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Can Injected Lithium Granules Trigger ELMs?

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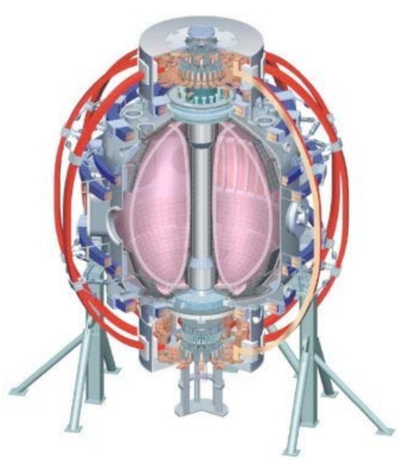


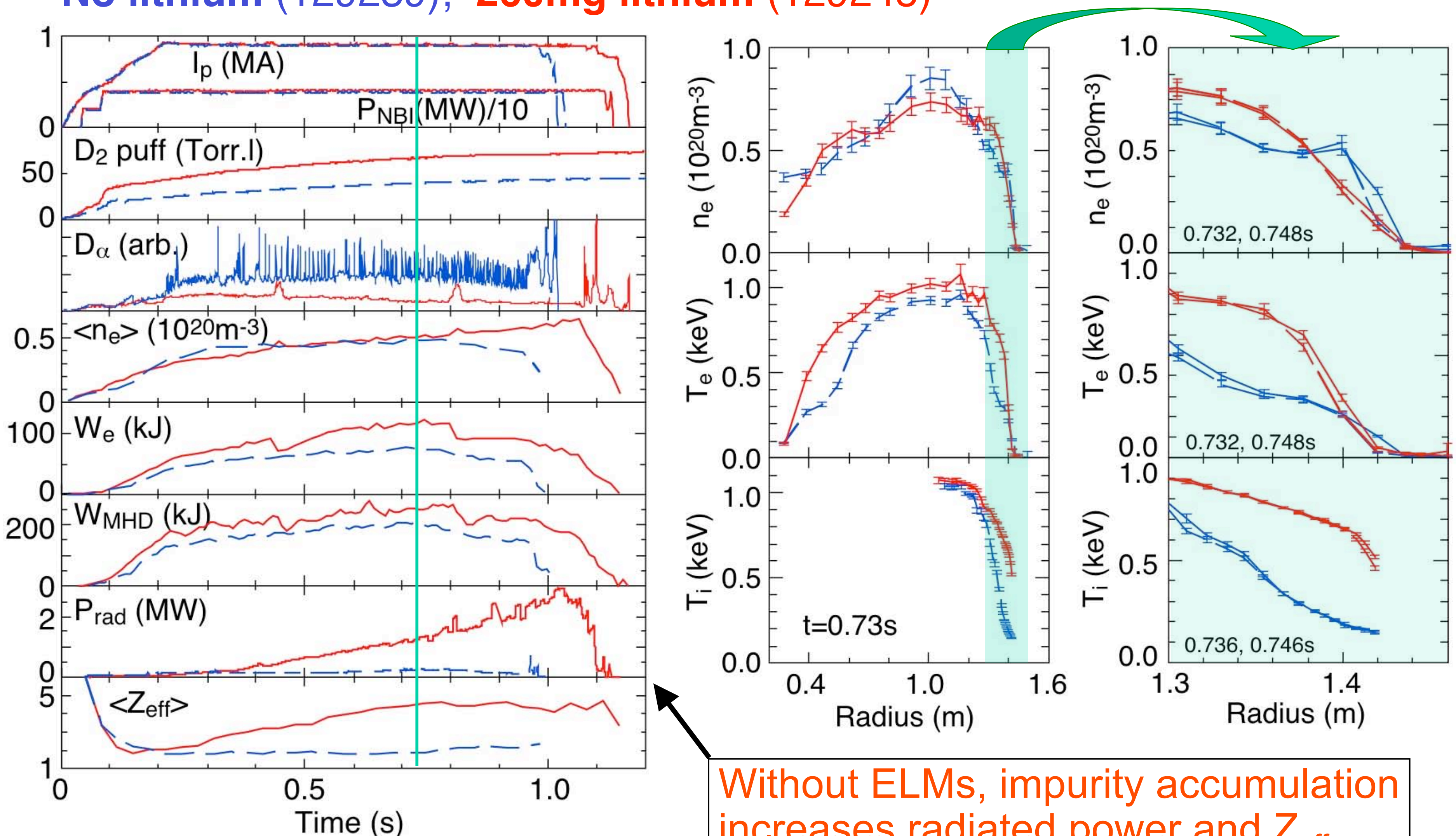
Introduction

- Large ELMs are a serious problem for ITER [1].
- Pacing by D pellets is a viable ELM mitigation technique on DIII-D.
- Li evaporated onto PFCs in NSTX eliminates ELMs but allows High-Z impurity accumulation [2,3]. (Fig 3)
- Hence there is an optimal ELM level: large and frequent enough to purge impurities, but not large enough to affect H-mode or damage PFCs.
- This work explores the possibility of pacing ELMs by high-frequency injection of small Li granules.

1. A. Loarte et. al. Plasma Phys. Control. Fusion **45** (2003) 15.
2. D. K. Mansfield et. al. J. Nuc. Mater. **390-391** (2009) 764.
3. R. Maingi et. al. Phys. Rev. Lett. **103** (2009) 075001.

Lithium Coating Reduces Deuterium Recycling, Suppresses ELMs & Improves Confinement in NSTX

No lithium (129239); **260mg lithium** (129245)

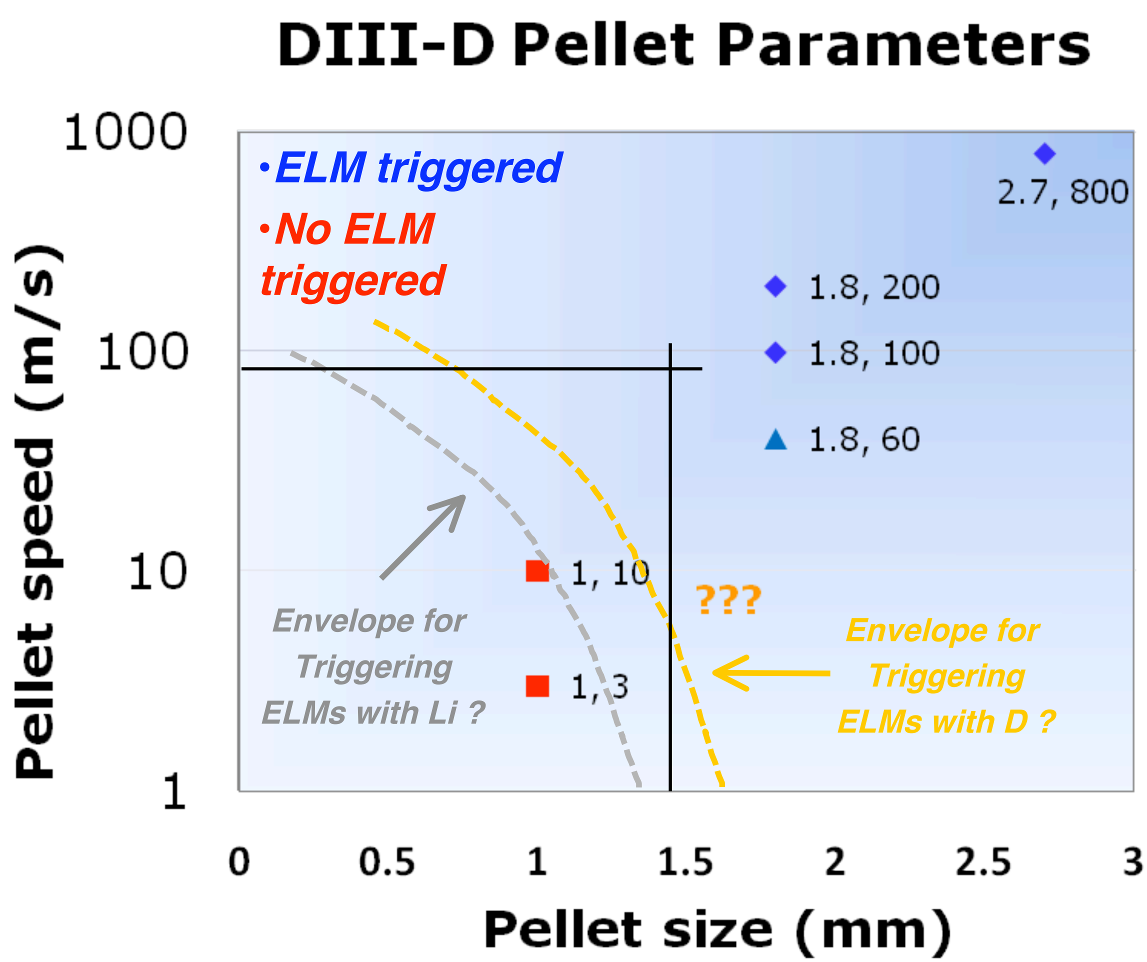


Without ELMs, impurity accumulation increases radiated power and Z_{eff}

H. Kugel, B. LeBlanc, R.E. Bell, M. Bell

Lessons Learned from Successful ELM Pacing Experiments on DIII-D using D Pellets

- DIII-D results indicate thresholds of D pellet sizes and speeds exist for reliable ELM pacing.
- A hypothetical curve is drawn by hand on the right indicating where a threshold boundary may exist. (shown in yellow)
- A second hypothetical curve for Li granules is shown (in grey). This curve is meant to indicate that lower speeds and small sizes may be needed with Li granule injection.
- The crossed lines indicate the chosen design parameters for the prototype Li impeller shown in Fig 9.

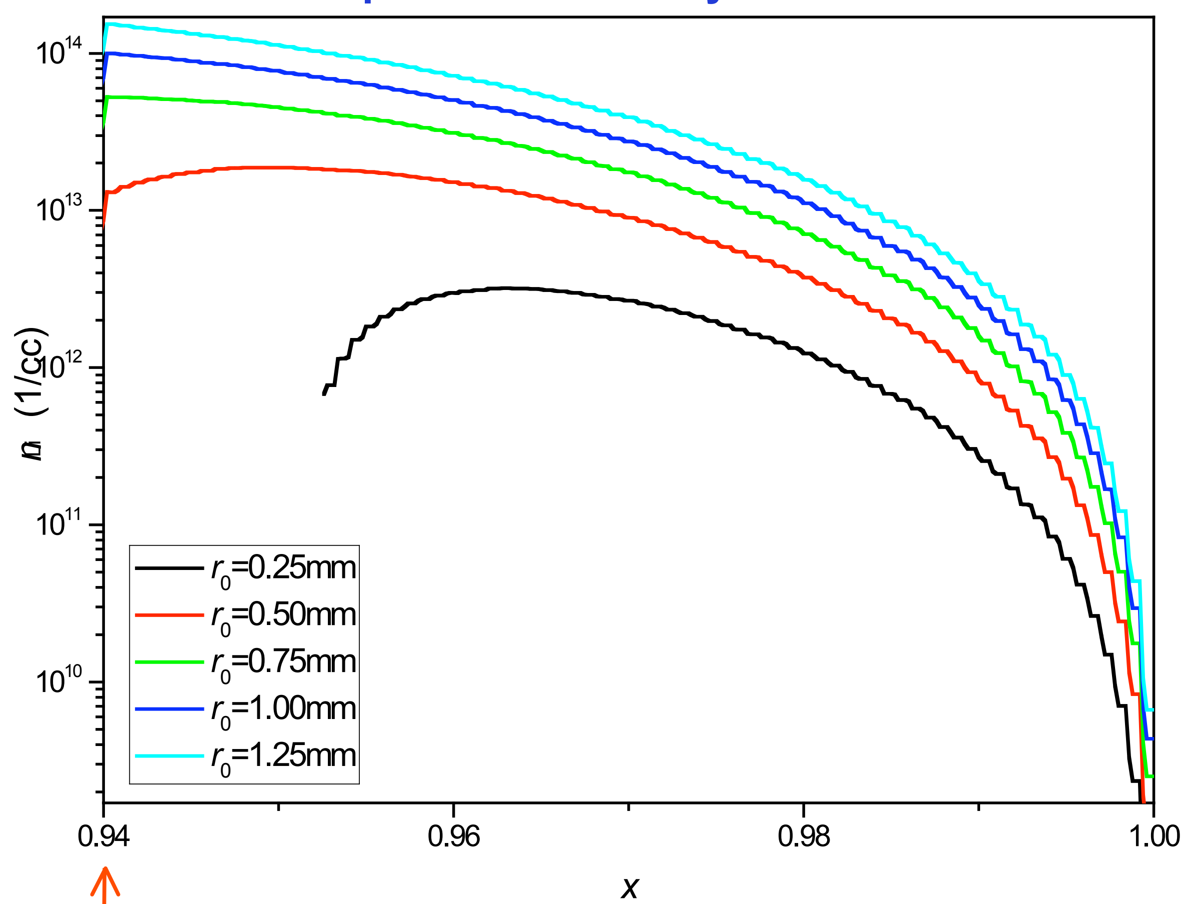


L. R. Baylor

Calculated Pedestal Deposition for 50 m/s Lithium Granules with Diameters from 0.5 to 2.5 mm

- **Linear temperature and density profiles assumed for pedestal:**
  - T_e (r/a = 1) = 0
  - T_e(r/a = 0.94) = 1 keV
  - n_e(r/a = 1) = 0
  - n_e(r/a = 0.94) = 5 x 10^{13} cm^{-3}
- **Reasonable approximation to DIII-D pedestal (R = 1.67 m, a = 0.65 m)**
- **Neutral Gas Shielding Ablation model for Li employed**
- **Li granules larger than d ~ 1mm penetrate well beyond the pedestal at 50 m/s**

Deposited Li Density vs r/a

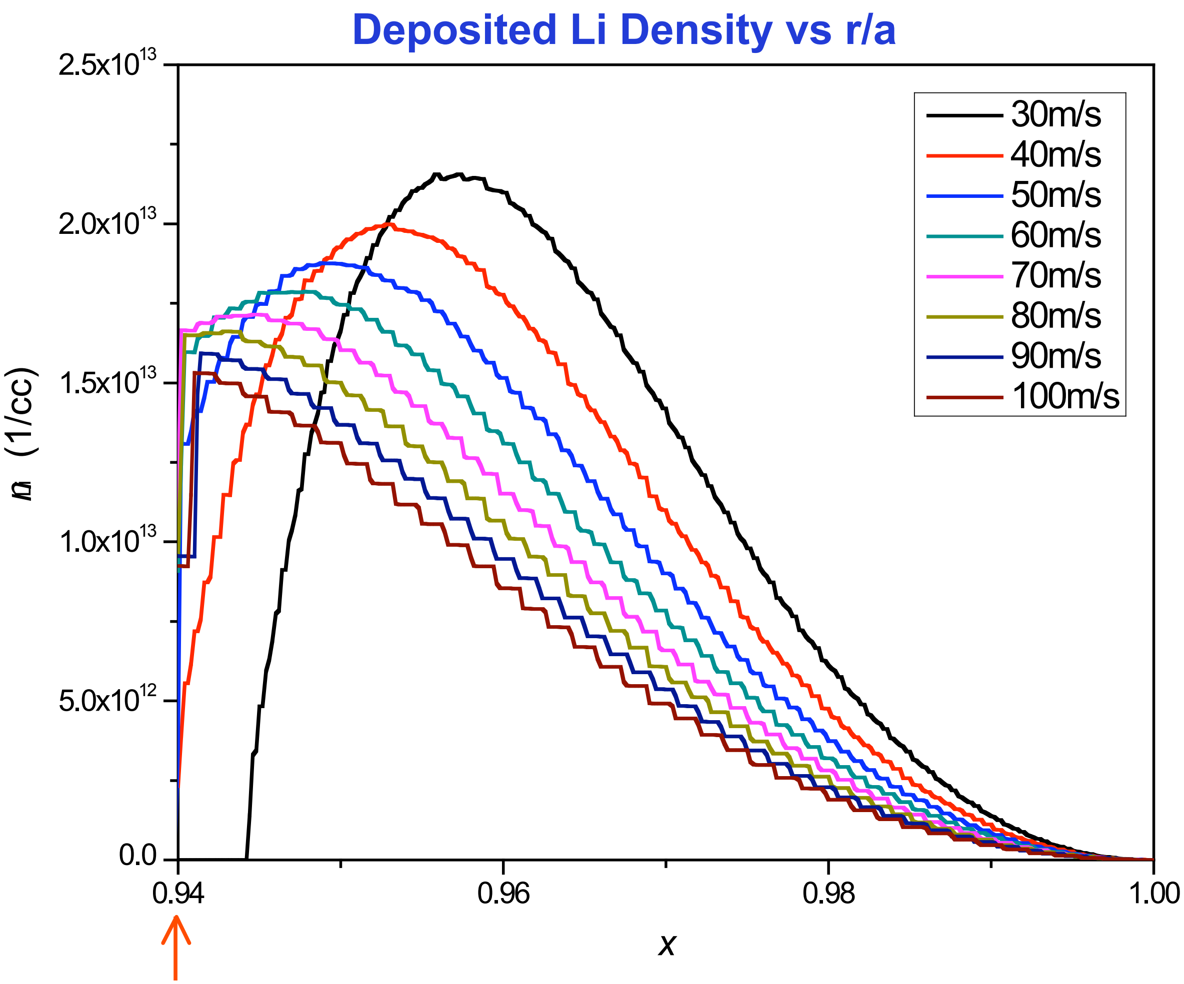


Top of Pedestal

Paul Parks, Wen Wu

Calculated Pedestal Deposition for 1 mm Li Granules with Injection Speeds from 30 to 100 m/s

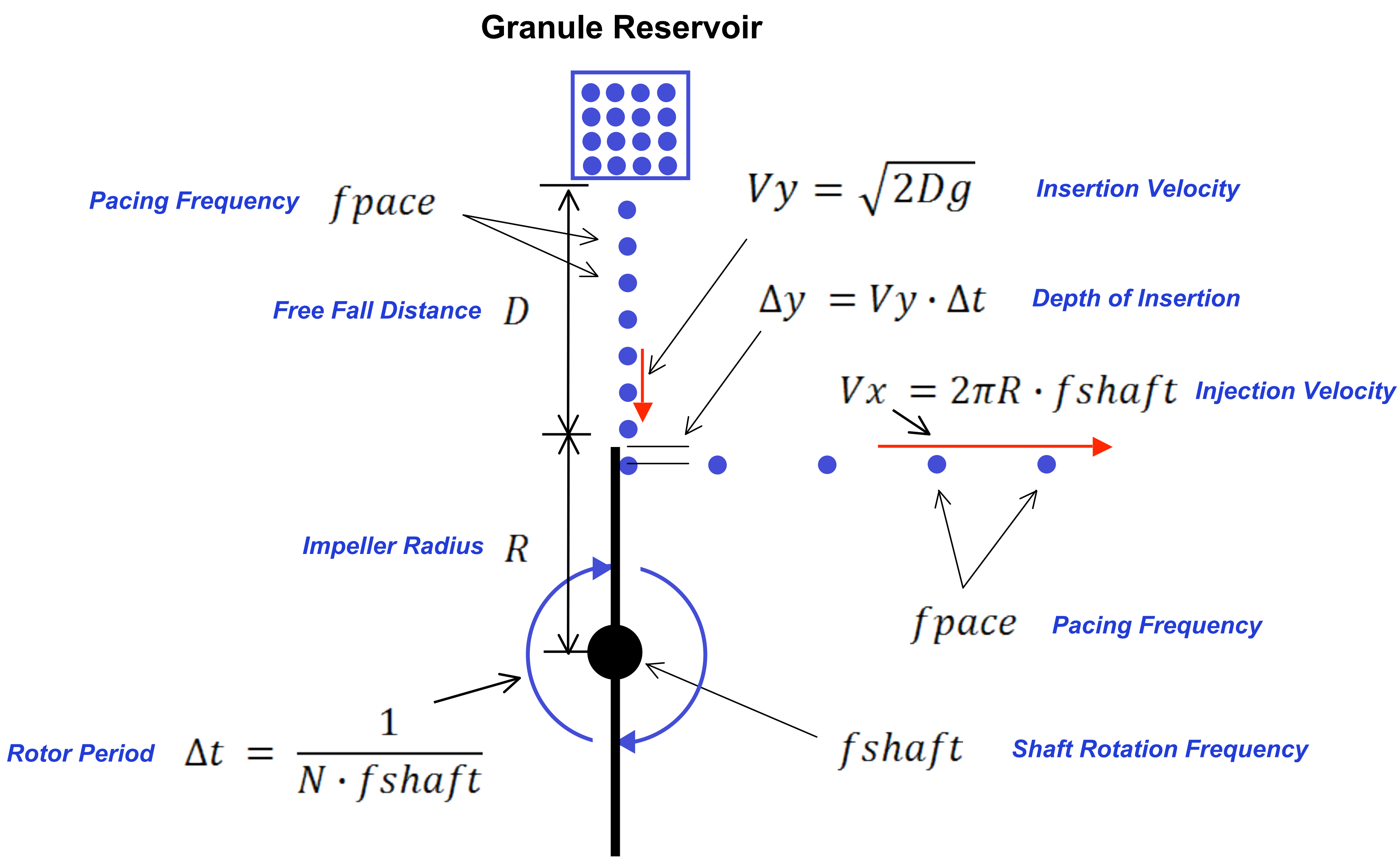
- **Linear temperature and density profiles assumed for pedestal:**
  - **T_e (r/a = 1) = 0**
  - **T_e(r/a = 0.94) = 1 keV**
  - **n_e(r/a = 1) = 0**
  - **n_e(r/a = 0.94) = 5 x 10^{13} cm^{-3}**
- **Reasonable approximation to DIII-D pedestal (R = 1.67 m, a = 0.65 m)**
- **Neutral Gas Shielding Ablation model for Li employed**
- **Results similar to D pellet ablation which does trigger ELMs on DIII-D**



Top of Pedestal

Paul Parks, Wen Wu

The Scheme: Redirecting a Regular Stream of Falling Lithium Granules with a Rotating Impeller



Choice of Prototype Design Parameters

- Assume Li granule diameter (from Figs 5 & 6): d = 1mm
- Assume granule injection velocity (from Figs 5 & 6): Vx = 60 m/s
- Assume shaft rotation frequency: *fshaft* = 167 Hz (10,000 RPM) (reasonable value for commercial rotary feed thru)
- Design for an Injection efficiency φ ~ 95%*
- The choices above constrain both impeller radius and fall distance:

  R = 60 mm D = 0.37 m

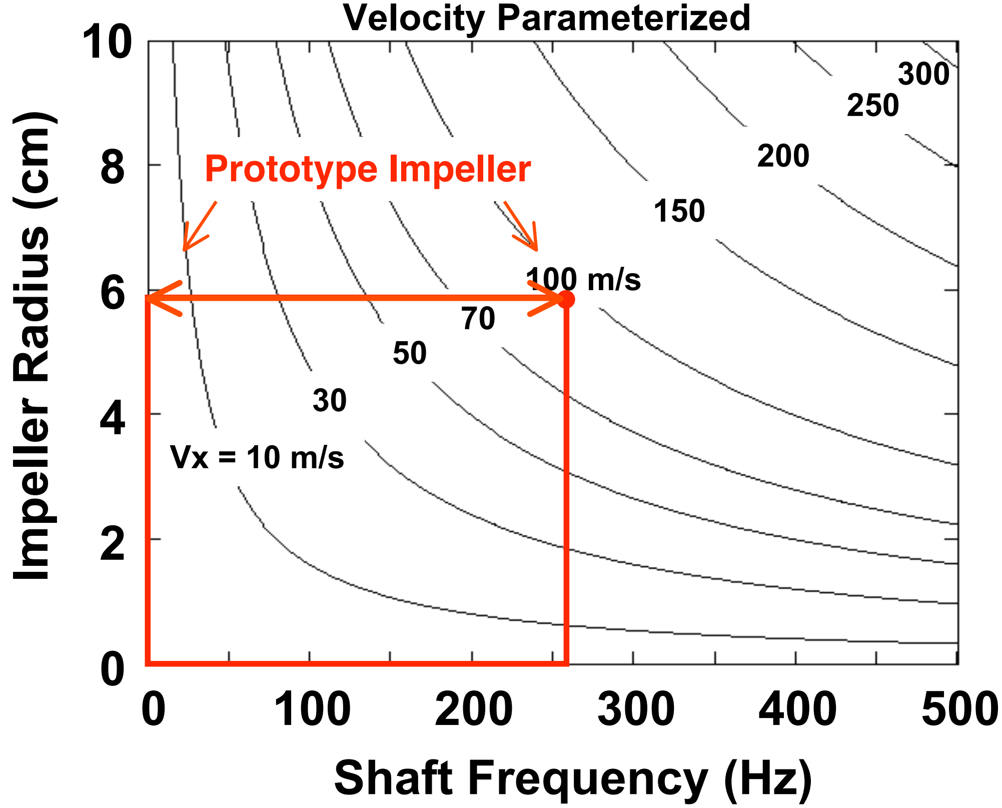
* See Fig 15 for an explanation of injection efficiency φ.

A Reasonable Range of Impeller Parameters and Those Chosen for the Prototype Impeller

Design Considerations

- **Maximum impeller radius of 10cm allows hardware to remain “compact”.**
- **Max f_{shaft} = 500 Hz achievable with commercial vacuum feed-thrus.**
- **Using the max parameters above, V_x = 300 m/s can be achieved.**
- **The red area envelopes the NSTX prototype impeller parameters.**
- **f_{shaft} up to 260 Hz and speeds up to 95 m/s for impeller radius 6 cm have been achieved.**

Impeller Radius vs Shaft Frequency with Velocity Parameterized



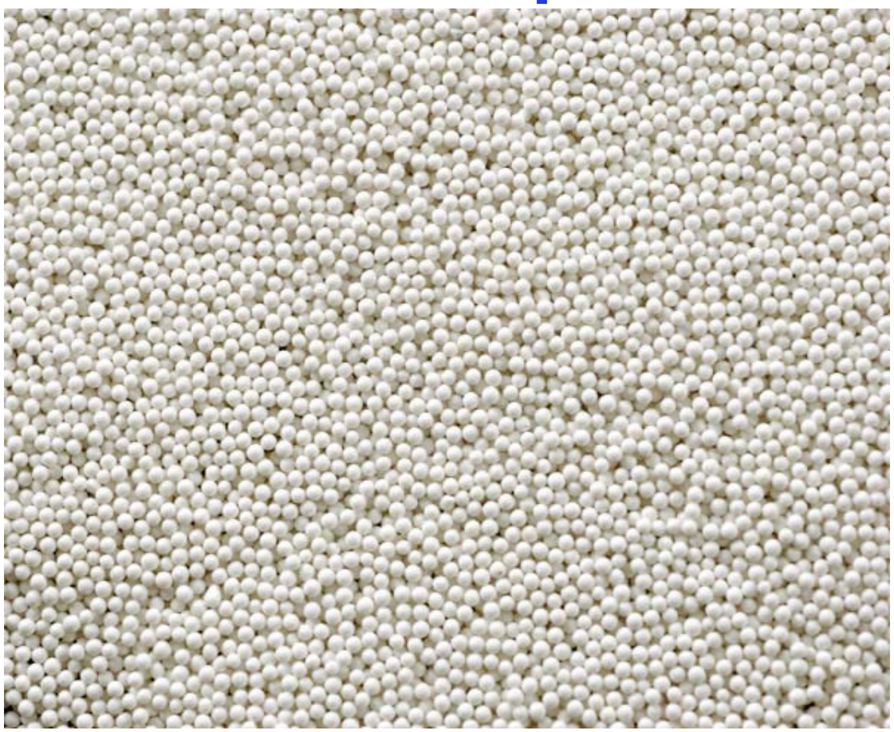
$$Vx = 2\pi R \cdot fshaft$$

Injection Velocity — *Impeller Radius* — *Shaft Rotation Frequency*

1 mm (Nominal) Surrogate Porcelain Spheres & Unscreened Commercial Lithium Granules

- Presently using porcelain spheres – will soon use screened Li granules

Porcelain Spheres

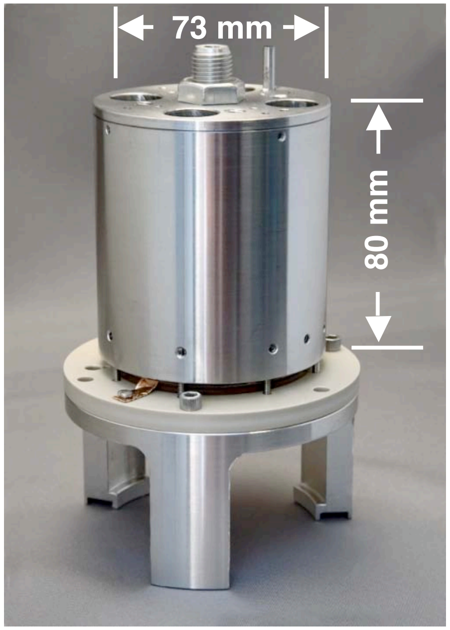


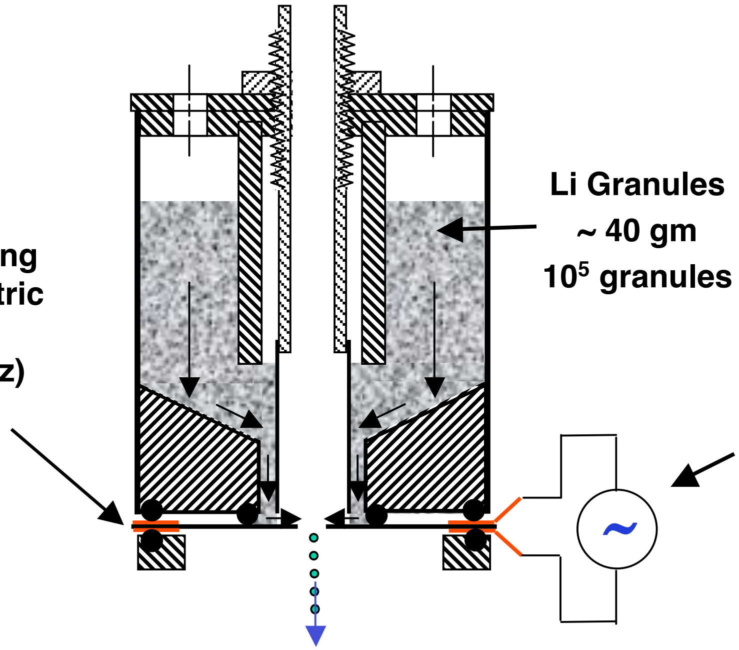
10 mm

Lithium Granules

10 mm

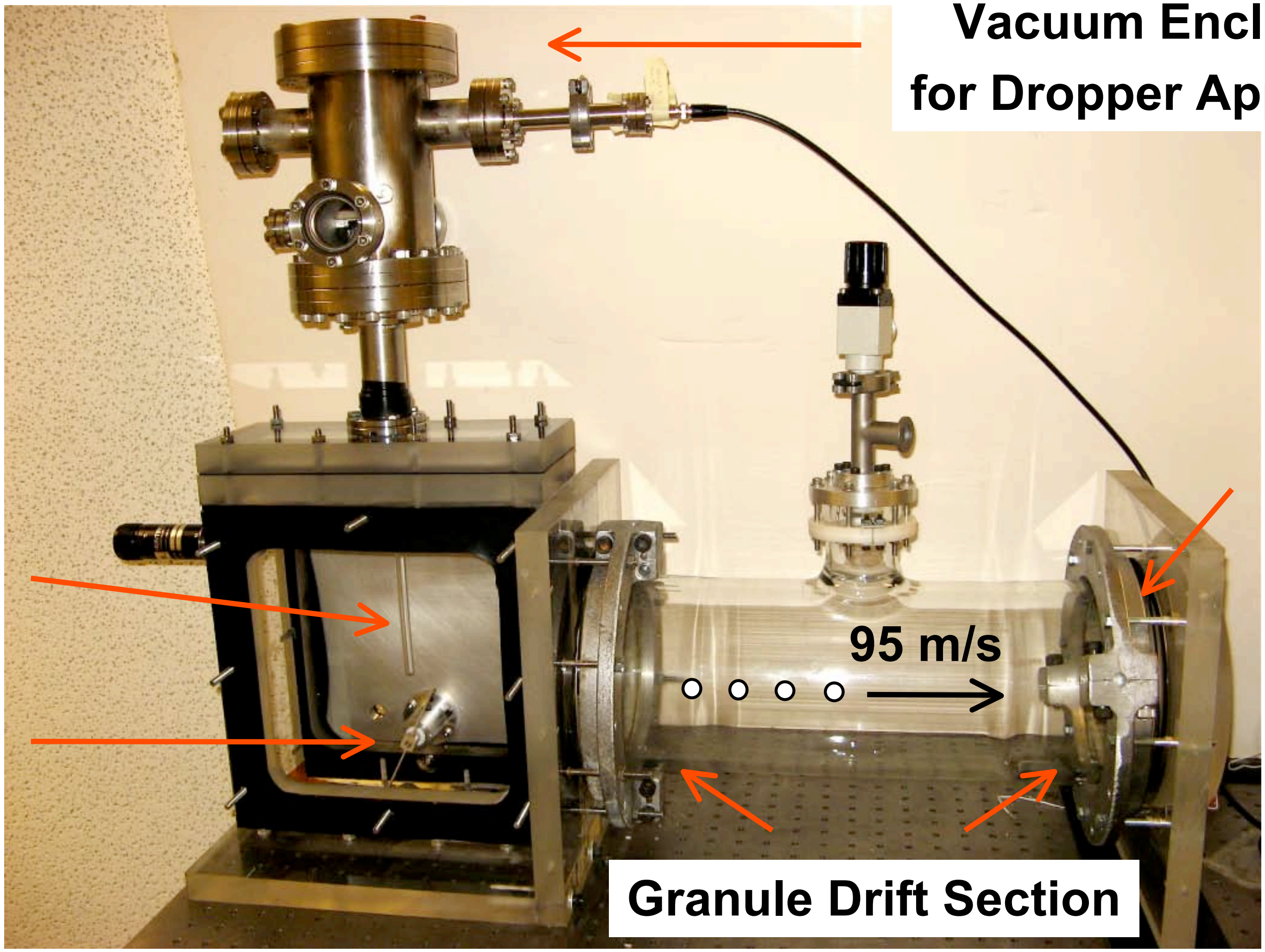
The Li Granule Dropper Apparatus (Unsynchronized)





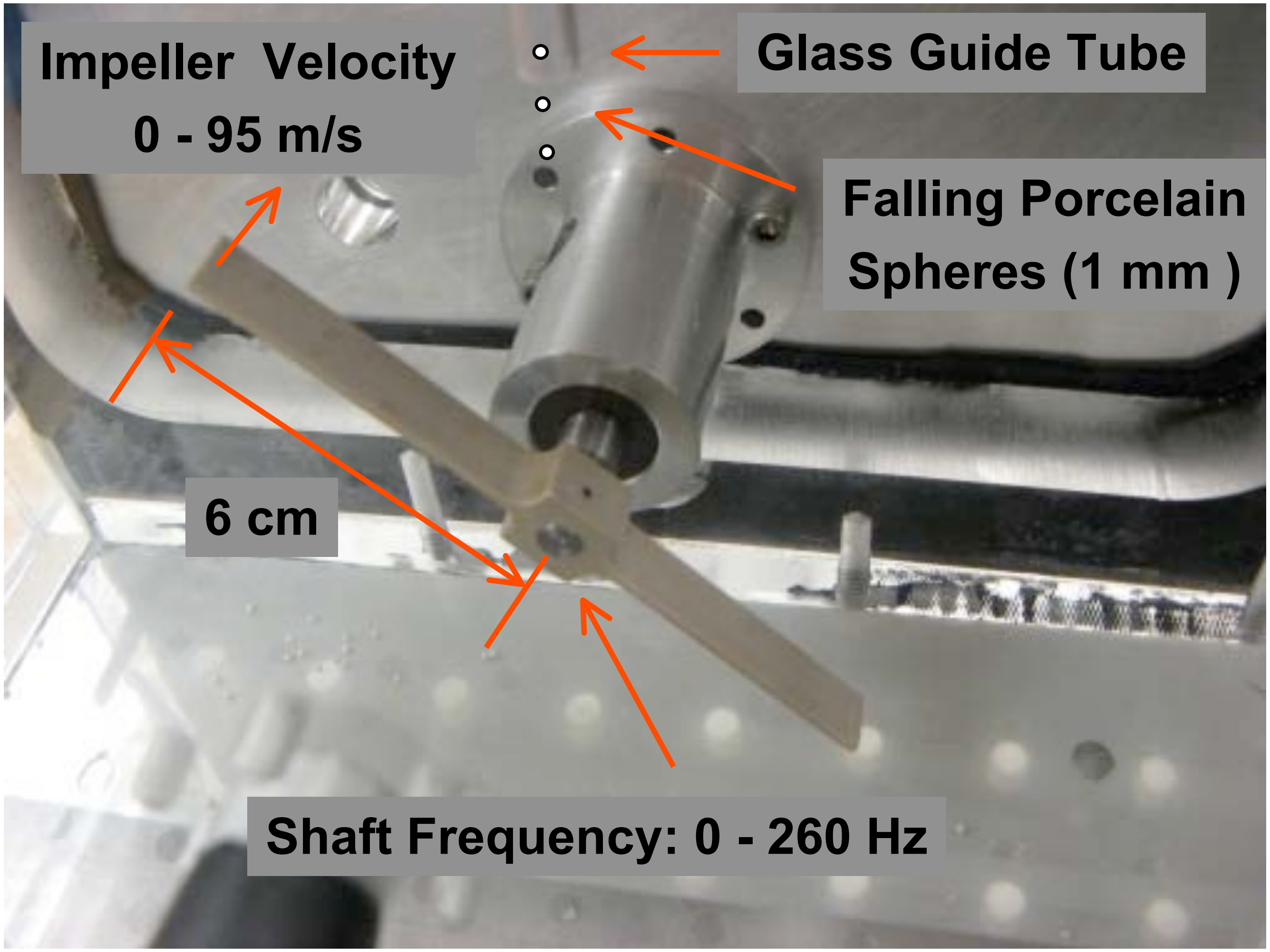
- Hardware also has been used to drop Li powder in NSTX
- 1 mm spheres can be dropped at average frequency 0 - 70 Hz depending on voltage applied

The Prototype Li Granule Injector Test Station



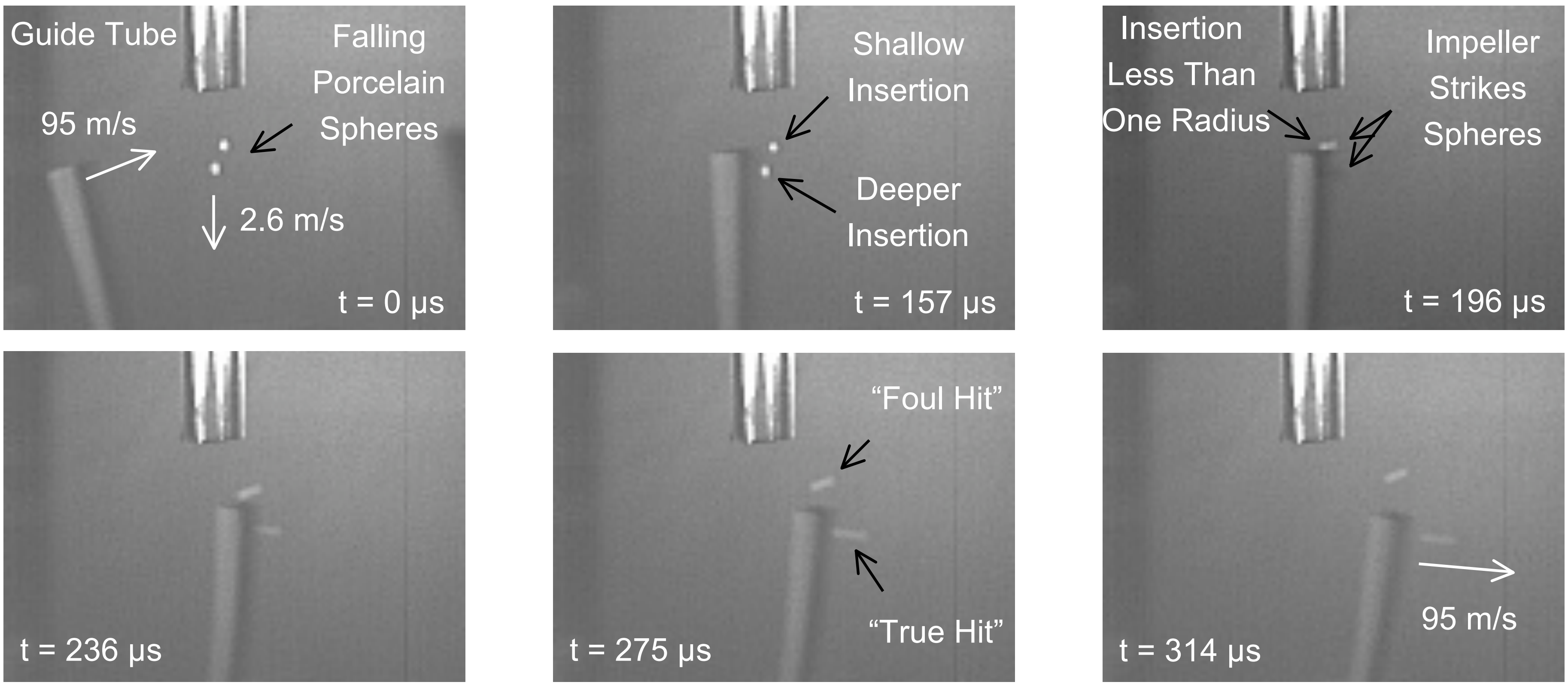
The Prototype Impeller:
Material: “Peek”, Radius: 6 cm, Velocity 0 - 95 m/s

- Presently driven by small electric motor – eventually to be driven by air motor



Video Example of Inefficiency Owing to a Lack of Synchronization Between Falling Spheres and Impeller

- Two unsynchronized granules dropping into a rotating impeller with different insertion depths.
- The granule falling less than one radius receives a “foul hit” and is lost to the injection process.
- The granule penetrating more than one radius receives a “true hit” and is injected at 95 m/s.



Injection Efficiency

- We define injection efficiency (φ) as ratio of “true hits” to total number granules inserted per time. (See Fig 14 for definition “true” vs “foul” hits).
- “True” hit rate + “Foul” hit rate = Total granule insertion rate.
- For fixed shaft frequency and granule size, ϕ depends only of the fall distance D:

$$\varphi \sim \left(1 - \frac{fshaft \times granule\, dia}{\sqrt{2Dg}}\right)$$

- If D is large enough to allow deep gravitational insertion between impeller passes (~ 10 granule diameters) then ϕ ~ 95%.
- The prototype impeller system is designed for ϕ ~ 95% (i.e. D = 0.37 m).
- With future synchronization, ϕ ~ 100% is possible at smaller D.

Previous Experience with Clumps of Lithium Powder Injected into the NSTX SOL

- A few clumps of Li powder were *inadvertently* dropped into NSTX in 2008 during commissioning of a Li powder dropper system.

- These events were captured using a high-speed color camera.

- A speed of ~ 5 m/s and size of ~ 2mm is assigned to these "granules/clumps"

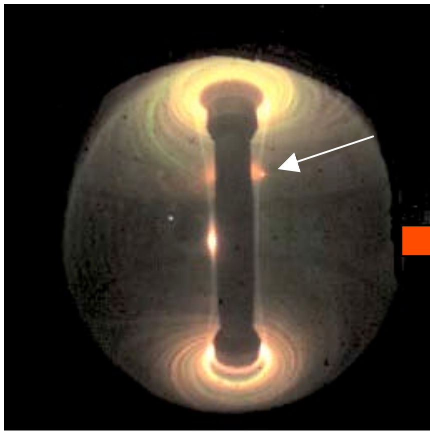
- Four examples of are displayed in Fig #.

- The first three are not ELMs. The last one is an ELM.

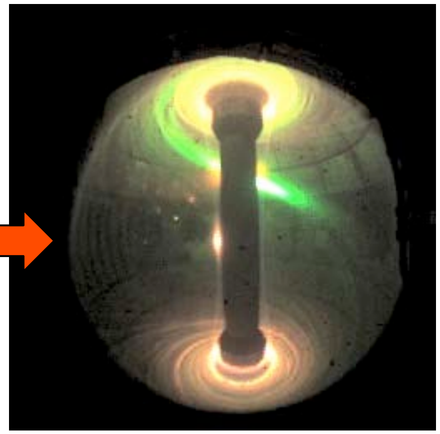
- We thus have one example of a Li "granule" that appears to trigger an ELM.

Examples of Edge Perturbations from Low-Velocity (~5m/s) Lithium Granules (~2mm) in Four Discharges (2008)

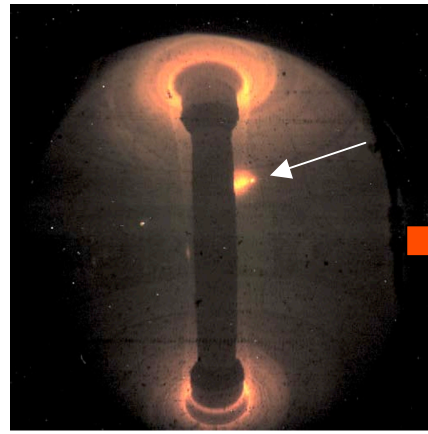
135064 @ 272 ms



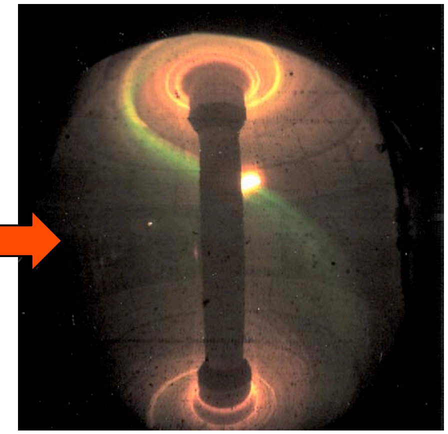
135064 @ 280 ms



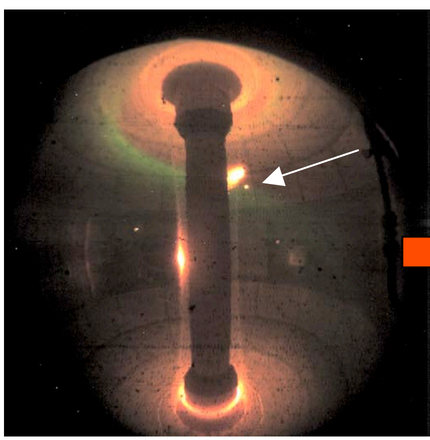
130389 @ 353 ms



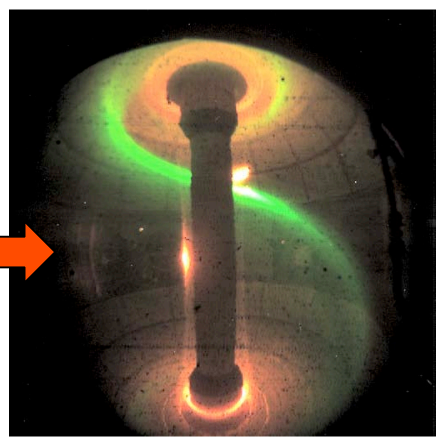
130389@ 356 ms



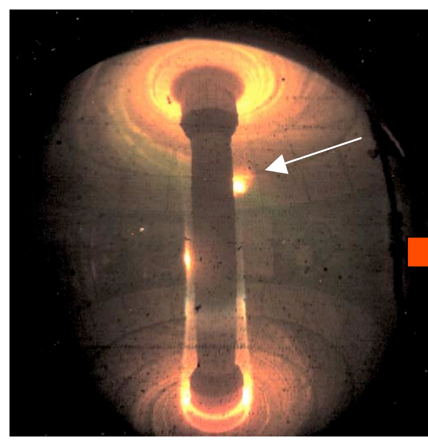
130387@ 191 ms



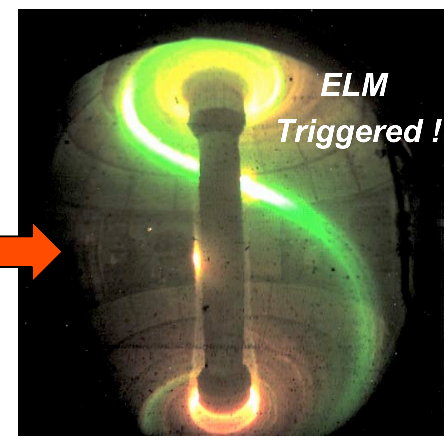
130387 @ 197 ms



130385@ 393 ms



130385 @ 400 ms



LiD is Another Interesting Candidate for ELM Pacing

Physical Properties of D, Li and LiD

	Mass Density (gm/cm^3)	Atomic Density ($10^{22}/cm^3$)	Electron Density ($10^{22}/cm^3$)	Melting Temp (°K)	Boiling Temp (°K)
D	0.20	6.0	6.0	18.6	23.6
Li	0.52	4.5	13.5	454	1615
LiD	0.82	5.5	22	969	N/A*

- **For the same size granule/pellet, Li (LiD) ablates 2.25 (3.66) times as many electrons as D.**

* In vacuum, LiD dissociates before it boils

Summary

- A prototype impeller has been shown to inject ~ 1 mm Li granules at speeds to ~ 95 m/s with average "pacing" frequencies in the range 0 - 70 Hz.
- The unsynchronized injection efficiency is in the range of 90 - 95 % .
- At present, 1 mm porcelain spheres (5 x heavier than Li) are being used in lab tests.
- Any size granule up to ~ 2.5 mm would be viable using the dropper system presently employed [4].
- Modeling of Li ablation in a DIII-D type pedestal indicate that Li is a reasonable candidate to trigger ELMs
- The next step in development will be to replace the porcelain spheres with Li granules.

[4] D. K. Mansfield et. al. Fusion Eng. and Design. (accepted for publication)