Direct Measurement of ELM related Momentum Transport in the Edge of HL-2A H-mode Plasmas

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Abstract. We report the direct measurement of poloidal and toroidal turbulent momentum transport in the scrape-off layer of ELMy H-mode plasmas of the HL-2A tokamak. The measurement was conducted by using multi-functional reciprocating Langmuir probe and Mach probe arrays. The Reynolds stress, convective momentum flux, and the nonlinear momentum flux were measured and compared. It was found that the Reynolds stress term was the dominant term for turbulent momentum transport, and the other two terms were roughly an order of magnitude smaller than the Reynolds stress during ELMs. We found that poloidal turbulent momentum was transported from the scrape-off layer towards the separatrix during ELMs. The inferred residual stress also peaked during the same period. This indicated that additional poloidal momentum associated with turbulence was locally generated, and transported inward towards the separatrix during ELMs. This is a clear evidence that the origin of the poloidal momentum exists in the scrape-off layer. The toroidal momentum transport in the scrape-off layer during ELMs were also measured. The contribution to toroidal momentum transport by the three terms, Reynolds stress, convective and nonlinear fluxes, were all of roughly the same magnitude, which strongly encourages the consideration of the convective and nonlinear term in the theoretical and simulation work of intrinsic rotation studies.

1. Introduction

The spontaneous rotation of plasma, i.e. plasma self-organizes to form a large scale rotation in either poloidal or toroidal directions, is a very widely observed phenomenon in fusion devices and laboratory plasma devices. Numerous efforts [1-6] have been focused on this topic to search for the origin of the momentum source that can possibly inject momentum into the plasma and drive the flow. In the cases when apparent external momentum source is absent, the only possibility that momentum can be generated is through the momentum exchange across plasma boundary. Among the many suggested mechanisms, momentum flux induced by electrostatic turbulence is a promising candidate for the origin of spontaneous rotation, which is consistent with many experiments. Although there are many evidences pointing to the diretion that the source of momentum must exist in the scrape-off layer (SOL), a finite residual stress, which is a direct proof of turbulent momentum source, is yet to be experimentally demonstrated in tokamak devices. In addition, how the turbulent momentum is transported from the SOL into the pedestal is still not fully understood.

Therefore, a direct measurement of the turbulent momentum flux is of high interest.

$$S_{r\theta}^{total} = <\tilde{v}_r\tilde{v}_\theta> + \frac{<\tilde{v}_r\tilde{n}><v_\theta>}{<n>} + \frac{<\tilde{v}_r\tilde{v}_\theta\tilde{n}>}{<n>} \qquad (1)$$

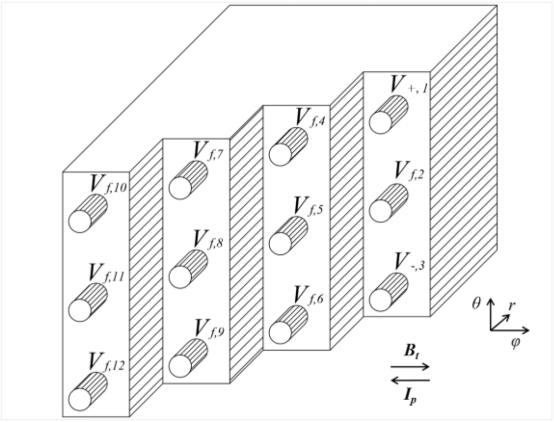

Figure 1 A specially designed Langmiur probe array was installed on the mid-plane of the HL-2A tokamak. This array is able to measure electron density and temperature, plasma potential, poloidal velocity, and Reynolds stress, etc. $V_{+,1}$ and $V_{-,3}$ is a double probe, and combined with $V_{f,2}$, form a triple probe. All other channels are for floating potential measurement.

The total turbulent momentum flux can be decomposed into three terms, as shown by equation (1). These are the Reynolds stress, convective momentum flux, and the momentum flux driven by nonlinear interactions, respectively. The above equation (1) is regarding the poloidal momentum transport, while the turbulent toroidal momentum transport can also be decomposed into similar terms. Most of this paper is to present the experimentally measured Reynolds stress, convective stress that is mediated by particle flux, and the nonlinear stress resulted from nonlinear interactions. The results for both poloidal and toroidal momentum transport are reported.

2. Experimental setup

In order to measure all the three terms for the poloidal momentum transport, a specially designed Langmiur probe array was built and installed on the mid-plane of the HL-2A tokamak, shown by figure 1. This Langmiur probe can simultaneously measure the plasma density, electron temperature, Reynolds stress, plasma poloidal velocities, etc..

Fluctuating ExB radial velocity were inferred by the measured potential difference in the poloidal direction $\tilde{v}_r = (\tilde{V}_{f,6} - \tilde{V}_{f,4})/2d_\theta B_t$, and the fluctuating poloidal velocity was approximated by $\tilde{v}_\theta = (\tilde{V}_{f,2} - \tilde{V}_{f,8})/2d_r B_t$。 Here $d_\theta = 6mm$ is the spatial separation of tips in the poloidal direction, which is far less than the poloidal turbulent correlation length 2-3 cm, and $d_r = 2.5mm$ is the spatial separation of tips in the radial direction, which is also far less than the turbulent correlation length in the radial direction 1-2cm [7]. The Reynolds stress is then computed as $RS = < \tilde{v}_r \tilde{v}_\theta >$, where the <…> indicates the time average. The plasma density is inferred from the ion saturation current $I_{1,3} = (V_3^- - V_1^+)/R_s$, where $R_s = 50\Omega$ is the shunt resistor that the ion current flew through. The electron temperature is inferred as $T_{e1,2} = (V_1^+ - V_{f,2})/ln2$. Combining the ion saturation current and electron temperature, we can infer the plasma density as $n_{e1,3} = I_{1,3}/(0.61\mathrm{eA}_{eff} C_s)$, where $C_s = \sqrt{kT_e/m_i}$ is the ion sound speed and A_{eff} is the effective current collection area. The particle flux is computed as $P = < \tilde{v}_r \tilde{n} >$.

The experiments were conducted in the ELMy H-mode deuterium discharges on the HL-2A tokamak [8, 9], which is a medium-sized tokamak with major radius 1.65m and minor radius 0.4m. The plasma current was 160kA and the toroidal magnetic field was roughly 1.36 Tesla.

Figure 2 shows a typical discharge during which the measurement was conducted. The plasma was neutral beam heated with a power about 0.9 MW (figure 2(e)), and both gas puffing and supersonic molecular beam injection (SMBI) [10] was used as fueling techniques to maintain the plasma density, as shown by figure 2(f).

3. Experimental results

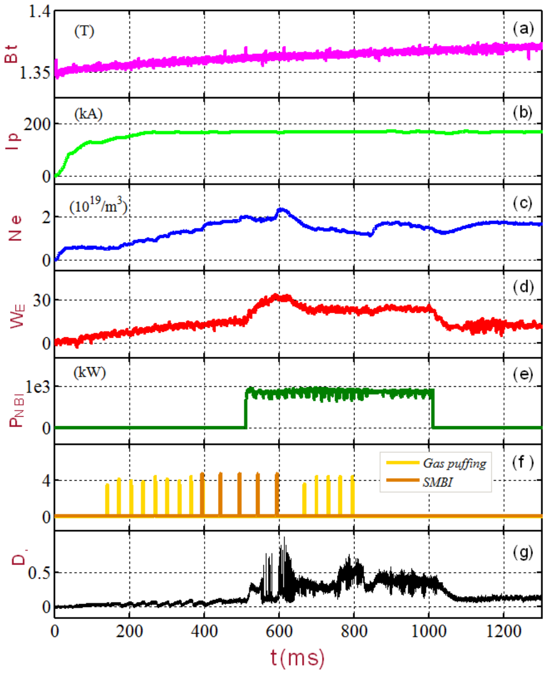

Figure 2 (a) Toroidal magnetic field; (b) plasma curent; (c) line average electron density; (d) plasma stored energy; (e) neutral beam injection heating power; (f) gas puffing and supersonic molecular beam injection for fueling; (g) D_{alpha} signal in the divertor region as an indication for plasma confinement.

The plasma transitioned into high confinement mode (H-mode) at t=552 ms, and dropped out of H-mode at t=640.5 ms. The Langmuir probe started to move towards the plasma at t=520 ms, remained stable at the same spatial position during t=605-760 ms, and started to pull out afterwards. All of data for poloidal momentum transport were taking during t=616-630 ms, when the probe parked in the SOL region about 5 millimeters outside the separatrix.

Figures 3(a) shows the D_{alpha} signal measured in the divertor region, and figure 3(b)-(d) show the plasma density, electron temperature, and ExB poloidal velocity, measured by the mid-plane Langmuir probe array, respectively. The probe was positioned about 5 millimeters outside the separatrix during the measurement. The blue lines are with time resolution of 1 microsecond. And the quantities indicated by the red lines have been smoothed with a window of 100 microseconds, which more clearly show the trend of density, temperature, and velocity during ELMs. It is clear that during ELMs electron density and temperature fluctuated violently, and their mean values indicated by their fluctuations envelopes increased dramatically. This is consistent with the idea that ELM bursts a pack of heat and particles from the pedestal into the SOL region and therefore resulting in large perturbations. However, another pronounced feature of figure

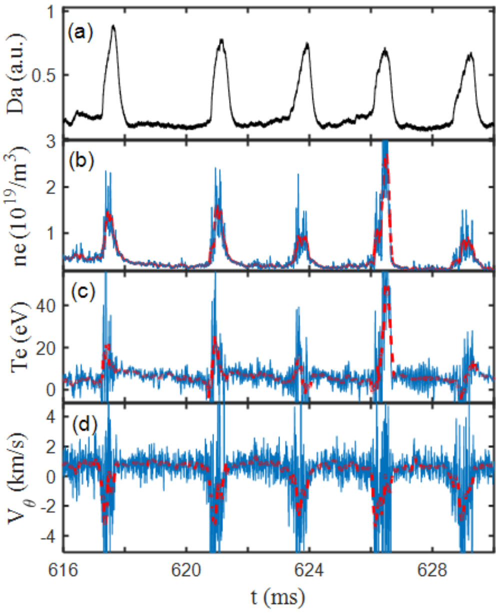

Figure 3 (a) D_{alpha} signal in the divertor region; (b) plasma density; (c) electron temperature; (d) ExB poloidal velocity. These were measured by a Langmuir probe array parked about 5 millimeters outside the separatrix during ELMy H-mode.

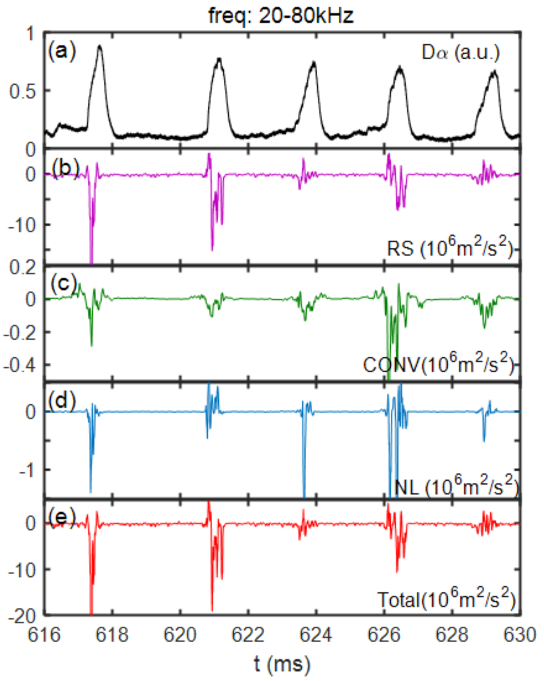

Figure 4 (a) D_{alpha} signal in the divertor region; (b) Reynolds stress; (c) convective momentum flux; (d) nonlinear momentum flux; (e) total momentum flux. Note that Reynolds stress is the dominant term, the other two terms are much smaller. All of the fluctuations have been filtered by a band-pass filter with cut-off frequencies 20-80 kHz.

3(d) is that the measured ExB velocity increased dramatically in the ion diamagnetic direction during the ELMs. This means that the plasma in the SOL region obtained large momentum in the ion diamagnetic direction during the ELMs. From the momentum conservation it means that either large momentum in the ion diamagnetic direction was locally generated or momentum in the electron diamagnetic direction was transported away from this region. Either process shall be accompanied by a drastic increase of Reynolds stress. This is exactly what is shown in figure 4(b), where Reynolds stress pulsed negatively during the ELMs. The convective momentum flux, the second term $\frac{<\tilde{v}_r\tilde{n}><v_\theta>}{<n>}$ in the right-hand-side (RHS) of equation (1), and the nonlinear momentum flux, the third term $\frac{<\tilde{v}_r\tilde{v}_\theta\tilde{n}>}{<n>}$ in the RHS of equation (1), were roughly one order of magnitude smaller than the Reynolds stress. The contribution to turbulent momentum transport from the convective and nonlinear terms were also orders of magnitude smaller than the Reynolds stress term between ELMs, as shown by figure 5. All of the fluctuations have been filtered by a band-pass filter with a cut-off frequency range 20-80 kHz. The auto-spectra of electron density, temperature and potential are shown in figure 6(a)-(c). This frequency range covers the peak of the density perturbations. The contributions by other frequency ranges are presented in figures 7(a)-(f), which also clearly show that Reynolds stress is the dominant term for turbulent momentum transport.

The fact that Reynolds stress pulsed negatively during ELMs at this location, figures 4(b), 7(a) and 7(d), indicated that either momentum in the electron diamagnetic direction was transported inward towards the pedestal or momentum in the ion diamagnetic direction was transported outside towards the chamber wall. This was a clear evidence that net momentum in the electron diamagnetic direction was injected into the separatrix during ELMs. And it was consistent with the idea that the large amount of heat injected into SOL by ELMs was converted into net poloidal momentum, then was transported into sepatratrix to spin up the plasma [1].

A straightforward test of this idea is that the residual stress [1], which is considered as an indication of momentum source, shall be finite and not negligibly small compared to either the total momentum flux or the Reynolds stress. The decomposition of Reynolds stress into the diffusive, pinch, and residual terms are shown in equation (2) [5, 11].

$$< \tilde{v}_r\tilde{v}_\theta > = -< \tilde{v}_r^2 > \tau_c \frac{\partial <V_\theta>}{\partial r} + v_r^{eff} < v_\theta > + S_{r\theta}^{Res} \qquad (2)$$

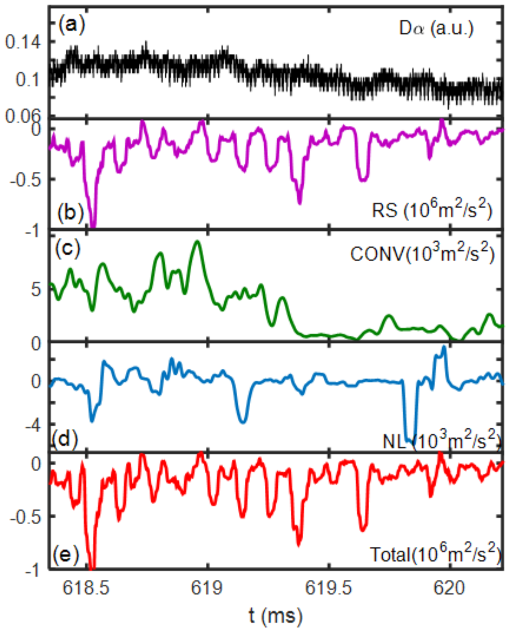

Figure 5 Contribution to momentum flux between ELMs. (a) D_{alpha} signal in the divertor region; (b) Reynolds stress; (c) convective momentum flux; (d) nonlinear momentum flux; (e) total momentum flux. All of the fluctuations have been filtered by a band-pass filter with cut-off frequencies 20-80 kHz.

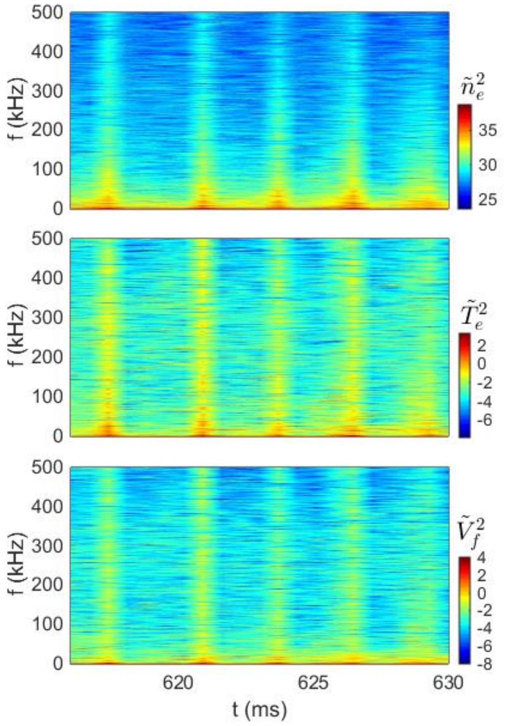

Figure 6 Auto-spectra of (a) electron density, (b) temperature, and (c) floating potential fluctuations at 5 mm outside the separatrix.

The first term in the RHS of equation (2) is the diffusive stress due to turbulent momentum diffusion, and the second term is the stress component due to radially directed poloidal momentum pinch, and the third term is the residual stress term, which is the indication of momentum source if it is finite. Since the total stress, the term on the left-hand-side (LRH) of equation, the diffusive stress, and the pinch can all be synthesized by quantities measured by the Langmiur probe array, we can then infer the residual stress from equation (2).

Figure 8(a)-(h) show the inferred residual stress and all relevant terms from equation (2). Figure 8(a) is the D_{alpha} signal measured in the divertor region; figure 8(b) is the ExB poloidal velocity; figure 8(c) is the Reynolds stress $<\tilde{v}_r\tilde{v}_\theta>$; figure 8(d) is the radially directed poloidal momentum pinch; figure 8(e) is the locally measured electron density, which is not relevant to the synthesizing of the residual stress but it can clearly indicate the timing of ELMs together with the D_{alpha} signal; figure 8(f) is the mean squared radial velocity $<\tilde{v}_r^2>$ that has been used to synthesize the diffusive stress term $\gamma_{diff} = -<\tilde{v}_r^2>\tau_c\frac{\partial<V_\theta>}{\partial r}$ shown by figure 8(g), due to turbulent diffusion; and figure 8(h) is the inferred residual stress. It is clear from figure 8(h) that the residual stress pulsed positively during each ELM, and its intensity was finite and not negligibly small compared to the Reynolds stress. Negative pulses of the pinch term and diffusive stress term indicated that momentum in the electron-diamagnetic direction was transported inward towards the separatrix due to turbulent processes. This is exactly what was expected if there was momentum source existed in the SOL region, and served as the origin to spin up the plasma inside the separatrix. However, the microscopic physical process that served as the momentum source is still not clear, and the ion-neutral collision can be a straightforward candidate. Further clarification needs the measurement of the neutral flow poloidal rotation velocity, and

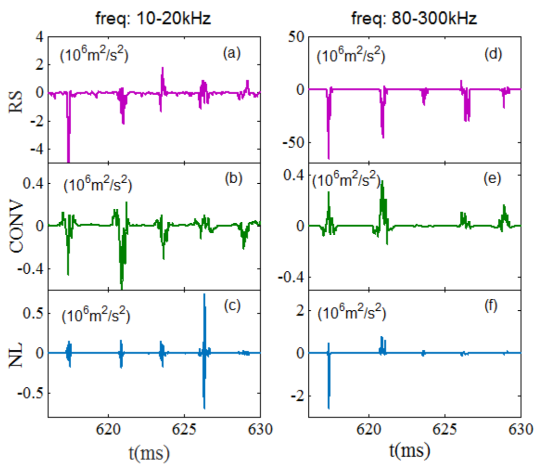

Figure 7 Contribution to total momentum transport by turbulence with different frequencies through Reynolds stress, convective and nonlinear flux. (a), (b), (c) are for turbulence in the range of 10-20 kHz, and (d), (e), (f) are for turbulence in the range of 80-300 kHz. Turbulence in both frequency ranges are with Reynolds stress as the dominant term for momentum transport.

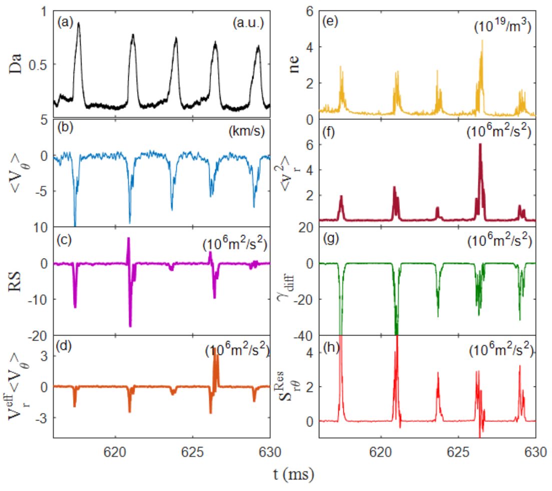

Figure 8. Inferring of the residual stress. (a) D_{alpha} signal in the divertor region; (b) ExB poloidal velocity; (c) Reynolds stress; (d) radially directed poloidal momentum pinch; (e) locally measured electron density; (f) mean squared radial velocity $< \tilde{v}_r^2 >$; (g) diffusive stress term due to turbulent diffusion $-< \tilde{v}_r^2 > \tau_c \frac{\partial <V_\theta>}{\partial r}$; and (h) the inferred residual stress.

the spatially resolved ionization rate of neutrals in the SOL region. So far, none of these diagnostics is available on the HL-2A tokamak.

One might wonder how does the toroidal velocity evolve during ELMs as people usually mean the toroidal velocity instead of poloidal when discussing intrinsic or spontaneous rotations. The toroidal rotation is closely related to the plasma confinement according to the empirical Rice scaling [3], and therefore is critical for high performance fusion plasmas. In order to measure the parallel Reynolds stress, we built another multi-functional probe array and installed it on the mid-plane of the HL-2A tokamak. This probe array was comprised of one Mach probe that could measure the toroidal rotation, two Mach probes that could measure the poloidal rotation speed, and one triple probe together with a few floating potential channels that could be used to measure the plasma density, potential and electron temperature.

Due to the restriction of space, the geometry of this probe is not presented in this paper. The experiment was conducted in similar conditions as what presented before. The parallel total stress (essentially the toroidal total stress, but denoted by “||” thereafter) can also be decomposed into three parts as shown by equation (3). This equation is very similar to equation (1). Figure 9(a) is the D_{alpha} signal in the divertor, which is a good indication of particle recycling and confinement; figure 9(b) is the parallel Reynolds stress $< \tilde{v}_r \tilde{v}_{||} >$; figure 9(c) is the convective toroidal momentum flux $\frac{<\tilde{v}_r \tilde{n}><v_{||}>}{<n>}$, which is essentially the momentum transport mediated by the particle flux; figure 9(d) is the nonlinear momentum flux $\frac{<\tilde{v}_r \tilde{v}_{||} \tilde{n}>}{<n>}$.

$$S_{r||}^{total} =< \tilde{v}_r \tilde{v}_{||} > + \frac{<\tilde{v}_r \tilde{n}><v_{||}>}{<n>} + \frac{<\tilde{v}_r \tilde{v}_{||} \tilde{n}>}{<n>} \quad (3)$$

The sign convention here is that negative toroidal velocity is in the co-current direction, and positive radial velocity is pointing towards the vacuum chamber. Therefore, the negative pulses

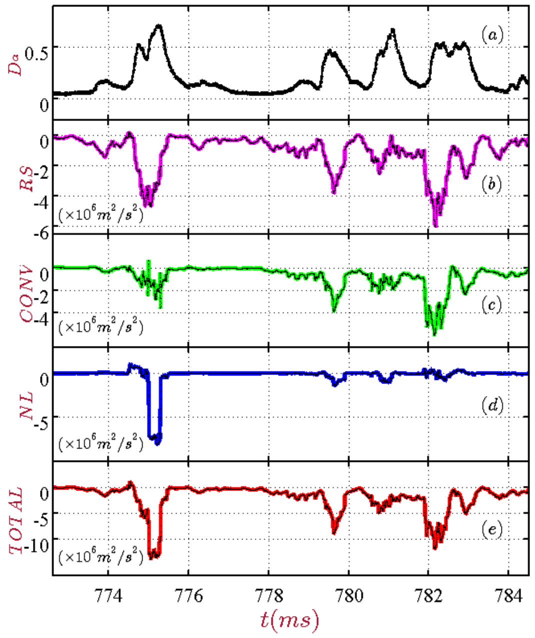

Figure 9 (a) Dalpha signal in the divertor region; (b) Parallel Reynolds stress; (c) convective toroidal momentum flux; (d) nonlinear toroidal momentum flux; (e) total toroidal momentum flux. Note that Reynolds stress is about the same magnitude as the other two terms. This is different from the case of poloidal rotation as presented in figure 4.

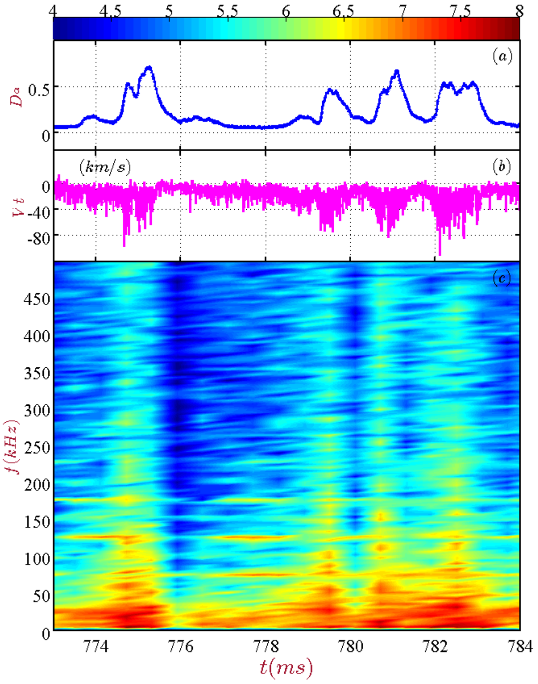

Figure 10. (a) D_{alpha} signal in the divertor region; (b) Toroidal rotation velocity (negative values correspond to the plasma current direction; (c) Spectrum of toroidal velocity fluctuation.

of stress in figure 9(b)-(d) means that either the co-current momentum was transported outward towards the chamber wall, or counter-current momentum was transported inward towards the separatrix. The toroidal velocity also showed a broadband characteristic, similar to density and potential fluctuations, as shown by figure 10. One pronounced feature was that the convective and nonlinear momentum fluxes were not negligibly small compared to the Reynolds stress, which is different from the poloidal stress as shown in figure 4. This finding strongly urges the consideration of the convective and nonlinear terms in theoretical and simulation work of intrinsic rotation studies, which has been generally neglected until very recently [12]. Further decomposition of the Reynolds stress into diffusive, pinch, and residual components would give insight of the momentum transport mechanism. However, the toroidal velocity gradient was not available here and therefore the diffusive term could not be synthesized. Further experiments to measure the toroidal residual stress on different fusion devices have been planned, and will be reported in future conferences.

In summary, both poloidal and toroidal momentum fluxes induced by electrostatic turbulence were experimentally measured in ELMy H-mode plasmas in the SOL of the HL-2A tokamak. The measurement was taken by specially designed multi-functional probe arrays, and the probe arrays parked at the position roughly about 5 millimeters outside the separatrix. It was found that the poloidal Reynolds stress was the dominant term for the poloidal momentum transport during ELMs, and the other two terms, i.e., the one associated with particle flux and the one associated with nonlinear interactions, were negligibly small. This is different from the case of toroidal momentum transport, where the convective and nonlinear terms were of the same magnitude as the toroidal Reynolds stress term. This finding strongly encourages the consideration of these two terms in the theoretical and simulation work of searching the origin of intrinsic rotations. The residual stress of poloidal momentum transport was also inferred, which combined with the fact that both of the diffusive and convective momentum pulsed negatively during ELMs, indicated that poloidal momentum was locally generated and then transport inward towards the separatrix. This is a clear evidence that the poloidal momentum originates in the SOL and then propagates inwardly to spin up the plasma. Further cross machine comparison of the measured residual stress is highly favorable. And the experiment to measure toroidal residual stress is also of high interest. One thing that needs to pay attention to is that we did not measure the magnetic fluctuations, which presumably should play an important role during ELMs. The momentum transport induced by magnetic fluctuations will also be measured in future experiments.

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