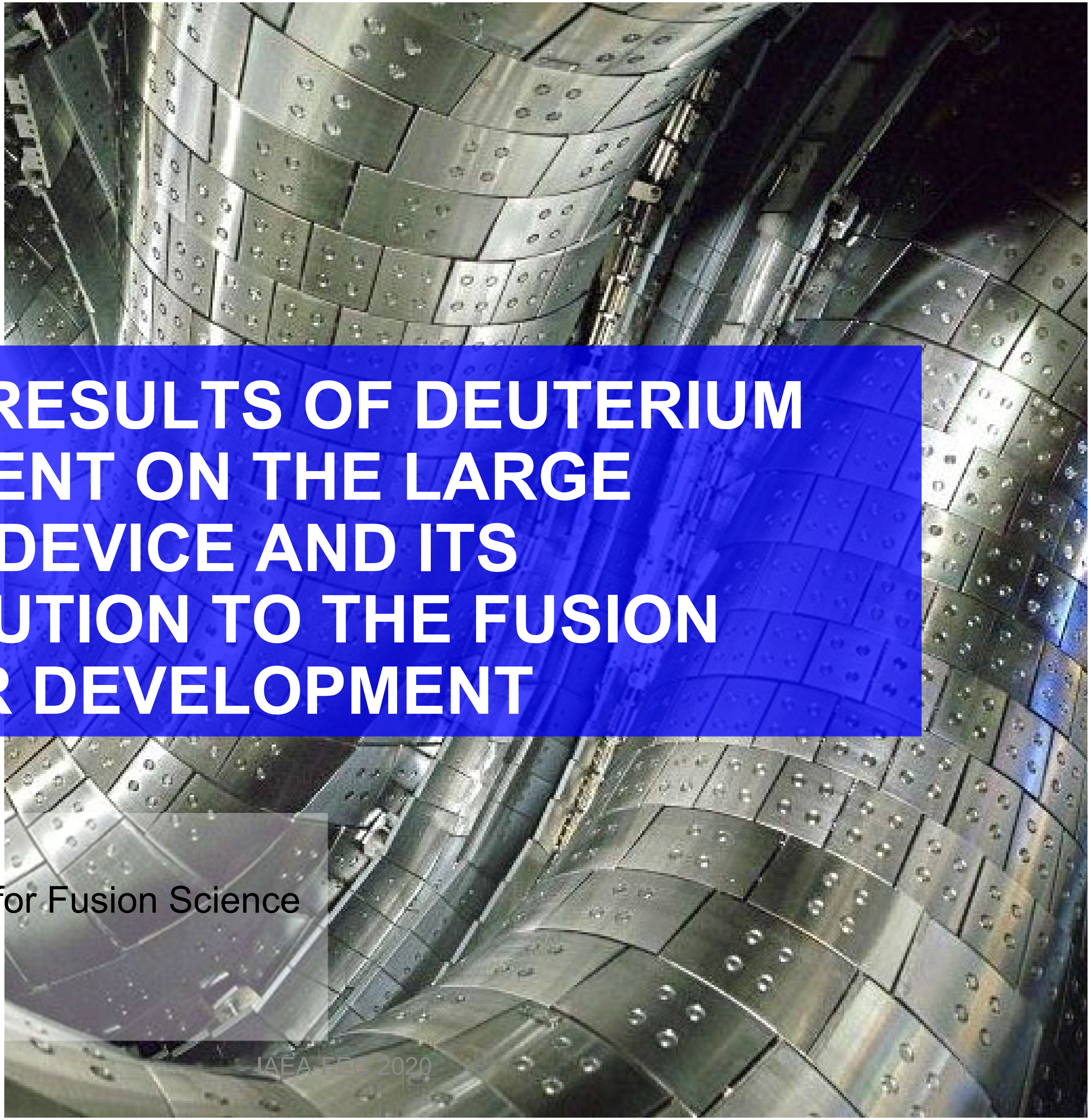

RECENT RESULTS OF DEUTERIUM EXPERIMENT ON THE LARGE HELICAL DEVICE AND ITS CONTRIBUTION TO THE FUSION REACTOR DEVELOPMENT

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National Institute for Fusion Science

IAEA-FEC 2020

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   - Objectives of the LHD Deuterium Experiment
   - LHD (Large Helical Device)
2. Recent achievements and activities at D-exp.
   - Extension in temperature domain
   - Isotope Effect and Isotope related studies
   - RMP induced H-mode
3. SUMMARY

Objective of Deuterium Experiment

1. Realization of high-performance plasmas by confinement improvement and by the improved heating devices and other facilities

   ⇒ Extend the operational region of LHD to the reactor relevant plasmas

2. Exploration of the isotope effect study in plasma confinement

   ✓ Isotope effect is long underlying mystery in plasma physics

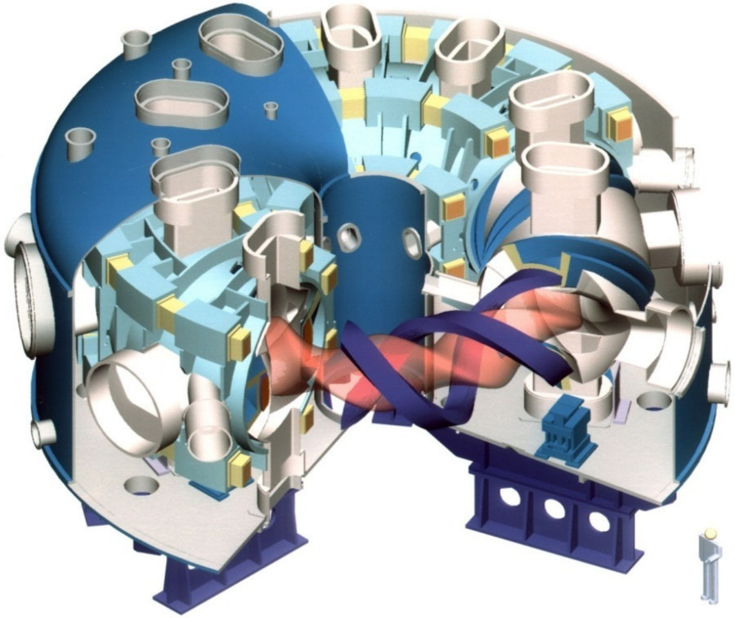
   ⇒ The information of isotope effect in helical system will lead to the comprehensive understanding on plasma physics

3. Demonstration of the confinement capability of energetic particles (EPs) in helical system and exploration of their confinement studies

   ⇒ Perspective understanding on EP physics for burning plasmas will be provided for toroidal plasmas

4. Extended studies on Plasma-Wall Interactions (PWI) and tritium retention studies

LHD (Large Helical Device)



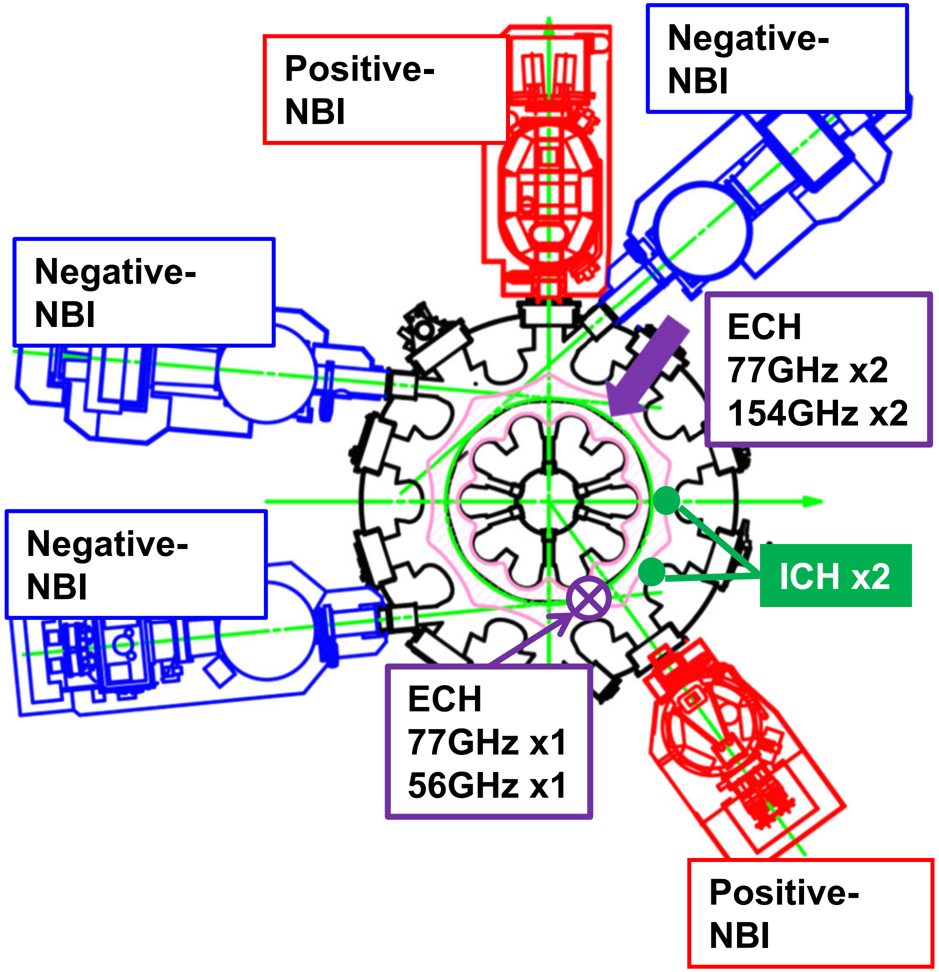
One of the largest superconducting machine in the world

Specifications

- Mode numbers : *l*/*M*=2/10
- All superconducting system
  helical coils, poloidal coils and bus lines
- Plasma major radius: 3.55-4.1 m
- Plasma minor radius: ~0.6 m
- Plasma volume: 30 m^3
- Toroidal field strength: 3 T
- 10 pairs of RMP coils

March 31st, 1998 1st plasma
March 7th , 2017 Deuterium Experiment

Heating System on LHD



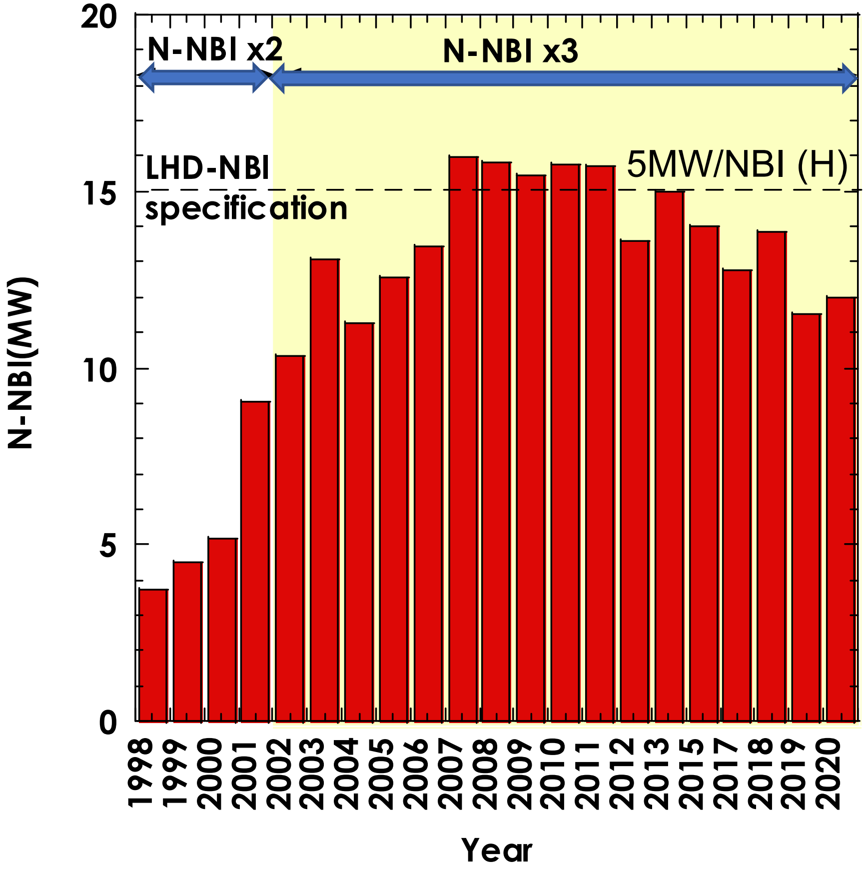
Heating Systems

- Negative-NBI (tangential)x 3 (180-190keV), H16MW, D8MW
- Positive-NBI (radial) x 2 (40-80keV), H12MW, D18MW
- ECH (77GHz x 3, 154GHz x 2, 56GHz) 5.5MW
- ICH (38.47MHz) x 2 2 MW

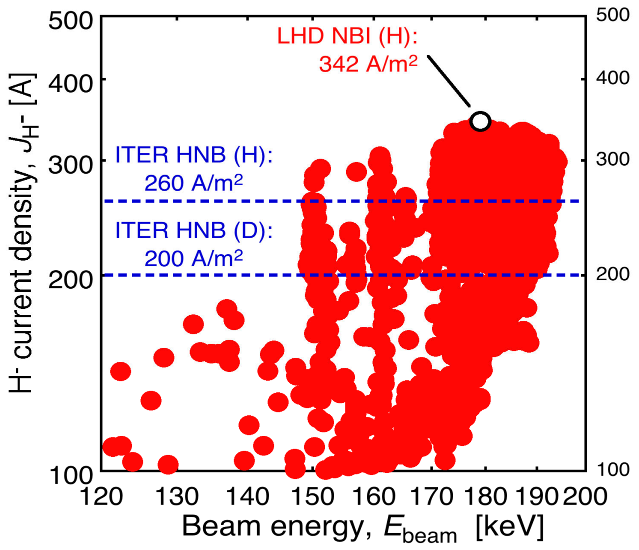
LHD has been demonstrated the reliable operation of Negative-ion based for more than 20 years.

N-NBI improvement for D-operation
⇒ Tsumori, K. (ID: 763)
N-NBI optics
⇒ Kisaki, M. (ID:734)

It was proved that the specification of ITER-NBI can be fulfilled simultaneously using negative-ion source at the real operation for plasma injection.



	ITER-NBI	LHD-NBI
J_{H^-}	> 260A/m^2	340 A/m^2
I_e/I_{H^-}	<1	0.25
$\theta_{div.}$	3-7mrad	5mrad



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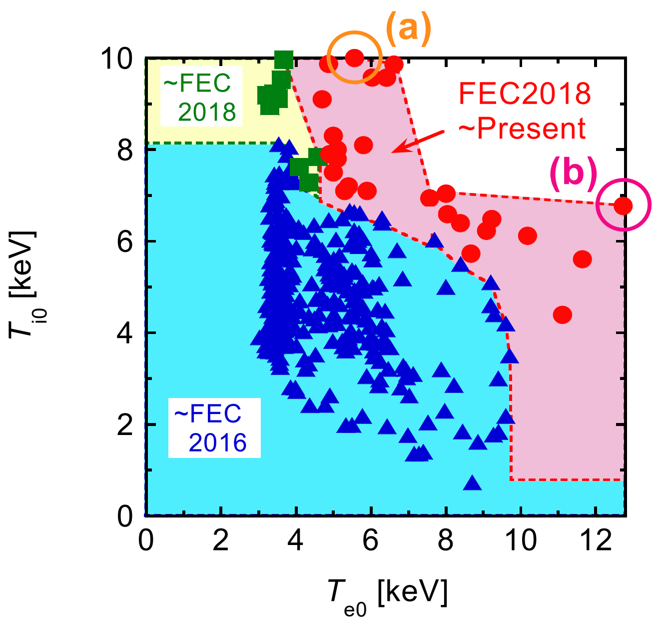
Extension of high-temperature regime

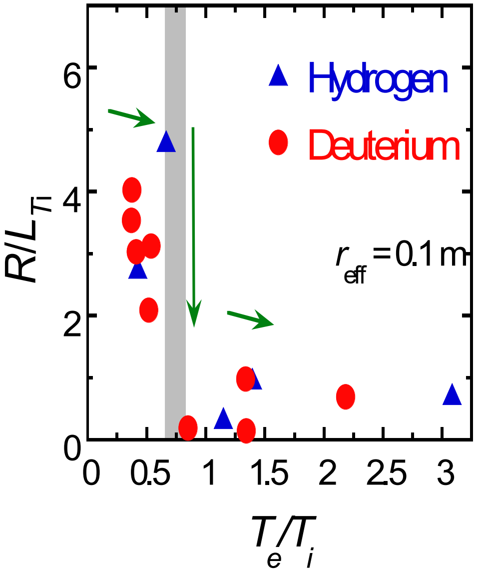
Expansion in Temp.:
⇒ Takahashi, H. (ID:781)
EIC suppression:
⇒ Ohdachi, S. (ID:800)
EIC effect on EP:
⇒ Ogawa, K. (ID: 688)

From previous FEC:

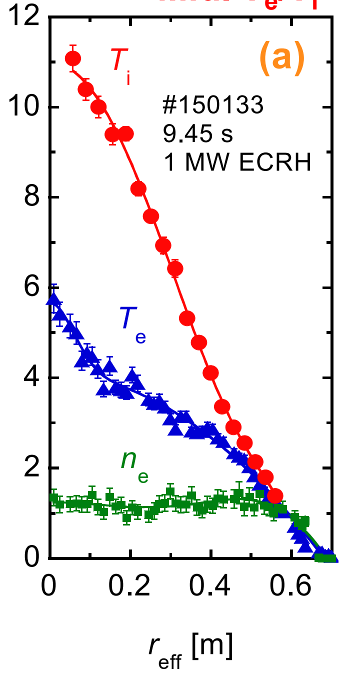
- The operation regime with **the simultaneous high T_i and high T_e was successfully extended**.
- It was found;
  - The EP driven resistive InterChange mode (EIC) should be suppressed to avoid the loss of EPs to increase the ion temperature and can be suppressed by increasing T_e.
  - The ratio of T_e/T_i should be kept below 0.75 to keep better ion thermal confinement property.

⇒ Moderate ECH heating is important in extending the parameter.

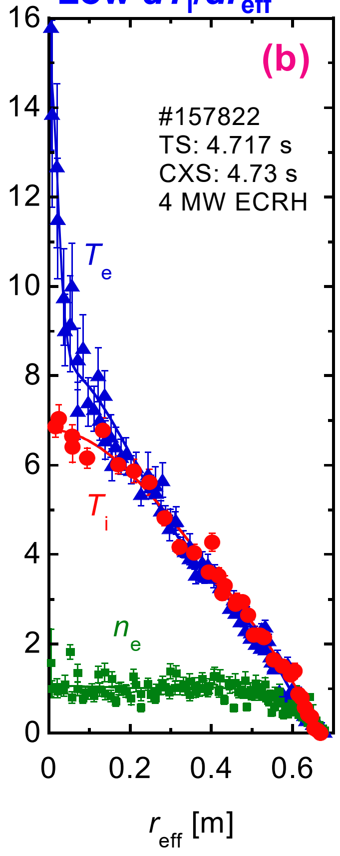




NBI: ~30 MW,
ECH: ~1 MW,
-> **No EICs,**
Mid. T_e/T_i



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



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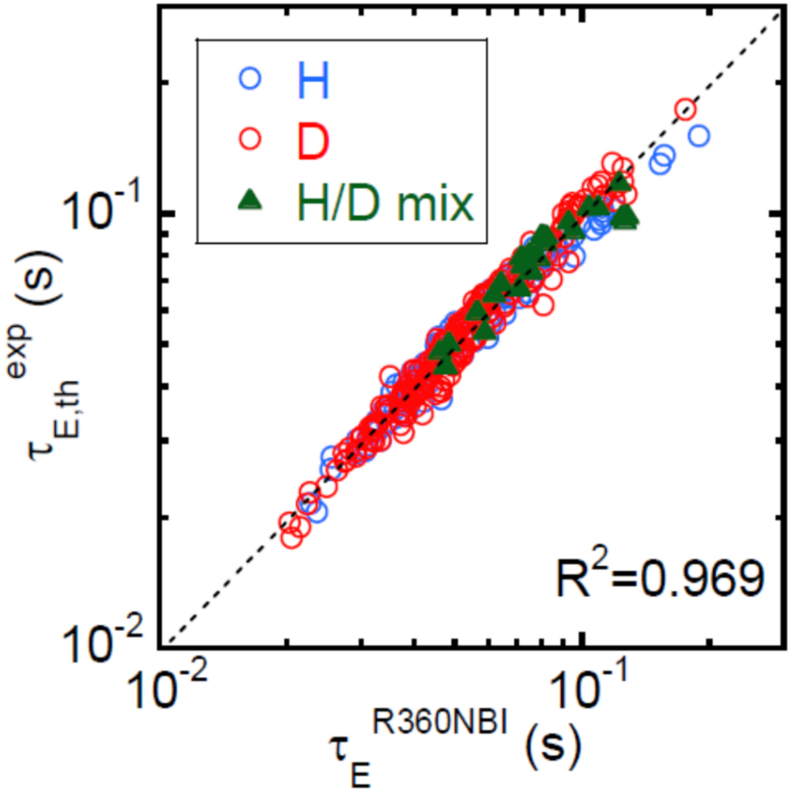
3. SUMMARY

Yamada, H. (ID:718)

Isotope Effect for L-mode plasma

- The existence of Mass dependence in addition gyro-Bohm nature was confirmed using H, D, He, and their mixture L-mode dimensionally similar plasmas.



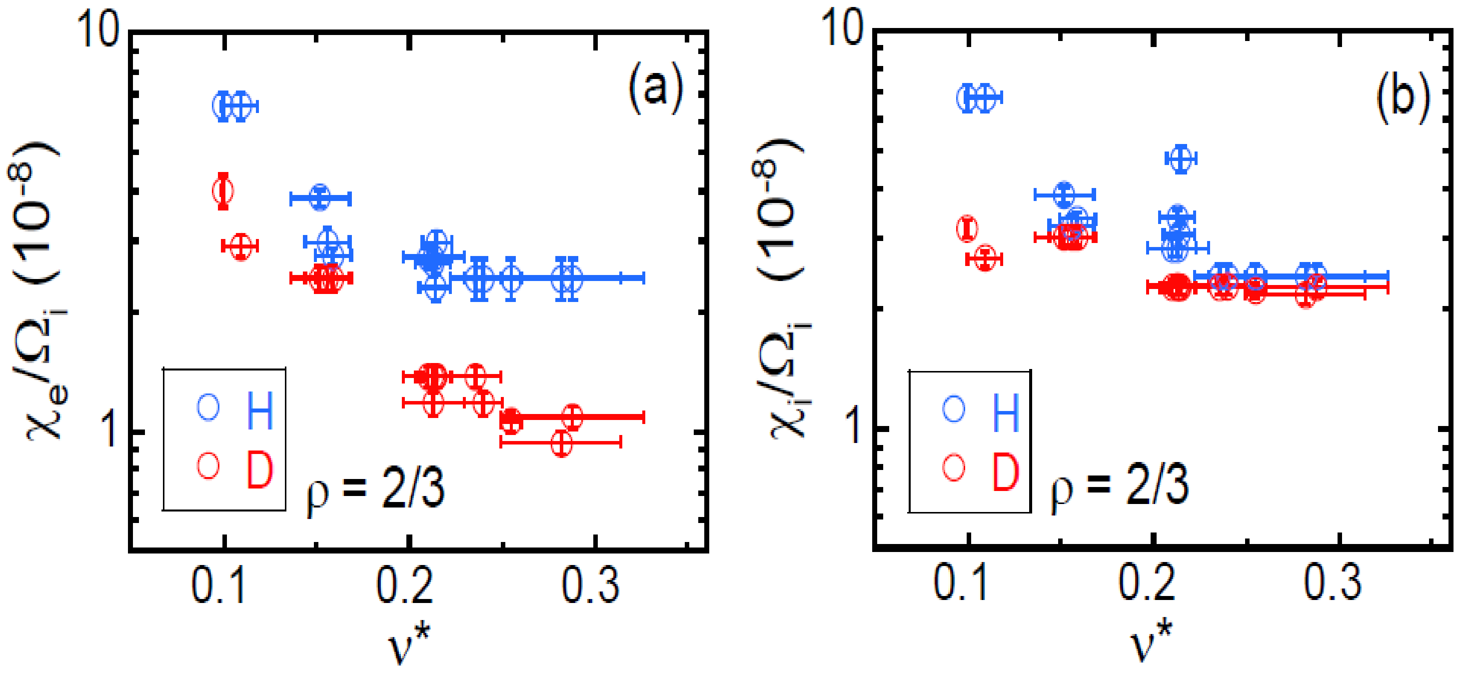
Dimensionless energy confinement time scaling with 4 dimensionless parameter, i.e., M, ρ^*,ν^*, β.

$$\tau_E{}^{R360NBI}\Omega_i \propto M^{0.94}\rho^{*-3.02}\upsilon^{*0.15}\beta^{-0.23}$$

Gyro-Bohm nature: $\tau_E\Omega_i \propto M^0\rho^{*-3}$.

Yamada, H. (ID:718)

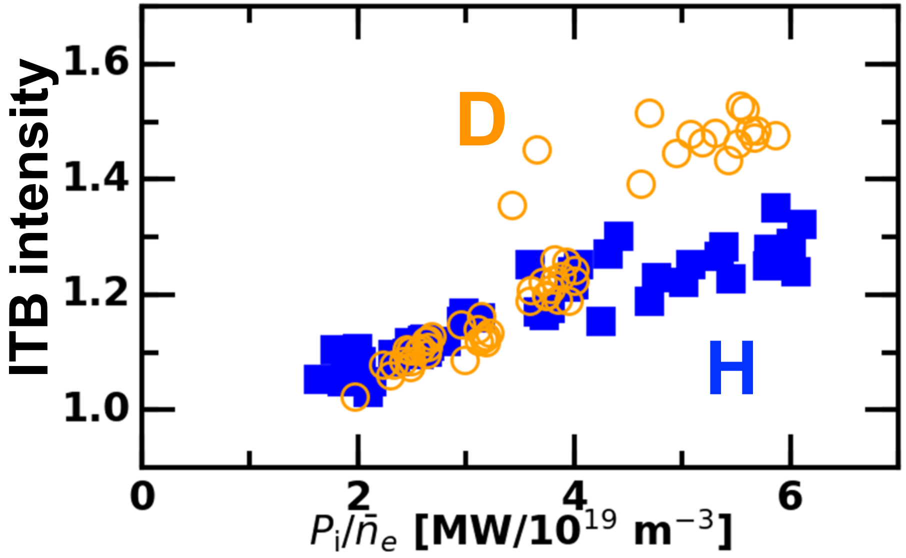
The local thermal transport property is also investigated for dimensionally similar plasmas



An improvement in $\chi e/\Omega_i$ for D plasmas is found especially for high collisional region of ν* >0.2. On the other hand, the difference in $\chi i/\Omega_i$ is less significant.

Kobayashi, T. (ID: 832)

Isotope effects of the plasmas with internal transport barrier (ITB) are investigated defineing an ITB intensity

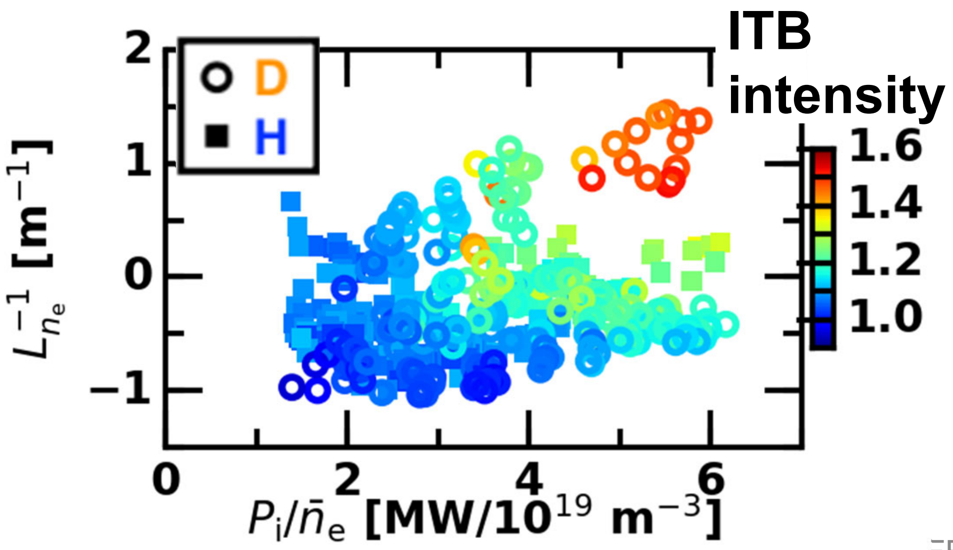


- ITB intensity is a measure:
  "How much T_i profile deviates from the LHD L-mode scaling ($\chi \propto T_i$)"

T. Kobayashi+, Plasma Phys. Control. Fusion **61** 085005 (2019)

- ITB intensity in D is larger than that in H when $P_i/\bar{n}_e$ > 4 MW/10^{19} m^{-3}.

T. Kobayashi+, Sci. Rep. **9** 15913 (2019)



- Principal component analysis reveals that ITB becomes stronger when both $P_i/\bar{n}_e$ and $L_{n_e}^{-1}$ are simultaneously large.
- Radial electric field shear plays a minor role.

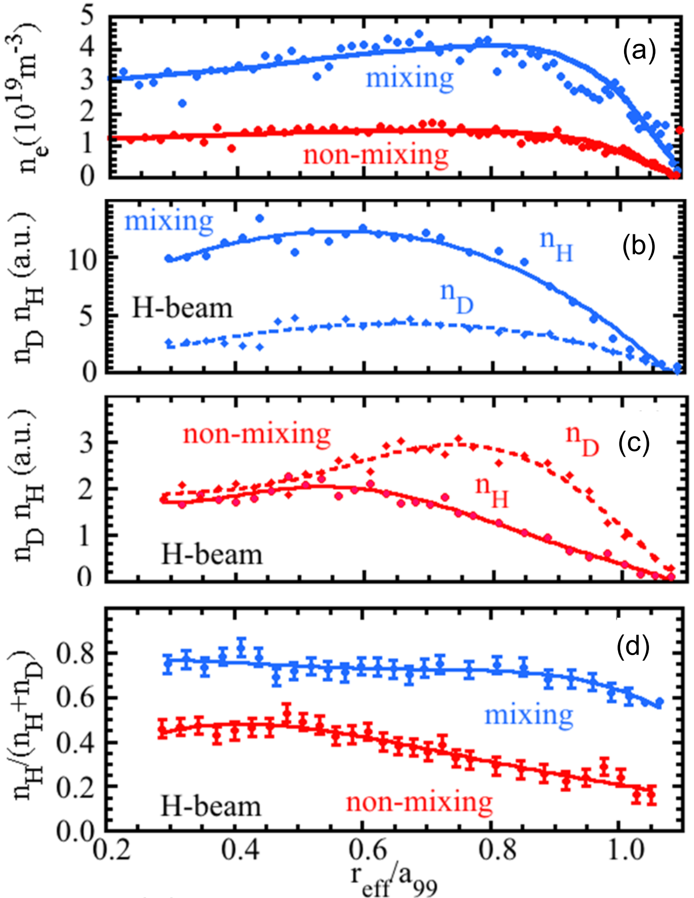
T. Kobayashi+, this conference (CN-832)

Ida, K. (ID: 692)

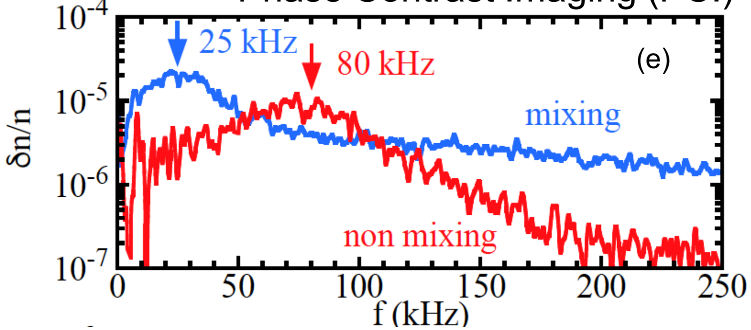
Control of isotope fraction (D/(D+T) ratio) is a crucial issue for the control of the fusion power in future reactors.

- ✓ Investigation of hydrogen isotopes behavior in their mixture plasmas is important.
- ✓ A theoretical paper by Bourdelle (NF2018) suggests the isotope mixing state appears at ITG dominant plasmas and non-mixing state does at TEM dominant plasmas.

⇒ Isotope mixing/non-mixing plasmas are observed in LHD.



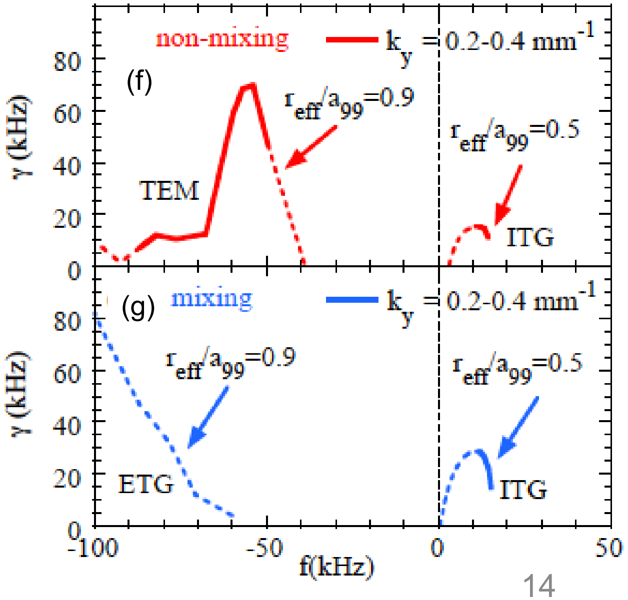
Phase Contrast Imaging (PCI)



Mixing state
Low frequency peak

Non-mixing state
High frequency peak

GKV Simulation shows
Low frequency peak
for ITG mode
and
High frequency peak
for TEM



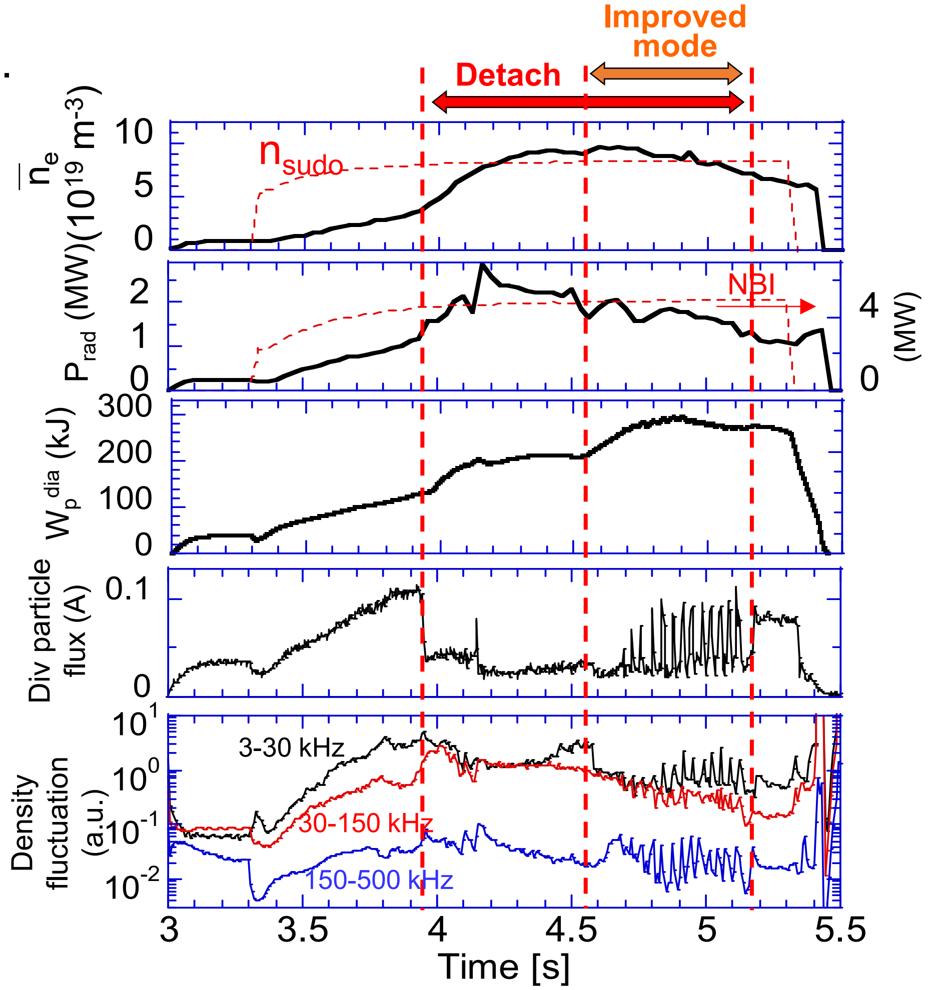
CONTENTS

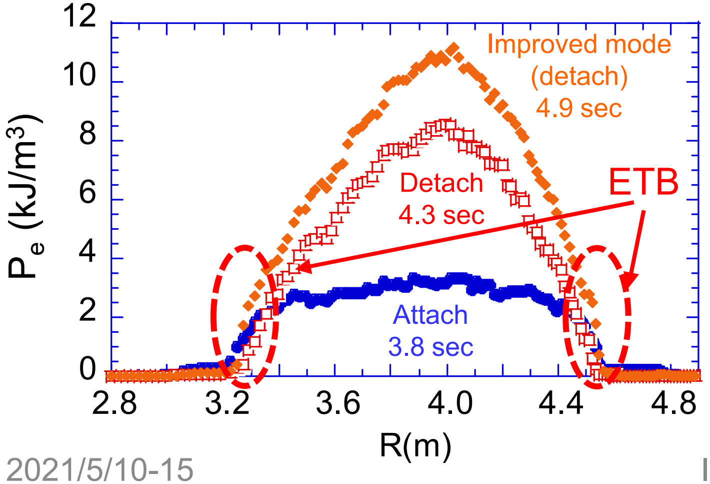
New improved confinement regime, “RMP induced H-mode”, was found in LHD

Kobayashi, M. (ID: 837)

- ➢ Density was lamped up during the discharge.
- ➢ Stable sustainment of the divertor detachment is realized by an RMP application.
  - ✓ Significant reduction in Div. flux.
  - ✓ $P_{rad.}$ reaches ~60% of $P_{heat.}$
- ➢ The improvement of confinement observed at the onset of the detachment and the Edge Transport Barrier (ETB) was formed.
- ➢ Further improvement in confinement was observed during the detached phase.

⇒ RMP induced H-mode

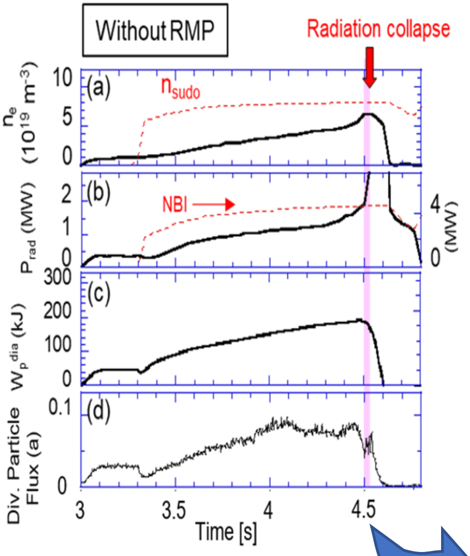


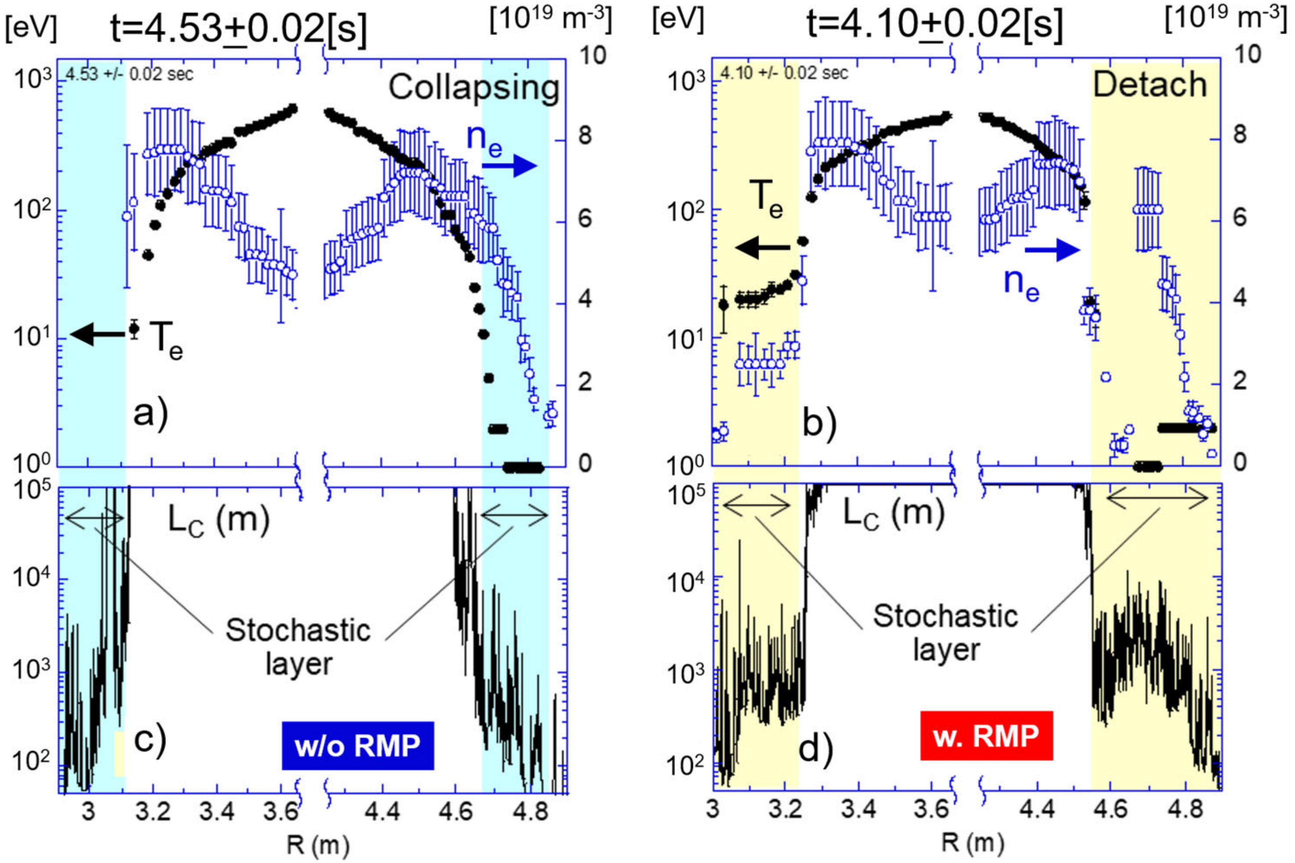


Simultaneous achievement of reduced divertor heat load and good core confinement

An application of RMP(m/n=1/1) is the key to maintain stable divertor detachment.

- ✓ The stochastic region Te<~20eV expanded by the RMP enhances the radiation by carbon impurities at the peripheral.
- ✓ Steep gradient in L_c might play an important role in the stable sustainment of the radiative region.



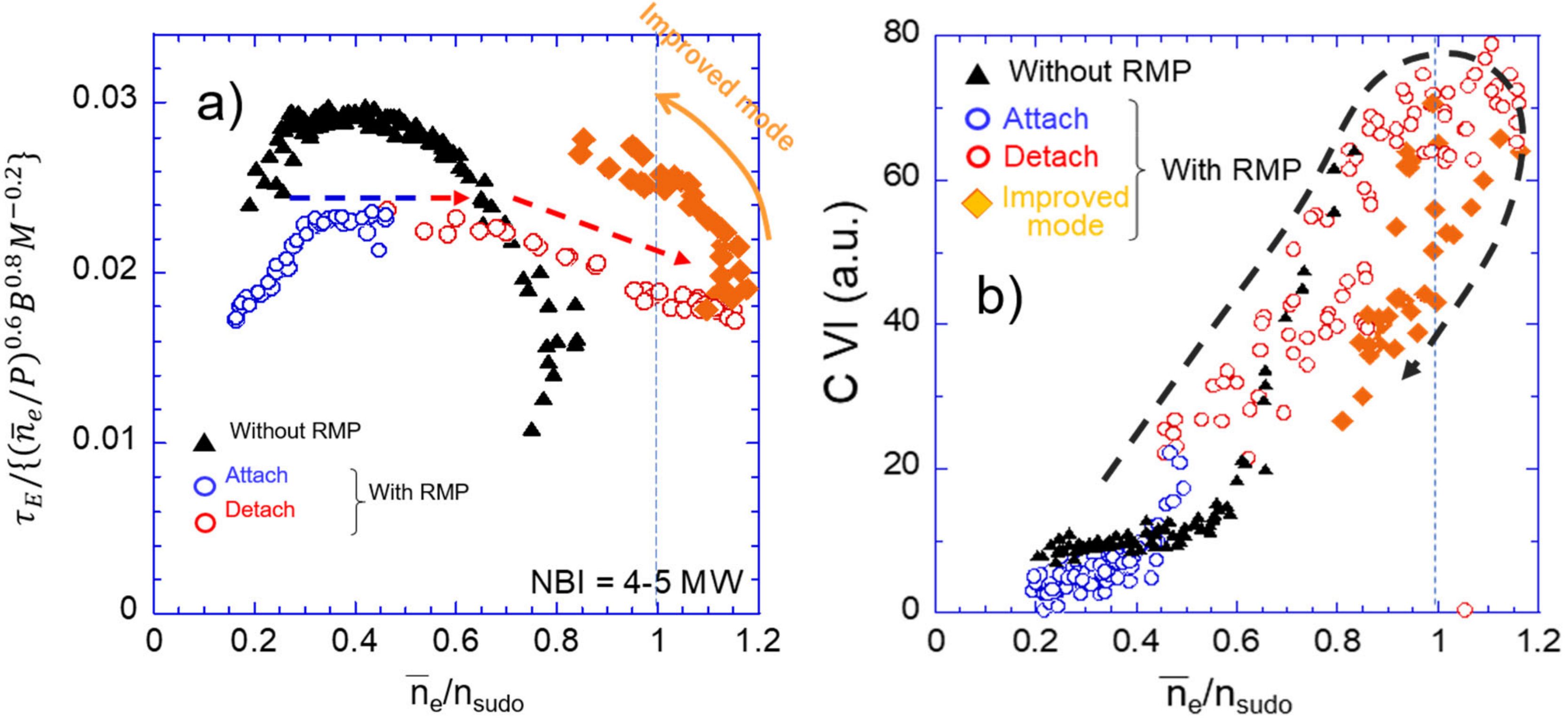


Kobayashi, M. et al.

An Improved confinement after detachment is observed

Kobayashi, M. (ID: 837)

- The reduction of an impurity line intensity (CVI) is also observed at the onset of the improved confinement



The triggering mechanism of the improved confinement transition is not understood, yet. The impurity behavior might play a role at the triggering event.

Kobayashi, M. et al.

SUMMARY

- ➢ The extension of high temperature domain significant in the deuterium experiment.
  - ✓ T_{i0}=10.6keV&T_{e0}=5.6keV, T_{i0}=6.8keV & T_{e0}=12.7keV achieved, simultaneously.
  - ✓ The suppression of EIC is the key to extend the domain
    - The EIC can be suppressed by ECH
  - ✓ The T_e/T_i ratio is better to be kept below 0.75 to obtain good ion confinement.
  - ✓ Moderate ECH is effective both for EIC suppression and for T_e increase without T_i degradation.
- ➢ Isotope effect scaling for L-mode plasmas are expanded for H, D, He and their mixture dimensionally similar plasmas.
  - ✓ Co-existence of Mass dependence in addition gyro-Bohm nature ($M^0\rho^{*-3}$) was confirmed: $\tau_E{}^{R360NBI}\Omega_i \propto M^{0.94}\rho^{*-3.02}\upsilon^{*0.15}\beta^{-0.23}$.
  - ✓ Local thermal confinement properties are also examined: The χ_e/Ω_i improved for D plasmas, while the difference in χ_i/Ω_i is less significant.
- ➢ Isotope effect for ITB plasmas is also investigated using ITB intensity.
  - ✓ Clear isotope effect is found when $\boldsymbol{P_\mathrm{i}/\bar{n}_\mathrm{e}}$ > 4 MW/10^{19} m^{-3}.
  - ✓ PCA reveals the ITB intensity is larger when both $\boldsymbol{P_\mathrm{i}/\bar{n}_\mathrm{e}}$ and $\boldsymbol{L_{n_\mathrm{e}}^{-1}}$.

SUMMARY –continued-

- ➢ Behavior of hydrogen isotopes in their mixture plasma is investigated.
  - ✓ A theory suggests the mixing state will appear for ITG dominant case, while the non-mixing case will appear for TEM dominant case.
  - ✓ Mixing/non-mixing states are observed, experimentally.
    - For the mixing state, a low frequency turbulence peaked at ~25kHz observed, while a relatively high frequency turbulence peaked at ~80kHz observed for the non-mixing state.
    - GKV simulation suggested ITG turbulence appears at low frequency range(~10kHz) and TEM turbulence appears at high frequency range (~60kHz).
- ➢ New improved confinement regime, called RMP induced H-mode, was newly found.
  - ✓ Stable sustainment of divertor detachment was realized by an application of RMP (m/n=1/1).
    - $P_{rad.}$ reached ~60% of the NB injection power (P_{NB}) and a significant reduction in divertor flux is observed.
    - Expansion of low temperature stochastic region by the RMP is the key to realize stable divertor detachment.
  - ✓ Confinement improvement was observed during the detached phase.
    - The triggering mechanism of the improvement is not clear, yet.
    - Reduction of impurity might affect the improvement.
  - ✓ A reduction of diverter flux and good core plasma confinement realized, simultaneously.

List of LHD-related presentations (1)

Performance optimization and operation scenario development

- H. Takahashi, “Performance Integration of High Temperature Plasmas in the LHD deuterium operation”, (ID: 781)
- T. Yokoyama, “Characterization and sparse modeling of radiation collapse and density limit in LHD”, (ID: 712)
- T. Tsujimura, “Improved performance of ECRH by real-time deposition location control and perpendicular injection in LHD”, (ID: 835)
- Y. Morishita, “Integrated Transport Simulation of LHD Plasma Applying Data Assimilation Technique”, (ID: 843)

Transport and heating physics

- K. Ida, “Transition between isotope-mixing and non-mixing states in hydrogen-deuterium mixture plasmas in the Large Helical Device”, (ID: 692)
- H. Yamada, “Investigation of isotope effect on confinement and thermal transport characteristics in L-mode plasmas on LHD”, (ID: 718)
- T. Kobayashi, “Isotope effects in internal transport barrier strength on Large Helical Device”, (ID: 832)
- K. Tanaka, “Magnetic configuration effects on turbulence driven transport from LHD and W7X identical experiments”, (ID:840)
- M. Nunami, “Improved prediction scheme for turbulent transport by combining machine learning and first-principle simulation”, (ID: 716)
- Y. Yamamoto, “Mechanism of toroidal flow generation by electron cyclotron heating in HSX and LHD plasmas”, (ID: 824)
- T. Moritaka, “Isotope effects in ion temperature gradient modes with radial electric field in Large Helical Device”, (ID: 791)

List of LHD-related presentations (2)

Edge and Divertor Plasmas, Atomic and Molecular Processes

- M. Kobayashi, “Core plasma transport change and divertor heat load mitigation during divertor detachment operations with RMP application in hydrogen and deuterium plasmas in LHD”, (ID: 837)
- G. Motojima, “Effects of partially installed tungsten coated divertor tiles on the LHD plasma and plasma-wall interactions”, (ID: 715)
- K. Mukai, “Steady-state sustainment of divertor detachment with multi-species impurity seeding in LHD”, (ID: 757)
- D. Katoh, “Assessment of W density in LHD core plasmas using visible forbidden lines of highly charged W ions”, (ID: 755)
- S. Masuzaki, “Distribution of remaining tritium in the LHD vacuum vessel”, (ID: 721)

High-beta, MHD, and EP Physics

- K. Ogawa, “A Comprehensive Study of Energetic Particle Transport Due to Energetic Particle Driven MHD Instabilities in LHD Deuterium Plasmas”, (ID: 688)
- H. Matsuura, “Observation of Nuclear Elastic Scattering Effect by Energetic Protons on Deuteron Slowing-Down Behavior in the Large Helical Device”, (ID: 739)
- S. Ohdachi, “Suppression of the energetic particle driven interchange mode in the Large Helical Device”, (ID: 800)
- Y. Takemura, “RMP effect on slowing down of locked-mode-like instabilities in helical plasmas”, (ID: 733)
- M. Sato, “Supercritical stability of the Large Helical Device plasmas due to the kinetic thermal ion effects”, (ID: 788)
- K. Ichiguchi, “Non-resonant global mode in LHD partial collapse with net toroidal current”, (ID: 797)
- R. Seki, “Hybrid simulations of fast ion transport and losses due to the fast ion driven instabilities in the Large Helical Device”, (ID: 720)

Development of high-power-heating devices contributing to ITER/DEMO

- K. Tsumori, “Challenges toward Improvement of Deuterium Injection Power in LHD Negative-Ion-Based NBIs”, (ID: 763)
- M. Kisaki, “Study of negative ion beam optics in real and phase space”, (ID: 734)