Multi-Machine Modelling of ELMs and Pedestal Confinement: From Validation to Prediction

Stanislas Pamela

S.Saarelma, I.Lupelli, C.Maggi, C.Roach, C.Giroud, I.Chapman, A.Kirk, J.Harrison, F.Militello, S.Smith, L.Frassinetti, D.Dickinson, N.Aiba, H.Urano, G.Huijsmans, M.Becoulet, T.Eich, M.Hoelzl, A.Lessig, F.Orain, S.Futatani, SK.Kim, OJ.Kwon, JW.Ahn, F.Liu, JET Contributors & MAST team

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Outline

- Motivations
- The JOREK code
- JET simulations
- Eich scan
- Ideal & non-ideal stability
- Nonlinear stability
- The future

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- **Motivations**
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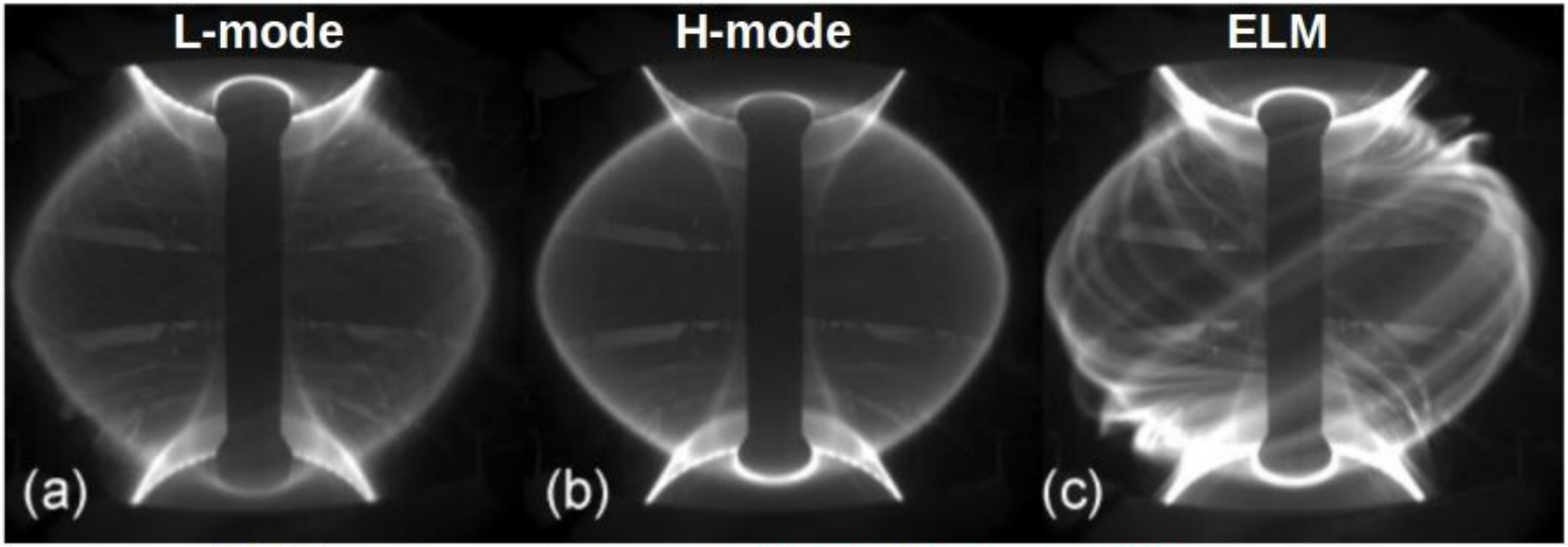
Edge-Localised Modes

- Pedestal pressure limited by MHD instabilities (ELMs)

- Good: ELMs flush impurities out of plasma
- Bad: High heat-fluxes on divertor
- Bad: They degrade confinement



MAST exp *[G.Hommen, REV SCI INSTRUM 81 (2010)]*

Edge-Localised Modes

- Pedestal pressure limited by MHD instabilities (ELMs)

- Good: ELMs flush impurities out of plasma
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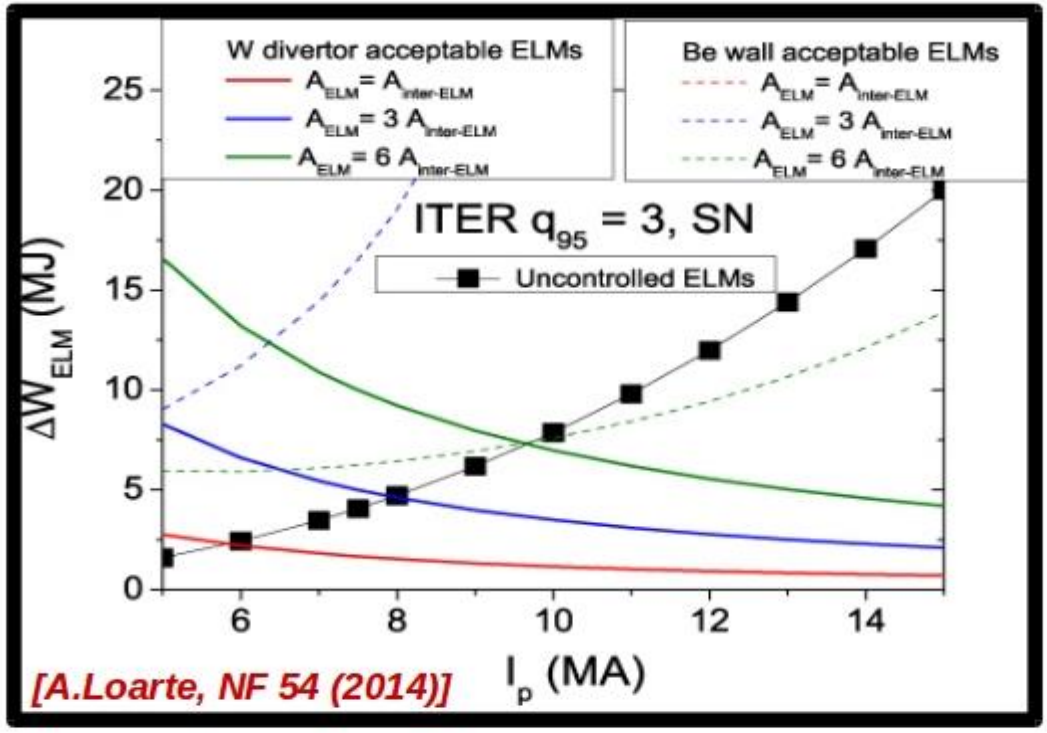
→ Need ELMs to be as small as possible (20*MW.m*$^{-2}$ limit on ITER)



[A.Loarte, NF 54 (2014)]

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The JOREK Code

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

X-point geometry :

- **Flux-aligned poloidal grid (finite Bezier elements)**
- **Fourier modes in toroidal direction**

Reduced MHD model : **(using $\eta \sim 10 \times \eta_{spitzer}$)**

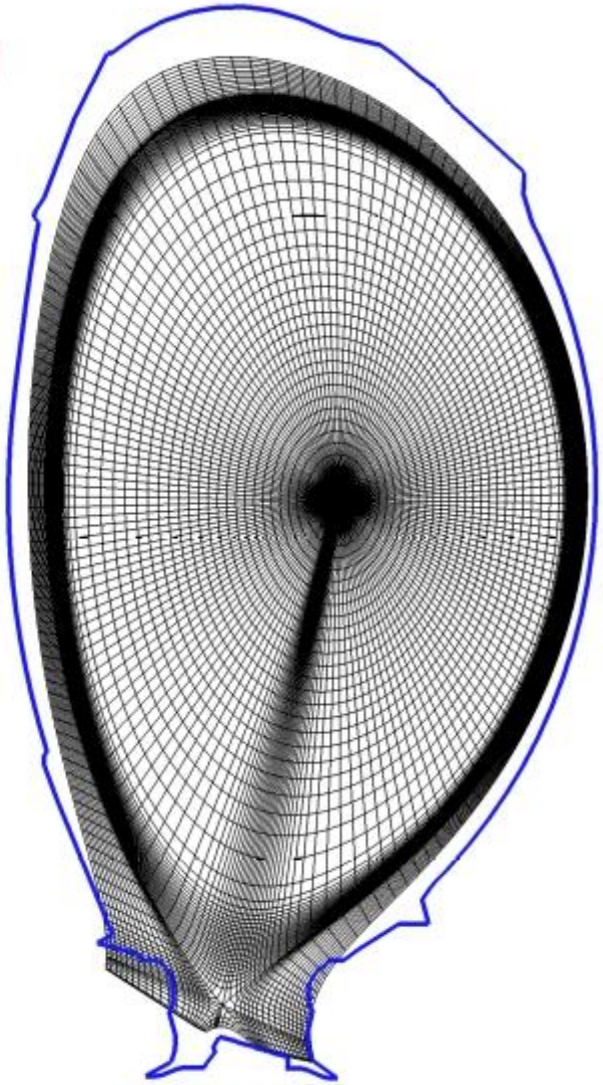
$$\rho \frac{d\vec{v}_E}{dt} = - \rho \vec{v}_{*i} \cdot \nabla \vec{v}_E - \nabla_\perp p + \vec{J} \times \vec{B} + \mu \nabla^2 (\vec{v}_E + \vec{v}_{*i}),$$

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

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

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

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



JET grid

MPI-openMP parallelisation :

- **ARCHER (UK)**
- **MARENOSTRUM (Spain)**
- **HELIOS-IFERC (Japan)**
- **MARCONI (Italy)**

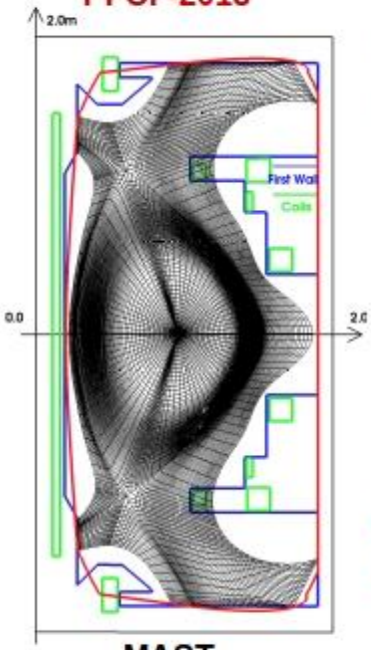
JOREK Validation

- Many devices simulated

- Different devices have different diagnostic capabilities
  → code validation must be adapted w.r.t. device

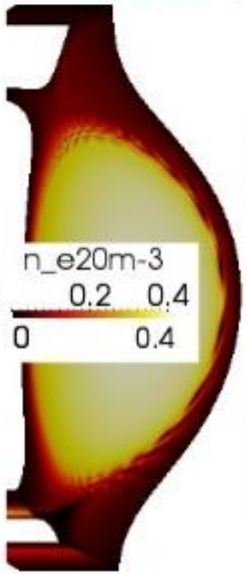
eg. - filament rotation
- X-point lobes
- divertor heat-flux
- momentum loss

S.Pamela
PPCF-2013



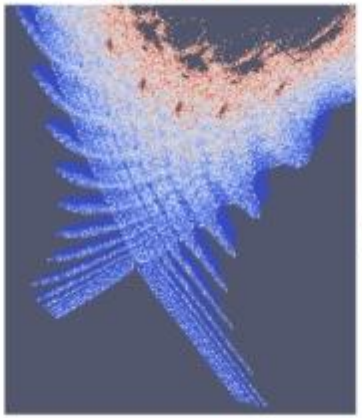
MAST

M.Becoulet
IAEA-2016



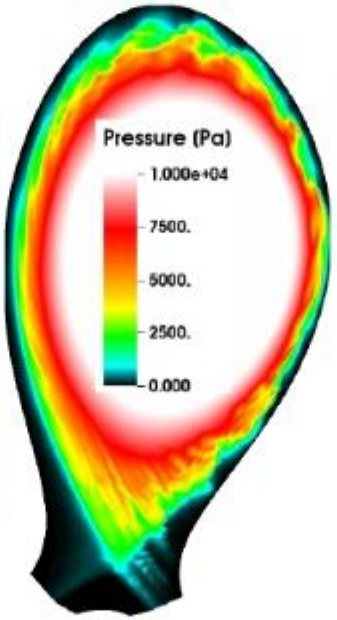
KSTAR

JW.Ahn
ITPA-2016



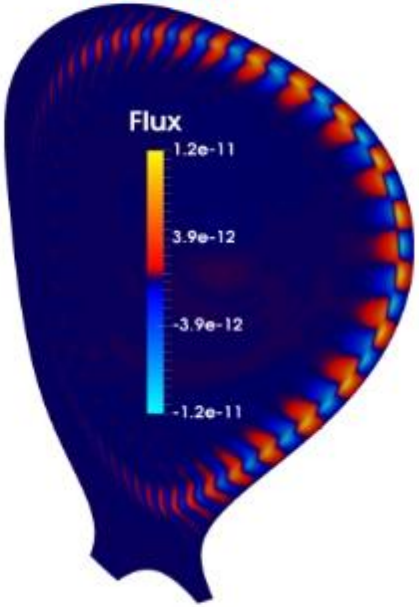
DIII-D

I.Krebs
PoP-2013



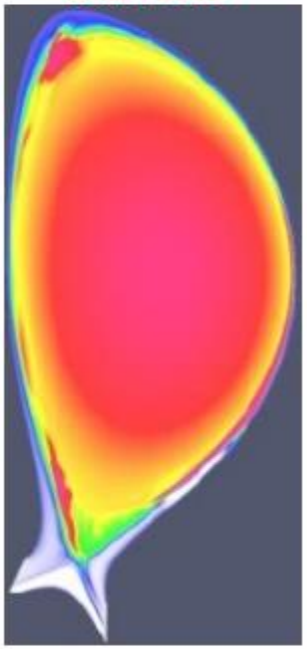
AUG

S.Pamela
IAEA-2016



JT-60U

S.Futatani
IAEA-2016



ITER

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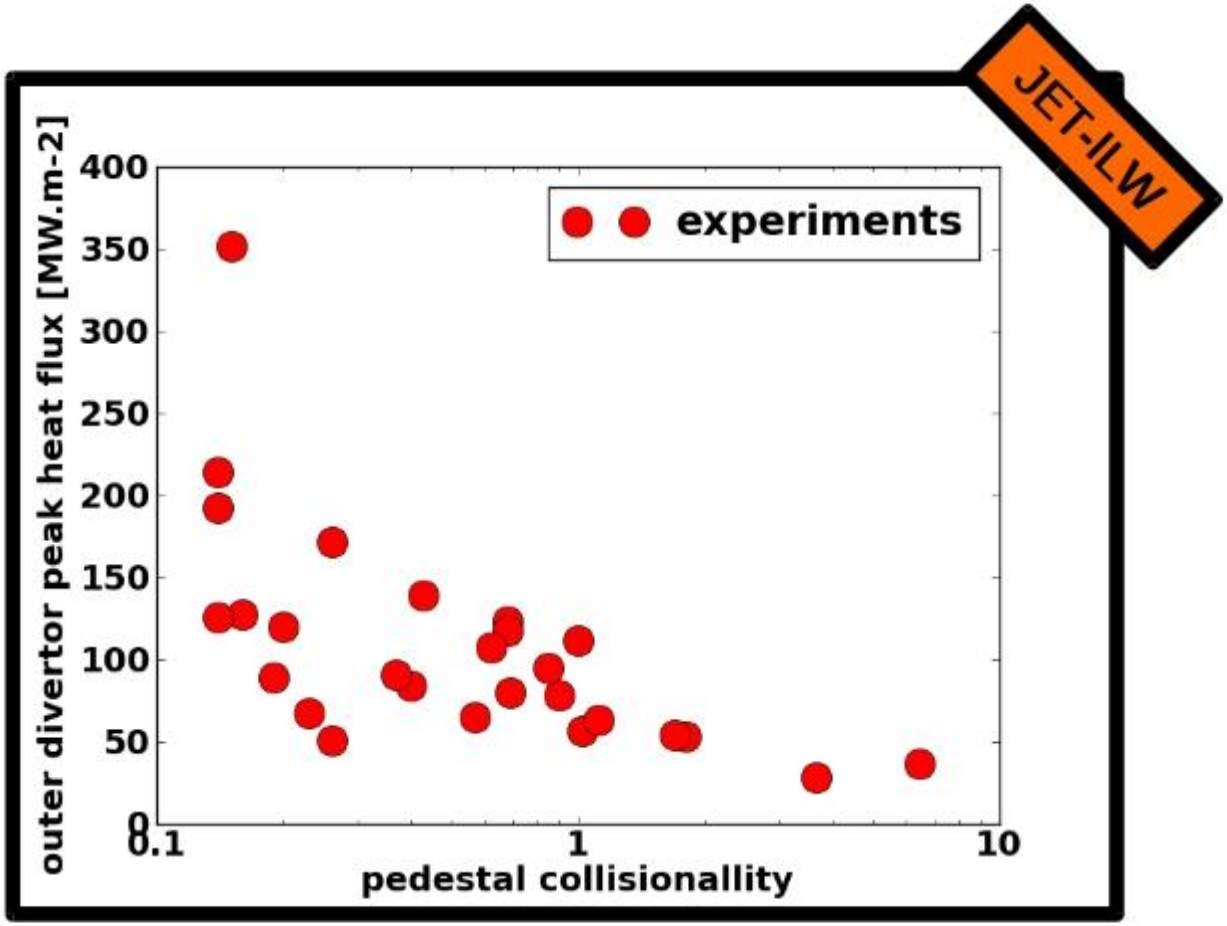
JET Divertor Heat Fluxes

- In experiments, heat flux increases at low ν^*_{ped} (IR camera)



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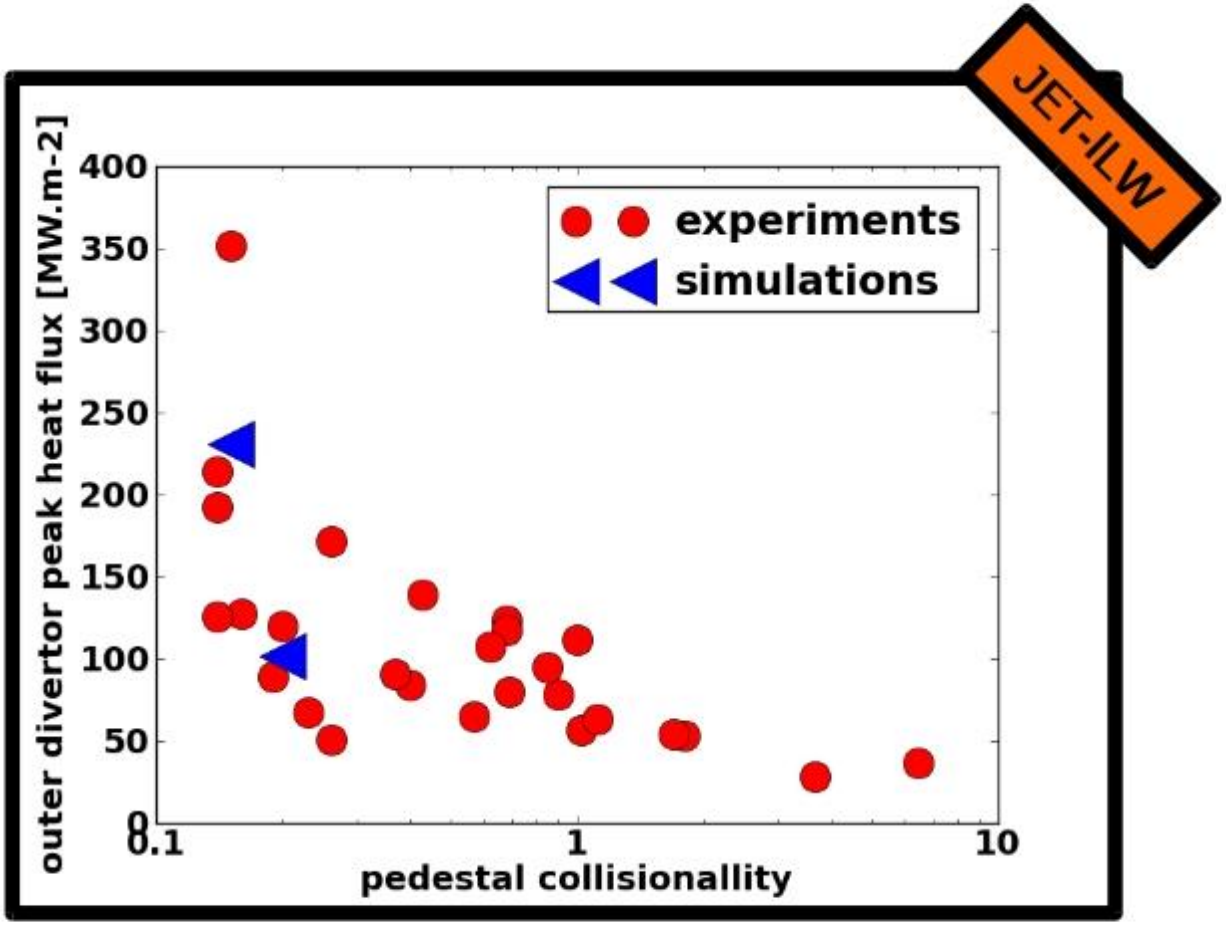
  → JOREK can describe energy transport



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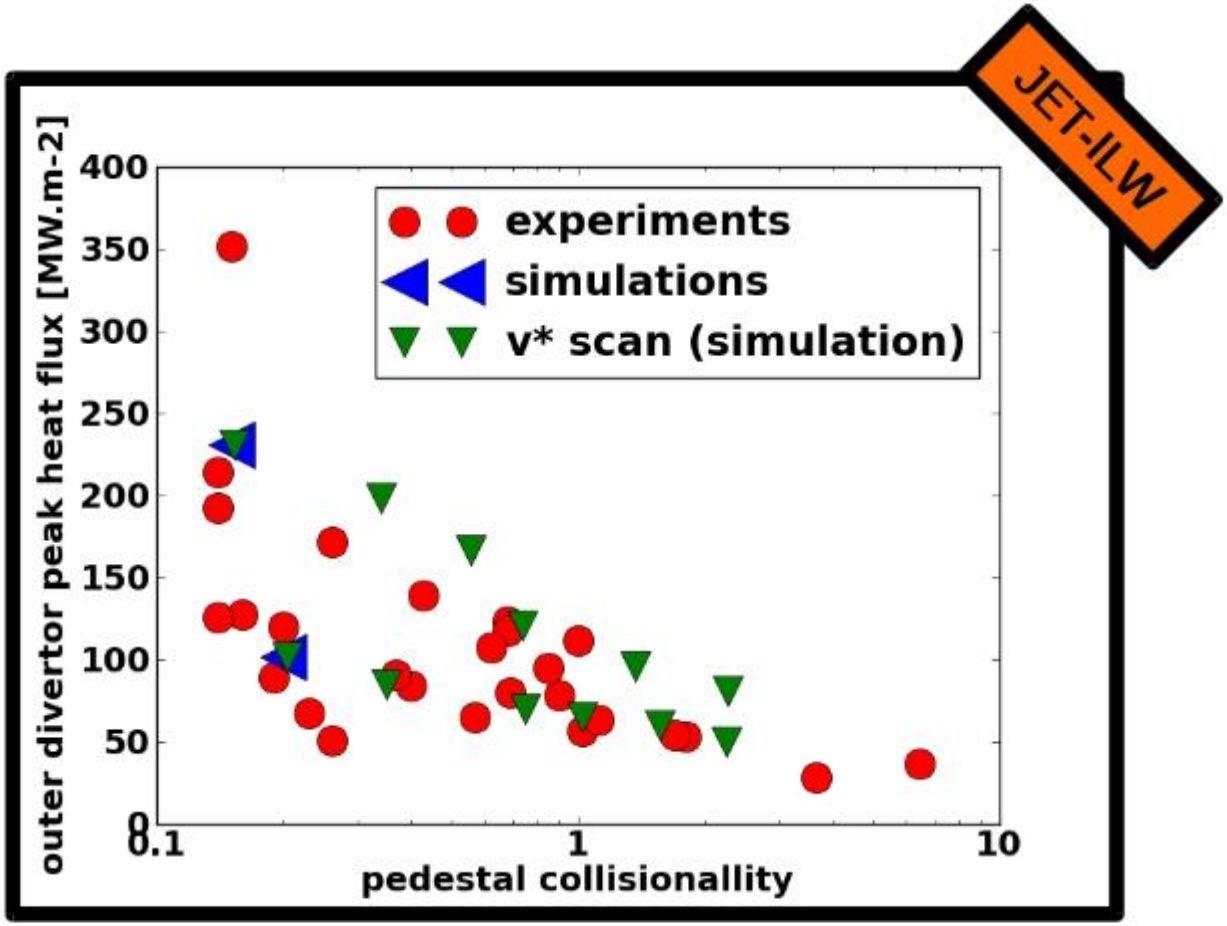

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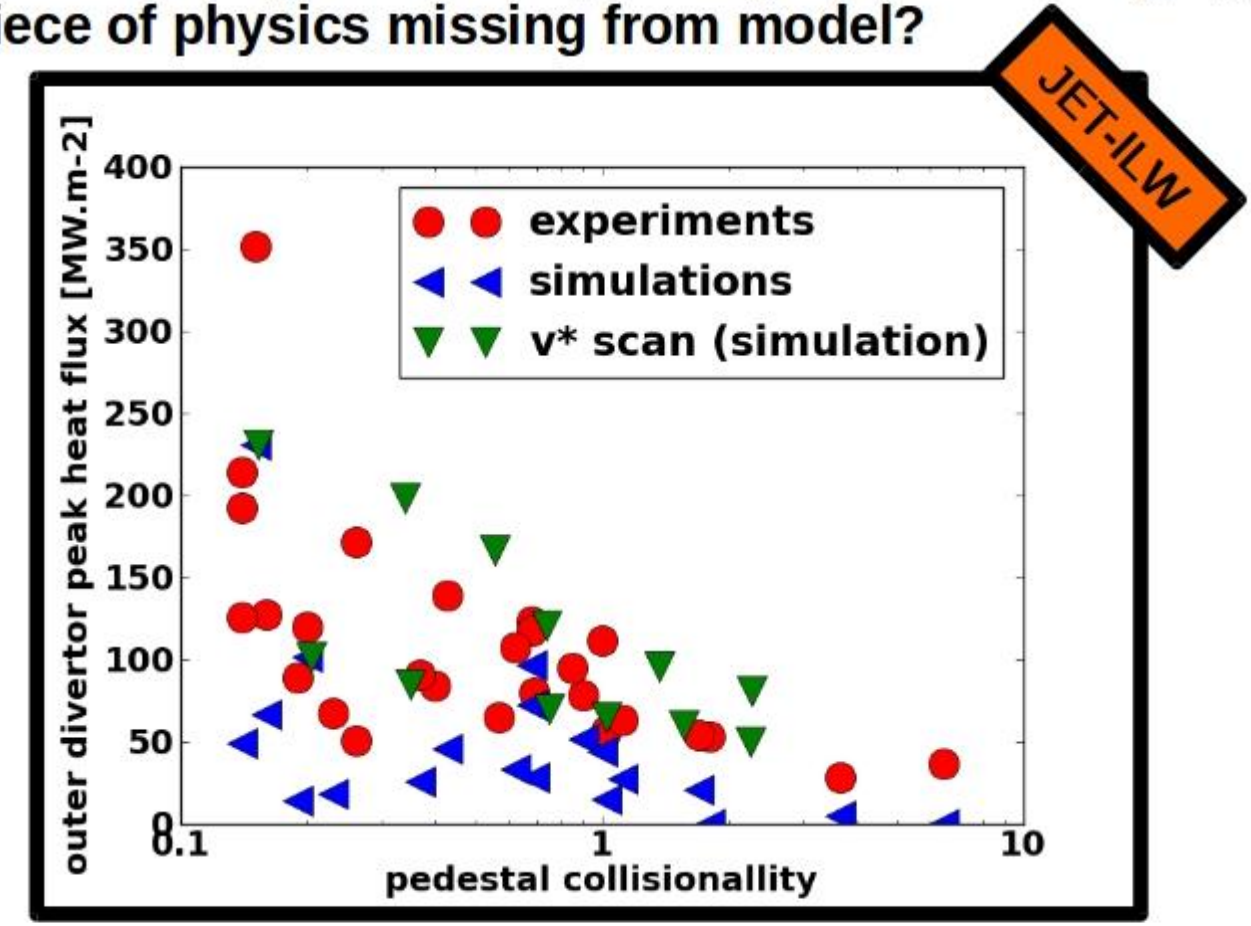
  → Piece of physics missing from model?



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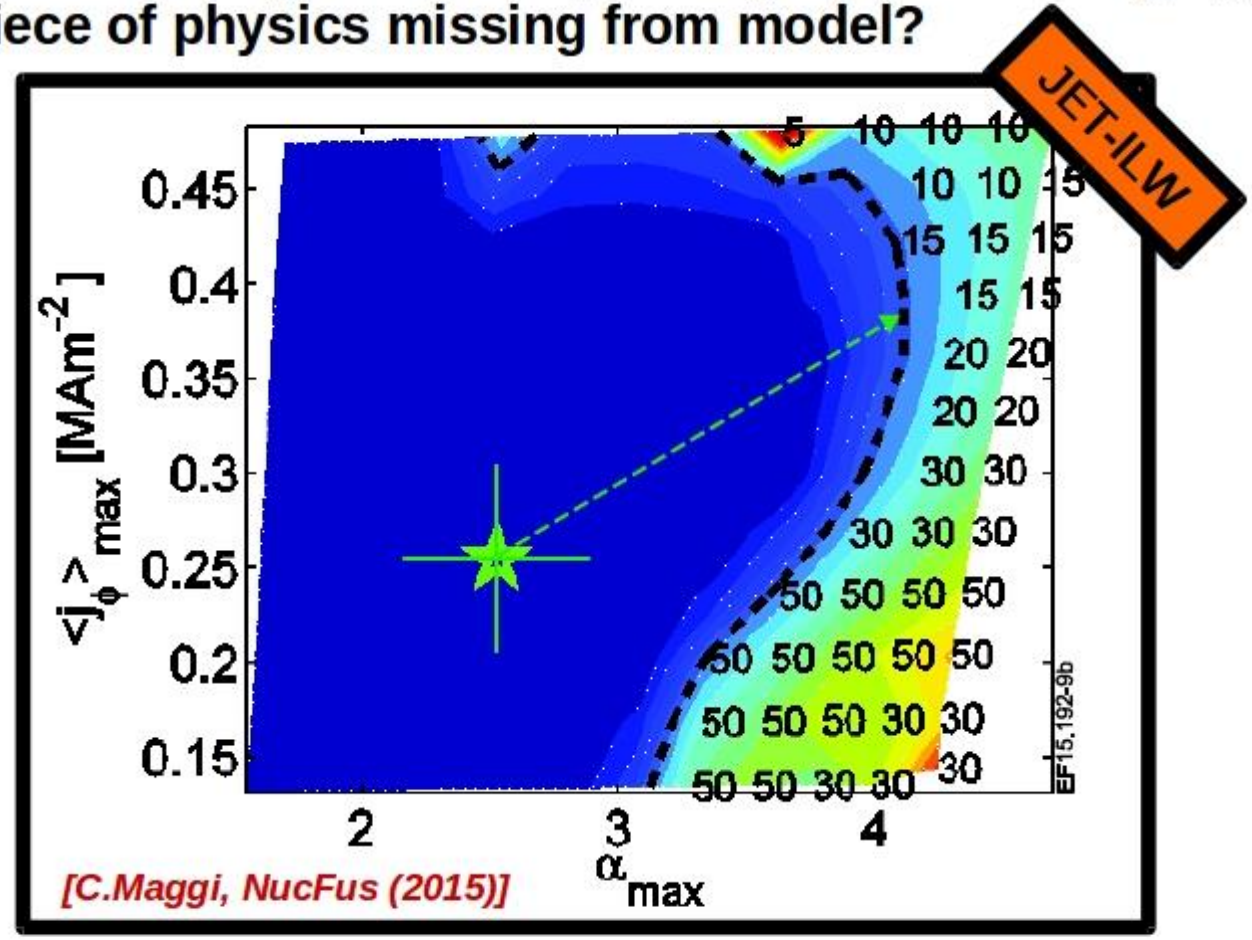

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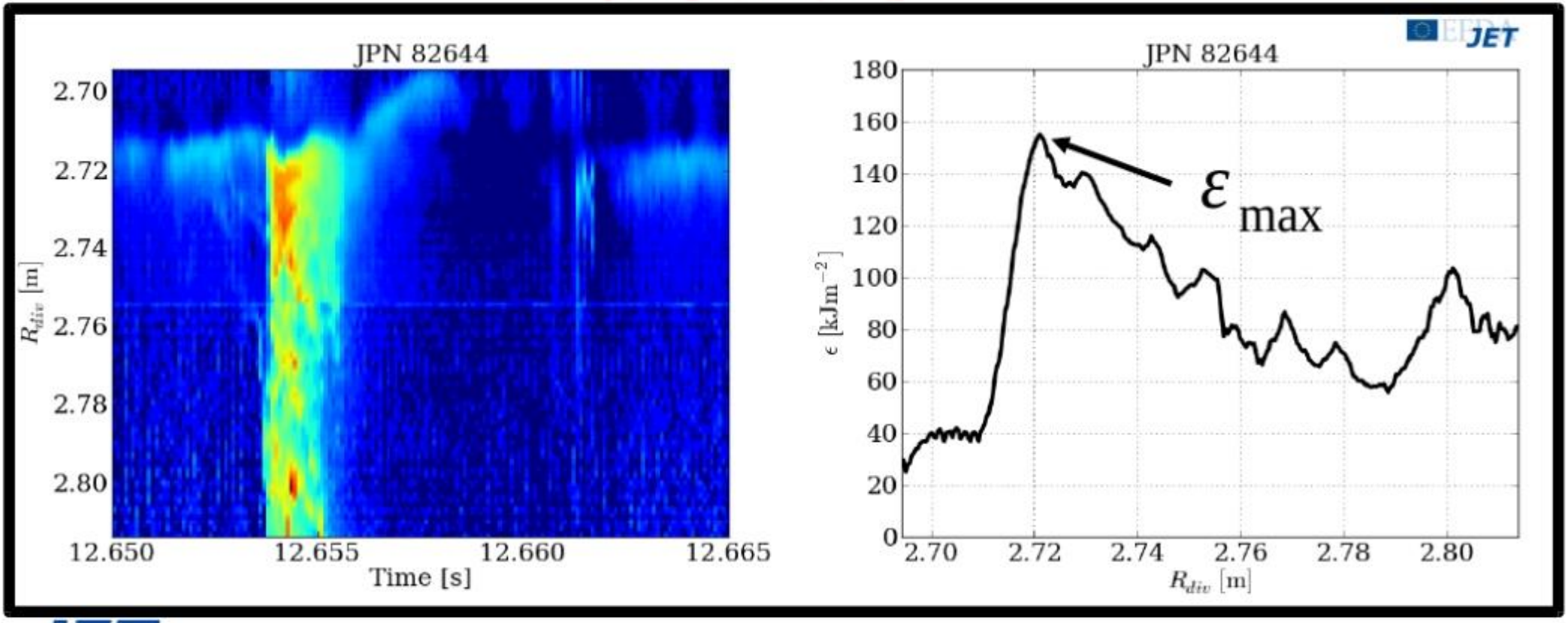
Eich Scaling: Parallel Energy ε_{II}

- Parallel energy = time integral of heat-flux

$$\varepsilon_{II} = \int_{t\_ELM} q_{II}(s,t)dt$$

[B.Sieglin, EPS (2013)]



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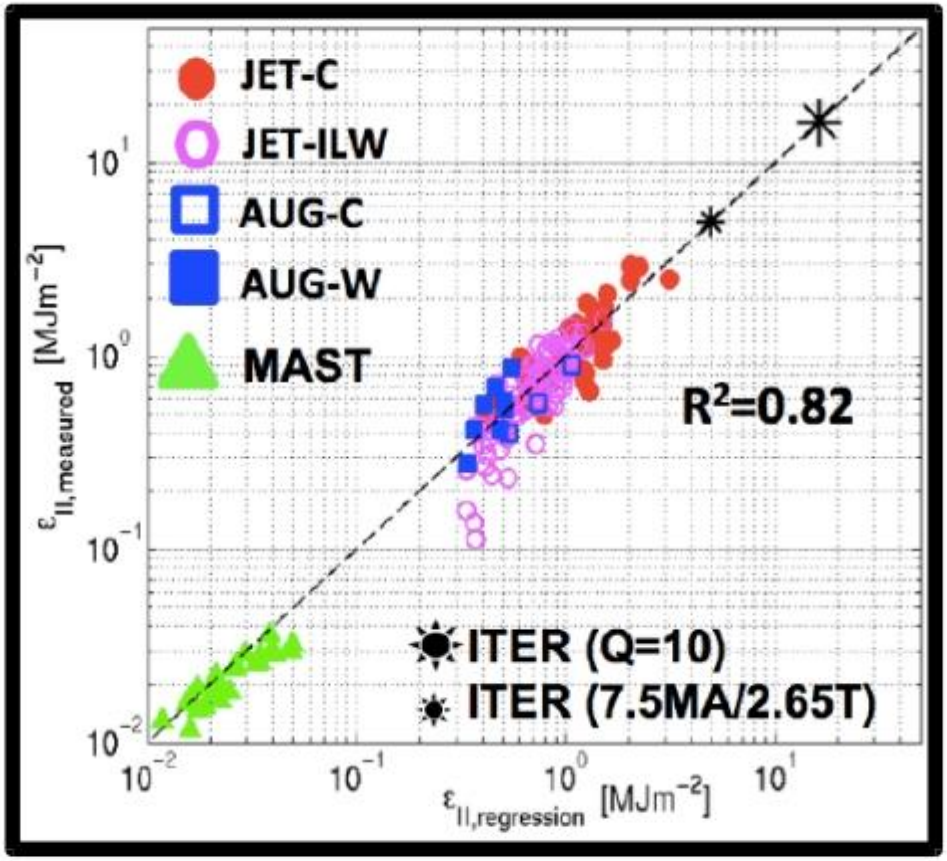
$$\varepsilon_{II} = \int_{t\_ELM} q_{II}(s,t)dt$$

- Eich Scan shows dependency on p_{ped}, $\sqrt{\Delta W_{ELM}}$ and R_{geo}

$$\varepsilon_{II} = 0.28 \pm 0.14 \frac{MJ}{m^2} \times n_{e,ped,top}^{0.75\pm0.15} \times T_{e,ped,top}^{0.98\pm0.1} \times \Delta E_{ELM}^{0.52\pm0.16} \times R_{geo}^{1\pm0.4}$$

[T.Eich, PSI (2016)]



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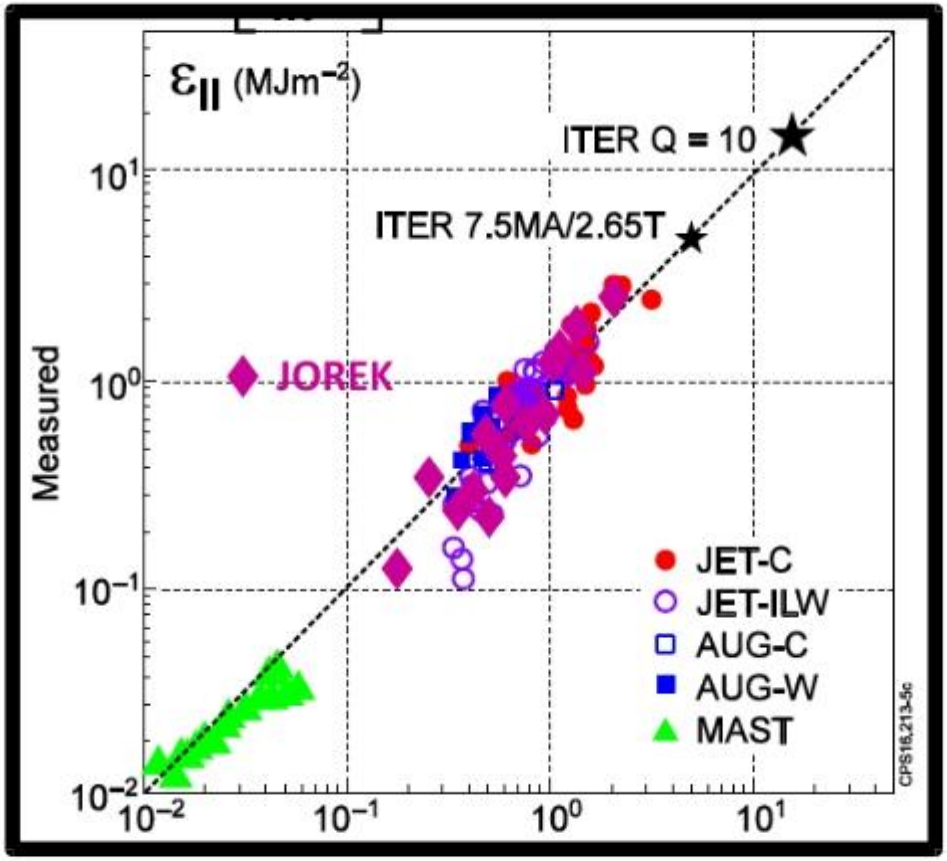

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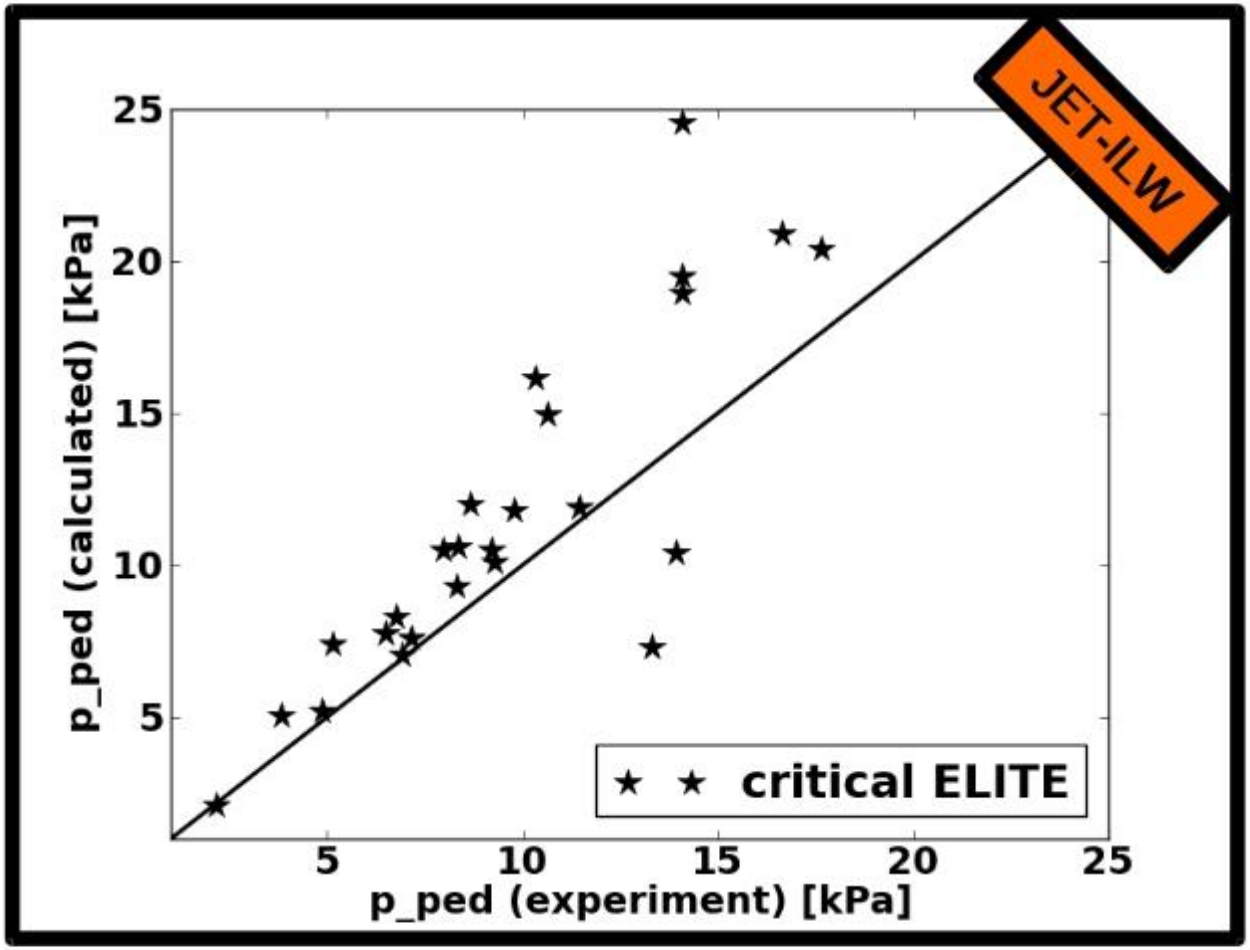
MHD Stability

- JET-ILW pre-ELM P_e^{ped}
- Discrepancy between ideal MHD and experiment



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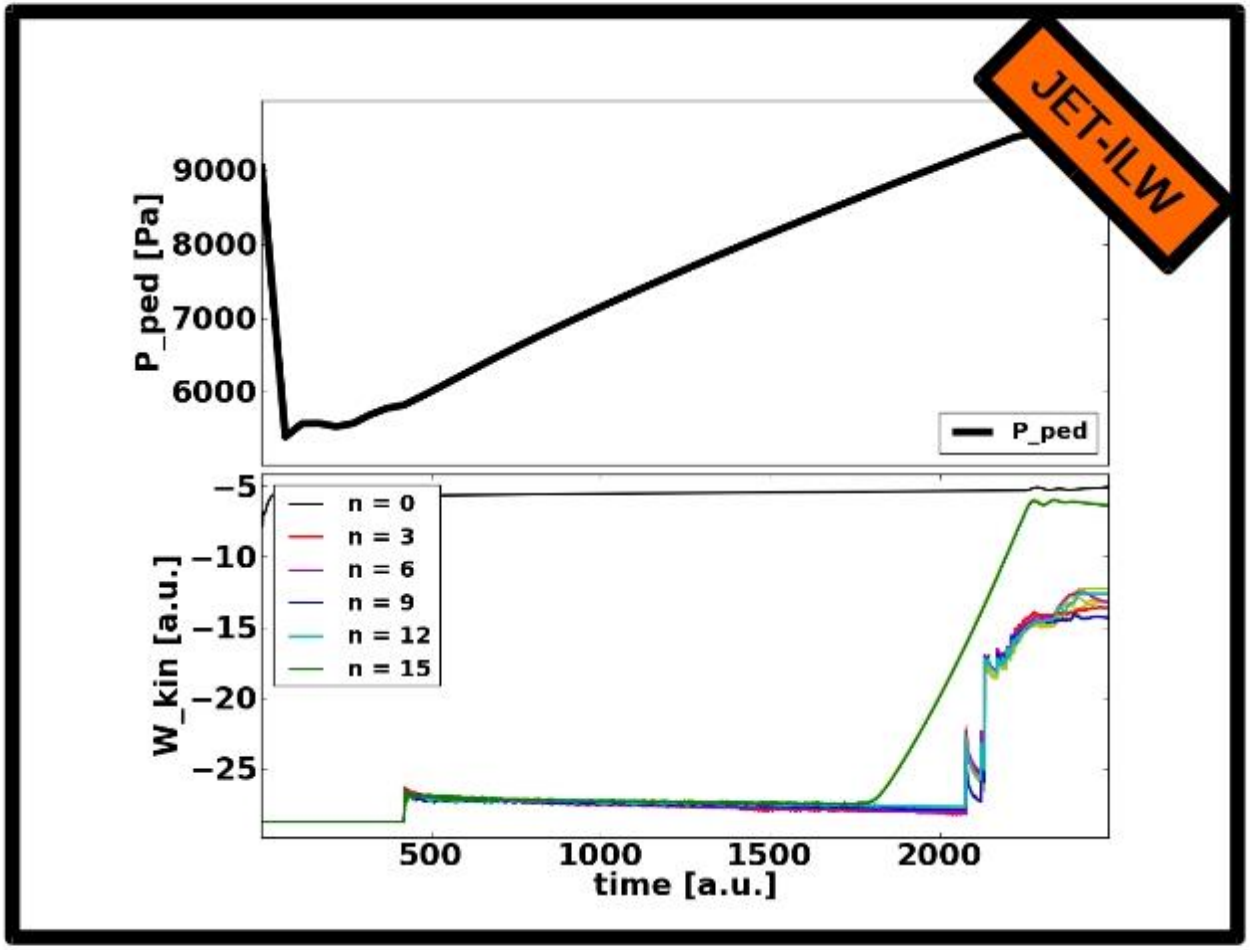
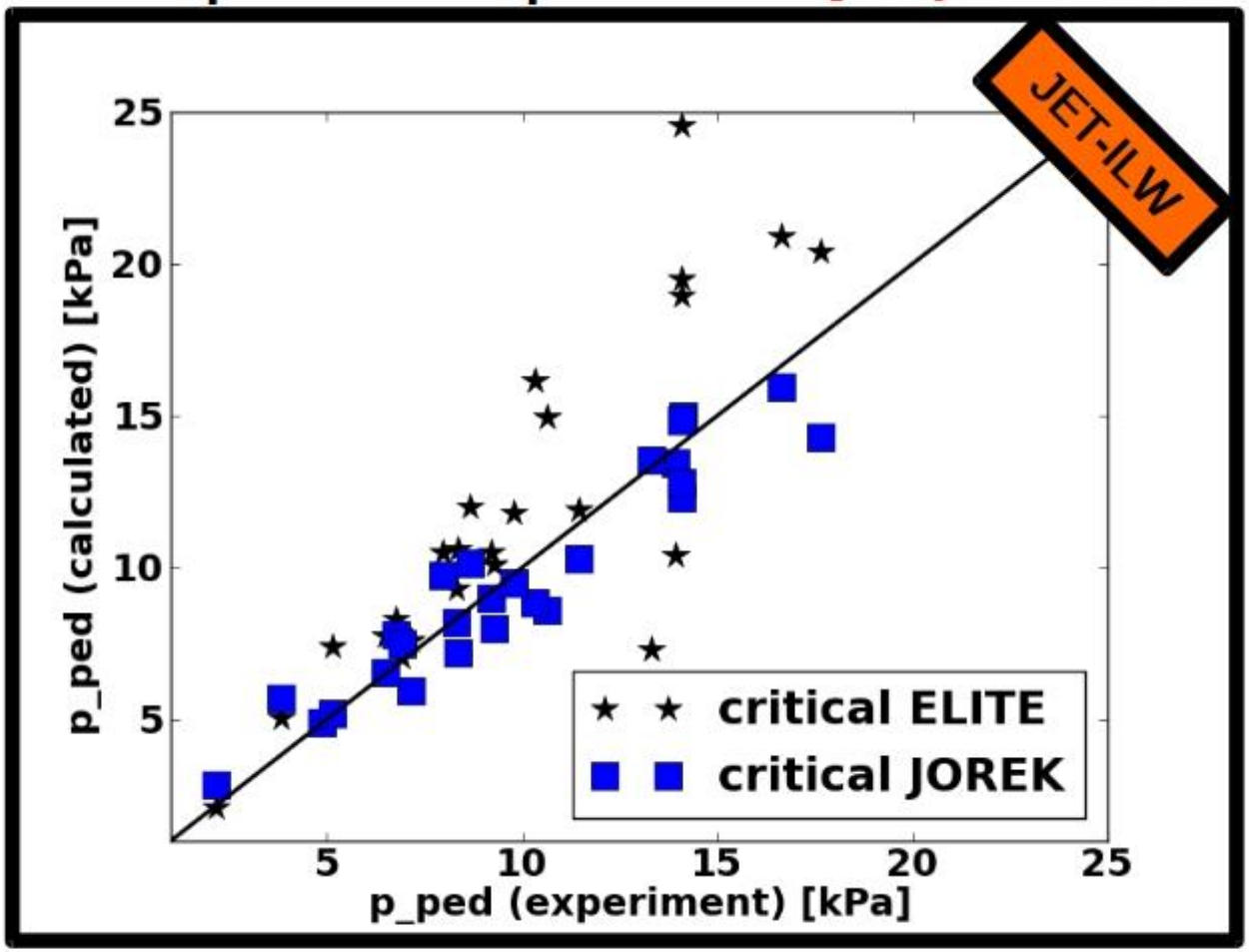
- JET-ILW pre-ELM P_e^{ped}
- Discrepancy between theory and experiment
- Non-ideal simulations (resistivity, viscosity, diamagnetic etc.)



MHD Stability

- JET-ILW pre-ELM P_e^{ped}
- Discrepancy between theory and experiment
- Non-ideal simulations (resistivity, viscosity, diamagnetic etc.)
- JOREK predicts MHD activity at experimental p_{ped}

→ Could improve EPED predictions [P.Snyder – NucFus.2011]



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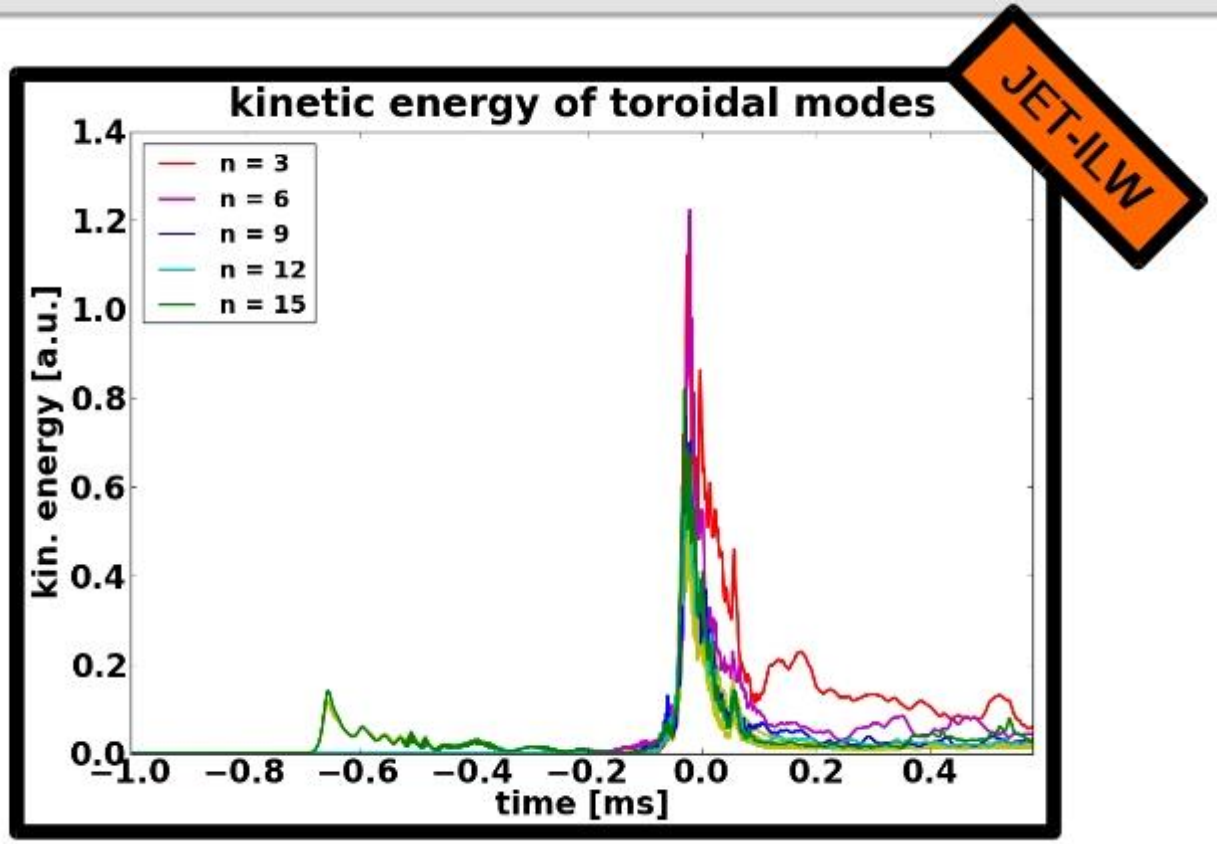
Nonlinear Mode Coupling

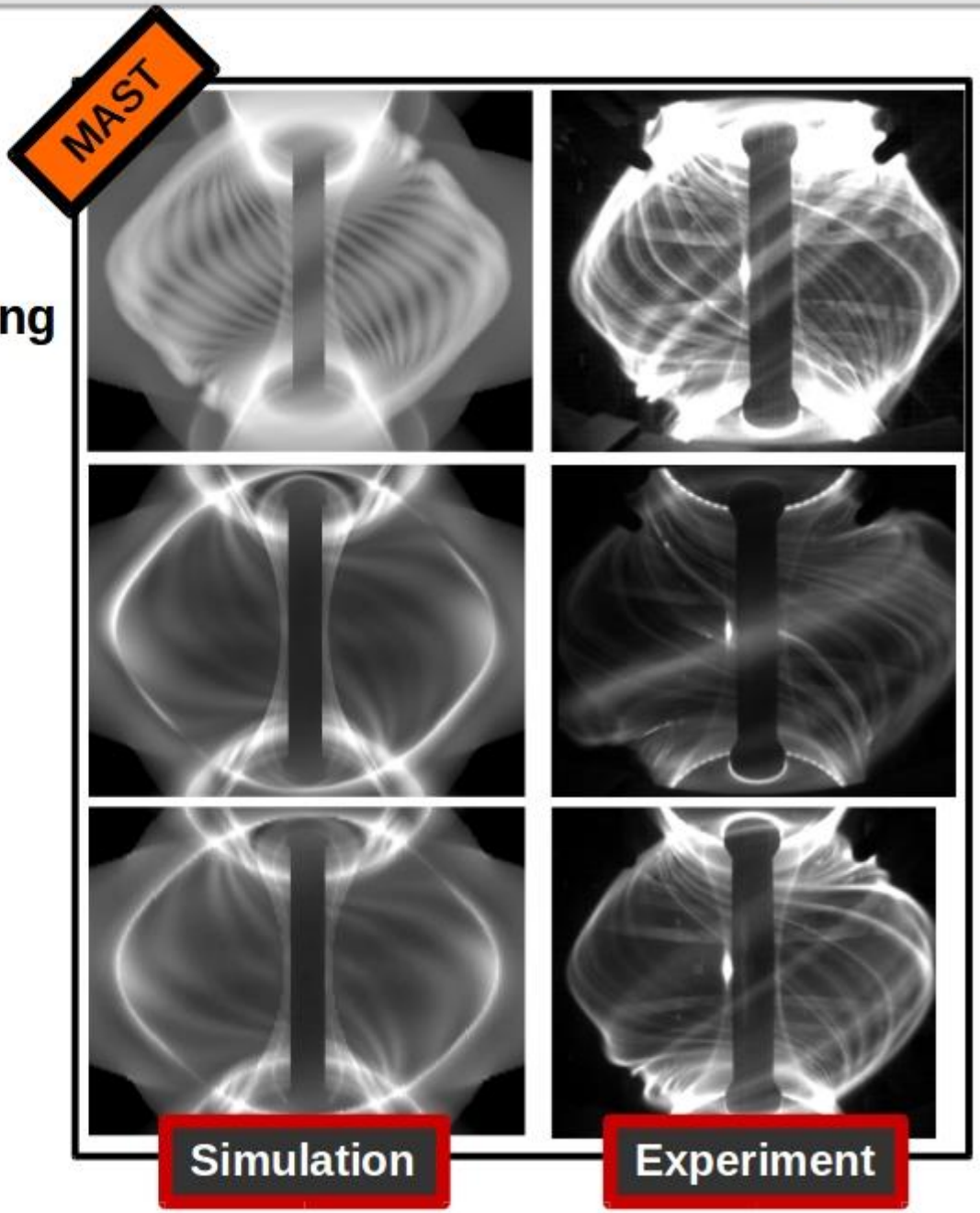


- In most cases, ELM is quasi-linear
- Nonlinear coupling could be a necessary ingredient for ELM dynamics

Nonlinear MAST Simulations

- Mode coupling needed for realistic filament structures

- Multiple filaments merge and resulting filament expelled through separatrix



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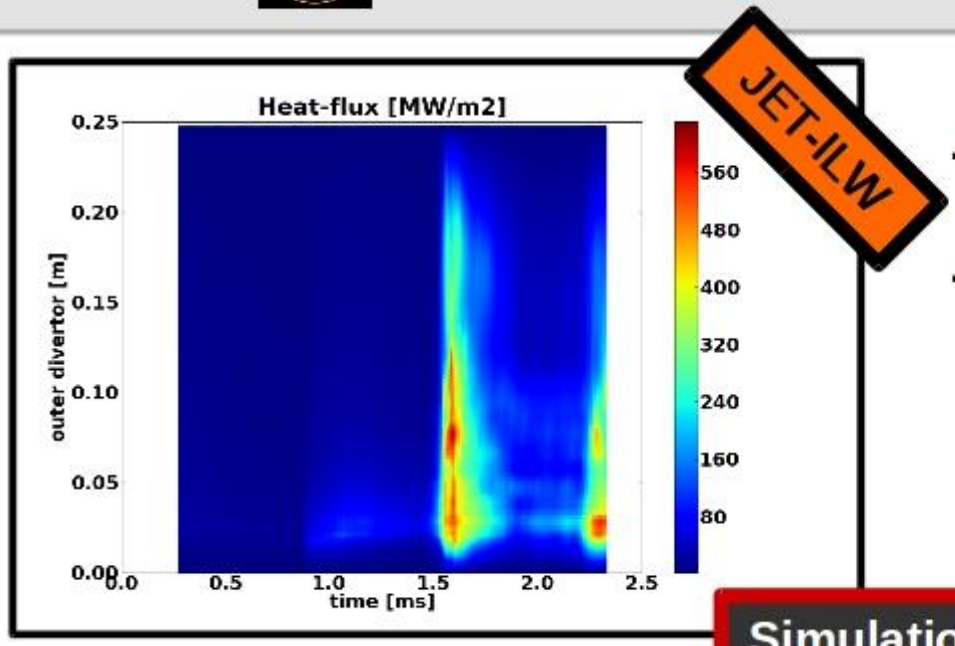
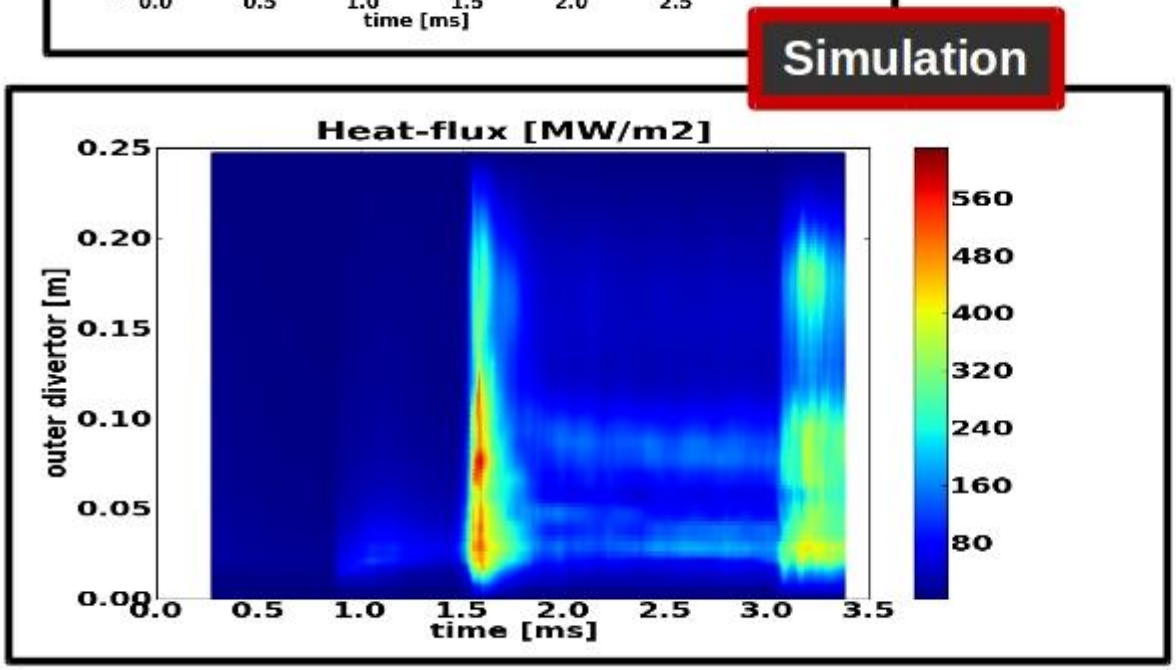
Multiple ELMs



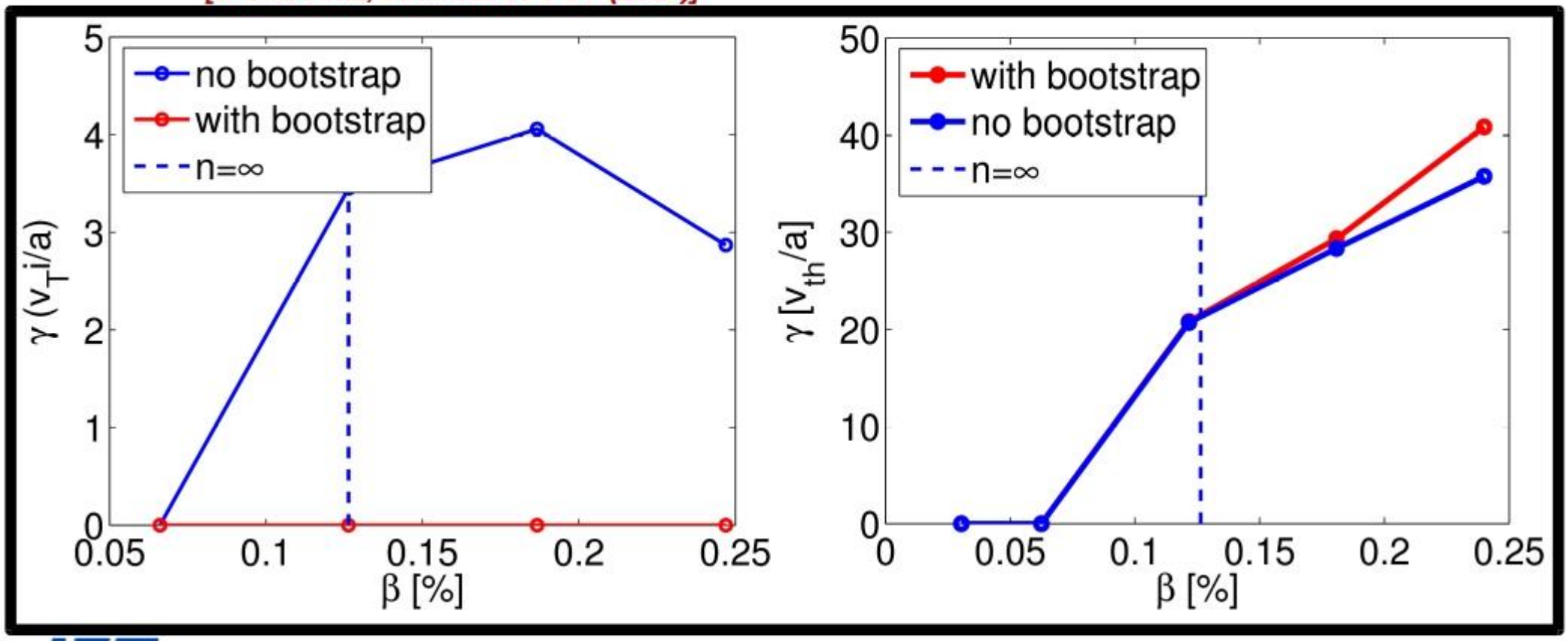
- ELM frequency depends on heating
- 2nd ELM size depends on heating



KBM Stability

MAST: The local (left) and global (right) KBM growth rates at the most unstable pedestal location as a function of β.

[S.Saarelma, submitted PPCF (2016)]



Conclusion

- Validation of JOREK under way
- The energy transport is reproduced
- ELM stability is the main issue
- Nonlinear stability could be key
- Multiple ELM-cycles are needed

Please visit www.jorek.eu