Divertor heat flux mitigation with low-Z powders in DIII-D

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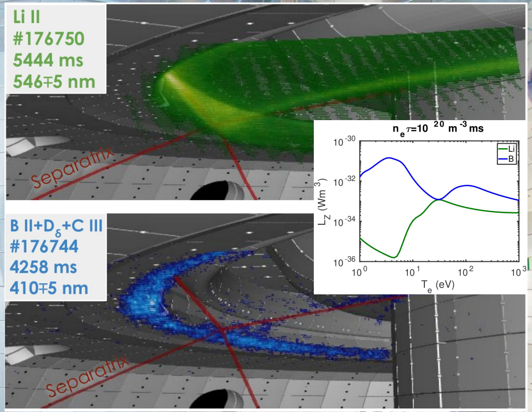

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Outline

Controlling the core-edge interface with impurity powders

Divertor power exhaust with Li, B, BN powders

Powder transport modeling

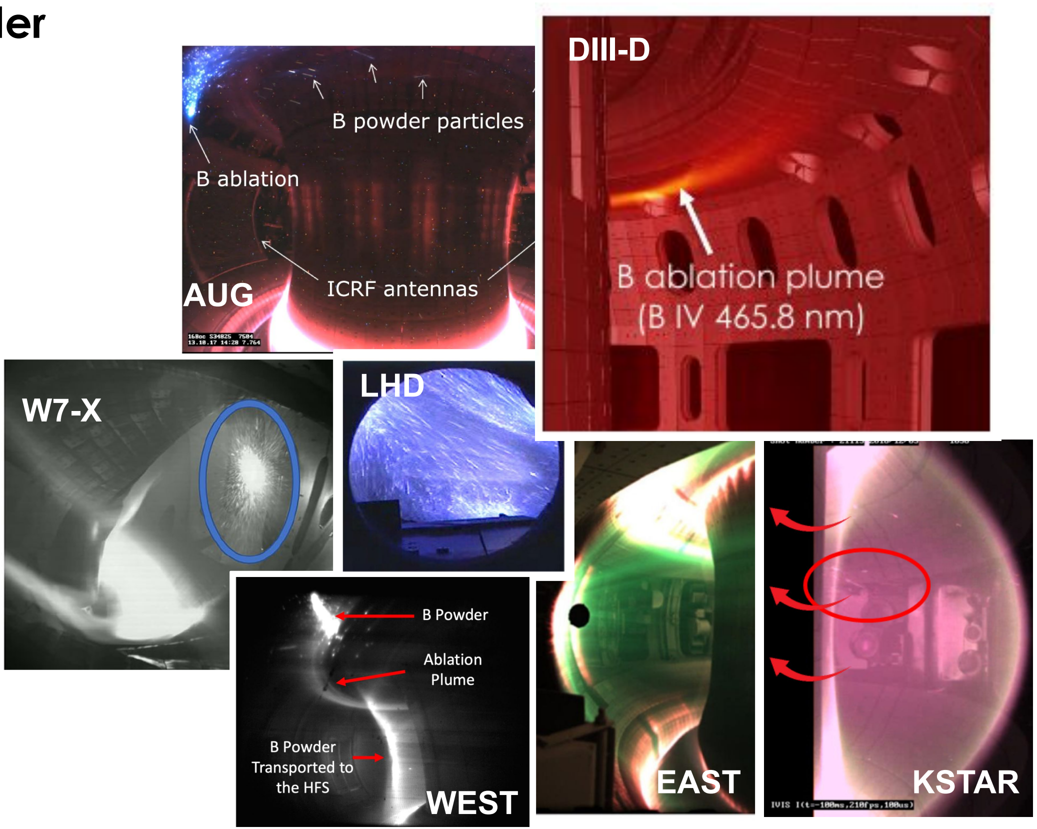
Conclusions

The injection of materials in powder form is used to tame the interactions at the core-edge and plasma-wall interfaces

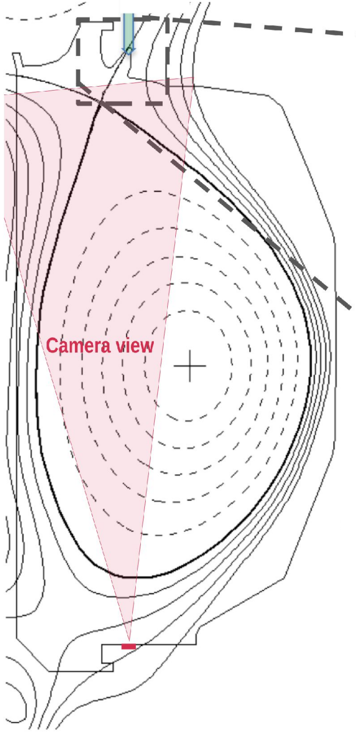
Steady increase of use cases for powder injection at a diverse set devices and configurations:

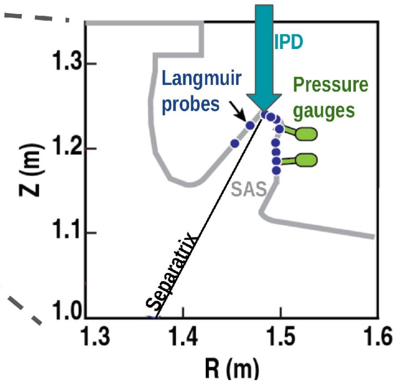
- **ELM & pedestal control**
- **Real-time wall conditioning**
- **Impurity transport**

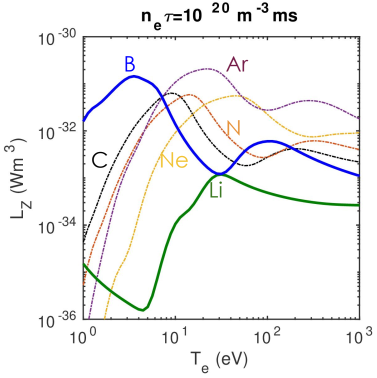
A. Bortolon et al, Nucl. Fusion 2016
R. Maingi et al, Nucl. Fusion 2018
A. Bortolon et al, Nucl. Mat. En. 2019
A. Bortolon et al, Nucl. Fusion 2020
F. Nespoli et al, Nucl. Mat. En. 2020
Z. Sun et al, Nucl. Mat. En. 2019
R. Lunsford et al, Nucl. Fusion 2019
E. Gilson et al, Nucl. Mat. En. 2021
F. Effenberg et al, Nucl. Mat. En. 2021
G. Bodner et al, Nucl. Fusion 2022
F. Effenberg et al, Nucl. Fusion 2022



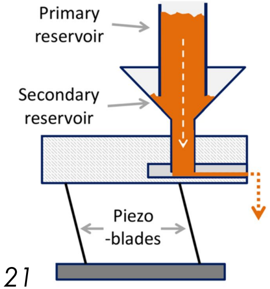
Powders were injected into upper closed divertor during DIII-D H-mode plasmas to enhance power exhaust

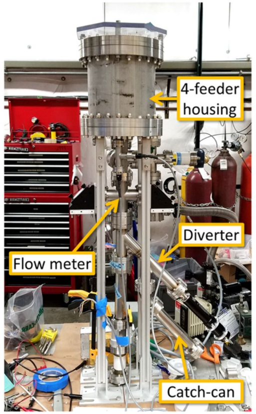






- **ELMy H-mode**, P_{NBI}~6 MW, I_p=1 MA, B_t=2 T, Upper Single Null, closed small angle slot (SAS) divertor
- **PPPL Impurity Powder Dropper**
  - Li, B, BN powders (40-150 um)
  - flow rates 3-200 mg/s, atomic rates 10^{20}-10^{22} atoms/s, (1-300 Torr-l/s), particle speed: 5-6 m/s

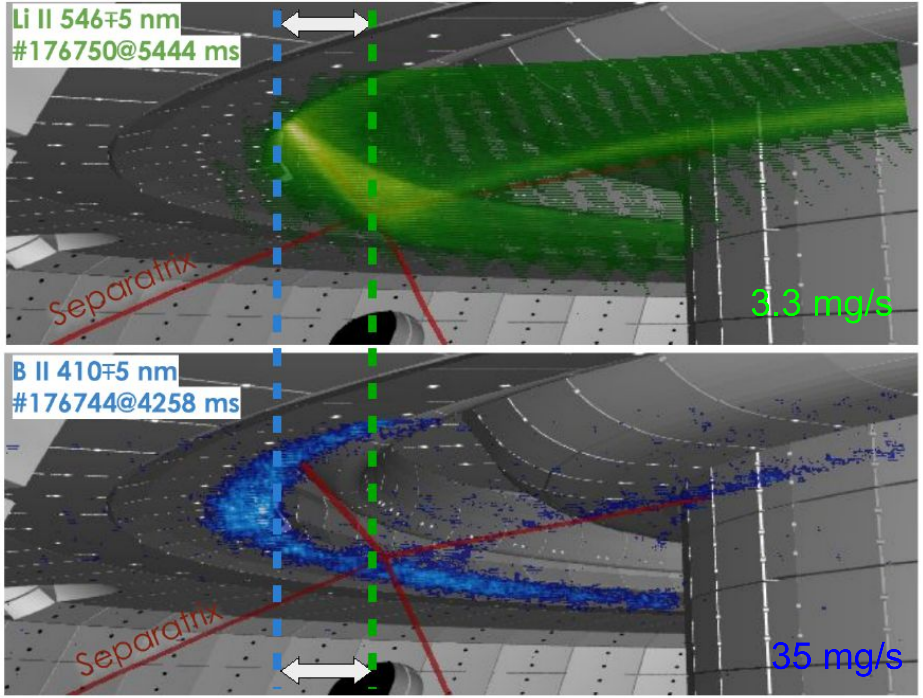


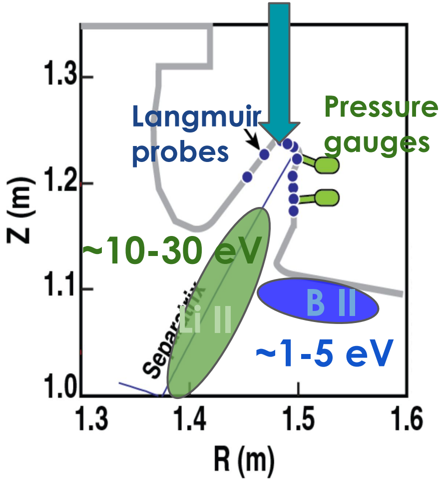


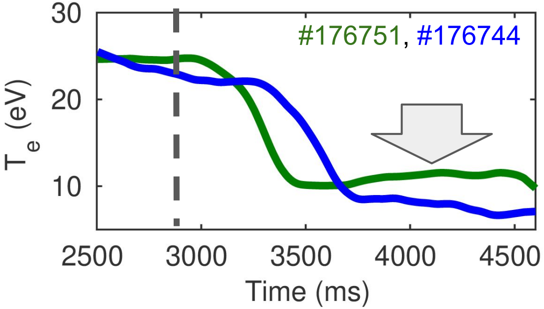
A. Nagy et al, Rev. Sci. Instrum. 2018 89, 10K121

Boron effective radiator in the far scrape-off layer while lithium radiates closer to the near scrape-off layer

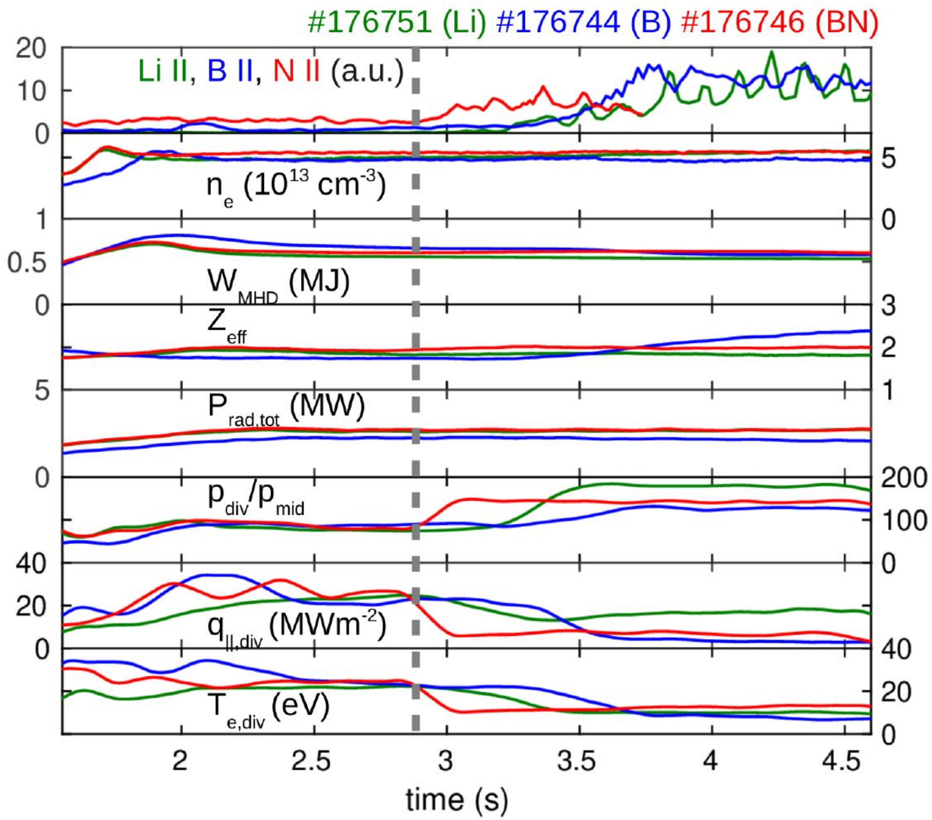
Tangential camera imaging of spatial line emission







Low Z powders reduced T_e and divertor $q_{||peak}$ even at lower rates w/o deteriorating H-mode

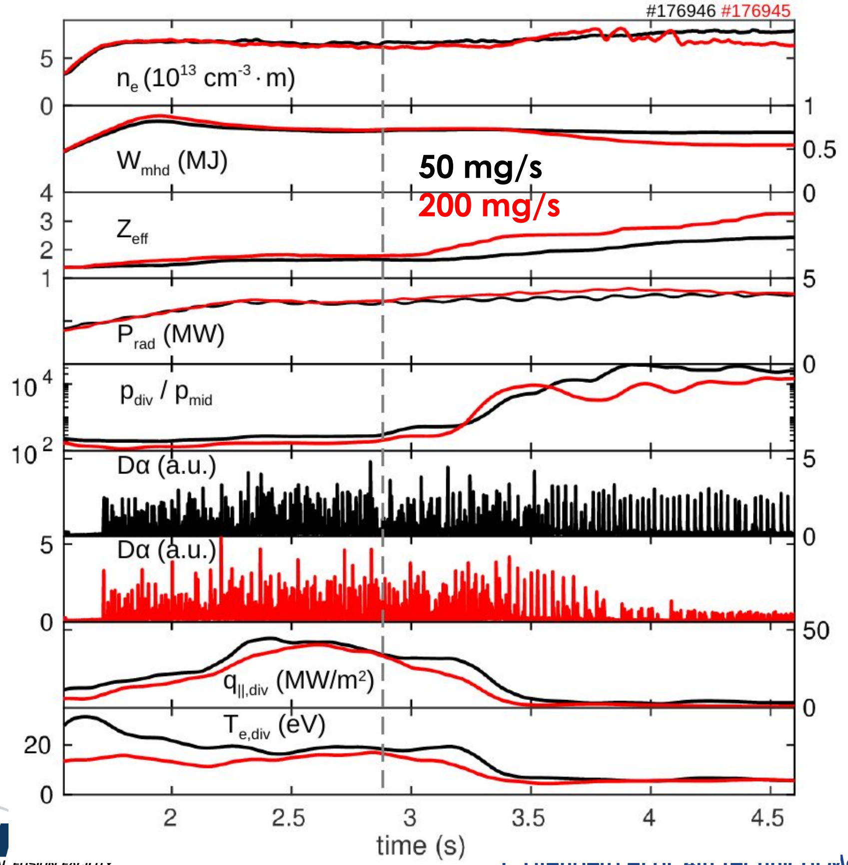


Results for low-moderate rates

- Li (40 um), BN (65 um) more efficient than B powder (150 um)
- $T_{e,div}$ reduces to <10 eV
- Divertor neutral compression enhances by 3x (Li) vs 1.5x(B)
- Max Z_{eff} increase for B powder 1.8->2.4

Effectiveness of cooling depends on powder type

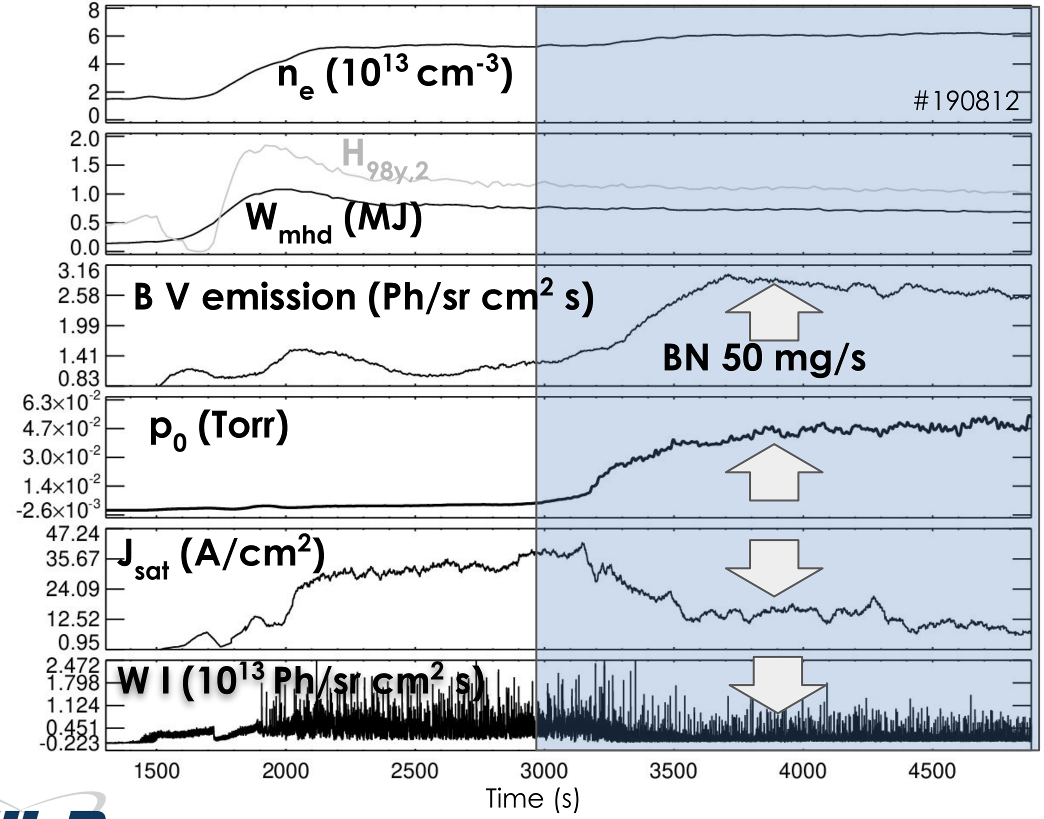
Boron nitride powder so far most successful for divertor dissipation and detachment

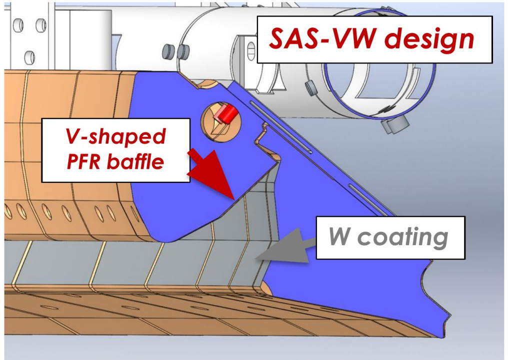


- BN (65 um) injected at ~50-200 mg/s
- Divertor neutral build-up, sustained detachment of heat and particle fluxes
- ELM frequency and amplitude reduced at the target
- -> Optimize scenario to prevent loss in confinement

F. Effenberg et al 2022 Nucl. Fusion 62 106015

New experiments in DIII-D W SAS-divertor demonstrated reductions of W source and detachment with BN powder





- BN (65 um) injected at ~50 mg/s
- Sustained detachment
- W source (W I) reduces

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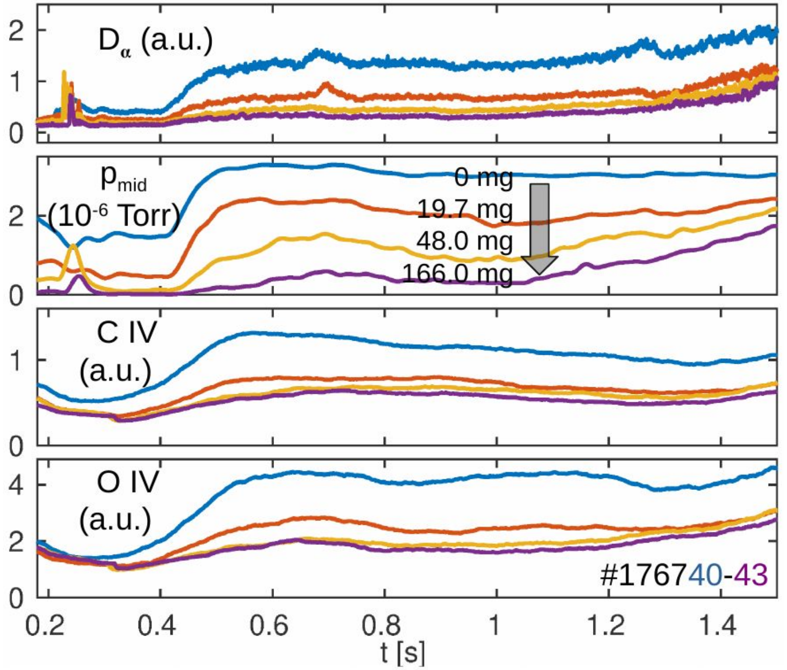
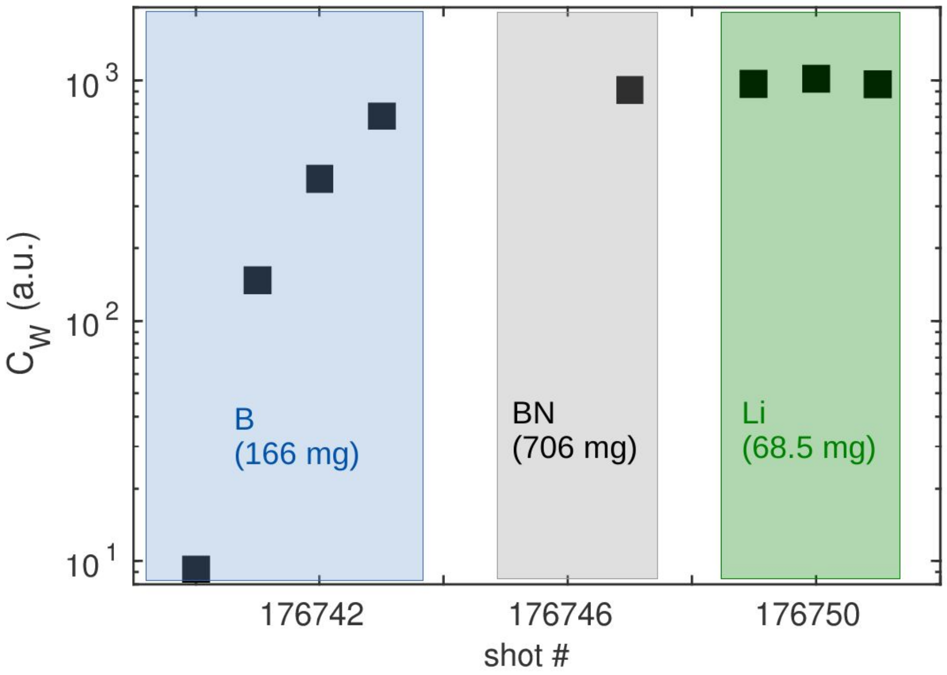
Powder injection reduces recycling and intrinsic impurities, allows access to lower collisionalities

Reduces main chamber neutrals & impurities fluxes



Improves wall conditions (C_W=D gas/e^--density)



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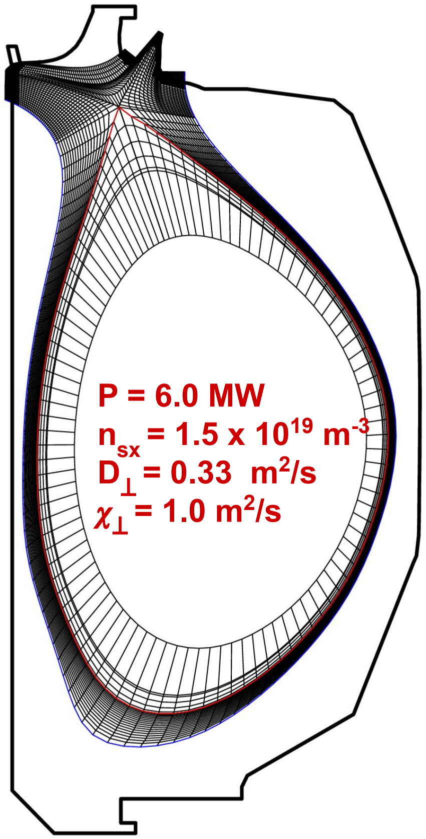
3D plasma fluid and kinetic edge transport (EMC3-EIRENE) was coupled to dust transport (Dust Injection Simulator)

- **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):

$$R_f = \sum F_{drag,nZ} + F_{drag,n0} + F_E + F_{grav} + F_{centr.}$$

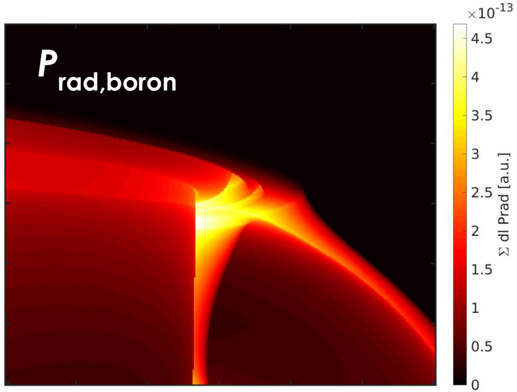


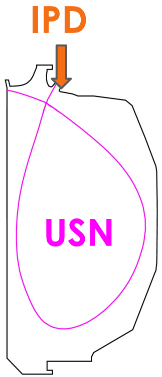
Y. Feng et al, Contrib. Plasma Phys. 54 (4-6) 2014
F. Nespoli et al, PoP 28, 073704 2021
F. Effenberg et al, NME 26, 100900 2021

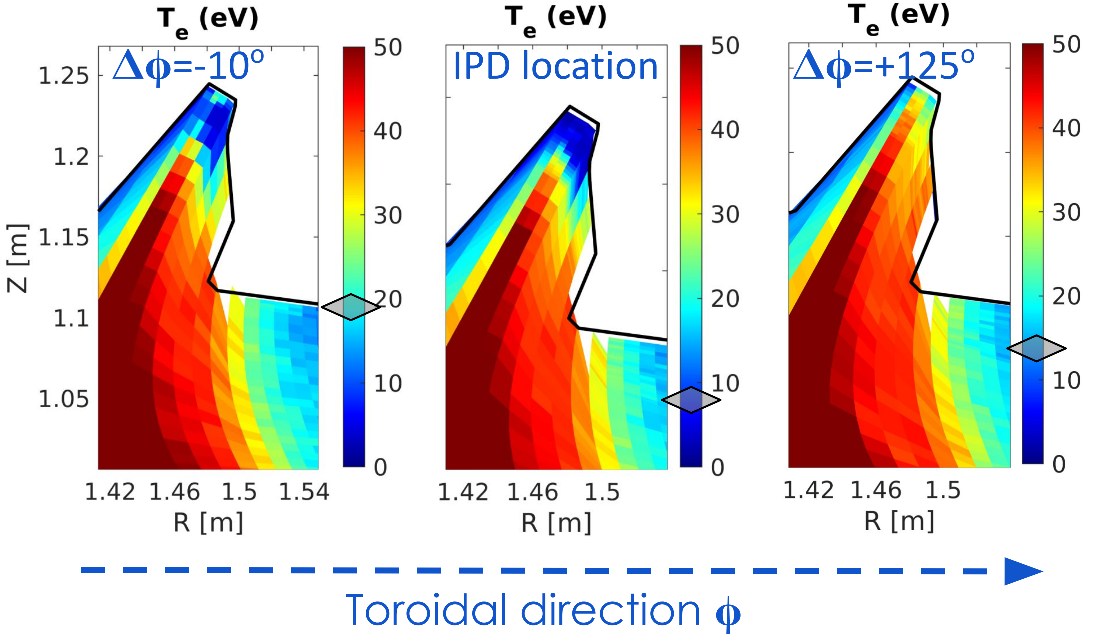
3D modeling with EMC3-EIRENE & DIS shows cooling of SAS divertor plasma due to enhanced boron radiation

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

Total boron radiation density

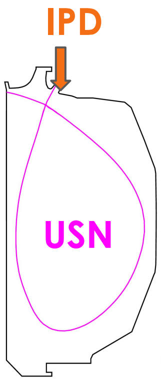


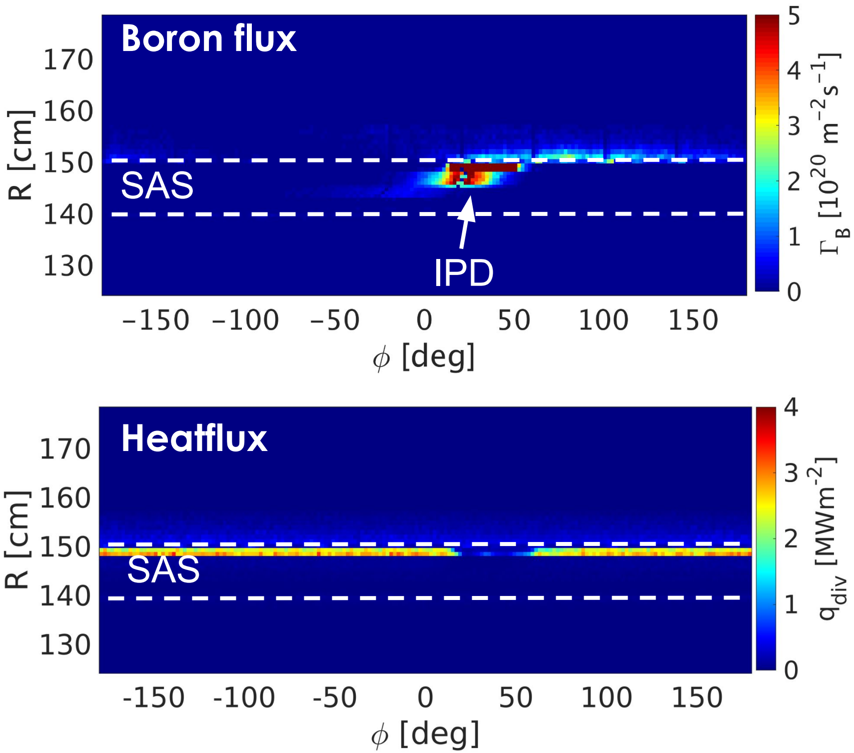




3D modeling with EMC3-EIRENE & DIS shows localized boron deposition & cooling effect in SAS near injection location

- **Full-torus simulation of B powder injection into closed small angle slot (SAS) divertor**
  - B powder, 35 mg/s, 150 um, no recycling
  - Drop in divertor $q_{||,div}$ shows strongest drop near injection location





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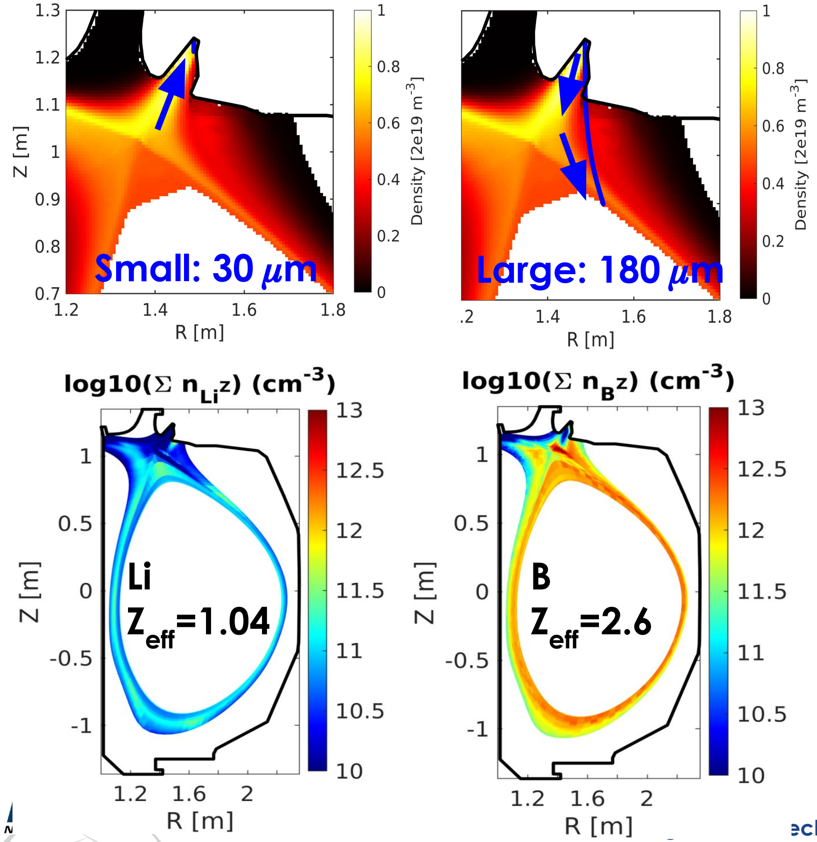
Powder transport modeling shows smaller particle size & species determine screening & divertor dissipation



Conclusion from modeling (EMC3-EIRENE & Dust Injection Simulator)

- Larger B particles (>70 um) escape the divertor, heavier particles (>180 um) may reach the pedestal
- Full ablation and retention of small powder particles in divertor may lead to localized cooling
- Li and BN particles show better impurity screening/retention in divertor
- Larger (150 um) B particles increase Z_{eff} similar to experimental trend

F. Effenberg et al APS 2021

Conclusions

- Low Z powder injection into C and W divertor during DIII-D H-mode promote detachment and improve wall conditions at the same time
- (Smaller) BN and Li powder particles appear to be more efficient than (larger) B powder particles for divertor dissipation; BN is most suitable for detachment so far
- Coupling of plasma boundary codes with dust transport code (e.g., EMC3-EIRENE & DIS) allows to study 3D effects of powder species, particle size, deposition and detachment systematically