Neutron Flux Measurements in ICRF Mode Conversion Plasmas on HT-7

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Abstract. Ion cyclotron resonance heating (ICRH) combined with lower hybrid current drive (LHCD) experiments have been carried out on HT-7. Ion cyclotron range of frequencies (ICRF) experiments has been carried out at three frequencies, which correspond to different heating scenarios. It was observed the fusion neutron flux only increased remarkably in mode conversion (MC) scheme with the ion-ion hybrid resonant layer near the centre of plasma. The neutron flux is about 1.39 powers of ICRF power. However, the high neutron flux is most possibly due to the nonlinear 3/2 harmonic deuterium heating by the mode converted ion Bernstein wave (IBW), which could produce a high energy tail on the ion energy distribution. The neutron flux during the phase of ICRH is improved by cooperating with lower hybrid wave (LHW), which is because LHW could improve the single wave absorption and background electron temperature thus inducing a higher ion temperature by collisions. And best ion temperature has been carried out at $90^{o}+0^{o}$, corresponding to the phase of ICRF and LHW separately, though the neutron flux does not increase obviously due to lower energy confinement time.

1. Introduction

Neutron diagnostics have been applied in ICRF plasmas on HT-7 for measurement of the fusion reaction product, which give a direct measure of the ICRF heating. The neutron emission strength is recorded by ^{3}He proportional counters. Their response to thermal neutrons is 133 c.s^{-1} per n.cm^{-2}.s^{-1}, used to detect high energy neutrons in the range of 1-15MeV, and are operated in pulse-counting mode. ICRH combing with the LHCD experiments have been carried out on HT-7. Resonant absorption of the ICRF wave takes place when the cyclotron frequency of the ions, or a harmonic, is close to the wave frequency [1]. The 1.5 MW ICRH systems with frequency of 25-70MHz is one of the major methods for auxiliary heating, and the 1.2MW LHW at frequency of 2.45GHz is used for current drive both in sustaining plasma discharges and assisting the plasma start-up [2].

The versatility of the system, exploited in the recent HT-7 experiments with D plasmas, provided a unique opportunity to assess the physics and performance of ICRH schemes. These schemes comprise mode conversion (MC) scheme, fast wave direct electron heating and hydrogen minority ions at their second harmonic resonance. It was observed that fusion neutron flux only increases remarkably at frequency of 24MHz and toroidal field of 1.8T in the MC scheme with the ion-ion hybrid resonance layer near the centre of tokamak. The discharge have been simulated with TORIC code [3, 4], however, it turns out electron damping is dominant. In frequency of 40MHz, the neutron flux does not change as the ICRF injected, if other parameters keeping the same. The ICRF wave at 40MHz heats the electrons through electron Landau damping (ELD) and transit-time magnetic pumping (TTMP), since there is no resonant layer in the plasma. In the second harmonic scheme of hydrogen ion at 56MHz, neutron flux increases slightly mainly due to the increase in electron density caused by the injected ICRF wave. However, in frequencies of 40MHz and 56MHz, the ICRF waves did not heat main ions obviously.

In the second campaign operation of HT-7, it is also observed the fusion neutron flux increases remarkably in ICRH MC experiments, which is operated at frequency of 27MHz and toroidal field of 1.95T. The ion temperatures have been provided by charge exchange recombination spectroscopy (CXRS) [5], which indicate an increase in ICRF cooperating with LHCD plasmas. The LHW plays an important role in improving background electron temperature thus helping the increase in ion temperature by collisions. And different combination phases of ICRF and LHW have been carried out to find a better heating effect.

2. ICRF MC experiments on HT-7

The main parameters of HT-7 superconducting tokamak are: plasma current I_p=100-250kA, toroidal field B_t=2T, major radius R=1.22m, minor radius a=0.27m, central electron temperature T_e=0.5-3.0keV, central ion temperature T_i=0.2-1.5keV, central line-averaged plasma density n_e=(1-6)×10^{19}m^{-3} and circular cross-section. There are more than 20 kinds of diagnostic that have been used for daily experiments. The antenna was installed at x=-30cm on the high field side (HFS) in the mid-plane and matched by three step tuners [6].

The ICRF experiments have been carried out at three frequencies on HT-7, which correspond to different heating scenarios. However, the fusion neutron flux increased strongly with the ICRF power if exceeding 0.1MW, which means an anomalous ion heating rather than electron heating close to MC layers as in standard MC heating scenario [7]. In discharge 106301, assuming the H/H+D is 23% from the experiment experiences [8], the 24MHz fast magnetosonic wave was emitted from the HFS propagating inwards and reaches the hybrid resonance at x=-3cm, where $\varepsilon_\perp = n_\parallel^2$. The MC slow wave propagates backwards to the HFS and deposits its power to electrons by ELD. The fast wave transmits through the evanescent layer and strikes the cyclotron layer $\omega = \Omega_H = 2\Omega_D$ at x=+18.7cm. Resonant wav-particle interactions are responsible for the absorption of the wave energy and lead to plasma heating, as shown in FIG.1. The fusion neutron flux increases immediately, where the plasma current is 160kA, central line-averaged electron density is up to 2.5×10^{19}m^{-3} , LHW power is 300kW and ICRF power is 260kW. Among others the increase in electron density also makes a contribution in the fusion neutron flux. And the gamma-ray and hard x-ray are unchanged still keeping at a very low level, which exclude the contribution of photo-neutrons from runaway electrons. Seen from the electron cyclotron emission diagnostics (ECE), central electron temperature is constant or decreased in the ICRH phase. Neutron-gamma count spectra, recorded by BC501A liquid scintillator in FIG.2, shows the increase in neutron flux when ICRF wave was injected. Before ICRH, the neutron flux is too low to be discriminate at 400ms, however, at 600ms the neutron flux increases obviously during the phase of ICRH.

Though the spectra system has not been calibrated, it still permits n/γ discrimination on the basis of pulse-shape analysis, which could be well used at a gamma background.

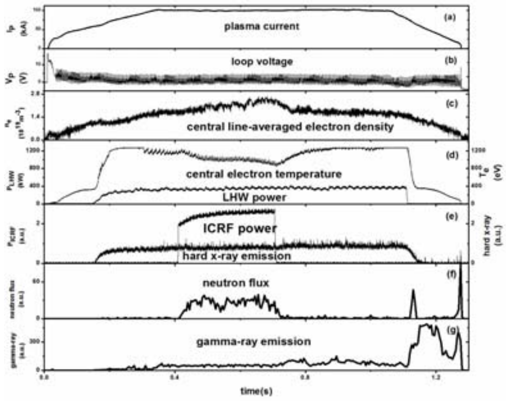
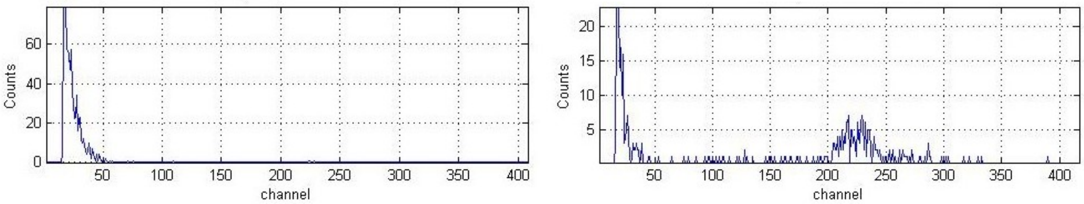


FIG.1. Shot 106301. (a) plasma current, (b) loop voltage, (c) central line-averaged electron density, (d) central electron temperature and LHW power, (e) ICRF power and hard x-ray emission, (f) neutron flux, (h) gamma-ray emission.



(a) (b)

FIG.2. Neutron-gamma count spectra. (a) 400ms before ICRH phase, (b) 600ms during ICRH phase.

The injected ICRF power also affects the neutron flux closely. The strong scaling of fusion neutron flux with ICR power is summarized in FIG. 3. The neutron flux roughly depends on 1.39±0.07 powers of ICRF power at fixed plasma current, central line-averaged electron density etc. in HT-7 MC heating experiments. Derived from the least square fitting, neutron flux $Y=(4.44\pm1.69)P_{ICRF}^{(1.39\pm0.07)}$. There is no direct measurement of ion temperature in this campaign HT-7 experiments. The main ion temperature derived from neutron flux is increased by a factor of 9 at 0.3MW ICRF power, if the increase in neutron flux is only due to thermal D-D reactions. But possible contribution in neutron flux due to energetic ions cannot be excluded.

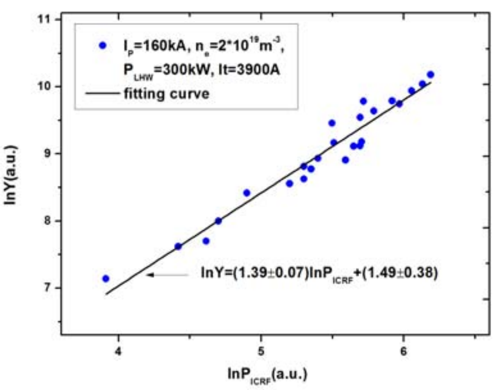


FIG. 3. Dependence of neutron flux on ICRF power. Y is neutron flux, P_{ICRF} is ICRF power in kW.

In the second campaign of HT-7 operation in the same year, there was ion temperature measurement provided by CXRS. The experiments were carried out at a frequency of 27MHz and a toroidal magnetic field of 1.95T, the neutron flux also increase obviously, as in FIG. 4. In ohmic heating (OH) discharge, 109888, for which the plasma current is 180kA, central line-averaged electron density is up to $3\times10^{19}m^{-3}$, the neutron counting rate is low. When the 570kW ICRF wave is injected, in discharge 109890, neutron counting rate increases, which gives a measure of heating. For comparison, in ICRH discharge 109897, cooperated with 300kW LHW with the same radio frequency (RF) power et al., the neutron counting rate is greatest. Their ion temperatures profiles are given by CXRS, separately are shown in FIG. 5. The highest ion temperature is about 0.64keV in OH discharge and 0.84keV in only ICRH experiment. Though the highest ion temperature is still about 0.85keV, the whole ion temperatures are higher. That is because LHW could the background electron temperature and then improve the single pass absorption of ICRF, thus passing part of their energy to ions by collisions. The electron density and temperature in discharge 109897, before and during the phase of ICRF, are also provided by the Thomson Scattering [9], in FIG.6, which indicates an increase induced by the ICRF and LHW.

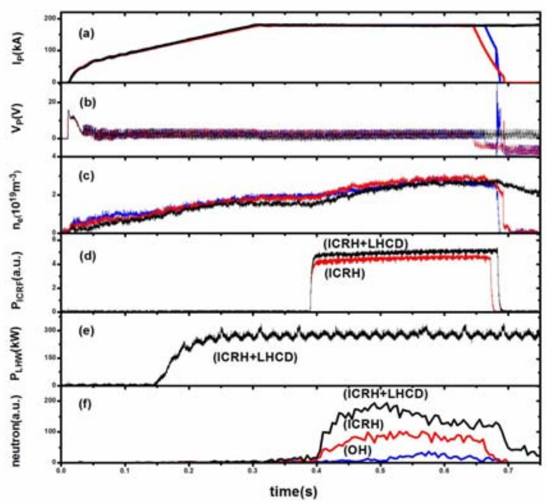


FIG. 4. Shot 109888(blue), 109890(red) and 109897(black). (a) plasma current, (b) loop voltage, (c) central line-averaged electron density, (d) ICRF power, (e) LHW power, (f) neutron flux.

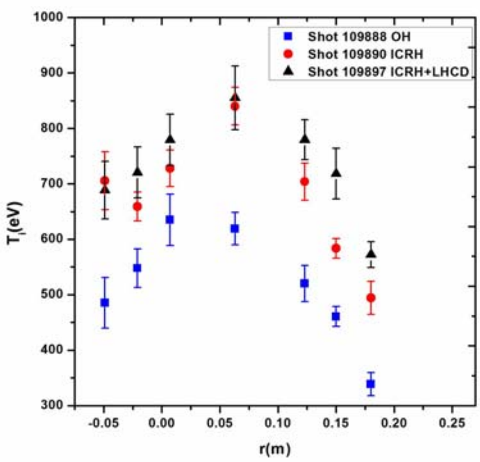
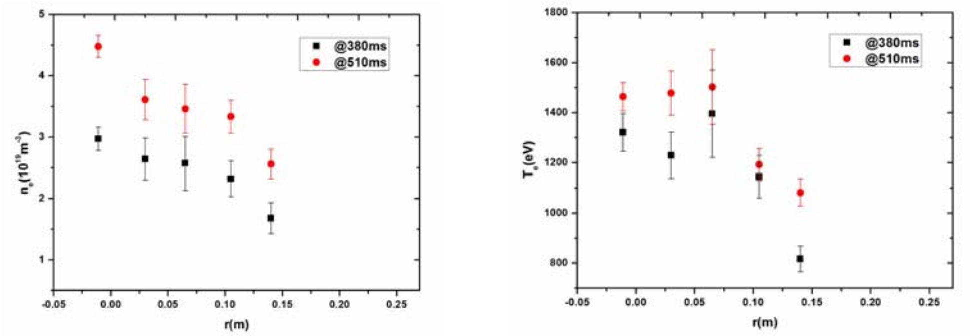


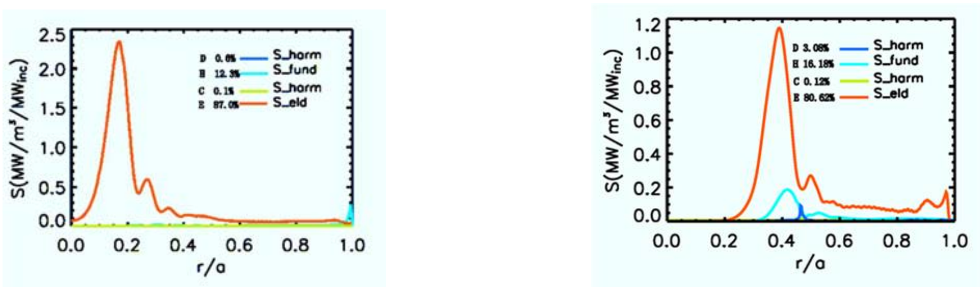
FIG. 5. Ion temperature between 500ms and 580ms of shot 10988, 109890 and 109897.



(a) *(b)*

FIG. 6. Shot109897 (a) electron density and (b) electron temperature.

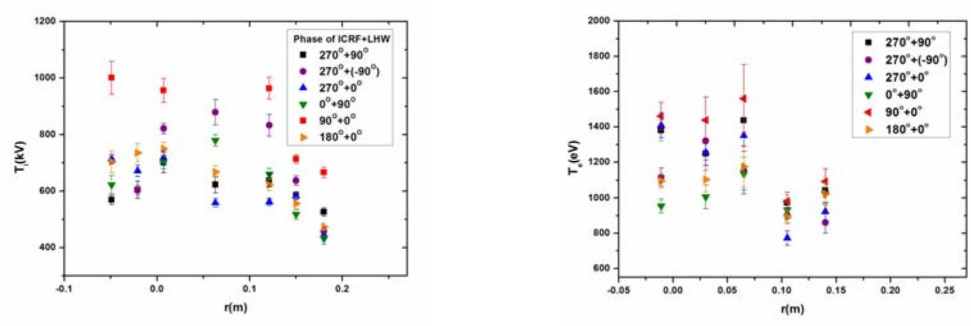
The profiles of power deposition of discharges 106301 and 109897 are shown in FIG.7, simulated by TORIC code, turning out Electron damping is dominant, which is inconsistent with the remarkable fusion neutron flux increase. There are several possibilities to account this anomalous ion heating: (a) high harmonic cyclotron resonance of impurities such as O, C and B. However, there are no cyclotron resonant layers of these impurities near the centre of HT-7 for ICRF MC Cases; (b) fundamental hydrogen and second harmonic deuterium resonant heating. Their resonant layers are located at x=+18.73cm on the low field side, for discharge 106301 and x=+12.78cm for 109897 on the low field side separately. However, the absorption for deuterium second harmonic resonance is weak in HT-7 [10], and is also weak for fundamental hydrogen heating due to less favorable polarization. (c) Fast wave and IBW heating ions by cyclotron resonance. There is a possibility that fast wave and IBW heat the deuterium ion by nonlinear mechanism. Indeed the deuterium 3/2 harmonic resonance layer is located at x=-17.3cm and -21cm for those discharges. And the radio of the left to right hand polarization is about 0.2 and 0.27 by using $E+/E-=(\omega-\omega_{CD})/(\omega+\omega_{CD})$ [11].The fast wave propagates to the resonant layer, also does the backwards IBW. These multiple wave absorptions are stronger, which lead to ion heating by resonant wave-particle interactions. This causes a formation of high energy tail on the ion energy distribution function. Energetic particles usually play a crucial role in the power absorption. A high energy tail start to develop on the distribution function of the resonant ions, as it evolves, more ions interact strongly with wave and the absorption strength is further enhanced if the machine size and the plasma current are large enough to confine the energetic ions [10]. The change of electron density and temperature were small. Since the increase of plasma storage energy does not support a significant increment in main ion temperature for this heating experiment, the product of energetic particles may be partially responsible for that.



(a) *(b)*

FIG.7 Profiles of power deposition for (a) 24MHz, 1.8T and (b) 27MHz, 1.95T.

The ICRF in collaboration with LHCD experiments also have been carried out at different phases for seeking better coupling with the plasma. The plasmas have been operated at I_P=180kA, B_t=2.0T, P_{ICRF}=520kW, P_{LHW}=280kW and central line-averaged electron density is up to $2.8\times10^{19}m^{-3}$. And the phases of ICRF and LHW are combined as in FIG.8, it is found the maximum ion and electron temperature occur at 90^o+0^o, corresponding to the phase of ICRF and LHW separately. While the fusion neutron flux has no obvious change, which is due to lower energy confinement time at this phases combination. However, more effective experiments need to be developed.



(a) *(b)*

FIG.8. (a) ion temperatures and (b) electron temperatures at different phases combination of ICRF and LHW.

3. Discussions

The operation of ICRF system cooperated with LHCD during the D-D MC heating experiments was effective. The obvious fusion neutron flux increase shows an anomalous ion heating, because the increases in electron density and ion temperature detected could not afford this all. The most possible reason account for this may be energetic particles produced by deuterium nonlinear resonance heating. The neutron flux depends on ICRF power as $Y=(4.44\pm1.69)P_{ICRF}^{(1.39\pm0.07)}$ if the ICRF power exceeds 0.1MW. Neutron flux is improved by cooperating with LHW during the phase of ICRH, showing a higher ion temperature. This is because LHW could improve background electron temperature and then the single wave absorption, thus passing part of its energy to ions by collisions. The combination phases of ICRF and LHW are also carried out on HT-7, which shows a best ion temperature at 90^o+0^o, corresponding to the phase of ICRF and LHW separately. But due to lower energy confinement time, the fusion neutron flux does not increase obviously. In future, EAST is equipped with higher ICRF power, and diagnostics will provide direct ion temperature measurement. This provides possibility to investigate anomalous increase of neutron flux by excluding contribution from direct ion heating in ICRF MC Scenarios. The much better accessibility and higher single pass absorption are expected since phased double strap antenna and higher electron/ion temperature of target plasma.

Acknowledgments
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