Continuation of Li Aerosol Injection Experiments on NSTX

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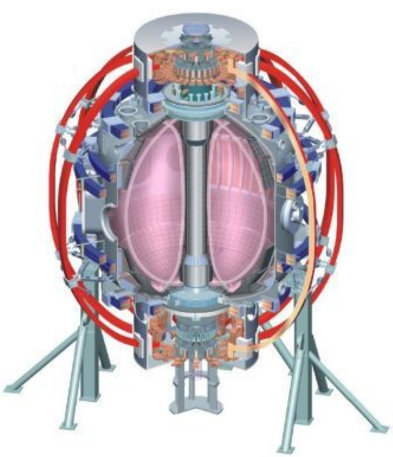

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Abstract

- During the 2009 NSTX run campaign, efforts continued to develop a system capable of injecting a lithium aerosol into the NSTX scrape-off layer in real time. To that end, two devices which simply drop spherical lithium powder particles (44 micron diameter) in a controlled manner were installed on NSTX. After an initial success with a single dropper during the 2008 campaign, the first use of a dual dropper system has been encouraging. Lithium fluxes in the range of 70 - 170 mg/s have been well tolerated by 950 kA discharges with 4 MW NBI heating. This lithium flux corresponds to 3 $x10^6$ - 6 $x10^6$ aerosol droplets/sec and is stoichiometrically equivalent to 90 - 220 Torr L/s of D_2.

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Introduction

- A simple device has been used to introduce a Li aerosol into NSTX discharges. Fluxes up to ~170 mg/s were injected into the NSTX SOL without trauma to the NBI-heated discharges.

- Using high speed videos, individual aerosol particles have been seen to persist for 5 – 50 ms in the SOL.

- Upon evaporation and ionization, Li ions introduced into the SOL follow open field lines and implant into the NSTX carbon divertor surfaces where they appear to reduce recycling, improve energy confinement and frustrate core impurity build-up.

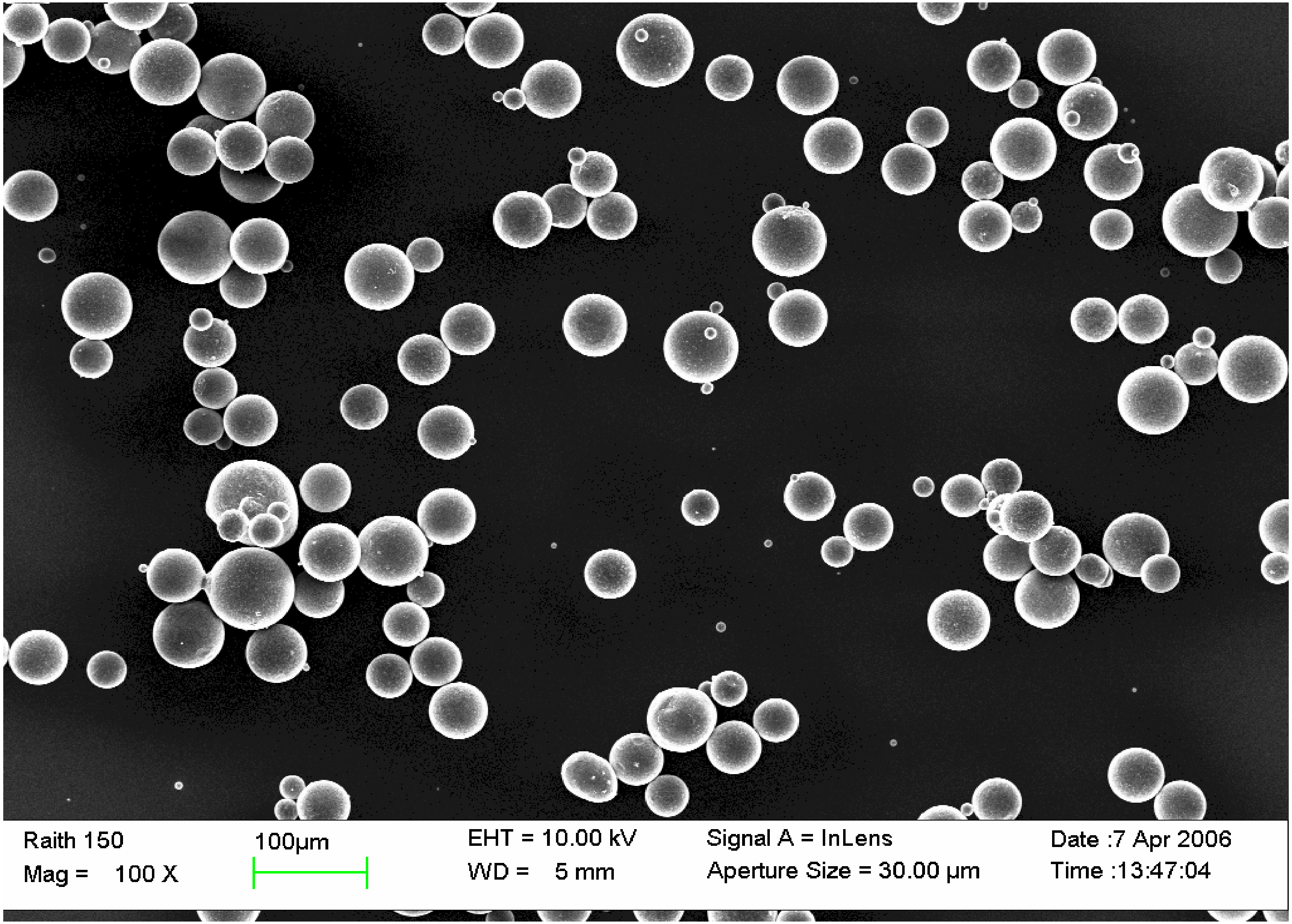
- The injected lithium has led to H-mode discharges with reduced Ohmic flux consumption, increased energy confinement, broader current distributions, higher Te and Ti, higher neutron emission and lower central impurity accumulations as compared to discharges without lithium.

- These results are similar to those reported concerning aerosol injection in TFTR[1]. Further, this technique compares reasonably well with evaporation from the NSTX dual LITER system[2].

The Solid Aerosol Employed – Li Powder

- The lithium aerosol employed is supplied by FMC Corporation and has been trade marked as SLMP™ – Stabilized Lithium Metallic Powder™.
- Each spherical particle (average diameter ~ 44 μm) is stabilized against incendiary reaction with air by a ~ 40 nm mantle of microcrystalline lithium carbonate. The resulting particles are 98.5% Li and 1.5% Li_2CO_3 by composition. A SEM image of the aerosol particles is shown in Fig 4.
- A second type of powder protected by ~ 40 nm of long chain paraffin (< 0.01% CH_2) is presently under investigation as a candidate aerosol for use on NSTX.
- Aside from being stabilized, it is important to note that both powders are *designed to flow*. This feature makes piezoelectric manipulation of the lithium possible.

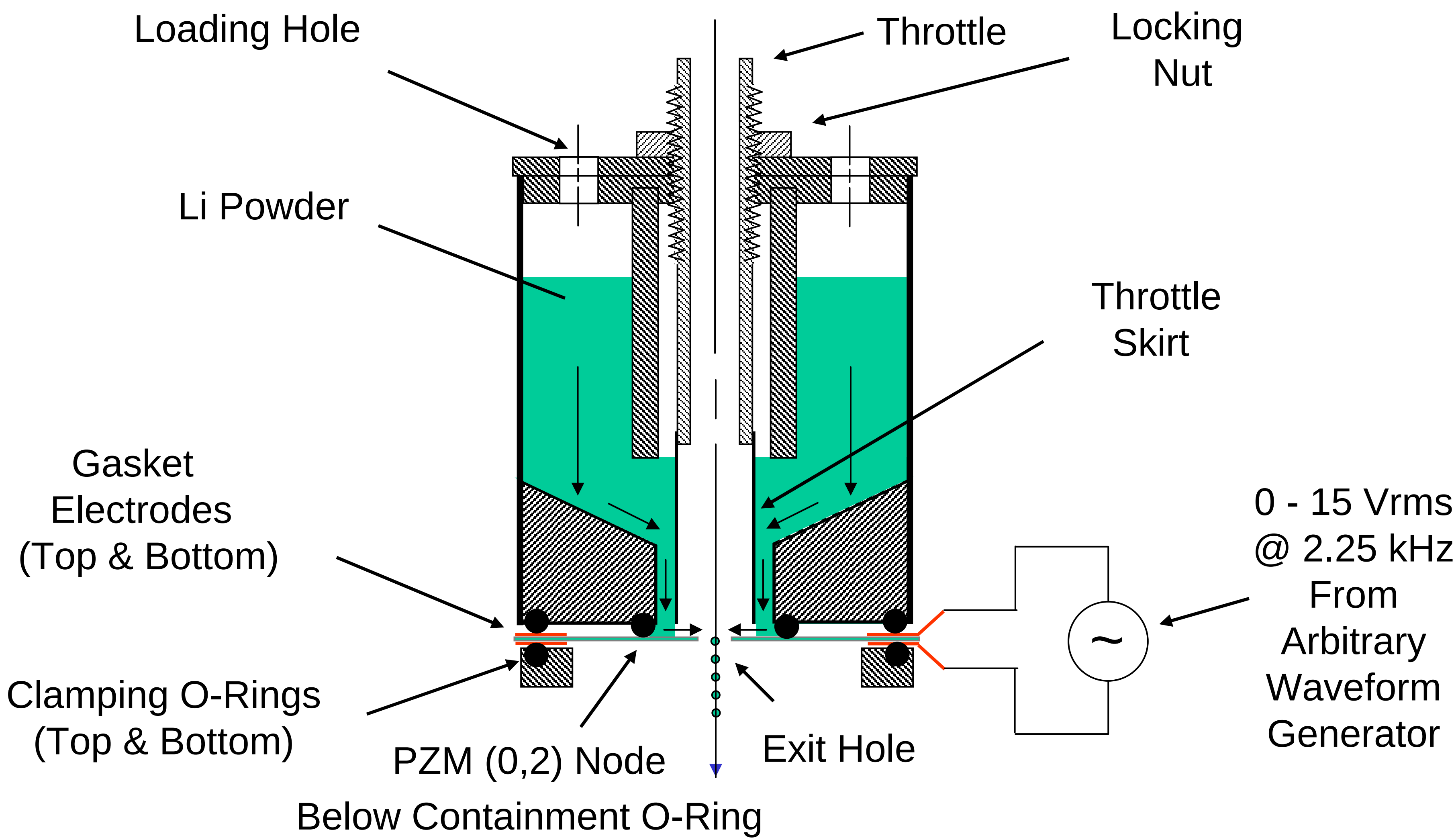
SEM Image of FMC Stabilized Metallic Lithium Powder (SLMPTM)



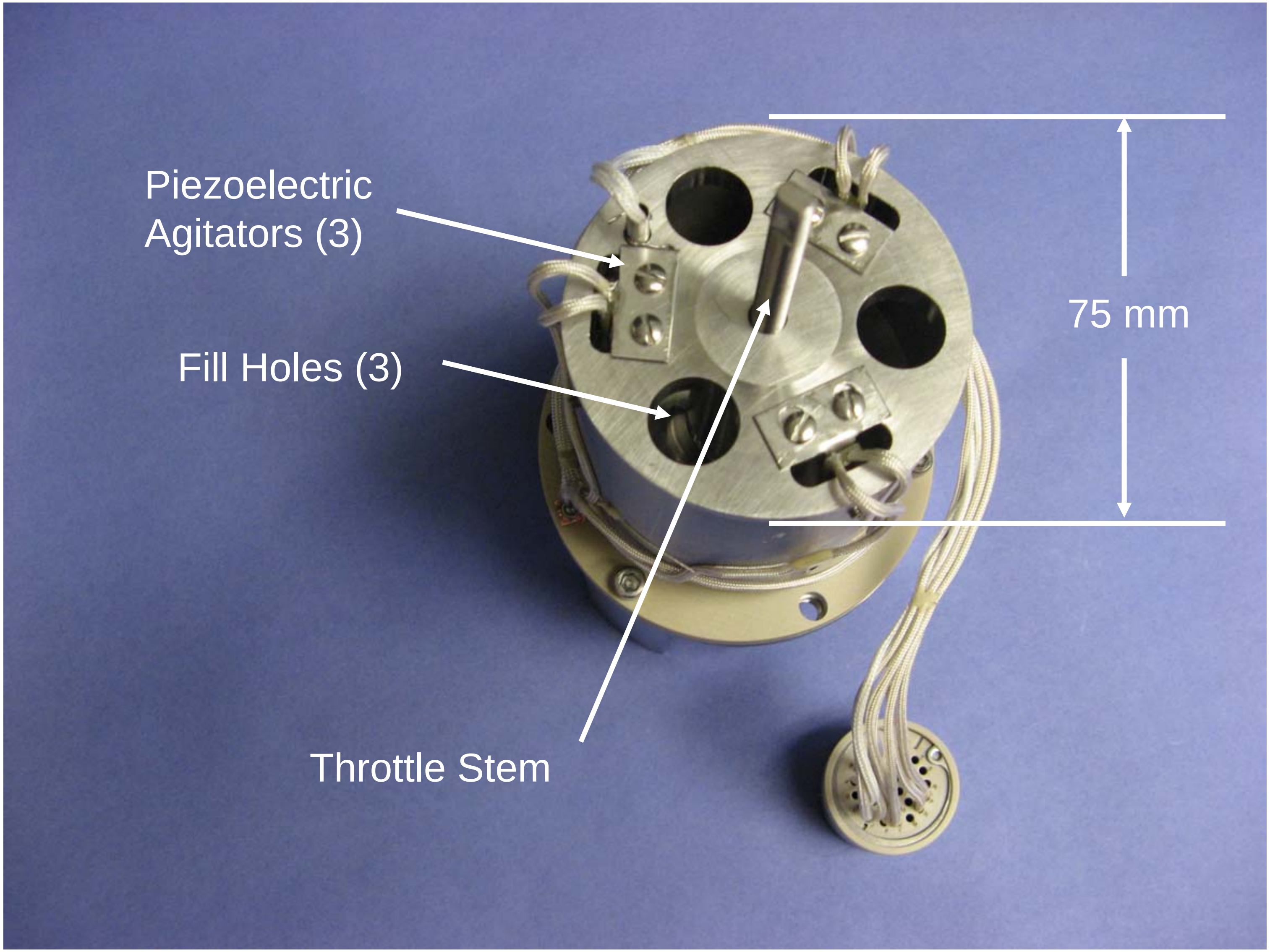
The Aerosol Injection Hardware (Dropper)

- The hardware appears in Figs 7 & 8. The heart of the device is a circular piezoelectric membrane (PZM) with a 2.5 mm diameter hole at its center. The PZM resonates in the (0,2) drumhead mode. Particles flow onto the PZM from a reservoir located above. They then diffuse inward to the hole when the membrane is driven at resonance (2.25 kHz).
- Timing and modulation of the droplet flux is controlled by an arbitrary waveform generator operating at 2.25 kHz. Amplitudes of 1 to 15 Vrms were typically used to drive the PZM in the experiment. Although flux modulation (up to 10 Hz) is possible, in these experiments the flux rate was fixed during a discharge.
- The locations and trajectories of the two droppers/injectors are shown in Fig 9. By changing the injection timing, essentially all NSTX locations were accessible to the lithium droplets.

A Schematic of the Dropper / Injector



Top View of Injector/Dropper Assembly

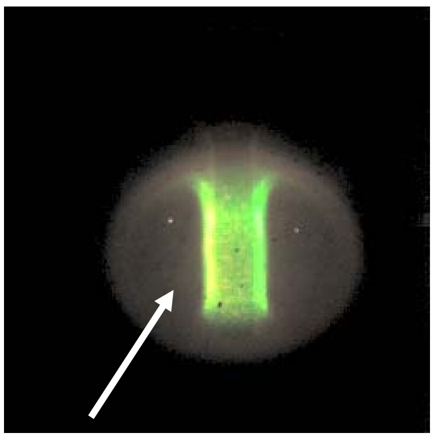


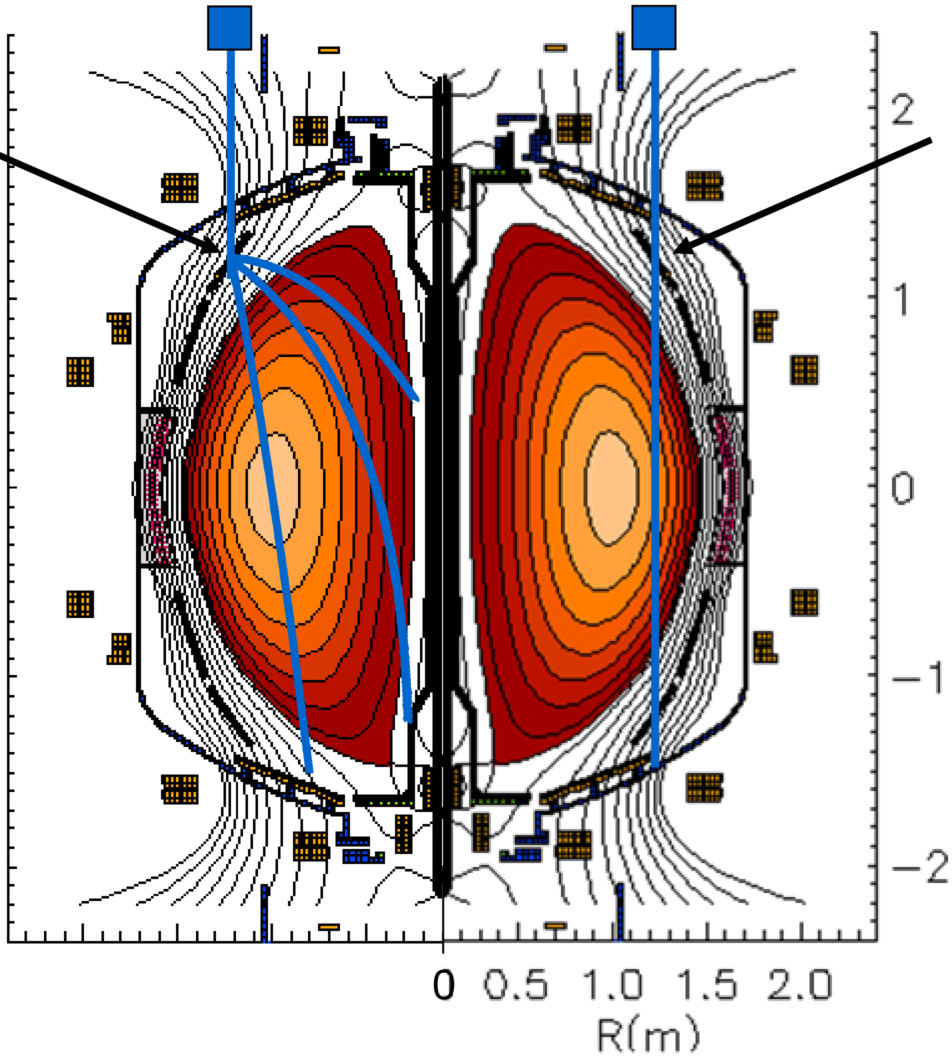
Li Dropper Locations and Trajectories on NSTX Allow a Variety of Injection Scenarios

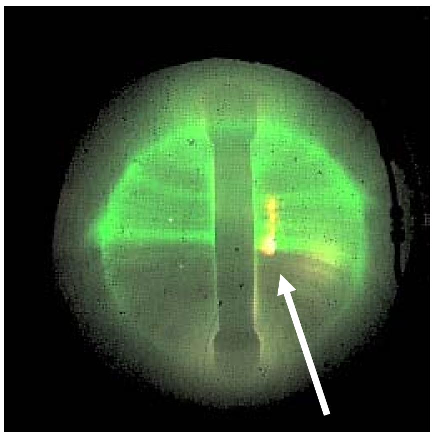
Bay C Dropper | **Bay I Dropper**

Particles Scatter off Splash Plate (45 degree)

Particles Drop Straight Down Into SOL







Li Droplets on NSTX Center Stack at Breakdown Using Bay C Unit

Li Droplets Into Plasma SOL at t = 25 ms Using Bay I Unit

The Experiment

- Injection of Li aerosol was accomplished successfully into 0.95 MA, lower-single-null, H-Mode discharges heated with 4 MW of NBI. Data traces from these discharges are displayed in Figs 11 and 12. Some High speed video images of one of these discharges (135063) are shown in Figs 13 - 16. The timing of the videos with respect to the data is indicated by red vertical lines in Fig11.

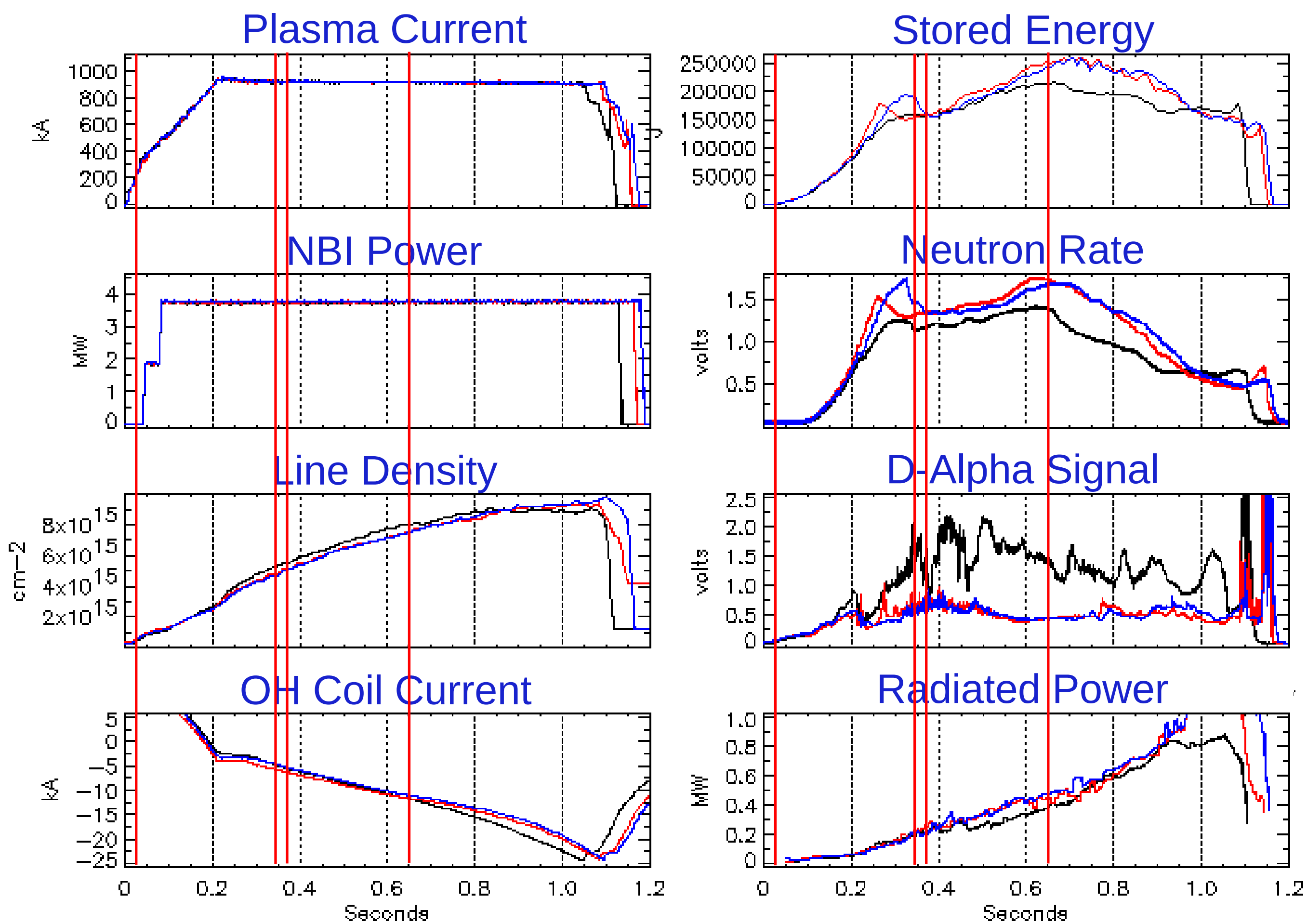
- Because the lower divertor had not been pre-treated with Li from the LITER system, some ELM activity was observed just after the H-mode transition in 135063. This activity was eliminated in real time, however, as more Li was accumulated from the aerosol deposition.

- As the ELMs disappeared, a crisp green (Li^{+1} radiation) edge appeared and correlated with a rise in the measured neutron rate while not exhibiting an increase in radiated power. This, together with the concomitant disappearance of MARFE activity (the blue feature in Figs 14 & 15) as well as the data displayed in Figs 11 and 12 suggest that the influx of impurity was at least retarded by the action of the aerosol.

Li Aerosol Injection Caused Reproducible Increase in Confinement without Increasing Core Impurity Accumulation

Shots: 135049 No Lithium, 135059 and 135063 Constant (100 mg/s) Li Aerosol Injected

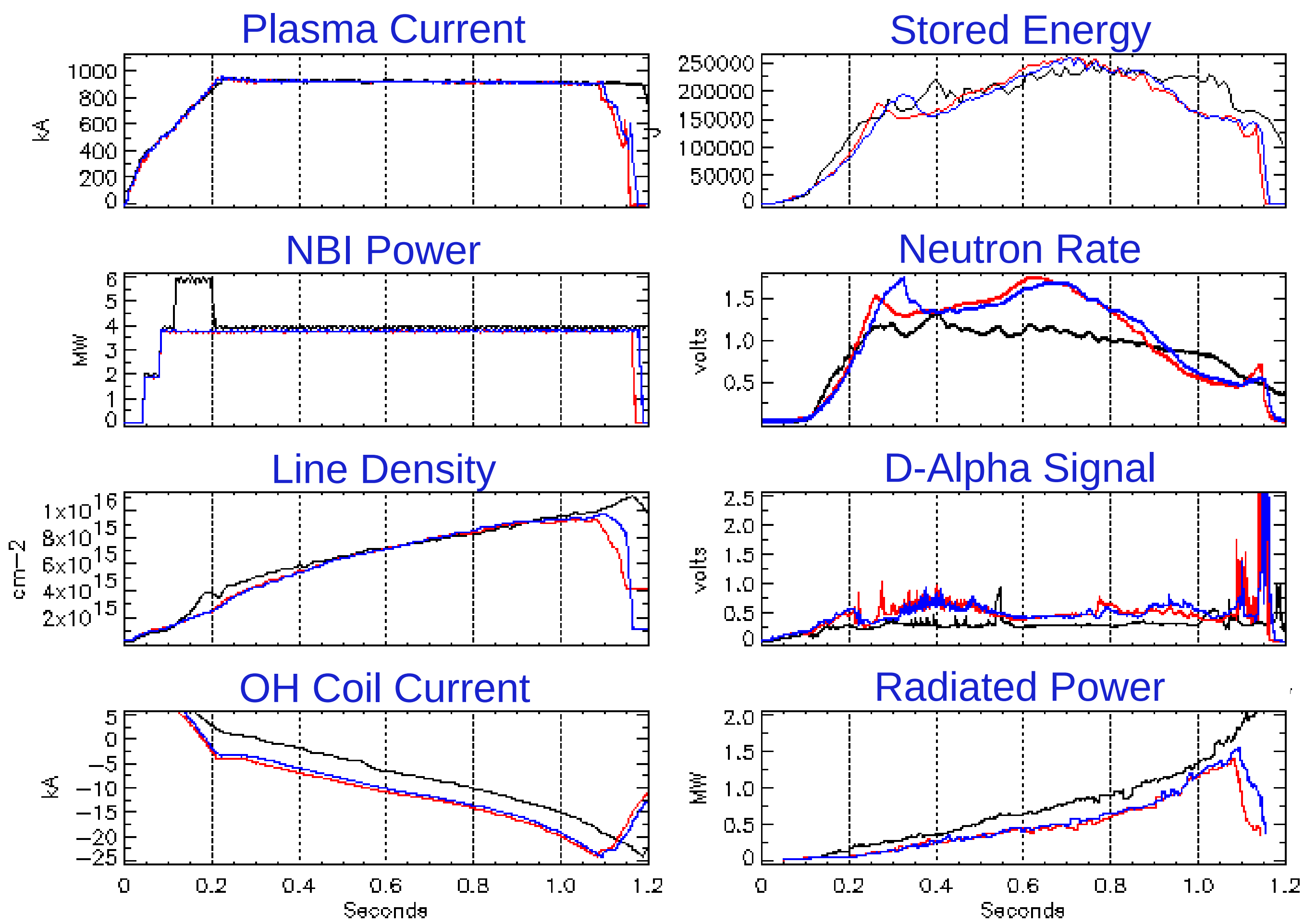
All shots enter H-Mode at ~ 215 ms



Red Vertical Lines Indicate Times of Video Images Figs 13 – 17 – Shot 135063

Li Aerosol Injection Resulted in Less Impurity Radiation than LITER-treated Discharges with Similar Stored Energy

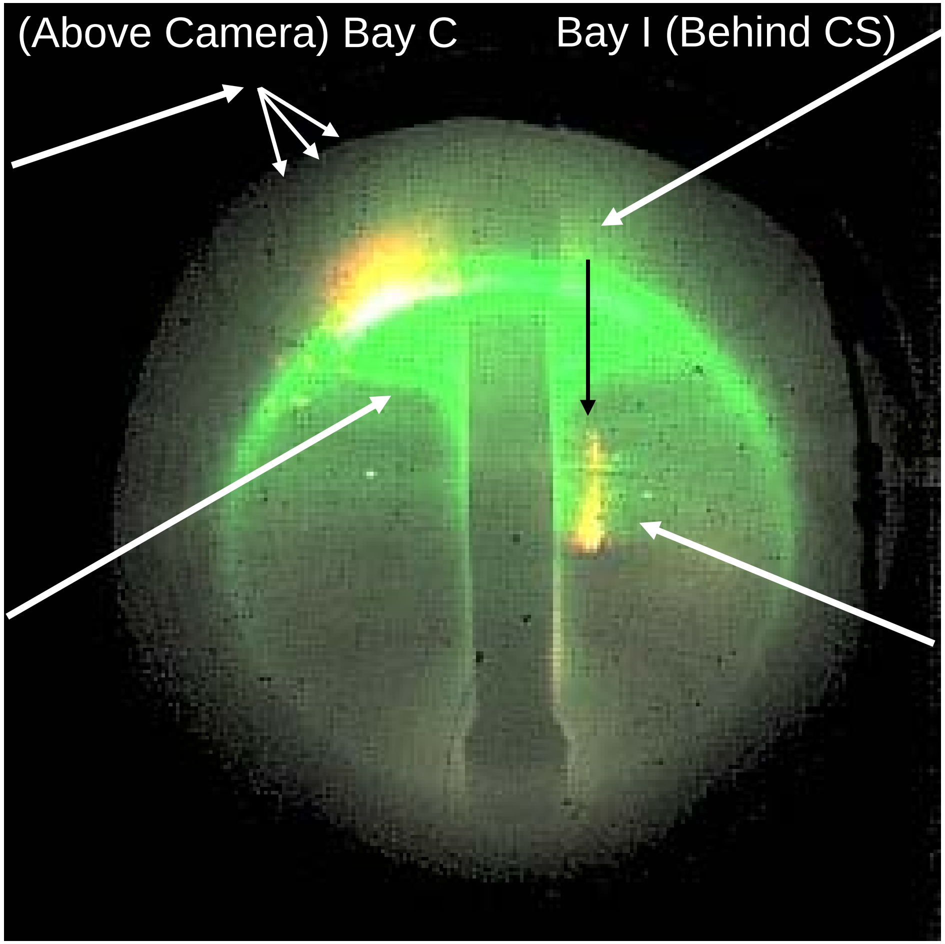
Shots: 135695 Pre treated LITER, 135059 and 135063 Constant (100 mg/s) Li Aerosol Injected



Time Evolution of an Li Aerosol Assisted H-Mode
t = 23 ms – Li Particles First Enter the SOL

Li droplets scatter into the plasma from a plate located here - out of the field of view at Bay C and above the camera

Shot 135063 t = 23 ms



Li droplets fall into the plasma from a tube located here at Bay I.

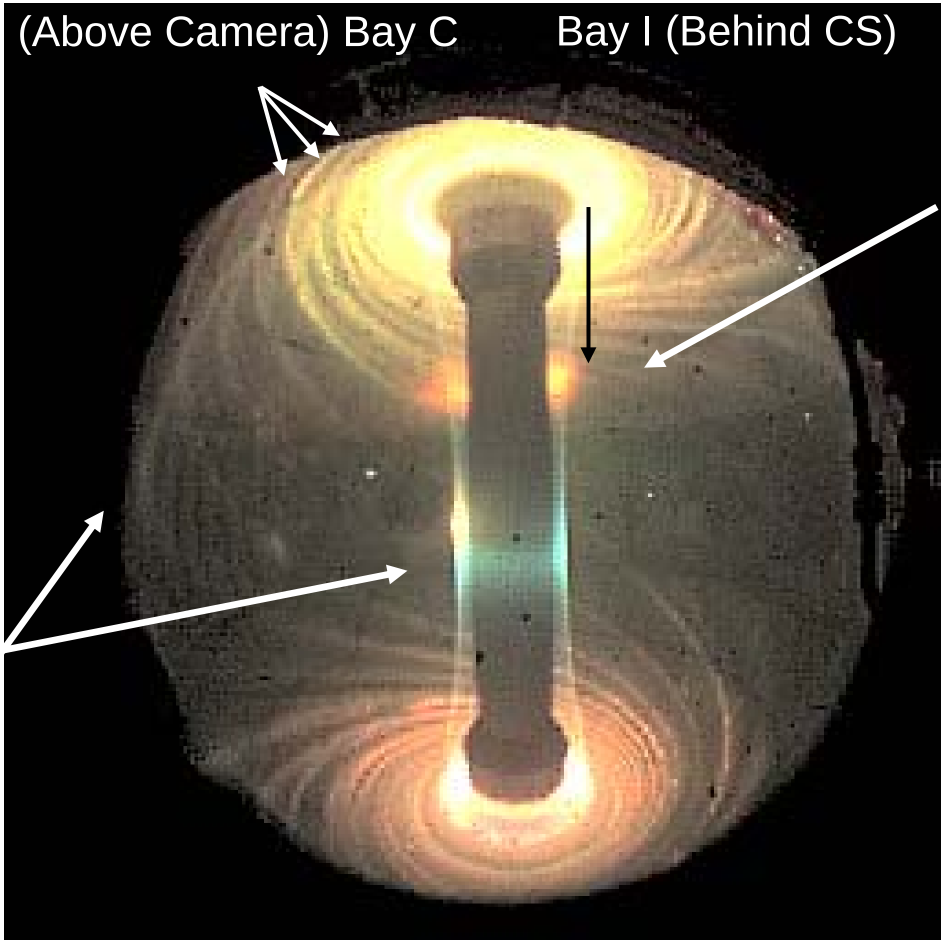
Li^{+1} radiates strongly in the green. These ions travel along open field lines until they implant into carbon surfaces. At this time they implant into the CS.

Evaporating Li droplets appear yellow. About 4 million droplets/ sec are entering the SOL. This equals 100 mg/s of Li or 135 TL/s of D_2.

Time Evolution of an Li Aerosol Assisted H-Mode
t = 347 ms – ELMs and MARFEs Present

Because the plasma has grown, Li droplets enter the SOL out of the field of view. A few of those droplets are seen at the extreme upper left.

Shot 135063   t = 346 ms

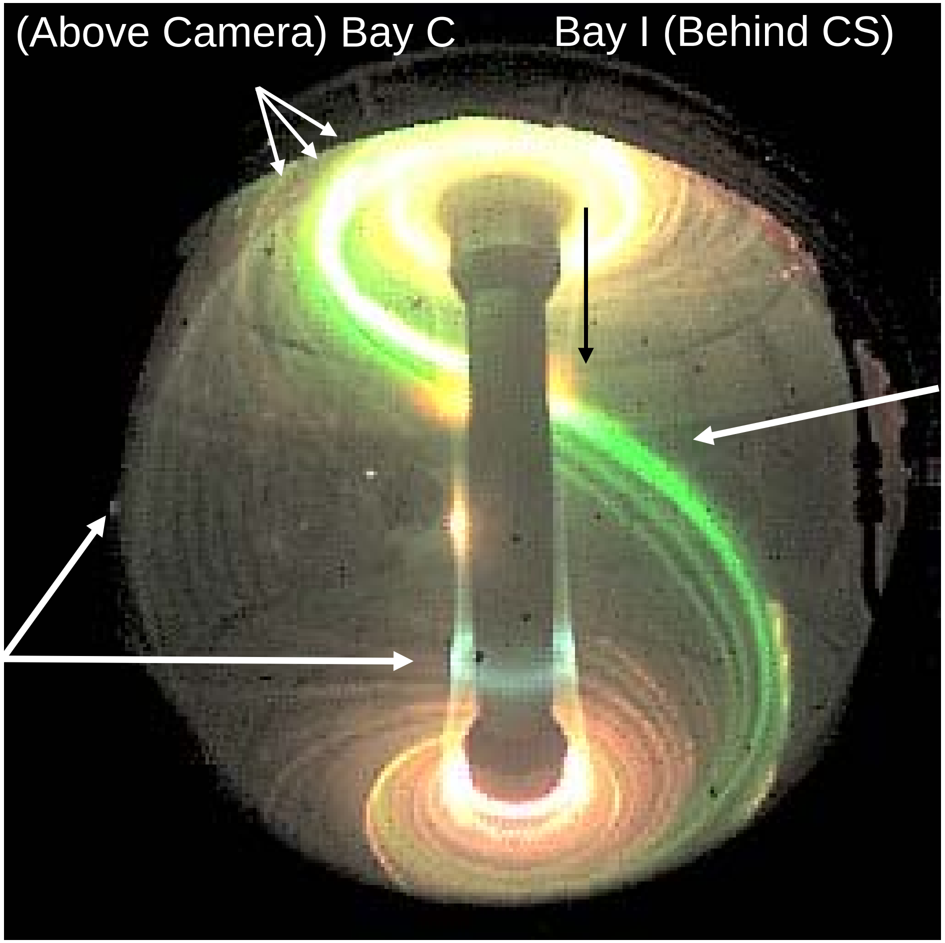


Li droplets fall into the SOL from a tube located at Bay I but are immediately swept behind the CS as they evaporate. This sweeping of the aerosol begins when NBI injection starts.

Filamentary ELMs and robust blue MARFEs observed during this phase of the discharge. The plasma edge also has a faint blue tint.

Time Evolution of an Li Aerosol Assisted H-Mode
t = 369 ms – ELM Interacts with Li Droplets in SOL

Shot 135063   t = 369 ms



Strong interactions of ELM filaments with the aerosol droplets in the SOL are seen until the ELMS finally disappear. (See Fig 16)

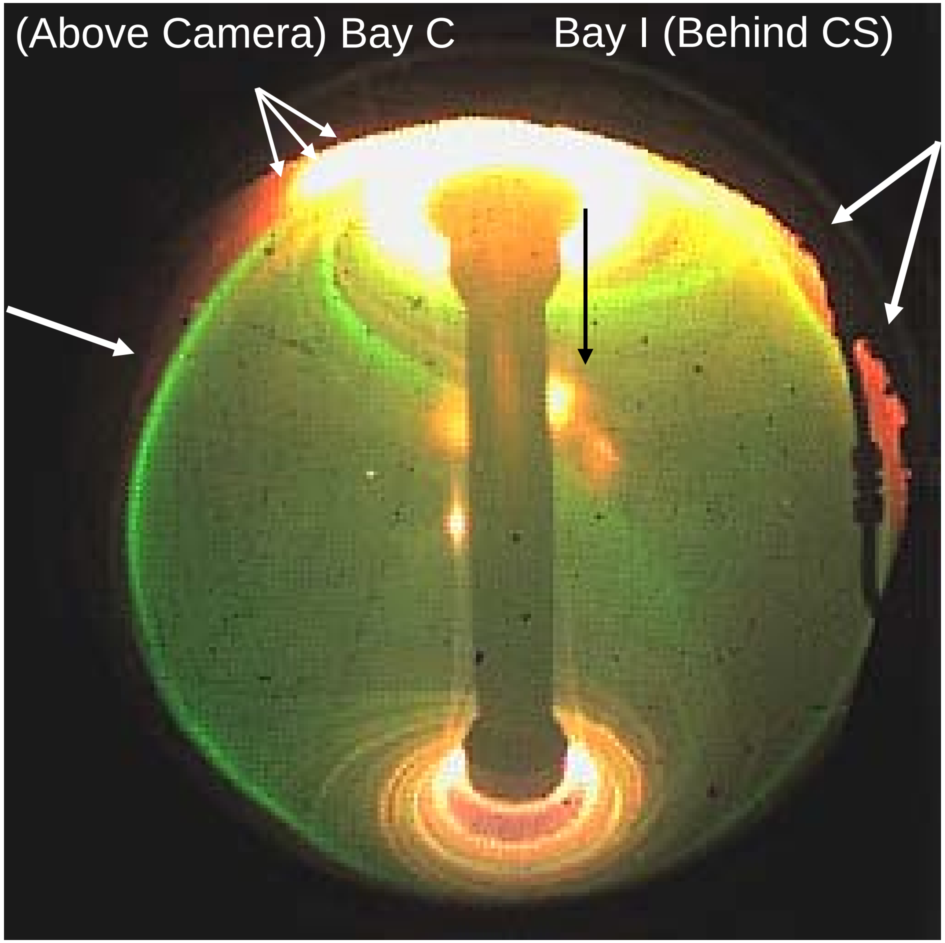
ELM filaments, robust blue MARFEs and a faint blue edge still observed.

Time Evolution of an Li Aerosol Assisted H-Mode
t = 655 ms – Quiescent Edge, Good Confinement, No ELMs

Both the ELMs and the blue MARFEs are eliminated at about t = 550 ms. The plasma edge becomes crisp, quiescent and green (Li^{+1} radiation).

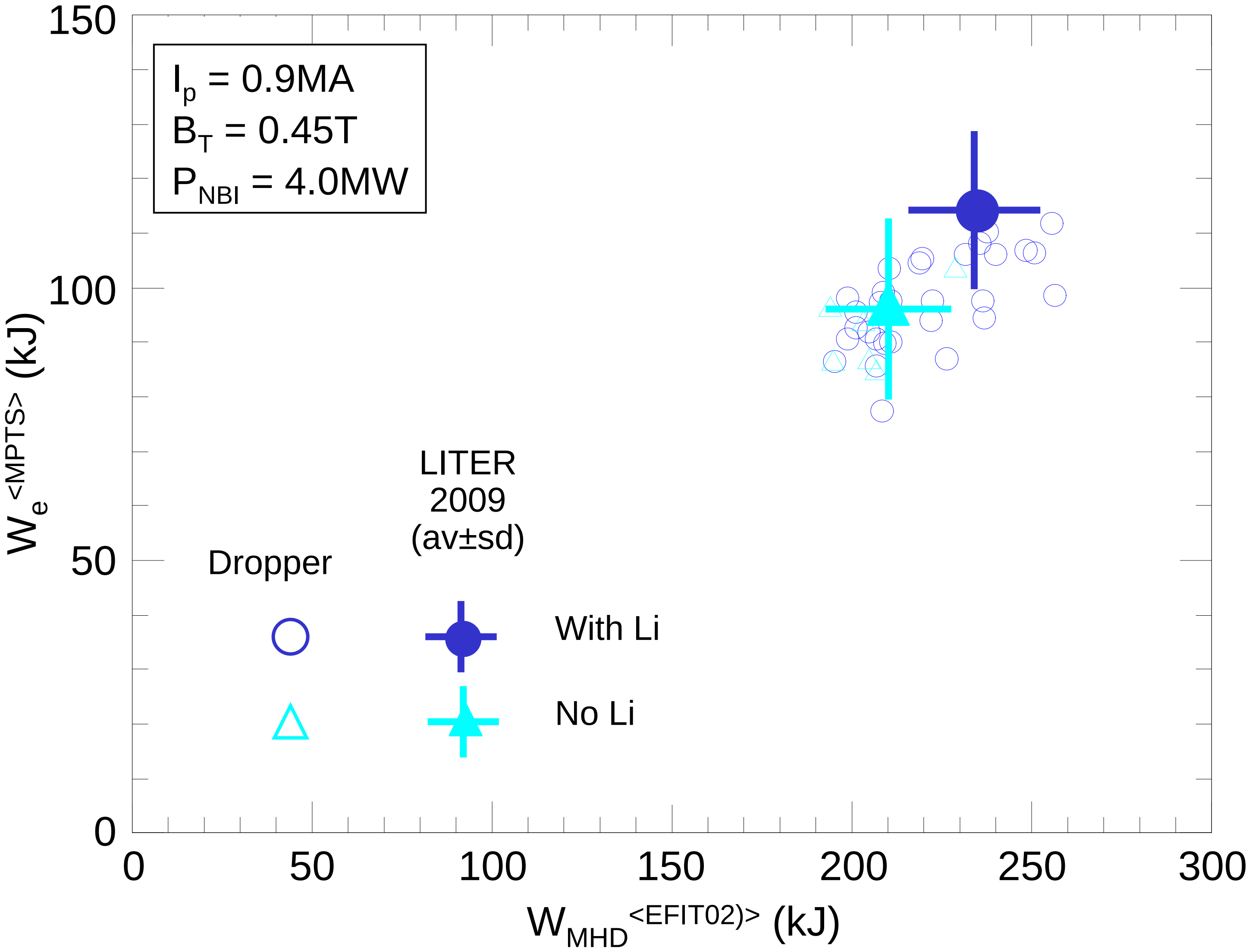
This corresponds to the time of maximum stored energy, Te, Ti and neutron rate (See Fig 11).

Shot 135063   t = 655 ms



Particles injected from Bay C are hidden outside the field of view, however some of are seen here.

A Comparison of the 2009 Aerosol Results with the Results from the Dual LITER System



Conclusions

- NSTX discharges are remarkably tolerant of a large influx of Li droplets introduced into the SOL - even before the H-Mode transition.
  - No delay seen for Li droplet fluxes of 70 – 180 mg/s before H-mode
  - NSTX discharges seemed to tolerate a Li influx roughly as high as the D_2 influx being employed in the same shot.
- It is possible to improve H-mode performance by suppressing filamentary ELMs as well as MARFEs during a discharge using real-time Li aerosol injection (See Fig 11).
- LITER-treated discharges with similar stored energy radiate more than aerosol-treated discharges and have a lower neutron rate (See Fig 12).
  - This suggests that the Li aerosol tends to decrease the influx of impurities as well as to improve the core energy confinement

Conclusions (cont.)

- After an initial "learning curve" was overcome, plasmas produced using Li aerosol injection alone, exhibited total stored energies that equaled or exceeded the stored energies attainable using pre-deposited Li from the dual LITER system. Several of these discharges employed Li from only one dropper/injector and therefore used considerably less lithium. These discharges had electron stored energies that were reasonably similar to but lower than the best LITER discharges (See Fig 17).

Future Plans

- We hope to exploit the ability of the dropper/injector to target *surgically* different areas of NSTX for Li injection. An example of this ability is seen in the left video image in Fig 9. That image shows droplets that have been directed to the center stack just before plasma breakdown. This particular tactic could perhaps be used to reduce early OH consumption in NSTX when the discharge is limited only by the center stack. Other areas of interest include the strike point of upper single null discharges.
- An obvious experiment is to look for synergies with the dropper/injector using the two other Li techniques available on NSTX - the dual LITER evaporator system and the Liquid Lithium Divertor presently being installed for the 2010 campaign.

References

1. D. K. Mansfield, *et al*., Nucl. Fusion **41** (2001) 1823
2. H. Kugel *et al*, Phys. Plasmas **15** (2008) 56118