MICROGRANULE INJECTION INTO NSTX-U DISCHARGES FOR EDGE DIAGNOSTIC RESEARCH

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Overview

- Injector mechanically drives solid impurity granules into discharge Low Field Side (LFS).
- Granule injection provides well characterized spatially localized density source.
- Injection experiments performed on EAST and DIII-D, injector installed and tested on NSTX-U.
- Benchmarked neutral gas shielding (NGS) model simulates ablation rate and mass deposition location in NSTX-U discharges.
- Extended imaging suite will be utilized to validate NGS model when NSTX-U resumes operation.

Granule Triggered ELMS

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

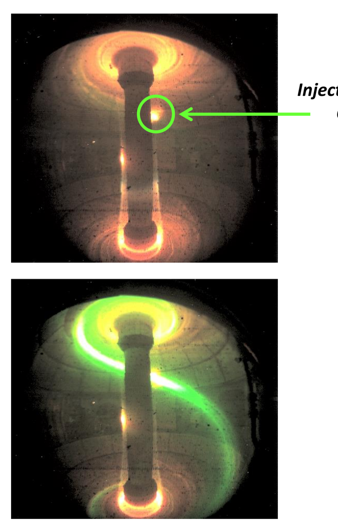
ELM intensity is inversely proportional to frequency

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

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

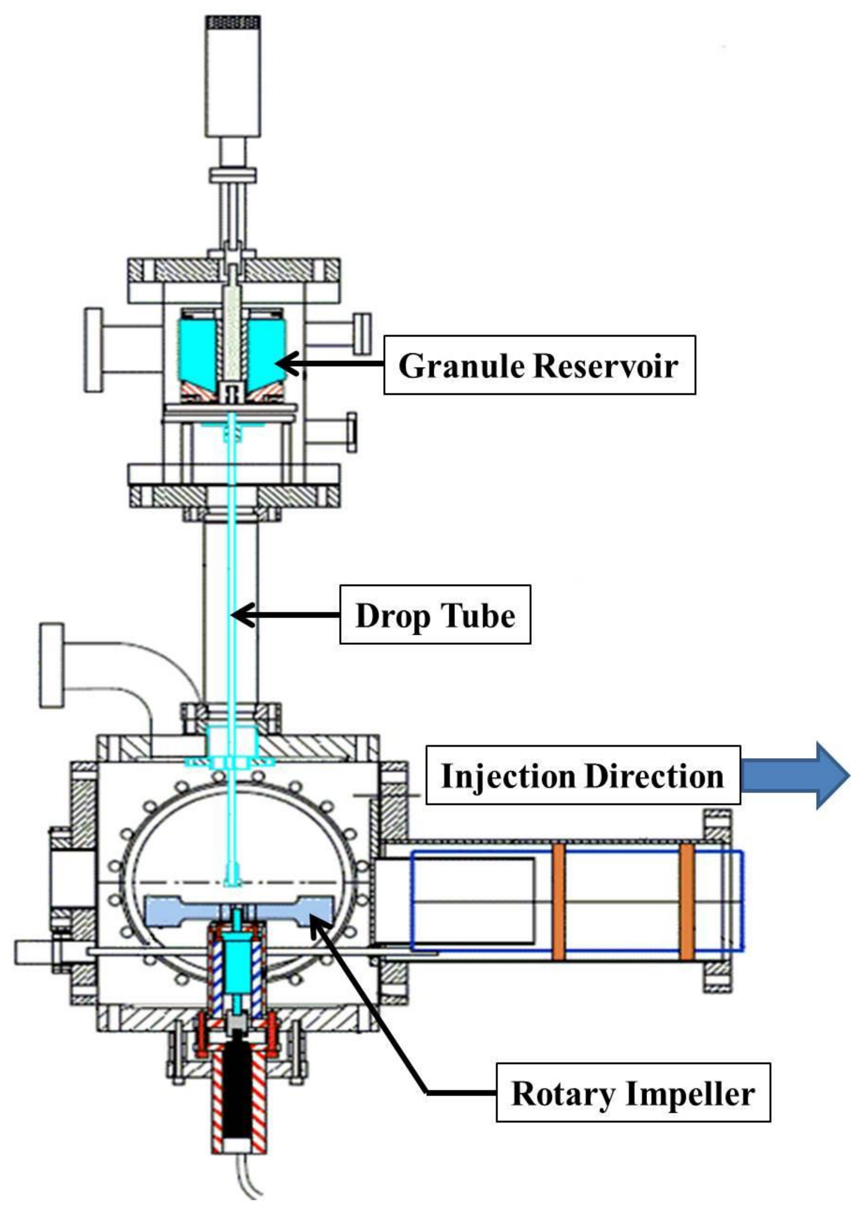
Paced ELM heat fluxes are now reduced to a level tractable for the PFCs

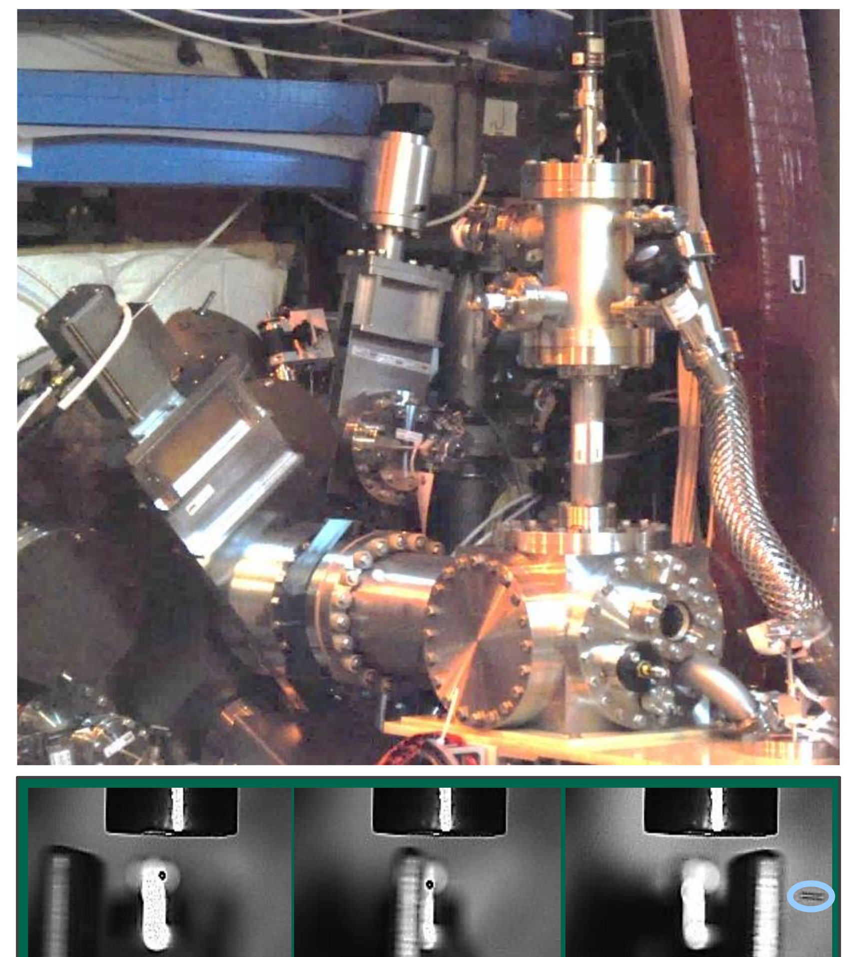
Baseline mitigation strategy for ITER



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

Granule Injector Installed on NSTX-U





Injection of a 700 micron carbon microsphere. Exposure time is 50 μsec, interframe time is 200 μsec. Motion blur of the rightmost granule gives an estimated velocity of 45 m/sec.

Granule sizes : *900μm, 700μm, 500μm, 300μm*

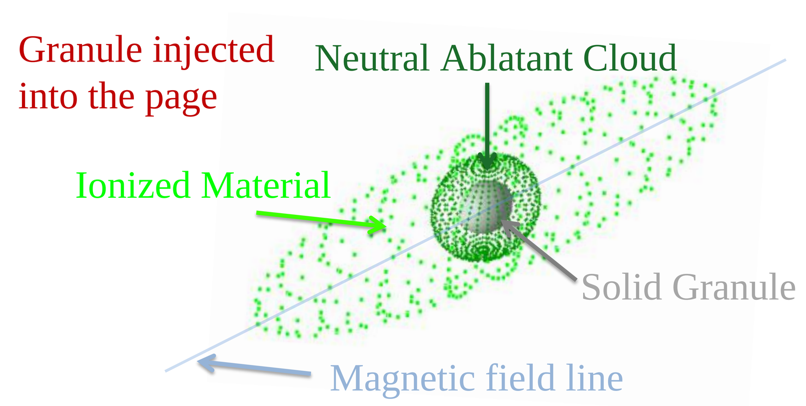
Injection Species : *Li, B_4C, C*

Injection Velocity : *50 – 150 m/sec*

Granule Injection Frequency : *10 – 500 Hz*

Neutral Gas Shielding (NGS) Model for Granule Ablation

- 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



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

$$-\frac{dr_g}{dt} = \frac{\eta f_B q_s}{n_0\left[\Delta H + T_S\left(\frac{5}{2} + \frac{5}{6} M_C^{\,2}\right)\right]} \qquad Q_{inv} = c m_p \frac{d}{dt} T_s$$

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

Adapted from Parks et al. Nucl. Fusion 34 (1994) & Kocsis et al. PPCF 41 (1999)

Ablation rate of the injected granule

$$q_s = \frac{1}{2}\, n_e T_e \left(\frac{8T_e}{\pi m_e}\right)^{1/2}$$

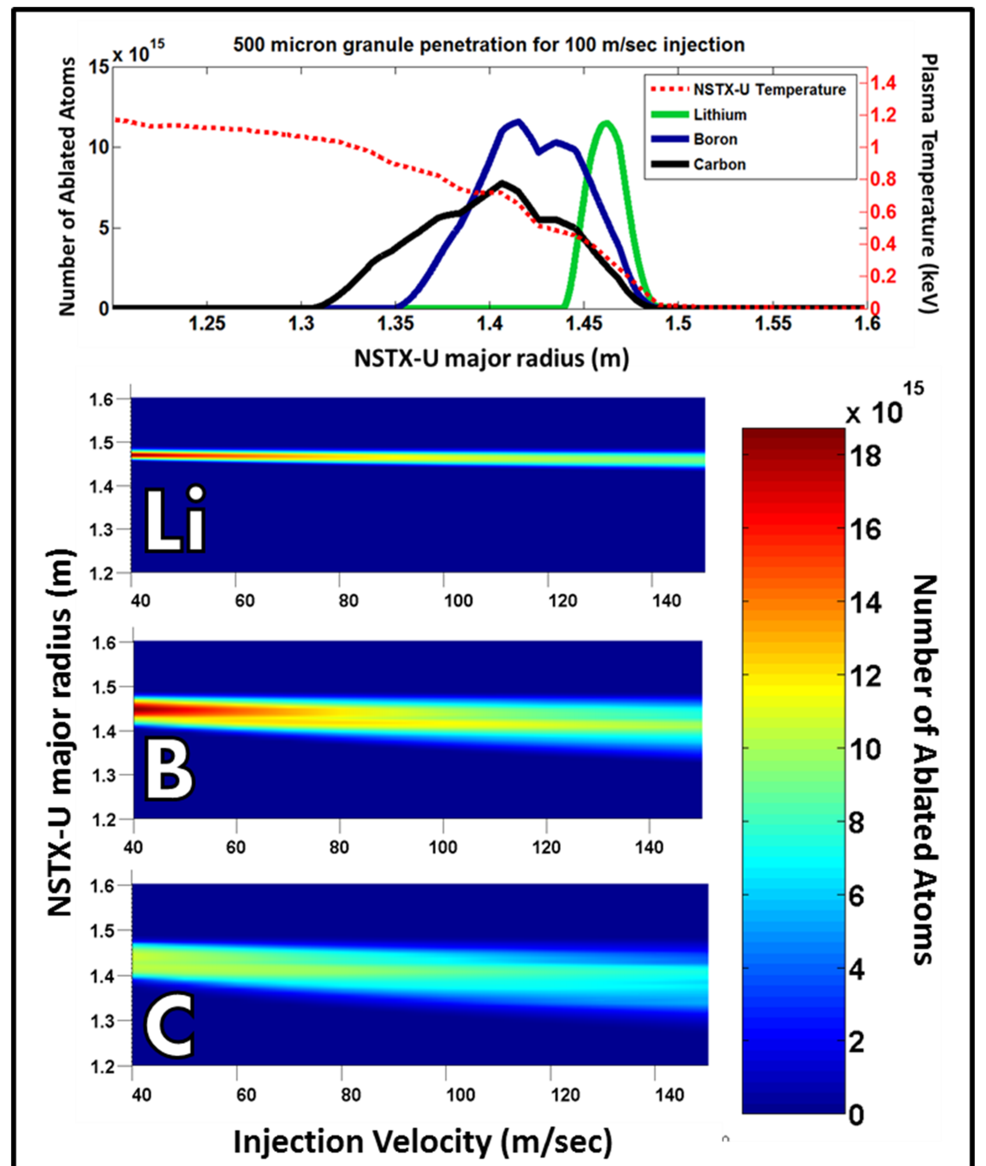
$$G = 4\pi q_s \eta \xi_g f_B$$

$$\xi_g = \frac{r_g^{\,2}}{n_g}\left[\Delta H + \frac{10}{3} T_S\right]^{-1}$$

Cloud shielding parameter (η) is calibrated using ablation time envelope from DIII-D injection experiments

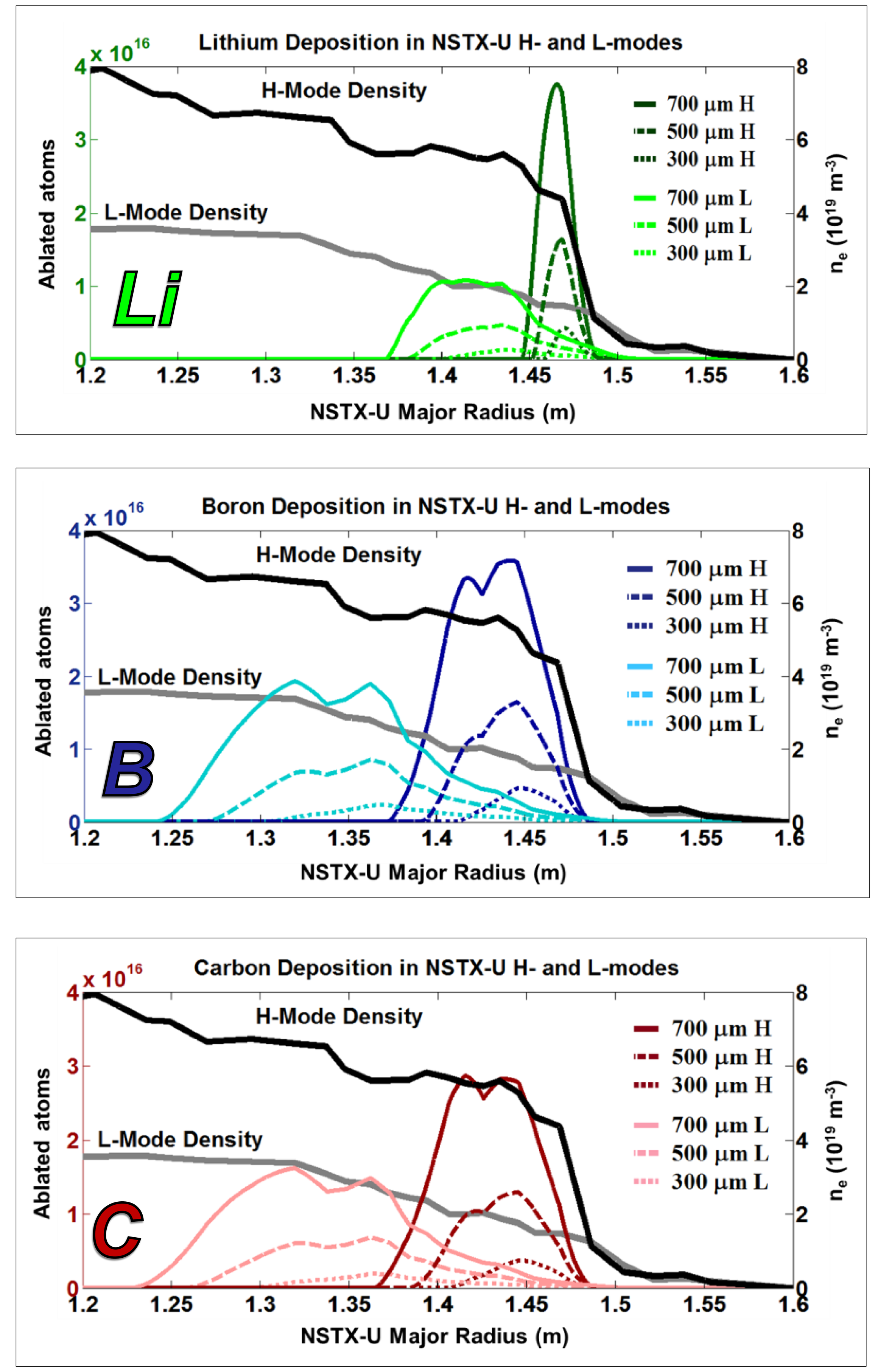
- r_g = Granule Radius
- n_g = Granule Density
- ΔH = Sublimation Energy
- T_C = Cloud Temperature ($T_C = 0.7T_S$)
- T_S = Surface Temperature (Granule Boiling/Sublimation Temp)
- M_C = Cloud Mach Number ($M_C = 1$, sonic flow)
- f_B = Field directed heating anisotropy and Flux screening parameter
- η = Cloud Shielding Parameter

Injection Velocity Scan of Calculated Ablatant Deposition Location



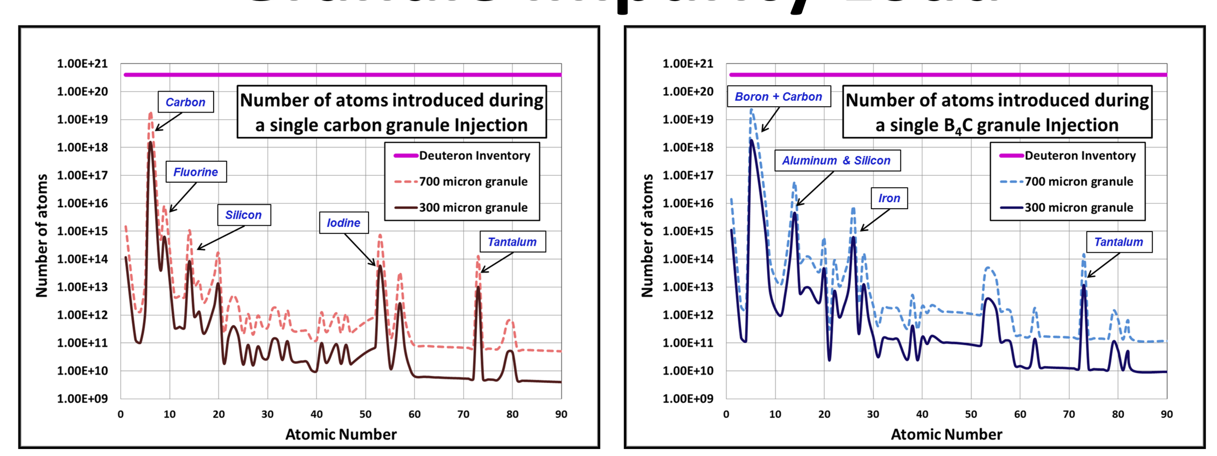
NSTX-U Granule Penetration Projections

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

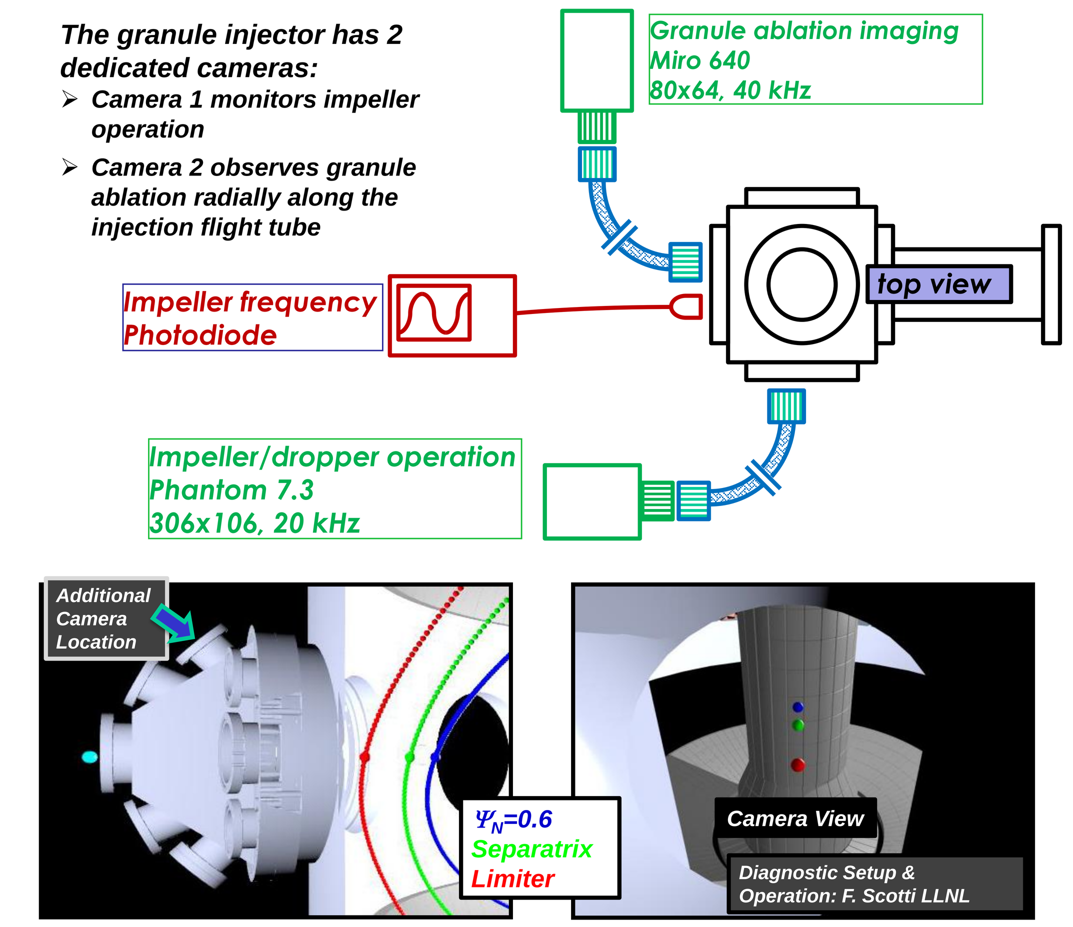


Simulations of multi-species granule injections of various sizes at 50 m/sec injection velocity.

Granule Impurity Load



Extended Ablation Imaging Suite



Additional cameras will be fielded on NSTX-U during LGI experiments through diagnostic collaboration with LLNL allowing direct measurement of injection velocity and penetration depth to validate NGS model.

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Granule Injector Uses in Next Step Devices

The Granule Injector is an extremely flexible tool for ELM pacing, edge physics, and impurity transport studies

- Triggered ELMs for impurity flushing in discharges with low natural ELM frequency
- High frequency pacing of ELMs for ITER (Beryllium Granules)
- Boron granule injection for steady state wall conditioning
- High-Z granule injection for impurity transport research

Upcoming Research

- Examine ablation rates and penetration depths of multiple granule species.
- High speed camera measurements of granule ablation and plasmoid formation. Compare to pellet ablation models.
- Compare characteristics of stimulated ELMs to spontaneous ELMs and MHD codes (JOREK, M3DC1).
- Determine minimum granule size, injection frequency and input velocity required for reliable ELM triggering.
- Monitor core impurity transport caused by granule instigated bursting in naturally ELM free lithiated discharges.

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