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Photon Temperatures of Hard X-Ray Emission of LHCD Plasmas and Current Drive Efficiency in the HT–7 Tokamak

J. YOUNIS[1], B. N. WAN[1], S. Y. LIN[1], Z. Y. CHEN[2], Y. J. SHI[1], J. F. SHAN[1], F. K. LIU[1]

1. Institute of Plasma Physics, Chinese Academy of Sciences, Hefei 230031, P R China
2. Department of Physics, Yunnan Normal University, Kunming 650092, P R China

A comprehensive study of photon temperatures (Tph) of hard X-ray emission in the lower hybrid current drive (LHCD) plasmas and the current drive efficiency of lower hybrid waves in HT-7 tokomak is presented through a simple correlation. The photon temperature increases with increasing plasma current while it decreases with increasing plasma density. The current drive efficiency increases with the increase of the density in fully accessible condition of LHCD, with the decreased photon temperature T_{ph} and increased population density of the fast electrons at fixed plasma current. These experimental results reveal that photon temperature depends mainly on global effects of the fast electron population, synergy between the fast electron and the loop voltage and the coulomb slowing down.

Keywords: photon temperature, hard x-rays, current drive efficiency, HT-7 tokamak

1. Inroduction

Steady state operation of tokamak is the ultimate goal to realize a commercial fusion reactor. On the other hand, high performance, such as in advanced tokamak operation modes, is needed for the economic use of fusion reactors [1]. Lower hybrid (LH) waves are routinely used to drive currents in tokamak plasmas non-inductively, thus significantly extending the tokamak operation space to long-pulse, steady state discharges**.** In recent years lower hybrid (LH) waves have been successfully utilized for electron and ion plasma heating, to sustain and ramp-up toroidal plasma current, and to stabilize sawteeth in tokamak Investigations carried out in the HT-7 tokamak are contributing to these issues relevant to fusion reactors and the underlying physics. HT-7 is a medium sized tokamak with superconducting toroidal coils. Its main purpose is to explore high performance plasma operation under steady-state conditions. Since the very beginning of LHCD experiments in tokamaks, it has been recognized that hard X-ray emission from fast electrons provides considerable information on the LH wave power deposition profile and the fast electrons energy distribution. The measurement of the FEB emission in the hard X-ray energy range is the most efficient means for the investigation of LHCD experiments in plasma physics [2]. The photon temperature is just a parameter to characterize the level of anisotropy of the fast electron tail, which is determined by the exponential-like decrease of the FEB energy spectrum. The photon temperature is a commonly used parameter, to analyze qualitatively how the tail evolves with radio frequency wave parameters. The photon temperature indicates the “hardening” of the X-ray spectra, resulting from the interaction of fast electrons with residual loop voltage. It contains information of the energy distribution of fast electrons driven by the LH waves and residual electric field. For higher T_{ph}, the fraction of the energetic fast electrons population is larger, which means more plasma current carried by the fast electrons. The current drive efficiency is one of the most important parameter in non-inductive current drive for the evaluation of lower hybrid current drive experiments [3]. The experimental current drive efficiency is defined as $\eta = I_{rf} n_e R/P_{LH}$, where I_{rf} is the current driven by the lower hybrid waves, n_e is the central line average density, R is the major radius of the plasma and P_{LH} is the injected LH wave power absorbed by the plasma through landau damping. A fully non-inductive CD efficiency $\eta_o = I p n_e R/P_{LH0}$ is obtained when loop voltage approaches zero. P_{LH0} is the required LH power to attain zero loop voltage. The current related to RF power can be estimated by $I_{rf} = -(\Delta V/V_{OH}) I_p$, where $\Delta V = V_{LH} - V_{OH}$ is the loop voltage change between the LHCD phase and ohmic phase if total plasma current is unchanged. The purpose of this paper is to give a description of current drive efficiency in the LHCD plasma of HT-7 tokamak through such a simple way which is directly linked to the population and averaged velocity of fast electrons.

author's e-mail: jawad@ipp.ac.cn

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2. Experimental Results and Discussion

HT-7 is a medium sized tokamak with superconducting toroidal coils and water-cooled graphite limiters in circular cross section [4]. It has a major radius of R_0 = 1.22 m, minor radius of a = 0.27 m, one toroidal water-cooling belt limiter at high field side and a new set of actively cooled toroidal graphite limiters at the bottom and top of the vacuum vessel. A LH power (P_{LH}) up to 1.2 MW at 2.45 GHz is available presently in the HT-7 machine. The power spectrum of the launched wave can be adjusted in the range $1.25 < n_{//} < 3.45$ by means of feedback control of the phase difference between adjacent wave guides of the couplers, where $n_{//}$ is the peak index of parallel refraction of the launched wave. The HT-7 tokamak is normally operated at I_p = 100–200 kA, B_t = 2 T, line-averaged density $n_e = (0.5 - 4) \times 10^{19}$ m^{-3}, in the limiter configuration. The hard X-ray diagnostics system in HT-7 is the main tool to measure FEB and consists of a vertical X-ray detector array. On HT-7 the CdTe detector was also used in the vertical array since 2001 for its excellent performance and successful application. The CdTe detector here can detect an energy range of X-ray from 20 keV to 200 keV, which is the energy range of non-thermal bremsstrahlung emitted by the fast electrons driven by lower hybrid wave. In the present experiments the feed back controls were applied to keep plasma current, the position and central line averaged density constant.

A typical waveform of the LHCD discharge is shown in the Fig. 1. The plasma current is 150 kA, the line averaged density $n_e = 1.6 \times 10^{19}$ m^{-3}, 230 kW LHCD was launched from 0.32 s to 1.1 s.

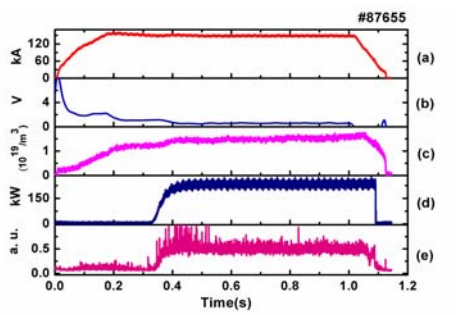

Fig. 1 Waveforms of LHCD discharge no. 87655. (a) is the plasma current, (b) the loop voltage, (c) the center line –average density, (d) the LH power, (e) the center line-integrated FEB emission intensity

For the plasma current scanning experiments it is experimentally and numerically observed that photon temperature increases with the increase in plasma current[5], which is mainly due to the interaction of the residual loop voltage and the fast electrons driven by lower hybrid waves. The population of fast electrons is higher at high plasma currents. Both increment of photon temperature and population of fast electrons at higher plasma currents leads to higher lower hybrid current drive efficiency.

During the plasma density scan experiment, LH power with 500 kW at $n_{//}$ = 2.35 was injected into target plasma having current of 150 kA. The plasma densities scanned shot by shot were (1.2, 1.7, 2.1, 2.5) x10^{19} m^{-3}. The photon temperature of central sight line is derived from FEB spectra, T_{ph} decreases with increasing plasma density [5,6]. At plasma density of 1.2x10^{19} m^{-3} and a fixed plasma current 150 kA, the CD efficiency is lower, that is only 0.33 m^{-2}A/W. The population of fast electron produced by the lower hybrid waves indicated by HX-ray intensity normalized by the line averaged density is low as can be seen in the Fig. 2.

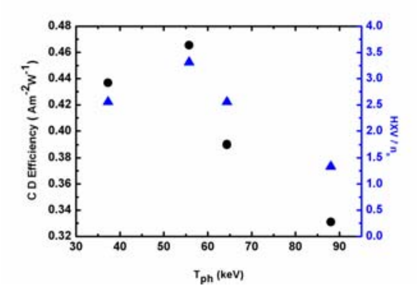

Fig. 2 Lower hybrid current drive efficiency and ratio of intensity of fast electron to density of fast electron versus Photon temperature at I_p= 150kA , P_{LH} = 500kW $n_{//}$ =2.35, (circle and triangle represent CD efficiency and ratio of fast electron population to density respectively).

At the lower line average plasma density of fixed plasma current, the electron temperature of the target plasma is higher, which will generate more resonant electrons with LHW on one hand. On another hand the less frequent collision with bulk electrons at lower plasma density can sustain the fast electron produced by LHW for longer time, which is partially responsible for higher photon temperature, due to lower slowing down time. At higher plasma density of 2.1x10^{19} m^{-3}, the CD efficiency is about 0.44 m^{-2}A/W, while the fast electron population is much higher than the low plasma density case as seen in Fig. 2. For higher density region the target

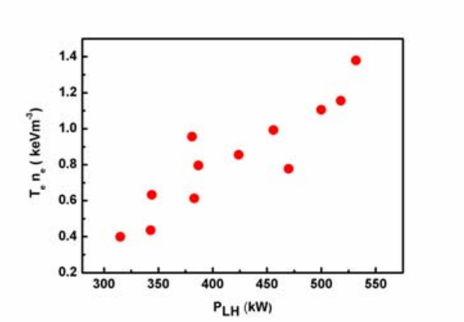

Fig. 3 Δ $T_e n_e$ versus lower hybrid Power at n_e= 1.5x$10^{19}$$m^{-3}$, I_p= 150kA, P_{LH} = (188-532)kW, $n_{//}$ =2.35.

plasma has low temperature at fixed plasma current and faster slowing down will leads a lower photon temperature. The increased population of fast electrons contributes the increased CD efficiency significantly.

Figure 3 shows the increment of $\Delta T_e n_e$ with the LHCD power, which gives a measure of the energy transferring to bulk electrons from LHW. This heating is mainly through the collision of the bulk electrons by the fast electrons generated by LHCD, which slows these fast electrons down. The slowing down time of fast electrons, which is generated primarily at the resonance energy of LHCD [7], is inversely proportional to the bulk electron density. It can be clearly seen from the increment rates of $\Delta T_e n_e$ against LHW power in figures 3 and 4 for the densities of 1.5x10^{19} m^{-3} and 1.0x10^{19} m^{-3}.

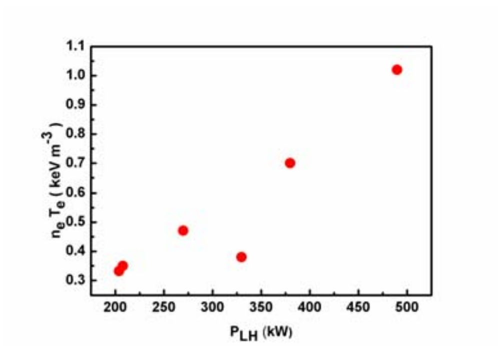

Fig.4 Δ $T_e n_e$ versus lower hybrid Power at n_e= 1.0x$10^{19}$$m^{-3}$, I_p= 150kA, P_{LH} = (204-490)kW.

The slowing down via collisions can be responsible for the energy transferring to the bulk electrons from the fast electrons, which may account for the behavior of the photon temperature versus density. the population of the fast electrons generated by LHCD plays dominated role in generation of the current carried by fast electrons.

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