Experimental Investigation of Deuterium and Nitrogen-seeded H-mode Plasmas in KSTAR with a Tungsten Divertor and Carbon First Wall

Junghoo Hwang[1*], Hyungho Lee[2], Richard A. Pitts[3], Andrei Pshenov[3], Yoon Seong Han[1], Eunnam Bang[2], Seungmin Bong[1], Minseok Kim[4], Giwook Shin[2], Juhyeok Jang[2], Changmin Shin[1], Junhyeok Yoon[1], Chanyeong Lee[1], Hyun-Seok Kim[2], Jae-Sun Park[5], and Wonho Choe[1**]

[1]KAIST, Republic of Korea, [2]KFE, Republic of Korea, [3]ITER, France, [4]PU, U.S.A., [5]ORNL, U.S.A.

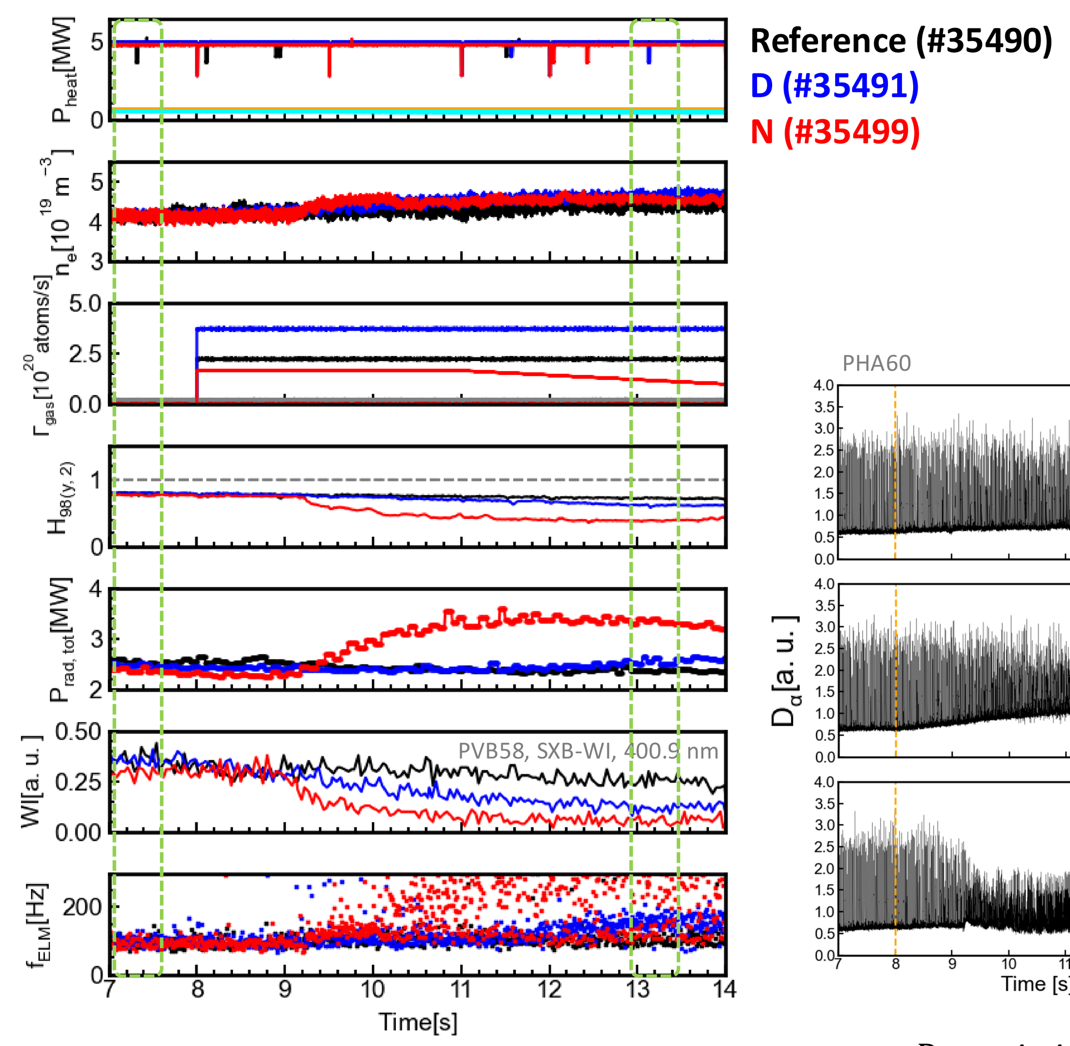
[*]junghoo.hwang@kaist.ac.kr, [**]wchoe@kaist.ac.kr

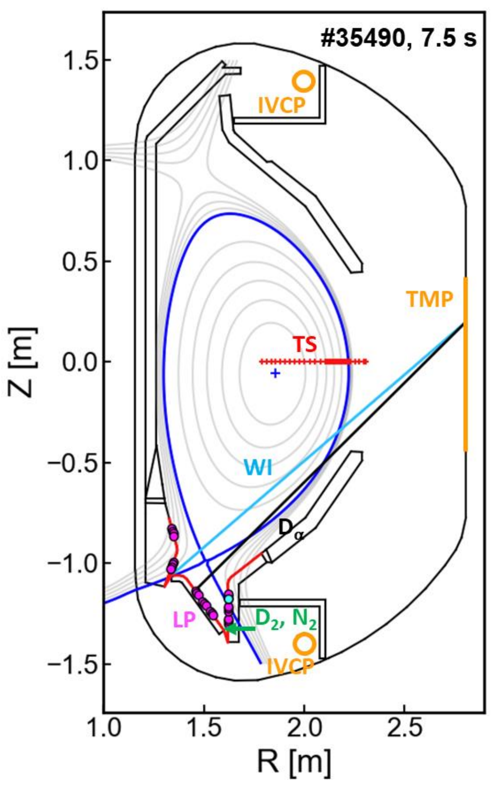
ABSTRACT

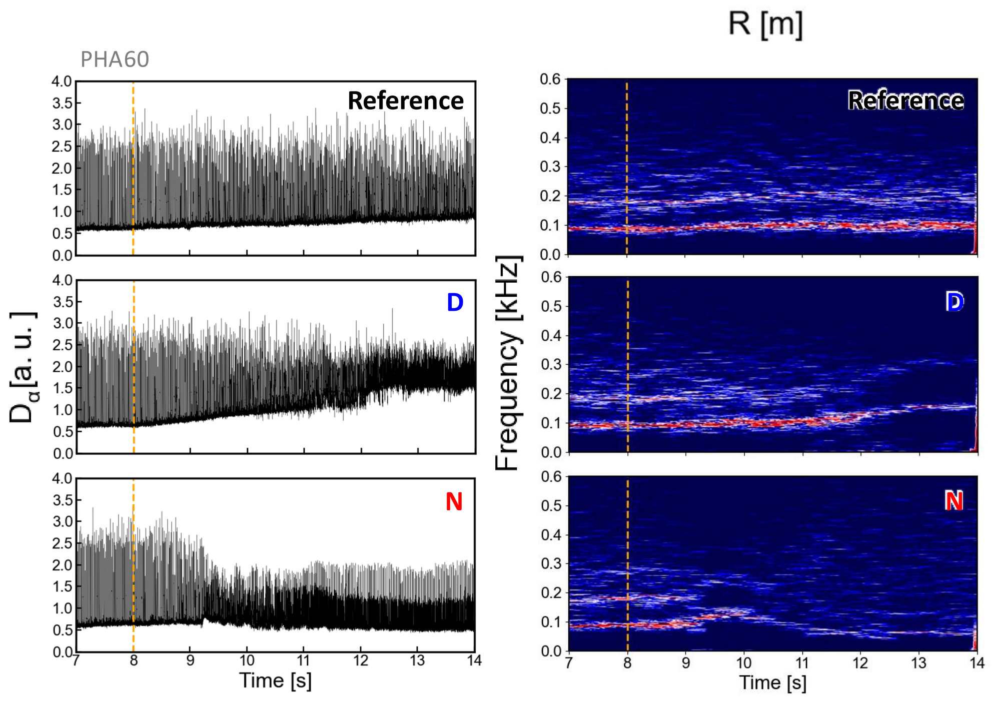
- KSTAR H-mode experiments with the new W divertor investigated detachment and tungsten transport using D fuelling and N seeding.
- The two gases produced clearly different core and edge plasma responses.
- D fuelling alone did not achieve strong detachment with 6 MW heating, whereas N seeding led to near complete detachment marked by an abrupt drop in outer target electron detachment.
- Core radiation also differed, with N seeding producing much stronger on-axis radiation and pronounced W density peaking than D fuelling.
- This behaviour is consistent with weakened neoclassical temperature screening at higher ion-ion collisionality [2,3].
- Overall, N seeding effectively promotes divertor detachment but aggravates core W accumulation, requiring additional control of inward W transport for core-edge compatible operation.

EXPERIMENTAL DISCHARGES

- I_p = 0.5 MA, B_T = 1.9 T, q_{95} = 5.8, P_{heat} = 6.0 MW (5.0 MW NBI + 1.0 MW on-axis ECRH)
- Forward B_T direction (ion $B \times \nabla B$ drift toward the active lower X-point)
- Divertor D_2 and N_2 injection rates were varied between the discharges
- Three representative discharges were selected: a **reference** ($\Gamma_{D2} = 2.2 \times 10^{20}$ atoms/s), a **D-fuelled** ($\Gamma_{D2} = 3.8 \times 10^{20}$ atoms/s), and an **N-seeded** discharges ($\Gamma_{N2} = 1.7 \times 10^{20}$ atoms/s)







D_α emission intensity and its power spectrogram

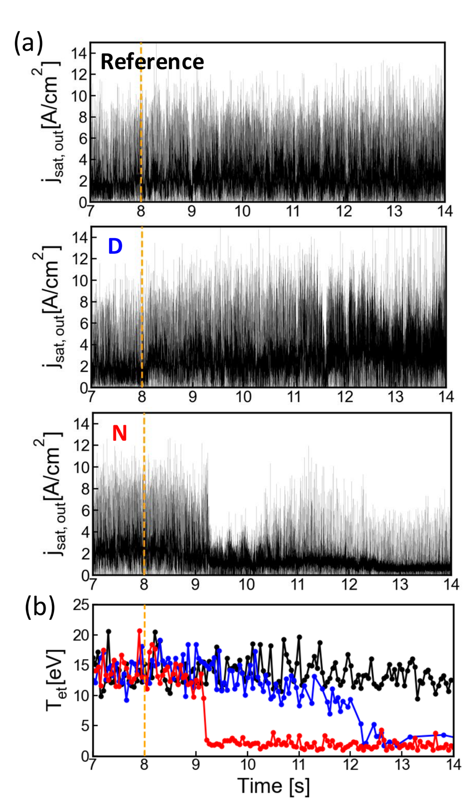
With D fueling,

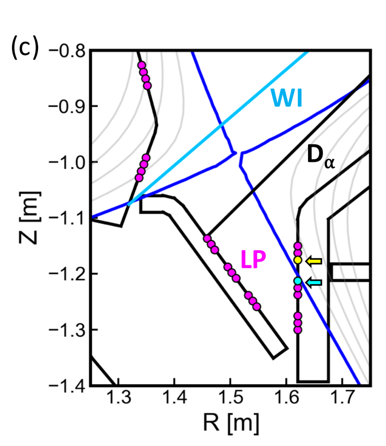
- $P_{rad,tot}$ stayed nearly unchanged, while the confinement ($H_{98(y,2)}$) dropped by ~20%.
- WI line emission at the inner divertor reduced.
- f_{ELM} increased by up to a factor of ~2 from an initial ~90 Hz, accompanied by smaller ELMs.

With N seeding,

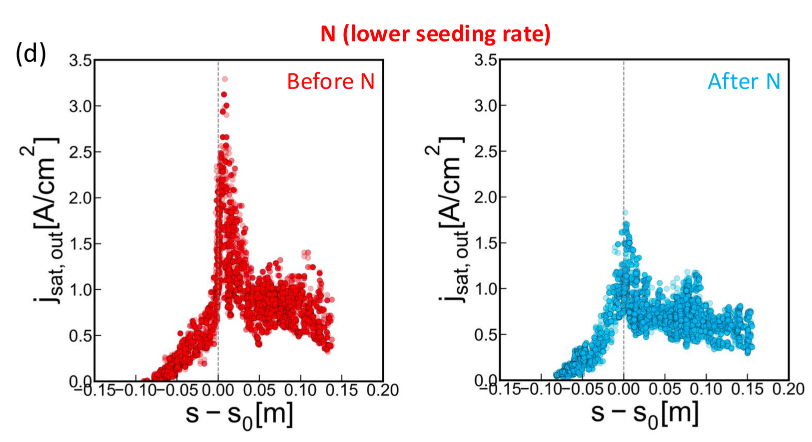
- $P_{rad,tot}$ rose to ~50% of P_{heat} and $H_{98(y,2)}$ decreased by ~50%.
- WI line emission at the inner divertor further reduced.
- Abrupt transition to higher frequency ELMs at ~9.3 s, with f_{ELM} ~100-500 Hz.

DETACHMENT EVOLUTION AND RADIATION DISTRIBUTION





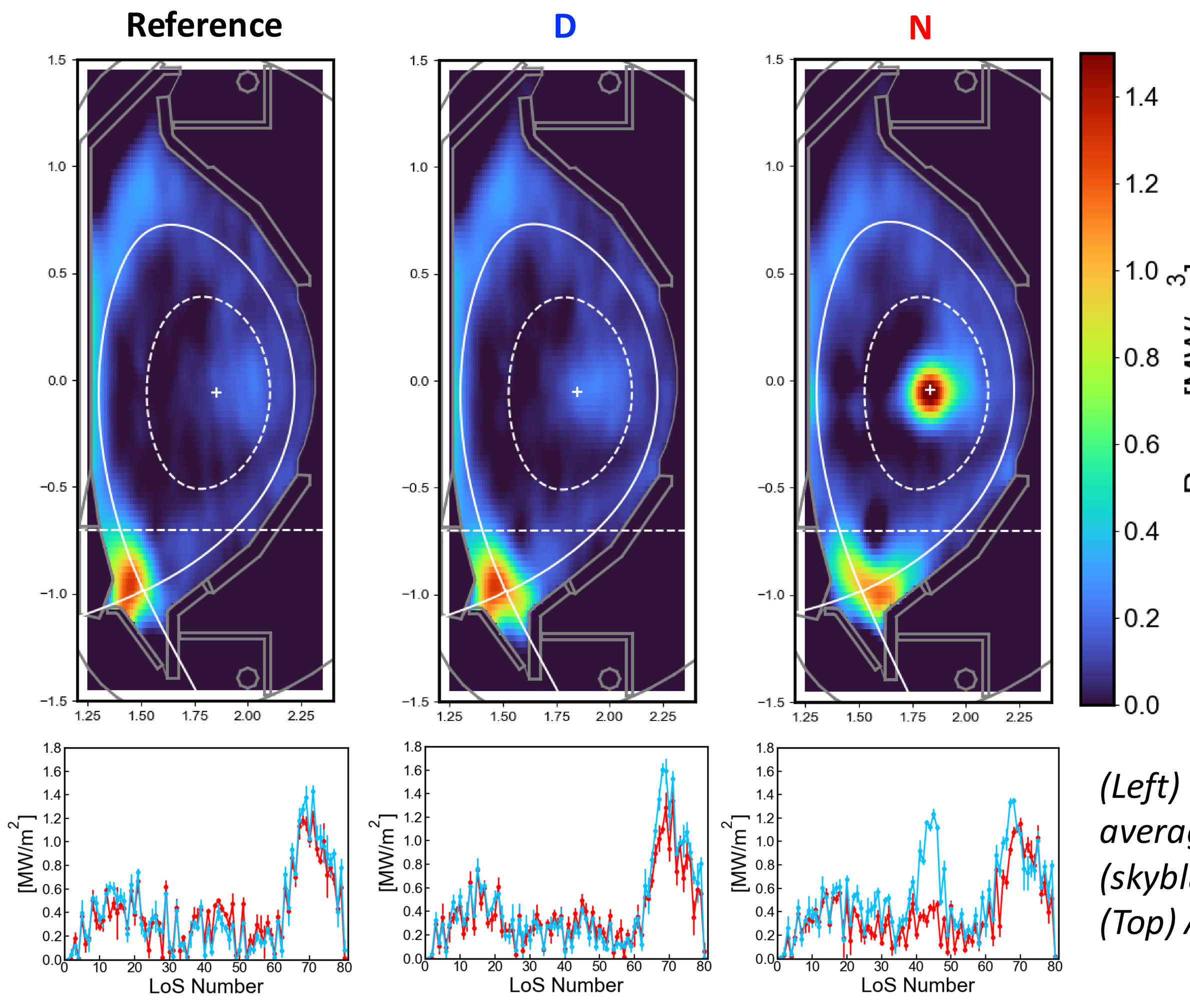
Poloidal locations of Langmuir probes (yellow: j_{sat}, cyan: T_{et})



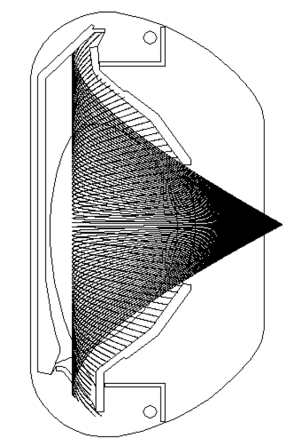
Radial profiles of ELM-filtered $j_{sat,out}$ for the N-seeded discharge with lower seeding rate

Outer target ion saturation current density $j_{sat,out}$ at the separatrix, Electron temperature T_{et} ~4 cm outside the separatrix

- In both D-fuelled cases (Reference, D), $j_{sat,out}$ remained unchanged, indicating that 6 MW H-modes could not achieve detachment with fuelling alone.
- Strong N seeding produced a significant drop in $j_{sat,out}$ and an abrupt T_{et} collapse ~1 s after injection, indicating complete outer target detachment.
- Radial profiles (from strike point sweeping) also show reduced ion flux near the strike point.



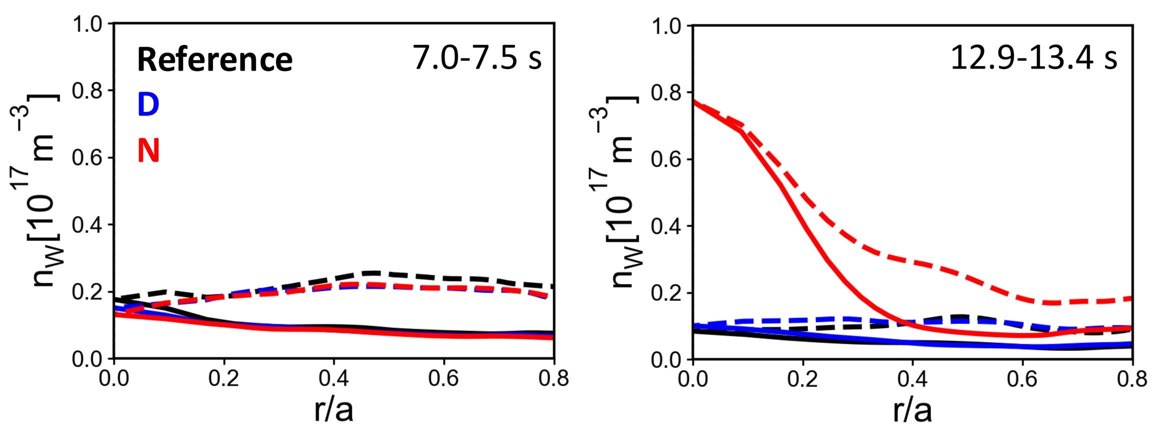
Imaging bolometer (tomographically reconstructed): 2D distributions of total radiated power ($P_{rad,tot}$), average over the gas-injected phase (12.9-13.4 s)



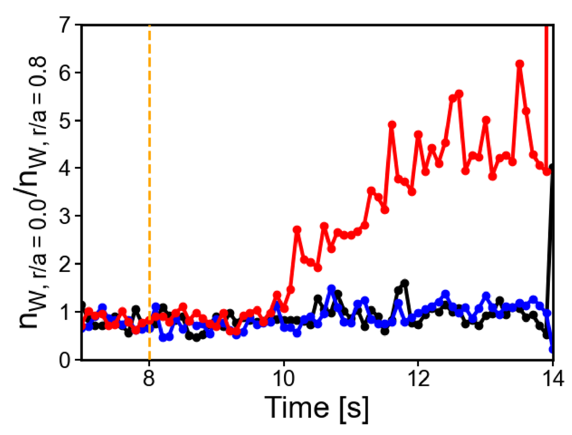
(Left) Line-integrated radiated power, average over 7.0-7.5 s (red) and 12.9-13.4 s (skyblue)
(Top) A fan of lines-of-sights used

Reference	D	N	
Weak radiation at LFS side	Slight radiation increase at LFS	Strong on-axis radiation	**Core**
Strong radiation peak at the inner divertor	Broader radiation peak with shift toward the X-point	Further horizontal shift and radiation peak at the outer SOL	**Divertor**

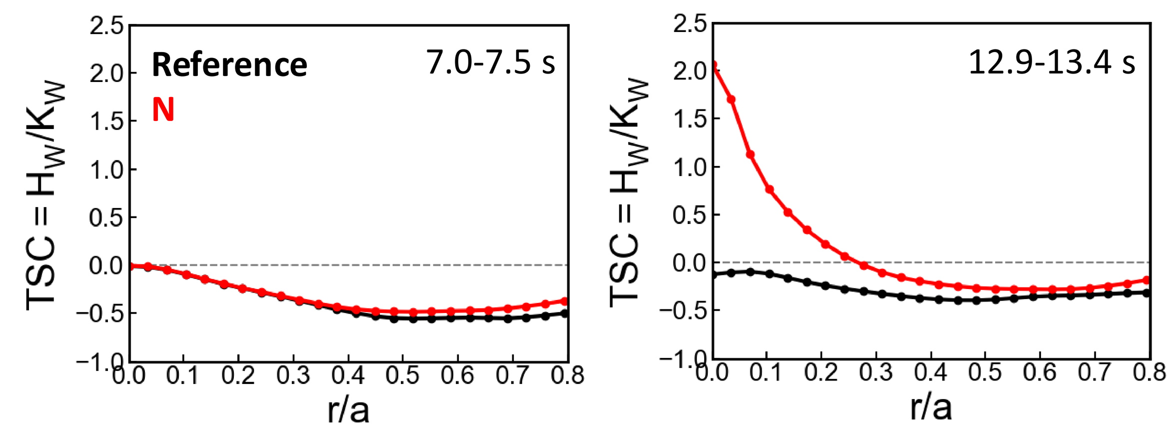
CORE TUNGSTEN IMPURITY BEHAVIORS



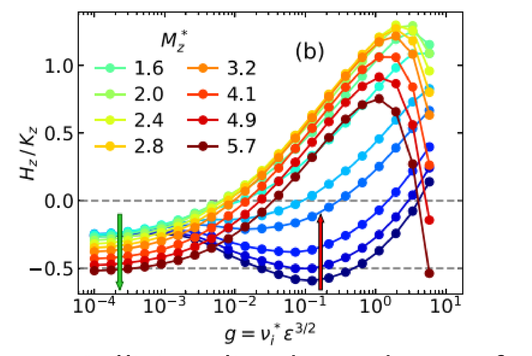
W density ($n_W = P_{rad,tot}/n_e L_W$ [4]) profiles: Flux surface averaged (solid) and outer midplane (dashed)



On-axis peaking of n_W, $n_{W,r/a=0.0}/n_{W,r/a=0.8}$



Temperature screening coefficient averaged over all charge states, TSC = H_W/K_W [2], calculated from FACIT [2,5,6]



Collisionality dependence of TSC for W^{44+} ion [2]

TSC < 0: temperature screening
TSC > 0: temperature peaking

- D fuelling: n_W slightly increased near the magnetic axis compared to the reference case.
- N seeding: a much larger increase, accompanied by stronger on-axis peaking (reaching up to ~ 1% of $\bar{n}_e$).
- $\nu_{NW} \gg \nu_{DW}$ ($\nu_{ab} \propto Z_a^2 Z_b^2$) → W transport is determined by background N. With continuous N_2 seeding, collisionality increased due to N concentration increase along with T_i reduction, which was further exacerbated by W accumulation.
- This resulted in neoclassical temperature peaking (inward convection, TSC > 0) [2,3].
- Toroidal rotation (of C^{6+} ions) was reduced by ~20-30% as well.
- For a full description of W accumulation, pedestal transport and its source need to be analyzed.

CONCLUSION

- Gas injection experiments in H-modes with the new lower W divertor (and carbon first wall) in KSTAR show distinct core and edge responses to D fuelling and N seeding.
- Even strong D fuelling did not produce significant detachment at the outer divertor target for the 6 MW input power discharges.
- With N seeding, abrupt ('cliff-edge') drops in target ion flux and electron temperature were observed indicating strong detachment, likely caused by power exhaustion due to strong X-point radiation.
- N seeding also caused strong on-axis core radiation peaking, attributed to increased W concentrations and consistent with weakened neoclassical temperature screening at higher ion-ion collisionality.
- Additional NBI or ICRH could mitigate this by raising T_i, lowering collisionality, and strengthening screening.
- Modelling analysis with SOLPS-ITER [7] and NEO [8,9] is planned.

ACKNOWLEDGEMENTS / REFERENCES

This work was supported by the National Research Foundation of Korea (NRF) funded by the Korean government (Ministry of Science and ICT) (RS-2022-00155960) and R&D Program of "Development of SOL-divertor operation scenarios in burning plasma regime for conceptual design of fusion reactor (CN2502-2)" through the Korea Institute of Fusion Energy (KFE) funded by the Government funds. The views and opinions expressed herein do not necessarily reflect those of the ITER Organization. The author wishes to thank Choongseok Chang for valuable comments on neoclassical W transport.s

[1] H.H. Lee, et al., 3rd iFPC, Seoul (2024).
[2] D. Farardo, et al., Plasma Phys. Control. Fusion 65 (2023) 035021.
[3] H.J. Lee, et al., 4th iFPC, Daejeon (2025).
[4] T. Putterich, et al., Nucl. Fusion 50 (2010) 025012.
[5] P. Maget, et al., Plasma Phys. Control. Fusion 64 (2022) 069501.
[6] D. Fajardo, et al., Plasma Phys. Control. Fusion 64 (2022) 055017.
[7] S. Wiesen, et al., J. Nucl. Mater. 463 (2015) 480-484.
[8] E.A. Belli and J. Candy, Plasma Phys. Control. Fusion 50 (2008) 095010.
[9] E.A. Belli and J. Candy, Plasma Phys. Control. Fusion 54 (2012) 015015.