EXPERIMENTAL OBSERVATION OF ZONAL FLOW-LIKE OSCILLATION IN CHINESE FIRST QUASI-AXISYMMETRIC STELLARATOR-TEST DEVICE

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The neoclassical and turbulence transport are widely believed to determine the plasma performance in stellarators [1]. Chinese first quasi-axisymmetric stellarator (CFQS) has been done for the optimization of neoclassical transport by shaping the magnetic geometry [2, 3], however, it is unclear how about the turbulence transport. To this end, the simulation work on impact of quasi-axisymmetric magnetic topology on the nonlinear interaction was performed by using the code GKV [4], the study results indicate that the zonal flow might be generated in CFQS. At present, the first quasi-axisymmetric (QA) magnetic configuration with a field strength of 0.1T has been successfully achieved [5], thus it provides a good experimental platform for the validation of theoretically-predicted zonal flows in the CFQS -Test device.

The dedicated experiment has been carried out in Helium plasma on the CFQS-Test device (averaged minor radius is 0.25 m, major radius is 1.0 m and toroidal periodic number N is 2). To investigate the long-rang correlation (LRC) characteristics of the electrostatic fluctuations, we develop two sets of Langmuir probe systems toroidally separated by about 2300 mm. One is a reciprocating probe system (labeled as 1# probe) localized at toroidal angel 0 degree outer mid-plane, which can measure the radial profiles of equilibrium and fluctuating parameters with an approximately velocity of 0.1 m/s. Another is a stationary probe system (labeled as 2# probe), which is mounted vertically upward from bottom port. The radial measurement could be flexibly adjusted shot by shot in term of the experimental requirement. Figure 1 presents experimental observations of a low frequency oscillation peaking at f ≈ 1.0 kHz detected in CFQS-T plasma discharge (heating power: P ≈ 6 kW, line-averaged density: $n_{el} \approx (2\text{-}4) \times 10^{17}$ m^{-3} and the magnetic intensity: $B_t = 0.05$T). Figure 1 (a plots the trajectory of the reciprocating probe (1# probe) in one discharge #93043, where $\Delta r=0$ represents the approximate position of the last closed flux surface (LCFS) identified by VMEC code, the positive and negative sign means outside and inside the LCFS, respectively. In this experiment, the 1# probe system is set to move inward from SOL ($\Delta r_1 = +4$ cm) to core plasma ($\Delta r_1 = -10$ cm, magnetic axis), and then it returns back. Meanwhile the 2# probe is fixed at $\Delta r_2 = -2.5$ cm. As shown in figures 1 (b)-(c) are the time-frequency spectrum of the cross-power and coherence between two floating potential fluctuations ($\tilde{V}_{f1}$ and $\tilde{V}_{f2}$) toroidally separated by 2300 mm. One can clearly see that a coherent mode peaking at f ≈ 1 kHz with a significant correlation could be directly detected, as the two toroidally-separated probe measured positions pass through the same magnetic surface, represented by the vertical red-dotted line in figure 1. The similar measurement were performed in other fusion devices, such as TJ-II [6], CHS [7] and HL-2A [8]. For further clarifying the phase shift of the observed

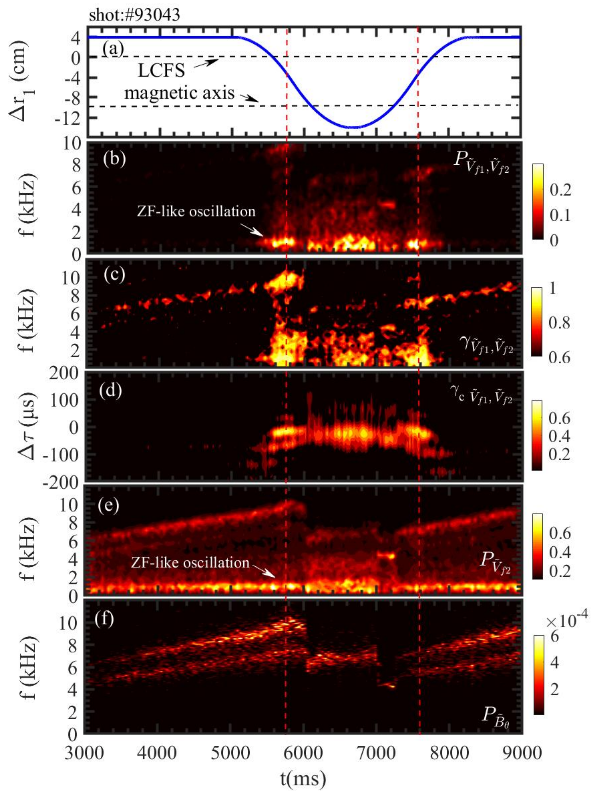

Figure 1. The trajectory of Langmuir probe (1# probe) (a), the time-frequency spectrum of cross-power (b), correlation (c) and cross-correlation function (d) between two floating potentials ($\tilde{V}_{f1}$ and $\tilde{V}_{f2}$) toroidally separated by 2300 mm, the floating potential ($\tilde{V}_{f2}$) (e) measured by the stationary probe (2# probe) and the magnetic fluctuations ($\tilde{B}_\theta$) (f).

coherent mode, we estimate the cross-correlation function (CCF) by using the two floating potential fluctuations as described above and presented it in figure 1 (d). It is found that the phase shift keeps nearly-zero, demonstrating that this coherent mode are constant on flux surface, possessing the long-range toroidal correlation (LRC) characteristics. Figure 1(e) depicts the time-frequency spectra of the floating potential fluctuation measured by the stationary probe (2# probe), which displays the quasi-stable evolution of the coherent mode peaking at 1 kHz together with a chirping mode from 6 kHz to 10 kHz (left for future study). No magnetic activity associated with the 1.0 kHz coherent mode was found in this discharge, as seen in figure 1 (f). These results given here indicate that this coherent mode essentially attributes to electrostatic nature with a significant long-range correlation.

In general, the bicoherence $b^2(f_1, f_2)$ is used to study the generation mechanism of the coherent mode, and the summed bicoherence $\sum b^2(f)$ is a rough measurement of the three-wave coupling. As shown in figure 2(a) is the squared bicoherence computed with the floating potential measured by the stationary probe (2# probe). The color from black to white corresponds to weak to strong bicoherence intensity. It is clearly seen that the significant bicoherence mostly occurs in the low frequency range (10-20 kHz), except for the 20-40 kHz. A significant peaking at f=1.0 kHz is found in the summed bicoherence as sketched in figure 2 (b). These results given here demonstrate that the coherent mode is mainly generated by the nonlinear coupling of the ambient turbulence. Figure 2 (c)-(e) plot the cross power, coherence and phase shift between the envelopes of density fluctuation filtered in 5-50 kHz ($\widetilde{\mathrm{Is}}^{\mathrm{env}}_{5-50\,\mathrm{kHz}}$) and the radial electric field ($\widetilde{E}_r$), which clearly demonstrate that the phase shift between $\widetilde{\mathrm{Is}}^{\mathrm{env}}_{5-50\,\mathrm{kHz}}$ and $\widetilde{E}_r$ are nearly $\pi/2$ at the mode frequency of 1.0 kHz, which is well consistent with the theoretical prediction by predator-prey model [9]. In summary, these results given here provide a strong experimental evidence for the existence of zonal flow-like oscillation in CFQS-T plasmas. Detailed results will be presented in this conference.

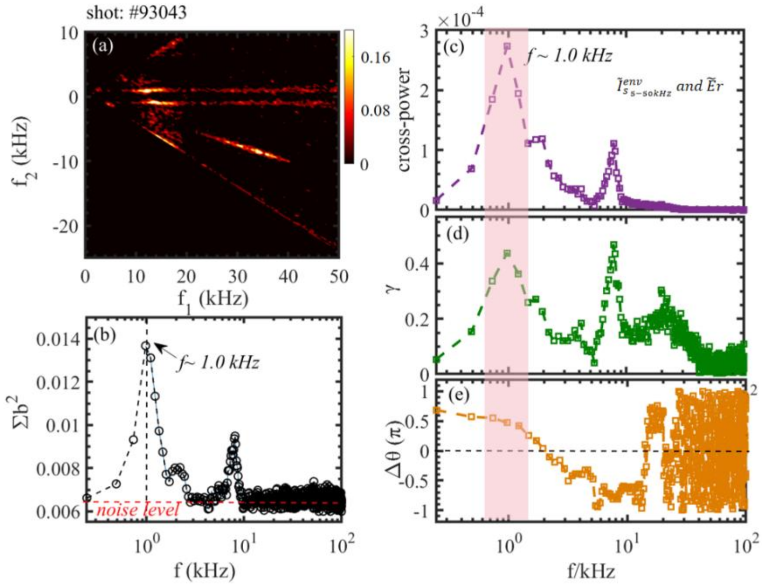

Figure 2. The contour of the squared auto-bicoherence of floating potential fluctuations $<\tilde{\Phi}_f\tilde{\Phi}_f\tilde{\Phi}_f^*>$ for Δ_t =4000-5000ms (a) and the resulting summed bicoherence $\sum b^2(f)$ (b). The cross-power (c), correlation (d) and phase shift (e) between $\widetilde{\mathrm{Is}}^{\mathrm{env}}_{5-50\,\mathrm{kHz}}$ and $\widetilde{E}_r$ measure by the stationary probe (2# probe).

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REFERENCES

[1] P. Xanthopoulo et al. *Phys. Rev. X* 6, 021033 (2016)
[2] H. F. Liu et al. *Nucl. Fusion* 61, 016014 (2021)
[3] A. Shimuzu et al. *Plasma and Fusion Research* 13, 3403123 (2018)
[4] M. Nakata et al. the 27th International Toki Conference on Plasma and Fusion Research, Toki, Japan, 19-22, Nov. 2018, oral talk
[5] J. Cheng et al. 24th International Stellarator Heliotron Workshop, 9-13 Sep. 2024, Hiroshima, Japan, invited talk
[6] M. A. Pedrosa et al. *Phys. Rev. Lett.* 100, 215003 (2008)
[7] A. Fujisawa et al. *Phys. Rev. Lett.* 93, 165002 (2004)
[8] X. Chen et al *Nucl. Fusion* 64, 106065 (2024)
[9] P. H. Diamond et al. *Plasma Phys. Control. Fusion* 47, R35 (2005)