EUROfusion

Non-linear MHD simulations of ELM control via pellet injection in fusion plasmas

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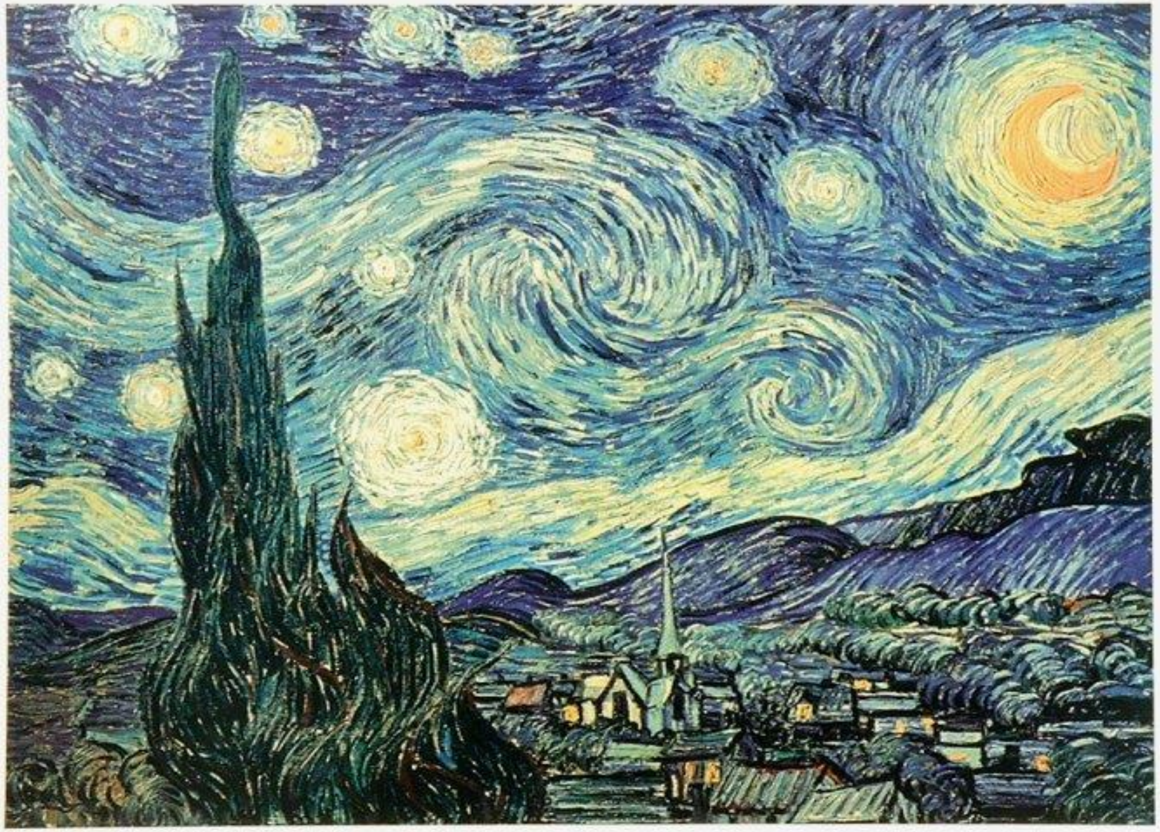
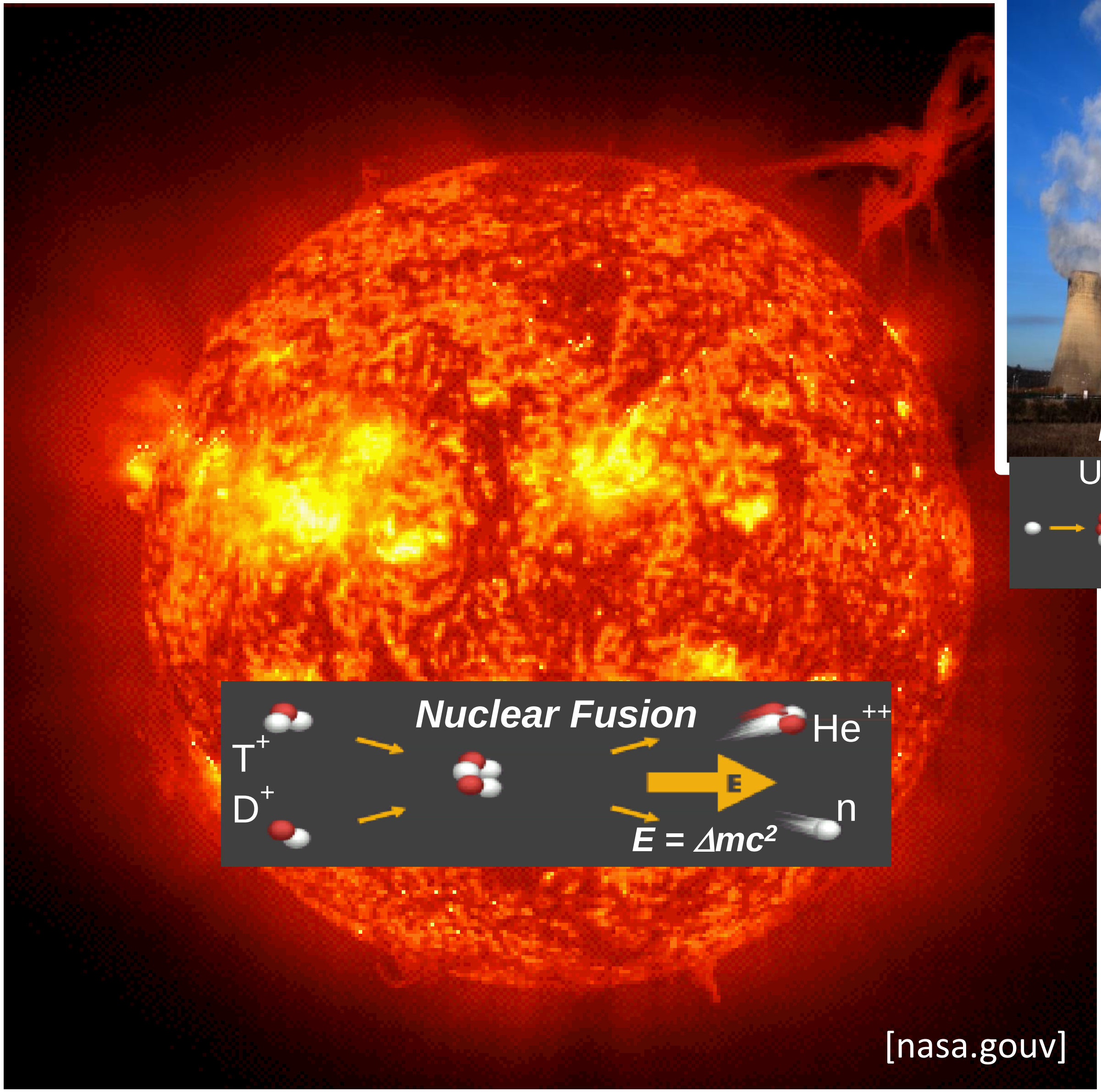
What makes stars shine?



“The starry night”, V. Willen van Gogh

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

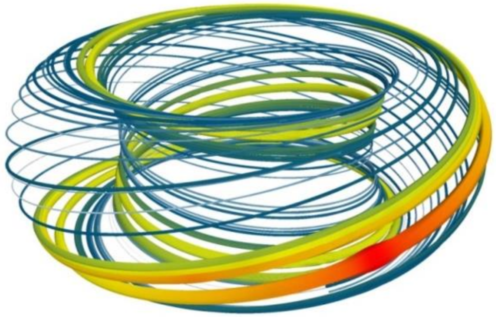
What makes stars shine? – Nuclear fusion



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

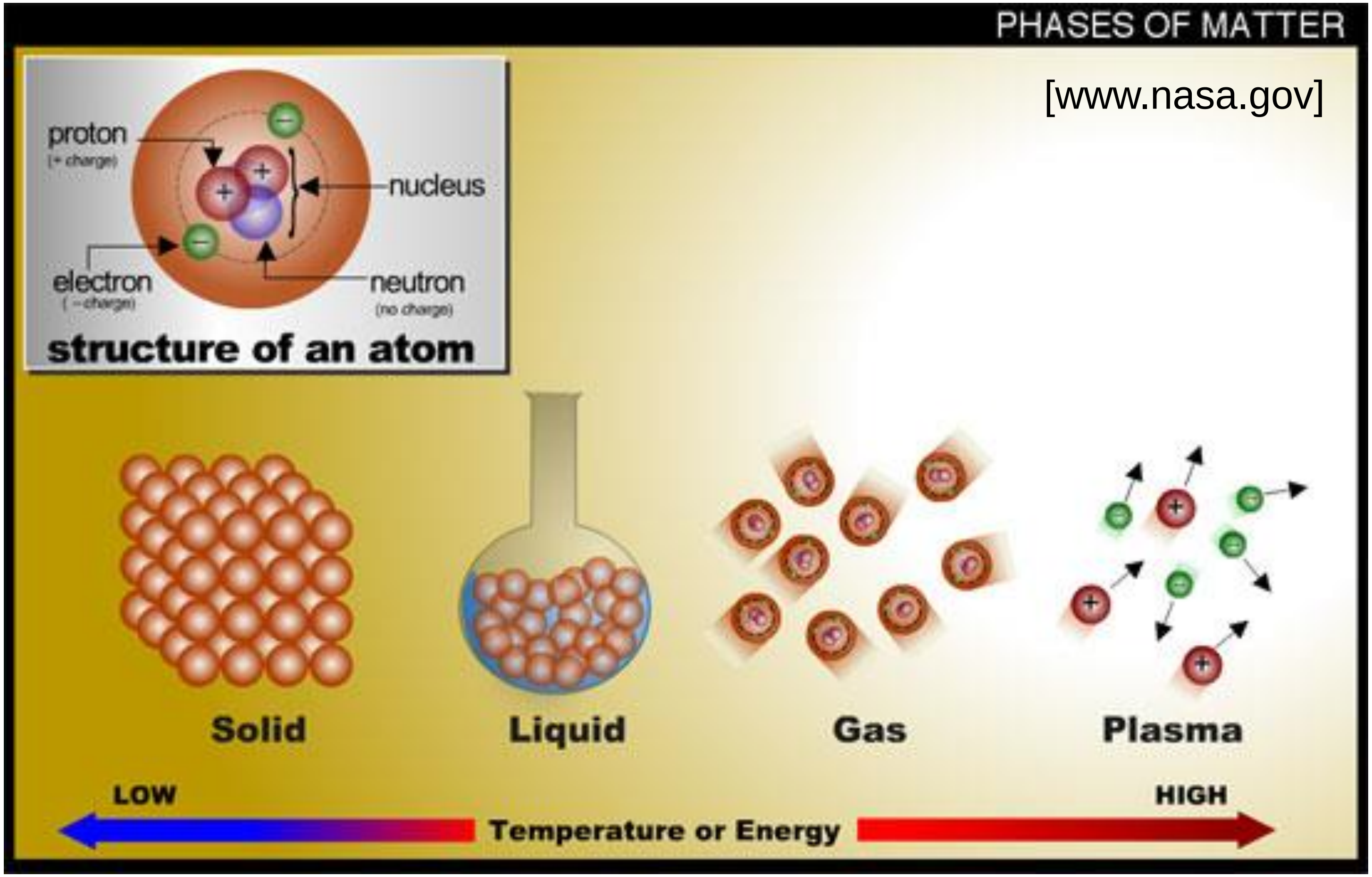
JOREK Modelling of pellet triggered ELM

Conclusions and Perspectives

What is plasma?

For achivement 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]

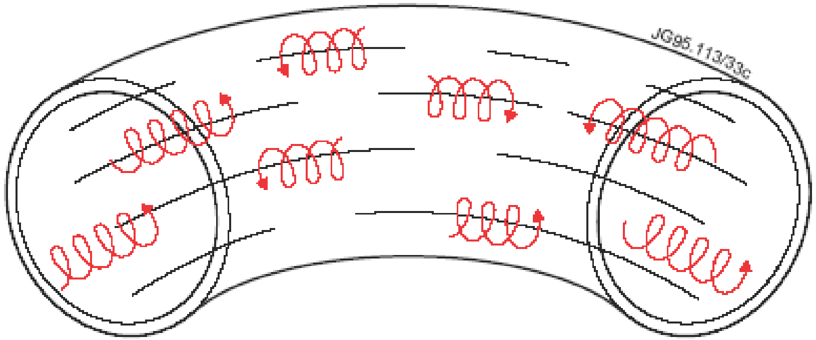
[wikipedia.org]

Fusion reactor on Earth

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

➔ **How can we confine the high-temperature plasma?**

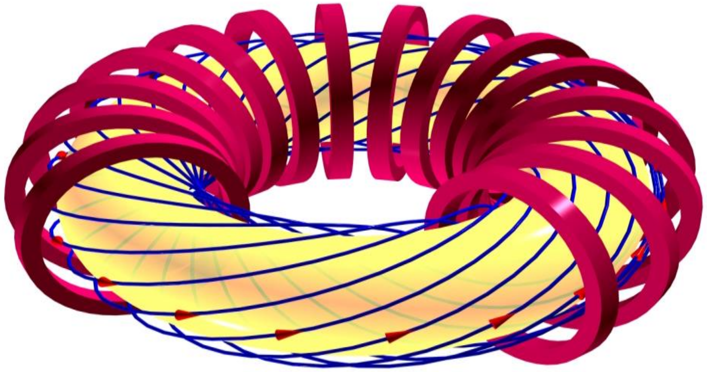
- On ***Earth***: plasmas can be confined in Magnetic field lines
  = Magnetic Confinement



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

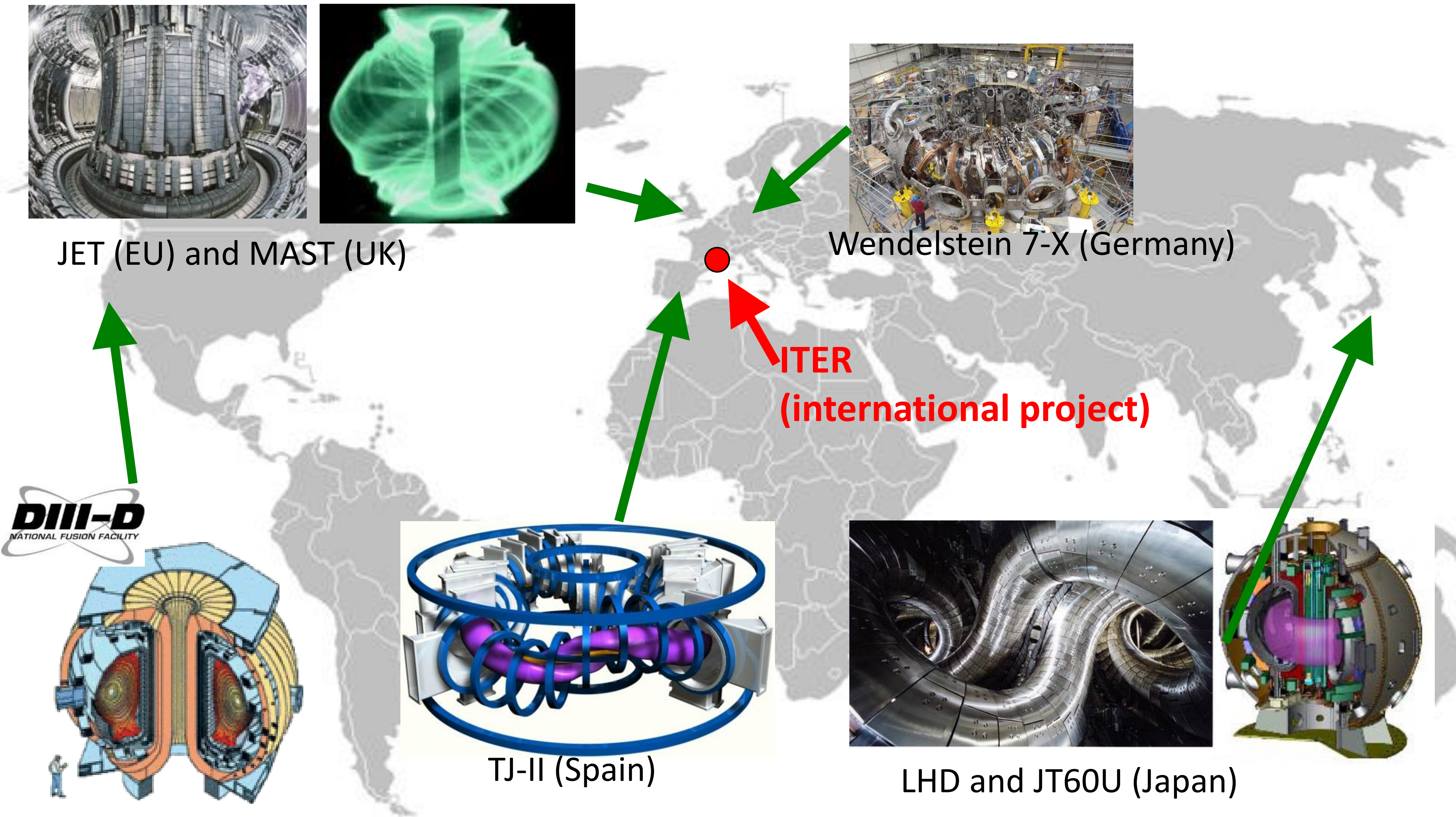
- ***Toroidal*** (Donut shaped) system avoids plasma hitting the end of the container

  ➔ **Tokamak**

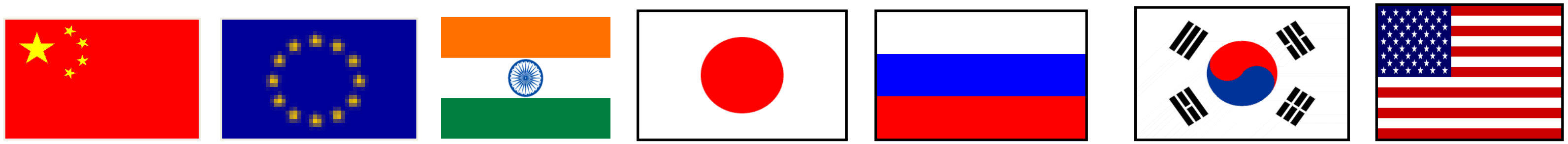


Fusion plasma reactors in the world

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



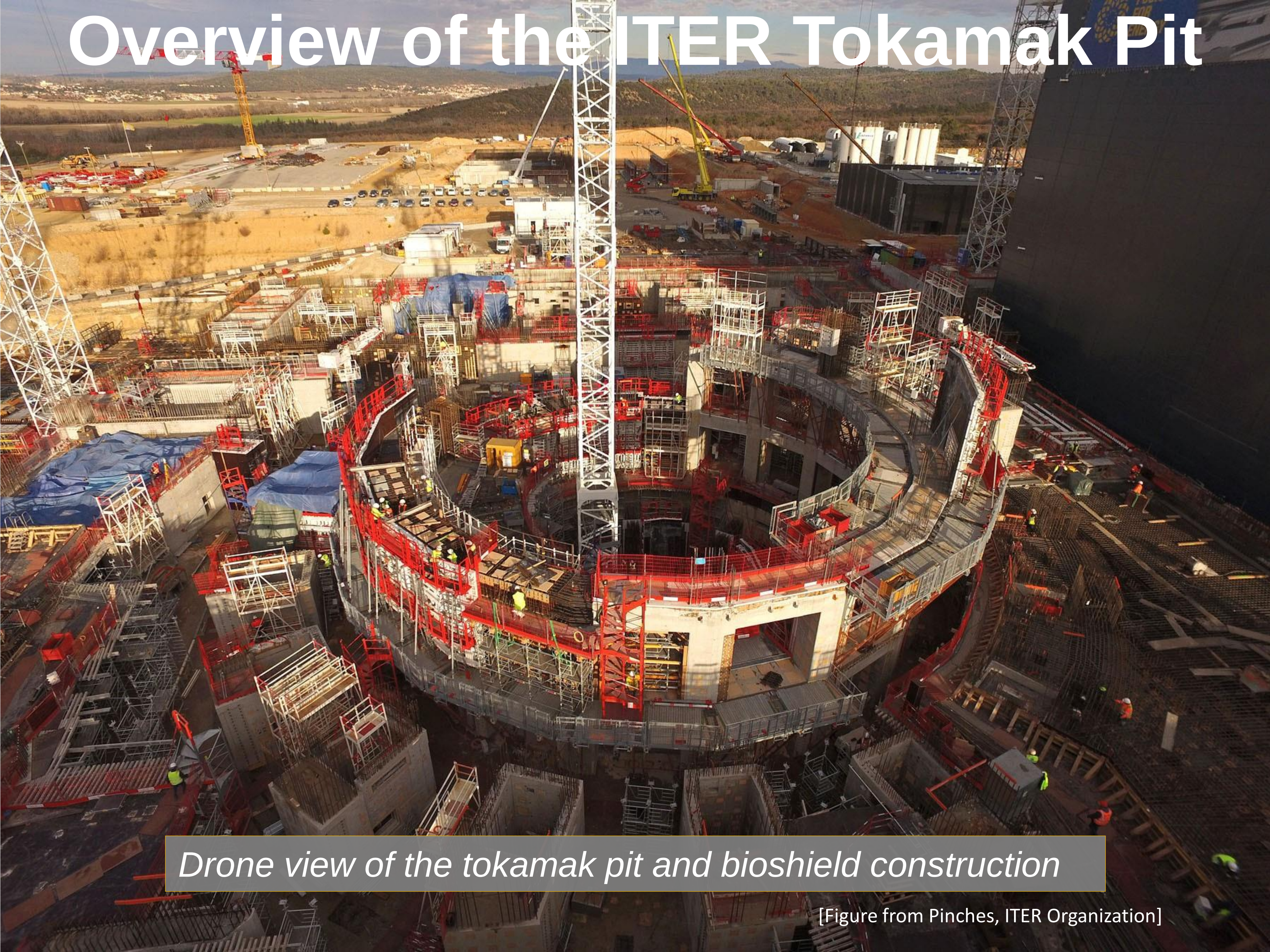
What is ITER? [www.iter.org]



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)

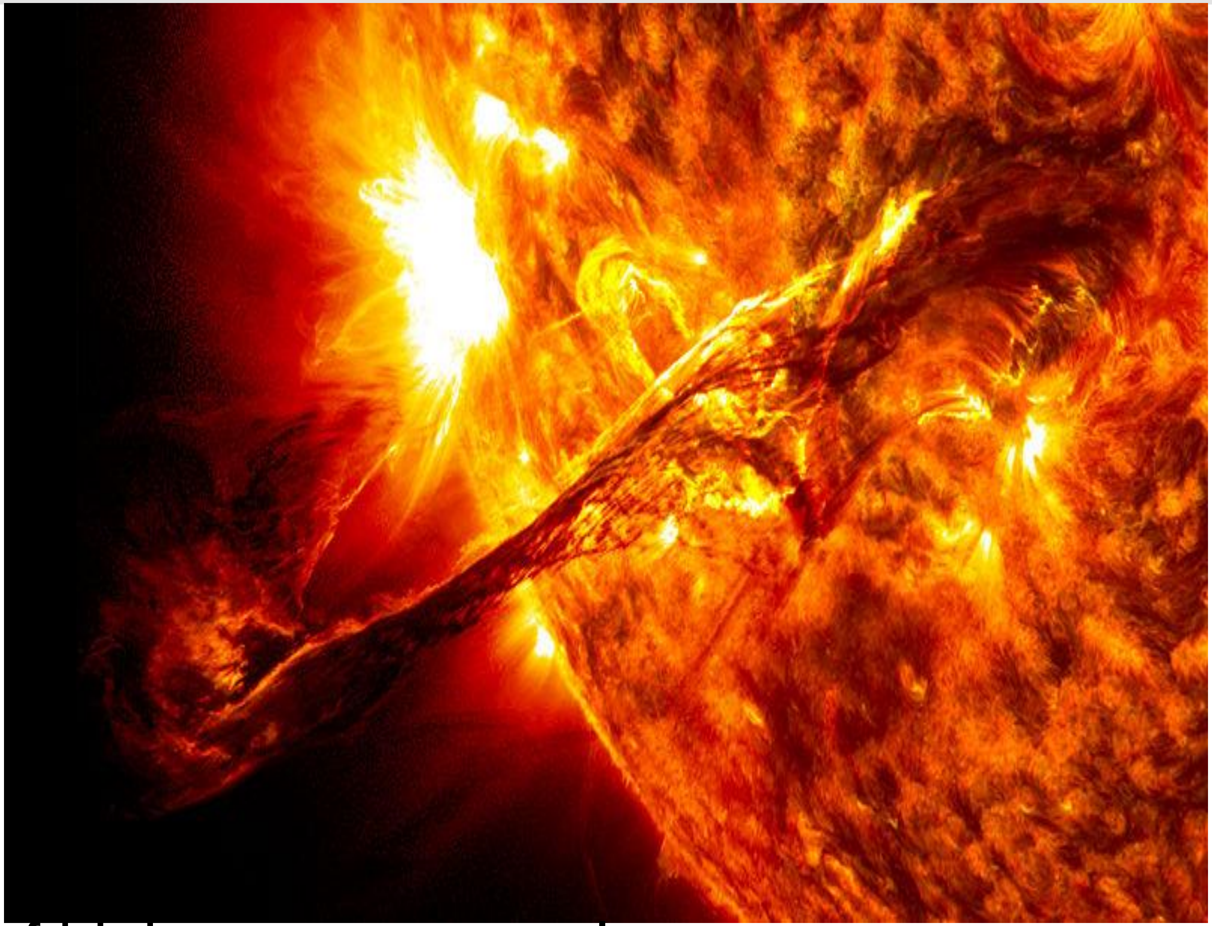
Overview of the ITER Tokamak Pit



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)**

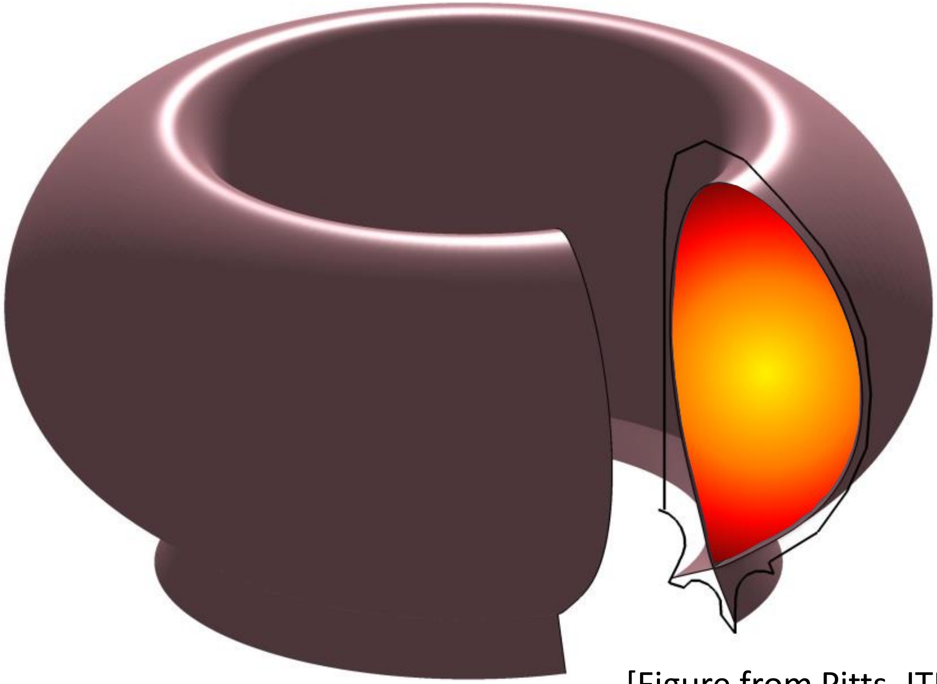
➔ **Big challenge for the control of the plasma**

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 ~200 microseconds
  - Periodic and bursty behaviors

} **ELM**



[Figure from Pitts, ITER Organization]

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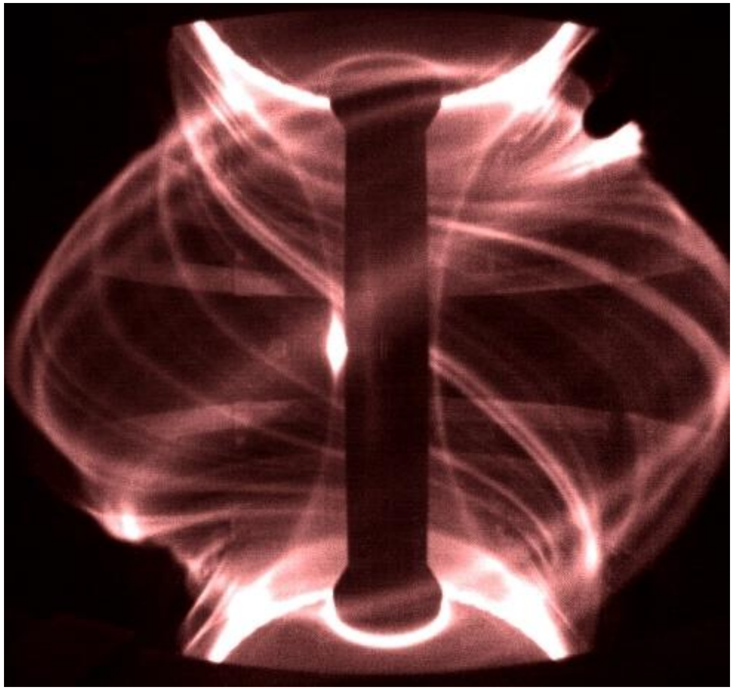
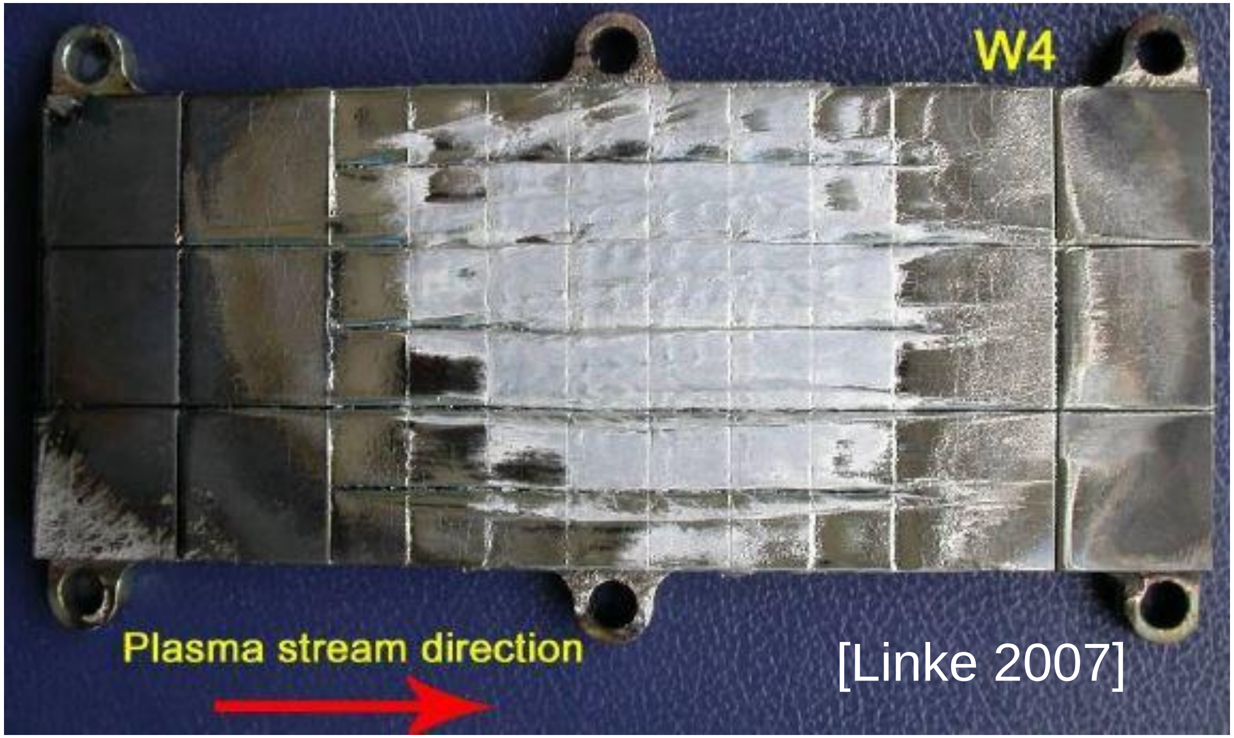
ELM



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

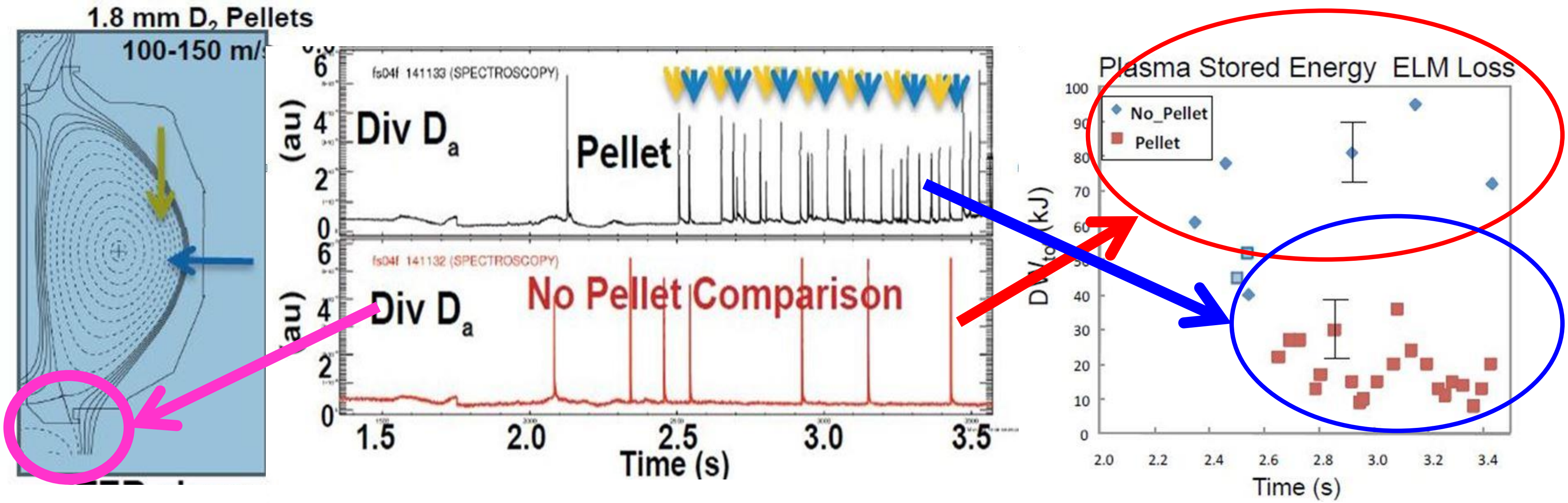
Edge Localized Modes (ELMs)



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



Divertor

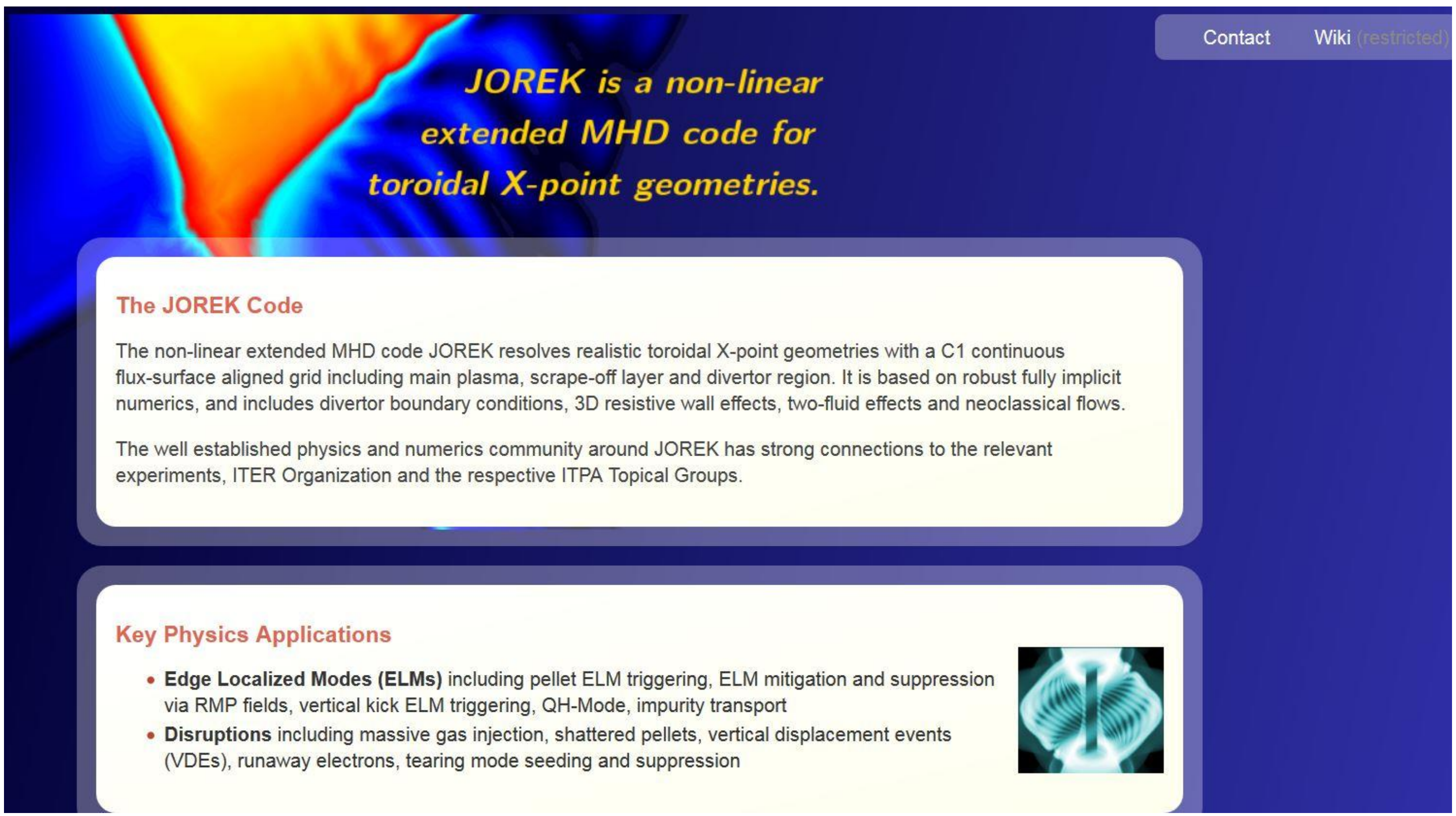
[Baylor APS 2010]

- 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, developped by Dr. G. Huijsmans (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/**]

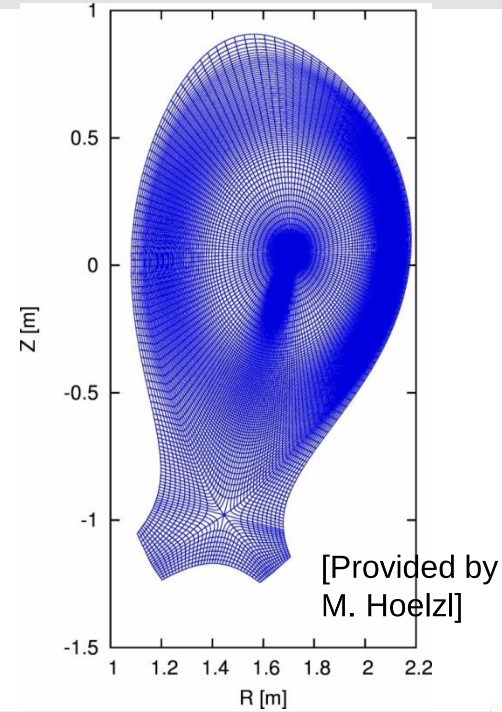


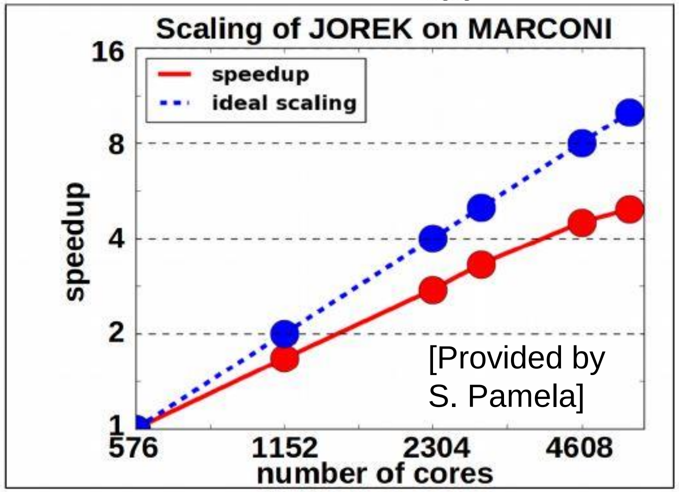
Non-linear MHD code JOREK

- **JOREK collaborations (>30 members, >10 international institutions):**
  - JOREK main development and application
    - Involved institutes: CEA, IPP Garching, ITER, CCFE, Eindoven etc.
  - Pellet triggering of ELMs
    - S. Futatani etc.
  - ELM mitigation/suppression by external fields
    - F. Orain, M. Becoulet, K. Wittawat, etc
  - Disruptions (MGI, REs, etc)
    - E. Nardon, C. Sommariva, V. Bandaru, M. Hoelzl, etc
  - Simulation of ELMs
    - G. Huijsmans, S. Pamela, M. Becoulet, F. Orain, M. Hoelzl, A. Lessig 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, etc.
  - 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, A. Ratnani 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 880-1800 cores
- MareNostrum III-IV (BSC), Marconi-Fusion (CINECA), HELIOS-IFERC (Japan), CURIE (France), hydra (Germany), etc





Non-linear MHD code JOREK

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

$$\kappa_{\|} \sim T^{5/2}$$
$$\eta \sim T^{-3/2}$$
$$\mu \sim T^{-3/2}$$

- Magnetic field and the velocity

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

- Mass density

$$\frac{\partial\rho}{\partial t} = -\nabla\cdot(\rho\boldsymbol{v}) + \nabla\cdot(D_\perp\nabla_\perp\rho) + S_\rho$$

Coupled with the pellet ablation model

- Poloidal momentum (vorticity)

$$\boldsymbol{e}_\varphi\cdot\nabla\times\left(\rho\frac{\partial\boldsymbol{v}}{\partial t} = -\rho\left(\boldsymbol{v}\cdot\nabla\right)\boldsymbol{v} - \nabla\left(\rho T\right) + \boldsymbol{J}\times\boldsymbol{B} + \mu\Delta\boldsymbol{v}\right)$$

- Parallel momentum

$$\boldsymbol{B}\cdot\nabla\times\left(\rho\frac{\partial\boldsymbol{v}}{\partial t} = -\rho\left(\boldsymbol{v}\cdot\nabla\right)\boldsymbol{v} - \nabla\left(\rho T\right) + \boldsymbol{J}\times\boldsymbol{B} + \mu\Delta\boldsymbol{v}\right)$$

- Temperature

$$\frac{\partial(\rho T)}{\partial t} = -\rho\boldsymbol{v}\cdot\nabla T - T\boldsymbol{v}\cdot\nabla\rho - \gamma\rho T\nabla\cdot\boldsymbol{v} + \nabla\cdot\left(\kappa_\perp\nabla_\perp T + \kappa_{\|}\nabla_{\|}T\right) + S_T$$

- Poloidal flux

$$\frac{1}{R^2}\frac{\partial\psi}{\partial t} = \eta(T)\nabla\cdot\left(\frac{1}{R}\nabla_\perp\psi\right) - \boldsymbol{B}\cdot\nabla u$$

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]

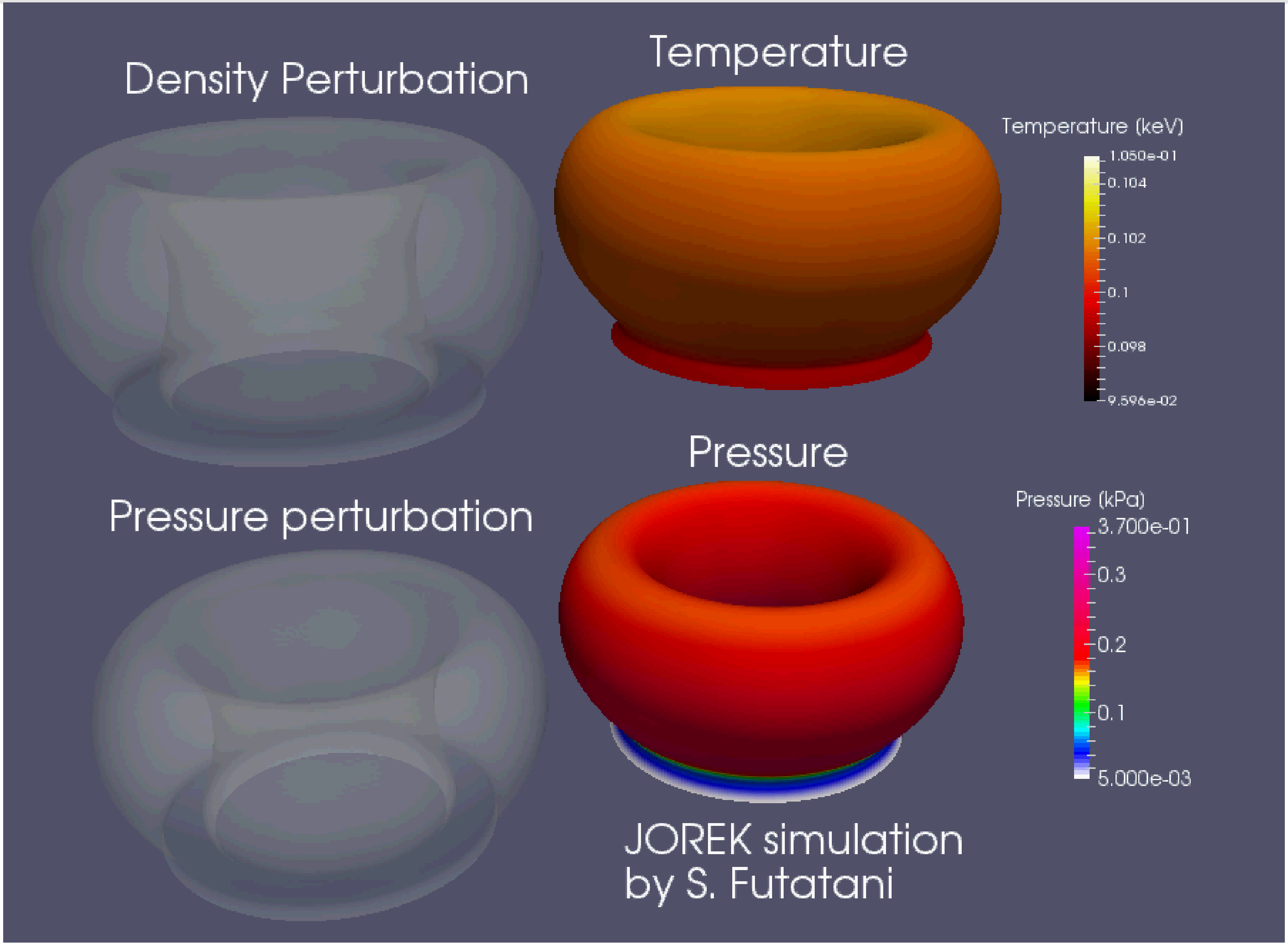
JOREK solves a very complex, multi-physics which requires HPC

Non-linear MHD physics ⇄ Interactions ⇄ **Pellet ablation physics**

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

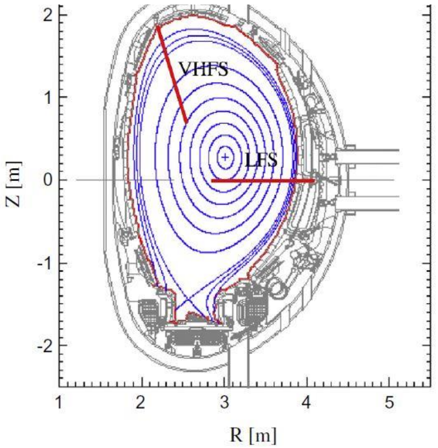
The HELIOS Supercomputer system at IFERC-CSC.

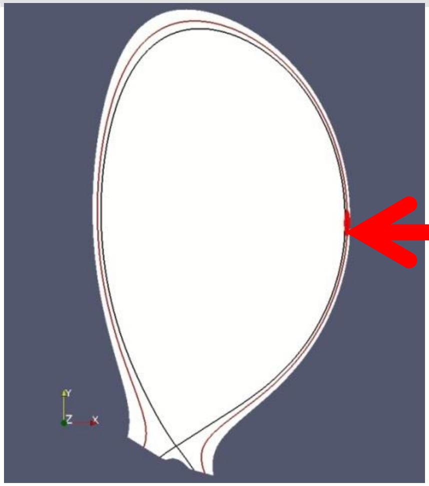
Mechanism of pellet triggered ELM



Pellet injection in JET plasma (#84690)

[Frigione et al.,JNM 2015]

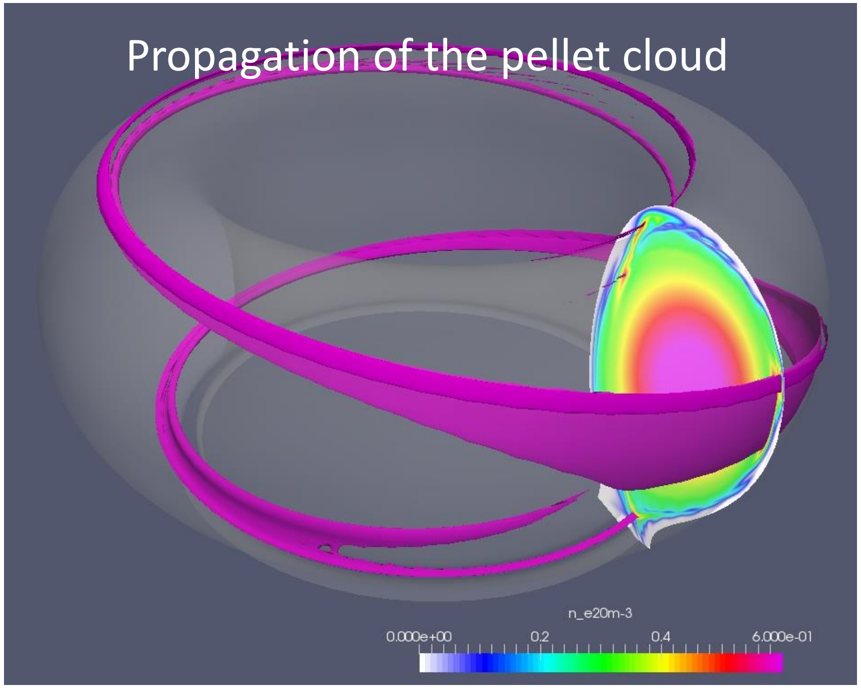


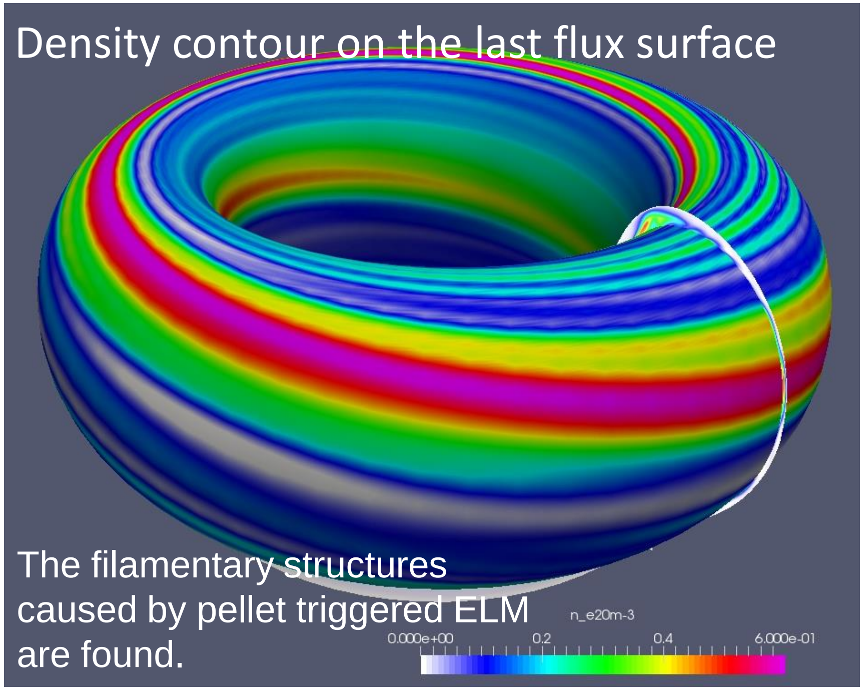


The pellet is injected from outer midplane in JET plasma (#84690).

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

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





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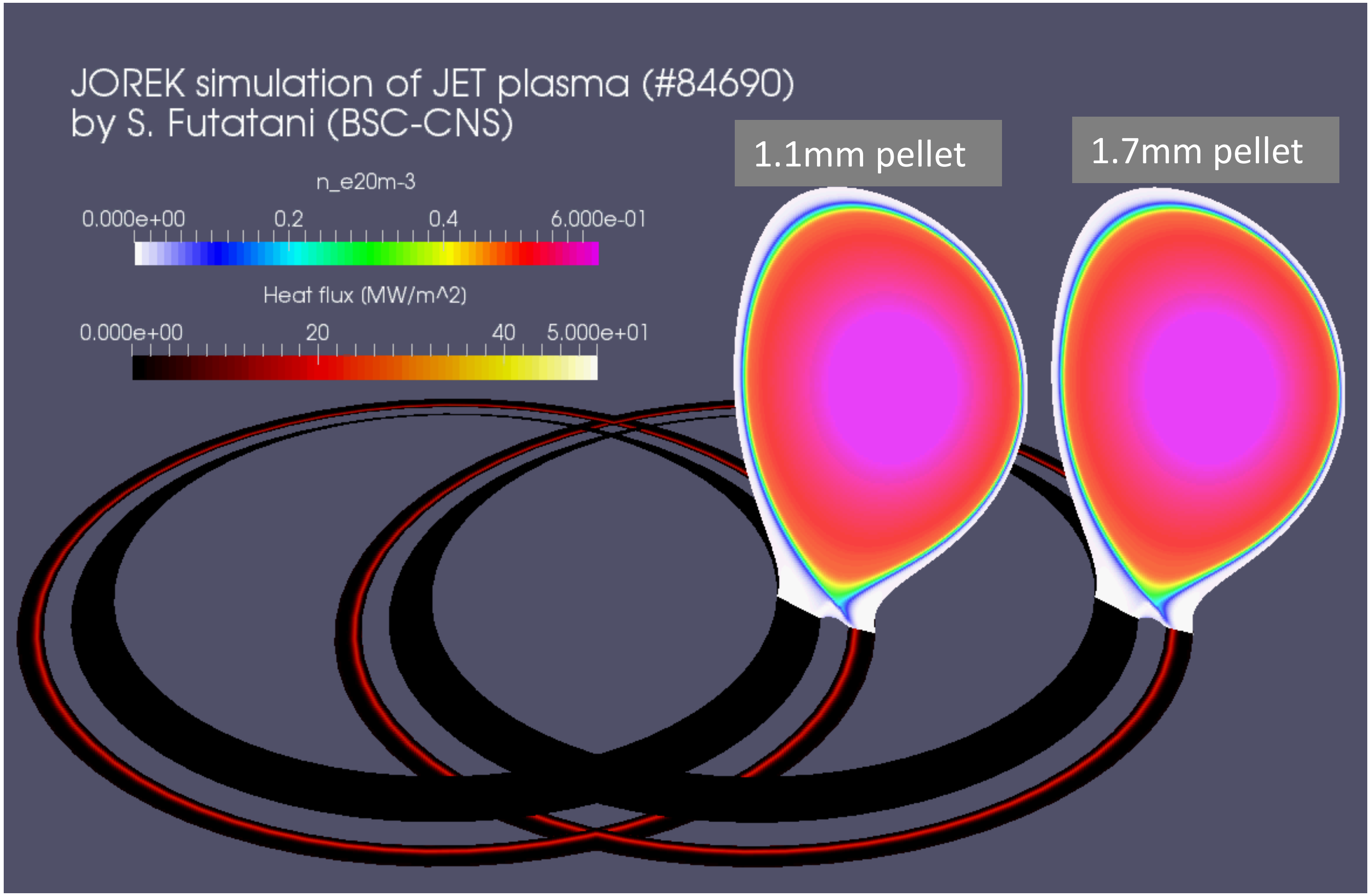
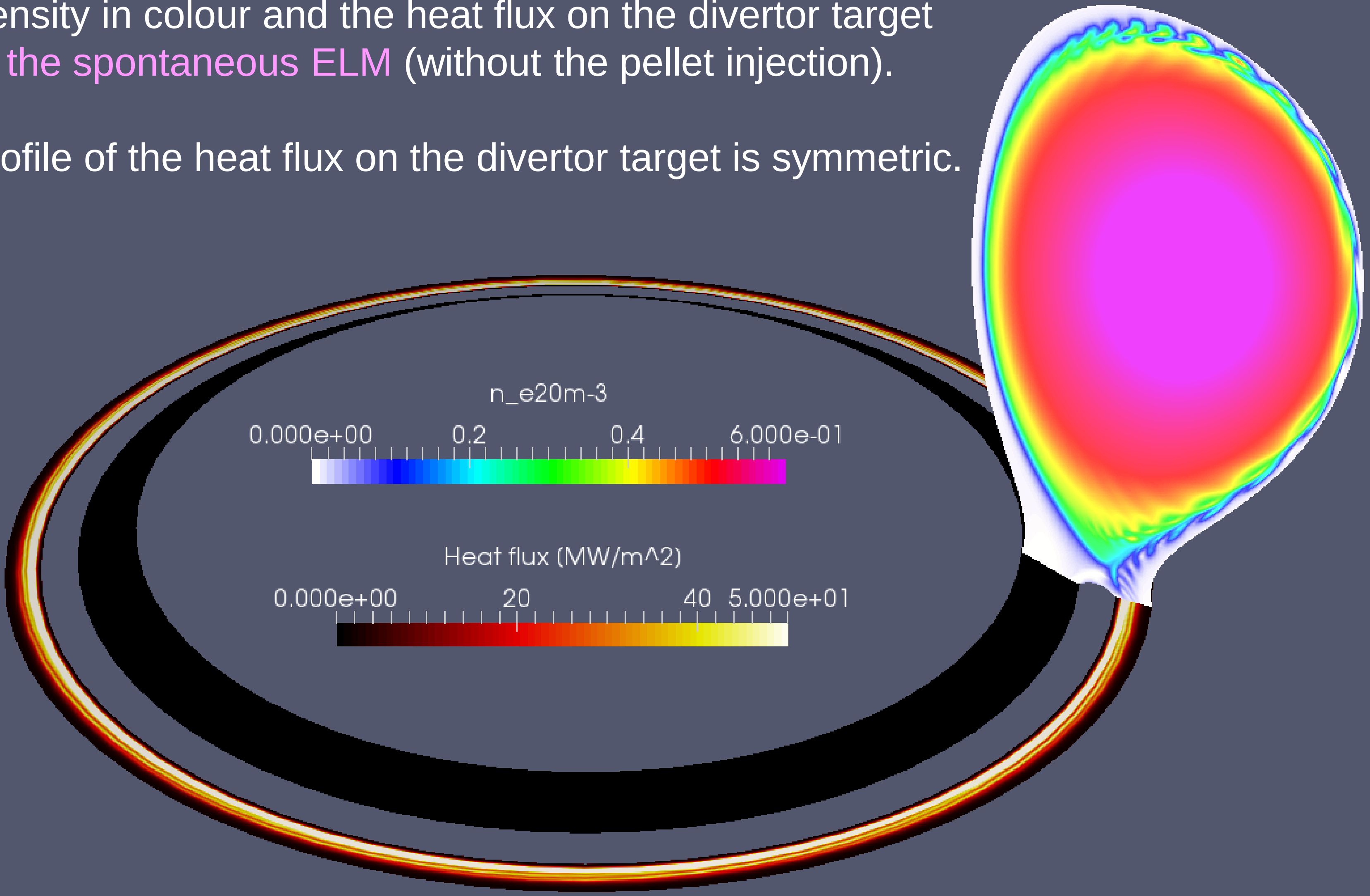


1.1mm pellet (left) and 1.7mm (right) from outer midplane with 78m/s.
5sec-23sec : spontaneous ELM **60sec - : pellet triggered ELM**

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).

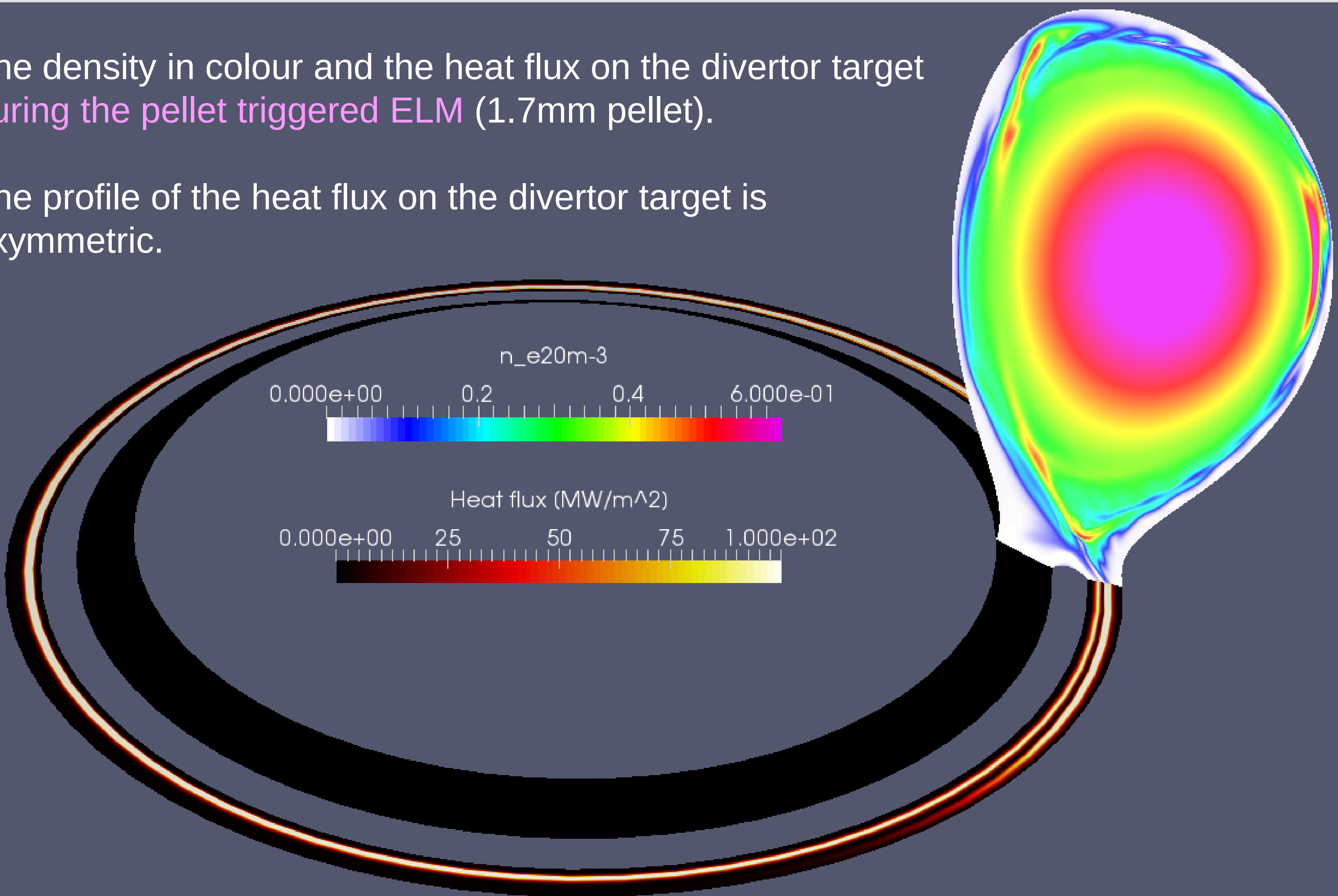
The profile of the heat flux on the divertor target is symmetric.



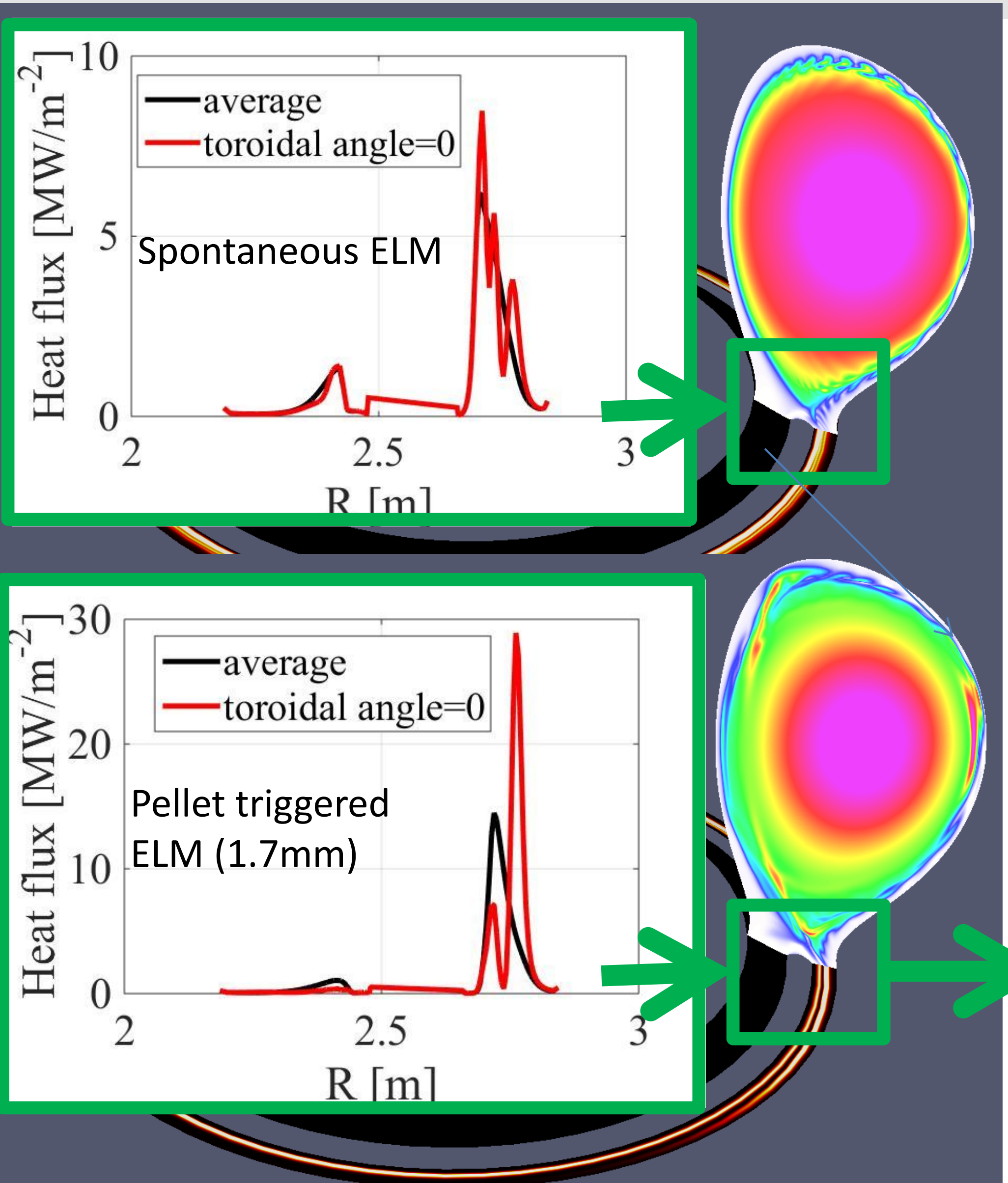
Distribution of the heat flux (by pellet)

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.

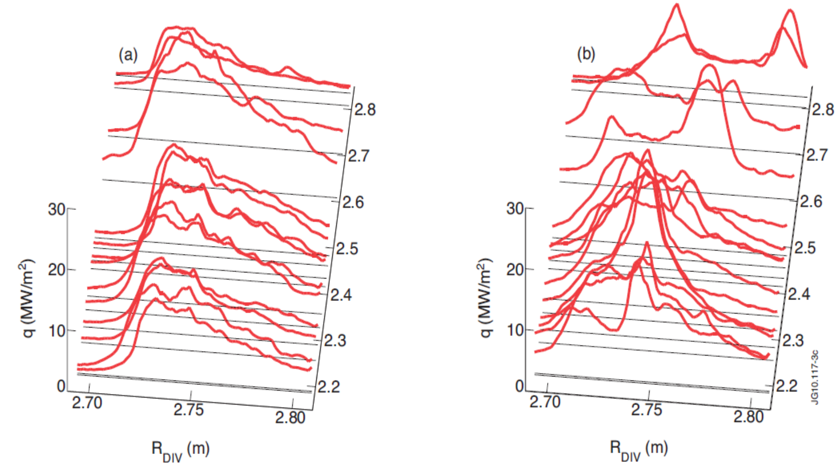


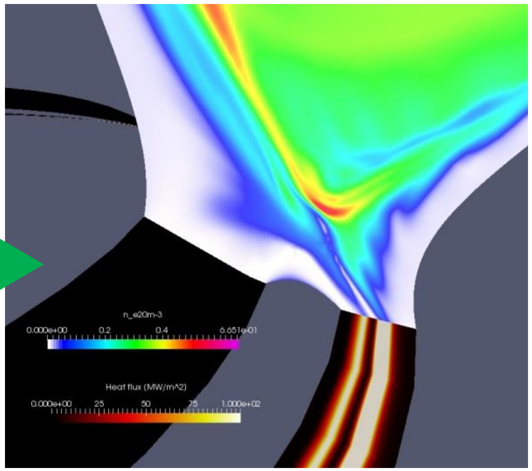
Heat flux on the divertor target



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.