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 JOERK code
  www.jorek.eu
  The JOERK team
  Eurofusion ENR project
  Numerical details
  The reduced-MHD model
  Running JOERK on HELIOS-CSC

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

- Conclusion
  Summary
  Future work
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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

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

Full domain with core, SOL and X-point:
- Cubic finite-elements
- Flux-aligned poloidal grid
- Fourier series in toroidal direction
  \[G.\text{Huysmans, Nuc. Fus. 2007}\]
  \[O.\text{Czarny, Journ. Comp. Phys. 2008}\]

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
  \[P.\text{Henon, Parallel Comput. 34 (2008)}\]
Reduced MHD Model

\[ \vec{B} = \vec{B}_\phi + \vec{B}_p = \frac{F_c}{R} \vec{e}_\phi + \frac{1}{R} \nabla \psi \times \vec{e}_\phi, \]

**perp. momentum**

\[
\rho \frac{\partial \vec{v}_E}{\partial t} = - \rho \vec{v}_* \cdot \nabla \vec{v}_E - \nabla \nabla p + J \times \vec{B} + \mu \nabla^2 (\vec{v}_E + \vec{v}_*)
\]

**par. momentum**

\[
\rho \frac{\partial \vec{v}_p}{\partial t} = - \rho \vec{v}_p \cdot \nabla \vec{v}_p - \nabla \nabla \nabla p + \mu \nabla^2 (\vec{v}_p - \vec{v}_{NBII})
\]

**Ohm's law**

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

**Continuity**

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

\[ j = -R^2 \nabla \phi \cdot J = \frac{1}{\mu_0} \Delta^* \psi \]

\[ p = \rho T \]

**Energy**

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

<table>
<thead>
<tr>
<th>Job Size</th>
<th>Poloidal Elements</th>
<th>Harmonics</th>
<th>Nodes</th>
<th>Hours</th>
<th>Node Hours</th>
</tr>
</thead>
<tbody>
<tr>
<td>Typical job size:</td>
<td>20,000</td>
<td>5</td>
<td>50</td>
<td>~240</td>
<td>~12,000</td>
</tr>
<tr>
<td>Large job size:</td>
<td>30,000</td>
<td>15</td>
<td>150</td>
<td>~200</td>
<td>30,000</td>
</tr>
<tr>
<td>XL job size:</td>
<td>20,000</td>
<td>20</td>
<td>~300</td>
<td>(short tests)</td>
<td></td>
</tr>
</tbody>
</table>
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Devices Simulated

- MAST
- AUG
- JET
- KSTAR
- ITER
- DIII-D
- JT-60U
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

[Figures: Large edge pressure gradient in H-mode drives ballooning modes]
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


\[
\begin{align*}
\text{Resistive:} & \quad V_{\text{mode}} = V_{E \times B} + V_\parallel \cdot b_\theta \\
\text{Ideal:} & \quad V_{\text{mode}} = V_{E \times B} + V_\parallel \cdot b_\theta + V_i^*/2.
\end{align*}
\]
Filament Rotation

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

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)]
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 DIII-D
- 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:
\[
\frac{\partial(\rho T)}{\partial t} = -v \cdot \nabla(\rho T) - \gamma \rho T (\nabla \cdot v) + \nabla \cdot (\kappa_\perp \nabla_{\perp} T + \kappa_\parallel \nabla_{\parallel} T) + \frac{2}{3R^2} \eta_{\text{Spitzer}} J^2 - \xi_{\text{ion}} \rho_n R_{\text{ion}}(T) - \rho \rho_n L_{\text{rays}}(T) - \rho^2 L_{\text{brem}}(T)
\]

Neutral density:
\[
\frac{\partial \rho_n}{\partial t} = \nabla \cdot (D_n : \nabla \rho_n) - \rho \rho_n R_{\text{ion}}(T) + \rho^2 R_{\text{rec}}(T) + S_n
\]

- 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
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

ITER simulations of ELMs, RMPs and pellets published.

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

[F.Orain, PoP 20 (2013)]
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 DIII-D
- 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:

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- The opinions expressed in this presentation do not necessarily state or reflect those of ITER Organisation.
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