Mitigation of ELM peak heat loads on NSTX-U through impurity granule injection

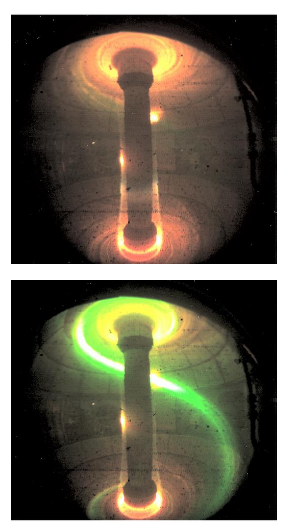
R. Lunsford[1], A. L. Roquemore[1], D. K. Mansfield[1], A. Bortolon[1], M. Jaworski[1], R. Kaita[1], R. Maingi[1]
[1]Princeton Plasma Physics Laboratory, Princeton NJ 08543

ABSTRACT

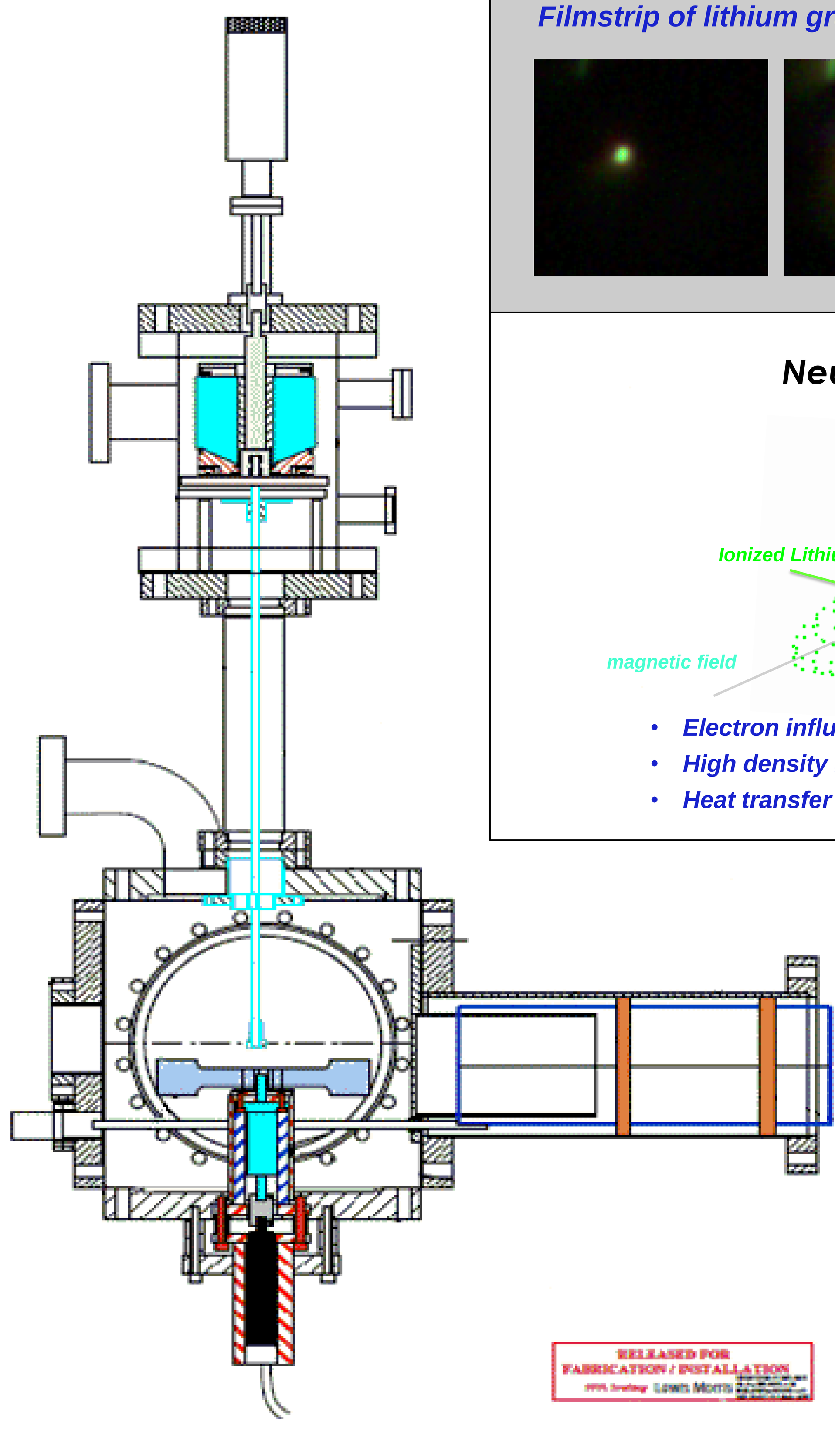
Controlling the peak heat load associated with an Edge Localized Mode (ELM) is especially crucial in Spherical Tokomaks where the small major radius provides minimal opportunity for radial relaxation of the heat profiles prior to connection with the divertor. Thus it is critical to develop a method for mitigation of these events to ensure stable operation of next generation ST devices. As it has been shown that there is an inverse relationship between the ELM frequency and the peak heat flux delivered during the mode, a system has been developed for NSTX-U whereby ELMs will be paced at a rate 10+ times higher than the natural ELM frequency by injection of impurity microgranules into the edge plasma. Granules of low Z impurity species (Li, B, C) are radially driven into the midplane edge of the discharge through impact acceleration with a rapidly rotating impeller. The rotation speed of the impeller determines the granule injection frequency within a range of 50 – 150 m/sec. In addition, the impeller frequency, coupled with the input rate of the granules, sets the overall particle injection frequency at up to 200 Hz. The granules, upon impact with the edge plasma, ablate and generate an overdense flux tube within the H-mode pedestal. This drives the flux tube into an unstable region of the peeling-ballooning pressure space thus resulting in the production of an ELM. These paced ELMs are then able to regulate the pedestal in a controlled manner, thus moderating the peak heat flux to a level tolerable to the plasma facing components. Utilizing the compact nature of the ST geometry, global fast camera imaging of the edge filamentary structure generated by the ELM is recorded as it is mapped from the midplane to the divertor region. This information, accompanied with other diagnostics allows a characterization of the mass deposition location and pedestal penetration for the granules as well as a comparison of the characteristics of spontaneous and stimulated ELMs.

Stimulating ELMs through granule injection

1. Injected granules create an asymmetric high density filament
2. Sonic expansion of cold plasma leads to perpendicular pressure gradients
3. Flux tubes become ballooning unstable resulting in an edge localized mode (ELM)



Injection of low velocity (~5m/s) lithium clumps (~2mm) into NSTX (2008)



Pacing ELMs reduces peak heat flux

ELM intensity has been observed to be inversely proportional to ELM frequency

$$\Delta W_{ELM} \times f_{ELM} \sim const$$

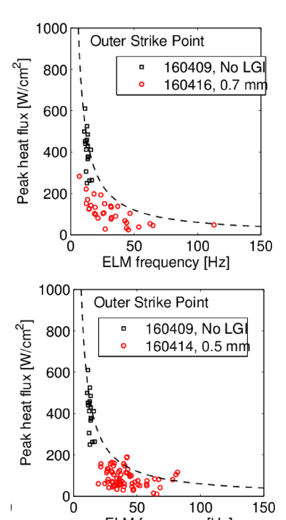
Rapid triggering of ELMs (pacing) should lead to a reduction in the peak ELM intensity.

Paced ELM heat fluxes are now reduced to a level tractable for the plasma facing components.

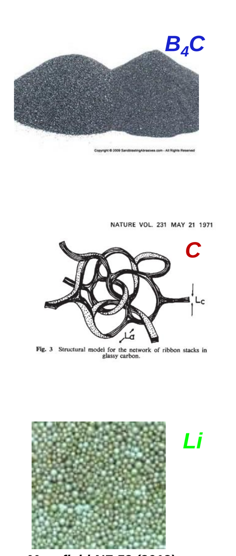
This effect has been seen in deuterium pellet pacing and also with lithium granule pacing in DIII-D high torque scenarios (shown at right)*

The heat flux reduction is less pronounced in similar experiments in JET, AUG, and DIII-D low torque scenarios necessitating further study.

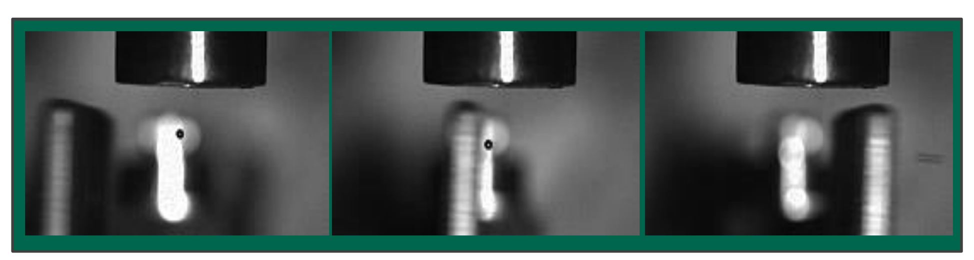
** See L. Baylor et al. Phys Rev Lett. 110, 245001 (2013)*



Electron inventory calculation for multi-species particle injection

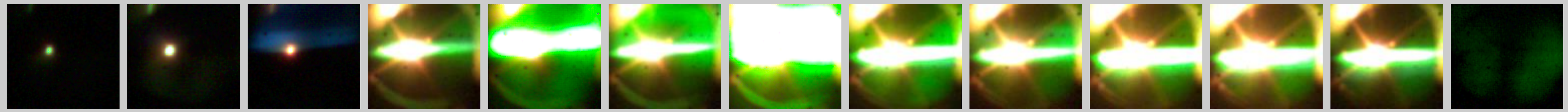


	Deuterium Slush	Lithium	Boron Carbide	Carbon (Vitreous)
Density	.237 g/cm ^{3}	.534 g/cm ^{3}	2.52 g/cm ^{3}	2.09 – 2.23 g/cm ^{3}
Mass in a 1mm sphere (mg)	0.124	0.279	1.319	1.131
Atomic Weight (g/mol)	4.028	6.94	55.255	12.011
Number of atoms/molecules	1.855E+19	2.426E+19	1.438E+19	5.670E+19
Number of electrons	1.855E+19	7.279E+19	4.170E+20	3.402E+20
Deuterium Multiplier	1.00	3.92	22.48	18.34
Sublimation Energy (eV/atom)	0.0155	1.65	5.3 (B)	7.5
Sublimation Energy Per Granule (J)	0.046	6.415	61.070	68.154
First Ionization Energy (eV)	13.6	5.3917	8.2980 (B)	11.2603
Second Ionization Energy (eV)		75.64	25.1548 (B)	24.3833

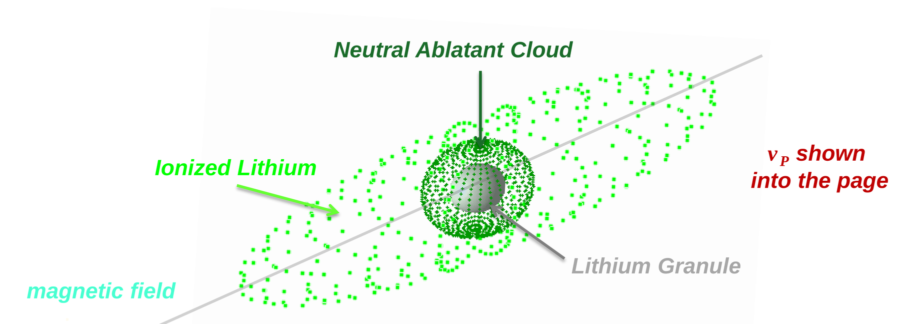


Horizontal injection of a 700 micron carbon microsphere. Exposure time is 50 microseconds and interframe time is 200 microseconds. Motion blur of the rightmost granule gives an estimated velocity of 45 m/sec.

Filmstrip of lithium granule injection and ablation from DIII-D Shot 160416: Initial Diameter ~ 800 microns, Interframe time = 50 μs



Neutral Gas Shielding (NGS)



- Electron influx sublimates the pellet surface
- High density neutral cloud forms around the granule
- Heat transfer ionizes the cloud which streams along field lines

NGS Model

$$4\pi\, r_p^{\,2}\, q_s = G[\Delta H + T_C(1 + {}^5/_6\, M_C^{\,2}) + {}^3/_2\,(T_C - T_S)] + Q_{inv}$$

$$-\frac{dr_p}{dt} = \frac{\eta f_B f_L q_s}{n_0\left[\Delta H + T_S\left(\frac{5}{2} + \frac{5}{6} M_C^{\,2}\right)\right]}$$

Adapted from P. B. Parks et al. NF 34 (1994) & G. Kocsis et al. PPCF 41 (1999)

r_g = Granule Radius
ΔH = Sublimation Energy (Li = 1.6 eV/atom)
T_C = Cloud Temperature ($T_C = 0.7 T_S$)
T_S = Surface Temperature (T_S = 0.14 eV - Li Boil Point)
M_C = Cloud Mach Number (M_C = 1, sonic flow)

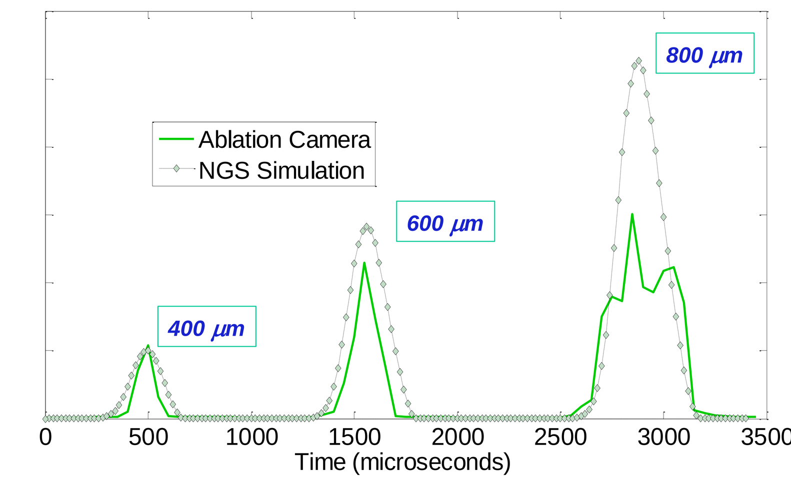
η = Cloud Shielding Parameter
f_B = Field directed heating anisotropy (~1/2)
f_L = Flux Screening Parameter (0.16 for H_2, 1 if no screening)
n_g = Granule Density

Ablation Rate of the Injected Granule

$$G = \frac{4\pi r_g^{\,2} q_s \eta f_B}{n_g}\left[\Delta H + \frac{10}{3} T_S\right]^{-1} \qquad q_s = \frac{1}{2}\, n_e T_e \left(\frac{8 T_e}{\pi m_e}\right)^{1/2}$$

$$Q_{inv} = c m_p \frac{d}{dt} T_s$$

We assume that the surface temperature rapidly equilibrates so that this term can be neglected



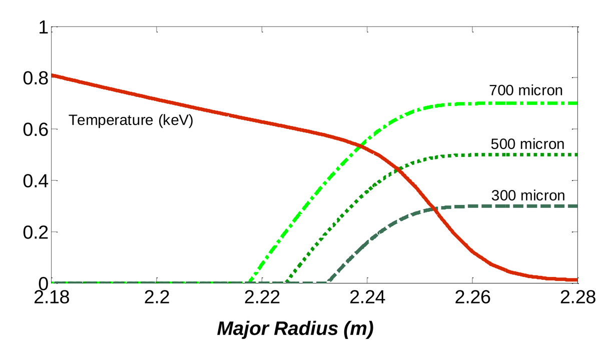
The ablation intensity is plotted vs time, NGS field parameters(η, f_B, f_L) are set to match calculated ablation time with measurements for a typical 800 micron granule and peak ablation intensity and NGS rate are normalized for the smallest granule size.

Camera saturation results in clipping of the intensity for the larger granules

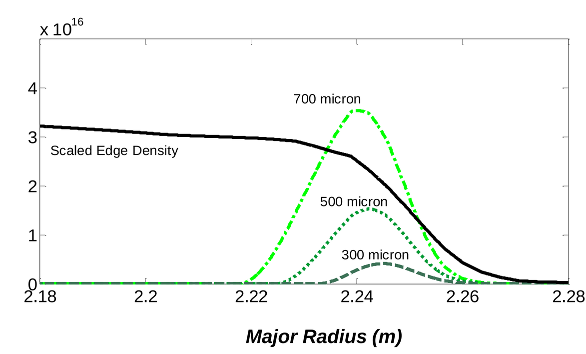
DIII-D Lithium Granule Injection Experiment

v_G = 90 m/sec

Granules ablate rapidly upon entering the pedestal region

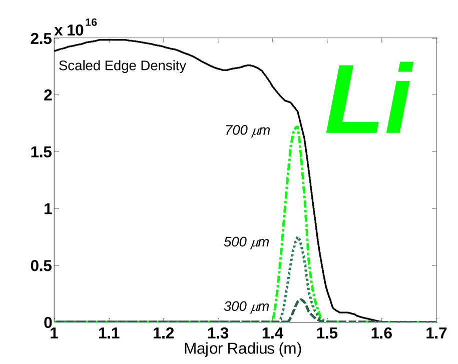


While some portion of the granule does penetrate deeply, the primary mass deposition is located further out

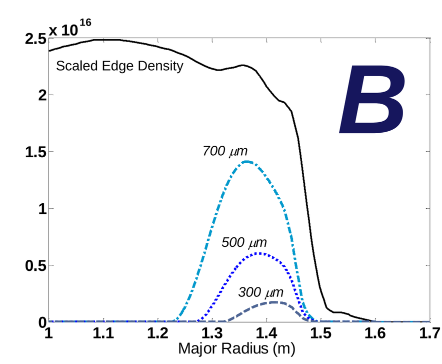


NSTX-U Granule Ablation and Penetration Projections

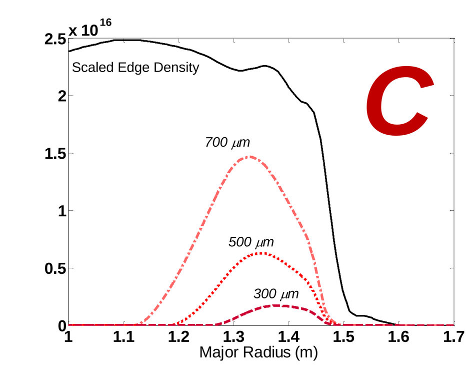
Using the calibration factors from the DIII-D Li injection experiments and NSTX legacy edge profiles we are able to project the ablation rates and penetration depths for the injected impurity granules



Note that the vertical axis represents ablated atoms and does not account for the electron load each species deposits at the plasma edge.



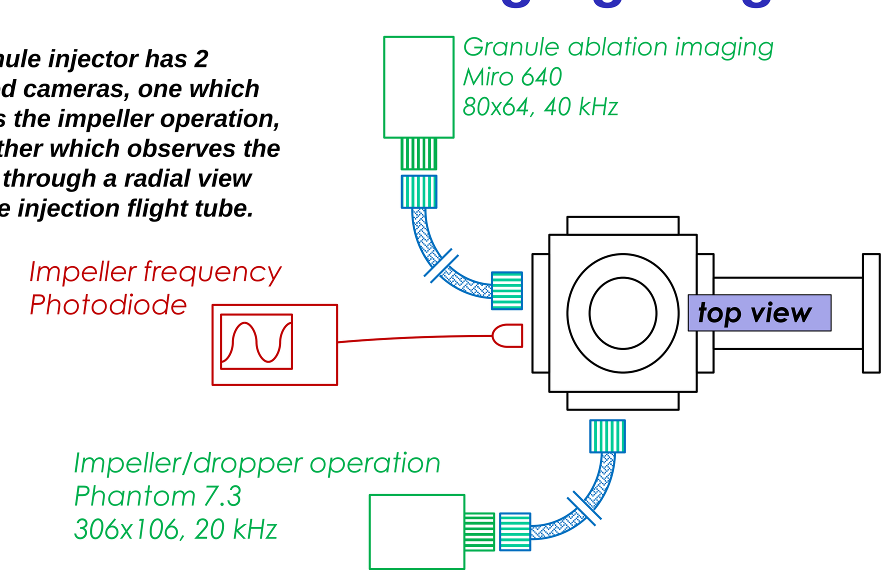
The same cloud shielding parameter was utilized for all impurity granule species to create an approximate profile, variations due to larger sublimation energies are expected



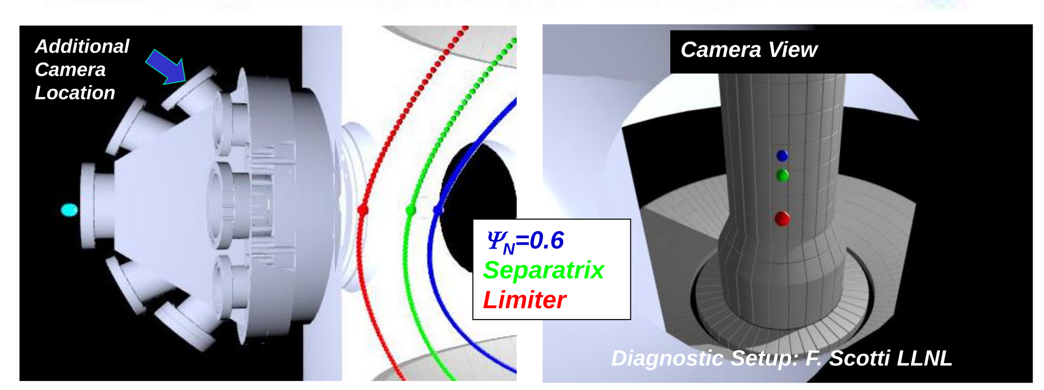
The larger penetration depths from the Carbon granules may indicate that smaller sizes are necessary for a similar triggering efficiency

Granule Ablation Imaging Diagnostics

The granule injector has 2 dedicated cameras, one which monitors the impeller operation, and another which observes the ablation through a radial view along the injection flight tube.



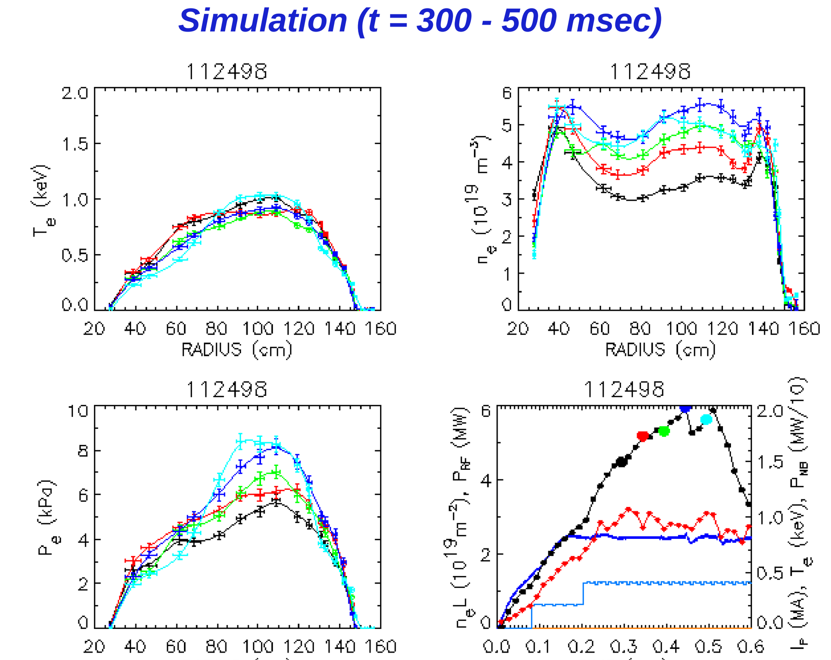
Lawrence Livermore National Laboratory



Additional cameras will be fielded on NSTX-U during LGI experiments through diagnostic collaboration with LLNL

This allows direct measurement of injection velocity and penetration depth.

NSTX Legacy Profile Data used for Granule Injection Simulation (t = 300 - 500 msec)



Planned Granule Injector Experiments

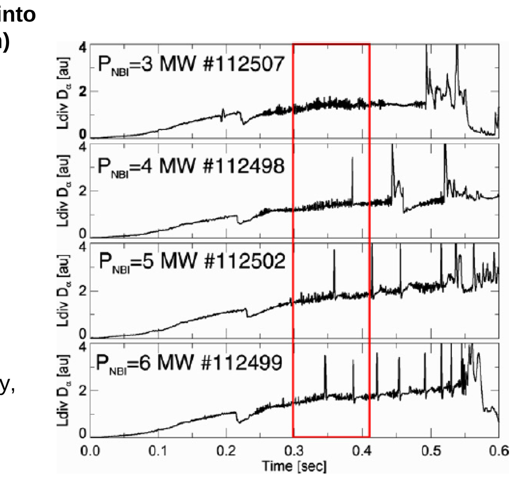
ELM pacing via multi-species granule injection and 3D field application for main ion control

Goal : Comparison of Boron Carbide and Carbon injection into low frequency ELM-y H-modes for ELM pacing (pre-Lithium)

- Examine ablation rates and penetration depths of multiple granule species.
- Compare characteristics of stimulated ELMs to both spontaneous ELMs and the simulation code JOREK.
- Are ELMs paced at 3-5 times the spontaneous natural frequency sufficient for divertor heat flux mitigation?

Experimental Plan

- Achieve NSTX-U discharges with low natural ELM frequency, based on NSTX results
- Inject granule of various sizes to observe ablation physics, determine pacing efficacy and monitor impurity transport
- Compare characteristics of spontaneous and stimulated ELMs.



R. Maingi et al. / Journal of Nuclear Materials 363–365 (2007) 196–200

Triggering ELMs with lithium granule injection and 3-D fields in lithiated discharges

Goal : Locate minimum edge perturbation required to initiate ELMs in a naturally ELM free discharge.

- Empirical study to determine the minimal lithium granule size, injection frequency and input velocity required for reliable ELM triggering.
- Monitor core impurity transport, both lithium intake and carbon efflux caused by granule instigated bursting in naturally ELM free lithiated discharges.
- High speed camera measurements of granule ablation and plasmoid formation to locate mass seeding within pedestal. Compare to pellet ablation models.
- Establish NSTX-U threshold for ELM triggering with solid granules and compare to limitations found elsewhere with D2 pellet triggering

Experimental Plan

- Access ELM-free NSTX-U H-Modes through lithium wall conditioning
- Inject Lithium Granules (700 mm, 500 mm, 300 mm) to determine lower mass density limit
- Reduce injection frequency to determine cumulative edge density effects, and reduce impeller velocity to look for lower input velocity limit

U.S. DEPARTMENT OF ENERGY | Office of Science