Transport Characteristics of Deuterium and Hydrogen Plasmas with Ion ITB in LHD

K. Nagaoka[1,2]
H. Takahashi[1,3], M. Nakata[1,3], K. Tanaka[1,4], K. Mukai[1,3], M. Yokoyama[1,3], H. Nakano[1,3], S. Murakami[5], K. Ida[1,3], M. Yoshinuma[1,3], S. Ohdachi[1,3], T. Bando[6], M. Nunami[1,3], S. Satake[1,3], R. Seki[1,3], C. Suzuki[1,3], H. Yamaguchi[1], M. Osakabe[1,3], T. Morisaki[1,3] and the LHD Experiment Group

[1]National Institute for Fusion Science, National Institutes of Natural Sciences
[2]Nagoya University, Graduate School of Science
[3]SOKENDAI, Department of Fusion Science
[4]Kyushu University, Interdisciplinary Graduate School of Engineering Sciences
[5]Kyoto University, Graduate School of Engineering
[6]National Institutes for Quantum and Radiological Science and Technology

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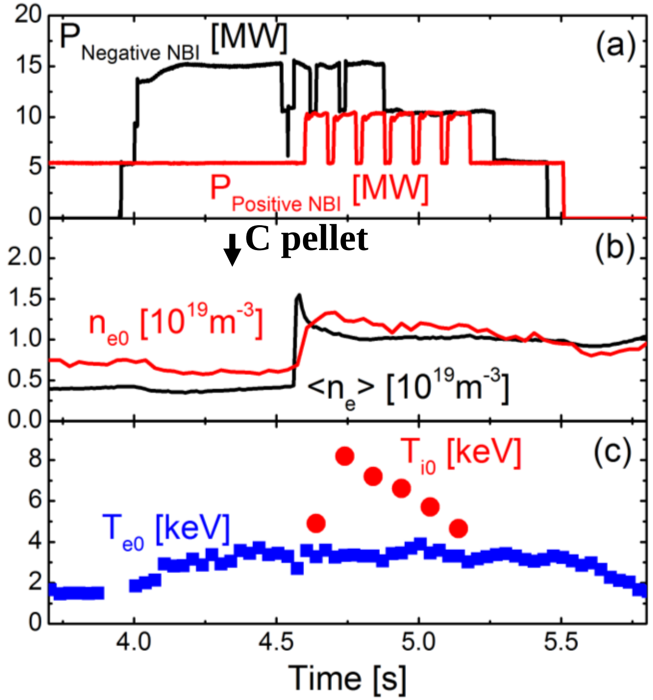
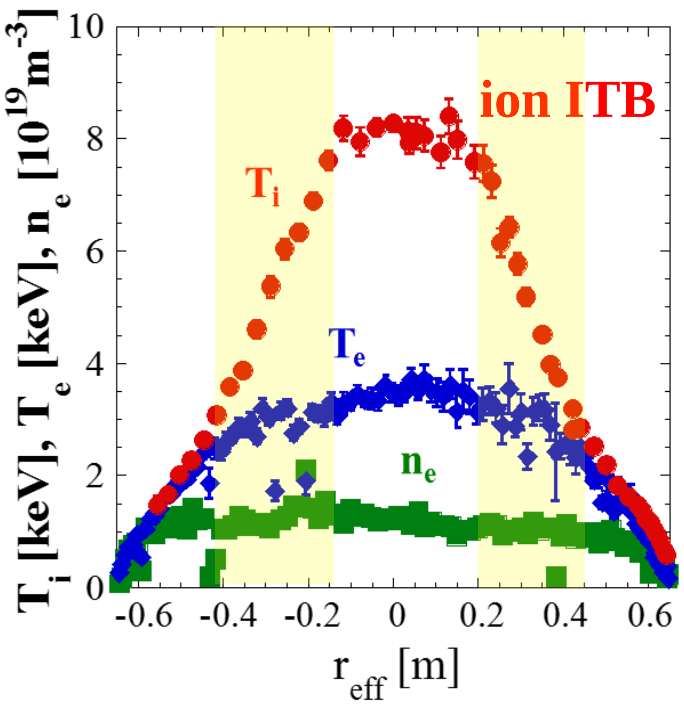
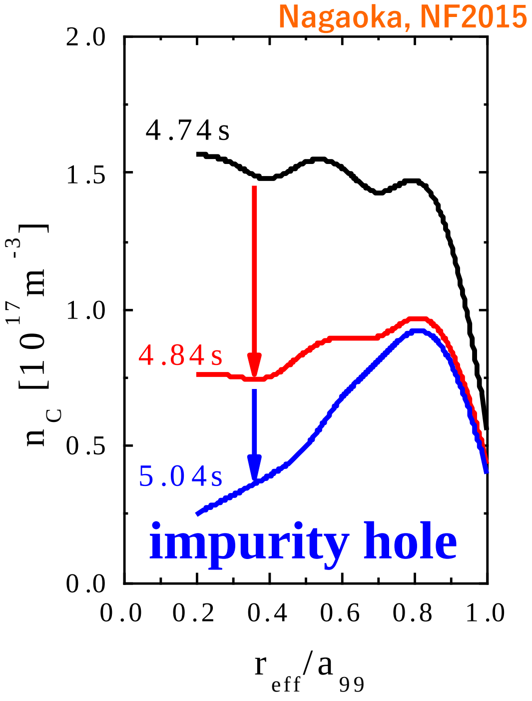
   - Nonlinear transport simulation (GKV)
4. Summary

Ion ITB formation in helical plasmas

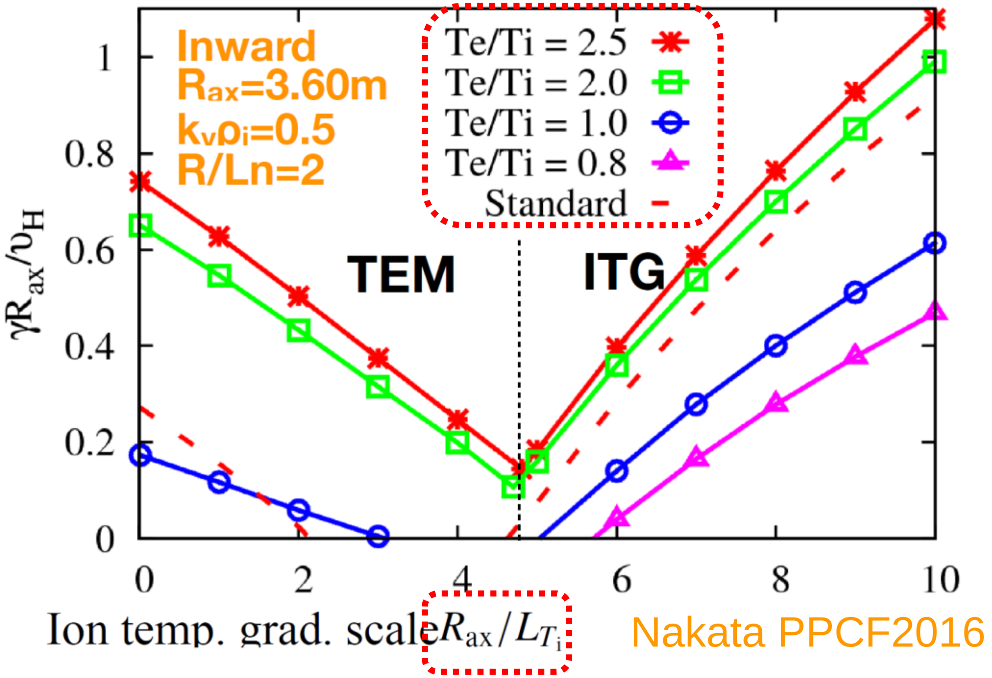






- The T_i is higher than the T_e in the core of NBI heated plasma.
- The peaked T_i profile with steep gradient (**ion ITB**) formed, and no ITB was observed in the T_e and density profiles.
- Significant reduction of anomalous ion heat transport with E_r<0 (ion-root).
- Carbon impurity was expelled from the core (**Impurity hole formation**)

ITG is dominated in high-T_i plasmas in LHD



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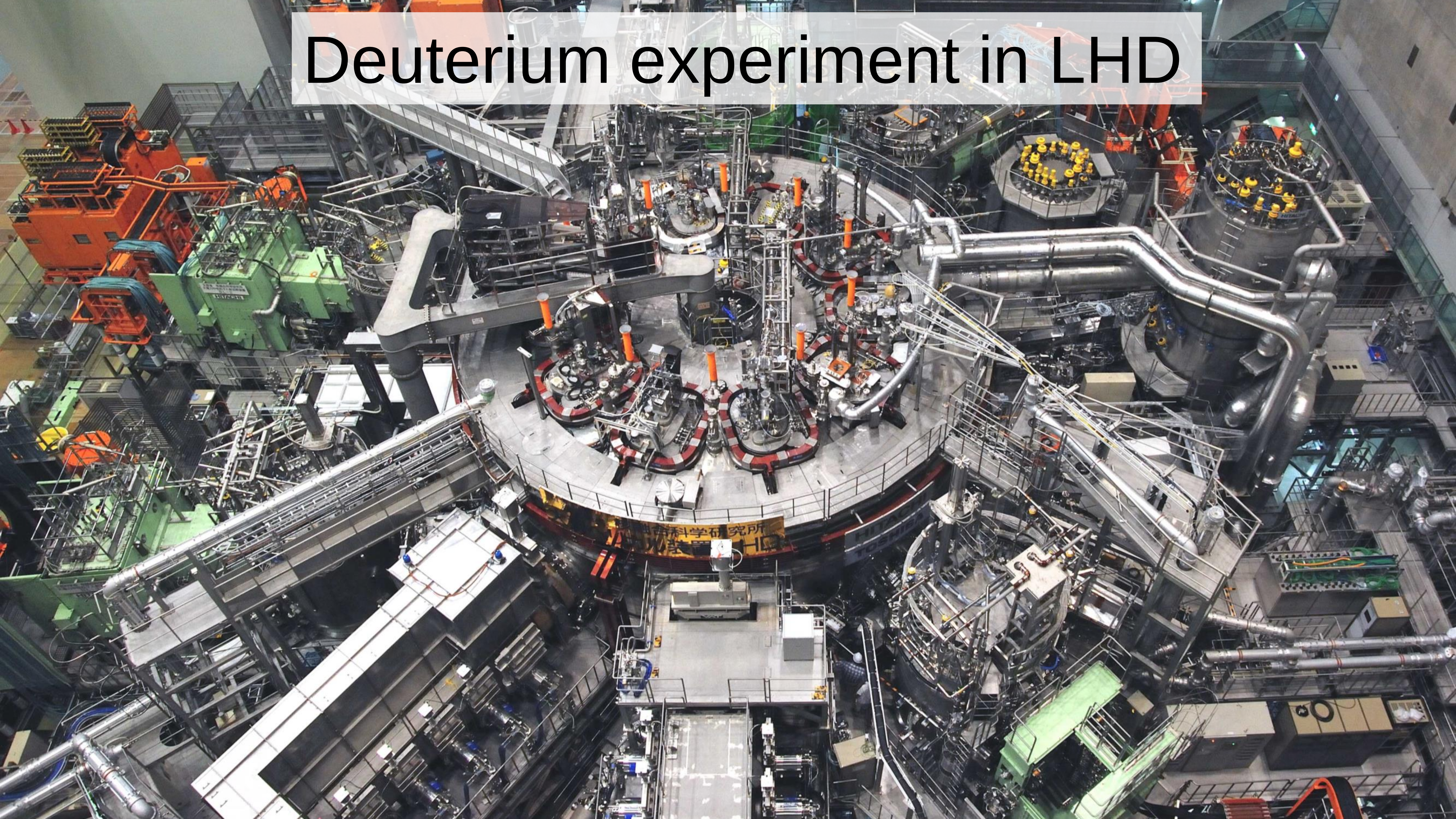
Gyrokinetic Vlasov code (GKV)
- 5 dimensions in phase space
- local flux tube
- Inward shifted LHD plasmas

In high-T_i regime (R/L_{Ti}~10), **ITG mode** is the most unstable

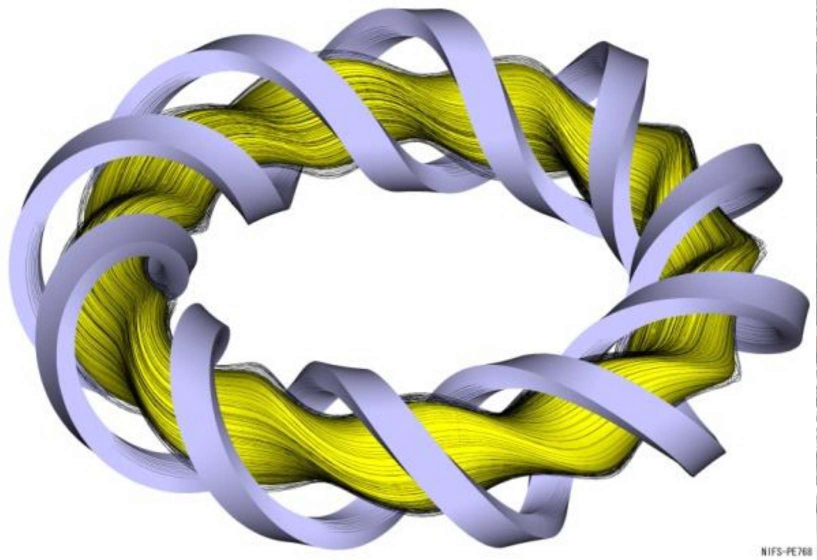
- Growth rate increases with R/L_{Ti} (= $-(R/T_i)(dT_i/dr)$)
- Growth rate increases with T_e/T_i as well

=> Therefore, we focus on R/L_{Ti} and T_e/T_i dependence

Deuterium experiment in LHD

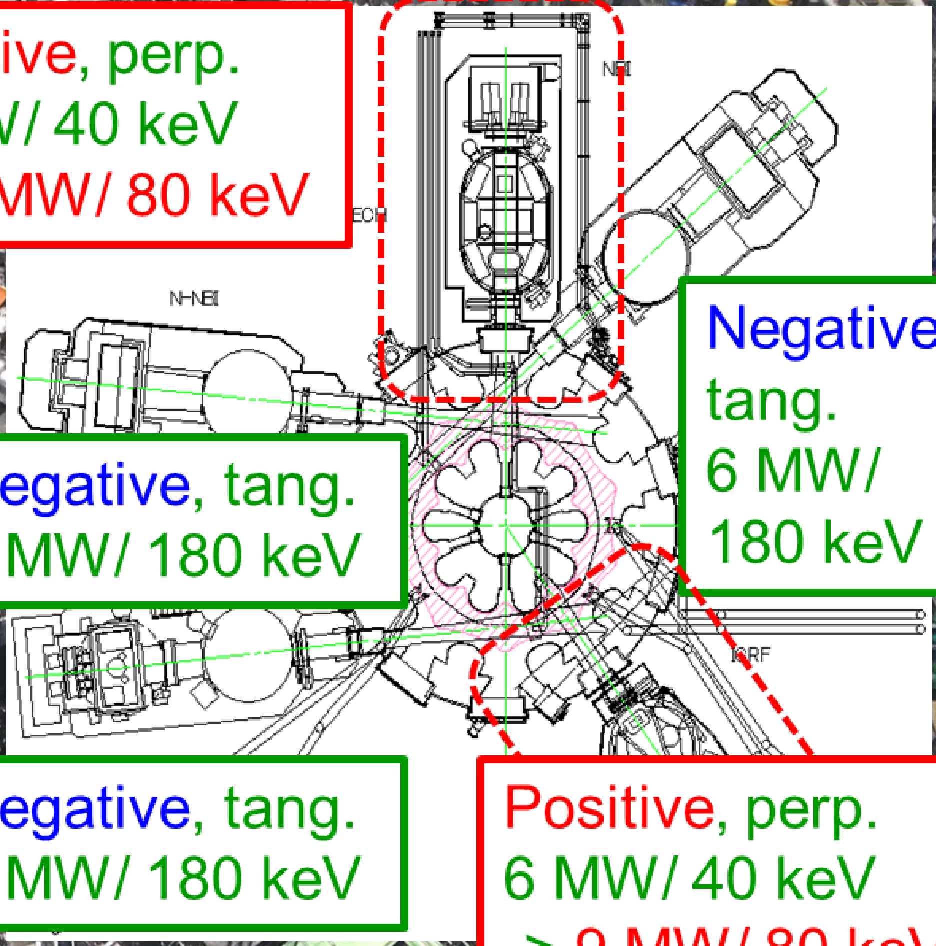


Deuterium experiment in LHD



Specifications

- Helical mode numbers: *l*/*m*=2/10
- All superconducting coil system
- Plasma major radius: 3.42-4.1 m
- Plasma minor radius: 0.63 m
- Plasma volume: 30 m^3
- Toroidal field strength: 3 T
- 20 RMP coils



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

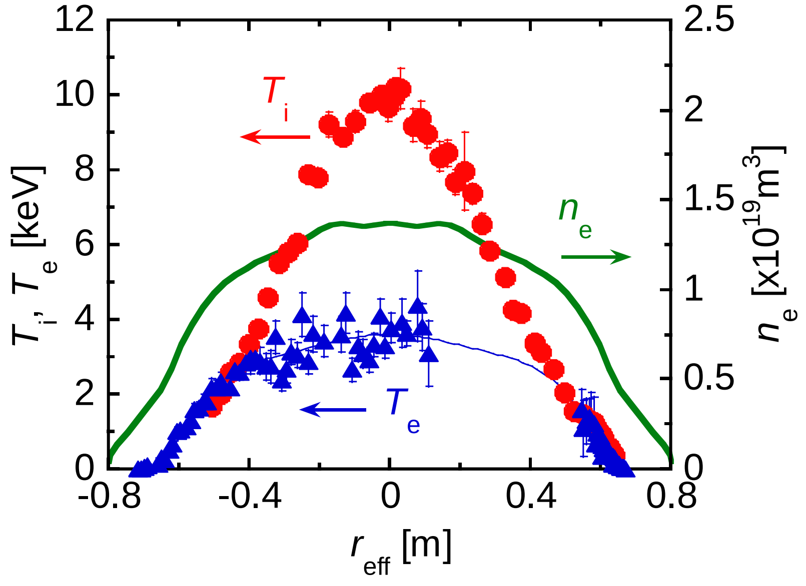
Negative, tang.
6 MW/
180 keV

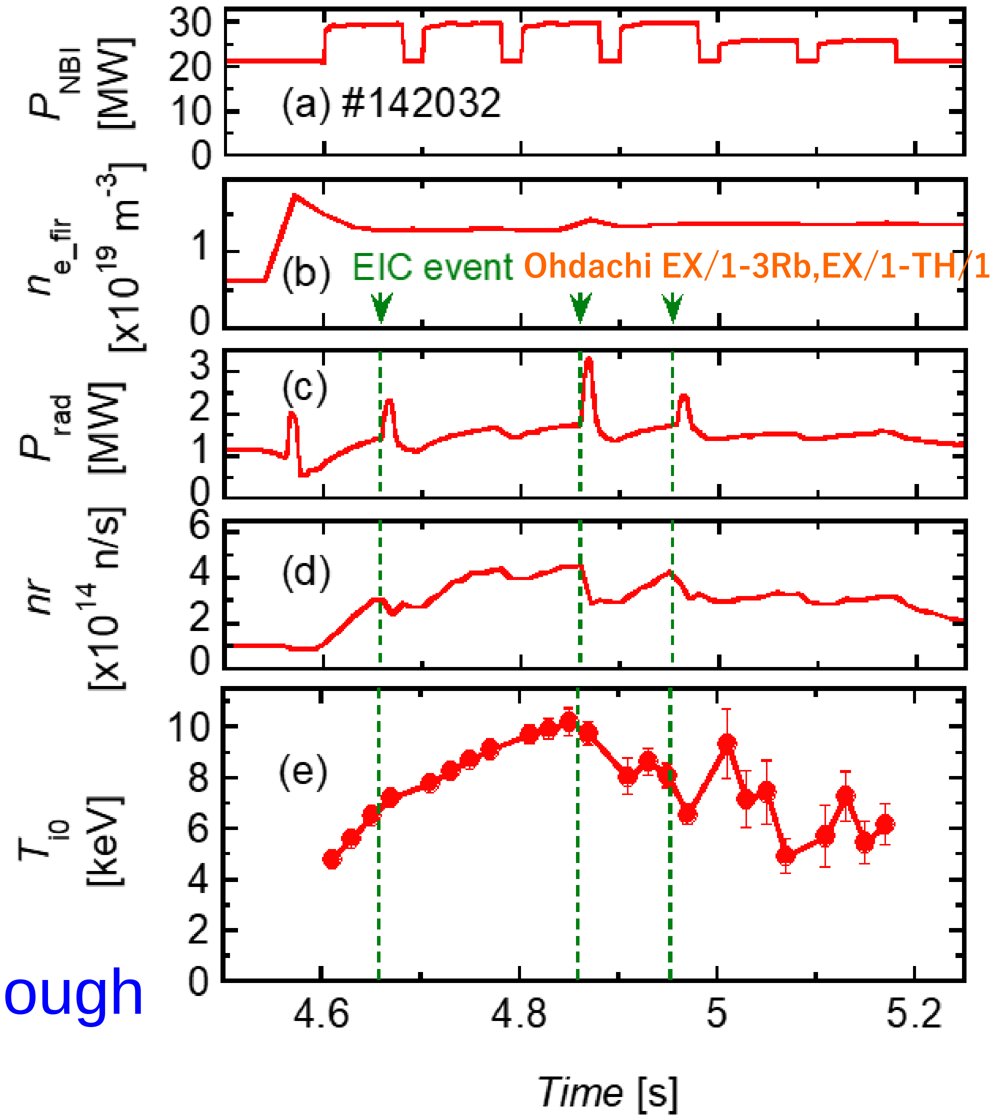
Negative, tang.
5 MW/ 180 keV

Negative, tang.
5 MW/ 180 keV

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

Extension of high-T_i regime（T_{i0}=10keV）

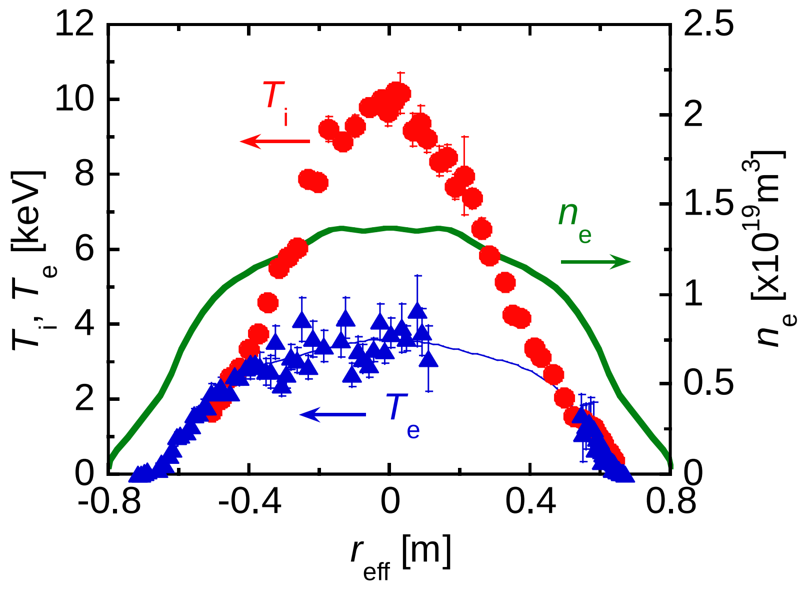


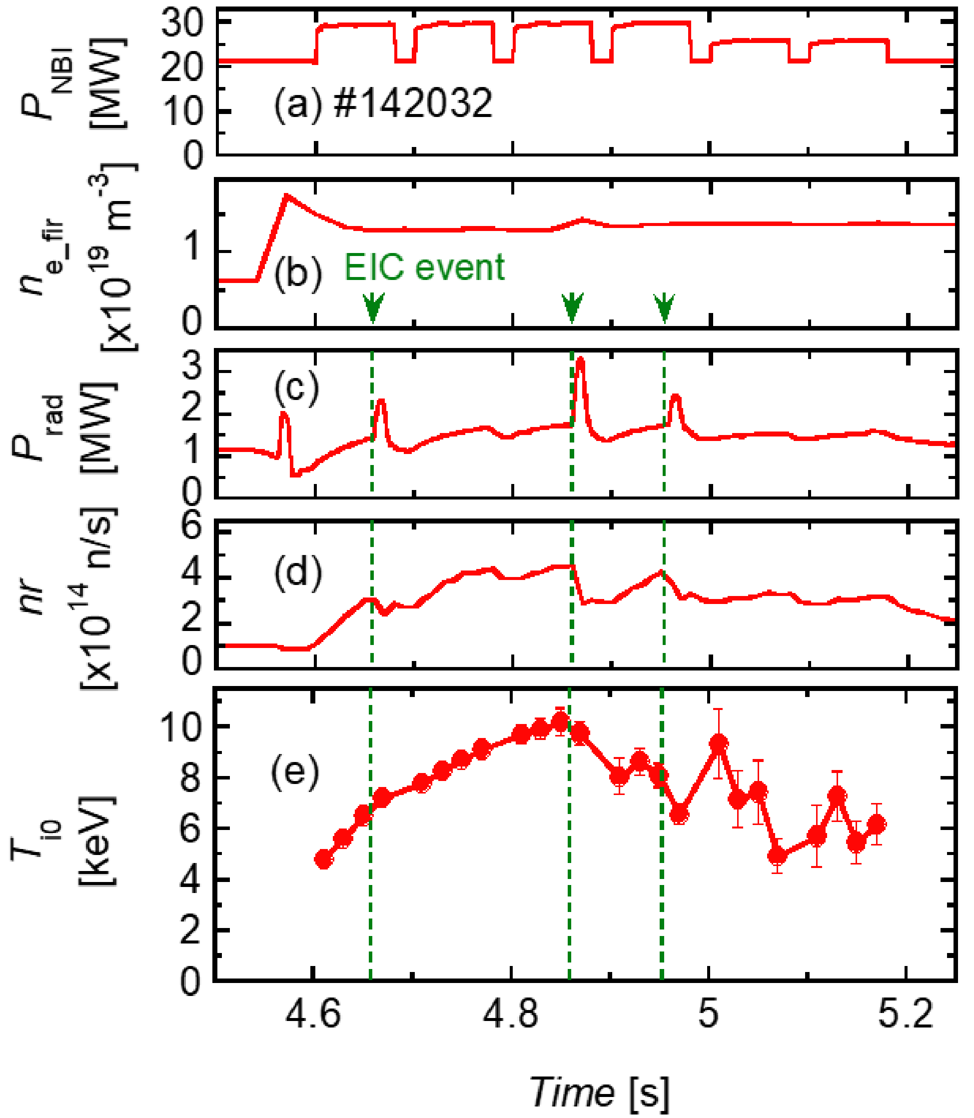


- T_{i0}=10keV ±0.2keV（Z_{eff}=~2）was achieved
- C pellet + He gas puff
- D beams（p-NBI）+ H beams (n-NBI)
- MHD bursts (EIC) degraded the neutron rate and T_{i0}

The ion heat transport with D is improved, although the D ion ratio is roughly 30% of ion density.

Extension of high-T_i regime（T_{i0}=10keV）





In order to evaluate the transport in more detail and discuss isotope effect, pure H plasmas and pure D plasmas are analyzed in this study.

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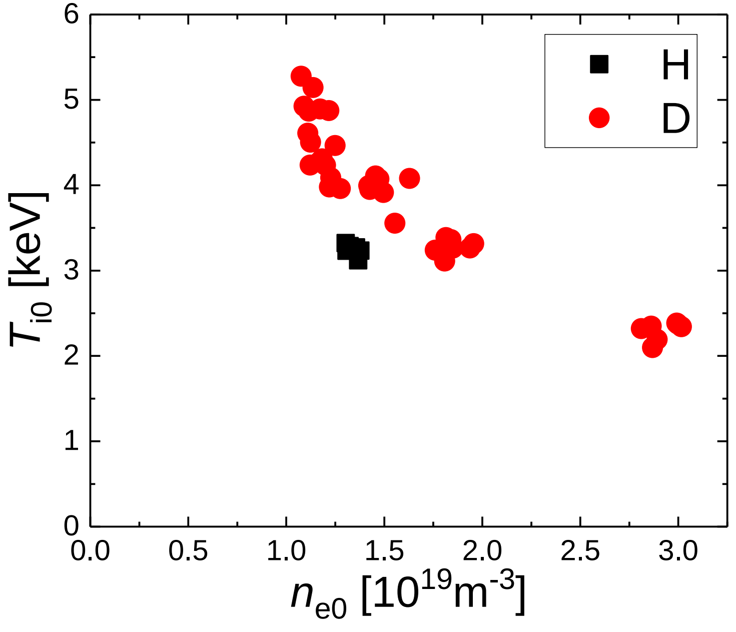
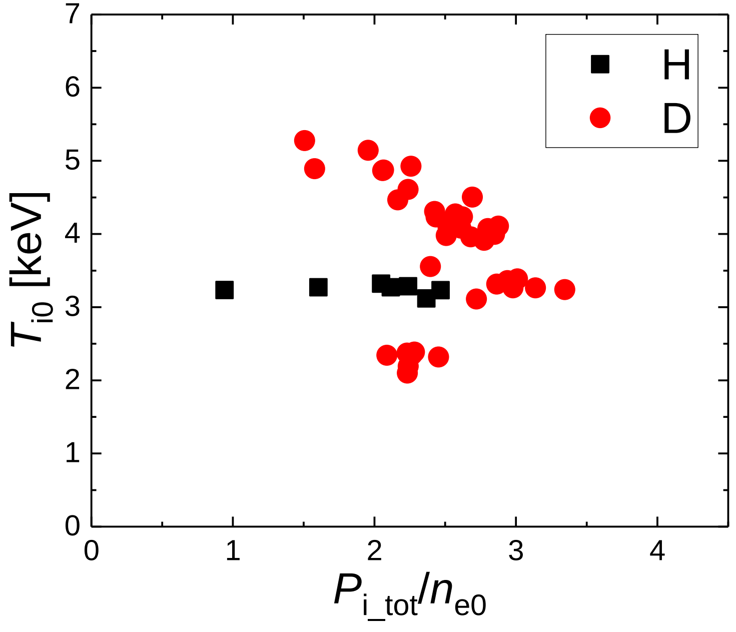
Pure Hydrogen and Pure Deuterium plasmas

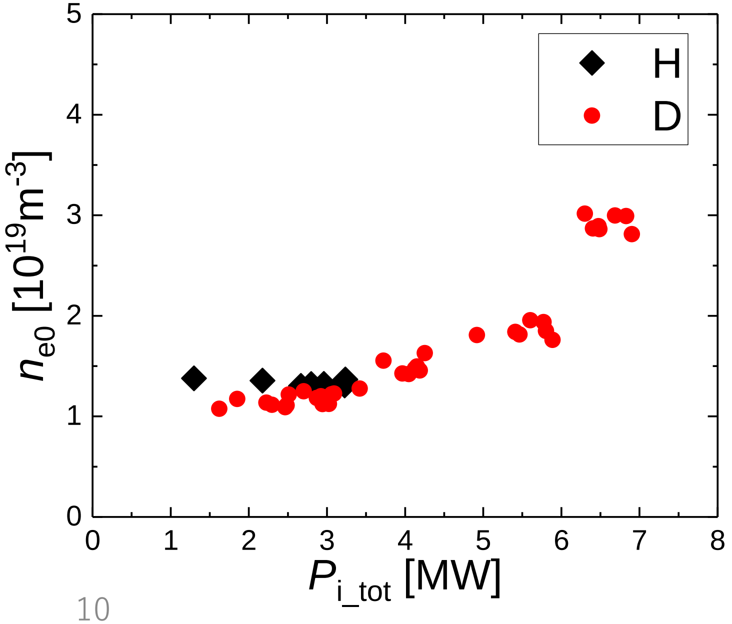
Target plasmas analyzed in this study are High Purity of ion species

H plasma: $n_H/n_e > 0.80$ with H gas puff + H beams

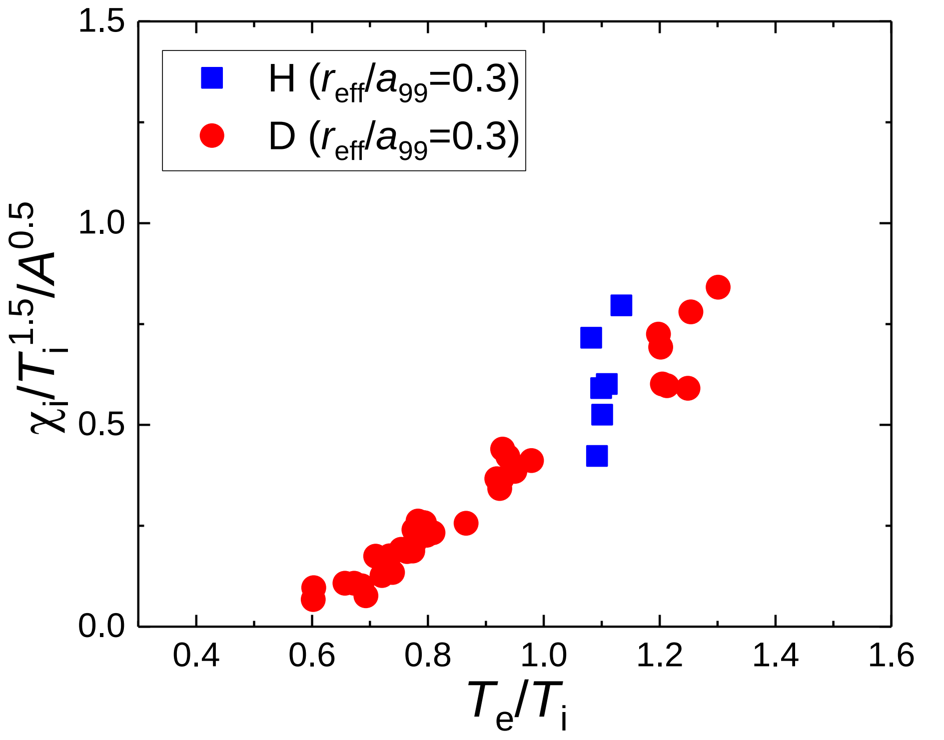
D plasma: $n_D/n_e > 0.80$ with D gas puff + D beams

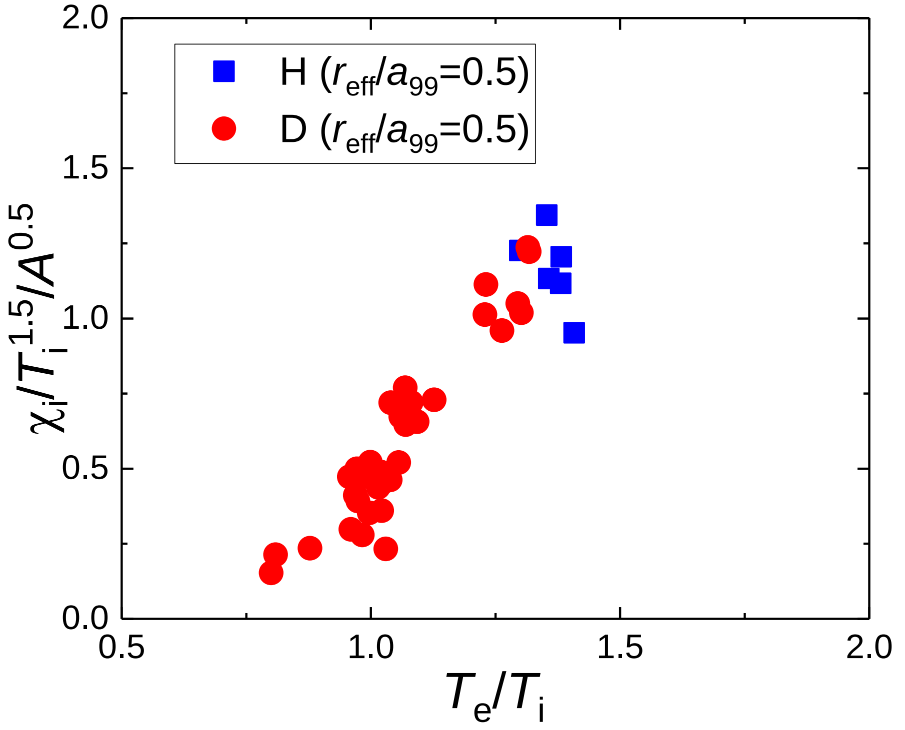






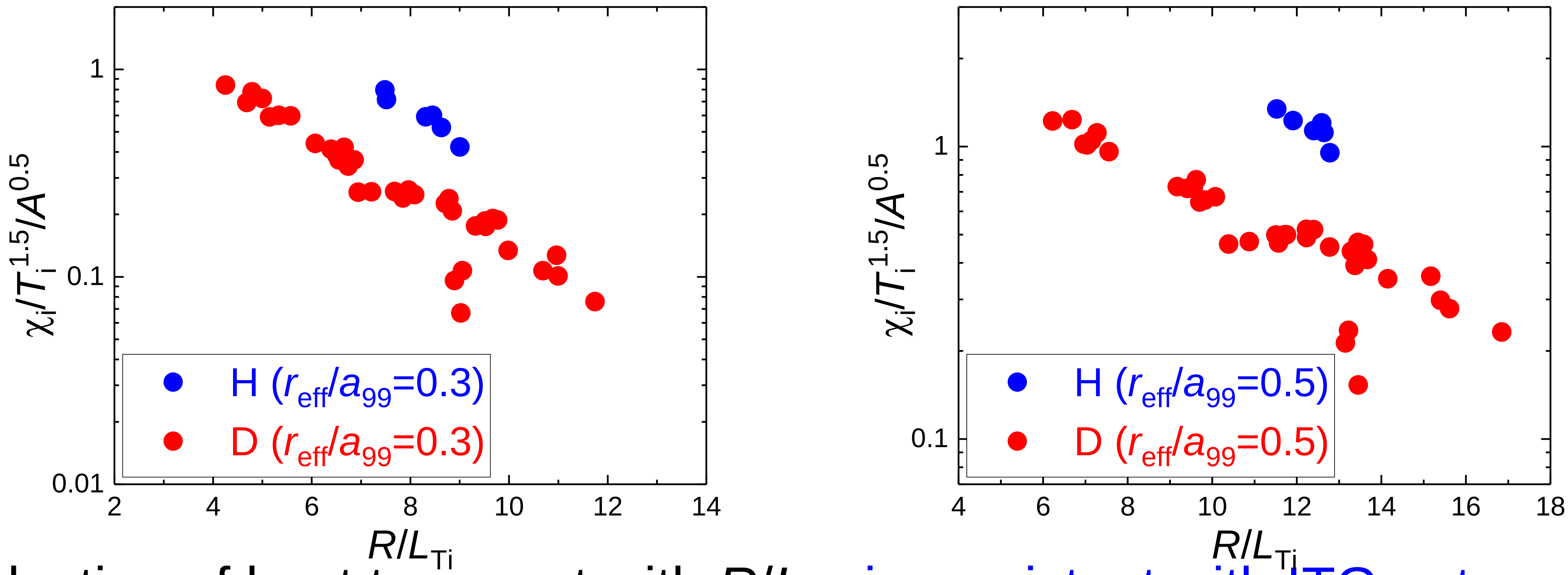
ITG like T_e/T_i dependence





- Significant increase of heat transport depending on T_e/T_i
  ＝＞ consistent with ITG turbulence
- No significant difference in T_e/T_i dependence between H and D plasmas

Transport suppression with (R/L_{Ti})



- Reduction of heat transport with R/L_{Ti}, inconsistent with ITG nature
  ＝＞ion ITB formation
- Transport suppression in D plasmas
  ＝＞another mechanism of transport suppression depending on ion mass

Turbulent suppression depending on ion mass and R/L_{Ti}

Radial electric field shear（ExB poloidal rotation）

$$\bar{\gamma}_{\mathrm{ExB}} = |dv_{\mathrm{ExB}}/dr|(R/v_{\mathrm{ti}})$$ Burrell PoP1997, Jolliet NF2012

$$\propto \rho^* \partial_\rho((k-1)R/L_T - R/L_n)/\partial\rho + (a/R)\partial_\rho\left(U_{||}/v_{\mathrm{ti}}\right)$$

- stabilization mechanism for both ITG and TEM
- finite Larmor radius effects may appear in high-Ti plasmas

  $\rho^*_{D:10\mathrm{keV}} = 1/90,\ \rho^*_{H:10\mathrm{keV}} = 1/130$

  ＝＞ ion mass dependence

The ExB shear is a potential candidate of physics mechanism of turbulent suppression, although it should be confirmed by further experiments and global transport simulations in near future.

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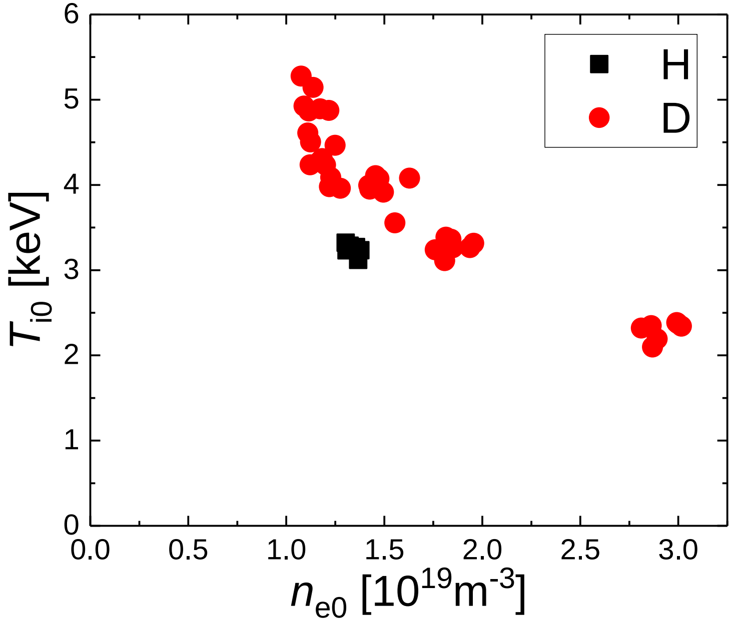
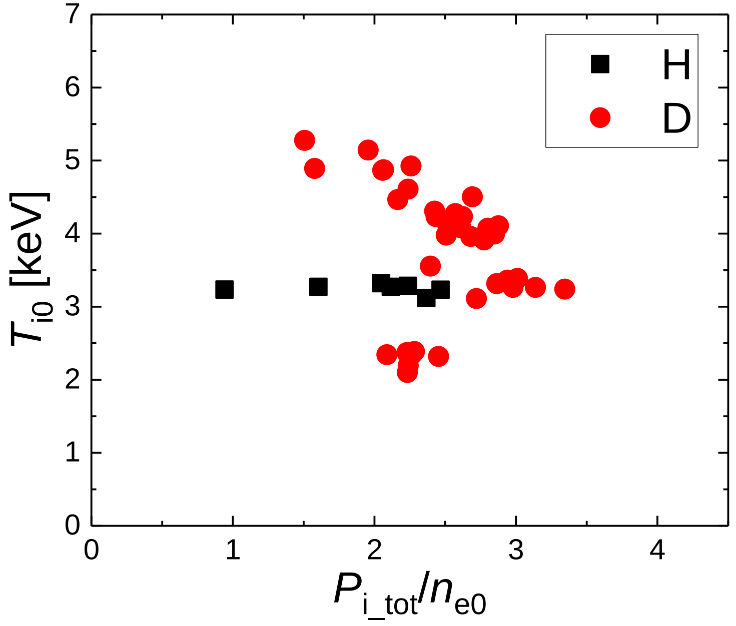
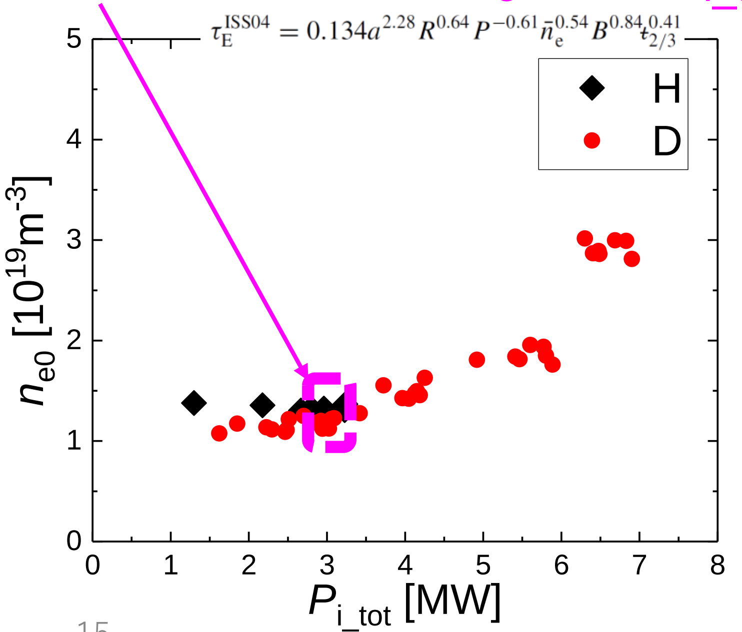
D plasma: $n_{\mathrm{D}}/n_{\mathrm{e}} > 0.80$ with D gas puff + D beam

Comparison with the same n_{e} and $P_{\mathrm{i\_tot}}$

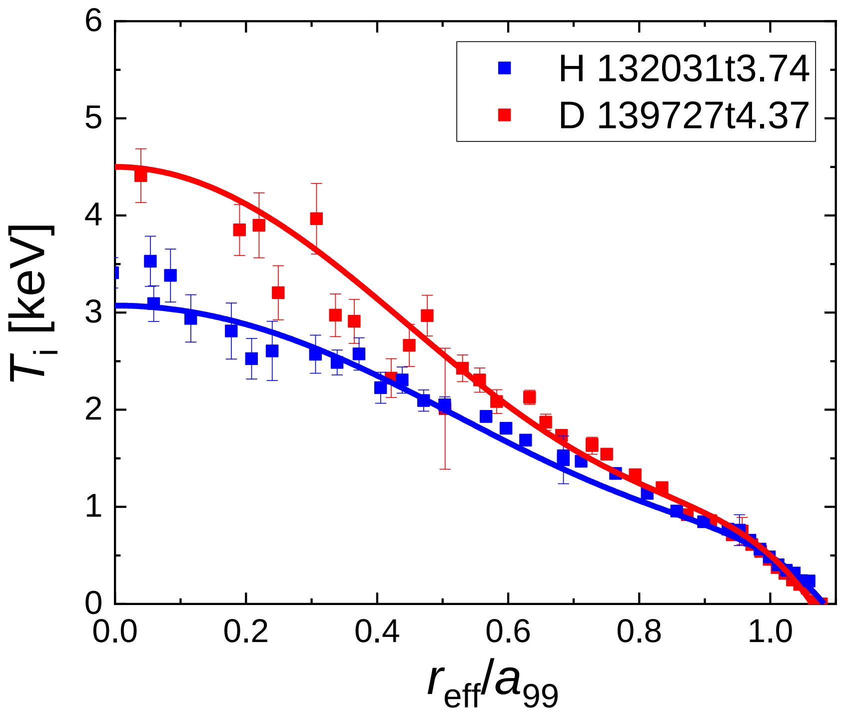


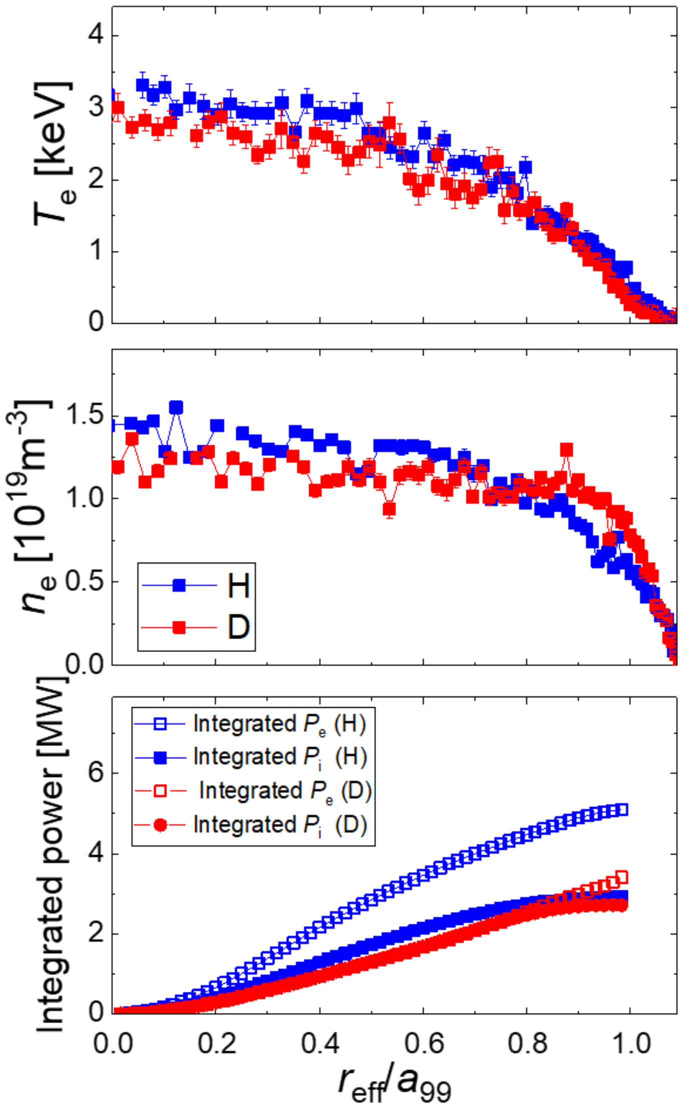




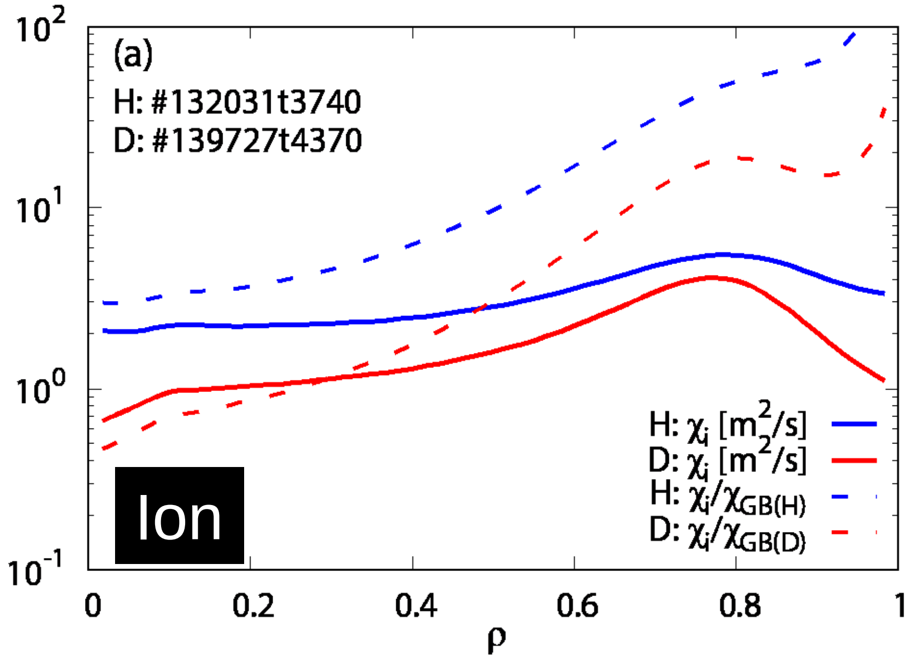
Comparison between H plasma and D plasma

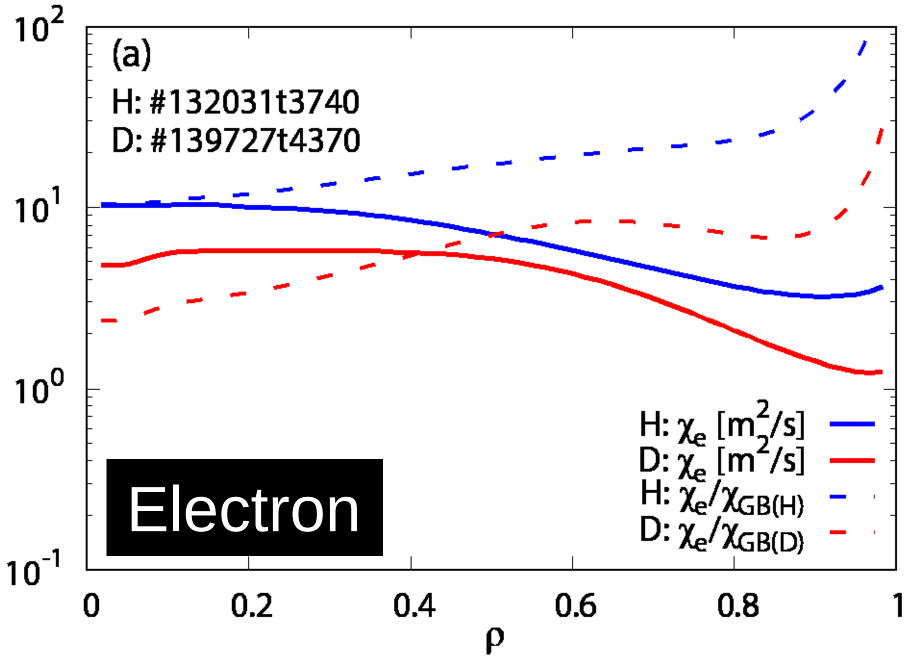
- Higher T_i in D plasma
- Steeper density gradient in the edge of D plasma
- Larger electron heating power in H plasma with a factor of 1.5
  =>higher T_e (20-30%)

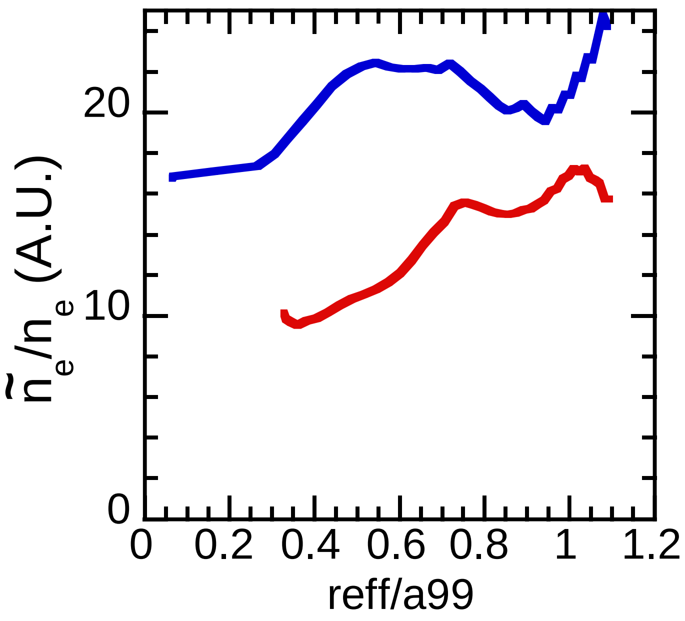




Transport analysis



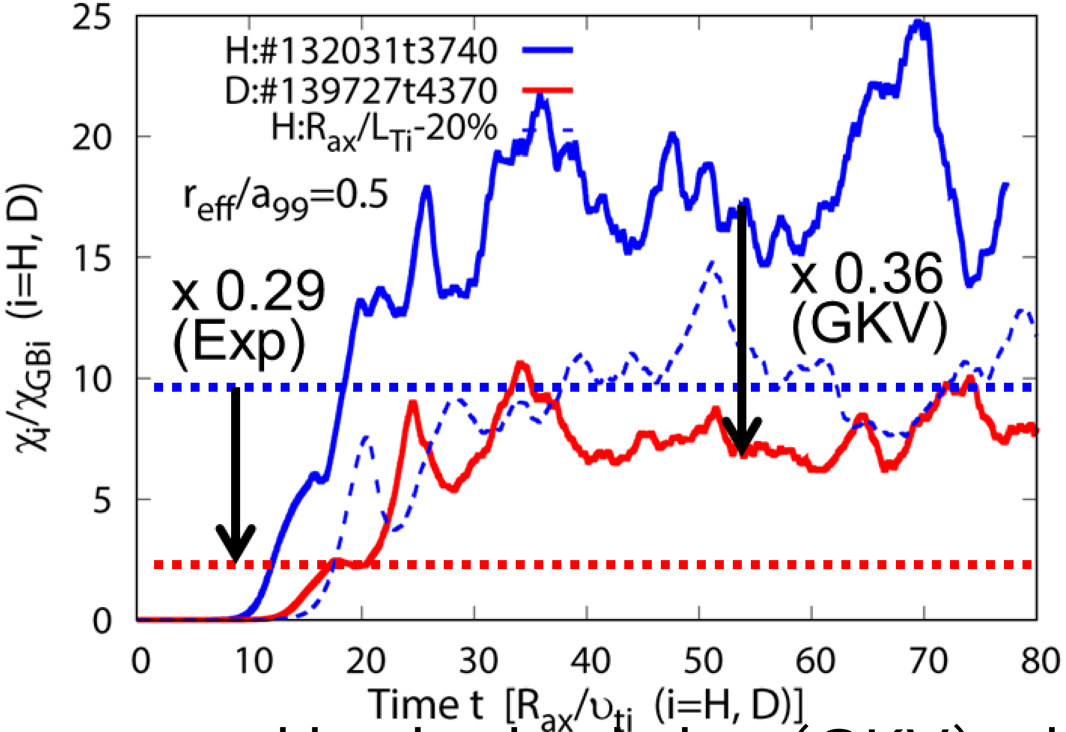


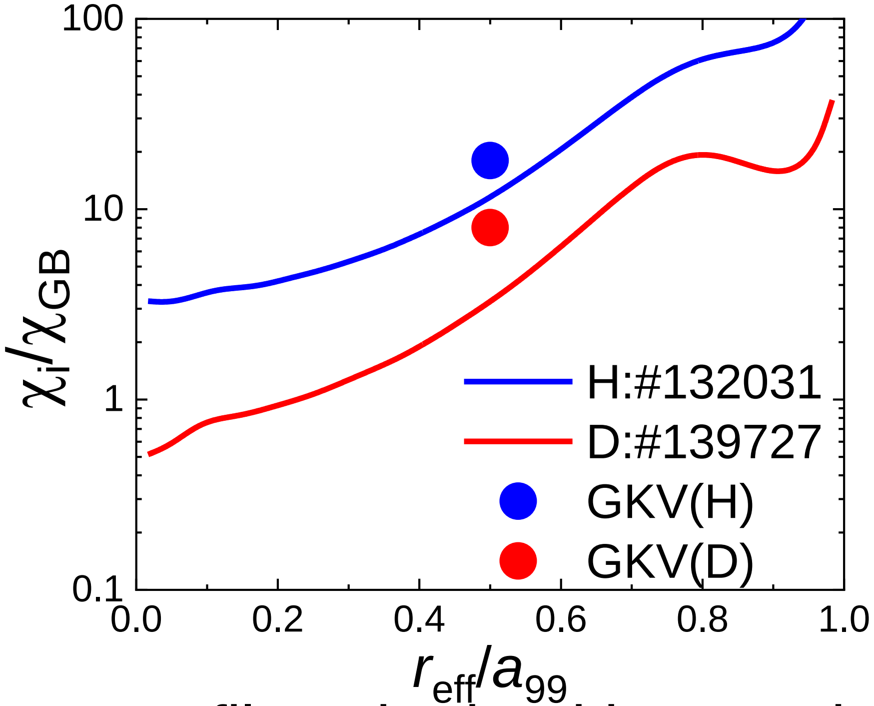


- Significant reduction of the ion heat transport in the core of both plasmas
  ＝＞Ion ITB formations
- Smaller heat transport in D plasma
- Density fluctuation (PCI) is smaller in D plasma
  ＝＞correlating with heat transport

Nonlinear GK simulations under Exp. conditions

Nakata EPS2018 &PPCF2018





Nonlinear gyrokinetic simulation（GKV）with plasma profiles obtained in experiment

- Destabilization of ITG mode and nonlinear saturation
- Transport level is reproduced with the accuracy of 20% in T_i gradient

  => Global effects such as Er-shearing will improve the discrepancy
- Reproduce the reduction of ion heat transport in D plasma

Nonlinear GK simulations under Exp. conditions

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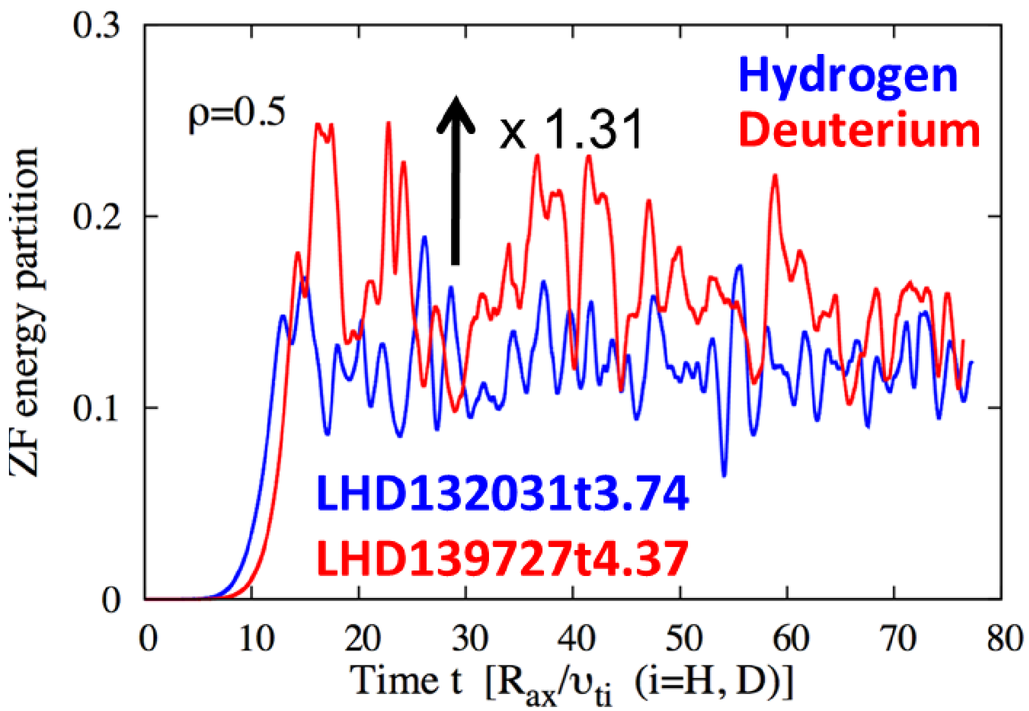
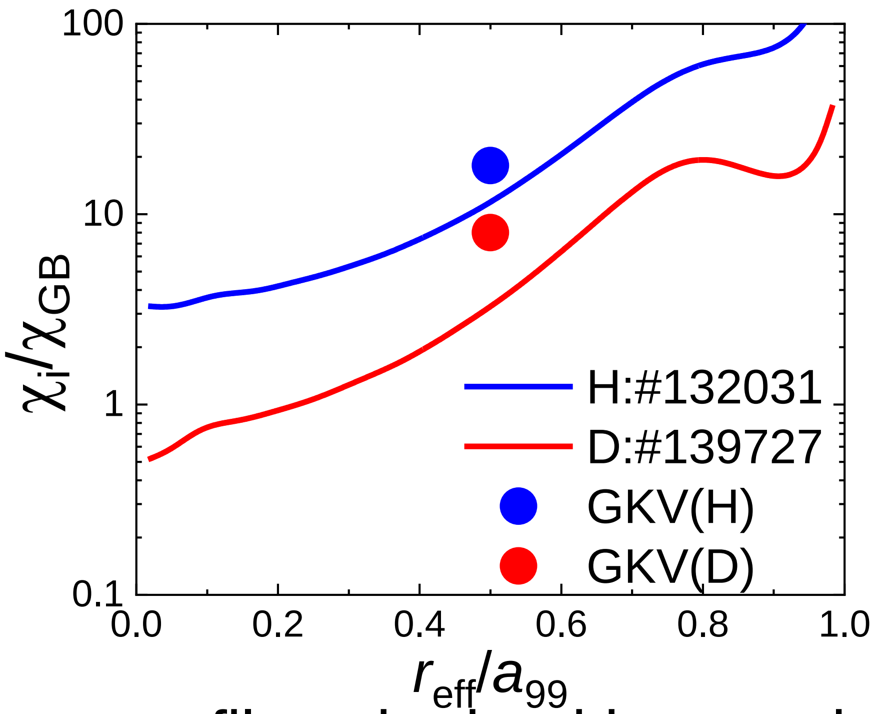




Nonlinear gyrokinetic simulation（GKV）with plasma profiles obtained in experiment

- ZF energy partition is larger in D plasma with factor of 1.3

  => ZF enhancement may contribute the transport reduction in D plasmas

Summary

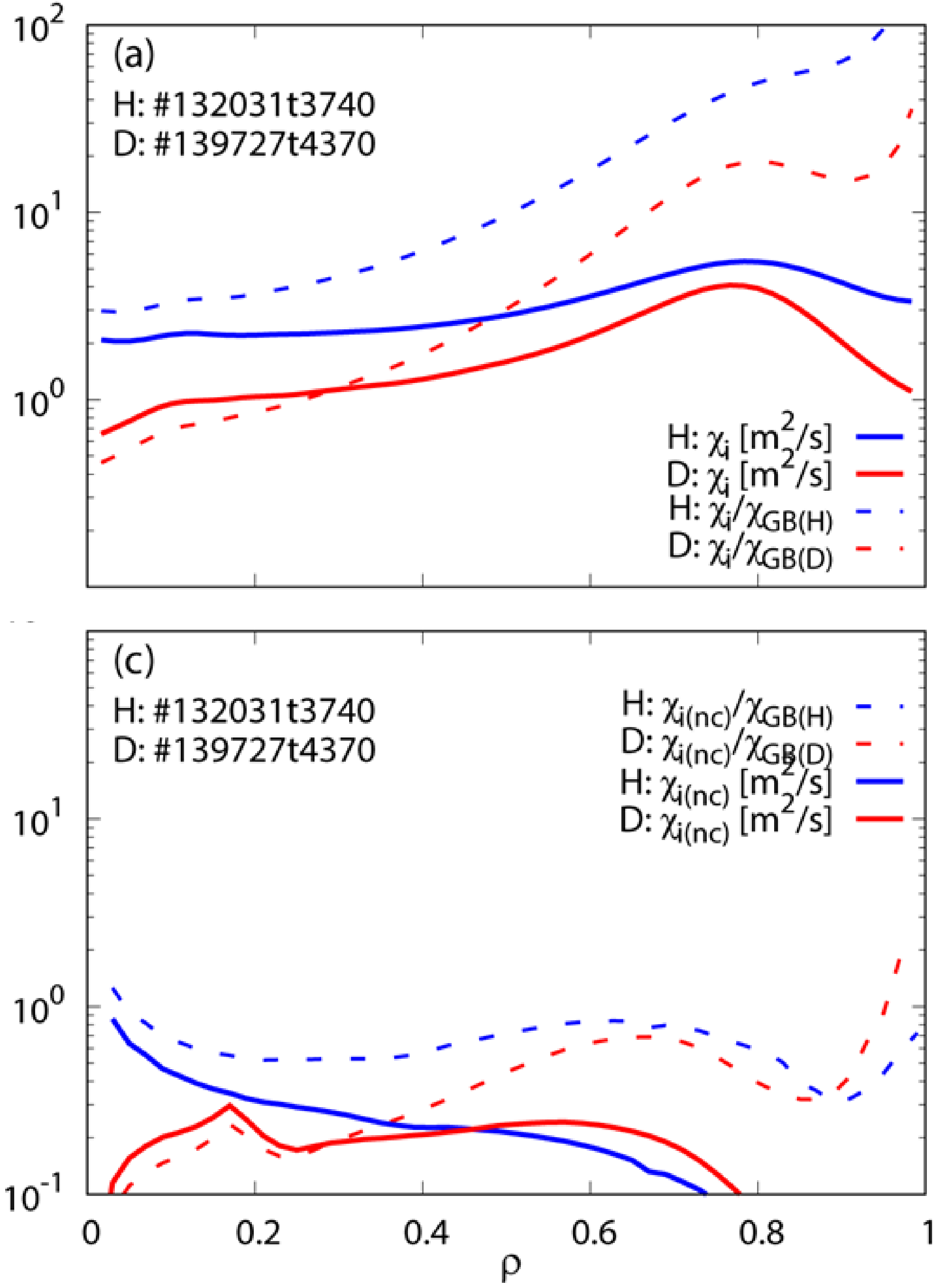
- In D experiments in LHD, ***T_{i0}*=10keV** was achieved, and transport analyses of Ion ITB plasmas and isotope effect were discussed.
- On Ion ITB formation
  - ✓ T_e/T_i dependence is ITG-like
  - ✓ Transport reduction with R/L_{Ti}
    ＝＞ ion ITB
    ＝＞ suggesting the improvement with ExB shear
- On isotope effect
  - ✓ Ion heat transport reduction in D plasma
  - ✓ Nonlinear sim.（GKV）reproduced the reduction of χ_i in D plasma, and observed the increase of ZF

These mechanisms contribute to the achievement of T_{i0}=10 keV in the helical plasma

Thank you for your attention!

Neoclassical transport

- Neoclassical transport calculation with FORTEC3D
- The solution with Er > 0 was obtained, and should be checked experimentally
- The NC transport is smaller than experimental evaluation
  => turbulent dominates the transport
- The difference of NC transport between H and D plasma is smaller and cannot explain the experimental observation



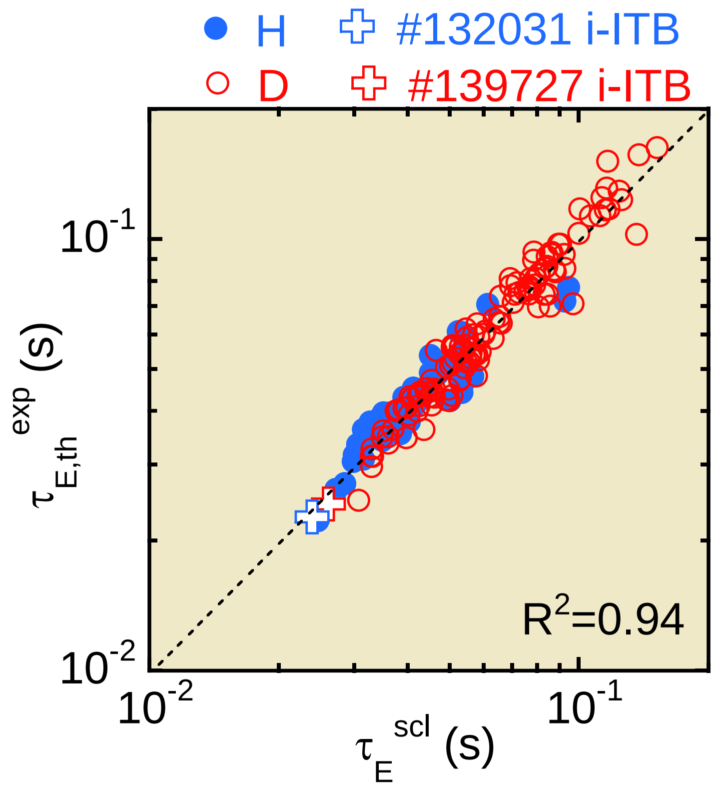
Strategy of evaluation of isotope effects in LHD

Global confinement

Scaling of confinement time

$$\tau \sim A^{x_1} \cdot \rho_*^{x_2} \cdot \nu_*^{x_3} \cdot \beta^{x_4}$$

- wide parameter regime



Local transport

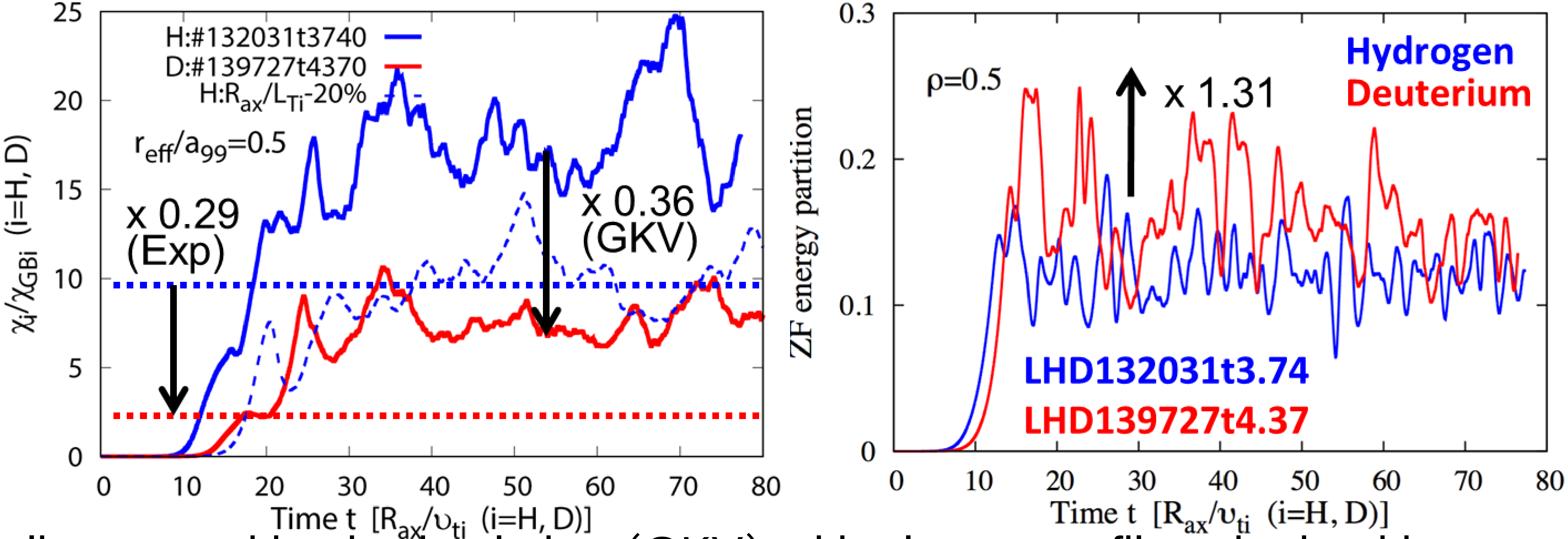
Dependence on local parameters, their gradients

$$\chi \sim A^{x_1} \cdot \rho_*^{x_2} \cdot \nu_*^{x_3} \cdot \beta^{x_4} \cdot (T_e/T_i)^{x_5} \cdot (R/T_T)^{x_6} \cdot (R/T_n)^{x_7} \cdots$$

- underlying physics
- excellent profile measurement

Nonlinear GK simulations under Exp. conditions

Nakata EPS2018　&PPCF2018



- Nonlinear gyrokinetic simulation（GKV）with plasma profiles obtained in experiment
  - => Destabilization of ITG mode and nonlinear saturation
  - => Reduction rate of heat transport reproduced the experiment
  - => ZF energy partition is larger in D plasma with factor of 1.3
- Global effects such as Er-shear effect will improve the discrepancy in the heat transport