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.

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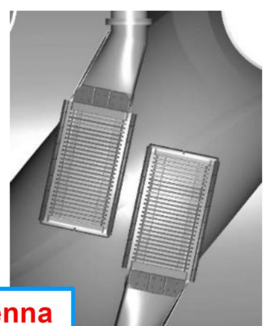
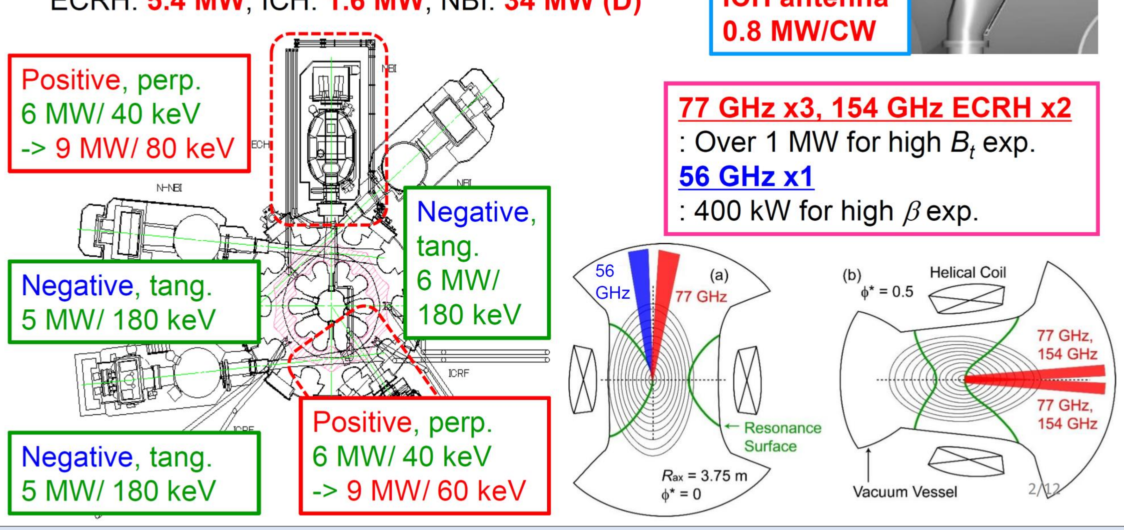
Heating system for the exps. (~Oct 2020)

- 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)





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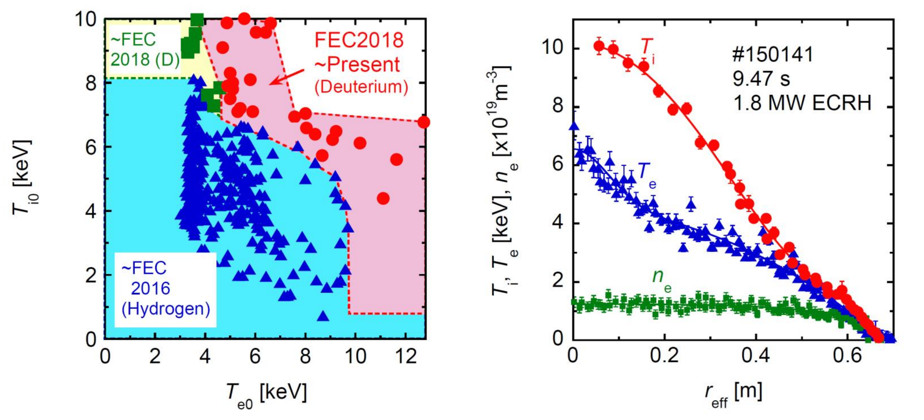
Performance integration of high temperature plasmas

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.



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Electron ITB with radiative divertor

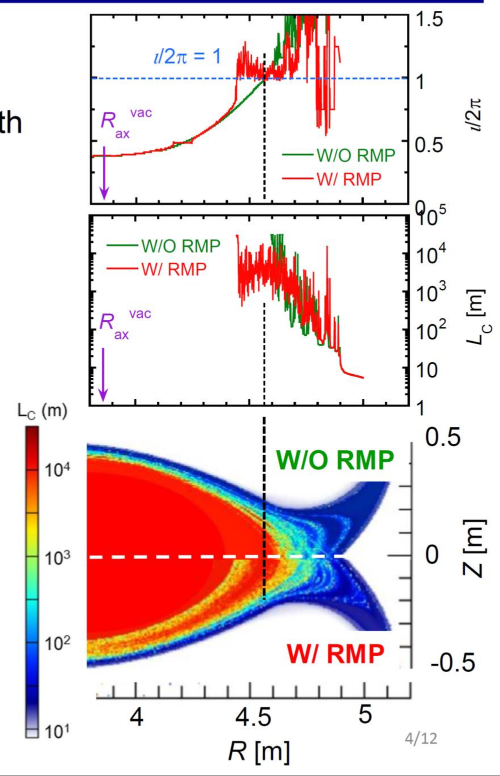
In the future reactor,
- A steady state sustainment of
- Improved confinement plasmas with
- Lower diverter heat load.

- 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



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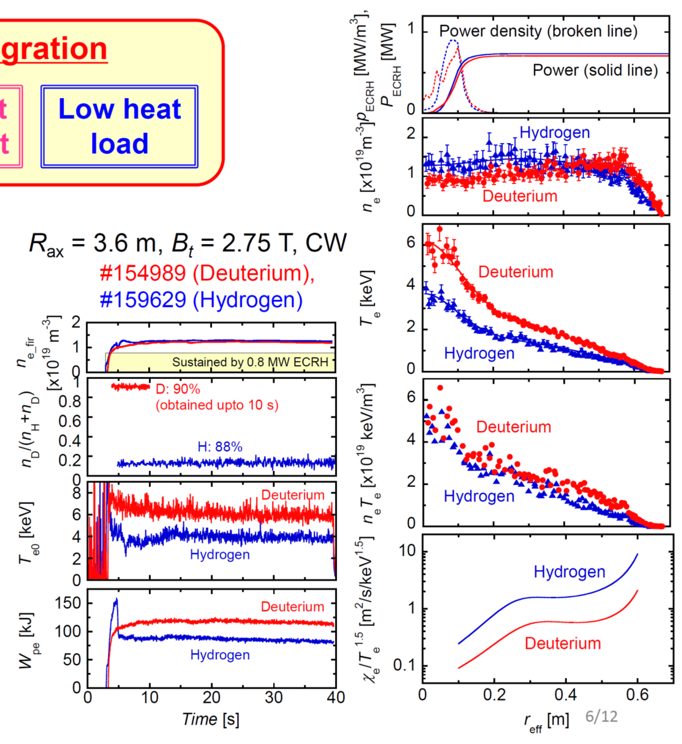
Steady state operation of e-ITB

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.



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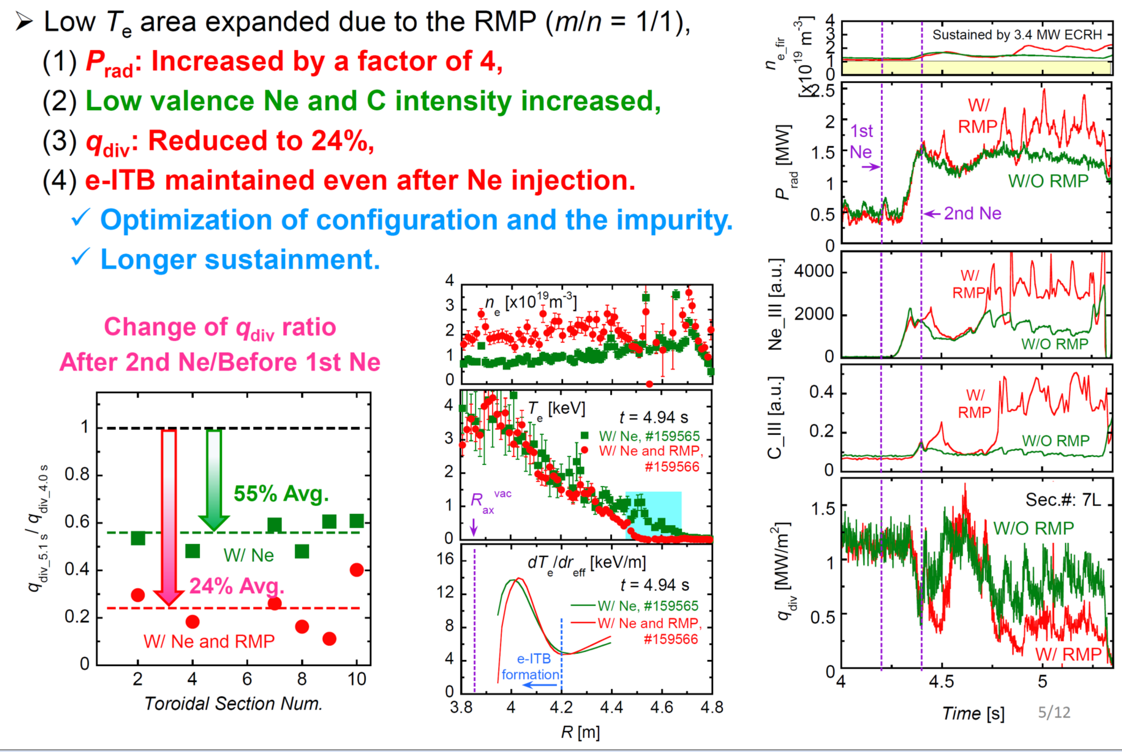
Electron ITB with radiative divertor

- 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.



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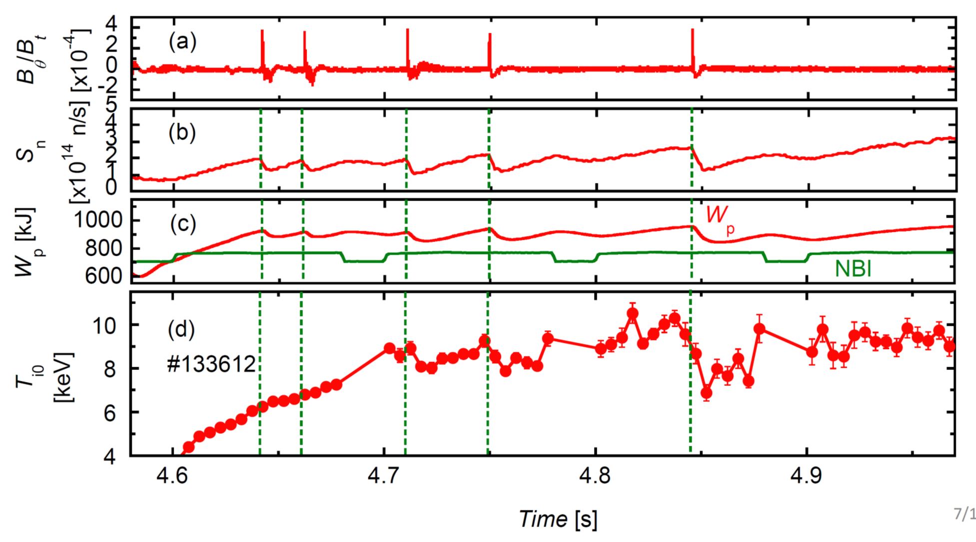
Thermal confinement of plasmas, of which T_i and T_e are simultaneously high

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.



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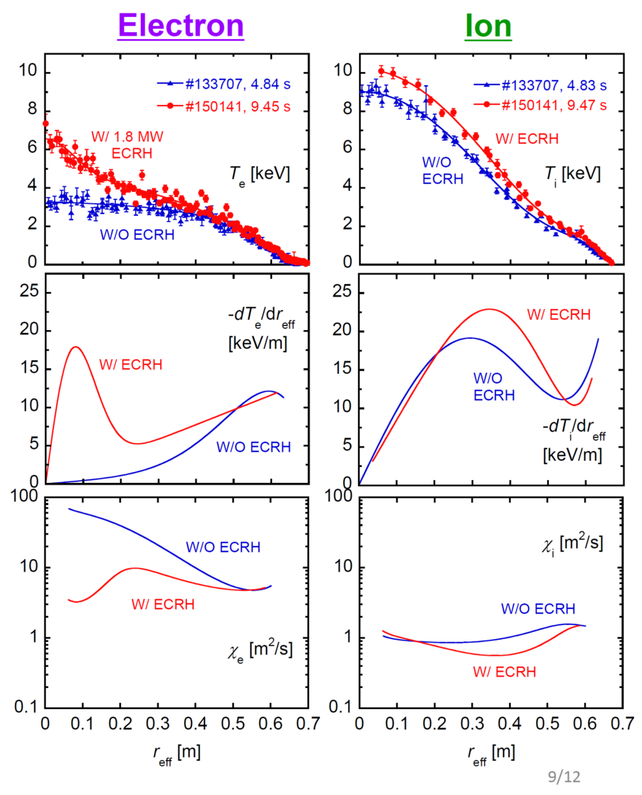
χ_e reduced W/O χ_i increase

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.



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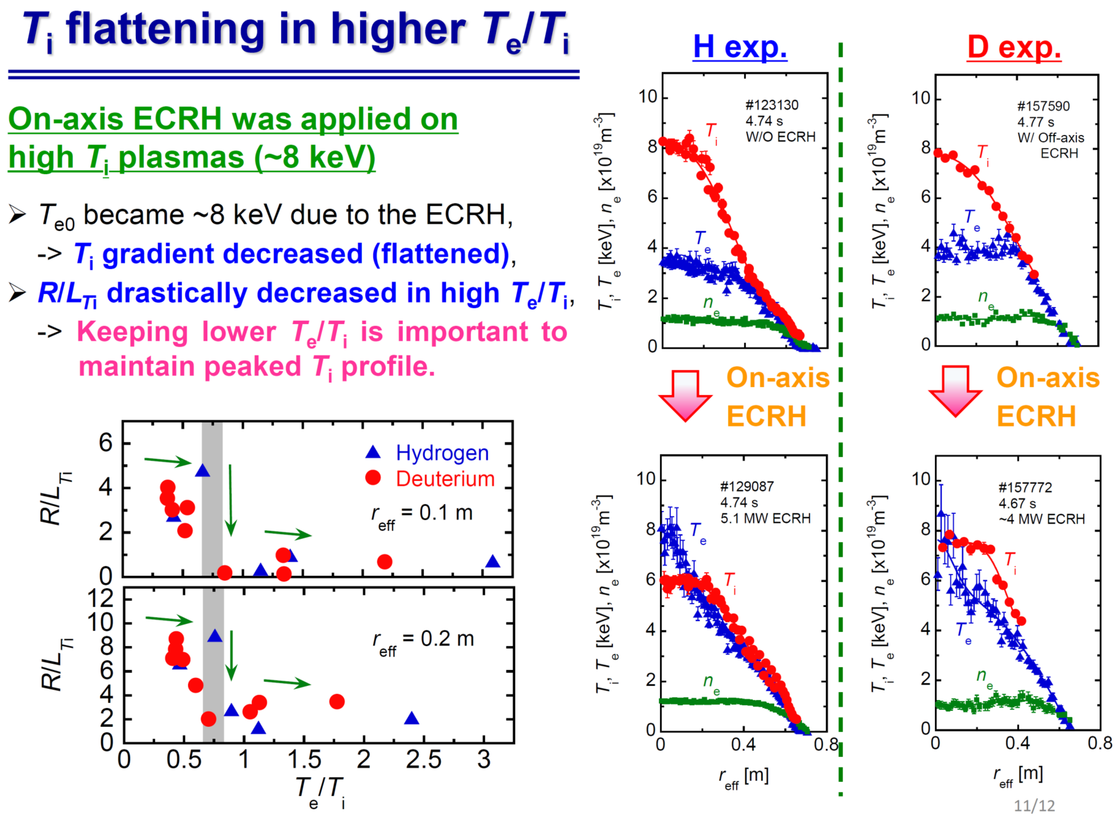
T_i flattening in higher T_e/T_i

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.



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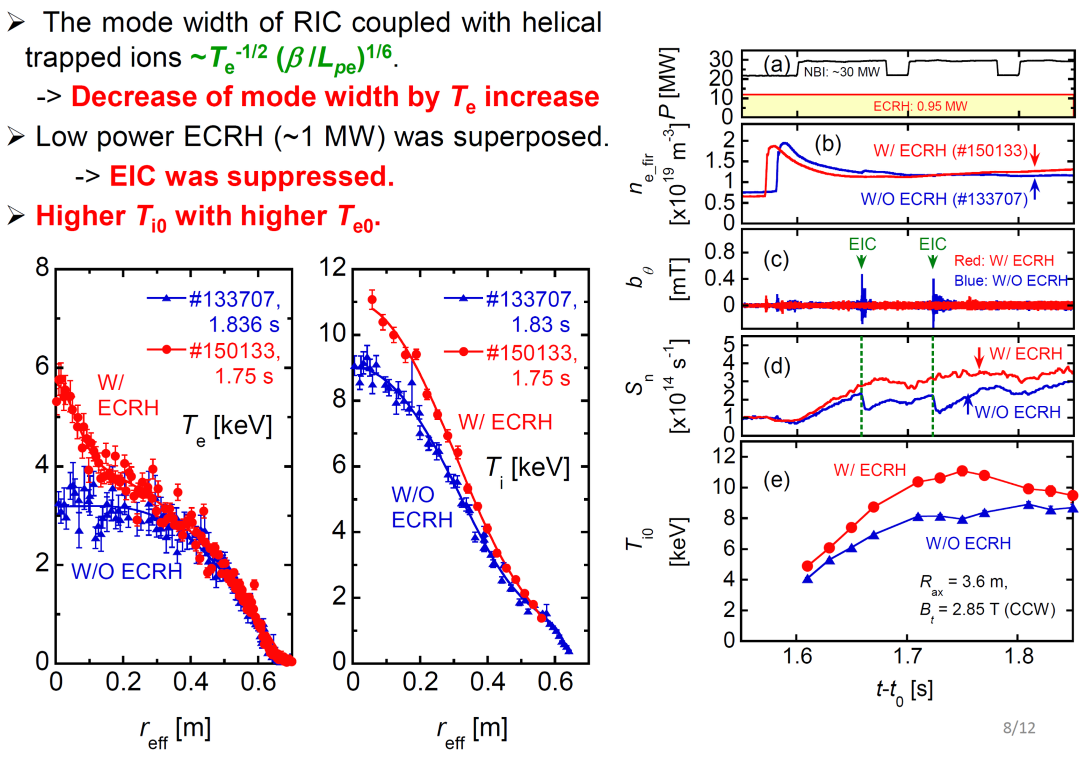
Higher T_i was successfully achieved

- The mode width of RIC coupled with helical trapped ions ~$T_e^{-1/2}$ $(\beta_i L_{pe})^{1/6}$.
  -> 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}.



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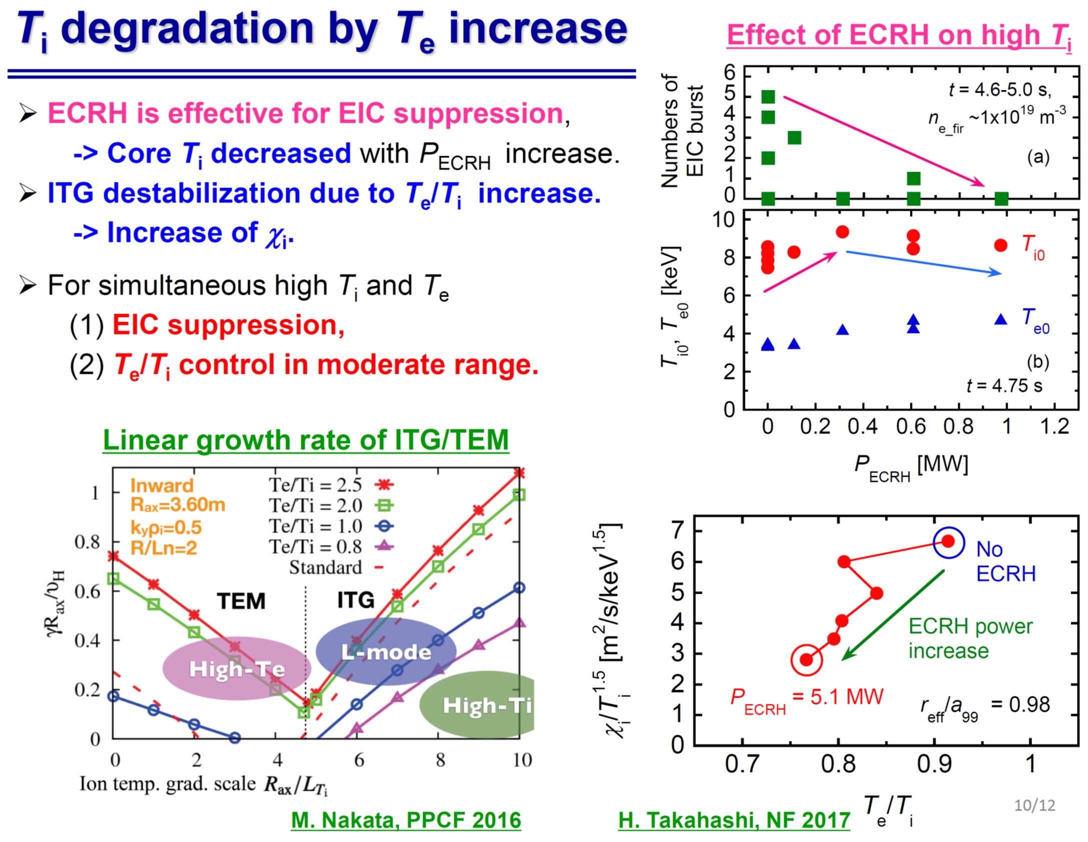
T_i degradation by T_e increase

- 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.

Linear growth rate of ITG/TEM



M. Nakata, PPCF 2016 | H. Takahashi, NF 2017

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Summary of extension of high-temperature regime

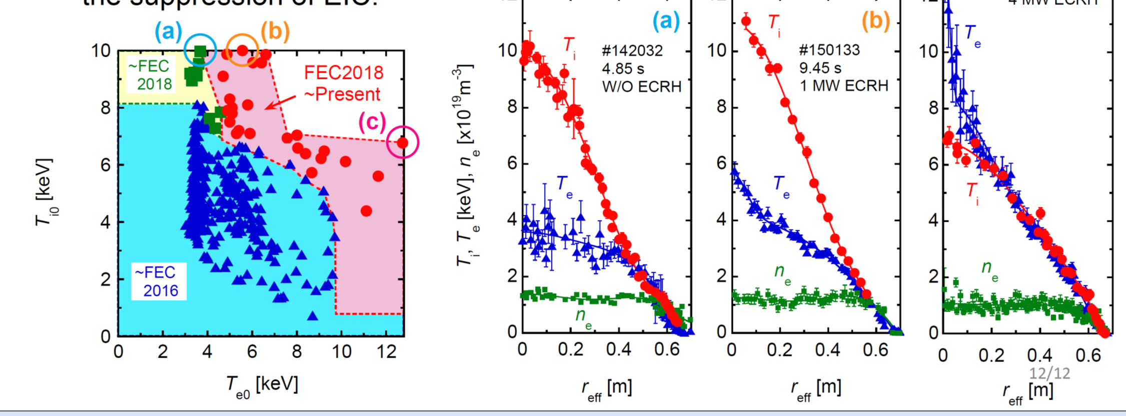
From H to D: High temperature regime was significantly extended in D operation.

From previous FEC:
- The operation regime with the 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}



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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 temperature 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.