Experimental analyses and numerical modelling of trace neon shattered pellet injection discharges on JET

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Highlights

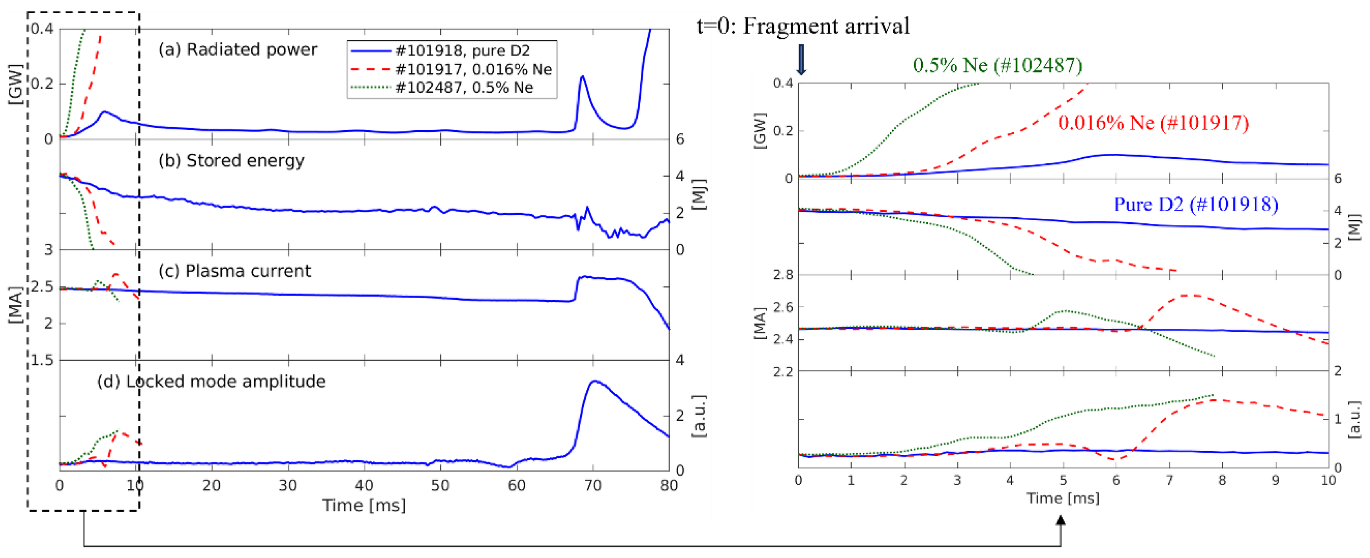
- **Trace neon shattered pellet injection (SPI)** discharges performed in final **JET** campaigns, demonstrating suppressed rocket motion of SPI fragments up to thermal quench (TQ) onset but much shorter pre-TQ compared to deuterium SPI
- **Interpretative modelling** on-going with the 3D non-linear MHD code **JOREK** [1] and the 1.5D transport code **INDEX** [2]

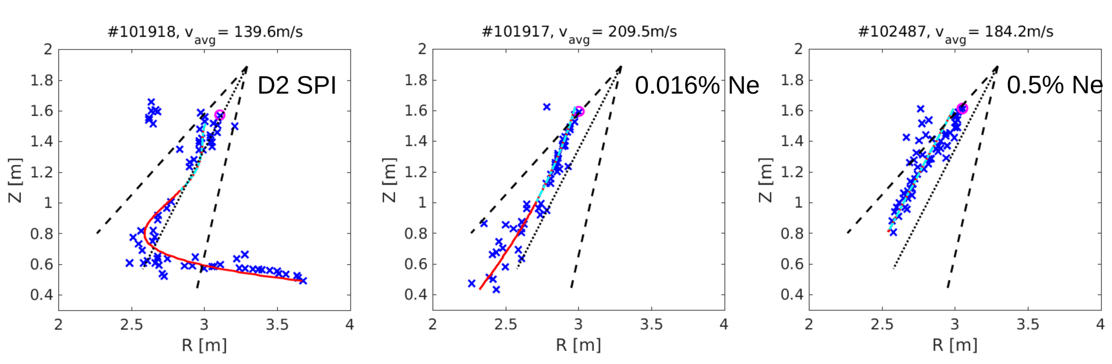
Background & Motivation

- **SPI:** technique used by the **ITER disruption mitigation system (DMS)** to mitigate thermal loads, mechanical forces & runaway electrons (REs) [3]
- **Hydrogen isotope** (such as deuterium -- **D2**) **SPI:** envisaged for **RE avoidance** by strongly increasing core density before thermal quench (TQ) [4]
- However, JET SPI experiments & JOREK modelling demonstrated that D2 SPI suffers from plasmoid drifts, hindering material assimilation & RE avoidance [5]
- **Plasmoid drift** [6]: ∇B drift that leads to charge separation and $\boldsymbol{E}\times\boldsymbol{B}$ **drift towards the tokamak LFS** → imbalanced ablation rate on the HFS and LFS of fragments → outward motion of solid fragments (**rocket motion/effect**) [7]
- **Trace neon SPI**: a small percentage of neon added to hydrogen-isotope SPI; envisaged to reduce pressure imbalance of the plasmoid via stronger local radiation, thus suppressing plasmoid drifts and facilitating RE avoidance [8]

JET trace neon SPI experiments

- Before SPI: H-mode plasma, 2.5 MA / 2.5 T, 4 MJ
- Pellet: 10 mm diameter, **350 m/s**, neon atomic mixture ratio 0.016% to 2% ($\sim1.26\times10^{19}$ neon atoms in 0.016% neon SPI); D2 SPI performed as reference



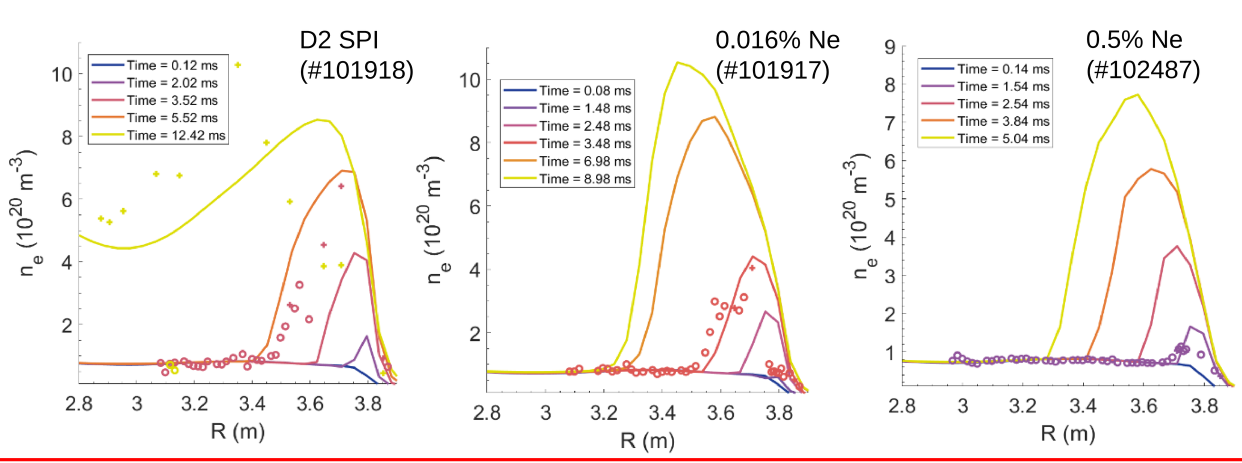


Much slower penetration:
- Blue crosses: inboard edge of D_α emission detected in fast camera [5]
- Red curve: fitted curve
- Cyan: trace chosen to estimate v_{avg}

- **Two key observations**: 1) evident rocket motion in D2 SPI, but not in trace neon SPI with 0.016% neon up to TQ onset, indicating weaker plasmoid drifts; 2) cooling time, defined as the duration between SPI arrival at the plasma edge ($\boldsymbol{t=0}$) and the I_p spike, drops from ~70 ms in D2 SPI to ~7 ms in 0.016% neon

Modeling with 1.5D INDEX code

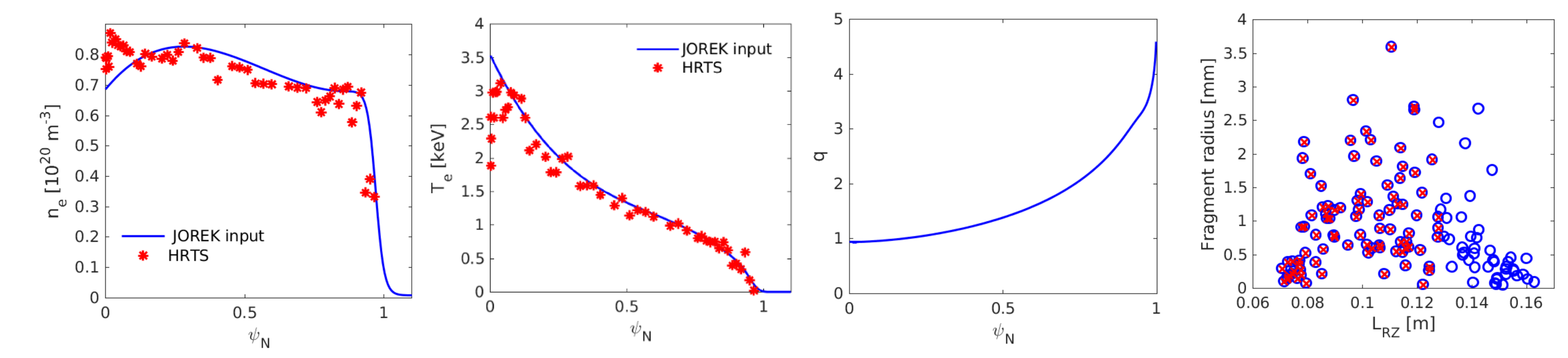
- Same input profiles and SPI setup as in JOREK simulations
- A back-averaging model [9-10] used for plasmoid drifts: ablated material distributed uniformly between fragment and $\psi_N=1$ here; fraction of ablated material shifted to fit TS data is 50%, 20% & 0 for D2, 0.016% & 0.5% neon SPI



- Comparing with Thomson scattering (TS) data shown in symbols:
  - **Fragments reach HFS before the rocket motion in D2 SPI** → increased core fueling

JOREK model & simulation setup

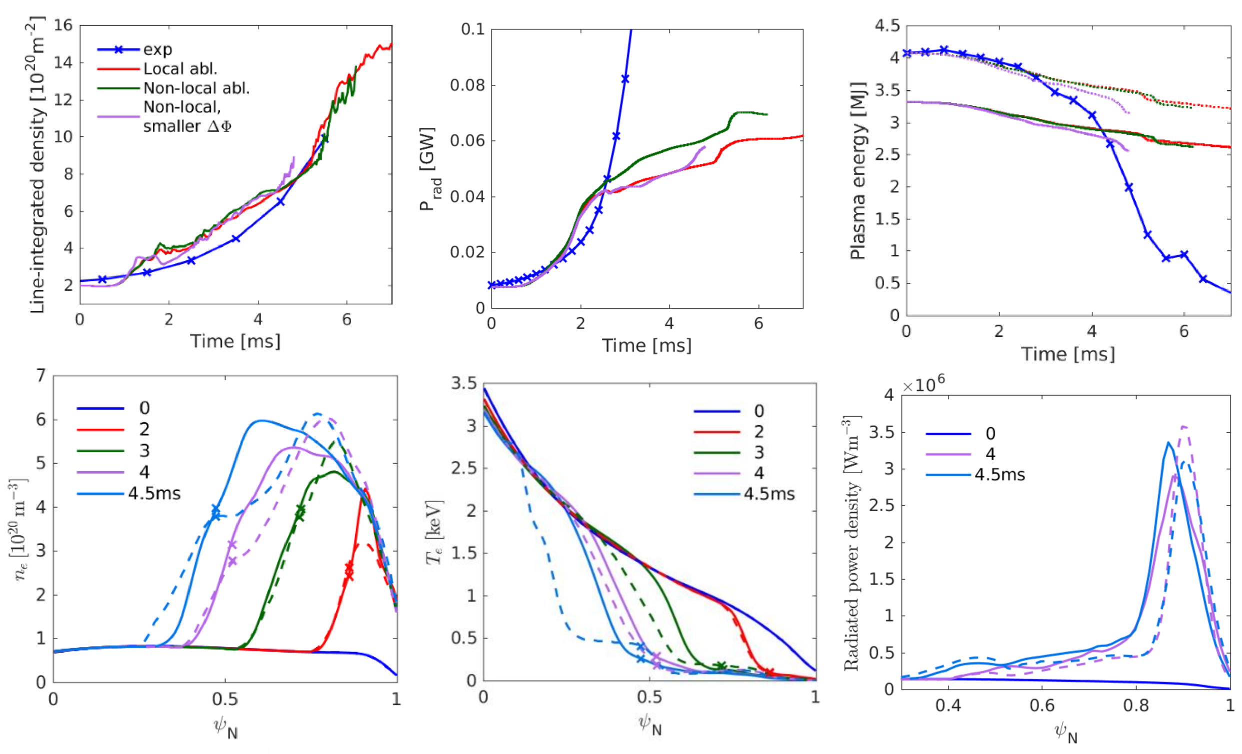
- Reduced MHD with parallel flows and extension to impurities [1]
- Coronal equilibrium (CE) for impurity radiation, including uniform **background** tungsten & neon; collisional-radiative (CR) model [11] available



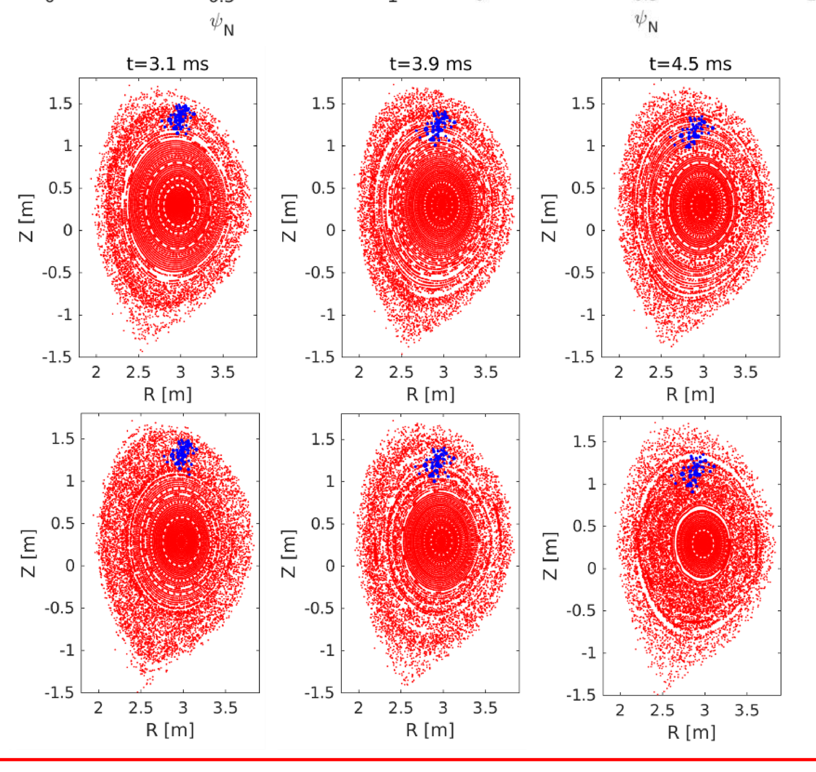
- Ablation rate $\propto T_e^{5/3} r_p^{4/3} n_e^{1/3}$, where T_e and n_e taken from fragment location (**local-ablation** model) or flux-surface-averaged (**non-local ablation**)
- Ablated source deposited around each fragment (no drift) or radially shifted by ΔR (with drifts) via a "teleportation" model [5], both with Gaussian shape
- Fragment size distribution follows a **fragmentation model** [12]; front fragments removed to consider material loss in shattering process, where the gas generated can take up to 20% of initial pellet mass [13]
- SPI **penetration velocity** is only about half of the injection velocity, possibly due to braking by shock waves generated in the gas created in the shattering process [15]

3D JOREK modeling results

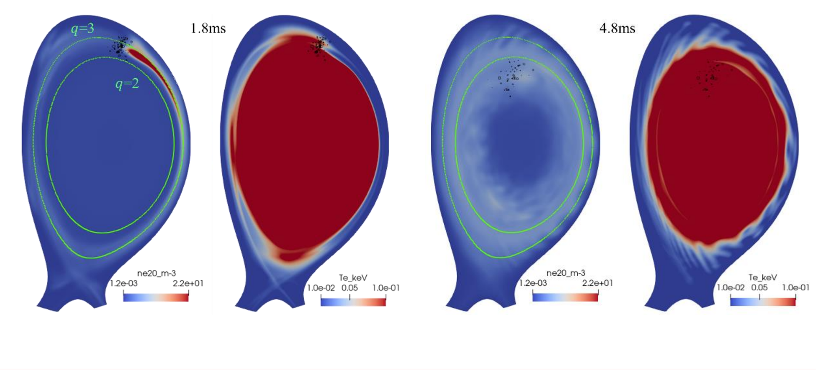
- **Modelling of #101917 (0.016% neon SPI)** as an example



- Drift ΔR=15cm [14]
- L_θ = 8cm, Δr = 4cm
- $\boldsymbol{\Delta\phi = 0.2}$ **vs 0.5**: lower P_{rad} due to different T_e and n_e evolution (dashed below); faster W_{th} drop due to stronger heat transport
- Left: comparing profiles of JOREK simulations with $\Delta\phi=0.5$ (solid) and 0.2 (dashed)



- Poincaré plots of simulations with $\Delta\phi=0.5$ (top) and 0.2 (bottom): similarly weak MHD activities; blue circles: remaining fragments
- Weak MHD activities probably due to insufficient local radiative cooling at $q=2$ (i.e., lack of 2/1 "T_e holes"), as seen below



Conclusions & Outlook

- **JET trace neon SPI experiments** performed, exhibiting suppressed rocket motion at least up to TQ onset & ~10x shorter cooling time compared to D2 SPI
- **INDEX and JOREK simulations** suggest that plasmoid drift is weaker in 0.016% neon than in D2 SPI and there is no evident drift with 0.5% neon SPI
- Difficult to directly recover the observed early TQ onset in trace neon SPI in 3D JOREK simulations, hypothesized to result from insufficient local cooling with toroidally oversized plasmoid typically used in 3D non-linear MHD modelling
- **Outlook**: artificially condensed radiation sinks to investigate the susceptibility of plasma to T_e holes and the necessary conditions to trigger the observed TQ

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