Impact of Magnetic Shear Modification on Confinement and Turbulent Fluctuations in LHD Plasmas

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Abstract. For the comprehensive understandings of transport phenomena in toroidal confinement systems and improvement of the predictive capability of burning plasmas in ITER, the impact of magnetic shear has been extensively investigated in the Large Helical Device (LHD) for comparison with tokamaks. Consequently, it was heuristically documented that the pronounced effect of magnetic shear, which has been hitherto considered to be ubiquitous and strongly impacts the core transport in the tokamak experiments, is not quite obvious. Namely, the kinetic profiles respond little under extensive modification of the magnetic shear in the core, although the local transport analysis indicates the sign of improvement in confinement transiently when the magnetic shear is reduced. It was thereby concluded that the magnetic shear in the core strongly influences the MHD activity, but it may only be one of the necessary conditions for the transport reduction, and some other crucial knobs, such as the density gradient or T_e/T_i ratio, would have to be simultaneously controlled. The low wavenumber turbulence seems to be suppressed under the weak shear, and the turbulent fluctuation intensity behaves in a consistent manner as a whole, following the conventional paradigm accumulated in the negative shear experiments in tokamaks. However, vigorous dynamics of turbulent fluctuations have occasionally been observed under the magnetic shear modification, which respond in much faster time scale than the characteristic time scale for either the magnetic diffusion or the profile evolution.

1. Introduction

The plasma current exhibits predominant role in the empirical energy confinement scaling, as represented by ITER98(y,2), and it is well known that there exists an optimum edge q-value in the experiment, although the governing physics therein involved has not yet been fully resolved. In addition, the intrinsic advantage of magnetic shear for the transport reduction has been often obscure partly due to the interplay of MHD activities but occasionally highlighted out of the shadow in the tokamak experiment, such as the high li mode in DIII-D (β_N~$4l_i$) as well as the scaling of the pedestal pressure (W_{ped}~$I_p^2 l_i$) [1-2]. In particular, spontaneous ITB formation in the T_e profile was pervasively found under the negative shear formation. The conventional linear model proposed to date considers that the magnetic shear influences the growth rate of turbulence and thus the anomalous transport, as expressed in a form for ITG turbulence: $\gamma_L = k_\theta \rho_s (c_s/a)(a/R)^{1/2} f(s) a^{1/2} (L_n^{-1/2} + L_T^{-1/2})(T_i/T_e)^{1/2}$, using the commonly accepted notations [3]. Accordingly, the estimate of the shearing rate as a competing term has long been an issue of vigorous controversy in the tokamak research, though an applicability issue and further discussion have thereto been left in the *cul-de-sac*. On the other hand, Ref. 4 advocates that the pellet enhanced performance mode in Tore Supra is characterized by a combination of three different stabilizing mechanisms, namely the density peaking, **E**×**B** shear and magnetic shear, based on the drift wave stability calculations. In order to extract the magnetic shear contribution out of various parametric dependences, a dedicated experiment has been designed and performed in LHD[5], where inherently weak negative shear is modified solely by the beam driven current. In other words, a large-scale helical device was selected in order to eliminate the influence of the poloidal magnetic field, of which spatial profile varies according to the dynamic evolution of the current density profile in tokamaks. Should the contributions of the magnetic geometry be the same between large tokamaks and helical devices, it may be deduced that the apparent difference in the confinement properties may be ascribed to the application of the plasma current. The tangential nNB (negative-ion based NB) was thereby switched from co- to ctr-direction and vice versa at different densities and T_i/T_e values. The influence of the modification in the local magnetic shear, evaluated using the MSE diagnostic, has been extensively investigated in terms of the changes in the kinetic profiles. In addition, the perpendicular pNB (positive-ion based NB) has also been applied at various densities for the ion heating to elucidate the involvement of T_e/T_i ratio. Furthermore, besides the pellet injection, modulated ECH was applied at 29Hz across the nNB switch for the perturbative transport analysis. This paper addresses the result and implications of the magnetic shear modification experiment for the transport reduction, aiming at the comprehensive understandings of transport phenomena appertaining to the toroidal confinement systems in common. Here, avoidance of the MHD effect has been practically one of the prime issues in designing the experiment. The dynamic behavior of turbulent fluctuations in density measured using the CO_2 laser PCI (phase contrast imaging) diagnostic is also discussed under the framework of the linear model mentioned above.

2. Active Magnetic Shear Modification Experiments in LHD

2.1 Impact on Kinetic Quantities

Since one of the major experimental difficulties in extracting the magnetic shear contribution out of the transport characteristics is to waive the MHD effect, we have adjusted the position of magnetic axis R_{ax} in a preparatory experiment, aiming at relocating the malign rational surface out of the core region. As shown in Fig. 1, an abrupt reduction in $dT_e/d\rho$ is observed when iota =0.5 surface resides in the low shear region for the case R_{ax} =3.6m when nNB was switched from co- to ctr-direction. For discharges with larger R_{ax} (R_{ax} =3.75m), which is less vulnerable to MHDs, due to the extended magnetic well structure over half the minor radius, no sign of apparent MHD was observed in the probe signals. Fig.1(left column) depicts that

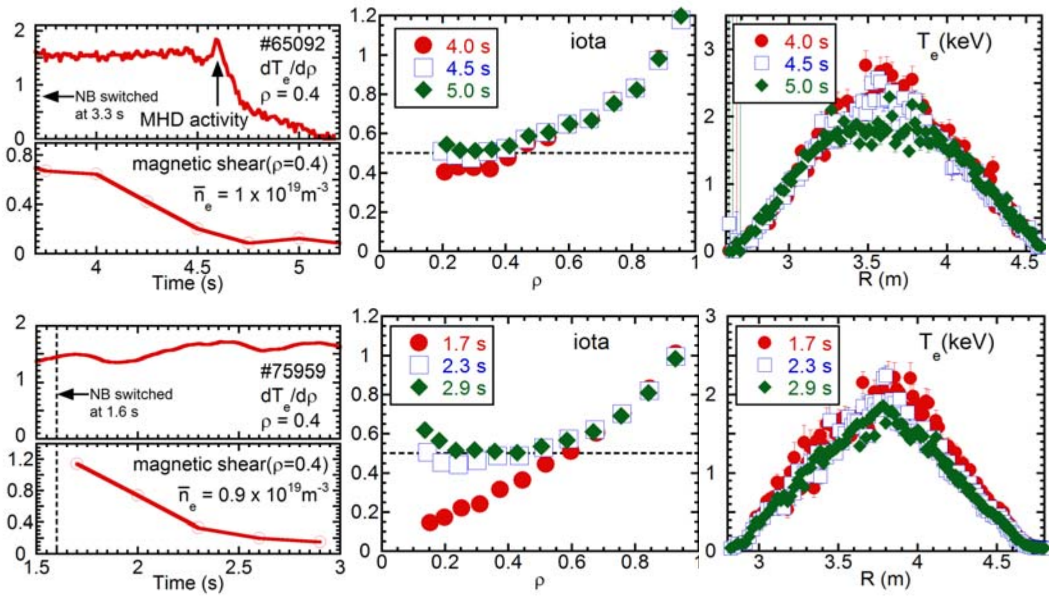

FIG. 1 Changes in $dT_e/d\rho$ and magnetic shear (left), iota profile(middle) and Te profile(right) are compared between the R_{ax}=3.60m(upper row) and R_{ax}=3.75m(lower row).

$dT_e/d\rho$ remains around 1.5 and the responses of T_e gradient and thermal diffusivity to the magnetic shear are quite subtle, although the magnetic shear at the ι=0.5 surface is decreased monotonically under the nearly constant heating power of 3.7MW. Indeed, in weak shear plasmas, MHD characteristics are largely modified by the magnetic shear predominantly at rational surfaces, and local flattening of the T_i profile has been occasionally observed in the case of R_{ax} =3.6m due to the island formation, which advertently obscures the influence of local magnetic shear on the transport properties [6]. As the magnetic shear is increased in the core, on the other hand, responses of T_i gradient and estimated thermal diffusivity to the magnetic shear generally become vague and they seem to correspond to the rotational transform. Accordingly, R_{ax} =3.75m was chosen throughout the rest of the campaign, and extended experiment has been performed, enhancing the range of magnetic shear with the long pulse nNB injection and field reversal. The typical discharge waveforms and

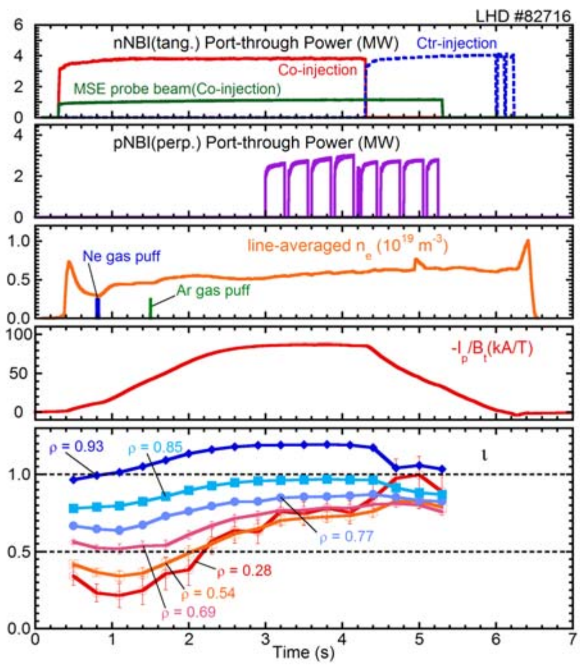

FIG. 2. Typical discharge waveforms for the magnetic shear modification experiment.

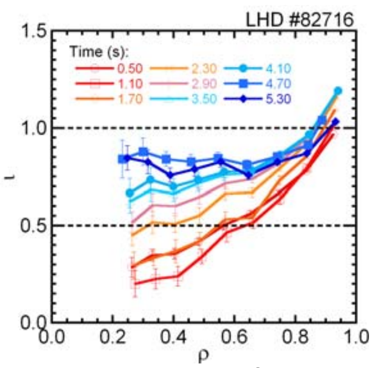

FIG. 3. Evolution of the iota profiles across the NB switch

corresponding iota profiles for the exploratory magnetic shear modification experiment in LHD are respectively shown in Figs. 2 and 3. As seen in the top subpanel, the tangential nNB was switched from co- to ctr-direction at 4.3s, sustaining the total heating power approximately the same at $\bar{n}_e = 6\times10^{18}\,m^{-3}$ under feedback control. Here, the toroidal magnetic field was set at 1.3T, and diagnostic beams for the MSE measurement as well as the CXS have been injected for 5s from 0.3s and 2.3s from 3s in the bursting manner, respectively. Ne gas puff at 0.8s was intended to enhance the NB deposition power, and the introduction of Ar at 1.5s was aimed at performing the simultaneous T_i measurement with the X-ray crystal spectrometer. A substantial amount of nNB driven current that reached I_p/B_t~90kA/T has been observed in the Rogowski signal, as depicted in the 4th row. Here, the flattening of iota profiles was observed, similar to the tokamak experiments. The temporal evolution of iota profile in Fig. 3, which corresponds to the bottom subpanel in Fig. 2 indicates that iota is substantially changed from 0.18 to 0.84 in the core region at ρ=0.28. The T_e and T_i profiles measured respectively with Thomson scattering and CXS diagnostics are shown in Fig.4, both of which indicate subtle changes, in spite of the substantial modifications in the rotational transform profile. The 180kV nNB power was considerably larger than the pNB power throughout the campaign, and the T_e/T_i ratio also remained at around 2, which may possibly be one of the reasons why noticeable reduction in the core transport was not observed. The moderately increasing density in the core region, due to the NB fuelling, turns to decrease after the beam is switched from co- to ctr-direction as indicated in Fig. 5, as a result of the changes in the deposition profile. However, the gas puffing efficiently supplies particles in the outer region, and the profile shape itself in the core region does not vary substantially as a whole without the apparent formation of the n_e gradient (Fig. 6). Here, the density profile was evaluated by the Abel inversion of the multi-channel FIR interferometer. In case the magnetic axis is located at R_{ax} >3.6m, hollow density profiles are often observed, which is considered to be ascribed to

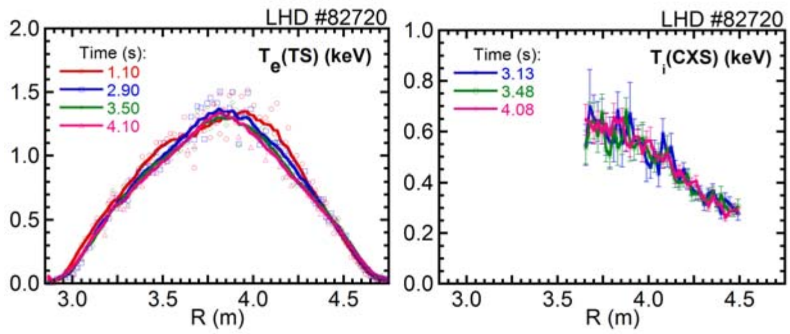

FIG. 4. Changes in T_e(left) and T_i(right) profiles across the NB switch

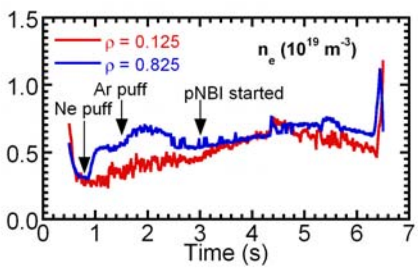

FIG. 5. Evolution of the density at different locations r=0.125 and 0.825

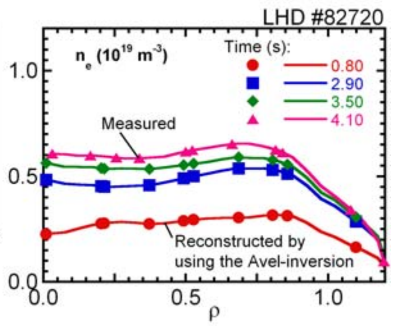

FIG. 6. Changes of n_e profiles across in the NB switch

the structure of turbulence modes. Accordingly, the range of L_n was limited in the experiment. Indeed, not only the equilibrium but also L_n, L_T and T_e/T_i are sustained at nearly constant values within a few percent during the magnetic shear modification. Therefore, it may be conjectured that dynamic changes in the magnetic shear do not simply modify the growth rate of the turbulence that enhances the anomalous transport.

2.2 Impact on Local Transport

Following the convention, the stationary power balance analysis has been performed, and it was confirmed that the electron thermal diffusivity χ_e stays around (5-10)m^2/s, and it remains roughly the same during the magnetic shear modulation, which is consistent with the documented subtle changes in the profile shape mentioned in the previous subsection. In order to understand the dynamic behavior of local transport, however, modulated ECH and pellet injection techniques have also been applied, and characteristics of both the heat and cold pulse propagations have been examined to the detail. Fig. 7 shows the profiles of amplitude and phase of T_e modulation measured by the ECE diagnostic across the beam switch. It was observed that the gradient of the phase at ρ=0.2 abruptly increased 0.1s after the beam switch, which is much shorter time scale than either the magnetic diffusion or profile evolution. An increase in the gradient of the phase corresponds to the reduction in thermal diffusivity. However, the appearance of the magnetic island in the core reduces the gradient, and accordingly the transport bounces back to degraded values. The temporal evolution of T_e and iota profiles indeed corroborate the result of perturbative experiment in a way that the profile shape is rather deformed 0.8s after the beam switch, and the iota value close to m/n=5/4 surface resides in the broad core region (Fig. 8). The result of analysis, related to the cold pulse propagation after the pellet injection is shown in Fig. 9. In comparison with the data obtained 0.25s before the NB switch, shown in the left column, it is clearly observed that the propagation delay time is enhanced inside ρ=0.2, 0.05s after the beam switch (middle column). This result implies that χ_e in the core region was reduced, being consistent with the result of the modulated ECH analysis. Nevertheless, clear transient responses in the thermal diffusivity described above were not quite obvious in terms of the density fluctuations evaluated using the PCI diagnostic [7], as indicated in Fig. 10. It might possibly be interpreted as that the variations in the density fluctuations in the core region was masked by larger fluctuation components in the outer

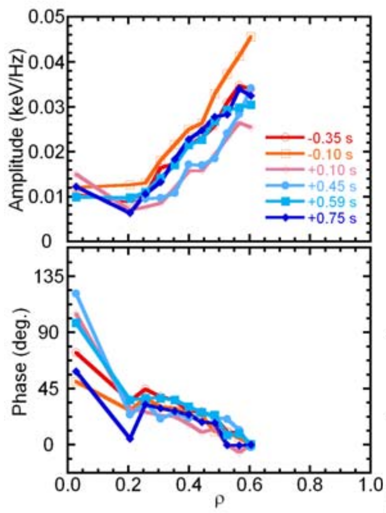

FIG. 7 The profiles of T_e amplitude and phase modulation during the modulated ECH

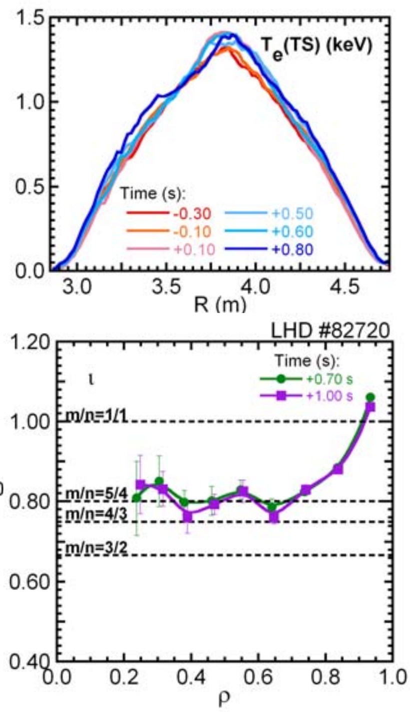

FIG. 8 The T_e and iota profiles during the modulated ECH

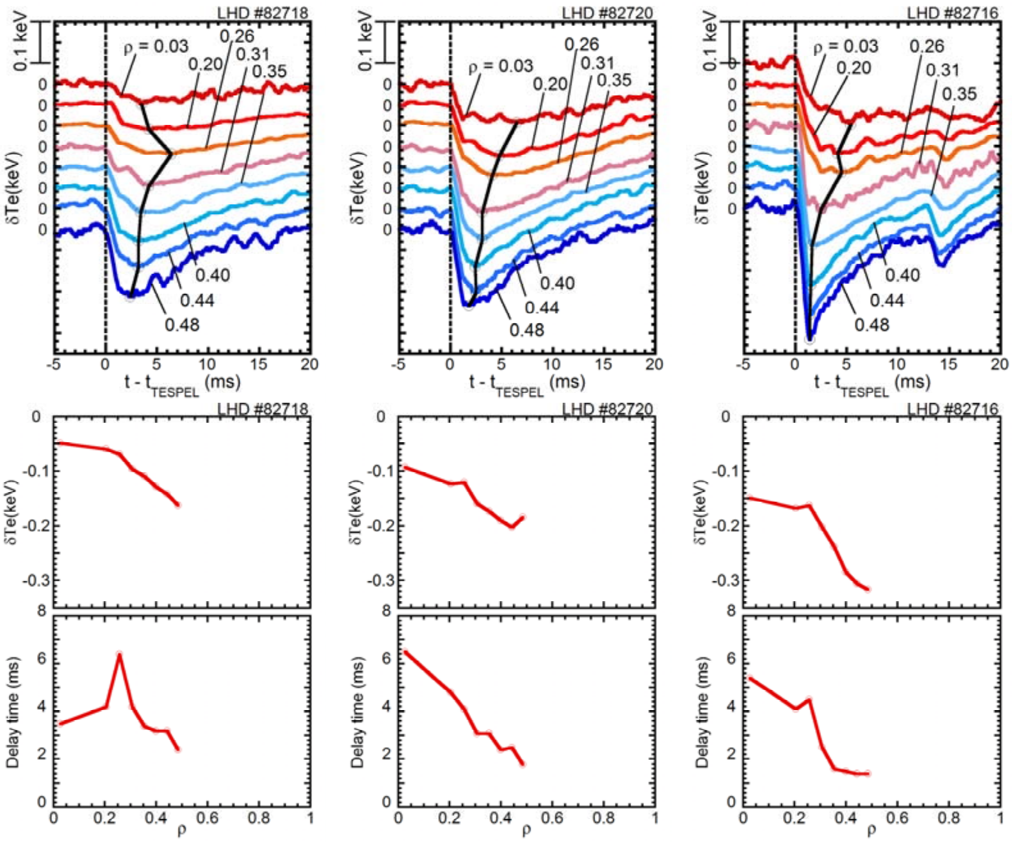

FIG. 9 The amount of T_e modulation at different spatial locations (top row), the maximum reduction in T_e after the pellet injection (middle row) and the delay time of T_e reduction (bottom row) for 0.25s before (left column), 0.05s after (middle column) and 0.65s after (right column) the pellet injection.

region of the plasma (Fig. 10). The PCI technique is based on the 2-D CO_2 laser interferometry, and it is intrinsically sensitive to k_θ~200m^{-1} at around mid-radius, though it is in principle the line-integrated measurement. Consequently, it could be deduced that the changes in the magnetic shear itself does not substantially impact the kinetic quantities in a steady state, though it may certainly be one of the control knobs, as it is clear that magnetic shear impacts the local diffusivity transiently, which has been documented using two different perturbative analyses. Accordingly, in order to sustain the profiles that would realize the reduced transport, concomitant reduction of either L_n or T_e/T_i ratio would be necessary.

2.3. Dynamic behavior of Turbulent Fluctuations under Magnetic Shear Modification

As indicated in the previous section, the line-integrated raw PCI diagnostic data which suffers from resolving the fluctuation components in the core region is not adequate, and extended analysis has been performed to resolve the spatial distribution, taking advantages of the relative alignment of the magnetic field and the polarization of the probing laser beam. Fig. 11 illustrates the contour map of density fluctuations. The turbulence intensity of low wavenumber (k=0.2-0.4mm^{-1}) components at ρ=0.5 observed at 1.1s decreases at 4.1s, as the magnetic shear

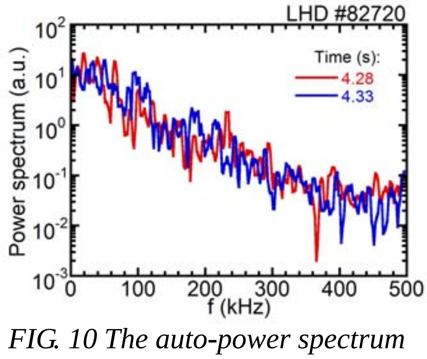

FIG. 10 The auto-power spectrum of the density fluctuations at 0.02s before and 0.3s after the NB switch

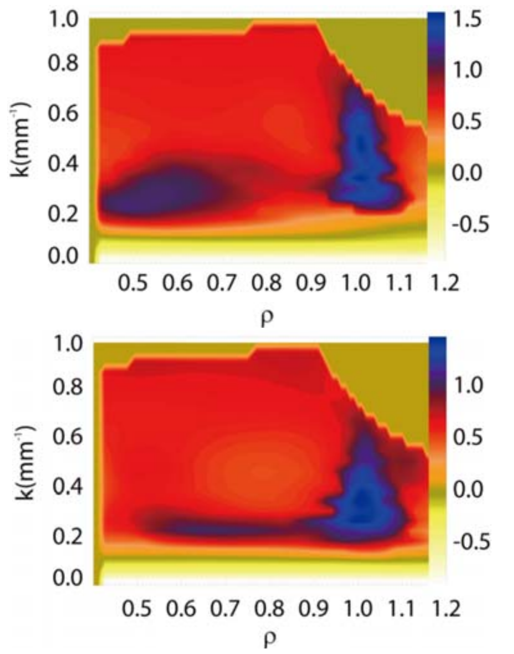

FIG. 11 Spatial distribution of the density fluctuations measured with the PCI diagnostic as a function of the wavenumber at 1.1s (upper) and 4.1s (lower). for #82720

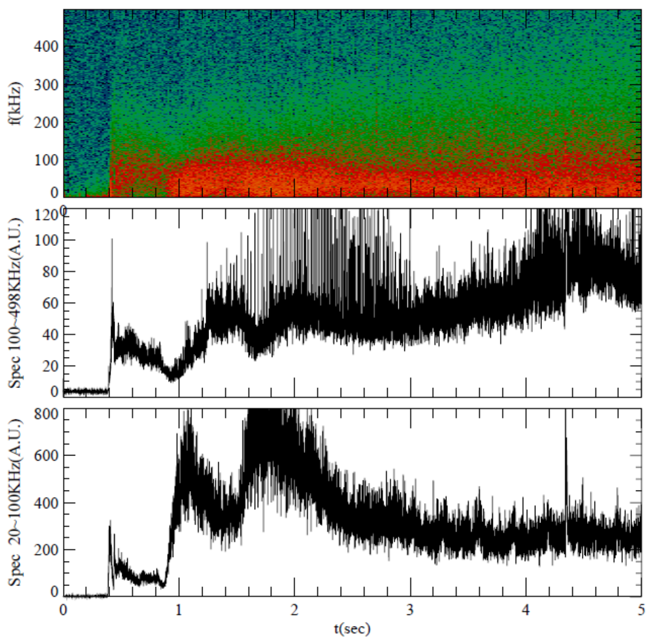

FIG. 12 Temporal evolution of the density fluctuations as a function of the frequency (top) and the fluctuation amplitude integrated in low (20-100kHz, middle) and high frequency (>100kHz, bottom) regions for #82720.

in the core region is reduced, although vigorous activity persists in the outer region. The fluctuation intensity is shown as a function of the frequency in Fig. 12. The high frequency part or the broadband component, which is related to the turbulence in the edge region, gradually increases after 3s, according to the reduction in the magnetic shear. On the other hand, the low frequency component, which is considered to reflect the core, apparently responds to the impurity gas puffing and gradually decreases toward 3s. Thus, density fluctuations seem to evolve in a consistent manner with the changes of the magnetic shear at a time constant related to the current diffusion time, following the conventional paradigm. However, an abrupt spike was also occasionally observed over the whole frequency region with much faster time scale. The spike in the signal observed around 4.4s coincides with the time of pellet injection.

2.4. Dynamics of MHD Activity under Magnetic Shear Modification

Although the malign MHD modes that would drastically reduce the gradient in the T_e or T_i profiles have been waived by expanding the major radius to R_{ax} =3.75m, minute instabilities have been often observed in the ECE signals when the core magnetic shear is reduced, as indicated in Fig. 13. The bursting and intermittent reduction in T_e coincides the spikes in the m/n=3/1 mode, however, it diminishes as the iota profiles evolve so that the m/n=3/1 rational surface disappears. In addition, it is noticeable that the m/n/=2/1 mode intensity decreases, as the low shear region somewhat extended over the m/n/=2/1 surface moves away. On the other hand, the m/n=1/1 mode intensity is quite small, as the magnetic shear at iota=1 surface is substantially large. Therefore, MHD behavior precisely reflect the conventional paradigm, related to the magnetic configuration, in contrast to the impact of magnetic shear on transport that would behave in a different manner, depending on the turbulence structure in the plasma.

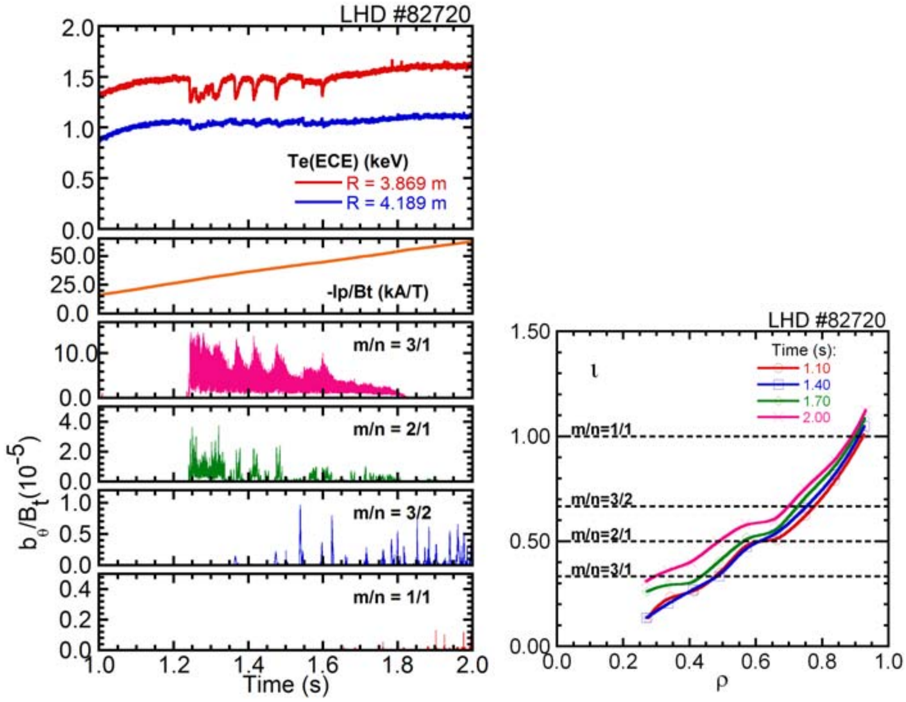

FIG. 13. MHD activities observed in the ECE signals during the magnetic shear modification in #82720 and corresponding probe signals (left). The changes in the iota profile evaluated with MSE (right).

3. Summary and Discussions

It was documented that the pronounced effect of magnetic shear in tokamaks was not obvious for plasmas with the turbulence structure pertaining to helical plasmas. Although the local transport analysis indicates the sign of transient reduction in transport and the low wavenumber turbulence seems to be suppressed when the magnetic shear is reduced, the kinetic profiles respond little. It could therefore be deduced that the magnetic shear in the core strongly influences the MHD, but it may only be one of the necessary conditions for the transport reduction, and some other crucial knobs, such as the density gradient or T_e/T_i ratio, might have to be simultaneously controlled.

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