

Effect of magnetic configuration on real-time wall conditioning in DIII-D

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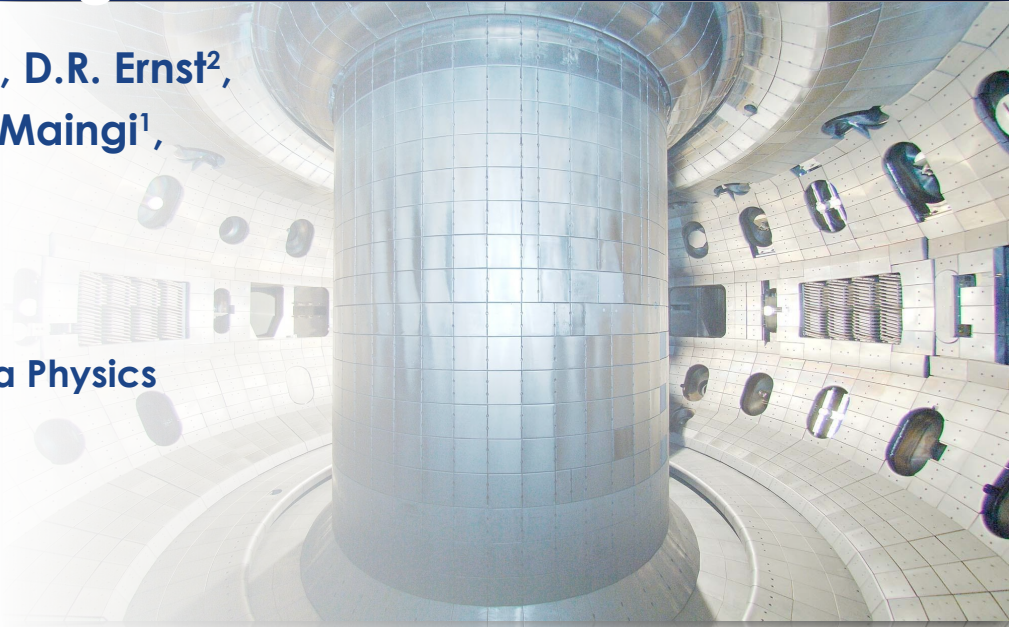
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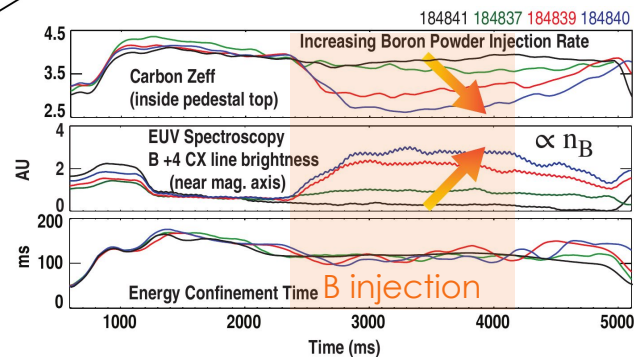
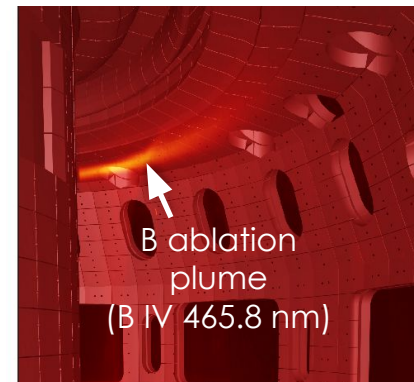
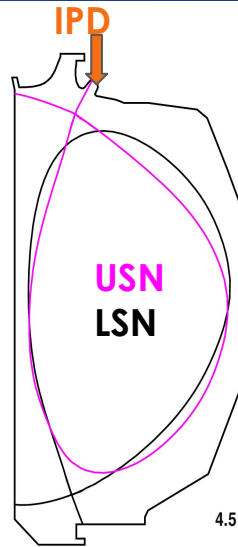


Real-time in-situ coatings could be key to achieve high-performance burning plasmas in future long pulse reactors

- **Challenge for long-pulse & high-performance operation**
 - Impurity influx and D_2 outgassing can prevent the achievement of target scenarios
 - Glow discharge boronization is not an option
- **Real-time wall conditioning (RTWC) could be alternative**
 - Use powder injection to deposit PFC coatings in-situ
 - Safe & repeatable at any time during plasma operation
- **This work: How well does RTWC work in various DIII-D configurations and plasma scenarios so far?**
 - Role of injection location on deposition and conditioning

The impurity powder dropper (IPD) has been used for RTWC in various scenarios and configurations in DIII-D

- **IPD delivers a range of powders**
 - B, BN, Li, B₄C, Si, SiC, ...
 - Particle size 5-150 μm
 - Rates 1-200 mg/s (~1-200 Torr-l/s)
- **Ablated powder is transported to plasma facing components (PFCs)**
 - Deposits coatings in-situ & in real-time
- **RTWC applied in USN, LSN during L- & H-mode plasmas**
 - Switch between LSN & USN ⇔ upstream vs downstream injection



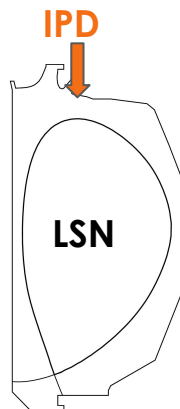
Boron powder injection into plasma crown (upstream) significantly reduces wall fueling in LSN H-mode

- **Before B injection density target exceeded**

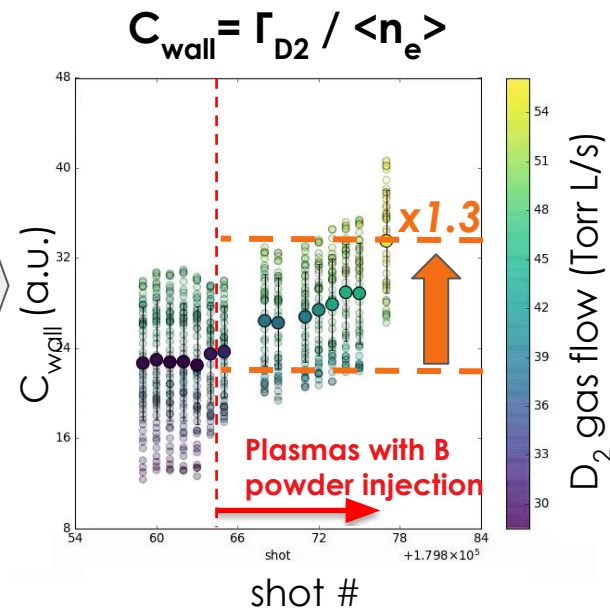
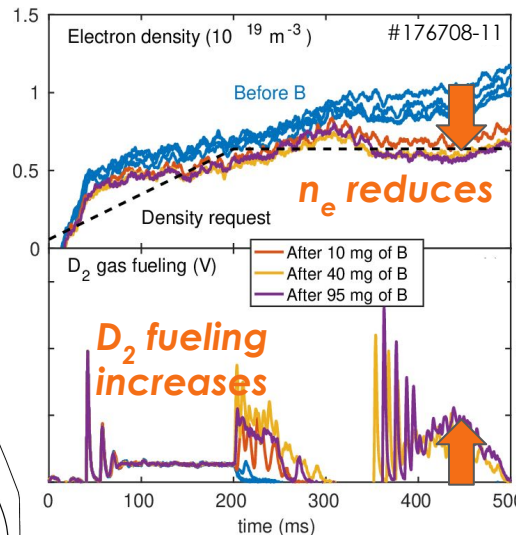
- Strong wall fueling

- **After B injection density target matched**

- Sustained by gas fueling
- Pumping wall



$\langle n_e \rangle$ vs feedback controlled D_2 fueling

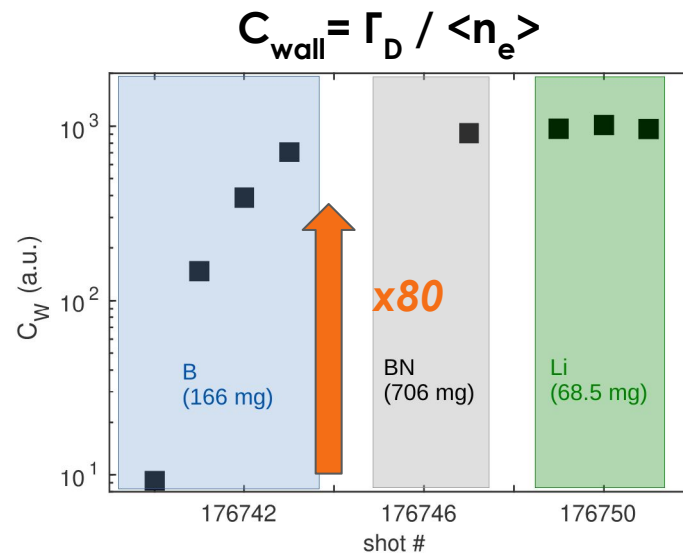
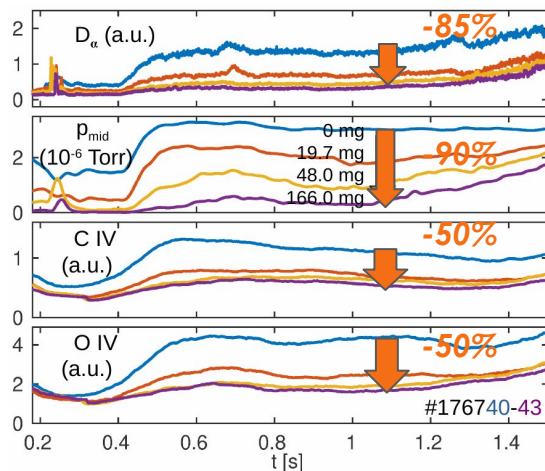
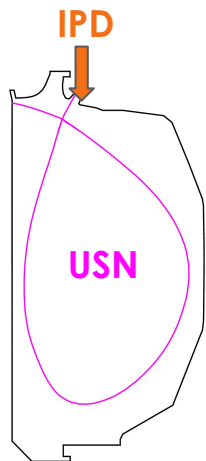


⇒ **Upstream injection works well**

A. Bortolon et al 2020 Nucl. Fusion 60 126010

Divertor (downstream) powder injection reduces recycling and wall fueling substantially during USN H-mode

- **Downstream B powder injection into small-angle slot (SAS) divertor**
 - Reduces O, C influx
 - Reduces wall fueling



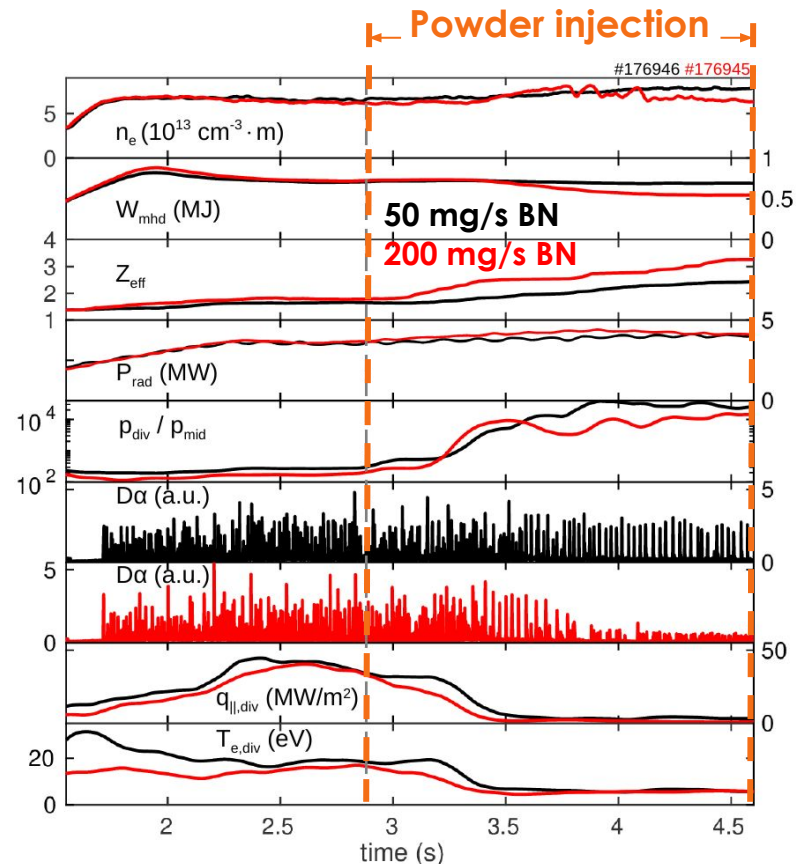
⇒ **Downstream injection works well despite divertor impurity screening**

Real-time boron and boron nitride powder injection can also promote detachment during H-mode

- **Real-time BN powder injection at higher rates shows additional effects on H-mode plasma besides RTWC**

- 65 μm BN injected at $\sim 50\text{-}200$ mg/s
- Divertor T_e , $q_{||\text{divertor}}$ drop, sustained detachment
- ELM-fluxes reduced in frequency and amplitude at the target

⇒ **Powders promotes detachment at high injection rates**



F. Effenberg et al 2022 Nucl. Fusion 62 106015

Florian Effenberg et al, APS-DPP Meeting 2022

3D plasma fluid and kinetic edge transport (EMC3-EIRENE) was coupled to dust transport (Dust Injection Simulator)

- **EMC3: 3D edge transport Monte Carlo code**
 - Braginski plasma-fluid model for D, T, H
 - Trace impurity fluid model
- **EIRENE: kinetic neutral transport code**



- **Dust Injection Simulator (DIS):**

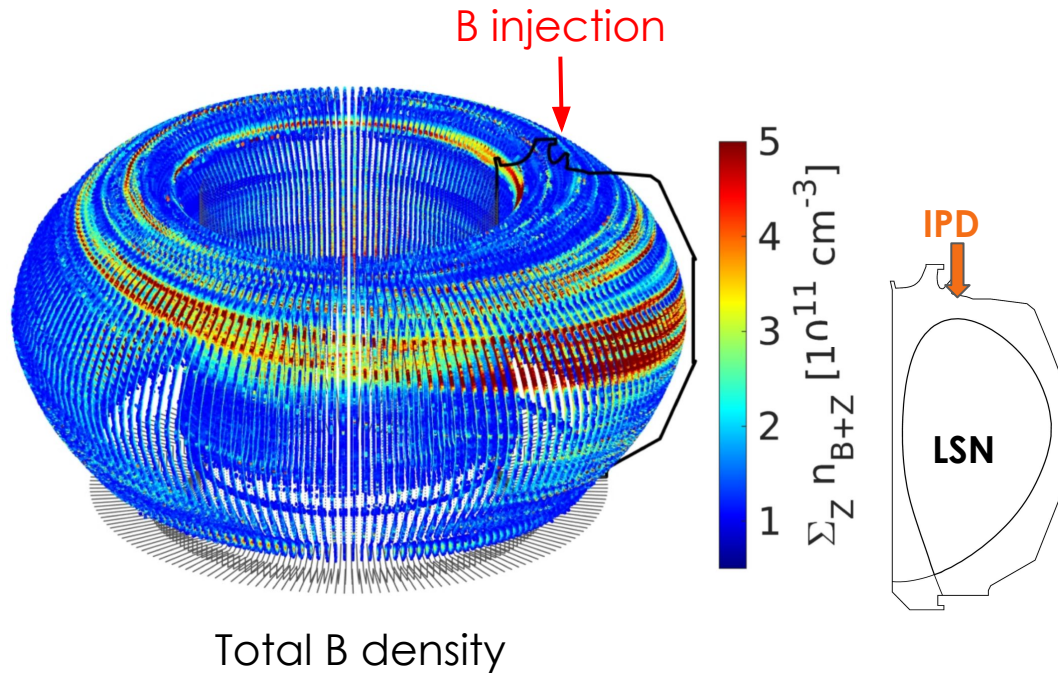
$$\mathbf{R}_f = \sum \mathbf{F}_{\text{drag},nZ} + \mathbf{F}_{\text{drag},n0} + \mathbf{F}_E + \mathbf{F}_{\text{grav}} + \mathbf{F}_{\text{centr.}}$$

Powder and impurity transport modeling is used to study

- Full-torus transport and B deposition
- Role of dust/powder particle size on impurity distribution

Y. Feng et al, *Contrib. Plasma Phys.* 54 (4-6) 2014
F. Nespoli et al, *PoP* 28, 073704 2021

EMC3-EIRENE full-torus modeling shows non-axisymmetric boron density distribution due to local source effect

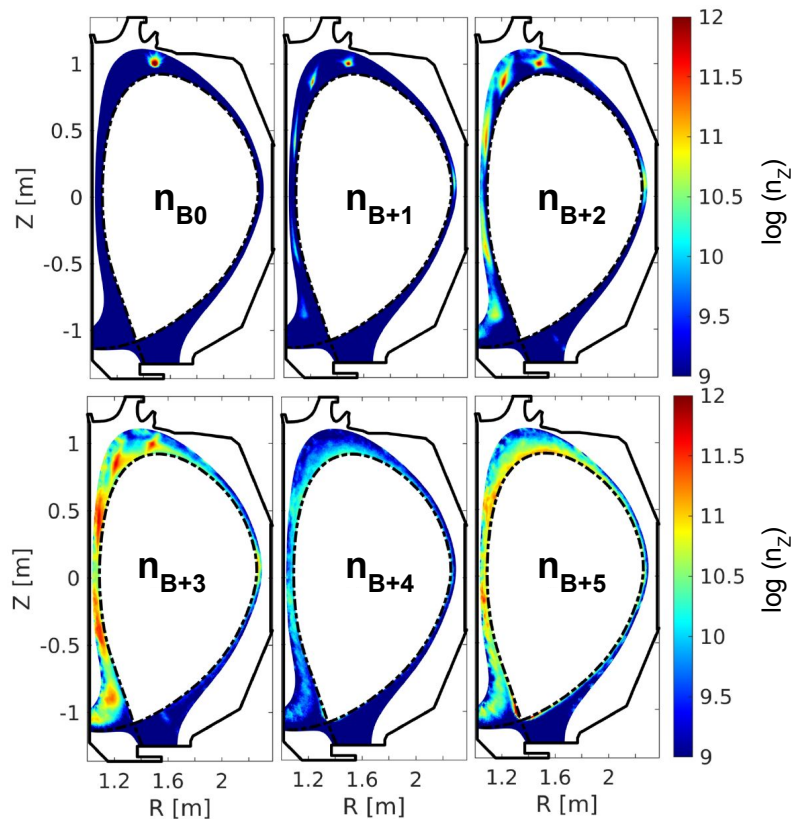


Ablation of B powder particle is modeled as distribution of isotropic point sources

- #179894 @ 3500 ms, reversed B_t equilibrium
- 3D full-torus modeling with EMC3-EIRENE
- $P_{NB} \sim 2.2 \text{ MW}$, separatrix density $\sim 1.5 \times 10^{19} \text{ m}^{-3}$
- $D_{\perp} = 1.0 \text{ m}^2 \text{ s}^{-1}$, $\chi_{\perp} = 0.33 \text{ m}^2 \text{ s}^{-1}$
- Boron injection rate typically 2-50 mg/s ($\Gamma_B \sim 10^{19} - 10^{20} \text{ s}^{-1}$)

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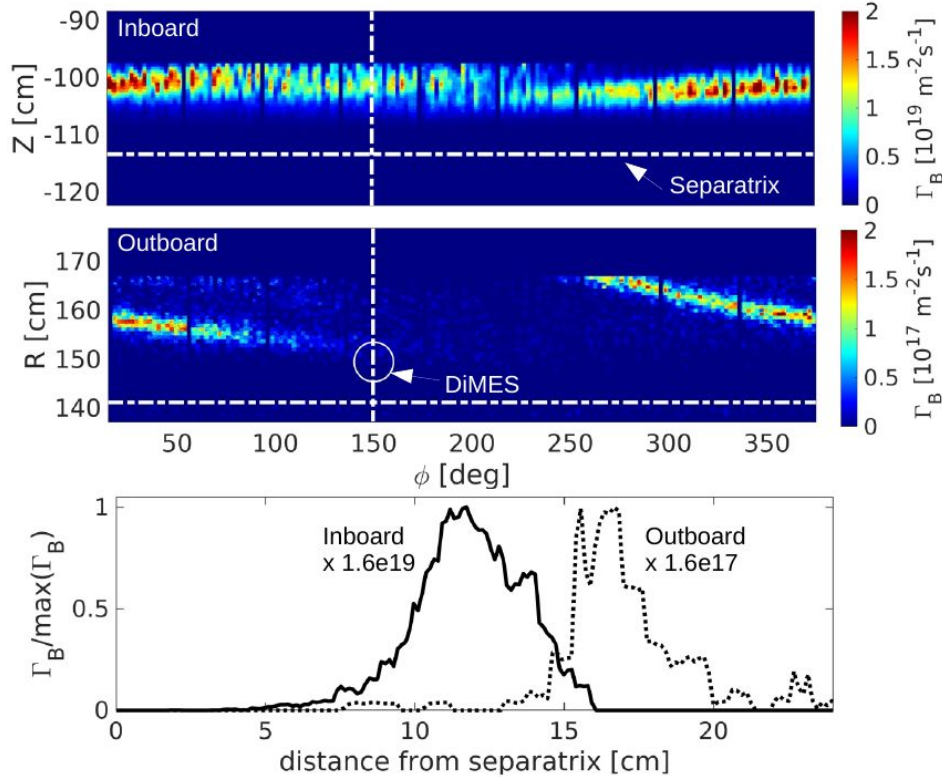
Most boron injected upstream into LSN scenario migrates to the inboard side/high field side



Features of the boron flux distribution

- ~90-99% B flux goes to the inboard target
- B flux distribution mostly insensitive to a perpendicular displacement of the source location
- Outboard B flux increases at higher injection rates when radiative dissipation within flux tubes induces partial impurity flow reversal
- Disclaimer: EMC3-EIRENE currently does not include drift-effects

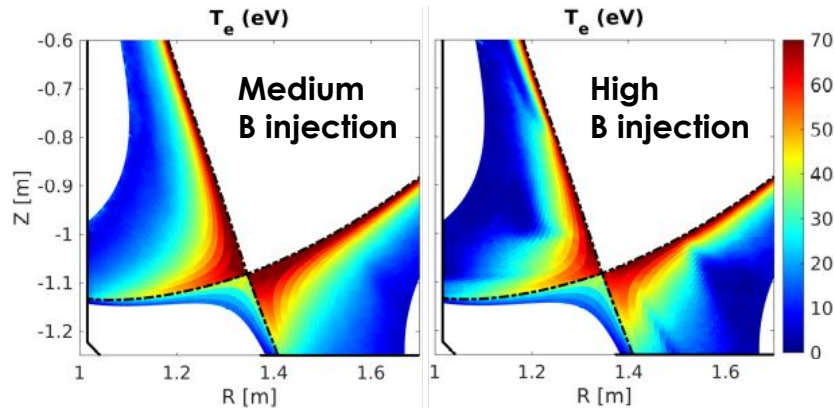
Divertor boron fluxes show asymmetric distribution and highest deposition in the far scrape-off layer



Boron divertor deposition

- Boron flux to inboard divertor $\sim 2 \times 10^{19} \text{ m}^2 \text{ s}^{-1}$, and $\sim 2 \times 10^{17} \text{ m}^2 \text{ s}^{-1}$ to outboard divertor
- Boron flux peaks in far SOL region $\sim 5\text{-}10$ cm beyond strikeline
- Local source causes striated deposition pattern diagonally across the targets due to perpendicular diffusion
- Deposition shows only weak dependence on source location

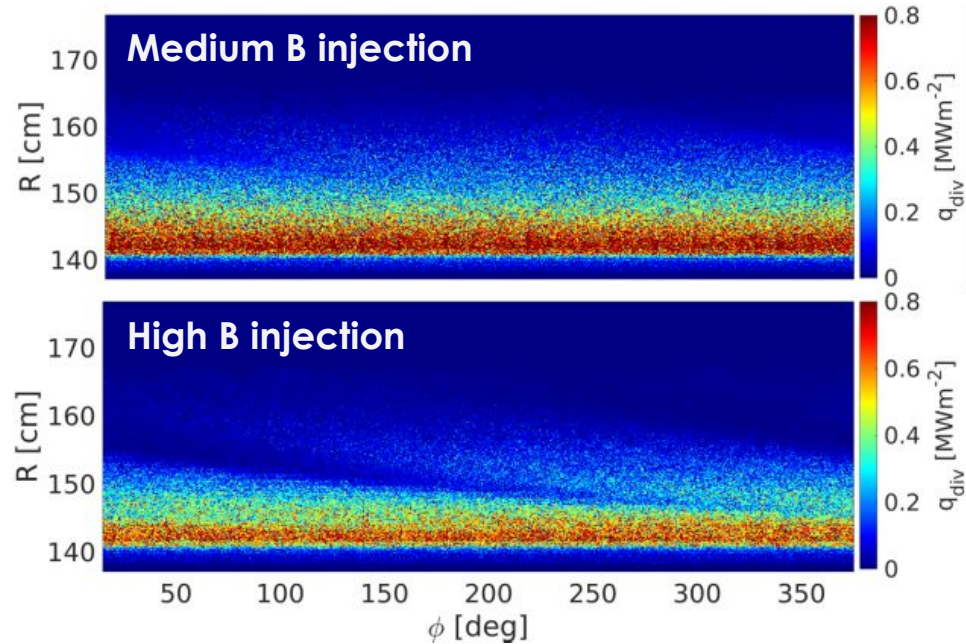
Higher boron injection rates cause non-axisymmetric cooling of divertor heat fluxes by radiative dissipation



Medium vs high boron flux

- $\Gamma_{\text{Boron}} = 10^{20} \text{ s}^{-1}$ vs 10^{21} s^{-1}
- local cooling and dissipation in flux tubes connected to B source $\Delta P_{\text{rad,B}} \sim \sum_z L_z n_e n_{\text{B+Z}}$
- Divertor heat fluxes decrease in far SOL region

Divertor Heat flux on outer target

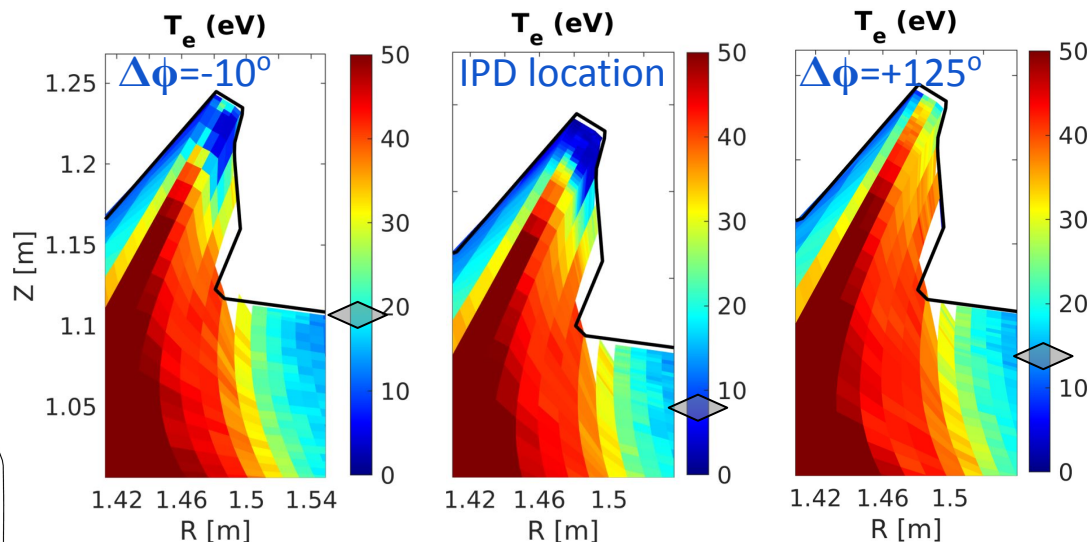
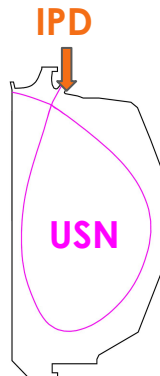
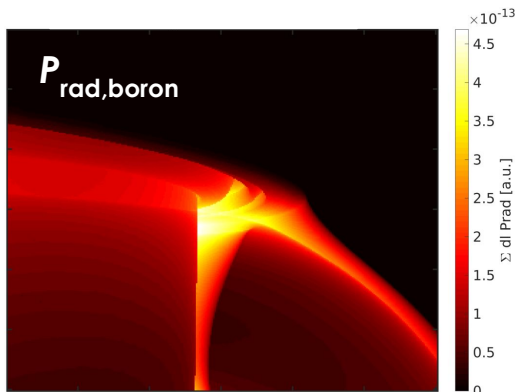


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3D modeling with EMC3-EIRENE & DIS shows cooling of SAS divertor plasma due to enhanced boron radiation

- Boron increases radiative power losses in upper divertor leading to drop in divertor temperature and heat flux

Total boron radiation density

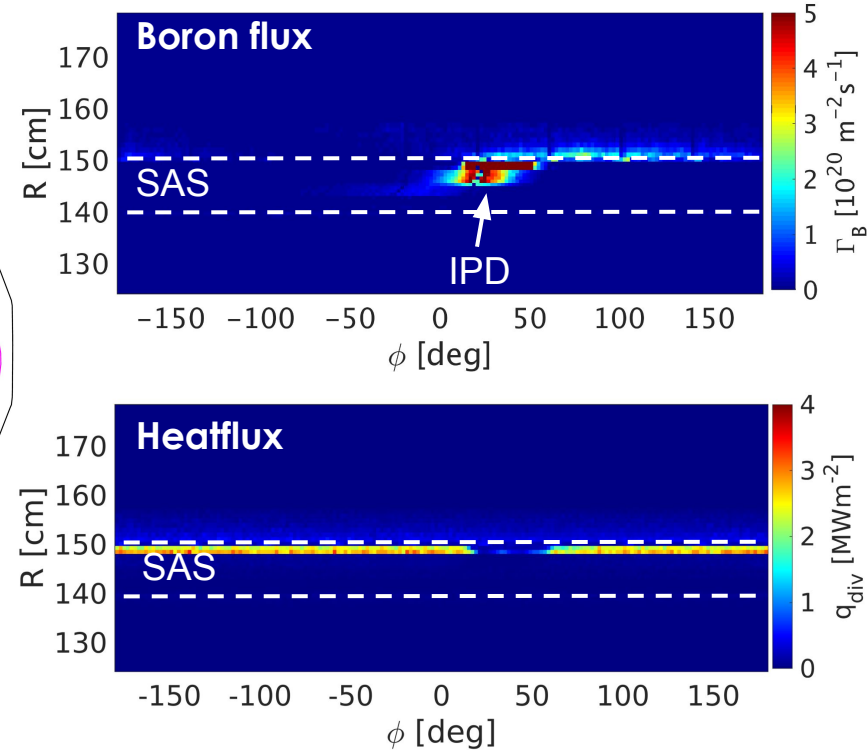
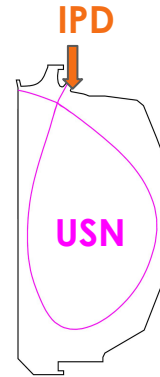


Toroidal direction ϕ

3D modeling with EMC3-EIRENE & DIS shows localized boron deposition & cooling effect in SAS near injection location

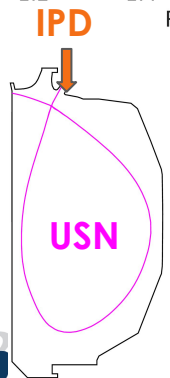
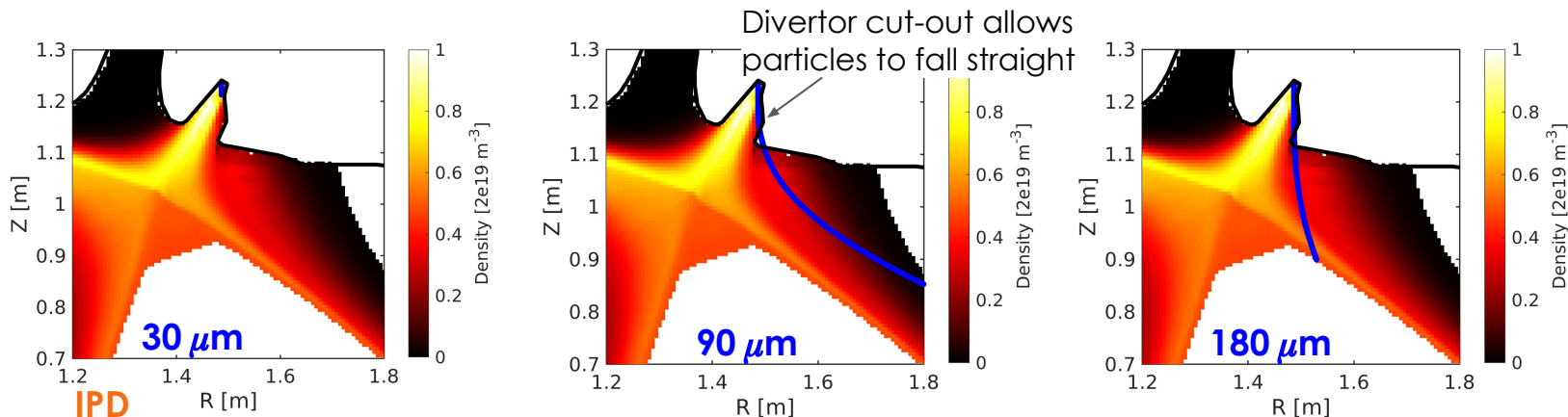
- **Full-torus simulation of B powder injection into closed small angle slot (SAS) divertor**

- B powder, 35 mg/s, 150 μm , no recycling
- Drop in divertor $q_{\parallel, \text{div}}$ shows strongest drop near injection location



Impurity leakage depends on particle size for downstream injection, larger powder particles can escape divertor

DIS: Single boron dust particle trajectories starting in small angle slot divertor



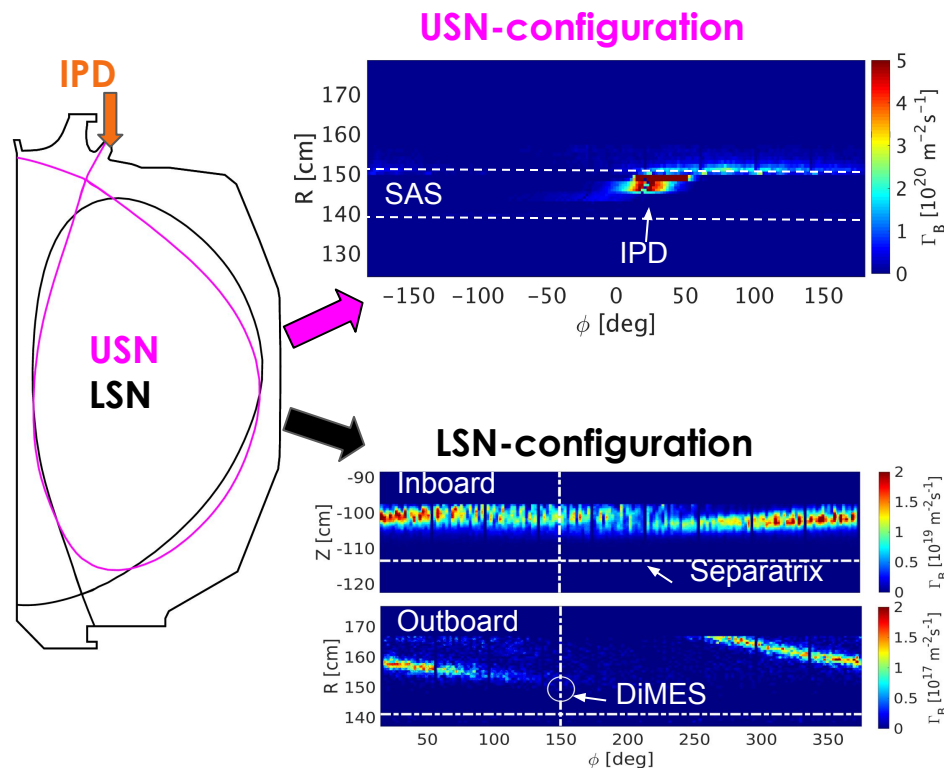
Powder particle size determines trapping of particle in divertor

- Small particles get ablated in the divertor
- Medium particles leak into far SOL and vacuum region
- Very large particles leak into confinement

Comparison shows toroidal asymmetries in boron fluxes in both configurations, more localized for USN injection

Toroidal asymmetry in B fluxes

- Due to the local IPD B source
- Deposition more local in USN scenario due to impurity retention and screening in SAS
- Erosion and re-deposition (neglected) might cause more even B deposition



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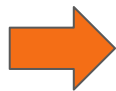
Summary & conclusions

- **Real-time wall conditioning is very effective in reducing recycling and impurities in DIII-D experiments for both up- & downstream powder injection**

*A. Bortolon et al 2020 Nucl. Fusion 60 126010
F. Effenberg et al 2022 Nucl. Fusion 62 106015*

- **EMC3-EIRENE modeling shows boron fluxes peak on PFCs in the far SOL**
- **3D modeling shows local source effect causes asymmetric deposition**
 - Upstream injection in LSN shows an homogenizing effect on B deposition due to transport and cross-field diffusion
 - Downstream injection in USN causes more asymmetric B deposition due to screening and retention in the closed SAS divertor

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Include erosion and re-deposition to model coatings on PFCs

References

DIII-D experiments & modeling

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Model development

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