Recent physics results from the ASDEX Upgrade Shattered Pellet Injector project

G. Papp[1*], P. Heinrich[1], P. Halldestam[1], A.H. Patel[1], S. Jachmich[2], P. de Marné[1], M. Lehnen[2†], U. Sheikh[3], J. Illerhaus[1], M. Miah[1], T. Peherstorfer[4], M. Dibon[2], M. Bernert[1], B. Sieglin[1], J. Artola[2], J. Hobirk[1], R. Fischer[1], W. Tang[1], M. Hoelzl[1], O. Ficker[5], J. Svoboda[5], the ASDEX Upgrade Team[1], and the EUROfusion Tokamak Exploitation Team[6]

[1]Max Planck Institute for Plasma Physics, Garching, Germany, [2]ITER Organization, St. Paul-lez-Durance, France, [3]Swiss Plasma Centre, EPFL, Lausanne, Switzerland, [4]Inst. for Applied Physics, TU Wien, Austria, [5]Institute of Plasma Physics AS CR, Prague, Czech Republic, [6]See the author list of E. Joffrin et al., 2024 Nucl. Fusion.

MAX-PLANCK-INSTITUT FÜR PLASMAPHYSIK

I. SHATTERED PELLET INJECTION (SPI)

Disruptions are violent off-normal events, in which the confinement of a tokamak plasma is abruptly lost. Unmitigated disruptions pose an intolerable risk to reactor-relevant tokamaks due to localised heat loads, vessel forces, halo- and eddy currents, and runaway electrons.

Disruption mitigation goals:

- Radiate away thermal energy isotropically to avoid localised heat loads. ($\longrightarrow f_{\mathrm{rad}}$)
- Suppress runaway electron generation.
- Reduce vessel forces by controlling τ_{CQ} (i.e. T_{e} shouldn't drop too fast).

Mitigation techniques rely on massive material injection to increase free electron density, and to introduce higher-Z noble gases (e.g. Ne or Ar) which cool isotropically via line radiation. However, a single injection might not be sufficient.

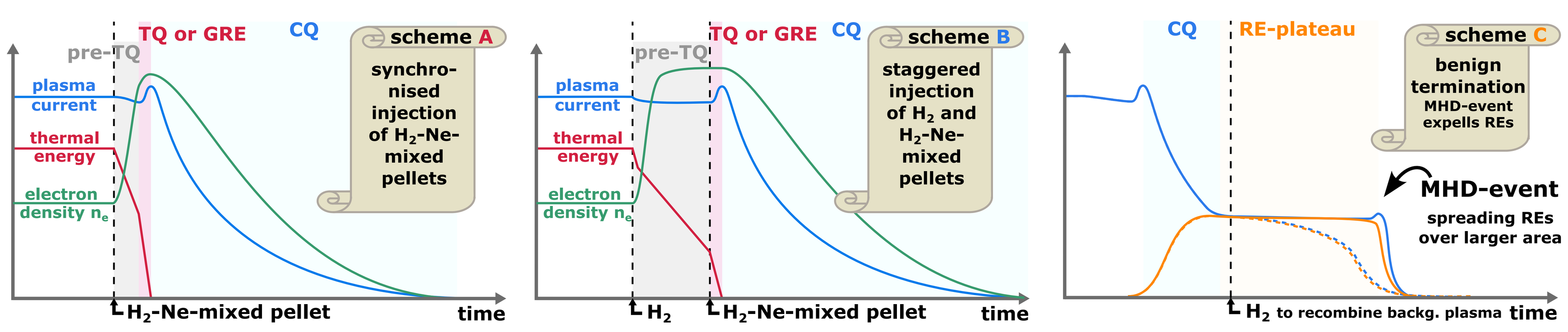
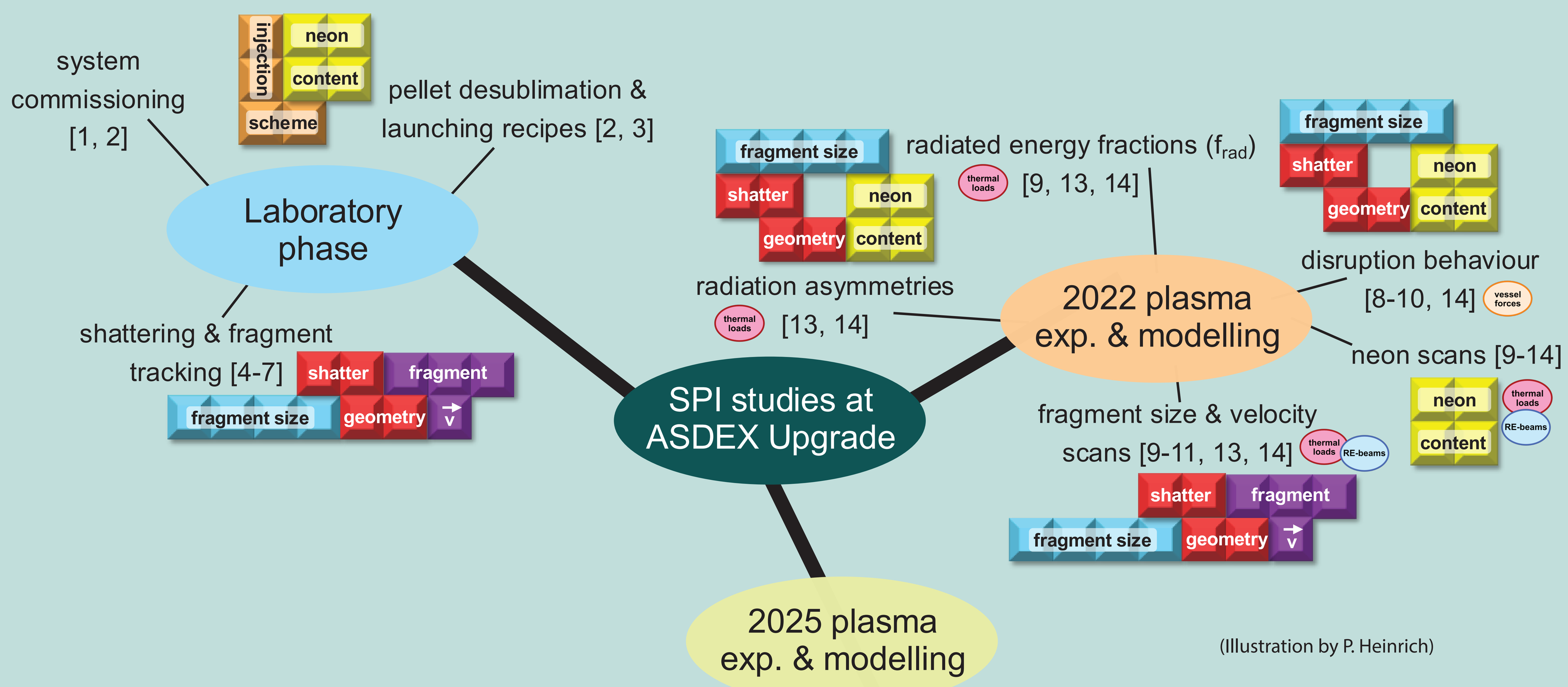


Figure 1: Illustration of ITER material injection schemes currently in consideration [14].

SUMMARY

- A uniquely flexible SPI system in support of ITER – crucial design input for ITER DMS
- Injection geometry impacts material assimilation, but not so much thermal load mitigation
- Significant impact on model validation using laboratory (peridynamics) and tokamak data (DREAM, INDEX, JOREK ...)



II. THE ASDEX UPGRADE SPI

SPI is the disruption mitigation method chosen for ITER. Hydrogen, neon, or mixtures of the two are frozen into pellets containing several times the plasma inventory and launched at several hundred m/s to the plasma. By breaking the pellet just before arrival, the surface-to-volume ratio is increased to improve assimilation.

Open questions:

- Is multi-injection viable?
- How to suppress plasmoid drift?
- Optimum fragment size distribution?
- Optimum penetration speed?

Together with ITER, we have developed a uniquely flexible SPI system for AUG [1,2]:

- 3 independent barrels
- Diameter range of 1–8 mm
- L/D range of $\approx 0.5-1.5$
- Speed range of 50–800 m/s
- Lab tested 12 shatter head designs
- 1400 fragmentation experiments

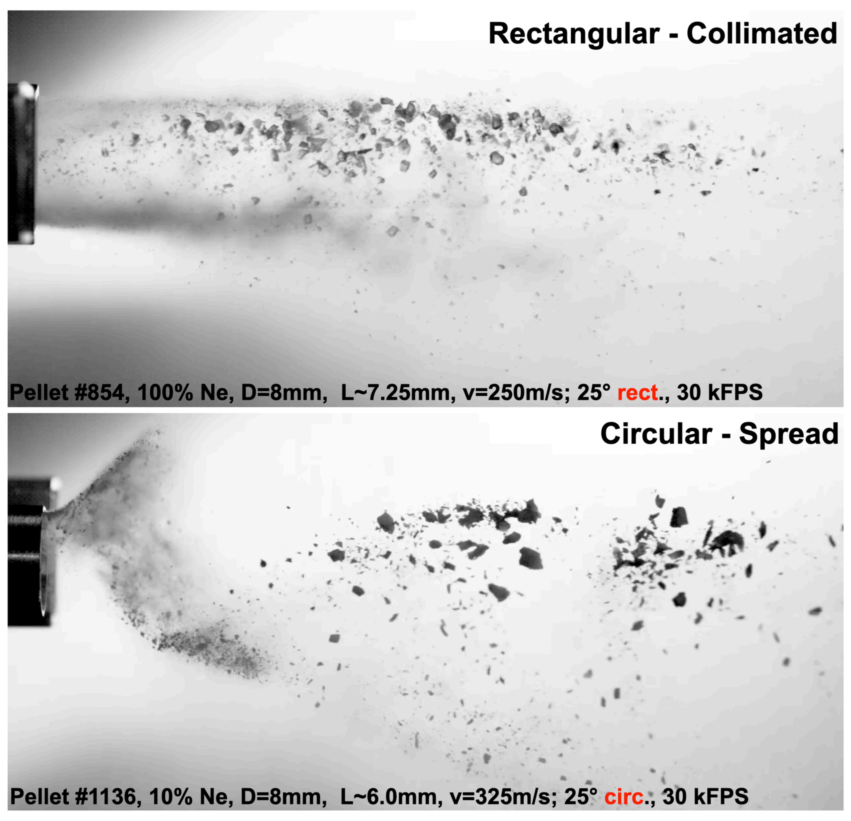


Figure 2: SPI fragment spread examples.

III. FRAGMENTATION EXPERIMENTS & ANALYSIS

The collected fragmentation videos were analysed using openCV [4] and machine learning [5]. We found major differences between data and the Parks model predictions. However, peridynamic modeling matches AUG data well [6,7].

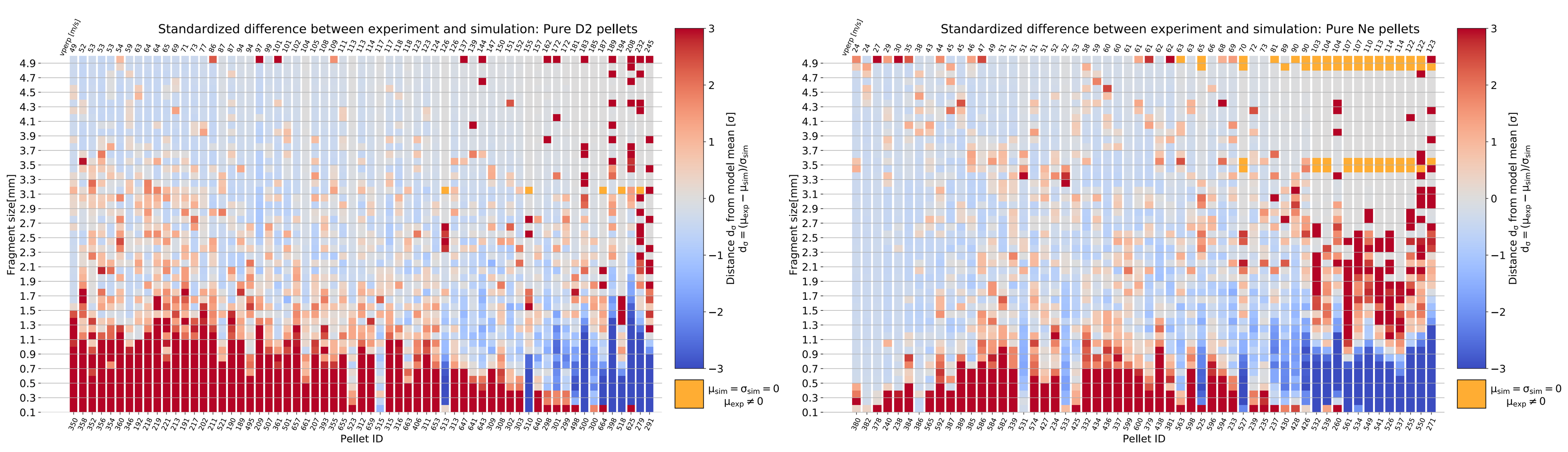


Figure 3: Deviation of experimental size distribution from the Parks model prediction [4].

Machine learning pipeline is used to automate the processing of all videos [5]. Successfully used for spatial spread analysis and design of new shatter heads. Size distribution analysis limited by optical resolution – the setup was designed using the Parks model.

IV. AUG SPI EXPERIMENTS

Over 200 AUG plasma discharges were executed in 2022. We explored a wide range of pellet and injection parameters to optimise thermal load mitigation and material assimilation. Preliminary dual injection shots were also done.

Thermal load mitigation seems sensitive to neon content (as expected). Saturation is reached at about 10% content. Except for intermediate neon concentrations, however, there is little impact of the shatter geometry [9,14]. While this means that no optimisation is possible here, it also means that we can choose the shatter head to optimise other aspects, such as material assimilation for runaway electron suppression. An important quantifier is f_{rad}, which is defined as the ratio of radiated energy to plasma energy, accounting for conducted energy and external heating.

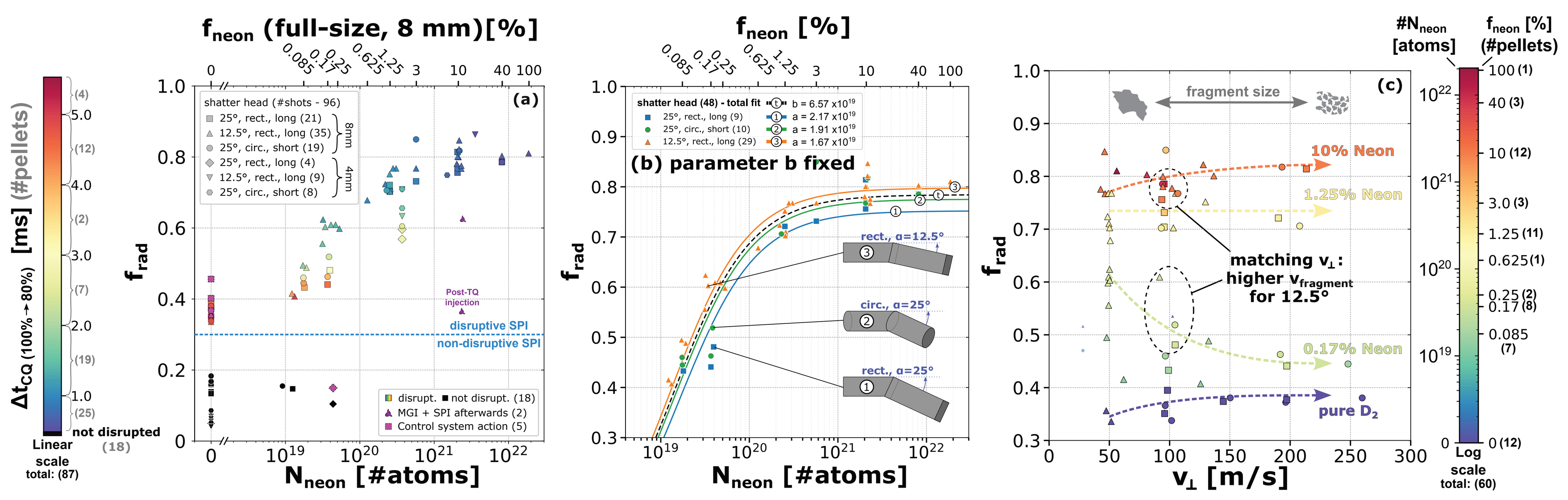


Figure 4: Dependence of radiated energy fraction on (a) neon content, (b) shatter head geometry and (c) fragment size [14].

Radiation asymmetries according to the data are between factors of 1.2 and 1.6. This is beneficial for ITER, as the fear of localised melting from the injection "flash" is reduced.

Material assimilation seems to be maximised with "large, fast" fragments for pure deuterium. This points to shallow shatter angle geometries. The AUG data provides confidence to the ITER choice of 15.5° shatter angle. More data is expected (required) from the 2025 campaign.

V. AUG SPI MODELING

There is ongoing modelling work with DREAM [10], INDEX [11] and JOREK [13] to understand the trends observed in the 2022 campaign as well as to design the experimental plan for 2025.

DREAM and INDEX suggest that larger, faster fragments are better for assimilation – as also seen in the experiments. While the radiated energy fractions are well-matched in DREAM and JOREK with the experiment at increased neon doping, all codes underpredict f_{rad} for pure deuterium pellets. The likely cause for this is background impurities, such as W.

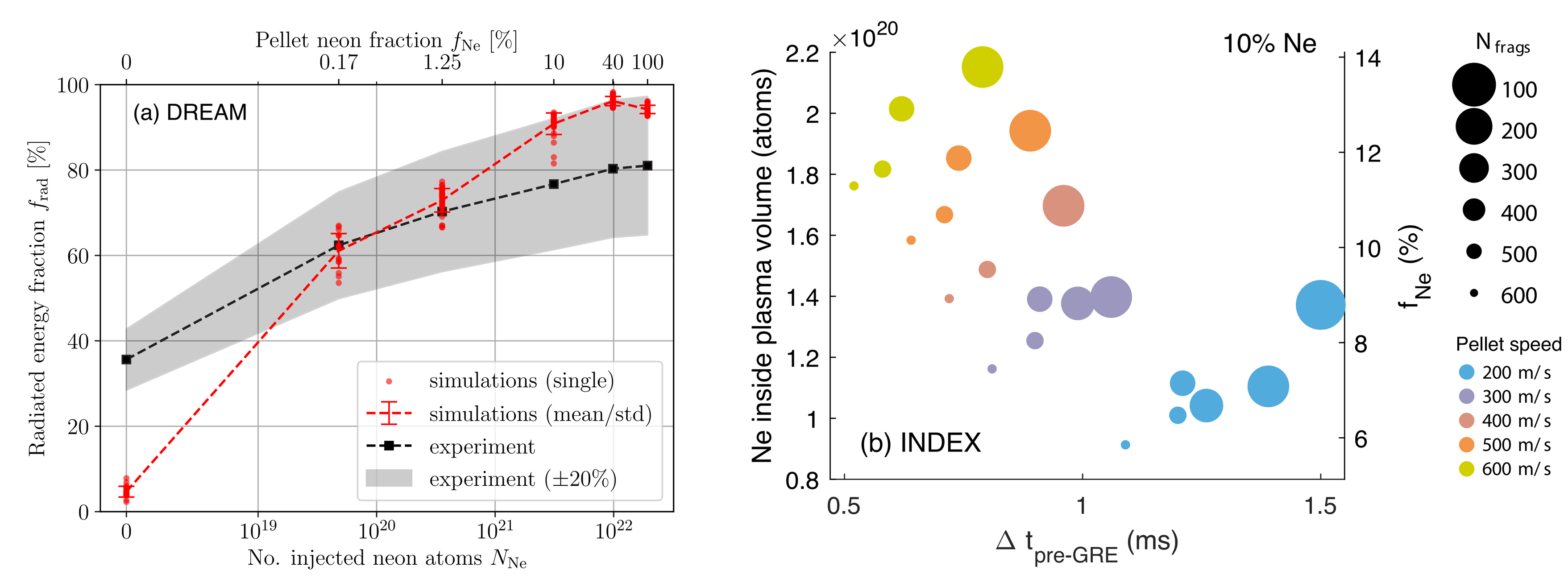


Figure 5: (a) Experimental validation of DREAM modelling of thermal load mitigation efficiency with different neon contents and size distributions [10]. (b) INDEX modelling of neon assimilation for thermal load mitigation as a function of fragment parameters [11].

REFERENCES

(This is a partial collection of our AUG-SPI publications so far)

[1] M. Dibon *et al.*, RSI 94 043504 (2023)
[2] P. Heinrich *et al.*, FED, 206 114576 (2024)
[3] Á. Kovács *et al.*, FED, 202 114303 (2024)
[4] T. Peherstorfer, M.Sc. thesis (2022)
[5] J. Illerhaus *et al.*, JoFE, 43 14 (2024)
[6] S. J. Lee *et al.*, NF, 54 106023 (2024)
[7] P. Matura *et al.*, accepted (2024)
[8] N. Schwarz *et al.*, NF, 63 126016 (2023)
[9] P. Heinrich *et al.*, NF, 65 056036 (2025)
[10] P. Halldestam *et al.*, JPP accepted (2025)
[11] A. Patel *et al.*, NF submitted (2025)
[12] G. Bodner *et al.*, NF accepted (2025)
[13] W. Tang *et al.*, NF submitted (2024)
[14] P. Heinrich, PhD thesis (2025)

Corresponding author: *gergely.papp@ipp.mpg.de;
AUG SPI overview

This work has been carried out within the framework of the EUROfusion Consortium, funded by the European Union via the Euratom Research and Training Programme (Grant Agreement No 101052200 — EUROfusion). Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or the European Commission. Neither the European Union nor the European Commission can be held responsible for them.