JOREK simulation of ITER Shattered Pellet Injection penetration with realistic fragment plume and rocket effect

D.Hu[1], F.J. Artola[2], E. Nardon[3], M. Kong[4], D. Bonfiglio[5], M. Hoelzl[6], W. Tang[6], S. Jachmich[2], G.T.A. Huijsmans[3], & the JOREK team[a]
[1]School of Physics, Beihang University, Beijing, China
[2]ITER Organization, Saint Paul-lez-Durance
[3]CEA, IRFM, Saint-Paul-lez-Durance, France
[4]École Polytechnique Fédérale de Lausanne (EPFL), Swiss Plasma Center (SPC), CH-1015, Lausanne, Switzerland
[5]Consorzio RFX and CNR-ISTP, Padova, Italy
[6]Max Planck Institute for Plasma Physics, Garching b. M., Germany
[a]See the author list of M. Hoelzl et al 2024 Nucl. Fusion 64 112016

Email: hudi2@buaa.edu.cn

Shattered Pellet Injection (SPI) is the primary Disruption Mitigation System (DMS) for ITER [1], the main purpose of which is the mitigation of thermal loads during the Thermal Quench (TQ) phase of disruptions. Aside from the heat load mitigation, SPI would also aim for helping with Current Quench (CQ) phase runaway electron avalanche suppression. To achieve both goals, deep and reliable penetration of injected materials into the axis region is desirable, as such deep deposition would ease the radiation heat flux asymmetry onto the first wall as well as increase the electron collision rate in the high current density region.

However, recent progress shows that more realistic consideration of pellet shattering as well as the subsequent ablation within the plasma could have significant impact on SPI penetration and material assimilation. On one hand, in the high injection velocity limit, the pellet shattering could leave only 1/3 of the original mass in the solid fragment plume [2], the rest is turned to dust, droplets or gas which could not penetrate deeply into the core. On the other hand, the plasmoid drift and the background plasma temperature gradient could cause an asymmetry in the ablation cloud around the fragments such that the ensuing pressure asymmetry acts as a “rocket force” on the fragment [3], which could change the fragments’ trajectory significantly if the they are small enough and slow enough. Furthermore, if the injection velocity is too slow, the TQ may set in prematurely before the fragments reach the core, imposing a lower limit on the injection velocity.

To investigate the most desirable injection scenario, JOREK [4] 2D and 3D simulations are carried out in this study, incorporating realistic fragment plume distributions provided by dedicated MD-CUBE shattering simulations [2] as well as a fitted model of the rocket force from the PELOTON code [3] applicable to ITER.

The dual-SPI plumes are injected from toroidally opposite outer mid-plane injectors. The combination of two sizes (28.5 mm and 19 mm in diameter, respectively) and two injection velocities (500 m/s and 300 m/s in pre-shattering pellet velocity, respectively) are used for the SPI parameter set up. Four cases are presented in this study, their exact settings are shown in

Table 1. For the 500 m/s cases, roughly 1/4 and 1/3 of the original mass is retained as solid mass after the shattering, for 28.5 mm and 19 mm pellets respectively. The rest of the mass is represented as very fine pseudo-MGI-fragments in our simulation. For the 300 m/s cases, roughly 2/3 and 7/10 of the original mass is retained, for 28.5 mm and 19 mm pellets respectively. The injectors are evenly divided between the toroidally opposite equatorial ports EQ-08 and EQ-17. The time delay between the two injector ports is assumed to be 1 ms.

Cases	Ne atoms	H atoms	Injection velocity (m/s)
Case A (2 × 28.5 mm)	$2 \times 1.8 \times 10^{22}$	$2 \times 1.8 \times 10^{24}$	500
Case B (6 × 19 mm)	$6 \times 4.5 \times 10^{21}$	$6 \times 4.5 \times 10^{23}$	500
Case C (2 × 28.5 mm)	$2 \times 9 \times 10^{21}$	$2 \times 1.8 \times 10^{24}$	300
Case D (4 × 19 mm)	$4 \times 4.5 \times 10^{21}$	$4 \times 4.5 \times 10^{23}$	300

Table 1, the combination of SPI parameters used in this study.

Rocket effect is represented by a scaling law fitted from PELOTON simulations [3] for ITER. The pressure asymmetry scaling law takes the following form [5]:

$$\mathrm{d}P = (1.42bar)\left(\frac{T_e}{2keV}\right)^{1.22}\left(\frac{n_e}{10^{20}/m^3}\right)^{0.25},$$

while the corresponding velocity change due to such rocket force is:

$$\frac{d\boldsymbol{v_p}}{dt} = \left(\mathrm{d}P \times \frac{4\pi r_p^2}{\frac{4}{3}\rho_p \pi r_p^3}\right)\boldsymbol{e_R}.$$

Here T_e is the ambient electron temperature in eV, n_e is the ambient electron density in m^{-3}, r_p is the fragment radius, ρ_p is the pellet mass density and $\boldsymbol{e_R}$ is the major radial direction. The pressure asymmetry has only a very weak dependence in the fragment size, which is not represented in the scaling law. The fragment is assumed to be spherical, and all fragment shape effect is neglected. Only the rocket effect as a result of plasmoid drift is considered here.

A so-called "degraded H-mode" is used as the target plasma, which represents the precursor confinement degradation before the disruption onset [6]. The equilibrium electron temperature, electron density, current density and safety factor q profiles are shown in Figure 1. The thermal energy before SPI is about 190 MJ, with total plasma current 15 MA and toroidal magnetic field 5.3 T.

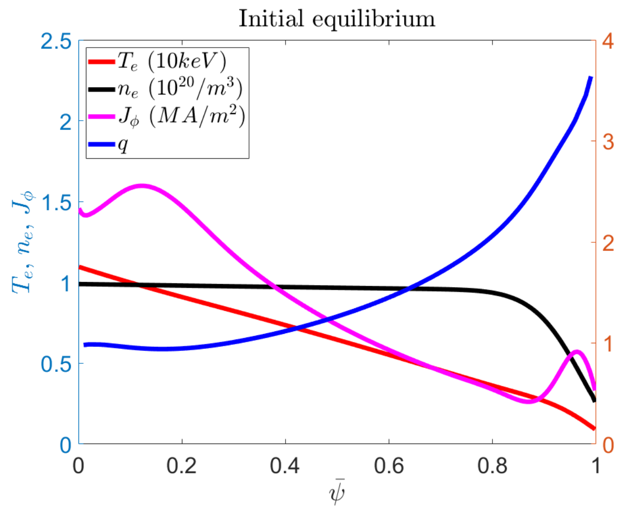

Figure 1 The initial degraded H-mode equilibrium profile.

Axisymmetric 2D JOREK simulations are first carried out to assess the impact to the SPI penetration. Rocket effect is found to have profound impact in the fragment plume trajectory and thus their penetration, as is shown in Figure 2. The final neon density profiles by the end of assimilation are shown for case A, case C and case D with and without rocket effect. It is apparent that, for all cases, rocket effect results in reduced injection penetration, and none of the fragments in the cases with rocket effect are able to reach the magnetic axis, as opposed to the cases without the rocket effect where all cases show some impurity density deposition in the axis region. For case A, even without the rocket effect, the axis density deposition is small compared with the other cases, this is due to the small solid mass fraction after the shattering for the 500 m/s cases, thus the fragments are totally ablated before they could reach the core.

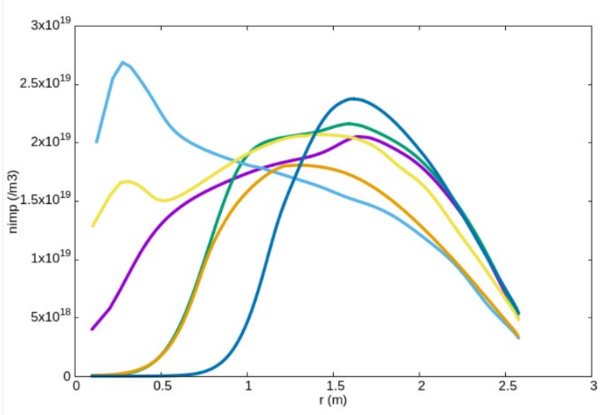

Figure 2 The 2D comparison of neon density profile by the end of assimilation, with case A w/o rocket effect (purple) and w rocket effect (green), case C w/o rocket effect (cyan) and w rocket effect (orange), case D w/o rocket effect (yellow) and w rocket effect (blue). Rocket effect is found to decrease the penetration significantly in 2D.

The reason for such reduced injection penetration is the alteration of fragment velocity and trajectory by the rocket force, as is shown in Figure 3, where the major radial position and velocity evolution for the 10 initially largest fragments are shown for JOREK 2D simulation of case D. It can be seen that the fragments experienced significant outward velocity change, to the point that some fragments are even pushed back by the rocket force and fly towards the low field side. Such rocket effect is stronger for slower injection case, both due to the longer flying time resulting in larger momentum change and the initially smaller inward momentum. Hence, on one hand, the SPI penetration is limited by the smaller solid mass fraction in the high injection velocity case. On the other hand, it is also limited by the rocket effect in the low injection velocity limit.

However, the situation is not so bleak in the 3D case, as the MHD instabilities provides

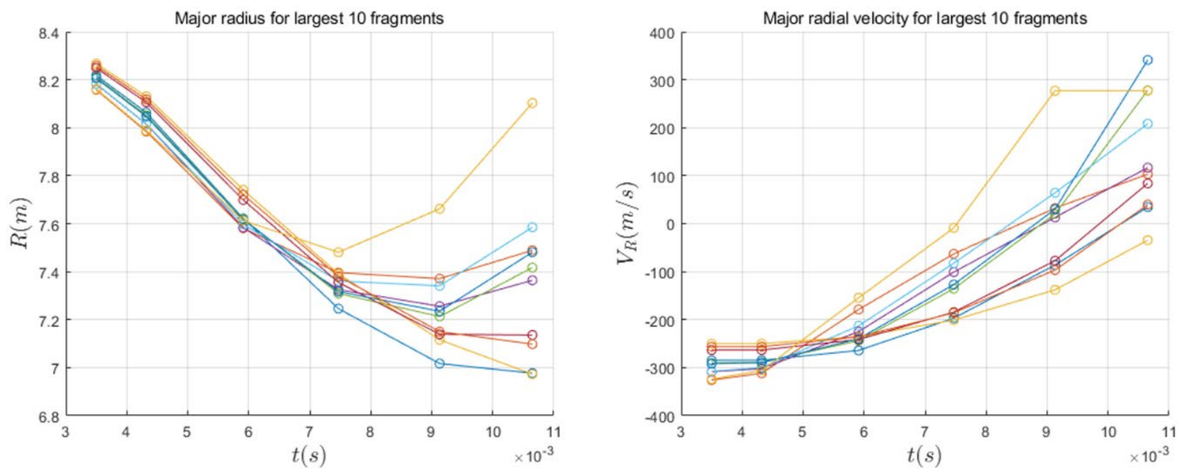

Figure 3 The major radial position (left) and velocity (right) for the 10 initially largest fragments from JOREK 2D simulation of case D

their own transport of the injected particles. As is shown in Figure 4, where the flux averaged neon density at t=0ms (purple), 4ms (green), 5.8ms (cyan), 7.7ms (orange) and 9.4ms (yellow) are shown for JOREK 3D simulation of case D with rocket effect. The core region exhibits significantly better density rise compared with the 2D cases with rocket effect, as a result of MHD instability induced perpendicular convection and core mixing, although by that time the fragments in the 3D case did not reach the axis region neither. Hence good core density rise is still achievable so long as the fragment could deposit the particles deep enough so that the dominant MHD instabilities could "see" them.

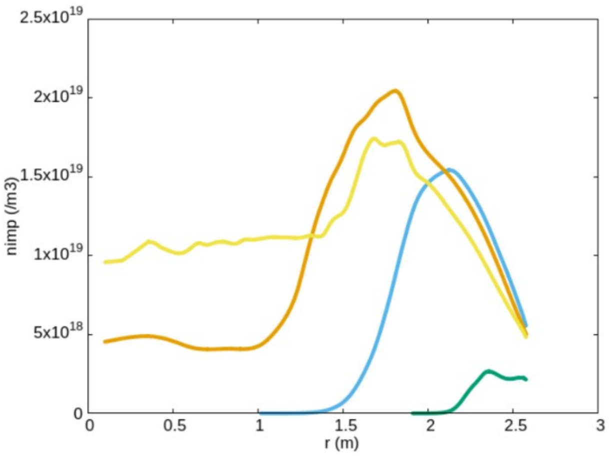

Figure 4 The neon density profile at t=0ms (purple), 4ms (green), 5.8ms (cyan), 7.7ms (orange) and 9.4ms (yellow) for JOREK 3D simulations of case D.

Overall, the injection penetration after SPIs with various combinations of injection velocity, mixture-ratio and injectors are compared in the 2D parameter scan and 3D simulations are carried out for the most relevant scenarios to evaluate the ultimate TQ mitigation efficacy. The small solid mass fraction as well as the rocket effect are found to inhibit the injection penetration in both the high and the low injection velocity limit, preventing density rise in the axis region in 2D simulations, which is detrimental to the disruption mitigation target. However, it is found that, in 3D simulations, the core MHD modes could contribute to the core density rise via perpendicular convection of injected particles when the TQ occurs and the internal resistive kink/tearing modes becomes dominant, enhancing the mitigation efficacy.

References

[1]. M. Lehnen, K. Aleynikova, P.B. Aleynikov et al., "Disruptions in ITER and strategies for their control and mitigation" J. Nucl. Mater., 463, 39-48 (2015).

[2]. P. Matura, "Technical Report (D03) - Simulations of ITER pellets and shatter geometry", IDM-5KX6U2, 2025

[3]. J. Corbett, R. Samulyak, F J Artola et al., "Numerical model for pellet rocket acceleration in PELOTON", Plasma Phys. Control. Fusion, **68** 025016 (2026)

[4]. M. Hoelzl, G.T.A. Huijsmans, S.J.P. Pamela et al., "The JOREK non-linear extended MHD code and applications to large-scale instabilities and their control in magnetically confined fusion plasmas", Nucl. Fusion **61** 065001 (2021)

[5]. R. Samulyak, "D3-Report on the ITER simulations with the code PELOTON", IDM- CC7AWD, 2025

[6]. Riccardo V. and Loarte A. (the JET EFDA Contributors) "Timescale and magnitude of plasma thermal energy loss before and during disruptions in JET" Nucl. Fusion **45** 1427