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Isotope effect in turbulent transport in high density FT-2 tokamak discharges

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In contrast to theory expectations, in numerous experiments the isotope effect results in the improvement of tokamak energy confinement as the hydrogen isotope mass increases [1]. This effect is beneficial and important for the success of Iter, where a mixture of heavy hydrogen isotopes will be used as a fuel.
The influence of the plasma isotope content on turbulence parameters and, consequently, on the global confinement, was under detailed study at the FT-2 tokamak [2] in comparable hydrogen and deuterium ohmicaly heated discharges within the density range <ne> ˜ (2 - 4) × 1019 m-3. At these densities, an explicit effect of the influence of the plasma isotopic content on particle transport was demonstrated both experimentally and in gyrokinetic calculations, while no noticeable effect was found in the energy confinement. In experiments with higher densities <ne> ˜ (7-9) × 1019 m-3, on the contrary, a significant effect of the isotope content on the global energy confinement was discovered recently [3]. With increasing density, the well known transition from linear ohmic confinement (LOC) to saturated ohmic confinement (SOC) regime has been found in hydrogen. That differs significantly from the scenario in deuterium plasma, where ⊠E(ne) dependence does not saturate. At the maximal achieved plasma densities (<ne> ˜ 9 × 1019 m-3), the total energy confinement time in deuterium is two times higher than in hydrogen plasma. In such high-density discharges in deuterium the signatures of a transition to the H-mode are found, caused solely by density increase, while the hydrogen plasma remains in L-mode in all comparable discharge scenarios.
In this work the further development of the isotope effect study at the FT-2 is presented, both in quasi-stationary plasma and in dynamic regimes. The experimentally detected features of the improved confinement transition in the high density deuterium plasma (<ne> ˜ (7-9) × 1019 m-3) were analyzed in terms of bifurcation in particle transport equation with non-linear dependency of diffusion coefficient on rotation shear [4]. Values of the plasma poloidal rotation shear predicted by the neoclassical theory and the trapped electron mode (TEM) instability growth rate provided by the analytical theory inherent to the FT-2 tokamak were compared. The TEM instability growth rate was also estimated using numerical simulation with a linear version of the GENE code. According to the analysis, in the hydrogen discharges the rotation shear and the characteristic TEM growth rate were comparable, while in the deuterium plasma the shear was superior in respect to the growth rate in almost the entire volume, and at the highest plasma densities there was a multiple excess. This fact apparently explains the improvement in confinement in deuterium and the possibility of transport barrier formation on the density profile. This conclusion was confirmed by the Langmuir probe measurements showing a noticeable decrease of density fluctuation level in the vicinity of the limiter during this L-H transition. Besides this the main parameters of the turbulent modes in these regimes were estimated using special series of experiments involving a set of microwave diagnostics as well as the linear gyrokinetic GENE code and the full-f code ELMFIRE.
In addition to experiments with ohmically heated quasi-stationary plasma, in the same density range (<ne> ˜ (5-9) × 1019 m-3) dynamic fast current ramp up (CRU) experiments were also performed, in which at lower plasma density an improvement of the energy confinement was observed [5]. In these experiments the comparable pairs of discharges in hydrogen and deuterium were realized, possessing similar density profiles, as well as the same current and loop voltage. The measurements of the shear of poloidal rotation (including non-stationary), associated with the geodesic acoustic mode (GAM), as well as the level of short-wave turbulence in these discharges were carried out with the use of the correlation Doppler enhanced scattering diagnostics. Measurements of the turbulence level in the vicinity of the last closed magnetic surface were provided by Langmuir probes.
In hydrogen and deuterium discharges with fast current ramp up and its subsequent relaxation, the evolution of the radial profile of the poloidal rotation shear was measured with the correlation Doppler enhanced scattering at r/a > 0.67. The values of the shear were at the level of 200–270 kHz which is 10–30% higher than the characteristic value of the instability growth rate calculated in the linear approximation. After the current ramp up, the electron energy fluxes were at maximal level during 2 ms, and then during the next 5 ms their slow decrease was observed both in deuterium and in hydrogen. In the latter case, the suppression effect was stronger, and the flux in hydrogen was lower than in deuterium. The mean poloidal rotation shear in hydrogen and deuterium were comparable. The GAM oscillations were observed in the current relaxation stage (34-38 ms). During this period GAMs were much larger in hydrogen than in deuterium, so that the effective poloidal rotation shear for hydrogen was significantly higher than the instability growth rate, which should lead to the TEM suppression. It should be noted that the level of small-scale (sub-millimeter) turbulence measured with the UHR backscattering diagnostics at the plasma periphery in the hydrogen discharges remained at the same level as before the current ramp up, while in deuterium it increased by a factor 2-10.

In the high density deuterium discharge possessing energy confinement time of about 4 ms and in a comparable in density hydrogen discharge, the lower hybrid (LH) ion heating experiments were performed. The experimental measurements of the poloidal velocity shear were carried out at r/a > 0.76 before the RF-pulse and at r/a > 0.85 after it. Before the RF-pulse, the mean shear values were in the 200 kHz range for the hydrogen discharge, and 320 kHz for the deuterium one, at the same radius r/a ˜ 0.85. After the RF-pulse, the shear values for hydrogen turned out to be the same, whereas for deuterium, they increased by several times. The GAM activity was observed before the RF-pulse by the Doppler enhanced scattering, whereas after the RF-pulse it was not detected. The shear of the nonstationary rotation associated with the GAM before the RF-pulse in deuterium was larger than in hydrogen, but it was observed in a very narrow radial range due to the strong collisional damping at the periphery of the discharge. After the RF-pulse, the mean values of the rotation shear in deuterium exceeded the typical growth rates of the TEM instability so much that it became possible to explain the decrease in the fluctuation level observed with probes and enhanced scattering in spite of the GAM suppression.
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