Impact of Boron Powder Injection on Wall Conditioning and Confinement in WEST L-Mode Plasmas

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[2]CEA, IRFM, F-13108 Saint-Paul-Lez-Durance, France
[3]Oak Ridge National Laboratory, Oak Ridge, TN, USA
[4]École Polytechnique – LPP, Paris, France
[5]http://west.cea.fr/WESTteam

Commissariat à l'énergie atomique et aux énergies alternatives - www.cea.fr

Princeton Plasma Physics Laboratory - www.pppl.gov

NSTX-U/Magnetic Fusion Science Meeting
March 4th, 2022
Princeton, NJ (Virtual)

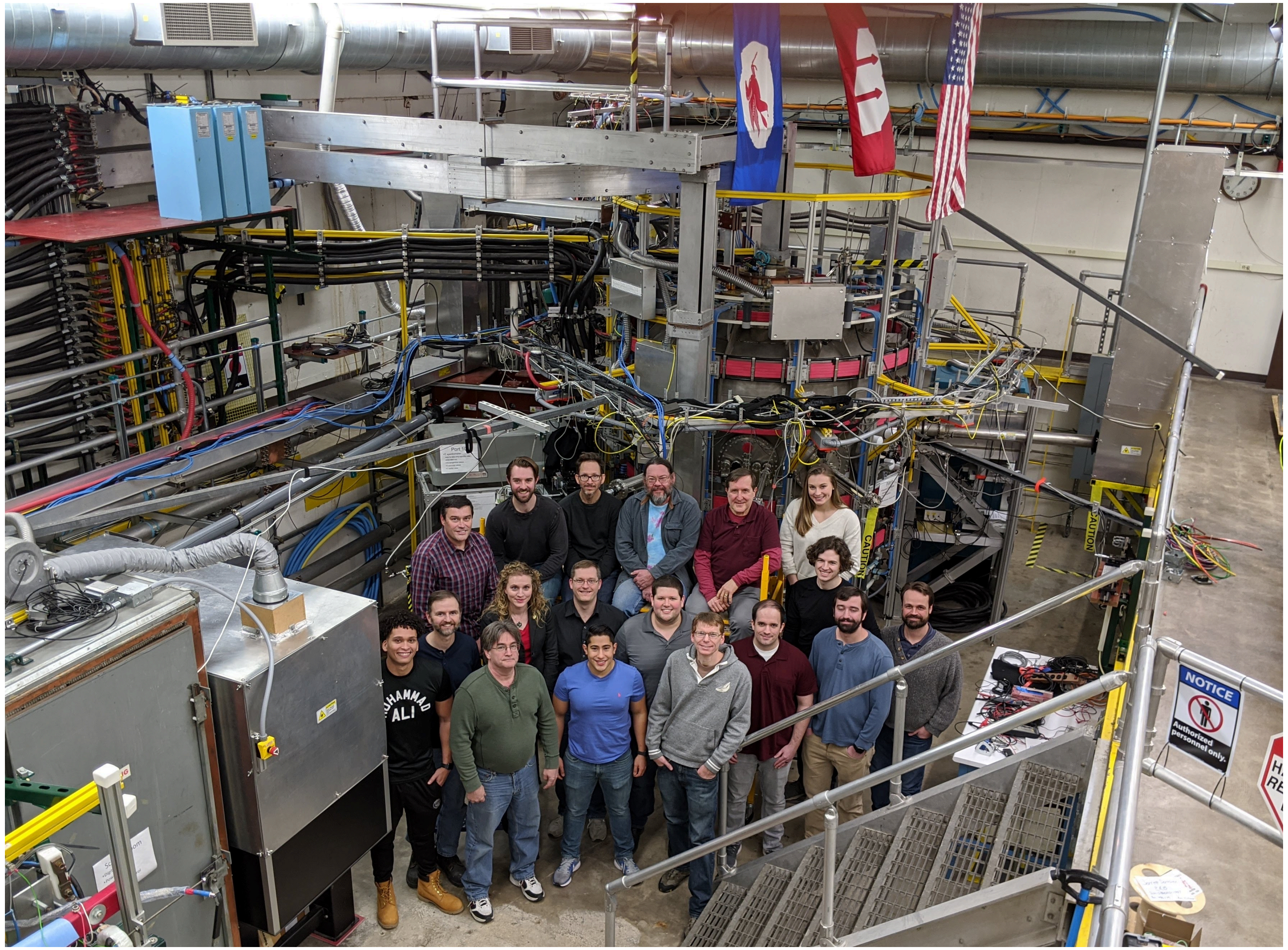
Talk Outline

1. Educational/Professional Background
2. Overview of Boron Powder Injection Experiments in WEST
3. Impact of Powder Injection on Wall Conditioning
4. Improvements in Confinement from Powder Injection
5. Conclusion/Future Directions

Educational Background

University of Wisconsin-Madison

- B.S. in Engineering Physics
- M.S. in Nuclear Engineering and Engineering Physics
- PhD in Nuclear Engineering and Engineering Physics

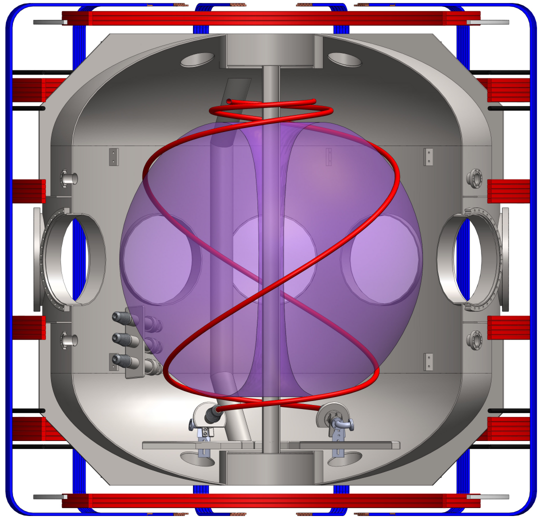


Professional Experience

- Graduate Research Assistant (2015-2020)
  - Responsible for alignment, calibration, operation, and analysis of PEGASUS TS diagnostic
  - Investigated electron heating during plasmas produced and driven by local helicity injection

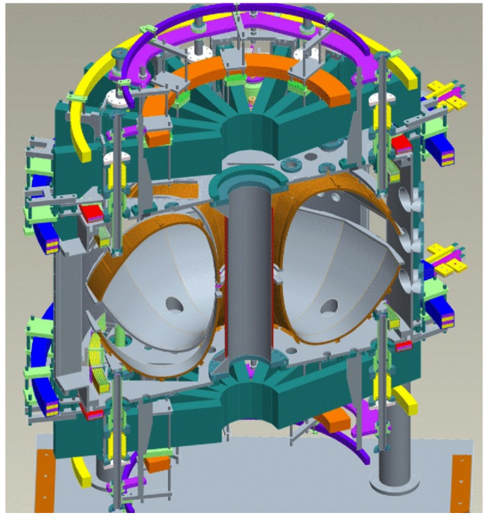
- Associate Research Physicist (2020-Present)
  - Wrote data analysis package for the LTX-β HFS TS system
  - Aided in the laser alignment and calibration of ST40 TS system
  - Responsible for operation of WEST IPD and subsequent data analysis

PEGASUS (Madison, WI)



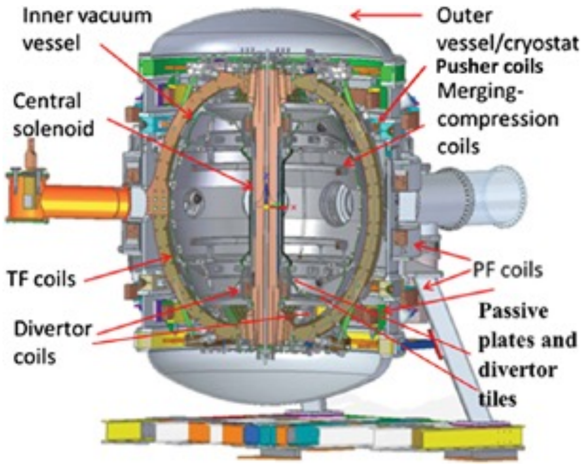
Bodner et al. 2021 *Phys. Plasmas.* **28** 102504

LTX-β (Princeton, NJ)



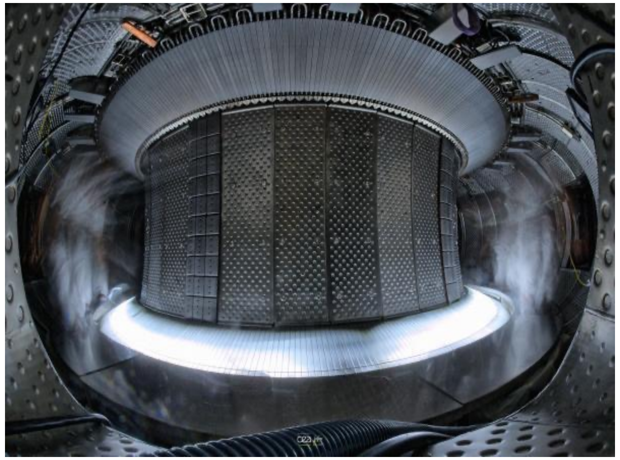
Schmidt et al. 2014 *Rev. Sci. Instrum.* **85**, 11E817

ST40 (Oxfordshire, UK)



M. Gryaznevich et al 2022 *Nucl. Fusion* **62** 042008

WEST (Cadarache, FR)



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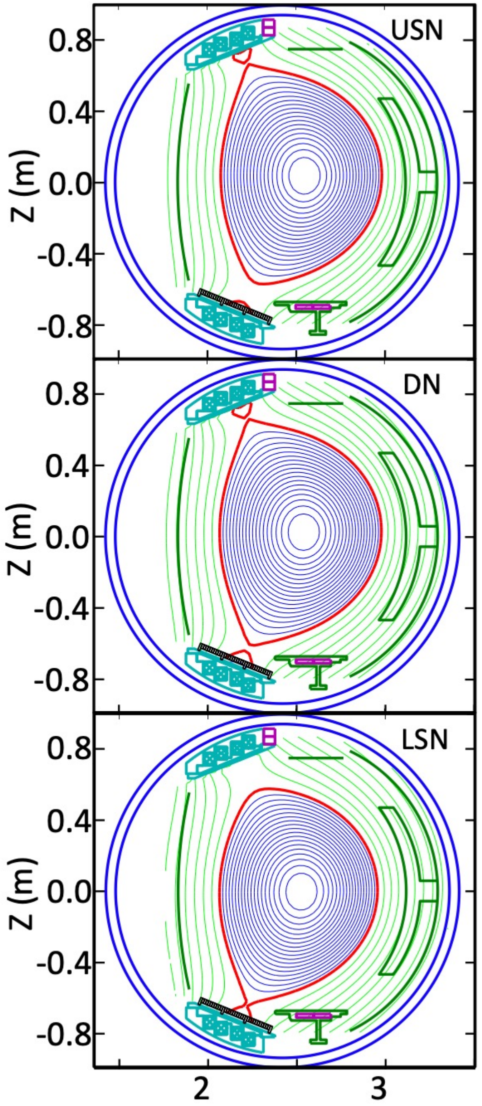
Tore Supra has been Converted into WEST (W Environment in Steady-state Tokamak) to Support ITER Operation

- Scientific objectives of WEST:
  - Testing of ITER-grade PFUs
  - Investigation of long pulse H-mode and steady-state operation

- WEST is a full-W superconducting tokamak specializing in long pulse operation with LHCD and ICRH

- Long pulse capabilities allow for detailed investigations of potential power exhaust issues in a reactor
  - ITER-like heat flux: 10-20 MW/m^2

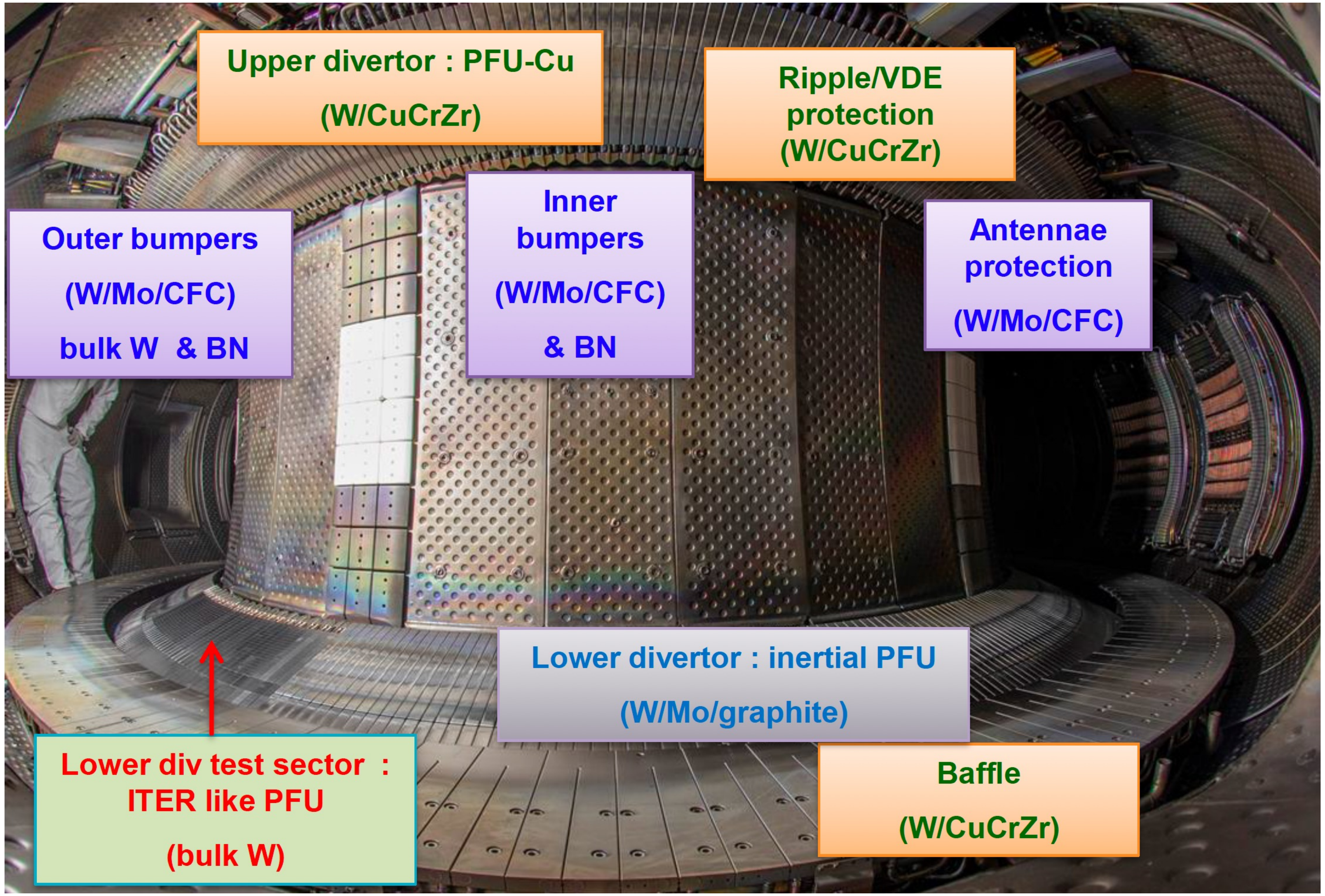
WEST Configurations and Parameters



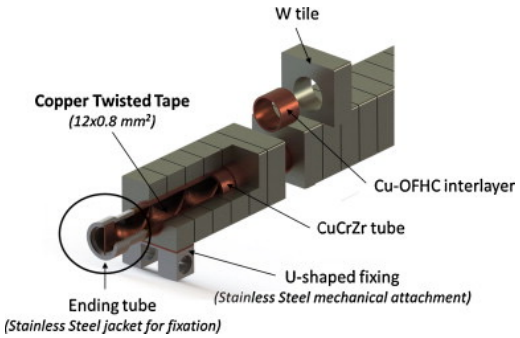
I_p (q_{95} ~ 2.5)	1 MA
B_T	3.7 T
R	2.5 m
a	0.5 m
A	5-6
Max κ	1.35
δ	Up to 0.5
V_p	15 m^3
n_{GW}	$1.5x10^{20}$ m^{-3}
P_{ICRH}	9 MW
P_{LHCD}	7 MW
$t_{flattop}$ (0.8 MA)	1000s

C. Bourdelle et al. 2015 *Nucl. Fusion* **55** 063017
P. Maget and J. Hillairet. WEST Exp. Plan. Meeting (3/22/21)

Full-W Environment of WEST



ITER-like Plasma Facing Units (PFUs)

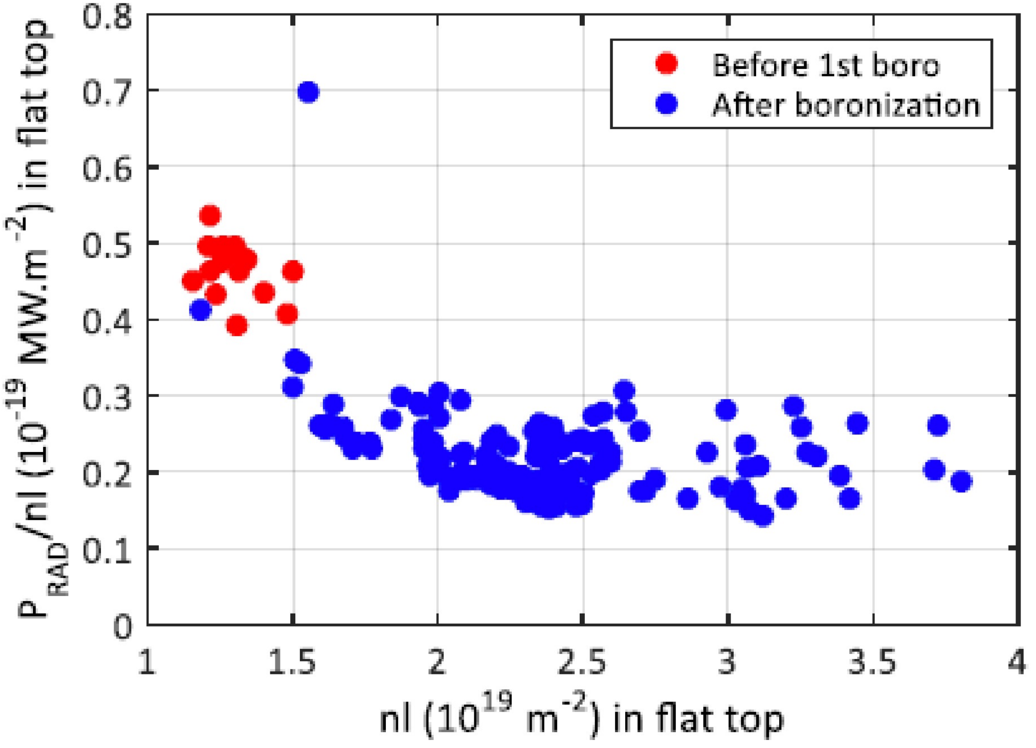


E. Tsitrone and the WEST Team. *IO Seminar*. 2020
“Testing and operating ITER-grade PFCs in WEST (TF-W1): Overview of WEST phase 1

Wall Conditioning Needed For Metal-Walled Machines, Alternate Methods Needed for Superconducting Tokamaks

- Vessel wall can act as an unpredictable source of fueling and impurities
  - Sputtering of high-Z material into the plasma can degrade confinement[1]
- Glow Discharge Boronization (GDB) is a proven method to condition plasma-facing components
  - Needed on WEST to expand operating space[2]
- Standard GDB techniques require de-energization of the magnetic field coils
  - Not conducive to a superconducting tokamak or steady-state pilot plant
  - Requires toxic/explosive diborane gas

Impact of Boronization on the WEST Operating Space



Courtesy of D. Douai

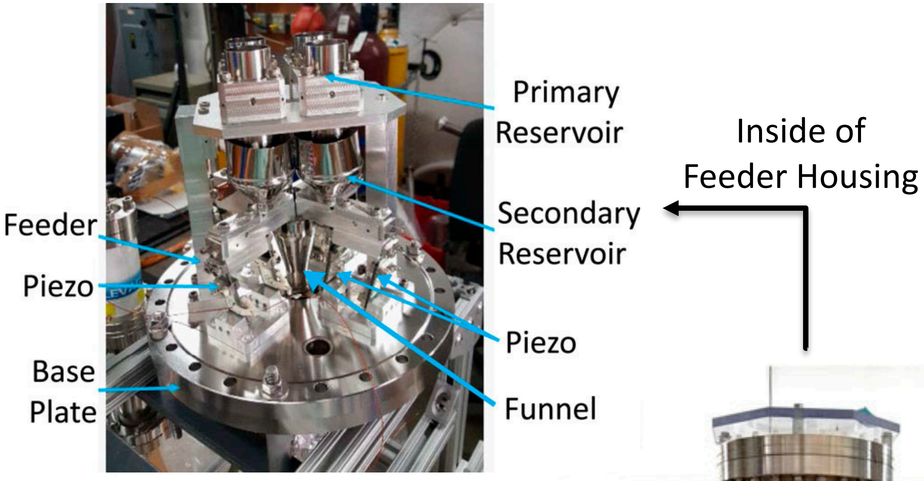
[1]E. Joffrin *et al* 2014 *Nucl. Fusion* **54** 013011

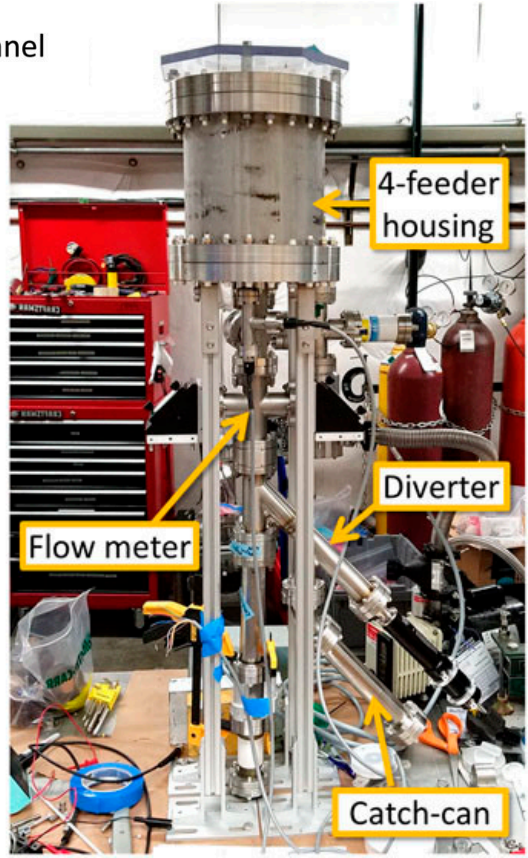
[2]J. Bucalossi *et al.* 2022 *Nucl. Fusion* **62** 042007

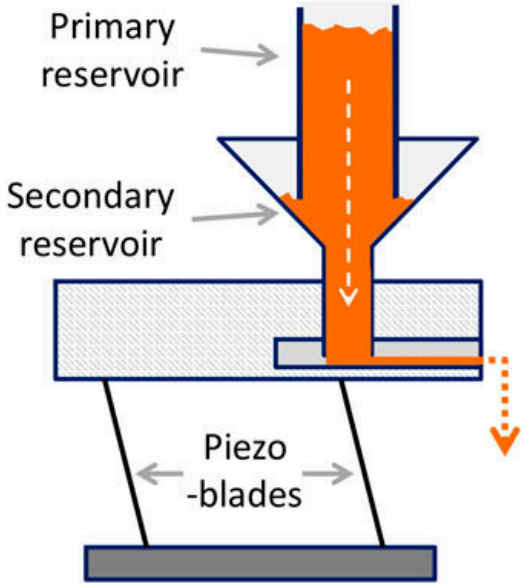
P. Maget & J. Hillairet et al. WEST Experimental Planning Meeting (3/22/21)

Impurity Powder Droppers (IPDs) Provide Real-Time Wall Conditioning By Dropping Low-Z Powders into Plasma

- Designed by PPPL, installed on: AUG, EAST, W7-X, LHD, DIII-D, and WEST
- IPDs have 4 individual feeders which can each hold 25 g of low-Z powder
- Powder drop rate is controlled using piezo-electric blades
  - The oscillation rate of the blades is proportional to a user-provided drive voltage
  - Drop rate is monitored using a fiber optic coupled flowmeter







A. Nagy et al., 2018 *Rev. Sci. Instrum.* ***89*** 10K121

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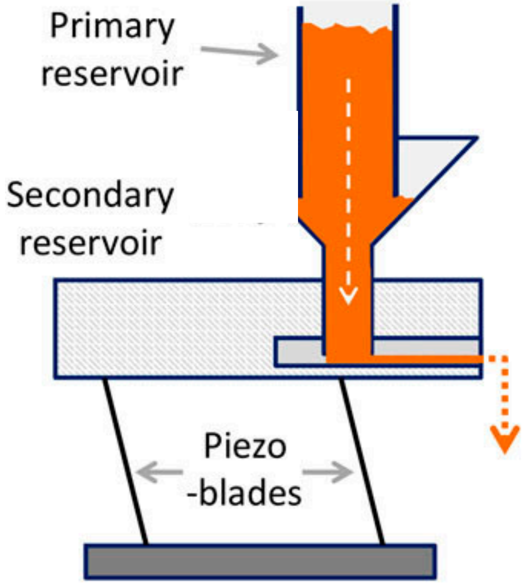
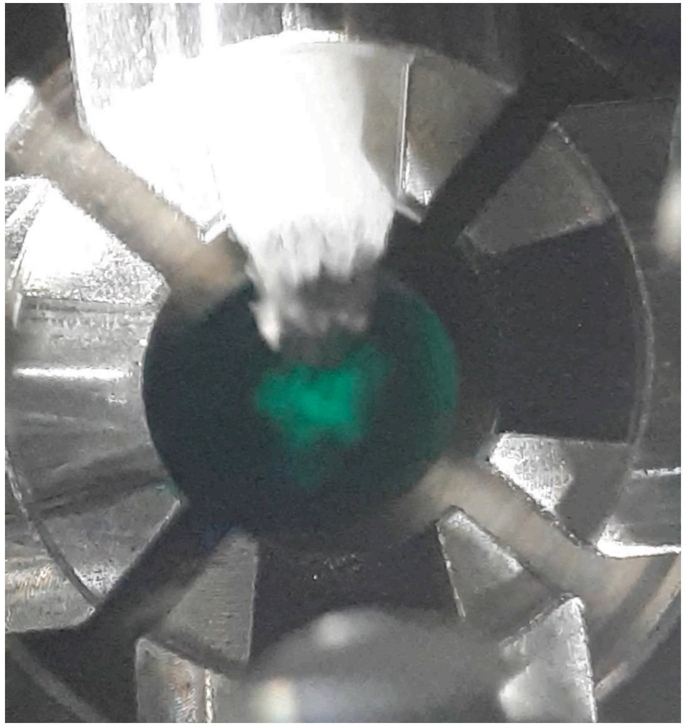


Powder Drop During Calibration



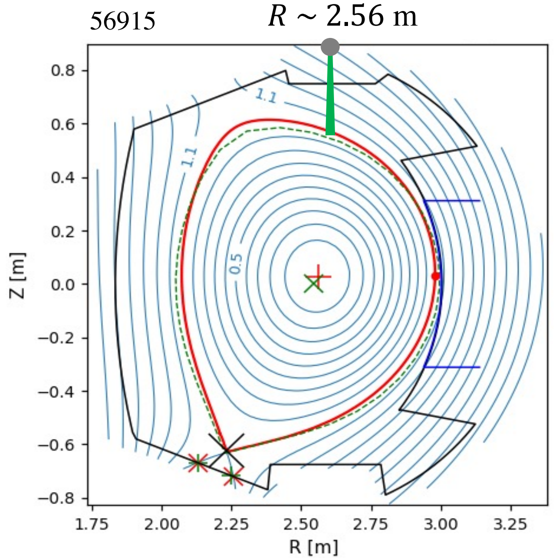
A. Nagy et al., 2018 *Rev. Sci. Instrum.* ***89*** 10K121

IPD Installed on WEST Through Collaboration Between DOE-PPPL and CEA-IRFM

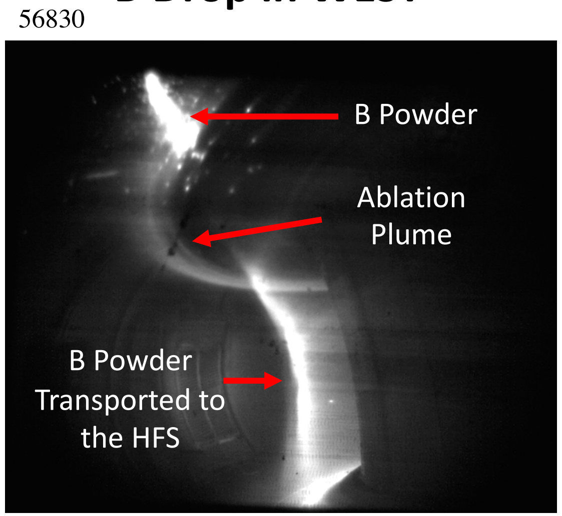
- Objectives for the IPD collaboration:
  - Provide real-time wall conditioning of W PFCs, especially LHCD and ICRH antenna limiters
  - Facilitate H-mode access by limiting the W influx
- WEST allows for evaluation of the IPD in a reactor-relevant environment on long-pulse time scales
- B powder is ablated by the tokamak plasma and then transported around the machine by toroidal flows

IPD Installed on WEST

IPD Location



B Drop in WEST



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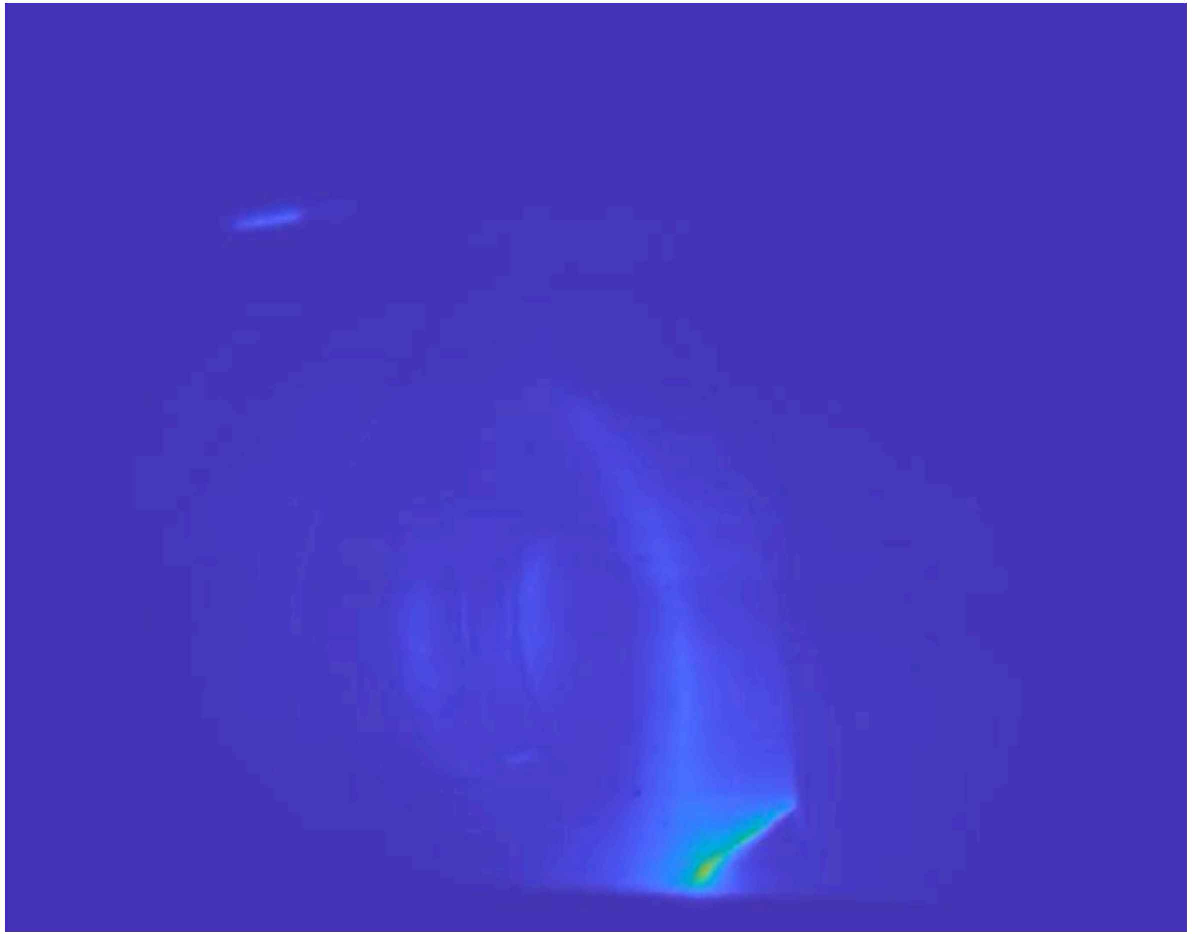
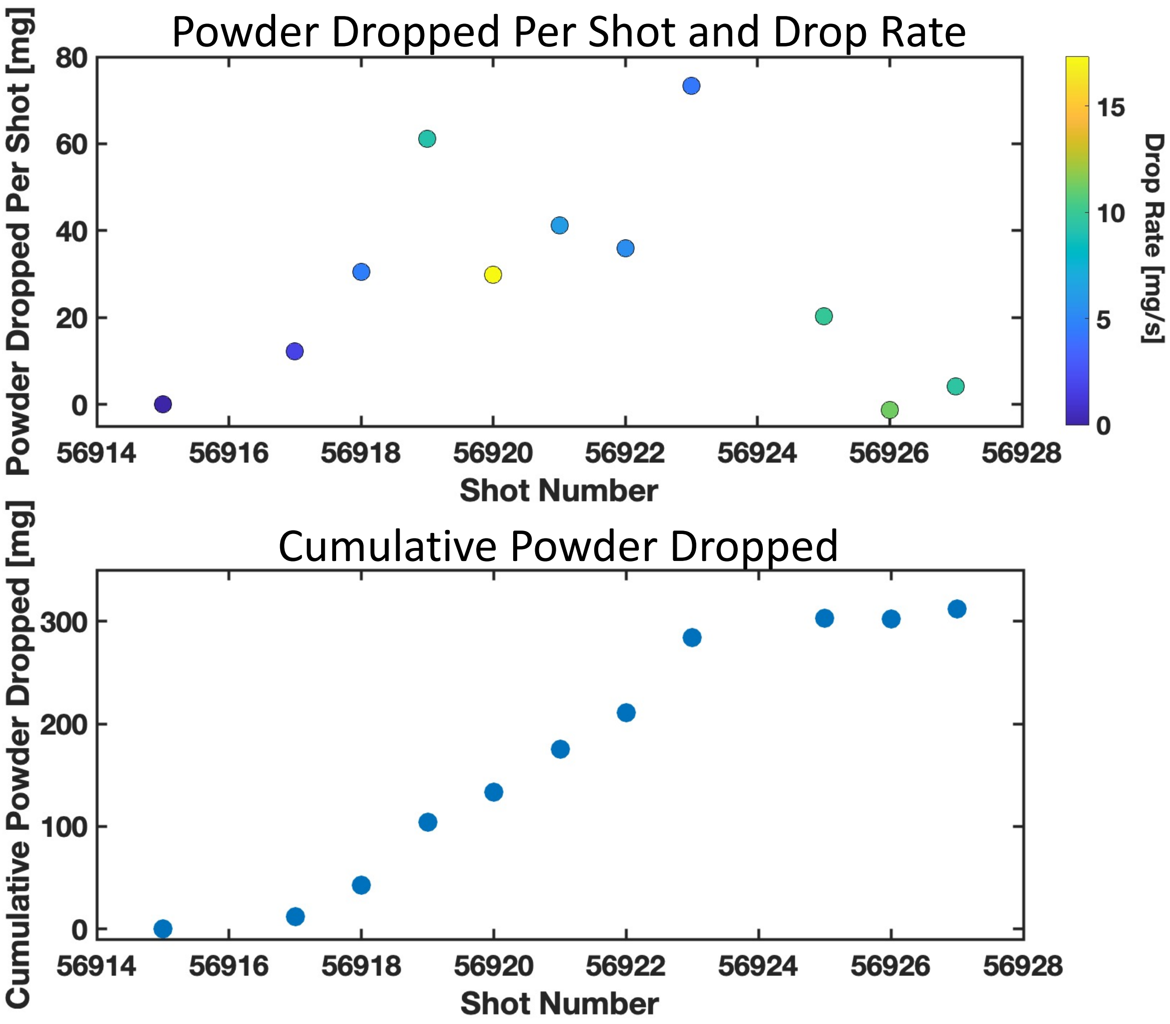
56830 B Drop in WEST LSN Discharge



Initial Powder Injection Experiments Used to Determine the Optimal Drop Rate

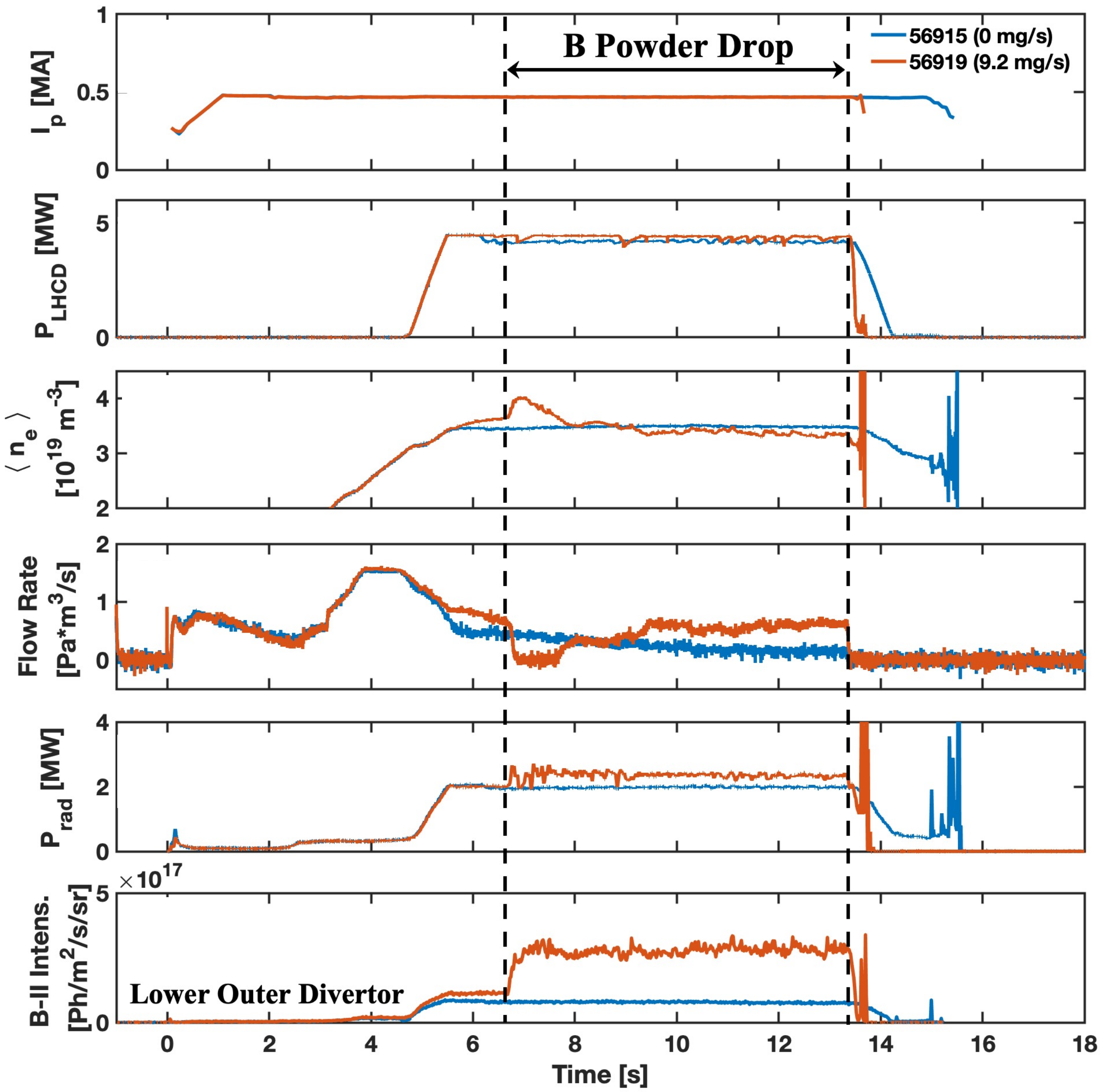
- B powder was dropped into 10 LSN L-Mode WEST discharges
  - 56915 was reference discharge (no powder dropped)
- Optimal drop rate was found to be 9 mg/s to 17 mg/s
  - Large drop rates (≥ 17 mg/s) were more prone to disruptions
  - Increased input power may permit larger drop rates in the future[1]
- Cumulative B dropped: 310 mg
  - About 1.5% of 1 reservoir
  - IPD has 4 reservoirs (25,000 mg/reservoir)



[1]Bortolon et al. 2019 *Journ. Of Nucl. Instrum.* **19** 384-389

Impact of B Powder Injection Observed Primarily in n_e and P_{RAD}

- WEST L-Mode discharges robust to powder injection
  - I_p = 0.5 MA, B_T = 3.7 T, P_{LHCD} = 4.5 MW, n_e = 3.5×10^{19} m^{-3}, q_{95} = 4.3
  - Minimal effect on LHCD coupling
- Increase in n_e during initial phase of powder drop, not sustained
  - n_e decreases slightly during I_p flat-top despite increased fueling
- Sustained increase in radiated power (~20%) observed during B drop



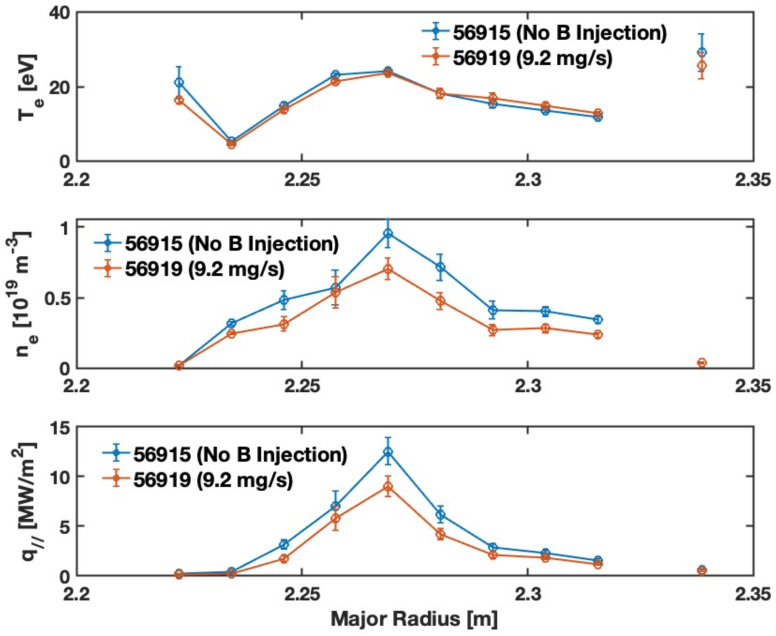
Divertor Langmuir Probes Show a Constant Decrease in SOL n_e during B Powder Injection

- Decrease in n_e more evident in the SOL (~50% reduction for 9.2 mg/s of B powder)
  - More evidence of reduced wall recycling

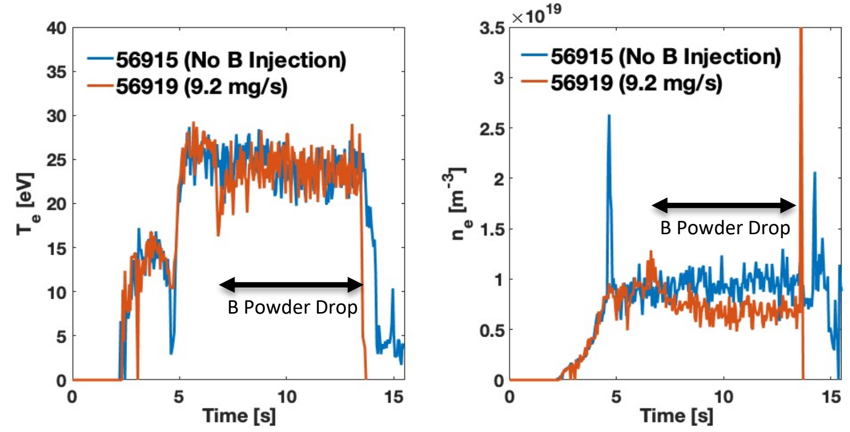
- Small drop in the SOL T_e during the initial drop phase, then signal returns to nominal pre-drop level

- $q_{\parallel}$ at the divertor reduced during powder injection due to decrease in density

Divertor Langmuir Probe T_e, n_e, and $q_{\parallel}$ from 7-13 s



Divertor Langmuir Probe $T_e(t)$ and $n_e(t)$ at R= 2.28 m



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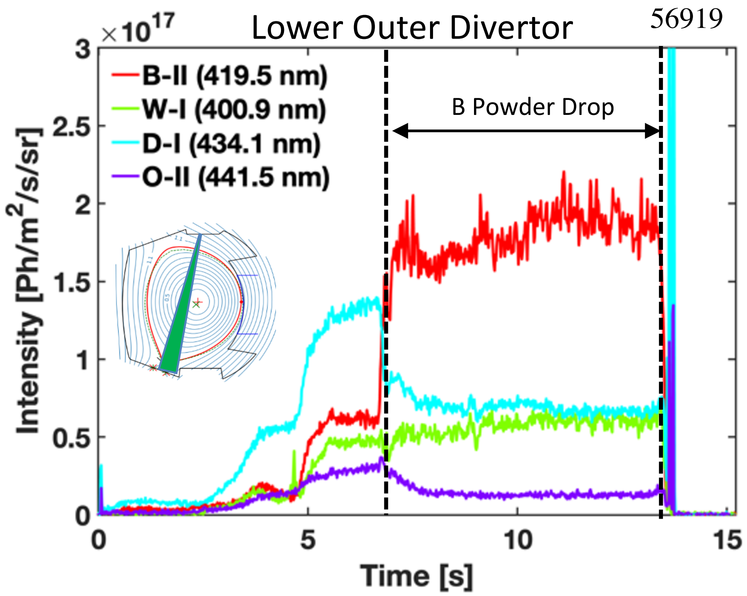
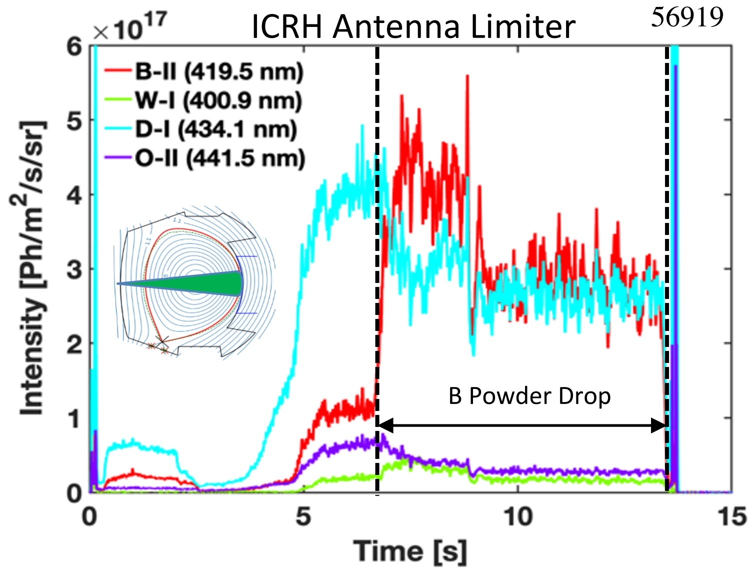
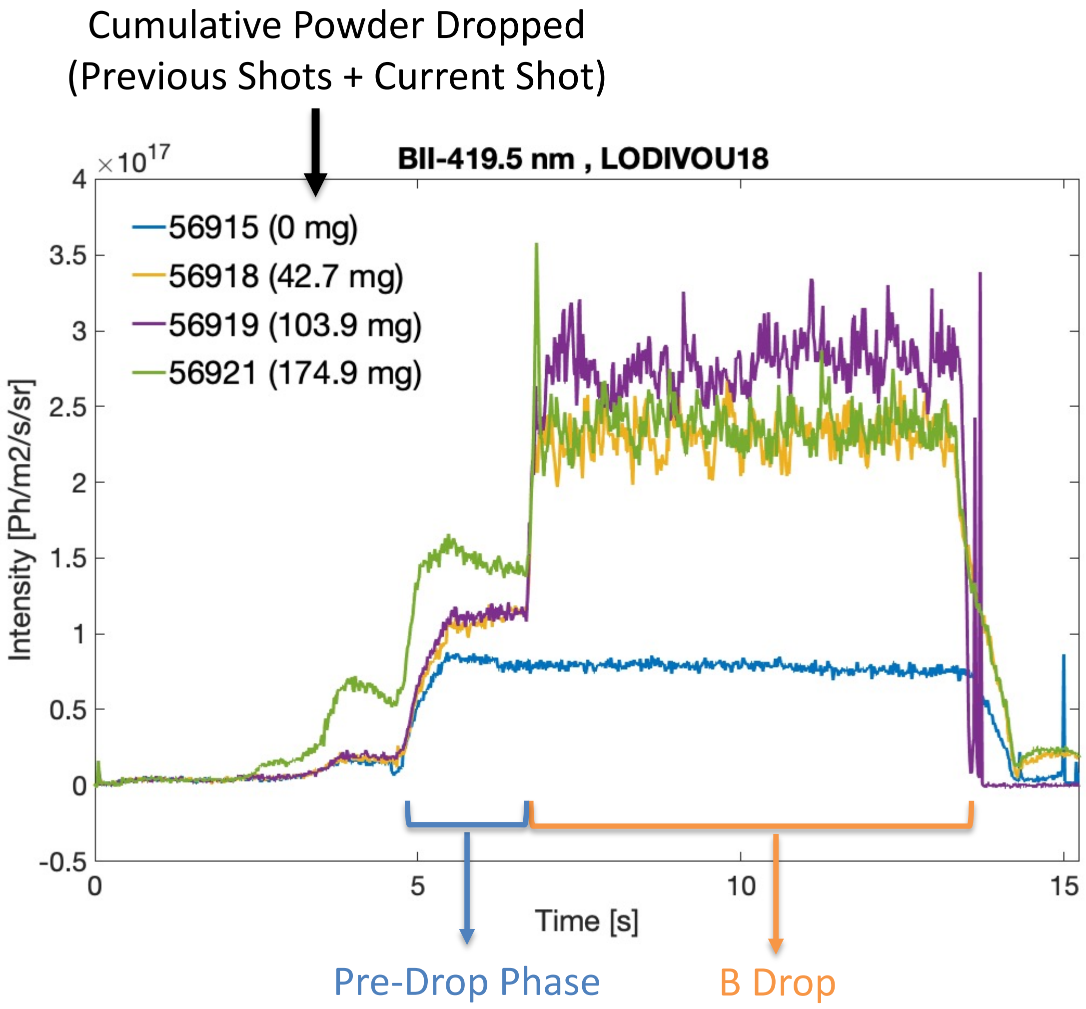
Extensive Visible Spectroscopy System Used To Evaluate Impact of Powder Injection on SOL Impurity Concentrations

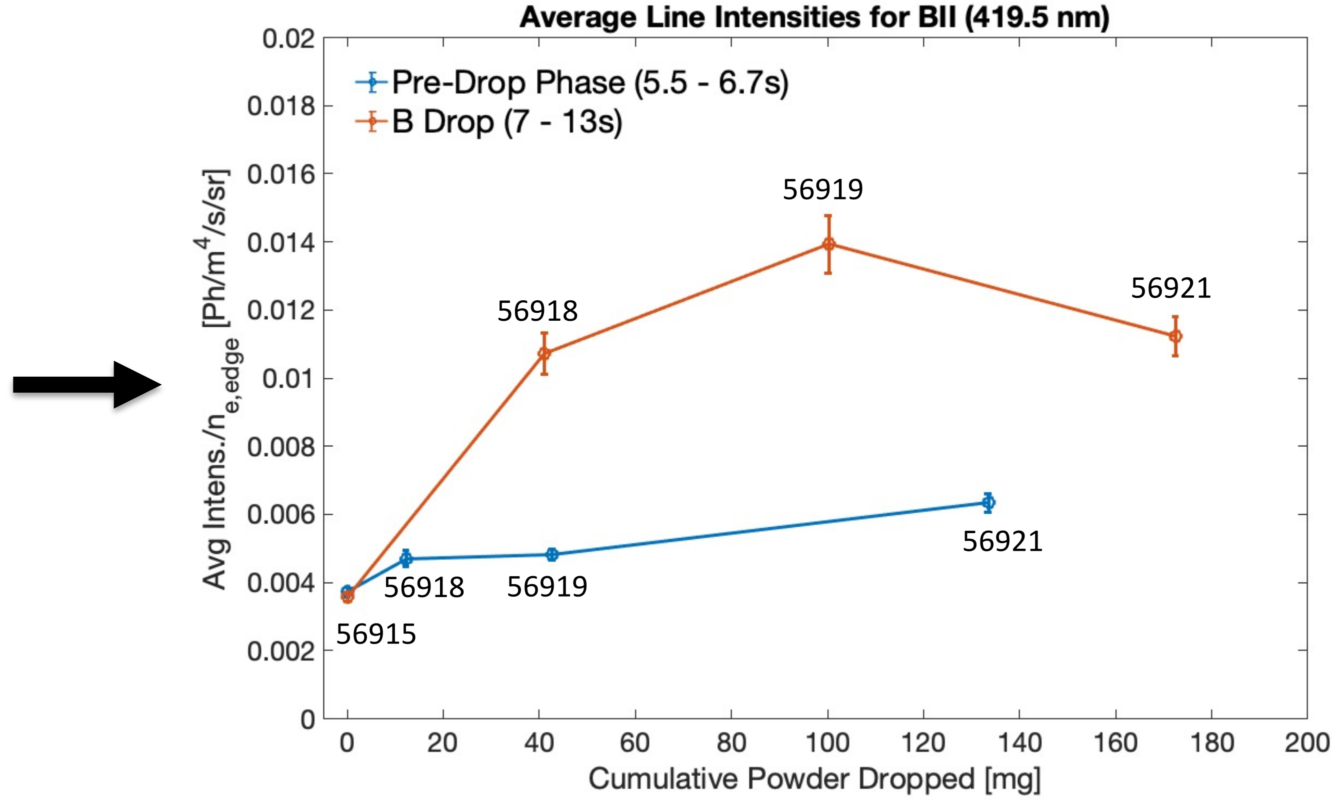
- Analysis focused on lower divertor and ICRH antenna limiter due to LSN configuration and limiter position
- Powder injection led to large increase in B-II line intensity and reduction in D_γ and low-Z impurity line intensities
- Increase in W-I line intensity at both the lower divertor and ICRH antenna limiter
  - B becomes dominant sputtering mechanism
  - Similar results observed in powder injection experiments on AUG[2]





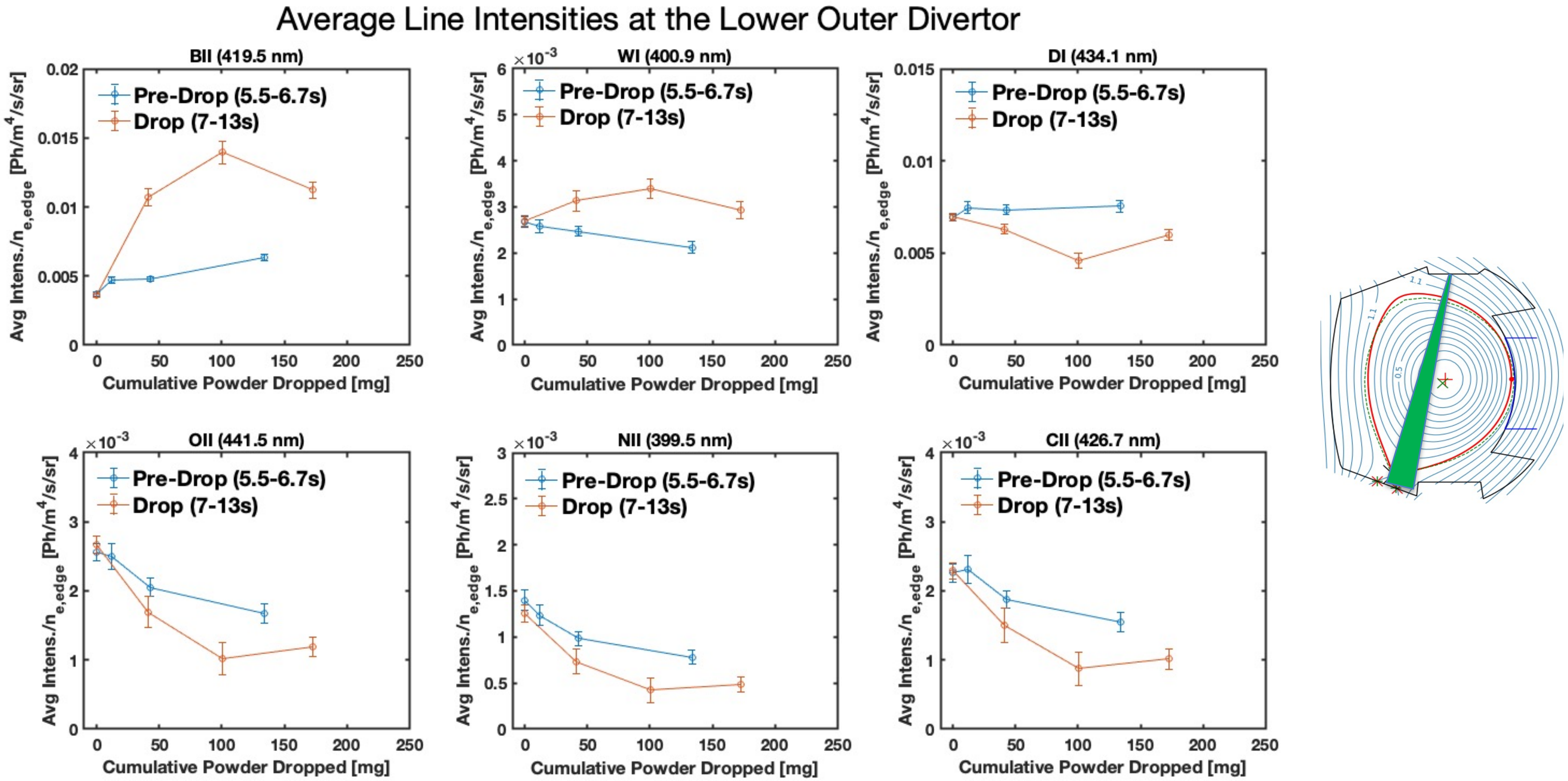
Time-Averaging of Visible Spectroscopy Signals Shows Evolution of Spectral Lines Over Several Shots





- Line intensities normalized to edge interferometry channel to account for any n_e variations

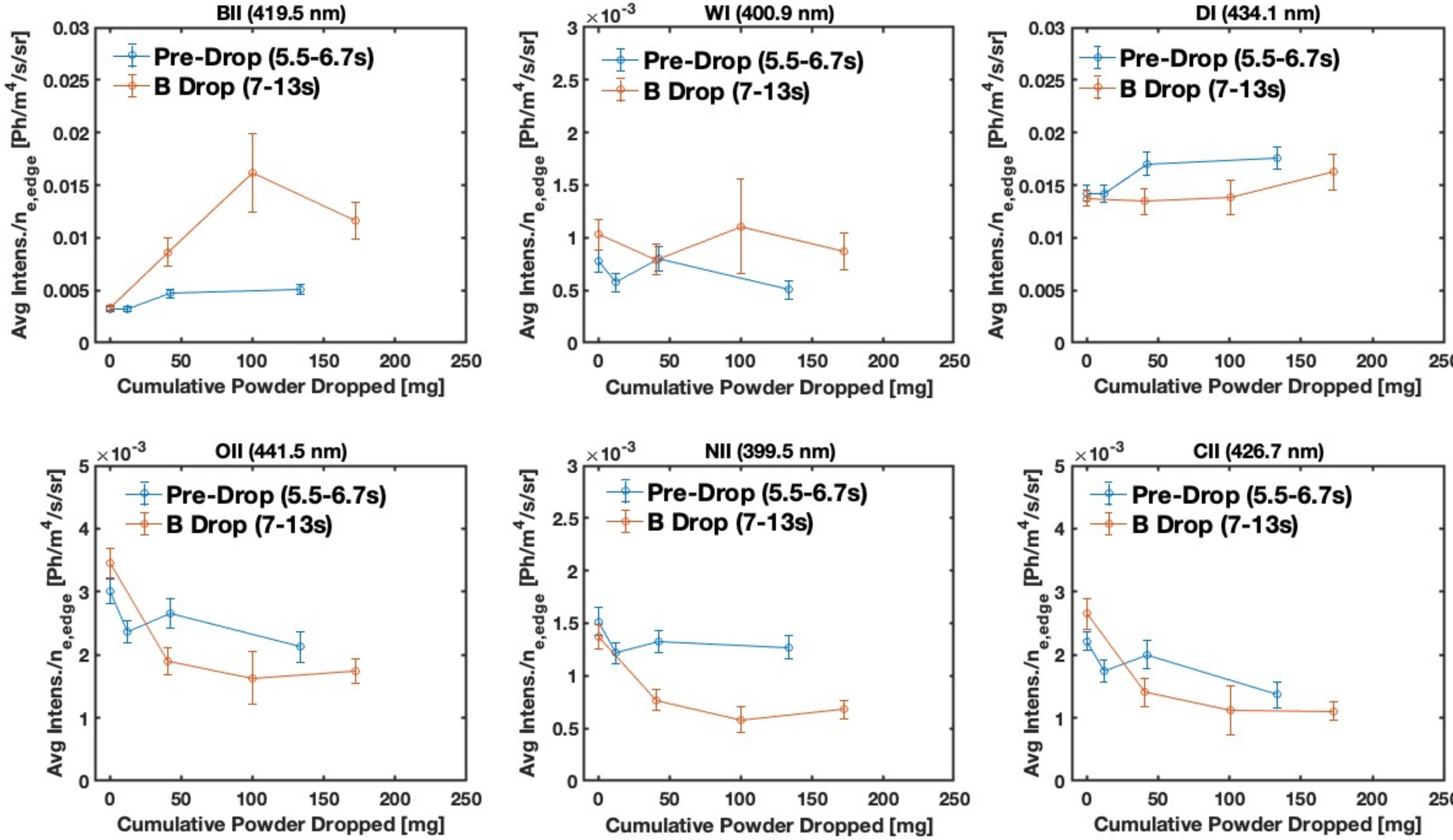
Conditioning of the Lower Outer Divertor Improves As More B Powder is Injected

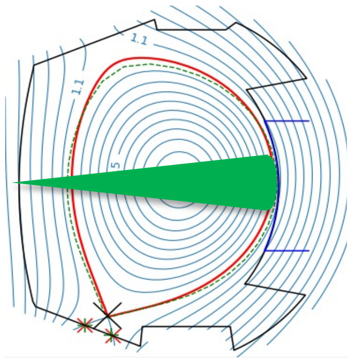


- Increase of pre-drop B-II signal may be evidence of thin-film deposition
- Decrease in pre-drop levels of W-I and O-II are encouraging signs of cumulative wall conditioning

Similar Indications of Improved Conditioning Observed at the ICRH Antenna Limiter

Average Line Intensities at the ICRH Limiter





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Estimates of Particle Flux Using S/XB Coefficients Confirm Trends From Visible Spectroscopy

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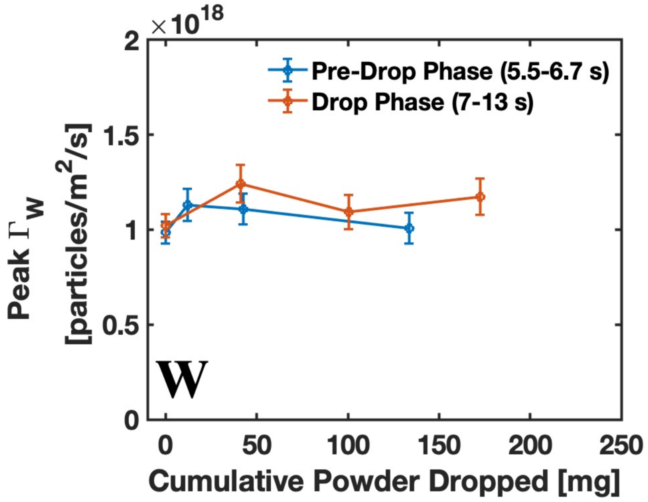
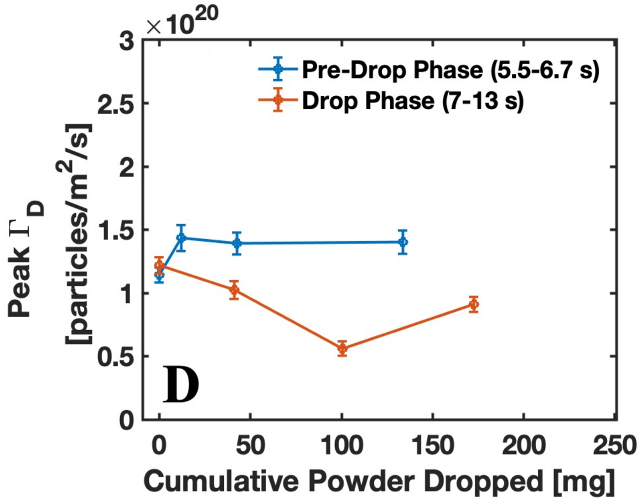
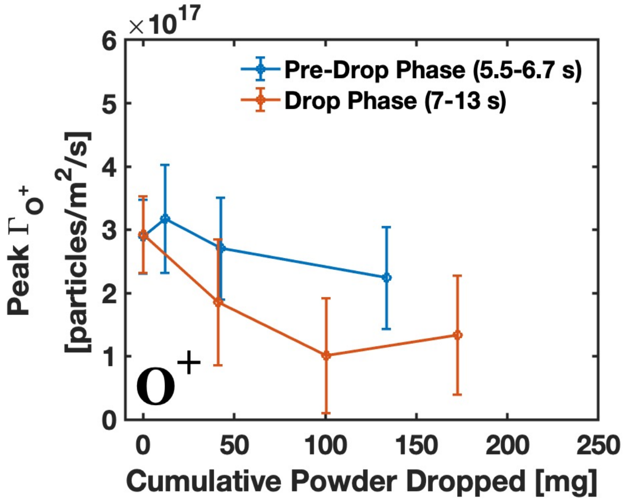
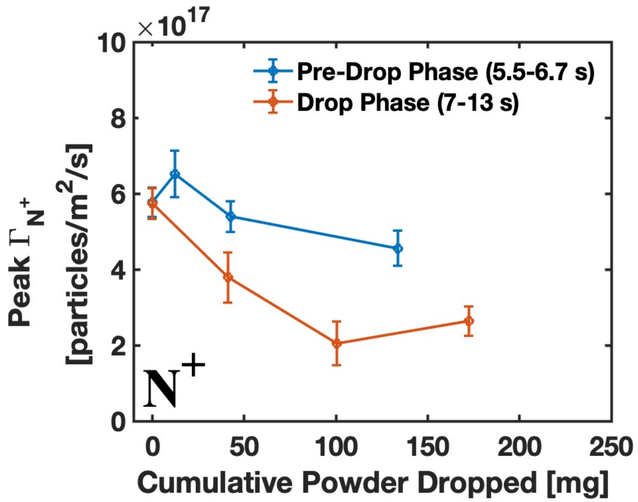
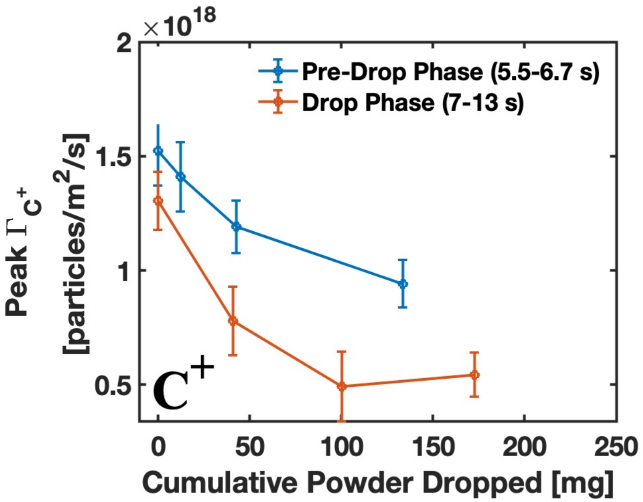










$$\Gamma_A = \frac{S}{XB}(T_e, n_e)\phi_A$$

Spectroscopy (ϕ_A)

DLPs (T_e, n_e)

ADAS and ColRadPy[1] ($\frac{S}{XB}$)

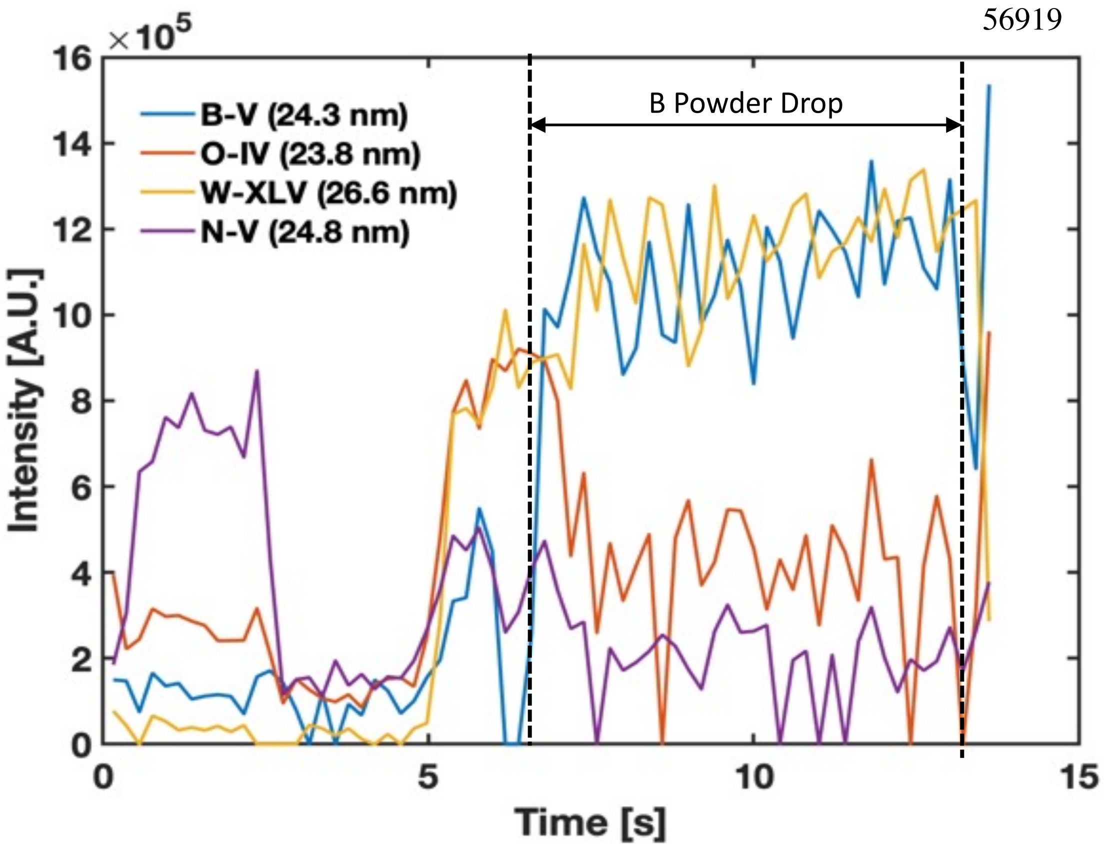
[1] C.A. Johnson et al., 2019 *Nuclear Materials and Energy* **20** 100579

VUV Line Intensities Suggest B and W May Sputter Into Plasma During Powder Injection

- VUV data only available from the WEST real-time VUV system
  - Single central viewing chord
  - 22-30 nm wavelength range

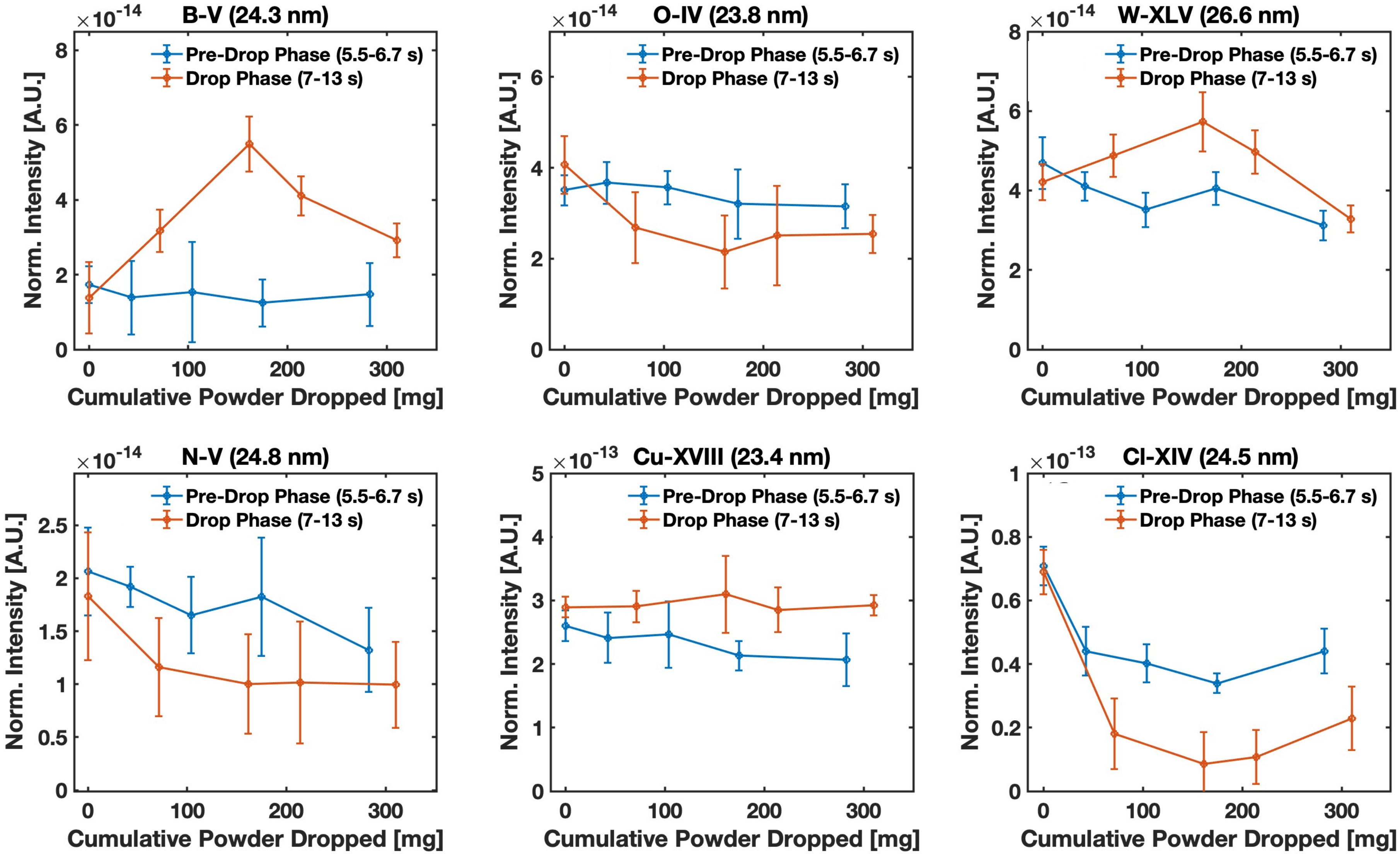
- B-V and W-45+ line intensities increase during the B drop
  - Decrease in O-IV and N-V

- Difficult to determine radial penetration due to lack of edge T_e and knowledge of charge-state distribution



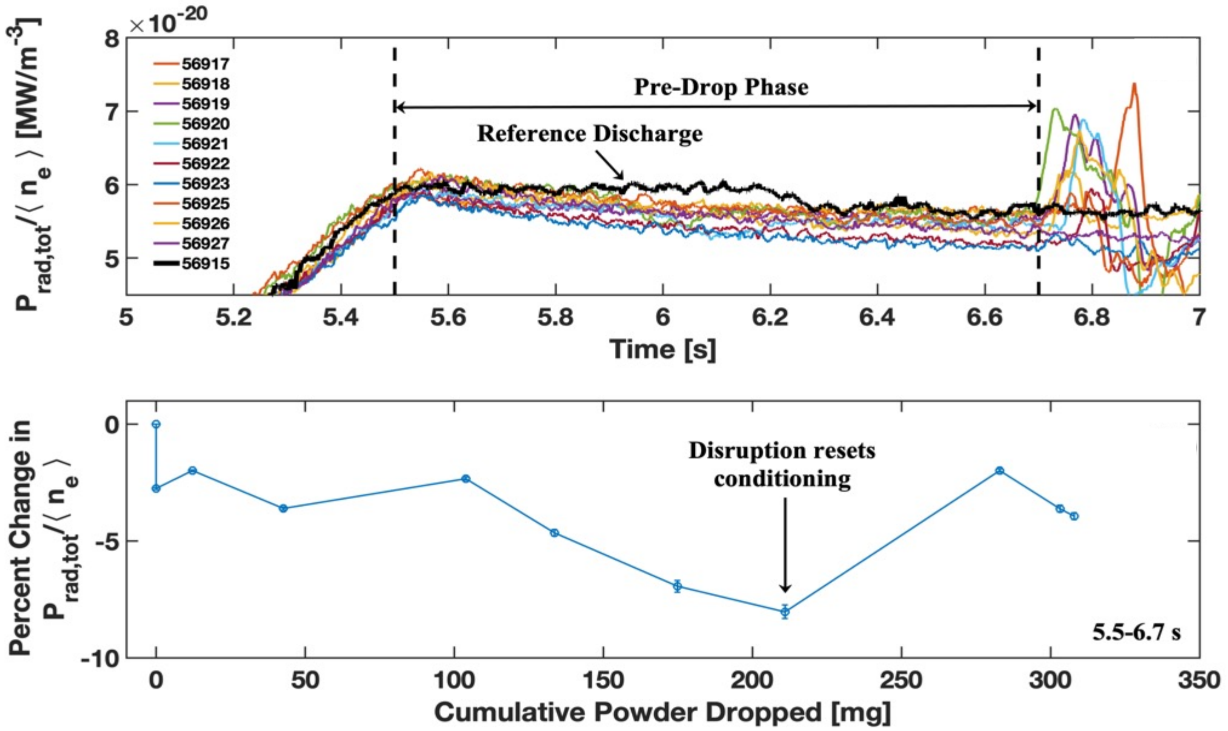
Sputtering of B and W not Observed in Pre-Drop Phase of Discharges Following B Injection

56915 56918 56919 56921 56923



Evidence of Wall Conditioning Observed in Total Radiated Power

- Pre-drop $P_{rad,tot}$ decreases as more B powder is injected
- Disruptions may remove the deposited low-Z films and degrade the conditioning effect
  - May also produce large out-gassing from the walls



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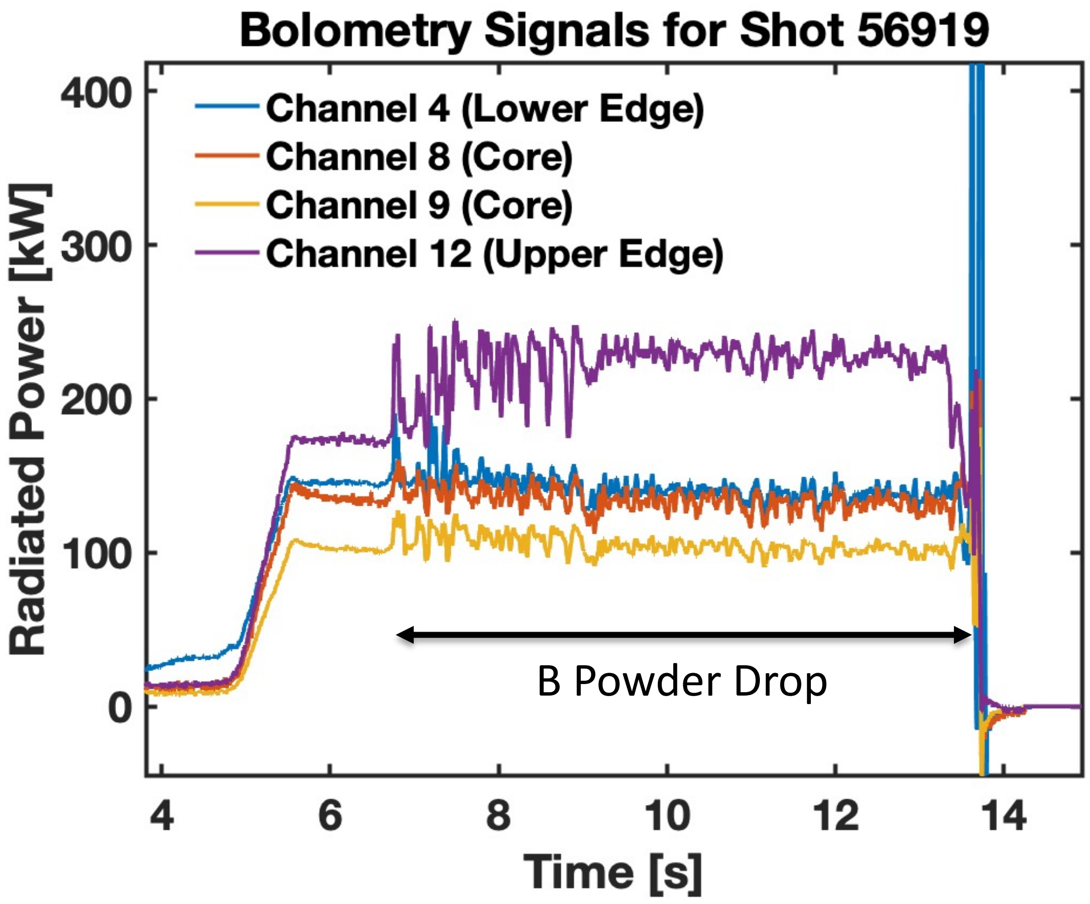
- Increase in P_{rad} localized to upper edge, near injection site



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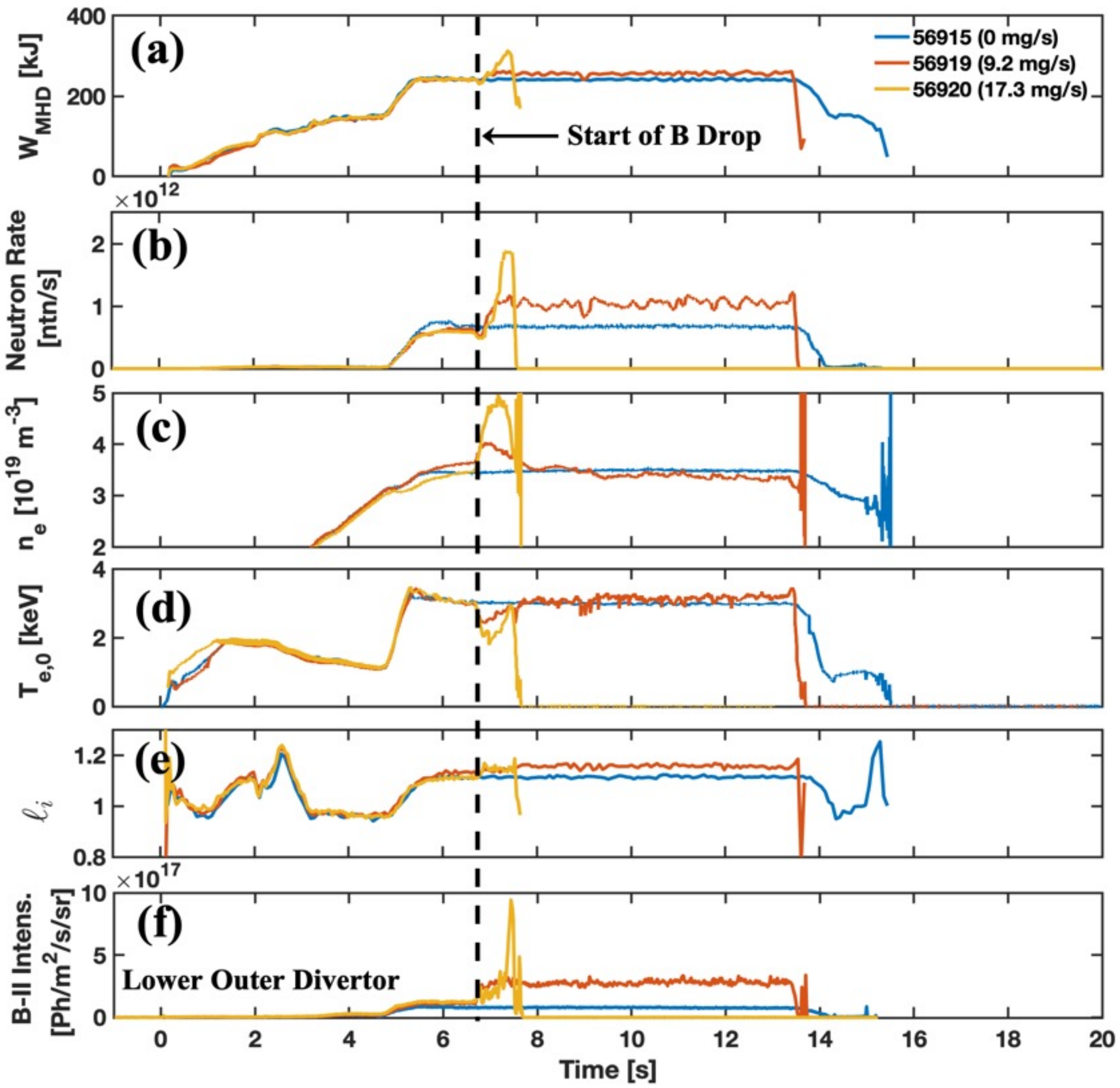
Improvements in Global Confinement Observed During Boron Powder Injection

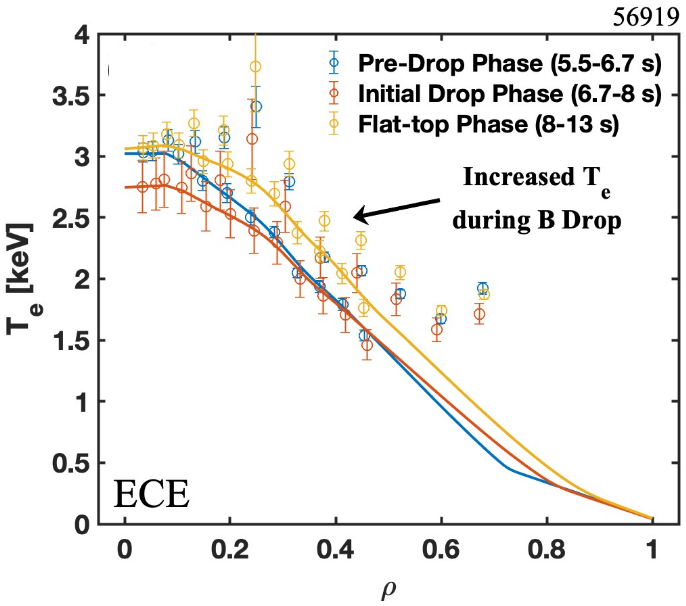
- W_{MHD}, neutron rate ($\propto T_i$), and T_e increased despite constant I_p and P_{LHCD}
- W_{MHD} increases up to 25% in one case, however discharge disrupts due to rapid increase in n_e and P_{rad}
  - Increase in W_{MHD} and neutron rate not transient, lasts entire drop duration
- Similar increase in confinement have been observed on AUG[1,2], W7-X[3], and LHD[4]

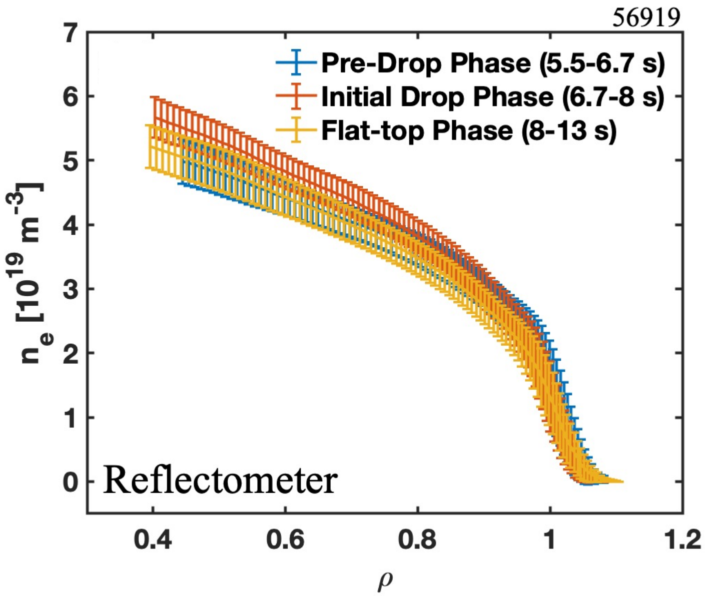


[1]R. Lunsford et al. 2019 *Nucl. Fusion* **59** 126034
[2]A. Bortolon *et al.* 2019 *Journ. Nucl. Instrum.* **19** 384-389
[3]R. Lunsford *et al.* 2021 *Phys. Plasmas* **28** 082506
[4]F. Nespoli *et al.* 2022 *Nat. Phys.*

T_e Profile Broadens Significantly During Powder Injection

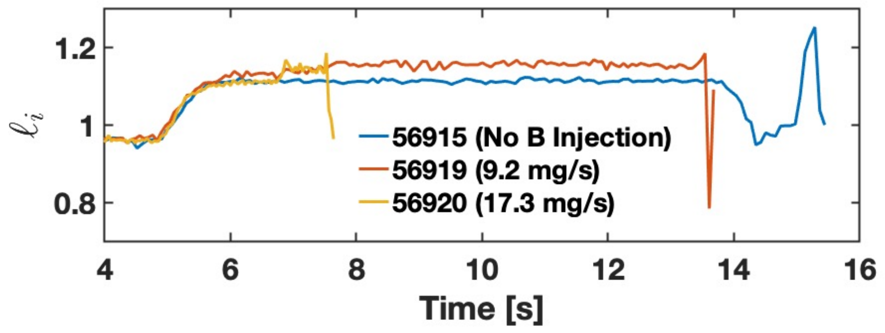
- $T_{e,0}$ decreases during initial drop phase, presumably due to n_e rise
- During flat-top phase, $n_{e,0}$ is slightly higher and T_e profile is much broader
  - ECE data unreliable past $T_e(\rho) \sim 0.5$ due to pollution from LHCD
- Core density peaking and/or change in the edge gradient play a role in improved performance



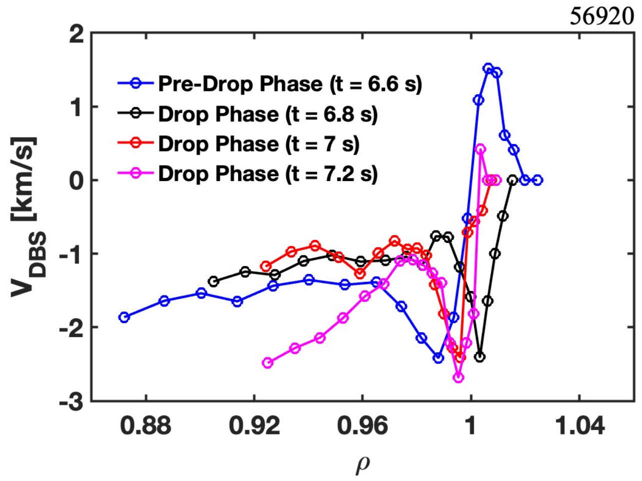


Improvements in Confinement Not Related to L-H Transition

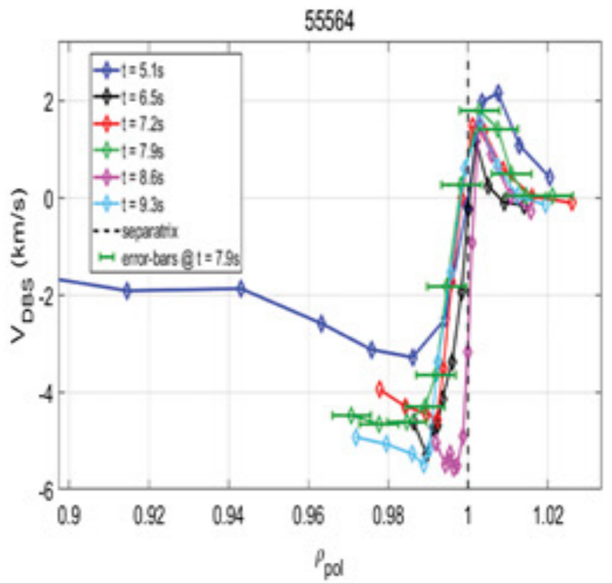
- No evidence of pedestal formation
  - Small rise in n_e during initial injection, but not sustained like increased W_{MHD}
  - Doppler reflectometry shows no formation of deep E_R well
- Plasma inductance slightly increases
  - Previous WEST L-H transitions showed decreases in ℓ_i (from increased bootstrap current)



Powder Injection Experiments



Previous L-H Transition in WEST

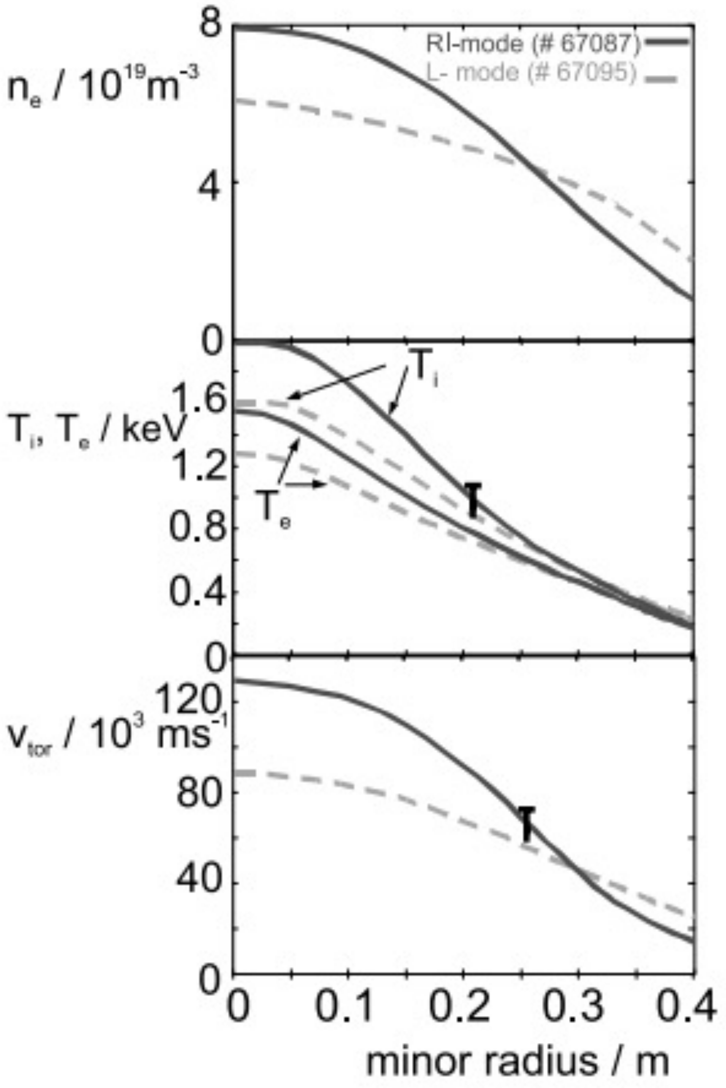


L. Vermare et al. 2022 *Nucl. Fusion* **62** 026002

Likely Mechanisms for Turbulence Suppression Are Core Density Peaking And/Or Fuel Dilution

- Impurity injection in TEXTOR L-Modes led to the radiative-improved mode[1]
  - H-mode like confinement, high radiation fraction, and no ELMs
  - Core density peaking dominant mechanism for turbulence suppression

Radiative-Improved Mode in TEXTOR



[1]B. Unterberg et al., 2005 *Fusion Sci. Technol.* **47** 187

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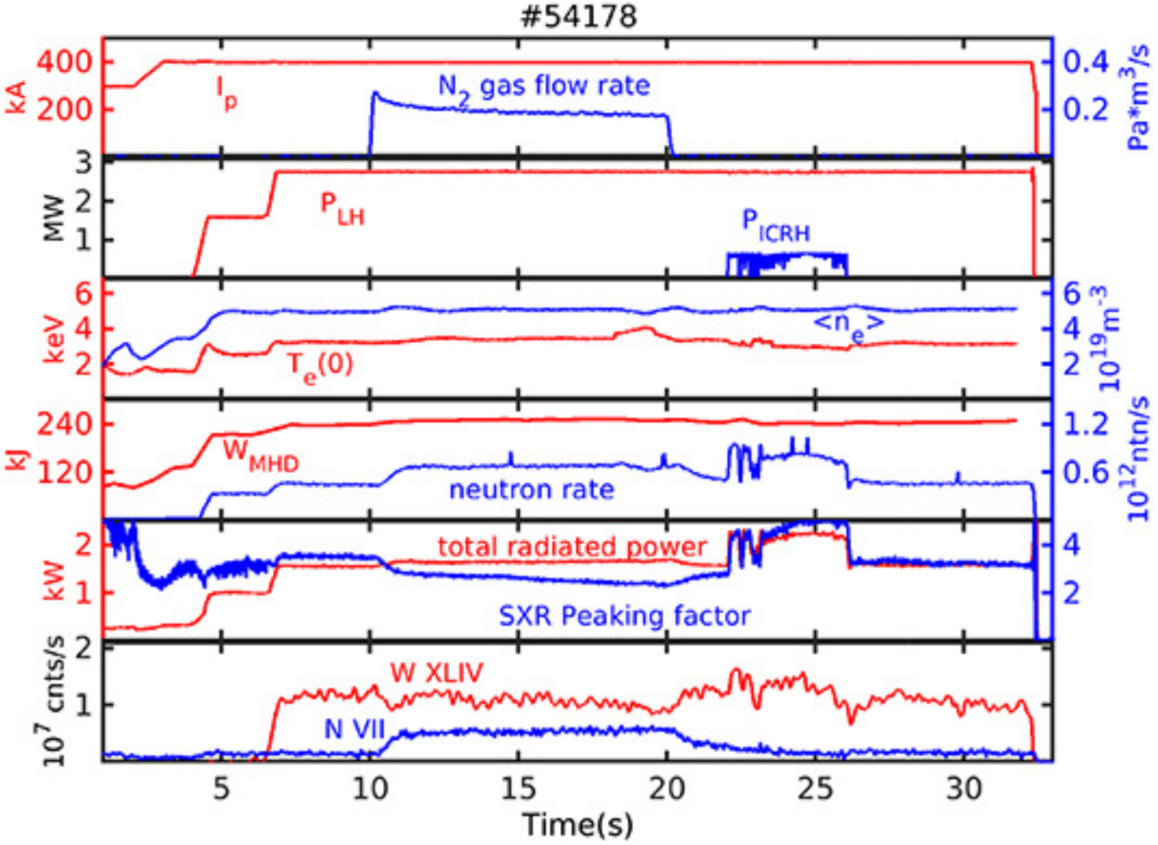
  - T_i increases due to main ion dilution which increases Z_{eff}, changes the current diffusion/shear, and suppresses ITG turbulence

N_2 Seeding Experiments in WEST L-Mode Plasmas



[1]Yang et al. 2020 Nucl. Fusion **60** 086012

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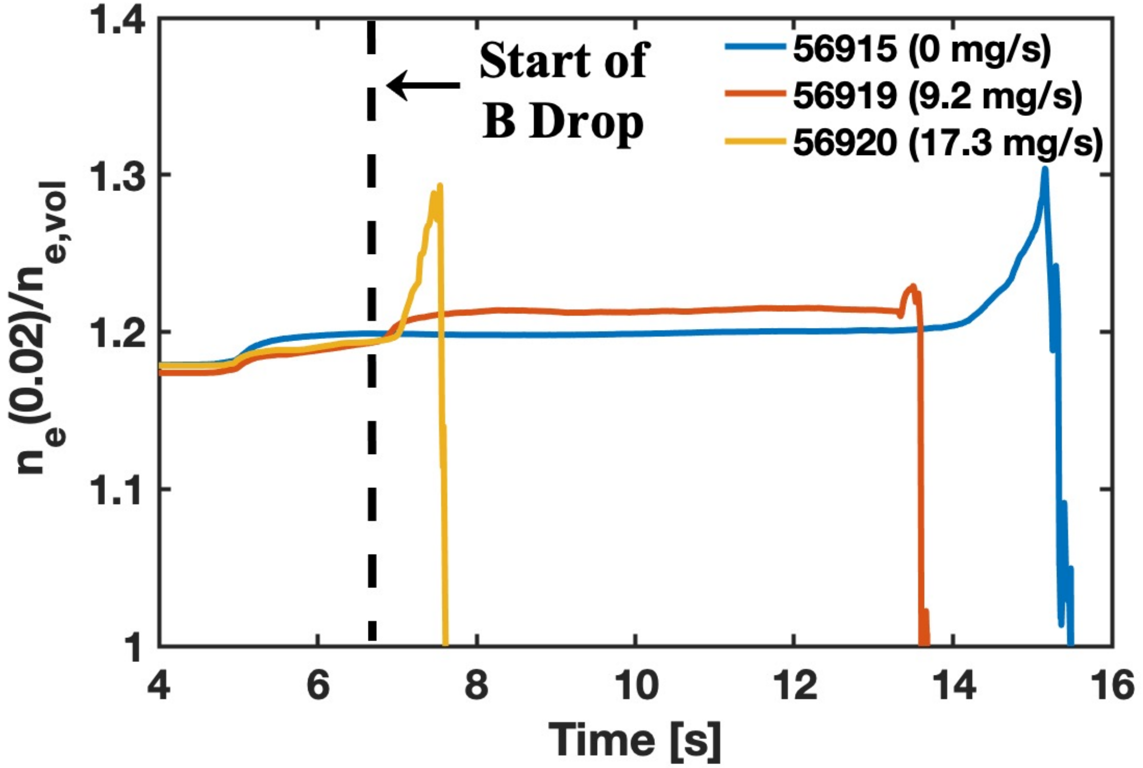
- Current picture is unclear for WEST powder injection discharges
  - Need interpretative modelling

Density Peaking Ratio of WEST Discharges with Powder Injection



Simulations Underway to Identify Mechanisms Behind the Improved Performance

- Experimental measurements complemented by fast integrated modelling code, METIS[1]
  - METIS combines 0D scaling laws with 1D current diffusion models and 2D equilibria
  - Generates data needed for gyrokinetic modelling

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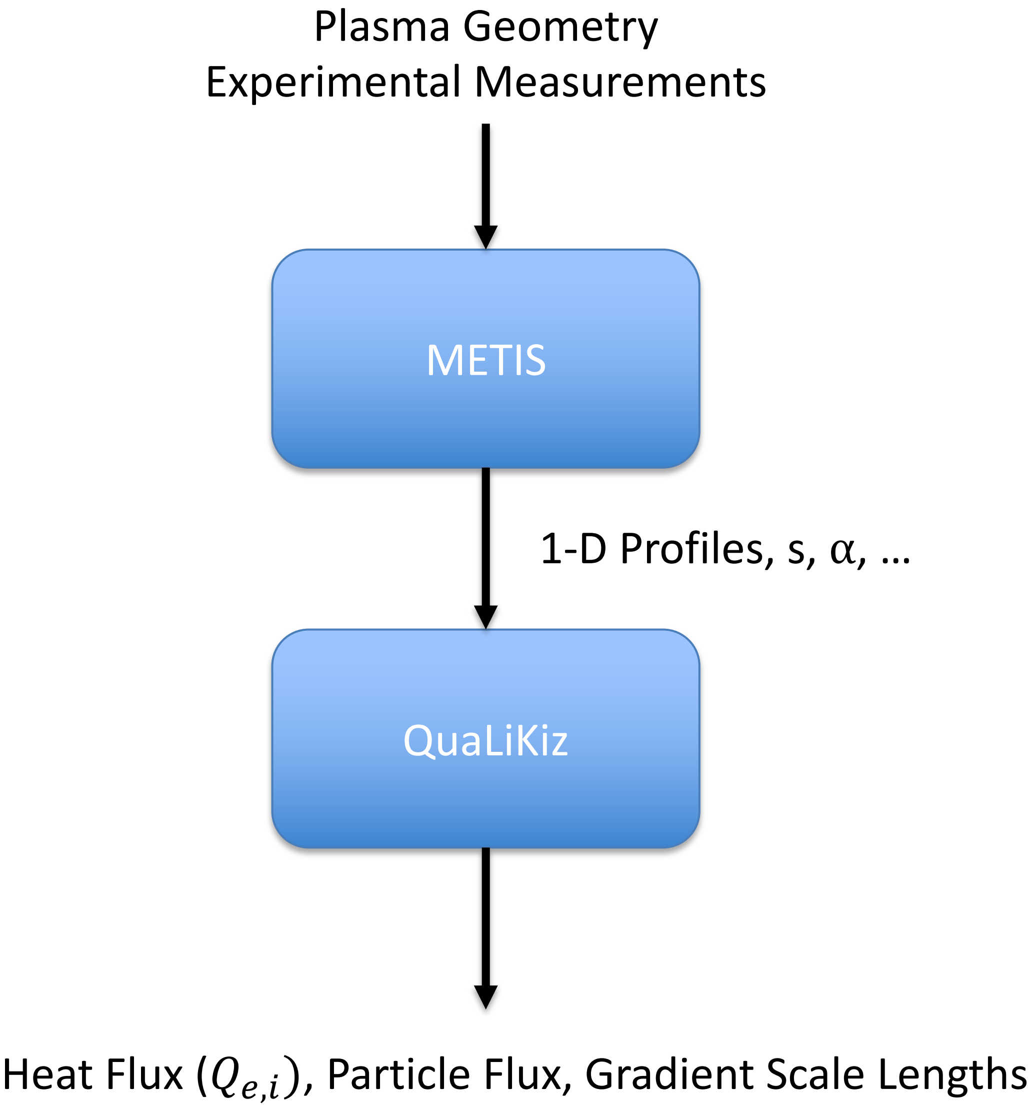

[1]J.F. Artaud *et al.* 2018 *Nucl. Fusion* **58** 105001
[2]C. Bourdelle et al., 2015 *Plasma Phys. Control. Fusion* **58** 014036

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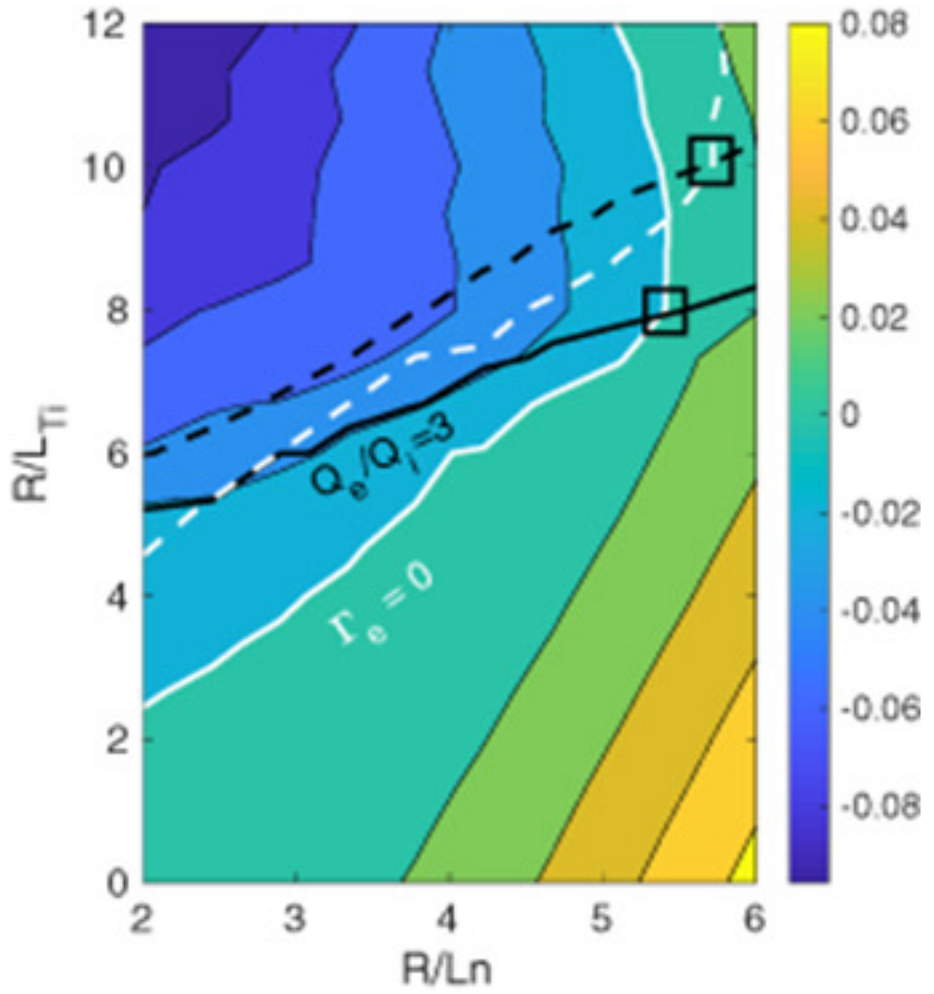
Normalized Electron Flux for WEST Discharges with and w/o N_2 Seeding



Yang et al. 2020 Nucl. Fusion **60** 086012

[1]J.F. Artaud et al., 2018 *Nucl. Fusion* **58** 105001
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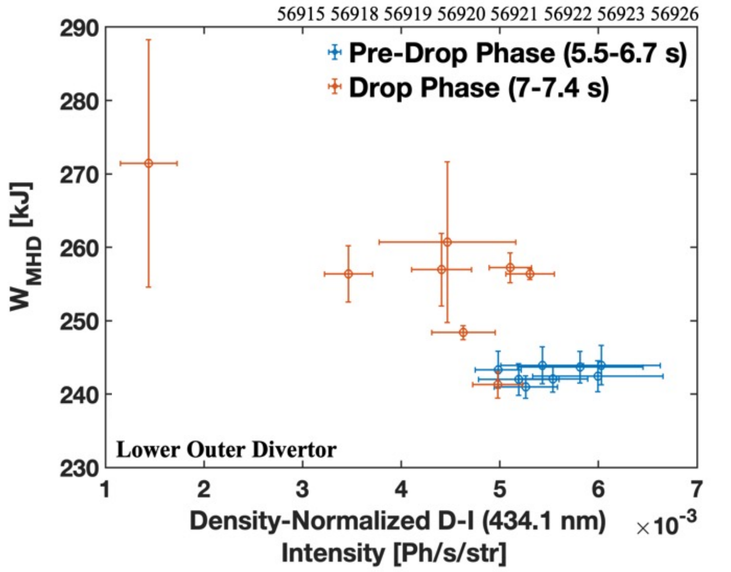
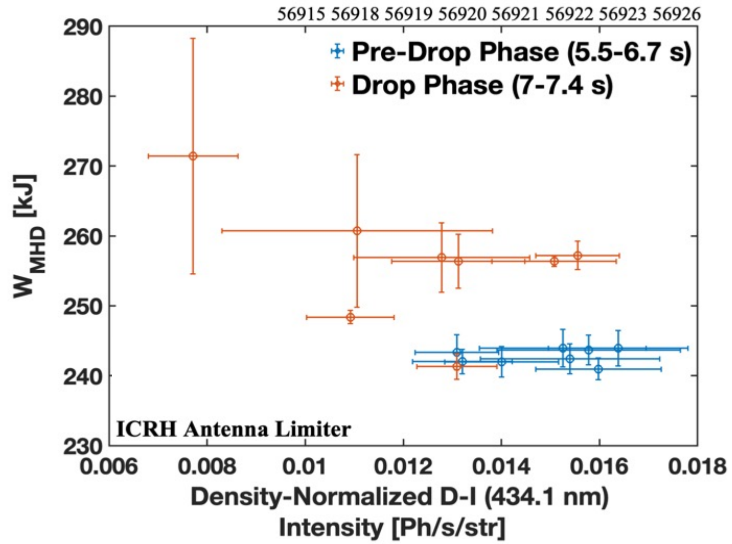
Empirical Correlations Show Possible Link Between Recycling and Improvements in Stored Energy

- Edge density normalized D_γ signal taken as proxy for the D recycling flux
- As the divertor recycling decreases, W_{MHD} during B injection increases
- Decrease in recycling may lead to additional fuel dilution
  - Further increases Z_{eff}

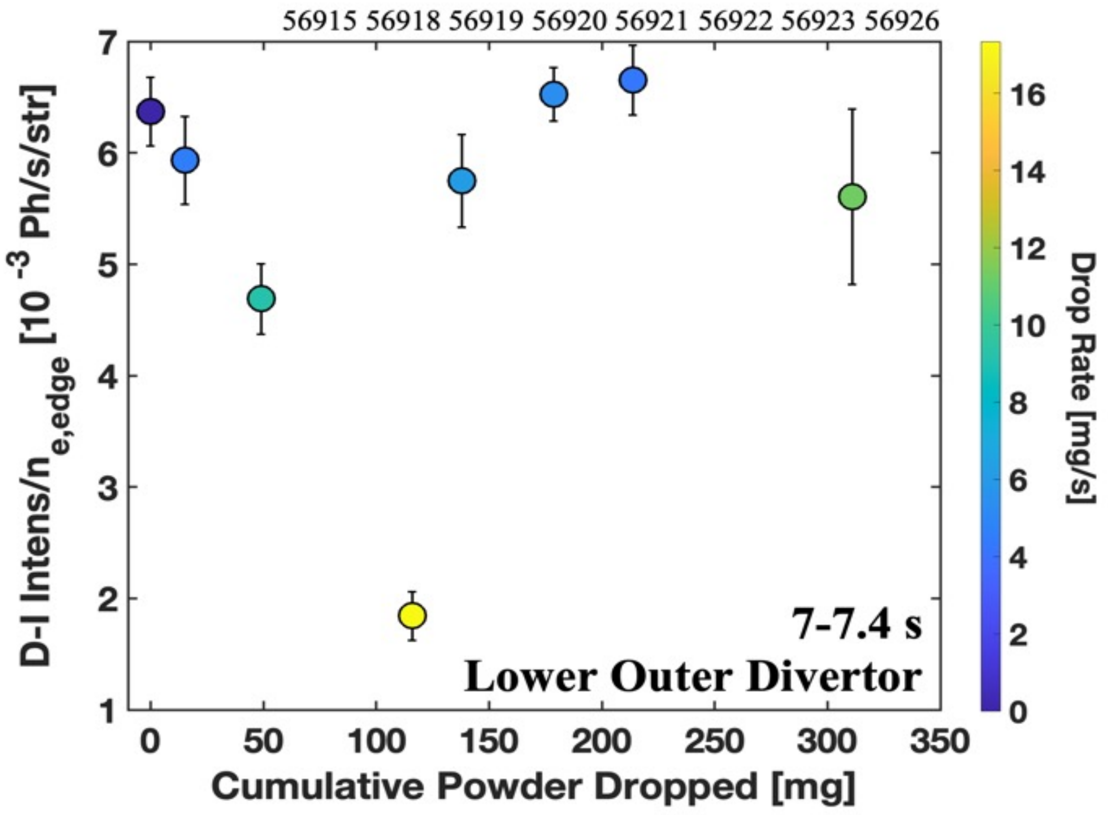




Decreases in Recycling Dependent on the Powder Drop Rate Rather Than the Cumulative Powder Dropped

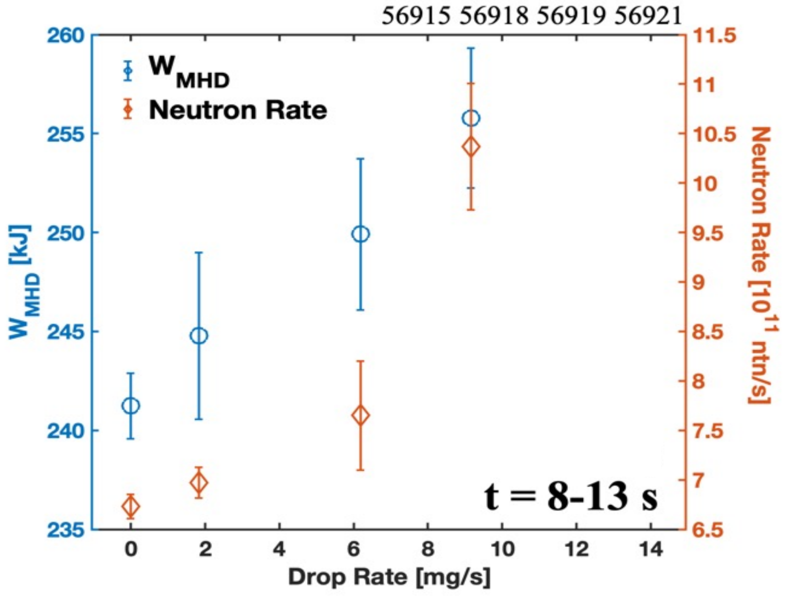
- Lowest levels of recycling achieved with large drop rates
  - High drop rates prone to disruption due to rapid increases in n_e

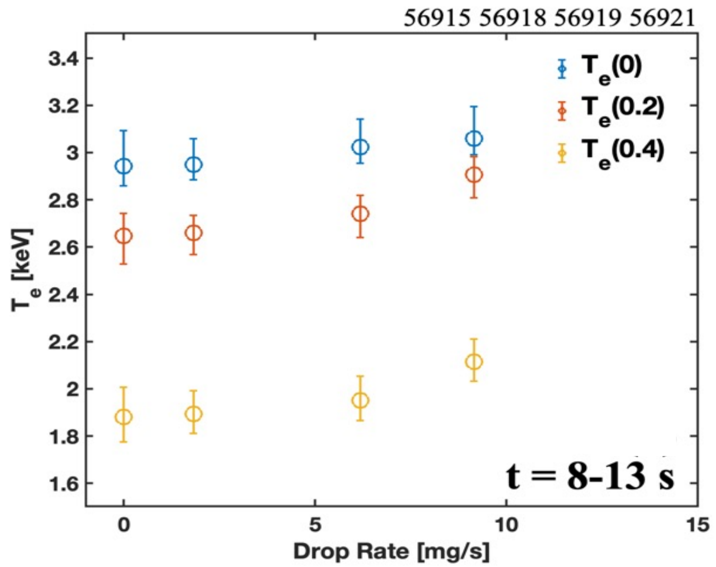
- Minimal changes in recycling with cumulative powder dropped is consistent with time-averaged measurements
  - Recycling only affected during powder injection, not after



Higher Drop Rates Lead to Larger Improvements in Confinement

- W_{MHD}, neutron rate, and T_e increase with drop rate
  - Possibly non-linear for neutron rate
- T_e profile becomes increasingly broad as drop rate is increased
- Motivates higher drop rates for future experiments
  - P_{aux} > 4.5 MW may be required to sustain drop rates > 17 mg/s





Talk Outline

1. Educational/Professional Background
2. Overview of Boron Powder Injection Experiments in WEST
3. Impact of Powder Injection on Wall Conditioning
4. Improvements in Confinement from Powder Injection
5. Conclusion/Future Directions

Boron Powder Injection Has Led to Improvements in Wall Conditioning and Plasma Confinement

- For the most part, B powder injection was non-perturbative to WEST L-Mode discharges

- Visible and VUV spectroscopy measurements show clear reductions in D and low-Z impurity signals during B powder injection

- As more B powder was dropped, pre-drop impurity signal levels and P_{RAD} were reduced
  - Increase in B-II signal over several pulses may be evidence of thin-film deposition
  - Reduction of SOL O^+ and W particle flux

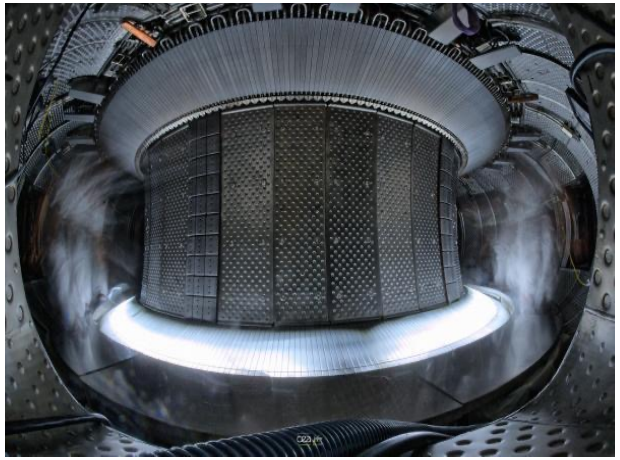
- Improved confinement observed in several pulses with B powder injection
  - Increase in W_{MHD} may be correlated with the level of recycling
  - High drop rates achieve the lowest levels of recycling and highest improvements in confinement (requires high P_{aux} to avoid disruptions)

- Initial results are very encouraging and prompt further exploitation of the IPD on WEST
  - C6 campaign will feature longer drop durations, higher drop rates, and greater diagnostic availability
  - BN powder will also be used to conduct power exhaust studies with the full ITER-like PFU lower divertor

Future Directions as an RM2

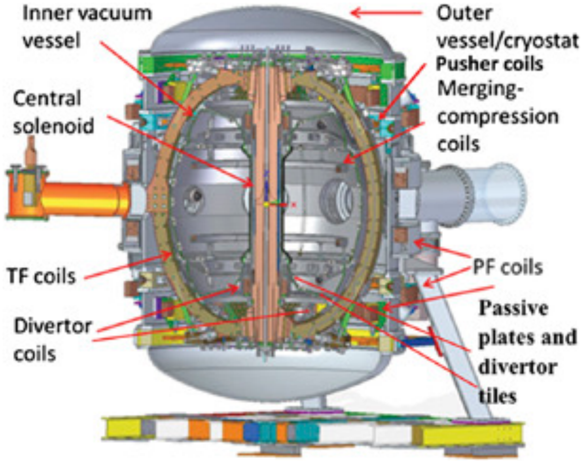
- Use IPD to support long-pulse H-mode operation in WEST
- Support PPPL-IRFM collaboration to install RTTS on WEST
  - Pedestal studies in a full-W environment on reactor-relevant time scales
- Support operation of NSTX-U and ST40 TS systems
  - Pedestal scalings at high toroidal field (ST40)
  - Pedestal studies at low collisionality and high bootstrap fraction (NSTX-U)

WEST (Cadarache, FR)



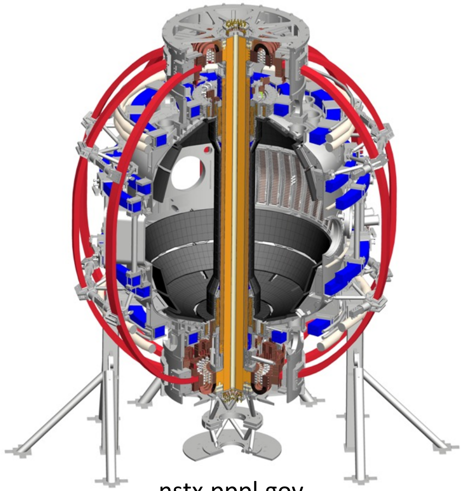
irfm.cea.fr

ST40 (Oxfordshire, UK)



M. Gryaznevich et al 2022 *Nucl. Fusion* **62** 042008

NSTX-U (Princeton, NJ)



nstx.pppl.gov