Isotope effect in confinement in high density FT-2 tokamak regimes.

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The isotope content of a hydrogen plasma influence the plasma confinement in a tokamak in two ways. For heavier isotopes it reduces, firstly, the plasma anomalous diffusivity and, secondly, - the power threshold for the LH transition [1]. Both effects are crucial for fusion applications of the tokamak plasma confinement scheme.

In the present paper we study interplay of these effects in the FT-2 tokamak high density ohmic discharges. Detailed study of general transport properties of the FT-2 tokamak [2] showed similar behavior of energy confinement for hydrogen (H) and deuterium (D) ohmic plasmas at densities up to $\langle n_e \rangle \approx 4\cdot10^{19}$ m^{-3}. However some signs of essential difference in τ_E behavior for different isotopes were discovered at higher densities. To confirm this isotopic discrepancy special series of ohmic discharges were performed in H and D plasmas within the chord averaged density range $\langle n_e \rangle \approx (5–9)\cdot10^{19}$ m^{-3}. In this paper we present the results of energy confinement study in these high density regimes (HDR). Improvement of confinement with growing density is observed in D-discharges in contradiction to well known LOC to SOC transition observed at the same densities in H-plasma. At the same time clear signs of improved confinement transition effect are seen for D-discharges including the turbulence suppression at the edge provided by Langmuir probes.

Experimental/modeling approach

Special series of HDR ohmic discharges is performed at FT-2 tokamak (a = 0.08 m, R = 0.55m, I_{pl} ~ 32-35 kA, B_T ~ 2.2 T, q_{95} ~ 3-3.5) in two different working gases: hydrogen (H) and deuterium (D). The energy confinement time is calculated using the ASTRA code transport modeling based on the experimental data – T_e and n_e (Thomson scattering diagnostics, microwave interferometry), T_i (NPA diagnostics), radiation losses (bolometric diagnostics). Z_{eff} is a fitting parameter to reach the coincidence of measured and calculated loop voltages $U_{p\ exp} = U_{p\ calc}$, under the assumption of neoclassical plasma conductivity.

Energy confinement in high density regimes

Energy confinement time is calculated as $\tau_E = W / (P_{OH} – dW/dt)$, where W - plasma thermal energy content, P_{OH} - the ohmic heating power.

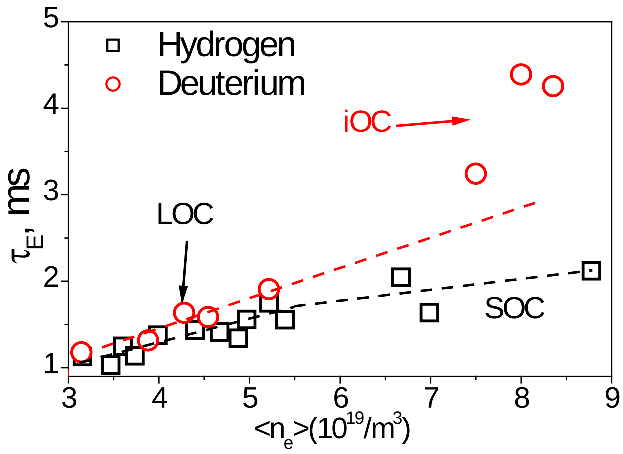

Figure 1: Energy confinement time dependence on chord averaged density

Fig. 1 shows energy confinement time dependence on chord averaged density. No visible isotope effect on global energy confinement is observed at low/medium densities up to $<n> \approx 5{\cdot}10^{19}$ m^{-3}. At higher density energy confinement growth saturates in H-discharges. According to empirical estimation of the LOC to SOC transition density [3] $n_{cr} \approx 0.65{\cdot}A^{0.5}{\cdot}B_T/(Rq)$, for hydrogen we come to $n_{LOC\text{-}SOC} \approx 7{\cdot}10^{19}$ m^{-3}, that does not contradict to experimental points. For D-discharges at these densities the growth of τ_E is not saturated in agreement with the threshold density scaling. Moreover the growth is stronger than that observed in LOC (see the dashed red curve in fig. 1). In the vicinity of tokamak operational density limit $<n_e>_{lim} \approx 9\times10^{19}$ m^{-3} the energy confinement time in D is twice as high as in H. Detailed analysis of these highest density regimes exhibits significant discrepancy in the discharge scenarios, based on a smooth density growth up to the maximum values. While H-plasma does not exhibit any peculiarities of main plasma parameters behavior with the growing density, D-discharges show evident qualitative transition in terms of energy and particle confinement. D_β dynamics show essential (~ 5-fold) decrease that starts at some critical central density $n_{0cr} \approx 7{\cdot}10^{19}$ m^{-3} where transition to improved confinement is supposed (fig. 2).

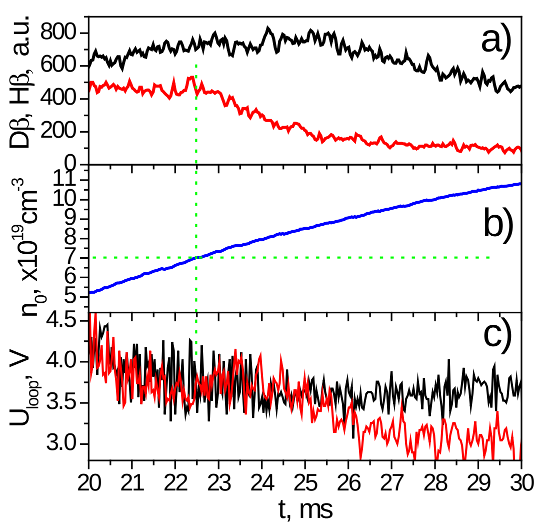

Figure 2: a) H_β/D_β line emission, b) typical central density and c) loop voltage for H- (black) and D-plasma (red)

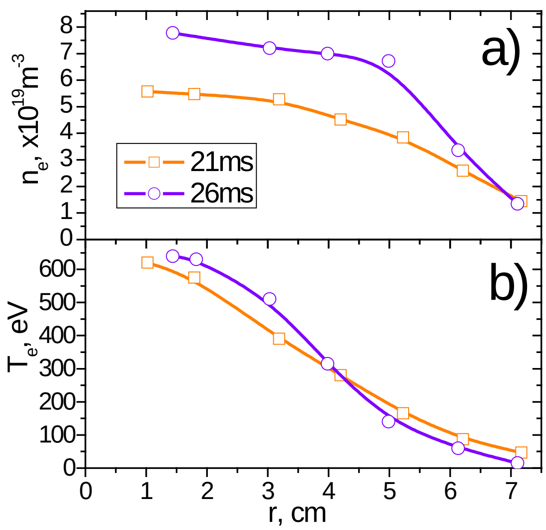

Figure 3: D-plasma, electron density (a) and temperature (b) profiles before (orange) and after (violet) transition to iOC

Detailed time-resolved measurements of T_e and n_e profiles [4] were provided for D-discharges within time window where D_β drop is observed (t = 22-26 ms). Fig.3 demonstrates flattening of the electron density profile in deuterium within r/a < 0.6 region and it's steepening at the edge, presenting features of edge transport barrier formation.

Probe measurements

Turbulent fluctuations at plasma periphery were measured in high density regimes with 5-electrode Langmuir probe, placed close to LCFS (r = 78 mm) [5]. Fig. 4 shows dynamics of floating potential (φ_1 and φ_3) power spectra on the 1st and 3rd pins both for H- and D-plasma, measured at the time interval 21-26 ms where D_β drop is observed. Significant decrease of the probe signals (in the frequency range 0 – 1.56 MHz) in deuterium occurring simultaneously indicates the turbulence suppression accompanying possible transition to an improved confinement resulting in the energy confinement time growth in the D-discharge. It should be underlined that the H-discharge does not show any significant changes in the turbulence level under similar conditions.

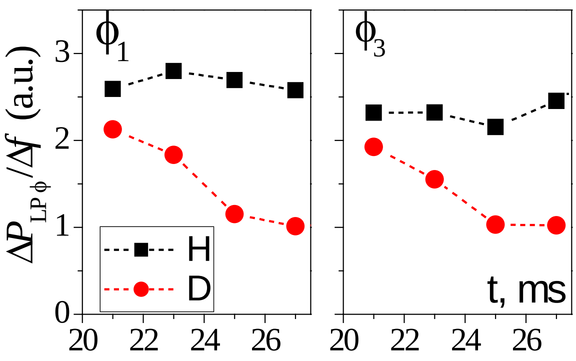

Figure 4: The spectral power density evolution, measured in hydrogen (black) and deuterium (red) by two (left and right) pins of the 5-electrode Langmuir probe, separated poloidally

Discussion

Bifurcation in particle and heat transport equations was thoroughly described in [6] and applied to several scenarios such as GAM-initiated or pellet-initiated confinement improvement [7, 8]. According to that analysis, diffusion coefficient depends on the ratio of radial electric field shear $\omega_{E\times B} = \frac{B_\theta R}{B_T}\frac{\partial}{\partial r}\frac{E_r}{B_\theta R}$ and turbulence growth rate $\gamma = \left(\frac{a}{R}\right)^{3/2}\frac{\omega_{dr}^2}{\nu_{ei}}\eta_i$ [9]; in case of $\omega > \gamma$ diffusion is being locally suppressed, and if particle source is high enough, self-sustaining improved confinement regime with transport barrier formation is possible [6].

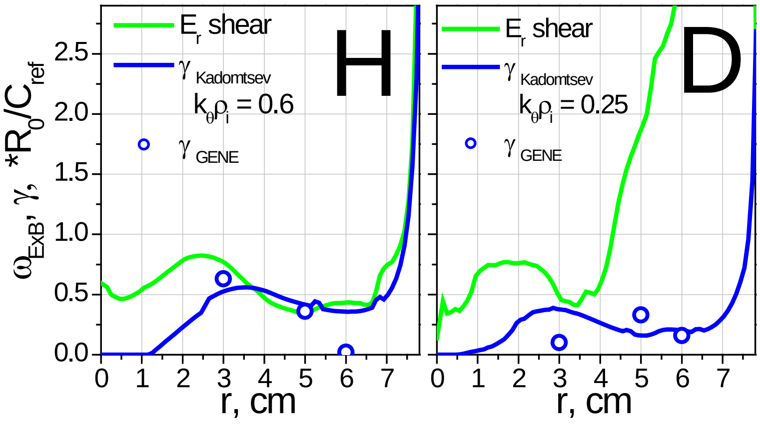

Figure 5: Radial electric field shear and turbulence growth rate for high density cases in hydrogen (left) and deuterium (right); $C_{ref} = (T_i/m_i)^{1/2}$

In high density case the particle source is significantly higher than the value required for the improved confinement regime existence, thus the key role in defining whether this regime occurs belongs to the turbulence suppression effect. TEM mode was supposed dominant, which is in agreement with the gyrokinetic simulation with GENE linear code. Comparison between growth rate and E_r shear for HDR cases is shown in fig. 5. For deuterium E_r shear substantially exceeds turbulence growth rate thus making turbulence suppression possible. For hydrogen shear is comparable with turbulence growth rate, and its effect on confinement could not lead to any significant modification of diffusion. This is in agreement with the observed difference between HDR D-plasma case, which possesses the characteristic features of H-mode, and hydrogen plasma without confinement improvement.

Conclusions

Clear isotope effect is found in high density regimes both in energy and particle channels. Energy confinement time is twice higher in deuterium than in hydrogen at $n \approx (8\text{-}9)\cdot 10^{19}$ m^{-3}. The particle confinement in D-plasma possesses features of H-mode: strong D_β line emission drop, growth of peripheral density gradient, suppression of turbulence at the plasma edge. The explanation of the isotopic difference in the improved confinement onset and consequently in transport is based on relation between E_r shear and turbulence growth rate, calculated both with gyrokinetic simulation and using analytical estimations.

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