Helium fuelling for edge plasma parameters control in the thermonuclear experiments

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In deuterium–tritium plasmas of ITER helium produced in fusion reactions could be applicable as diagnostic test instrument for plasma parameters control in the divertor SOL. Also the He additionally injected fraction of plasma could be useful for monitoring of the ITER full-W divertor in stationary or slow transient cycles during non-active H/He phases of DT operations [1, 2].

I. This paper describes FT-2 ($R = 0.55$ m, $a = 0.08$ m, $B_T \leq 3$T, $I_{pl} = 19 \div 40$ kA) tokamak experiments where additional helium puffing into the hydrogen/deuterium plasma is considered as diagnostic tool [3]. The feature of sensitivity of the helium line emission to electron temperature and density can be applied as effective diagnostics for these plasma parameters.

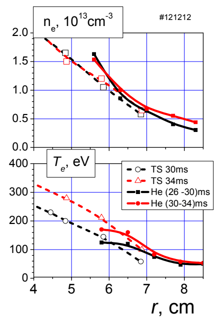

Fig. 1 Comparing of $n_e(r)$ and $T_e(r)$ measured by spectroscopic and TS diagnostics methods in CRU experiment.

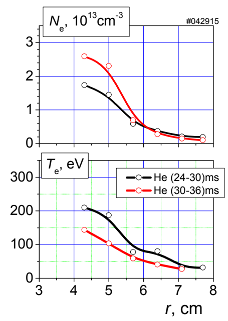

Fig. 2 $n_e(r)$ and $T_e(r)$ measured by He lines ratio method in LHCD experiment

The region of pulsed gas puffing was observed through an upper port of tokamak vessel. The AvaSpec double-channel absolutely calibrated spectrometer (553 – 765 nm and 410 – 495 nm) was used for simultaneous measurements of the chosen spectral lines in the cloud of the injected gas localized near the bottom of the diagnostic cross section. The plasma cross section was scanned in the horizontal plane from the high field side (HFS) of the torus. Using series of well reproducible discharges, the radiation profiles were measured from shot to shot with a spatial resolution of 0.5 cm. Variations of $n_e(r)$ and $T_e(r)$ at the plasma edge were monitored by the method based on the proportionality of the ratio between the singlet helium lines $R_1(n,T_e)$ = HeI(668nm)/HeI(728nm) ($1s3d^1D$ - $1s2p^1P/1s3s^1S$ - $1s2p^1P$) and the singlet triplet lines $R_2(T_e,n_e)$ = HeI(728nm)/HeI(706nm) ($1s3s^1S$-$1s2p^1P/1s3s^3S$-$1s2p^3P$), correspondingly. The factors R_1, R_2 interconnected the intensity ratios of the above lines to the plasma parameters and Calculated by ADAS code are given in different papers [3 and 4]. One has to notice that application of this spectroscopy method for $T_e(r)$ and $n_e(r)$ measurements involves specific difficulties [4]. Some of them are the effects of the radiation trapping of the resonance line (I_{501}) [5] and dependence of intensities of triplet lines (I_{706}) from the fraction of metastable atoms, which varies as helium penetrates into the plasma. That is why it is necessary to take into account the percentage of atoms in the 2^3S state for experimental correction of R_2.

For experimental verification of the calculated factors R_1 and R_2 the pure helium ohmic heating (OH) plasma experiment with passive spectroscopy was performed. The relationship between the line intensity ratios and plasma parameters is resulted by $n_e(r)$ and $T_e(r)$ progressive approximation approach. Characteristic features of that calibration method are based on comparing of spectroscopic data versus $T_e(r)$ and $n_e(r)$ measurements, provided by multi-pass intracavity Thomson scattering (TS) [6] and microwave interferometer. Results of spectral measurements of $n_e(r)$ and $T_e(r)$ on the base of the corrected line intensity ratio R_1 and R_2 of the HeI emission in the dynamical diverse tokamak experiments are presented here.

We arranged H/He experiment with fast plasma current ramp up (CRU) from 20kA up to 32kA started at 30ms with 0.5ms rise time. As the result the rise of T_e with changeless $n_e(r)$ profile observed by He lines ratio at out radii (r > 6cm) of the plasma cross section are well satisfied with the TS data shown in Fig. 1. Integral time of spectral measurements is 4 ms. For lower hybrid heating (LHH) experiment in D/He plasma an increase of the density and central $T_e(r = 0\text{cm})$ followed by cooling of the plasma periphery during RF pulse applied at 30ms (F = 920 MHz, Δt_{RF} = 6ms) are feature of the plasma parameters change discussed in [3, 6 and 7]. The similar characteristic variation of the $n_e(r)$ and $T_e(r)$ data has been obtained with the HeI line intensity ratio method measured at exterior radii (r > 4cm) as it is shown in Fig. 2.

II. The paper also focuses on the influence of He fuelling of H/D plasma on the

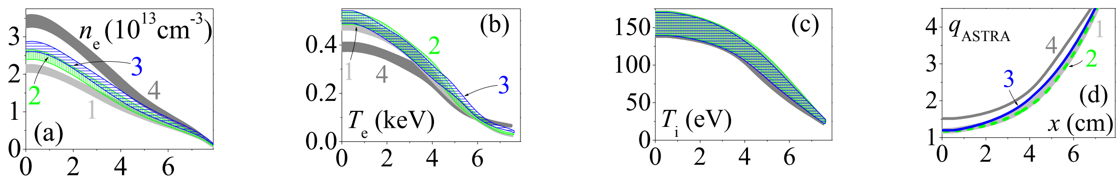

Fig. 3. *Regime with intensive He puffing. Experimental radial profiles of (a) the density; (b) electron and (c) ion temperature. (d) The safety factor profile. (1 - 25 ms, 2 - 27 ms, 3 - 29 ms and 4 - 38 ms)*

anomalous heat transport development and suppression controlled by interaction of multi-scale turbulence, characterized by microwave Doppler backscattering diagnostics: correlative enhanced scattering and reflectometry [8]. The medium-scale geodesic acoustic mode (GAM) turbulence impacted by He puffing is compared with dynamics of the turbulence level profiles. The preliminary set of measurements characterizing GAMs was carried out in hydrogen discharge with a low plasma current 20 kA and toroidal magnetic field 2.2 T. Similar initial parameters and profiles (shown in Fig. 3 for different time moments, together with ASTRA code reconstruction for the safety factor q) were chosen in hydrogen regime with helium fuelling. During the time interval 25-38 ms in H/He regime the plasma current decreases from 21.5 till 20.5 kA and Z_{eff} increases from 2 till 3.2. The ratio of the densities for helium He^{2+} and hydrogen H^+ at $x \sim 5$ cm was roughly estimated as $n_{He2+}/n_{H+} \sim 6$ [3].

The correlative Doppler enhanced scattering technique [8, 9] was implemented for local measurements of the turbulence radial wave number spectra, turbulence level $|n|_0^2$ and Doppler shift (f_D) of the frequency spectrum: $f_D = k_\theta V_\theta/(2\pi)$, where V_θ is the poloidal phase velocity and k_θ is the fluctuation poloidal wave number. The frequency shift is composed of the drift-wave frequency and the Doppler frequency shift associated with plasma poloidal rotation. The spectrum of the $f_D(t)$ dependence in H regime averaged over 8 FFT realizations taken one by one within 1.6 ms interval between dashed lines (shown in Fig. 4) is presented in Fig. 5(a) by pink curve 1. An intensive spectral line is clearly seen in this spectrum at $F \sim 54$ kHz. The black solid line 2 corresponds to a mean noise level, which can be attributed to perturbations of a radial electric field E_r and density, as well as distortions of the upper hybrid resonance and magnetic surfaces [8]. The ratio of the line's amplitude to a noise level at peak's frequency is a contrast $C = 3.5 \pm 1.1$. The radial profiles of the spectral line's contrast C and frequency F at $t \sim 29$ ms are shown in Fig. 5(b,c) by circles. The mean value of the $f_D(F)$ noise in the terms of contrast corresponds to the level $C = 1$. The grey curve in Fig. 5(b) is the standard deviation of this noise. It should be explained that the line's frequency F was determined only for cases when the contrast error bars were not crossing this grey curve in Fig. 5(b). The theoretical estimations of GAMs frequency (F_G) are also plotted in Fig. 5(c).

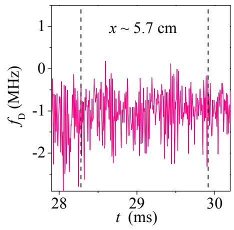

Fig. 4. Time trace of the Doppler frequency shift f_D.

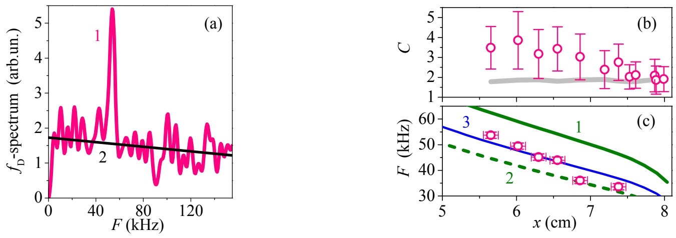

Fig. 5. H regime. (*a*) The spectrum of f_D time trace. Radial profiles of the dominating line's (*b*) contrast and (*c*) frequency.

The olive curve 1 was obtained with formula [8]: $F_G^2 \approx (7T_i/4 + Z_i T_e)(2\pi^2 R^2 m_i)^{-1}$, where $m_i = m_H$ (the ion hydrogen mass) and $Z_i = 1$ (for H^+). An application of this formula with $T_i = 0$ gives the dashed olive curve 2 (as well as dashed curves in Fig. 6(b)). The blue curve 3, which is the most appropriate for experimental points, is based on the analytical prediction for GAMs frequency, obtained in [10] for plasma with two ion species, when the O^{8+} impurity component was taken into account. This result demonstrates one of arguments [8] that the dominating line in the $f_D(F)$ spectrum corresponds to the GAM. The influence of the isotope effect on GAM frequency was checked in H/He regime. Olive curves 1 (solid) and 2 (dashed) in Fig. 6(b) were calculated as F_G estimates for pure hydrogen H^+ case with $m_i = m_H$, $Z_i = 1$ in the same manner as it was done in Fig. 5(c). Two underlying blue curves 3 (solid) and 4 (dashed) in Fig. 6(b) were calculated as F_G estimates for pure helium He^{2+} case with $m_i = 4m_H$, $Z_i = 2$. As it is clearly seen experimental F-values have shifted from the region between two olive curves to an area between blue ones in accordance with the isotope dependence of the GAM frequency.

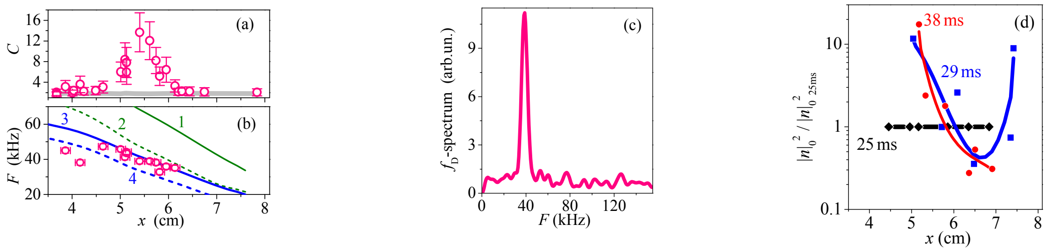

Fig. 6. H/He regime. Profiles of the dominating line's (a) contrast and (b) frequency at $t \sim 27$ ms. (c) The f_D spectrum at $x \sim 5.4$ cm, $t \sim 27$ ms. (d) The turbulence level profiles normalized by its value at $t \sim 25$ ms.

An example of the $f_D(F)$ spectrum in H/He regime at $x \sim 5.4$ cm is shown in Fig. 6(c) for the same time point as in Fig. 5(a). Exactly in this time the contrast of the main peak reaches the highest value $C \sim 13.7 \pm 3.8$. As it seen from the $C(x)$ profile in Fig. 6(a) GAMs oscillations in H/He regime are more intensive and they are observed in a narrower zone, compared to the H case shown in Fig. 5(b). This effect is explained by growth of the Landau damping in the gradient zone and by suppression of the low frequency turbulence [11] at $x > 6$ cm as demonstrated by its typical level $|n|_0^2$ in the logarithmic scale in Fig. 6(d). It should be stressed that in H/He regime the turbulence level significantly increased at $x = (5\text{-}6)$ cm for $t > 25$ ms that leads to the local enhancement of the GAM amplitude (C) relative to pure H case or the initial stage of H/He regime ($t = 25$ms) without visible improvement in the energy confinement in investigated case. However an evidence of diffusion modulation by GAMs revealed in other experiments and numerical simulations [12] supports the possibility of the density profile steepening, finally leading to the L-H transition.

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References

1. S. Carpentier-Chouchana, T. Hirai, F. Escourbiac et al. *Phys. Scr.* **T159** (2014) 014002
2. A.S. Kukushkin, H.D. Pacher,V. Kotov et al. *Nucl. Fusion* **53** (2013) 123025
3. S.I. Lashkul, A.B. Altukhov, V.V. D'yachenko et al. *Plasma Phys. Rep.* **38** (2012) 851
4. E de la Cal. *Plasma Phys. Control. Fusion* 43 (2001) 813–823
5. Shin Kajita et al. Phys. Plas. 13, 013301 2006
6. S.I. Lashkul et al Proc. 7th Int. Workshop, Nizhny Novgorod (2009), vol. 2, pp. 312 – 317
7. S.I. Lashkul, A.B. Altukhov, A.D. Gurchenko et al. *Nucl. Fusion* 55 (2015) to be published
8. A.D. Gurchenko, E.Z. Gusakov. A.B. Altukhov et al. *Plasma Phys. Control. Fusion* **55** (2013) 085017
9. A.D. Gurchenko, E.Z. Gusakov, S.I. Lashkul et al. *Plasma Phys. Rep.* **39** (2013) 337
10. Guo W, Wang S and Li J 2010 *Phys. Plasmas* **17** 112510
11. Gurchenko A D, Gusakov E Z, Kouprienko D V, Leerink et al 2010 *Plas. Phys. Control. Fusion* **52** 035010
12. L.G. Askinazi, V.I. Afanasyev, A.B. Altukhov et al., *Nucl. Fusion* 55 (2015) to be published