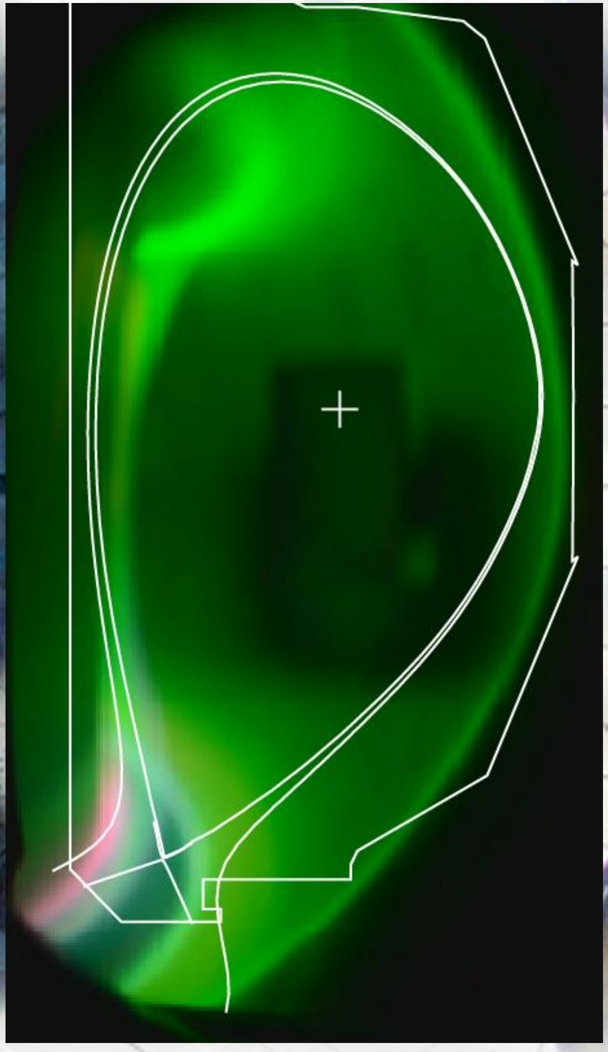
The impact of low-z powder injection on intrinsic impurities in DIII-D



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Poster Overview

- Gravitationally introduced impurity powders and horizontally launched granules are injected into DIII-D ITER baseline discharges to determine effects on baseline impurity concentrations.
- Li aerosol reduces core C by up to 4x, but can be counteracted by addition of C granules.
- If C granules are introduced first, Li powder has minimal effect
- Addition of Li generates periods of suppressed ELM activity proportional to the quantity of Li introduction.
- B powder also reduces core C, but not as strongly as Li.
- Experiments generate benchmarking data for transport codes inform favorable conditions in future tokamaks.

Motivation : Impurity Transport Differences between NSTX and DIII-D

NSTX Lithiated ELM Free H-modes:
Carbon density starts at ~1% builds to 10%
$n_{Li} \sim .01 n_C$ [3]

DIII-D Li Enhanced H-Modes:
300 msec Elm free pedestal enhancements
n_C in core lower than ELMy H-mode levels
$n_{Li} \sim 8 n_C$ [1]

Both results were found to be consistent with neoclassical transport theory

Preliminary XGC calculations show both results could be explained with a carbon threshold effect

PPPL mass injectors at DIII-D used to drive specific impurity concentration conditions

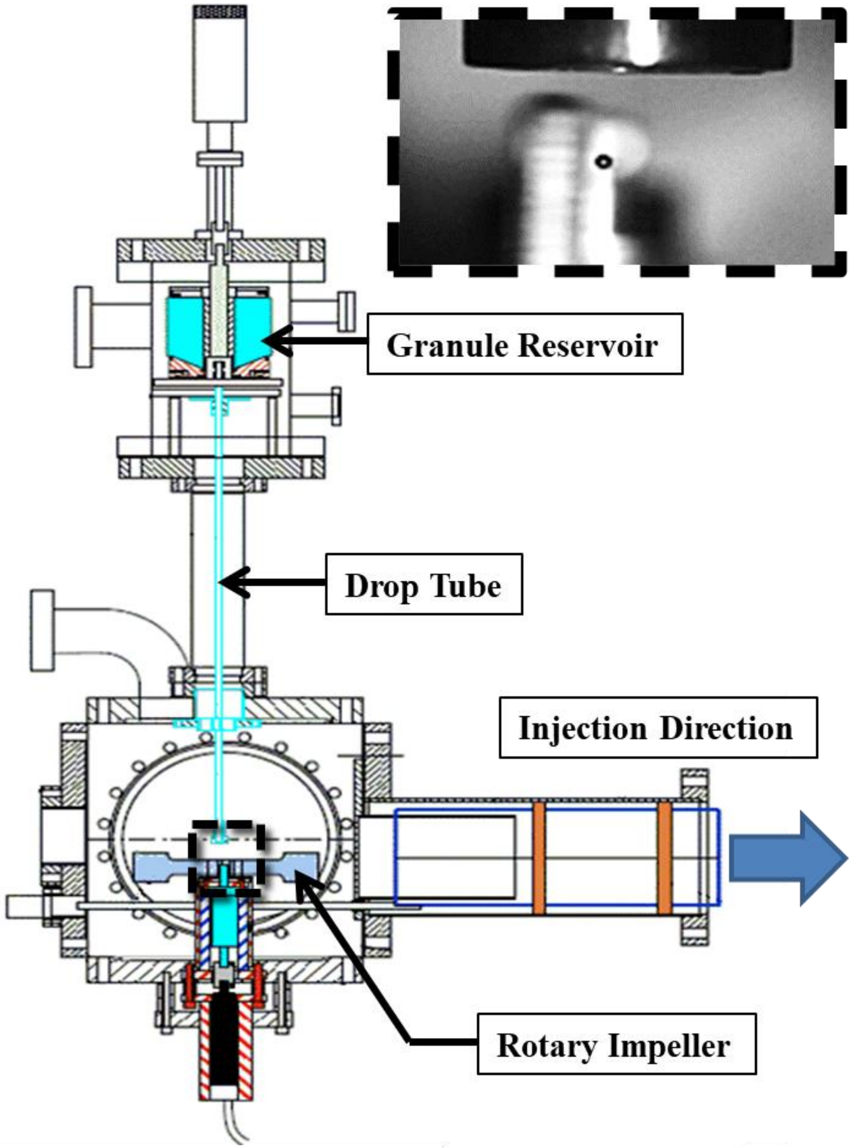
	DIII-D[1]	NSTX[2][3]
Delivery method, Rate	**Dropper, 18 mg/s**	**Inter-shot evaporation, 150-300 mg**
ELMs	**Delayed**	**Eliminated**
P_{RAD}, Impurities without ELMs	**Steady**	**Increasing**
D recycling	**Unchanged**	**Reduced**
Core Li	**High**	**Low**
Edge fluctuations	**Increased**	**Decreased**
Pedestal Width	**Increased**	**Increased**
Pedestal Height	**Increased**	**Increased**
H-factor	**Increased**	**Increased**

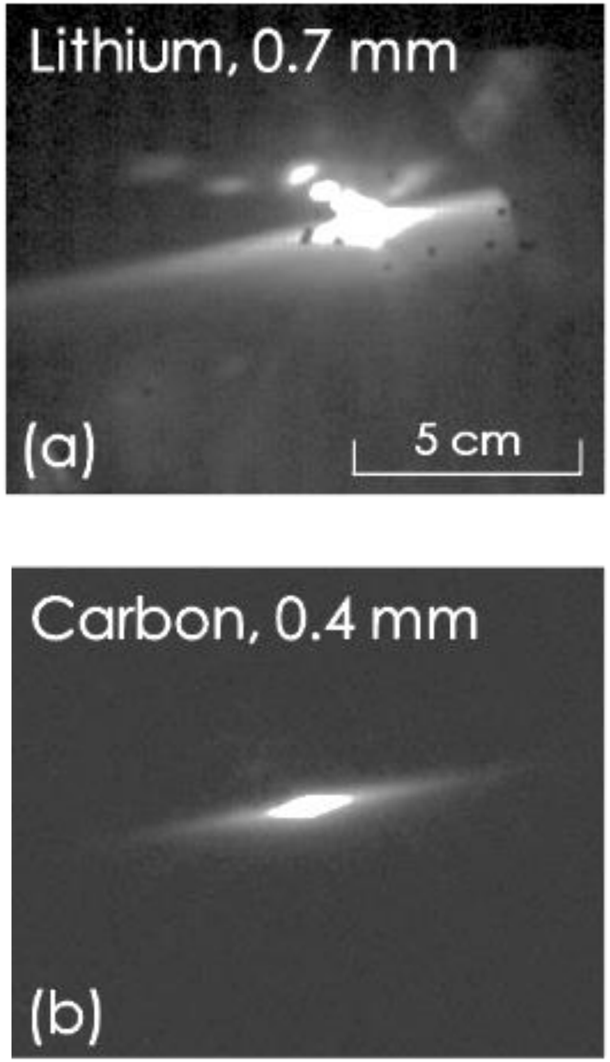
[1] T.H. Osborne et al., Nucl. Fusion 55 (2015) 063018
[2] R. Maingi et al., Nucl. Fusion 52 (2012) 083001
[3] F. Scotti et al., Nucl. Fusion 53 (2013) 083001

Granule Injector provides horizontal injection

Impurity Granule Injector (IGI)

- Granules in reservoir gravitationally accelerated
- Rotary impeller stage provides high speed horizontal injection
- New feeder allows quasi-periodic injections
- Spherical pellets of C(400 mm), Li (700 mm)
- Up to 150 Hz possible
- 50-120 m/s
- Midplane injection





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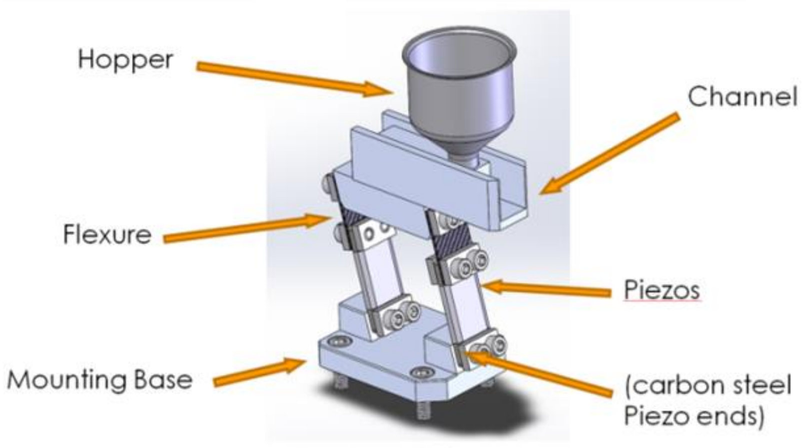
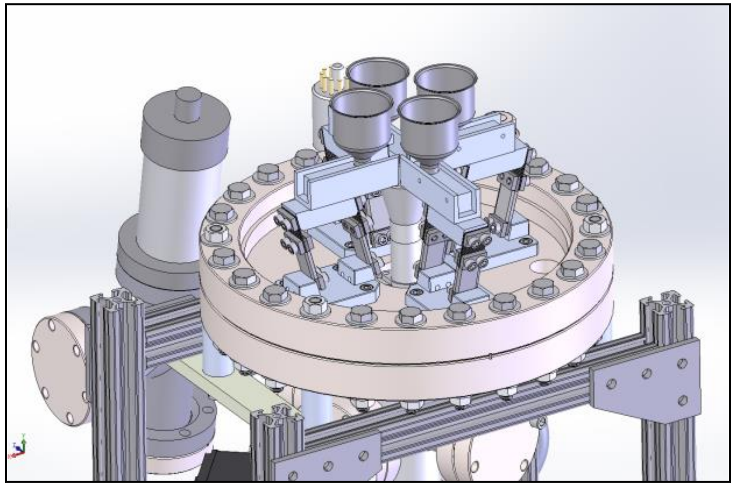
Impurity Powder Dropper (IPD) provides gravitational upper divertor injection

- Multi-impurity injection system based on linear piezoelectric powder feeder
- 4 feeders with separate reservoirs (30 ml) around central drop tube
- Tested with multiple materials
  - B, BN, Li, Si, SiC, Sn…
  - particle size 5-100 µm
  - calibrated rates 2-200 mg/s
- Calibrated with accelerometer, while optical flow-meter confirms mass injection rate
- Injection of stabilized lithium powder & boron powder



Feeder with hopper



Boron Nitride BN

A. Nagy et al., Rev. Sci. Instr. 2018

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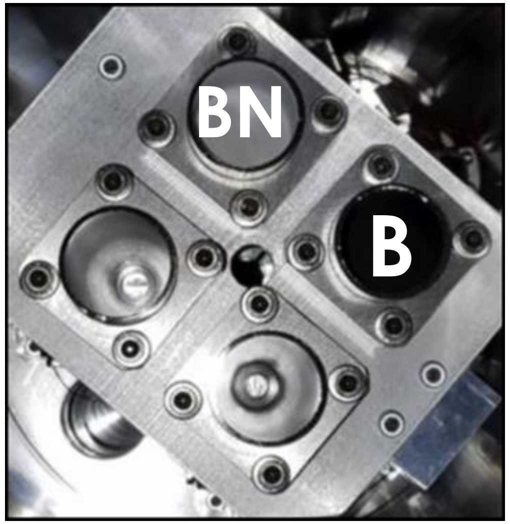
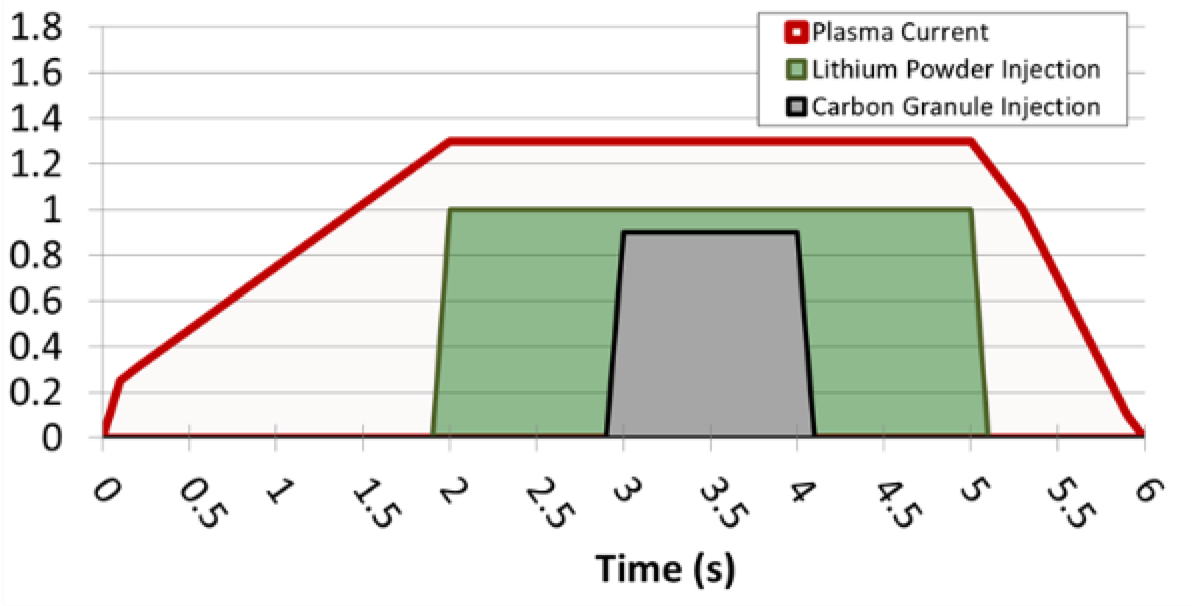
IPD units installed on AUG, DIII-D, EAST, KSTAR & LHD



Images from first IPD installation on ASDEX Upgrade

- 2.5 m drop tube connects IPD with crown of AUG discharge (blue circle)
- Chamber 1 loaded with 5 μm BN powder
- Chamber 2 loaded with 70 μm B powder

Injection timing during impurity injection experiments

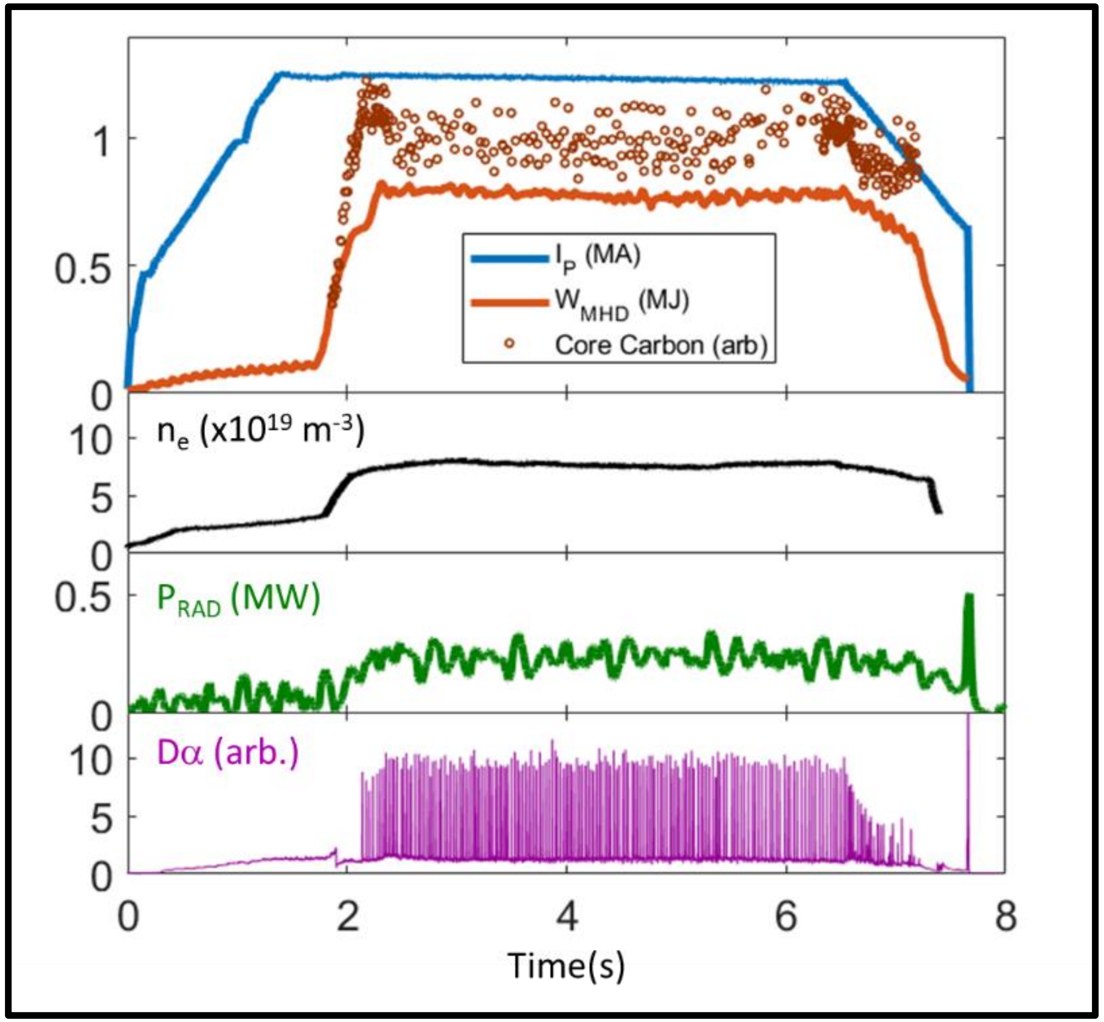


Powder Dropper	Granule Injector
	C Granules
Li Powder	
Li Powder	C Granules
B Powder	
B Powder	C Granules
B Powder	Li Granules
	Li Granules

- Series of single impurity and mixed impurity plasmas
- Powder Dropper and Granule Injector triggered during discharge flat-top
- Actuator timings can be swapped to determine primacy effect

Injection program for impurity transport discharges

- Injections into 9 MW NBI heated ITER baseline discharges
- I_P = 1.3 MA, B_T = -1.73T, q_{95} = 4.4, $1.9<\beta_N<2.3$
- The core carbon concentration is provided by charge exchange
- Carbon concentration normalized to provide unitary baseline for future comparisons.



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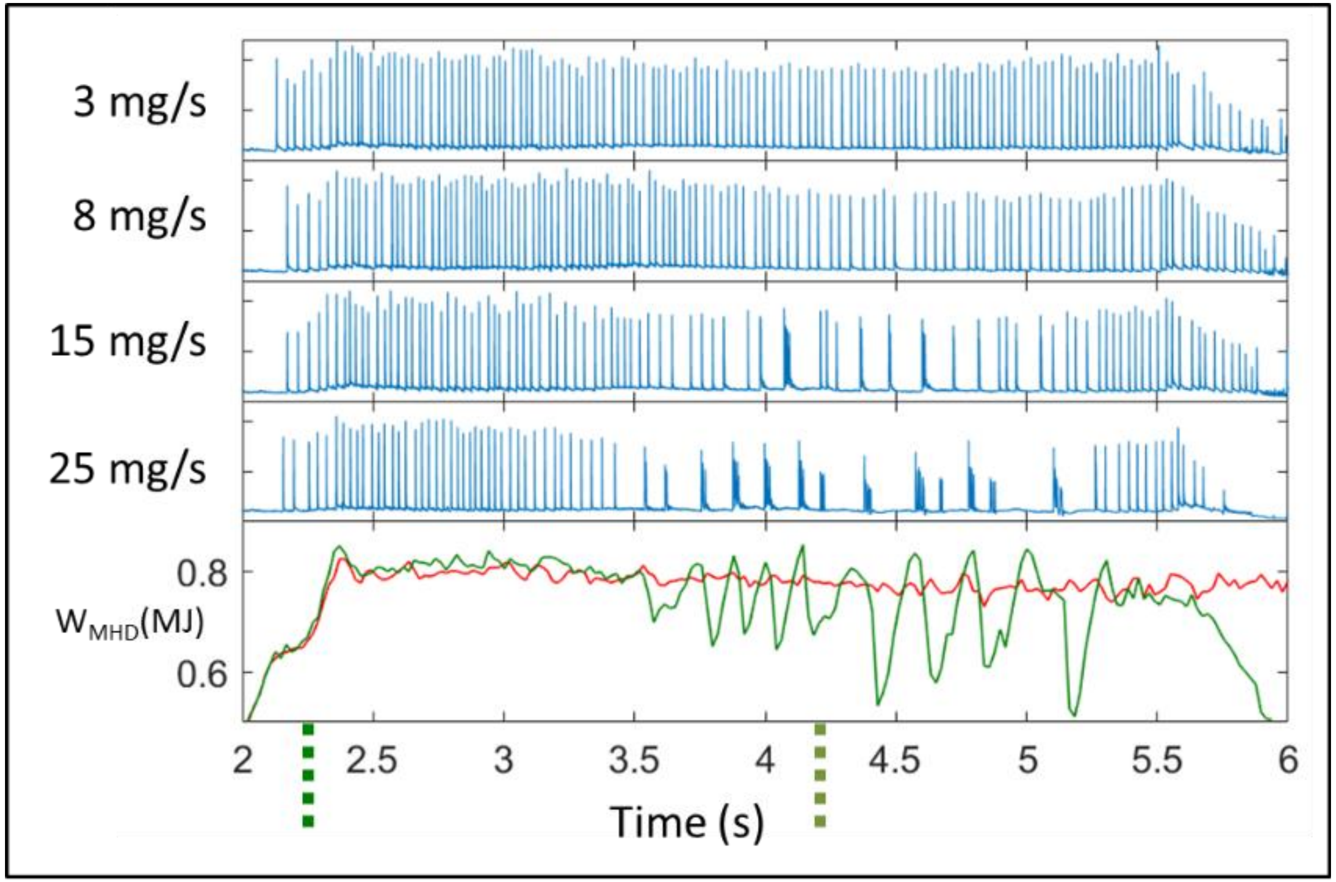
Increasing levels of Li injection lead to extended periods of ELM free activity

- Dα signals show the effect of increasing lithium introduction on the ELM cycle
- Vertical scales for the Dα panels are arbitrary
- Bottom panel shows evolution of plasma W_{MHD} for the baseline (red) and 25mg/s (green) injections
- Terminating these ELM free sections are very large ELMs that can contain up to 30% of the total stored energy.
- The high power IBS results seem to be consistent previously discovered with "Bursty Chirping Mode"*

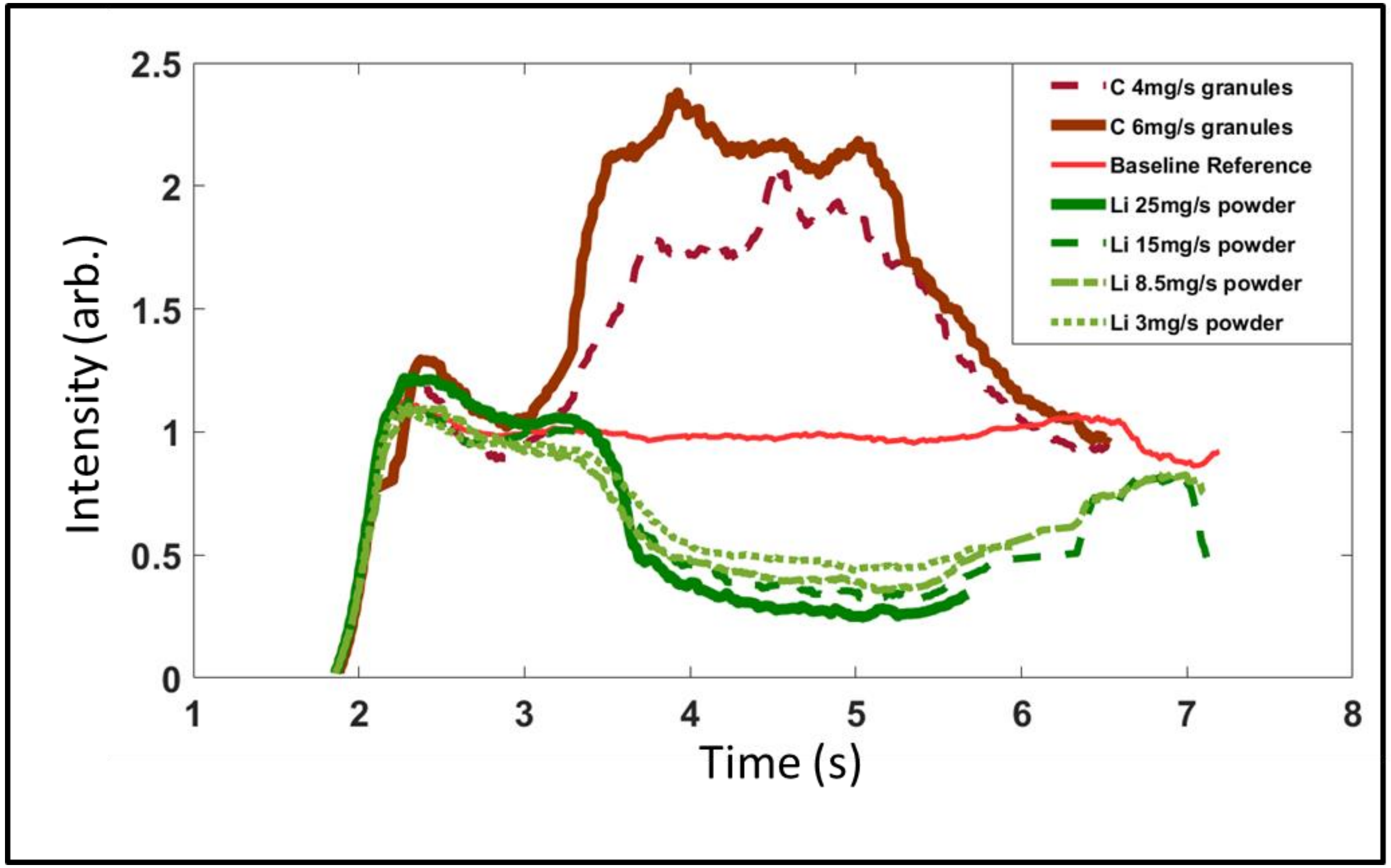


Dα signals, W_{MHD} Baseline, W_{MHD} 25 mg/s Li Injection

*** T.H. Osborne et al., Nucl. Fusion 55 (2015) 063018**

Results of Li and C single species impurity injection on core carbon signals

- Central line is normalized core carbon signal level
  - Average of open circles shown in time history on previous slide, all signals normalized to this level
- Green lines are C concentration after Li injection
  - Signal level decreases slightly with higher Li injection amounts
- Red lines are C concentration after C granule injection



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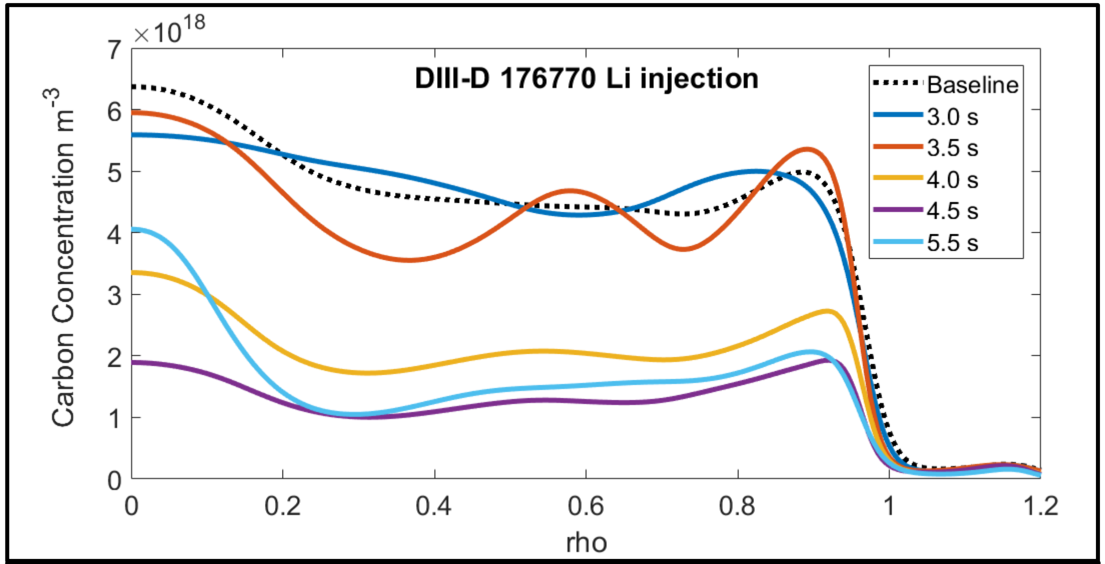
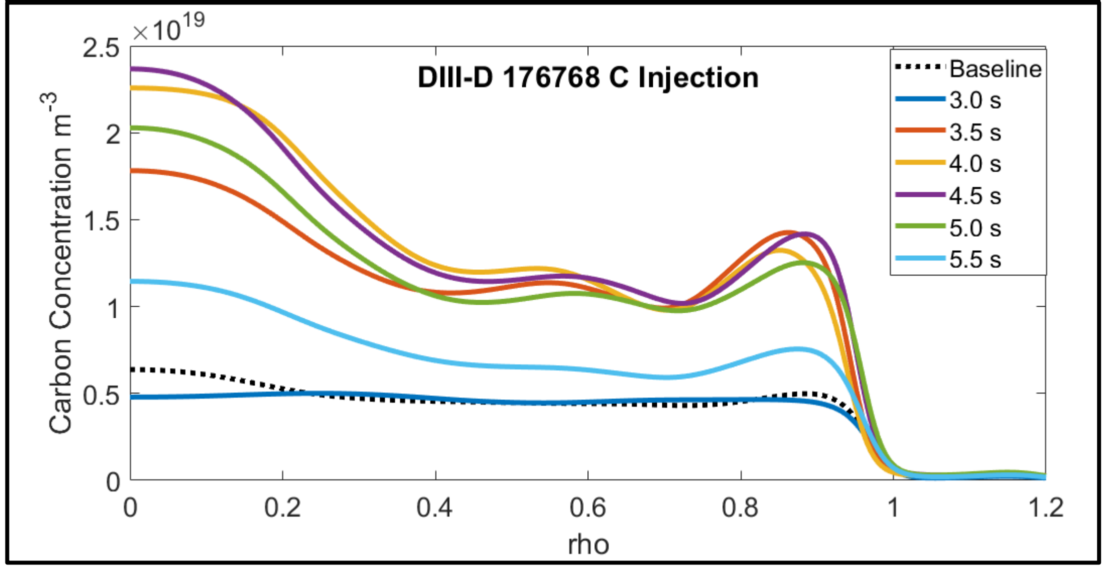
Radial profiles of impurity flushing show species specific effects

- Black dotted line in each trace is the reference discharge carbon concentration profile.
- Li injection leads to depression of carbon concentration over the full profile by nearly 3x.
- Profile recovery occurs from inside out
- Extended C granule injection leads to full profile elevation followed by core peaking of C signal as seen in progression from 3.5s to 4.0s.
- Peaking decays when C stopped





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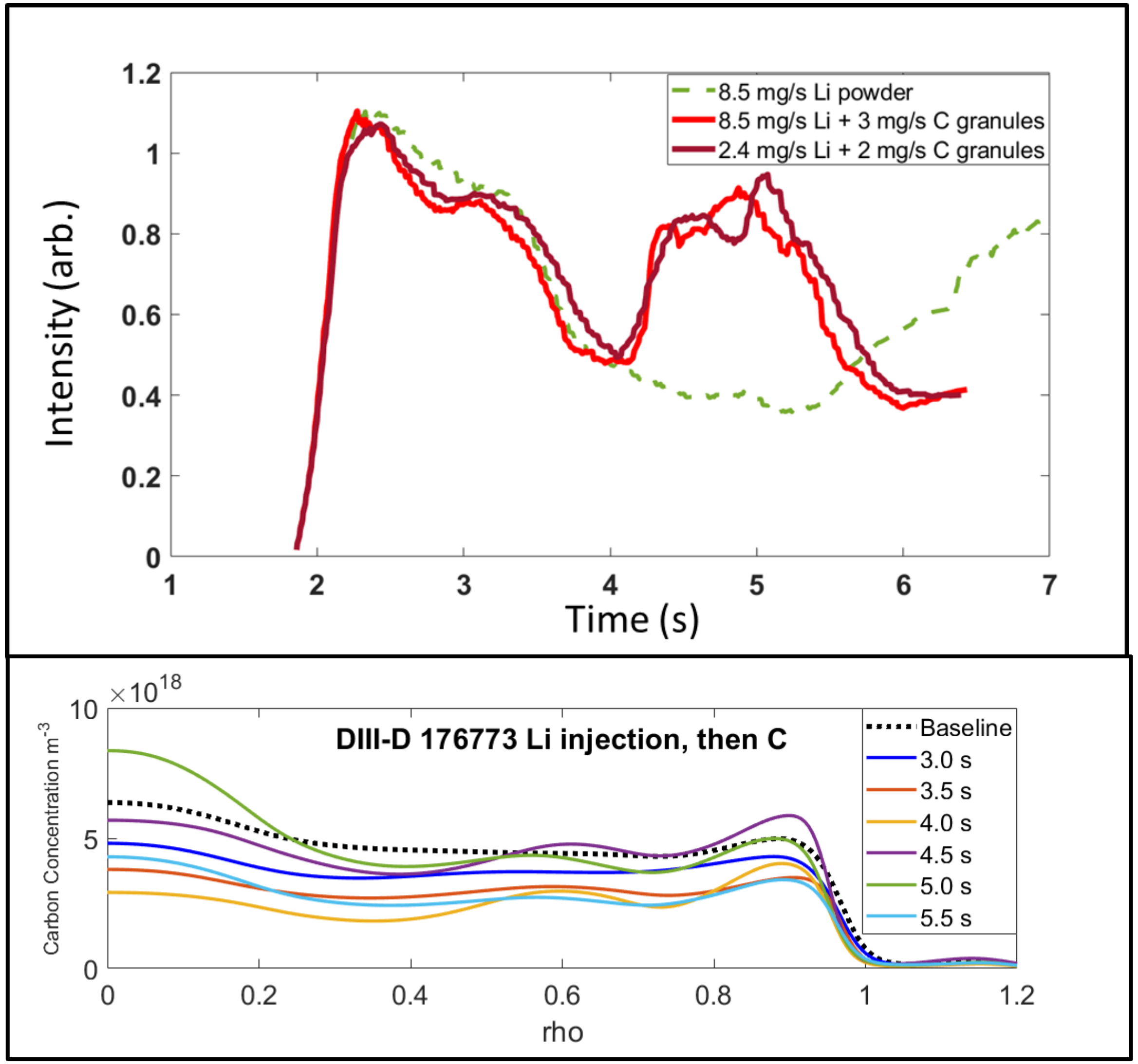
Modification of core carbon through utilization of multiple impurity species

- Green line is C concentration after Li injection at midrange level
- Red lines show that reintroduction of C returns the signal to baseline levels
- C injection stopped at t = 5s, Li injection continues, core levels return to previous suppressed quantities
- Early traces in lower panel show the depression of C with Li injection as seen in single impurity injection discharges.
- Once C granules are injected in DIII-D 176773 (8.5 mg/s Li & 3 mg/s C), profile peaks towards the discharge core but rho > 0.3 is largely unaffected.



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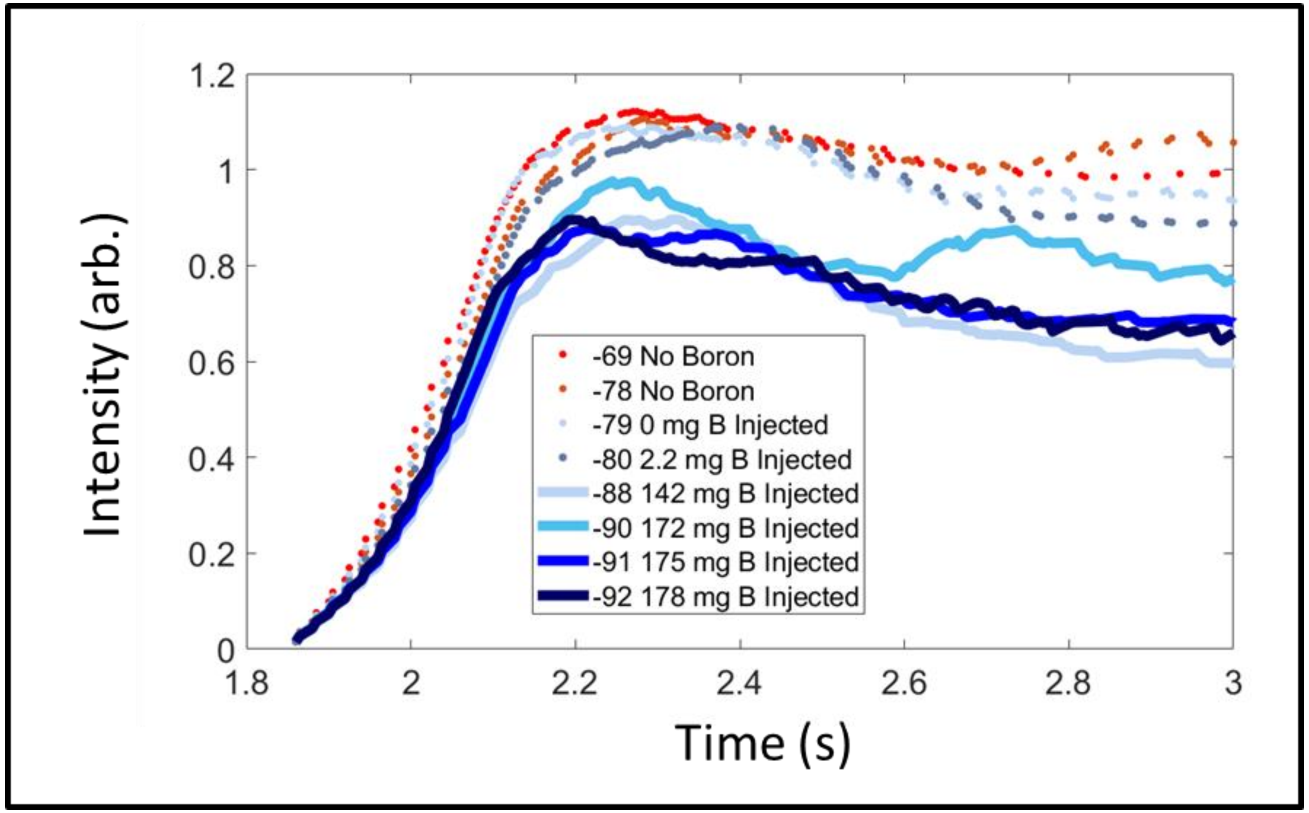
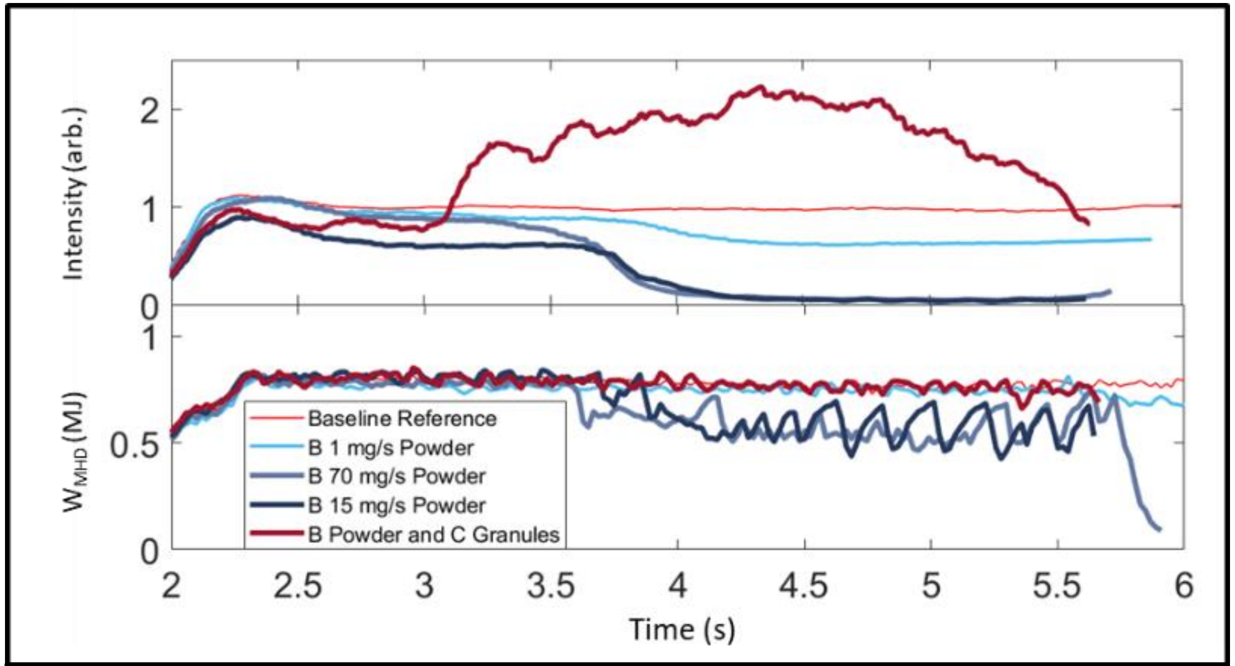
Mild conditioning indicators after large boron injections

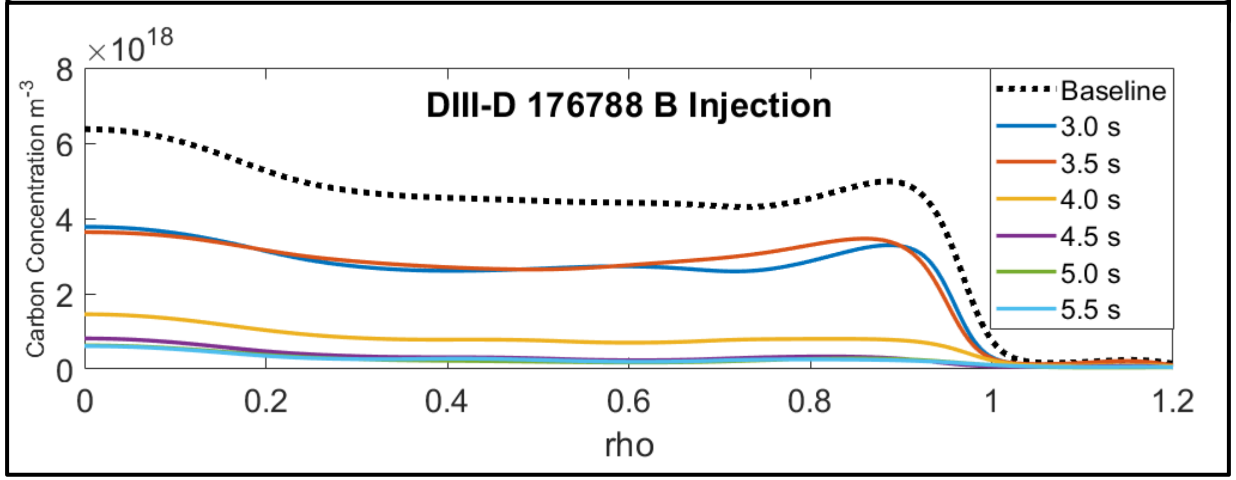
- Injection into discharge 176780 was larger than anticipated depositing 140 mg of B powder.
- Several subsequent attempts were required to recover standard operational conditions
- Once discharges were running again a lowered overall Carbon baseline level was observed.
- The numbers in the key at right indicate the amount of B injected at the time of the measurement.



Injection of B powder also reduces core C, but not as efficiently as Li

- Plasma more sensitive to B powder injections with regards to H-mode stability
- Boron powder injection levels are also harder to regulate leading to only gross control of injection rates.
- Levels 15 mg/s (DIII-D 176788)and above lead to a transition out of H-mode and a substantial loss of stored energy.
- Like Li, when C granules are injected B powder injection is unable to moderate the increased level of core carbon.
- B profiles show evidence of conditioning prior to injection and flushing during injection





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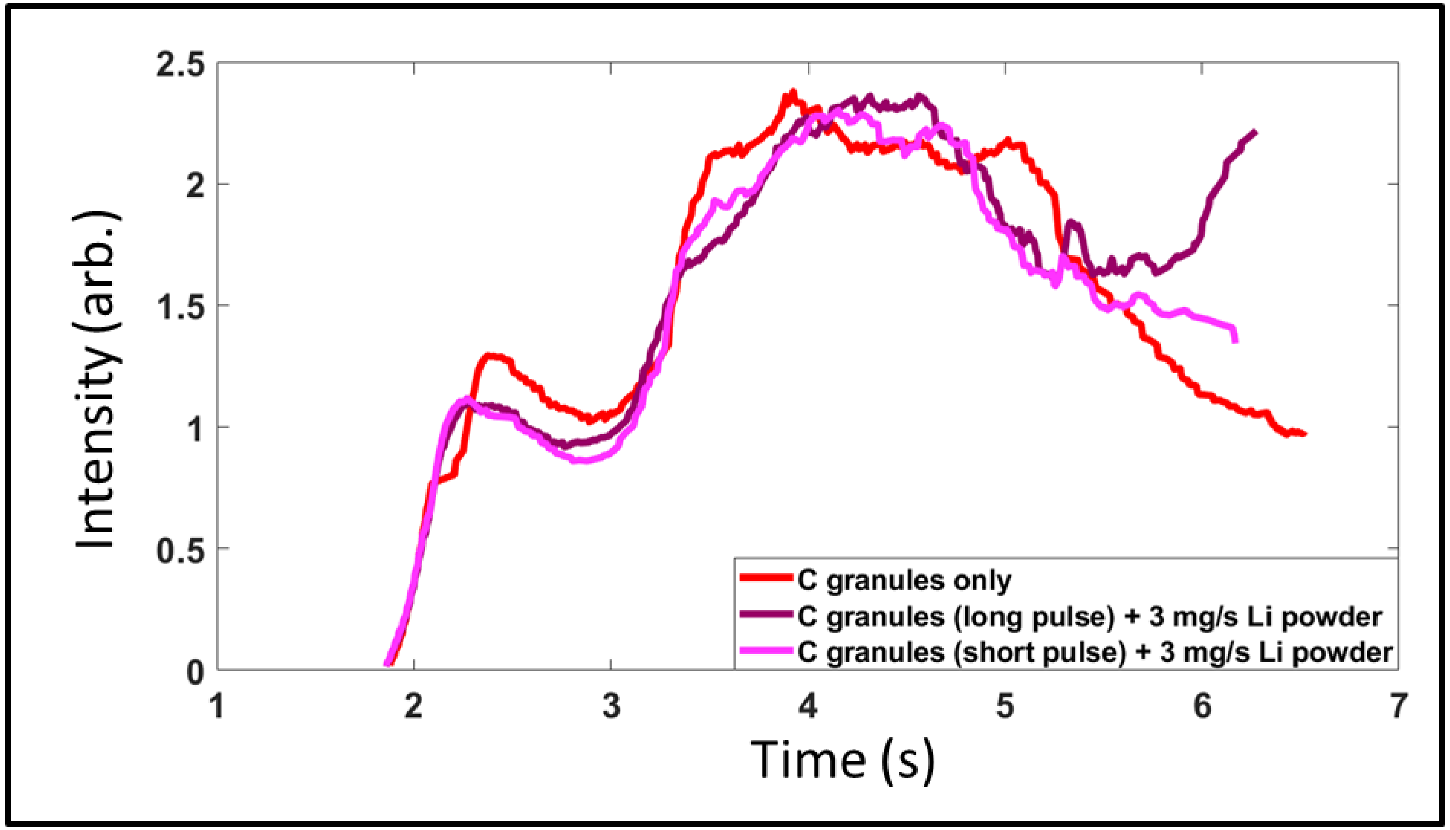
Reversal of species introduction order leads to persistent elevated core carbon

- Carbon granules introduced during the early time
- C and Li combined pulses included 1- 3.5s long C injection and 1 -2.5s long C injection.
- Stopping the carbon earlier did not appear to modify the pumpout rate.
- Li injection was unsuccessful at flushing the elevated core carbon concentration



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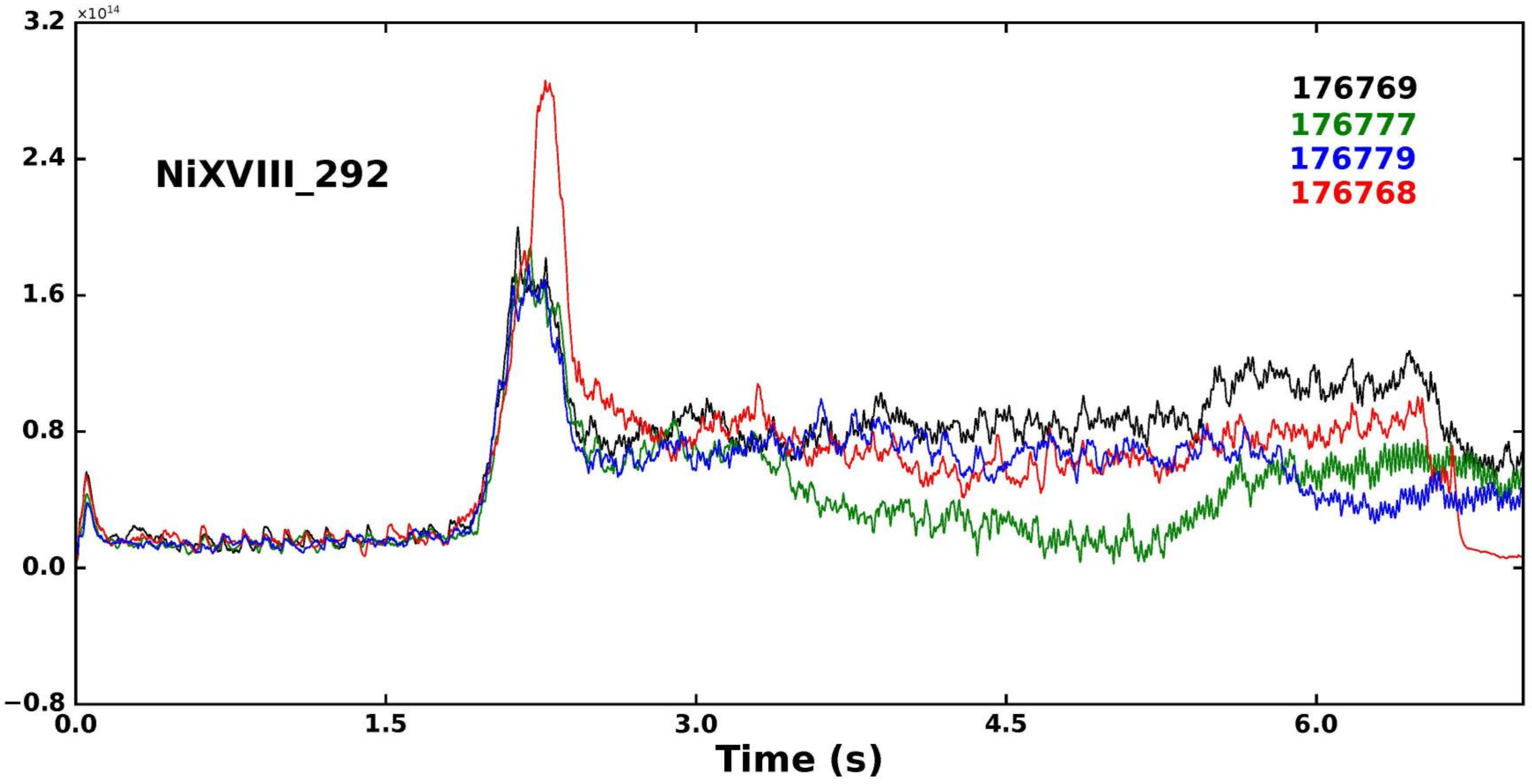
High Z Impurity (Nickel) also reduced during injection

176769 : Baseline Discharge
176777 : Li Powder Injection
176779 : B Powder Injection
176768 : C Granule Injection

In all cases lower levels of Ni are observed post injection

Reduction is much stronger with Li powder injection

B powder and C granules show similar minimal effect



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Conclusions

- These experiments extend previous mass injection programs to high power ITER baseline discharges and are able to confirm prior observations of ELM free periods (Li injection) and inter-shot conditioning effects (B Injection)
- While Li and B powder are able to reduce core C concentrations below baseline level they cannot compensate for the continued introduction of C from the granule injector. Whether this is a result of the injection method or a threshold effect which shields core C is still under investigation.
- A carbon threshold level beyond which the Li is not able to affect the core could explain differences in core impurity penetration seen in similar discharges in NSTX and DIII-D
- These measurements providing benchmarking data for neoclassical transport codes such as NEO and XGC.
- Future simulations will help determine if the corresponding variations in impurity transport can be explained by present understanding and will inform favorable transport conditions in future tokamaks.

A global program of controlled impurity injection

Introduction of impurities has been shown in many cases to improve plasma performance and enhance wall conditions in multiple devices

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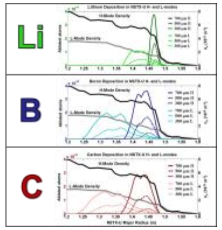

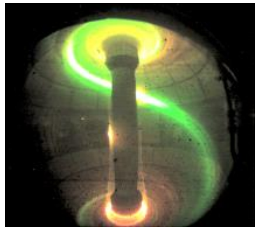

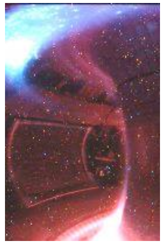

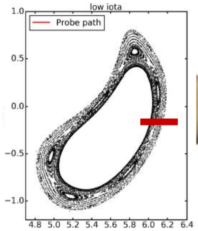

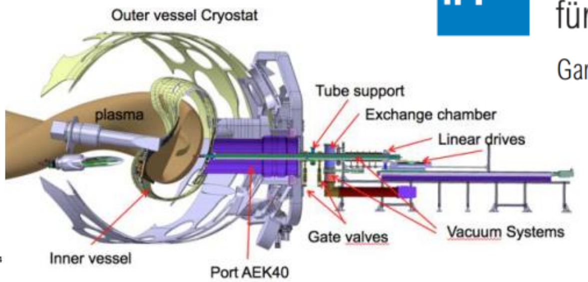

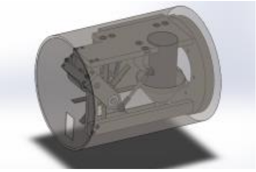

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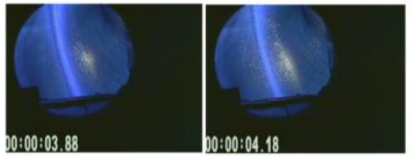

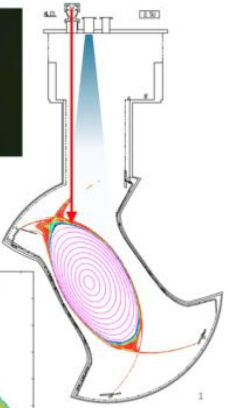

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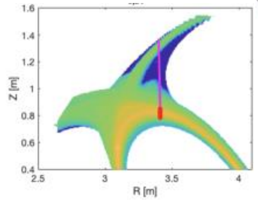

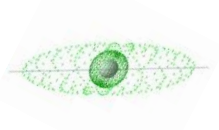

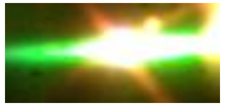

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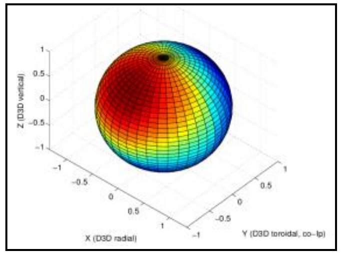

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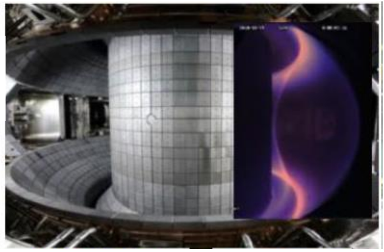

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