Complex Plasma Systems Research Section

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1. Introduction

Nuclear fusion energy has some attractive features as a future option for the base-load electrical power source and thus magnetic field confinement fusion research is thus being conducted all over the world. To realize fusion reactor, there are however several urgent issues that need to be resolved. We are thus performing the Heliotron J experiment to solve these issues: for example, (1) improvement of plasma energy confinement, (2) enhancement of fueling ability. To solve these problems through experiments, excellent diagnostic tools are needed.

Results in FY2024 featured in this report are about the development of advanced diagnostics and discovery of improved confinement state.

2. Development frequency comb reflectometry

Two types of frequency comb reflectometer have been developed to observe particle avalanche, turbulence spreading, and staircase formation at the periphery of Heliotron J. One is for frequency comb Doppler backscattering measurements. One is for frequency comb Doppler backscatter measurements with a comb frequency bandwidth of 12-26 GHz and a comb spacing of 0.5 GHz. The corresponding O-mode cutoff density is 0.2-0.9x10^{19} m^{-3}, and 24 spatial points in the peripheral region of a typical discharge with average density > 0.5 x10^{19} m^{-3} are measured simultaneously. From these measurements, we aim to identify turbulence spreading by observing the spatio-temporal structure of the plasma flow velocity in the poloidal direction and micro density fluctuations. The other is for FM frequency comb reflectometer, in which the base frequency of the comb is swept at 0.5 GHz for 0.5 ms while maintaining the comb spacing. This allows us to observe the time-varying structure of the staircase by surveying a wide plasma region in a short period of time. In addition, by modulating the frequency in a triangular wave shape, the Doppler shift in the radial direction can be obtained from the difference in the beat frequencies of the incident and reflected waves in the phases where the frequency of the incident microwave is increasing (up) and decreasing (down). This Doppler shift can be used to identify convective ballistic propagation of density perturbations such as particle avalanche. Both systems use an ultrafast digital storage oscilloscope to directly digitize the incident and reflected waves, and digital signal processing instead of conventional analog mixers and fixed filters to enable very flexible and fast detection. Both systems have completed bench tests.

The backscattering system was applied to the Heliotron J experiment to observe the flow velocity, which can be estimated from Doppler frequency. Figure 1 shows the time evolution of the flow velocity. While the plasma is in steady state, the flow velocity has large fluctuations, but the average value is negative. It is necessary to confirm whether these large fluctuations are due to plasma or noise. When obtaining the Doppler frequency using the center-of-gravity method, there is a trade-off between frequency resolution and time resolution. If the time resolution is increased, the frequency resolution decreases, and the influence of noise increases in the region where the Doppler shift is small. Therefore, it is necessary to set the optimal resolution for both.

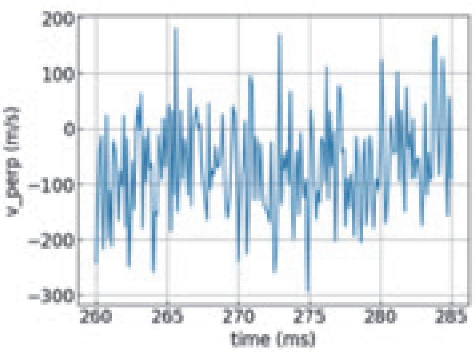

Fig. 1 Typical temporal evolution of flow velocity. Comb frequency component of 20 GHz was used.

The spatial structure of the time-averaged velocities is shown in Figure 2. Error bars indicate the standard deviation of the time variation. The horizontal axis is the injected Comb frequency, but the corresponding cutoff density is greater at higher frequencies, so the cutoff layer is located more in the center of the plasma. At lower frequencies, on the other hand, the cutoff layer is located at the periphery of the plasma, thus the velocity profile with respect to the injection frequency corresponds to the radial profile of the flow velocity. Figure 2 shows that the flow velocity, which is almost zero at the center, increases negatively toward the periphery of the plasma. If a flow is formed in the periphery, it is expected to suppress the edge turbulence.

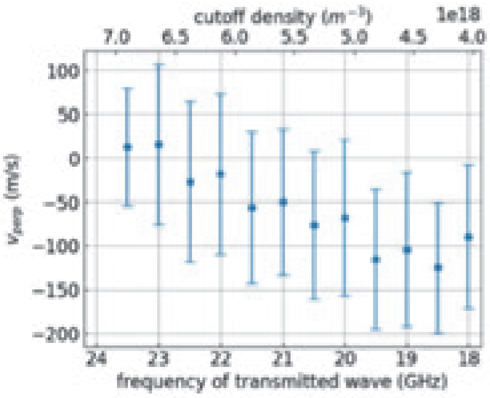

Fig. 2 Radial profile of time-averaged flow velocity.

3. Noble Island Identification Method

The stochastic structure in the peripheral region is a common feature in helical fusion devices due to the intrinsic resonant perturbation even in the vacuum magnetic field. A region with stochastic field lines and remanent islands is formed outside the last closed flux surface (LCFS). A numerical method to distinguish the closed magnetic surface from stochastic field lines is regarded as a useful tool to characterize helical confinement.

In this study, we implemented an algorithm that extracts a field line's dominant resonant poloidal/toroidal mode number m/n from the rotational transform. The magnetic islands or closed flux surfaces enclosed by the field line can be identified based on the shape of the m/n resonant periodic structure of the field line trajectory in the Poincaré plot. The method was applied to the vacuum field of a Heliotron J device as an example, as shown in Fig. 3.

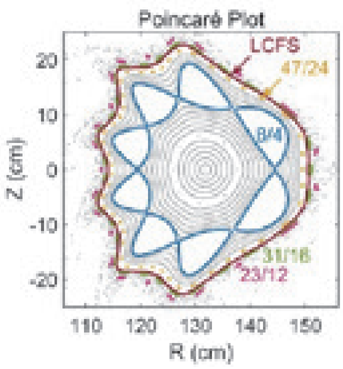

Fig. 3 Several identified magnetic islands with their mode number in Heliotron J.

As increasing the current in the inner vertical coils, large islands with a mode number of $8/4$ emerged outside the LCFS and then were enveloped by the LCFS. We observed an increase in the volume of the confined region corresponding to the expansion of LCFS and its enveloping of external magnetic islands, which is a preferable feature for better confinement of a helical fusion device. In principle, the volume of each island and stochastic region can be assessed quantitively for various configurations using this method.

4. Fluctuation and turbulence study in High-confinement mode (H-mode)

The high-confinement mode (H-mode) is essential for improving the energy confinement time and is crucial for achieving fusion energy. However, compared to tokamaks, the achievable energy confinement improvement in stellarators/heliotrons is limited (~30%). Therefore, we investigate fluctuations and edge cross-field transport during the H-mode transition in Heliotron J. The experiment is conducted in the so-called n/m = 4/9 configuration, which is a favorable magnetic configuration for the H-mode transition. During the H-mode transition, we observe a characteristic low-frequency (LF) fluctuation with a frequency of approximately 14 kHz in several fluctuation diagnostics. As shown in Fig. 4, the LF fluctuation extends over a long radial range and correlates with the edge cross-field transport. The LF fluctuation also modulates the micro-scale density turbulence in the edge region, which is measured by Doppler reflectometry. At the H-mode transition, the edge density turbulence is reduced in association with the enhancement of the radial electric field. Additionally, the modulation of the turbulence amplitude by the LF fluctuation is suppressed, and the edge cross-field transport induced by the LF fluctuation is reduced, which is confirmed by the Dα emission and divertor probes. On the other hand, the LF fluctuation itself persists after the H-mode transition, as detected by the electron cyclotron emissions, magnetic probes, and edge poloidal rotations. This indicates that the coupling between the LF fluctuation and turbulence plays a significant role in the edge transport driven by the LF fluctuation. Although the precise identification of the LF fluctuation remains unresolved and is left for future work, one possible candidate is pressure-driven MHD instability.

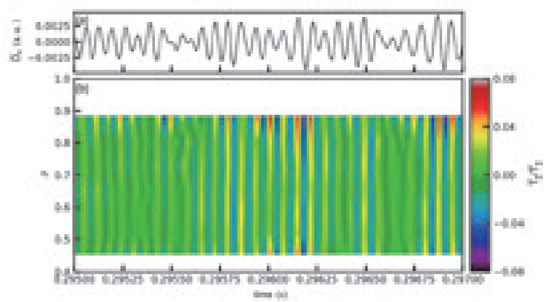

Fig. 4 Spatio-temporal evolution of low-frequency fluctuation. (a) Dα emission indicating the edge transport, and (b) radially elongated temperature fluctuation.

Collaboration Works

長﨑百伸，小林進二，稲垣滋，門信一郎，金史良，Univ. Wisconsin（アメリカ）, Oak Ridge National Laboratory（アメリカ）, Max Plank Institute（ドイツ）, Stuttgart Univ（ドイツ）, CIEMAT（スペイン）, Australian National Univ.,（オーストラリア）, Kharkov Institute（ウクライナ）, Southwest Institute of Physics（中華人民共和国），先進ヘリカルシステムにおける周辺プラズマ・ダイバータ研究

長﨑百伸，小林進二，稲垣滋，門信一郎，金史良，Wisconsin University（米国）, CIEMAT（スペイン）, Max-Plank Institute（ドイツ），先進ヘリカルシステムにおける周辺揺動解析

長﨑百伸，大島慎介，小林進二，稲垣滋，門信一郎，金史良, Stuttgart Univ., CIEMAT, 先進ヘリカル磁場配位の最適化に向けたネットワーク拠点形成

小林進二，長﨑百伸，稲垣滋，門信一郎，金史良，CIEMAT（スペイン）, Kurchatov Institute（ロシア）, ORNL（アメリカ），先進ヘリカル磁場配位の最適化に向けたネットワーク拠点形成

稲垣滋，核融合科学研究所・双方向型共同研究，高分解共焦点マイクロ波反射計の開発

稲垣滋，核融合科学研究所・双方向型共同研究, 2 次元画像計測を使った MHD 不安定性研究

稲垣滋，核融合科学研究所・双方向型共同研究，電磁的な突発揺動発生に関するモデリング

稲垣滋，核融合科学研究所・双方向型共同研究，ヘリオトロン J における壁コンディショニング研究

門信一郎，核融合科学研究所・双方向型共同研究，ダイバータを模擬した定常プラズマへのガス入射に対する発光過程の応答

門信一郎，核融合科学研究所・双方向型共同研究，磁場分布制御を活用したプラズマ構造形成制御とプラズマ輸送改善

門信一郎，核融合科学研究所・双方向型共同研究，ドレスト重水素原子輝線スペクトルを用いたプラズマ中のマイクロ波電場計測

門信一郎，核融合科学研究所・双方向型共同研究，ヘリオトロン J における EUV 分光を用いた不純物発光線強度比データの蓄積

門信一郎，核融合科学研究所・双方向型共同研究，高速カメラによるペレット溶発雲の 2 次元分光

門信一郎，核融合科学研究所・双方向型共同研究，実用炉用熱流束計測システムの精度向上のための基礎研究

門信一郎，核融合科学研究所・双方向型共同研究，Heliotron J の磁場構造が不純物輸送に及ぼす影響に関する数値モデル研究

門信一郎，京都大学 × 堀場製作所包括連携協定「HONMAMON（ほんまもん）共創研究」，フュージョンエネルギー確立を目指したプラズマ発光の可視化に関する研究

金史良，核融合科学研究所・双方向型共同研究，電子内部輸送障壁に対する磁場の三次元効果の解明

金史良，核融合科学研究所・双方向型共同研究，高エネルギー粒子駆動モードと背景乱流の相互作用

金史良，核融合科学研究所・一般共同研究，核燃焼プラズマに向けたトーラスプラズマの閉じ込め・輸送に関する研究

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1. Grant-in-Aid for Scientific Research
金史良，若手研究，磁場閉じ込めプラズマにおける雪崩輸送の計測法の開発

2. Others
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