Change of fluctuation properties during non-local temperature rise in LHD from 2d phase contrast imaging

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Abstract. Fluctuation properties are analyzed in the Large Helical Device (LHD) for discharges exhibiting a non-local core temperature rise in response to edge cooling by injection of a Tracer Encapsulated Solid Pellet (TESPEL). Edge ion gyro-scale density fluctuation amplitudes, measured with a 2D CO₂ phase contrast imaging system, are found to increase as the core temperature is rising and is therefore anti-correlated with a reduction of the total heat flux. This suggests that another mechanism, such as turbulence de-correlation has a stronger role on the heat flux than change of the density fluctuation level. The core fluctuation properties, in particular the phase velocity, change immediately in response to the edge temperature reduction, and possibly change of gradient, unresponsive to core gradients, suggesting a possible non-local transfer mechanism between the edge and core. Comparing different cases, it appears that the excitation of a fluctuation branch with higher core frequency and phase velocity (∼6km/s) is an essential ingredient for the core Tₑ rise. After pellet injection, the amplitude of higher k components increases, implying a reduction of correlation length. One possible interpretation is that there may be increased E × B shear.

1. Introduction
In both Tokamaks and Heliotron/Stellarator devices, electron heat transport can exhibit peculiar behavior in some instances, such as profile stiffness [1, 2], in steady state, and non-local transport, [3, 4, 5, 6], under perturbation. Some theoretical explanations for these phenomena assert that there may exist long range correlations between turbulence, as well as non-local turbulence triggering. The system is thought to require a global treatment rather than a simple local, diffusive-like picture [7, 8]. Most of the experimental evidence has come only from change of the profiles; little data has been presented about the changes in the turbulence properties, which may provide new information to explain these phenomena. In this work, measurements of turbulence...
from a 2D CO2 laser phase contrast imaging system are presented for discharges exhibiting non-local transport induced by pellet perturbation.

In the Large Helical Device (LHD), non-local transport can be observed after edge cooling by injection of a Tracer Encapsulated Solid Pellet (TESPEL). Specific details and classification of this behavior in LHD has been reported in detail in [9, 10]. Similar behavior has been observed in Tokamaks [11, 12]. In summary, for LHD, in low collisionality, high field discharges, a TESPEL pellet is injected into the edge, penetrating up to $\rho \sim 0.8$. The edge temperature decreases, while the core temperature rises, with a delay whose time-scale depends on collision frequency and magnetic configuration. The local transient thermal diffusion coefficient takes on negative values, invalidating a local diffusive transport model. The core heat flux has a much closer correlation with the temperature gradient at the edge than in the core, consistent with a non-local transport model.

Some explanations are based on the idea of turbulence spreading; that is, that the local fluctuation amplitude is not simply a function of local intensity of turbulence, but rather, satisfies a diffusion-like equation [7]. An elegant model of this behavior has been proposed by [13], based on fractional calculus, demonstrating directly the non-local interaction and global behavior, based on random-walk turbulence simulations. However, in published literature, the results of this model do not predict a non-local temperature rise. Other models can predict up-gradient transport [8], but are still insufficient to produce a core temperature rise. Generally, there are still many possible theories for these phenomena and no single theory can universally explain all the observations [6].

The 2D phase contrast imaging diagnostic can measure the spatial profile of a quantity closely related to the density fluctuation amplitude with wave-numbers in the ion gyro-scale range $(1 - 9 \text{cm}^{-1})$. While electron gyro-scale fluctuations are expected to play a role in electron energy transport, ion gyro-scale fluctuations are also expected to play a part. The main result from measurements presented here is that the ion gyro-radius scale fluctuation amplitude increases when the total heat flux reduces causing a temperature rise. This is opposite of the classical picture of fluctuation suppression causing confinement improvement, rather, that there is a change of the mutual phase and/or coherence between density, velocity and temperature fluctuations associated with an increase of density fluctuations. Changes of the poloidal phase velocity and radial wave-number spectrum are also associated with this phenomenon and may play a key role in producing the temperature rise.

In section (2), the phase contrast imaging measurements will be introduced, together with other diagnostic systems used in this analysis. In section (3), the non-local temperature rise phenomenon is described, and two reference discharges are introduced, where a non-local rise occurs and when a drop occurs. In section (4), PCI fluctuation measurements for these discharges are presented, and the time history of fluctuation response is compared with the flux and gradients. Finally, in section (5), the results are summarized and an interpretation is given.

2. 2D Phase contrast imaging system and other diagnostics

Fluctuation properties are measured using a 2D phase contrast imaging system. This can measure the spatial profile of the density fluctuation amplitude and also can resolve the $k$ spectrum within the band $1 - 9 \text{cm}^{-1}$. It employs a 2D imaging principle to split the line-integrated fluctuation signal into contributions from different layers along the line of sight, according to the “magnetic shear” principle [14, 15, 16]. The sightline is vertical passing at $R = 3.603 \text{m}$, so penetrates from the edge to the core, depending on the magnetic axis position of the plasma ($R_{\text{ax}}$), so that core and edge fluctuation components (from both top and bottom) can be separated. The system cannot, however, fundamentally recover the local fluctuation amplitude because of line-integration effects unless the spectrum is isotropic, which it generally is not [17]. The line-integrated $\tilde{N}$ signal is split into contributions along the line of sight and is
related to the local amplitude ˜n according to ˜N^2(ρ) = ˜n^2(ρ)l_zl_{res}, where l_z represents the ratio of fluctuation spectral density propagating exactly perpendicular to the probing beam to the total fluctuation power (related to longitudinal correlation length), and l_{res} is an instrumental resolution which increases with measured fluctuation wavelength. For typical measurements, the peak wavelength is such that the instrumental width is around half a radius, or less near the edge because the average wavelength is generally smaller than in the core.

Electron temperature is measured with an ECE polychromator [18]. For the plasmas studied here with configuration $R_{ax} = 3.5m$, the accessible region, according to the measured frequencies, is between $ρ = 0.2$ and $ρ = 0.8$. It has been confirmed that the ECE is almost always in the blackbody regime, even in the edge [19], so that the deduced perturbed heat flux is not affected by change of opacity.

3. Non-local electron heat transport phenomenon

While electron heat transport may have non-local and non-diffusive characteristics (which may be evident by profile stiffness), a heat pulse experiment is one clear method to illustrate non-diffusive/non-local transport. In low density, high temperature LHD discharges, the plasma temperature response, measured by ECE [18], to pellet injection shows a non-diffusive response. In particular, the edge temperature decreases, as expected, while the core temperature increases. This response is characteristic of both Tracer Encapsulated Solid Pellet (TESPEL) injection (however the injection is only the polystyrene outer with no internal tracer), as well as in hydrogen ice pellet injection. Nevertheless, TESPEL injection allows small controlled perturbation to the edge. Detailed descriptions and classification of this phenomenon have been given in [9, 10, 20]; here we introduce this phenomenon with respect to the discharges studied in this paper, which were from the 10th (2006-7) experimental campaign, while further discharge types were studied before, but without PCI fluctuation measurements.

In this study two different scenarios are compared: when pellet injection induces a non-local core temperature rise, and when it produces a core temperature drop. The main extrinsic differences between these are the introduction of an extra Ar gas puff just before pellet injection. Though the Ar gas puff alone can produce a non-local temperature rise, the combination with a pellet produced a drop in this case. Since there is a clear difference of the time evolution of fluctuation phase velocity, this comparison provides clear evidence of the link between fluctuation phase velocity and the non-local temperature rise.

The time history of electron temperature and density in the non-local temperature rise case (#71160) is plotted for various $ρ$ in figures 1 (a) and (b). Conditions for this shot are: $R_{ax} = 3.5m$, $B = 2.93T$, $n_{eo} \sim 0.4 \times 10^{19}m^{-3}$, and $T_{eo}$, before pellet injection, is $\sim 4keV$, with ECR heating only (subscript $eo$ denotes core value) by all three sets of gyrotrons of frequencies 168GHz (0.6MW), 84GHz (0.62MW) and 82.7Ghz (0.36MW) which deposit on axis at the fundamental and second harmonics respectively. The injected TESPEL pellet size is 700μm. The changes in the turbulence properties here are very similar that of an Ar gas puff (as reported in [20]). The edge temperature decreases, while the core temperature increases. The pellet ablation is evident from an increase of the edge density. This is cross-checked with spectroscopic measurements of the emission from the pellet, which show it ablates within 1ms and penetrates only up to $ρ = 0.8$. The density pulse propagates inwards, in addition to the core temperature rise. On the other hand, density and temperature evolution for shot #71169, where the core temperature decreases upon pellet ablation, is plotted in figures 2 (a) and (b). Conditions for this shot are: $R_{ax} = 3.5m$, $B = 2.93T$, $n_{eo} \sim 0.6 \times 10^{19}m^{-3}$, $T_{eo} \sim 4keV$, with only ECR heating. An prompt additional Ar gas-puff is introduced prior to pellet injection at $t = 0.5s$ as presented in [20]. Comparing the density between these two shots, figure 1 (b) with 2 (b), the density does not rise in the edge with Ar gas puff as clearly as without Ar gas puff, possibly related to a difference of the edge temperature due to cooling by the Ar gas puff.
For the shot with non-local temperature rise, a transient transport analysis is carried out in order to compare with fluctuation properties. The heat flux is evaluated from the power balance equation:

\[
\frac{dW(\rho)}{dt} + \nabla \cdot q = S_{\text{ht}}(\rho) - S_{\text{at}}(t, \rho) \tag{1}
\]

where \( W = 3/2nk_BT_e \) is the stored electron energy density (\( k_B \) being the Boltzmann constant), \( q \) is the electron heat flux, where the radial component only is analyzed and positive indicates outward flux. \( S_{\text{ht}} \) is the power source due to heating, and \( S_{\text{at}} \) is the lower lost due to atomic processes associated with pellet ablation. This equation is then split into equilibrium and perturbed components, i.e. \( q = q_{\text{eq}} + q_{\text{pert}} \) such that \( \nabla \cdot q_{\text{eq}} = S_{\text{ht}}(\rho) \), and,

\[
\frac{dW(\rho)}{dt} + \nabla \cdot q_{\text{pert}} = -S_{\text{at}}(\rho, t) \tag{2}
\]

This separation is valid if the heat source is not perturbed by the change. To a degree, the heat source may be perturbed by the significant density and temperature change in the edge, however this is likely to be small on account of the ECRH beam refraction being small at this low density. Moreover, there may be a time delay between the resonant production of energetic electrons and their relaxation with the thermal population, indicating any prompt change is not due to change of heating. The radiation measured by a bolometer shows a spike only within a few ms after pellet ablation followed by a reduction of by about 50kW from the pre-injection value, relaxing back to the initial value over the timescale of the temperature relaxation. This indicates a change of bremsstrahlung and/or line radiation after pellet ablation independent of \( S_{\text{at}} \). The magnitude of the change is however significantly smaller than the \( dW/dt \sim 500\text{KW} \) after pellet ablation and the heating power of \( \sim 1.5\text{MW} \). Therefore, \( q_{\text{pert}} \) is evaluated from:

\[
q_{\text{pert}}(r) = -r^{-1} \int_{0}^{r} 1.5 \frac{\partial n(r')}{\partial t} T(r') r' dr' + (-r^{-1}) \int_{0}^{r} 1.5n(r') \frac{\partial T(r')}{\partial t} r' dr' + (-r^{-1}) \int_{0}^{r} S_{\text{at}}(r') r' dr'
\]

(3)

where the terms \( q_n \) and \( q_T \) are the components evaluated from density and temperature changes, individually. Previous analysis has focused on evaluating only \( q_T \), though towards the edge, \( q_n \) is also important because of pellet fuelling. Furthermore, it is not possible to evaluate \( q_S \) because of uncertainties in the atomic processes, but since the pellet does not penetrate into \( \rho < 0.8 \), \( q_S = 0 \) in this region. For \( \rho > 0.8 \), the lack of accounting for \( q_S \) means that the true \( q_{\text{pert}} \) is more negative (i.e. inwards) than the measured \( q_{\text{pert}} \).

Because temperature measurements are not available for \( \rho > 0.8 \), a different approach must be taken for evaluating \( q_{\text{pert}}(\rho = 1) \). Given that the diamagnetic stored energy is

\[
W_{\text{dia}} = \int 1.5k_B(n_eT_e + n_iT_i)dV, \tag{4}
\]

\( q_{\text{pert}}(\rho = 1) \) is evaluated from:

\[
q_{\text{pert}}(\rho = 1) = -0.5[\frac{(2\pi)^2aR_{\text{maj}}}{3}]^{-1}dW_{\text{dia}}/dt, \tag{5}
\]

assuming \( T_i = T_e \) and \( n_e = n_i \), where \( a \) is the average plasma minor radius \( a = 0.6\text{m} \) and \( R_{\text{maj}} \) is the major radius of 3.5m.

The values of \( q_{\text{pert}} \), including the component \( q_T \) for \( \rho = 0.5, 0.8, 1.0 \) are plotted in figure 1 (c). At \( \rho = 0.8 \), \( q_T \) is initially outwards, with a duration much longer than the pellet ablation time, then becomes inwards, though considering \( q_n + q_T \), the flux is actually inwards owing to the heat pulled in by the inward particle flux. The \( q_T \) at \( \rho = 0.5 \) is always inwards, while
\( q_{\text{pert}} = q_T + q_n \) has an outwards transient just after pellet injection, followed by a phase of inwards flux. The transient outwards flux at the beginning is a result of a slight reduction in density at \( \rho = 0.5 \) as in figure 1 (b), but as this is only slight, it may be an artefact of the Abel inversion procedure. The calculated flux at \( \rho = 1 \) from the diamagnetic stored energy is smaller than that at \( \rho = 0.8 \), since the area through which the energy is flowing is larger at \( \rho = 1 \), but may possibly be slightly underestimated because \( T_i < T_e \) in these EC heated discharges (here the kinetic electron stored energy component alone is 80% of the diamagnetic stored energy).

At all locations, the components \( q_n \) are badly noisy because of low density. The main point is that the flux in the core, as well as at the edge, responds promptly to pellet injection.

The normalized temperature and density gradients at \( \rho = 0.5, 0.8 \) are plotted in figure 1 (d). The temperature and density gradient change rapidly at \( \rho = 0.8 \). The magnitude of the change of temperature gradient is only slight, and in fact appears to change sign, possibly because of some systematic profile error of the ECE measurement. Nevertheless the time-scale for the change is the important information here. Even though the temperature gradient may not be reliable at \( \rho = 0.8 \), there is distinctly a sudden decrease in \( dT/dt \) after pellet injection. In fact, it is suspected that the temperature decrease is more pronounced outside \( \rho = 0.8 \) because of pellet cooling, but measurements are not available here due to limited access of the ECE measurement. At \( \rho = 0.5 \), the density gradient hardly changes in response to pellet injection while the temperature gradient changes over a larger timescale.

Therefore, comparing flux and gradients, it is clear that there is a strong correlation between both core and edge flux and the edge temperature gradient, and there is little correlation between core gradients and core flux, suggesting a non-local response from the edge to the core. Further analysis of the gradient/flux relationship shows phases of negative and transient diffusion coefficient, defined as \( \chi_{\text{tr}} = \partial(q_{\text{pert}}/n)/\partial(-\nabla T) \) [10, 20]. However, the fluctuation level does not appear to change in any clear way with \( \chi_{\text{tr}} \).

### 4. Analysis of fluctuation properties

PCI signals are analyzed as follows. The spatially resolved density fluctuation amplitude spectrum, \( S(\omega, k, \rho; t) \), where \( \rho \) is flux coordinate, is calculated from a cartesian/polar transformation of \( S(\omega, k_x, k_y; t) \), the 3D Fourier transform of the time series of the image sequence \( \hat{N}(x, y, t) \), for a selected time window. The transformation is \( k^2 = k_x^2 + k_y^2 \), angle \( \theta = \tan^{-1}(k_y/k_x) \), and \( \rho \) is determined uniquely from \( \theta \) from the known magnetic field line pitch angle dispersion.

A contour plot of \( S(k, \rho) \) (integrated over all frequencies) for \( \#71160 \) at \( t = 0.58, 0.615s \), before and after pellet injection, is shown in figures 3 (a) and (c). Negative (positive) \( \rho \) indicates the component measured below (above) the midplane. The dashed grid characterizes the spatial-\( k \) resolution. The amplitude is seen to be strongly peaked at the edge, reducing towards the core, although with some increased instrumental broadening because the average \( k \) reduces towards the core, possibly because the ion gyro-radius is larger there.

The angular frequency \( \omega \) is converted to phase velocity via \( v = \omega/k \), and integration over all measurable \( k \) is performed to generate the dataset \( S(v, \rho; t) \), and is plotted for times before and after pellet ablation in figures 3 (b) and (d). It is clear that there is a distribution of velocities for a single \( \rho \). The phase velocity, being the component perpendicular to the line of sight, is observed to reverse about the mid-plane, characteristic of the poloidal propagation component, and is mostly up/down symmetric, however not completely; this point is discussed later. Before pellet ablation, in (b), the phase velocity is higher at the edge than the core, having a positive shear. On the other hand, after pellet ablation, (d), the velocity around \( \rho = 0.5 \) appears to have become bi-modal, with the existence of a branch at higher velocity with substantially higher phase velocity than before pellet ablation. The velocity of the peak of the distribution at \( \rho = 0.5 \) has increased from \( \sim 2\text{km/s} \) to \( \sim 4\text{km/s} \). Since the velocity around \( \rho = 1 \) has reduced slightly,
Figure 1. Time evolution of profiles, transport, gradients and fluctuations in discharge #71160 exhibiting a core temperature rise in response to pellet injection. (a) Temperature for various $\rho$ measured with ECE diagnostic, (b) density for various $\rho$ from Abel inversion of FIR interferometer measurements; SNR ratio is somewhat marginal in this case, (c) calculated total $q_{pert} = q_n + q_T$ (solid lines) and component $q_T$ (dashed lines) at $\rho = 0.5, 0.8, 1.0$ (red, black, green) (the value at $\rho = 1.0$ is derived from diamagnetic loop voltage), (d) normalized temperature (thin lines) and density (thick lines) gradients at $\rho = 0.5, 0.8$, (e) fluctuation amplitude at $\rho = 0.5, 0.8, 1$ (red, black, green), (f) branch-separated average fluctuation phase velocity at same locations, where the size of the dots represent the relative amplitude of that branch, (g) time evolution of diamagnetic velocity computed from density/temperature profiles at $\rho = 0.5, 0.8$. 

| Time (s) | $T_e$ (keV) | $q_{pert}$ (kW/m$^2$/s) | $q_T$ (kW/m$^2$/s) | $q_n$ (10$^{20}$ m$^{-3}$) | $\varphi$ | $\eta_{\varphi}$ |
|---------|-------------|--------------------------|---------------------|--------------------------|---------|-----------------|
| 0.58    | 2.0         | -20                      | -15                 | 0.2                      | 0.25    | 0.25            |
| 0.59    | 2.5         | -20                      | -15                 | 0.5                      | 0.5     | 0.5             |
| 0.60    | 3.0         | -20                      | -15                 | 0.74                     | 0.74    | 0.74            |
| 0.61    | 3.5         | -20                      | -15                 | 0.99                     | 0.99    | 0.99            |
| 0.62    | 4.0         | -20                      | -15                 | 0.25                     | 0.25    | 0.25            |
| 0.63    | 4.5         | -20                      | -15                 | 0.5                      | 0.5     | 0.5             |
Figure 2. Time evolution of profiles, and fluctuations in the case where the core temperature decreases in response to pellet injection and Ar gas-puff injection at $t = 0.5 - 0.51s$ (#71169). (a) Temperature for various $\rho$, (b) density for various $\rho$, (c) fluctuation amplitude at $\rho = 0.5, 0.8, 1.0$ (red,black,green) and (d) branch-separated fluctuation phase velocity at same locations, where the size of the dots indicate the relative amplitude of the branch.

Figure 3. Analysis of fluctuation properties for single time-windows (a,b) before pellet ablation and (c,d) after pellet ablation. Fluctuation amplitude distribution (log color scale) over $\rho, k$ in (a,c) and over $\rho, v$ (log color scale) in (b,d).
this gives a strong negative velocity shear (as well as a small positive velocity shear for the lower velocity branch) over the outer region of the plasma.

There are distinct changes in the asymmetry properties (amplitude, phase velocity) after pellet ablation. In particular, in figure 3 (d), there is a component with $v \approx -4\text{km/s}$ peaked at location $\rho = +0.5$ on the top, while on the bottom there is a component at $v \approx 4\text{km/s}$ peaked at a different radial location, $\rho = -0.8$. On the other hand, the component peaked at $\rho = +1$ with $v \approx -2\text{km/s}$ is more symmetric with respect to the component at $\rho = -1$ with $v \approx 2\text{km/s}$. This could be explained as follows. The diagnostic measures only components which propagate exactly horizontally, or perpendicular to the injected laser beam. Because the laser beam passes outside the magnetic axis for this magnetic configuration ($R_{\text{ax}} = 3.5\text{m}$), the top measured components propagate both poloidally and (slightly) radially outwards and the bottom measured components propagate poloidally and (slightly) radially inwards. Therefore the asymmetry may be interpreted as an asymmetry of the radial wavenumber spectrum of turbulence. In figures 1, 2 and 4, we plot only quantities on the upper side, however the results are similar if lower side quantities are plotted.

Having shown the amplitude and velocity measurements for time slices, attention is now turned towards the dynamical evolution of the amplitude and velocity for $\rho = 0.5, 1.0$, by analyzing 1ms time windows as a function of time. The change of phase velocity and $k, \omega$ spectrum before and after pellet ablation are subtle and can be shown more clearly by analyzing the time evolution of the spectrum as a function of velocity, $\omega$ and $k$ in figure 4. The splitting of the velocity distribution into a bimodal distribution is clear in figure 4 (a). The width of the frequency and $k$ spectra expands to higher values, as evident in figures 4 (c) and (d). At $t = 0.611s$, after pellet ablation, the dispersion relation $S(k, f)$ is plotted in (b). Lines showing phase velocity of $2\text{km/s}$ and $6\text{km/s}$ are indicated for reference. The higher velocity branch exists at high frequency and at lower $k$ while the lower velocity branch has a dominant component at low frequency, low $k$ but also a significant component at higher $k$. In addition, the frequency and $k$ width of the lower velocity branch is much broader than that of the high velocity component, implying it has a shorter intrinsic decorrelation length/time [21]. Examining figure 4 (a), it appears that the amplitude of both higher and lower velocity branches is significantly oscillating in time. Such oscillation of the amplitude envelope may be an indirect indication of the action of a Zonal flow or other large scale structure in a predator-prey system [22]. More details of this analysis applied to the non-local temperature rise in LHD is given in [23].

The dynamical evolution of the total fluctuation amplitude and scalar velocity at $\rho = 0.5, 0.8, 1.0$ is plotted for the core temperature rise case in figures 1 (e) and (f), to be compared with the evolution of profiles, flux and gradients. Scalar velocities for each $\rho$ are extracted from figure 4 (a) using a simple branch cutting technique, which cuts between the local minima in $S(v)$ and calculates the average velocity within each branch. This allows for the possibility that there may be more than one velocity for a single $\rho$. The relative size of each point in figure 1 (f) indicates the relative amplitude for each branch, defined by the square root of the integral between the local minima of $S(v)$.

Analysis of the total amplitude at $\rho = 0.8, 1.0$ is considered as follows. There is a reduction until $t = 0.605s$, followed by an increase beyond the initial level at around $t = 0.61s$, after which time the perturbed heat flux at both locations is still inwards, or in other words, the total heat flux is smaller than the pre-pellet-injection value. The tendency is most clear at $\rho = 1.0$, although here the heat flux can only be measured from diamagnetic voltage. Though the increase above the initial level is smaller at $\rho = 0.8$, the flux is more reliably derived from the pressure. This increase is opposite to the widely held view that confinement improvement should be associated with density fluctuation suppression. In order to explain this, since $q_{\text{anom}} = \langle \tilde{n}\tilde{v}\rangle T + \langle \tilde{v}\tilde{T}\rangle n$, there must be some de-correlation between density and velocity, or velocity and temperature. This de-correlation is difficult to measure directly, but there is evidence for a reduction of correlation
Figure 4. Time history of (a) velocity (linear color scale), (c) frequency (log color scale) and (d) wavenumber (log colour scale) resolved spectra for #71160 at $\rho = 0.5$. The dispersion relation $S(f, k)$ is indicated in (b) for $t = 0.611s$, together with two lines of phase velocity 2km/s and 6km/s.

The analysis of the scalar average velocity of each branch at $\rho = 0.5, 0.8, 1.0$ is considered as follows. After pellet injection, the velocity at $\rho = 1.0$ remains single-valued, and decreases rapidly by a factor of around 2, recovering slowly. On the other hand, the velocity at $\rho = 0.5, 0.8$ immediately splits into two branches, one with high velocity, and one with low velocity. For $\rho = 0.5$, this split is maintained until $t = 0.625s$, which correlates with the time at which $q_{\text{pert}}(\rho = 0.5)$ switches from inwards to outwards. The change in velocity at $\rho = 0.5$ occurs much more quickly than the change in the local temperature and density gradients as shown in figure 1 (d). This indicates a possible non-local interaction from the edge, where the temperature and density gradients change immediately.

It has been shown that the measured phase velocity profile often conforms closely with the measured and calculated $E \times B$ velocity [24, 25], though is offset by ion and/or electron diamagnetic drifts. The change in phase velocity after pellet ablation may be due to either of
these contributions, (1) \( E \times B \) rotation, (2) diamagnetic drift velocity, or (3) both. Though \( E \times B \) rotation is not measured here, its change may be inferred from the change in phase velocity. To clarify the effect of the change in diamagnetic velocity, this is computed from the density, temperature profiles and is plotted for \( \rho = 0.5, 0.8 \) in figure 1 (g). It is clear that there is no distinguishable change at \( \rho = 0.5 \), while there is a strong reduction of \( \sim 4 \text{km/s} \) at \( \rho = 0.8 \). At \( \rho = 0.5 \), the data suggests case (1): that the increase may be due to \( E \times B \) rotation, and that rotation rise is clearly non-locally triggered from the edge. At \( \rho = 0.8 \), the story is more complicated. The fluctuation splits into 2 branches, one with higher velocity, and one with lower velocity. The change in velocity of each branch after pellet ablation is around +3km/s for the upper and −2km/s for the lower branch, which is comparable to the change in diamagnetic velocity. One possible interpretation is that there are 2 simultaneously propagating modes with respect to plasma \( E \times B \) rotation, the higher speed branch in the ion diamagnetic direction (with respect to the plasma rotation), the lower speed branch in electron diamagnetic direction (with respect to the plasma rotation). However, according to this interpretation, the difference of velocity between the 2 modes (measured here to be \( \approx 5 \text{km/s} \)) should be equal to \( 2v_{dia} \), while the measured \( v_{dia} \) reduces towards zero immediately pellet ablation. This might suggest that either one or both of the modes are propagating at speeds significantly different from the diamagnetic drift velocity, or that the diamagnetic drift velocity may not be evaluated correctly at this radius due to unreliable temperature gradient from ECE (which changes sign here after pellet ablation as in figure 1 (d)). Tests of the spatial resolution of PCI measurements indicate that \( \rho = 0.5, 0.8 \) can be distinguished (so the changes are not strongly cross-coupled) and are exemplified in the difference in the time history of the upper branch of the phase velocity.

Regardless of the interpretation, it appears from figure 1 (f) that there is a strong phase velocity shear for the higher velocity branch, located between \( \rho = 0.8 − 1.0 \) for the initial time \( t = 0.6−0.61 \text{s} \) and then the shear layer moves inwards to \( \rho = 0.5−0.8 \) for \( t = 0.61−0.625 \text{s} \). If this were related to \( E \times B \) shear, then this could explain confinement improvement and turbulence decorrelation. Such kind of non-local \( E \times B \) shear mechanism has not been widely considered theoretically. One such model [26] describes the production of velocity shear a critical ingredient in the non-local temperature rise.

We now analyze the change of fluctuation amplitude and phase velocity when the core temperature decreases, as plotted in figures 2 (c) and (d). For both the \( \rho = 1.0, 0.8, 0.5 \), the fluctuation amplitude increases promptly (most pronounced at \( \rho = 0.5 \)), and there is no transient decrease phase as in #71160. More importantly, an increase in velocity is not observed at any location after pellet ablation unlike for the non-local temperature rise. Analysis of several other discharges, without Ar gas-puff, show the same behavior when the core temperature decreases: no increase in velocity at \( \rho = 0.5, 0.8 \). This change is even evident from the raw signals in terms of an increase or not of high frequency fluctuation power. Therefore, comparison of #71160 and #71169 shows that increase of velocity at \( \rho = 0.5 \) is a necessary ingredient for the non-local temperature rise.

5. Summary and interpretation
The main results are summarized as follows:

- The excitation of a high velocity component in addition to a low velocity component towards the core, which has negative phase velocity shear, is necessary for confinement improvement and core temperature rise. Whether this is due to a change in bulk plasma \( E \times B \) rotation, or change fluctuation velocity in the plasma frame, is unproved at this stage. There is no distinguishable change of diamagnetic drift in figure 1 (g) at \( \rho = 0.5 \), though there is a significant perturbation at \( \rho = 0.8 \) which may therefore affect the measured shear. In the future, improved CXRS measurements may be made to confirm the role of \( E \times B \) velocity,
however so far the SNR has been marginal in these regimes. It may turn out that the source of phase velocity shear may not be so important for confinement improvement.

- Fluctuation level can be larger when $q_{\text{pert}}$ is inwards, or equivalently when the total flux is reduced, contrary to the widely held belief that fluctuation suppression is necessary for confinement improvement. It is speculated that decorrelation of temperature, density and potential resulting from increase in magnitude of $E \times B$ shear has a stronger effect than increased fluctuation level.

- A non-local trigger exists for the increase of core velocity and drive of strongly negative velocity shear. This may relate to turbulence spreading [7], although the total fluctuation level is not equivocally seen to increase, (only in the high frequency band), or possibly is consistent with SOC models [26]. Another possible simple interpretation is that profiles are modified such that a transition from the electron to ion root exists in the plasma, transiently forming an electron internal transport barrier (eITB). The discharge conditions for non-local temperature rise are close to that for eITB [10]. Some discharges which exhibit a much more prompt core temperature rise than shown here appear to have a bifurcation in the fluctuation phase velocity profile around $\rho = 0.7$, indicating they may already possess an eITB before pellet injection. In such discharges, the change of edge profiles in response to the pellet may immediately increase the $E \times B$ shear at $\rho = 0.7$, leading to a prompt increase in core temperature. In the discharge #71160 presented here, the velocity shear layer is formed initially at the edge and then moves in (as in figure 1 (f)), therefore introducing a time delay before the maximum core temperature.

A possible mechanism is described. Because temperature is not measured towards the edge, speculation is made that the temperature decreases immediately after pellet injection near the edge leading to a local flattening of the temperature profile. Thomson scattering measurements in other discharges have partially confirmed this. This may be responsible for the reduction of edge fluctuation level initially. The change in profile at the edge facilitates a non-local change of phase velocity at $\rho = 0.5$ resulting in improved confinement, allowing the temperature to increase in the core, up to a point where the higher velocity branch barrier is no longer maintained, the confinement degrades and the temperature finally relaxes to its pre-pellet-injection state.

There are still many unexplained phenomena associated with the non-local temperature rise. Further experimental and theoretical investigation is necessary to clarify the mechanism and relieve some of the speculation. The presence of a low frequency turbulence modulator has been recently demonstrated [23], and, may be another element to consider.

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