S6－4 Flows and Structural Formation in Macroscopic Fusion Plasma

マクロな核融合プラズマにおける流れと構造形成

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In a research field of toroidal plasmas, it is an interesting finding that the structure is able to bifurcate. Examples include H-mode, internal transport barriers, and the other improved confinement modes. Intensive studies of the phenomena over two decades have revealed that the bifurcation can be caused by nonlinearity of perpendicular flow (or radial electric field), an interplay between the flow and turbulence. This paper presents structural bifurcation that has been observed in CHS as a good example to show structural bifurcation and a role of flow (or electric field) in structural formation. In addition, a CHS experiment to identify zonal flow -another substantial player in the structural formation in toroidal plasmas- is introduced.

1. Introduction

In toroidal plasmas, turbulence is driven by gradients in thermal variables, while the gradients are determined by the turbulence-driven transports. Therefore, the structure of the toroidal plasmas is governed by turbulence, and the research of turbulence property is one of the key issues for the structure formation of the plasma.

The research of improved confinement modes over more than two decades has revealed that the turbulence can be regulated by shear of flow (or *radial electric field*) spontaneously generated in the plasma. Note that the radial electric field is connected with the plasma flow through ExB drift in magnetically confined plasmas. Nonlinear property of electric field itself can produce sufficient shear to reduce plasma turbulence. Besides, turbulent Reynolds stress can be a mechanism to generate plasma flow and its shear [1].

Recently, a new member, zonal flow [2], comes into this community to determine the plasma transport. The nonlinear links or interactions between these members (e.g., turbulence, zonal flows, mean flows, thermal variables, and so on) are considered to make plasma structure bifurcate and produce a number of interesting structures in toroidal plasmas.

The paper introduces i) the bifurcation phenomena in CHS as an example [3], ii) the relationship between flow, turbulence and structure iii) the CHS experiment on the first identification of zonal flow, and iv) several remaining problems of structural formation of toroidal plasmas.

2. **Structural Bifurcation in Toroidal Plasmas**

A number of improved confinement modes have identified in toroidal plasmas, such as H-mode, VH-mode, revised shear modes, RI-mode and so on. Many of the improved confinement modes show the bifurcation characteristics deeply associated with the bifurcation characteristics of radial electric field. In particular, neoclassical theories have expected that the radial electric field should have bifurcation properties in toroidal helical plasmas.

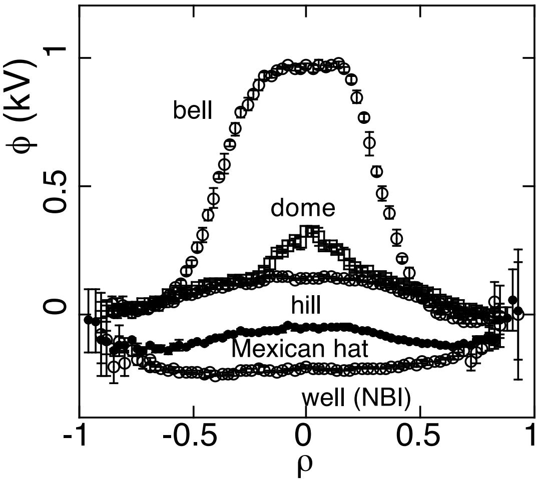

Fig. 1. Characteristic patterns of the CHS potential profile. In dome and bell patterns, the transport barrier is created at the radius where discrete change of the gradient (or electric field) occurs

In fact, potential profile in CHS helical device shows bifurcation properties caused by the neoclassical theories. As is shown in Fig. 1, five representative patterns have been identified in CHS; well, Mexican-hat, hill, dome and bell. In these patterns, the three patterns of hill, dome and bell clearly shows bifurcation characteristics, and transport barrier formation are confirmed at the radial positions where the strong electric field shear exist; the normalized radius of ~0.3 and ~0.6 for dome and bell patterns, respectively. Repetitive transitions between these three states, dubbed *electric pulsation*, have been observed to demonstrate the bifurcation nature.

3. Relationship between Flows and Turbulence and electric field shear generation

A number of experiments have indicated that sufficiently large electric field shear should suppress the plasma turbulence and form transport barriers. According to theories, the radial electric field shear can be related to the fluctuation amplitude or transport coefficient as follows,

$$D \propto \frac{D_L}{1+\beta(dE/dr)^{\alpha}},$$

where dE/dr is radial electric field shear. Then, the investigation of barrier formation is focused on the generation mechanism for radial electric field shear. For the two patterns in CHS, dome and bell, the fluctuation reduction has been confirmed in the E_r-shear layer experimentally.

In the formation of the internal transport barriers (ITBs) of CHS (bell and dome), the scenario of the structural bifurcation is as follows. First, radial electric field at a radial position can bifurcate owing to neoclassical property, and E_r-shear is formed between the regions belonging to the two different E_r-branches. Then, the created E_r-shear reduces the fluctuation and the fluctuation-driven transport at the shear layer. A transport barrier is formed at the E_r-shear layer. This *scenario* is exactly the concepet initially proposed for H-mode transition.

4. Presence of Zonal Flows in a Toroidal Plasma

In theories and simulations, the zonal flow has attracted attention as an element to determine the turbulence level and transport. However, the zonal flow has not been identified in experiments.

The zonal flow is a rapidly varying radial structure with poloidal and toroidal symmetry (m=n=0). Therefore, one of the essential points for zonal flow identification is to find fluctuation of flow or radial electric field with a long-range correlation. Its presence has been recently have confirmed for the first time with dual HIBPs in CHS.

The system has found the existence of electric field fluctuation (f< ~1 kHz) which shows long-distance correlation in low frequency range, as is shown in Fig. 2. The confirmed zonal flow has characteristic radial length of ~1.5 cm and life time of ~1.5 ms. This observation leads to the fact that a meso-scale structure should interfuse into the time-averaged potential structure. The experimental confirmation of the zonal flow substantiates a new paradigm that zonal flow and turbulence should be a system to determine the plasma transport.

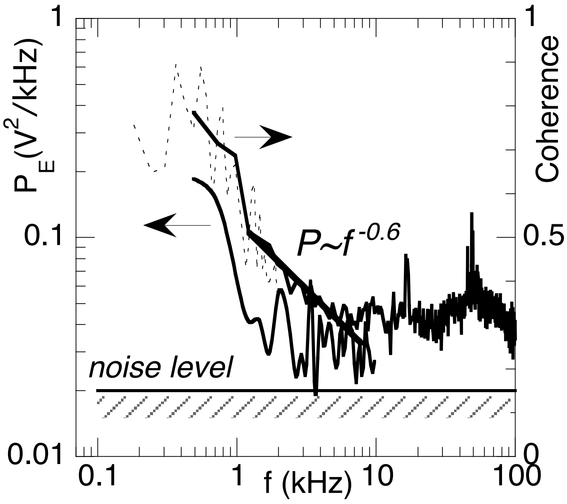

Fig. 2: Power spectrum and coherence of electric field fluctuations in two toroidal locations in CHS.

5. Remaining Problems for Structural Formation in Toroidal Plasmas

The formation mechanisms of ITBs in toroidal helical devices are rather clear, as is seen in the CHS case. However, a number of unsolved problems remain for structural bifurcation for the other improved confinement modes, such as H-mode. Although the E_r-shear effect on the transport reduction is involved in H-mode or edge transport barrier (ETB) formation, a number of processes are expected to be associated with E_r-shear generation for ETBs, such as parallel viscosity, turbulent Reynolds stress, neutral drag, and so on.

Even in L-mode structure, many intriguing phenomena are still unsolved in the physics mechanisms, such as non-local nature of transport. In other words, a change happening at a local point can propagate to another point in a much faster timescale than the diffusive one. A possible candidate to explain the non-local nature could be nonlinear interactions between different scale fluctuations.

In summary, investigation of turbulence in terms of mulit-scale ranges is essential for further understanding of structural formation in toroidal plasmas, as well as E_r-generation mechanisms to regulate and bifurcate the turbulence characteristics.

References

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