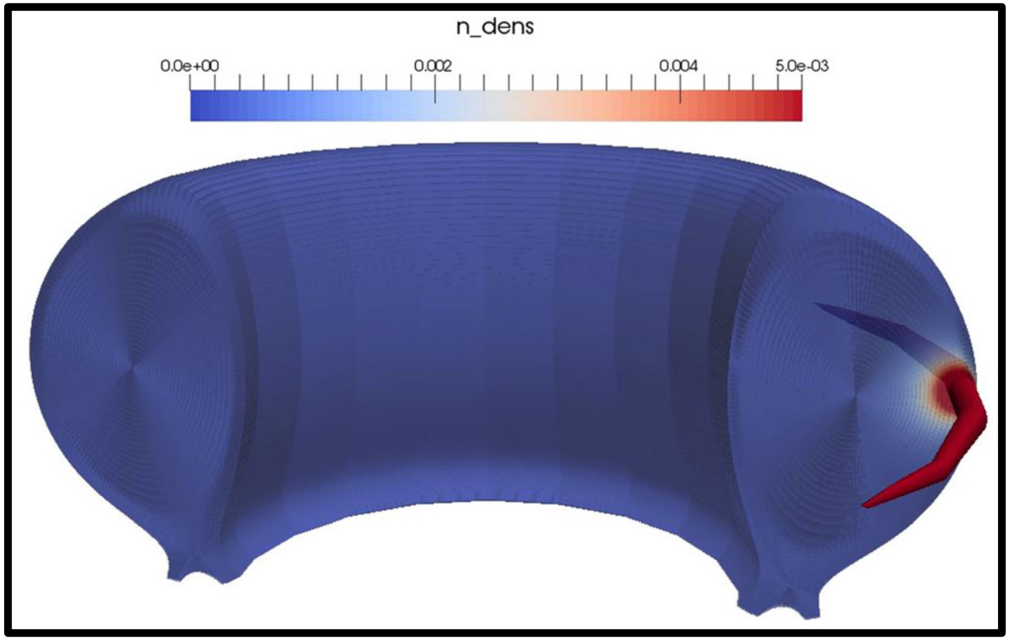
Mitigation of Disruptions with MGI

- More work needed to push resistivity closer to experimental values
→ try to match agreement with magnetic probes

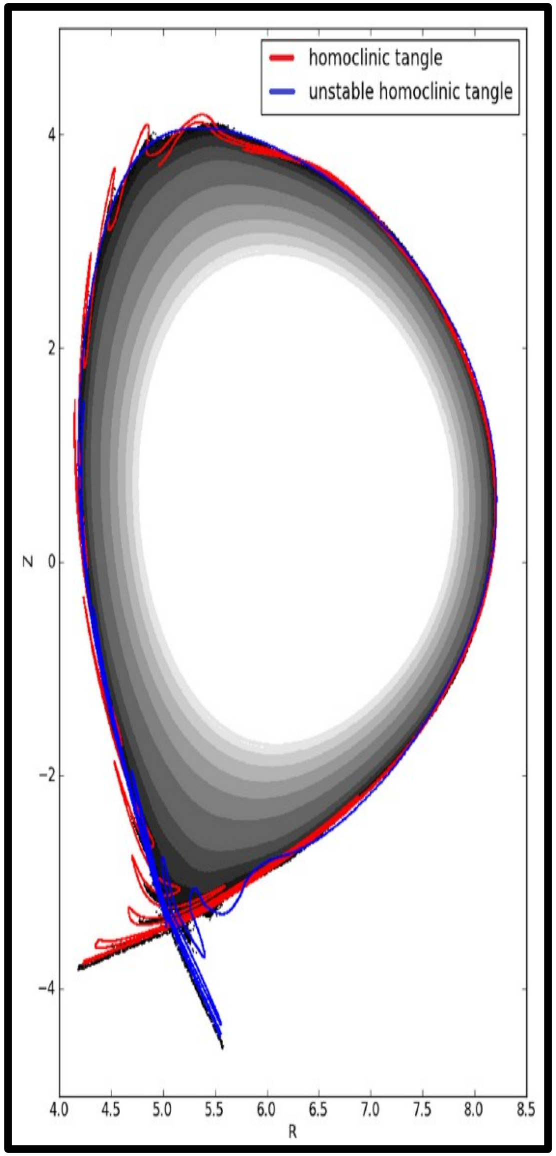


[A.Fil, *PoP 22 (2015)*]

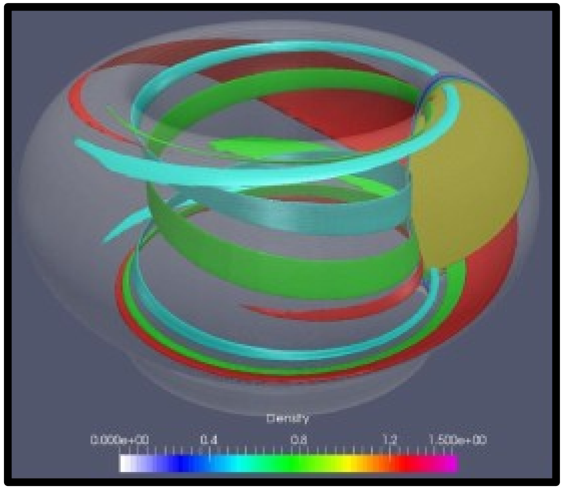


ITER Simulations

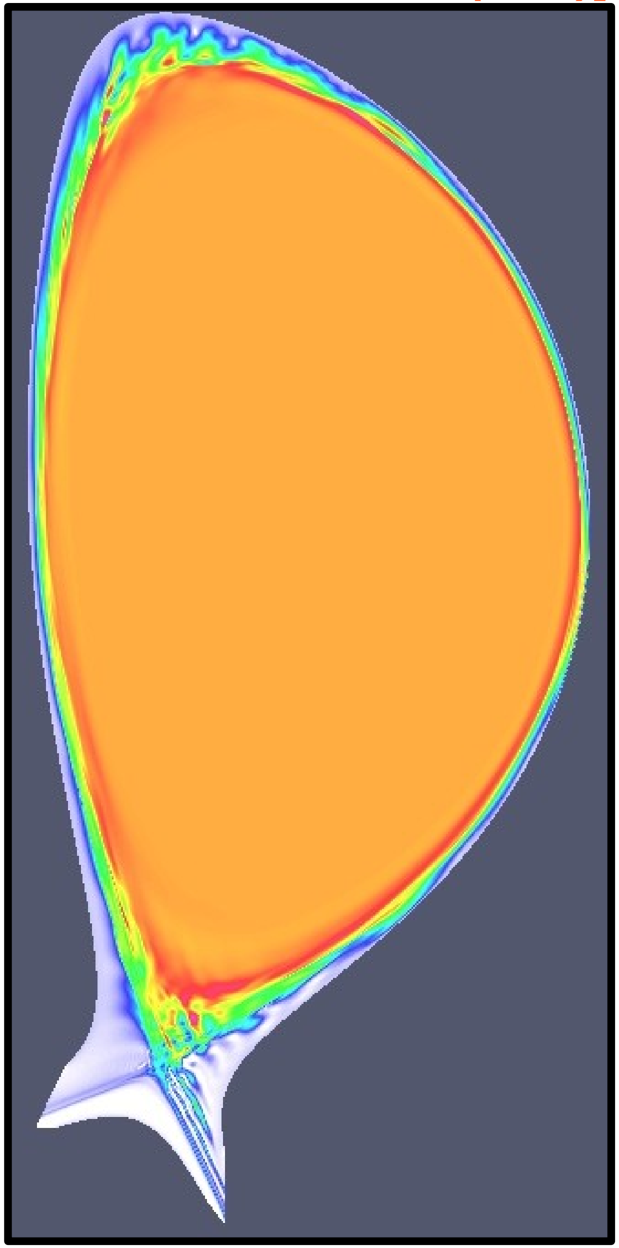
[F.Orain, *PoP 20 (2013)*]



ITER simulations of ELMs, RMPs and pellets published.



[S.Futatani, *Nuc.Fus. 54 (2014)*]



Summary

- Please visit www.jorek.eu !

- Large JOREK team across Europe

- Eurofusion ENR project is progressing well

- ELMs simulation close to quantitative validation

- Now working on multiple type-I ELM cycles

- Mitigation of ELMs by RMPs is coming closer to experiments

- Pellet-triggered ELM simulations already achieved on many devices

- First non-linear QH-mode simulations show good agreement with DIIID

- MGI disruptions have successfully reproduced thermal quench

Acknowledgments

THANK YOU!

Many Thanks to the CSC-team on behalf of all HELIOS users.

HELIOS has enabled the JOREK team to obtain many important results in the last years!

References/Acknowledgements

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- Czarny O and Huysmans G., J. Comput. Phys. 227, 7423 (2008)
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