Optimization of Shattered Pellet Injection (SPI) Composition for Maximal Assimilation

J. L. Herfindal[1], D. Shiraki[1], M. Lehnen[2], L. Baylor[1], E. Hollmann[3], C. Marini[3], N. Eidietis[4], J. McClenaghan[4]

[1]Oak Ridge National Laboratory, 1 Bethel Valley Road, Oak Ridge, TN, 37830, USA
[2]ITER Organization, Route de Vinon-sur-Verdon – CS 90 046, 13607 St Paul Lez Durance Cedex, France
[3]University of California San Diego, 9500 Gilman Drive, La Jolla, CA 92093-0417, USA
[4]General Atomics, PO Box 85608, San Diego, California 92186-5608, USA
Email: herfindaljl@ornl.gov

Shattered pellet injection (SPI) experiments on DIII-D varied the pellet composition to maximize assimilation while not triggering an early thermal quench, providing guidance on the optimal parameter space for the SPI mitigation scheme on ITER. Assimilation of pure D_2 shattered pellets with the same injection speed was erratic and unpredictable, resulting plasma density increases by a factor between three to 12. This variability can be attributed to the random nature of pellet shattering, as the largest density increases occurred when there was a single dominant fragment after shattering, rather than multiple smaller fragments. A larger fragment led to deeper penetration, increased radiation from plasma impurities, and a faster shutdown. However, adding small amounts of Ne (<1.2% by atoms of the total pellet) resulted in more consistent and predictable shutdown timeframes, as the shutdown became impurity-dominated rather than governed by MHD effects in pure D_2 SPI. An optimal Ne concentration increased the density by a factor of 20, whereas higher or lower Ne levels resulted in lower assimilation fractions.

Optimizing the initial SPI injection is crucial for ITER's proposed two-stage mitigation scheme, which involves an initial injection of pure D_2 (or slightly doped) followed by a second high-Z SPI to radiate the remaining thermal and magnetic energy [1]. This approach gradually lowers plasma temperature while increasing density to reduce the probability of runaway electron formation and allow sufficient time for a second high-Z SPI injection. This time window, known as the cooling duration–time between SPI arrival and the end of the thermal quench–was found to vary between 5 and 40ms as shown in Figure 1. Despite similar pellet and plasma parameters, the extreme variation in plasma cooling duration appears to depend on the ratio of plasma stored energy to the number of injected D_2 atoms as well as the shard fragment size.

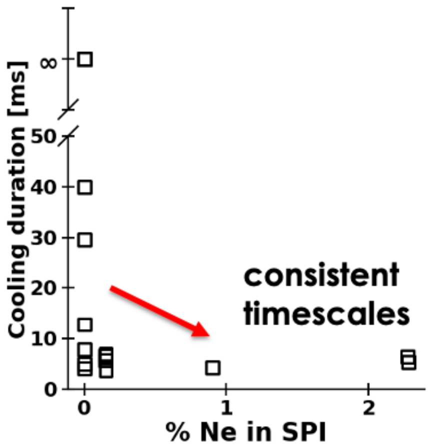

Figure 1: Plasma cooling duration (CD) was erratic for pure D2 SPI but stabilized to a consistent value with the addition of Ne

Pellets fired at similar speeds (~300 m/s) led to drastically different plasma shutdown characteristics depending on the shattering process. In one case, the pellet shattered into a single dominant fragment (Figure 2a), which penetrated deep into the plasma, increased the density, and enhanced intrinsic impurity radiation, leading to a rapid plasma collapse. In contrast, in other SPI-mitigated plasmas, the pellet shattered into many smaller fragments (Figure 2b), leading to lower overall assimilation and less impurity radiation.

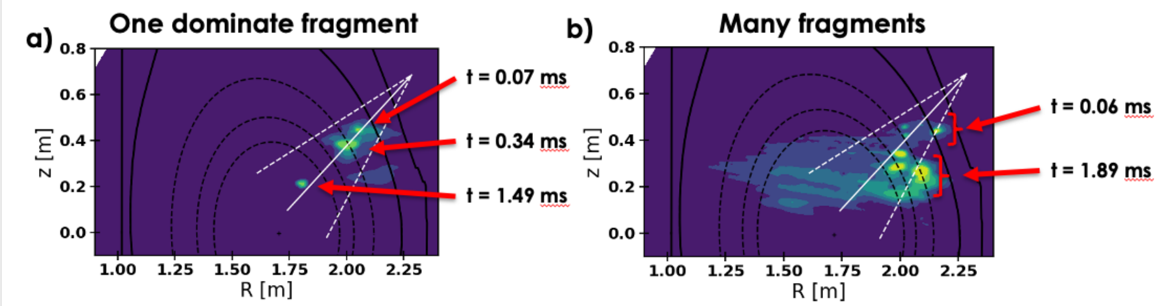

Figure 2: Composite visible camera images illustrating one large fragment (left, a) contrary to multiple smaller fragments (right, b) ablating within the plasma after the pure D2 pellet was shattered.

The addition of small amounts of Ne to the pellet is expected to reduce the outward ejection of ablated material by decreasing the ExB drift through lower pressure in the ablation cloud [2]. Thomson scattering measurements confirm that adding small amounts of Ne does result in deeper deposition of the ablated material prior to the thermal quench. However, line-integrated density measurements show a peak increase in electron density at a specific Ne concentration. Figure 3 shows the average pre-thermal quench increase in number of electrons as a function of the percentage of Ne added to the SPI. The black dashed line represents the number of electrons injected due to the Ne, illustrating that the increase in assimilated electrons is not caused by the additional Ne atoms but by the enhanced assimilation of the D_2 within the pellet. The maximum increase in electron density occurs at an intermediate Ne concentration, with any further increase resulting in lower assimilation, despite having similar assimilation times, as shown in Figure 1.

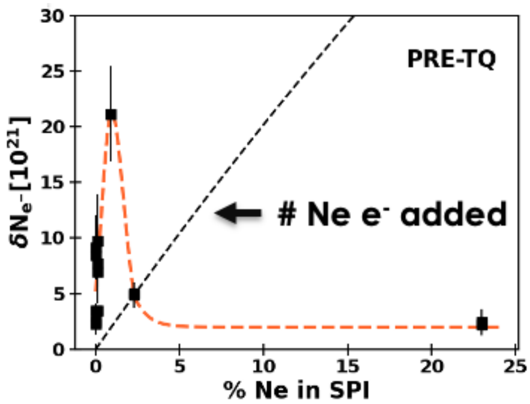

Figure 3: Increase in the number of electrons within the plasma for various levels of Ne content within the SPI. The total number of injected electrons due to the additional Ne concentration is shown in the black dashed line.

The results suggest that adding small amounts of Ne to the pellet are beneficial for the first stage in ITER's two-stage SPI mitigation scheme. Specifically, Ne enhances assimilation and provides the consistent shutdown timescales needed to properly time the secondary injection for radiating the remaining plasma energy.

References:
1. O. Vallhagen et al., Nucl. Fusion 62 112004 (2022)
2. A. Matsuyama, Phys. Plasmas 29, 042501 (2022)

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