Investigation of Broadband Fluctuation-induced Inward Transport at The Edge of HL-2A NBI Heated Plasma

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Inward transport, characterized by its counter-gradient nature, defies the conventional expectation that particles and energy move from regions of high density and temperature to low. Instead, it facilitates the movement of particles against the density gradient, contributing to the establishment of density transport barriers. These barriers are essential for enhancing plasma confinement and improving the overall performance of fusion reactors. Observations of inward transport across multiple fusion devices, including the H-1[1], TEXTOR[2], and HL-2A[3, 4], have highlighted its significance. In these experiments, inward transport has been shown to play a crucial role in mitigating the adverse effects of anomalous transport, which is primarily driven by plasma turbulence. By counteracting the loss of particles and energy across magnetic field lines, inward transport helps to optimize plasma conditions and increase the efficiency of fusion reactions.

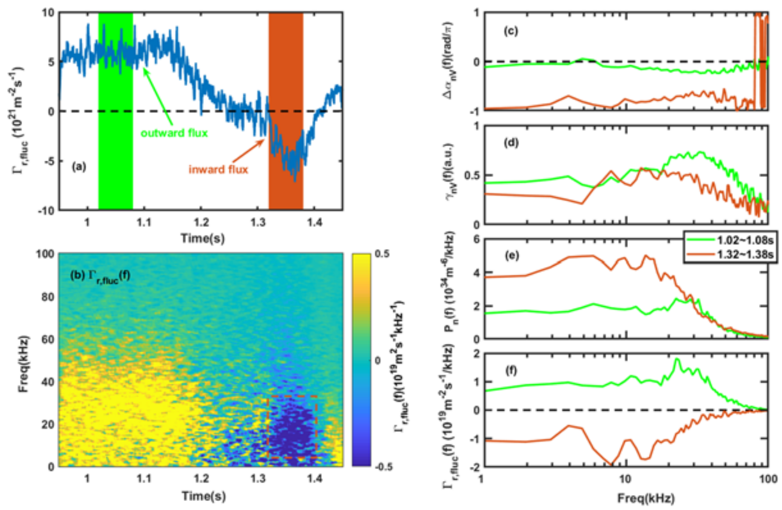

Figure 1 (a) The evolutions of fluctuation-induced radial particle flux $\Gamma_{r,fluc}$, (b) the time-frequency spectra of fluctuation-induced particle flux. Frequency resolved of (c) cross-phase between density and velocity fluctuations α_{nV}, (d) coherency γ_{nV}, power spectral density of (e) electron density P_n and (f) fluctuation-induced radial particle flux $\Gamma_{r,fluc}$.

Experiments were conducted on the HL-2A tokamak, a medium device with specific parameters. A radially reciprocating Langmuir probe array was used to measure the edge electron density and electric field fluctuations. We observed a gradual transition in the transport direction across a broad frequency spectrum, changing from outward to inward flux, as shown in Fig 1(a). This transition is characterized by significant variations in the amplitude of density fluctuations, as shown in Fig 1(e), while radial velocity fluctuations remained relatively stable. Pronounced changes in the spatial structure of turbulence were identified, with fluctuations below 40kHz exhibiting a pronounced reduction in poloidal and radial wavelengths, indicating enhanced turbulence coherency, as shown in Fig 1(d). In addition, the heat conduction flux displayed an inward trend that diverges from particle flux variations, highlighting the distinct evolution patterns of these fluxes.

Our experimental findings reveal a notable enhancement in Reynolds stress amplitude $\langle \tilde{V}_r \tilde{V}_\theta \rangle$ during the onset of inward particle transport. This amplification aligns precisely with the frequency band that predominantly contributes to inward transport (<40kHz), a period also marked by a pronounced increase in the coherence $\gamma_{VrV\theta}$, as shown in Fig 2 below. Given that enhanced density amplitude is the primary driver of increased inward flux, our results indicate a significant correlation between Reynolds stress amplification and density fluctuation modulation. This suggests that Reynolds stress is a pivotal factor in altering turbulence structure and characteristics. It is likely that the enhanced Reynolds stress facilitates inward particle transport, which could be instrumental in forming a particle transport barrier. This barrier is crucial for improving plasma confinement performance. Our research advances the understanding of turbulence's organized nature during inward transport and offers key insights for enhancing plasma confinement.

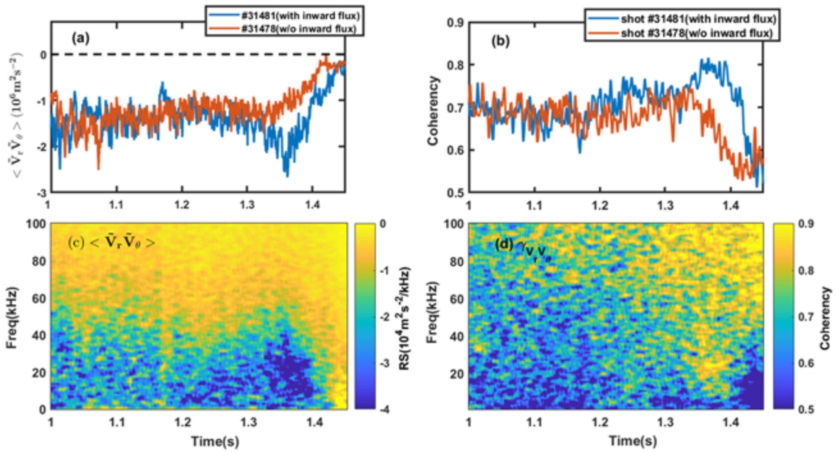

Figure 2 Time evolution of (a) Reynolds stress $\langle \tilde{V}_r \tilde{V}_\theta \rangle$, and (b) the coherency $\gamma_{VrV\theta}$. Time-frequency spectra of (c) Reynolds stress $\langle \tilde{V}_r \tilde{V}_\theta \rangle$, and (d) the coherency $\gamma_{VrV\theta}$ for shot #31481 with inward flux. The red dashed box indicates the region where the Reynolds stress $\langle \tilde{V}_r \tilde{V}_\theta \rangle$ and coherence $\gamma_{VrV\theta}$ are enhanced, which is significant for data exhibiting inward flux (# 31481).

This work is supported by the National Magnetic Confinement Fusion Science Program of China (under Grant Nos. 2022YFE03100004 and 2022YFE03060003), the Natural Science Foundation of China (under Grant Nos. 12405268, 12175227, 11875255, 12375226, and 11975231), the China Postdoctoral Science Foundation (under Grant Nos. 2022M723066) and the Fundamental Research Funds for the Central Universities (under Grant No. WK2140000016)).

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