Topic : FIP

ELM Pacing with High Frequency Multi-species Impurity Granule Injection in NSTX-U H-Mode Discharges

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We report on ELM triggering and pacing experiments in NSTX-U, including comparisons to pellet ablation models. The ability to control Edge Localized Modes(ELMs) is required for successful operation of next generation plasma devices such as ITER. For discharges with a naturally low ELM frequency, on the order of a few Hertz, the impurity ejection provided by the ELMs is projected to be insufficient to control the buildup of impurities within the plasma core. To maintain a low Z_{eff}, the period between the ELMs must be smaller than the edge to core transport times of the sputtered divertor and first wall material. During the hydrogen/helium operational phase of ITER, the intrinsic ELM frequency is anticipated to be too low to provide sufficient impurity exhaust, and must be augmented through one or more techniques[1]. As the plasma current is increased, the spatial footprint of the energy exhausted to the plasma facing components by ELMs narrows; at some point, the unmitigated peak heat flux can exceed material integrity limits. Previous experiments[2] have demonstrated that there is an inverse relationship between the frequency of the triggered ELM and the peak heat flux contained within the mode. Thus to generate the required mitigation, a rapid triggering of ELMs is employed to reduce the peak heat flux. While recent results have called into question the efficacy of pacing in metal walled tokamaks[3], ELM pacing is one of a few baseline ELM heat flux mitigation strategies for ITER.

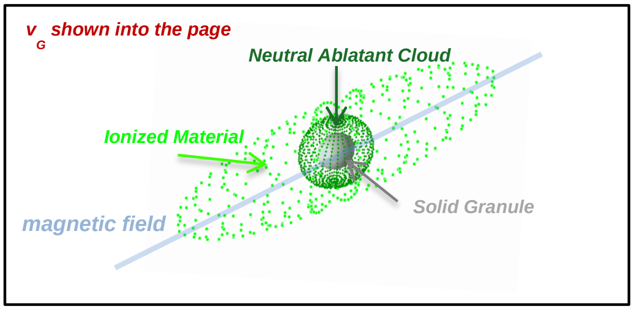

Figure 1: Ablation characteristics of an injected solid granule.

At NSTX-U multiple sizes and types of solid impurity granules are injected into the low field side of the plasma to determine their ELM triggering and pacing capability. Examining the penetration depths, and mass deposition locations of sub-mm lithium, boron carbide (B_4C) and carbon granules, we can assess the optimal size and composition for minimally perturbative ELM triggering. The solid granules are horizontally propelled into the plasma edge by means of a rapidly rotating dual bladed turbine impeller as described in [4]. Rapid electron heat conduction along the magnetic field lines causes the outer layer of the granule to rapidly ablate (Figure 1). The ablatant forms a dense neutral cloud shielding the granule from the surrounding plasma. Further heat input results in an ionization of the ablatant material that is conducted away from the granule along field lines at ion acoustic speed. This quasi-stasis of granule and neutral cloud is maintained until the granule can no longer replace the ablatant material lost to ionization. The mass deposition of these granules into the edge of the discharge leads to a peaking of the localized plasma pressure, and the creation of an overdense flux tube which becomes 3-D ballooning unstable, resulting in an ELM.

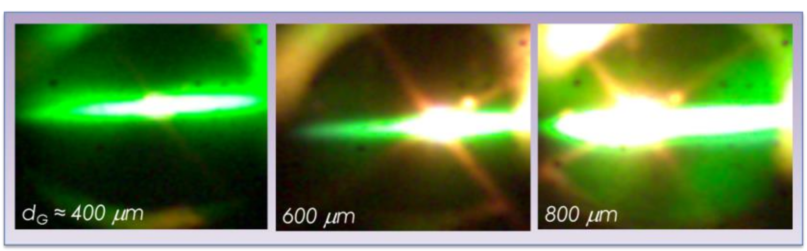

Figure 2: Granule Ablation images from DIII-D Lithium Granule Injection experiments

Utilizing a neutral gas shielding model[5], benchmarked by injection of multiple sizes of lithium granules into DIII-D plasmas[4], as shown in Figure 2, we project the pedestal atomic deposition characteristics for the three different species of granules. Injections are calculated using edge characteristics from NSTX H-mode discharges with low natural ELM frequencies. As shown in the upper panel of Figure 3, variations in the depositional barycenter can range from 5 cm for lithium to 17 cm for the same size and velocity carbon granule. We estimate that these penetration depths will be reduced by a factor proportional to $q_s \sim n_e T_e^{3/2}$ as the full NSTX-U capabilities are realized.

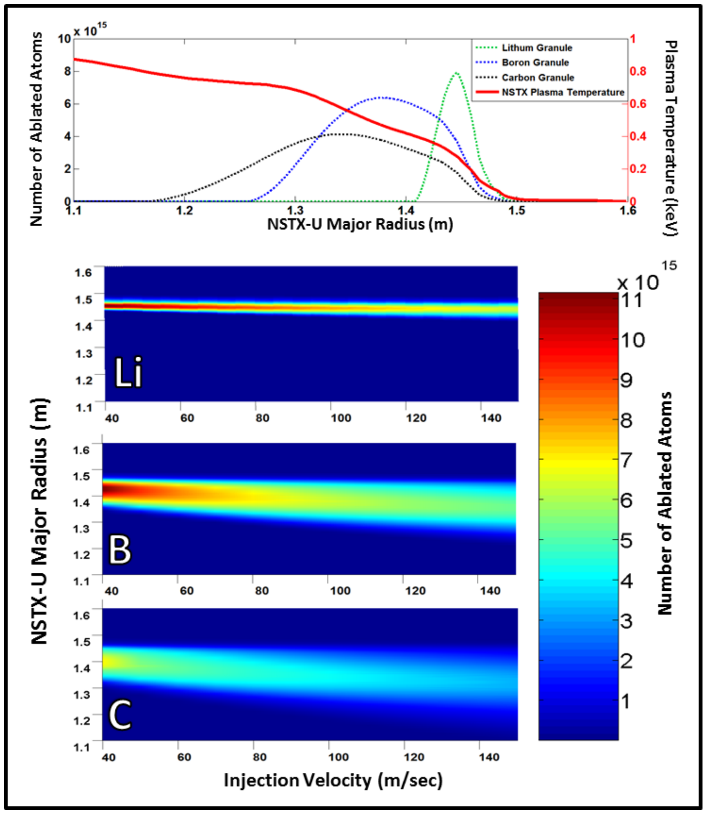

Figure 3: Mass deposition location for injected granules of differing species. The top panel displays the ablatant deposition for three 500 micron granules injected at 100 m/sec. The bottom three panels illustrate the variation in mass deposition location for alternate injection velocities. In these graphs the granule injection direction is from top to bottom.

Altering the injection velocity of the granule, presented in the lower three intensity graphs in Figure 3, can further modify the mass deposition location, allowing tuning of ELM triggering. By reducing the rotation speed of the impeller, the peak mass deposition location is translated closer to the top of the pedestal. At this location the pressure profile generated by the granule can be added to the preexisting pedestal pressure gradient, leading to a set of characteristics advantageous for ELM triggering while affecting a minimal perturbation to the core plasma.

Using multiple high-speed cameras to precisely track the granule injections and monitor the ablation duration and penetration depths in NSTX-U, a fractional mass deposition location can be extrapolated. Fast infrared camera measurements are used to characterize the variations between triggered ELMs and the inter-ELM period. In addition comparisons are also made between stimulated and spontaneously occurring ELMs. These measurements provide a comparison of the ELM peak heat flux mitigation factor, as well as variations in the ELM footprint due to the triggering mechanism. The results of ELM pacing experiments and comparisons with the constructed ablation model in NSTX-U will be reported.

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