High Performance Computing for Non-linear MHD Simulations for Fusion Plasmas

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What makes stars shine?

"The starry night", V. Willen van Gogh

Can we use the energy of shining stars as an alternative energy source?
What makes stars shine? – Nuclear fusion

\[ E = mc^2 \]

D + T \rightarrow He^{++} + n

E = \Delta mc^2

[nasa.gouv]
Outline

Introduction
- Plasma / Fusion reactor / ITER Project

Physics background
- What is ELM?
- JOREK - Nonlinear MHD code
  - www.jorek.eu
  - The JOREK team and themes
  - Numerical details and physics model
  - Mechanism of pellet triggered ELM

JOREK Modelling of pellet triggered ELM

Conclusions and Perspectives
What is plasma?

For achievement the fusion → Plasma state is needed

- Plasma is the 4th state of matter, obtained at high temperature (>10^5 degrees)
- Plasma is an ionized gas which consists of ions and electrons.
Galaxy fusion reactor in the universe

Key parameters for the fusion = high-temperature and high-density

How can we confine the high-temperature plasma?

- In **stars**: plasma particles are confined mainly by *gravity*.
Fusion reactor on Earth

Key parameters for the fusion = high-temperature and high-density

⇒ How can we confine the high-temperature plasma?

- On Earth: plasmas can be confined in Magnetic field lines = Magnetic Confinement

• Charged particles spiral around magnetic field lines.

• Toroidal (Donut shaped) system avoids plasma hitting the end of the container

⇒ Tokamak
Fusion plasma reactors in the world

Tokamaks and Stellarators (not listed all here) in the world

- JET (EU) and MAST (UK)
- TJ-II (Spain)
- LHD and JT60U (Japan)
- Wendelstein 7-X (Germany)
- ITER (international project)
What is ITER? [www.iter.org]

ITER is a major international collaboration in fusion energy research involving China, the EU (plus Switzerland), India, Japan, the Russian Federation, South Korea and the United States.
Overview of the ITER Tokamak Pit

Drone view of the tokamak pit and bioshield construction

[Figure from Pinches, ITER Organization]
Eruption of high temperature plasma

= solar flares (for sun)

= ELMs (for Magnetically confined plasma)

⇒ Big challenge for the control of the plasma
Edge Localized Modes (ELMs)

- Fusion plasma has a strong pressure gradient at the plasma boundary.

- Edge pressure gradient is limited by an MHD instability (ballooning mode)
  - A crash of the edge profile occurs
  - Release of hot plasmas onto a plasma facing components
  - ELM removes up to 10% of the plasma energy in ~200 microseconds
  - Periodic and bursty behaviors

[Figure from Pitts, ITER Organization]
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*Fast camera image of ELM (MAST) [A. Kirk et al.]*
Edge Localized Modes (ELMs)

ELMs lead to a large erosion of and a limited lifetime of the plasma facing components. Requires physics understanding of ELMs and ELM control.

- Techniques to control ELM:
  - stabilisation by external magnetic perturbations
  - triggered by pellet injection (pellet: deuterium solid ice cube)
  - Etc…

[Linke 2007]
Demonstration of ELM pacing by pellets without fueling

- Pellets can control the ELM frequency
- Heat flux of the pellet triggered ELMs on the fusion reactor wall becomes small.

Theoretical and Numerical Modelling studies are needed.
Non-linear MHD code JOREK

- **JOREK** has been developed with the specific aim to simulate ELMs, developed by Dr. G. Huijsmans (CEA/Univ. Eindhoven).
  - See [https://www.jorek.eu/](https://www.jorek.eu/)

**The JOREK Code**

The non-linear extended MHD code JOREK resolves realistic toroidal X-point geometries with a C1 continuous flux-surface aligned grid including main plasma, scrape-off layer and divertor region. It is based on robust fully implicit numerics, and includes divertor boundary conditions, 3D resistive wall effects, two-fluid effects and neoclassical flows.

The well established physics and numerics community around JOREK has strong connections to the relevant experiments, ITER Organization and the respective ITPA Topical Groups.

**Key Physics Applications**

- **Edge Localized Modes (ELMs)** including pellet ELM triggering, ELM mitigation and suppression via RMP fields, vertical kick ELM triggering, OH-Mode, impurity transport
- **Disruptions** including massive gas injection, shattered pellets, vertical displacement events (VDEs), runaway electrons, tearing mode seeding and suppression
Non-linear MHD code JOREK

- European Enabling Research Project (PI: M. Hoelzl)
- JOREK collaborations (>30 members, >10 international institutions):
  - JOREK main development and application
    - Involved institutes: CEA, IPP Garching, ITER, CCFE, Eindhoven, UPC etc.
  - Pellet triggering of ELMs / Shattered pellets for disruption
    - S. Futatani, D. Hu etc.
  - ELM mitigation/suppression by external fields
    - F. Orain, M. Becoulet, K. Wittawat, M. Hoelzl, etc
  - Full orbit particle tracer
    - D. Van vugt, A. Dvornova, C. Somariva, etc.
  - Disruptions (MGI, REs, etc)
    - E. Nardon, C. Sommariva, V. Bandaru, M. Hoelzl, D. Meshcheriakov, F. Wieschollek, etc
  - Simulation of ELMs
    - G. Huijsmans, S. Pamela, M. Becoulet, F. Orain, M. Hoelzl, A. Cathey etc
  - Solvers (PaStiX, HIPS, Interface MURGE)
    - P. Ramet, P. Henon, X. Lacoste, Univ. Bordeaux/INRIA
  - Full MHD model/numerical methods
    - B. N’Konga, G. Huijsmans, H. Guillard, S. Pamela
  - Resistive Wall/Free boundary version (VDEs, RWMs, vertical kicks, ...)
    - M. Hoelzl, J. Artola-Such, etc
  - Numerical methods
    - B. N’Konga, E. Sonnendruecker, H. Guillard, E. Franck etc
Non-linear MHD code JOREK

- Numerical features:
  - Discretisation: Xpoint geometry
    - Cubic finite elements flux-aligned poloidal grid
    - Fourier series in toroidal angle
  - Time stepping:
    - fully implicit Crank-Nicholson
    - Solver sparse matrices (PastiX library)
    - GMRES iterative solver with physical preconditioner
  - Parallelisation using MPI/OPENMP
    - ~30000 poloidal elements
    - Typically 1880-3800 cores
- MareNostrum III (BSC), Marconi-Fusion (CINECA), HELIOS-IFERC (Japan), CURIE (France), hydra (Germany), etc
Non-linear MHD code JOREK

- Reduced MHD model (JOKE also has the full MHD model).
- Braginskii parallel conductivity
  \[ \kappa_\parallel \sim T^{5/2} \]
- Spitzer resistivity
  \[ \eta \sim T^{-3/2} \]
- Mach-1 boundary condition, free flow on divertor target
  \[ \mu \sim T^{-3/2} \]

- Magnetic field and the velocity
  \[ B = \left( \frac{F_0}{R} \right) e_\varphi \left( \frac{1}{R} \right) \nabla \psi(t) \times e_\varphi \]
  \[ \mathbf{v} = -R \nabla u(t) \times e_\varphi + \mathbf{v}_\parallel(t) \mathbf{B} \]

- Mass density
  \[ \frac{\partial \rho}{\partial t} = -\nabla \cdot (\rho \mathbf{v}) + \nabla \cdot (D_{\perp} \nabla_{\perp} \rho) + S_\rho \]

- Poloidal momentum (vorticity)
  \[ e_\varphi \cdot \nabla \times \left( \rho \frac{\partial \mathbf{v}}{\partial t} = -\rho (\mathbf{v} \cdot \nabla) \mathbf{v} - \nabla (\rho T) + \mathbf{J} \times \mathbf{B} + \mu \Delta \mathbf{v} \right) \]

- Parallel momentum
  \[ B \cdot \nabla \times \left( \rho \frac{\partial \mathbf{v}}{\partial t} = -\rho (\mathbf{v} \cdot \nabla) \mathbf{v} - \nabla (\rho T) + \mathbf{J} \times \mathbf{B} + \mu \Delta \mathbf{v} \right) \]

- Temperature
  \[ \frac{\partial (\rho T)}{\partial t} = -\rho \mathbf{v} \cdot \nabla T - T \mathbf{v} \cdot \nabla \rho - \gamma \rho T \nabla \cdot \mathbf{v} + \nabla \cdot (\kappa_{\perp} \nabla_{\perp} T + \kappa_\parallel \nabla_{\parallel} T) + S_T \]

- Poloidal flux
  \[ \frac{1}{R^2} \frac{\partial \psi}{\partial t} = \eta(T) \nabla \cdot \left( \frac{1}{R} \nabla_{\perp} \psi \right) - B \cdot \nabla u \]
Pellet model and implementation in JOREK

- Realistic pellet ablation model (NGS model [Gal, NF(2008)]) is implemented in JOREK:
  - Pellet moves at fixed speed and direction
  - Pellet is modelled as an adiabatic localized time-varying density source

\[ N' = 4.12 \times 10^{16} \cdot r_p^{1.33} \cdot n_e^{0.33} \cdot T_e^{1.64} \]

- JOREK simulations have been performed with HELIOS (IFERC-CSC, Japan) and Mare Nostrum (BSC-CNS, Barcelona).
Mechanism of pellet triggered ELM

- Density Perturbation
- Temperature
- Pressure perturbation
- Pressure

JOREREK simulation by S. Futatani
ITER 15MA/5.3T Q=10 plasma

According to the design of future ITER pellet injector, four sizes are studied:
- $4.0 \times 10^{21} \text{D}$,
- $3.0 \times 10^{21} \text{D}$,
- $2.0 \times 10^{21} \text{D}$,
- $1.0 \times 10^{21} \text{D}$

The pellet injection speed is 300m/s. The pellet injection from Xpoint region is presented.

Pedestal pressure leading to spontaneous ELM is 150kPa.

112.5 kPa of the marginal stability limit between stable and unstable.

75 kPa of the pedestal pressure is very stable.
Plasma dynamics after the pellet injection
(example movie of JET plasma)

JOREK simulation of JET plasma (#84690)
by S. Futatani (BSC-CNS)

1.1mm pellet
1.7mm pellet
The time evolution of the plasma energy, for $4.0 \times 10^{21} \text{D}$, $3.0 \times 10^{21} \text{D}$, $2.0 \times 10^{21} \text{D}$, $1.0 \times 10^{21} \text{D}$.

The magnetic energies evolution ($n=8-10$) shows there is a big difference between $4.0 \times 10^{21} \text{D}$ and $2.0 \times 10^{21} \text{D}$. $\rightarrow$ The threshold of the pellet size to trigger an ELM.

Need to wait the case of $3.0 \times 10^{21} \text{D}$ in order to find the threshold precisely.
The density plot and the potential contours of the largest pellet $4.0 \times 10^{21}$D are shown.

The destabilization of the plasma by the pellet injection can be observed.
The maximum values of the sum of the high-\(n\) modes (\(n=6-10\)) of magnetic energy are plotted as a function of the pellet size.

There is a big difference between \(4.0 \times 10^{21} \text{D}\) and \(2.0 \times 10^{21} \text{D}\).

The threshold of the pellet size to trigger an ELM.
Toroidally asymmetric heat flux on the divertor target caused by a pellet triggered ELM

This is consistent with the result of JOREK simulation of JET plasma and DIII-D plasma [Futatani, NF 2014; IAEA 2016].
Conclusions

• JOREK has been performed to study the non-linear MHD physics.
• JOREK allows us to compute the ELM physics and calculate the heat flux onto the plasma facing components.
• Qualitative agreements with the experiment results of JET are observed via simulation.
• The simulations has been performed for ITER size plasma, the results show the qualitative agreement with JET simulation

Future works

• JOREK pellet simulation will be performed including more physics effects to allow for a more quantitative comparison.
• Further development of the optimization of JOREK will be carried out.
Appendix : What is fusion?

Fission (energy source for these 50 years)

Fusion (it’s going to work…)

Advantages of nuclear fusion:
(1) Fuel supply is water, therefore no resources problem.
(2) Fusion is "cleaner" than fission, i.e. less radioactive by-products. Good for environments.
(3) Better control of the nuclear reactions, i.e. fusion can be stopped at any moment by switching off the plasma

Disadvantages of nuclear fusion:
- Technical and financial difficulty to achieve.... (Fusion power plant costs a lot...!)
- Physics problems (plasma instabilities, plasma control, etc...)
The pellet is injected from outer midplane in JET plasma (#84690).

The pellet injection velocity is 78 m/s. Four pellet sizes have been investigated (not all cases are listed here):

- 1.1mm
- 1.7mm
Distribution of the heat flux (by natural ELM)

The density in colour and the heat flux on the divertor target during the spontaneous ELM (without the pellet injection).

The profile of the heat flux on the divertor target is symmetric.
Distribution of the heat flux (by pellet)

The density in colour and the heat flux on the divertor target during the pellet triggered ELM (1.7mm pellet).

The profile of the heat flux on the divertor target is axymmetric.
Heat flux on the divertor target

Heat flux profile on the divertor target ELM [Wenninger et al. (2010)].

(a) spontaneous ELM

(b) pellet triggered

Pellet density source creates another channel to the divertor target. ➔ Distribution of the heat flux in a wide area.
Appendix : Energies evolution with a pellet injection in JET plasma (#84690)

The simulation has been performed with \( n=0-10 \) toroidal modes without a pellet, until the natural ELM crash.

After the pellet injection (\( t=15415 \) [us]), toroidal modes evolve according to the pellet ablation.

Large pellet excites the MHD activities.