EUROfusion

Non-linear MHD modelling of pellet triggered ELMs in JT-60SA

S. Futatani[1,2], S. Pamela[2], E. de la Luna[3], L. Garzotti[2], J. Garcia[4], G.T.A. Huijsmans[4], M. Hoelzl[5], A. Cathey[5], the JOREK Team[6]

[1]Universitat Politècnica de Catalunya, Barcelona, Spain , [2]EURATOM/CCFE, Fusion Association, Culham Science Centre, Abingdon, Oxon OX14 3DB, UK, [3]Laboratorio Nacional de Fusion, CIEMAT, 28040 Madrid, Spain, *[4]CEA, IRFM, F-13108, St-Paul-Lez-Durance, France, [5]Max Planck Institute for Plasma Physics, Boltzmannstr. 2, 85748 Garching, Germany, [6]See in M Hoelzl et al 2020 Nucl. Fus. sub,* https://arxiv.org/abs/2011.09120

Email : shimpei.futatani@upc.edu

Introduction

Pellets in JT-60SA

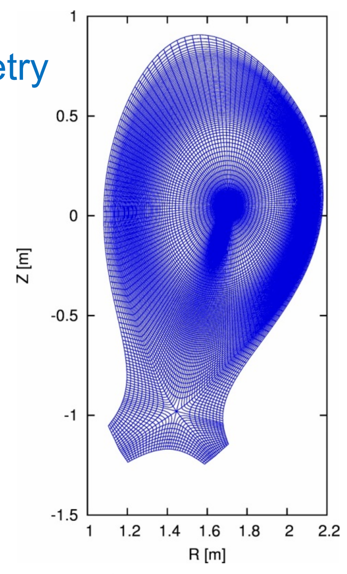
- JT-60SA is a fully superconducting tokamak device jointly designed, built and exploited by Japan and Europe [Barabaschi P et al. 2019 NF 59 112005], presently being commissioned.
- Pellet injection will be used for the operation of JT-60SA in order to control the density profile and the ELM frequency.
- The conceptual design for the JT-60SA pellet injection system has been carried out [P.T. Lang et al., Fusion Engineering and Design 123 (2017)] in the framework of the joint research activities for the preparation of the tokamak exploitation [Giruzzi G et al. 2020 Plasma Phys. Contr. Fusion 62 014009].

Motivation of the work

- It is essential to estimate the pellet condition to trigger the ELM and the fueling efficiency in the relevant plasma scenarios, from theoretical and numerical point of view.
- JOREK, the non-linear MHD (magnetohydrodynamics) simulation code, has been performed to analyze the plasma MHD response by pellet injection in JT-60SA.
- This work aims to improve the understanding of physics process involved in ELM control by pellet injections in order to provide estimates of pellet injection performance for JT-60SA.

Non-linear MHD code : JOREK

- JOREK has been developed with the specific aim to simulate ELMs [Huysmans, NF 2007, Czarny JCP 2007, M Hoelzl et al 2020 NF. sub, arXiv:2011.09120]. See www.jorek.eu for more information.
  - –domain with closed and open field lines, X-point
  - –non-linear reduced MHD (and full MHD) in toroidal geometry
    - Density, temperature, electric potential (perp. flow), parallel velocity, poloidal flux
    - Ideal wall conditions on walls,
    - Mach one, free outflow at divertor target
- Magnetic field and velocity field $\vec{B} = \left(\frac{F_0}{R}\right)\vec{e}_\varphi + \left(\frac{1}{R}\right)\nabla\psi(t)\times\vec{e}_\varphi \qquad \vec{v} = -R\nabla u(t)\times\vec{e}_\varphi + v_{\|}(t)\vec{B}$
- Density $\frac{\partial\rho}{\partial t} = -\nabla\cdot(\rho\vec{v}) + \nabla\cdot(D_\perp\nabla_\perp\rho) + S_\rho$
- Temperature $\frac{\partial(\rho T)}{\partial T} = -\rho\vec{v}\cdot\nabla T - T\vec{v}\cdot\nabla\rho - \gamma\rho T\nabla\cdot\vec{v} + \nabla\cdot(\kappa_\perp\nabla_\perp T + \kappa_{\|}\nabla_{\|}T) + S_T$
- Poloidal momentum $\vec{e}_\varphi\cdot\nabla\times\left[R^2\left(\rho\frac{\partial\vec{v}}{\partial t} = -\rho(\vec{v}\cdot\nabla)\vec{v} - \nabla(\rho T) + \vec{J}\times\vec{B} + \mu\Delta\vec{v}\right)\right]$
- Parallel momentum $\vec{B}\cdot\left(\rho\frac{\partial\vec{v}}{\partial t} = -\rho(\vec{v}\cdot\nabla)\vec{v} - \nabla(\rho T) + \vec{J}\times\vec{B} + \mu\Delta\vec{v}\right)$
- Poloidal flux $\frac{1}{R^2}\frac{\partial\psi}{\partial t} = \eta(T)\nabla\cdot\left(\frac{1}{R}\nabla_\perp\psi\right) - \vec{B}\cdot\nabla u$
- Boundary conditions : Ideal wall condition on surfaces parallel to magnetic field, Bohm condition: Parallel flow = sound speed

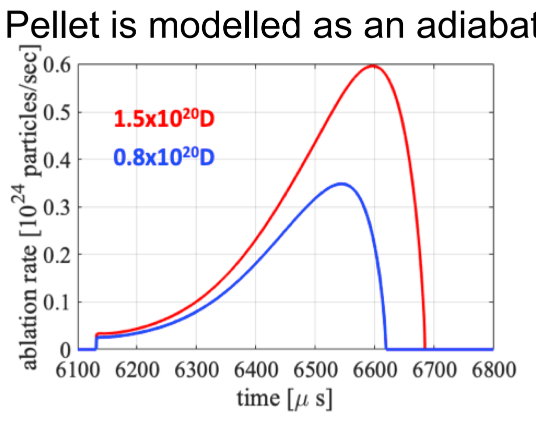


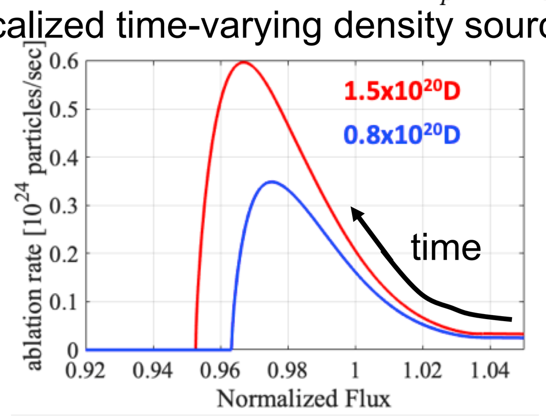
flux-aligned grid, provided by M. Hoelzl (reduced resolution)

Pellet model : Neutral Gas Shielding (NGS)

Realistic pellet ablation model (NGS model [Gal, NF(2008)]) is implemented in JOREK :

- Pellet moves at fixed speed and direction $N' = 4.12\times10^{16}\cdot r_p^{1.33}\cdot n_e^{0.33}\cdot T_e^{1.64}$
- Pellet is modelled as an adiabatic localized time-varying density source

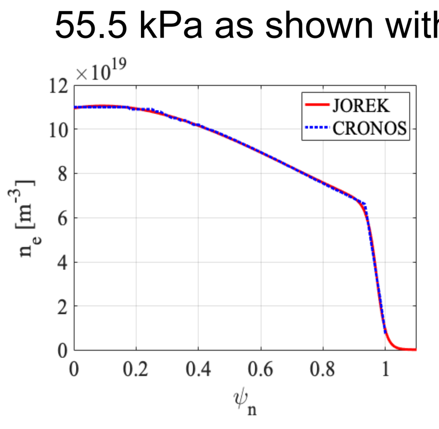


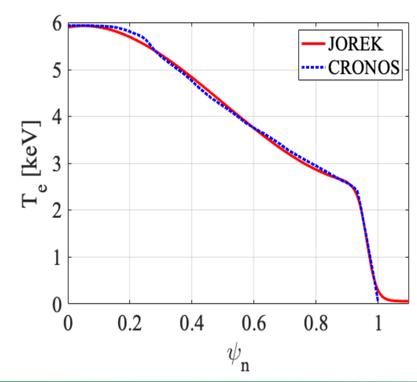


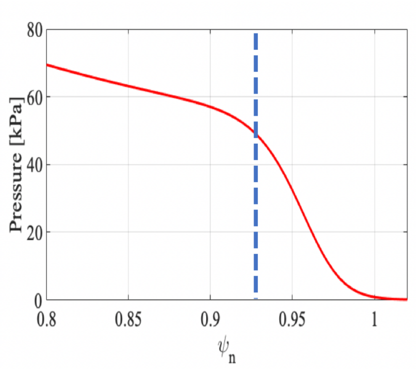
Profile of pellet ablation rate in JT-60SA obtained by JOREK simulation.

JT-60SA ELMy H-mode equilibrium

- The target plasma equilibrium is reproduced from the calculation of ELMy H-mode, high current and high power scenario (5.5 MA, 41 MW, single null divertor) by a CRONOS simulation.
- The pressure profile shows that the location of the pedestal top is at Ψ_N=0.93, 55.5 kPa as shown with the dashed-line.





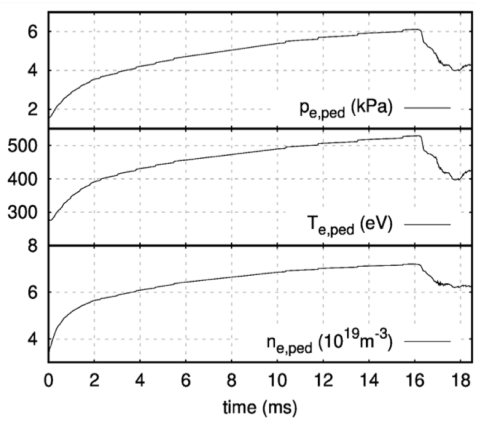


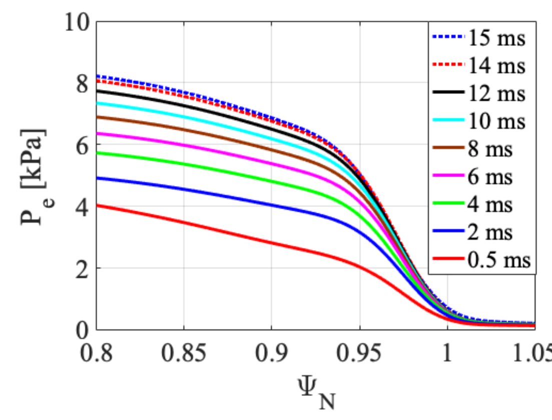
Previous simulations of pellet triggered ELM

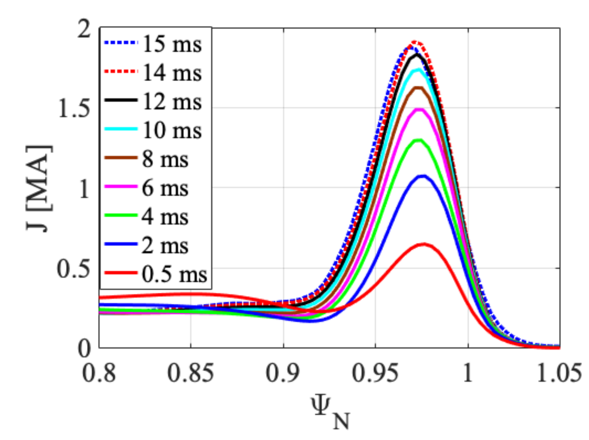
Transition from no-ELM to pellet ELM triggering during pedestal build-up

Motivation and Aim of the work

- When injecting deuterium pellets into type-I ELM simulations at different phases during pedestal build up, a “lag-time” is observed; pellet injections at earlier stages leading no ELM crash while the pellet injections at later stages trigger ELMs.
- Qualitative comparison to respective experimental observations from [PT Lang et al, NF 44, 665 (2004)] are performed.
- JOREK simulations were improved by including realistic plasma background (diamag. + ExB) flows based on simulations of type-I ELM cycles in ASDEX Upgrade [Cathey A. Hoelzl M. et al., NF 60 124007 (2020)].
- For the present set-up, a spontaneous ELM appears at ~16 ms.
- Pellets are injected at different time points during pedestal build-up [Futatani, Cathey, Hoelzl, et al., NF 61 (2021) 046043].

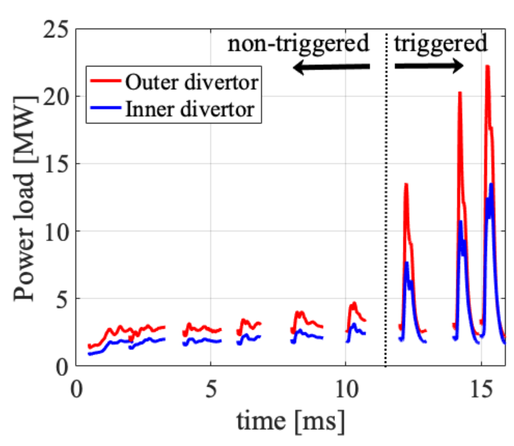


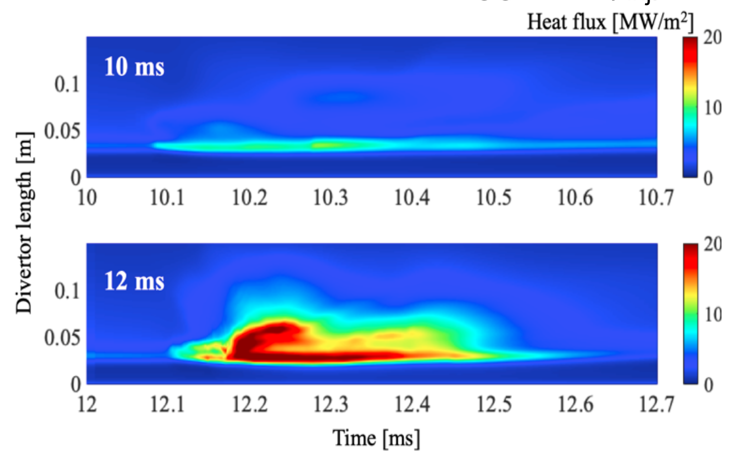


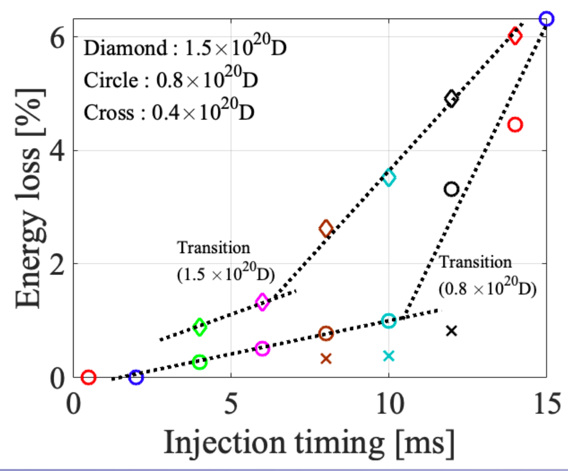


First simulation of “lag-time”

- The injected pellet conditions are the same for all injection timings; 0.8x10²⁰D [atoms/pellet], injected from high field side (HFS) with an injection velocity of 560 ms⁻¹.
- There is a sharp transition in the peak of the integrated power load onto the divertor targets between cases where no ELM is triggered ($t_{inj.}$ < 12 ms) and the case where an ELM is triggered ($t_{inj.}$= 12 ms).



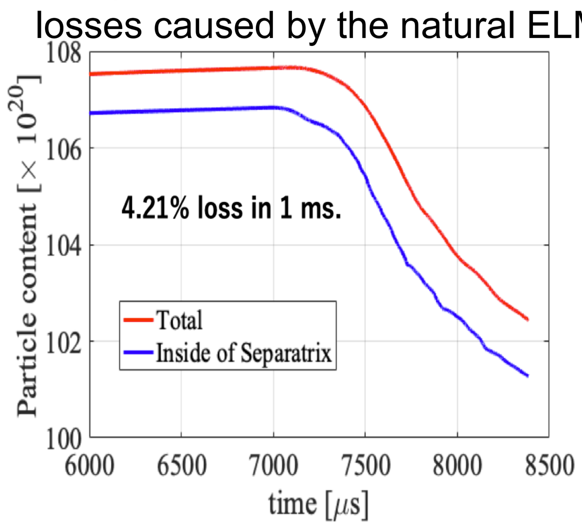


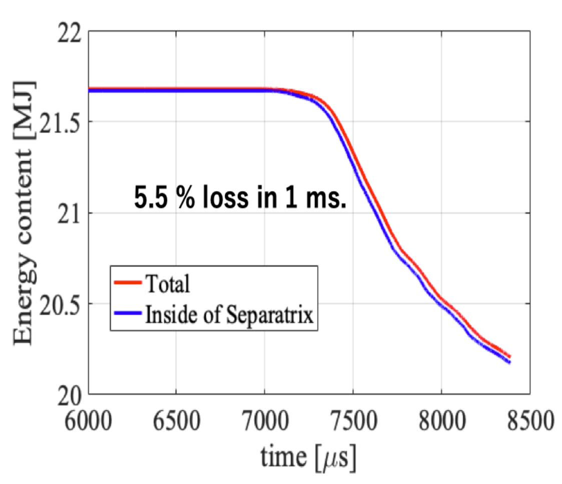


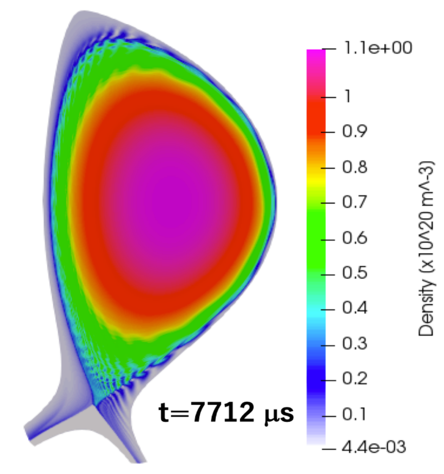
- **1.5x10²⁰D pellet**
  - **Triggers an ELM > 8 ms**
- **0.8x10²⁰D pellet**
  - **Triggers an ELM > 12 ms**
- **0.4x10²⁰D pellet**
  - **Never triggers an ELM**

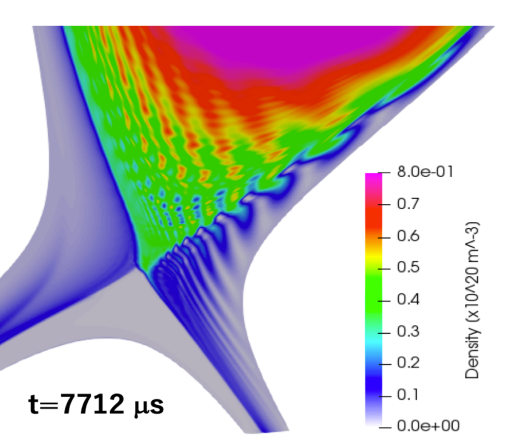
Spontaneous ELM in JT-60SA

- The MHD stability has been analysed with single-n simulations (*n*=10) varying the plasma parameters such as resistivity and viscosity.
- The simulations are performed with η=3.6x10⁻⁸ [Ωm] while the Spitzer resistivity is 1.8x10⁻⁹ [Ωm].
- The simulations have been performed without plasma background flows.
- The particle loss is 4.21 % in 1 ms, and the energy loss is 5.5 % in 1 ms. The JOREK simulations show the large particle/energy losses caused by the natural ELM.



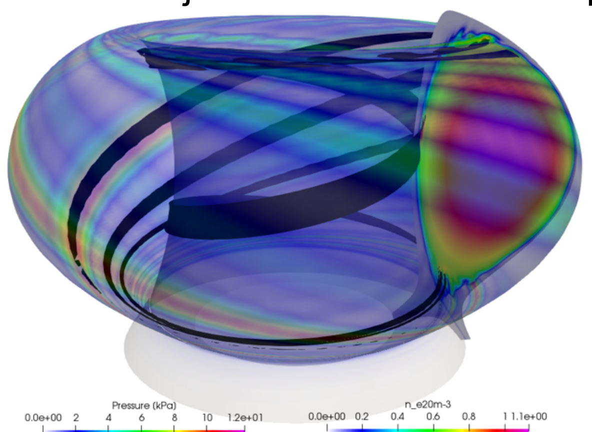


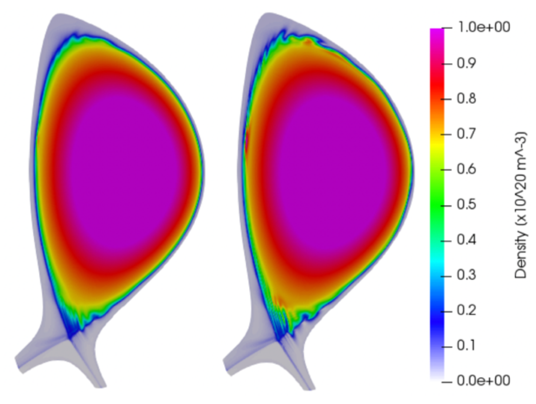




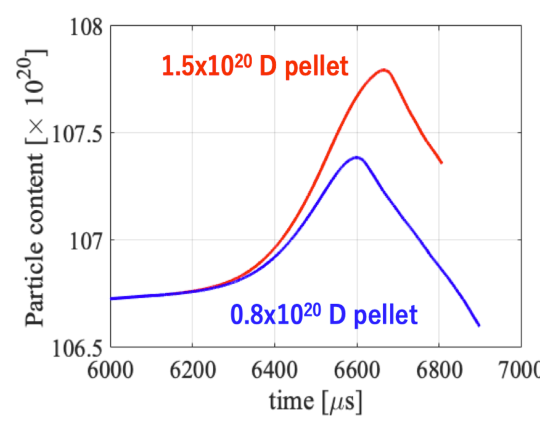
Pellet injections in JT-60SA

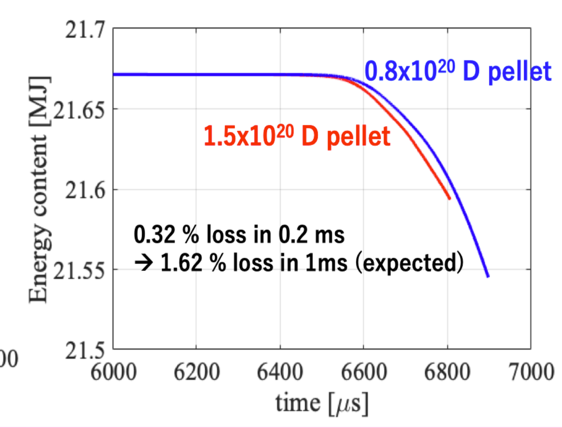
- The pellets of 0.8x10²⁰D and 1.5x10²⁰D sizes are injected into the pre-ELM plasma equilibrium which is prepared from CRONOS scenario simulation.
- The pellet ablation time is ~500-700 μs according to the injected pellet size. The pellets reach the full ablation in the pedestal region. (See figures in “Pellet model : Neutral Gas Shielding (NGS)”)
- The pressure contour plot on the last flux surface during the pellet triggered ELM shows the very localized expansion of ballooning mode structures along the magnetic field lines together with the expansion of the pellet cloud (shown by black-band).
- The ELM is triggered during the pellet ablation, and some of the pellet particles are released from the plasma before the pellets reach the full ablation. The energy loss due to the pellet triggered ELM is 0.32 % in 0.2 ms. It is expected to be much smaller (~ 20 %) compared to the natural ELM, however these simulations are still to be seen as preliminary.
- Pellet injections into the 27 kPa pedestal pressure plasma which corresponds to post-ELM condition do not trigger an ELM.





0.8x10²⁰D (t=6544 μs). 1.5x10²⁰D (t=6597 μs)





Acknowledgements

This work has been carried out within the framework of the EUROfusion Consortium and has received funding from the Euratom research and training program 2014–2018 and 2019–2020 under Grant Agreement No. 633053. In particular, contributions by EUROfusion work packages Enabling Research (EnR) and WPSA is acknowledged. The authors gratefully acknowledge members of the JT-60SA Integrated Project Team for data exchange and fruitful discussions.

Conclusions and Perspectives

- JOREK simulations have been performed for a high current and high-power scenario (5.5 MA, 41 MW, single null divertor) obtained from a CRONOS calculation. The pedestal top pressure of the plasma is 55.5 kPa, which produces a large spontaneous ELM.
- The pellets of 0.8x10²⁰D [atoms/pellet] and 1.5x10²⁰D [atoms/pellet] are injected into the 55.5 kPa pedestal pressure plasma. The plasma is already approaching a spontaneous ELM crash, therefore any pellet sizes can trigger an ELM. However, the thermal energy loss caused by pellet triggered ELM is much smaller than the energy loss of natural ELM, ~20 % (preliminary results).
- The multi-ELM simulations in JT-60SA and the pellets injection in the inter-ELM regime with more realistic plasma parameters (resistivity, viscosity etc.) will be performed for the future work.

UPC CCFE CULHAM CENTRE FOR FUSION ENERGY cea IPP JT-60SA Advanced Superconducting Tokamak BA-Satellite Tokamak Program MINISTERIO DE EDUCACIÓN Y CIENCIA Ciemat Centro de Investigaciones Energéticas, Medioambientales y Tecnológicas

This work has been carried out within the framework of the EUROfusion Consortium and has received funding from the Euratom research and training programme 2014-2018 and 2019-2020 under grant agreement No 633053. The views and opinions expressed herein do not necessarily reflect those of the European Commission.