Hydrogen volume recombination and a rotating radiation belt observed in the peripheral region of high-density toroidal plasmas

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Although the knowledge on high-temperature plasma physics has been dramatically improved in these decades, which results in the international agreement on ITER (International Tokamak Experiment Reactor) cite decision in 2006, there still remain many unsolved physical and technological problems for realizing a thermo nuclear fusion reactor as the ultimate energy source on the earth. Divertor heat load reduction is one of such problems. In a magnetic confinement nuclear fusion reactor, the main plasma is filled in nested toroidal magnetic surfaces generated by external magnetic coils and, in the case of tokamaks, the plasma current. To avoid direct interaction between the hot plasma and the vacuum vessel wall, the magnetic configurations are generally designed to have one or two x-point(s). The main plasma confined in the region enclosed by the last-closed-flux-surface (LCFS) is connected to the so-called divertor region, through the x-point. In this divertor configuration, plasma is separated from the vacuum vessel wall while it is attached to the plates set in the divertor region. It is expected that the divertor plates will suffer from severe damages due to the enormous heat load of over 10 MW per square meter in the future fusion reactor. Divertor heat load reduction has been realized in many magnetic confinement devices by increasing the divertor plasma density or by introducing impurities such as neon to enhance the radiation loss. With these methods, the temperature of the divertor plasma decreases and therefore the divertor heat load decreases. This is called divertor detachment.

High-temperature and high-density plasma experiments have been conducted in the Large Helical Device (LHD), where the plasma is confined in the nested toroidal magnetic surfaces generated by helically and toroidally wound super-conducting magnetic coils, which is called the heliotron configuration. Plasma current is not necessary in LHD. This is one of the major advantages of the heliotron configuration compared with tokamaks. LHD is equipped with four rows of divertor plates, which are connected to the main plasma through two x-points. In the high-density regime, complete detachment takes place when the edge density reaches a threshold and the hot plasma boundary shrinks below the LCFS. The completely detached state is self-sustained in some cases. This is called the Serpens mode. A rotating helical radiation belt, named the serpent, appears in the Serpens mode phase. A clear Balmer series is observed at complete detachment and the intensity ratios such as Hbeta/Halpha and Hgamma/Halpha increases. Especially in the Serpens mode, these intensity ratios become larger when the serpent passes by the measurements. This suggests that volume recombination is occurring in the completely detached plasmas and enhanced in the serpent.

The effective fueling efficiency improves at complete detachment and continued gas-fueling results in an excess of density increase that leads to radiative collapse. The threshold edge density for complete detachment, which increases with the square root of the heating power, therefore determines the operational density limit of attached plasmas. The volume-averaged densities are larger in pellet-fuelled plasmas than those in the gas-fueled plasmas at the threshold for complete detachment. The maximum volume-averaged density in LHD has reached 3 times 10 to twentieth per cubic meter, by applying pellet injection. This is a resultant from the strongly peaked density profile in pellet-fueled plasmas. Indeed, the edge densities are similar to the threshold edge density for complete detachment even in the pellet-fueled cases. At complete detachment, the edge density becomes about twice larger than that in the attached phase.