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

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

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→ Need ELMs to be as small as possible (20MW.m⁻² limit on ITER)

[Diagram showing ELM behavior with magnetic field strength and plasma current, with reference to A. Loarte, NF 54 (2014)]
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X-point geometry:
- Flux-aligned poloidal grid (finite Bezier elements)
- Fourier modes in toroidal direction

Reduced MHD model: (using $\eta \sim 10 \times \eta_{\text{spitzer}}$
\[
\frac{d\vec{v}_E}{dt} = -\rho\vec{v}_* \cdot \nabla\vec{v}_E - \nabla_\perp p + \vec{J} \times \vec{B} + \mu \nabla^2 (\vec{v}_E + \vec{v}_*),
\]
\[
\rho \frac{\partial\vec{v}_\parallel}{\partial t} = -\rho\vec{v}_\parallel \cdot \nabla\vec{v}_\parallel - \nabla_\parallel p + \mu \nabla^2 (\vec{v}_\parallel - \vec{v}_{\text{NBI}}),
\]
\[
\frac{\partial \psi}{\partial t} = \eta (j - j_A) + R [\psi, \Phi] - \frac{\delta^* R}{\rho} [\psi, p_e] - \frac{\partial \Phi}{\partial \phi} + \frac{\delta^*}{\rho} \frac{\partial p_e}{\partial \phi},
\]
\[
\frac{\partial \rho}{\partial t} = -\nabla \cdot (\rho \vec{v}_{\text{tot}}) + \nabla \cdot (D_\perp \nabla_\perp \rho) + S_\rho,
\]
\[
\rho \frac{\partial p}{\partial t} = -\vec{v}_E \cdot \nabla p - \gamma p \nabla \cdot \vec{v}_E + \nabla \cdot (\kappa_\perp \nabla_\perp T + \kappa_\parallel \nabla_\parallel T) + S_T,
\]

MPI-openMP parallelisation:
- ARCHER (UK)
- MARENOSTRUM (Spain)
- HELIOS-IFERC (Japan)
- MARCONI (Italy)
- 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
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JET Divertor Heat Fluxes

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  → JOREK can describe energy transport
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  \[\rightarrow\] Piece of physics missing from model?
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[C. Maggi, NucFus (2015)]
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Eich Scaling: Parallel Energy $\varepsilon_{II}$

- Parallel energy = time integral of heat-flux

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

[B.Sieglin, EPS (2013)]
Eich Scaling: Parallel Energy $\varepsilon_{II}$

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

$$\varepsilon_{II} = 0.28 \pm 0.14 \frac{MJ}{m^2} \times n_{e,ped,\text{top}}^{0.75 \pm 0.15} \times T_{e,ped,\text{top}}^{0.98 \pm 0.1} \times \Delta E_{ELM}^{0.52 \pm 0.16} \times R_{geo}^{1 \pm 0.4}$$

[Text Credit: T.Eich, PSI (2016)]
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MHD Stability

- JET-ILW pre-ELM $P_e^{\text{ped}}$
- Discrepancy between ideal MHD and experiment
- JET-ILW pre-ELM $P_e^{\text{ped}}$
- Discrepancy between theory and experiment
- Non-ideal simulations (resistivity, viscosity, diamagnetic etc.)
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- JOREK predicts MHD activity at experimental $p_{\text{ped}}$
  → 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
- 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
MAST: The local (left) and global (right) KBM growth rates at the most unstable pedestal location as a function of $\beta$. 

[S.Saarelma, submitted PPCF (2016)]
- 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