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

Florian Effenberg, A. Bortolon, L. Casali\textsuperscript{a}, R. Lunsford, I. Bykov\textsuperscript{a}, H.Q. Wang\textsuperscript{a}, F. Scotti\textsuperscript{b}, M. Fenstermacher\textsuperscript{b}, H. Frerichs\textsuperscript{c}, J.D. Lore\textsuperscript{d}, A. Nagy, Y. Feng\textsuperscript{e}, B.A. Grierson, F. Laggner, R. Maingi, R. Nazikian, D. Thomas\textsuperscript{a}, DIII-D Team

\textsuperscript{a}PPPL, \textsuperscript{b}LLNL, \textsuperscript{c}UW, \textsuperscript{d}ORNL, \textsuperscript{e}IPP

Presented at the
28\textsuperscript{th} IAEA Fusion Energy Conference
Hosted by the government of France
May 10-15, 2021

fefenbe@pppl.gov  https://orcid.org/0000-0002-4846-4598
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

**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

Versatile applications
- Injection in solid powder form extends and facilitates use of materials such as B, B$_4$C, 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, …

PPPL Impurity Powder Dropper (IPD)
[A. Bortolon et al 2020 Nucl. Fusion 60 126010, https://doi.org/10.1088/1741-4326/abaf31]

-> This work: radiative divertor power exhaust
Impurity powders injected into the closed small-angle slot divertor in DIII-D H-mode discharges

Advanced divertor scenario
- Upper Single Null, closed Small Angle Slot (SAS) divertor
- H-mode, 1 MA, 2 T, fwd $B_t$, $P_{NB} \approx 6$ MW, $n_e \approx 5 \times 10^{19}$ 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

- $T_{e,div}$, $q_\perp$ 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 $J_{\text{sat}}$

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

- $T_{e,\text{div}}$ drops by ~75%, $q_{||}$ detaches
- $J_{\text{sat}}$, $n_{e,\text{div}}$ drops in near SOL increases in far SOL
- $\rightarrow$ 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 $Z_{\text{eff}}$
- Reduction in ELM activity ($D_\alpha$)
- Increase in divertor neutral pressure by factor $\sim$10
Radiative divertor modeled with coupled plasma fluid and kinetic edge transport Monte Carlo code EMC3-EIRENE

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 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 $f_{\text{rad}} = 40\%$, 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 $P_{rad} \sim \Sigma n_e n L_z$

- 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 $f_{rad}$:
  $P_{rad}/I_{Li} \sim 35$ W/A vs. $P_{rad}/I_{B} \sim 880$ W/A

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

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

#particles needed for fixed $f_{rad}$:
$P_{rad}/I_{Li} \sim 35$ W/A vs. $P_{rad}/I_{B} \sim 880$ W/A
- 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

This material is based upon work supported by the U.S. Department of Energy, Office of Science, Office of Fusion Energy Sciences, using the DIII-D National Fusion Facility, a DOE Office of Science user facility, under Awards DE-AC02-09CH11466, DE-FC02-04ER54698, DE-AC52-07NA27344, DE-FG02-07ER54917, DE-SC0020357 and DE-AC05-00OR22725.

Disclaimer: This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.