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Global calculation of neoclassical impurity transport including the variation of electrostatic potential

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ABSTRACT

- We investigate neoclassical impurity transport in an impurity hole plasma using a global neoclassical simulation code FORTEC-3D.
- By the global simulation, we find the ambiolar radial electric field (E_r) which changes the sign from negative to positive along the minor radius.
- With such an E_r, the radial carbon flux (Γ_C) can be outwardly directed even where $E_r < 0$ and the carbon density profile is hollow.
- The sign-changing property of E_r in an impurity hole plasma has been experimentally confirmed and our result is qualitatively consistent with it.

BACKGROUND

- Since the presence of impurity ions in the core plasma can degrade the performance of fusion reactor, understanding the impurity transport process to prevent the impurity accumulation is a crucial task.
- According to neoclassical theory and experiments, impurity ions are usually expected to accumulate in the core of stellarators when $E_r < 0$.
- However, a notable exception, the formation of **"impurity hole"**, is observed in LHD (Large Helical Device).
- An impurity hole is a hollow structure of an impurity density profile in the core where $E_r < 0$.
- An experiment shows that, in an impurity hole plasma, $E_r < 0$ at $r/a < 0.55$ but $E_r > 0$ at the outer region [1],

r: radial coordinate
a: minor radius

[1] T. Ido et al., *Plasma Phys. and Control. Fusion*, 52(12), 2010.

METHODS AND SETUP

THE PLASMA PROFILE

- We investigate three different cases, **A**, **B** and **C**, each corresponding to a different carbon density (n_C) profile (Fig.1).
- For case **A**, the n-T profiles, including the n_C profile, are the same as those used in previous studies[2,3]: the hollow structure of the n_C profile is formed at an off-axis region ($r/a > 0$).
- However, some measurement data indicates impurity holes are formed around the magnetic axis.
- For case **B**, the carbon density gradient ∇n_C near the axis is thus flatten.
- For case **C**, on the other hand, ∇n_C near the axis is steepen.

SELF-CONSISTENT CALCULATION OF Φ_1, E_r and Γ_I

- We solve the quasi-neutrality condition to evaluate the variation of electrostatic potential on the flux surface Φ_1, the ambipolar condition to determine the ambipolar E_r and a drift-kinetic equation for multiple ion species including Φ_1 simultaneously.
- Local Γ_e is used to determine E_r and $\delta f_e = 0$ is assumed to evaluate Φ_1.

[2] A. Mollén, et al., *Plasma Phys. and Control. Fusion*, 60(8), 2018.
[3] M. Nunami, et al., *Phys. of Plasmas*, 27(5), 2020.

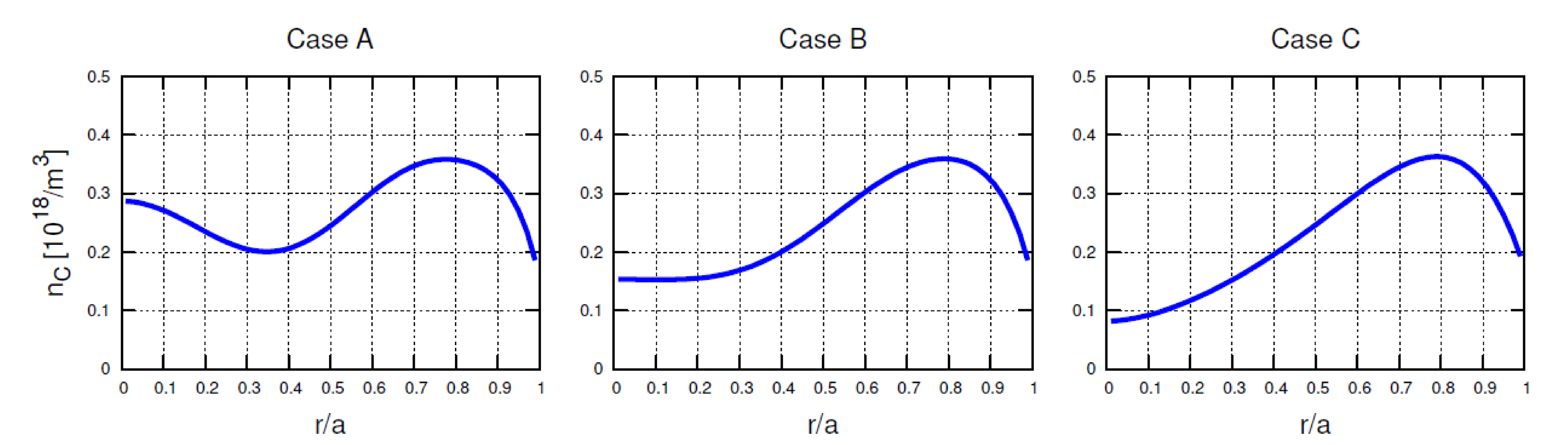

Fig.1 The radial profiles of carbon density for each case.

OUTCOME

THE AMBIPOLAR E_r

- For case **A**, the sign of the local solution (cyan points) of the ambipolar condition is negative for almost the entire radius.
- The sign of the global solutions (red line for the case w/Φ_1 and green lines for the case w/o Φ_1) is negative near the axis but transits to positive around $r/a = 0.25$ (Fig.2).
- The local calculation also finds an electron root (blue points) but only partially at $r/a > 0.8$.
- Qualitatively similar solutions are obtained for case **B** and **C**

THE CARBON FLUX Γ_C

▸ Case **A**

- Regardless of the effect of Φ_1, Γ_C is outwardly directed where the sign of E_r is negative ($r/a < 0.25$) and where the n_C profile is hollow (from $r/a \sim 0.2$ to $r/a \sim 0.6$) (Fig.2).
- The effect of Φ_1 tends to drive the flux more.

▸ Case **B**

- The Γ_C without Φ_1 is close to zero, but when Φ_1 is considered, the flux is driven outwardly for the entire radius (Fig.3).

▸ Case **C**

- Γ_C near the axis is negative regardless of the Φ_1-effect (Fig.3).
- This indicates the steep ∇n_C becomes a dominant driving force for Γ_C .

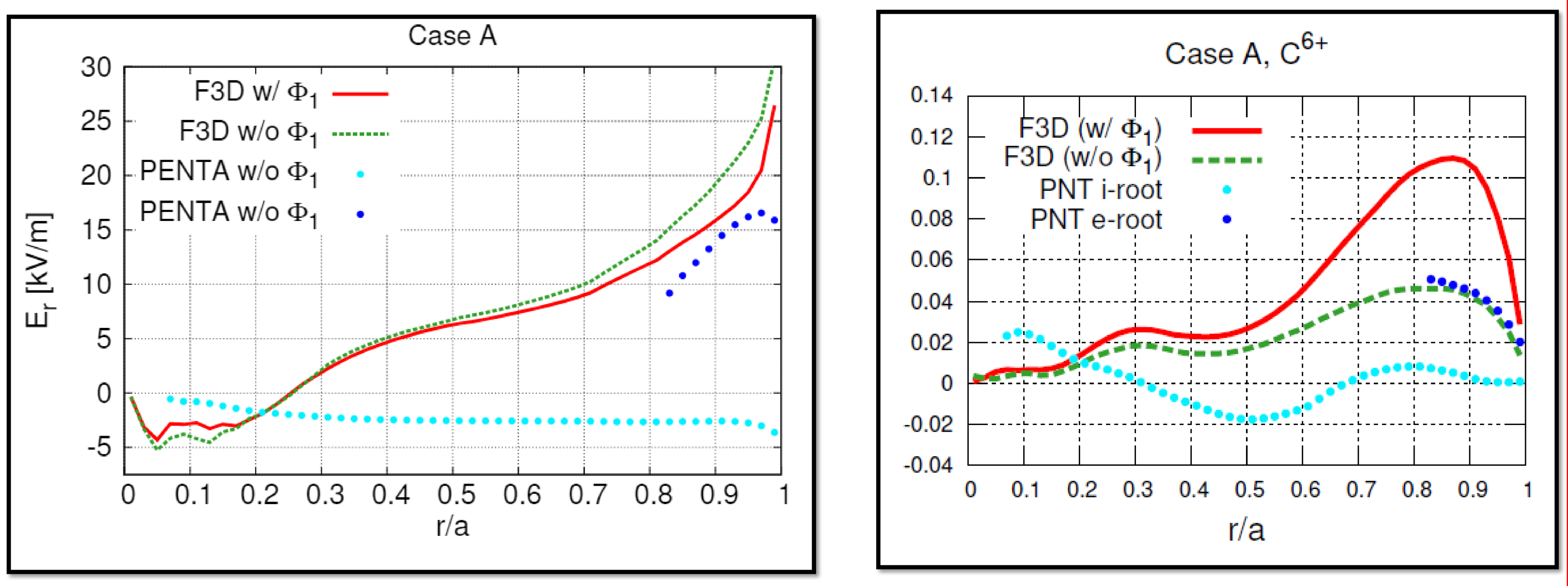

Fig.2 The radial profiles of E_r (left) and the carbon flux (right) for case ***A****.*

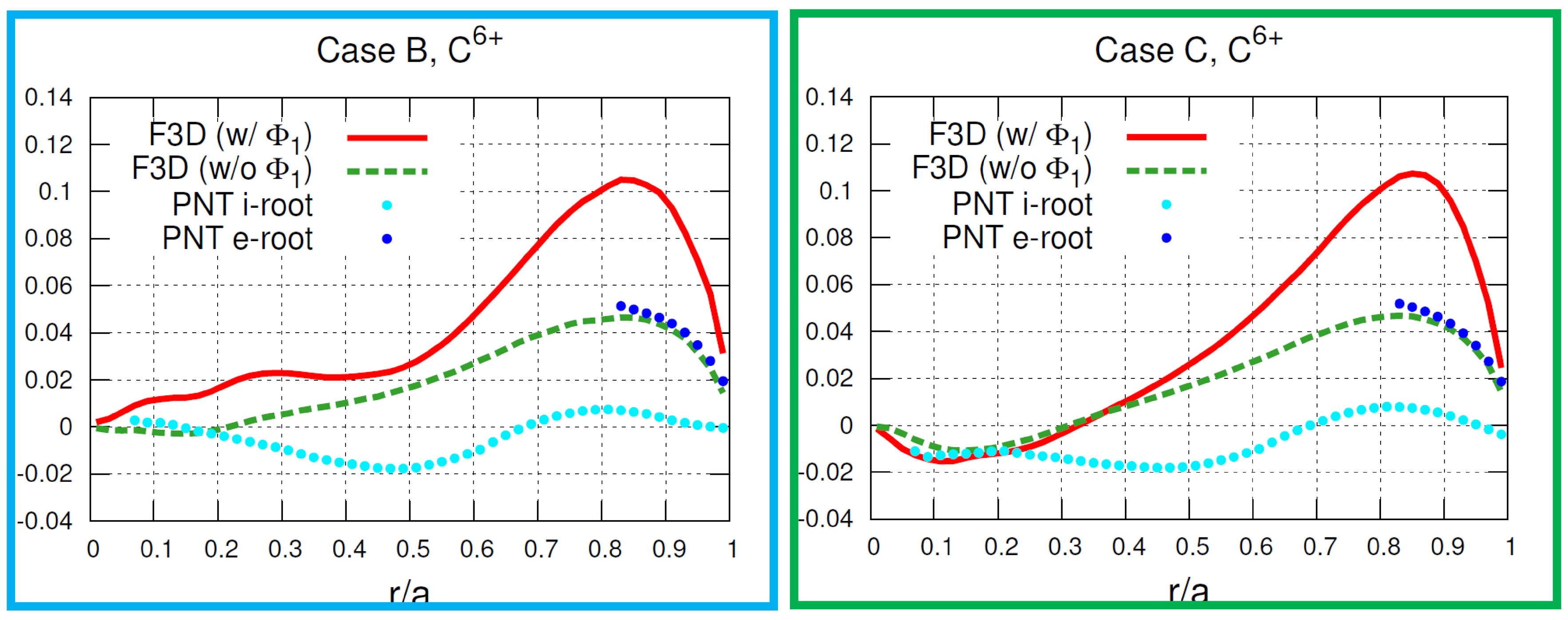

Fig.3 The radial profiles of carbon flux for case ***B*** *(left) and* ***C*** *(right).*

CONCLUSION

- By global simulation, we find ambipolar E_r which changes the sign from negative to positive along the radius and the carbon flux can be outward.
- Further, it is found that the outward carbon flux balances with the inward turbulent flux within factor 2 ~ 3 (omitted in this presentation).
- Yet, several points remain to be improved or further investigated, e.g.,

1. Validity of adiabatic electron is yet to be checked by global simulation.
2. Discrepancy in the transitioning point needs further investigation: $r/a < 0.25$ in the simulation while $r/a < 0.55$ in the experiment.