Understanding the Dynamics of Cold Pulse Nonlocality Phenomena

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**Abstract.** Resolving the long standing question of whether tokamak transport is local or non-local is crucial for successful predictive modeling of ITER. Though most theoretical and modeling schemes are based on the local Fickian formulation, there are many conspicuous experimental results suggesting otherwise. Most notable of these is the cold pulse nonlocality in which edge cooling produces a central temperature rise on a time scale drastically shorter than the bulk confinement time. In this paper, we present experimental and theoretical results which illuminate the enigma of the cold pulse and support the hypothesis that the associated central temperature rise is due to the formation of a transient thermal barrier structure. We present fluctuation measurements which support this conclusion. Experiments show that Supersonic Molecular Beam Injection (SMBI) into a LOC plasma results in fast edge cooling and the subsequent central heating. Sequential SMBI sustains the elevated core temperature if the interval between SMBI pulses is shorter than one confinement time. Microwave reflectometry studies of the response of core turbulent density fluctuations to SMBI show that small scale, high frequency fluctuations are reduced in this state with sustained increase of $T_{e(0)}$. Theoretical studies have focused on the elucidation of the origin of the rapid profile response to the peripheral cooling. Studies of model simulations of cold pulse experiments recover all of the elements of non-locality – i.e. the inversion, a transient thermal barrier due to the self-consistent shearing and a fast response. Further studies reveal that the key to the inversion and transient thermal barrier is diamagnetic shearing, self-consistently produced in response to dynamic profile perturbations. Thus, we propose that the long standing mystery of turbulent nonlocality phenomena is ultimately rooted in a simple but strongly nonlinear feedback loops in the transport dynamics, and that dynamic shearing can produce the transient barrier structures required to explain the cold pulse phenomenology.

1. Introduction

Understanding energy transport under various conditions in tokamak plasmas is crucial for projecting confinement properties to ITER. However, a number of dramatic observations involving transient behaviour pose serious challenges to our understanding of the underlying processes. One of the most puzzling observations, defying the assumption of locally
determined transport, was provided by cases of cold pulse propagation experiment: a fast and strong cooling in the edge plasma induces significant heating in the central plasma on a timescale much shorter than a diffusive propagation time scale. This phenomenon is now universally known as non-local transport. From the first observation of the effect at TEXT in 1995 [1] to subsequent reports on many other tokamaks and a helical device [2, 3, 4, 5, 6, 7], non-local responses induced by edge cold pulses have puzzled scientists who focus on plasma transport. Although more than 15 years have passed after the first observation in the TEXT tokamak, the dynamics still remain unclear. The cold pulse experiments present several unresolved puzzles. These include, but are not limited to: how does edge cooling provoke central heating on a time scale more than an order of magnitude shorter than the global energy confinement time? How does the edge cooling provoke an apparent change in transport state, or ‘transient ITB’? The existence of cutoff density $n_{\text{cutoff}}$ above which the core temperature rise is not observed, what sets the cutoff density? In this paper, we will report on the possibility to sustain the ‘transient ITB’ state for multiple energy confinement times by repetitive SMBI on HL-2A. This remarkable result, together with the observation of core turbulence suppression on HL-2A and appearance of a second order transition of electron heat transport on LHD [6], suggests that what we have been calling a ‘nonlocality event’ is, indeed, better thought of as global changes in profile morphology induced by edge perturbations. This new profile morphology is seemingly meta-stable and can be sustained until the density hits the cut-off value. We note that spontaneous reversals in Ohmic plasma intrinsic rotation [8, 9] are another example of large scale profile morphology changes induced by small perturbations — in that case by increasing the density to the onset level for Ohmic confinement saturation. Another is the novel tokamak state with global stationary temperature oscillations discovered by Giruzzi, et al [10]. All of these phenomena are suggestive of a sort of transport bifurcation, leading to a metastable transport barrier-like state.

2. Experimental results

HL-2A is a medium-sized tokamak with major radius $R = 1.65m$ and minor radius $a = 0.4m$. The experiments discussed here are performed in deuterium plasmas with toroidal plasma current $I_p = 160–380$ kA, toroidal field $B_t = 1.3–2.4$ T, the line-averaged density $n_e = 0.5-1.5\times10^{19}$. The Supersonic Molecular Beam Injection (SMBI) is driven by a magnetic-electric valve and can be injected with Hydrogen, Deuterium or Helium with a pressure of 0.2–3 MPa and duration of 0.5–10 ms.

A typical shot of SMBI experiment which induces the non-local response is shown in figure 1, with $B_t = 2.31$ T, $n_e = 1.0\times10^{19}$ m$^{-3}$, $I_p = 250$kA. From the time evolution of $T_e$ at different radii, it is found that after the injection of SMB, the region outside $\rho>0.42$ is cooled, while the core $T_e$ increases. The inversion radius for the change in $T_e$ is observed to be outside the $q = 1$ surface. The core $T_e$ rise is about 18 % and the duration of the process is about 30 ms which is comparable to one energy confinement time $\tau_E$. The short duration of the core temperature rise induced by a single SMBI raises the question as to whether it can be extended beyond one energy confinement time $\tau_E$. This was tested and fulfilled by repetitive SMBI on HL-2A. By keeping the interval of each SMBI shorter than one energy confinement
time, sequential firing of the SMBI can effectively sustain the increased core temperature, which appears to follow in response to the edge perturbation, as shown in figure 2. The duration of sustainment is four times longer than the confinement time $\tau_E$. This method is difficult to use continuously, since the increase of core temperature will stop once the density exceeds the cutoff density for nonlocality, which is inevitable because of the fuelling from sequential SMBI. The sensitivity of nonlocality to density is demonstrated in figure 3: the core $T_e$ rise is more than 600 eV when the electron density $n_e$ is around $0.7 \times 10^{19} \text{ m}^{-3}$, it decreases to 150 eV when $n_e$ is around $1.36 \times 10^{19} \text{ m}^{-3}$ and becomes invisible when $n_e$ is larger than $1.5 \times 10^{19} \text{ m}^{-3}$, which is close to the cutoff density $n_{\text{cutoff}}$ for nonlocality. Once the density reaches $n_{\text{cutoff}}$, the core $T_e$ stops increasing even with continued SMBI. However, by combining the application of ECH and SMBI, the sustainment can last much longer. ECH is observed to enhance nonlocality and increase the cutoff density for nonlocality and the density pumpout associated with ECH provides a good method to slow the density rise. A typical observation of the sustainment by SMBI during ECH is illustrated in figure 4. In shot 16404, off-axis ECRH (250 kW, $\rho_{\text{dep}}=0.35$) is applied from 330 ms to 630 ms which induced a slight increase of electron temperature in the whole plasma. The edge temperature ($\rho>0.62$) decreases slightly after the injection of SMBs at 350 ms, while core temperature ($\rho \leq 0.62$) rise is strongly enhanced and sustained by sequential firing of SMBI. From the evolution of the temperature profile, it can be seen that a significant change of global temperature profile is induced by edge cooling of sequential SMBI, as shown in figure 5. This peaked profile structure is sustained by sequential firing of SMBI and the duration is around 8 global energy confinement time in this shot. The core temperature increases by 60% and the plasma stored energy increases by more than 80% after the application of SMBI.

Figure 1. nonlocality induced by a single SMBI. Left: ECE $T_e$ time traces at different radii; right: electron temperature profile before and after SMBI.

Figure 2. Ohmic discharge: sustainment of nonlocality by sequential SMBI, ~ 4 energy confinement time $\tau_E$ by sequential firing of SMBI. From top to bottom: line average density, the plasma stored energy $W_e$, ECE temperature at different radii and the SMBI signal.
Figure 3. Experimental time traces of electron temperature for periodic SMBI in Ohmic regime. The core temperature rise becomes weaker as density increases and becomes undetectable after \( \approx 480 \) ms, which can be associated with a cutoff density value of \( \approx 1.5 \times 10^{19} \text{ m}^{-3} \).

Figure 4. Core Te rise is sustained up to 8 energy confinement times \( \tau_E \) by sequential SMBI in an ECH discharge. Evolution of parameters in shot \#16404 with SMBI. From top to bottom: the electron density, the plasma stored energy \( W_e \), ECE temperature at different radii and the ECRH and SMBI signal (\( B_t = 1.32 \) T, \( n_e = (0.5-1.5) \times 10^{19} \text{ m}^{-3}, I_p = 180 \text{ kA} \)).

Figure 5. shot \#16404, evolution of temperature profile after application of ECRH and SMBI. The black line represents the Ohmic regime, red line is low power ECRH and the green one after the application of sequential SMBI.

Figure 6. shot \#16404: the spectrum evolutions of the density fluctuations with sequential SMBI, measured by a 26.5 GHz reflectometer. In figure 6, the line averaged density is about \((0.8-1.5) \times 10^{19} \text{ m}^{-3}\) and the cutoff surface of 26.5 GHz is estimated as \( r/a = 0.4-0.7 \). The density fluctuations are suppressed during sequential SMBI. After each firing of the SMBI, the fluctuation decreases.

The O-mode reflectometers are introduced to measure density fluctuation. Figure 6 shows the spectrum evolutions of the density fluctuations with sequential SMBI, which is measured by 26.5 GHz reflectometer. In figure 6, the line averaged density is about \((0.8-1.5) \times 10^{19} \text{ m}^{-3}\) and the cutoff surface of 26.5 GHz is estimated as \( r/a = 0.4-0.7 \). The density fluctuations are suppressed during sequential SMBI. After each firing of the SMBI, the fluctuation decreases.
within 1 ms, which is also the timescale for the response of global profile structure change to SMBI. The turbulence then relaxes back to the fluctuation level before applying SMBI in around 10 ms. Although there is only one reflectometer channel for the density fluctuation measurements in this shot, as the cutoff surface of reflectometer is moving outward as the gradual increase of density by sequential SMBI, fluctuation profiles can be deduced by choosing different times in the same discharge. Figure 7 shows the fluctuation profile change 2 ms before and after SMBI. In this figure, the central fluctuation (ρ<0.62) decreases much firing of SMBI.

From the global energy confinement time measured by diamagnetic diagnostics, it seems that there may be a correlation between this cutoff and the critical density for transition from the linear Ohmic confinement regime to the saturated regime on HL-2A. This has been proved on C-MOD (J. Rice, this conference).

3. Theoretical study

A semi-empirical model has been developed to explain the SMBI results. This is based on diamagnetic E×B shear flow suppression of turbulent transport. A simple model of such a process gives the thermal diffusivity as

\[ \chi = \frac{\chi(t=0)}{1 + (v_E' / \gamma_0)^2}. \]  

(1)

Here, \( \chi(t=0) \) is the unperturbed thermal diffusivity, \( v_E' \) is the radial derivative of the E×B drift velocity and \( \gamma_0 \) is the typical growth rate of the turbulent modes. The turbulent modes are assumed to be drift kinetic modes with \( k_\perp \rho_s \sim 1 \), where \( k_\perp \) is the mode number perpendicular to the magnetic field and \( \rho_s \) is the Larmor radius of an ion at the sound speed. As a first step, a simple approximation for the term in the denominator of equation 1 can be used to give

\[ \chi = \frac{\chi(t=0)}{1 + \alpha \rho_s^2}, \]  

(2)

where \( \alpha \) is a free parameter. The model of equation 2 is now tested against the experimental data from the shot #16404, discussed in section 2. Equilibrium and density profiles are taken from the experiment and the electron temperature profile is evolved, for a single SMBI, using

Figure 7. shot #16404: density fluctuation profiles before and after applying SMBI.
the 1.5D transport code CRONOS [11]. The unperturbed thermal diffusivity is inferred from the experimental measurements prior to SMBI and then a series of simulations, each with a different value of the $\alpha$ parameter, are performed to find the value of $\alpha$ that best reproduces the measured electron temperature profile. The resulting simulation is shown in figures 8 and 9. The $T_e$ profile before and after SMBI is seen to be well reproduced, figure 8. The time evolution, figure 9, of the profile is also well produced, although the model under-predicts the rate of the temperature rise in the core immediately after the SMBI. In the derivation of equation 2 the radial extent of the local $E \times B$ shear flow has been approximated by the machine size. A more appropriate scale would be the local electron temperature length scale, $L_{Te}$, and a more detailed expression, based on this assumption, is expected to better represent the experimental results. Crucially, all of these models are local, in that they take a local thermal diffusivity dependent on local parameters and their derivatives.

![Figure 8. Measured (solid) electron temperature profiles (keV) from shot #16404 before and after first SMBI. The simulated profiles from the semi-empirical model above (dashed) are overlaid.](image)

![Figure 9. Measured (solid) electron temperatures (keV) at a series of radii plotted against time (seconds) for the shot of figure 8. The simulated profiles from the semi-empirical model above (dashed) are overlaid.](image)

Theoretical studies have focused on elucidation of the origin of the rapid profile response to peripheral cooling. A simple, part theoretical-part phenomenological, model which incorporates turbulence intensity evolution, turbulence heat transport and temperature profile evolution and $E \times B$ shearing has been developed [12]. This model has two ‘fast feedback loops’ – one via turbulence spreading [13] and one via diamagnetic $E \times B$ shearing, produced by collisional electron-ion coupling and electron $\nabla T_e$ evolution. Analysis of turbulence spreading dynamics reveals the possibility of a Fisher-Kolmogorov intensity front which traverses the cross section in $\tau_f \lesssim 1 \text{ ms}$, at a front speed $v_f \sim V*$, the diamagnetic velocity. Interestingly, our results indicate that such fast propagation of turbulence intensity pulses can explain the apparent ‘resiliency’ of temperature profiles to off-axis heating, since spreading acts to rapidly and (effectively) globally re-distribute the turbulence – and thus transport – response to a localized heating source, across the entire profile. This result explains the long standing mystery of approximate profile invariance during edge and center heating experiments. Studies of model simulations of ‘cold pulse’ experiments recover all of
the elements of ‘non-locality’ – i.e. the inversion, a transient thermal barrier due to self-consistent shearing and a fast response. Further studies reveal that the key to the inversion and transient thermal barrier is diamagnetic shearing, self-consistently produced in response to dynamic profile perturbations. Thus, we propose that the long standing mystery of turbulent transport ‘nonlocality’ phenomena is ultimately rooted in simple but strongly nonlinear feedback loops in the transport dynamics, and that dynamic shearing can produce the transient barrier structures required to explain the cold pulse phenomenology.

4. Summary and discussion

In this paper, we present experimental and theoretical results which illuminate the enigma of nonlocality and support the hypothesis that the associated central temperature rise is due to the formation of a transient thermal barrier structure. We present first-of-a-kind fluctuation measurements which support this conclusion. New experimental results build on the observation that Supersonic Molecular Beam Injection (SMBI) into LOC plasma results in fast edge cooling and central heating, like the cold pulse. Sequential SMBI is observed to sustain the elevated core temperature if the interval between SMBI pulses is shorter than one confinement time. With this method the rise in core temperature has been sustained for as long as four $\tau_e$ (confinement times). The duration of increased $T_e(0)$ is limited only by the cut-off, likely due to collisional electron-ion equilibrium (J.E. Rice et al, this conference). Response of the global $T_e(r)$ profile to SMBI is observed to be larger in ECH discharges, for which the rise in central temperature can persist for as long as $8 \tau_e$, for sequential SMBI. ECH also increases the density cut-off and so points toward electron collisionality as the key dimensionless parameter characterizing the cold pulse cut-off.

New microwave reflectometry studies of the core density fluctuation turbulence response to SMBI show that small scale, high frequency fluctuation levels are reduced in the state with sustained increase of $T_e(0)$. Interestingly, the drop in small scale fluctuations is accompanied by an increase in large scale fluctuations. The degree of turbulence suppression varies with location on the temperature profile – i.e. turbulence is suppressed where the temperature gradient increases, but remains essentially unchanged near the inversion radius, where $\nabla T_e$ is also unchanged. Also noteworthy, turbulence fluctuation intensity tracks temporal profile evolution during sequential SMBI, in that the central turbulence level decreases following a given SMBI and then increases and returns to its initial level prior to the next SMBI. Taken together, the profile structure evolution, the possibility of long-time sustainment and the dynamic and spatially resolved fluctuation studies all support the hypothesis that the nonlocality phenomenon is produced by a transient thermal barrier, which is a dynamic, metastable state intrinsic to the plasma. The remaining question, then, concerns the dynamics of this transient barrier.

References