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Steady-state sustainment of divertor detachment with multi-species impurity seeding in LHD

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Abstract

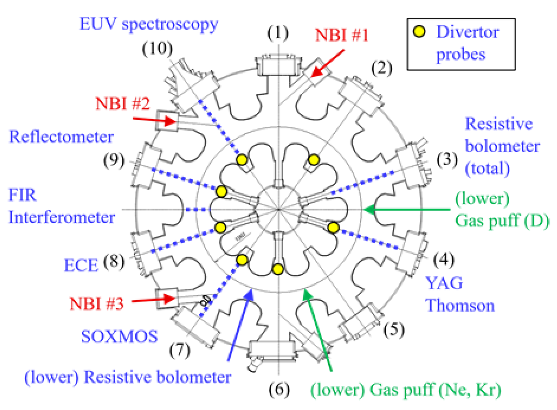
- Multi-species impurity seeding is an advanced operation scenario to mitigate the divertor heat load for realization of fusion reactors.
- In the Large Helical Device (LHD), divertor detachment was successfully sustained using higher-Z (Kr) and lower-Z (Ne) superimposed seeding.
  - Plasma radiation could be enhanced even at the upstream region in the edge plasma compared with Ne only seeded plasmas with suppression of impurity accumulation toward the central plasma.
- The pre-seeded Kr emission was drastically enhanced after the subsequent Ne seeding.
  - Kr atoms could ionize close to LCFS due to the reduction of edge T_e by the Ne seeding.
  - Thermal force with inward direction should increase with the increase of the number of impurity charge states in the ergodic region.
  - Inward transport due to negative E_r, which is generated in the ergodic layer after the Ne seeding, could retain the seeded impurities.
  - Outward transport due to a steep temperature gradient, which is generated in the core plasma after the Ne seeding, could suppress the impurity accumulation.
  - These should be keys to the enhancement of the Kr emission and the sustainment of the detachment.
- Multi-species impurity seeding is more effective and promising for the detachment in fusion reactors with the prevention of the dilution.

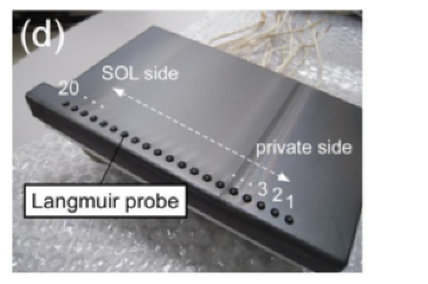
1. Introduction

- Divertor detachment is one of the crucial issues to realize a fusion reactor.
  Divertor heat load should be mitigated stably.
  Furthermore, to handle the power exhaust, it is necessary to enhance plasma radiation not only in the divertor region but also in the upstream region with suppression of dilution.
- Therefore, multi species impurity seeding of higher-Z and lower-Z impurities is proposed in JT-60SA [1].
  Moreover, the COREDIV code predicted that additional Kr seeding is effective for divertor detachment [2].
- In LHD, we have investigated detachment using Ne or Kr seeding individually [3-5].
  However, the characteristics of divertor detachment in multi-species impurity seeded plasmas have not been investigated.
  Thus, in this study, we attempted to superimposed seeding using Kr and Ne in anticipation of experiments on tokamak devices.
- The cooling rate of Ne has the maximum at the T_e ~ 30 eV.
  On the other hand, the rate of Kr takes a local minimum at T_e ~ 30 eV,
  it is expected that these impurities could enhance plasma radiation complementarily.

[1] GAŁĄZKA, K. *et al.*, Contrib. Plasma Phys. **58** (2018) 751-757.
[2] ZAGÓRSKI, R. *et al.*, Nucl. Fusion **57** (2017) 066035.
[3] MASUZAKI, S. *et al.*, J. Nucl. Mater. **438** (2013) S133.
[4] MUKAI, K. *et al.*, Nucl. Fusion **55** (2015) 083016.
[5] TANAKA, H. *et al.*, Nucl. Mater. Energy **12** (2017) 241-246.

2. Experimental setup on LHD





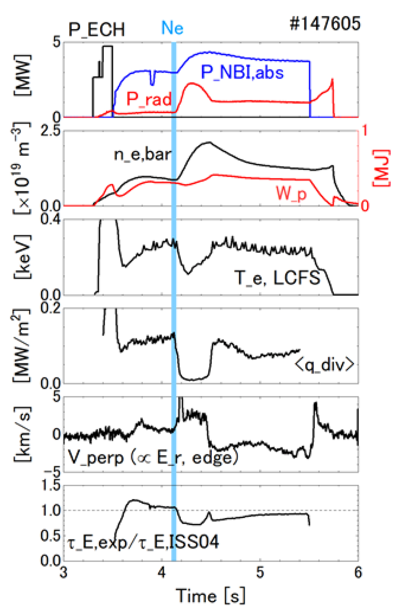
TANAKA, H. *et al.*, Nucl. Mater. Energy **12** (2017) 241-246.

- R = 3.9 m, a ~ 0.6 m
- V ~ 30 m³
- 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

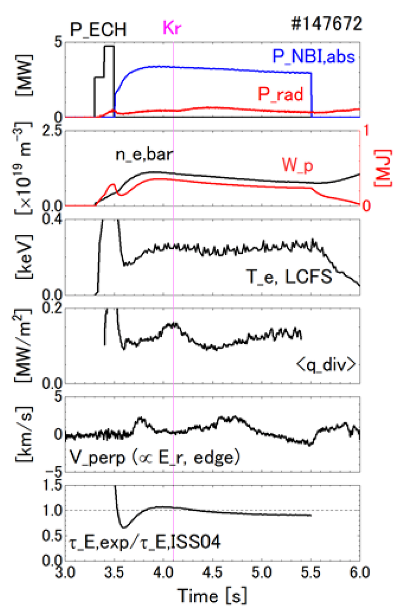
3. Divertor detachment in Ne seeding



- Seeded amount: 0.09 Pa·m³
  Flow rate: 1.8 Pa·m³/s
- The plasma was detached after the Ne seeding and it continued for ∽ 0.3 s.
- $\langle q_{div} \rangle$ decreased by ~ 90%.
- Maximum f_{rad} is 56%.
  Although NBI port-through power is constant, $P_{NBI,\,abs}$ increased with increasing $n_{e,\,bar}$ due to the increase in heating efficiency.
- $\tau_{E,\,exp}/\tau_{E,\,ISS04}$ ∽ 0.7

MUKAI, K. *et al.*, Nucl. Fusion **55** (2015) 083016.

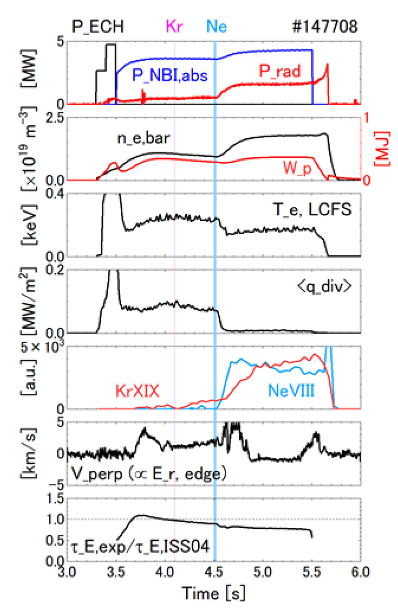
4. Kr seeding experiment



- Seeded amount: 0.024 Pa·m³
  Flow rate: 3.0 Pa·m³/s
- The plasma response was modest.
- $\langle q_{div} \rangle$ decreased by ~ 43%.
- Maximum f_{rad} is 21%.
- $\tau_{E,\,exp}/\tau_{E,\,ISS04}$ ∽ 0.9

MUKAI, K. *et al.*, Nucl. Fusion **55** (2015) 083016.

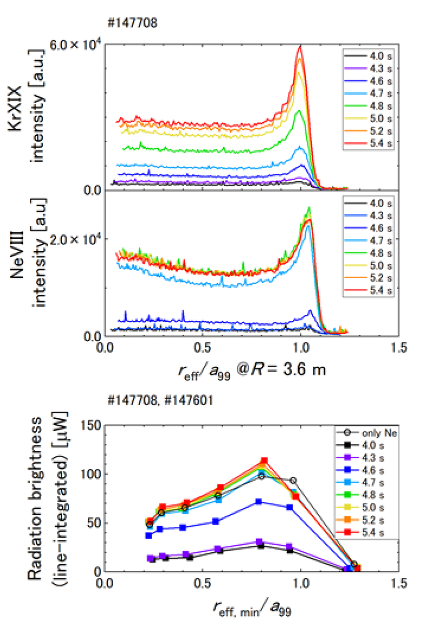
5. Divertor detachment in Kr+Ne seeding

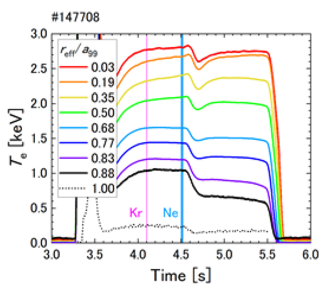


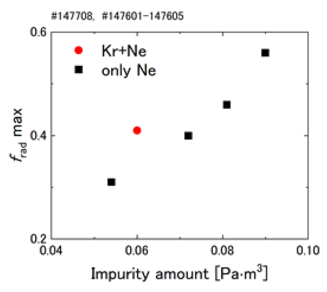
- Ne was seeded 0.4 s after the Kr seeding since the plasma response of Kr is slower than Ne.
- The plasma was detached after the Ne seeding and it continued for ∽ 1 s.
- f_{rad}, during the detachment was ~ 40%, (10% higher than multi-pulse Ne seeding)
- $\langle q_{div} \rangle$ decreased by ~ 17% after Kr seeding and drastically decreased by ∽ 90% after Ne seeding.
- $\tau_{E,\,exp}/\tau_{E,\,ISS04}$ ∽ 0.8 (10% higher than Ne only seeding)
- After the Ne seeding, both KrXIX and NeVIII emissions suddenly increased.

MUKAI, K. *et al.*, Nucl. Fusion **55** (2015) 083016.

6. Radiation behavior in Kr+Ne seeding

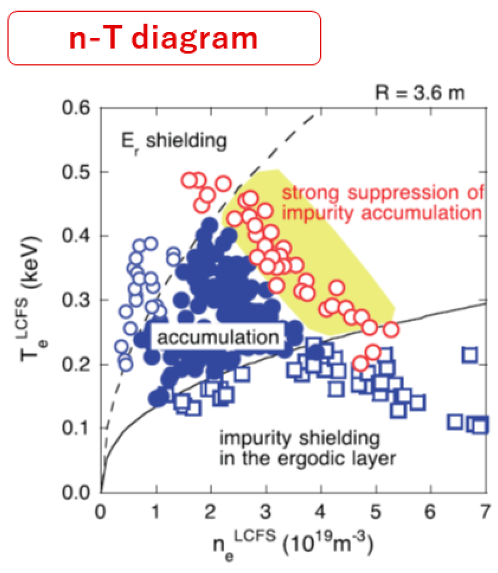






- KrXIX and NeVIII profiles localized near LCFS.
  Kr and Ne can be ionized up to KrXXVI and NeX.
  Radiation profile localized $|r_{eff,\,min}/a_{99}|$ ~ 0.8.
- ⇒ Radiation was enhanced in the upstream region compared with the Ne only seeding under the same f_{rad} ~ 0.4.
- T_e was recovered $|r_{eff,\,min}/a_{99}| < 0.8$ after t = 4.7 s, while edge T_e reduction was sustained.
- ⇒ Impurity accumulation could be suppressed.
- Kr+Ne seeding needs a small amount of impurities compared with Ne only seeding to obtain a certain f_{rad}.
- ⇒ Kr+Ne seeding is effective and can prevent the dilution.

7. Impurity screening/accumulation behavior in LHD

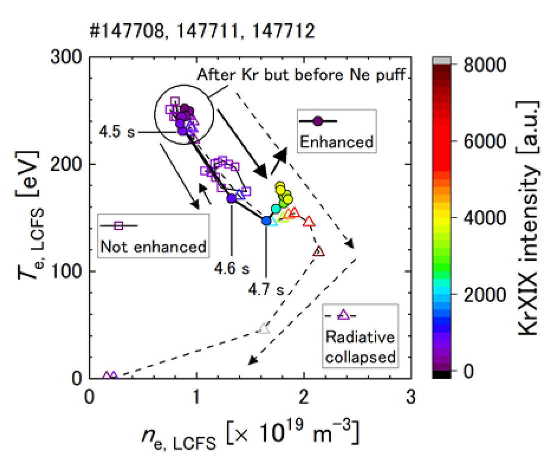


- Accumulation / shielding of C and Fe was evaluated experimentally.
- NBI heating, H plasma
- R_{ax} = 3.6 m, B_t = -2.75 T
- $dP_{rad}/dt > 0$ -> accumulation

①Shielding by **positive E_r** (Dashed line)
②Shielding by **friction force** in ergodic region (Solid line)
③Shielding in **high-power heating** (○)
Increase of ∇T_i and Mach number

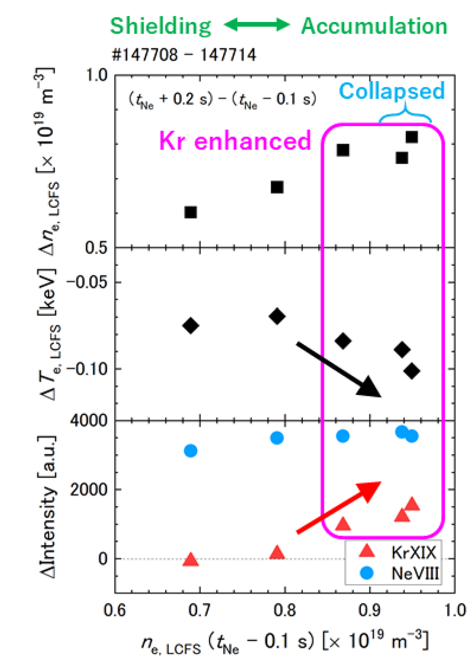
NAKAMURA, Y. *et al.*, Nucl. Fusion **57** (2017) 056003.

8. Why did Kr emission enhanced?



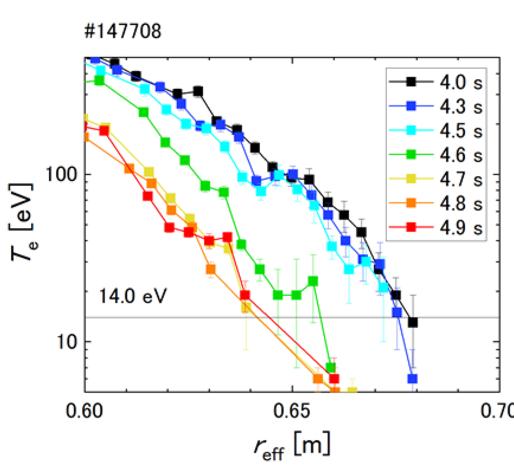
- Due to Ne seeding, $n_{e,\,LCFS}$ increased and $T_{e,\,LCFS}$ decreased.
- When $T_{e,\,LCFS}$ was reduced below ~ 150 eV by Ne seeding, KrXIX was enhanced.
- When $n_{e,\,LCFS}$ increased above ~ 2×10^{19} m^{-3}, plasmas were radiative collapsed.
- Amount of seeded Kr and Ne were same.
- ⇒ $n_{e,\,LCFS}$ and $T_{e,\,LCFS}$ before the Ne seeding of these discharge were around border between shielding-accumulation region.
- ⇒ A small difference in the $n_{e,\,LCFS}$ - $T_{e,\,LCFS}$ characteristics before the Ne seeding strongly affects the response of the Kr enhancement.

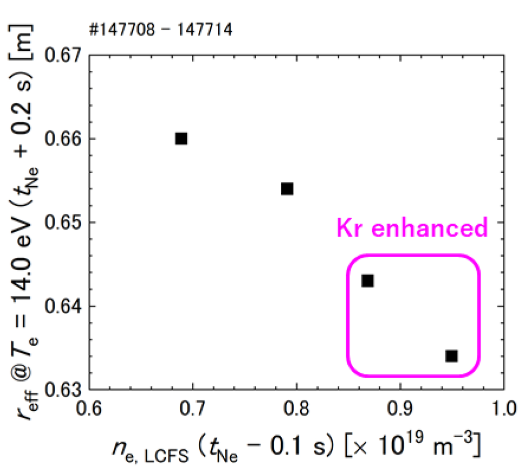
9. Dependence of background $n_{e,\,LCFS}$



- $\Delta n_{e,\,LCFS}$ increased with the increase of $n_{e,\,LCFS}$ before Ne seeding.
- ⇒ Ne ionization was enhanced due to an increase of Ne accumulation at the ergodic layer.
- When $n_{e,\,LCFS}$ before Ne seeding was above 0.8×10^{19} m^{-3}, further $\Delta T_{e,\,LCFS}$ decrease was observed and KrXIX emission intensity was enhanced while the NeVIII emission intensity saturated.

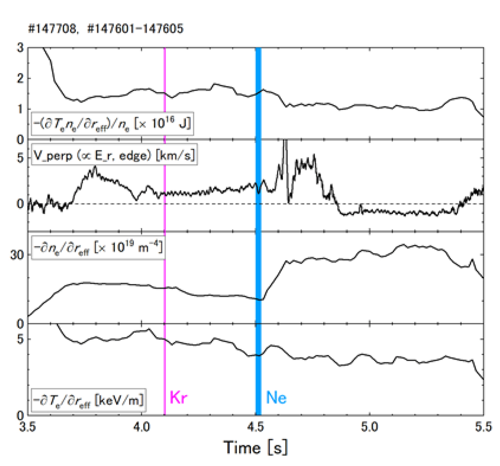
10. Kr penetration was promoted by edge T_e reduction due to Ne seeding





- The first ionization energy of Kr is 14.0 eV.
- The position where T_e = 14.0 eV was shifted inward due to the edge T_e reduction by Ne seeding.
- ⇒ Deeper penetration of Kr atoms due to edge T_e reduction by Ne seeding can be considered as the key to the KrXIX emission enhancement.

11. Inward transport of Kr ions in ergodic layer was promoted due to Z increase



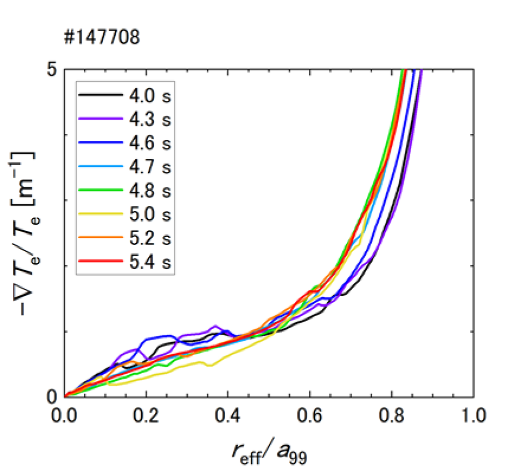
- Kr was ionized near the LCFS but outside the LCFS.
  ⇒ Inward transport in ergodic layer is required.
- The parallel momentum balance on impurity ions in the ergodic layer can be described as;

$$m_I \frac{\partial V_{I//}}{\partial t} = -\frac{1}{n_I}\frac{\partial T_I n_I}{\partial s} + ZeE_{//} + m_I \frac{V_{i//}-V_{I//}}{\tau_s} + 0.71Z^2\frac{\partial T_e}{\partial s} + 2.6Z^2\frac{\partial T_I}{\partial s}$$

OISHI, T. *et al.*, Nucl. Fusion **58** (2018) 016040.

- After Ne seeding,
  - ✓ $-\frac{1}{n_e}\frac{\partial T_e n_e}{\partial r}$ (inward) slightly decreased.
  - ✓ E_r was positive (outward).
  - ✓ Friction force (outward) increased with the increase of $|\nabla n_e|$ due to Ne seeding.
- ⇒ Thermal force (inward) should increase with the increase of Z since $|\nabla T_e|$ slightly decreased.
- $-E_r$ after t = 4.9 s can affect the sustainment.

12. Accumulation of Kr ions can be prevented by steep temperature gradient



- While inward transport occurred in the ergodic region, impurity accumulation toward the central plasma was suppressed.
- ⇒ Outward transport occurred in the central plasma
- It is assumed that impurity sources can be neglected in $|r_{eff}/a_{99}| < 0.7$ since plasma radiation mainly occurred $|r_{eff}/a_{99}| > 0.7$.
  The radial particle flux Γ_I^{nc} of the impurity ion, I, is predicted by neoclassical theory as;

$$\Gamma_I^{nc} = -D_{1,I}n_I\left\{\frac{\nabla n_I}{n_I} - \frac{ZeE}{kT_I} + \left(\frac{D_{2,I}}{D_{1,I}} - \frac{3}{2}\right)\frac{\nabla T_I}{T_I}\right\},$$

TRIBALDOS, V., Phys. Plasmas 8 (2001) 1229.
SUDO, S. et al., Plasma Phys. Control. Fusion 56 (2016) 043001.

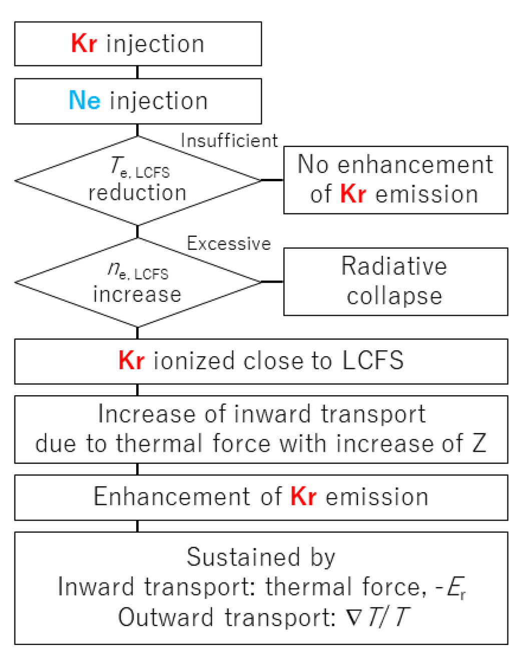
- Since impurities penetrate from outside, ∇n_I inside $|r_{eff}/a_{99}|$ = 0.7 should be positive (inward).
- $\nabla T_e/T_e$ decreased drastically $r_{eff}/a_{99} > 0.6$ after the Ne seeding and the increased $\nabla T_e/T_e$ was sustained until the end of the discharge.
- ⇒ Outward transport occurred due to the steep $\nabla T_e/T_e$.
- The information of T_i and E_r are required for detail discussion.

13. Summary & future work

- Multi-species impurity seeding is an advanced operation scenario to mitigate the divertor heat load for realization of fusion reactors.
- In the LHD, divertor detachment was successfully sustained using **Kr**+**Ne** superimposed seeding.
- Plasma radiation could be enhanced even at the upstream region in the edge plasma compared with Ne only seeded plasmas with suppression of impurity accumulation toward the central plasma.
- The pre-seeded **Kr** emission was drastically enhanced after the subsequent **Ne** seeding.
- Multi-species impurity seeding is more effective and promising for the detachment in fusion reactors with the prevention of the dilution.

➢ Further radiation enhancement
- Optimization of the impurity seeding (Additional Ne seeding with moderate flow rate)
- Control of the edge profile using div. pumping

➢ Sustainment with feedback control
- Fast Thomson scattering and/or ECH in the edge plasma can be used.



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