

Recent results of Deuterium Experiment on the Large Helical Device and its contribution to the fusion reactor development

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In the recent deuterium experiment on the Large Helical Device (LHD), we have succeeded to expand the temperature domain to higher region both in electron and ion temperatures as shown by the red region in Fig.1. We found a clear isotope effect in the formation of Internal Transport Barrier (ITB) in high temperature plasmas. In the deuterium plasmas, we have also succeeded to realize the formation of the Edge Transport Barrier (ETB) and the divertor detachment, simultaneously. It is found that the Resonant Magnetic Perturbation (RMP) has an important role in the simultaneous formation of the ETB and the detachment. A new technique to measure the hydrogen isotope fraction was developed in LHD in order to investigate the behavior of isotope mixed fuel ions. The technique revealed that the non-mixing state and the mixing state of hydrogen isotopes can be realized in plasmas.

One of the objective of deuterium experiment is the achievement of the reactor relevant high temperature plasmas in order to investigate the problems arising in the helical type fusion reactor. As shown in Fig.1, the ion temperature of 10keV was achieved at the electron temperature of around 4keV. This was reported at the last IAEA-FEC(FEC2018). The operational domain was extended to the direction of higher electron temperature range. The electron temperature of 6.6keV was achieved keeping the ion temperature of 10keV. For lower ion temperature plasmas ($T_{i0} \sim 7\text{keV}$), the electron temperature range was extended over $\sim 12\text{keV}$. It is found that the extension in higher electron temperature region of high ion temperature plasmas is an effective way to suppress the Energetic particle driven InterChange mode (EIC), which often prevents the access of high ion temperature plasmas in LHD. This is preferable feature for the future reactor scenario development 1.

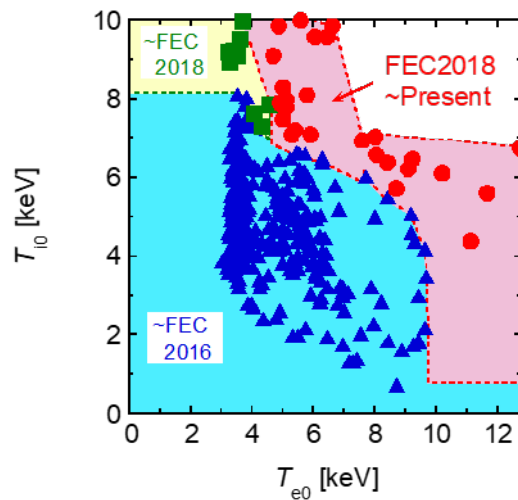


Fig.1 Achieved central ion and electron temperature domain on LHD. The blue region indicates the temperature domain achieved during hydrogen experiments. The yellow region was extended domain during the first deuterium experiment which was reported at FEC2018 and the red region is the extended region after FEC2018.

Figure 1: Fig.1 in the text

The isotope effect is a long underlying mystery in plasma physics because the most of experimental observations in tokamak plasmas show favorable effect by the ion mass on the energy confinement time (τ_E) while

the theoretical prediction based on the gyro-Bohm model shows unfavorable effect by the mass, i.e., $\tau_E \propto M^{-1/2}$. A series of dedicated experiment using dimensionally similar L-mode hydrogen and deuterium plasmas in LHD showed that the energy confinement time scaling for L-mode plasmas had a non-significant dependence on mass ($M^{0.01}$). On the other hand, a clear isotope effect was observed for the formation of Internal Transport Barrier (ITB) in LHD as shown in Fig.2. Here, the profile gain factor $G_{1.0}$ is defined as

$$G_{1.0} = \int nT(r)dV / \int nT_L^{\text{ref}}(r)dV$$

Figure 2: No figure

and T_L^{ref} is the expected temperature profile for L-mode plasmas with same heating condition. As shown in the figure, the ITB intensity, i.e., $G_{1.0}$, is clearly larger for deuterium at the density range below $2 \times 10^{19} \text{ m}^{-3}$.

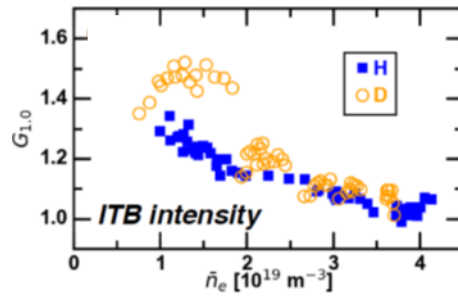


Fig.2 Density dependence of ITB intensity ($G_{1.0}$) for hydrogen (H) and deuterium (D) plasmas

Figure 3: Fig.2 in the text

The realization of both divertor heat load mitigation and the good core confinement property is an important issue in developing future reactor scenarios. For divertor detached deuterium plasmas which are realized by the RMP application, we have succeeded to improve the confinement of 38% with a formation of ETB. Thus, we call this improved confinement mode as the RMP induced H-mode. As shown in Fig.3, a steep pressure gradient was formed in deuterium plasmas at the edge region inside the $m/n=1/1$ island which was produced by the RMP. This formation of the steep edge pressure gradient with the detachment has never been observed in hydrogen plasmas. The thermal transport analysis based on TASK3D-code shows significant reduction in the thermal diffusivity at the edge region ($r/a \approx 0.8$) which indicates the formation of ETB.

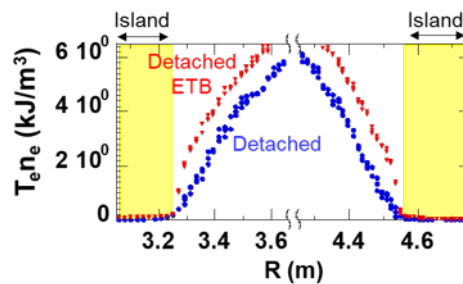


Fig.3 Radial profiles of edge plasma pressure in deuterium plasmas with RMP application, at detached phase (blue) and detached ETB phase (red), respectively. Edge magnetic island region is indicated with yellow color.

Figure 4: Fig.3 in the text

In the future fusion reactor, the deuterium (D) and tritium (T) ions co-exist in plasmas and are assumed to be uniformly mixed with the ratio of D/T=1. On the other hand, it is not clear whether this assumption is always valid. To clarify the assumption, experiments to investigate the isotope mixing state were performed using Deuterium and Hydrogen mixture plasmas. It was found that the non-mixing state of isotopes can be realized when the centrally fuelled ion species are different from the ion species fuelled at the edge. Figure 4 shows a typical example of the non-mixing state where the tangential NBI fuels Hydrogen ions in the central region while the Deuterium is supplied at the peripheral region by a wall recycling (black symbols and curves). It was found this state can be changed to mixing state by an injection of ice pellet of hydrogen isotopes, i.e. either of Hydrogen or Deuterium. It was also found that a formation of hollow density profile due to the pellet injection plays an important role for changing the state.

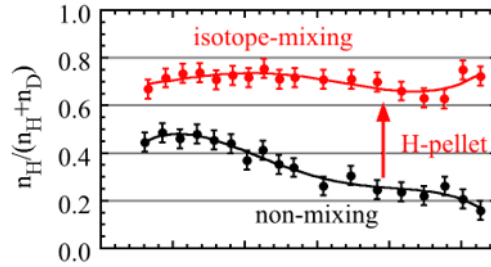


Fig.4 Hydrogen fraction profiles in the Hydrogen and Deuterium mixture plasmas.

Figure 5: Fig.4 in the text

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