

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

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## Acknowledgements:

**G. Huijsmans (CEA), S. Pamela (CCFE), A. Loarte (ITER), M. Hoelzl (IPP) and JOREK Team**



This work has been carried out within the framework of the EUROfusion Consortium and has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement number 633053. The views and opinions expressed herein do not necessarily reflect those of the European Commission.

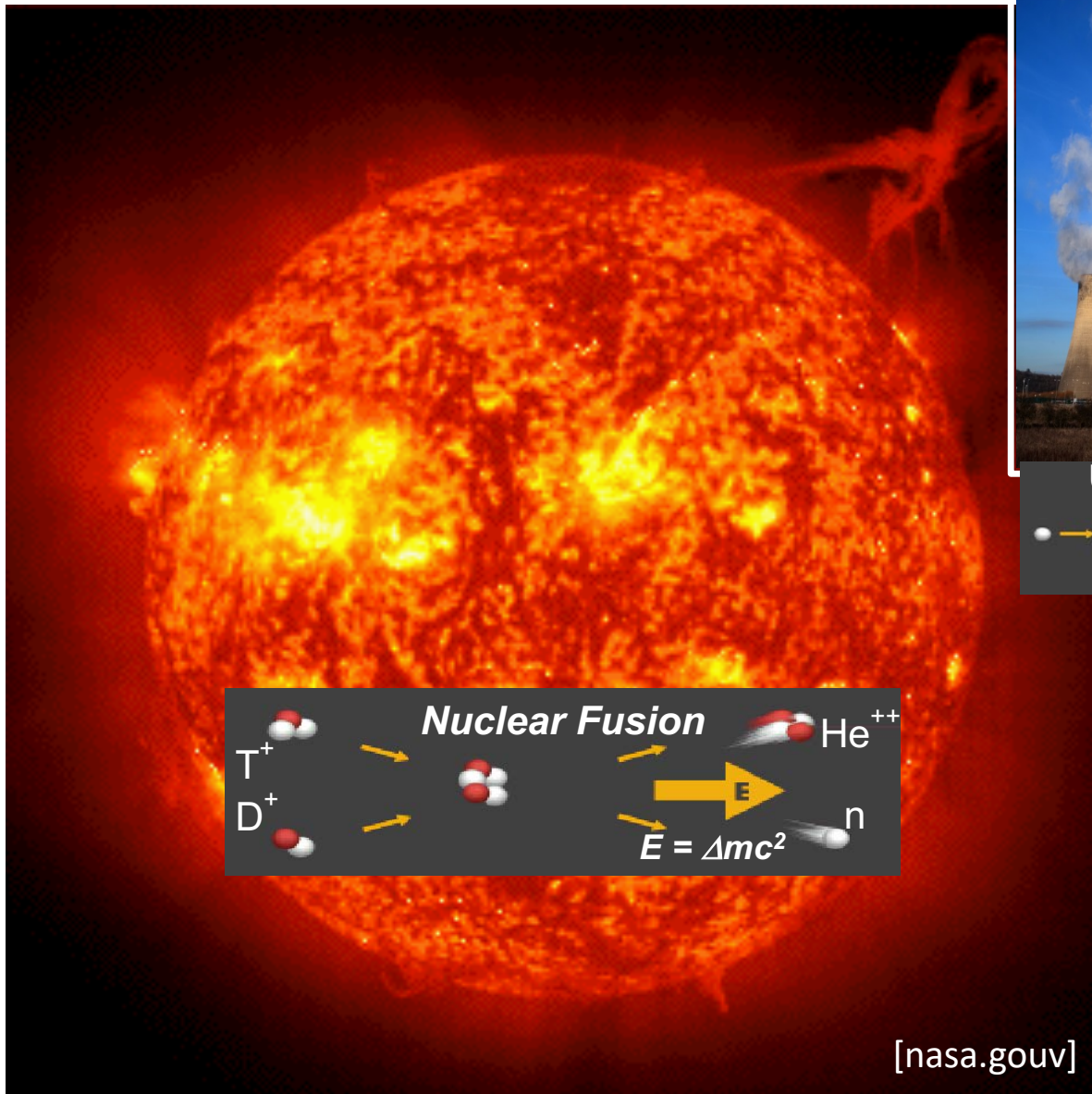
# What makes stars shine?



“The starry night”, V. Willen van Gogh

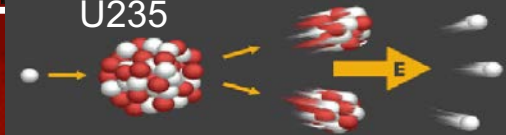
Can we use the energy of shining stars as an alternative energy source?

# What makes stars shine? – Nuclear fusion



**Nuclear Fission**

U235



[nasa.gov]



# Outline

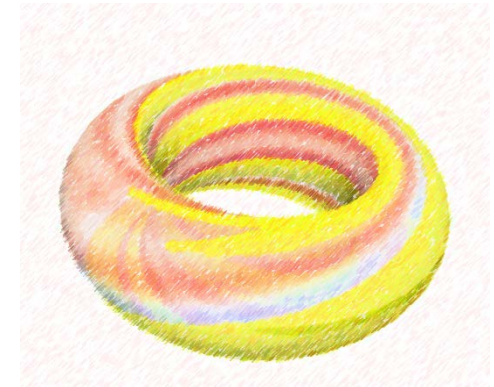
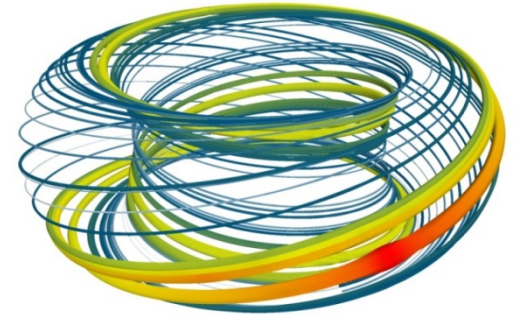


## Introduction

- Plasma / Fusion reactor / ITER Project

## Physics background

- What is ELM?
- JOREK - Nonlinear MHD code
  - [www.jorek.eu](http://www.jorek.eu)
  - The JOREK team and themes
  - Numerical details and physics model
  - Mechanism of pellet triggered ELM



## JOREK Modelling of pellet triggered ELM

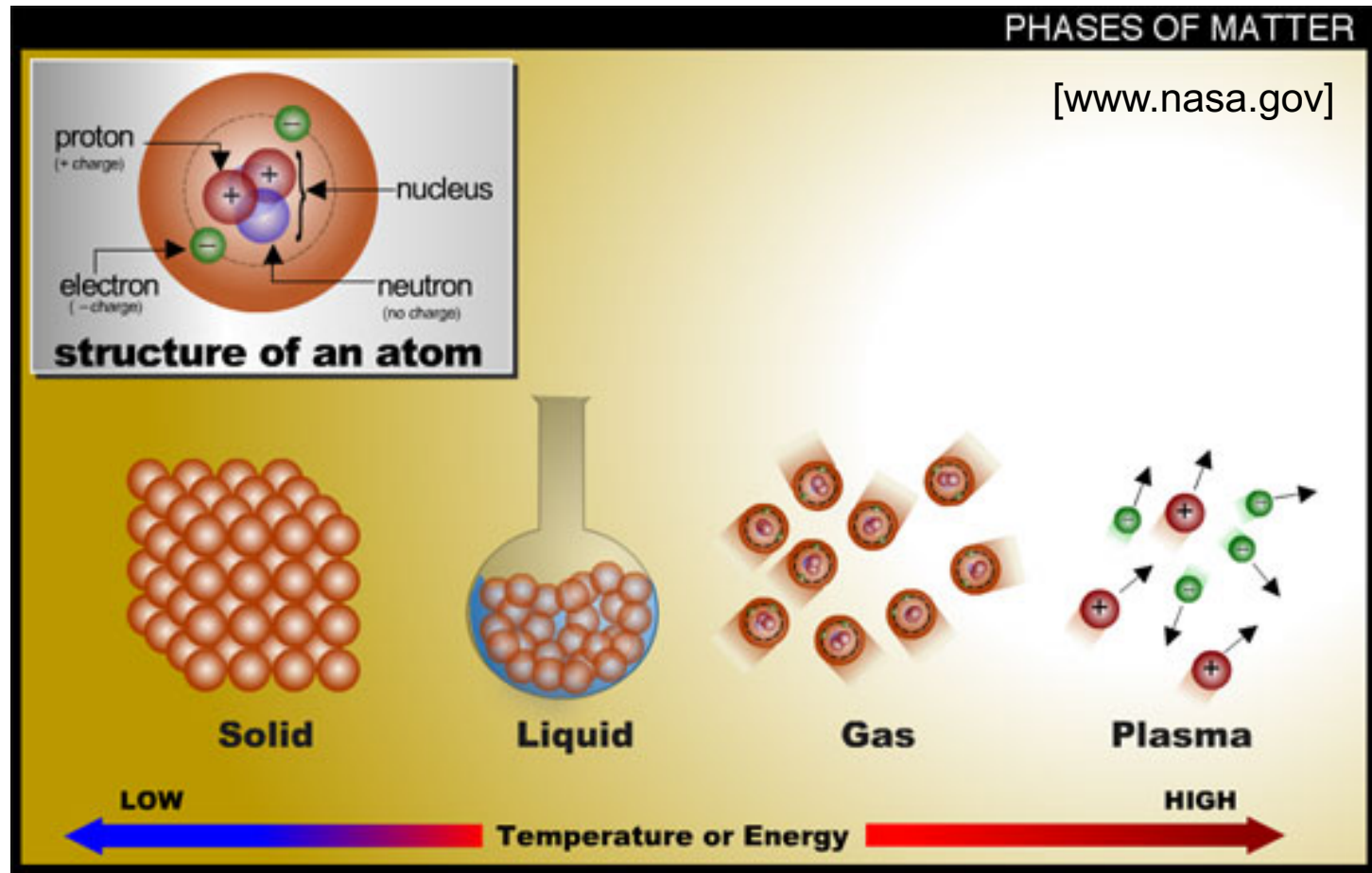
## Conclusions and Perspectives

# 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**.



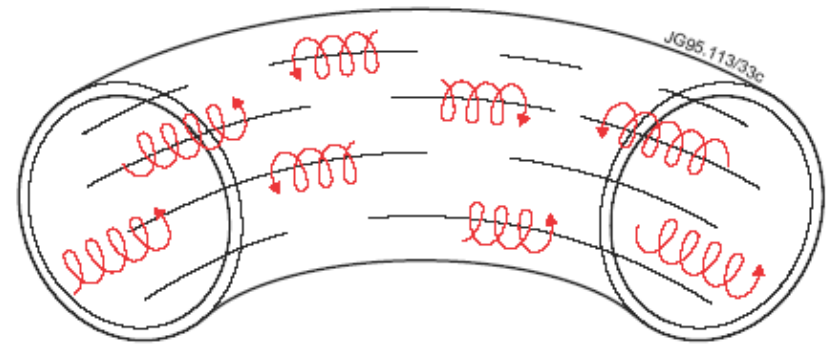
# Fusion reactor on Earth



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

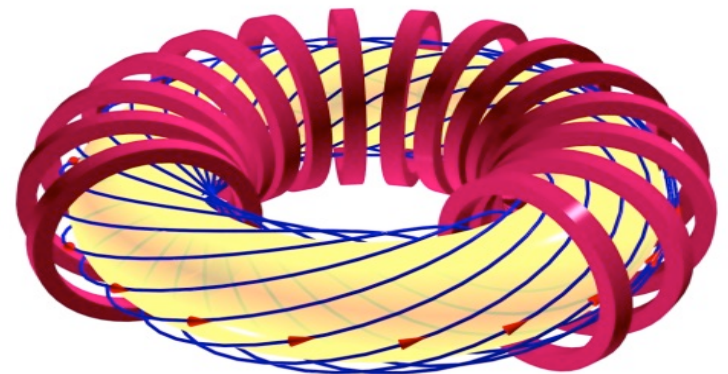
- On **Earth**: plasmas can be confined in Magnetic field lines  
= **Magnetic Confinement**

- Charged particles spiral around **magnetic field lines**.



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

→ **Tokamak**

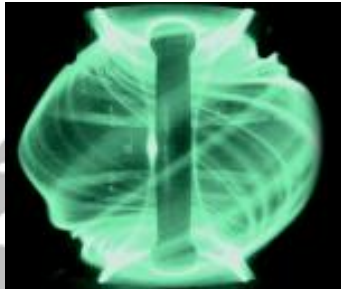
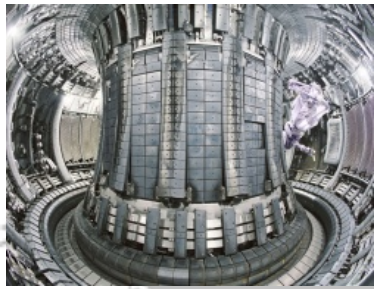




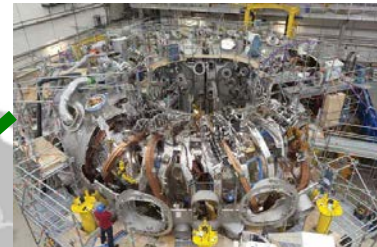
# Fusion plasma reactors in the world



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

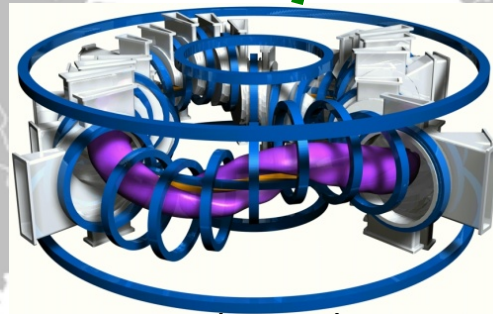
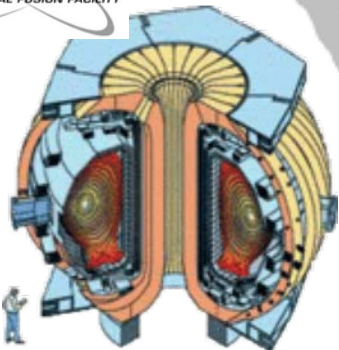


JET (EU) and MAST (UK)

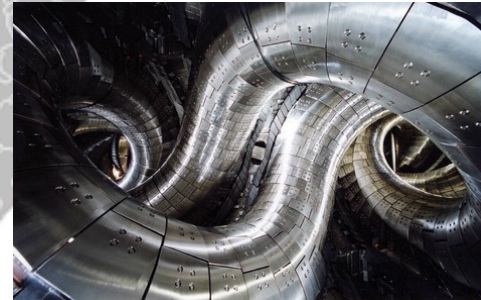


Wendelstein 7-X (Germany)

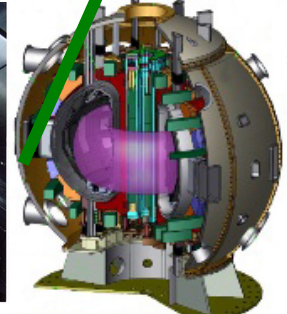
ITER  
(international project)



TJ-II (Spain)



LHD and JT60U (Japan)





# What is ITER? [www.iter.org]



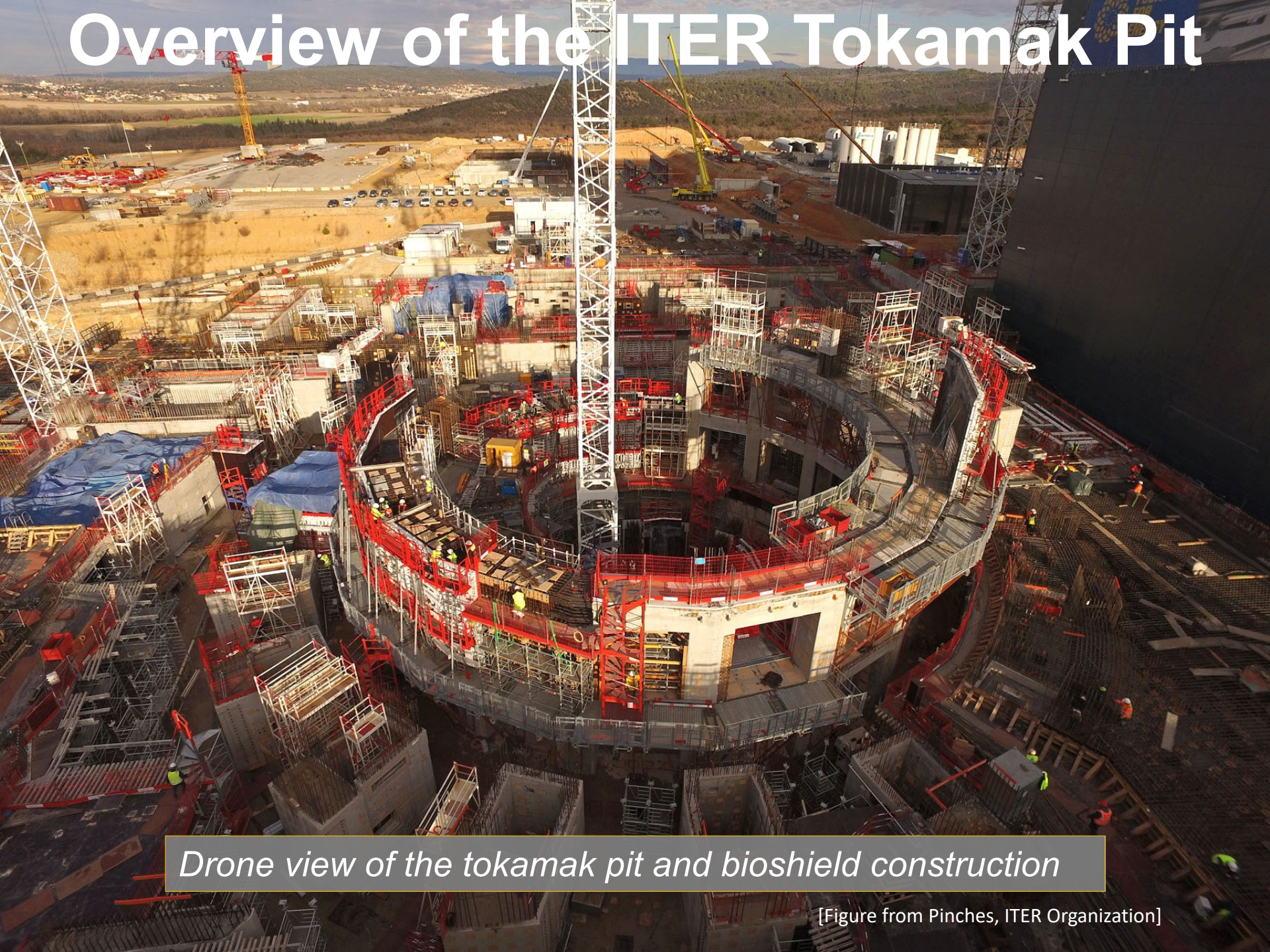
ITER is a major international collaboration in fusion energy research involving China, the EU (plus Switzerland), India, Japan, the Russian Federation, South Korea and the United States



## ITER site (January 2017)



# Overview of the ITER Tokamak Pit



*Drone view of the tokamak pit and bioshield construction*

[Figure from Pinches, ITER Organization]



# 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**

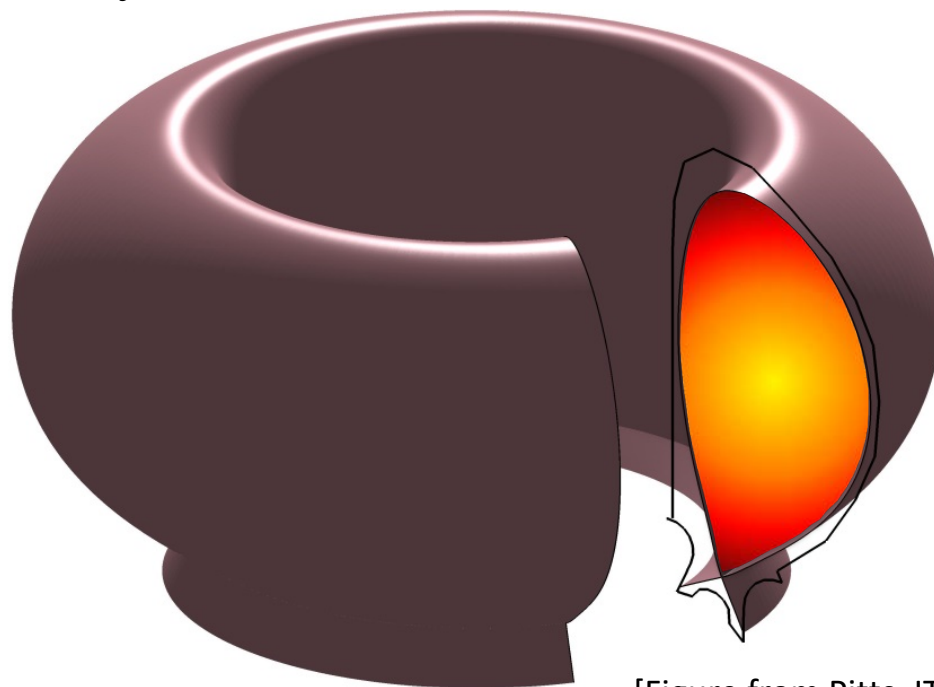


# Edge Localized Modes (ELMs)



- 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  $\sim 200$  microseconds
  - Periodic and bursty behaviors

**ELM**



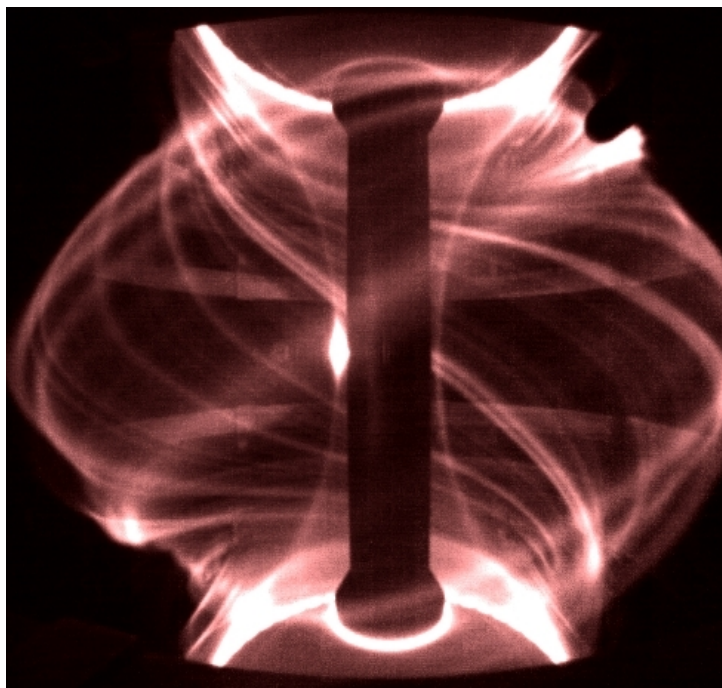
[Figure from Pitts, ITER Organization]

# Edge Localized Modes (ELMs)



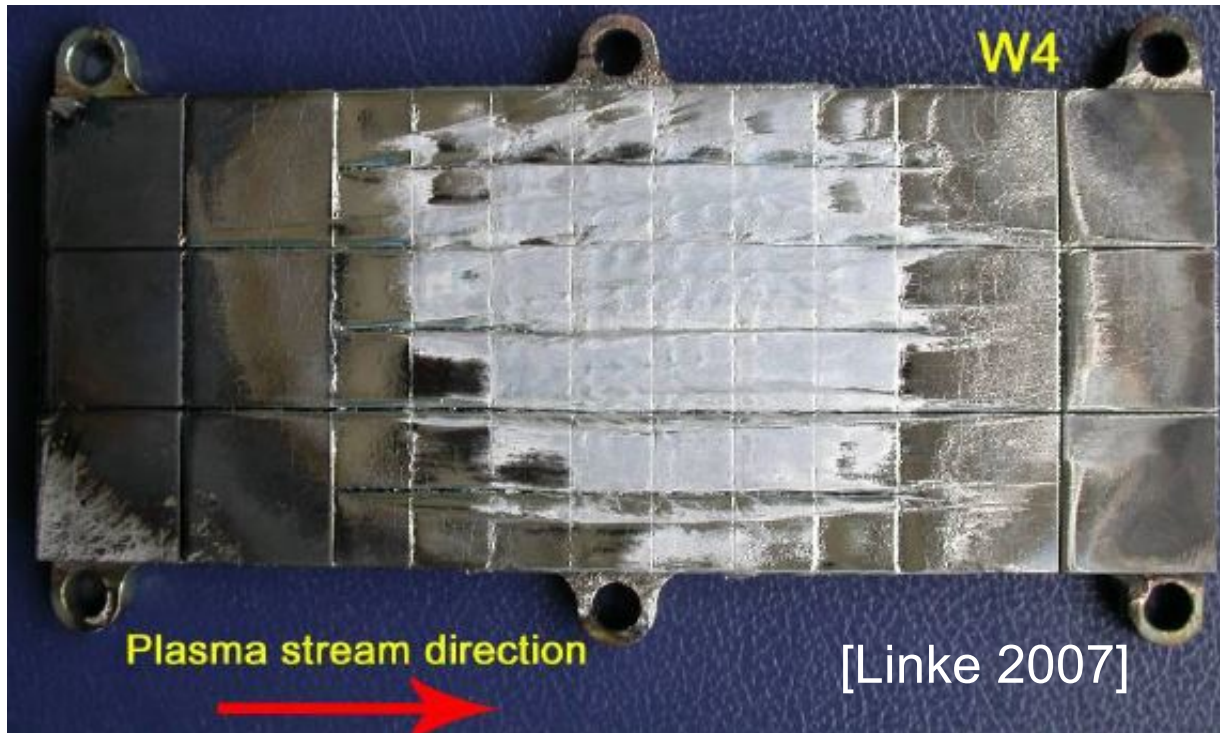
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**ELM**



*Fast camera image of ELM (MAST) [A. Kirk et al.]*

# Edge Localized Modes (ELMs)

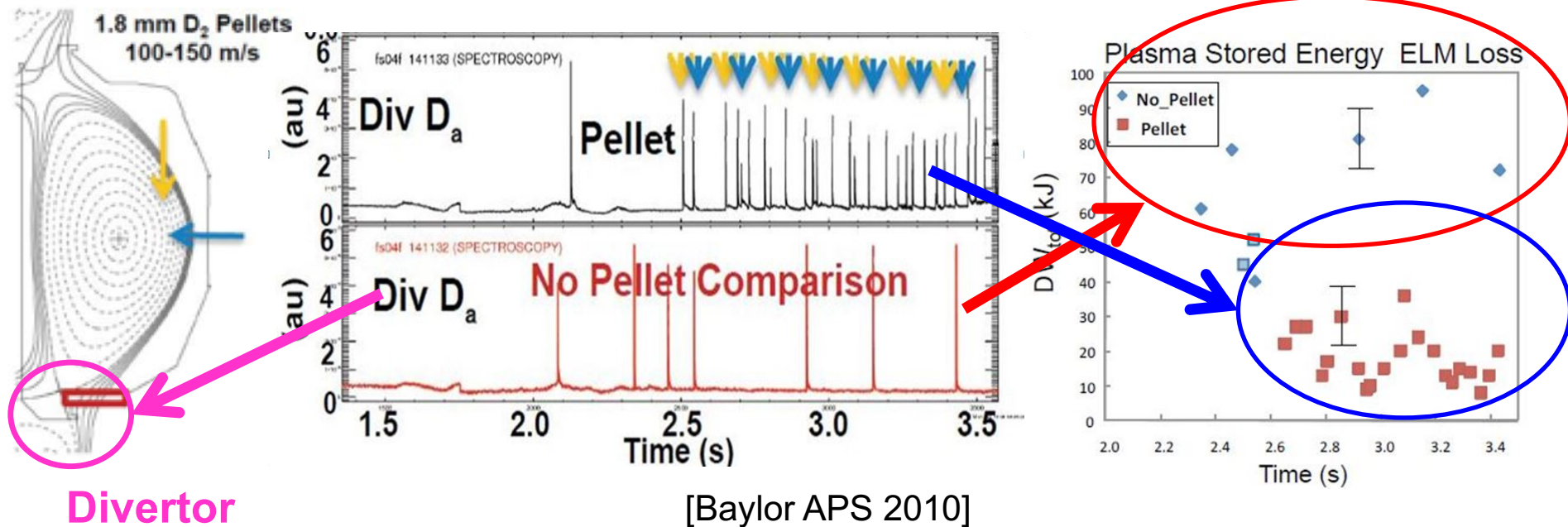


ELMs lead to a large erosion of and a limited lifetime of the plasma facing components. ➔ Requires physics understanding of ELMs and ELM control

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



# 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. Huysmans (CEA/Univ. Eindhoven).
  - G.T.A. Huysmans, Plasma Phys. Control. Fusion 47, B165 (2005)
  - G.T.A. Huysmans and O. Czarny, Nuclear Fusion 47, 659 (2007)
  - O. Czarny and G. Huysmans, J. Comp. Phys. 16, 7423 (2008)
  - See [<https://www.jorek.eu/>]

*JOREK is a non-linear extended MHD code for toroidal X-point geometries.*

**Contact** **Wiki** (restricted)

### 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, QH-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 JOEREK

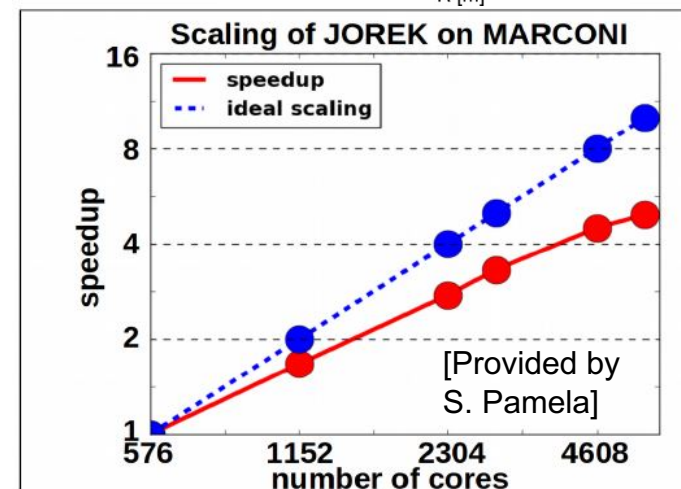
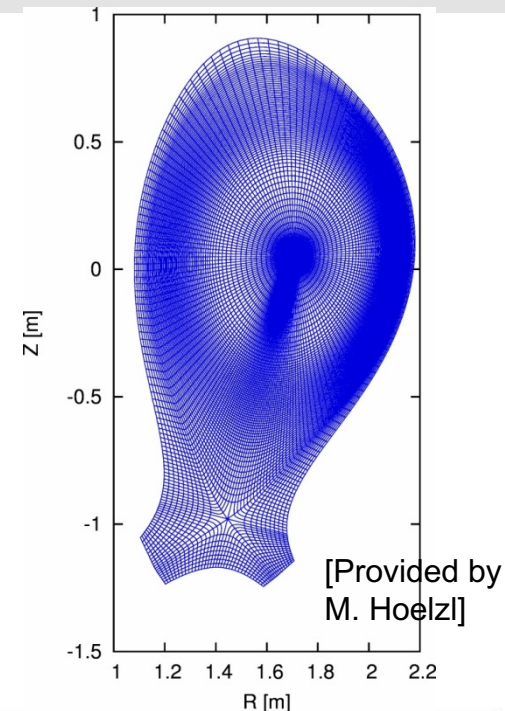
- **European Enabling Research Project (PI: M. Hoelzl)**
- **JOEREK collaborations (>30 members, >10 international institutions):**
  - JOEREK main development and application
    - Involved institutes: CEA, IPP Garching, ITER, CCFE, Eindhoven, UPC etc.
  - Pellet triggering of ELMs / Shattered pellets 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 JOEREK

- Reduced MHD model (JOEREK also has the full MHD model).
- Braginskii parallel conductivity
- Spitzer resistivity
- Mach-1 boundary condition, free flow on divertor target

$$\begin{aligned}\kappa_{\parallel} &\sim T^{5/2} \\ \eta &\sim T^{-3/2} \\ \mu &\sim T^{-3/2}\end{aligned}$$

- Magnetic field and the velocity

$$\mathbf{B} = \left(\frac{F_0}{R}\right) \mathbf{e}_{\varphi} + \left(\frac{1}{R}\right) \nabla \psi(t) \times \mathbf{e}_{\varphi} \quad \mathbf{v} = -R \nabla u(t) \times \mathbf{e}_{\varphi} + \mathbf{v}_{\parallel}(t) \mathbf{B}$$

- Mass density  $\frac{\partial \rho}{\partial t} = -\nabla \cdot (\rho \mathbf{v}) + \nabla \cdot (D_{\perp} \nabla_{\perp} \rho) + S_{\rho}$  ← Coupled with the pellet ablation model
- Poloidal momentum (vorticity)  $\mathbf{e}_{\varphi} \cdot \nabla \times \left( \rho \frac{\partial \mathbf{v}}{\partial t} = -\rho (\mathbf{v} \cdot \nabla) \mathbf{v} - \nabla (\rho T) + \mathbf{J} \times \mathbf{B} + \mu \Delta \mathbf{v} \right)$
- Parallel momentum  $\mathbf{B} \cdot \nabla \times \left( \rho \frac{\partial \mathbf{v}}{\partial t} = -\rho (\mathbf{v} \cdot \nabla) \mathbf{v} - \nabla (\rho T) + \mathbf{J} \times \mathbf{B} + \mu \Delta \mathbf{v} \right)$
- 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  $\frac{1}{R^2} \frac{\partial \psi}{\partial t} = \eta(T) \nabla \cdot \left( \frac{1}{R} \nabla_{\perp} \psi \right) - \mathbf{B} \cdot \nabla u$



# 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

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



$S_p$ : Density source

$r_p$ : pellet radius [m]

$n_e$ : plasma electron density [ $m^{-3}$ ]

$T_e$ : plasma electron temperature [eV]

**JOREK** solves a very complex, multi-physics which requires HPC

Non-linear MHD physics

Interactions

Pellet ablation physics

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



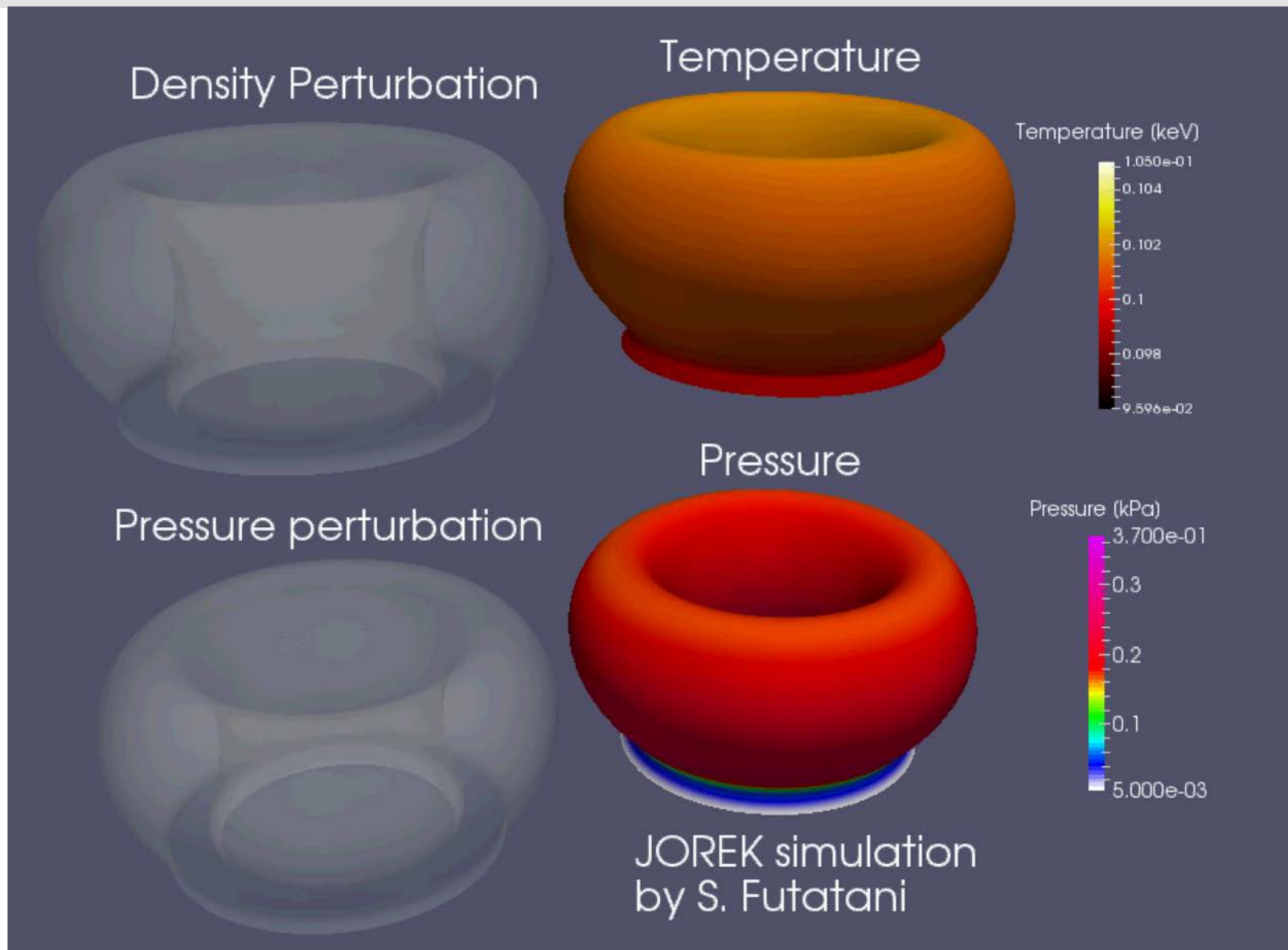
The HELIOS Supercomputer system at IFERC-CSC.



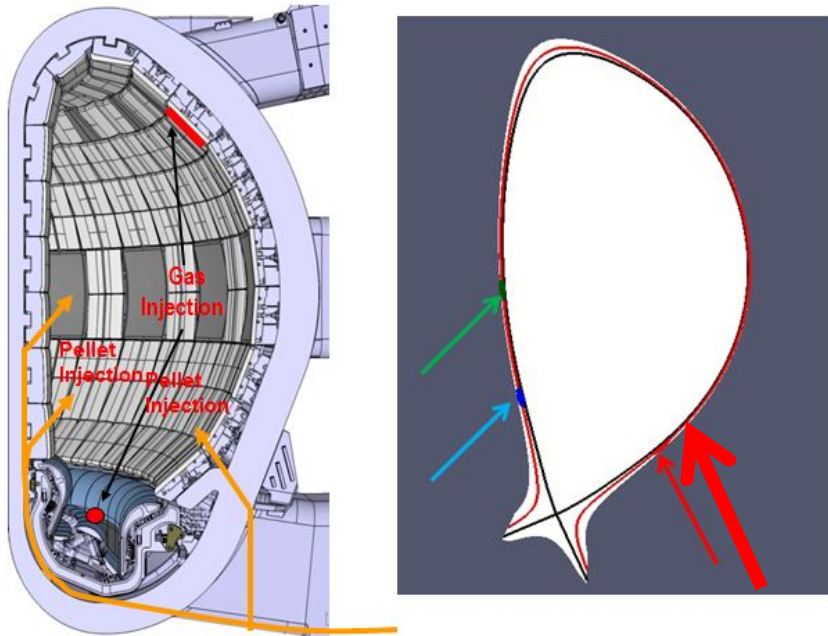
Mare Nostrum III in Barcelona



# Mechanism of pellet triggered ELM



# ITER 15MA/5.3T Q=10 plasma

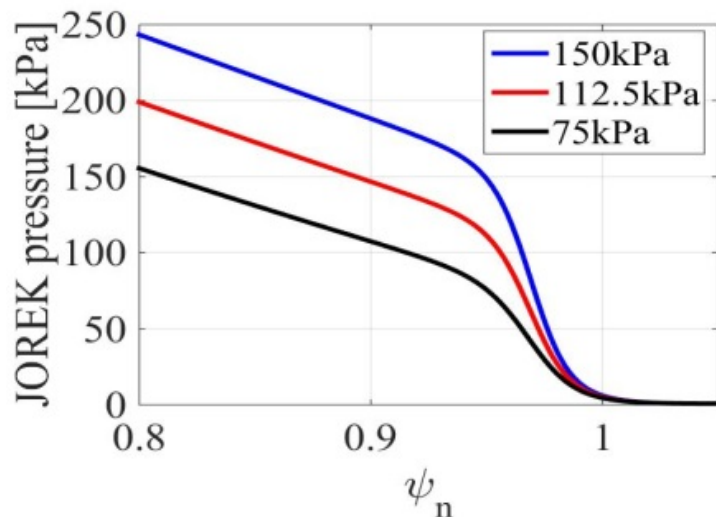


According to the design of future ITER pellet injector, four sizes are studied :

- $4.0 \times 10^{21} \text{D}$ ,
- $3.0 \times 10^{21} \text{D}$ ,
- $2.0 \times 10^{21} \text{D}$ ,
- $1.0 \times 10^{21} \text{D}$

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.

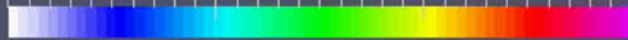
# Plasma dynamics after the pellet injection (example movie of JET plasma)



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

$n_{e20m-3}$

0.000e+00 0.2 0.4 6.000e-01



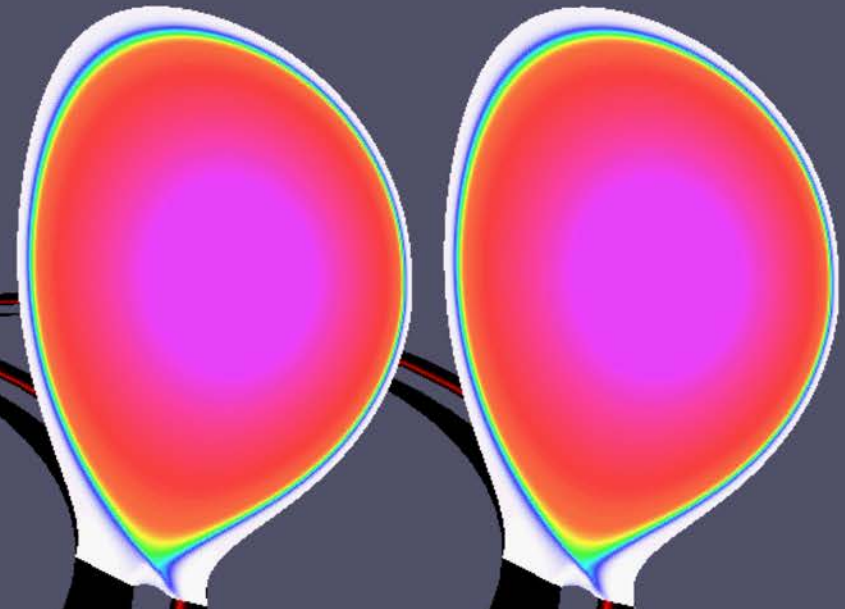
Heat flux (MW/m<sup>2</sup>)

0.000e+00 20 40 5.000e+01



1.1mm pellet

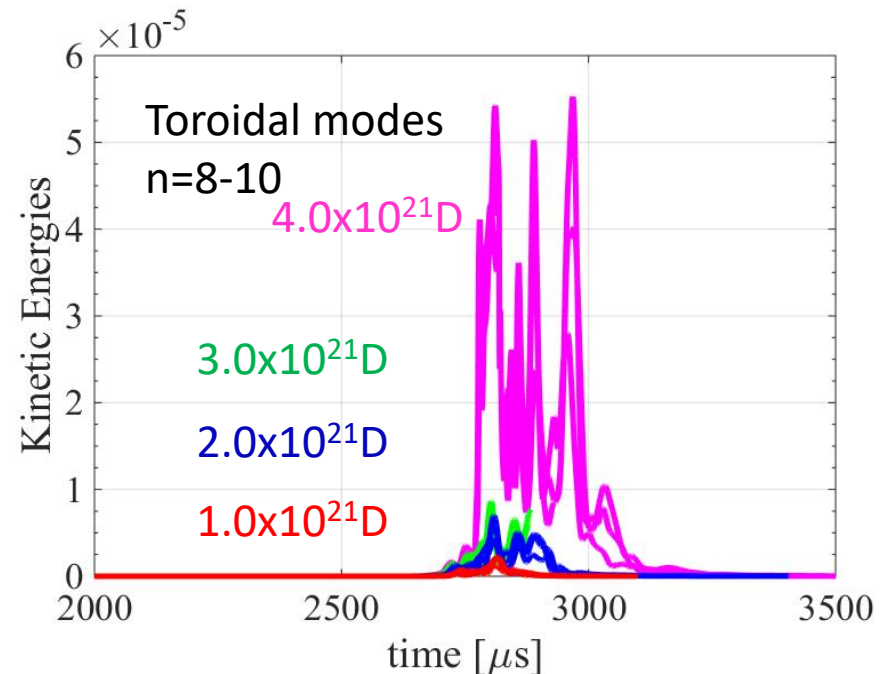
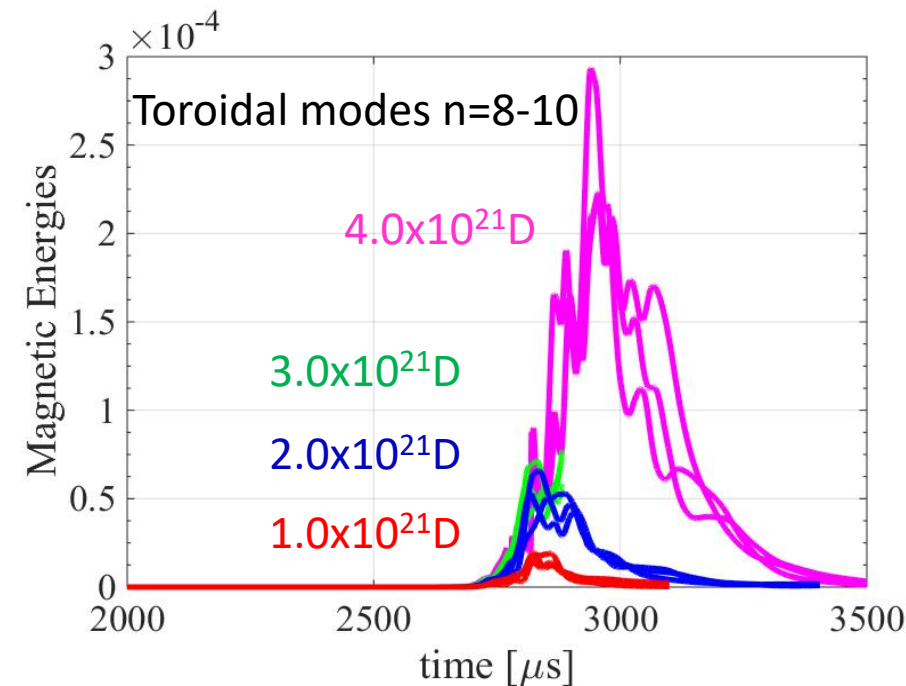
1.7mm pellet



# ITER plasma – pellet size dependence



- ❧ 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  $2.0 \times 10^{21} \text{D}$ . → 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.

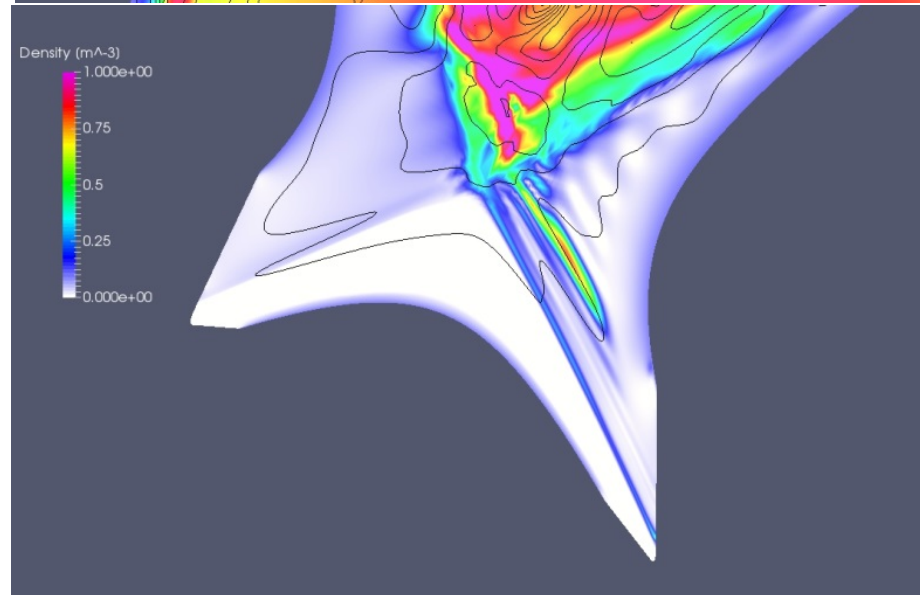
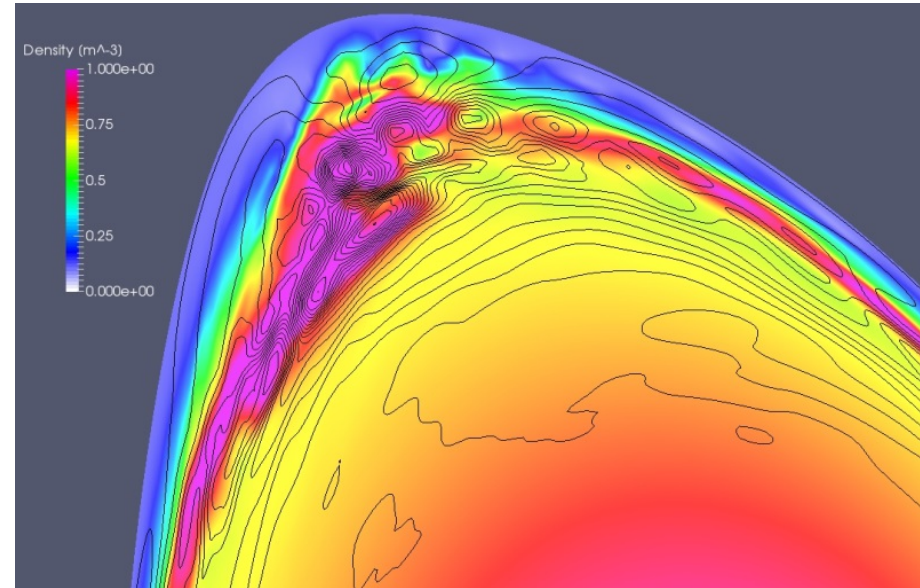
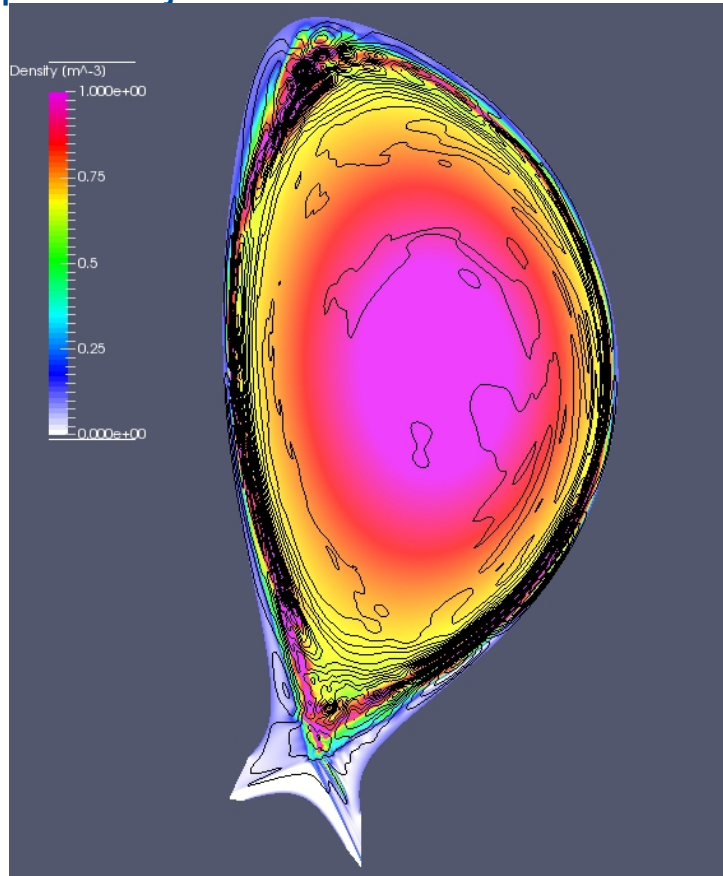




# ITER plasma – pellet size dependence



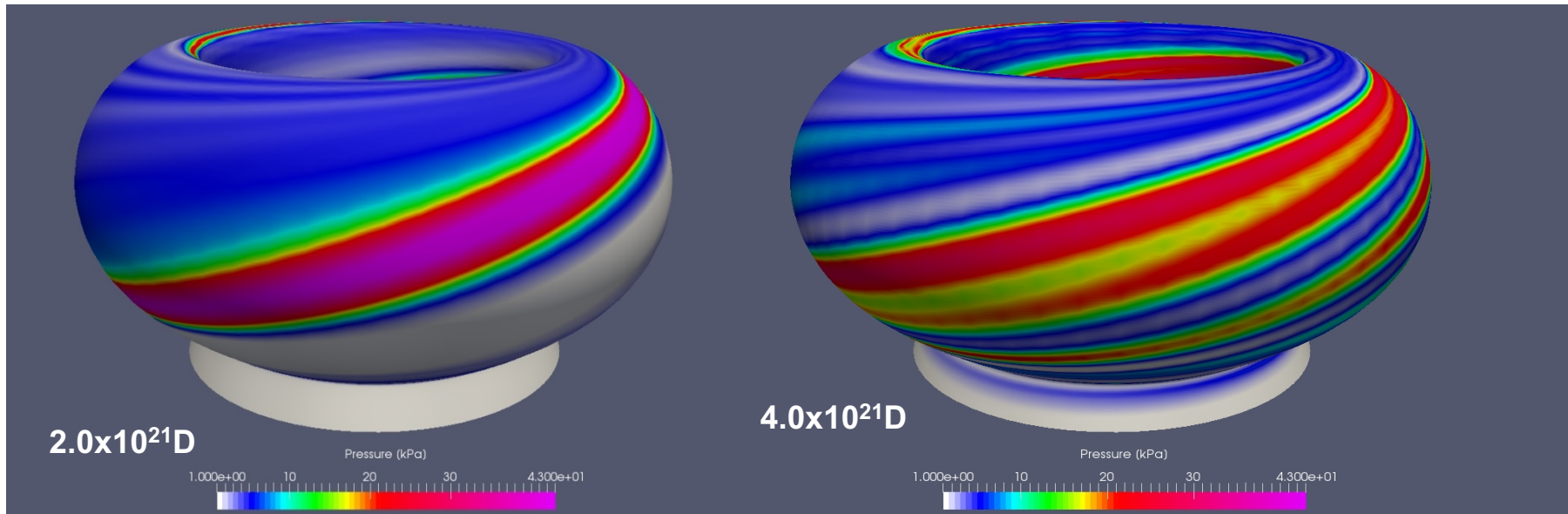
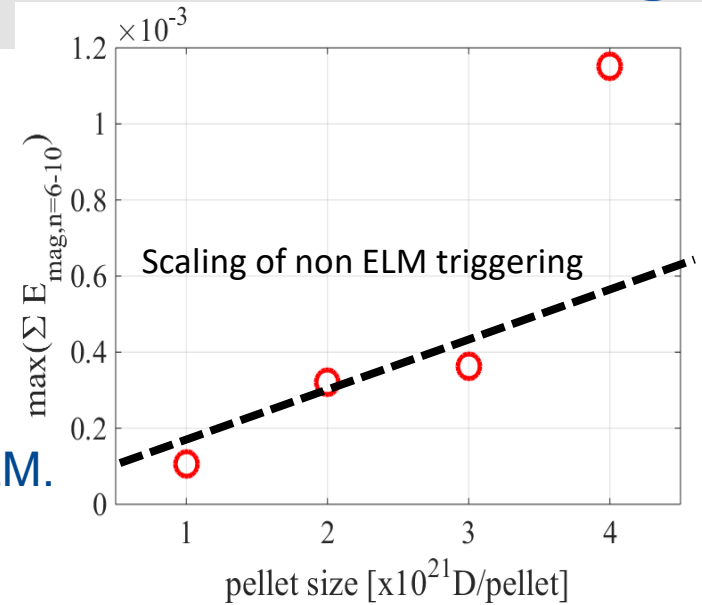
- ❧ The density plot and the potential contours of the largest pellet  $4.0 \times 10^{21} \text{D}$  are shown.
- ❧ The destabilization of the plasma by the pellet injection can be observed.



# ITER plasma – pellet size dependence



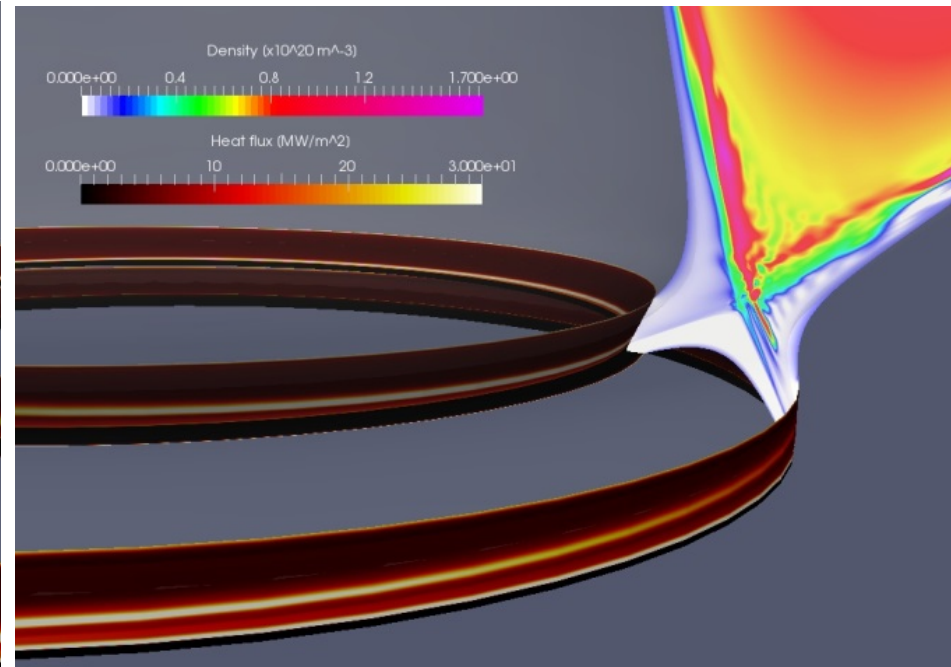
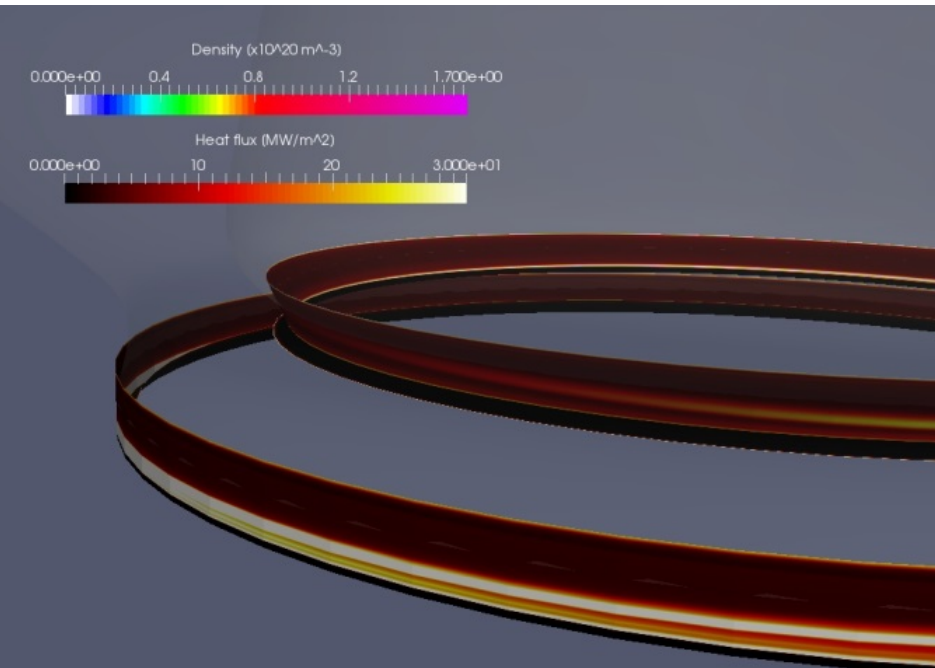
- « The maximum values of the sum of the high- $n$  modes ( $n=6-10$ ) of magnetic energy are plotted as a function of the pellet size.
- « There is a big difference between  $4.0 \times 10^{21} \text{D}$  and  $2.0 \times 10^{21} \text{D}$
- ➔ The threshold of the pellet size to trigger an ELM.



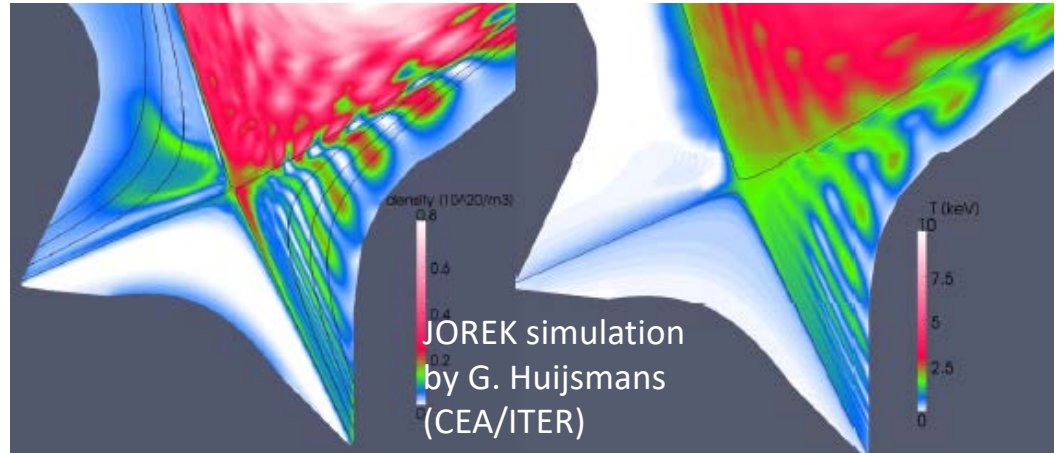
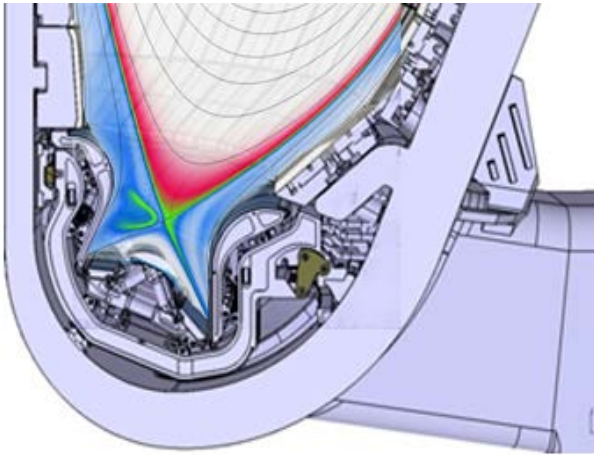
# Toroidally asymmetric heat flux on the divertor target caused by a pellet triggered ELM



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



# Conclusions and perspectives



## Conclusions

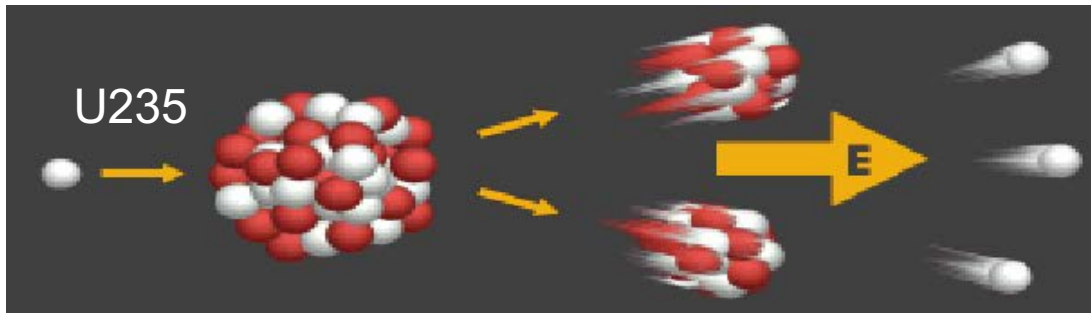
- JOREK has been performed to study the non-linear MHD physics.
- JOREK allows us to compute the ELM physics and calculate the heat flux onto the plasma facing components.
- Qualitative agreements with the experiment results of JET are observed via simulation.
- The simulations has been performed for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

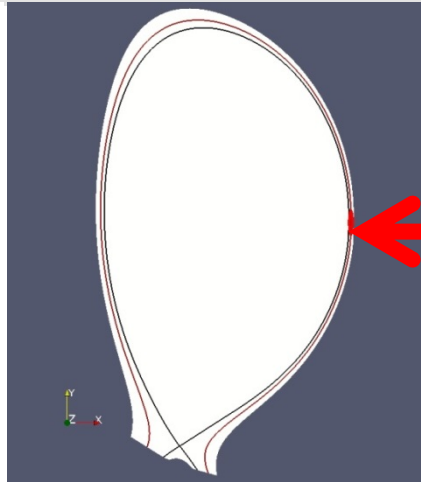
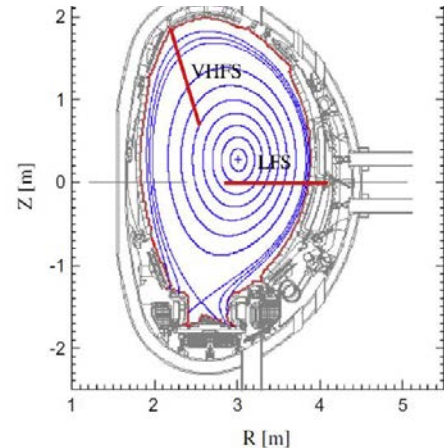
## Disadvantages of nuclear fusion:

- Technical and financial difficulty to achieve.... (Fusion power plant costs a lot...!)
- Physics problems (plasma instabilities, plasma control, etc...)

# Pellet injection in JET plasma (#84690)



[Frigione et al., JNM 2015]

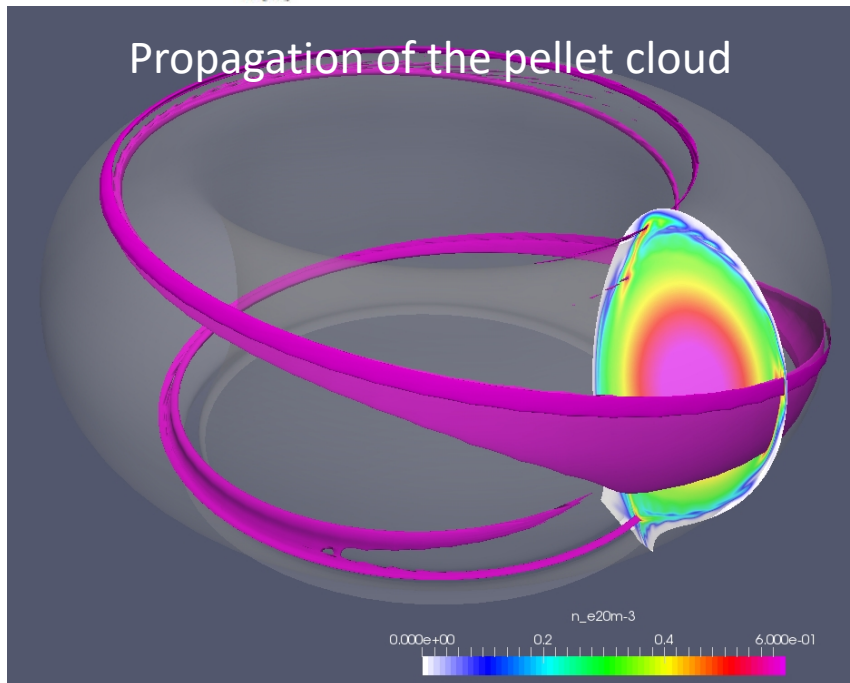


The pellet is injected from outer midplane in JET plasma (#84690).

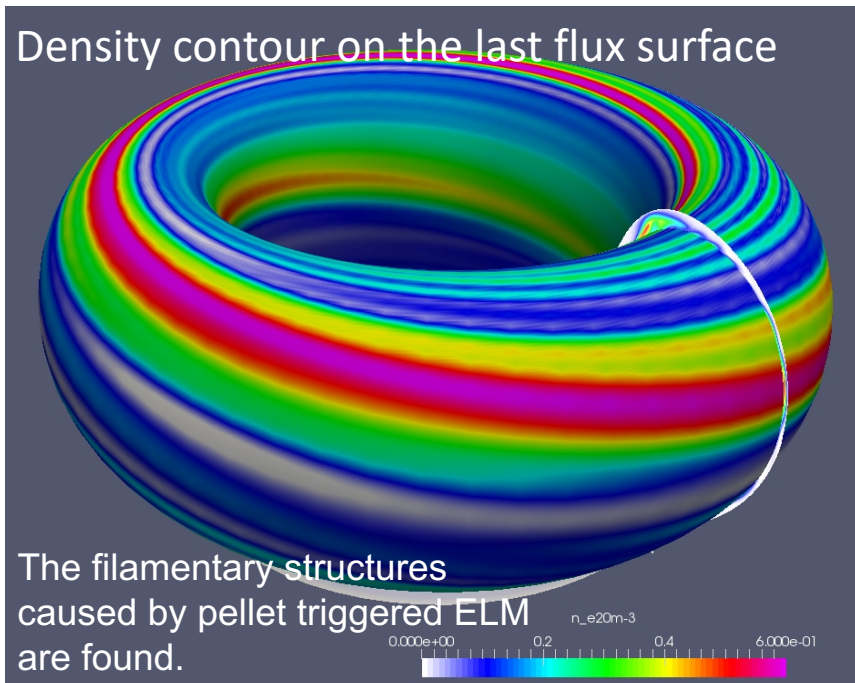
The pellet injection velocity is 78 m/s.  
Four pellet sizes have been investigated (not all cases are listed here) :

- **1.1mm**
- **1.7mm**

Propagation of the pellet cloud



Density contour on the last flux surface



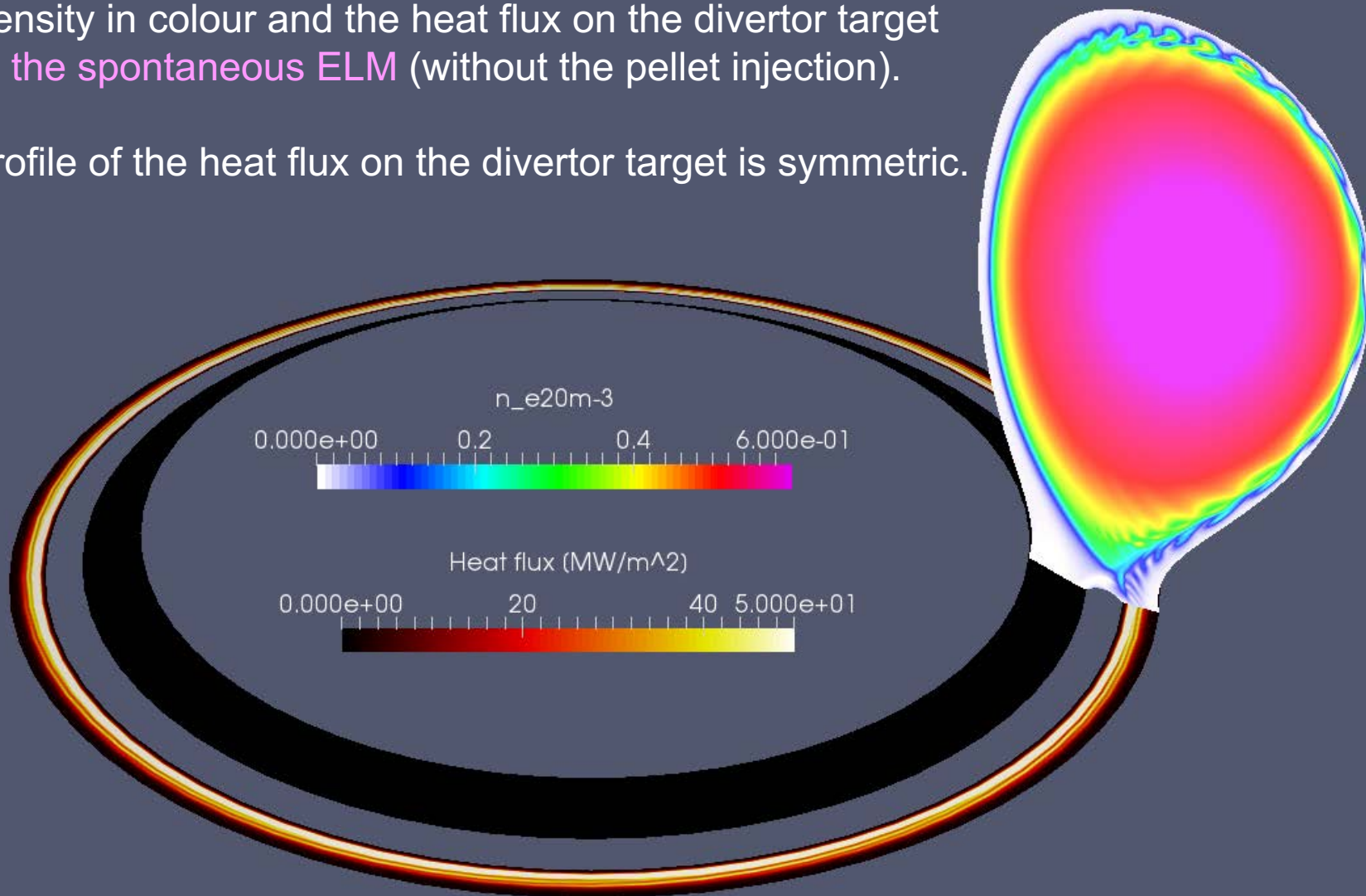
The filamentary structures caused by pellet triggered ELM are found.

# 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.



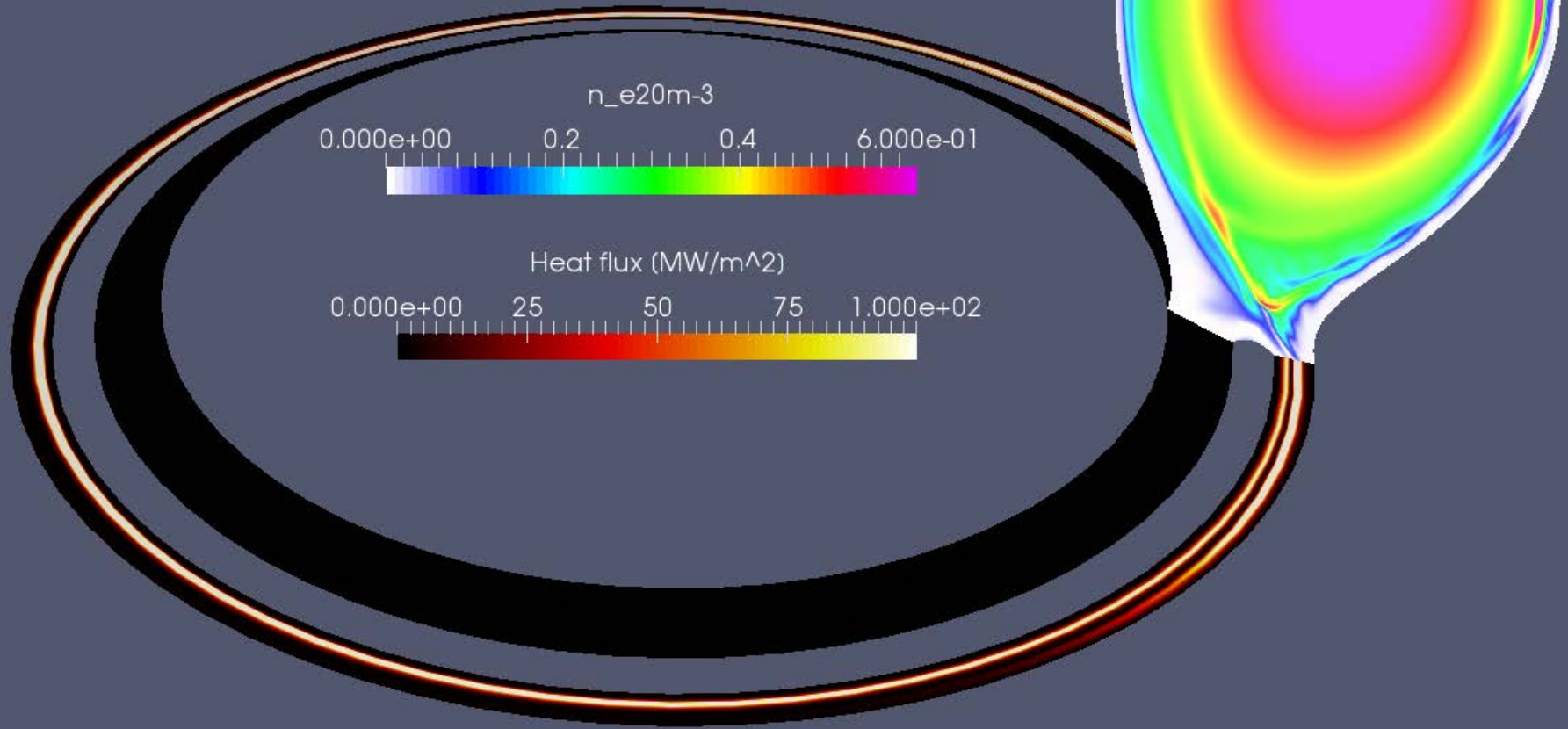


# Distribution of the heat flux (by pellet)

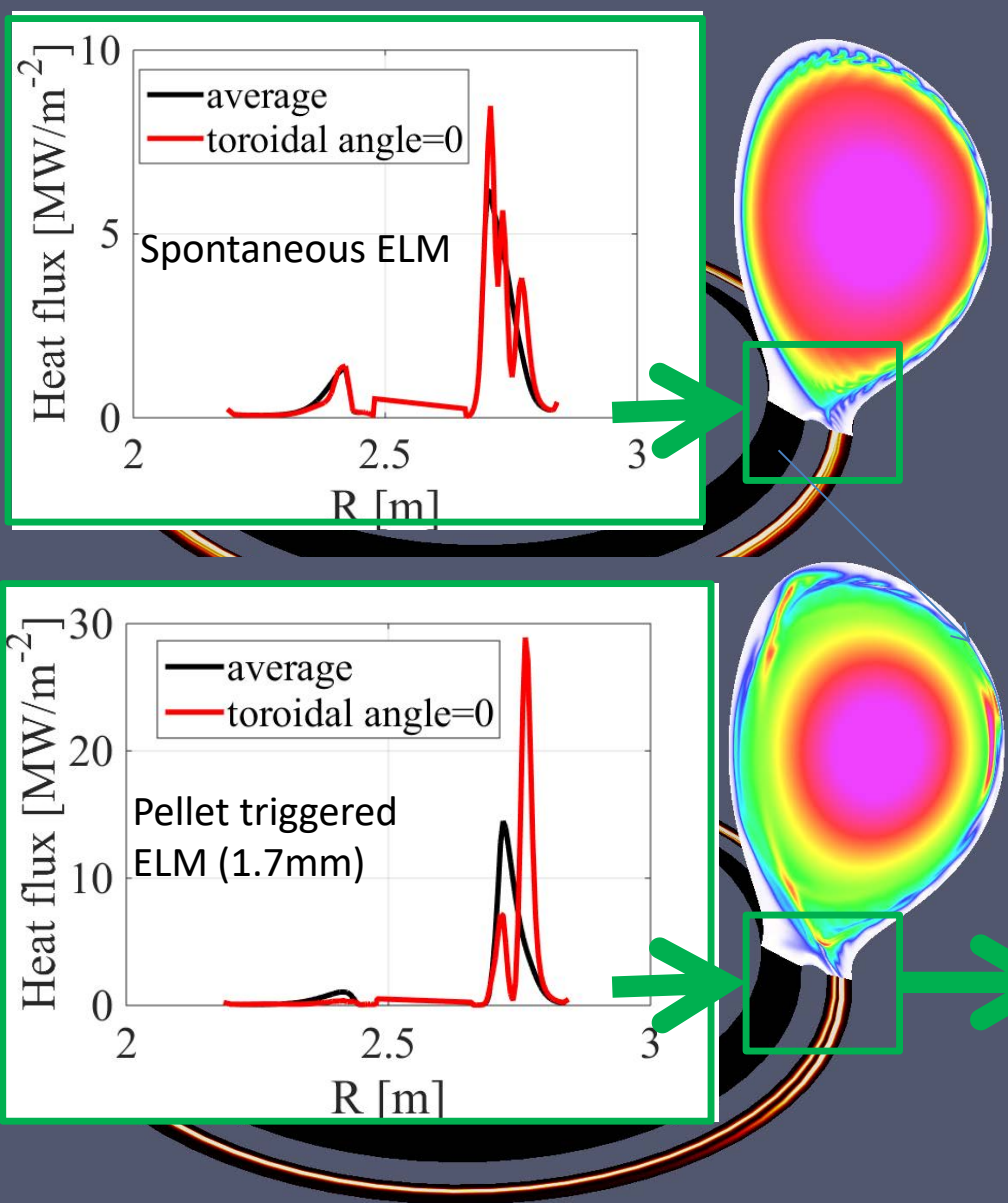


The density in colour and the heat flux on the divertor target during the pellet triggered ELM (1.7mm pellet).

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

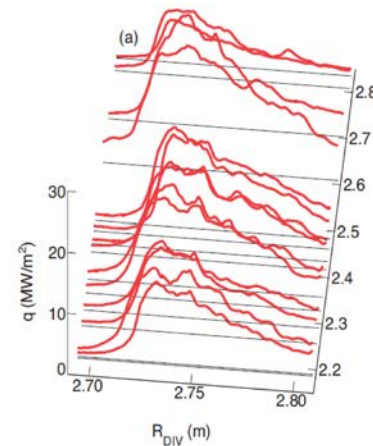


# Heat flux on the divertor target

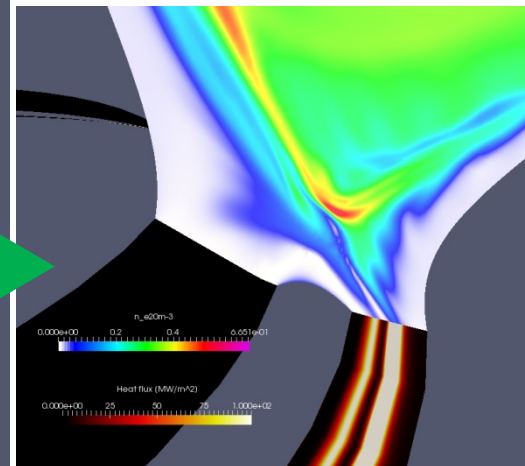
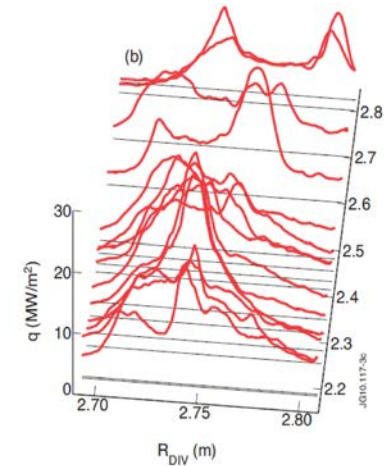


Heat flux profile on the divertor target ELM  
[Wenninger et al. (2010)].

(a) spontaneous ELM

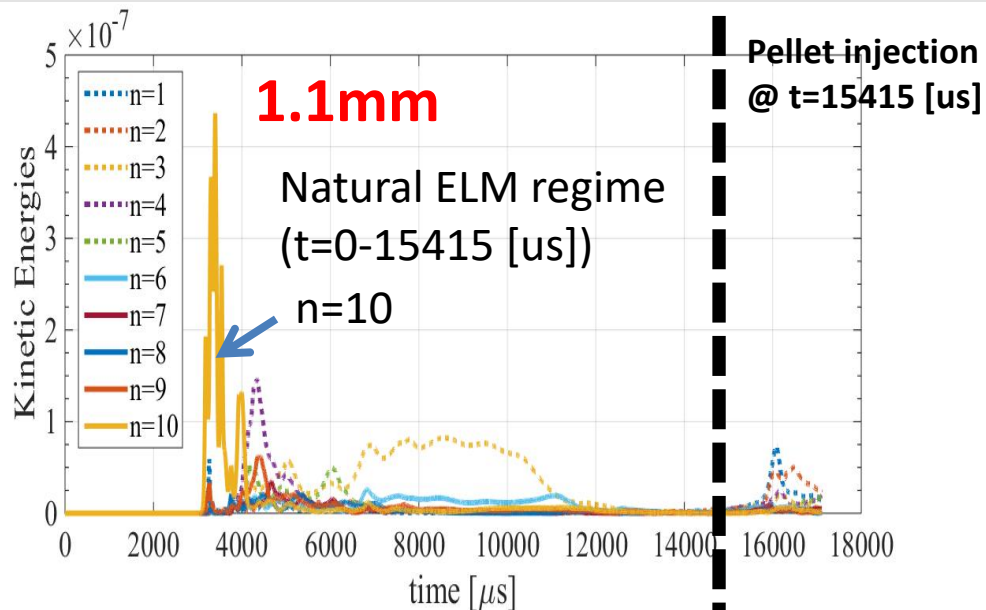


(b) pellet triggered



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.

