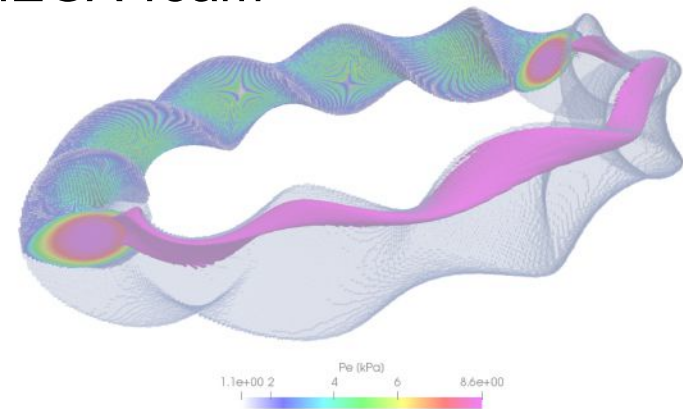


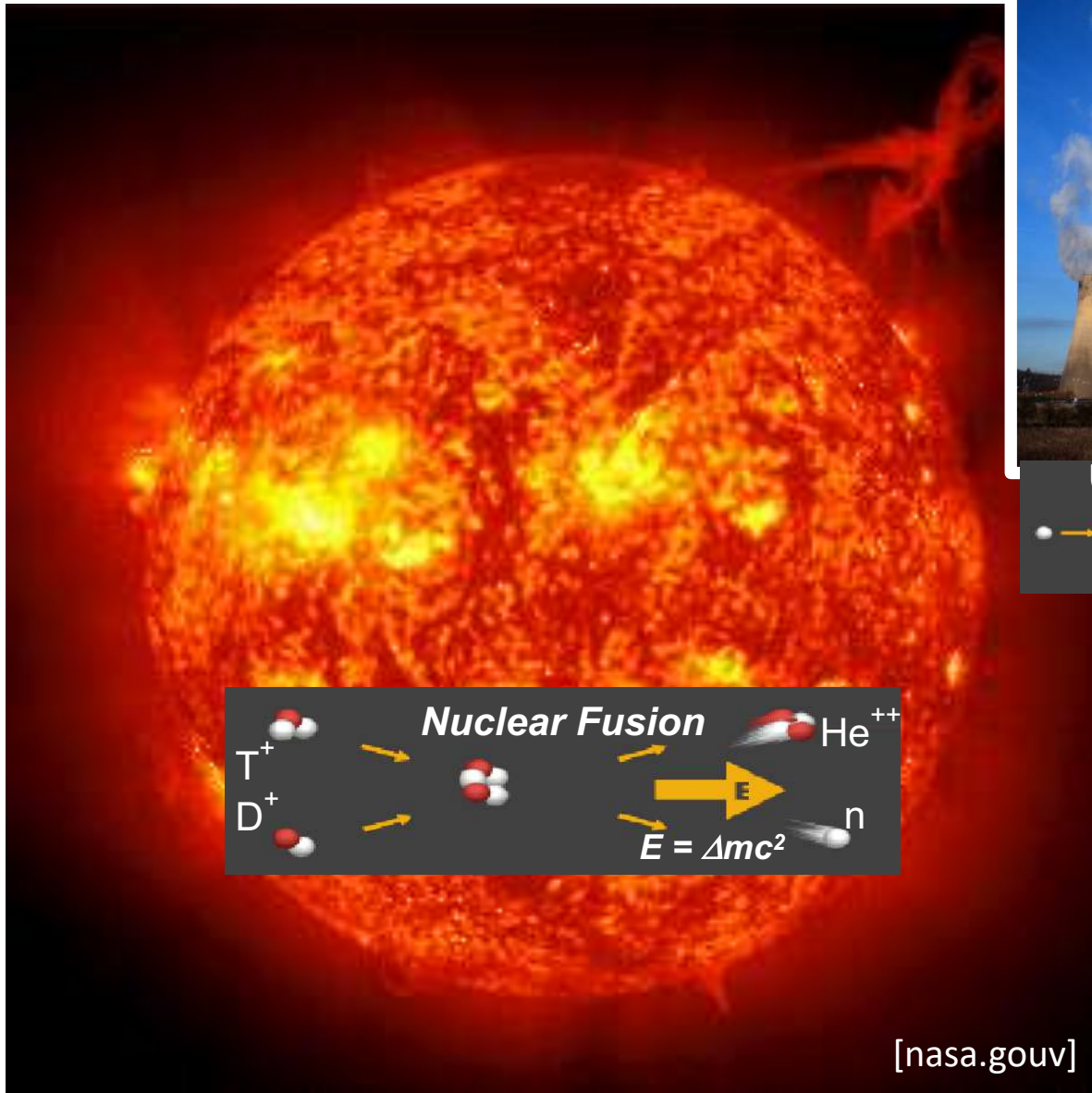
# High performance computing of non-linear MHD modelling for nuclear fusion research

Shimpei Futatani (Univ. Politecnica de Catalunya, Barcelona)

Acknowledgements : the JOREK Team and the MEGA Team



# What makes stars shine? – Nuclear fusion



[nasa.gov]

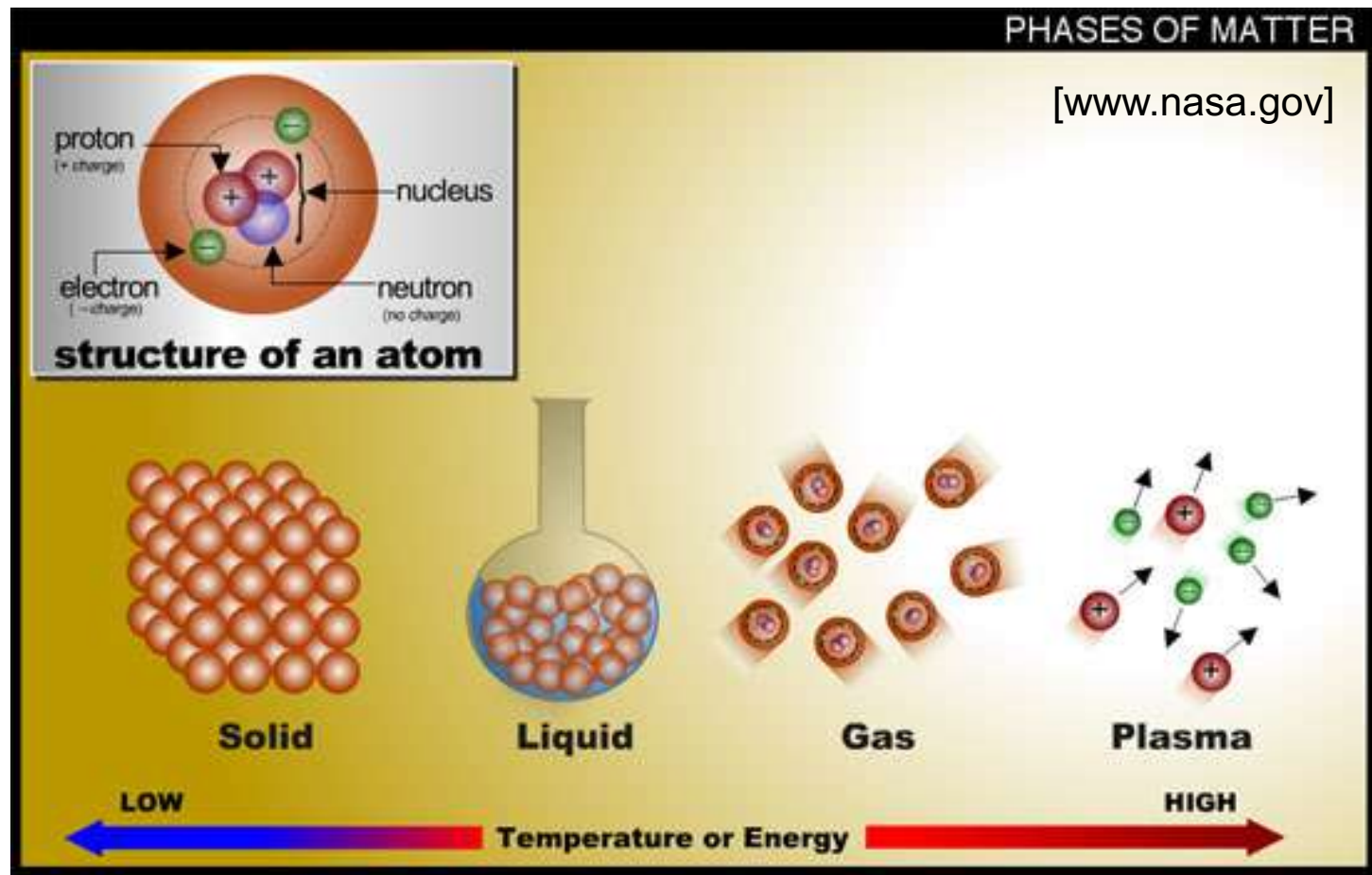


# What is plasma?



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**.



[[www.setterfird.org](http://www.setterfird.org)]



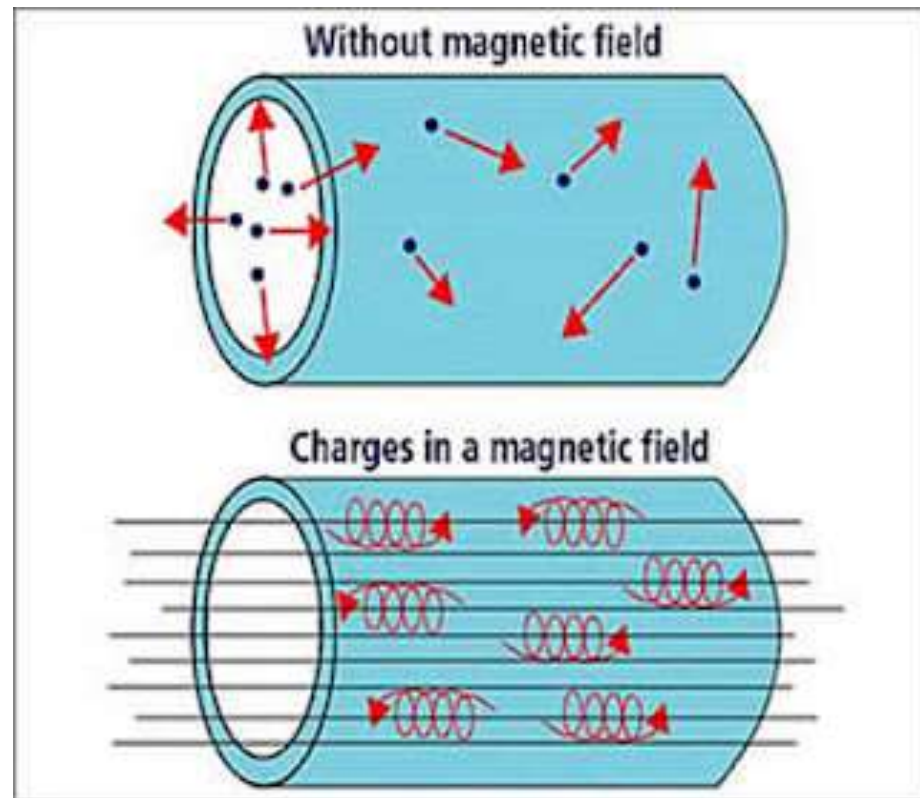
[[wikipedia.org](http://wikipedia.org)]

# Fusion on the earth – magnetically confinement

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

- Charged particles spiral around **magnetic field lines**.
- Application for research of plasma physics and technologies such as thruster, fusion etc.

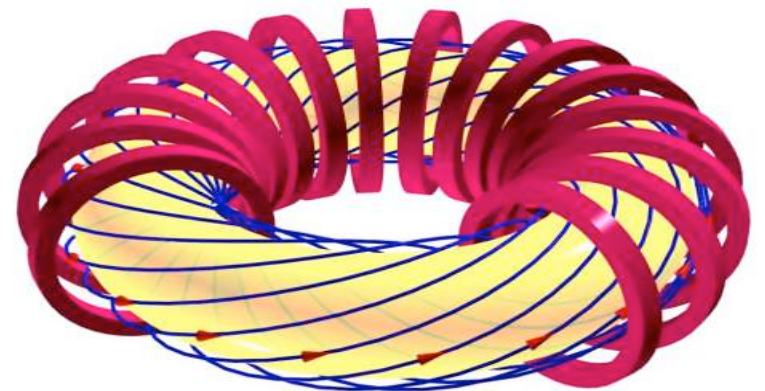
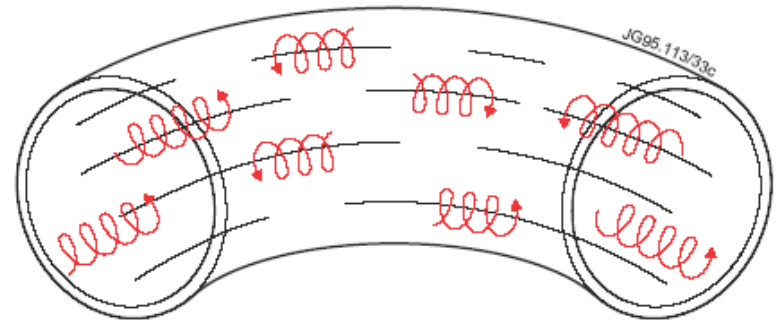


# Fusion on the earth – magnetically confinement

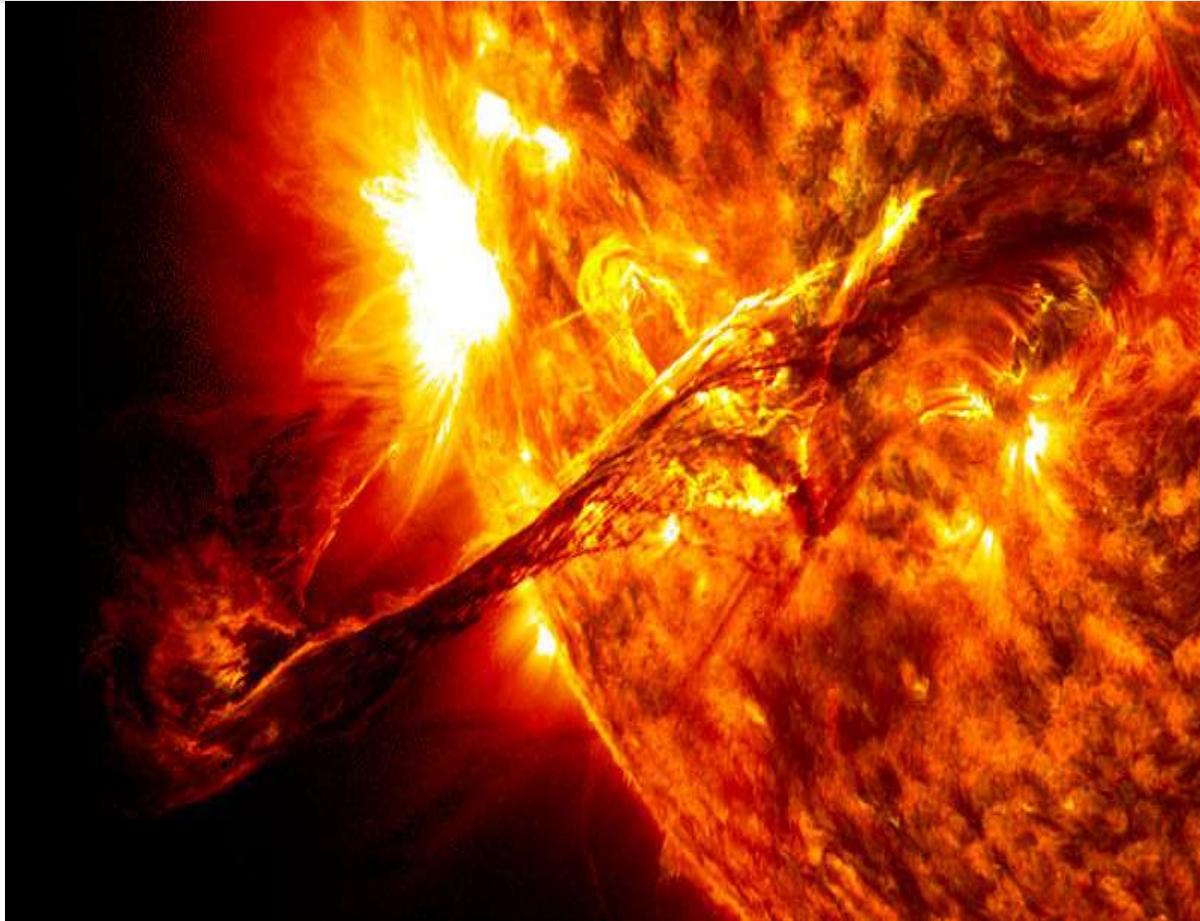
Key parameters for the fusion = **high-temperature** and **high-density**  
→ **How can we confine the high-temperature plasma?**

- In **stars**: plasma particles are confined mainly by **gravity**.
- 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**



# A big challenge for control of fusion plasma



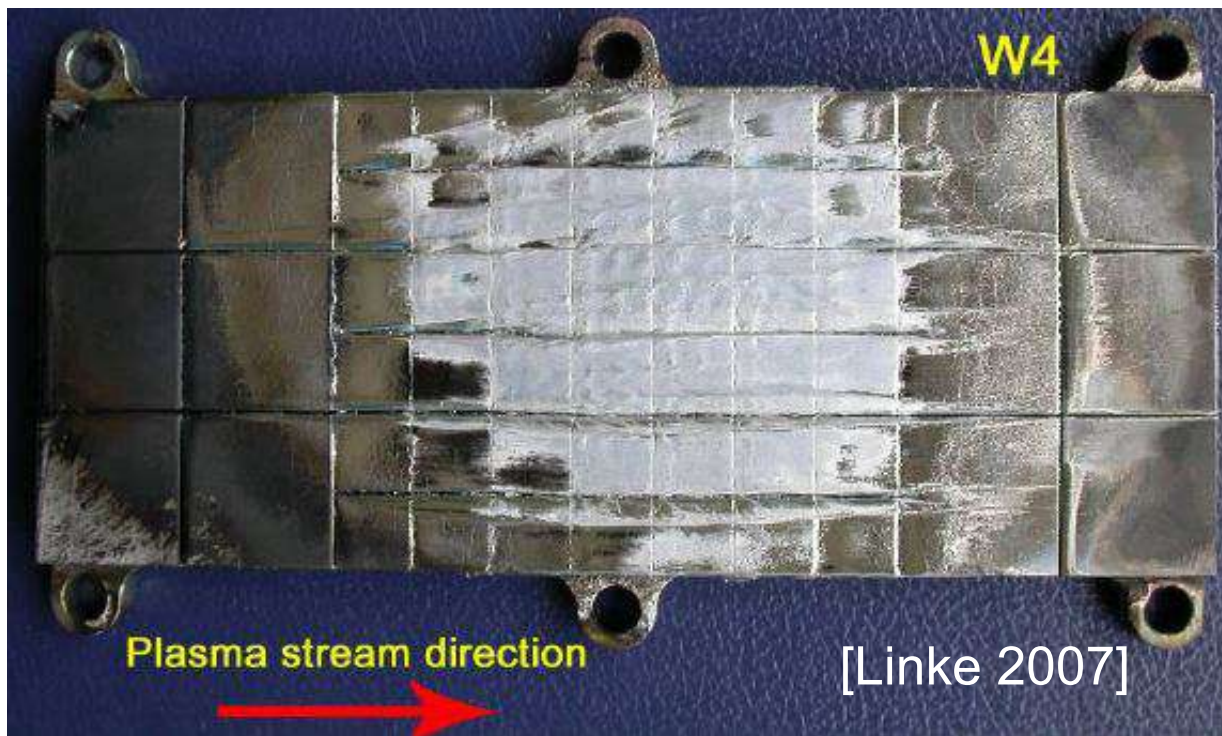
Eruption of high temperature plasma

= solar flares (for sun)

= ELMs (for Magnetically confined plasma)

→ Big challenge for the control of the plasma

# Edge Localized Modes (ELMs)



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...





# Magnetohydrodynamics (MHD)

Branch of plasma physics developed in the last century.

Magnetohydrodynamics (MHD) is the study of the magnetic properties and behaviour of electrically *conducting fluids*



[The Big Bang Theory, Warner Bros.]

## MHD

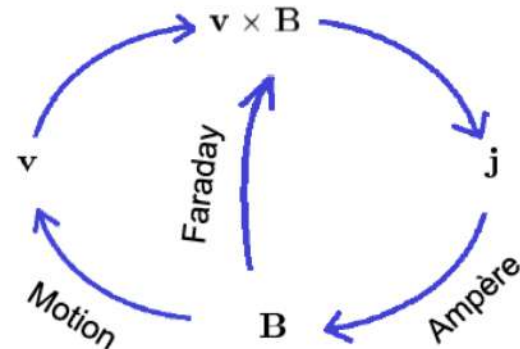
Navier-Stokes equation of fluid dynamics

$$\frac{\partial \mathbf{v}}{\partial t} + \mathbf{v} \cdot \nabla \mathbf{v} = -\frac{\nabla p}{\rho} + \frac{\mathbf{j} \times \mathbf{B}}{\rho} + \nu \nabla^2 \mathbf{v}$$



Maxwell's equations of electromagnetism

$$\frac{\partial \mathbf{B}}{\partial t} = \nabla \times (\mathbf{v} \times \mathbf{B}) + \lambda \nabla^2 \mathbf{B}$$



Complicated due to highly non-linear system (No analytical solutions)

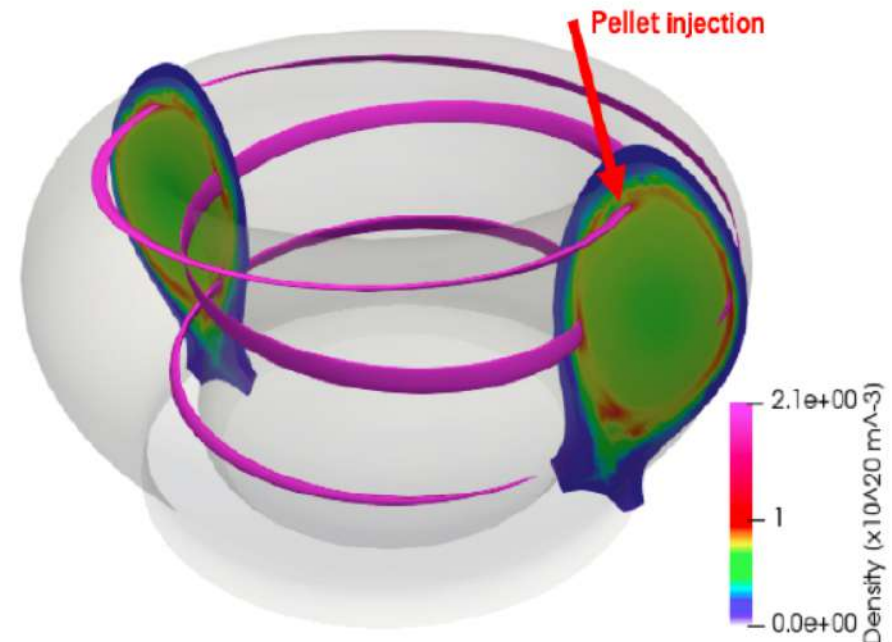
➔ **Numerical simulations**



# Non-linear MHD code JOREK

- **JOREK** : Non-linear extended MHD code which resolves realistic toroidal geometries.
  - G.T.A. Huysmans and O. Czarny, Nuclear Fusion 47, 659 (2007)
  - O. Czarny and G. Huysmans, J. Comp. Phys. 16, 7423 (2008)
  - M. Hoelzl, G.T.A. Huijsmans et al., Nuclear Fusion 61, 065001 (2021)
  - See [<https://www.jorek.eu/>]
- **MHD response by pellet injection is being studied.**

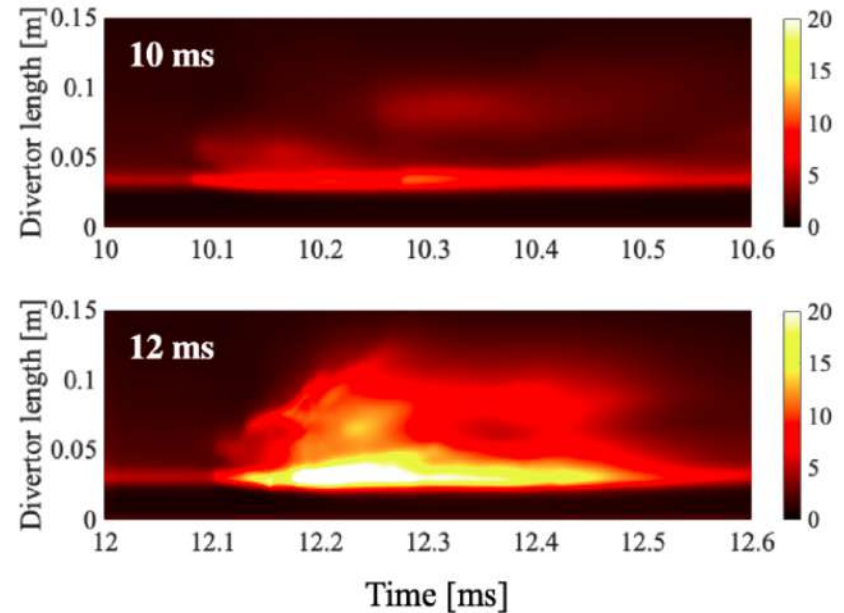
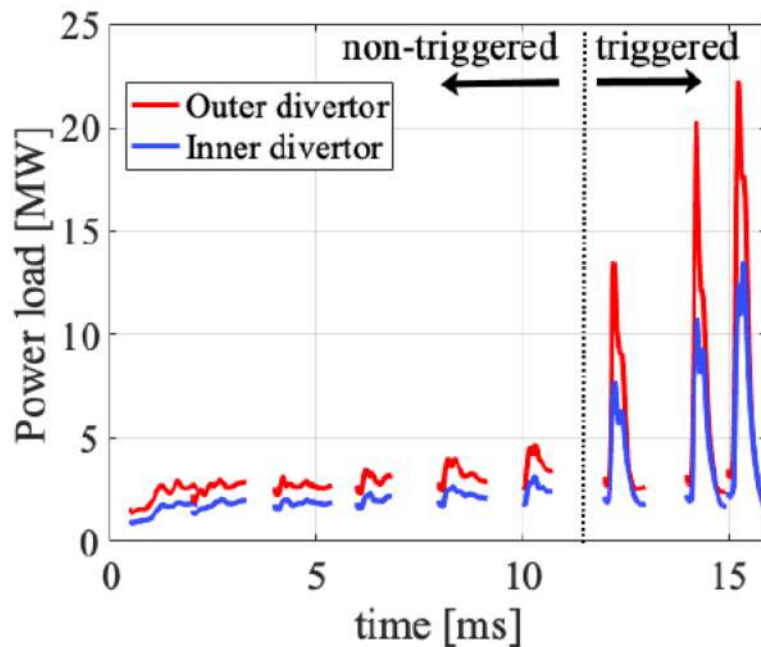
- The injected pellet ablates in the plasma
- The pellet could propagate along the magnetic field lines, creating localized pressure perturbation
- The 3D localized pressure perturbation triggers an ELM





# Non-linear MHD code JOREK

- Pellets are injected in the pedestal (plasma boundary profile) build-up.
- The pellet conditions (pellet size, injection velocity, injection location etc.) are the same, however the probability of ELM triggering is different.
  - Pellets injected in the early stage ( $<10$  ms), no ELM triggering
  - Pellets injected in the later stage ( $>12$  ms), ELM triggering

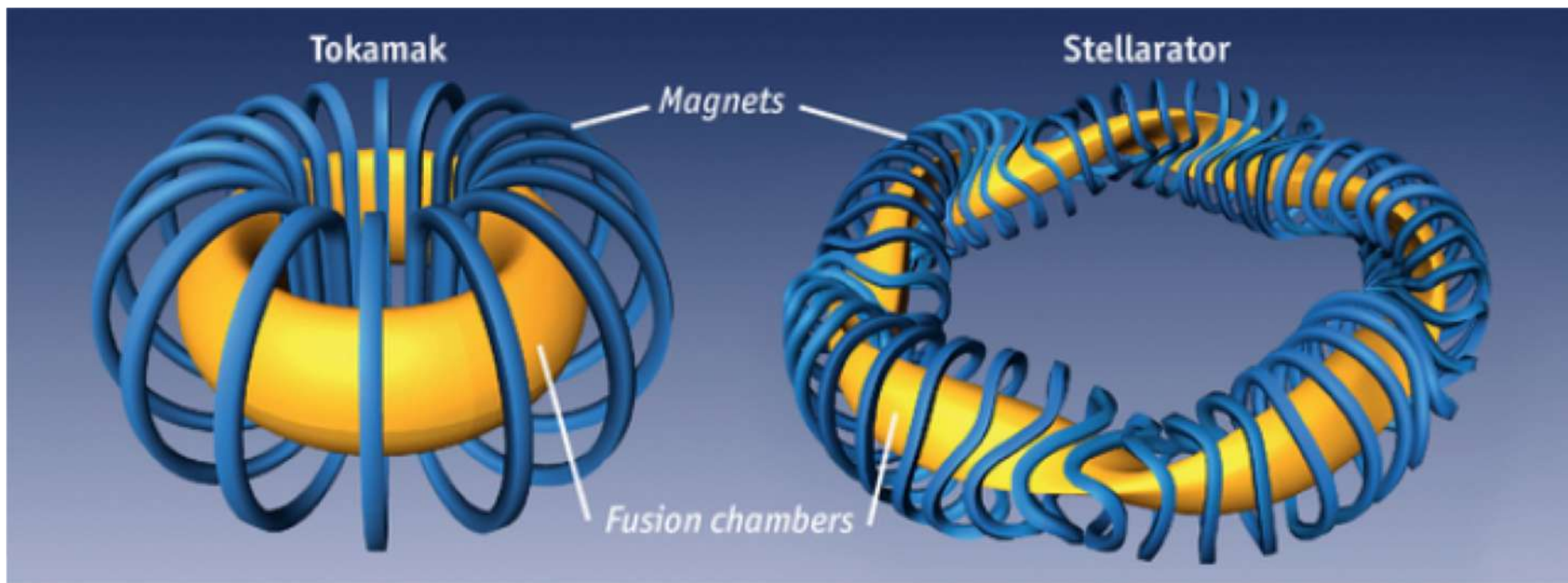


- The results have been published
  - S. Futatani, A. Cathey, M. Hoelzl, et al., Nuclear Fusion, 2021
  - A. Cathey, M. Hoelzl, S. Futatani, et al., Plasma Phys. Control Fusion 2021

# Simulations of stellarator plasma



- Stellarator is an alternative type of fusion reactor. It exploits strangely-shaped magnets that is hard to build but potentially easier to operate.
- The global MHD dynamics of the stellarator plasma has been studied with MEGA/MIPS code.

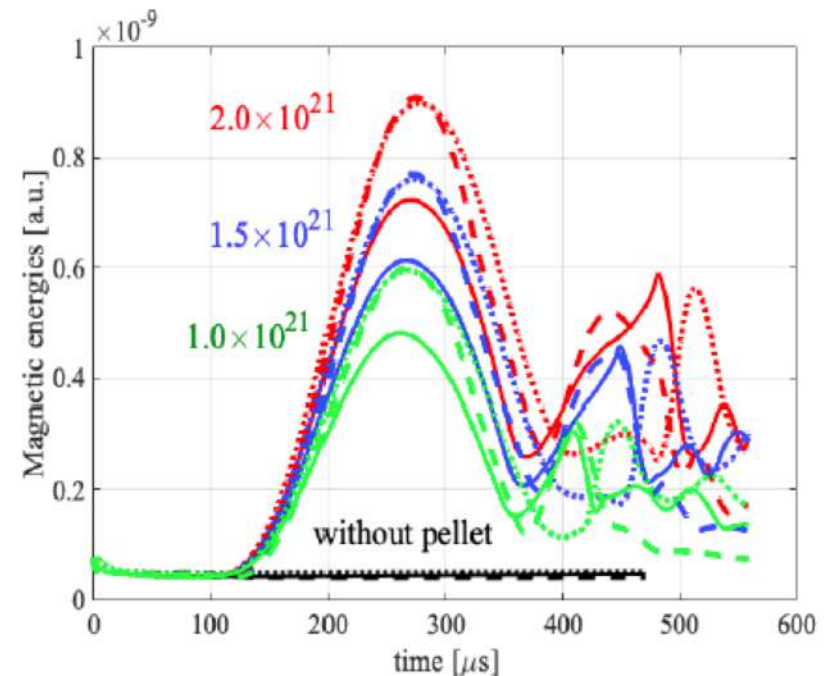
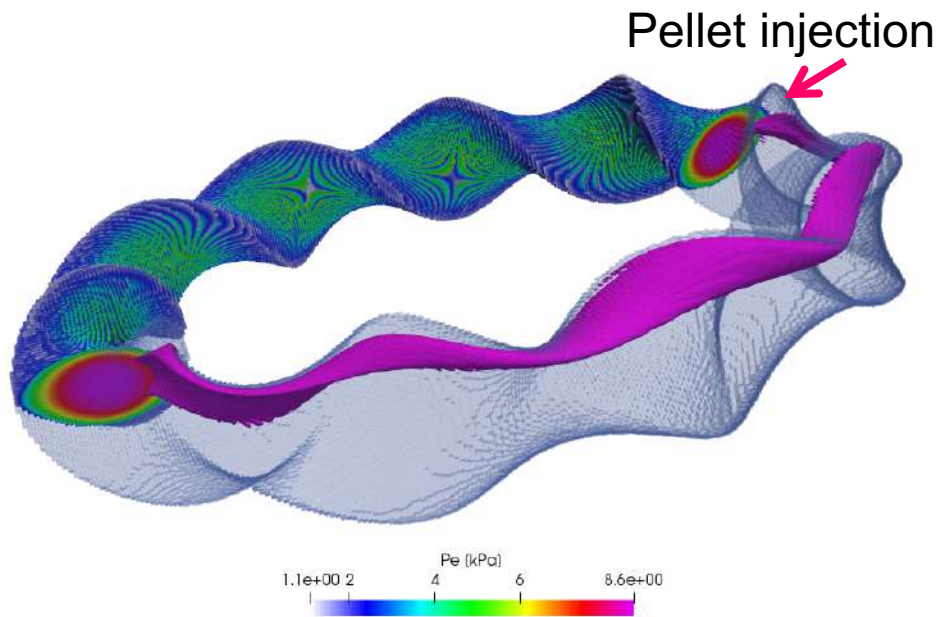


Economist.com

# Simulations of stellarator plasma



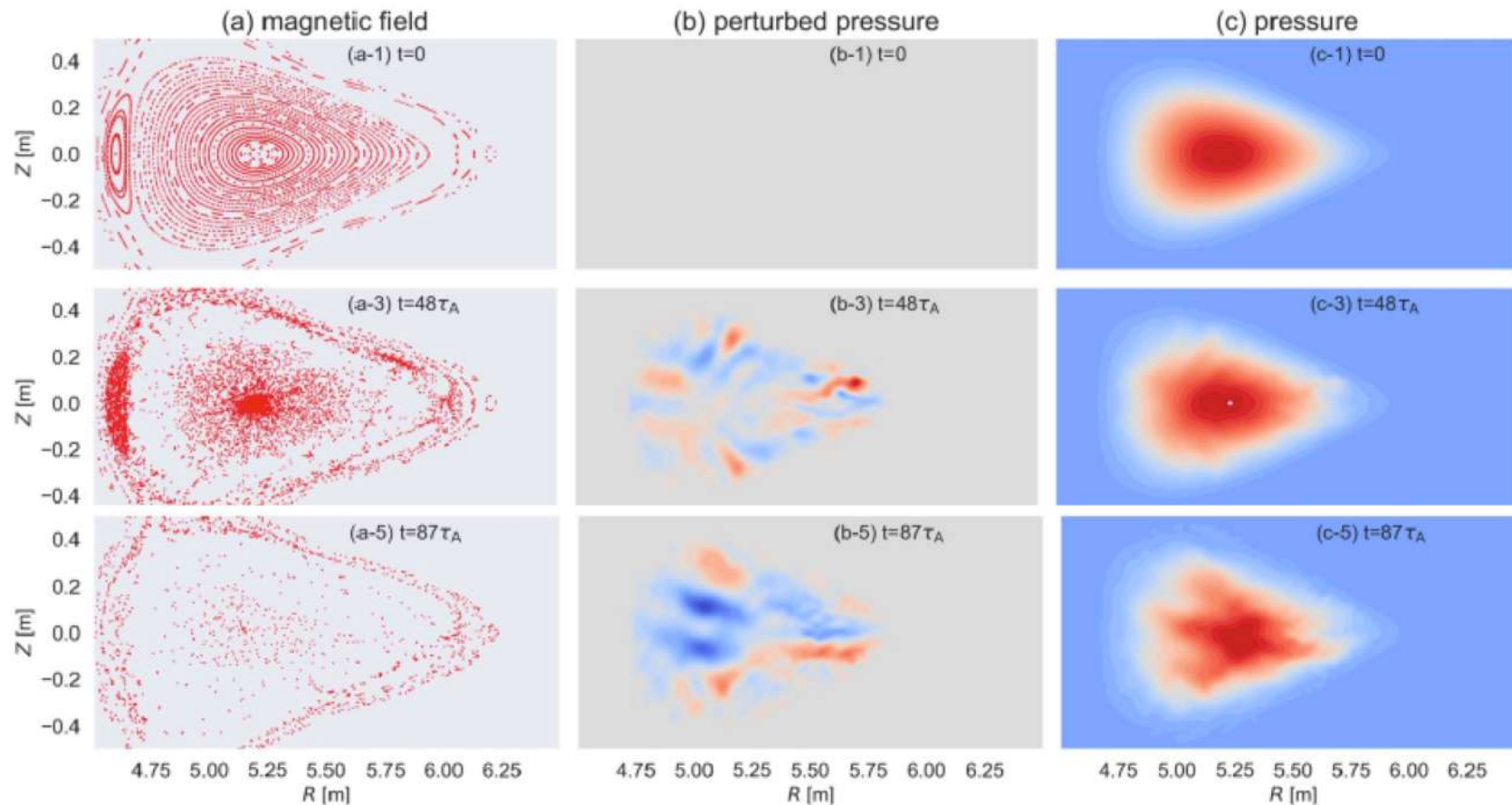
- Realistic pellet ablation model (NGS model [Gal, NF(2008)]) is implemented in MEGA/MIPS code.
- The pellet cloud propagates along the magnetic field lines.
- MHD modes are excited by the pellet injection.
- S. Futatani and Y. Suzuki, Plasma Phys. Control Fusion (2019)



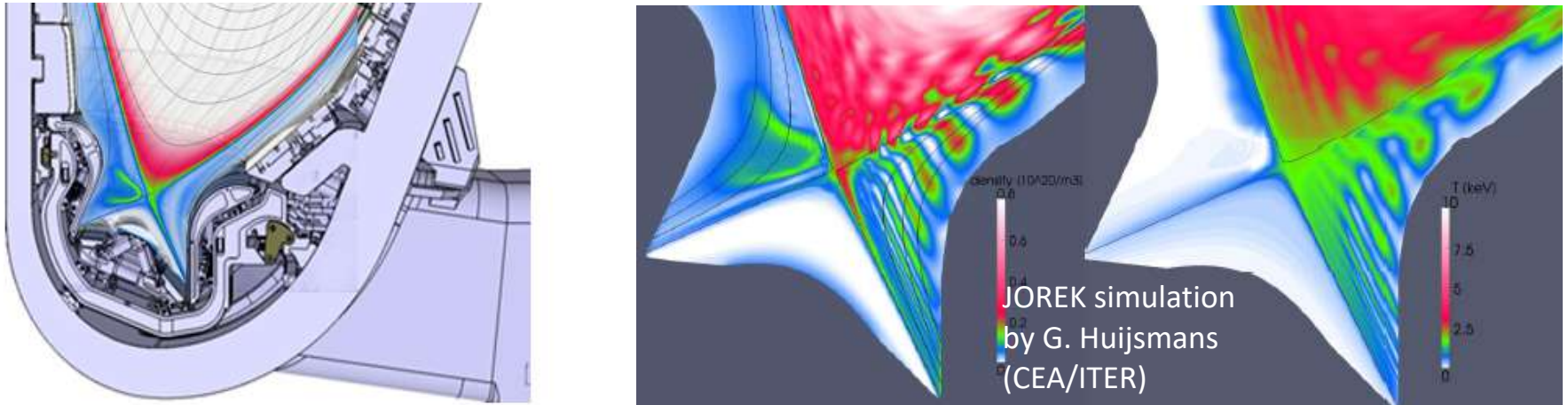
# Simulations of stellarator plasma



- Non-linear MHD simulation of core-collapse event has been studied.
- High- $n$  toroidal modes couples with low- $n$  toroidal modes and saturates.  
→ Core collapse event.
- Y. Suzuki, S. Futatani, J. Geiger, Plasma Phys. Control. Fusion (2021)



# Conclusions and perspectives



## 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 are observed via simulation.
- MEGA/MIPS has been performed to study the pellet effect in stellarator plasma.

## Future works

- JOREK pellet simulation will be performed including more physics effects.
- Improvement of physics model in MEGA/MIPS will be carried out.

**Acknowledgement : PRACE project computing resources.**