UTILIZING SOLID IMPURITY GRANULES FOR ELM PACING ON NSTX-U

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ABSTRACT

Periodic edge localized modes (ELMs) rapidly transport stored energy from the edge plasma to the divertor. These events result in abrupt heating of the plasma facing components (PFCs) which reduces their effective lifetime as well as generating a strong impurity influx. If the frequency of these ELMs can be increased through controlled triggering, also known as pacing, then the inverse relationship between the peak heat flux and the frequency of the ELMs can be utilized to prevent material damage that could result from otherwise unmitigated ELMs. At NSTX, the ability of small (300 – 1000 micron) impurity granules to trigger and pace these ELMs is being explored. In these experiments, ELMs are triggered by seeding a density perturbation within the edge-pedestal region through low speed injection and ablation of impurity granules, thus generating a localized instability. Granules are dropped from a reservoir and transit a vertical flight tube at which point a rotating impeller imparts horizontal momentum into the falling granules. This drives them into the edge of the discharge at speeds ranging from 50-150 m/s and average injection frequencies of up to 200 Hz depending upon the settings of the injector. Results from the initial laboratory injection tests of lithium, boron carbide (B_4C) and vitreous carbon granules and their subsequent implementation in NSTX-U experiments will be discussed.

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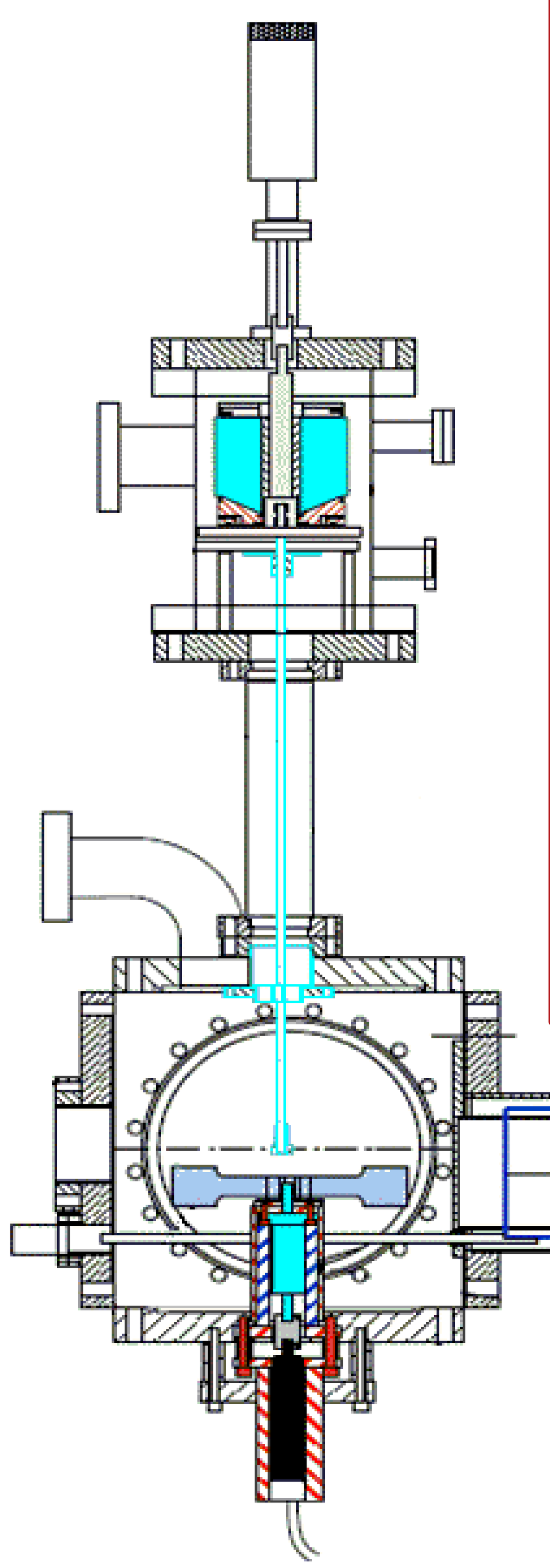
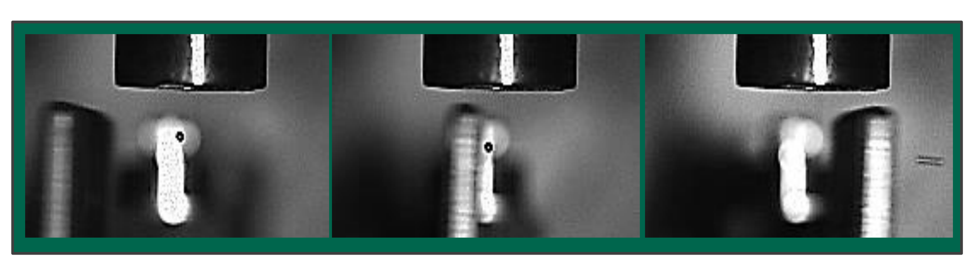


Ablation images of different size granules during ELM pacing experiments at DIII-D

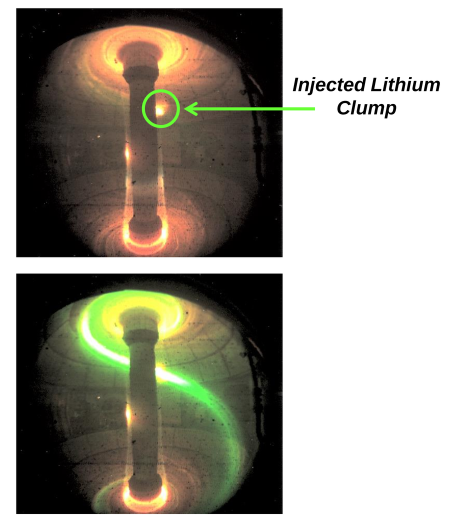


Horizontal injection of a 700 micron carbon microsphere. Exposure time is 50 microseconds and interframe time is 200 microseconds. Motion blur of the rightmost granule gives an estimated velocity of 45 m/sec.

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)

See Also : TP12.0012 A. Bortolon Thursday 9:30 a.m. High Frequency ELM Pacing by Lithium Pellet Injection on DIII-D



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

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

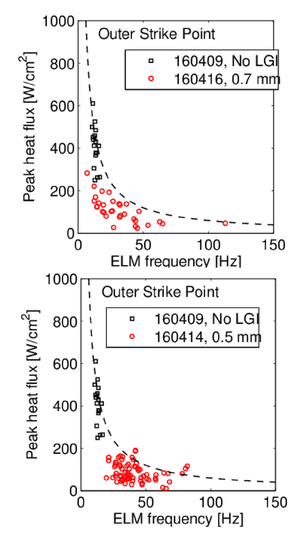
Rapid triggering of ELMs (pacing) should lead to a reduction in the peak ELM intensity.

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.

*TO6.00008 L. Baylor Thursday 9:30 a.m. Application of Pellet Injection to Mitigate Transient Events in ITER

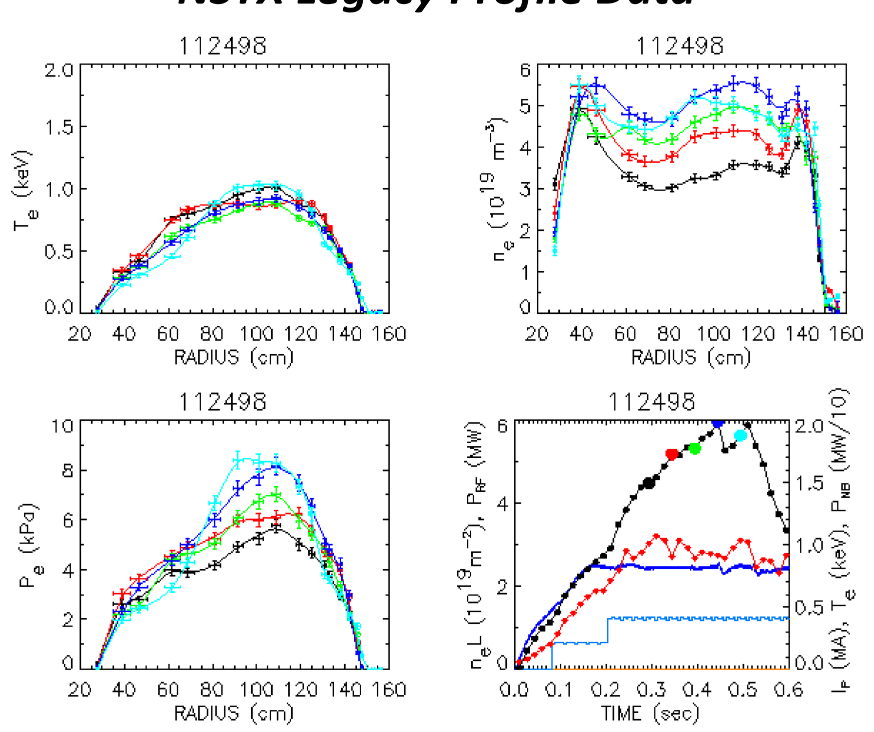


Results from DIII-D LGI ELM pacing experiment

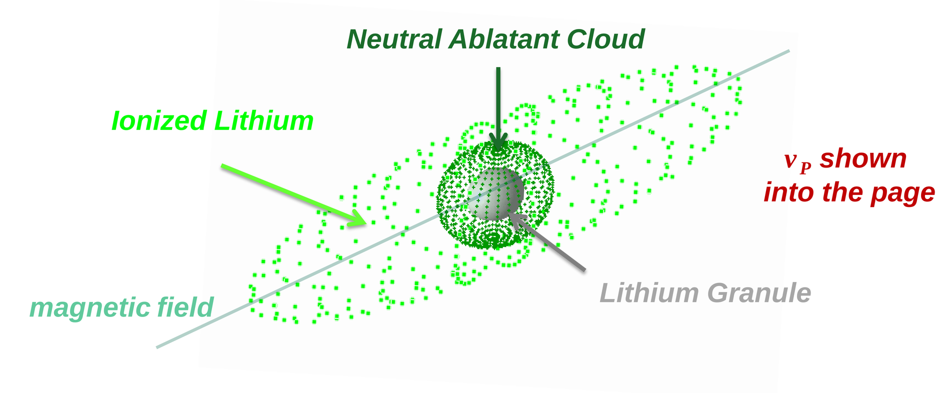
Electron inventory calculation for multi-species particle injection

	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	20.15	18.42
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

NSTX Legacy Profile Data



Neutral Gas Shielding (NGS)



- Electron influx sublimates the pellet surface
- High density neutral cloud forms around the granule
- Ablation rate of the shielded granule is controlled by the neutral cloud
- Heat transfer ionizes the cloud which streams along field lines
- Shielding is maintained until the granule source is exhausted

NGS Model

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

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

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 ($T_C = 0.7T_S$)
T_S = Surface Temperature (T_S = 0.14 eV - Li Boil Point)
M_C = Cloud Mach Number (M_C = 1, sonic flow)

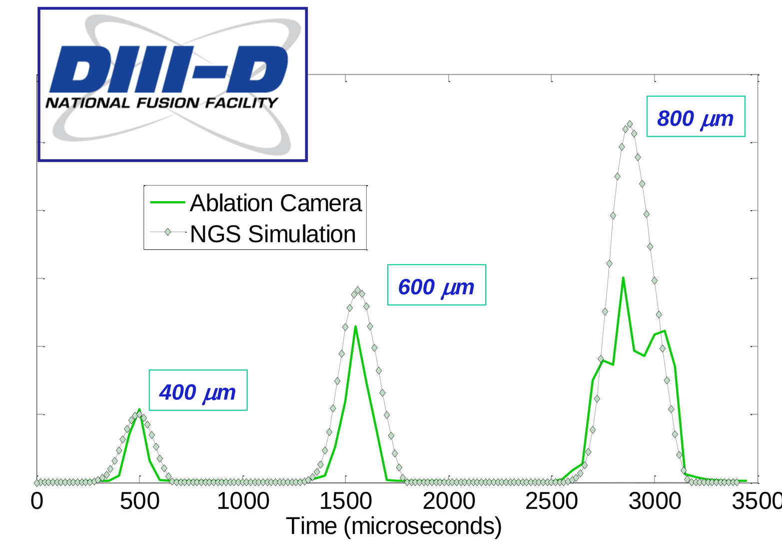
η = Cloud Shielding Parameter
f_B = Field directed heating anisotropy (~1/2)
f_L = Flux Screening Parameter (0.16 for H_2, 1 if no screening)
n_g = Granule Density

Ablation Rate of the Injected Granule

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

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

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

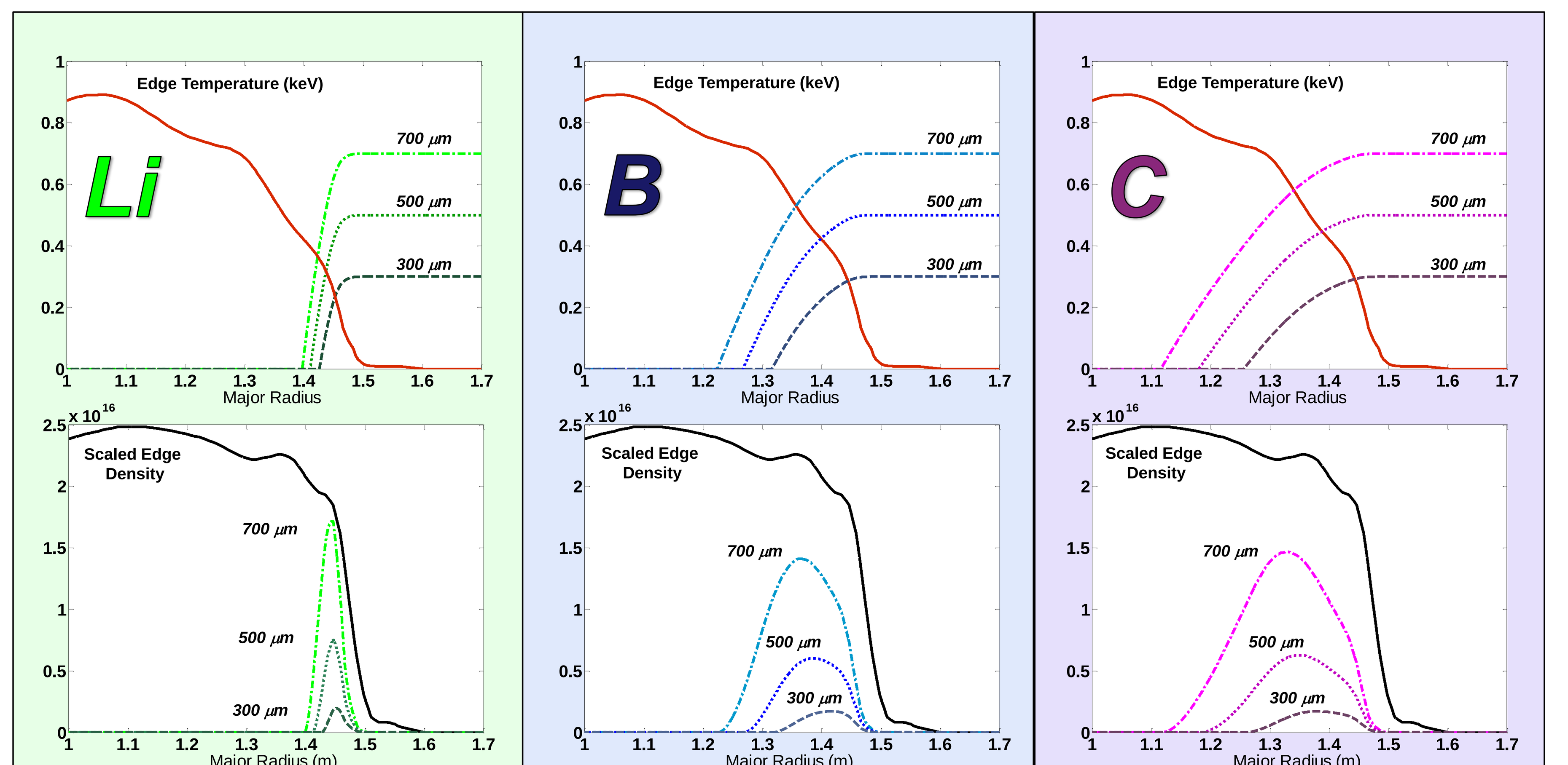


The ablation intensity is plotted vs time, NGS field parameters (η, f_B, f_L) are set to match calculated ablation time with measurements for a typical 800 micron granule. Peak ablation intensity and NGS rate are normalized for the smallest granule size.

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

NSTX-U Granule Ablation and Penetration Projections

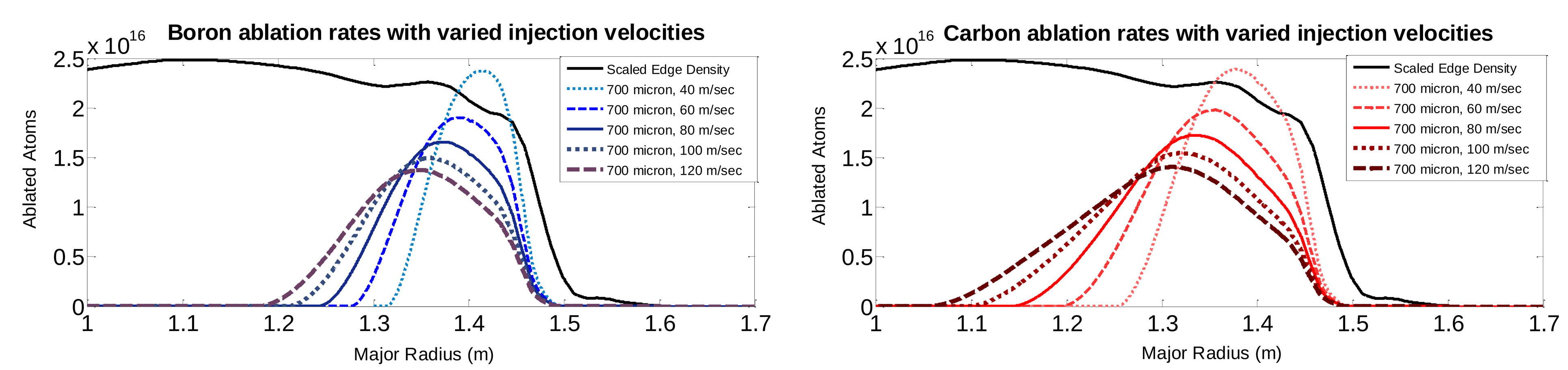
Using the calibration factors from the DIII-D Li injection experiments and NSTX legacy edge profiles we are able to project the penetration depths and ablation rates for the injected impurity granules



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 required for a similar triggering efficiency



By adjusting the rotation frequency of the impeller we can control the injection velocity of the granules. This in turn effects the mass deposition location which could help mitigate the impurity influx to the plasma core. As long as the granule can fully penetrate the steep gradient region prior to full ablation, the triggering efficiency should be maintained. Note that velocities below 40 m/sec are not practicable for horizontal injection due to excessive parabolic decay of the granule trajectory.

Planned Granule Injector Experiments

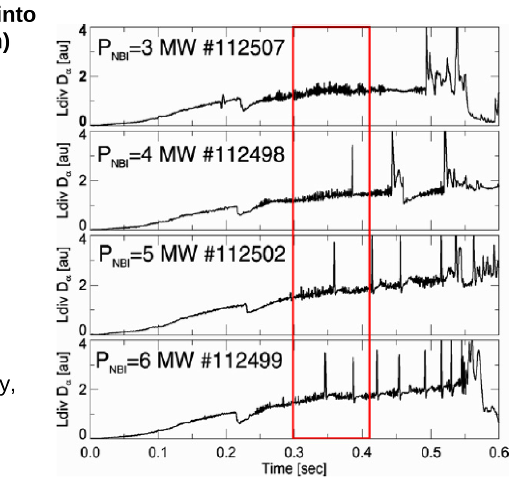
ELM pacing via multi-species granule injection and 3D field application for main ion control

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.



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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 μm, 500 μm, 300 μm) 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