

Development of new analyzing methods of plasma movement for imaging diagnostics and their applications to a linear magnetized plasma

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<https://hdl.handle.net/2324/7182515>

出版情報 : Kyushu University, 2023, 博士 (理学), 課程博士
バージョン :
権利関係 :



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Name

論 文 名 : Development of new analyzing methods of plasma movement for imaging diagnostics
and their applications to a linear magnetized plasma
(イメージング計測における新規プラズマ運動解析法の開発と直線磁化プラズマへの応用)

Title

区 分 : 甲

Category

論 文 内 容 の 要 旨

Thesis Summary

Research and development of magnetically confined plasma is being conducted worldwide toward realizing a fusion reactor. In magnetically confined plasma, a steep pressure gradient is formed, and turbulence develops due to various instabilities, such as drift wave instability. Heat and particle transport by turbulence is much larger than collisional transport and determines the confinement performance. Therefore, understanding the physical mechanisms of turbulence and its transport is required to realize an economical fusion reactor. Recent advances in observation techniques have revealed that in magnetically confined plasmas, microscopic fluctuations generate mesoscale structures such as zonal flows, streamers, as well macroscopic modes. It is well known that the interaction of these different-scale fluctuations strongly impacts structure formation and dynamics; therefore, measuring turbulence across the entire plasma cross-section is necessary to understand these phenomena. For the above reasons, imaging diagnostics for fluctuations, such as Beam Emission Spectroscopy (BES) and Electron Cyclotron Emission Imaging (ECEI), have been developed. Moreover, the methods for estimating plasma velocity and turbulence fields using these imaging diagnostics are also proposed. In the linear device PANTA, the turbulence tomography system has succeeded in observing the turbulence across the entire plasma cross-section. Tomography is a conventional tool to observe macroscopic saw tooth oscillations and collapse phenomena in magnetically confined plasma research. In addition, analysis methods for tomography images, such as Fourier rectangular function (FRF) expansion, have been developed.

In this study, new methods were developed for quantifying plasma fluctuations and movement from the plasma images, and these methods were applied to the tomography data of PANTA plasma to quantify the spatial structure and dynamics of fluctuations and verify these methods. First, based on the existing FRF expansion and Fourier analysis, a method to characterize the plasma rotation by decomposing the plasma fluctuations into azimuthal modes was proposed, capturing the rotation of each mode as polarization by analogy with optics, dividing it into circular, linear, and random states, and evaluating their power as a function of radius. By applying this method to tomography data, it was shown that the fluctuation characteristics of the individual azimuthal mode can be quantified as differences in the rotational state and that the addition of a random component to the rotational and standing wave components causes intermittent changes of the fluctuation amplitude due to changes of their phase relationship. Second, the methods for estimating the plasma velocity from the evolution of two-dimensional patterns were developed. One of the methods, called rotational movement analysis (RoMA), which evaluates the azimuthally averaged rotational velocity of the plasma (pattern) from changes in

the one-dimensional fluctuation pattern expanded by FRF, is developed. The method was applied to a plasma with a stationary rotation pattern to demonstrate the validity and confirmed that the estimated rotational velocity reflects the propagation velocity of fluctuations, and that the spectrum of the rotational velocity fluctuation has a peak at a specific frequency, indicating that the rotational velocity is modulated. The method for evaluating the error in estimated value caused by noise is also established. Moreover, RoMA is extended to two-dimensional velocity field estimation using the differential form of two mother functions. This method can estimate the two-dimensional velocity field continuously using the Fourier-Bessel function (FBF) expansion. The method was compared with the RoMA results, confirming that the average rotational velocity agreed well. On the other hand, the azimuthal asymmetry was observed in the local time-averaged velocity. For further validation, the method to evaluate the estimation error was established and showed that the observed asymmetry was larger than the estimation error.

The above developed methods were applied to a plasma with repeated transitions between two states, and significant analysis results were obtained, including the identification of the rotational state and rotational velocity as they change with the transitions and the causal relationship between the background structure of the plasma and the fluctuation state transition.

This thesis is organized as follows. Chapter 1 introduces a modern picture of plasma turbulence in magnetically confined plasmas and describes the necessity for turbulence tomography and the purpose of this study. Chapter 2 describes the details of the experimental setup and tomography system used in this study. Chapter 3 introduces the spectral analysis method used in this study, the reconstruction method for tomography images, and existing image analysis methods. Chapter 4 describes the newly developed method of modal polarization analysis and the results of its application. Chapter 5 describes the method for estimating rotational velocity using FRF expansion and the results of its application, the two-dimensional estimation method and its application results, and a comparison of the two methods. Chapter 6 reports the analysis results of transition phenomena using the developed methods. Chapter 7 summarizes the results.

In summary, this thesis proposes new analyzing methods to quantify the dynamics of fluctuations from plasma images: the modal polarization analysis and the velocity field estimation method. The modal polarization analysis can quantify the rotation state locally; the result shows that the evolution of fluctuation amplitude can be interpreted based on the rotation state. The velocity field estimation method suggests modulation of rotational velocity and spatial asymmetry of the velocity field. The analysis methods developed in this thesis are expected to contribute to understanding the structure formation and dynamics of plasma turbulence.