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

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Abstract

- Shattered Pellet Injection (SPI) is the primary Disruption Mitigation System (DMS) for ITER.
- Recent progress in MD-CUBE pellet shattering simulation reveals significant **solid mass loss** (up to 3/4!) for cases with 500 m/s, while those of 300m/s is more tolerable. In all cases, the Statistical Fragmentation model is found to underestimate the small size fragment population.
- Moreover, **rocket effect** may turn the fragment back mid-way toward the major radial direction, especially for slower, smaller fragments.
- **JOREK** simulations in both 2D & 3D integrating **MD-CUBE** shattering and **PELOTON** rocket force modelling are carried out to assess their impact on the disruption mitigation efficacy.
- 2D scans show **injection penetration is limited both in the high and the low injection velocity limits**, by the solid fragment loss and the rocket effect respectively.
- However, in 3D, core MHD instabilities are found to incur significant perpendicular density transport towards the axis, **enhancing the injection penetration**.
- **The ultimate negative impact on the mitigation efficacy from realistic fragment plume and rocket force are tolerable**, so long as the fragments could deposit particles deep enough so that the core MHD mode structure could "see" them, resulting in efficient inward transport.

Simulation setup

- An ITER "degraded H-mode" is used as the target plasma, representing the precursor confinement degradation before the disruption onset.
- Thermal energy before SPI is 190 MJ, plasma current 15 MA, toroidal magnetic field 5.3 T.
- Evenly arranged mid-plane neon-mixed hydrogen SPI from opposite toroidal ports EQ-08 & EQ-17. 28.5mm or 19mm in diameter, length-diameter ratio is 2. Injection velocity 500m/s or 300m/s.

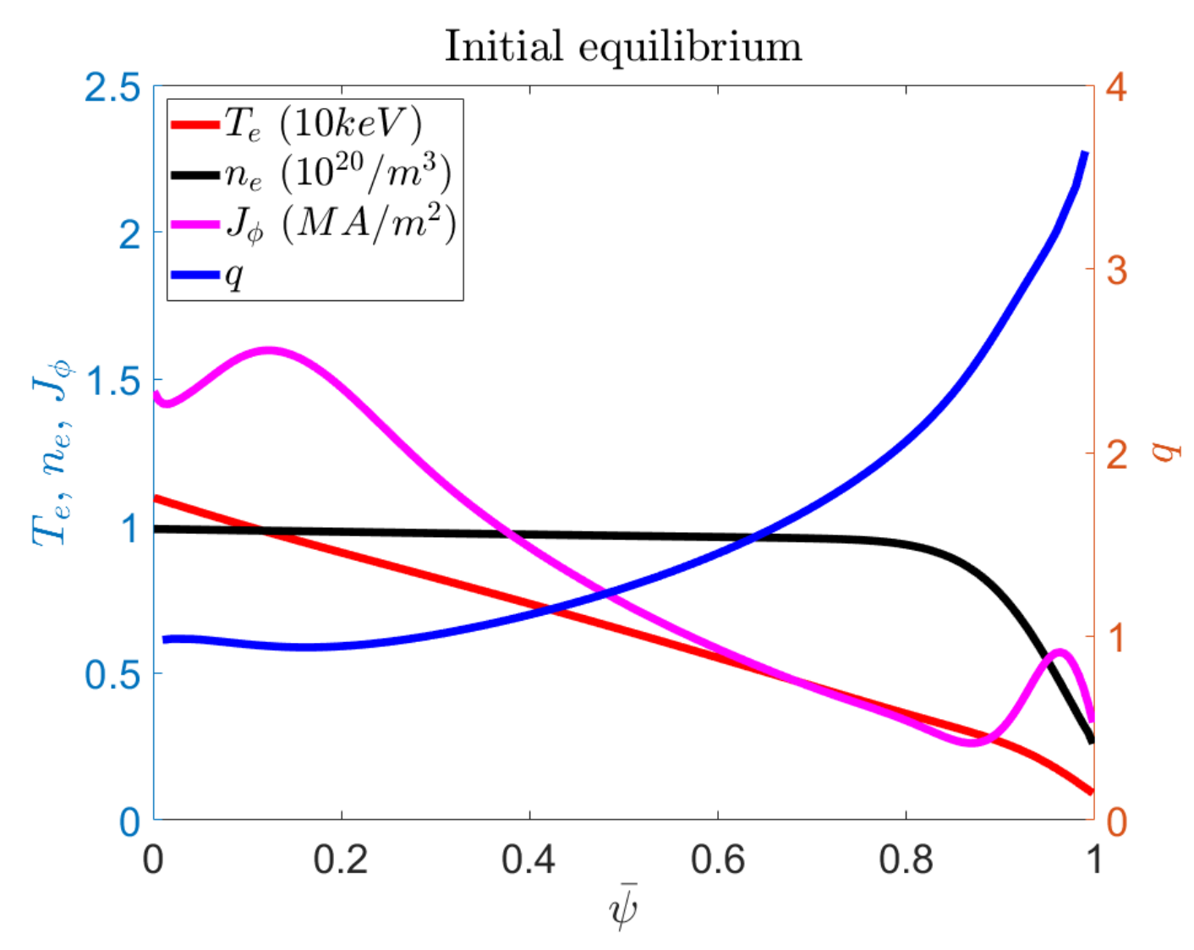

Figure 1 The initial degraded H-mode equilibrium profile.

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

- **Realistic fragment distribution** provided by **MD-CUBE** shattering process simulation with 15.5 shattering plate angle (ITER technical report, IDM UID 5KX6U2).

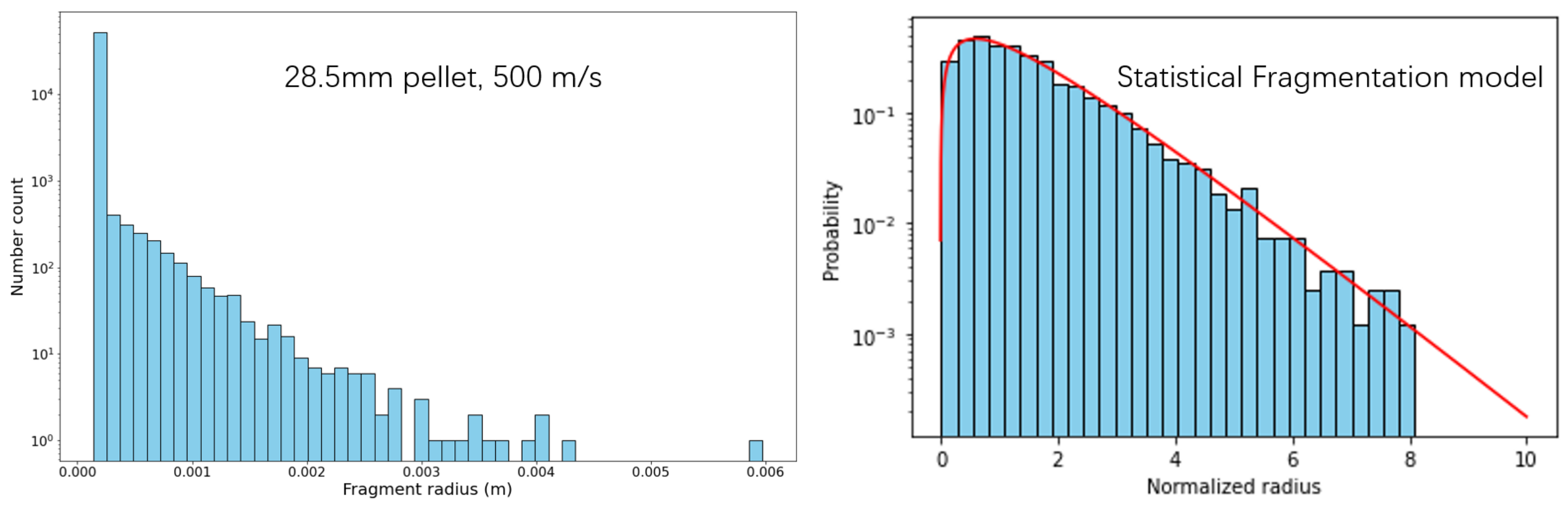

Figure 2 The comparison between the MD-CUBE simulation of fragment size distribution and the analytical Statistical Fragmentation model. The very small fragment fraction is underestimated in the analytical model.

- **Rocket effect** represented by fitted scaling law from **PELOTON** simulation for ITER (ITER technical report, IDM UID CC7AWD).
- Scaling law of rocket effect pressure asymmetry from PELOTON simulations:

$$\mathrm{d}P = (1.42bar)\left(\frac{T_e}{2keV}\right)^{1.22}\left(\frac{n_e}{10^{20}/m^3}\right)^{0.25}, \qquad \frac{d\boldsymbol{v_p}}{dt} = (\mathrm{d}P \times \frac{4\pi r_p^2}{\frac{4}{3}\rho_p \pi r_p^3})\boldsymbol{e_r}$$

- The effect is stronger for smaller fragments and slower injection (longer flying time).

The density penetration and the cold front propagation

- The rocket effect slows down the fragment and even turns them around, resulting in shallower density penetration and more apparent radiative temperature collapse.
- The 500m/s case retains smaller solid mass, hence exhibit shallow penetration & mild cooling.
- **The injection penetration is limited both at the high and the low velocity limit**!

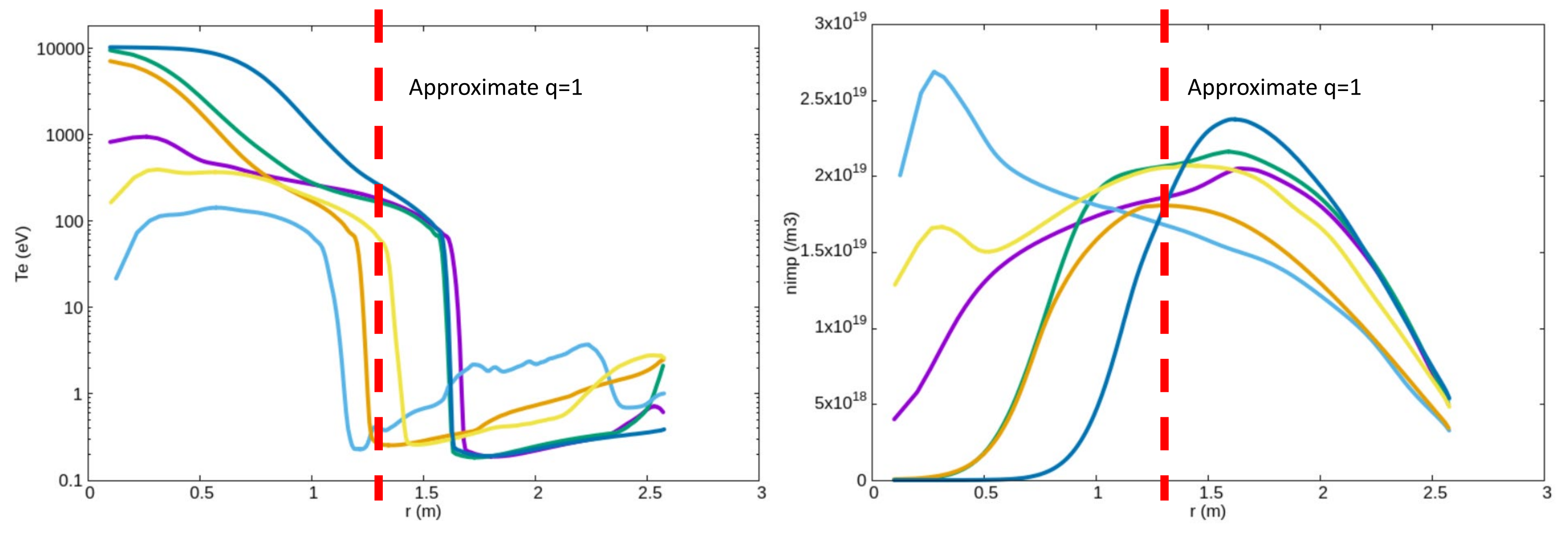

Figure 3 The 2D comparison of electron temperature and neon density profile by the end of assimilation, with case A w/o rocket effect (purple) and w rocket effect (green), case C w/o rocket effect (cyan) and w rocket effect (orange), case D w/o rocket effect (yellow) and w rocket effect (blue).

The fragment trajectory under the rocket force

- Due to the strong ablation and the rocket effect, none of the fragments reach the axis in 2D.

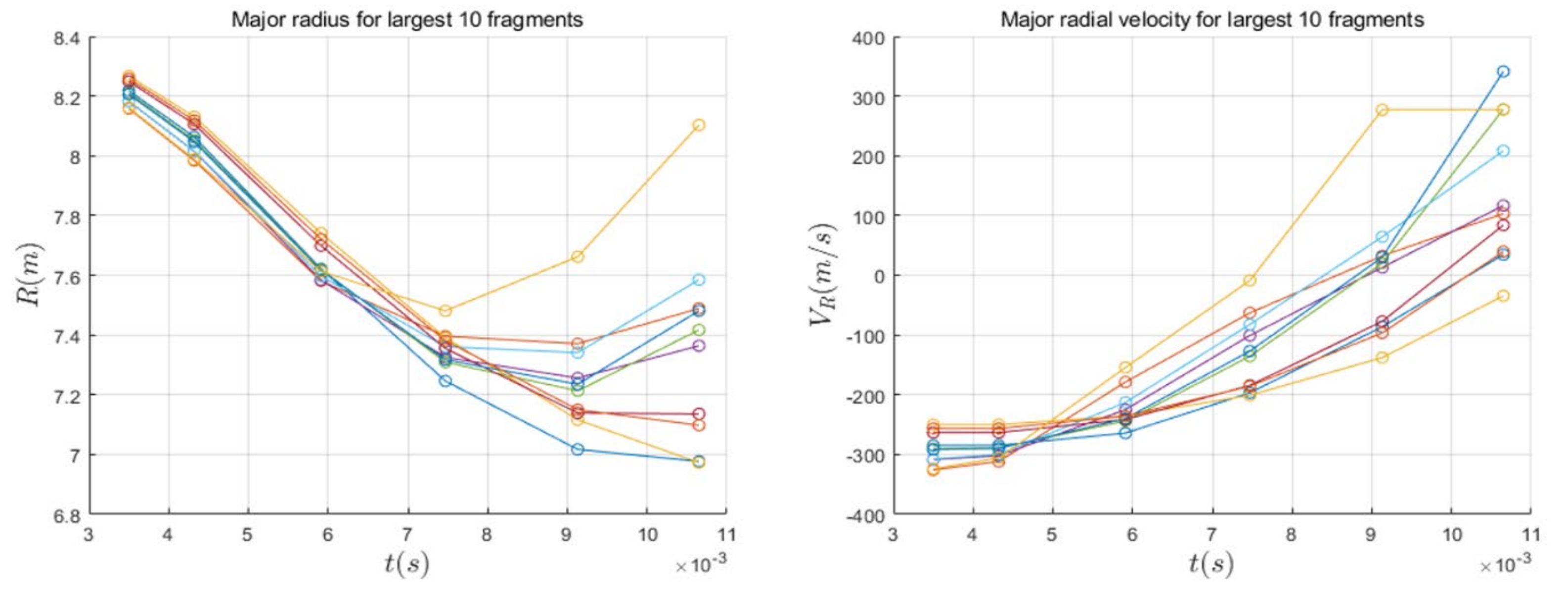

Figure 4 The major radial position (left) and velocity (right) for the 10 initially largest fragments from JOREK 2D simulation of case D.

- The rocket force is more pronounced for the slower fragments due to the longer flying time and smaller initial momentum. In the 500 m/s case (not shown here) the velocity change is not so drastic, although the penetration is still limited by the solid mass loss.

MHD induced transport & rocket effect in 3D

- Based on the 2D JOREK scan, case D is chosen for the 3D integrated simulation, with 1ms delay of the plume arrival time between the injector ports.
- MHD instabilities are found to provide significant contribution to the core particle mixing.

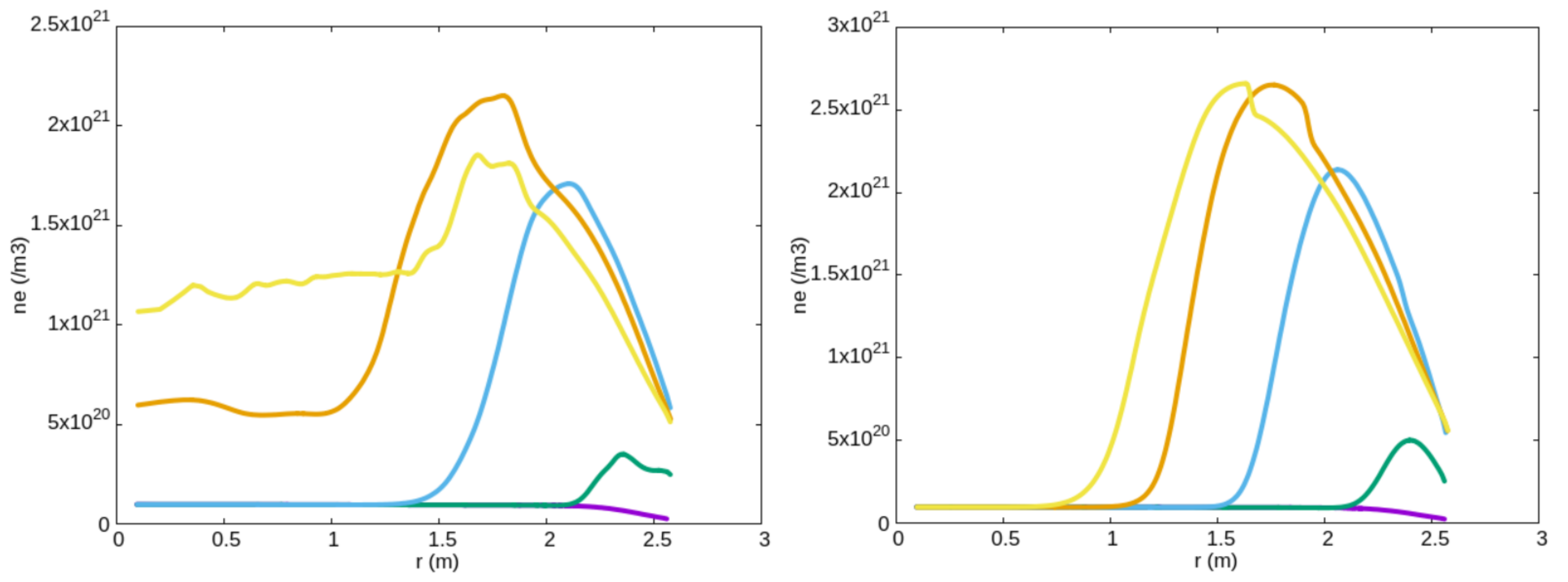

Figure 5 The electron density profile at t=0ms (purple), 4ms (green), 5.8ms (cyan), 7.7ms (orange) and 9.4ms (yellow) for JOREK 3D (left) and 2D (right) simulations of case D. The core density rise in the 3D case at the end of the simulation is due to perpendicular inward MHD transport induced by resistive kink/tearing modes in the core region.

- Rocket effect in 3D is also modulated by the MHD activities, since the confinement loss triggered by the first plume results in cooling before the arrival of the second plume, hence the second plume could penetrate deeper into the core region without significant momentum change.
- **The MHD transport coupled with the "shielding" of rocket effect for the second plume ensures much better core density rise in 3D compared with the 2D cases.**

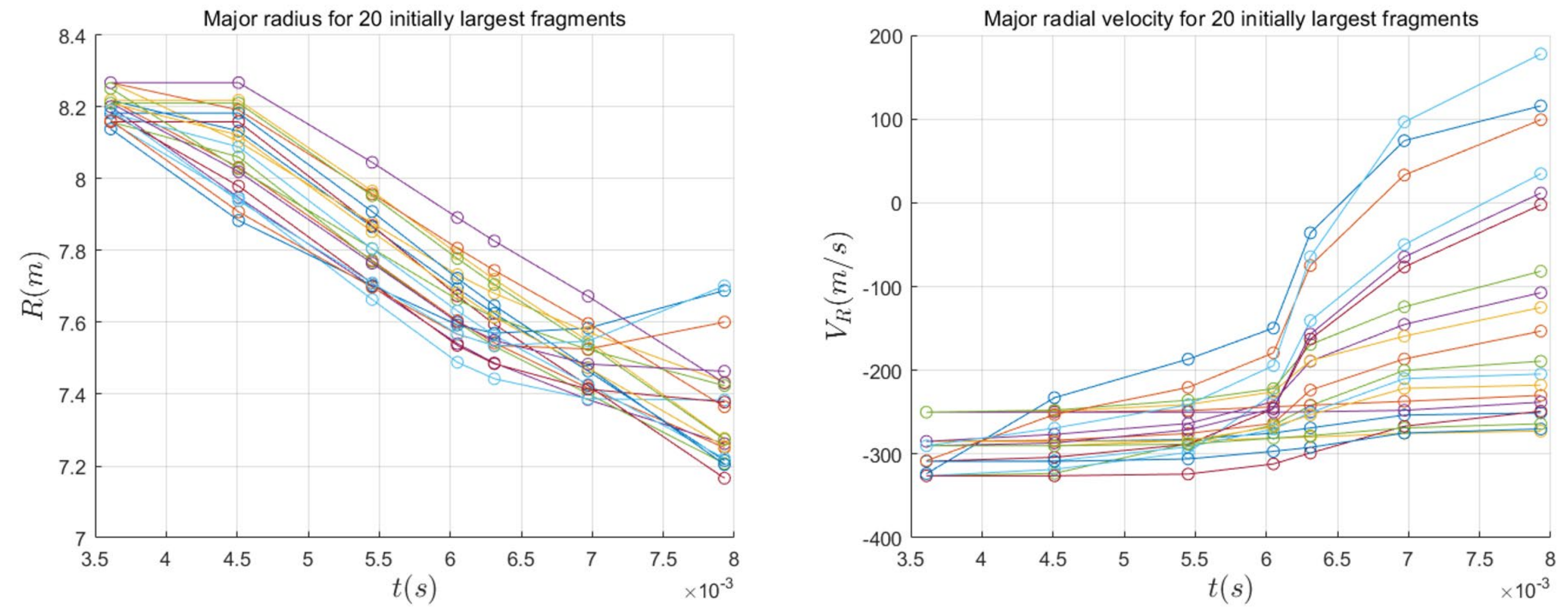

Figure 6 The major radial position (left) and velocity (right) for the 10 initially largest fragments from JOREK 3D simulation of case D. Two classes of fragments could be identified. The fragments belonging to the first plume (no delay in the major radial position evolution) experience strong rocket effect, while those in the second plume (with delay in the position evolution) only shows small velocity alteration.

Summary & Discussion

- 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
- **Solid fragment loss** as well as **rocket effect** are found to **inhibit the injection penetration** in both the high and the low injection velocity limit in ITER, undermining mitigation efficacy.
- The more realistic 3D result is not as pessimistic, as the MHD induced transport as well as the "shielding" of the following fragments help to enhance core density rise.
- **Good core density mixing could still occur via the nonlinear coupling between the MHD instabilities and the injected particles**, even without the fragment reaching the axis.
- Further 3D investigations are underway to determine the desirable injection parameter space under realistic fragment plume and rocket effect.
- In future devices with even higher plasma thermal energy and even larger size, alterative way of disruption mitigation might need to be considered, such as the shell pellet injection, or the electro-magnetic injection, to overcome the potentially more severe rocket effect there.

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