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Hydrogen isotope effect on H-mode in JT-60U
JT-60UのHモードにおける水素同位体効果

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The effects of hydrogen isotope on H-mode confinement and edge pedestal structure in JT-60U are summarized. The thermal energy confinement time is longer by 20-30% for deuterium than for hydrogen at a given absorbed power. At a given stored energy, spatial profiles of electron density, electron temperature, and ion temperature become identical between these two cases. However, the power required to sustain the identical profiles is twice larger for hydrogen than for deuterium, leading to larger heat diffusivity at the plasma core. Ion temperature gradient scale length for deuterium is smaller than for hydrogen. Hydrogen isotope enables us to investigate the physics picture which cannot generally be drawn as far as experiments are conducted with only one ion species. The characteristics of dimensionless parameters, isotope mass dependence of which exists only in $\rho*$, can break the strong correlation between β and $\rho*$ at the pedestal. This approach revealed that the pedestal width was not varied by $\rho*$ but determined by $\beta^{0.5}$.

1. Introduction

The knowledge of the influence of plasma isotopic composition on heat conduction in steady H-mode plasmas has important consequences from both physics and engineering points of view. The effects of the isotope mass M on energy confinement have been extensively studied in the late 1980s and the early 1990s. While many experimental results have focused particularly on ohmic and L-mode plasmas, there are also several results on the isotopic comparison for the case of H mode plasmas. In ASDEX, the ratio of the energy confinement time of deuterium to hydrogen becomes 1.5–2 in H-mode plasmas [1,2]. In DIII-D, the energy confinement time scales as M/Z_i^2, where Z_i denotes the ionic charge, indicating the superiority of deuterium confinement to hydrogen in H-mode plasmas [3]. In TFTR, the H-modes produced in deuterium–tritium plasmas have energy confinement enhancement larger by a factor of ~ 1.25 than the corresponding deuterium plasmas [4]. In JET, the energy confinement time in ELMy H modes shows very weak mass dependence ($\tau_{th} \propto M^{0.03}$) [5].

For all discharge types, energy confinement increases with isotope mass $\tau_{th} \propto M^{\zeta}$ with the exponent ζ greater than 0. However, little is known about the process responsible for energy confinement through variation of the isotopic composition. Herein, therefore, the effect of hydrogen isotopes on heat transport and the pedestal structure is characterized using hydrogen and deuterium H-mode plasmas in the JT-60U tokamak [6,7].

In the present understanding, H-mode confinement is characterized by separation into pedestal and core components. In many cases, both components are strongly correlated. The pedestal component plays a role as a boundary condition in determining the core heat transport through profile stiffness. On the other hand, a higher β_p improves stability of the plasma edge in the low magnetic field side. On the basis of this background, this study presents dependence of heat transport on the hydrogen isotope mass in conventional H-mode plasmas from the viewpoint of the TG scale length of ion temperature profiles at the plasma core.

2. Energy confinement in JT-60U tokamak

Dependence of confinement quality on isotopic composition was investigated for conventional H-mode plasmas in JT-60U. The thermal energy confinement time τ_{th} increases by a factor of approximately 1.2-1.3 for deuterium compared to that for hydrogen at a given heating power P_L [6]. When the thermal stored energy W_{th} was fixed, profiles for electron density n_e, electron temperature T_e, and ion temperature T_i became identical for both cases, whereas a higher heating power was required for hydrogen. The ion conductive heat flux Q_i for hydrogen became approximately two times that for deuterium,

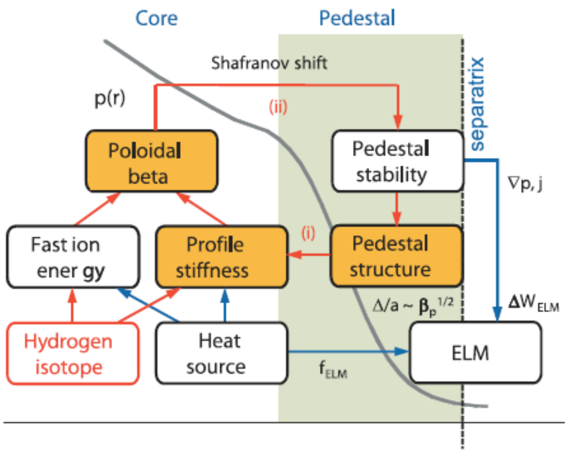

Fig.1: Schematic view of the influence of hydrogen isotopic composition on energy confinement in conventional ELMy H-mode plasmas involving the relation between edge pedestal structure and core heat transport.

corresponding to a required heating power to sustain the same W_{th} value that was two times as large for hydrogen. Hence, the ion heat diffusivity χ_i values for hydrogen were higher, explicitly throughout the minor radius, than those for deuterium at the same ion temperature gradient scale length L_{Ti}. The $\nabla T_i/T_i$, or the inverse of L_{Ti}, required for a given χ_i increased by a factor of approximately 1.2 for deuterium compared to that for hydrogen. These results lead to the conclusion that L_{Ti} decreases as the hydrogen isotope mass increases (hydrogen to deuterium) in H-mode plasmas [8].

The self-regulating physics mechanism determining the overall H-mode confinement was also investigated. The relationship between the total poloidal beta β_p^{TOT} and the pedestal poloidal beta β_p^{ped} was nearly identical, irrespective of the difference in isotope species, suggesting that a greater pedestal pressure observed for deuterium H-modes be obtained from a greater β_p^{TOT}. In addition to a smaller χ_i or L_{Ti} for deuterium contributed by the thermal component, the fast ion energy determined by the slowing down time of high energy ions $\tau_s \propto M^{1/2}T^{3/2}/n$ is one of the key factors leading to a greater β_p^{TOT} for deuterium [7].

3. Dimensionless parameter dependence of pedestal width

While the understanding of the physics behind the constraint of the edge pressure gradient has progressed, what determines the pedestal width has also intensively been addressed from the perspective of the dimensionless parameters. Various models of the pedestal width, based on $\boldsymbol{E}\times\boldsymbol{B}$ shearing suppression of the edge turbulence, predict an unfavorable size scaling of the pedestal width which becomes larger with the ion poloidal gyro radius ρ_{pi} [9]. However, the existence of ELMs can be a constraint to performing the dimensionless analysis on the pedestal width. Assuming the pedestal pressure is limited by ELMs to scale with I_p^{ξ}, the trajectory along a given normalized pedestal collisionality $\nu*$ ($\sim n/T^2$) reduces $\beta_{p,ped}$ ($\sim nT/I_p^2$) to $I_p^{\xi-2}$ and ρ_p* ($\sim T^{1/2}/I_p$) to $I_p^{\xi/6-1}$. Empirically, the exponent ξ ranges 1.0–1.5 in many devices. Then, the strong correlation of $\beta_p \propto \rho_p*^{0.67-1.2}$ has led in the past to difficulties in testing these models experimentally.

In order to solve the problem of the strong correlation generally existing between β_p and ρ_p*, one method is the experiment for the edge dimensionless analysis using hydrogen isotope species of hydrogen and deuterium. This approach is based on the isotope mass dependence that exists only in ρ_p* while the other dimensionless parameters are independent of the isotope mass, and thus the correlation between β_p and ρ_p* is broken. The experiment performed in JT-60U has shown that the pedestal width is unvaried in matched hydrogen and deuterium discharges with the same β_p, indicating that the pedestal width is not varied with ρ_p* [10]. Similar experiments were subsequently conducted in DIII-D, showing nearly no dependence of the pedestal width on ρ_p*, consistent with the JT-60U findings [11].

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