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# Radiative divertor experiments with Ne, N, and Kr seeding in LHD

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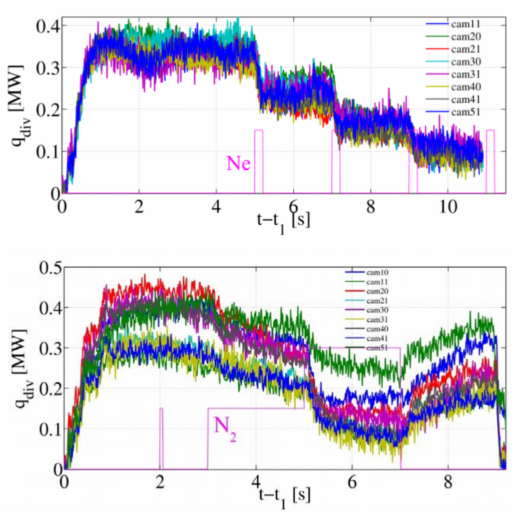
## Abstract


- Radiative divertor using impurity seeding is investigating to realize divertor heat load reduction with (i)Toroidal symmetry, (ii)High radiation fraction, (iii)Stable sustainment, (iv) High core plasma performance.
- In $N_2$ seeded plasmas, radiation enhancement strongly localized along magnetic field line in ergodic layer. It indicates that $N_2$ seeding is useful for additional radiative cooling.
- In Ne seeded plasmas, toroidal symmetry of divertor heat load reduction depends on $n_e$ and $T_e$ at LCFS before Ne seeding.
- Using Kr+Ne superimposed seeding, high-performance heat load reduction was achieved. Here, pre-seeded Kr emission was enhanced by Ne seeding. It indicates the controllability of radiation enhancement using another impurity seeding.

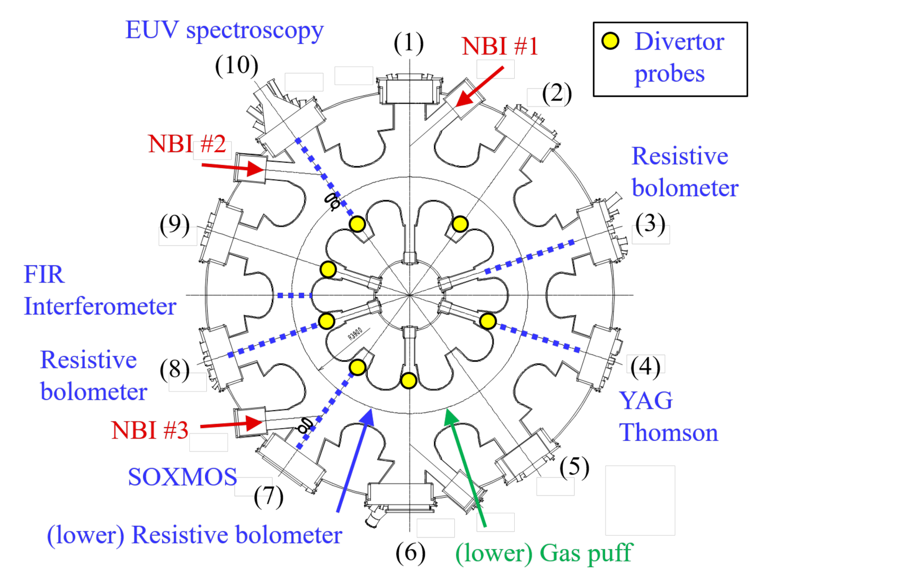

## Background

- "Toroidal symmetry", "high radiation fraction", "stable sustainment", and "high core plasma performance" is desired in helical devices.
- Ne: Symmetry, $N_2$: Asymmetry (also W7-X)
  - Q: What is the reason of toroidal asymmetry?
  - -> $\overline{n}_e$ (Ne, N) and $P_{NBI}$ (Ne) dependence
- Radiation fraction ($f_{rad} = P_{rad} / P_{NBI}$):
  ~ 50% (transitional), ~ 30% (stable)
  - Q: Can stable heat load reduction with higher $f_{rad}$ be achieved using multi-species impurity seeding with different cooling rate?
  - -> **Kr+Ne** superimposed seeding

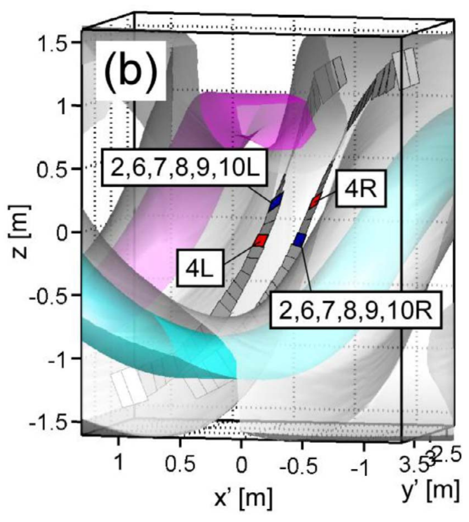


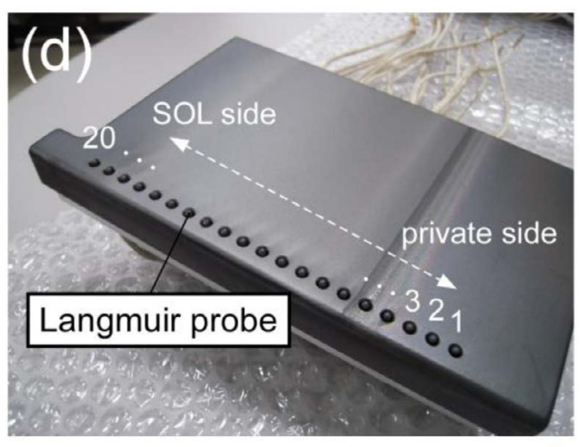
F. Effenberg *et al.*, NF 2019

## Experimental Setup on LHD




- $R$ = 3.9 m, $a$ ~ 0.6 m
- $V$ ~ 30 m$^3$
- $B$ ~ 3 T
- $L/M$ = 2/10
- $R_{ax}$ = 3.6 m
- $B_t$ = -2.75 T
- Heating: NBI #1-#3



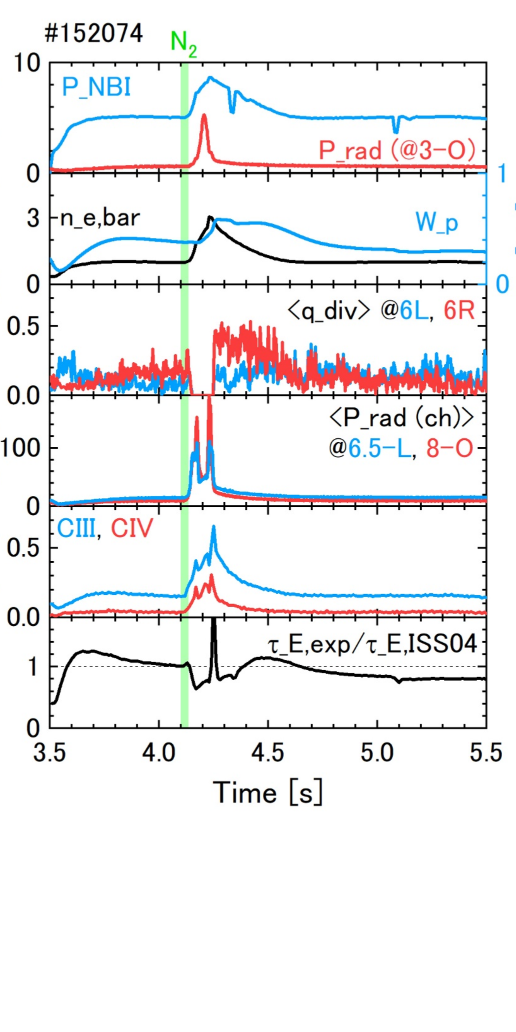



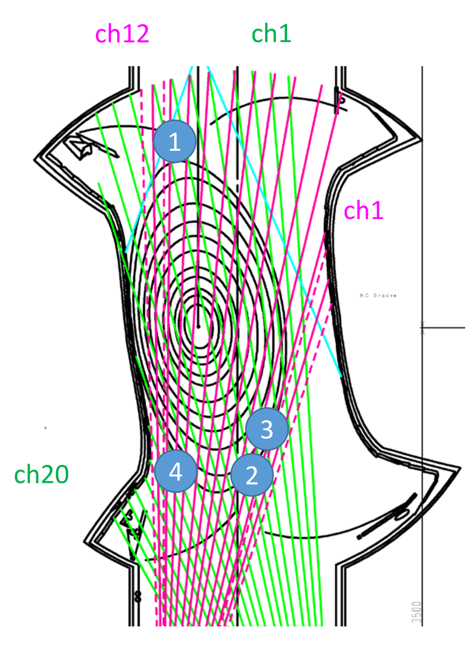

<Divertor probes>
- 7/10 toroidal sections
- L&R arrays / each section
- 20 pins / each array

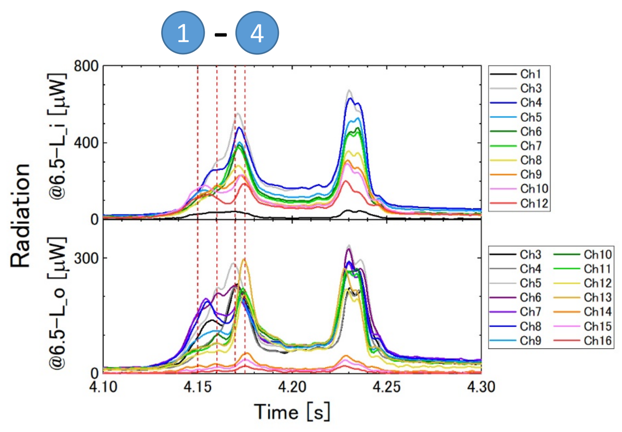
H. Tanaka *et al.*, NME 2017

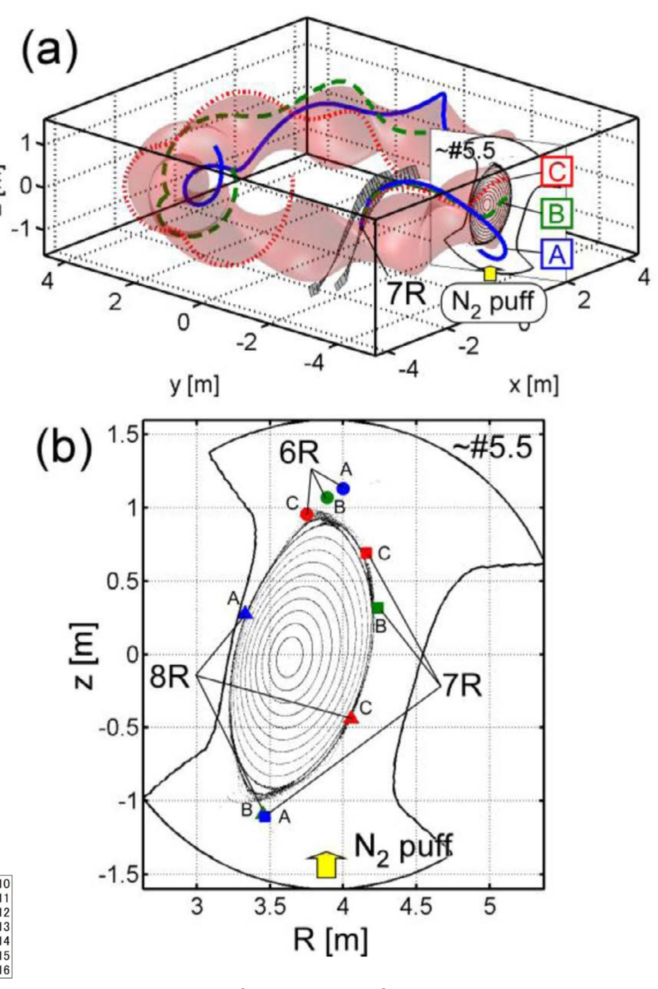
## Divertor Detachment in $N_2$ Seeding

- Plasma radiation enhancement occurred in ergodic layer along magnetic field line connected to $N_2$ seeding port.
- Plasma radiation is toroidally localized. (Toroidal section 3 → 6.5 and 8 → 3)
- This localization is weakened with increase of $n_e$.





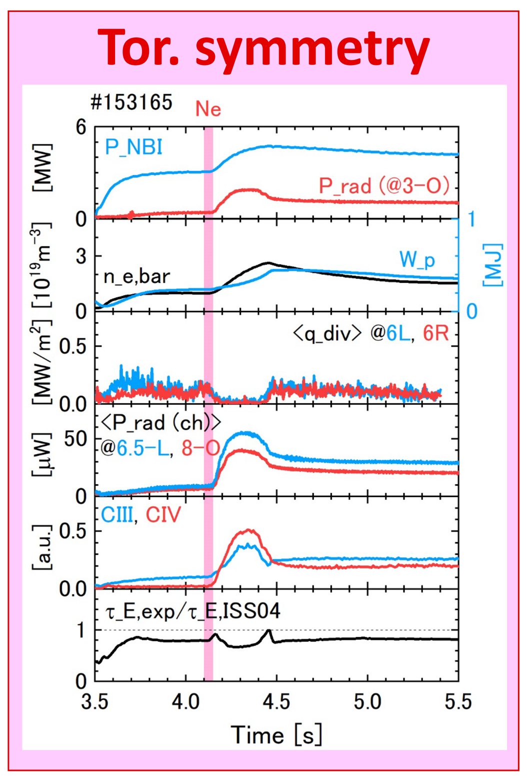


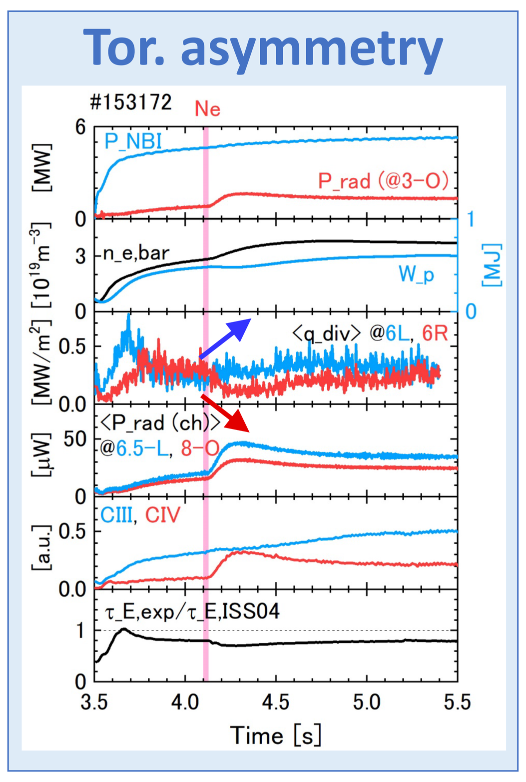


H. Tanaka *et al.*, NME 2017

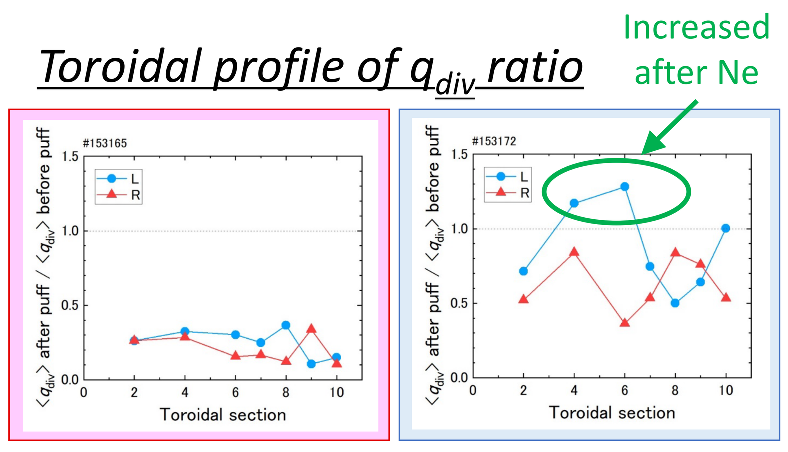
## Divertor Detachment in Ne Seeding

Toroidal symmetry of $q_{div}$ depends on $n_e$ and $T_e$ at LCFS before Ne seeding.



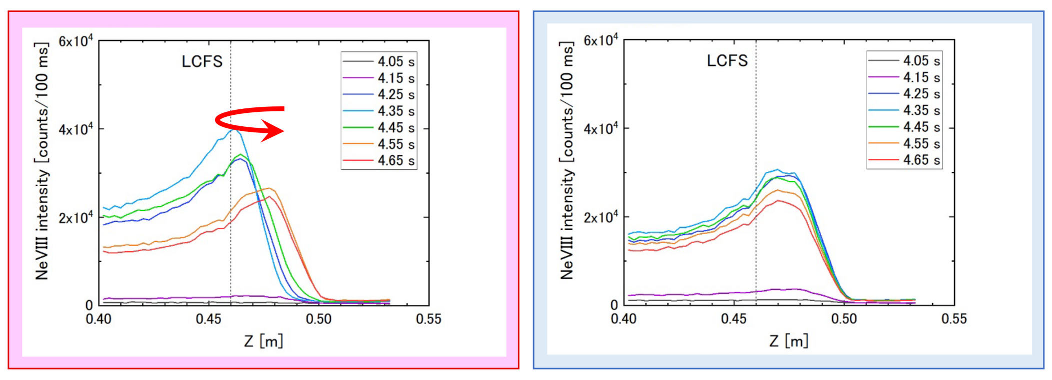




*Toroidal profile of $q_{div}$ ratio*

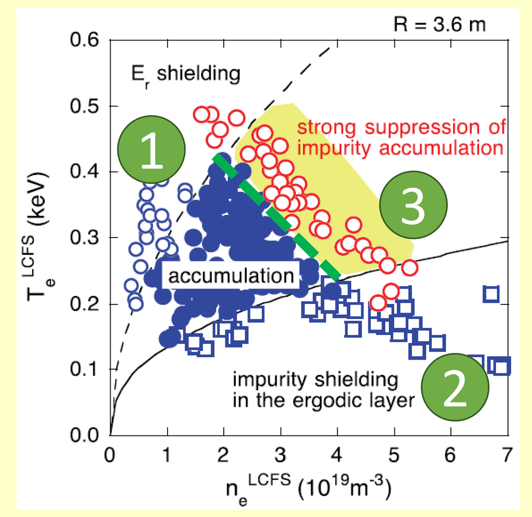



- Behavior of $q_{div}$ is different just after the Ne seeding.
- -> The symmetry / asymmetry is determined by the plasma condition before the Ne seeding.

*Time evolution of Ne profile*



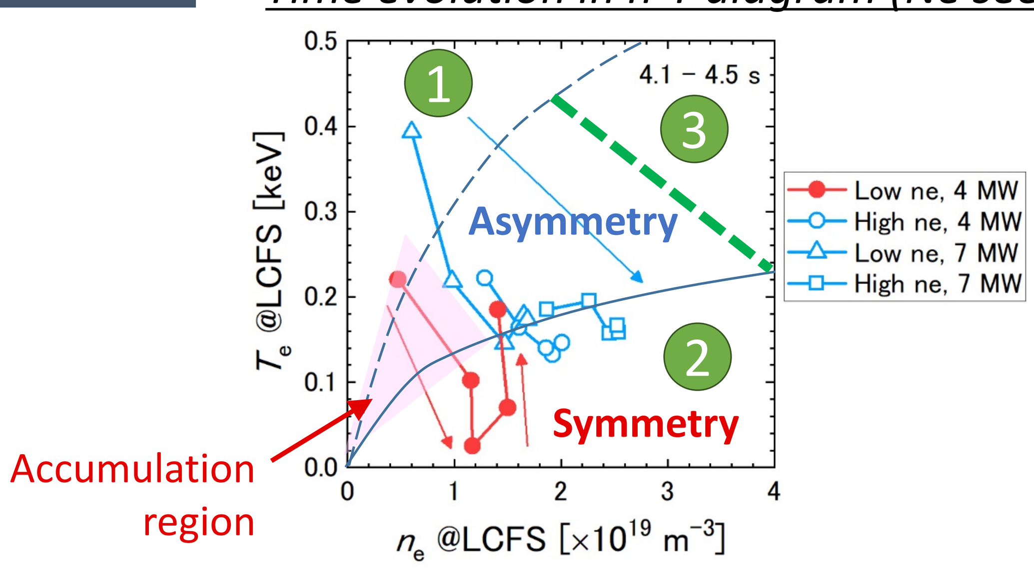
- In the case of symmetry, Ne reached around LCFS.
- $q_{div}$ increased with exhaust of Ne.
- -> Accumulation / shielding of Ne affect the symmetry / asymmetry.



**n-T diagram** (Y. Nakamura *et al.*, NF 2017)
- Accumulation / shielding of C and Fe was evaluated experimentally.
  1. Shielding by **negative $E_r$** (Dashed line)
  2. Shielding by **friction force** in ergodic region (Solid line)
  3. Shielding in **high-power heating**

  ○: Increase of $\nabla T_i$ and Mach number, and contribution of turbulence transport of impurities

*Time evolution in n-T diagram (Ne seeded plasmas)*

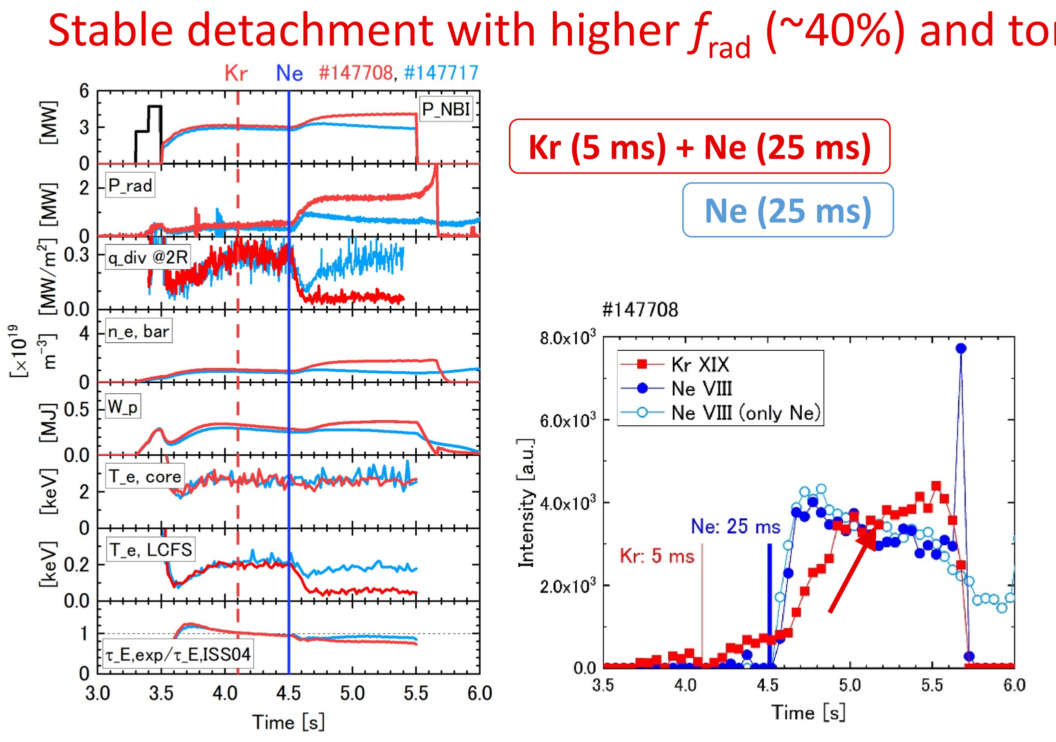



| Symmetry | Asymmetry |
|---|---|
| <Accumulation> | <Shielding> |
| Ne seeding | |
| Ne can reach LCFS | Ne cannot reach LCFS |
| $q_{div}$↓ with symmetry | $q_{div}$↓ with asymmetry |
| $n_{e\_LCFS}$ ↑, $T_{e\_LCFS}$ ↓ (due to Ne ionization) | |
| <Shielding> | <Shielding> |
| Ne exhaust, $q_{div}$ ↑ | |

- Characteristics of accumulation/shielding before Ne seeding is related to toroidally symmetric/asymmetric reduction of $q_{div}$.
- Shielding region ③ is different from previous study. → $T_i$ measurement is required.

## Divertor Detachment in Kr+Ne Seeding

Stable detachment with higher $f_{rad}$ (~40%) and toroidal symmetry was achieved.




- Kr emission was enhanced after Ne seeding.
- Ne emission was not affected by Kr.
- After Ne seeding, $T_e$ decreased only around plasma edge region.
- -> Kr emission region was expanded slightly inside LCFS.
- This detachment is occurred only in D plasmas.

## Conclusion

- <$N_2$> Radiation enhancement strongly localized along magnetic field line in ergodic layer. -> Availability for additional radiative cooling
- <Ne> Toroidal symmetry of $q_{div}$ depends on $n_e$ and $T_e$ at LCFS before Ne seeding. Further investigation of impurity shielding effect is required.
- <Kr+Ne> High-performance heat load reduction was achieved. It indicates the controllability of radiation enhancement using another impurity seeding. The isotope effect i.e. recycling should be investigated.

## Acknowledgements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