Comparison of Lithium Granule Induced ELM triggering threshold levels for EAST and DIII-D

R. Lunsford[1], Z. Sun[2], A. Bortolon[1], J.S. Hu[2], R. Maingi[1], A. Nagy[1]
and the EAST and DIII-D Teams
[1]*Princeton Plasma Physics Laboratory, Princeton, N. J. 08543, USA*
[2]*Institue of Plasma Physics, Chinese Academy of Sciences, Hefei, Anhui 230031, China*

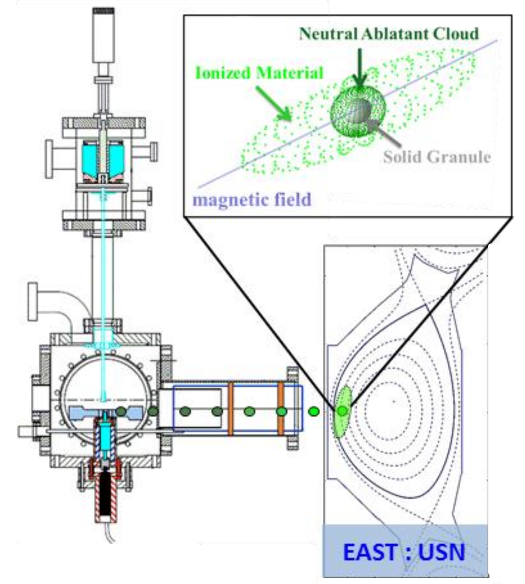

Figure 1 : Cross section of the Granule Injector and diagram of granule injection. The inset image of the granule ablation displays the character of the granule and surrounding neutral and ionized clouds formed during the ablation process.

Introduction - On both the EAST and DIII-D tokamaks the radial injection of lithium granules has been shown to trigger Edge Localized Modes (ELMs)[1,2]. The granules ablate upon entering the steep gradient region and the rapidly ionized ablatant becomes entrained within an overdense flux tube. This can lead to the generation of a ballooning instability, thus initiating an ELM. The control of ELMs in a manner that mitigates their impact on plasma facing surfaces is required for next step fusion devices such as ITER. It is anticipated[3] that the thermal cycling of unmitigated ELMs will rapidly shorten the effective divertor lifetime. To reduce this effect, one of the baseline strategies for ELM control is a rapid stimulated triggering of the ELMs, termed "pacing". The utilization of pacing as an effective mitigation strategy is dependent upon two connected tenets. First, there must be a demonstrated inverse relationship between the frequency of the triggered ELMs and the peak heat flux delivered to the PFCs and second, the ELMs must be triggered regularly and reliably. Any cessation in the production of stimulated ELMs could lead to a return of the natural ELM cycle, thus resulting in an intolerable energy release. While the former question is by no means settled, it is this second condition which we focus on here.

Apparatus and Experiment- Lithium granules with diameters ranging from approximately 300 microns to 900 microns have been radially injected into the edge of both EAST and DIII-D H-mode plasmas at velocities of 50 to 150 m/sec. The injector utilized for both these sets of experiments, and displayed in Figure 1, was modified from a powder

Figure 2 : Filmstrip of injected lithium granule displays the stages of the ablation event.

dropper designed at PPPL[4] and first tested on EAST[1]. The granules to be injected are held in a cylindrical reservoir at the bottom of which is located a piezoelectric disk with a central aperture. A central rod with a passageway ducts the granules to the top of the piezoelectric disk. When the piezoelectric disk is activated by an applied sinusoidal voltage waveform at 2250 Hz the piezoelectric disk vibrates at resonance and drives the granules on the face of the disk toward the central aperture. Gravitationally accelerated granules then pass through a drop tube into the primary chamber of the granule injector where they are redirected by a rapidly rotating dual bladed impeller. As granules are horizontally injected into the low field side of the discharge, they rapidly ablate due to heat convection from fast electrons. Ablated material from the granule forms a dense neutral cloud surrounding the granule and mitigating heat flux to the surface. Additional electron thermal influx results in ionization of this neutral cloud, and the new field aligned ions stream away from the high density region. Installed on both DIII-D and EAST are dedicated camera imaging systems which observe along radial injection trajectories and record the duration and extent of the granule ablation event. These stages of the ablation process are displayed in the EAST images contained within Figure 2. In the second frame of the sequence an initial luminous neutral cloud can be seen surrounding the granule. As the granule transits further into the discharge the field aligned ionized cloud is created and occults the source granule until the mass is exhausted. This model of granule ablation, termed the Neutral Gas Shielding (NGS) model[5], has been utilized effectively to describe the ablation characteristics of solid deuterium pellets as well as low-Z materials such as lithium[6].

To determine the triggering efficiency (the ratio of triggered ELMs to injected granules) from these injections, granules are individually tracked as they exit the dropper tube and are driven into the discharge. Multiple independent metrics are utilized to determine time of flight and correlate injections with ablations events recorded on a dedicated fast framing camera. On EAST, the ablation trace is then compared to observed peaks on the readout from the XUV diagnostic channel which crosses the granule trajectory, thus confirming time of injection. On DIII-D granule injection is confirmed by the signal from an in-vessel magnetic Mirnov probe. If an injection event, as independently recorded by these diagnostics, is found to be concurrent with a resultant peaking of the divertor Dα signal then the granule injection is determined to have been successful in the triggering of an ELM. To illustrate this a comparison between the XUV and Dα signals for representative time windows during four granule injection discharges on EAST is shown in Figure 3. In the uppermost frame, a 100 ms segment of discharge #70601 is displayed. During this time 11 granules, with an average diameter of 920 μm, were injected into the edge plasma. These injections, denoted by peaks in the black XUV trace, can be seen to have triggered a corresponding peak in the magenta Dα trace, indicating that each injected granule triggered an ELM. In the next two frames, the injection of granules averaging 740 microns and 510 microns in diameter respectively, also triggered ELMs at a greater than 90% efficiency. However when the granule diameter is reduced yet again, this time to an average of 290 microns, as shown in the fourth frame, the ELM triggering efficiency drops to less than 20% thus indicating that a triggering threshold has been crossed.

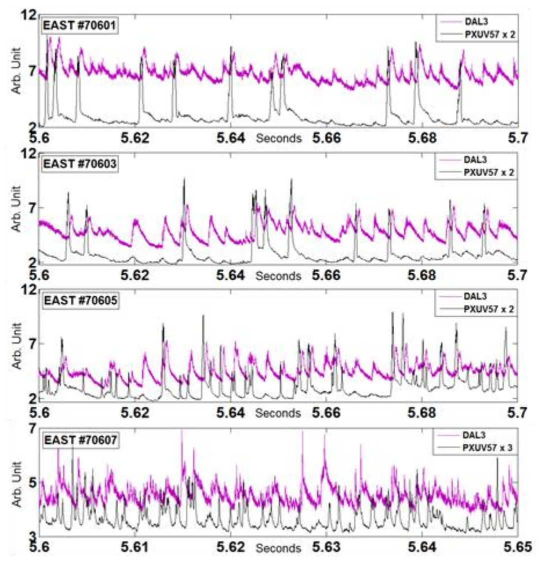

Figure 3 : Dα and XUV traces for four representative granule injection time windows for similar EAST discharges. Approximate granule diameter as follows #70601 : 900 μm, #70603 : 700 μm, #70605 : 500 μm, #70607 :

Discussion – The experiments on DIII-D and EAST utilized a variety of sizes of injected lithium granules which enable the characterization of a granule mass threshold necessary for reliable ELM triggering. The results of this comparison are displayed in Figure 4 and show similar yet distinct trends. In the DIII-D experiments, granule diameters larger than 700 microns demonstrated a triggering efficiency exceeding 80%, while granules with diameters of approximately 400 microns were only successful in triggering ELMs 20% of the time. Using the duration of ablation to benchmark a neutral gas shielding calculation as reported in Ref [7], we were able to determine the granule ablation rate and the approximate location of mass deposition for the various sized granules. For example, larger granules (~700 microns) injected into DIII-D penetrated 6 cm past the separatrix and deposited approximately 3 x 10^{18} Li atoms atop the H-mode pedestal, triggering an ELM. In contrast smaller granules (~300 microns), while still penetrating 4.5 cm, only deposited 3 x 10^{16} Li atoms at the pedestal shoulder. In contrast, triggering efficiency for the EAST granule injection experiments is almost perfect for granule sizes above 600 μm and when the granule diameter drops below 500 microns we begin to observe triggering efficiencies less than 50%. This elevated triggering efficiency demonstrated on EAST is most likely due to lower plasma stored energy. Whereas W_{MHD} and I_P for the DIII-D experiments was ~ 600 kJ and 1.2 MA respectively, the EAST experiments were undertaken with W_{MHD} and I_P at 175 kJ and 400 kA. As non-linear modelling of pellet triggered ELMs[8] correlates the triggering efficiency with the ability of a pellet to reach the pedestal top, we postulate that the variation in triggering threshold is the result of deeper granule penetration due to lower edge densities and temperatures, and analysis along these lines is ongoing.

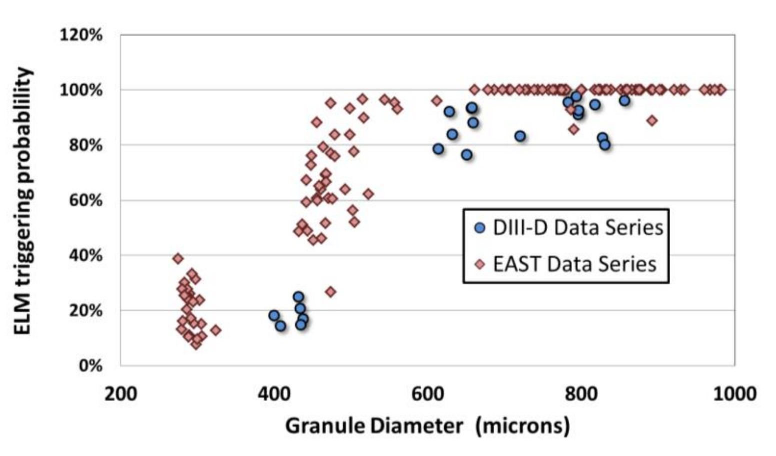

Figure 4 : ELM triggering probability for assorted granule sizes. Each data point, for both EAST and DIII-D, are representative of the average triggering probability observed during a subsection of an attempted ELM-pacing discharge.

Thus, these experiments demonstrate that there is a quantifiable prompt ELM triggering threshold for solid granules which correlates with discharge stored energy. However, it must be stated that there are pressing issues involving the ELM pacing mitigation strategy. JET and AUG both find an ELM trigger lag time after conversion to metal PFCs thus limiting the maximal pacing frequency[9]. In addition, Li-granule ELM pacing at DIII-D[2] displayed a bifurcated ELM structure whereby some of the ELMs display a reduced peak heat flux, but these are interspersed with a number of ELMs of at least the same peak intensity as the nominal spontaneous ELMs. Thus further investigation is required prior to extrapolation of this technique to future burning plasma devices.

Work supported in part by U.S. DOE under DE-AC02-09CH11466 and DE-FC02-04ER54698.

[1] D. K. Mansfield *et al*, Fusion Eng. and Design 85 (2010) 890

[2] A. Bortolon *et al*, Nucl. Fusion 56 (2016) 056008

[3] A. Loarte *et al*, Nucl. Fusion 54 (2014) 033007

[4] A.L. Roquemore *et al*, Fusion Eng. and Design 86 (2011) 1355

[5] P. B. Parks *et al*, Nucl. Fusion 28 (1988) 477

[6] R. Lunsford *et al.*, Nucl. Fusion 57 (2017) 076008

[7] R. Lunsford *et al.*, Fusion Eng. & Design 112 (2016) 621

[8] S. Futatani *et al*, Nucl. Fusion 54 (2014) 073008

[9] P.T. Lang *et al*, Nucl. Fusion 54 (2014) 083009