The features of the electron heat transport during high power ECRH & SMBI on HL-2A

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Abstract. With high power ECRH and supersonic molecular beam injection (SMBI), the electron heat transport has been investigated on HL-2A. This paper will show features of the electron transport during ECRH, especially new non-local phenomena triggered by SMBI, in which an electron transport barrier is formed and the confinement is improved. The diffusion coefficient both from steady-state analysis ($\chi^{hp}$) and the heat pulse propagation ($\chi^{pb}$) increase with the ECRH power and decrease with the electron density, which is in agreement with the L-mode scaling. The ratio $\chi^{hp}/\chi^{pb}$ is about 2.8 in Ohmic discharges; it increases to 3.3 with low power ECRH and decreases to 1.7 with the high power ECRH. The non-local transport phenomena induced by SMBI have been observed firstly on HL-2A. The density limit beyond which the phenomena disappear is apparently higher in the ECRH regime than in the Ohmic regime. Both the bolometer radiation and the H$^-$ emission decrease when the non-local effect appears. After the appearance of the non-local effect, it can be found that the region outside $r/a \sim 0.5$, just like usual result, is cooled by SMBI, while the core $T_e$ increasing gives a surprise. The core $T_e$ is increased by about 18%. This suggests that the injection of SMBI triggers the internal transport barriers.

1. Introduction

Electron heat transport in burning plasmas is one of the great challenges to realize controlled nuclear fusion. There are some phenomena, such as profile consistency, ITB and non-local effect, which have been debated for years. Up to now, and in spite of a wealth of results, these debates have not lead to a clear conclusion. During the last few years, the electron heat transport has been extensively investigated in tokamaks [1, 2, 3], in particular supported by the electron cyclotron resonance heating (ECRH) system. The good local power deposition of ECRH in the plasma permitted a detailed study of the electron heat transport [4, 5, 6]. New experimental observation in the study helps us to understand heat transport deeply. Heat transport study with the high power ECRH in HL-2A could provide complementarities for the database of transport analysis.

From the first observation of the non-local effect at TEXT-U in 1995 [7] to later reports on many tokamaks [8, 9, 10, 11], the non-local phenomena evoke much attention of the scientists who focus on plasma transport. Then, different edge cooling experiments have been widely performed in studying the new conundrum: impurity injection by laser ablation, ice pellet injection, carbon-based molecules injection, etc. But there is no report about the effect induced by a gas puffing. In 2006, the non-local effect has been observed after the SMBI in HL-2A. This is a new observation that a cold gas pulse can
also induce the non-local effect. This means the non-local effect can be investigated by the new experimental method. In this paper, we show the non-local effect induced by the SMBI both in ECRH regime and in the ohmic regime, and give preliminary analysis results about it.

In this paper, we focus on the electron heat transport with the high power ECRH and the SMBI in HL-2A. The paper is divided as follows: in section 2, the experimental arrangements are described. Section 3 gives the experimental results about electron heat transport in L-mode plasma and the non-local phenomena triggered by the SMBI, and both results are discussed in this section. The summary is presented in the last section.

2. Experimental arrangement

The HL-2A is a divertor tokamak (the major radius \( R = 1.65 \text{ m} \); the minor radius \( a = 0.4 \text{ m} \)) which can be operated in a limiter or a single null-divertor configuration with the following parameters: toroidal magnetic field \( B_t < 2.8 \text{ T} \); the average electron density and plasma current are \( n_e = (1-5) \times 10^{19} \text{ m}^{-3} \) and \( I_p = (250-430) \text{ kA} \), respectively [12]. More than 30 diagnostics have been developed on HL-2A in recent years. Among them, the key diagnostics for heat transport study are soft-x-ray array, Electron Cyclotron Emission (ECE) diagnostics and diamagnetic measurement. Four soft-x-ray arrays, each with twenty channels, are used. The x-ray signal results from plasma bremsstrahlung and recombination processes, both of which are strongly dependent on temperature and density. The ECE spectrum is measured by a 2 mm sweeping heterodyne radiometer. The range of the scanning frequency is between 104 and 181 GHz. Its temporal and spatial resolutions are 4 ms and 4 cm, respectively. There is also a high temporal resolution ECE system (up to 1 \( \mu \text{s} \)) which covers about 20 cm along the plasma midplane. In the SMBI experiment with \( B_t = 2.31 \text{ T} \), a whole second harmonic spectrum can be obtained. Under the usual discharge parameter in HL-2A, the calculation of optical thickness shows that inside \( r/a \approx 0.7 \), the plasma could be considered as the black body and the intensity of ECE 2nd harmonic is only proportional to the electron temperature. A one-point measurement Thomson Scattering system is developed to measure core plasma \( T_e \) of HL-2A tokamak, with the time resolution of 100 ms.

ECRH system with four 68 GHz / 500 kW / 1 s gyrotrons has been built up in HL-2A [13]. The ECRH power with fundamental O-mode up to 2 MW is injected from the low field side of the device. The deposit position of ECRH is determined by the toroidal magnetic field. When toroidal magnetic field varies from 2.43 T to 2.2 T, the resonance point can be replaced from the plasma core to the point at \( r = 16 \text{ cm} \). The wave energy deposits in a range of 3cm. The efficiency of the transmission system is more than 80 \%, so at least 1.6 MW power can be injected into plasmas.

A supersonic molecular beam injection (SMBI) has been successfully developed in the HL-1M tokamak [14]. SMBI is an improvement method of conventional gas puffing (GP). The source consists of a small chamber and a Laval nozzle. The working gas can be kept at a definite pressure \( P_o \) and temperature \( T_o \) in the chamber. Particles of the gas are accelerated by imposed pressure through the nozzle to get into the vacuum chamber of the tokamak. It is an attempt to enhance the penetration depth and fueling effect. The penetration depth is very important to trigger the non-local transport phenomena. \( I_n \) intensity profile measured by \( I_n \) detector array [15] and the density profiles measured by microwave reflectometry indicate that the penetration depth of the SMBI is more than \( r/a = 0.7 \) [16].

3. Experimental results

3.1. Electron heat transport during high power ECRH

High power ECRH discharges (larger than 1MW) have been investigated on HL-2A in 2006 experiment. Perfect heating efficiency has been observed and the temperature climbs to about 5 keV with the 1.6 MW ECRH. Figure 1 shows the results of a high power ECRH discharge with \( B_t = 2.42 \text{ T} \), \( n_e = 1.7 \times 10^{19} \text{ m}^{-3} \), \( P_{\text{ECRH}} = 1.3 \text{ MW} \) and \( I_p = 300 \text{ kA} \). The electron temperature during the ECRH is
almost two times higher than that in the ohmic heating phase, both the Thomson scattering and the ECE diagnostic show the similar result.

The electron heat diffusivities both from a steady-state analysis and a heat pulse propagation analysis have been obtained on the high power ECRH discharges. All the data are selected from HL-2A experimental data with \( P_{\text{ECRH}} = 1 - 1.6 \) MW, \( B_t = 2.31 \) T, \( n_e = (1-3) \times 10^{19} \) m\(^{-3}\). An estimate for \( \chi_{\text{e}}^{\text{ohm-pb}} \) at \( r/a = 2/3 \) can be obtained from the global power balance by using [17]

\[
\chi_{\text{e}}^{\text{ohm-pb}} = a^2 / (4 \tau_e)
\]

where \( \tau_e \) is the energy confinement time, defined by \( \tau_e = W / P \); here, \( W \) is the total storage energy, \( P \) is the total absorbed power, and \( a \) is the minor radius.

\[
\chi_{\text{e}}^{\text{hp}} = (r^2 - r_{\text{mix}}^2) / (8 t_p)
\]

where \( r \) is the radius at which the \( T_e \) perturbation is measured, \( r_{\text{mix}} \) is the sawtooth mixing radius and \( t_p \) is the time at which \( \Delta T_e \) reaches its maximum. In this article, \( \chi_{\text{e}}^{\text{hp}} \) is studied at \( r/a = 2/3 \) in the confinement region, where corresponds to that evaluated by the power balance analysis.

The power balance analysis shows that the \( \chi_{\text{e}} \) before ECRH, \( \chi_{\text{e}}^{\text{ohm-pb}} \) is \( 0.7 \pm 0.3 \) m\(^2\)/s, which is more than 2 times lower than that with the high power ECRH: \( \chi_{\text{e}}^{\text{ECRH-pb}} = 1.8 \pm 0.4 \) m\(^2\)/s. The \( \chi_{\text{e}}^{\text{hp}} \) estimated from the heat pulse propagation in ohmic discharges is \( 2.0 \pm 0.5 \) m\(^2\)/s. During ECRH, it increases to \( 3.5 \pm 0.8 \) m\(^2\)/s. In figure 2(a), \( \chi_{\text{e}}^{\text{hp}} \) is plotted versus input the ECRH power and it increases with the increasing power. As shows in figure 2(b), the heat pulse propagation studying show the similar result. It is a selection of divertor discharges with \( I_p = 350 \) kA, \( B_t = 2.31 \) T, \( n_e = (2-3) \times 10^{19} \) m\(^{-3}\). As can be seen from figure 3, both \( \chi_{\text{e}}^{\text{ohm-pb}} \) and \( \chi_{\text{e}}^{\text{hp}} \) decrease with the electron density.
Figure 2. (a) $\chi_{e}^{pb}$ as a function of input ECRH power $P_{ECRH}$. (b) $\chi_{e}^{hp}$ versus ECRH power $P_{ECRH}$. The dashed line in (b) represents the relation between $\chi_{e}^{hp}$ and $P_{ECRH}$. A selection of divertor discharge with $I_p = 350$ kA, $B_t = 2.3$ T, $n_e = (2 - 3) \times 10^{19} \text{ m}^{-3}$.

Figure 3. (a) Measured $\chi_{e}^{pb}$ values as a function of electron density $n_e$. (b) $\chi_{e}^{hp}$ as a function of electron density $n_e$, with $P_{ECRH} \approx 1.3$ MW, $I_p = 350$ kA, $B_t = 2.3$ T. The dashed line in (b) represents the relation between $\chi_{e}^{hp}$ and $n_e$.

A discrepancy appears between the two methods: in Ohmic discharges the $\chi_{e}^{pb}$ derived from power balance analysis is lower than the $\chi_{e}^{hp}$ derived from heat pulse propagation analysis by a factor of 2.8. From figure 4, it can be found that the factor will increase to 3.3 with lower power ECRH (400 kW - 700 kW). However the factor deceases with the high power ECRH and it decreases to 1.7 when the power is higher than 1 MW. This discrepancy has been reported in many other tokamak and ranges from a factor of 1 to 5 [19, 20, 21], a factor of 10 even was reported in TFTR [22].

In HL-2A, a threshold exists in the normalized gradient length $R/L_T \sim 12.5$ and a “medium” level of profile stiffness have been observed, as shown in figure 5. The word “medium” is used to differentiate from the “strong” stiffness profile whose gradients are very close to the threshold everywhere. According to the empirical model for electron heat transport based on the existence of a threshold [23], it is not difficult to understand the heat transport increasing with the ECRH power in HL-2A. In order
to keep temperature profile “stiff”, once the auxiliary heating power increases, the heat transport increases to prevent the temperature gradient exceeding the threshold. From the results of the heat pulse propagation analysis in HL-2A, the dependence $\chi_e \propto P^{0.4}$ and $\chi_e \propto n_e^{-1}$ (see figure 2(b) and figure 3(b)) are consistent with the results of other tokamaks, which predicts $\chi_e \propto P^{0.1\text{ to }0.5}$ and $\chi_e \propto n_e^{-(0\text{ to }1)}$ [24].

3.2. Non-local phenomena triggered by SMBI during ECRH

A typical shot of SMBI experiment which induces the non-local effect is shown in figure 6, with $B_t = 2.31$ T, $n_e = 1.0 \times 10^{19}$ m$^{-3}$, $I_p = 250$ kA, $P_{ECRH} = 800$ kW, $t_{ECRH} = 600 - 900$ ms, $t_{SMBI} = 810$ ms. From the time evolution of $T_e$ at different radii, it can be found that after the injection of SMB, the region outside $r \sim 20$ cm is cooled by it, while the core $T_e$ increases. The core $T_e$ is increased by about 18 % and the duration of the process is about 40 ms. From the temperature profile evolution, the reverse position is about 8 cm outside the $q = 1$ surface, as shown in figure 7. The inverse position is several centimetres outside the $q = 1$ surface, the calculation of EFIT shows that the position is inside the $q = 2$ surface.
A strong dependence of the non-local effect induced by SMBI on plasma density is observed: the effect appears only in a low density plasma, the most discharges are around $1.0 \times 10^{19} \text{ m}^{-3}$ and it disappears when the density is larger than $2.0 \times 10^{19} \text{ m}^{-3}$. In figure 8, three SMBs are injected before ECRH, during ECRH and after ECRH, respectively. The density before the injection of the first SMB almost equals to that of the second, the density before the last injection is much lower than the former two, as shown in figure 8(b). The non-local effect appears after the injection of the latter two SMBs, while the first one doesn’t induce such an effect. The effect always occurs with low density and the density limit becomes larger during the ECRH.
In comparison with present-day experiments on different tokamaks, the reported results are quite different with various tokamaks. The non-local effect is enhanced by ECRH in HL-2A. The auxiliary heating (with neutral beam injection in TFTR and ECRH in TEXT) progressively weakens the non-local effect, while the effect is significantly enhanced in the presence of ECRH in RTP and of LHCD in Tore Supra. In addition, the effect induced by SMBI in HL-2A lasts much longer than that induced by pellet injection in other similar size tokamak: the duration of HL-2A is about 40 ms, while it is only 5 ms in RTP.

Improved particle confinement and decreasing of the thermal radiation have been observed during the non-local effect. In figure 9, the bolometer channels represent radiation loss in low field side and high field side, respectively. The $H_\alpha$ channels represent the $H_\alpha$ emission close to (the northern channel) and far from (the eastern channel) the injection port. It can be found that both the bolometer radiation and the $H_\alpha$ emission decrease when the non-local effect appears. Meanwhile, the electron density significantly increases after the injection. It is clear that the plasma confinement has been improved.

**Figure 8.** (a) ECE $T_e$ time traces for shot 6351 with three SMB injections, with $B_t = 2.36$ T, $I_p = 300$ kA, $P_{ECRH} = 800$ kW. (b) the density time evolution in shot 6351.
This suggests that the injection of SMB triggers internal transport barriers, which weakens the inward propagation of the cold pulse and the outward heat diffusion. Further studies will be conducted in the coming experiment in HL-2A.

Figure 9. Parameters evolution in shot 6234 with SMBI during ECRH. From up to down: the low field side bolometer, the high field side bolometer, the east Hα, the north Hα, the electron density, the SMBI signal.

Regarding the so-called non-local effect, various models have been proposed, from empirical to theory based. There is a non-local thermal conduction model [25] which is consistent with the electron temperature profile consistency and related to the local thermal conductivity at the location $r/a \approx 0.7$. It is assumed that the cold pulse will induce the non-local effect once it deposits at that position. The SMB with directional motion and uniform speed can provide good localization and penetration into a certain region [16]. So the SMBI can induce the non-local effect, while the normal gas puffing can’t.

4. Summary

From the results of the heat pulse propagation analysis in high power O-mode ECRH discharges of HL-2A, the dependence $\chi_e \propto P^{0.4}$ and $\chi_e \propto n_e^{-1}$ are consistent with L-mode scaling, which predicts $\chi_e \propto P^{0.5}$ and $\chi_e \propto n_e^{-(0.1 \sim 1)}$. The ratio $\chi_h^{oh}/\chi_e^{oh}$ is about 2.8 in ohmic discharge, it increases to 3.3 with low power ECRH and decreases to 1.7 with high power ECRH. So the diagonal matrix element in ECRH
discharges is more important than that in ohmic discharges. A ‘medium’ profile stiffness has been observed in HL-2A plasma, the threshold of critical gradient length is about 12.5.

With low density, the non-local effect of edge cooling has been induced by the injection of SMB in the ECRH regime and the ohmic regime. In both regimes, the existence of a threshold on plasma density has been observed. The density limit in ECRH regime is apparently higher than that in the ohmic regime. After the appearance of the non-local effect, it suggests that an electron transport barrier has been probably formed at the position just outside the \( q = 1 \) surface and plasma confinement has been improved.

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