DE LA RECHERCHE À L'INDUSTRIE

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Non-linear ELM and RMP Modeling in Realistic Tokamak Geometries

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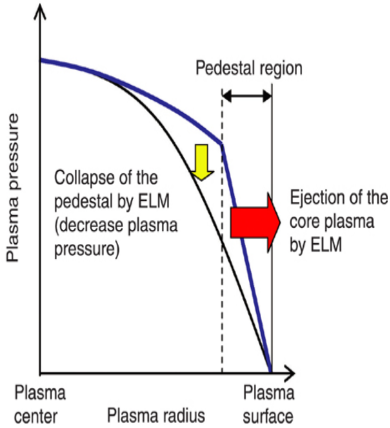
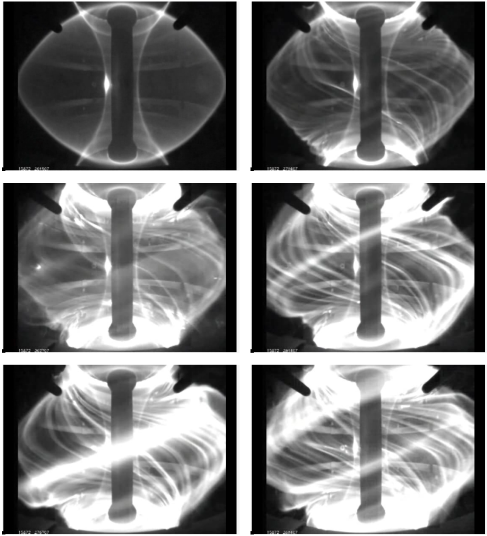
What is an Edge Localised Mode ?



MAST fast CCD camera [Kirk '06]



Periodic relaxation of **heat** & **density**

↳ steep ∇p (ballooning)

↳ large edge current (peeling)

ELMs are harmful instabilities for the PFCs

—the need to understand, predict & control ELMs in realistic geom.—

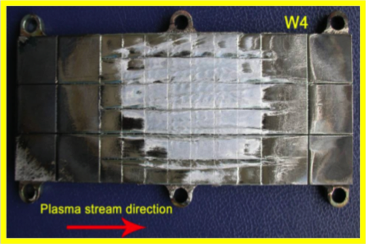
Limits pedestal height & global confinement

- erosion, droplets, melting of tungsten
- Q=10 in ITER: $\Delta W_{ELM}^{\mathrm{ITER}} \sim 17\mathrm{MJ} \sim 15\%\ W_{ped}$ [in $\sim$ 250-500 μs]
- acceptable ELM: $\Delta W_{ELM} \sim 2-3\mathrm{MJ}$

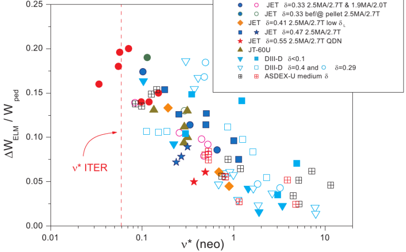
  ↳ divertor may only survive a few ELMs...

- e^- gun power load based on empirical extrapolation —not understood
- power load cycles (1000) at low power show intense material degradation

ELMy power load: e^- gun @Kurchatov



[Loarte, PPCF '03]



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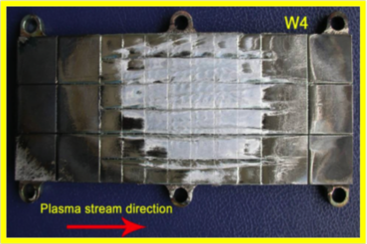
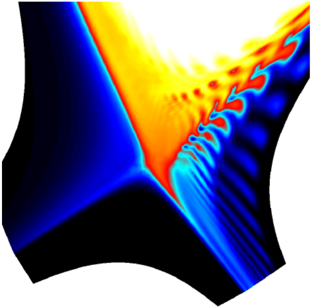


Common thread: what requirements for an accurate description of ELMs & RMPs ?

1. the tool: the reduced MHD code JOREK
2. evaluating the ELM energy deposition in ITER
3. added physics: diamagnetics & RMPs
4. going further: divertor physics

Requirements for an accurate description of ELMs & RMPs



❶ the tool: the reduced MHD code JOREK

❷ The ELM energy deposition in ITER

❸ Added physics: diamagnetics & RMPs

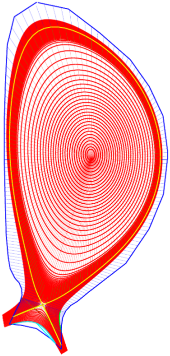
❹ Going further: divertor physics

JOREK: developed with the specific aim to simulate ELMs

- Originally developed at CEA Cadarache [Huijsmans '07, Czarny '08]
- Non-linear reduced MHD in toroidal geometry
  [next slide: dens., temp., elec. potential (perp. flow), para. velocity, polo. flux]
- Full MHD in development

[see A. Ratnani, tomorrow]

- Domain:
  - Closed & open field lines, X-point
  - b.c.: Mach one, free outflow at divertor target
- Discretisation:
  - Cubic Bezier finite elements in the poloidal plane
  - Fourier series in toroidal angle
- Time stepping: fully implicit Crank-Nicholson
- Solver sparse matrices (PastiX library): 10^7 degrees of freedom
- Parallelisation using MPI/OpenMP: typically 256 – 1500 processors



- Pellet ELM triggering [Huijsmans '10]
- ELMs in JET [Pamela '11]
- RMP field penetration [Bécoulet '12, Orain '13]

R-MHD equations,including: SOL flows, source $\mathcal{S}_{v_\varphi}$, two-fluid diamagnetic rotation & NC poloidal viscosity

1—density:
$$\frac{\partial}{\partial t}\rho = -\nabla\cdot(\rho\mathbf{v}) + \nabla\cdot(D_\perp\nabla_\perp\rho) + S_\rho$$

[Huijsmans '09, Orain '13]

2—temperature:
$$\rho\frac{\partial}{\partial t}T = -\rho\mathbf{v}\cdot\nabla T - (\gamma-1)\rho T\nabla\cdot\mathbf{v} + \nabla\cdot(\kappa_\perp\nabla_\perp T + \kappa_\|\nabla_\| T) + S_T$$

3—perp. and parallel momentum:
$$\mathbf{e}_\varphi\cdot\nabla\times\left(\rho\frac{\partial}{\partial t}\mathbf{v} = -\rho(\mathbf{v}\cdot\nabla)\mathbf{v} - \nabla(\rho T) + \mathbf{J}\times\mathbf{B} + \mu\Delta\mathbf{v} \; -\nabla\cdot\Pi^{neo} + \mathcal{S}_{v_\varphi}\right)$$
$$\mathbf{B}\cdot\left(\rho\frac{\partial}{\partial t}\mathbf{v} = -\rho(\mathbf{v}\cdot\nabla)\mathbf{v} - \nabla(\rho T) + \mathbf{J}\times\mathbf{B} + \mu\Delta\mathbf{v} \; -\nabla\cdot\Pi^{neo} + \mathcal{S}_{v_\varphi}\right)$$

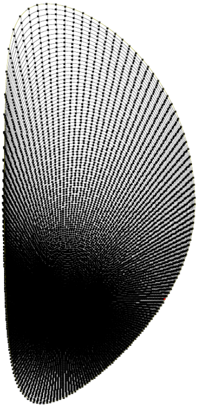
5—induction:
$$\frac{\partial}{\partial t}\mathbf{A} = -\eta\mathbf{J} \; -\frac{m}{\rho e}\nabla_\|(\rho T) \; + \mathbf{v}\times\mathbf{B} - F_0\nabla\phi$$

6—B field & closure:
$$\mathbf{B} = \frac{F_0}{R}\mathbf{e}_\varphi + \frac{\nabla\psi(t)}{R}\times\mathbf{e}_\varphi \quad ; \quad \eta = \eta_0\left(T/T_0\right)^{-3/2} \quad ; \quad \mathbf{v} = -R\nabla\phi(t)\times\mathbf{e}_\varphi + v_\|(t)\mathbf{B} \; + \mathbf{v}_\star$$

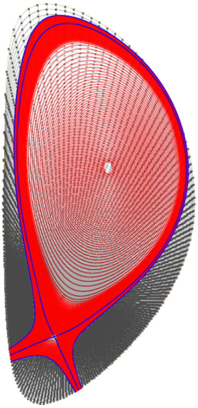
7—boundary conditions:

- Zero perturbations on wall aligned with last flux surface
- Bohm boundary conditions on the target: $v_\| = \pm c_s \quad ; \quad \kappa_\|\mathbf{b}\cdot\nabla T = (\gamma-1)nTc_s$

A typical run —e.g. in ITER geometry



- Initial grid: polar grid for Bézier elements
- Flux-aligned grid including X-point(s)
- Radial and poloidal grid meshing: divertor & wall b.c.
- Equilibrium flows: $n = 0$ harmonic
- Time-integration: $\forall n$ harmonics
- Postprocessing



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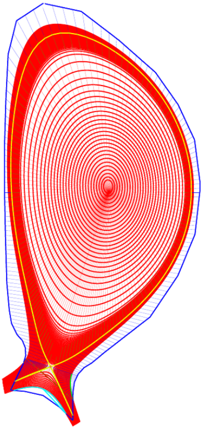

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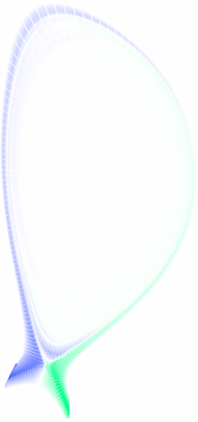

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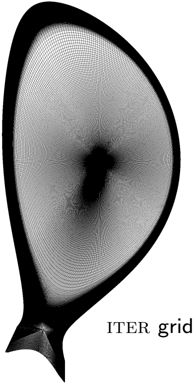

ITER grid

Requirements for an accurate description of ELMs & RMPs

❶ the tool: the reduced MHD code JOREK

❷ The ELM energy deposition in ITER

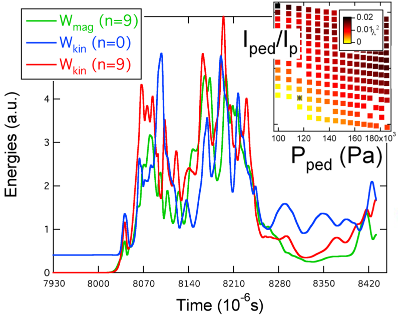
❸ Added physics: diamagnetics & RMPs

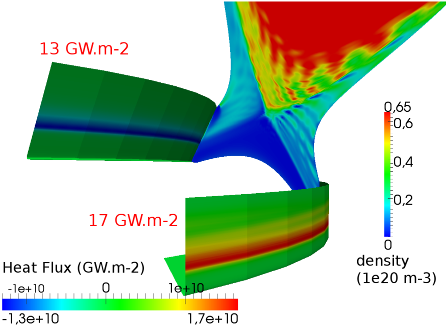
❹ Going further: divertor physics

F4E-GRT265: « Evaluation of edge MHD stability and uncontrolled ELM energy losses for ITER H-mode plasmas in non-active, DD and DT operational scenarios »

↳ known limitations ➟ a realistic ELM computation in ITER is yet out-of-scope

state-of-the-art: preliminary attempt to compute heat & particle deposition in 15MA/5.3T ITER [Maget '12, Dif-Pradalier & Bécoulet '13]

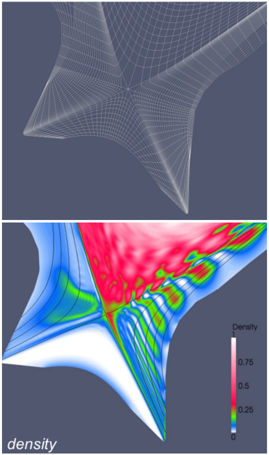




State-of-the-art. . .yet many unknowns

- **particle loss in ELM:** $\sim 3.4\%$
- **energy loss in ELM:** 5MJ out of 452.5MJ $\sim 1.1\%$ energy content

Resistivity	$\eta_0 = 10^{-6}$	10^{-10}
Parallel/perp. heat cond.	$\kappa_{\parallel}/\kappa_{\perp} = 810^{8}$	10^{11}



going beyond. . .

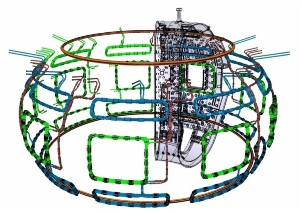
■ **grid:** • aligned v.s. adaptive [Ratnani]
• low η_0 ➠ large grid ➠ memory

■ **memory:** multi-harmonics needed for turb. & **E** $\times$ **B** shear ➠ large in implicit models

■ **time-stepping:** fast parallel dyn. v.s. perp.

■ **boundaries:** interaction with chamber magn. connection, free boundary [STARWALL]

➠ how does the ELM computation change when adding new physics ?



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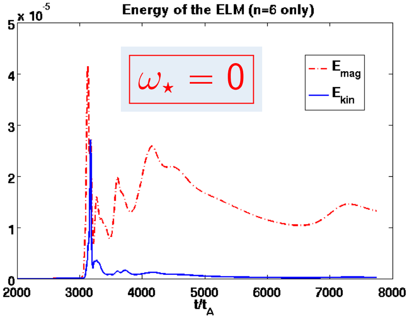
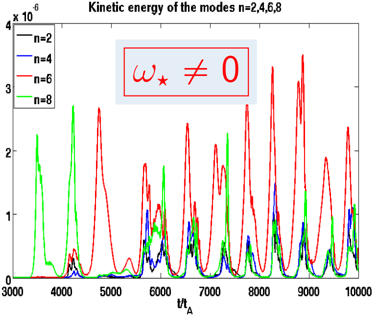
Diamagnetic rotation $\omega_\star$ seems instrumental to access crash cycles

why a cycle ?

- usually: initial unstable profiles ∇p, I ➠ single relaxation
- 1^{st} relax.: "unphysical" ? ➠ analog. sawteeth [q–profile, reconn. dyn.] [Lütjens '09]
- assess dynamics with self-consistent background flows, electric field & mode phasing





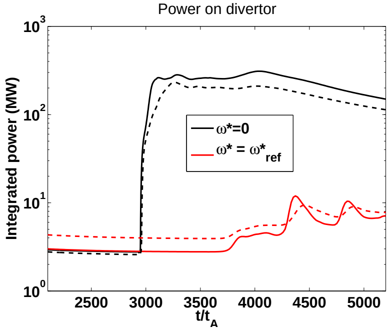
[Orain '13]

- when including dia. rotation...

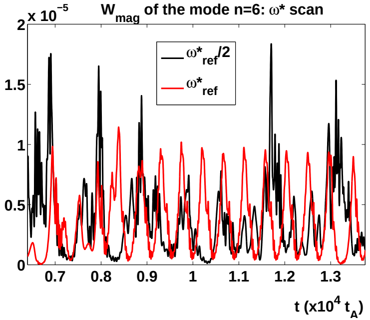
  ↳ heat deposited on divertor is reduced when $\omega_\star \neq 0$

- ELM freq. ↗ when $\omega_\star$ ↘

  ↳ ELM size & dynamics ➠ 2-fluid dia. rotation important



[Orain '13]



RMPs: some very contrasted results. . .beg for a better understanding

External coils apply static Resonant Mag. Perturb.

⇓

ergodic edge

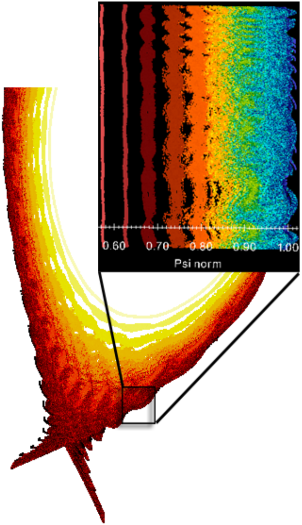
⇓

radial transport ↗

⇓

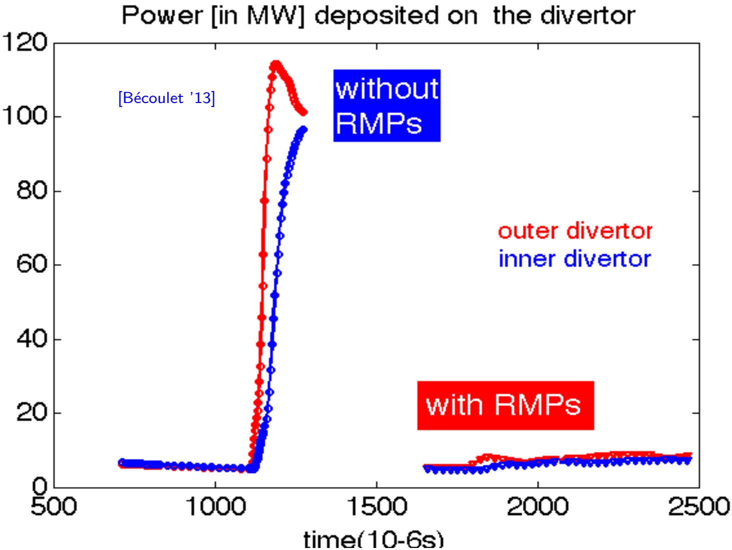
$\nabla p \searrow$ < instability threshold

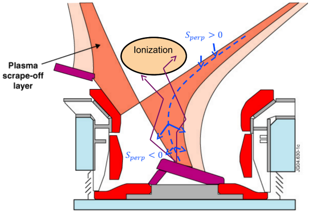
- same "vacuum ergodization", different effects: suppress, mitigate, trigger,. . .



- RMPs with plasma response
- RMPs / ELMs interaction
- Density pump-out
- Rotation braking

Ongoing work: ELMs are mitigated ➠ power in divertor is ∼ 10x smaller with RMPs





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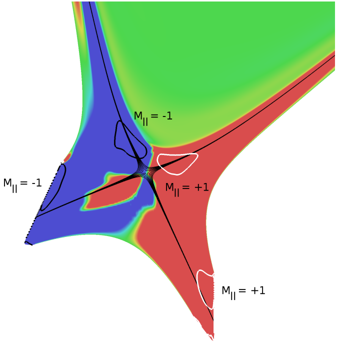
- Flows ➠ strong influence on onset & development of instabilities *[see $\omega_\star$]*
  - ↳ supersonic transitions in JOREK: a surprise ?
- $\{\mathcal{S}$, neutrals, geom.$\}$ ➠ strong influence on onset & structure of flows

Supersonic transition in the SOL driven by plasma source inversion



Importing divertor physics: sources, neutrals & geometry ➠ a strong impact on the SOL flows

- Flows ➠ strong influence on onset & development of instabilities *[see $\omega_\star$]*
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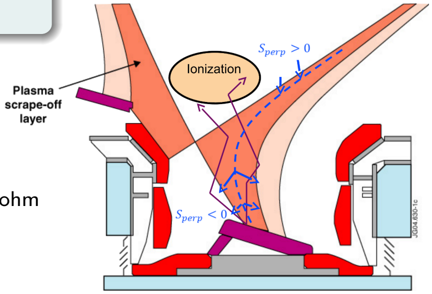
- $\{\mathcal{S}$, neutrals, geom.$\}$ ➠ strong influence on onset & structure of flows

Supersonic transition in the SOL driven by plasma source inversion

$$\mathcal{A} = \frac{2M}{1+M^2}$$ [Ghendrih '12, Bufferand '13]

$$\frac{\partial \mathcal{A}}{\partial s} \propto (\mathcal{S}_{\text{perp}} + \mathcal{S}_{\text{ionization}})$$

- If $\partial_s \mathcal{A} \leqslant 0$ target plates ➠ $M \geqslant 1$ satisfy Bohm
- $\underbrace{\mathcal{S}_{\text{perp}} + \mathcal{S}_{\text{ioniz.}}}_{\text{near target plates}} \begin{cases} < 0 & \text{➠ supersonic} \\ > 0 & \text{➠ subsonic} \end{cases}$



supersonic flows

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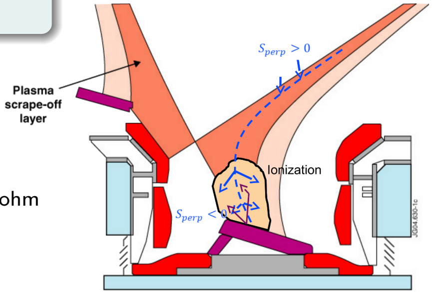

NO supersonic flows

- Flows ➠ strong influence on onset & development of instabilities *[see $\omega_\star$]*
  - ↳ supersonic transitions in JOREK: a surprise ?
- {$\mathcal{S}$, neutrals, geom.} ➠ strong influence on onset & structure of flows

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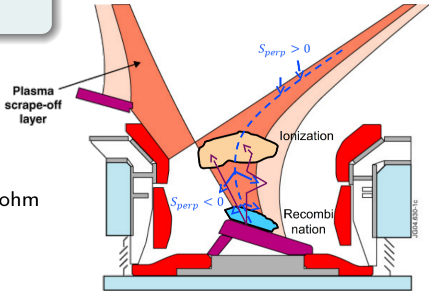
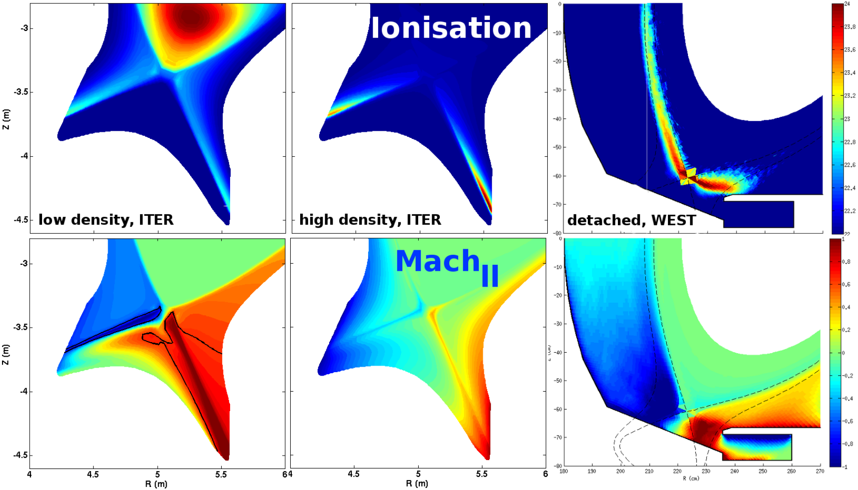


supersonic flows

SOLEDGE2D $\{n, u_{\parallel}, T\}$ + neutrals ➠ supersonic transitions understood in the SOL

[Bufferand '13]



supersonic **subsonic** **supersonic**

First series of ELM computation for iter [0^{th} order], validated by ITER

Diamagnetic flows $\omega_\star$:

- seem essential for ELM cycles
- reduce ELM size, increase freq.
- symmetrisation of the power deposition

ELM mitigation by RMPs

Supersonic flow transitions in SOL —divertor physics

- framework understanding becoming mature
- delicate balance: sources, neutrals [ionis.], **B** geom. ➠ all effects important

many numerical challenges remain, *e.g. talk tomorrow by A. Ratnani*

Additional material

non-linear reduced MHD in toroidal geometry

- density, temperature, velocity & poloidal flux
- ideal wall conditions on walls
- Mach one, free outflow at divertor target

closed & open field lines domain, X-point geom.

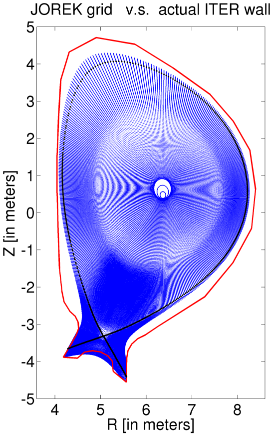
- cubic finite elements, flux aligned poloidal grid
- Fourier series in toroidal direction

time stepping, solver & parallelism

- fully implicit Crank-Nicholson
- sparse matrices (PastiX): $\sim 10^7$ degrees of freedom
- MPI/OpenMP over typically 256 – 1500 processors

getting closer to the experiment...

- exact geometry⋆⋆ & boundary conditions⋆⋆
- non-linear MHD over long time scales⋆ ($\mu s \rightarrow s$)
- realistic parameters⋆⋆⋆ [resistivity, parallel conductivity, collisionality]
- one/several modes⋆⋆⋆, background turbulence⋆⋆⋆⋆



ELM cycle & control

- ELMs *[G. Dif-Pradalier, M. Bécoulet, S. Pamela]*
- Resonant Magnetic Perturbations (RMPs) *[M. Bécoulet, F. Orain]*
- pellets injection, vertical kicks *[G. Huijsmans, S. Futatani]*

Disruptions

- VDE, β limit disruptions, density limit *[C. Reux, E. Nardon, A. Fil]*
- [NTMs control with ECCD *[IO+FOM]*]

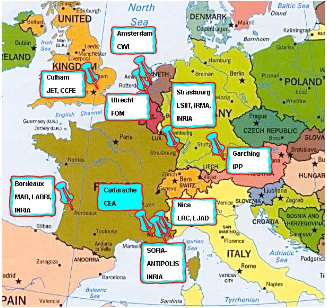
ANRs: ASTER (2006-2009), ANIKA (2009-2012), ANEMOS (2010-2013), A2T2 (2010-2013)

Grants: F4E-2011-GRT-265

"Jorek team": $\sim$30 throughout Europe

international:

JOREK	*[Huijsmans '07]*	
M3D–C1	*[Ferraro '09]*	
XGC0	*[Park '07]*	
BOUT++	*[Dudson '09]*	



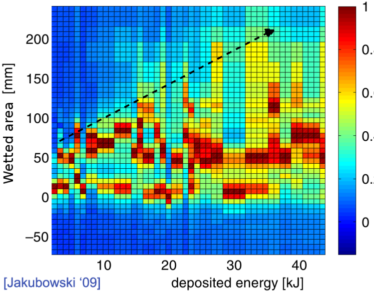
ELM size, wetted area & peak heat/particle load: the prediction for ITER is both uncertain & crucial

ELM ≡ MHD instability destabilised by pressure & current gradients in the H-mode pedestal

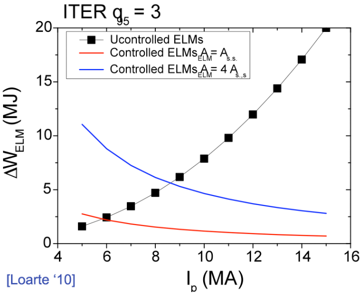
- stringent operational limits: $W_{ELM}/W_{ped} \sim 15\%$ in $\sim$ 250-500 μs

3 major players:

- **ELM energy content:** W_{ELM} ↗ when coll. ↘ *[Loarte '03, Pamela '10, Zarzoso '11]*
- **ELM energy deposition area:** does the power density ↗ when W_{ELM} ↗?
  wetted area during ELM increase with ELM size
- **peak heat load localisation:** changes during ELM *[Thomsen '10]*



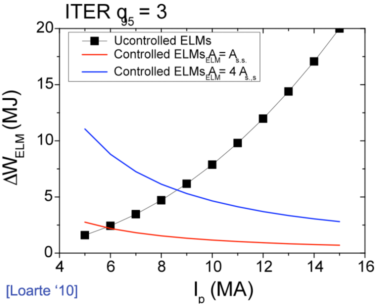
[Jakubowski '09]



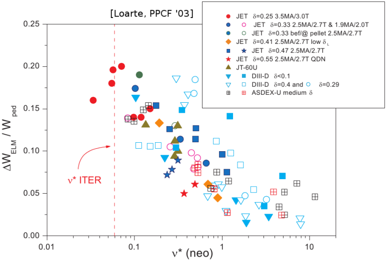
[Loarte '10]

Gr#265 ≡ study these aspects in **realistic iter geometry** and standard **[15MA, 6keV] scenario**

- Uncontrolled ELMs in ITER : $\sim$ 20MJ at 15MA, $Q = 10$
  - acceptable limit for material damage : 0.5 MJ m^{-2}, $\Delta W_{ELM}^{contr.} \sim 0.7$ MJ
- A significant broadening of ELM footprint could increase uncontrolled ELM operation from 6MA ($A_{ELM} = A_{ss}$) to 9MA ($A_{ELM} = 4A_{ss}$)
  - No large influence on ELM size limit at 15MA (small ELMs)



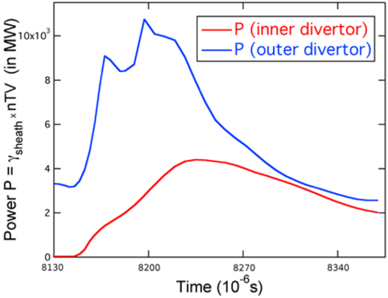
[Loarte '10]



Ongoing effort: assess energy & particle deposition for Iter

➠ realistic parameters challenging: $\nu_\star$, resistivity η, transp. anisotropy $\chi_\parallel/\chi_\perp$, size, shape. . .

- **particle loss in ELM:** ∼ 3.4%
- **energy loss in ELM:** 5MJ out of 452.5MJ ∼ 1.1% energy content
- near-symmetric power deposition for a large ELM



Resistivity	$\eta_0 = 10^{-6}$	10^{-10}
Parallel/perp. heat cond.	$\kappa_{\parallel}/\kappa_{\perp} = 810^8$	10^{11}

Diamagnetics	none
Neoclassics	none
Neutrals	none
Radiation	none
Harmonics	single [$n = 9$]
ELM cycle	single relax.

➠ what happens when relaxing some of the above limitations ?