Investigation of the Non-local transport phenomenon with SMBI on HL-2A

H.J. Sun 1), X.T. Ding 1), L.H. Yao 1), B.B. Feng 1), Z.T. Liu 1), Y.D. Gao 1), W. Li 1),
Y.D. Pan 1), X.R. Duan 1), Q.W. Yang 1)
1) Southwestern Institute of Physics, Chengdu, China

E-mail contact of main author: asufish@swip.ac.cn

Abstract. The non-local transport phenomena induced by supersonic molecular beam injection (SMBI) has been firstly observed in HL-2A tokomak in both the low density discharges and the higher density discharges. For low density (less than 2×10^{19} m^{-3}), besides the similarities with the phenomena induced by other methods in various Tokamaks, the results on HL-2A show some experimental progress in this effect: the duration of the core T_e rise induced by SMBI in HL-2A could be prolonged by changing the condition of SMBs injection; both the bolometer radiation and the H_α emission decrease when the non-local effect appears in low density. In higher density range (slightly higher than 2×10^{19} m^{-3}), the fast core T_e decrease response to the edge cooling, after the SMBs injection. Repetitive non-local transport phenomena induced by modulated SMBs allows Fourier transformation of the temperature perturbation, yielding detailed investigation of the pulse propagation. The investigation indicates that, although the fast core T_e response to edge cooling in higher density is opposite to that in low density, the nonlocality of electron heat transport appears in both the two conditions. Analytic results suggest a common underlying physical mechanism between the 'non-local' transport phenomena in the two different conditions.

1. Introduction

Understanding energy transport in magnetically confined plasma remains one of the main challenges for burning plasma. Local microinstabilities lead to local turbulence and hence local turbulent transport, that is presumed in the 'standard model' [1] for anomolous transport in plasma. This simple picture of locally diffusive transport has been successful in describing most perturbative experiments. However, a particular observation of transient transport experiments has yielded evidence of a new kind of feature: under suitable conditions, tokamak plasma responds in a non-local way to perturbations of the electron temperature. Non-local effect becomes a formidable challenge for the standard transport model and the development of an understanding of non-local effect could lead to profound new directions for anomalous transport research.

From the first observation of the effect at TEXT-U in 1995 [2] to later reports on many tokamaks, [3, 4, 5, 6] non-local transport phenomenon evokes much attention of the scientists who focus on plasma transport. Then, different edge cooling experiments have been widely used in studying the new conundrum: impurity injection by laser ablation, ice pellet injection, carbon-based molecules injection, etc. In HL-2A, non-local effect has been firstly observed after supersonic molecular beam injection (SMBI) in both the low and high density discharges, which provides a new experimental method to study the conundrum. Modulated SMBI is introduced to investigate the non-local transport feature of the plasma on HL-2A.

2. Experimental Setup

HL-2A is a divertor tokomak (the major radius $R = 1.65$ m; the minor radius a <0.40 m) which can be operated at limiter or single null-divertor configuration with the following parameters: toroidal magnetic field $B_t < 2.8$ T, the average electron density and plasma current are $n_e = (0.5\text{-}5) \times 10^{19}$ m^{-3} and $I_P < 350$ kA, respectively. [7] The experimental setup of the SMBI system in HL-2A and the detailed structure of the molecular beam valve with cooling trap are shown in figure 1. The SMBs are driven by an electric-magnetic valve and can be injected from both the low field side (LFS) and the high field side (HFS). [8] With the pressure 0.2 to 3 MPa and duration 1 to 10 ms, up to 50 SMBs can be injected from LFS, introducing a new modulated method to investigate electron heat transport.

More than 30 diagnostics have been developed on HL-2A in recent years. Among them, the key diagnostic for this experiment is ECE diagnostic. Two ECE systems have been installed on HL-2A: one scanning heterodyne radiometer and one fast multichannel ECE system. Under the common discharges parameters in HL-2A, the former can provide a whole electron temperature profile with temporal resolution 4 ms and spatial resolution 4 cm. The latter could be a compensation to measure temperature perturbation with good temporal resolution 2 μs.

3. Experimental results and transport analysis

3.1 Non-local effect with SMBI

For density lower than 2×10^{19} m^{-3}, a transient rise of the core electron temperature has been observed when SMBs are injected to induce fast cooling of the peripheral region. The gas pressure and pulse duration of SMBs are 0.5 MPa and 3 ms, respectively.

The typical shot of SMBI experiment which induces the non-local effect in ohmic regime is shown in figure 2, with $B_t = 1.45\ T$, $n_e = 0.7\text{–}1.5\times10^{19}\ m^{-3}$, $I_p = 190\ kA$. From the time evolution of T_e at different radii, it can be found that after the injection of SMB, the region outside $\rho \sim 0.5$ is cooled by it, while the core T_e increases. The reverse position is between $\rho = 0.45$ and $\rho = 0.52$ which is just outside q = 1 surface ($\rho \approx 0.4$). The core temperature rise has strong density dependence: it is more than 600 eV when the electron density n_e is around 0.7×10^{19} m^{-3}, it decreases to 150 eV when n_e is around 1.36×10^{19} m^{-3} and disappears when n_e is higher than 1.5×10^{19} m^{-3}. The duration of the process is about 30 ms which is comparable with the energy confinement time τ_e in HL-2A. However, the duration of the core T_e rise could be prolonged by changing the period of SMBI. In figure 3, the duration increases to more than 100 ms by shorten the injection period of SMBs to 25 ms. It can be found that both the bolometer radiation and the Hα emission decrease when the core T_e increase, accompanying with the increase of the storage energy. Obviously, the duration of plasma confining improvement is prolonged with the duration increase of core T_e rise.

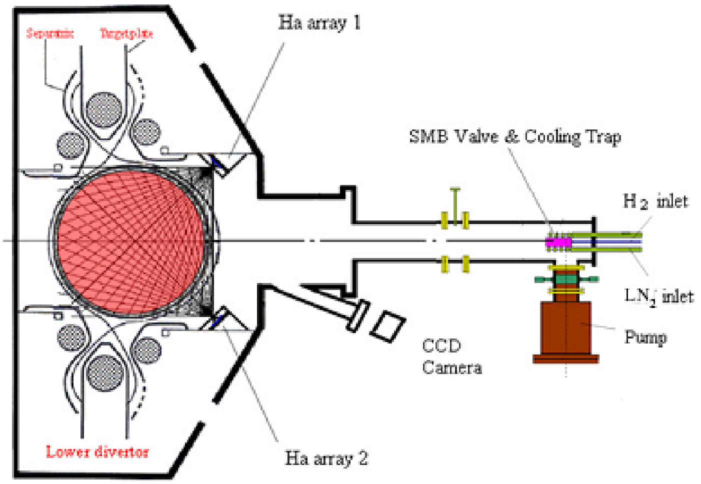
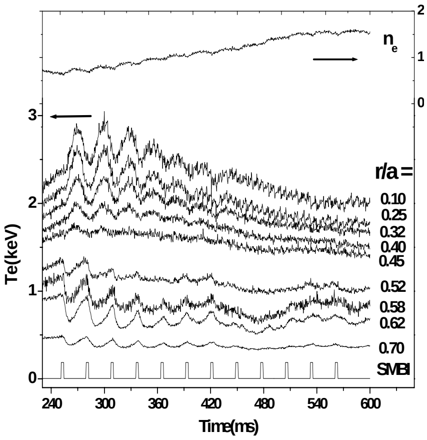


Figure 1. Experimental set-up of SMBI system in the HL-2A tokamak



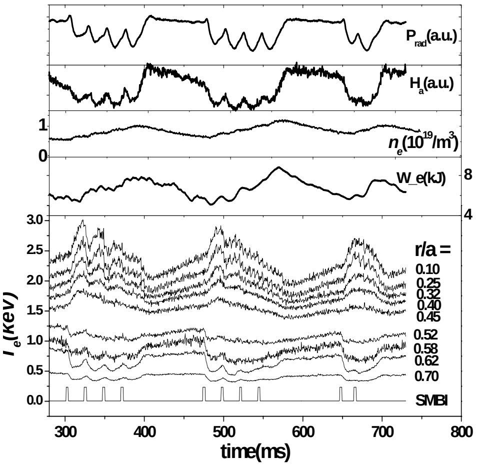


Figure 2. Time traces of ECE temperature at different radii and electron density n_e for shot 8363 in ohmic regime. (B_t = 1.45 T, n_e = 0.7 – 1.5×10^{19} m^{-3}, I_p = 190kA.)

Figure 3. Parameters evolution in shot 8364 with SMBI during ECRH. From up to down: the bolometer signal, the Ha signal, the electron density, the storage energy W_e, ECE temperature at different radii and the SMBI signal in ohmic regime.(B_t = 1.45 T, n_e = 0.6 – 1.2×10^{19} m^{-3}, I_p = 190kA.)

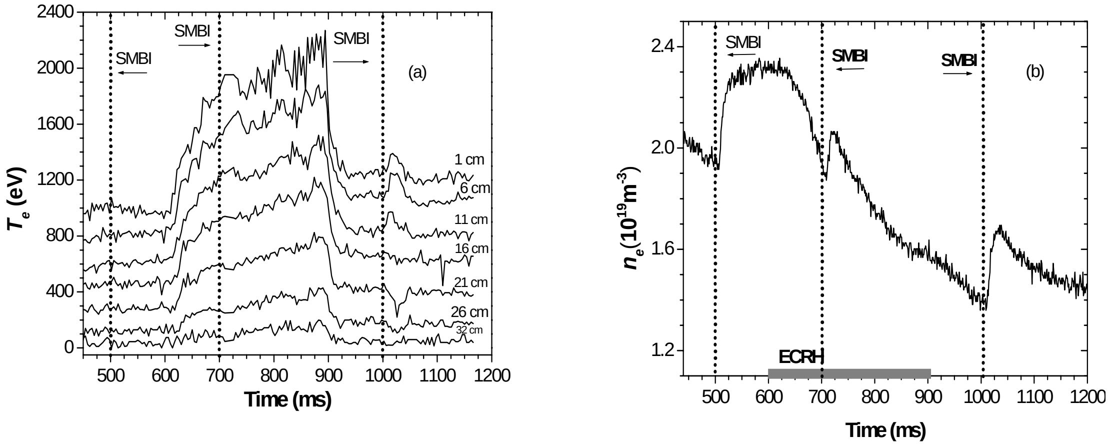


Figure 4. (a) ECE Te time traces for shot 6351 with three SMBS injection, with Bt = 2.36 T, Ip = 300 kA, P_{ECRH} = 800 kW.

(b) the density time evolution in shot 6351.

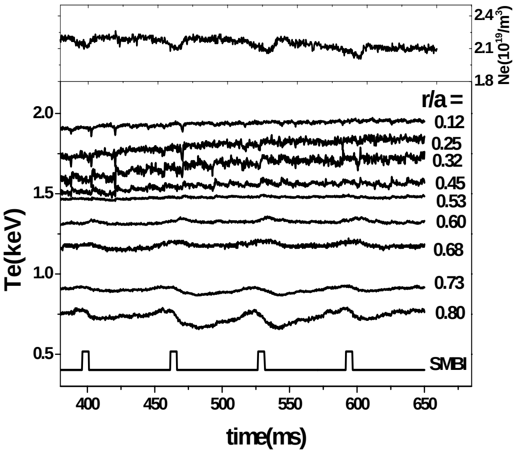


Figure 5. Time traces of electron density n_e and ECE temperature at different radii for shot 7541 in ohmic regime. (B_t = 1.45 T, n_e = 2.2×10^{19} m^{-3}, I_p = 180kA.)

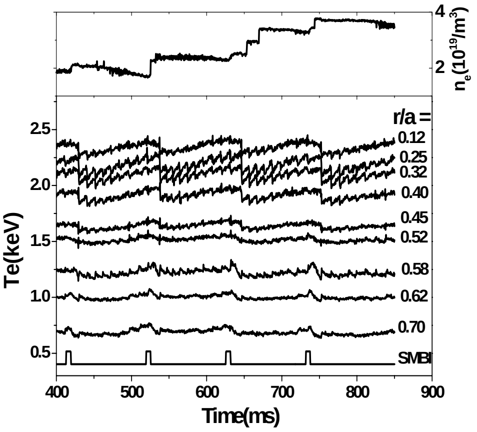


Figure 6. Time traces of electron density n_e and ECE temperature at different radii for shot 7598 in ohmic regime. (B_t = 1.45 T, n_e = 2-3.5×10^{19} m^{-3}, I_p = 180kA.)

In order to study the effect of the auxiliary heating to this phenomenon, three SMBs are injected before ECRH, during ECRH and after ECRH ($P_{ECRH} \approx 800\ kW$), respectively (see figure 4). The density before the injection of the first SMB almost equals to that of the second ($n_e \approx 2 \times 10^{19}\ m^{-3}$), the density before the last injection ($n_e \approx 1.3\ \times 10^{19}\ m^{-3}$) is much lower than the former two, as shown in figure 4(b). The non-local effect appears after the injection of the latter two SMBs, while the first one doesn't induce such an effect. Obviously, the density limit in ECRH regime is larger than that in ohmic regime in HL-2A.

For density higher than 2×10^{19} m^{-3}, with the same gas pressure and pulse duration as the lower density discharges (0.5 MPa and 3 ms), the common phenomenon appears after SMBI: inward-moving cooling responses are obvious within the plasma outside area and there is no perturbation in the core plasma T_e, as shown in figure 5. However, a transient reduction of the core T_e has been observed when the gas pressure and pulse duration increase to 12 MPa and 6 ms, respectively. In figure 6, the core T_e reduction is almost instantaneous to the injection of SMBs, indicating non-local propagation of the cold pulses. This is a new phenomenon, which will be investigated in detail with perturbative transport by modulated SMBI.

3.2 Fourier analysis and perturbative transport by modulated SMBI

The fast Fourier transform (FFT) is a common and popular method to investigate the propagation of the electron temperature perturbation. Repetitive non-local effect induced by modulated SMBs allows Fourier transformation of the temperature perturbation, yielding detailed investigation of this phenomenon. In our experiments, the low modulation frequency (10 Hz – 20 Hz) was chosen, which was separated from heat pulses caused by sawteeth (≥100 Hz).

Figure 8 shows the result of the Fourier transformation of the ECE temperature data for a low density discharge shown in figure 7, shot 8337. For all harmonics a strong decrease in amplitude and a clear phase jump occurs at $a\ \sim$ - 18 cm which is the reverse position. Two peaks in amplitude profile and two corresponding troughs in phase profile can be found for all harmonics and may indicate two perturbation sources occur in the regions outside and inside the inversion radius, respectively. The position of the outer initial heat pulse is found at $a\ \sim$ - 25 cm which depends on the deposition radius of SMBI and the behavior of the perturbation presents usual propagation features of SMBI cold pulse. The value of χ_e^{HP} deduced from Fourier analysis, showing agreement with the result from sawteeth pulse propagation[11], is in the range 2 – 3 m^2/s. In the inner region, the initial perturbation is found in the core, yielding a faster outward propagation, and χ_e^{HP} is in the range 6 – 8 m^2/s. Profiles of amplitude and phase at the first three harmonics are independent of frequency, suggesting that the non-local effect cannot be attributed to an inward heat convection. The steeper profiles around the interface, which means a reduction of heat transport, indicating an internal transport barrier formed in this area.

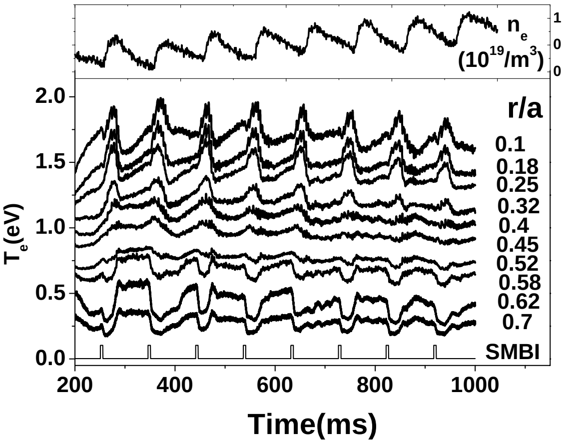


Figure 7. Time traces of ECE temperature at different radii and electron density n_e for shot 8337 in ohmic regime. ($B_t = 1.4$ T, $n_e = 0.7 – 1.0\times10^{19}$ m^{-3}, $I_p =$ 180kA.)

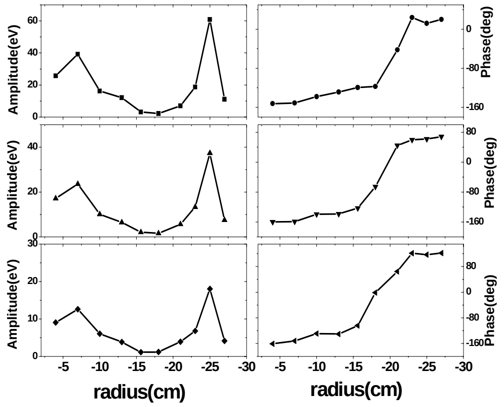


Figure 8. FFT data of shot 8337 for the first three harmonics

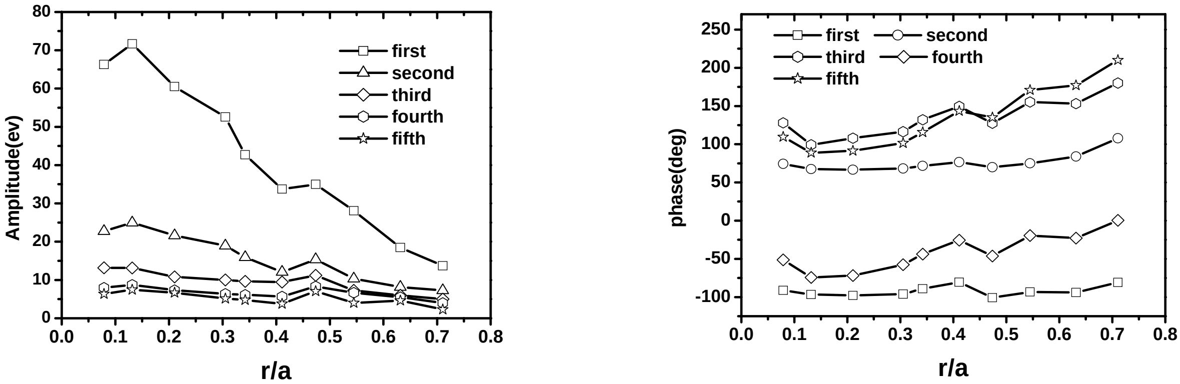


Figure 9. FFT data of shot 7598 for the first five harmonics, with SMBI at high density (2.6×10^{19} m^{-3}).

Figure 9 shows the result of the Fourier transform of a typical non-local discharge for the higher density (2.6×10^{19} m^{-3}), shot 7598. Similar with the lower density discharges, two different regions can be distinguished in the profiles of amplitude and phase from $\rho \approx 0.4$ which is just outside q = 1 surface. The outer initial pulse is found at $\rho \approx 0.48$ and $\chi_e^{HP, phase}$ is 2 - 3 m^2/s. Meanwhile, an even larger perturbation propagates outward from the core and $\chi_e^{HP, phase}$ is 4 - 5 m^2/s. In both the low density and high density discharges, profiles of amplitude and phase at the first five harmonics are independent of frequency, suggesting that the non-local effect cannot be attributed to an inward convection. The perturbations propagating from the two sides become much smaller around the interface which is always just outside q = 1 surface, suggesting an internal transport barrier formed in this area.

4. Discussion and summary

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 [9] which is consistent with the electron temperature profile consistency and related to the local thermal conductivity at the point $\rho_l \approx 0.7$. It is assumed that the cold pulse will induce the non-local effect once it deposites at this point. With the same pressure and period, the penetration depth of SMBs is in inverse proportion to density. Once the density increases to a certain value, it is difficult for SMBs to reach the point ρ_l, suggesting the reason why the non-local effect usually disappears when the density is higher than a certain limit. On HL-2A, the penetration depth of SMB is found to be direct proportion to gas pressure. [10]For higher density discharges, the SMBs can reach the point ρ_l by increasing the gas pressure. Thus, non-local transport phenomenon reappears in higher density discharges when the SMBs are injected with higher gas pressure. However, further modification of this model is necessary to explain the opposite phase of core temperature perturbation.

Non-local transport phenomenon appears in both higher density discharges and lower density discharges after SMBs injection on HL-2A. For lower density experiment, a stong dependence on plasma density has been observed. This phenomenon could be enhanced by ECRH and the duration of core temperature rise could be prolonged by changing the conditions of SMBI. With higher gas pressure, non-local transport phenomenon appears in higher density after SMBI. But the fast response of core temperature variation with higher density presents same polarity to edge cooling.

Fourier analysis of repetitive non-local effect shows that, although the fast core T_e response to edge cooling in higher density is opposite to that in low density, similarities of non-local transport phenomenon between the two conditions are obvious. The profiles of amplitude and phase can be divided into two different regions. The initial perturbation pulse in inner region is found propagting faster than the outer one. In both the two conditions, profiles of amplitude and phase at all harmonics are independent of frequency, suggesting that the non-local effect cannot be attributed to an inward convection. The similarities may suggest a common underlying physical mechanism between the ‘non-local’ transport phenomena in the two different conditions.

Acknowlegement

The authors would like to thank Prof. J.Q.Dong, for helpful advice and assistance on physical analysis, as well as other colleague for providing the necessary measurement data.

References

[1] Callen, J. D., “Transport Processes in Magnetically Confined Plasmas” phys.Fluids B, **4** (1992) 2142.

[2] Gentle, K. W., et al., “Strong Non-Local Effects in a Tokamak Perturbative Transport Experiment”, Phys. Rev. Lett. **74** (1995) 3620.

[3] Kissick, M. W., et al., **“**Conditions and behaviour related to non-local electron heat transport on TFTR” Nucl. Fus. **38** (1998) 821.

[4] Hogeweij, G. M. D., et al., “Recording non-local temperature rise in the RTP tokamak” Plasma Phys .Contr. Fusion **42** (2000) 1137.

[5] Zou, X. L., et al., “Edge cooling experiments and non-local transport phenomena in Tore Supra” Plasma Phys. Control. Fusion **42** (2000) 1067.

[6] Mantica, P., et al., “Nonlocal Transient Transport and Thermal Barriers in Rijnhuizen Tokamak Project Plasmas” Phys. Rev. Lett. **82** (1999) 5048.

[7] Yang, Q. W., et al., “Overview of HL-2A experiment results” Nucl. Fus. **47** (2007) S635.

[8] YAO, L. H., et al., **“**Plasma behaviour with hydrogen supersonic molecular beam and cluster jet injection in the HL-2A tokamak” Nucl. Fusion **47** (2007) 1399.

[9] Qu W X et al 2000 Nuclear Fusion and Plasma Physics 20 129 (in Chinese).

[10] Sun, H. J., et al., “Observation of MBI and Pellet Injection Penetration on HL-2A” 33th EPS Conf. on Controlled Fusion and Plasma Physics **301**(2006) P-2.173