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Performance Integration of High Temperature Plasmas in the LHD deuterium operation

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Introduction

Introduction

- In the LHD, the D experiment was initiated in March 2017.

  -> (1) Higher performance plasmas, (2) Isotope effect, (3) High energy ion.

- **Important goal:**

  -> **Demonstrate the scientific feasibility of helical-system rector;**

  - **Optimizing plasma performance**,
  - **Development of operation scenario**,
  - **Comprehensive understanding of physics**.

- The presentation shows the recent LHD results of the high-performance plasma experiments;

  (1) **The performance integration and the optimization of high temperature plasmas.**

  -> High T_i and high T_e, e-ITB with detachment, SSO of e-ITB.

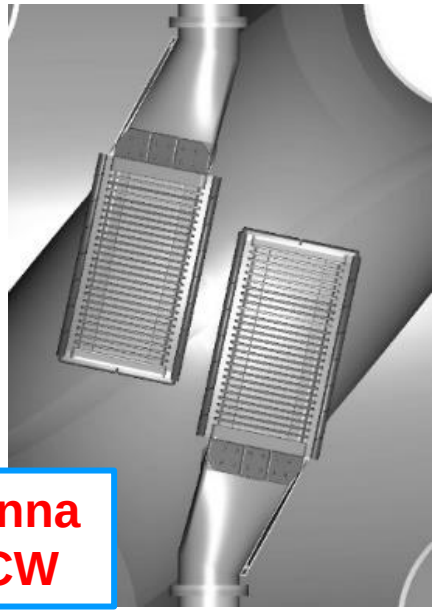
  (2) **Thermal confinement of plasmas, of which T_i and T_e are simultaneously high.**

Heating system for the exps. (~Oct 2020)

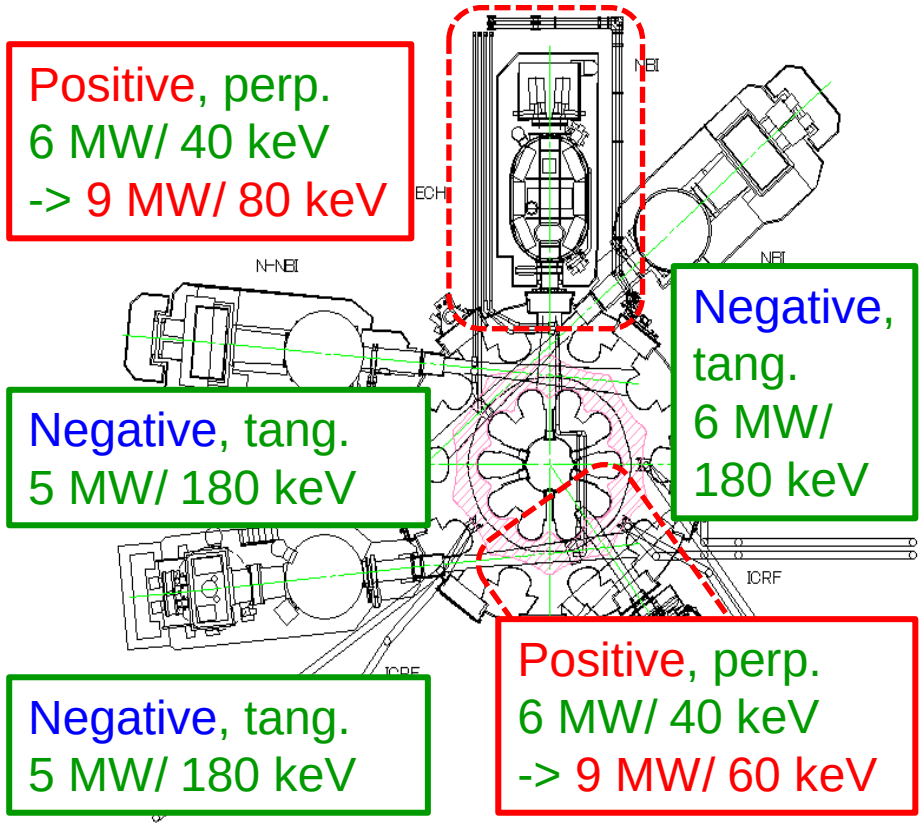
- ECRH: **Gyrotron x5** (**Over 1 MW** each) from 2014
- ICH: 1 pair of straps (**0.8 MW/CW each**, ~38 MHz)
- NBI: Neg. x3 (16 MW/ 180 keV (H)),
  Pos. x2 (**12 MW/ 40 keV (H)**) -> **18 MW/ (60) 80 keV (D)**

Total power;

ECRH: **5.4 MW**, ICH: **1.6 MW**, NBI: **34 MW (D)**



ICH antenna
0.8 MW/CW



Positive, perp.
6 MW/ 40 keV
-> 9 MW/ 80 keV

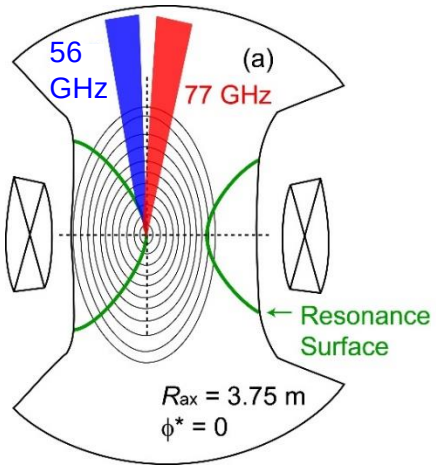
Negative, tang.
5 MW/ 180 keV

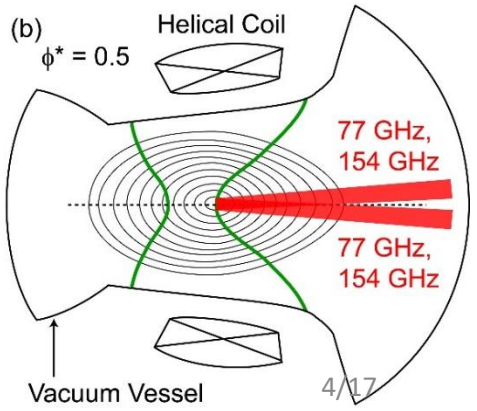
Negative, tang.
6 MW/
180 keV

Negative, tang.
5 MW/ 180 keV

Positive, perp.
6 MW/ 40 keV
-> 9 MW/ 60 keV

77 GHz x3, 154 GHz ECRH x2
: Over 1 MW for high B_t exp.
56 GHz x1
: 400 kW for high β exp.

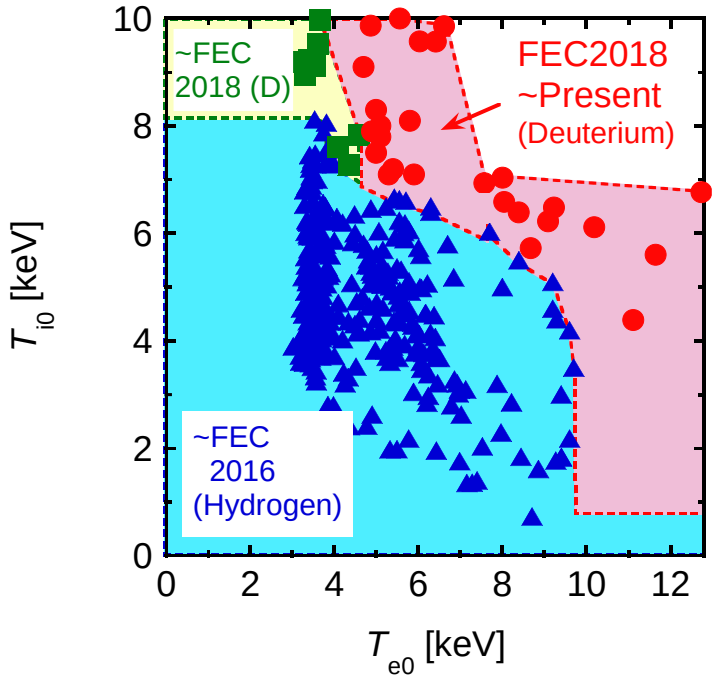


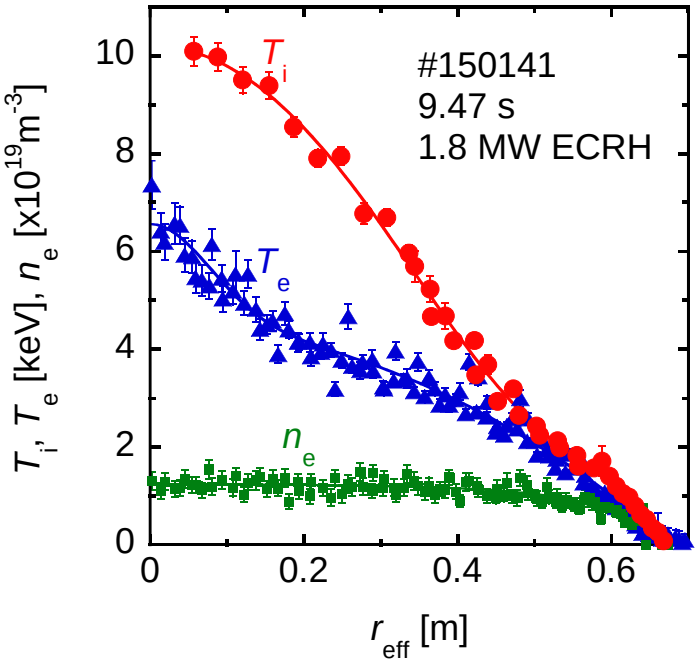


Performance integration and optimization of high temperature plasmas

High T regime was successfully extended

- The fusion reaction by α particle, both the T_i and the T_e are high.
  -> The turbulent is **strongly affected by the T_e/T_i** but **is unclear**.
  - **Realize a plasma both with high T_i and high T_e,**
  - **Clarify its ion thermal confinement characteristics**.
- Optimized plasma operation using **NBI & ECRH mix** to
  (1) suppress MHD, (2) avoid T_i degradation in ECRH superposition.
  -> **The high T regime was successfully extended**.





Electron ITB with radiative divertor

In the future reactor,

- ✓ **A steady state sustainment** of
- ✓ **Improved confinement plasmas** with
- ✓ **Lower diverter heat load**.

➢ We attempted the electron ITB formation with the reduced divertor heat load.

e-ITB formation,

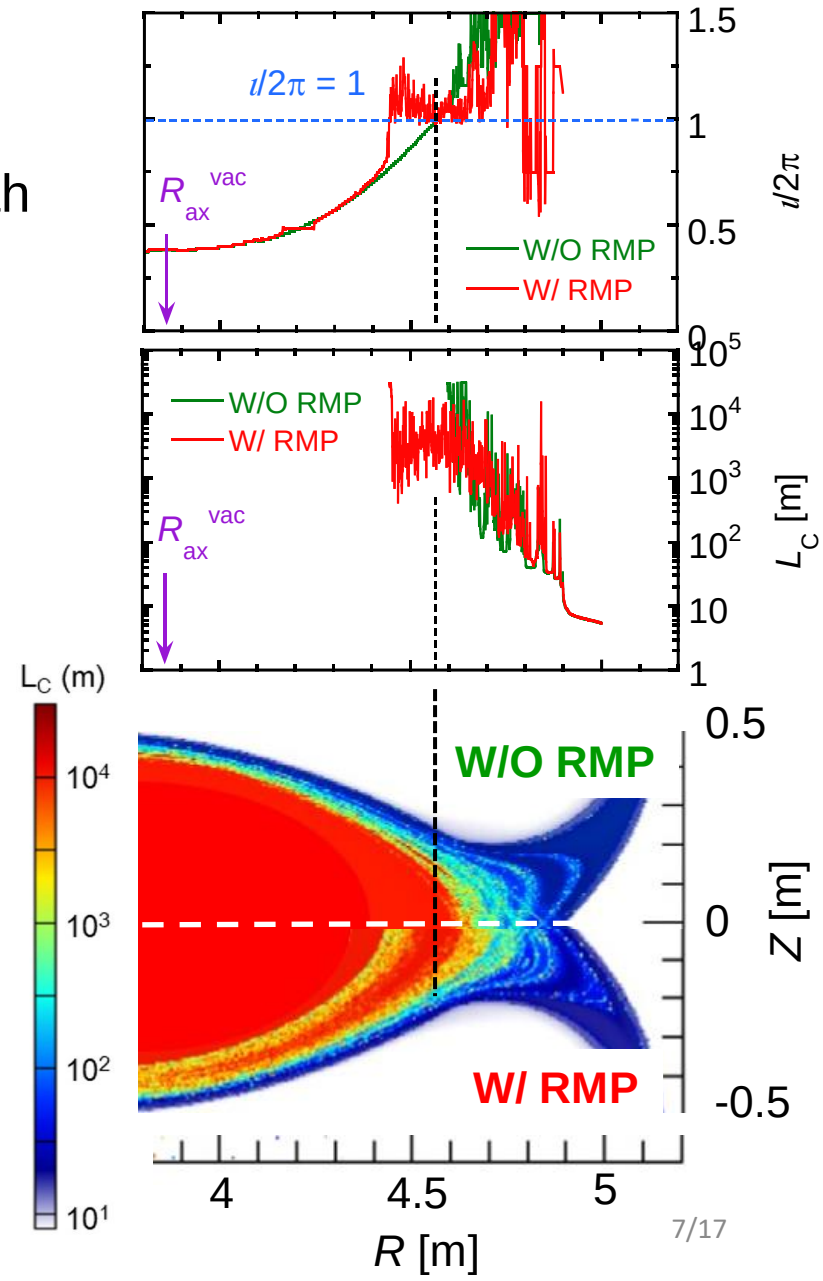
-> **High power ECRH to plasma core.**

Radiative divertor,

- ✓ **Ne feeding to increase the radiation.**
- ✓ **RMP to expand the edge low *T* area.**

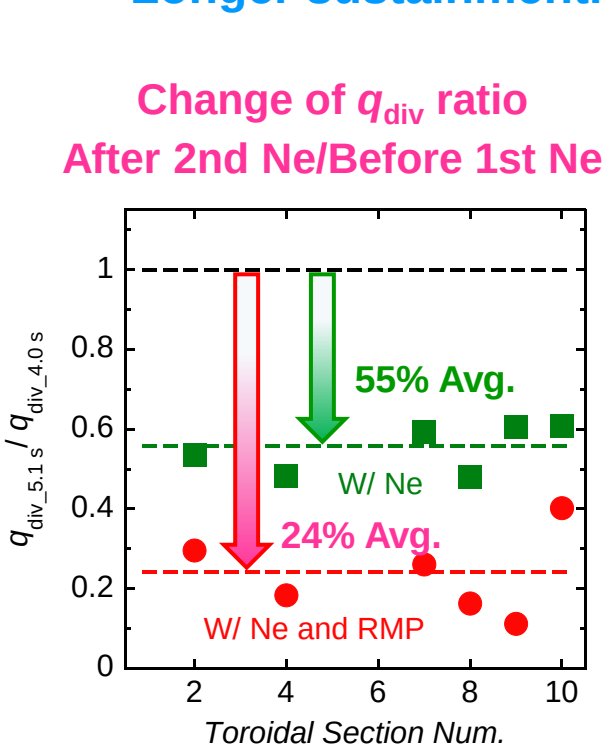
Performance integration

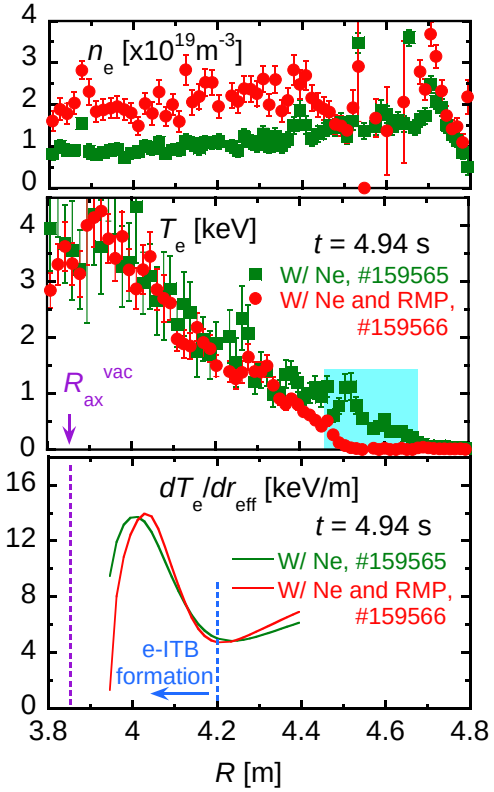
SSO | **Confinement improvement** | **Low heat load**

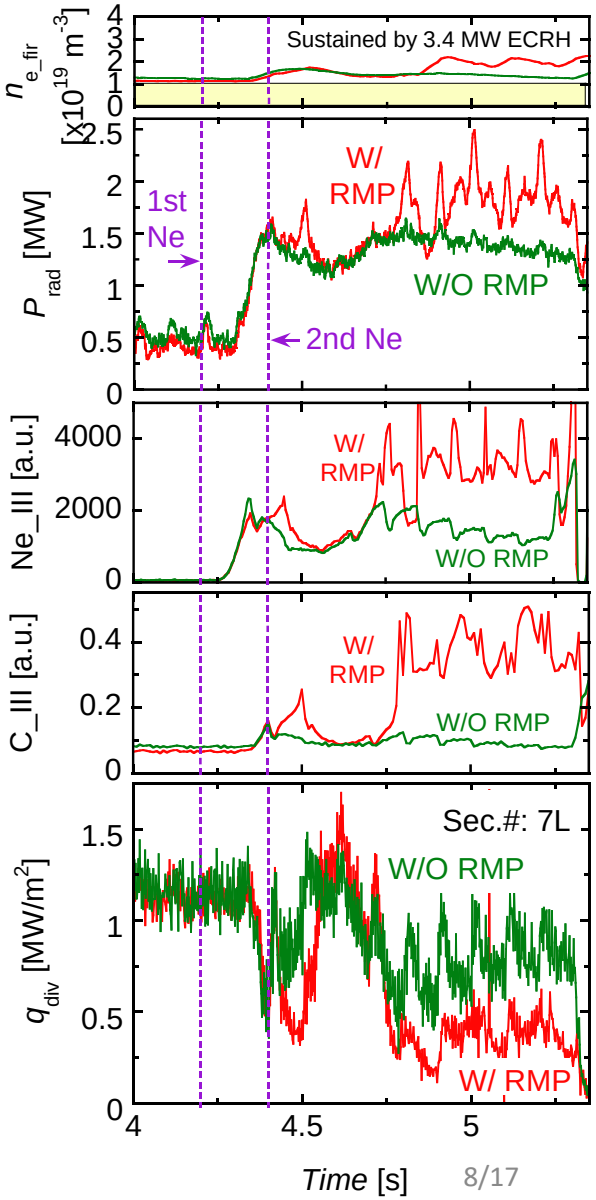


Electron ITB with radiative divertor

- Low T_e area expanded due to the RMP (m/n = 1/1),
  - (1) **P_{rad}: Increased by a factor of 4,**
  - (2) **Low valence Ne and C intensity increased,**
  - (3) **q_{div}: Reduced to 24%,**
  - (4) **e-ITB maintained even after Ne injection.**
    - ✓ **Optimization of configuration and the impurity.**
    - ✓ **Longer sustainment.**







Steady state operation of e-ITB

Performance integration

SSO | **Confinement improvement** | **Low heat load**

Higher performance in D operation

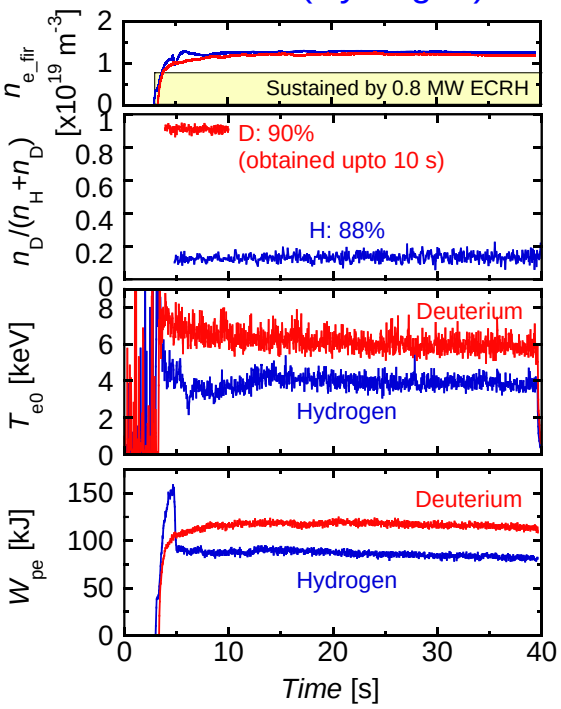
- Higher T_{e0} was obtained in D plasma with same ECH.
- T_{e0} ~6 keV could be steadily sustained for 35 s in D.
  - **SSO** of **e-ITB.**
  - **Higher T_e in D plasma.**

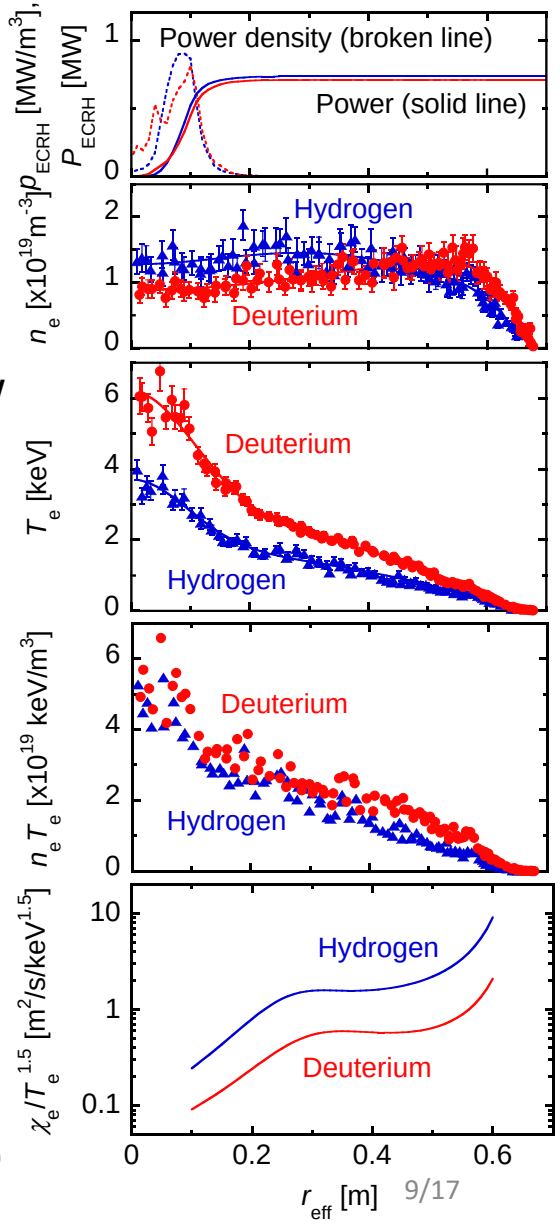
✓ **Lower divertor heat load will be combined.**

R_{ax} = 3.6 m, B_t = 2.75 T, CW

#154989 (Deuterium),

#159629 (Hydrogen)





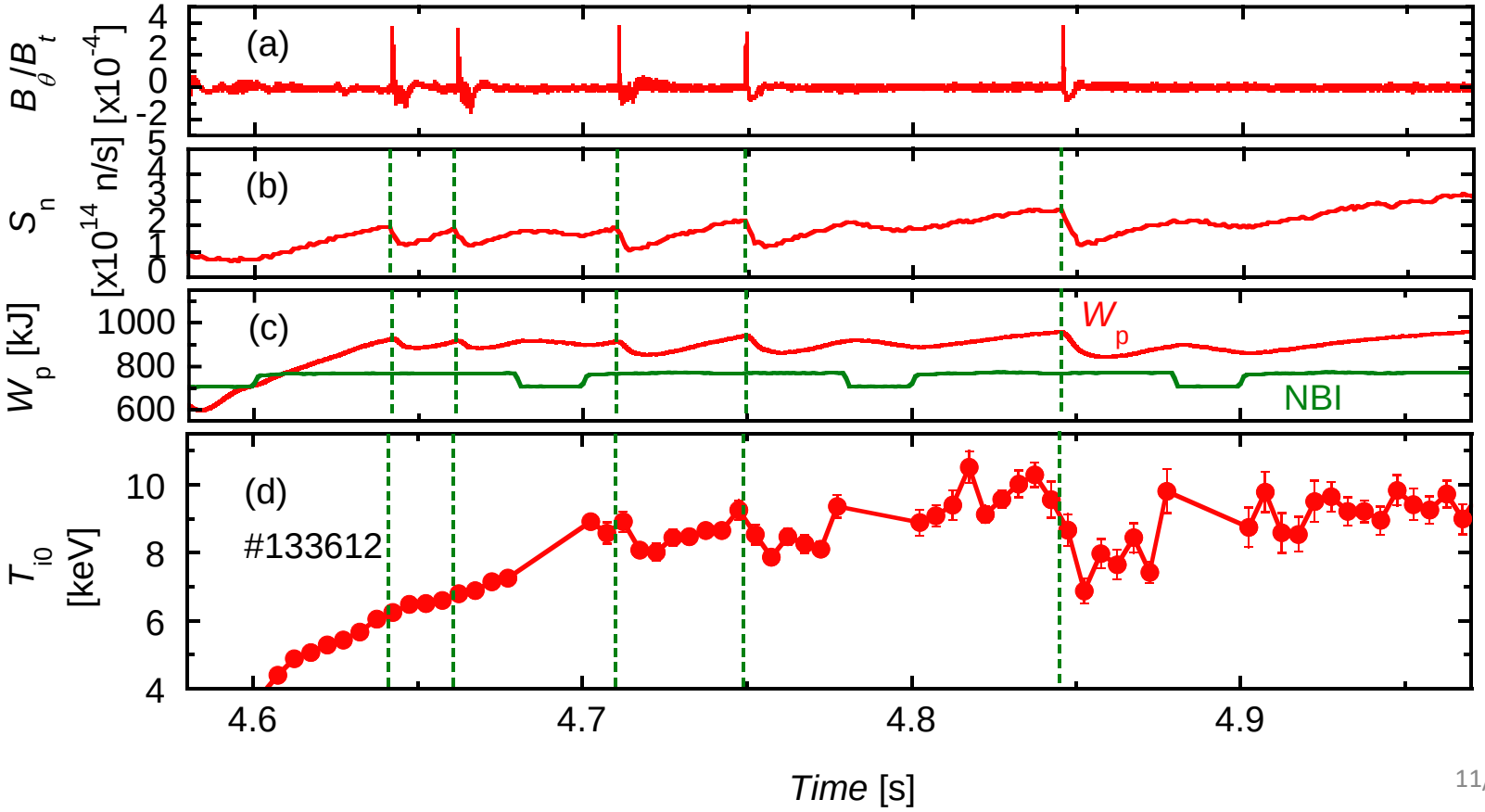
Thermal confinement of plasmas, of which T_i and T_e are simultaneously high

MHD event Limiting T_i increase

- In high T_i plasma, **Trapped Energetic Ions Driven Resistive Interchange Modes (EIC)** is frequently excited both for H and D experiment.
- The EIC accompanies the bursty loss of the high energy ions as shown in S_n.

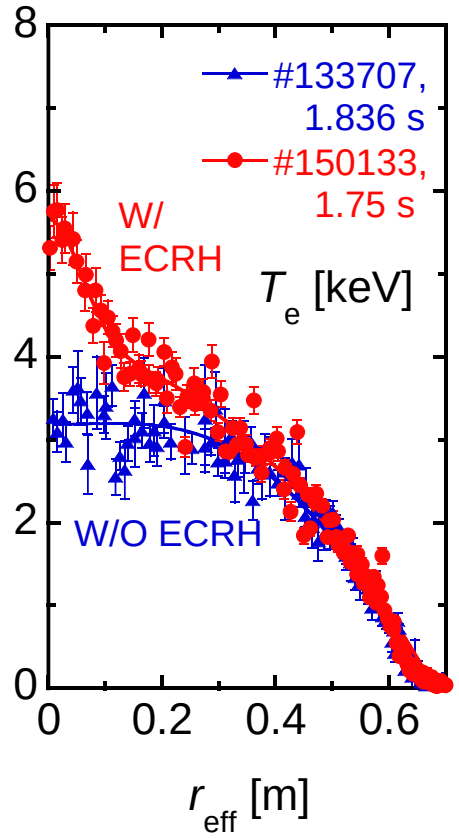
  -> Decrease in W_p and T_i.

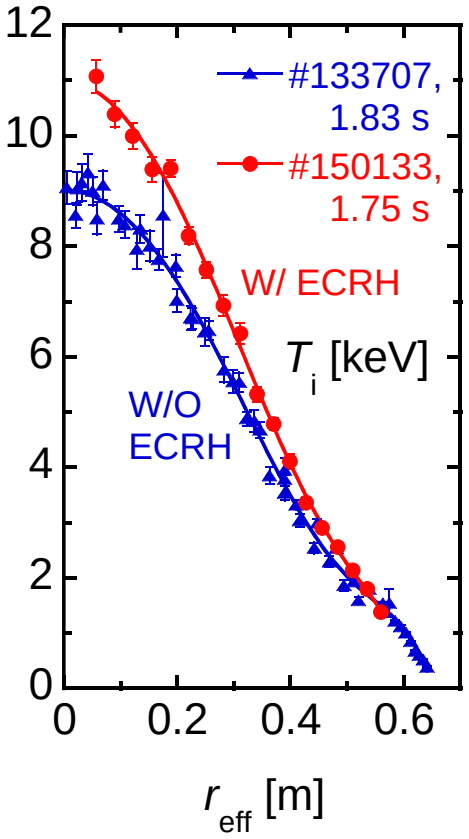
  -> The EIC should be suppressed for higher T_i and the steady sustainment.

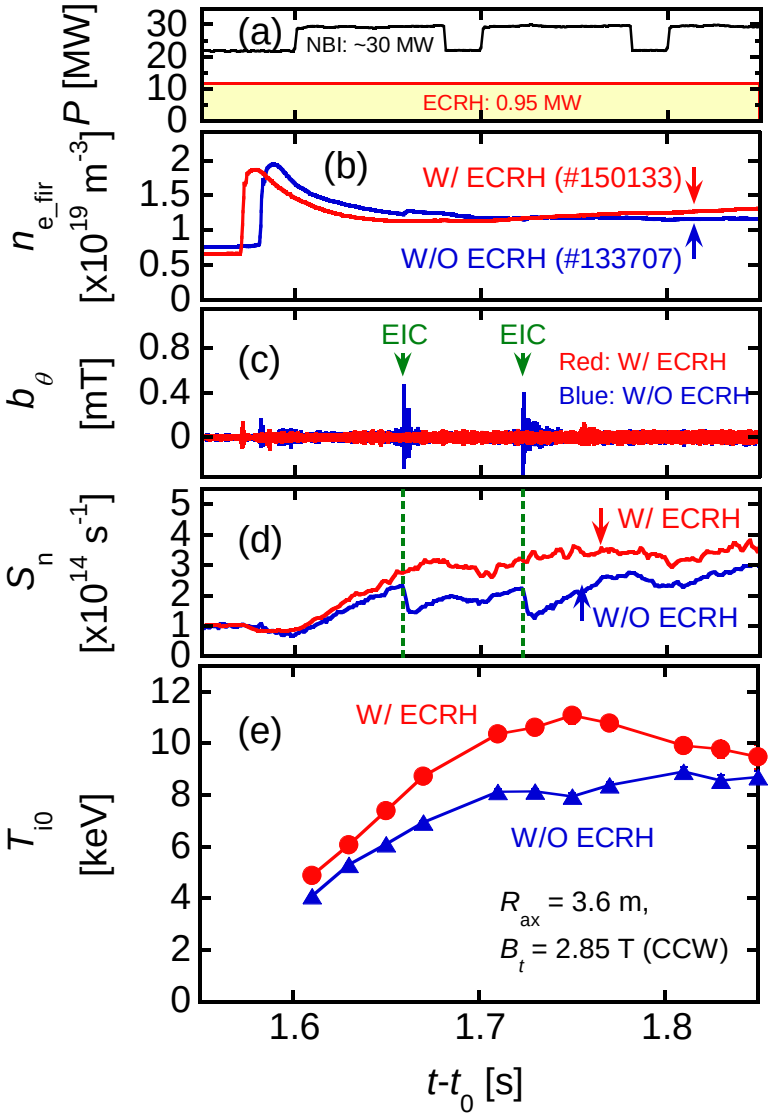


Higher T_i was successfully achieved

- The mode width of RIC coupled with helical trapped ions ~$T_e^{-1/2}$ $(\beta' L_{pe})^{1/6}$.
  -> **Decrease of mode width by T_e increase**
- Low power ECRH (~1 MW) was superposed.
  -> **EIC was suppressed.**
- **Higher T_{i0} with higher T_{e0}.**







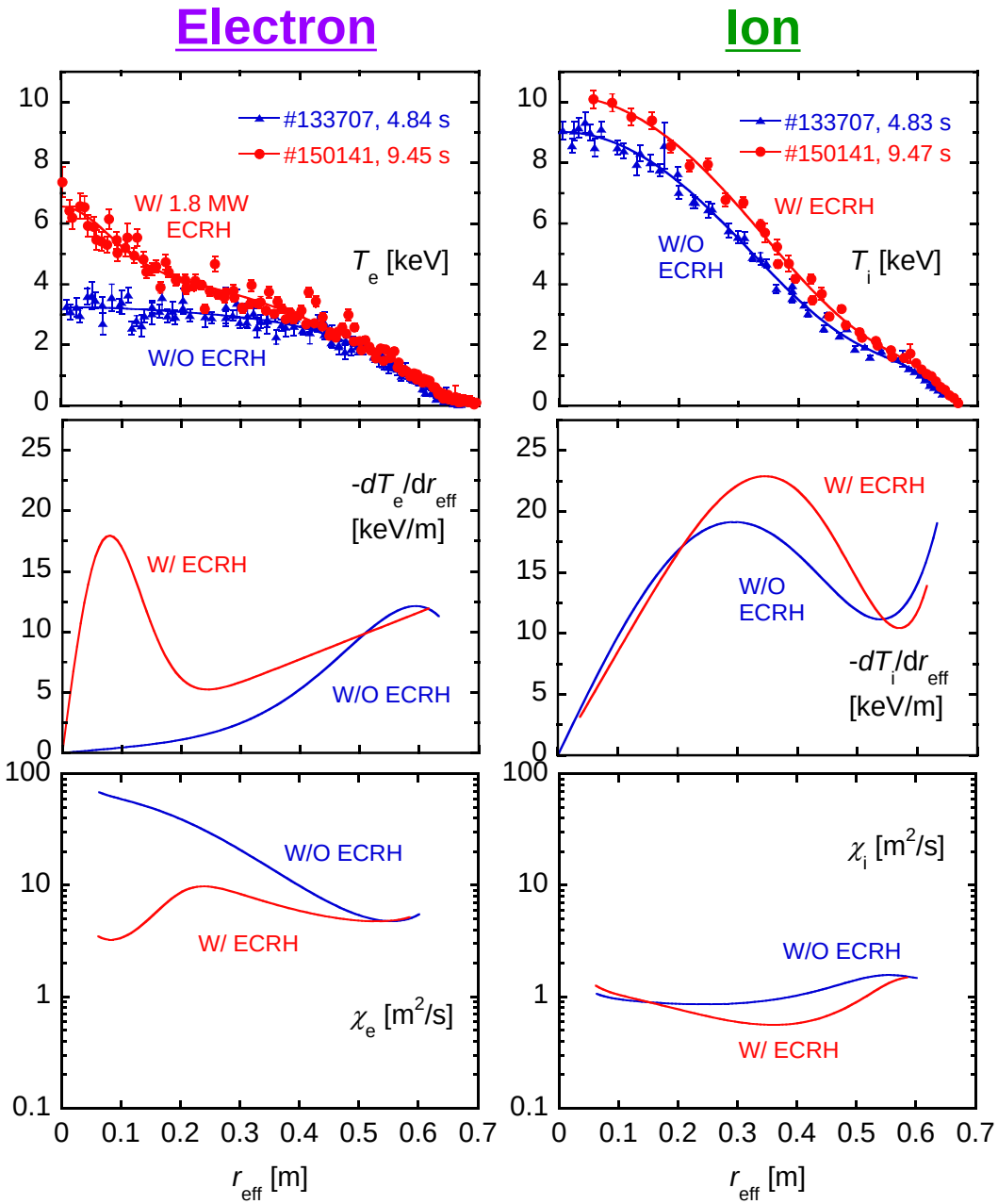
χ_e reduced W/O χ_i increase

Electron

- The dT_e/dr_{eff} increased, **especially in r_{eff} < 0.2 m due to the e-ITB formation.**
- **The χ_e widely decreased, especially in the ITB region**.

Ion

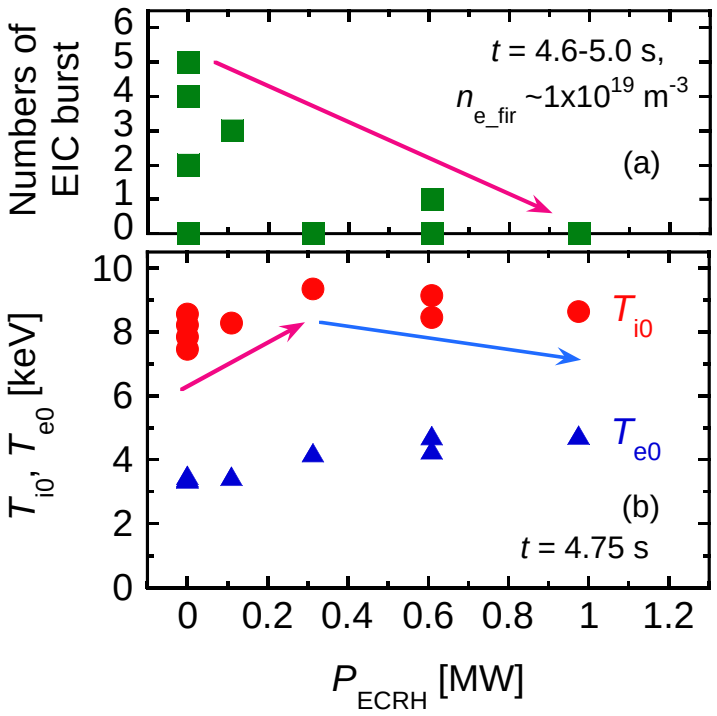
- Although **the dT_i/dr_{eff} slightly decreased around the plasma center**, **the dT_i/dr_{eff} increased around the half radius**.
- The χ_i reflected the tendency of dT_i/dr_{eff}. **the χ_i decreased** except for the plasma center.



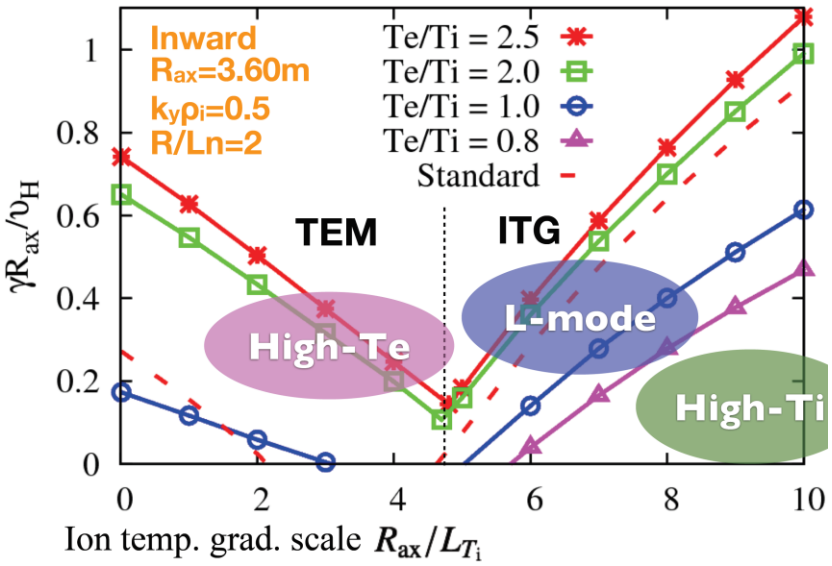
T_i degradation by T_e increase

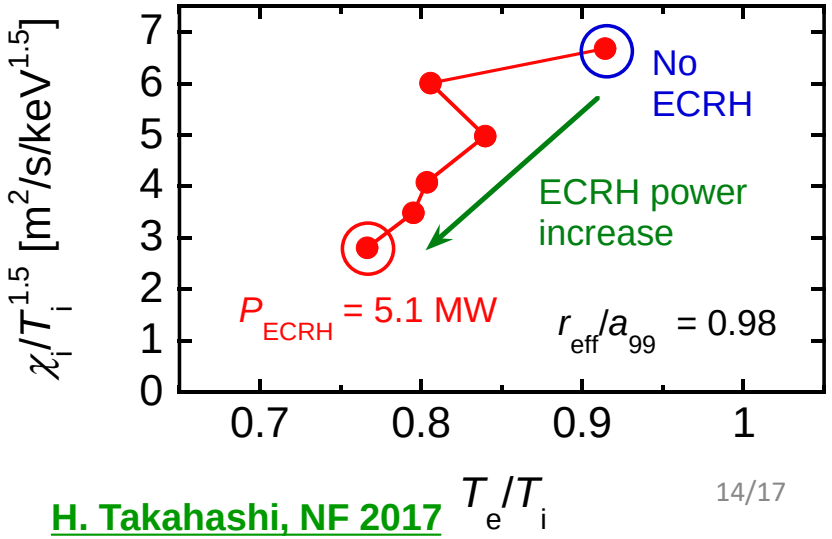
- **ECRH is effective for EIC suppression,**
  - **-> Core T_i decreased** with P_{ECRH} increase.
- **ITG destabilization due to T_e/T_i increase.**
  - **-> Increase of χ_i.**
- For simultaneous high T_i and T_e
  - (1) **EIC suppression,**
  - (2) **T_e/T_i control in moderate range.**

Effect of ECRH on high T_i



Linear growth rate of ITG/TEM





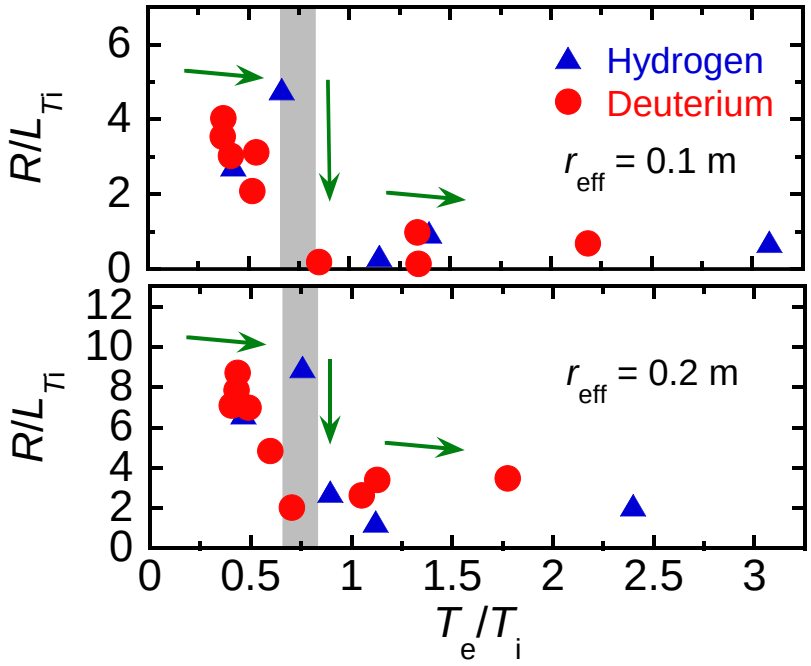
M. Nakata, PPCF 2016

H. Takahashi, NF 2017

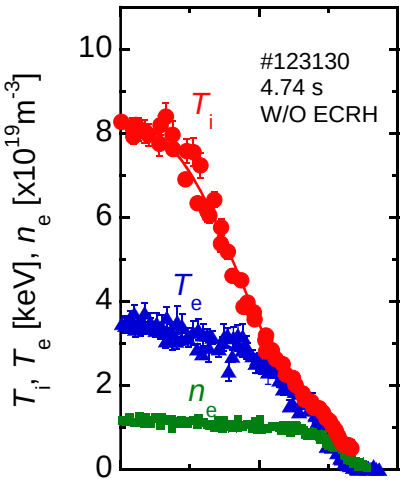
T_i flattening in higher T_e/T_i

On-axis ECRH was applied on high T_i plasmas (~8 keV)

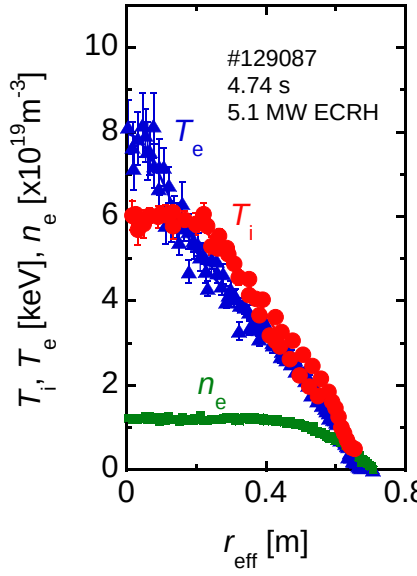
- T_{e0} became ~8 keV due to the ECRH,
  -> **T_i gradient decreased (flattened)**,
- **R/L_{Ti} drastically decreased in high T_e/T_i**,
  -> **Keeping lower T_e/T_i is important to maintain peaked T_i profile.**



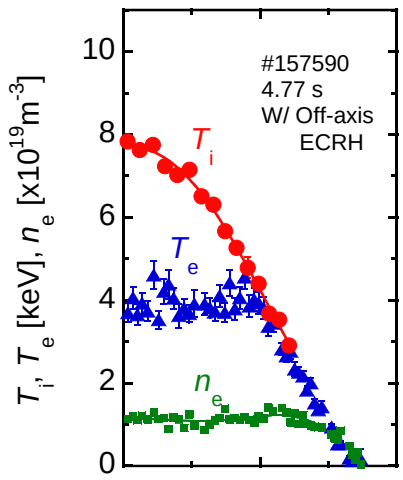
H exp.



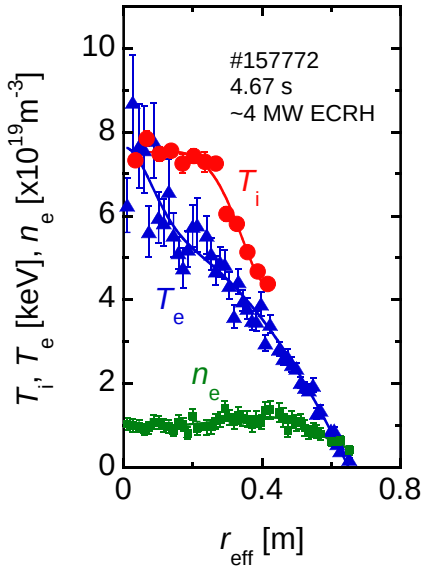
On-axis ECRH



D exp.



On-axis ECRH

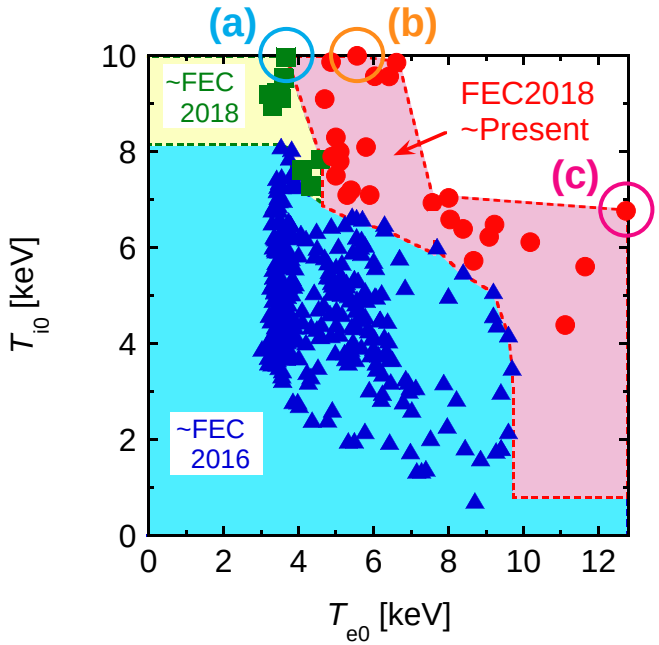


Summary of extension of high-temperature regime

From H to D: **High temperature regime was significantly extended in D operation.**

From previous FEC:

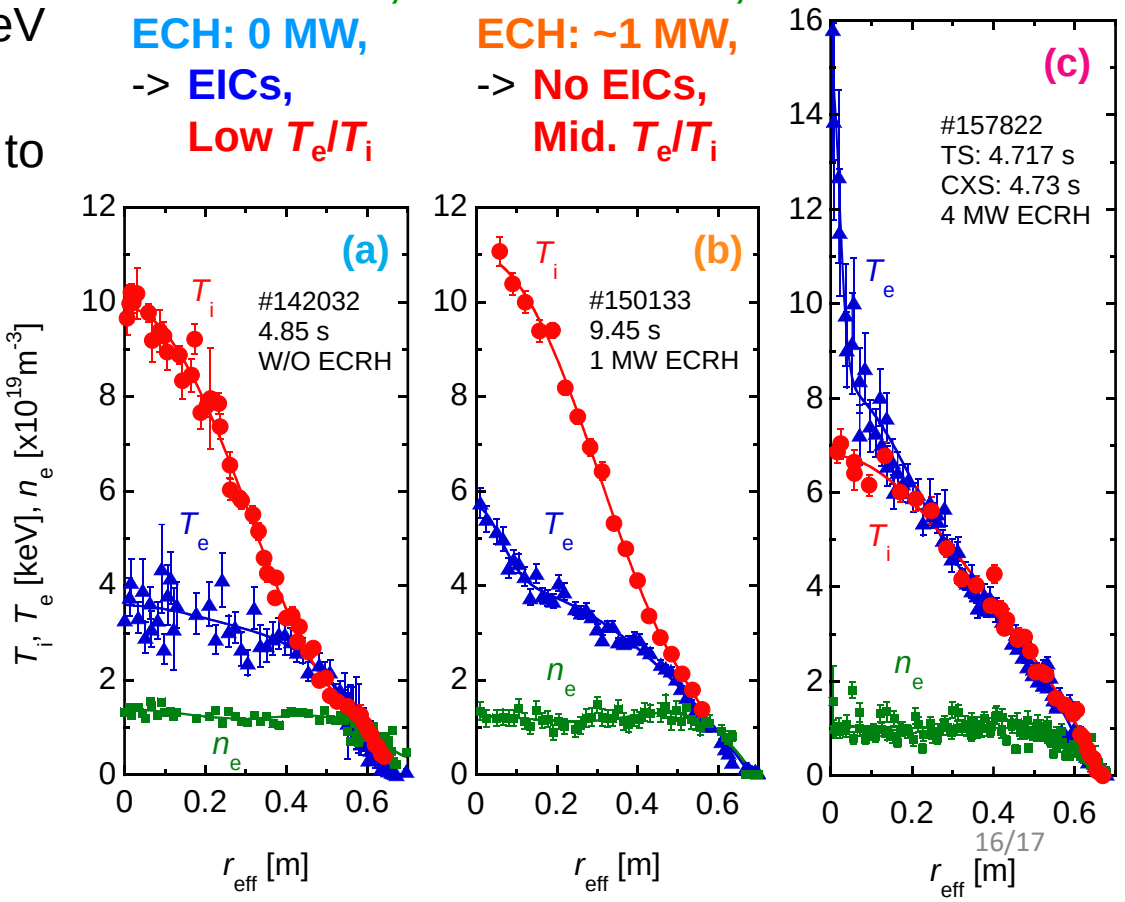
- The operation regime with **the simultaneous high T_i and high T_e was successfully extended**.
- ECRH was effectively utilized.
  - ✓ T_e increased with T_{i0} ~10 keV due to the T_e/T_i control.
  - ✓ **Higher T_i was realized** due to the suppression of EIC.



NBI: ~30 MW, ECH: 0 MW, -> EICs, Low T_e/T_i

NBI: ~30 MW, ECH: ~1 MW, -> No EICs, Mid. T_e/T_i

NBI: ~30 MW, ECH: 4 MW, -> High T_e/T_i, Low dT_i/dr_{eff}



Summary

- The important goal of the LHD project is to **demonstrate the scientific feasibility of helical-system rector.**
- The presentation showed the recent LHD operation oriented the goal,

(1) The performance integration/optimization of high *T* plasmas,

- ✓ Successful extension of simultaneous high T_i and high T_e.
- ✓ Electron ITB with low divertor heat load,
- ✓ Steady sustainment of electron ITB plasmas and the better thermal confinement in D.

(2) Thermal confinement of plasmas both with high T_i and high T_e,

- ✓ Suppression of EIC using ECRH -> Higher T_i achievement,
- ✓ Ion thermal confinement is sensitive to T_e/T_i

  -> Control moderate range -> High T_i maintained with increased T_e.