Active conditioning of ASDEX-Upgrade tungsten PFCs through boron particulate injection (FIP/2-3)

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"Real-Time" boronization through powder injection

- Plasma assisted wall conditioning uses solid B compounds instead of toxic and explosive B_2D_6 gas
- Deposition of B powders extends the effective lifetime of boronization coatings
  - Allows density-controlled, high-purity plasmas with reduced wall fueling and mitigated High-Z impurity sources
  - Maintains controlled wall conditions over a run campaign
  - Could be used to provide active boronization for future long pulse discharges

Outline

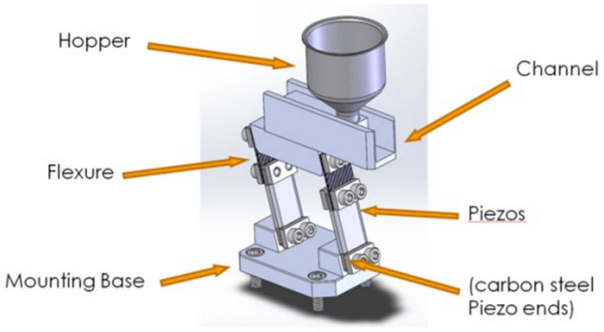
I. Experimental Apparatus

II. Boron Injection Experiments
   a) Boron Nitride Injection Series
   b) Boron Injection Series

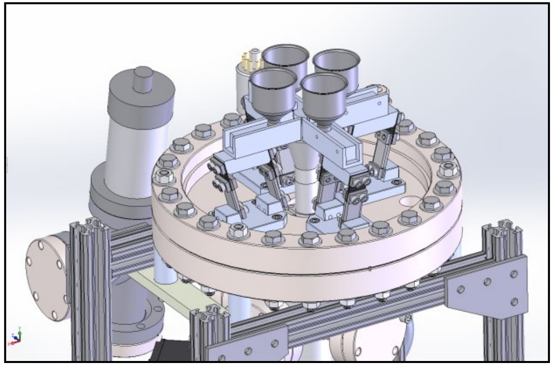
III. Conditioning Effects

Impurity powder dropper (IPD)

- 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
- Injection calibrated with accelerometer, optical flow-meter confirms mass injection rate

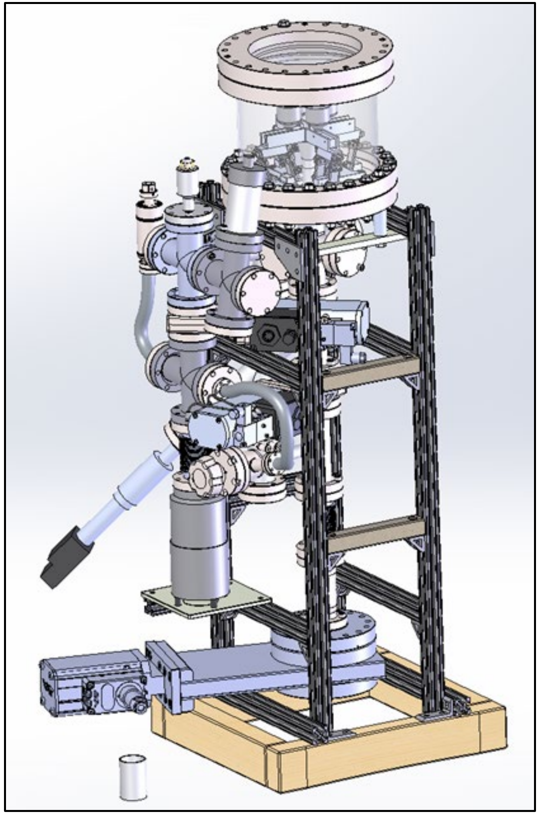


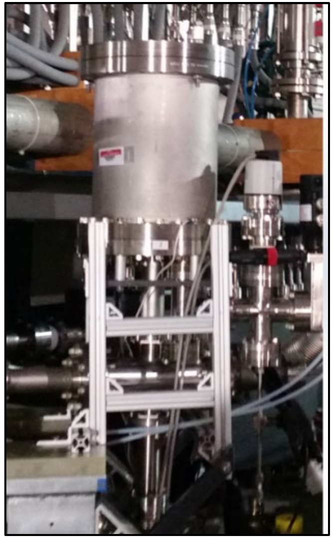
Feeder with hopper

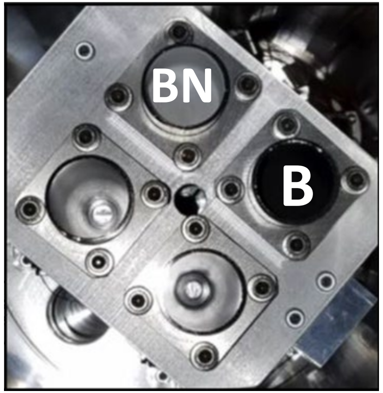


A. Nagy et al., Rev. Sci. Instr. *at press* 2018

IPD installed atop AUG during Fall 2017







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

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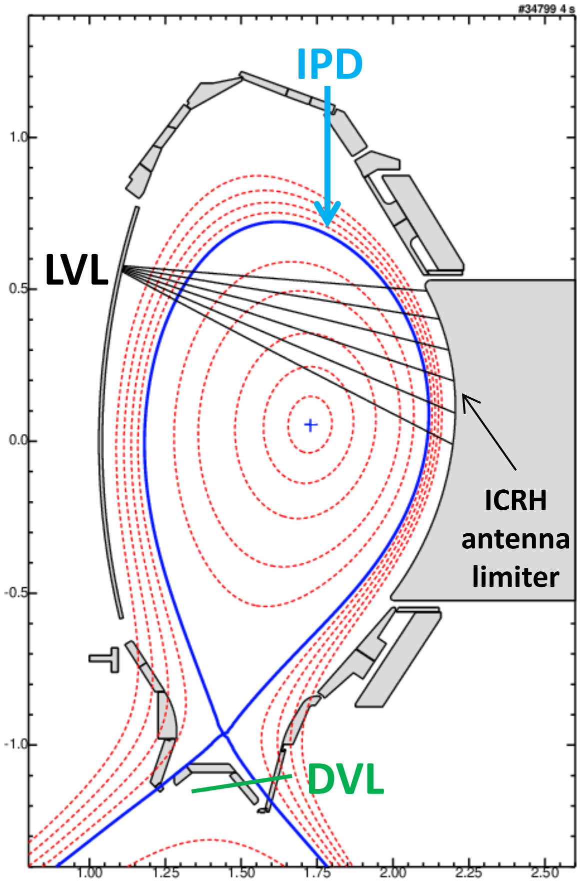
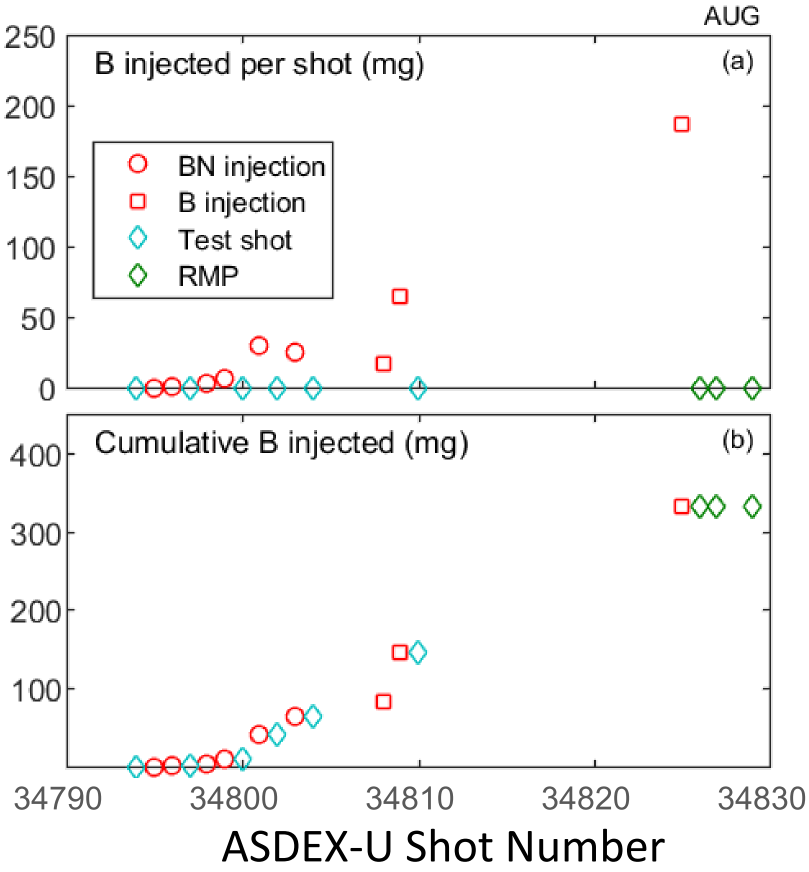
B/BN injected into conformal discharges to enhance coating

- Wall-conditioning discharge with conformal shape
  - SOL surfaces parallel to antenna limiter
- ELM-y H-mode discharges with I_P = 0.8 MA, B_T = 2.5 T, P_{NBI} = 10 MW, P_{EC} = 0.8 MW, n_e = 6.5x10^{19} m^{-3}
- Conditioning effects inferred from visible spectroscopy
  - Line emission from BII, OII, WI assumed representative of wall source
  - Views for divertor (DVL) and limiter (LVL)
- W impurity influx from ICRH antenna limiter inhibits low-collisionality operation
  - D_2 puff required to maintain robust ELM frequency



Wall conditioning by B powder injection

- Experiment scheduled to provide maximum chance to observe changing wall conditions (directly before standard D_2B_6 boronization)
- 9 conditioning discharges with BN or B
  - Constant injection rate for 1-3 s @ 2-75 mg/s
- 6 test discharges w/o IPD
  - Interleaved to assess changing wall conditions
- 3 attempts at ELM-suppression with RMP after completing conditioning discharge sequence
  - scenario tests access to low collisionality
- Total ~330 mg of B introduced in AUG



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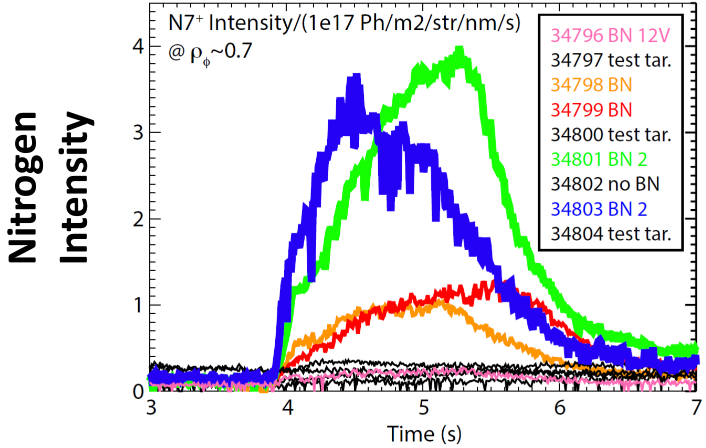
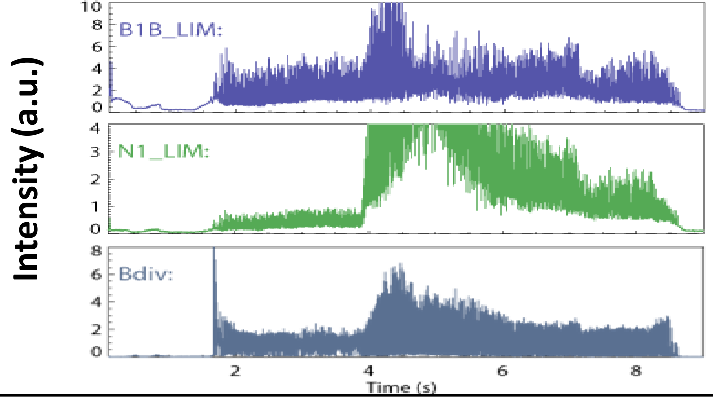
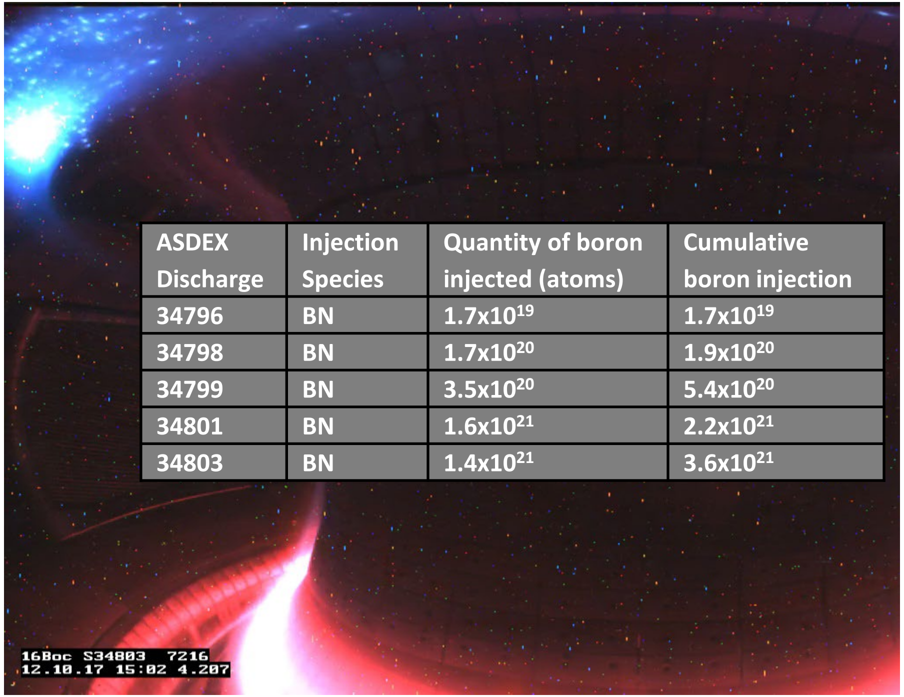
Boron nitride injection series





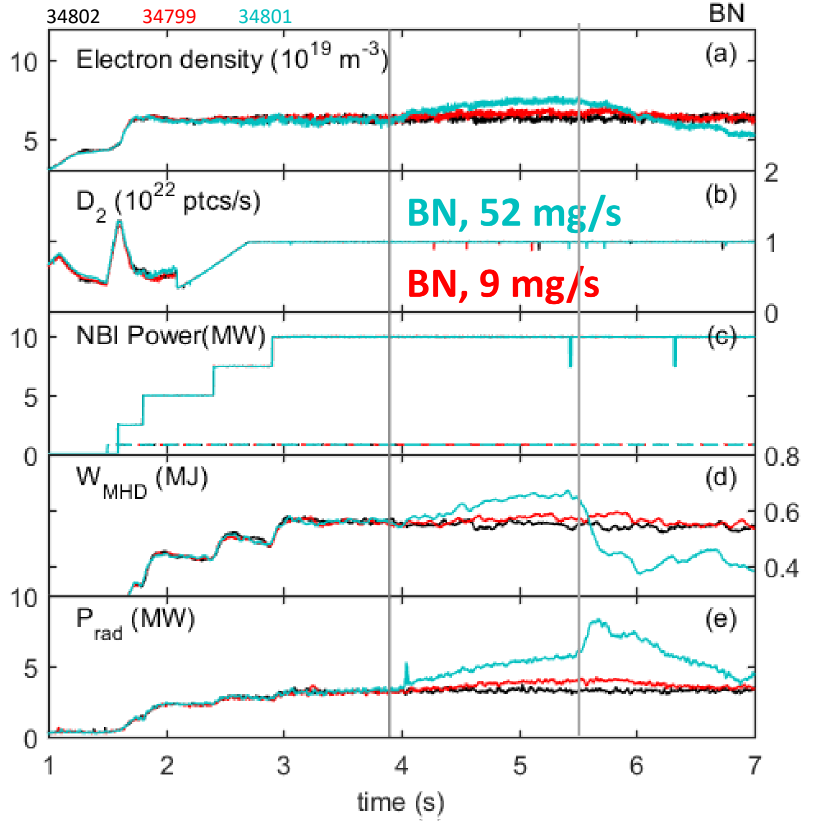


ASDEX Discharge	Injection Species	Quantity of boron injected (atoms)	Cumulative boron injection
34796	BN	1.7x10^{19}	1.7x10^{19}
34798	BN	1.7x10^{20}	1.9x10^{20}
34799	BN	3.5x10^{20}	5.4x10^{20}
34801	BN	1.6x10^{21}	2.2x10^{21}
34803	BN	1.4x10^{21}	3.6x10^{21}

BN input from 3.8-4.9 s
N radiation dominates, No N latency
B radiation at limiter and divertor

BN increases confinement similar to N_2

- **#34802** : Control Discharge
- **#34799 : 9 mg/s**
  - 5% increase of n_e and P_{rad}
  - Stored energy W_{MHD} unchanged
- **#34801 : 52 mg/s**
  - n_e +25% and P_{rad} +80%
  - W_{MHD} increases until core mode destabilized (β_N~2.7)
  - Confinement improvement associated with pedestal recovery
  - <u>Greater coupling to discharge than seen with N2 gas puff</u>



A. Bortolon et al., Submitted *J. Nucl. Mater. Energy* 2018

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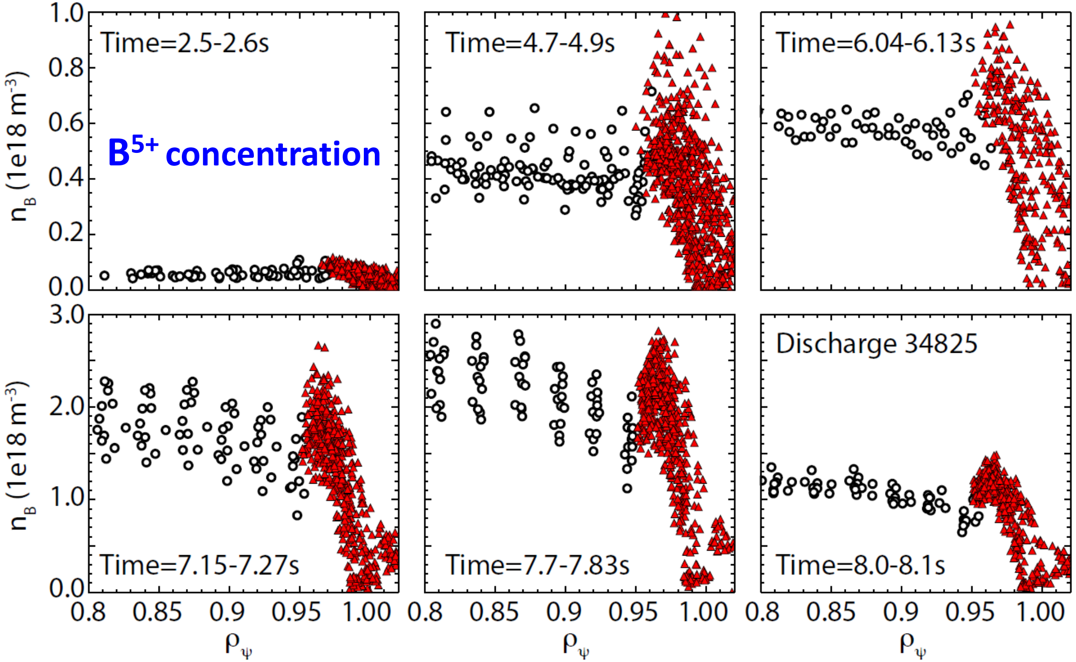
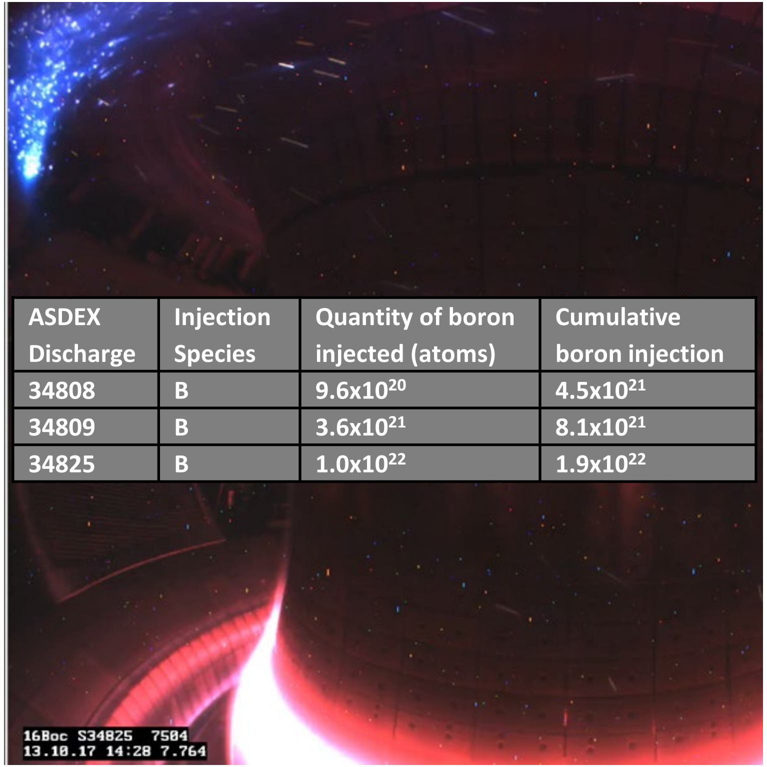
Metallic Boron Injection Series



Pure B input from 3.8-7.9 s

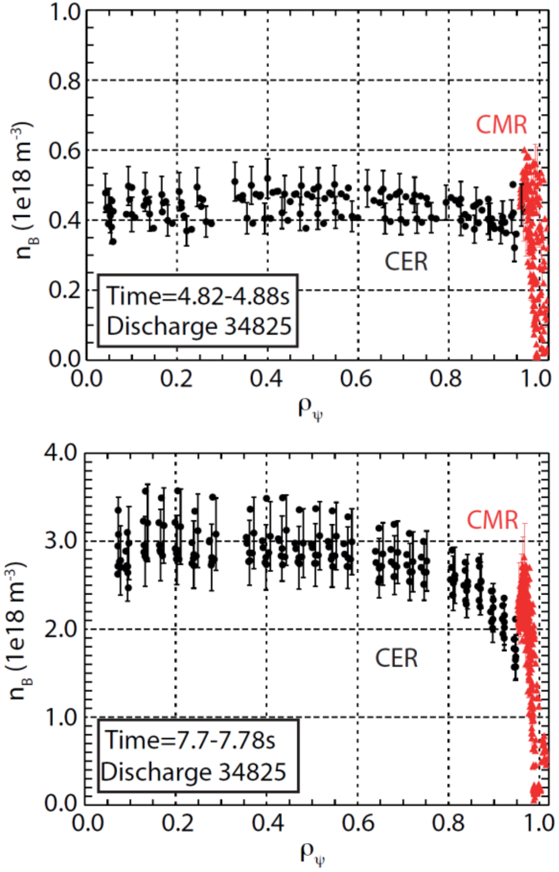
Less additional radiation, stable discharge

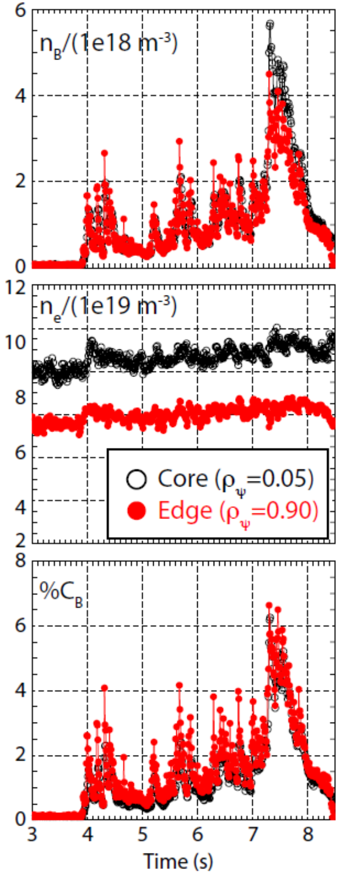
CEX shows B fully penetrates discharge

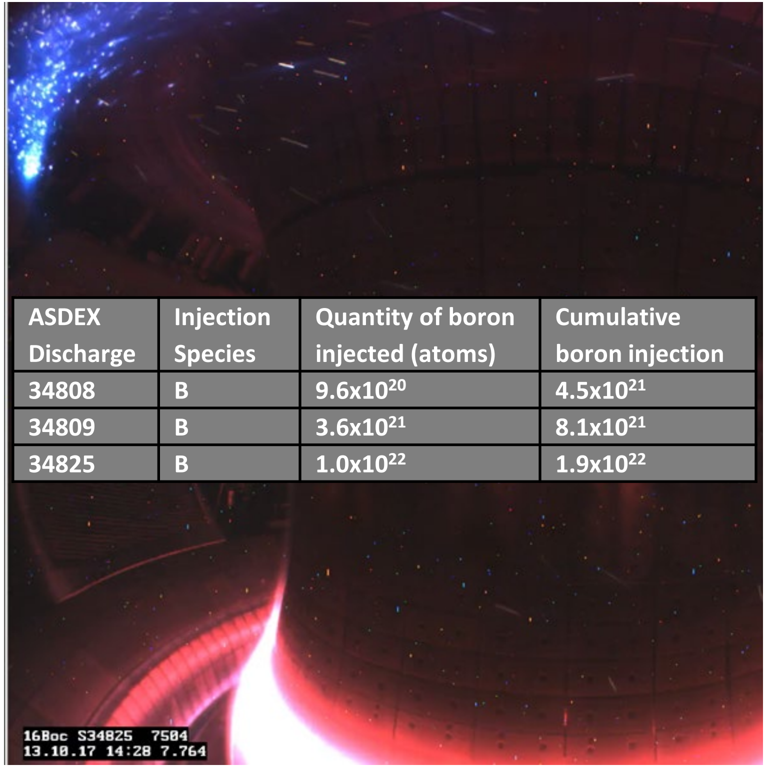


ASDEX Discharge	Injection Species	Quantity of boron injected (atoms)	Cumulative boron injection
34808	B	$9.6x10^{20}$	$4.5x10^{21}$
34809	B	$3.6x10^{21}$	$8.1x10^{21}$
34825	B	$1.0x10^{22}$	$1.9x10^{22}$

Metallic Boron Injection Series







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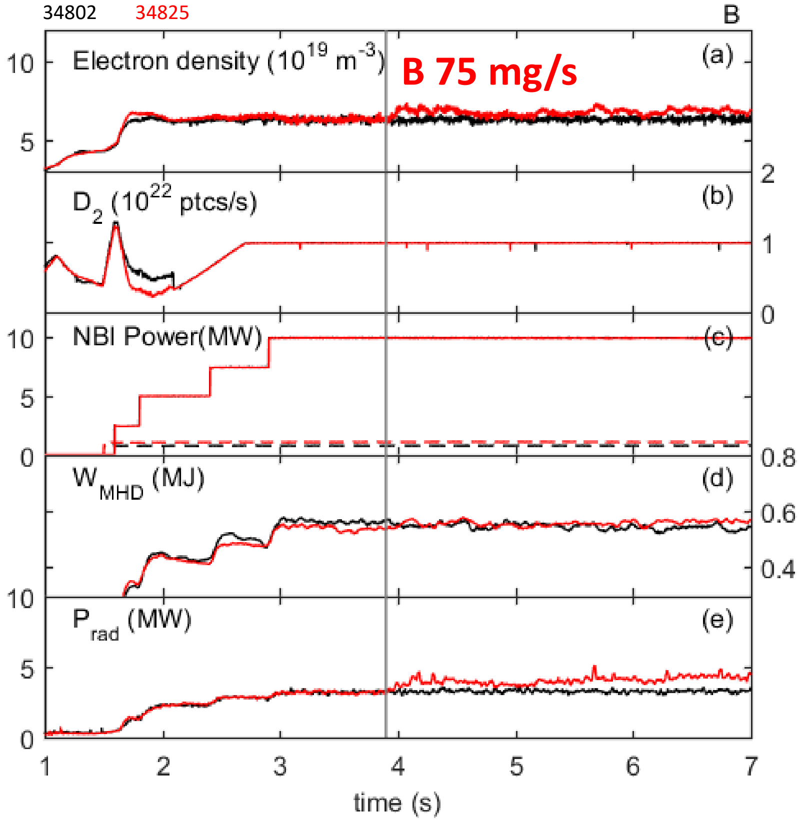
Boron injection well tolerated by plasma

- ELMy H-modes, f_{ELM}~70-100 Hz
  - 10 MW NBI, 1.2 MW ECRH
  - D_2 fueling throughout
- **#34825 : B injection, 75 mg/s**
  - Modest ~5% increase of n_e
  - Oscillations due to fluctuations in drop rate (B clumping)
- P_{rad} increase by 20%
- No effect on stored energy W_{MHD}



A. Bortolon et al., Submitted *J. Nucl. Mater. Energy* 2018

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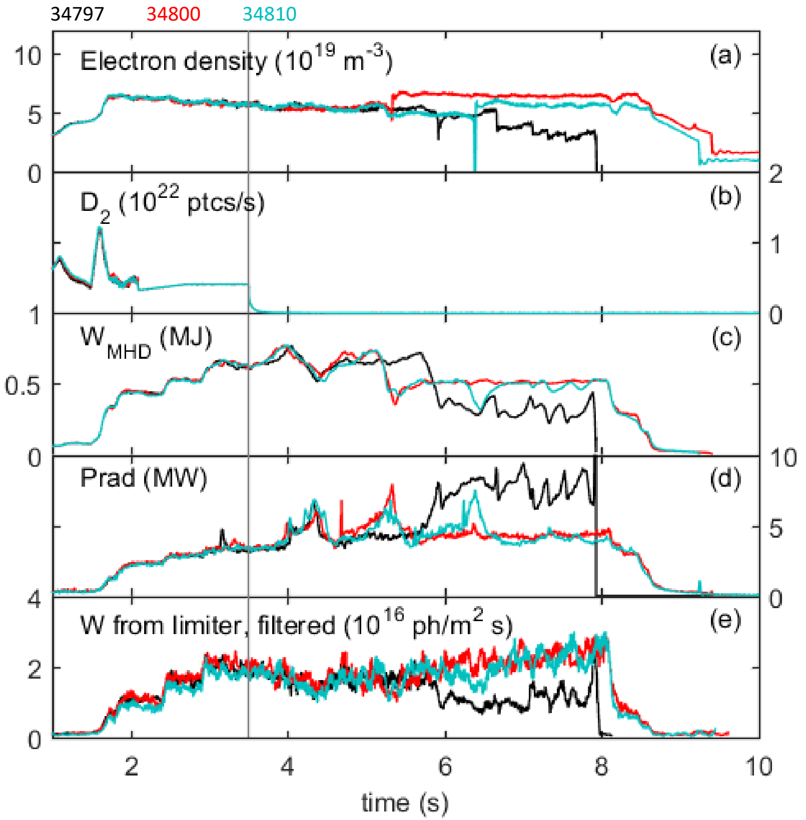
Low-density test shot shows slight improvement

#34797 : ~3.7 x 10^{18} B atoms injected
#34800 : ~1.3 x 10^{20} B atoms injected
#34810 : ~5.8 x 10^{21} B atoms injected

- Due to wall conditions test discharge scenario is unstable w/o gas puff
  - Core MHD
  - P_{rad} runs away
  - Radiative collapses → disruption
- After BN/B injection MHD persists
  - P_{rad} run away is avoided
  - Plasma sustained to completion



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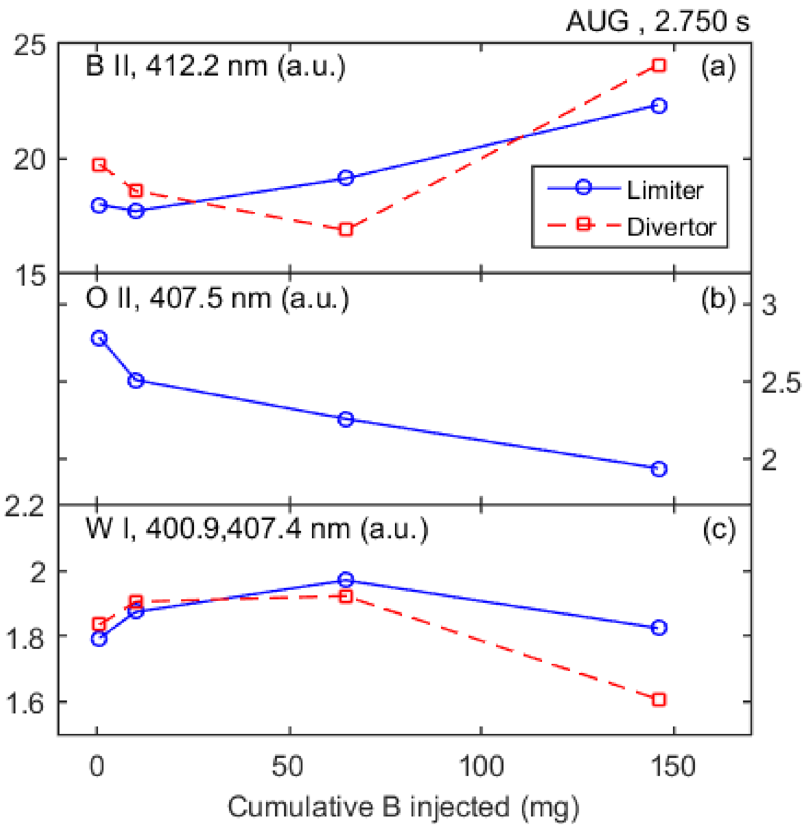
Wall condition observables improve during test-shot series

- Impurity source estimated from time-average of line emission
  - BII, OII and WI

- B from limiter increases → B coating
- O from limiter decrease → O gettering
- W source decreases for >100 mg B

- Similar trends observed in divertor



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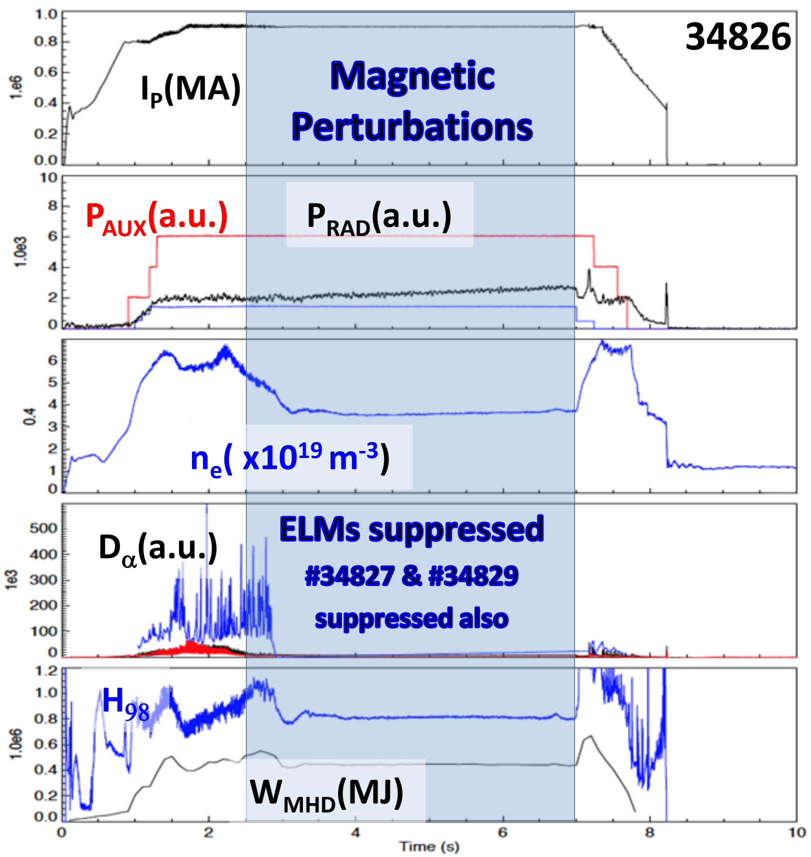
Boron injection assists successful RMP ELM suppression

1. Total boron injected : 330 mg
2. **#34826** : Attempted ELM-suppression

- D_2 puff stopped at t=2.25s
- n = 2 RMP from 2.5 – 7 s
- Full-shot ELM suppression achieved
  - Sufficient n_e pump-out maintained
  - 3 consecutive discharges
- Slow increase in P_{rad} and W radiation
  - Impurity sources recovering on discharge time-scales
- Need to confirm B injection is responsible



Summary

BN and B powder both successfully injected into auxiliary heated AUG plasmas

- **Boron Nitride**:
  - Observed increased B & N flux from limiters & divertor
  - P_{rad} increased by > 100% at highest rates
  - At high injection rates, confinement and stored energy increased by 20-30%, as observed with N_2 puffing
  - Crashed at $\beta_N > 2.7$
- **Elemental Boron**
  - Observed increased B flux from limiters & divertor
  - P_{rad} increased by 50% at highest rate
  - Discharge stable, B injection limit not reached

Conclusions and Outlook

- Initial AUG experiments suggest that boron powder injection can be used to augment borization coating during tokamak operation
  - Successful modification of edge impurity levels
  - Successful access to low density for RMP ELM suppression
  - Upcoming experiments planned to corroborate results and optimize technique
- Particulate wall conditioning could aid steady-state operation where initial coatings will erode rapidly
- IPD has been/is being installed on other devices
  - DIII-D results to be presented at APS 2018
  - Successful horizontal B_4C injection into W7-X
  - Experiments on EAST, KSTAR to address applicability to long pulse operation


Thank you!
IPD

Supplemetal Information

RGA Comparison of BN injection and N_2 gas puff

Performance enhancement observed with BN similar to N_2 gas puff

Greater coupling to discharge with smaller Nitrogen quantity

Reduction in Ammonia quantity

Suggestive of NH_3 mitigation possibilities for JET & ITER to prevent tritium sequestration

Full behavior not well understood, further study required

Inner Divertor – Partial Pressure of Residual Gasses