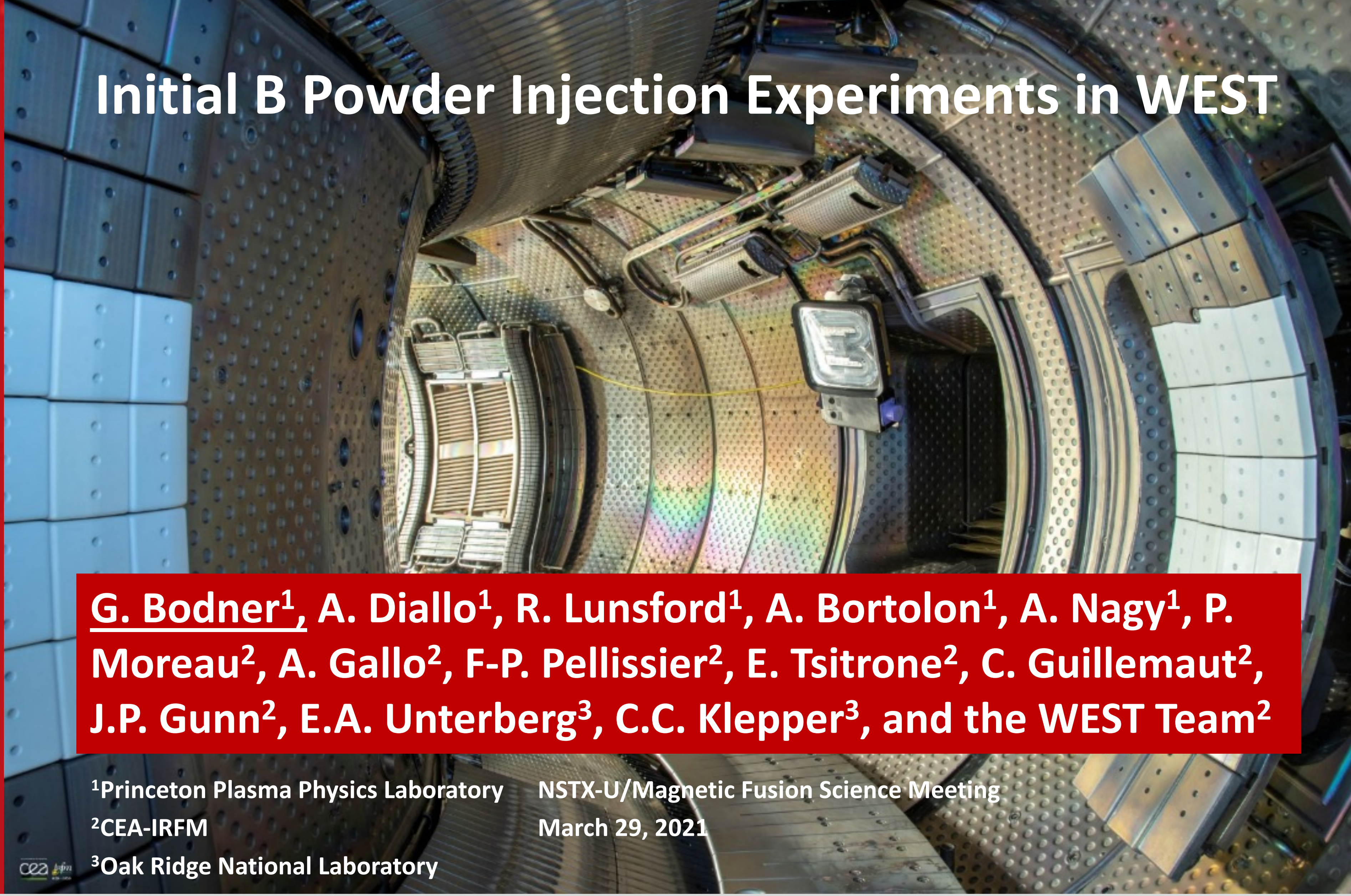
# Initial B Powder Injection Experiments in WEST



G. Bodner[1], A. Diallo[1], R. Lunsford[1], A. Bortolon[1], A. Nagy[1], P. Moreau[2], A. Gallo[2], F-P. Pellissier[2], E. Tsitrone[2], C. Guillemaut[2], J.P. Gunn[2], E.A. Unterberg[3], C.C. Klepper[3], and the WEST Team[2]

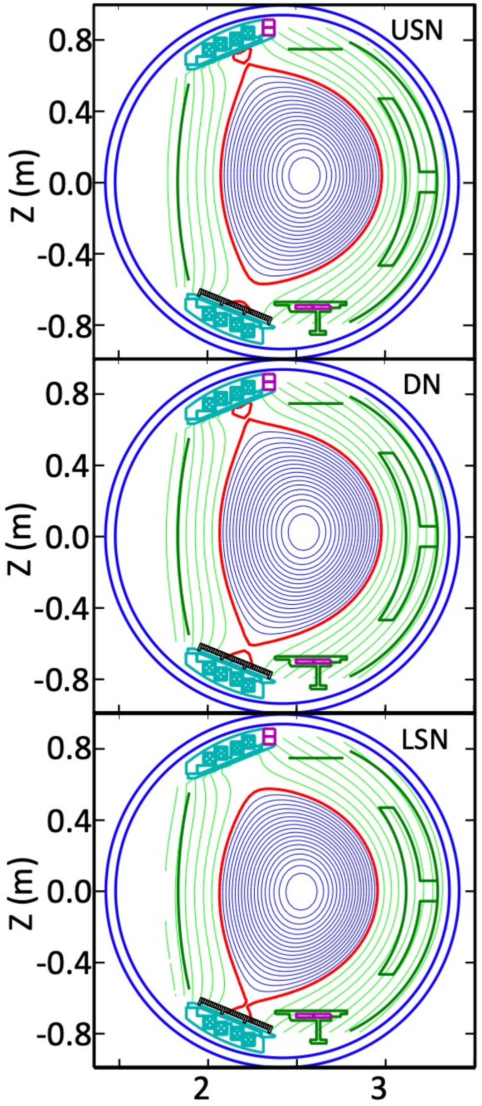
[1]Princeton Plasma Physics Laboratory
[2]CEA-IRFM
[3]Oak Ridge National Laboratory

NSTX-U/Magnetic Fusion Science Meeting
March 29, 2021

# 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 metal-walled 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 fluence: 10-20 $MW/m^2$ for 1000s

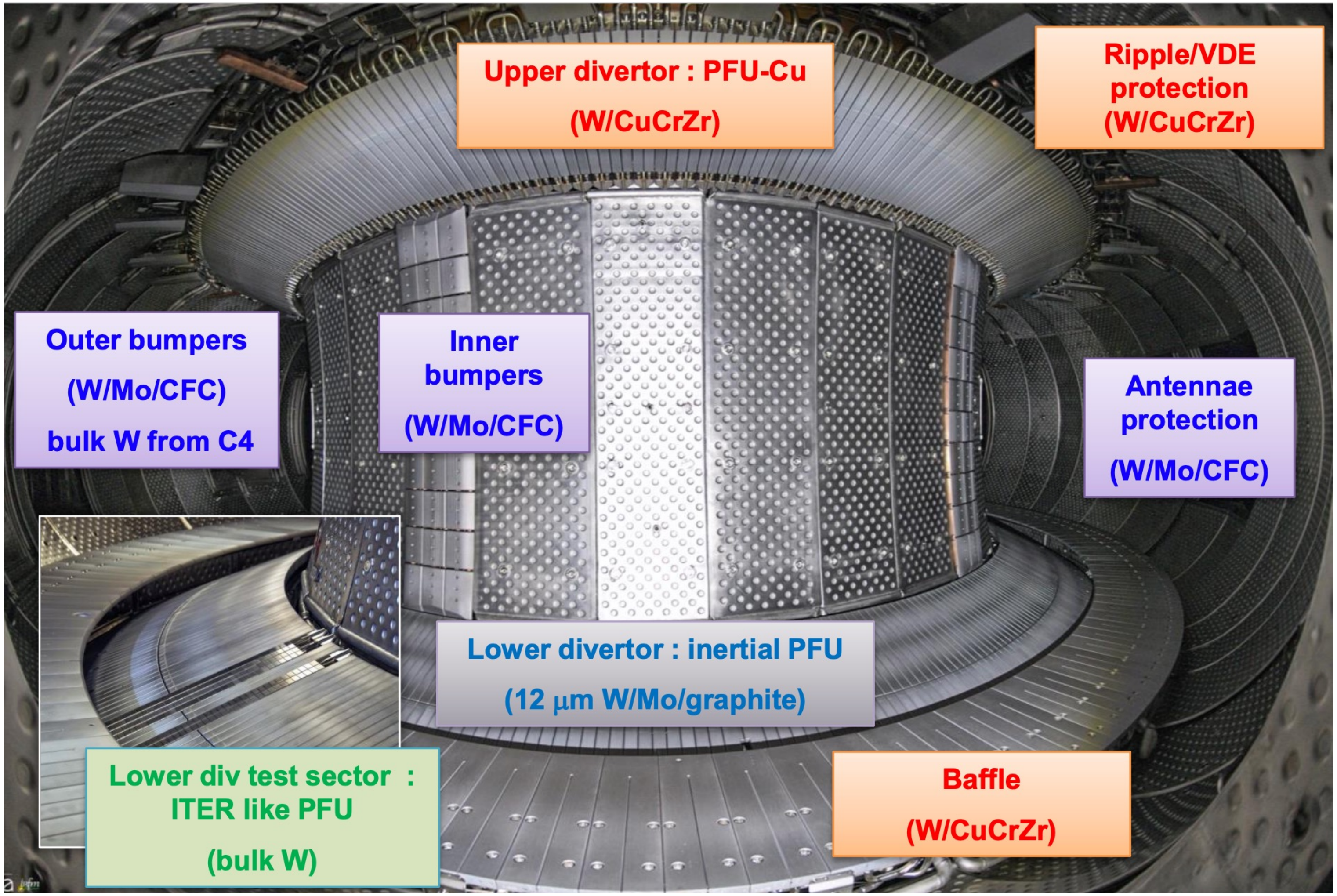
WEST Configurations and Parameters



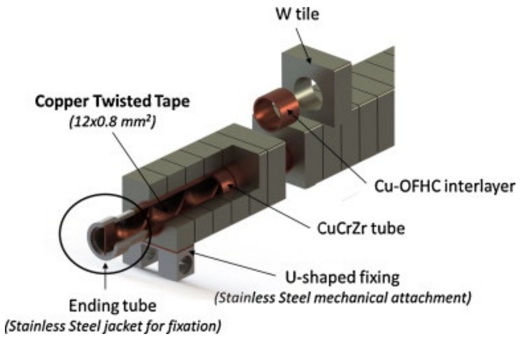

| | |
|---|---|
| **$I_p$ ($q_{95}$ ~ 2.5)** | 1 MA |
| **$B_T$** | 3.7 T |
| **R** | 2.5 m |
| **a** | 0.5 m |
| **A** | 5-6 |
| **Max $\kappa$** | 1.35 |
| **$\delta$** | Up to 0.5 |
| **$V_p$** | 15 $m^3$ |
| **$n_{GW}$** | $1.5 \times 10^{20}$ $m^{-3}$ |
| **$P_{ICRH}$** | 9 MW |
| **$P_{LHCD}$** | 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)

# WEST is a Fully Metallic Environment That Will Incorporate ITER-like Technology in the Lower Divertor




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

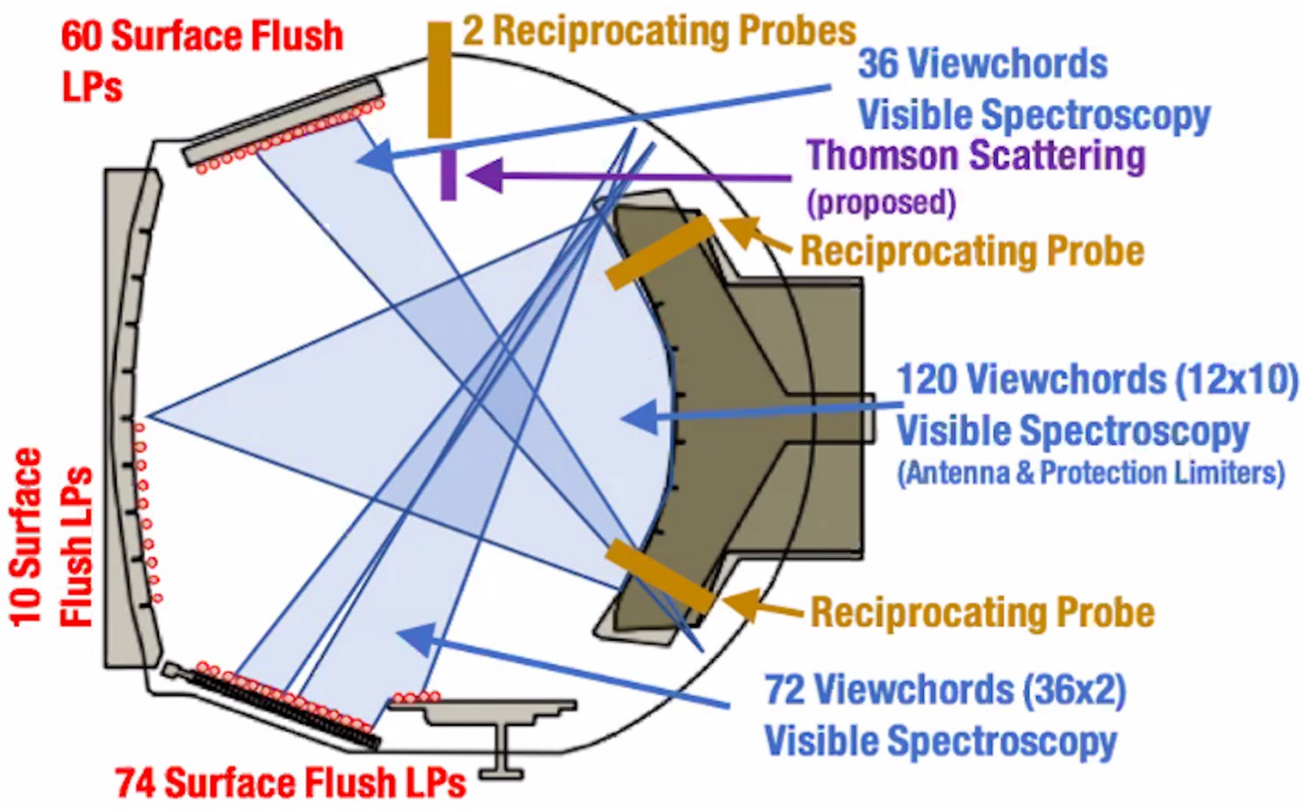
# WEST has an Extensive Set of Plasma Diagnostics to Characterize the PFCs

- Diagnostics available for C5 Campaign:
  - Interferometer
  - ECE
  - Reflectometer
  - Visible Spectroscopy
  - Divertor Langmuir Probes
  - Reciprocating Langmuir Probes
  - Magnetics
  - Bolometry

- Available for C6 Campaign (Sept. 2021):
  - UV Spectroscopy
  - Filterscopes
  - X-ray Cameras (PPPL Collab)

- Thomson Scattering (PPPL Collab - 2022)

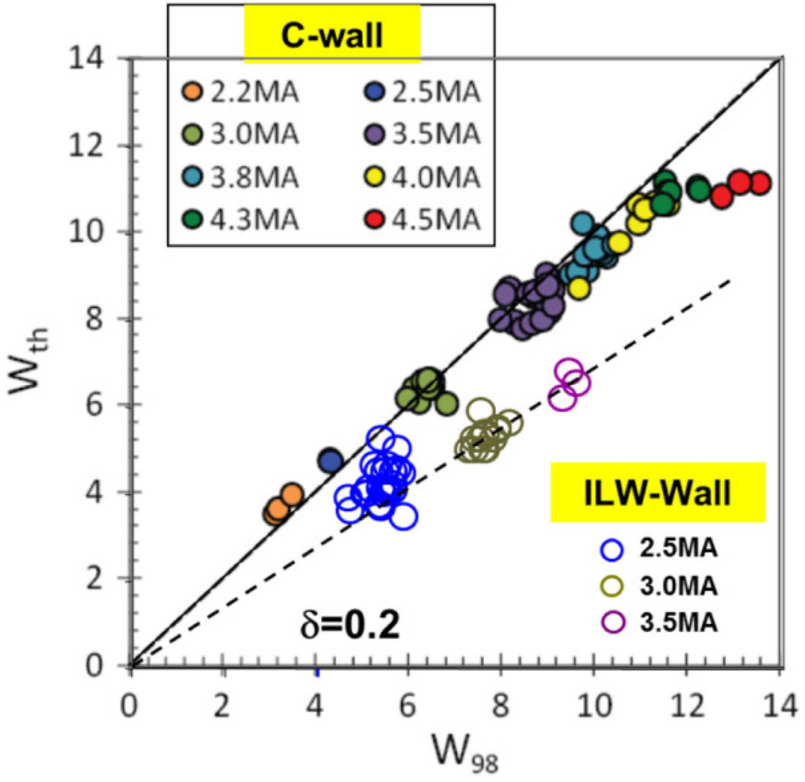
WEST Edge Diagnostics



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

- Wall conditioning (WC) is essential for reliable reactor operation
  - Vessel wall can act as an unpredictable source of fueling and impurities
  - Especially important for metal-walled machines
- Coating walls with low-Z films can prevent influx of impurities into plasma
  - Standard method (Glow Discharge Boronization) requires de-energization of magnets
  - Not conducive to a steady-state superconducting reactor
- Impurity Powder Droppers (IPDs) can provide WC without de-energizing the magnets
  - Uses the tokamak plasma to ablate solid low-Z powder

Impact of Metal Wall on Energy Confinement in JET




E. Joffrin *et al* 2014 *Nucl. Fusion* **54** 013011

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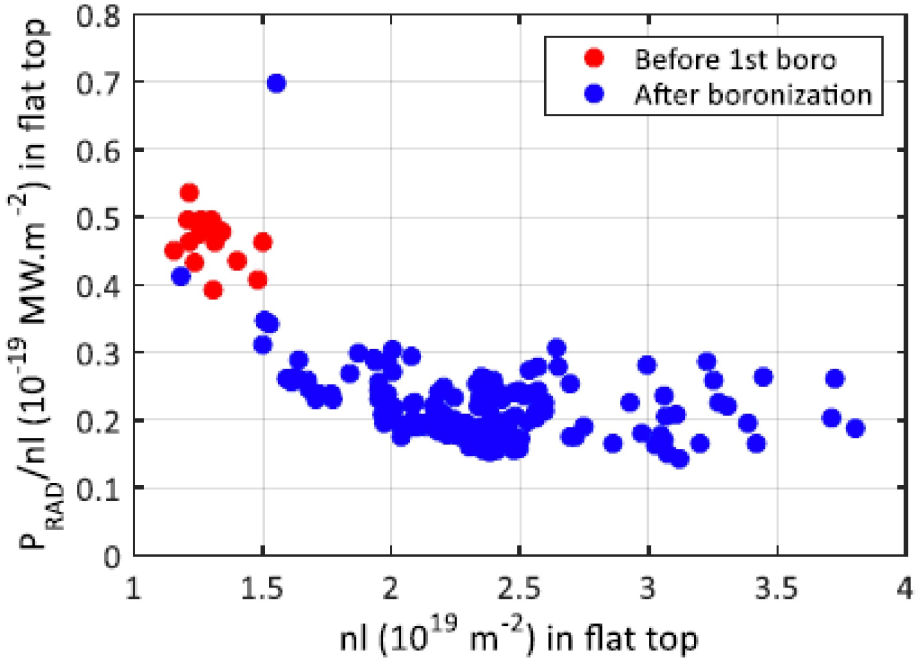
Impact of Boronization on WEST Operating Space




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

# IPDs Are Capable of Dropping Controlled Amounts of Powder of Various Z and Grain Size

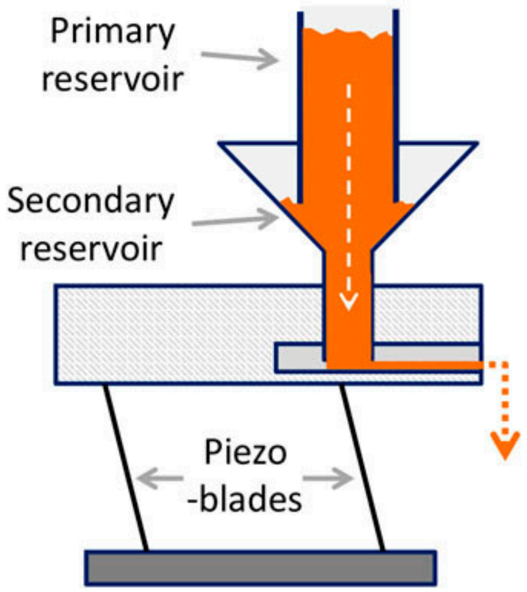
Impurity Powder Dropper Design

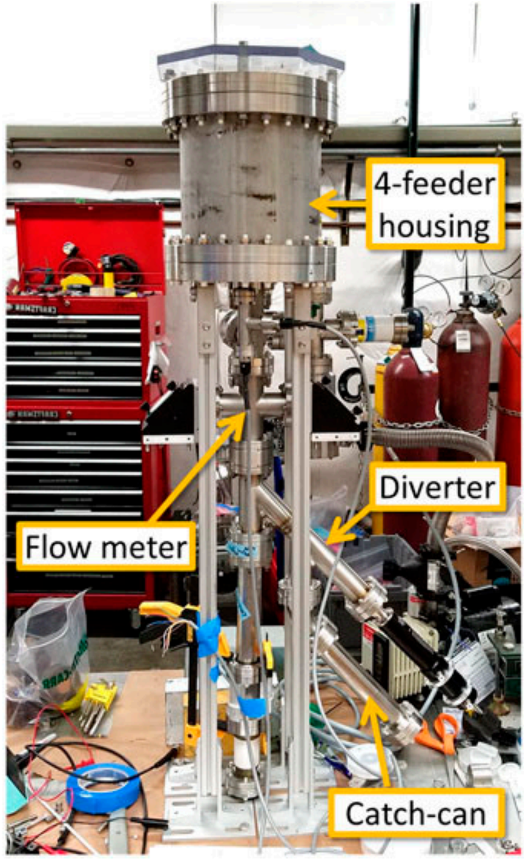
- IPD has 4 individual feeders which can hold various types of low-Z powders (B, BN, Li)

- Powder is dropped by actuating piezo—electric blades whose oscillation is proportional to the drive voltage

- Drop rates are monitored using a fiber-optic coupled flow meter

- IPDs have been implemented on:
  - DIII-D, KSTAR, EAST, AUG, WEST
  - W-7X, LHD




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

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

- Scientific Goals:
  - Investigate IPD as a possible mechanism for RTWC in WEST long pulse discharges
  - Possibly facilitate H-mode access on WEST

- Timeline:
  - Jan 4th : IPD installed on WEST (Q5B)
  - Jan 12th: First B drops in WEST plasmas
  - Jan 21st: First IPD experimental session
  - Jan 27th: Second IPD experimental session

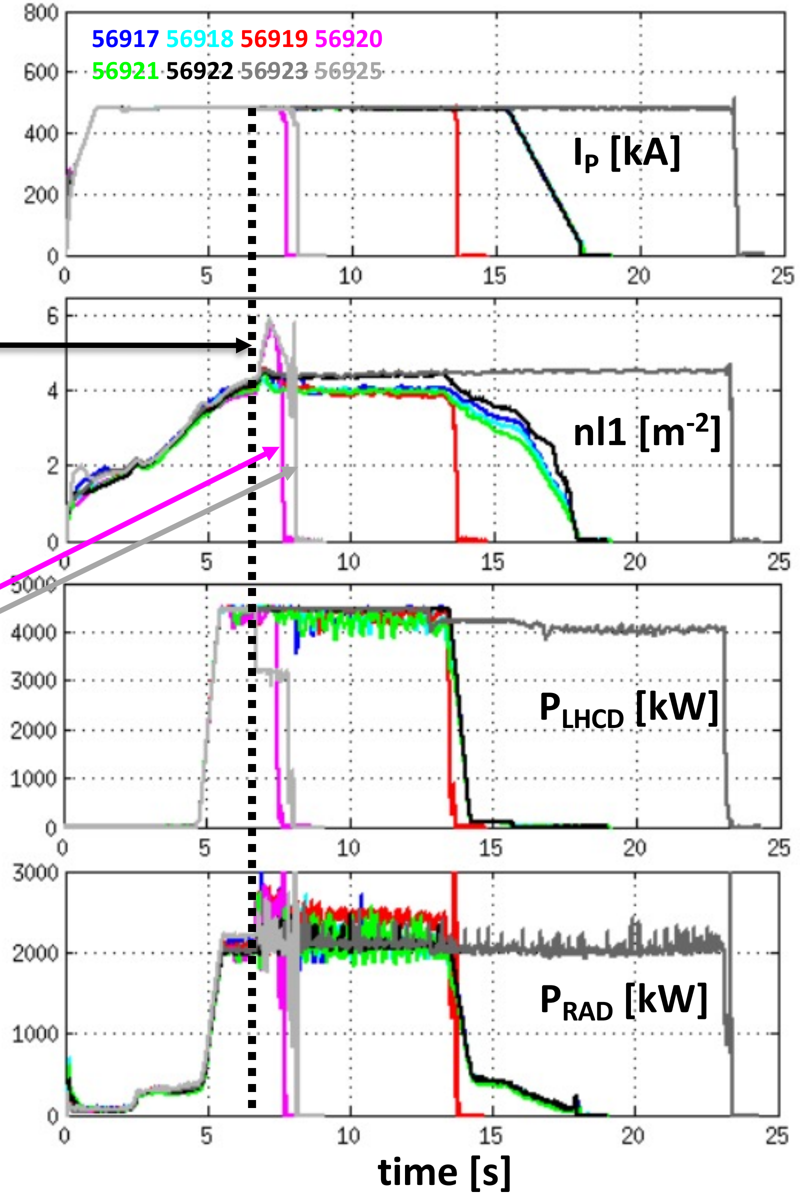
IPD Installed Above WEST

# B Powder Has Been Successfully Dropped in WEST

# B Powder Dropped in 10 LSN L-Mode Pulses

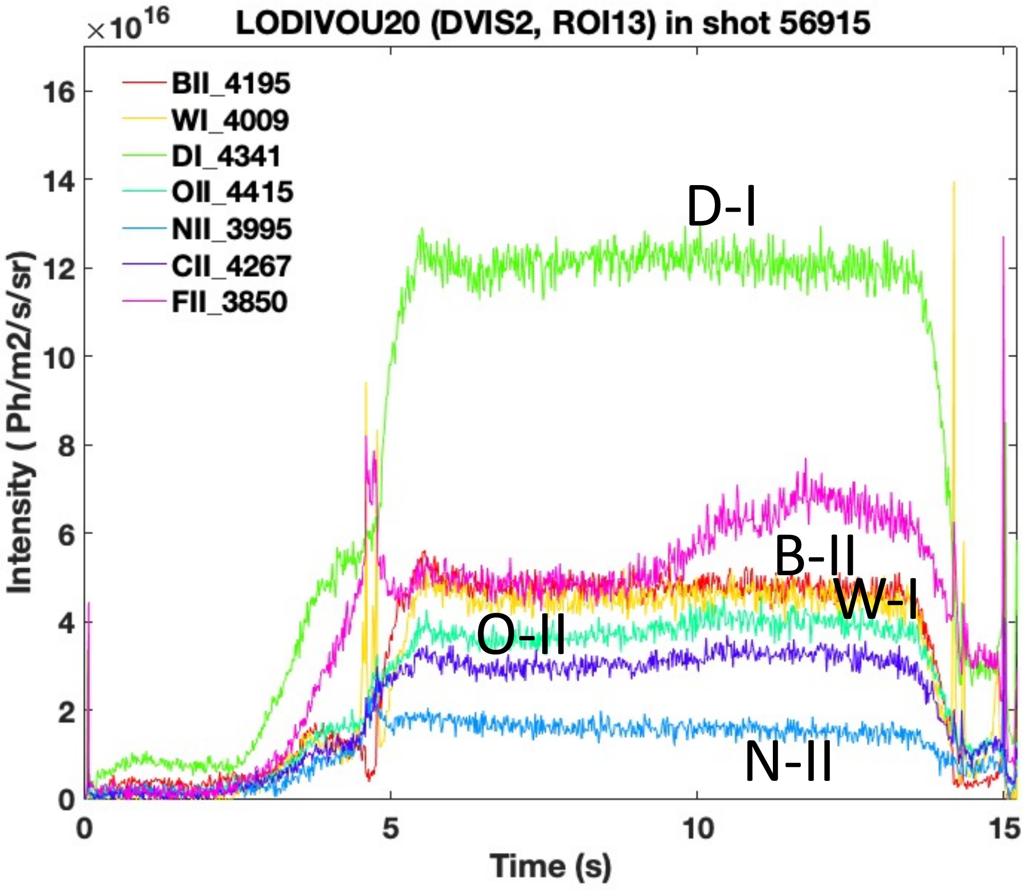
- Scenario: $I_p$ = 500 kA, $P_{LHCD}$ = 4.5 MW, $n_l$ = $4x10^{19}$ $m^{-2}$
- Two methods of B drops tested (Triggered around 6.6 s):
  - 8 shots continuous injection (7-16.5 s duration)
  - 2 shots w/pulsed injection (2 pulses, 0.4 s duration)
- B drop rate was scanned from 2 mg/s to 17 mg/s
- Cumulative B dropped: ~310 mg
  - IPD has 4 reservoirs (25,000 mg per reservoir)
  - About 1.5% of reservoir dropped
- Large drop rates can lead to large density rises which may cause disruptions

Start of B drop



# Visible Spectroscopy Shows Increases in B-II and W-I, Decrease in C-II, D-I, O-II, and N-II at the Lower Divertor

## No B Injection

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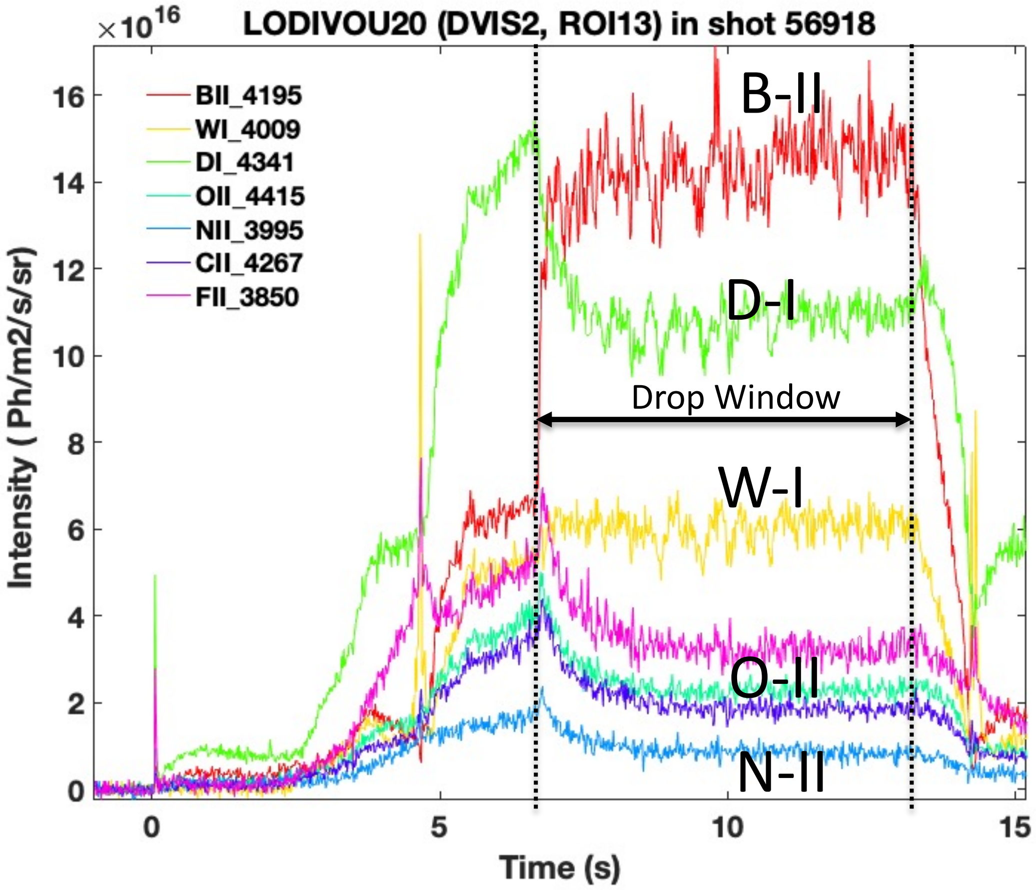
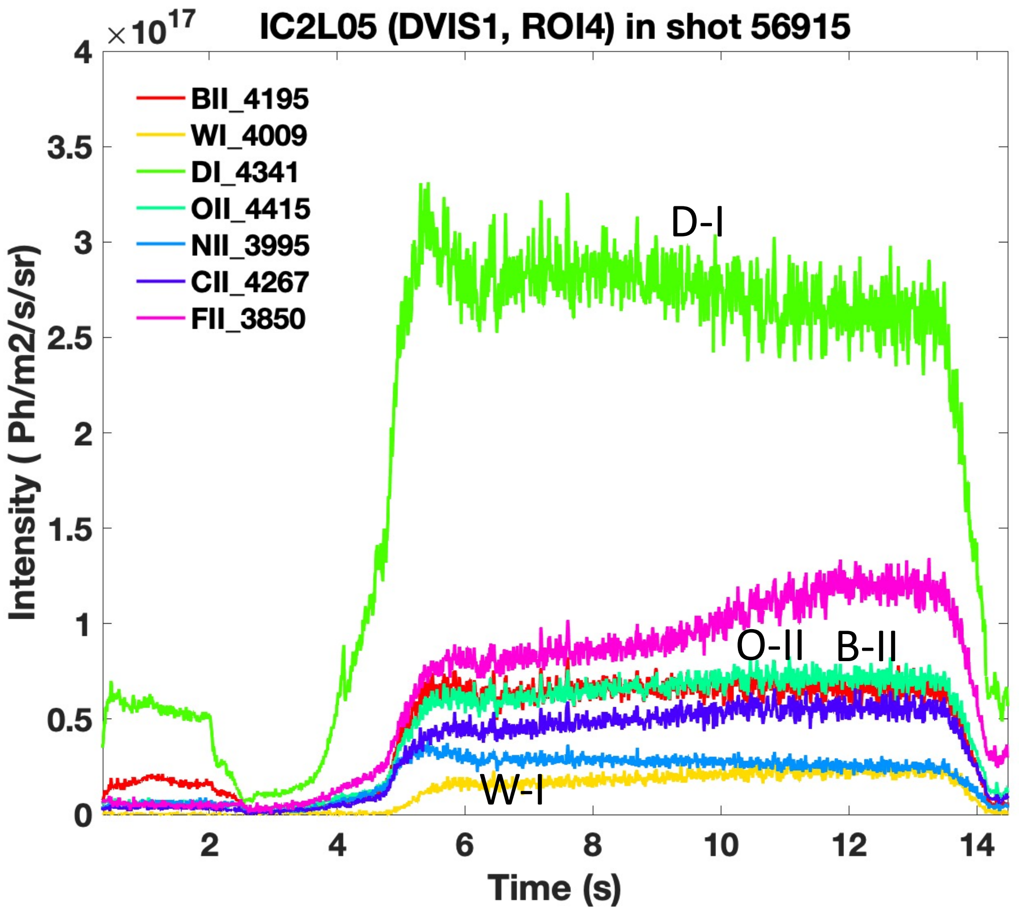


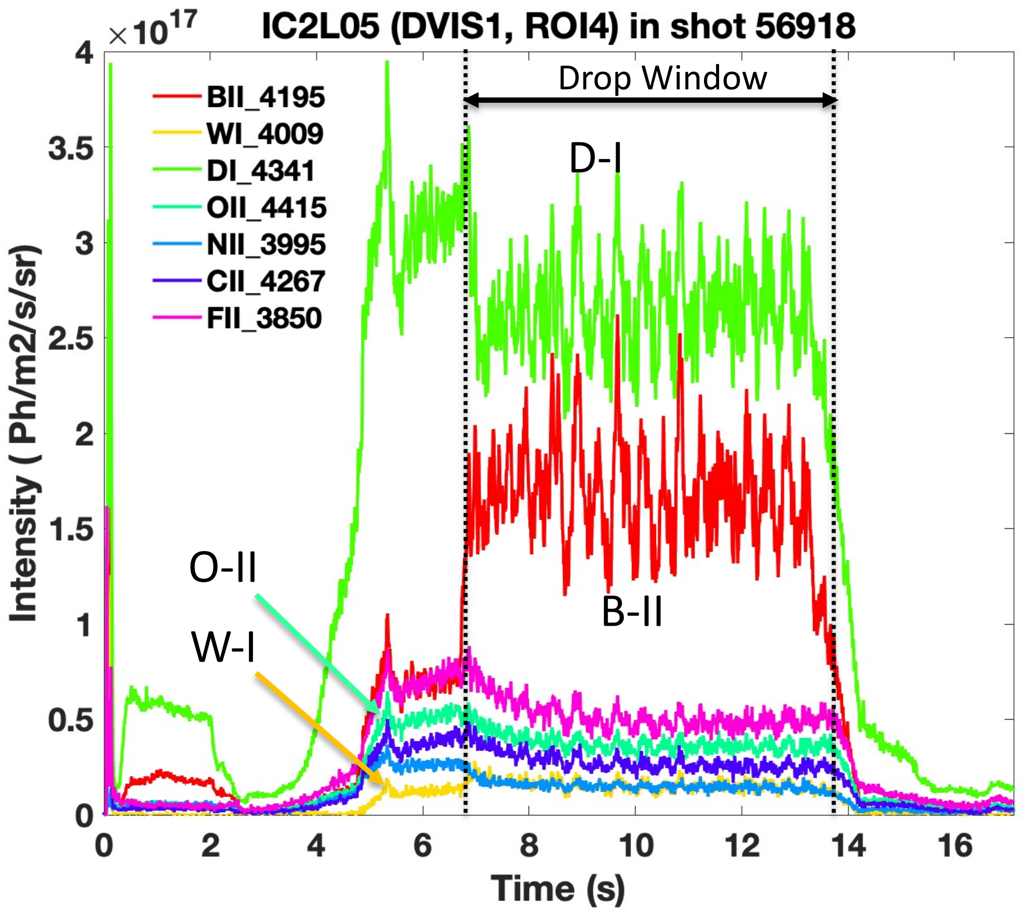

LOWER DIVERTOR

# ICRH Visible Spectroscopy Shows Similar Results

## No B Injection

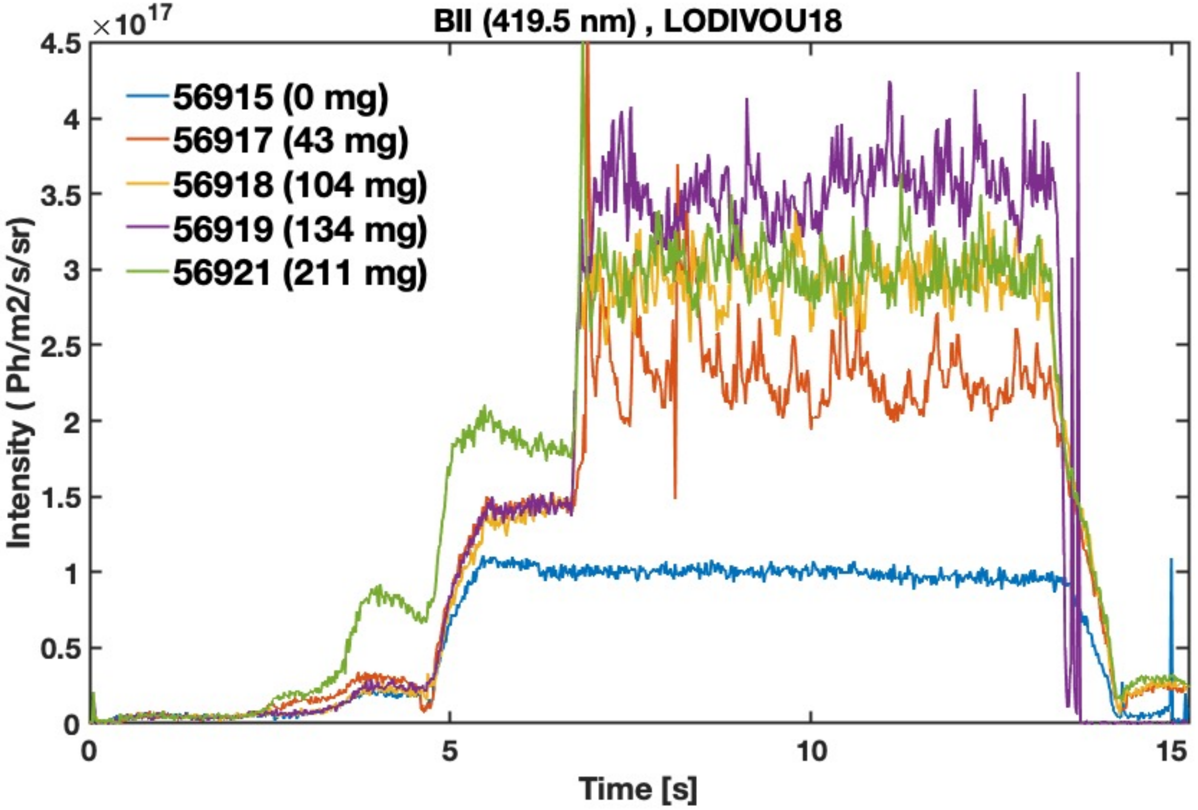



## B Injection




ICRH LIMITER (Antenna positioned 5 mm in front of the LH antennas)

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



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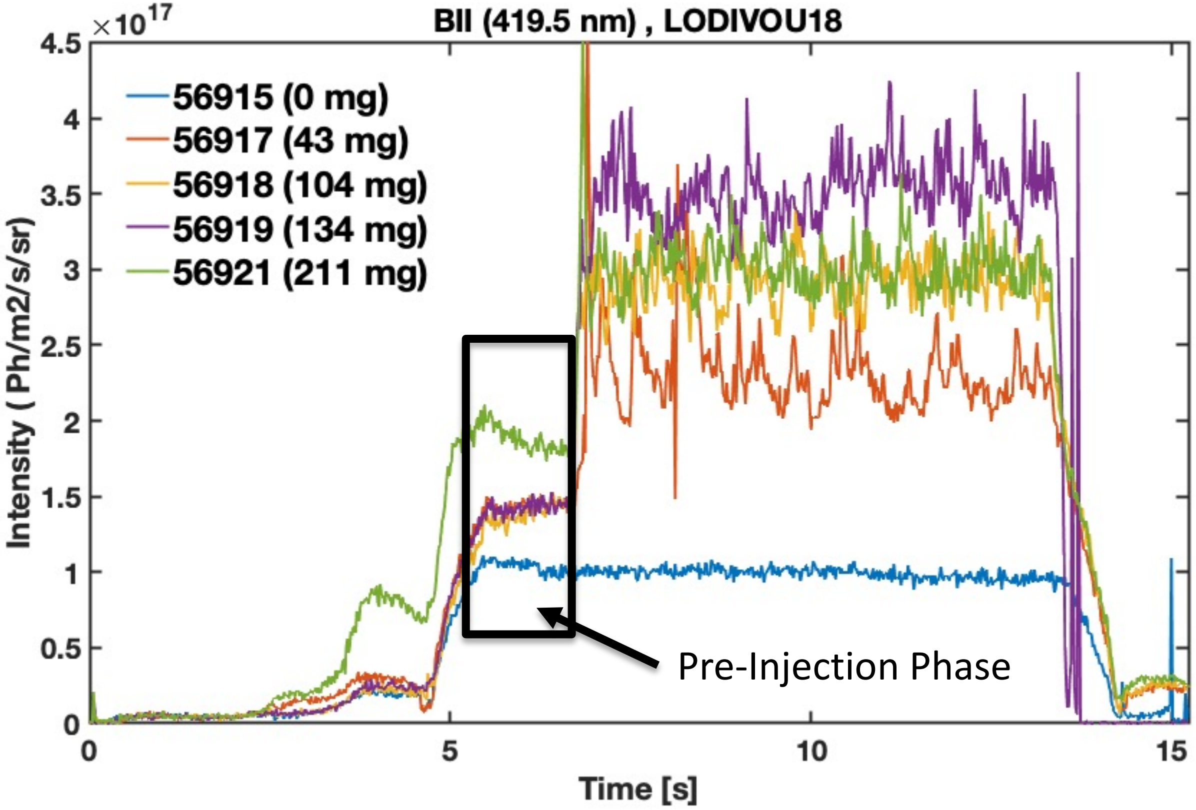

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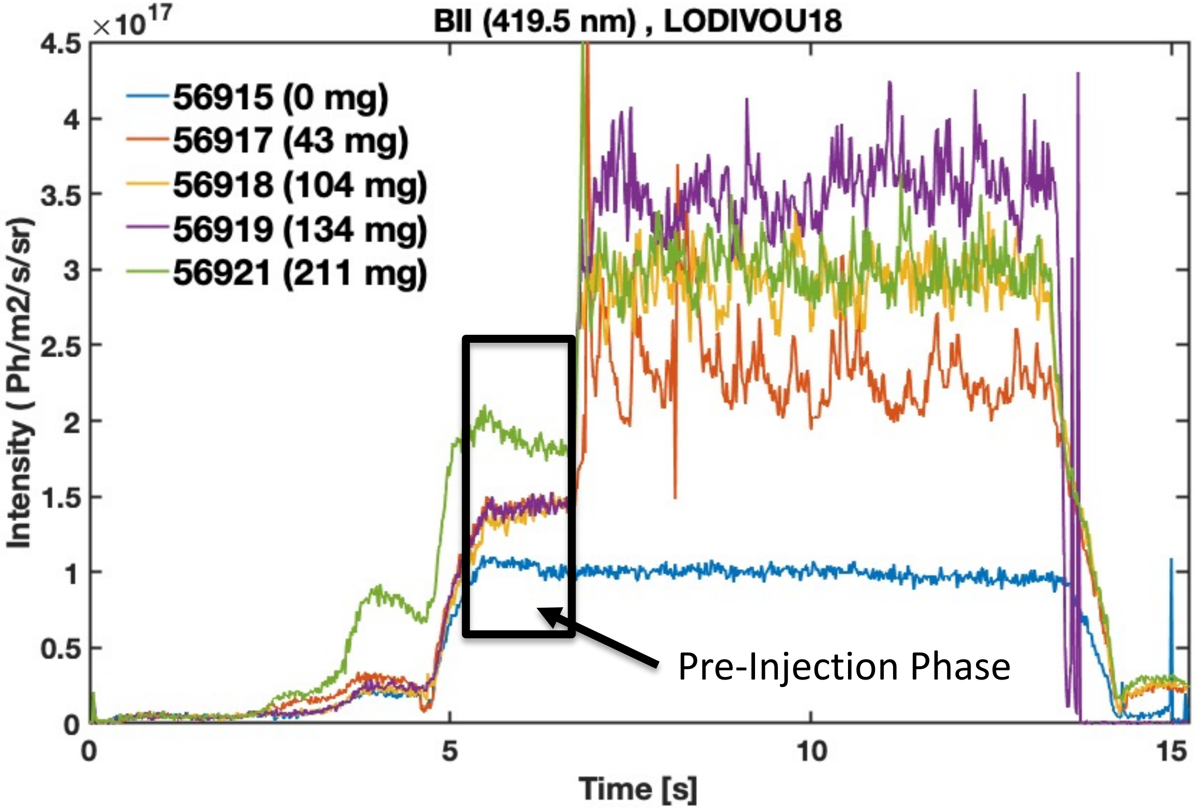
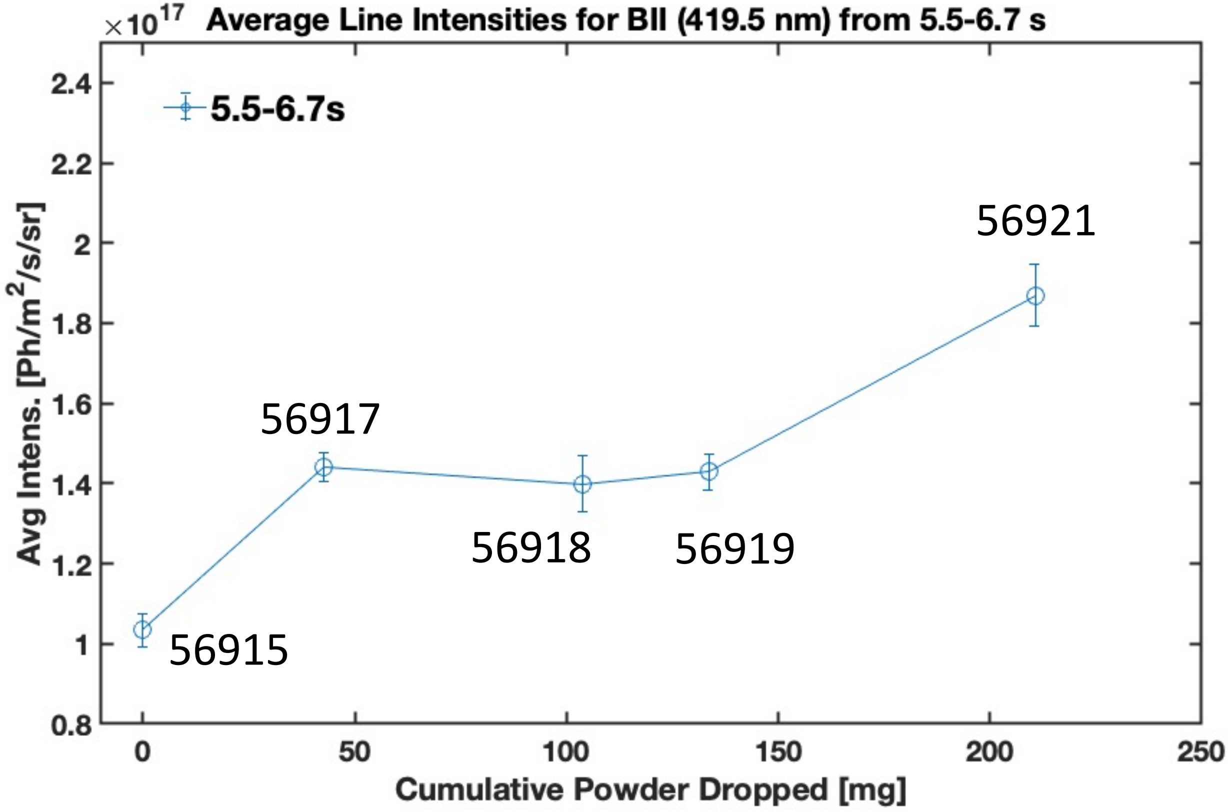
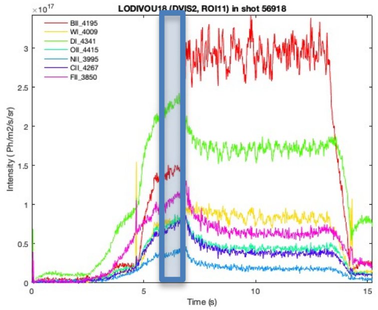
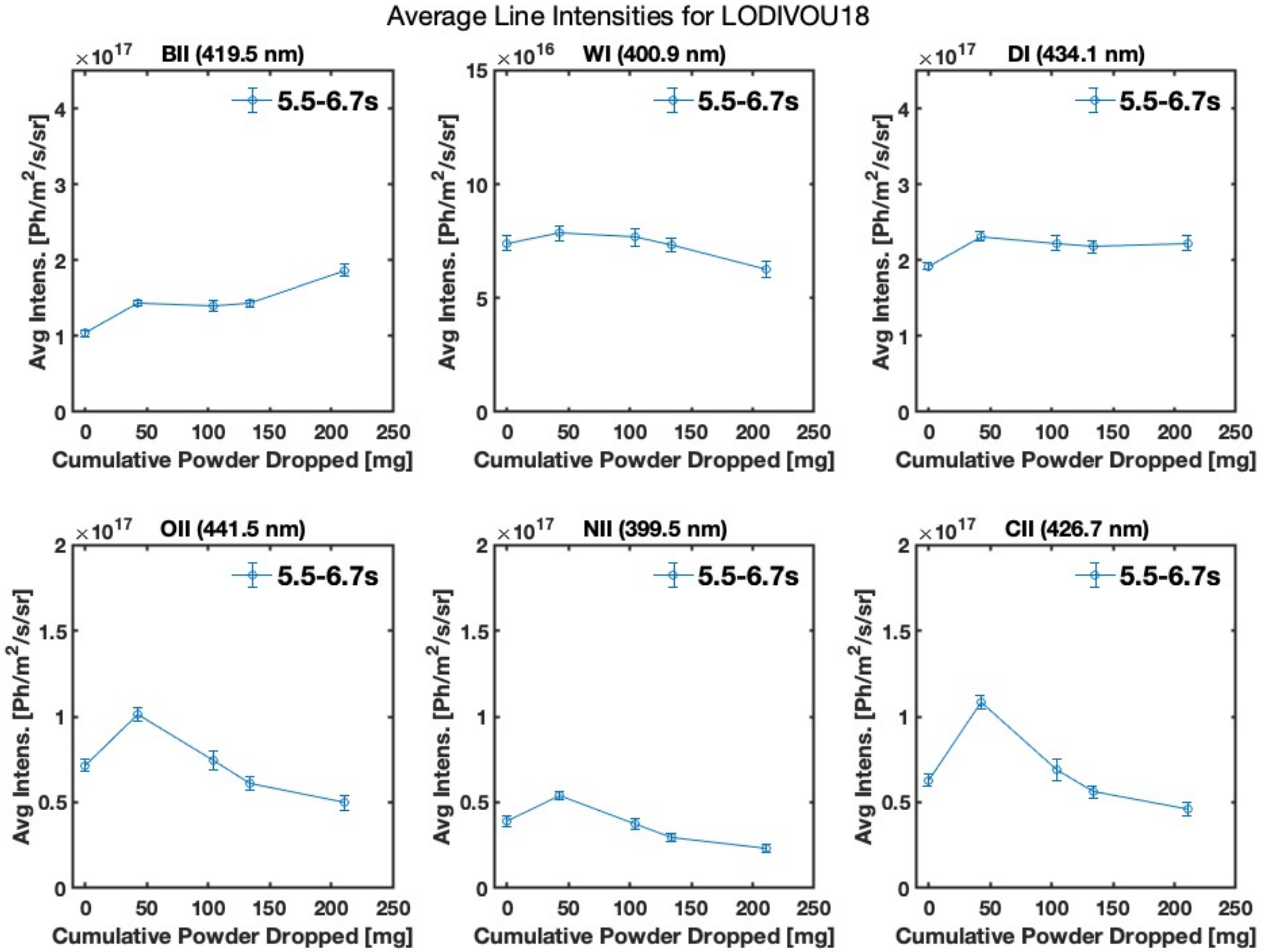


# Possible Indications of WC as Pre-Injection W, C, O, and N levels Decrease as More Powder is Injected

- These 5 pulses had the same density target
- Increase of B signal may be evidence of thin layer deposition on walls
- D-I signal only reduced during B injection






LOWER DIVERTOR VIEW

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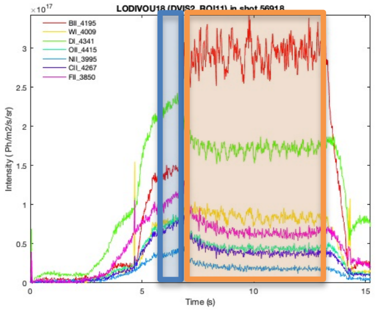
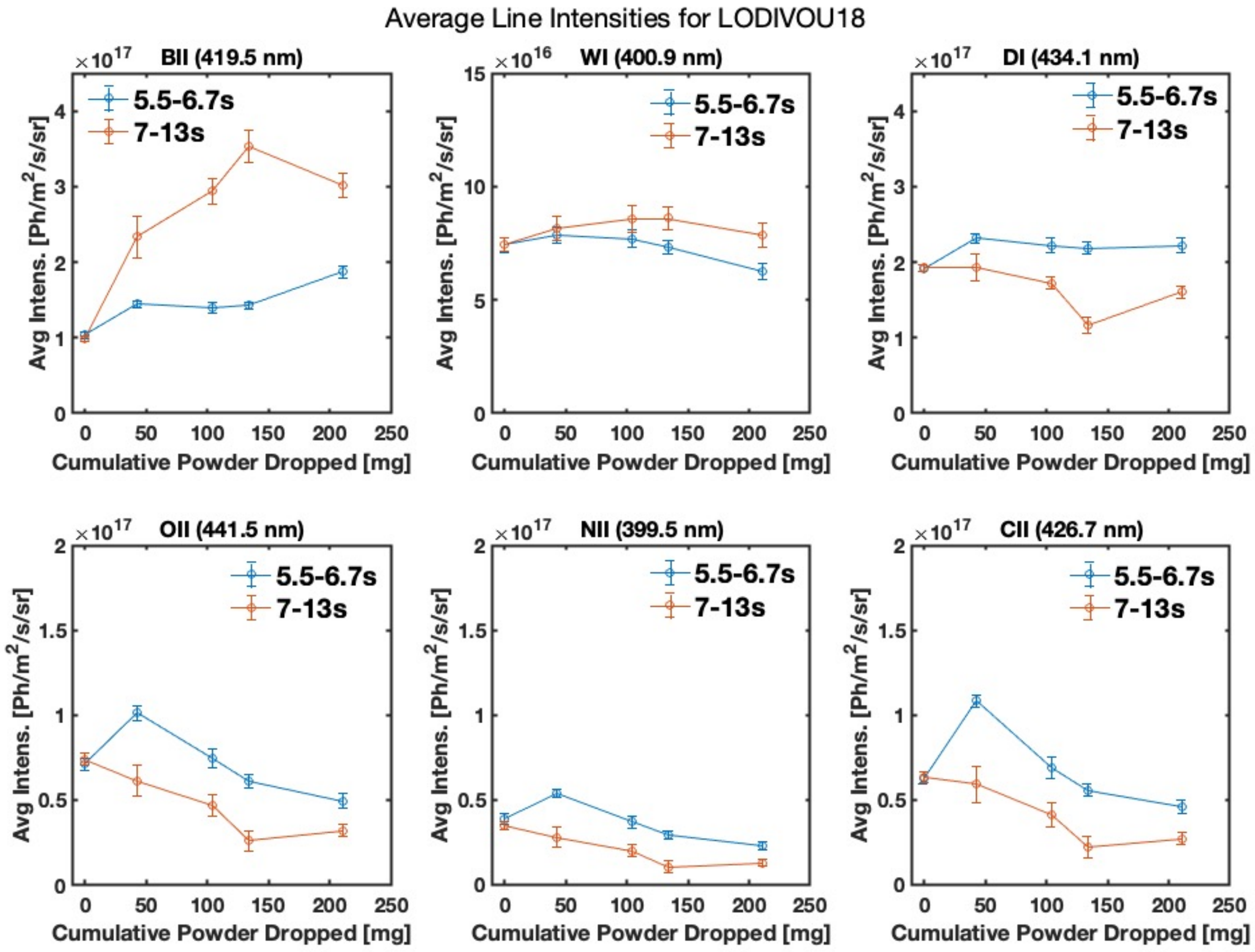
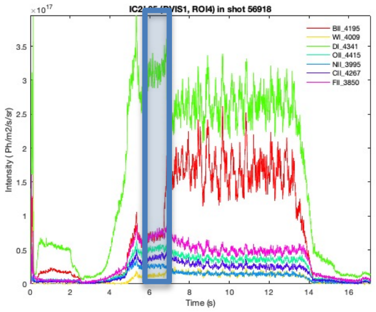


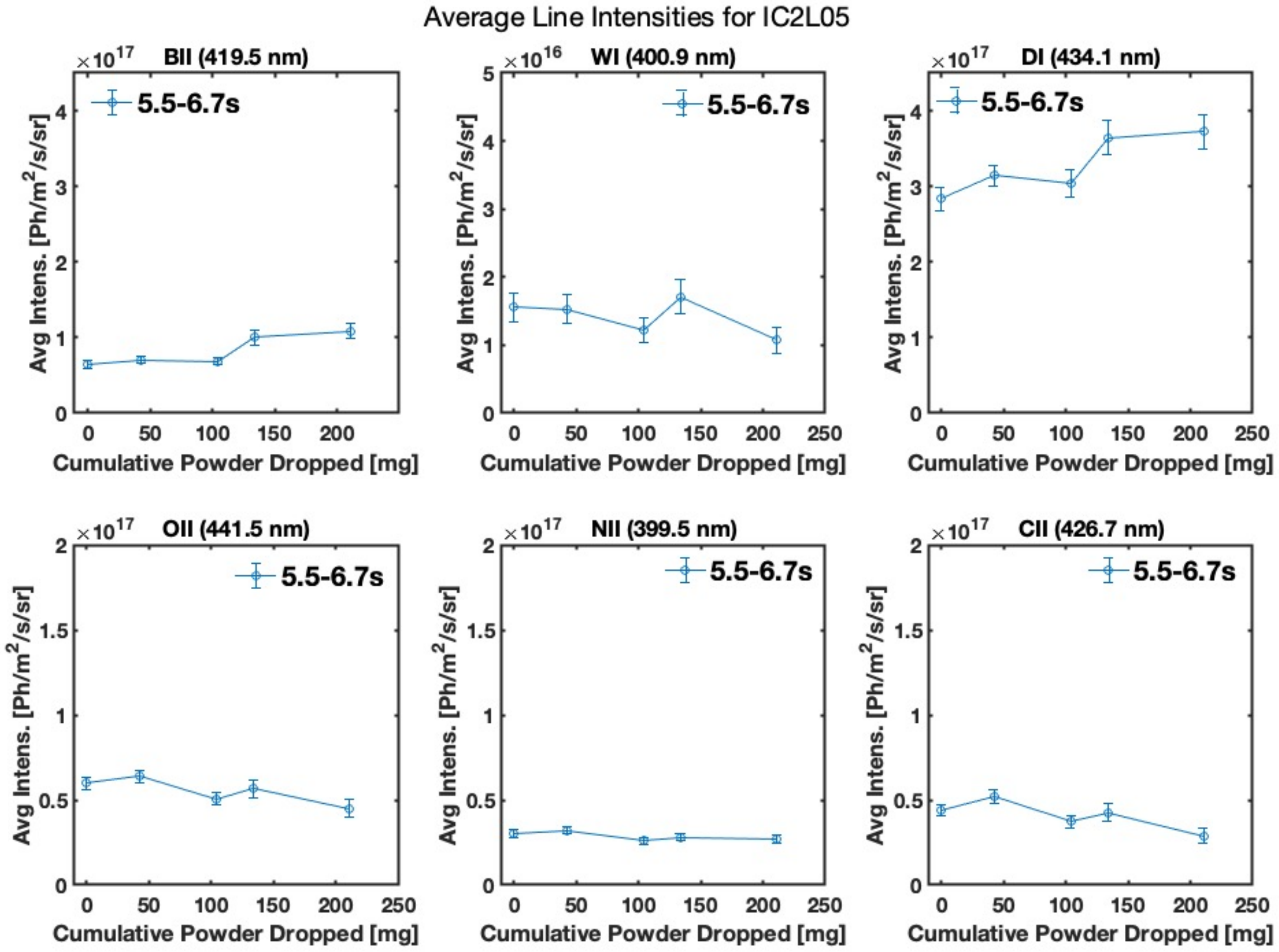




LOWER DIVERTOR VIEW

# ICRH Limiter Views So Similar Results, Possibly Less W Sputtering

- Reductions in C, O, and N signal levels with more B
- Pre-injection W signal decreases with more B
- Less W sputtering during B injection than in the lower divertor




ICRH LIMITER VIEW

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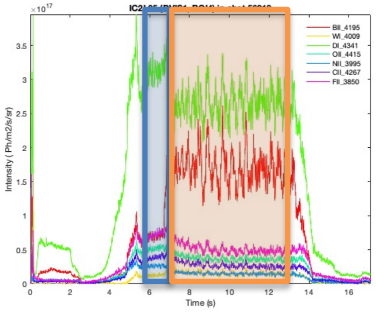
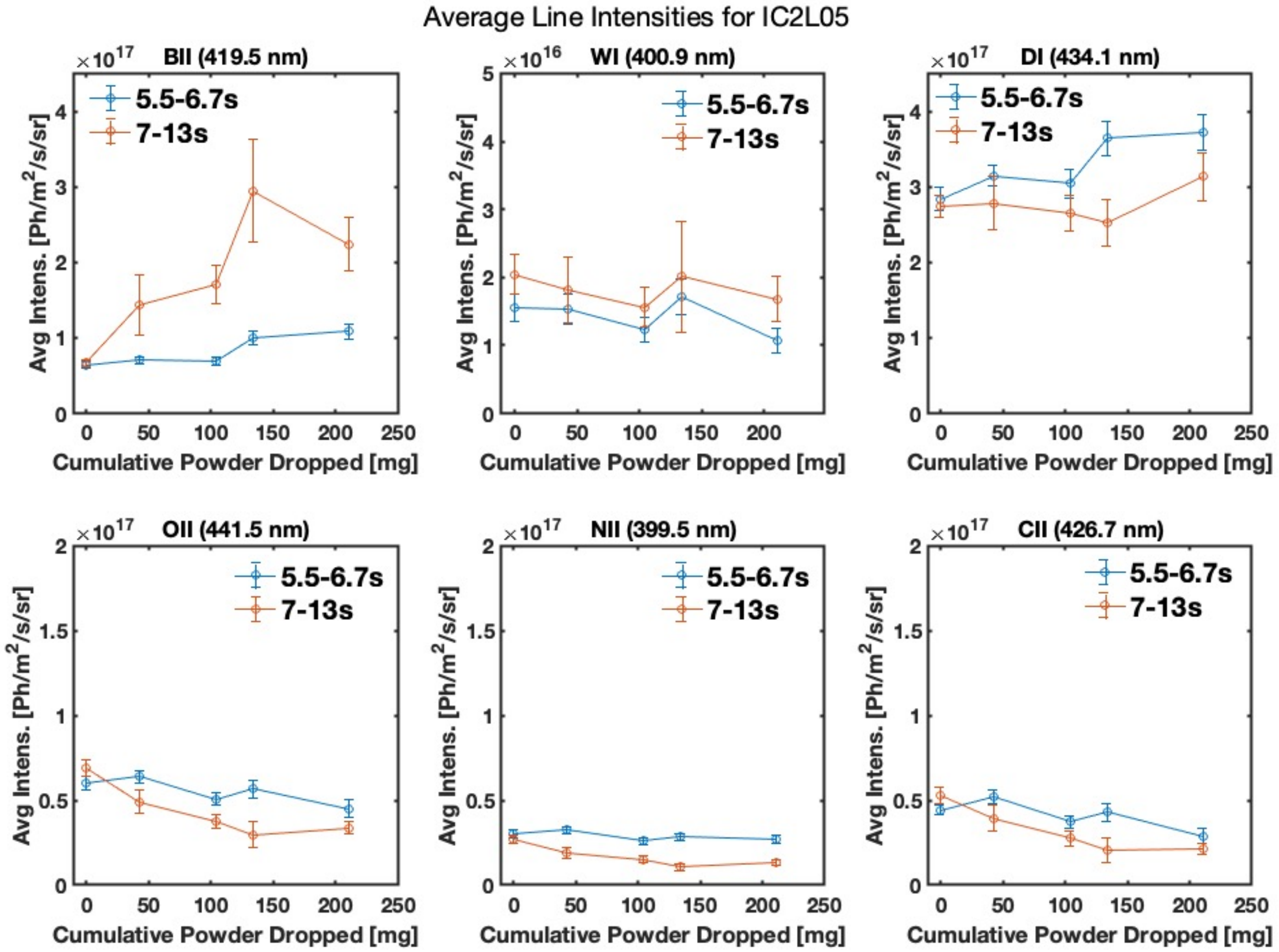
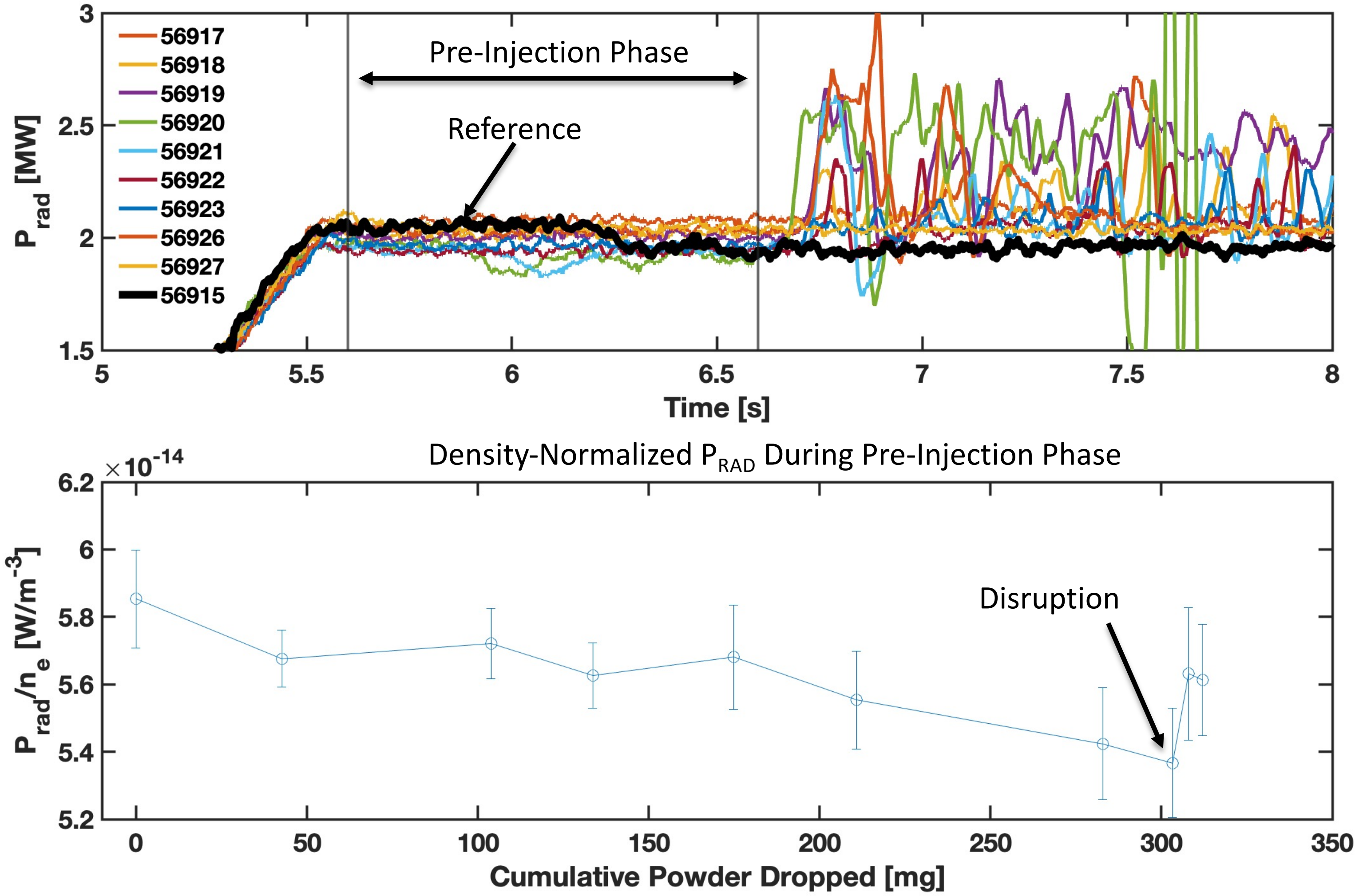




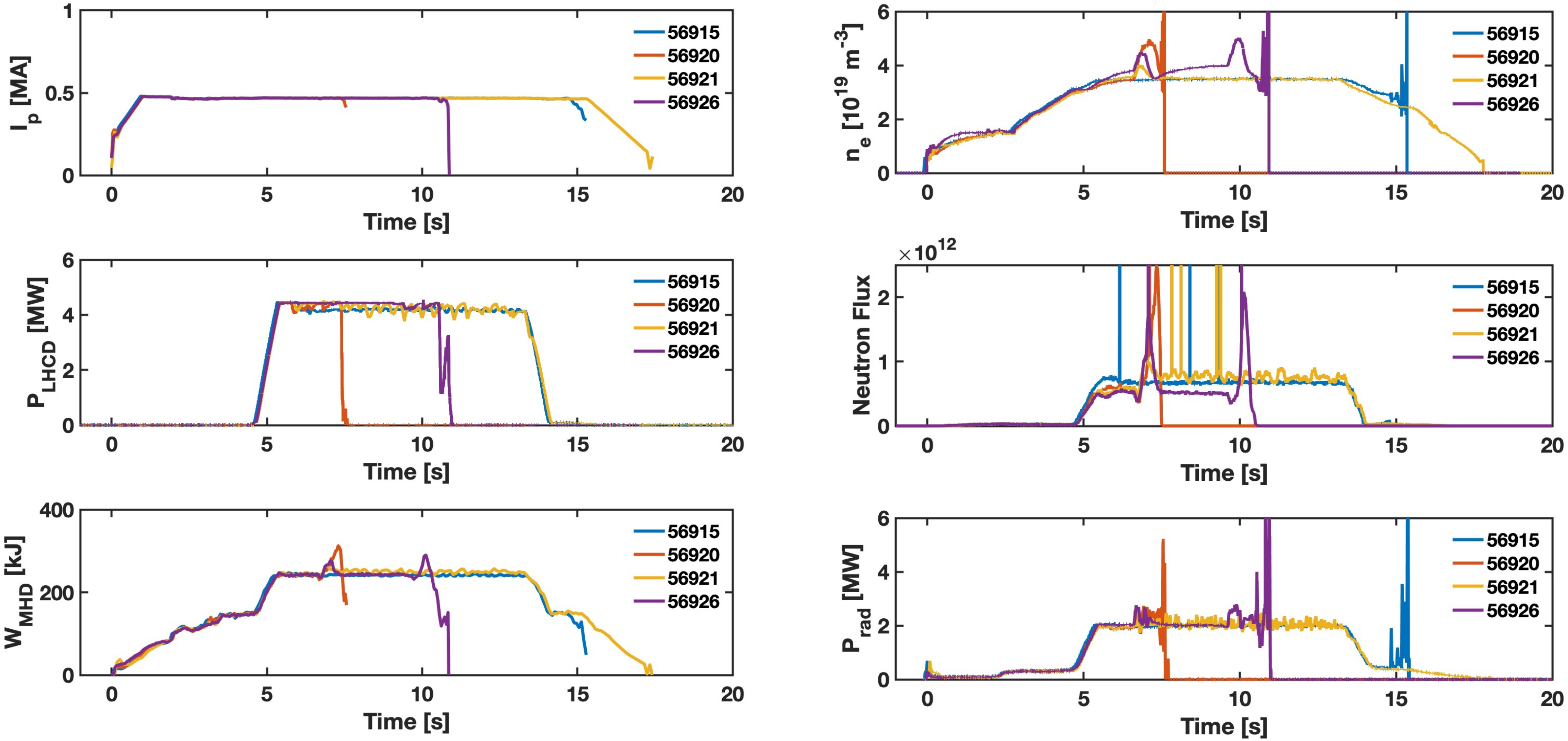

ICRH LIMITER VIEW

# Evidence of WC Can Additionally Be Observed in the Pre-Injection $P_{RAD}$

- Decrease in pre-injection phase of $P_{RAD}$ as more B powder is injected
- Large disruptions may reset the conditioning effect
- Radial distribution of $P_{RAD}$ not available for C5 campaign



# Three Pulses Showed Increases in Energy Confinement During B Powder Injection



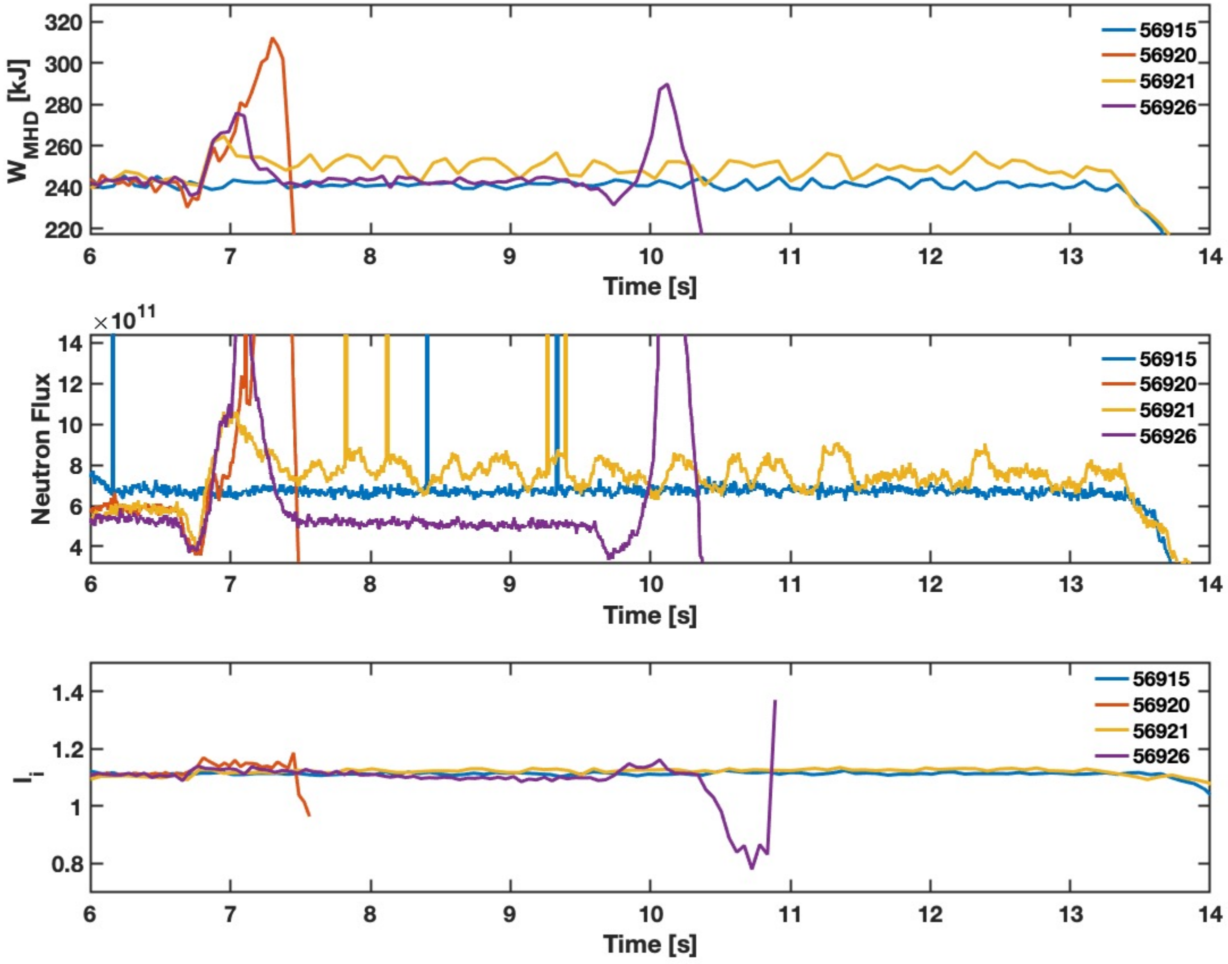

56920 – Disruption, 56926 - Pulsed Injection (400 ms pulse of B)

# More Analysis is Required to Understand Improvement in Confinement

- Increase in $l_i$ suggests no pedestal formation
  - Previous L-H transitions in WEST observe decrease in $l_i$ and rapid increase in $n_l$

- Reflectometry shows increase in edge $n_e$ only during beginning of B injection

- Improvement in confinement may be similar to $N_2$ seeding experiments



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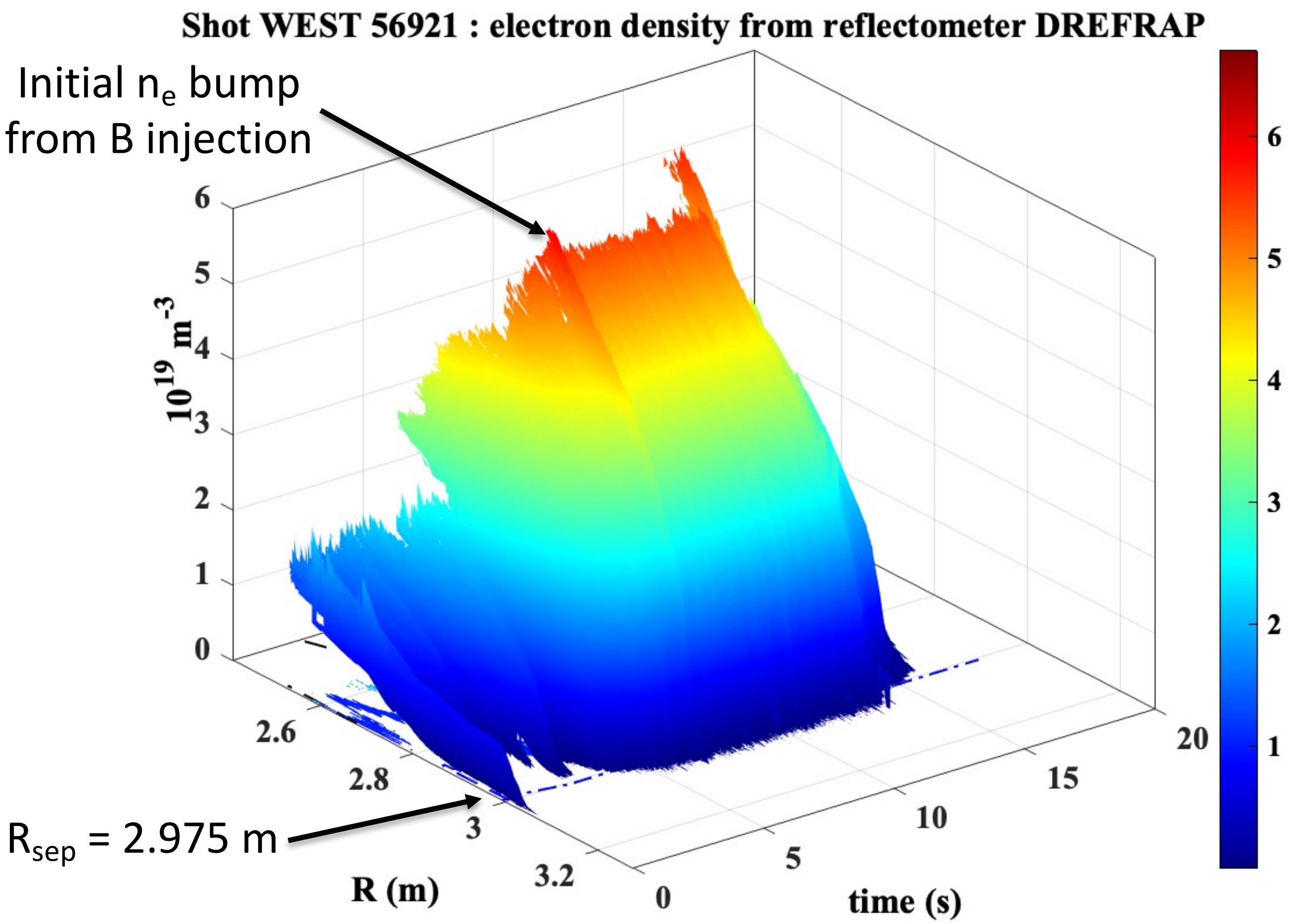
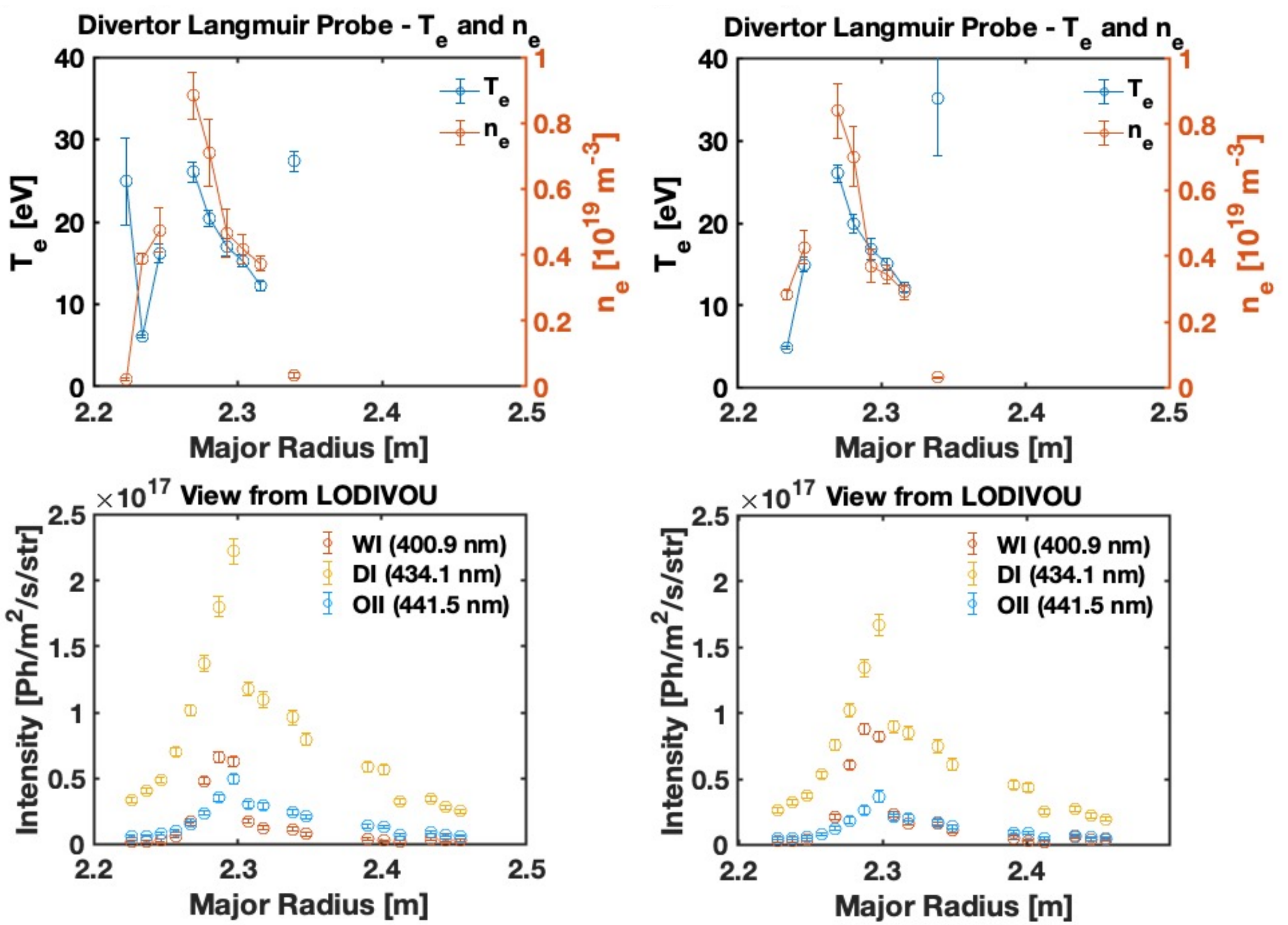


# Divertor Langmuir Probes Show Minimal Changes to SOL $T_e$ and $n_e$ During B Powder Injection

- Clear reduction in D-I and O-II across the visible spectroscopy profile
- Consistency of SOL $T_e$ and $n_e$ suggest reduction is due to decreased sputtering
- Off-axis peaking of VS profile may be due to errors in radial mapping

**Pre-Injection Phase (5.5-6.7 s)** | **Injection Phase (7-8.2 s)**



# Evidence of RTWC Have Been Observed In the Initial IPD Experiments On WEST

- Visible spectroscopy measurements show clear reductions of D, C, O, and N signal during B injection

- W sputtering observed in both the lower divertor and ICRH limiter during B injection

- As more B powder is dropped, pre-injection levels of W, C, O, N, and $P_{RAD}$ are reduced

- Improvement of confinement observed in several pulses
  - Effects are not transient and last the entire injection period
  - Not indicative of L-H transition

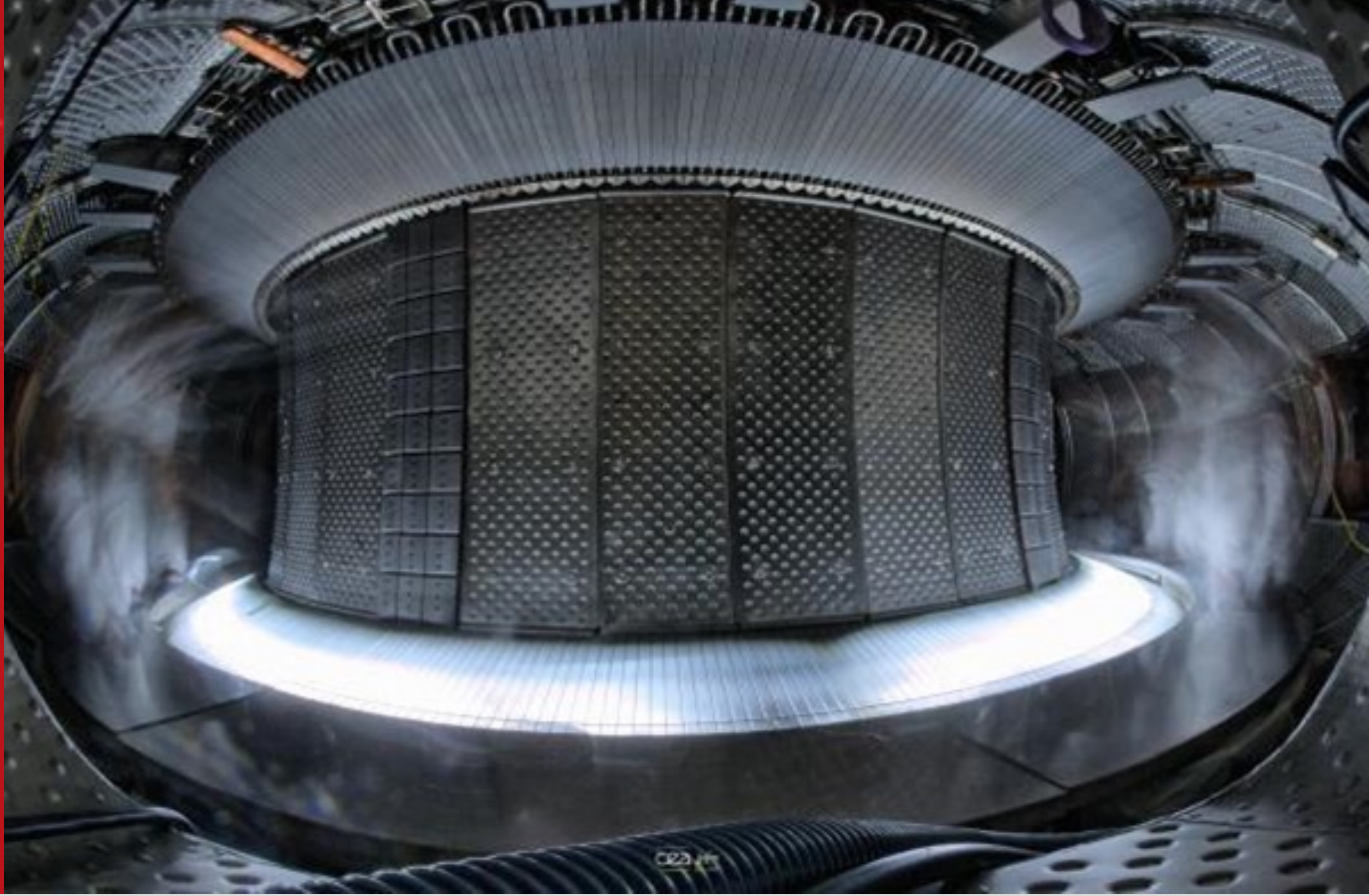
- Unable to access H-mode through IPD alone, may require larger quantities of powder
  - Initial results are still very encouraging

# Future Analysis/Experiments

- Future Analyses:
  - Combine visible spectroscopy data and divertor Langmuir probe measurements with ADAS database to calculate particle fluxes in the SOL
  - Doppler reflectometry measurements will provide further details about effect of B powder injection on TEM turbulence and $E_r$ profile
  - Modelling of B powder injection shots using METIS code to compensate for lack of key diagnostics
  - Material analysis of WEST C5 PFCs to evaluate B deposition (ORNL)

- C6 IPD experiments will extend on the results from the C5 campaign by:
  - Dropping larger amounts of B (More shots w/longer pulse durations)
  - Drop other types powder (BN)
  - Larger suite of diagnostics (Filterscopes, UV and X-ray spectroscopy)
  - Dropping powder in ICRF heated plasmas (PPPL collab)

# Backup Slides



# Reduction in C,O, and N Signals May Be Primarily Due to Reductions in Recycling

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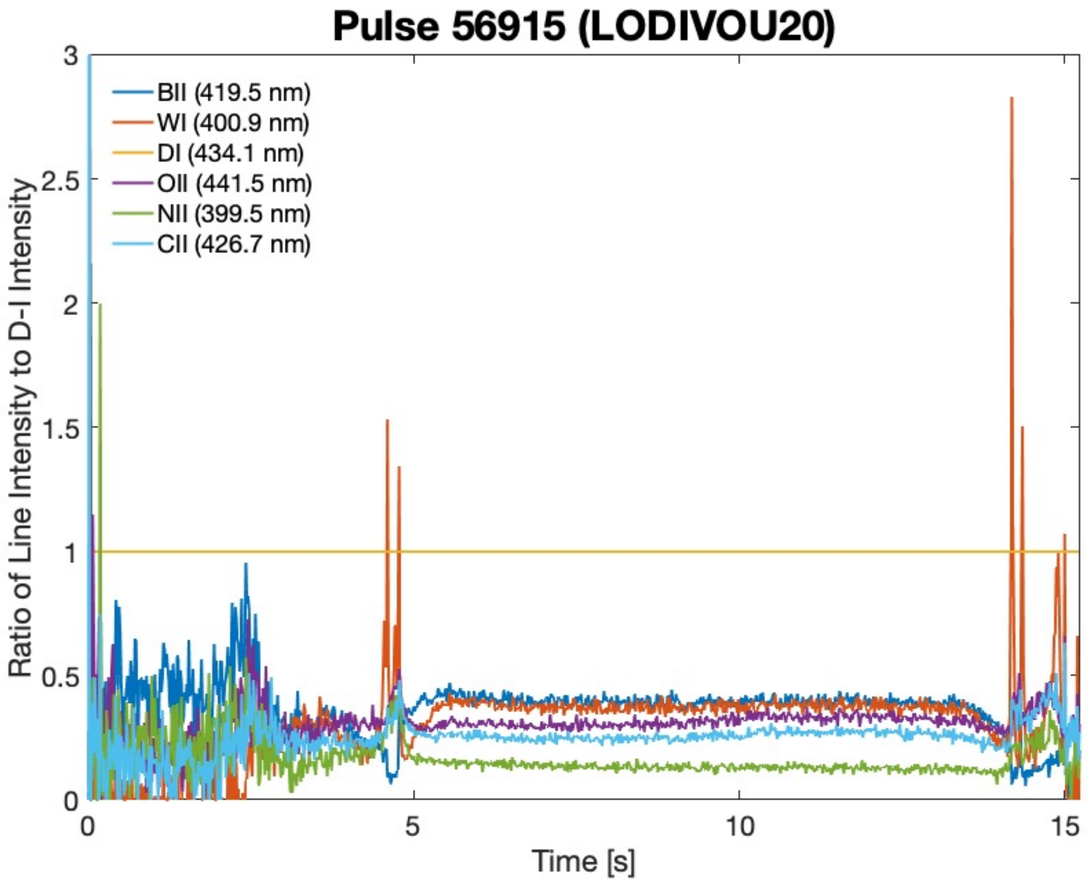


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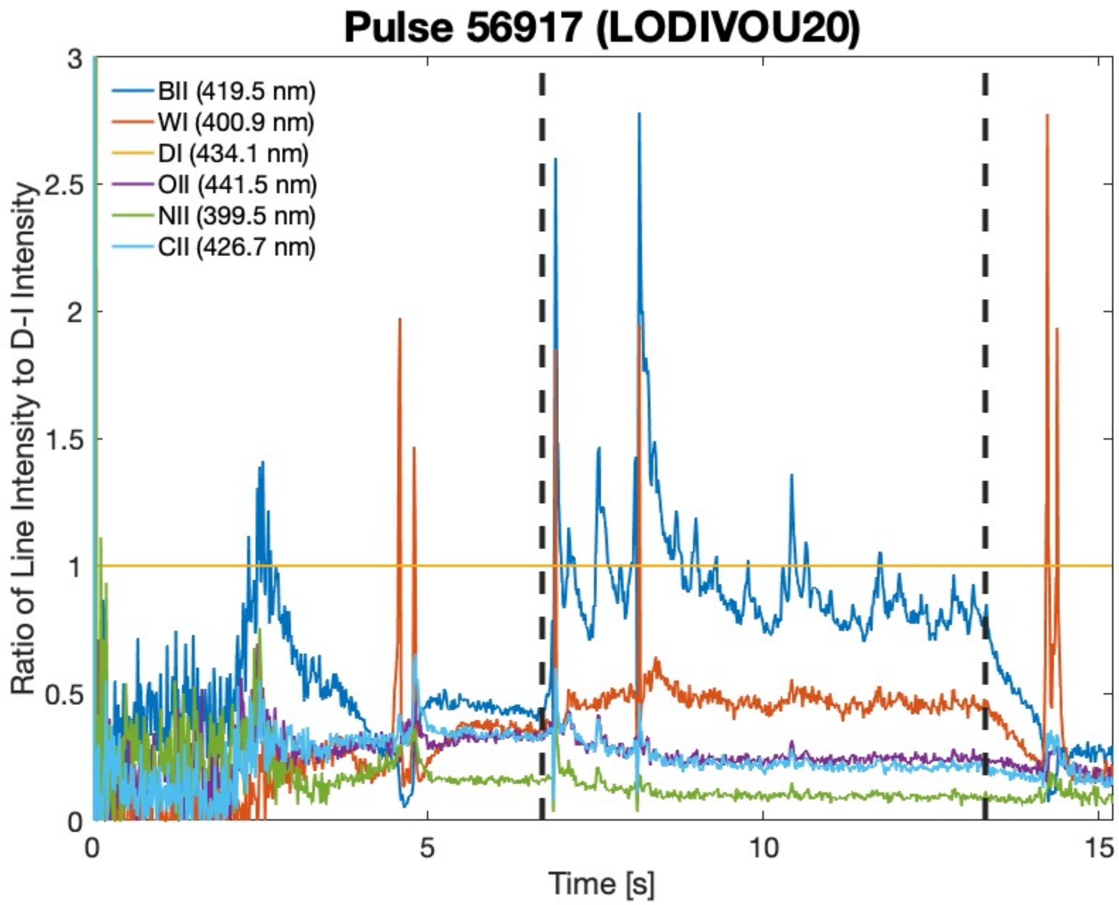

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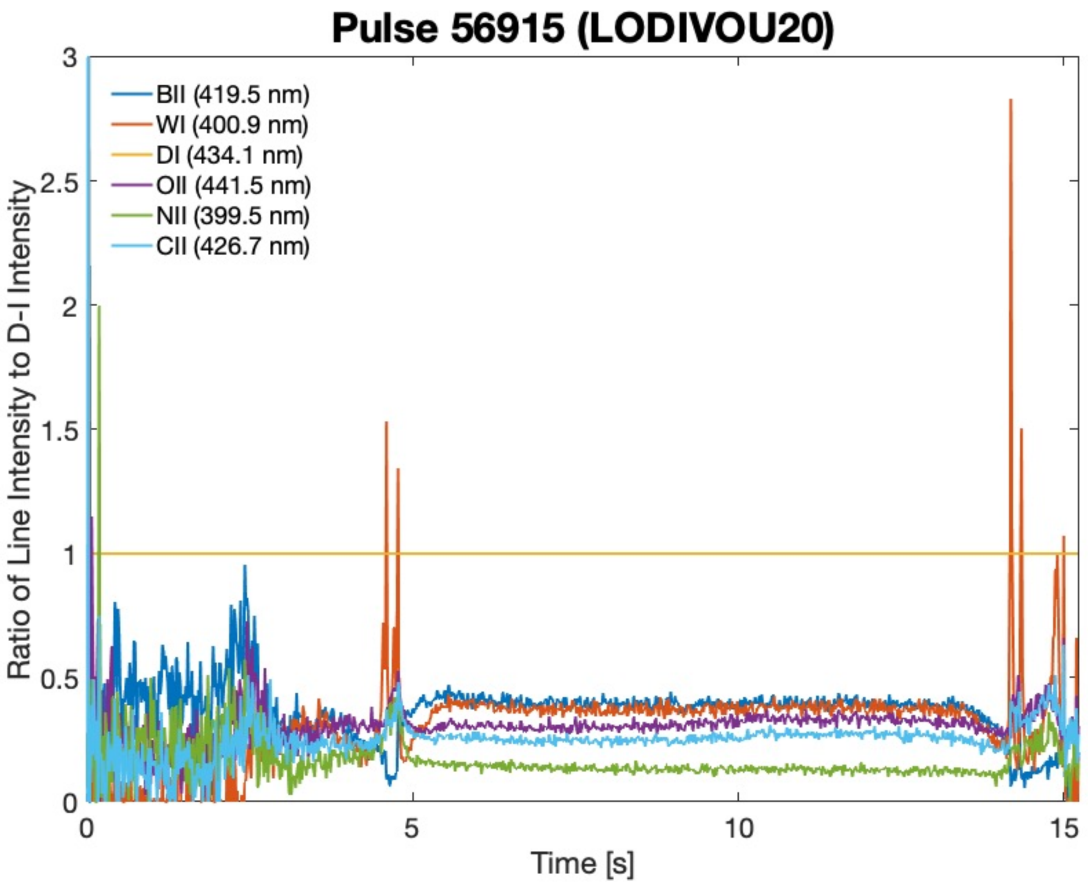


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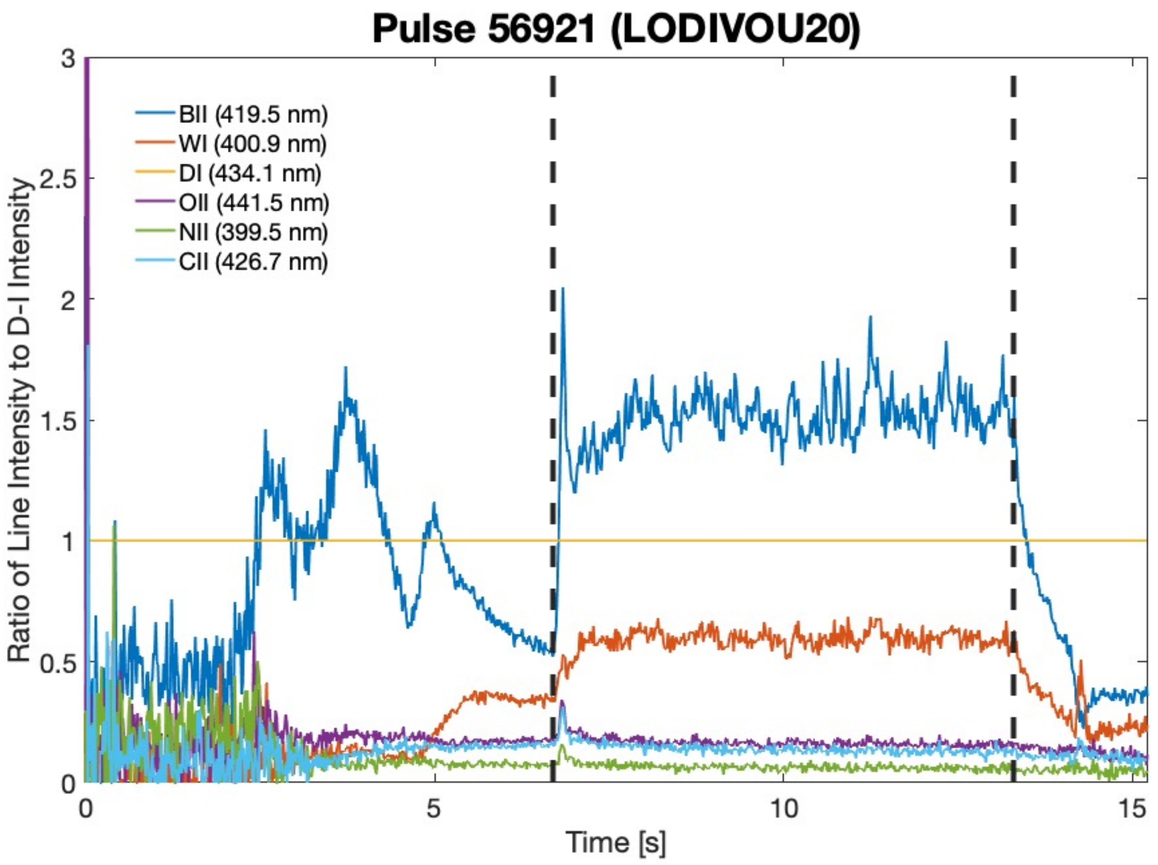
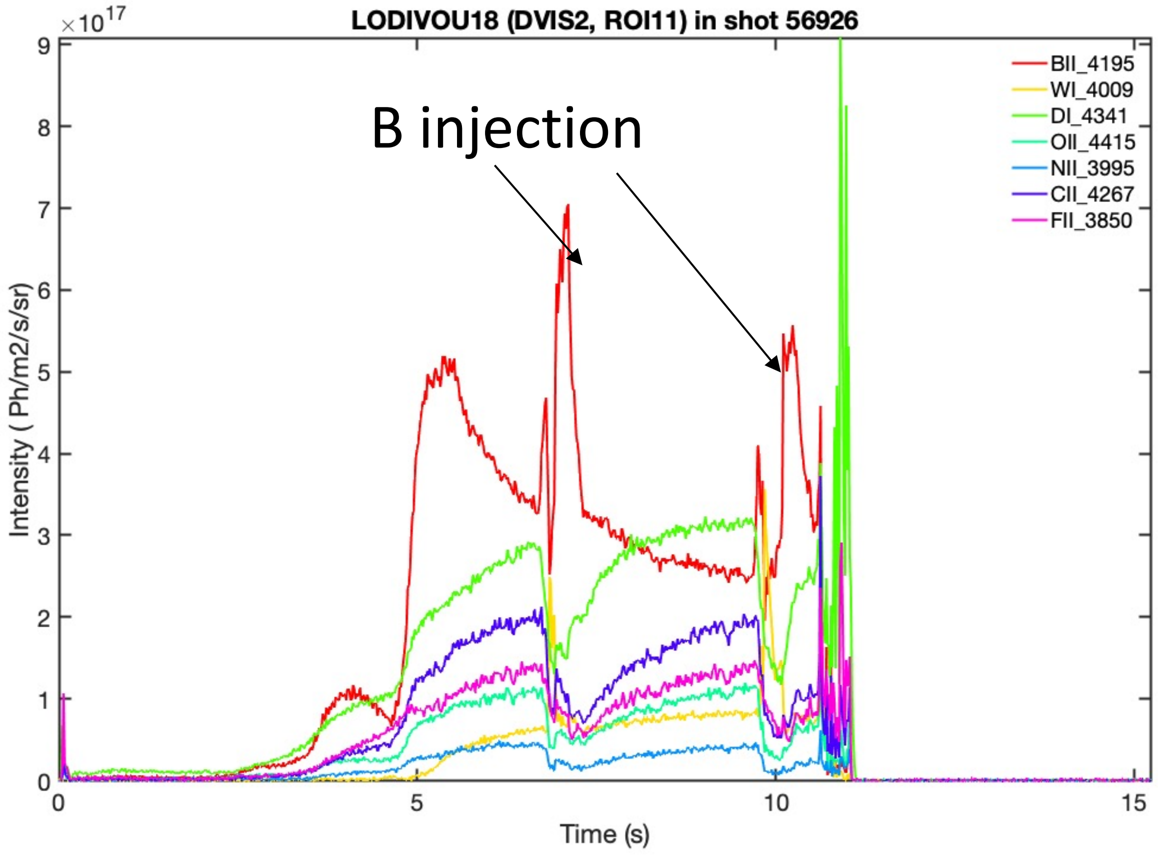


# Pulsed Operation of IPD Shows that D,C,O, and N Signals Recover Rapidly After Injection is Terminated

- Last two B spikes correspond to the pulses from the IPD
  - First two spikes may be the result of disruption from previous shot
- B signal intensities are much higher than previous shots
  - Possibly due to accumulation of B
- Large spikes of W during B pulses
  - Only observed in a few divertor LOS




**Lower Divertor**

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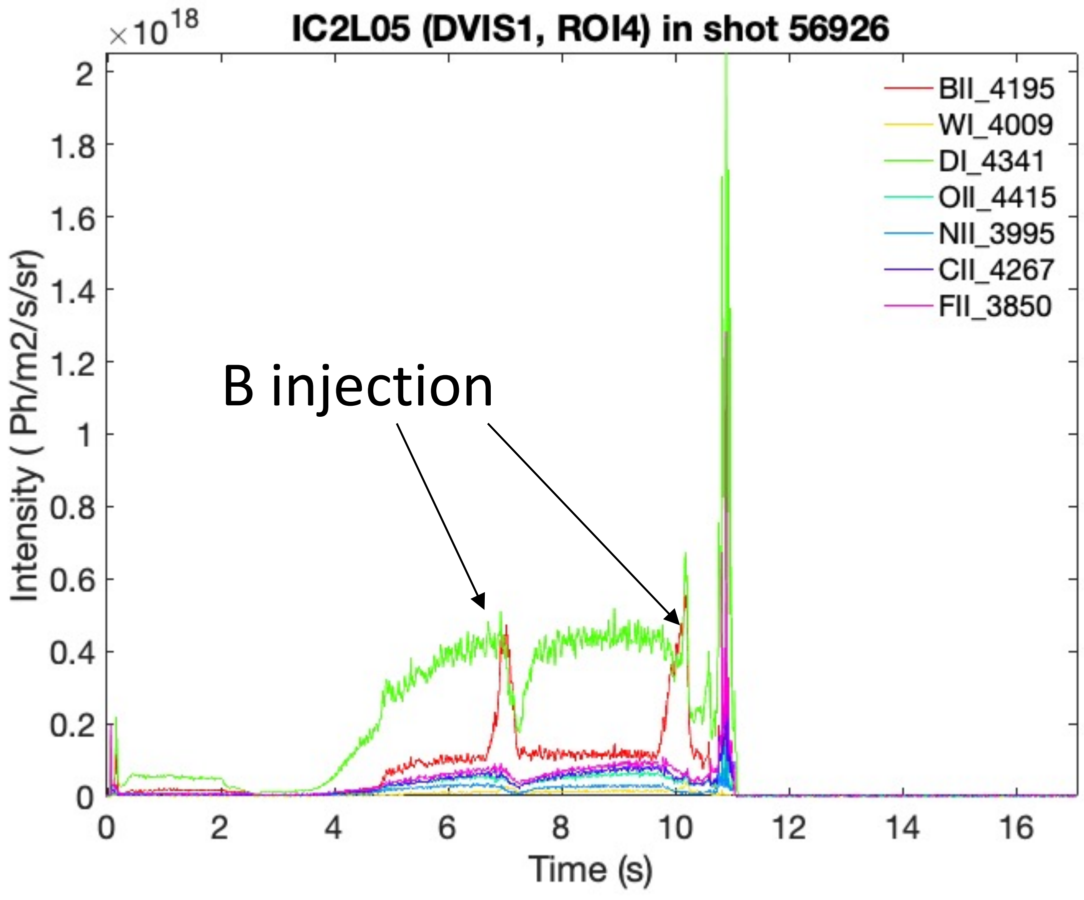
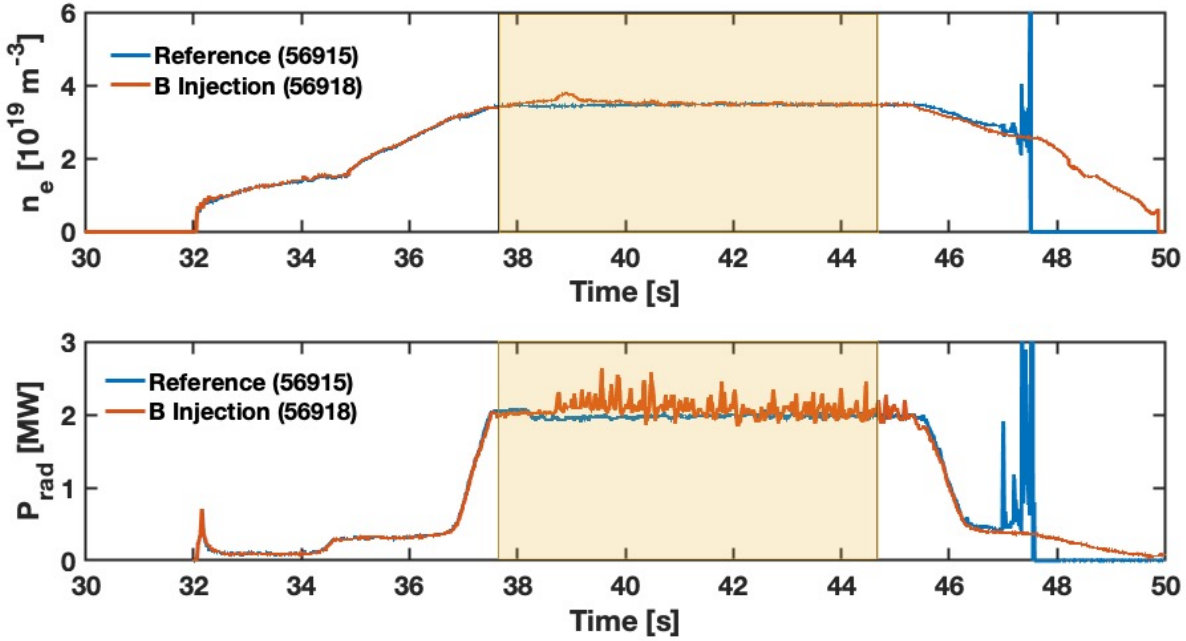
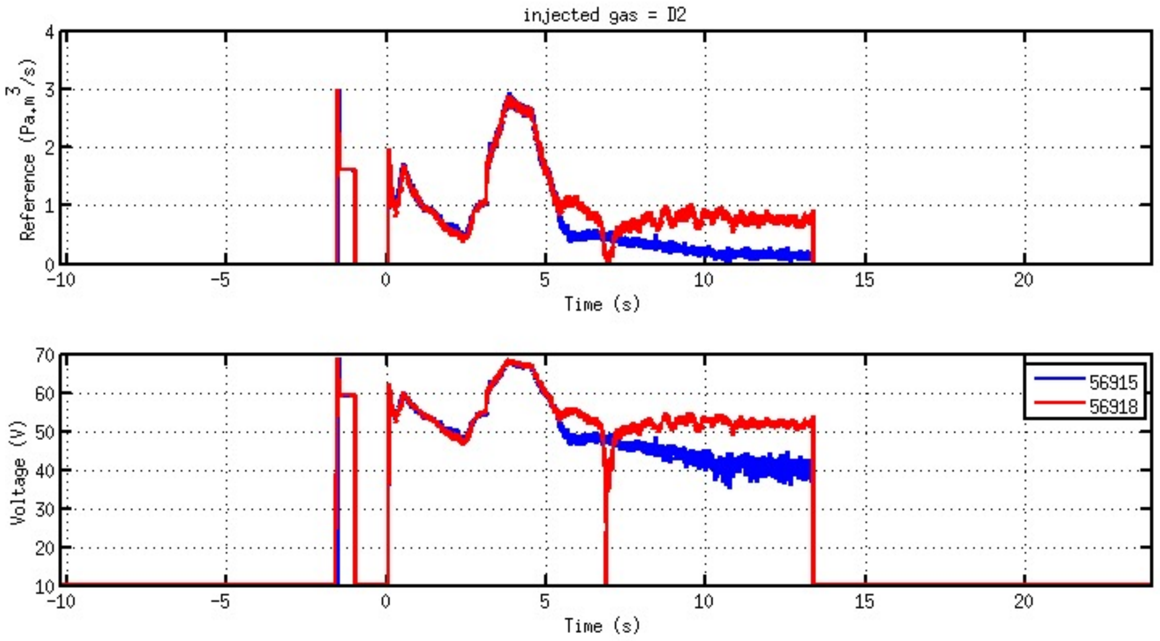



**ICRH Limiter**

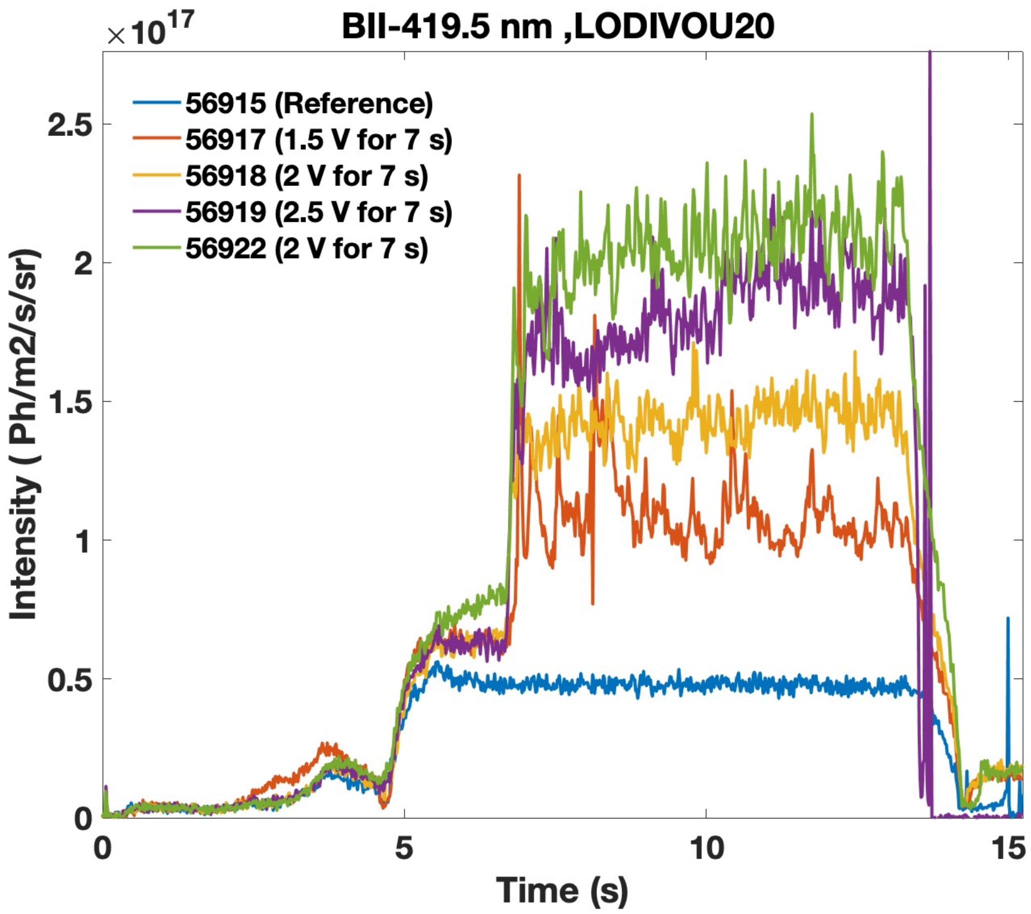
# Density Feedback System Decreases Neutral Fueling During B Injection

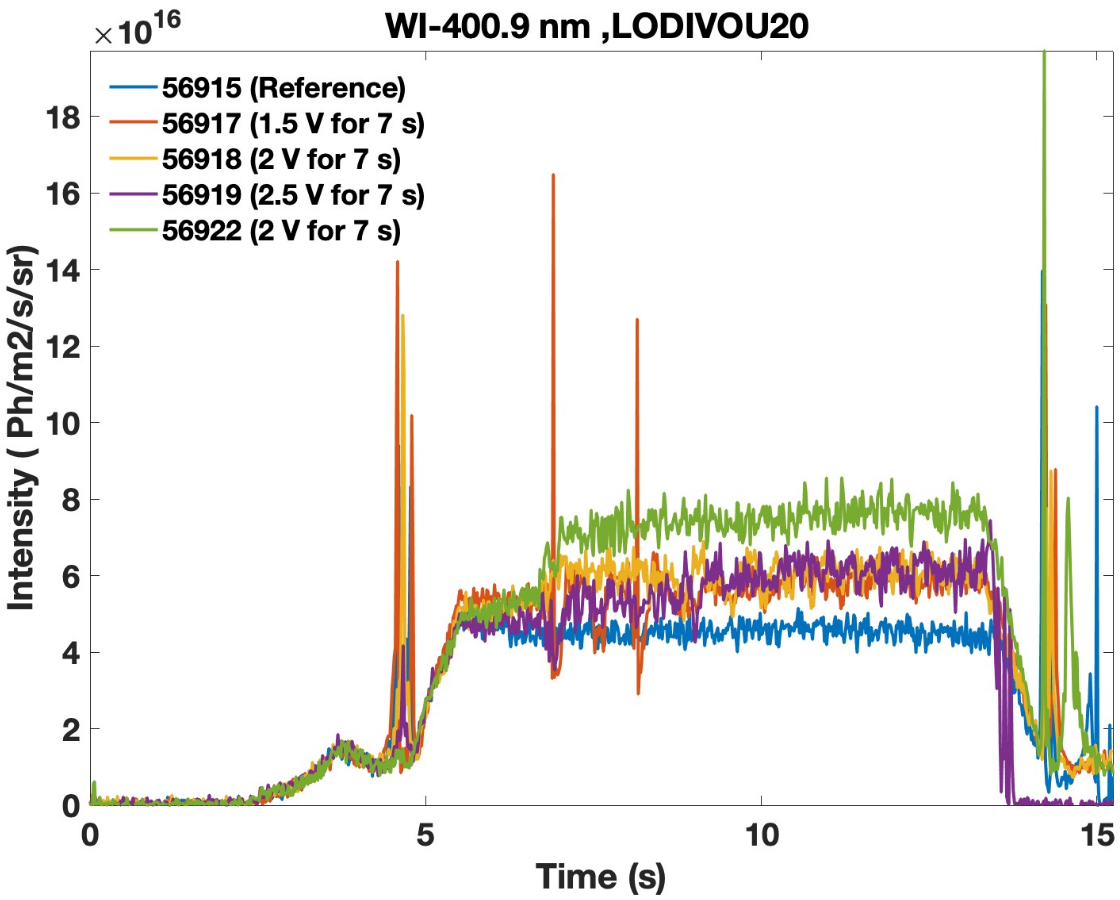
- Initial density spike may be result of feedback system attempting match $n_e$ target
  - Without feedback system, might see sustained increase in $n_e$ throughout the pulse



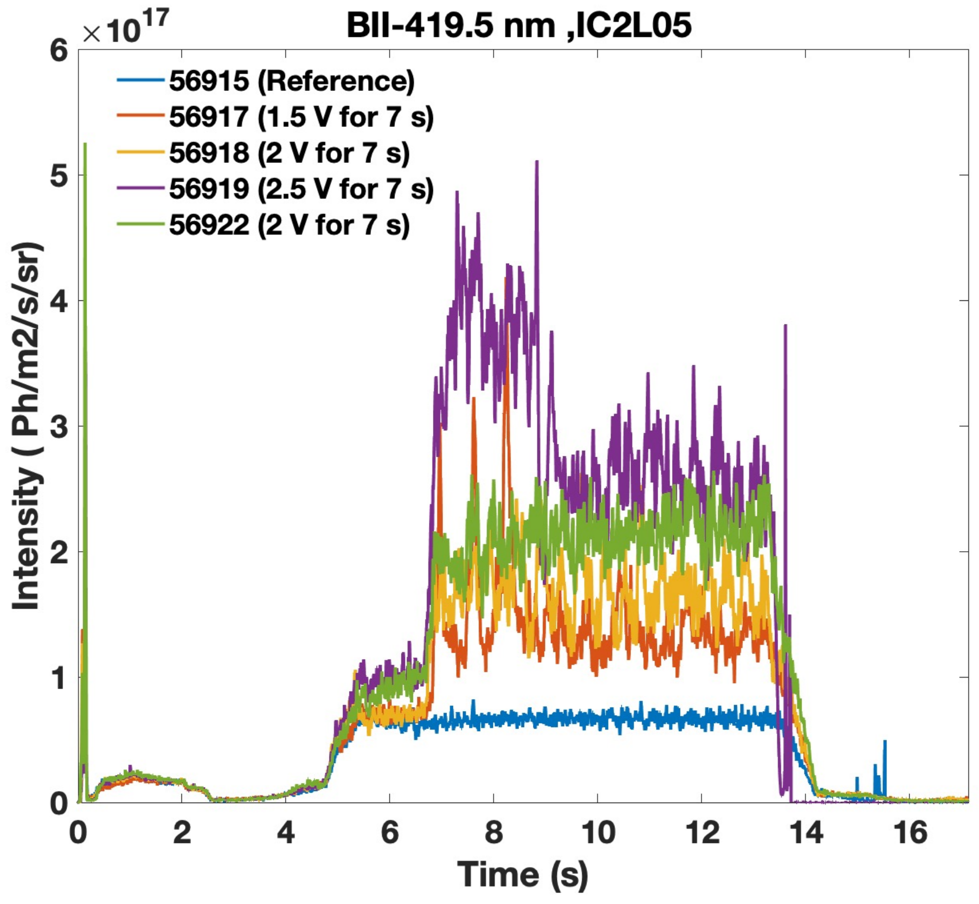
# Lower Divertor B and W Line Intensities Increase As More B is Injected

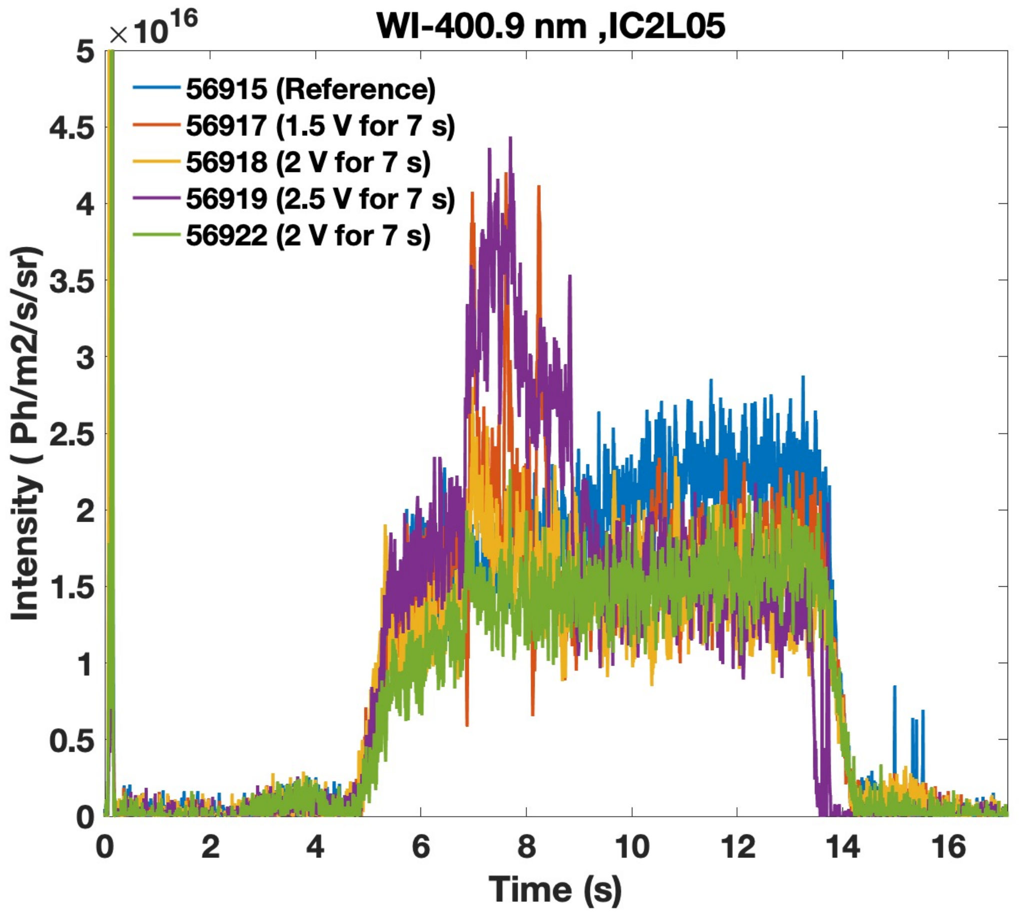



**Lower Divertor**

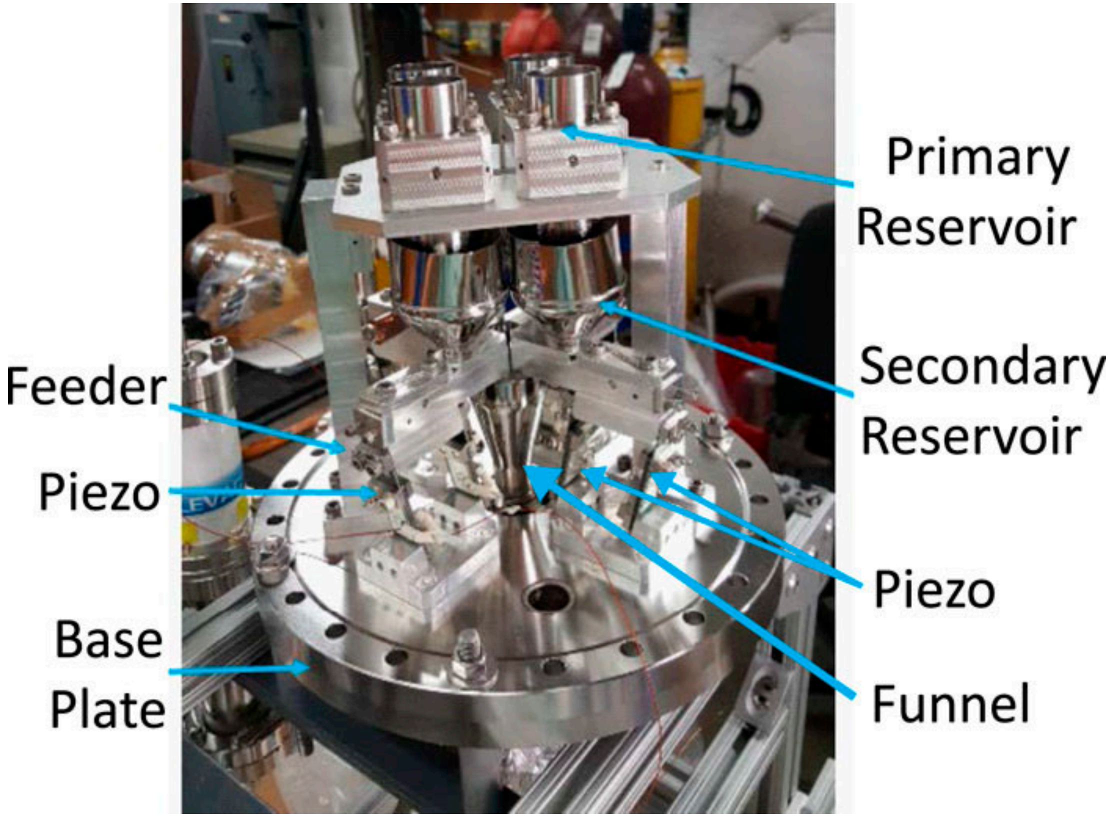
# ICRH Limited W Line Intensities Decrease As More B is Injected

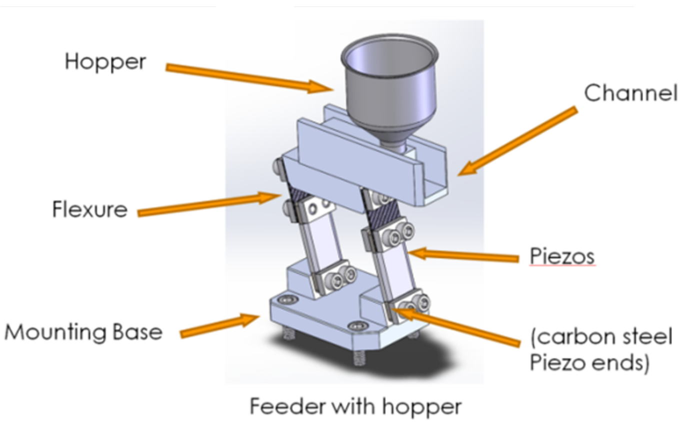


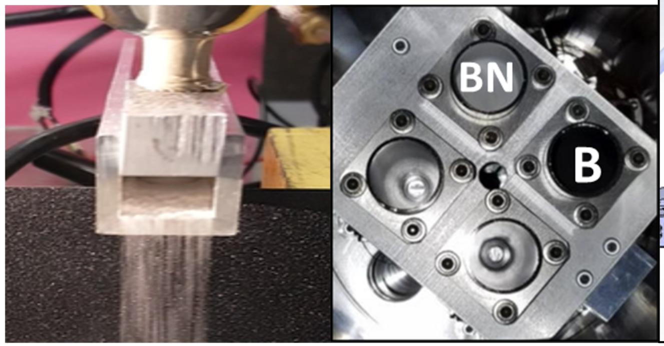



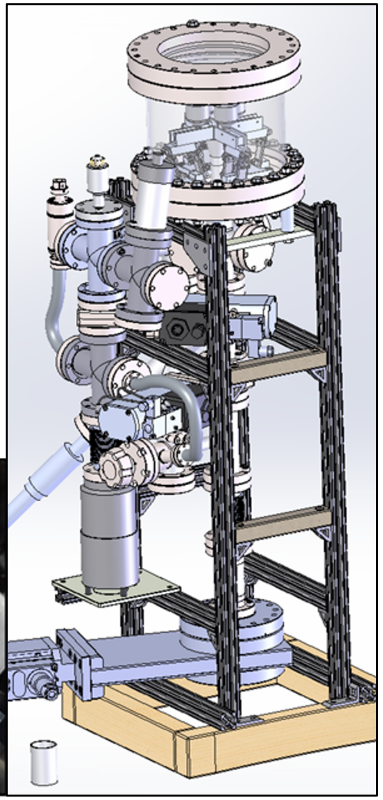

**ICRH Limiter**

# Impurity Powder Dropper



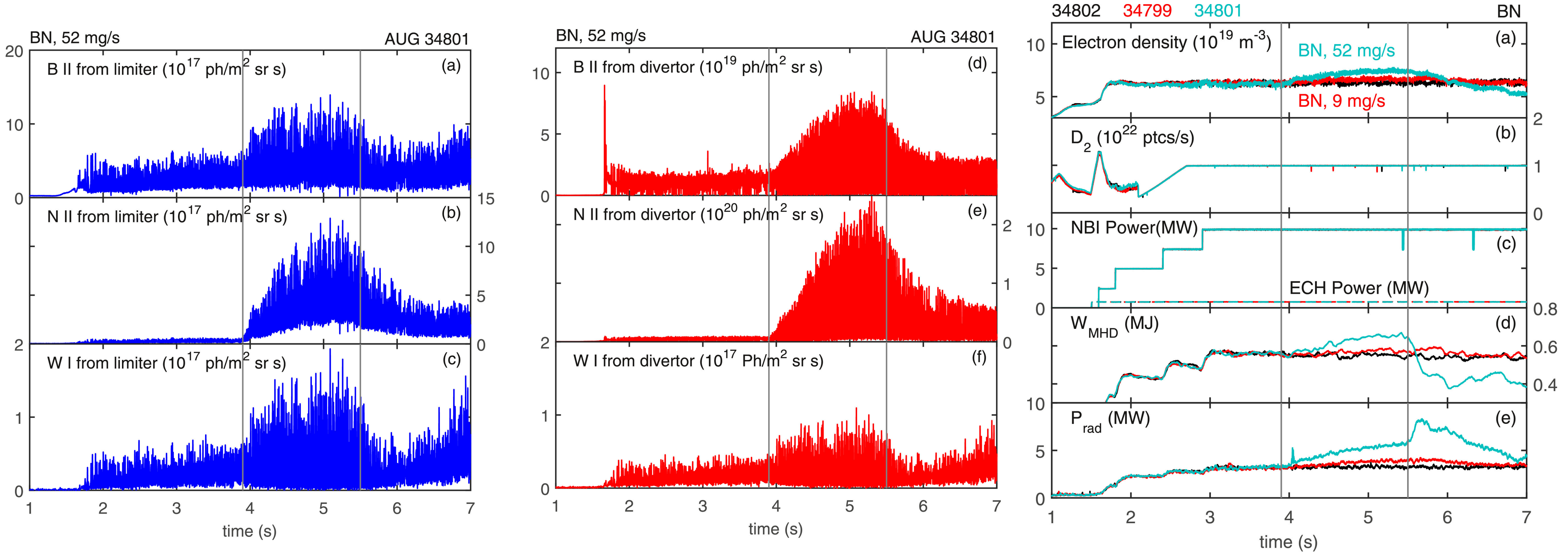



**A. Nagy et al., Rev. Sci. Instr. 2018**

# BN Drops in ASDEX-Upgrade




A. Bortolon et al. *Nuclear Materials and Energy* **19** 384-389 (2019)