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# Extension of Operational Regime in High-Temperature Plasmas and Effect of ECRH on Ion Thermal Transport in the LHD

H. Takahashi, K. Nagaoka, S. Murakami[1)], M. Osakabe, H. Nakano, K. Ida, T. I. Tsujimura, S. Kubo, T. Kobayashi, K. Tanaka, R. Seki, Y. Takeiri, M. Yokoyama, M. Nakata, M. Yoshinuma, I. Yamada, R. Yasuhara, T. Ido, A. Shimizu, H. Tsuchiya, M. Goto, T. Oishi, S. Morita, C. Suzuki, M. Emoto, K. Tsumori, K. Ikeda, M. Kisaki, T. Shimozuma, Y. Yoshimura, H. Igami, R. Makino, T. Seki, H. Kasahara, K. Saito, S. Kamio, T. Mutoh, O. Kaneko, T. Morisaki and the LHD experiment group

*National Institute for Fusion Science, Toki 509-5292, Japan,*
*[1)] Department of Nuclear Engineering, Kyoto University, Kyoto 606-8501, Japan*

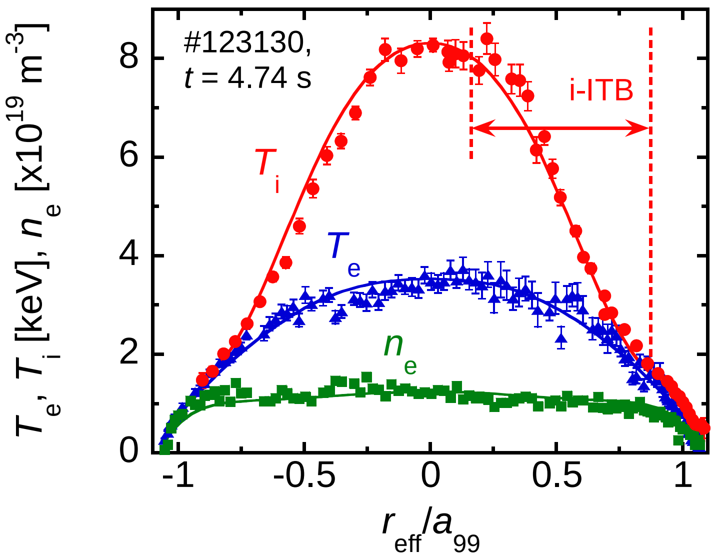
# Introduction

- In the future reactor, the fusion reaction is expected to be sustained under the electron heating, where both $T_i$ and $T_e$ are high.
- Thus the characterization of the thermal transport for the plasmas, of which $T_i$ and $T_e$ are simultaneously high, is necessary.
- In the LHD, the high temperature regime was decoupled because each condition was obtained in different heating condition.
- In recent years, an integration of high $T_i$ and high $T_e$ with the simultaneous formation of an ion ITB and an electron ITB has been successfully achieved in the LHD by the combination of NBI and ECRH.
- In the presentation, we show the

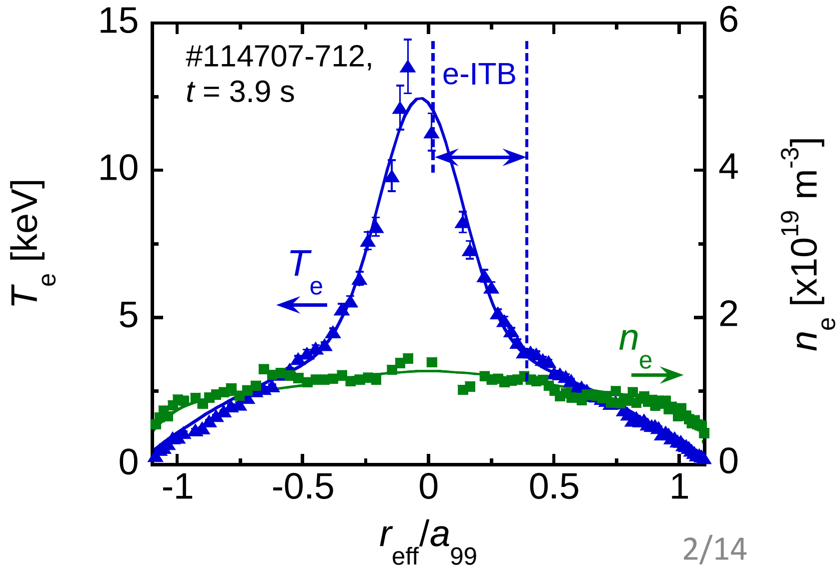
  (1) Characteristics of plasma with simultaneous high $T_i$ and high $T_e$,

  (2) Effect of the ECRH on the ion thermal transport.

**High $T_i$: i-ITB, NBI, $E_r < 0$**




**High $T_e$: e-ITB, ECRH, $E_r > 0$**

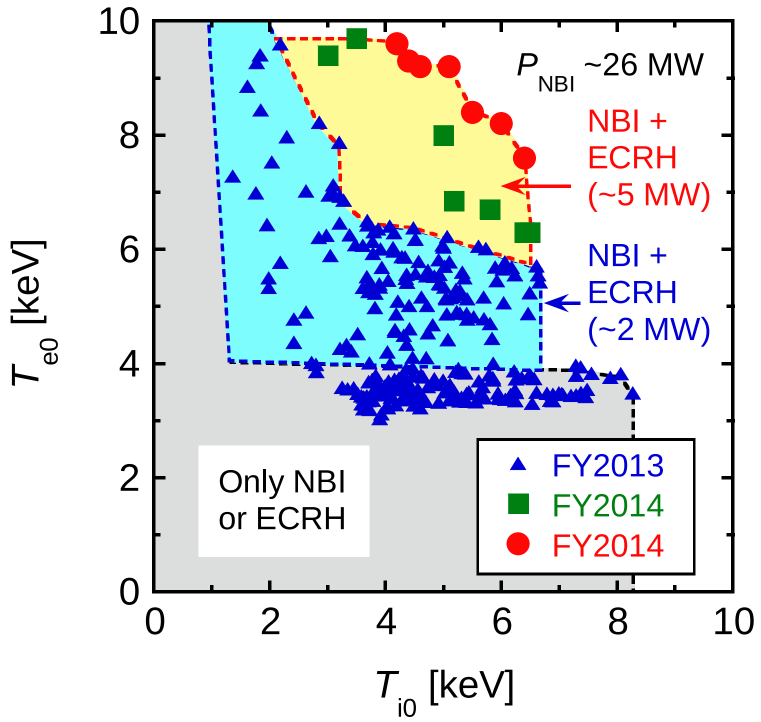


# Characteristics of plasma with simultaneous high $T_i$ and high $T_e$

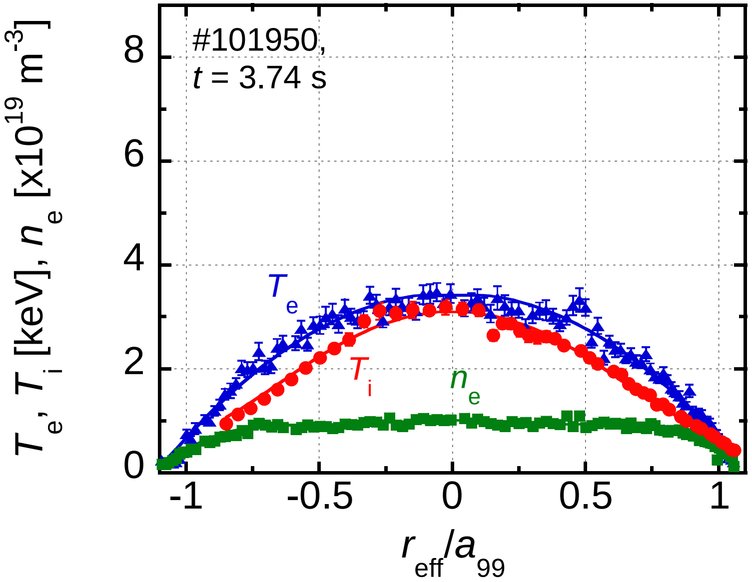
# Simultaneous achievement of high $T_i$ and high $T_e$

- In recent years, an integration of high $T_i$ and high $T_e$ has been tried on the LHD by NBI and ECRH mix.
- Although the i-ITB width became narrow by ECRH, the i-ITB maintained and e-ITB was formed

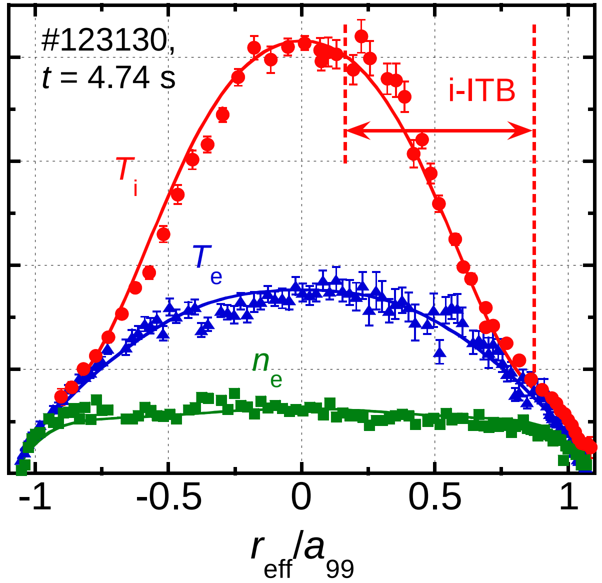
  -> **Simultaneous achievement of ITBs.**
- Operational regime in simultaneous high $T_i$ and high $T_e$ has been successfully extended.



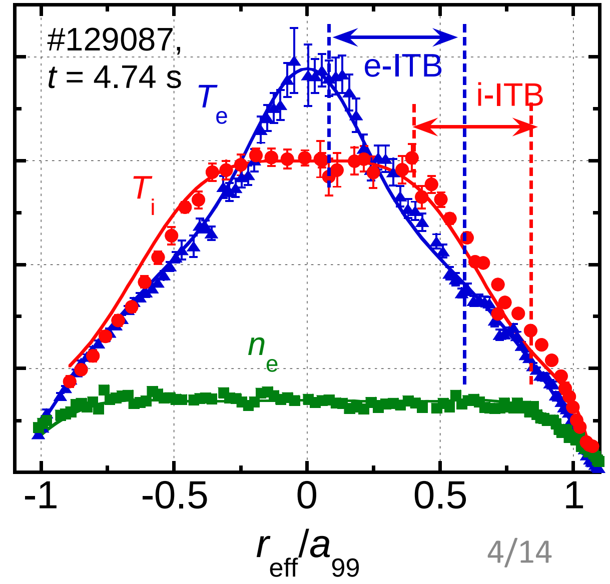

**No ITB (NBI: 28 MW)**




**Ion ITB (NBI: 26 MW)**




**Ion and Electron ITB (NBI 25 MW + ECH 5.1 MW)**



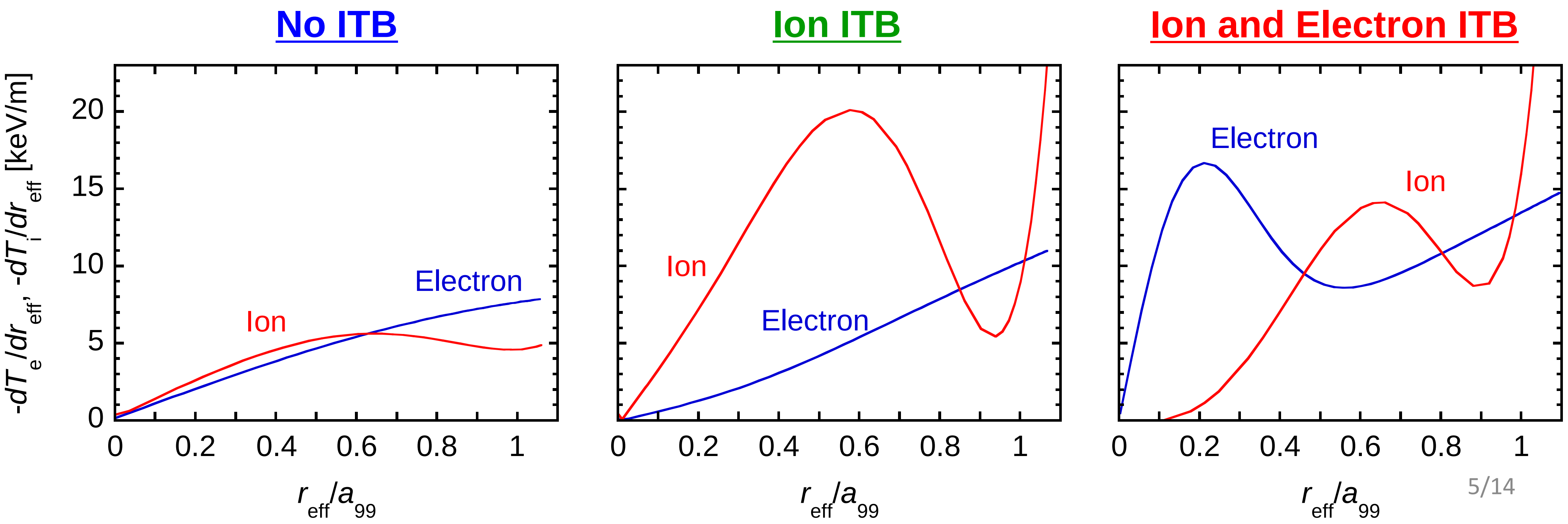
# Comparison of the temperature gradient profiles

## Ion ITB plasma (NBI alone)

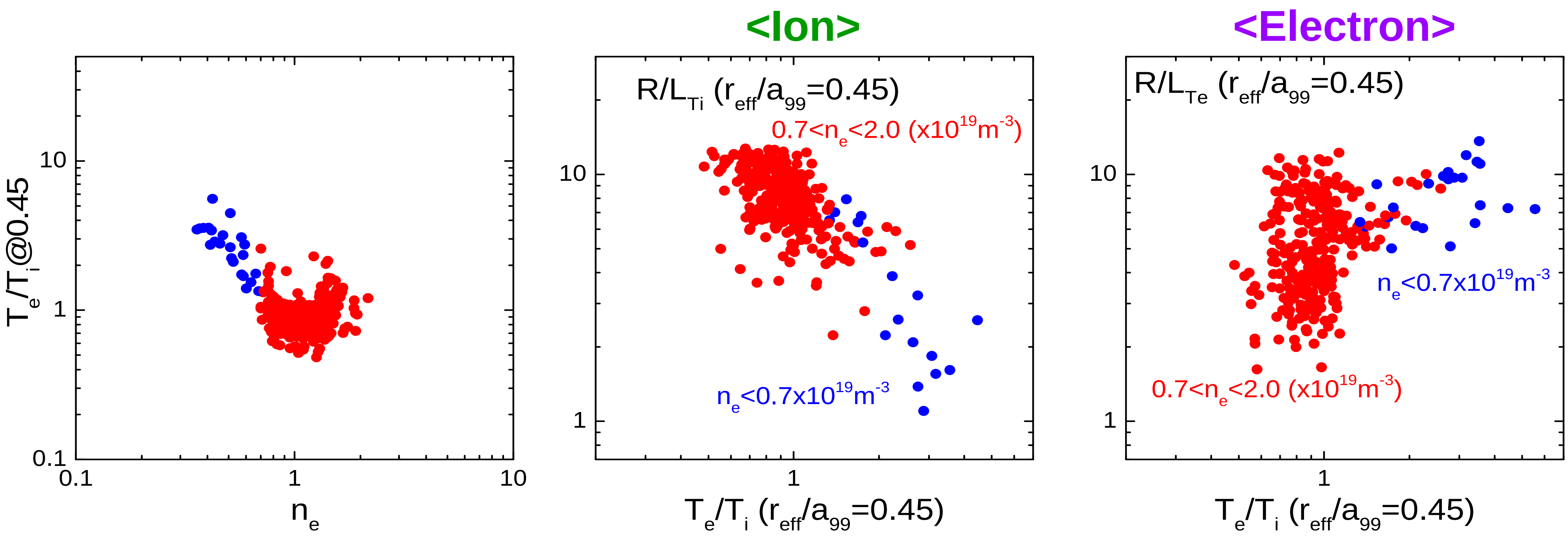
- The $dT_i/dr_{eff}$ increased not only in the core but also in the edge.

## Ion and Electron ITB (ECRH superposition on the NBI plasma)

- **Ion-ITB structure maintained** (slightly degraded).
- The $dT_i/dr_{eff}$ **degraded around the center** and **further improved in the edge**.
- **The $dT_e/dr_{eff}$ greatly increased in the core due to the e-ITB**.
- The ITB position is different between ion and electron.



# $T_e/T_i$ dependence of scale length of grad$T$




- $T_e/T_i$ rapidly increases in low $n_e$ regime due to the difference of thermal transport characteristics for ion and electron.
- Both $R/L_{Ti}$ and $R/L_{Te}$ were sensitive to $T_e/T_i$ but **the dependence was opposite**.

  **Ion**: $R/L_T$ improved **in lower $T_e/T_i$**,

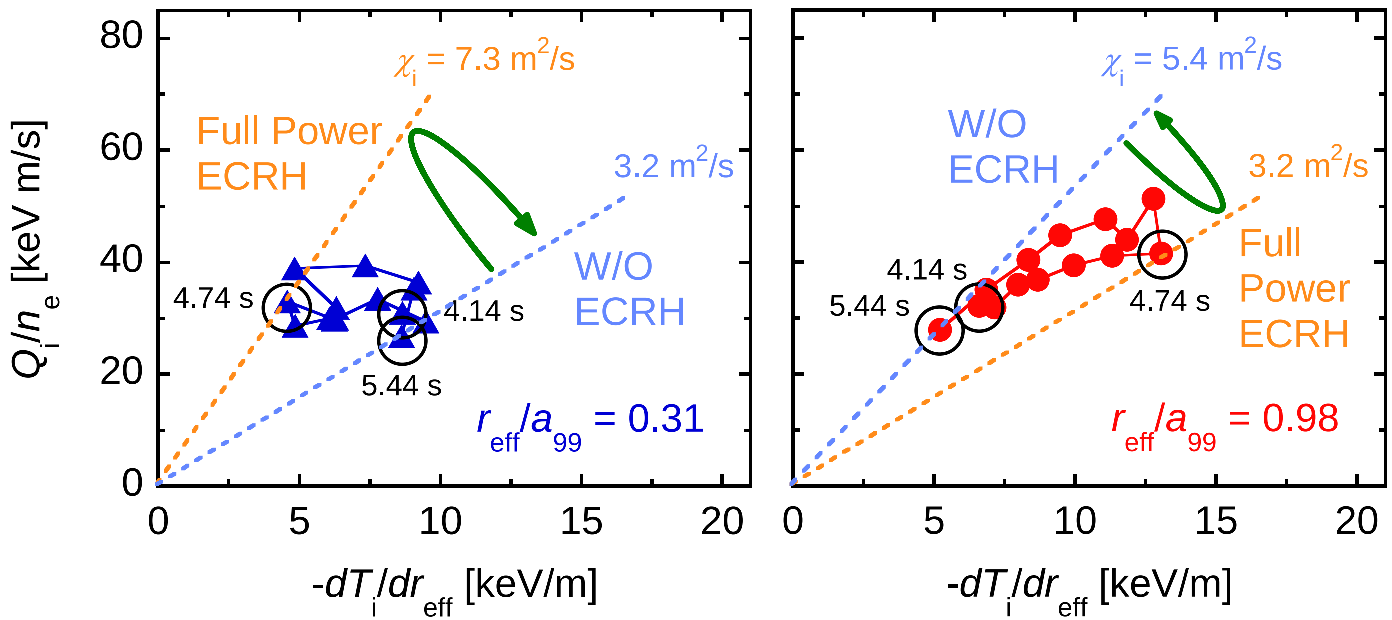
  **Electron**: $R/L_T$ improved **in higher $T_e/T_i$**.
- **The control and the optimization of $T_e/T_i$ is important to obtain the best performance of combined ITBs.**

# Effect of ECRH on the ion thermal confinement

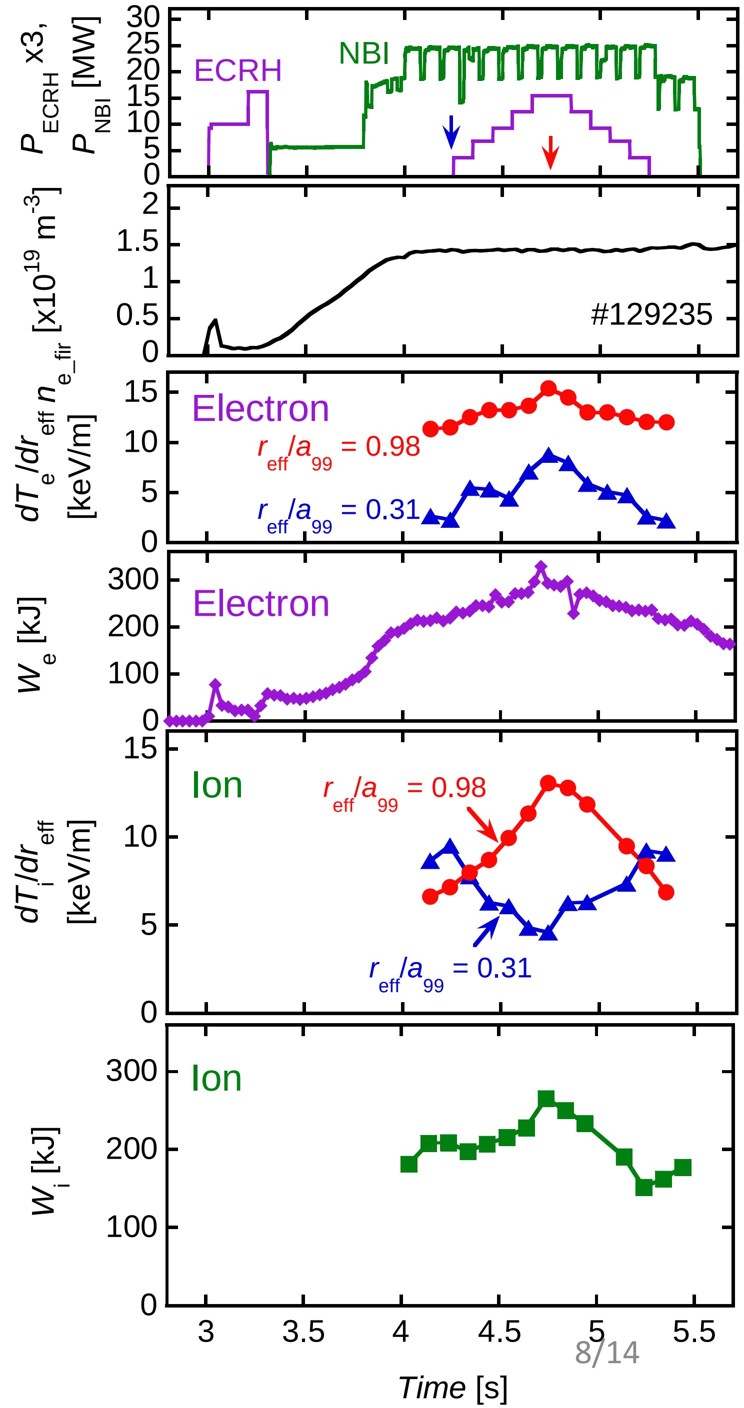
# Change in core and edge grad$T$

- The $dT_e/dr$ increased both core and edge.
- **Opposite dependence of the ion thermal confinement on the "on-axis" ECRH power between core and edge,**

  -> **Degraded at the "core"** and **improved at the "edge".**
- This is different phenomenon from a so-called transition because the thermal confinement monotonically changed with ECRH power, not non-linear.
- Not only $W_e$ but also ***W*<sub></sub>** $W_i$ **increased** due to the formation of the **pedestal-like structure** in the $T_i$ profile.




## On-axis ECRH superposition



# Lower $n_e$ case ($1 \times 10^{19}$ m$^{-3}$)

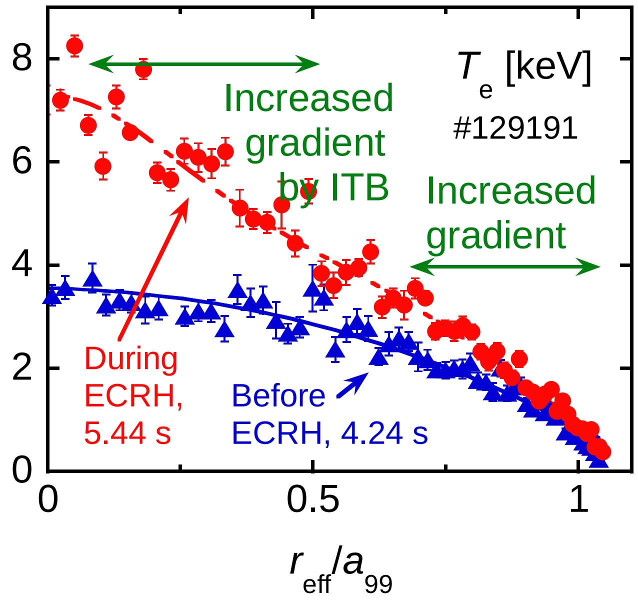
**Electron temperature**

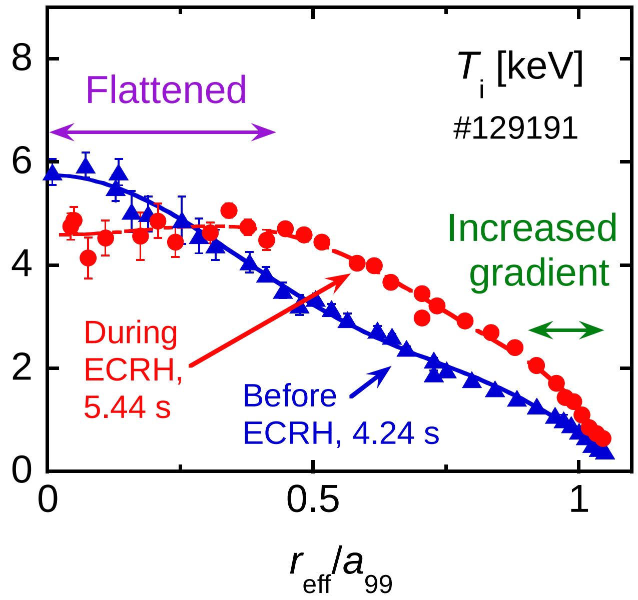
- **$T_e$ and the gradients increased in whole region, especially in the core due to the ITB.**

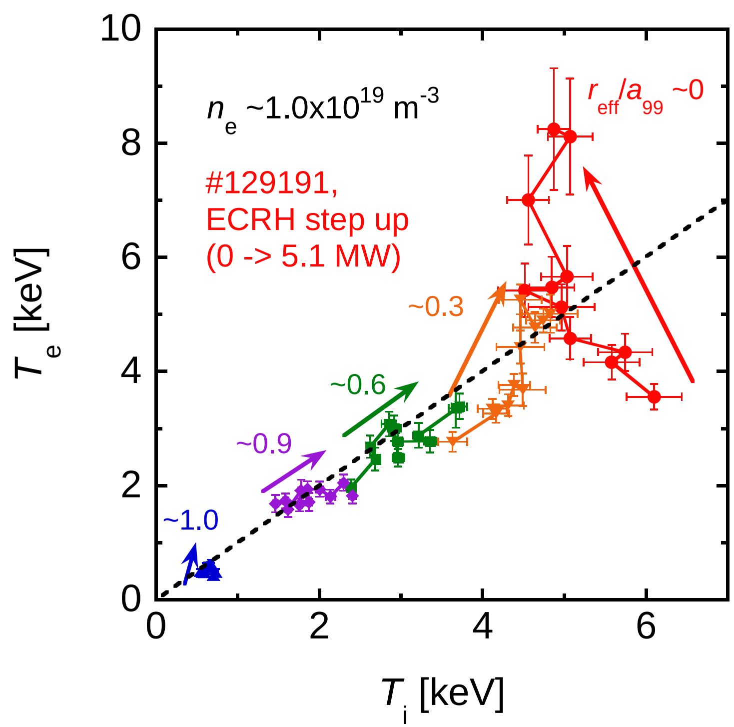
**Ion temperature**

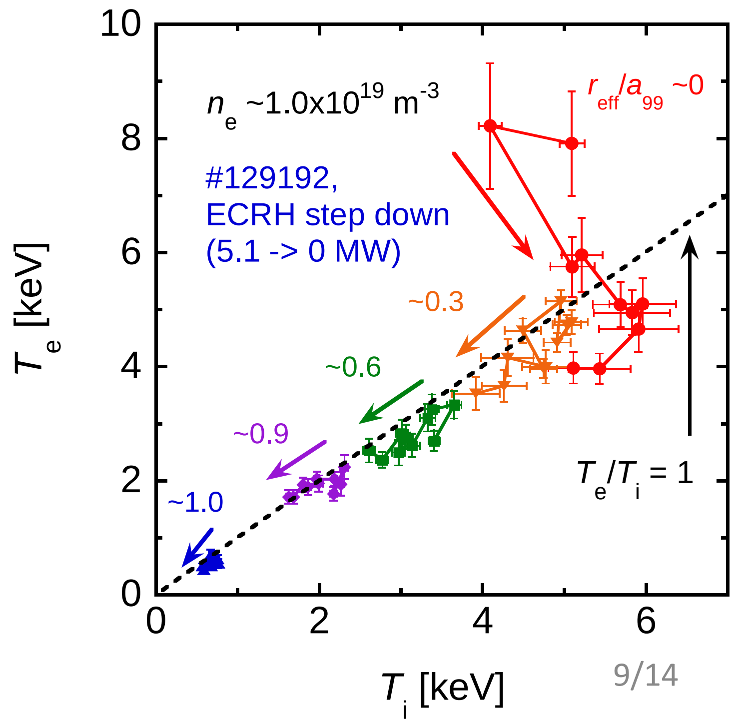
- In the central region, $T_e/T_i$ exceeded 1, then **both $T_i$ and its gradient degraded**, resulting in the **largely flattened $T_i$ profile.**
- The ***$dT_i/dr$* increased in the edge**, leading to the **$T_i$ increase in wide region** except for the center.

  -> Seesaw like mechanism.



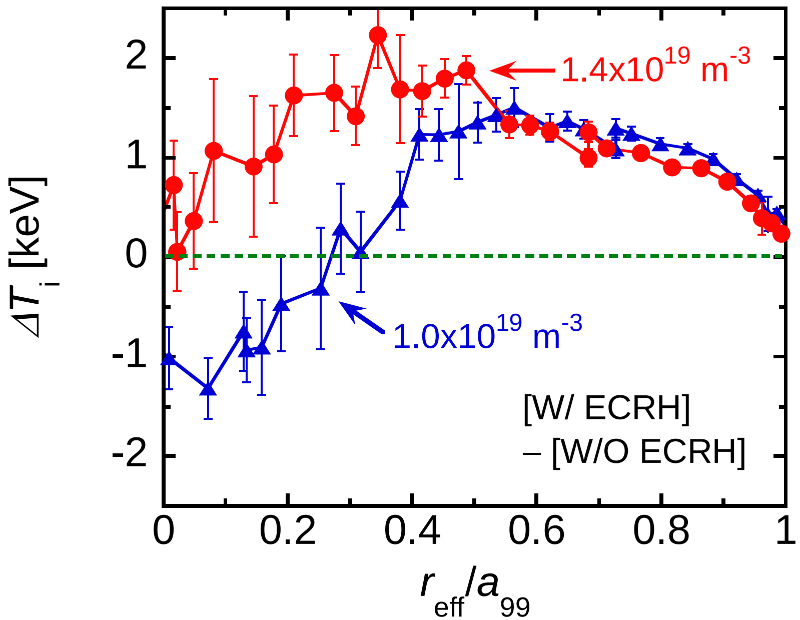



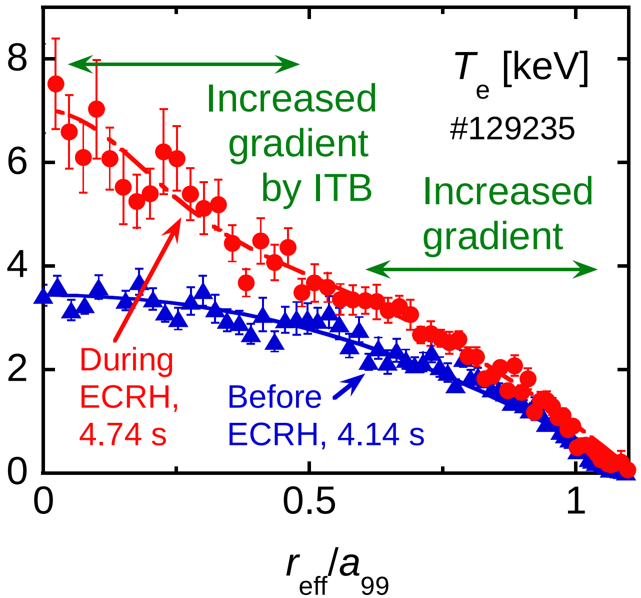
# Higher $n_e$ case ($1.4\text{x}10^{19}$ $m^{-3}$)

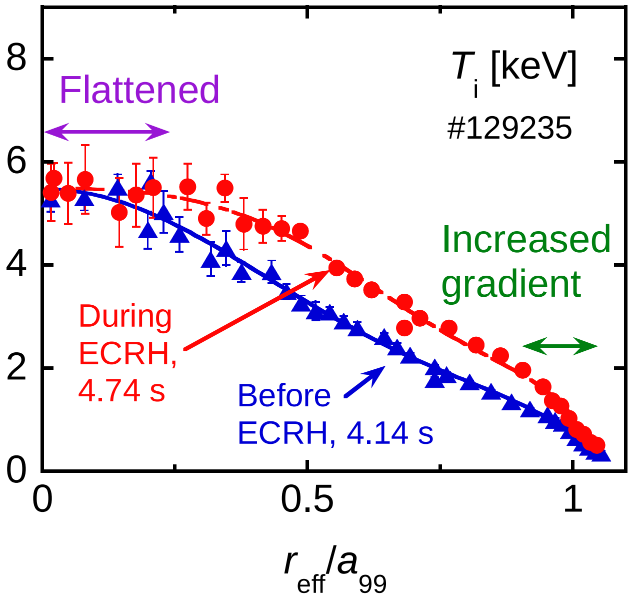
- Although the ***$dT_i/dr$* around the center degraded**, ***$T_i$* itself was not decreased** even $T_e/T_i$ exceeded 1 due to
  - (1) the improvement of peripheral $T_i$ gradient
  - (2) **the i-ITB maintained in more inward side** compared with lower $n_e$ by **decrease of the flattening area**.
- Core $T_i$ can be increased by on-axis ECRH in the situation:

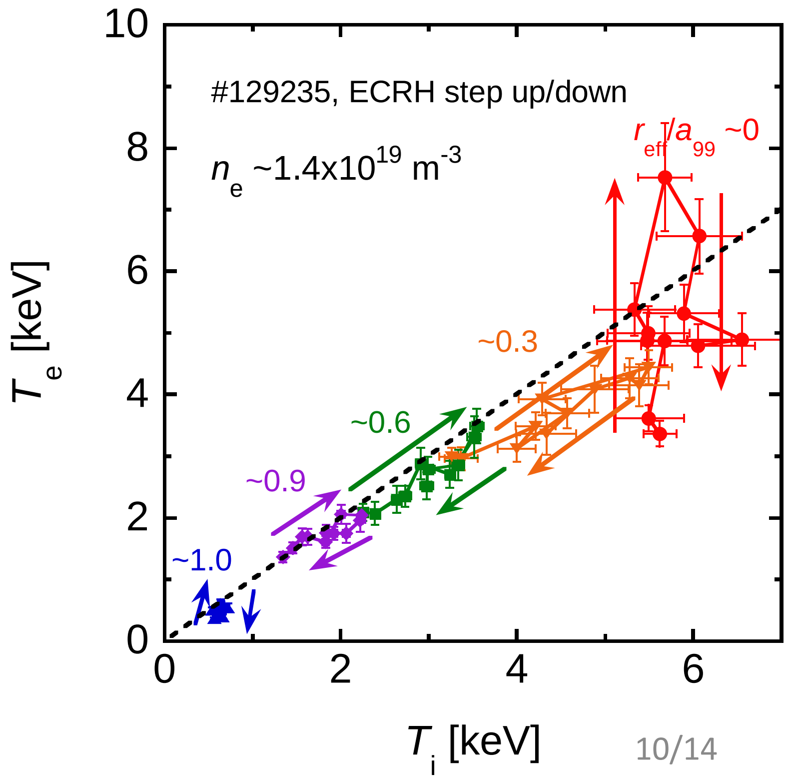
  **Improvement of edge *$T_i$*** > **Degradation of core *$T_i$***

- **This is possibly realized in high *$n_e$*** plasmas and is **attractive feature for a high *$T_i$* scenario for high *$n_e$* plasmas under electron heating dominant like DEMO**.



# Response of ion heat transport on ECRH

- $R/L_{Ti}$ **degraded in 56% (9 -> 4) at the core** but **improved in 50% (28 -> 42) at the edge**.
- $\chi_i$ **was small when the $T_e/T_i$ was small both at the core and the edge** even the dependence on $P_{ECRH}$ was opposite,

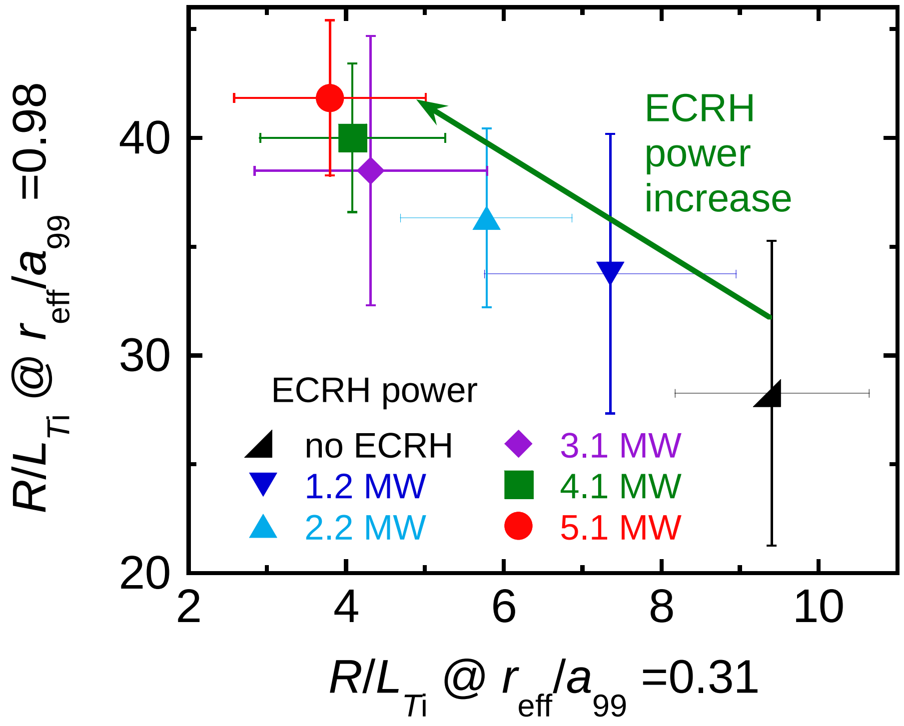
**Central region**: $T_e$ increased by ECRH

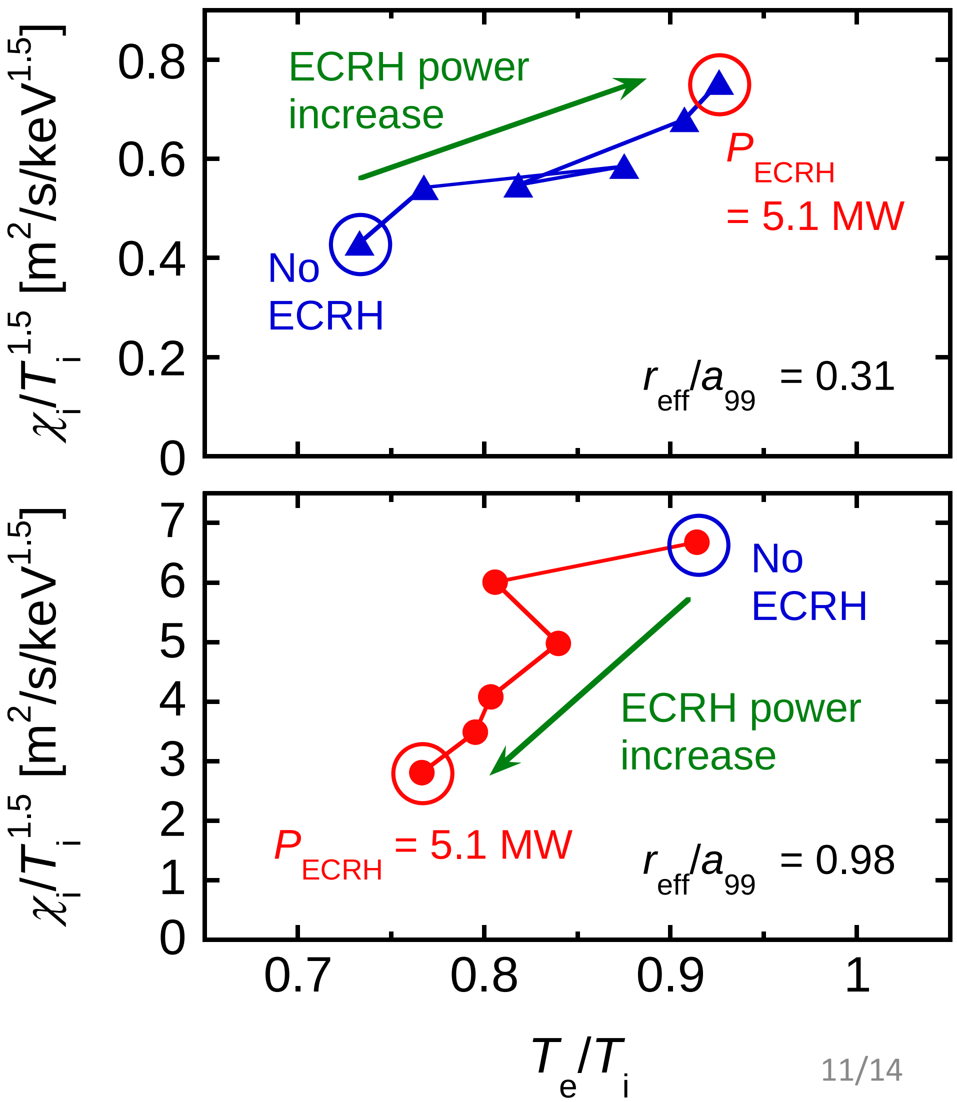
-> $T_e/T_i$ increased -> transport degraded

**Edge region**: $T_i$ increased by ECRH

-> Accordingly $T_e/T_i$ decreased

(<- **Why $T_i$ increased by ECRH?**)



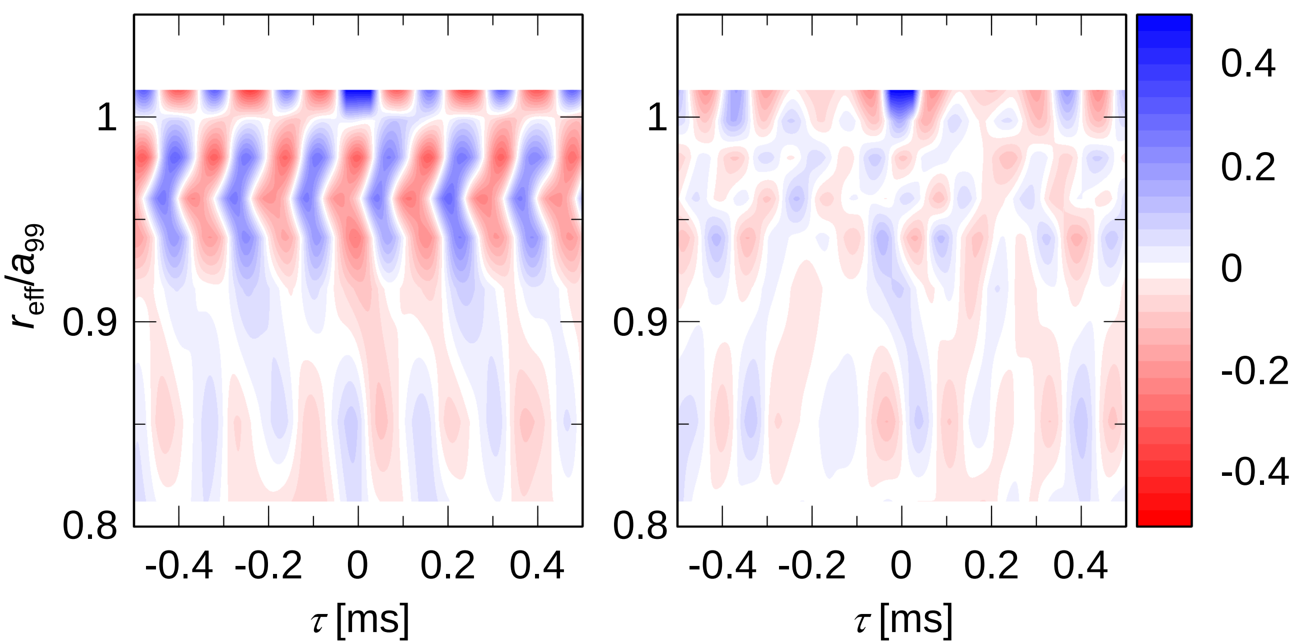
# Spatiotemporal structure of fluctuation

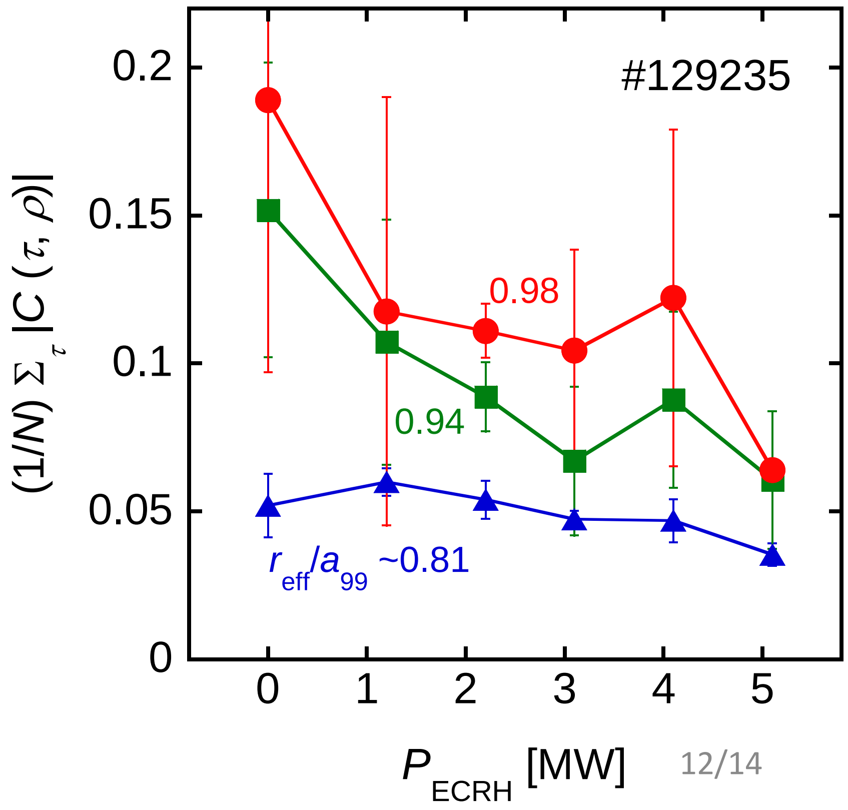
- The structure of the $n_e$ fluctuation at the edge was measured using mw-reflectometry.
- **The radial structure was segmentalized** by ECRH superposition.

  -> **The correlation length of the fluctuation decreased**.

- By increase of ECRH power, **the spatiotemporal coherence decreased** due to the change of the correlation length and the lifetime.

Cross correlation function (< 20 kHz)

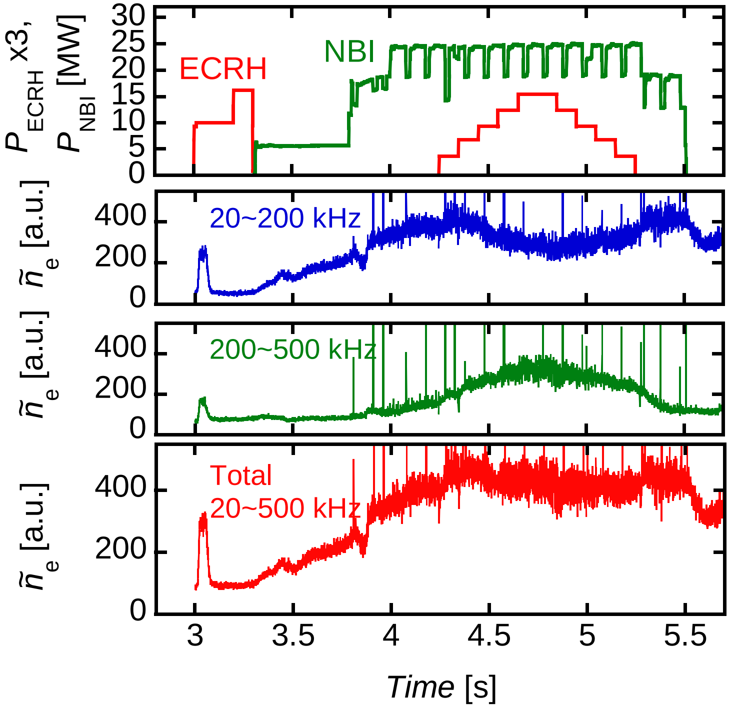


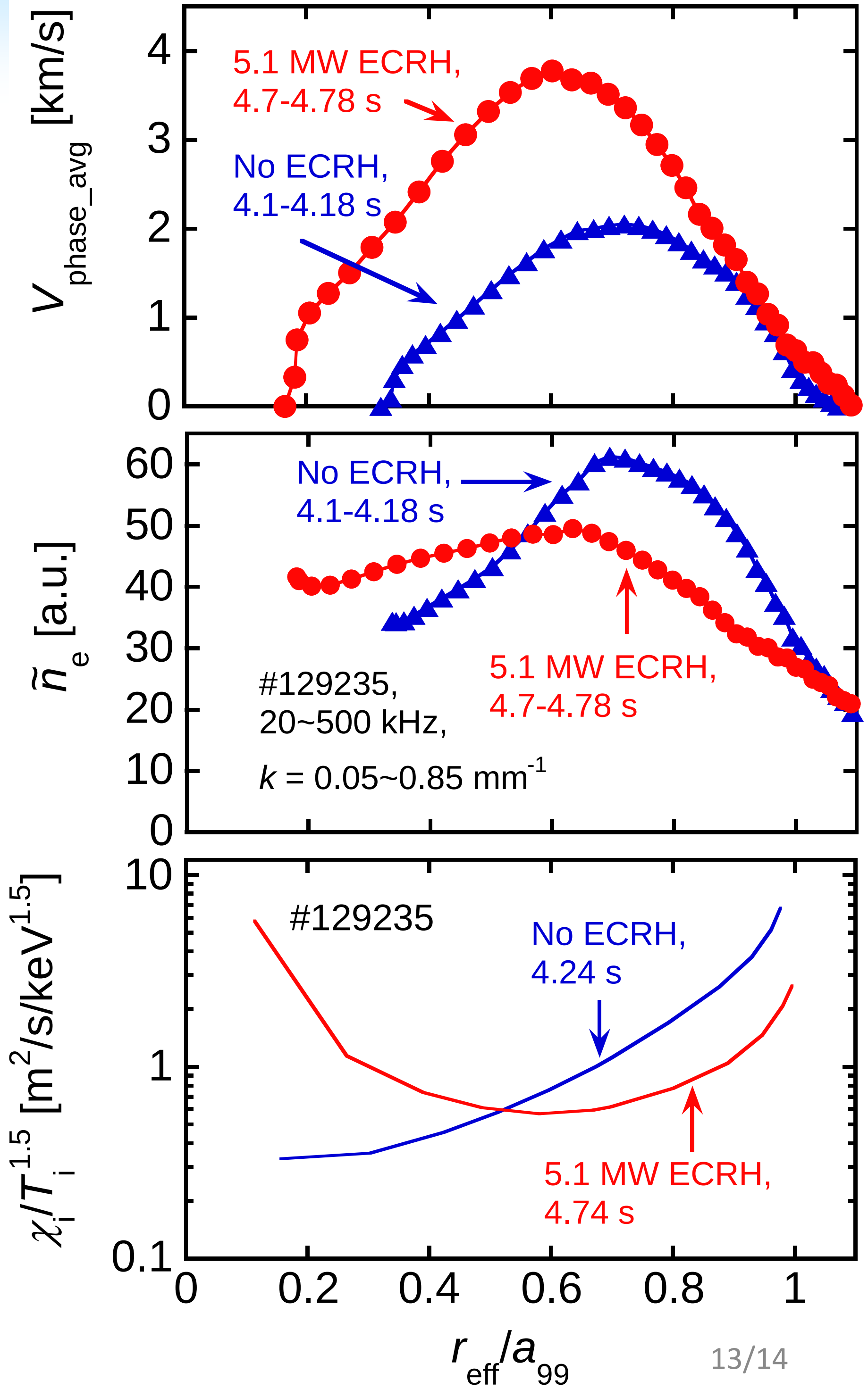



# Change in fluctuation amplitude

- PCI data showed **the decrease of $n_e$ fluctuation** with low frequency (< 200 kHz).
- The rotation in ion-dia. direction increased.
- **The change in the fluctuation amplitude coincidently correlated with the change in $\chi_i$.**

| Region | Fluctuation | $\chi_i$ |
|---|---|---|
| $r_{eff}/a_{99} < 0.5$ | **Increased** | **Degraded** |
| $r_{eff}/a_{99} > 0.5$ | **Decreased** | **Improved** |



# Summary

## Integration of high-$T_i$ and high $T_e$

- **An extension of high $T_i$ and high $T_e$ has been achieved** with the establishment of the **i-ITB and e-ITB simultaneously** by NBI and ECRH mix.

## Effect of ECRH on ion thermal confinement

- **Ion thermal confinement was found to be improved at the edge by "on-axis" ECRH** even **it degraded in plasma central region**.
- Core $T_i$ can be increased by on-axis ECRH **in high $n_e$** plasmas. The feature is **attractive for a high $T_i$ scenario with high $n_e$ under electron heating dominant such as DEMO**.
- **The fluctuation structure at the edge was segmentalized and the amplitude decreased**.

## Future prospect

- It has not been clarified **what agent modified the fluctuation, and improved the edge ion thermal confinement during "on-axis" ECRH**. The data accumulation is necessary.
  - Is the central ion thermal confinement improved or not by **"edge" ECRH**?
  - **Fluctuation measurement at the plasma center** (HIBP, etc...).

# Radial electric field in ITB plasmas

$E_r$ in core was measured using HIBP,

| Plasma | Heating | Core $E_r$ |
|---|---|---|
| L mode | NBI | **~0** |
| i ITB | NBI | **Negative** |
| e- & i-ITB | NBI + ECRH | **Positive** |

- Ion thermal transport was improved **both in the presence of positive and negative $E_r$**.
- **The effect on the ion thermal transport due to the difference of the $E_r$ polarity has not been clarified.**