

## Comparative lower hybrid ion heating experiments in hydrogen and deuterium high density plasma at FT-2 tokamak

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**Introduction.** Investigations of lower hybrid heating (LHH) of plasma ion component widely performed in 80<sup>th</sup> and 90<sup>th</sup> did not result in development of a reliable heating scheme. In majority of experiments excitation of parametric decay instabilities (PDI) accompanied by ion acceleration at densities exceeding a certain threshold value did not lead to a substantial ion heating. Only few experiments such as JFT-2, Wega, Petula-B and FT-2 had reported observation of significant ion temperature growth [1, 2]. Therefore all subsequent years the main application of the LH frequency range RF power in tokamaks was related to LH current drive, which is only effective at low plasma densities.

LHH experiments on FT-2 tokamak ( $a = 0.08$  m,  $R = 0.55$  m,  $19$  kA  $< I_p < 34$  kA,  $2$  T  $< B_T < 2.5$  T,  $q_{95} \sim 3\text{-}6$ ) are carried out from the early 80's to the present time with a goal to study the interaction of LH waves ( $f = 920$  MHz,  $P_{RF} \leq 200$  kW) with plasma. LH ion heating

accompanied by formation of the internal transport barrier (ITB) and effective LHCD generation at low plasma densities was observed and investigated [2-4]. In the present paper we revisit the ion LHH in high density regimes (HDR) of hydrogen (H) and deuterium (D) plasma. The magnetic

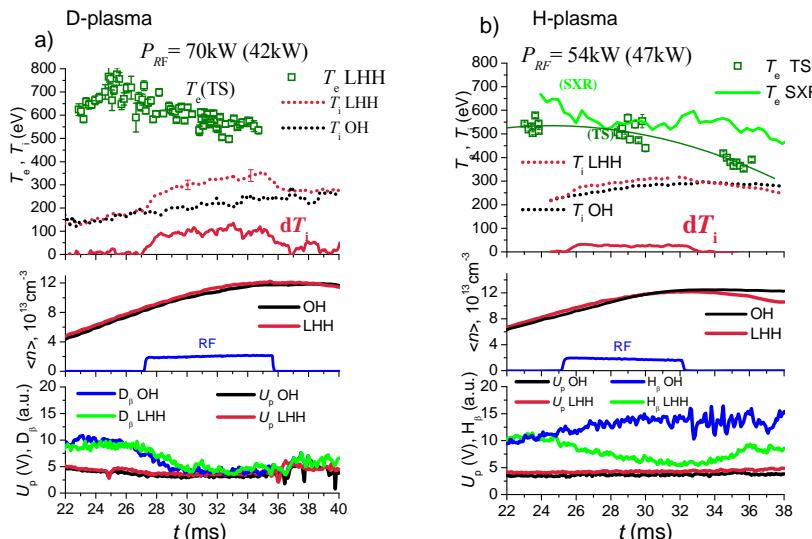


Fig. 1 (a, b).  $T_e$ ,  $T_i$  – central electron and ion temperature;  $dT_i$  central ion temperature increment during RF pulse in comparison with OH temperature  $T_i$ ;  $\langle n_e \rangle$  typical central density time history;  $H_\beta$  and  $D_\beta$  line emission and  $U_p$  - loop voltage for OH - plasma (black) and LHH with OH - (red).

field value  $B_T = 2.4$  T in these experiments was chosen to satisfy the condition for the RF frequency  $f_0 \approx \sqrt{f_{ce} f_{ci}}$ , under which the LH resonance in the deuterium plasma could appear only at the high density values  $\langle n_{e \text{ res, D}} \rangle \sim 1.4 \cdot 10^{20} \text{ m}^{-3}$  [4, 5] close to the Greenwald limit. In this way the interaction of the LH power with ion component predicted by the linear theory in

deuterium can take place only in the central plasma region, unlike hydrogen where it is expected in the gradient zone at  $\langle n_{e \text{ res}, H} \rangle \sim 3.5 \cdot 10^{19} \text{ m}^{-3}$ .

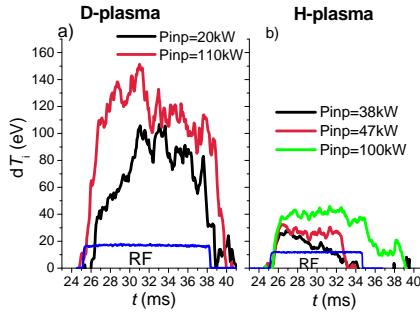


Fig. 2 (a, b). Temperature increments  $dT_i$  during RF pulse for different levels of input heating power  $P_{\text{input}}$  for both H- (a) and D- (b) plasma.

$\tau_E(\langle n_e \rangle)$  happens already at  $\langle n_e \rangle \sim 5 \cdot 10^{19} \text{ m}^{-3}$  (SOC mode).

**Experimental/modeling approach.** The main plasma parameters for HDR were determined using both standard and unique diagnostics such as multi-pass laser Thomson scattering (TS) diagnostics. To measure the ion temperature profile a neutral particle analyzer (NPA) allowing a vertical scan was used. The effect of flux attenuation of CX atoms in high density plasma was taken into account when modeling NPA data by the Monte Carlo

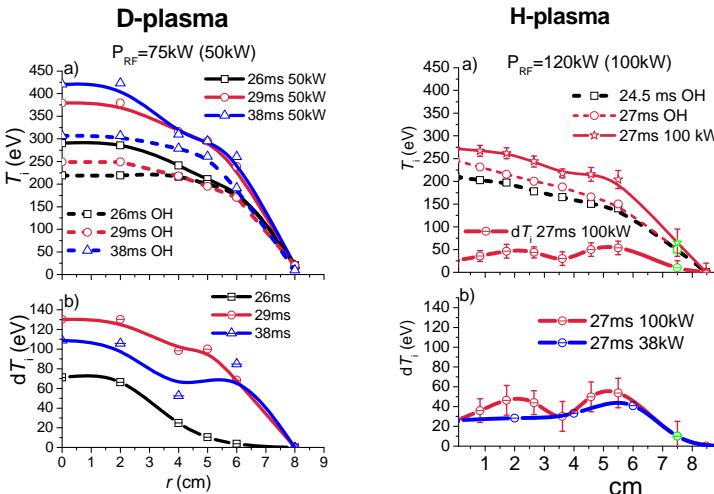


Fig. 3. (a)  $T_i(r)$  at  $P_{RF}=75 \text{ kW}$  ( $P_{\text{in}}=50 \text{ kW}$ ); (b) increments  $dT_i(r)$  both for D-plasma.

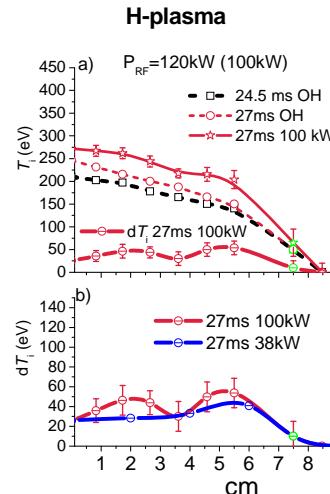


Fig. 4. (a)  $T_i(r)$  for  $P_{RF}=120 \text{ kW}$  ( $P_{\text{in}}=100 \text{ kW}$ ); (b)  $dT_i(r)$  for  $P_{\text{in}}=38 \text{ kW}$  and  $100 \text{ kW}$  both for H-plasma

Another important feature of that high density experiment is the effect of prolonged linear increase of the energy confinement time  $\tau_E(\langle n_e \rangle)$  with density growth recently discovered in deuterium ohmic heating regimes. The so-called LOC mode persists up to  $\langle n_e \rangle \sim 10^{20} \text{ m}^{-3}$  and is accompanied by a transition to the improved confinement mode (iOC) [6]. For hydrogen plasma, on the contrary, a saturation of the dependence

`DOUBL_MC` code. The ability of the NPA to measure both ion temperature profiles and to localize the region of direct RF power absorption by fast particle fluxes measurements was demonstrated by simulation with the Monte Carlo ASCOT code [3]. Special series of repetitive similar HDR ohmic discharges ( $I_p \sim 32-35 \text{ kA}$ ,  $B_r \sim 2.4 \text{ T}$ ,  $q_{95} \sim 3 - 3.5$ ) with increasing plasma density and

LHH pulse duration  $\tau_{RF} \sim 8 \div 13 \text{ ms}$  were performed in two gases (H/D). In the vicinity of tokamak operational density limit  $\langle n_e \rangle \approx 1.2 \cdot 10^{20} \text{ m}^{-3}$  the energy confinement time in D ohmic heated plasma was twice as high as in H plasma [6]. The RF power  $P_{RF}$  was launched by a two waveguide grill during the plasma current flat-top [4, 5]. Dynamics of the main

plasma parameters of HDR at  $P_{RF}=70$  kW ( $P_{in}=P_{RF}-P_{ref}=42$  kW for D-plasma) and  $P_{RF}=54$  kW ( $P_{in}=47$  kW for H-plasma) is presented in Fig. 1(a, b), featuring a significantly stronger central ion LHH in deuterium than in hydrogen plasma.

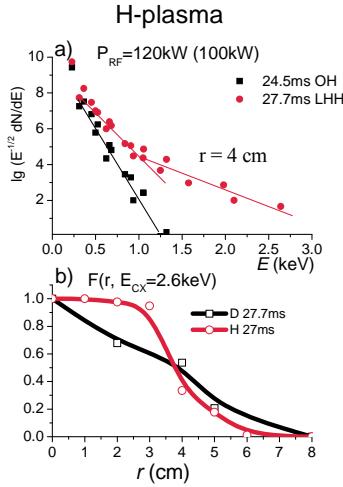


Fig. 5. (a) Energy distribution of CX atoms at LHH in H-plasma at 4cm.(b) normalized profiles of FN of  $E_{CX}=2600$  eV for D and H-plasma

$P_{RF}=120$  kW ( $P_{in}=100$  kW), respectively, during LHH pulse. Corresponding profiles of temperature increments  $dT_i(r)$  for D-plasma with respect to OH regime are presented in Fig. 3(b). They are characterized by the peak shape at the initial stage of D-plasma LHH in contrast to flatter profiles for H-plasma heating, Fig. 4(b). The different localization of RF power absorption by fast particles for hydrogen and deuterium plasma is confirmed by the normalized CX profiles of fast neutral (FN) of  $E_{CX}=2600$  eV (Fig. 5b). The fast particle “tail” formation in the energy distribution of CX atoms at LHH is illustrated in Fig. 5a for the chord signal of H-plasma at 4cm. The wider normalized profile of FN in H-plasma case, in accordance to the model calculations [3], may indicate peripheral RF power absorption in contrast to the sharp profile in the D-plasma where LH wave should be absorbed at plasma center.

**Discussion and conclusion.** So, for the first time the effective central LH heating of ions from  $T_i(0)=200$  eV to 450 eV was observed in the HDR in D plasma at  $P_{in}\approx 50$  kW, in contrast to the H plasma of similar parameters (Fig. 3a, b) where the heating effect at the  $P_{in}\approx 100$  kW is significantly weaker. Model calculations performed with the help of ASTRA code allowed estimating the value of the power  $P_{abs}$  absorbed by ions (from electrons and the RF wave) for both cases (Fig. 6). When RF power is switched on at initial stage where transport coefficients have not had time to change much the input power absorbed by the ion component in D-plasma is estimated as  $P_{abs}\sim 0.16P_{in}$  whereas in H-plasma - as  $P_{abs}\sim 0.22P_{in}$ . The remaining part of  $P_{in}$  is apparently absorbed by fast ions and lost on the limiter and the chamber wall due to charge exchange losses, which seems to be confirmed by measurements

At the same time, despite slightly reducing of energy confinement time from 2.2-2 ms to 1.9 ms (according to ASTRA simulation taking into account an additional  $P_{in}$ ) H - plasma at LHH demonstrates flattening of the electron density profile within  $r/a < 0.5$  region and it's steepening at periphery, presenting features of ITB formation with  $H_\beta$  line essential decrease. Fig.2 shows ion temperature increments  $dT_i(0, t)$  for different levels of input heating power  $P_{in}$  for both H- (a) and D- plasma (b).

There is several times stronger ion heating in deuterium than in hydrogen plasma. Fig. 3(a) and 4(a) illustrate the temporal variations of ion temperature profiles  $T_i(r)$  for D plasma at  $P_{RF}=75$  kW ( $P_{in}=50$  kW) and for H- plasma at

of radiation losses  $P_{\text{rad}}$  performed by the piezoelectric bolometer (Fig 7). As it is seen in the figure, dynamics of the central chord signal  $P_{\text{rad}}$ , which is determined by light radiation and CX FN flux, shows significant increase during RF pulse while  $H_{\beta}$  line emission decreases.

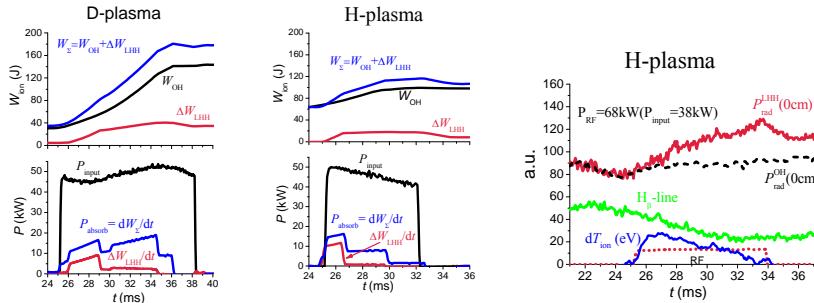


Fig. 6. Change in the energy content  $W_{\text{ion}}$ , J of the H/D ion component during OH and LHH. The power  $P_{\text{abs}} = dW_{\text{ion}}/dt$  absorbed by the body plasma ions from electrons and RF power

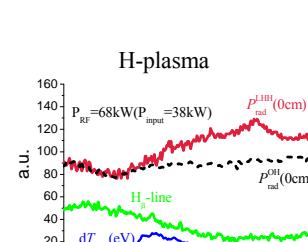


Fig. 7. Dynamic of the central bolometric chord signal  $P_{\text{rad}}$  and  $H_{\beta}$  line radiation during RF pulse

The presented experimental data indicate the central absorption of RF energy in D-HDR in contrast to peripheral one for H-HDR that corresponds to the theoretical concepts [7] and ray tracing calculations performed

using the method described in [8]. Namely, in the D-plasma the LH wave reaches the central plasma region where ions possessing perpendicular velocity greater than the LH wave phase velocity  $v_{\text{ph}}$  experience stochastic heating. The condition for the effective absorption of RF power is a strong slowing down of the wave, to the wavenumber value satisfying condition  $\omega/(k_{\perp}v_{T_i}) < 2\sqrt{2}$  [7]. As a result, a quasi-linear plateau is formed on the ion perpendicular velocity distribution function. A quasi-Maxwell "tail" of ions with an effective temperature  $T_{\text{tail}}$  is formed (see example in Fig. 5a). The heating of the main body of the ion distribution function happens due to collisions of the thermal ions with these hot "tail" ions. The later can also be lost due to the mechanisms of orbit losses and CX of FN (Fig. 7). The role of parametric instabilities in the propagation and absorption of LH waves at such high densities is not confirmed in the experiment because of the recently found effect of suppression of parametric activity at HDR for H/D plasma [9], which happens despite the probe measurements indicate both cooling of the periphery and growth of density in SOL.

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#### References

1. V.N. Budnikov, M.A. Irzak Plasma Phys. Contr. Fus. 38, A135 (1996).
2. S.I. Lashkul, V.N. Budnikov, A.A. Borevich et al. Plasma Phys. Control. Fusion .42 (2000), A169 – A174
3. T Kurki-Suonio, S. I. Lashkul and J A Heikkinen. Plasma Phys. Control. Fusion **44** (2002) 301–323
4. S.I. Lashkul, A.B. Altukhov, A.D. Gurevich et al. Nucl. Fusion 55 (2015) 073019
5. S.I. Lashkul, A.B. Altukhov, A.D. Gurevich et al. Plas. Phys. Reports, 2015, Vol. 41, No. 12, pp. 990–996.
6. D. Kouprienko, A. Altukhov, L. Esipov et al., 45th EPS Conf. on Pl. Ph, P4.1097 (2018)
7. Golant V E and Fedorov V I 1989 *RF Plasma Heating in Toroidal Fusion Devices* (New York, London: Consultants Bureau); (Moscow: Energoatomizdat) pp 69–96, 116–141
8. Yu.F. Baranov, V.I. Fedorov, Nuclear Fusion, v.20, #9, (1980), 1111-1118
9. S.I. Lashkul, A.Yu. Stepanov et al. EPJ Web of Conferences **149**, 03012 (2017)