Enhanced radiative divertor power exhaust through injection of low-Z powders in DIII-D

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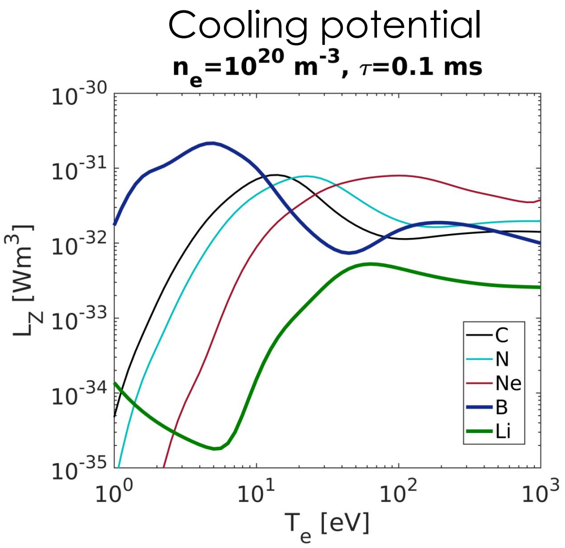
PPPL

Radiative divertor solutions for high power tokamaks are being assessed at DIII-D



Reactor: strike point detachment needed to protect PFCs

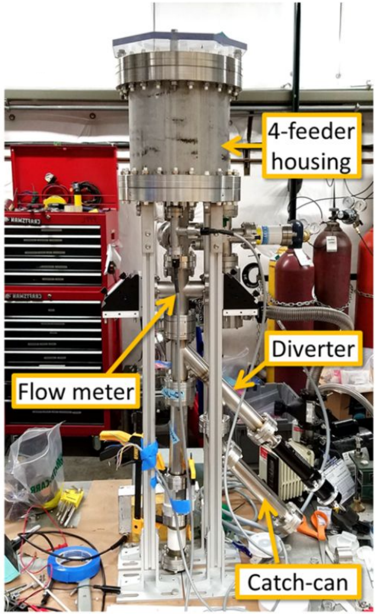
- Induce energy and momentum losses with impurity seeding
- Boron and nitrogen predicted to have potential for near strike-point dissipation
  [A. Yu. Pigarov, Physics of Plasmas 24, 102521 (2017); https://doi.org/10.1063/1.4986516]
- Lithium vapor box promising for evaporation-condensation cycle
  [R.J. Goldston et al, NME, Vol. 12, 2017, 1118-1121, https://doi.org/10.1016/j.nme.2017.03.020]

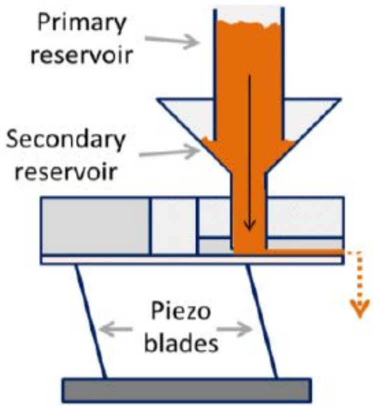
Core-edge integration requires

- Dissipative divertor to protect main PFCs
- Avoid plasma core performance degradation

This study -> Use B, Li & BN powders as alternate approach to enhance core-edge compatibility in DIII-D H-mode scenarios

Impurity powder dropper enables new applications to modify the core-edge and plasma-material interface





PPPL Impurity Powder Dropper (IPD)
[A. Nagy et al, RSI 89, 10K121 (2018), https://doi.org/10.1063/1.5039345]

Versatile applications

- Injection in solid powder form extends and facilitates use of materials such as B, B_4C, BN, Li, Si, SiC, …
- Particle size 5-100 μm
- Rates 1-100 mg/s, velocity ~ 5 m/s
- International use: ASDEX-U, DIII-D, EAST, KSTAR, LHD, W7-X, WEST
- Typical applications: real-time wall conditioning, ELM pacing, impurity transport, …

[A. Bortolon et al 2020 Nucl. Fusion 60 126010, https://doi.org/10.1088/1741-4326/abaf31]

-> <u>This work</u>: radiative divertor power exhaust

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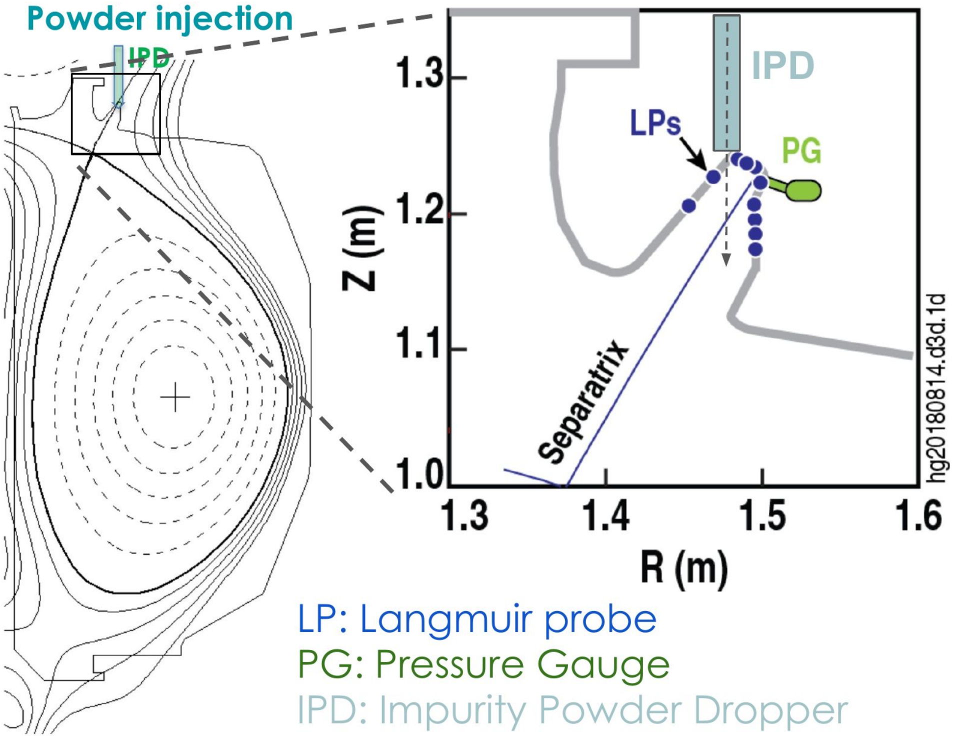
Impurity powders injected into the closed small-angle slot divertor in DIII-D H-mode discharges



LP: Langmuir probe

PG: Pressure Gauge

IPD: Impurity Powder Dropper

[H.Y. Guo et al 2019 Nucl. Fusion 59 086054, https://doi.org/10.1088/1741-4326/ab26ee]

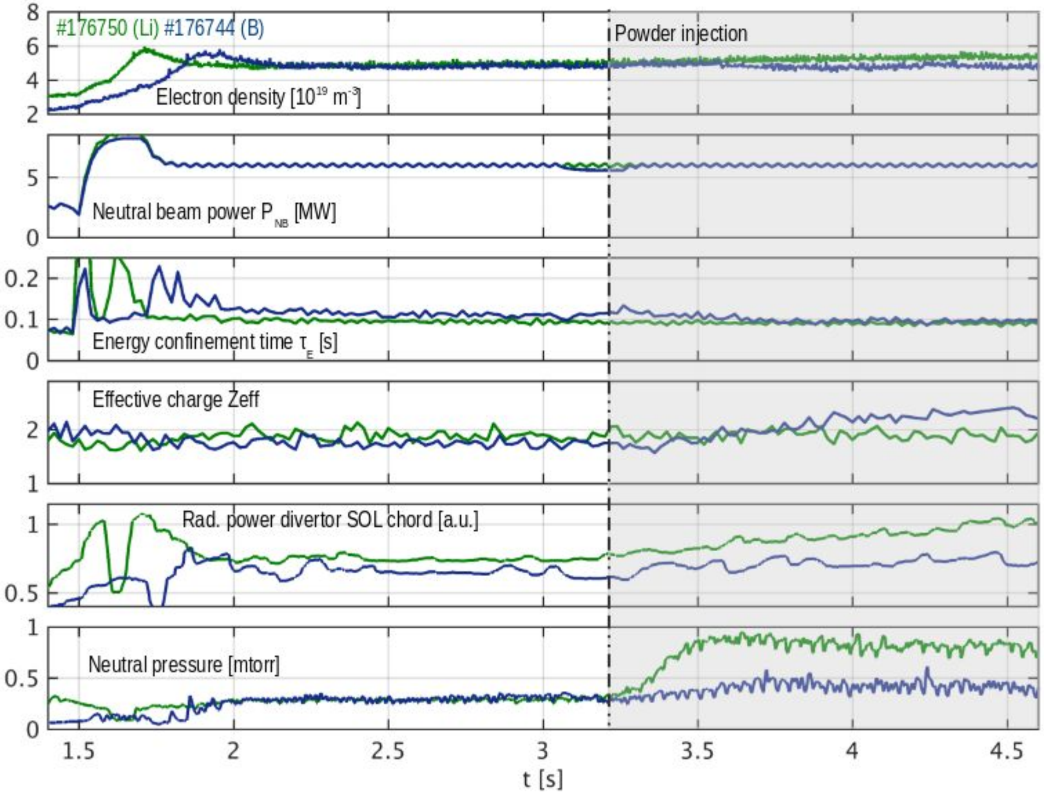
Advanced divertor scenario

- Upper Single Null, closed Small Angle Slot (SAS) divertor
- H-mode, 1 MA, 2 T, fwd B_t P_{NB}~6 MW, n_e~5×10^{19} m^{-3}

B & Li powder dropping at DIII-D

- Piezoelectric feeder
- Gravitational acceleration
- Injection rates: 3.3 & 35 mg/s (10^{20}-10^{21}at./s) in 2-s intervals

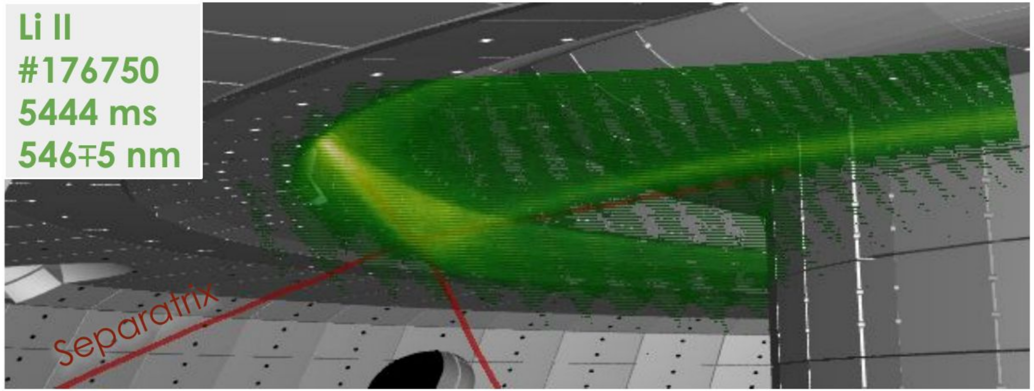
Powders increase divertor radiation and neutral pressure while H-mode performance is maintained

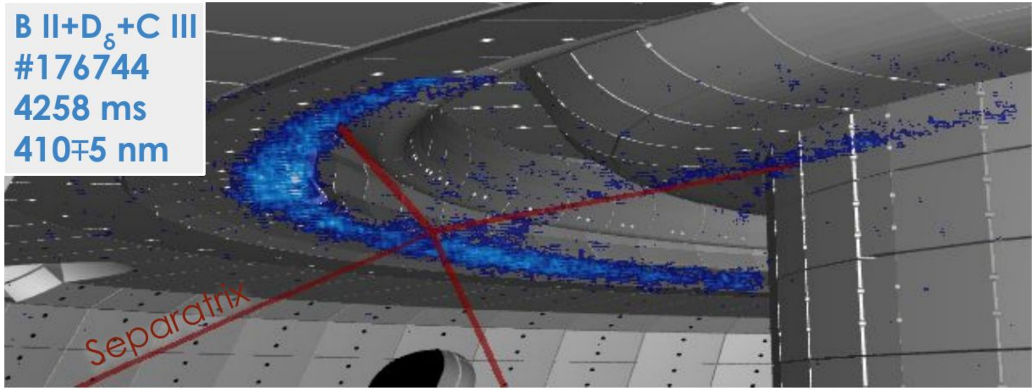


Comparable discharges:

- Li & B powder injection after 3.2 s at 3.3 & 35 mg/s (10^{20}-10^{21}at./s) in 2-s intervals
- Density marginally up/down (Li/B)
- Energy confinement reduces only marginally
- Increase of Zeff from 1.8 to 2.4 in case of B
- Divertor SOL radiation increased by 37% (Li) and 20% (B)
- Divertor neutral pressure increase x3 (Li) and x1.5 (B)

Tangential camera: emission enhanced near x-point for Li

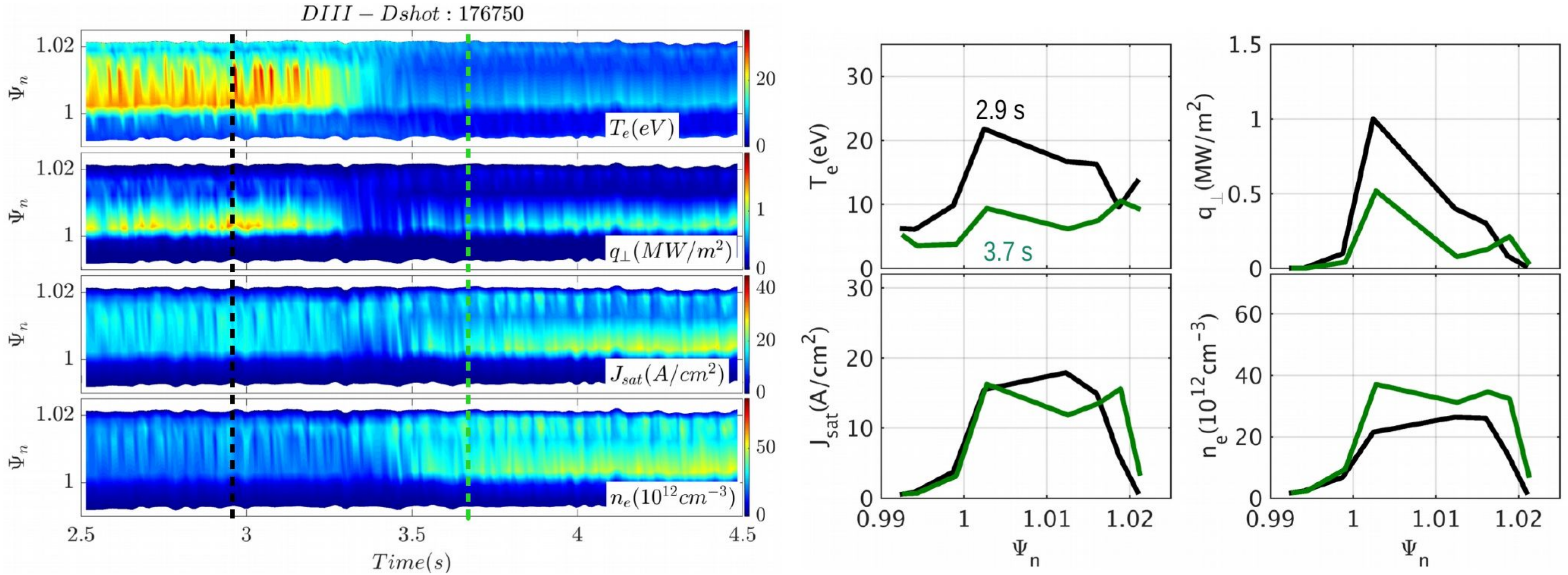


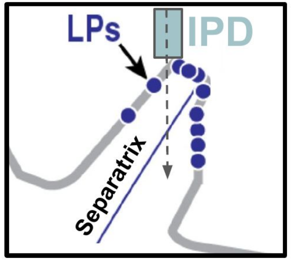


Emission during powder injection:

- Li II shows clear enhancement around separatrix leg and near x-point
- B II: background subtraction might have eliminated some contamination by D_δ and C III, mostly attached to divertor plates

Lithium: cooling of divertor temperature and heat flux



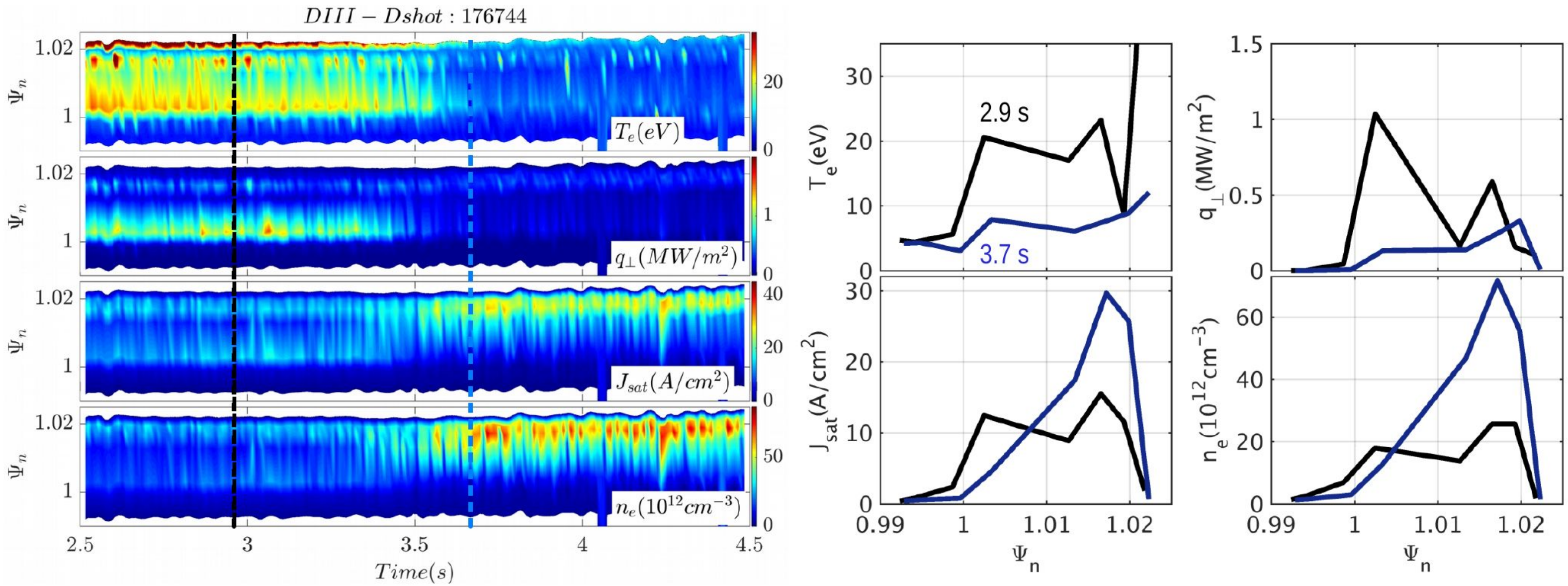


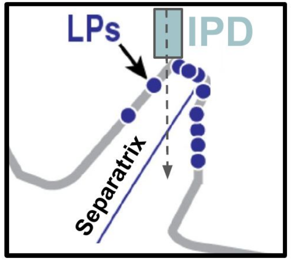
Langmuir probe data in small-angle slot (SAS) divertor

- $T_{e,div}$, $q_\perp$ drop by ~50%
- J_{sat}, $n_{e,div}$ moderately increase

-> Li powder injection causes colder and denser divertor

Boron: substantial drop of divertor T_e, $q_{||}$, and J_{sat}

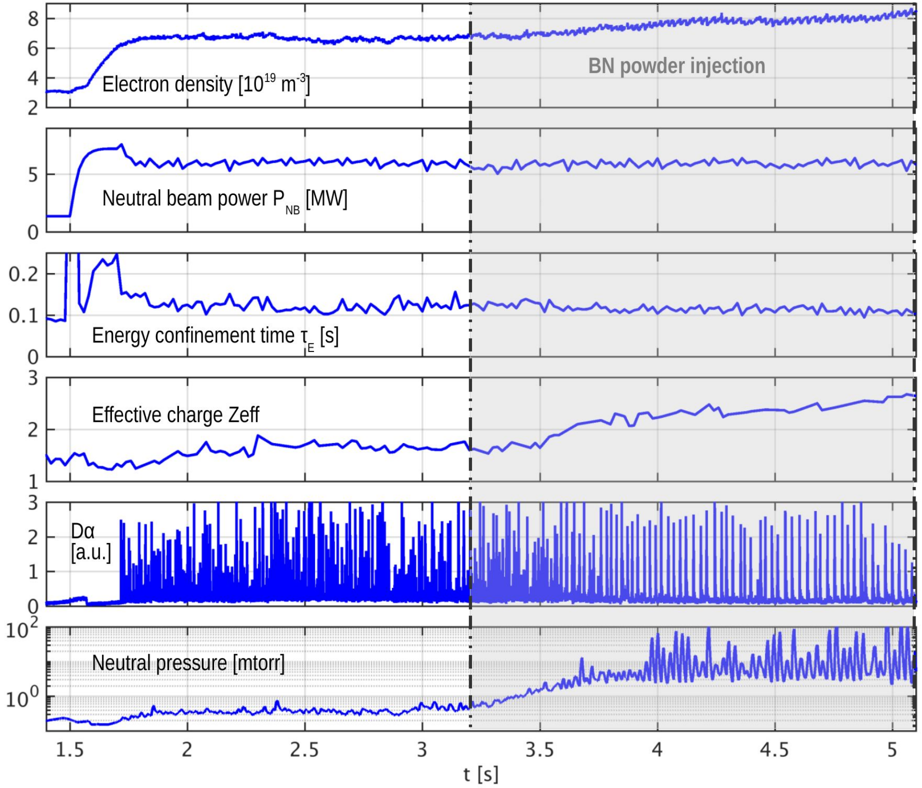




Langmuir probe data in small-angle slot (SAS) divertor
- $T_{e,div}$ drops by ~75%, $q_\perp$ detaches
- J_{sat}, $n_{e,div}$ drops in near SOL increases in far SOL

-> B powder is an effective dissipator

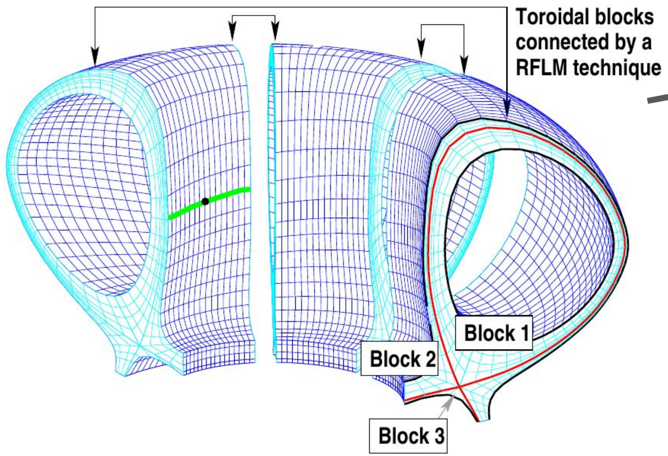
Boron nitride powders most effective for sustained divertor dissipation and ELM mitigation



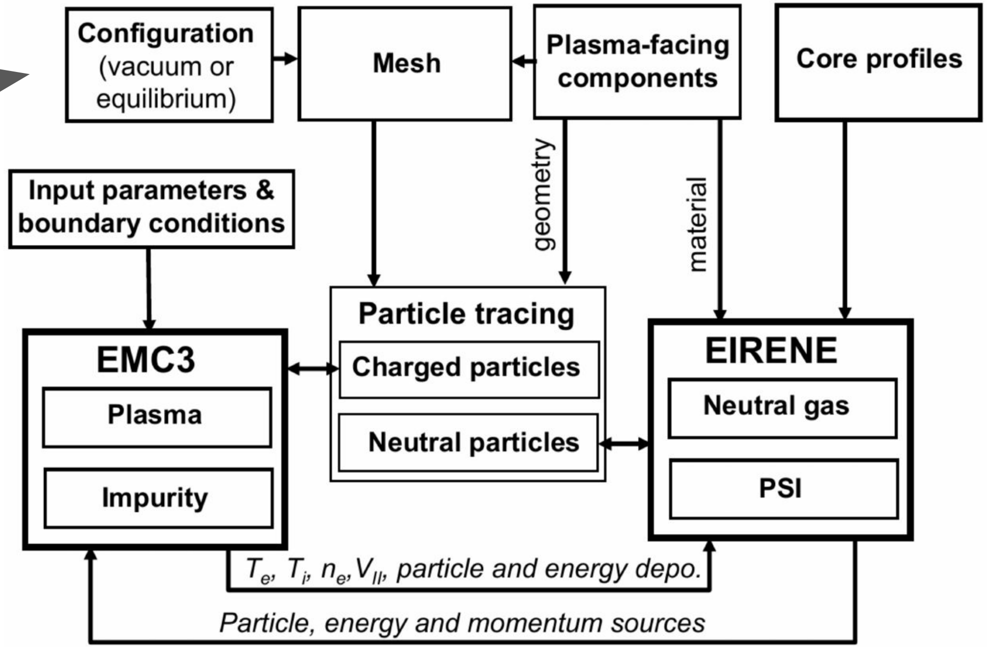
BN in reversed B_t

- 81 mg/s (2.3e22 e-/s)
- Increase in density and Z_{eff}
- Reduction in ELM activity (D_α)
- Increase in divertor neutral pressure by factor ~10

Radiative divertor modeled with coupled plasma fluid and kinetic edge transport Monte Carlo code EMC3-EIRENE



[H. Frerichs et al, Comp. Phys. Commun., 181 (2010), pp. 61-70, https://doi.org/10.1016/j.cpc.2009.08.016]

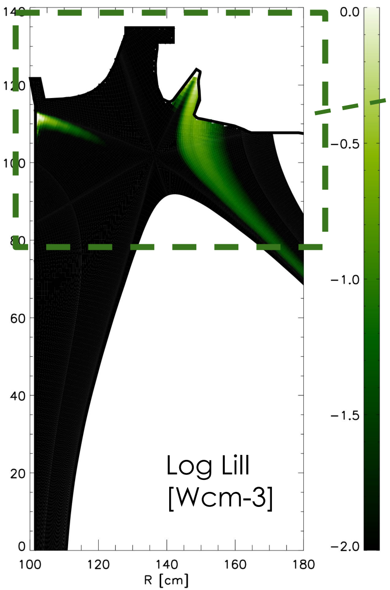


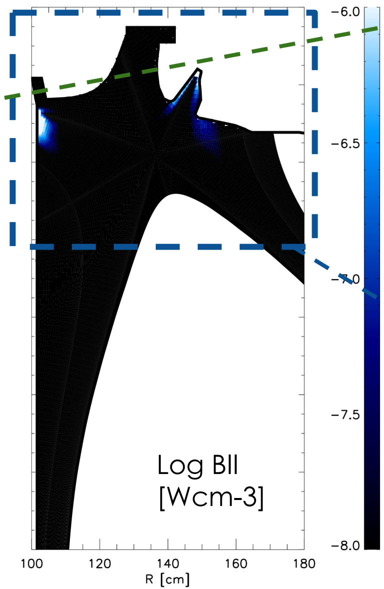
[Y. Feng et al., Contrib. Plasma Phys. 54(4-6), 426–431 (2014), https://doi.org/10.1002/ctpp.201410092]
[D. Reiter et al., Fusion Sci. and Techn., 47:2, 172-186 (2005), https://doi.org/10.13182/FST47-172]

Impurity transport:
- Trace impurity fluid model
- Coupled to main plasma through energy loss term

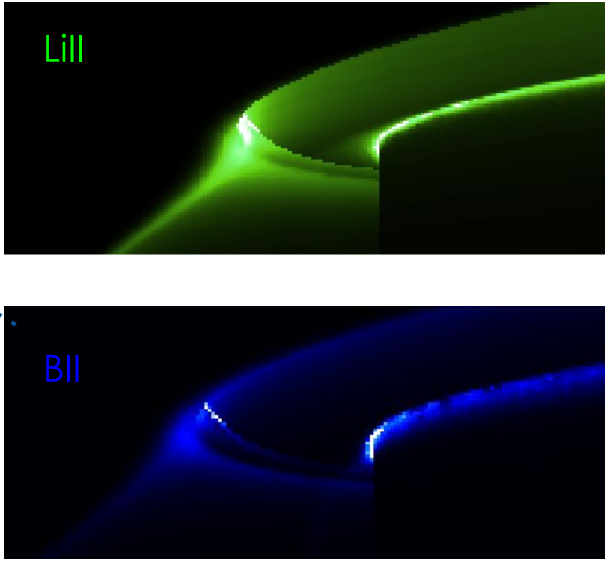
First modeling: Li II emission enhanced in in main SOL and at the separatrix, B II strongest near targets

2D line emission distribution (losses)





Synthetic camera diagnostic

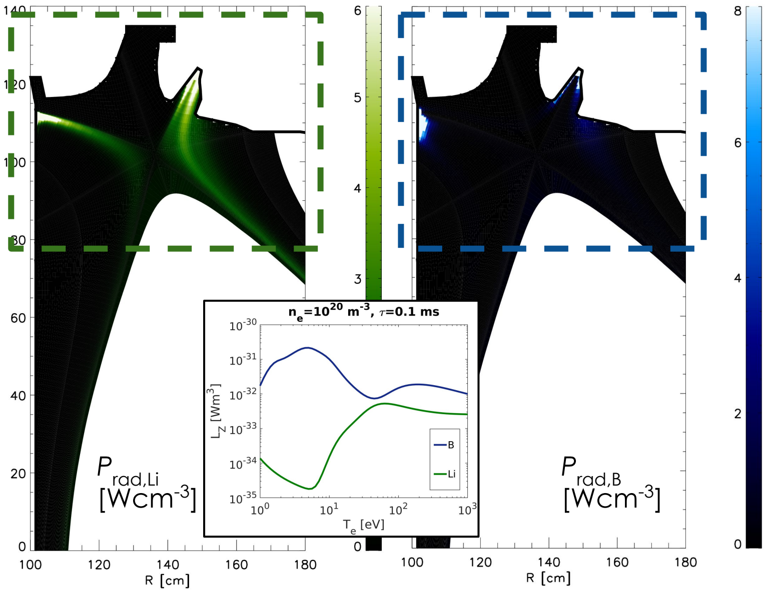


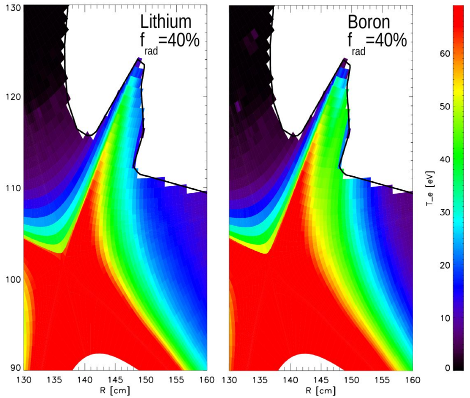
EMC3-EIRENE

- B an Li: sourced as atomic trace impurities
- Simplifying assumptions: comparable loss fraction f_{rad}=40%, carbon neglected
- Line emission: based on ADAS atomic data

First modeling of radiative lithium and boron divertor shows species dependent distribution of cooling effects

Modelled 2D total radiative power density $P_{rad} \sim \Sigma n_e n_z L_z$





Both Li & B reduce SAS electron temperature

- Li cools effectively in hot SOL domain
- B removes heat also in colder SOL
- Dissipation by carbon neglected

Main features of modelled radiative dissipation

- Li radiation favors near SOL & x-point radiation
- B radiation close to targets & far SOL
- B^{+1}, Li^{+2} main dissipators
- B more efficient dissipator wrt injected #particles needed for fixed f_{rad}: P_{rad}/I_{Li}~35 W/A vs. P_{rad}/I_B~880 W/A

Conclusions

- First-time demonstration of radiative divertor dissipation with low Z powders in DIII-D H-mode discharges
- Lithium and boron increased near-target neutral pressure by x3 and x1.5, reduce divertor temperature until detachment
- Boron nitride powder shows substantial reduction in ELM activity
- First EMC3-EIRENE modeling confirms species dependent radiation behavior and efficiency of lithium vs. boron (radiation zone at x-point vs. far SOL/target)
- Low Z powders enhance core-edge capability, create dissipative divertor while maintaining good energy confinement in H-mode

Acknowledgements

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