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論文の要旨

Summary (Abstract) of doctoral thesis contents

One of the most important subjects among researches on the magnetic fusion plasma is improvement of confinement property and stability of the plasma to realize an economical and safe burning fusion reactor. Much effort has been devoted to research of micro turbulence and MHD instability, and the understanding on plasma physics has been deepened over the decades. On the other hand, the turbulence appears electrostatic and different frequency or wave number range from MHD instabilities or behavior of magnetic flux surface, then studies on interactions of those two phenomena had been relatively scare. Recently, researches in a boundary region of turbulence and MHD activity is beginning to be accumulated experimentally, such as a discovery of the long-range correlation in LHD and the coupling between the transport and magnetic topology in DIII-D.

Non-linear coupling between MHD instability and low-k turbulence in toroidal plasmas is studied using by measuring the density fluctuations using Beam Emission Spectroscopy (BES). This work focuses on the Edge Harmonic Oscillation (EHO), which appears as a coherent mode at the frequency of about 10 kHz accompanied by several harmonics near the separatrix. This dissertation is composed of two parts, one of which includes the development and evaluation of the capability of BES system with specially designed sightlines in the Large Helical Device (LHD) as well as the spatio-temporal structure analysis of EHOs measured with the BES, and the other includes analysis on the non-linear coupling between EHO and turbulence measured in DIII-D tokamak.

A local density fluctuation diagnostic based upon the BES with lattice type optics configuration has been implemented on LHD to investigate the spatiotemporal and spectral characteristics of long wavenumber density fluctuations such as MHD activity. In most conventional BES systems, fiber images have round or rectangular shapes due to the configuration of fiber bundles, leading to the almost same wavenumber resolution in two directions on a focal plane. The unique optical fiber geometry which yields a lattice shaped sampling images in a plasma is applied in this system. The idea of the new lattice type fiber configuration is that utilizing the fiber bundle design that the images of fibers align along radial or poloidal direction to achieve both enhancement of photon flux and good wavenumber resolution in a particular direction. With vertically elongated slits, the sensitivity for waves in the radial direction increases, although that for waves in the poloidal direction decreases. In order to complement this reduced poloidal wavenumber resolution, another sets of horizontally elongated slits is deployed, forming lattice structure. As a probe beam, a perpendicularly injected neutral heating beam is used, and its accelerating energy is

typically 40 keV. The angle between the sight lines and the beam line is ~120° at the edge of the plasma, yielding a Doppler blue shift of ~3.0 nm in the Hαbeam emission. Each channel consists of 7 (or 8) 400-nm-diam fibers arranged in line along poloidal or radial direction. Each fiber bundle of an array for radial wavenumber measurement images 10 x 140 mm and has a radial spatial separation of 10 mm. Each fiber bundle of an array for poloidal wavenumber measurement images 70 x 10 mm and has a poloidal spatial separation of 20 mm. These two arrays are overlaid in a same region to form a lattice configuration and views 70 x 140 mm in total. The array for radial wavenumber measurement averages the signals for 140 mm in poloidal direction, while that for poloidal wavenumber measurement averages for 70 mm in radial direction. The collected light is transmitted to a spectrometer and is detected simultaneously with the 4 x 8 pixel avalanche photodiode camera with a sampling frequency of 200 kHz. Correlation analysis was applied to reconstruct the two-dimensional spatiotemporal structure of MHD activities detected in the edge region in high- ß discharge. The spatiotemporal structure of the low frequency density fluctuation of EHO was found to propagate in the electron diamagnetic direction at the phase velocity of 1.2 km/s, and have a finite radial propagation with the phase velocity of 0.4 km/s.

The coupling between the high frequency turbulence and EHO is studied in Quiescent H-mode plasmas, where EHOs exist, in DIII-D tokamak. QH-mode is an ELM-free operation with good energy confinement, constant density, and radiated power, with a pedestal localized electromagnetic mode (EHO) providing continuous particle transport. The nonlinear interaction between harmonics of the EHO and turbulence is important to understanding the mechanisms and dynamics of enhanced particle transport in QH-mode. The fundamental frequency of the EHO was typically ~10 kHz with long poloidal wavelength (k_θ~0.02 cm^{-1}) and broadband turbulence in the range of 50–200 kHz with correlation lengths of a few cm. The features and characteristics of QH-mode plasma turbulence in the wavenumber-frequency domain are crucial to understanding the mechanisms and dynamics of the enhanced particle transport. Frequency-wavenumber spectral analysis was applied to localized density fluctuation data measured with BES on DIII-D in the region of $0.8<\rho<1.0$, where ρ is the normalized minor radius. In the analysis, a Maximum Entropy Method is applied in the space domain, instead of FFT, to estimate a well resolved k-spectrum from truncated data. The broadband turbulence measured at ρ~0.9 was found to have poloidal phase velocity of ~10 km/s, which corresponds to the ExB velocity. Bispectral analysis has been applied to the localized density fluctuation data. The cross-bicoherence among the BES channels showed radially varying magnitude of phase coherence well above the noise floor between the EHO and broadband turbulence in the region of $0.8<\rho<1.0$. The envelope analysis is done for the high frequency turbulence by applying Hilbert transform to the density fluctuation data. It was found that the turbulence amplitude was modulated at the frequency of EHO. The phase and amplitude of the turbulence envelope is not constant in time, and different from the displacement of the magnetic flux surface.

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博士論文審査結果の要旨

Summary of the results of the doctoral thesis screening

　磁場閉じ込めプラズマにおいて乱流がプラズマの輸送を決定していること、及びプラズマの圧力勾配が増加するとMHD（電磁流体力学）不安定性によってプラズマ中に振動が発生し、閉じ込めを悪化させせることはよく知られている。しかしながら、時空間スケールの異なる乱流揺動とMHD振動では一般に計測法が異なるため､両者の結合についての研究はほとんどなされていない。そこで出願者はビーム放射分光が両者の有力な計測となることに着眼し、研究を進めた。ビーム放射分光法はプラズマ中に入射された中性粒子ビーム原子とプラズマとの衝突による励起に伴う光の強度の揺らぎからプラズマ中の密度揺動を計測する手法であり､MHD振動に起因する数kHzから数十kHzの密度揺動と静電乱流揺動に起因する数十kHzから数百kHzの密度揺動を同地点で同時に計測することができる。本論文では､MHD振動と乱流揺動の同時計測が可能なビーム放射分光法を用い、核融合科学研究所の大型ヘリカル装置(LHD)と米国ジェネラルアトミックス社のDIII-Dトカマクにおいて境界層高調波振動と呼ばれるMHD振動と乱流揺動との結合を調べた結果について述べている。

　まず、LHDにおいて、ビーム放射分光の視線を高度化し、ポロイダル方向及び径方向の2次元での密度揺動の観測を行った。ビーム放射分光の視線を通常の円形からスリット形状に変更してさらに格子状に配置することでポロイダル方向及び径方向の波数分解能を改善させ、境界層高調波振動による2次元密度揺動構造を初めて明らかにした。従来、径方向には伝播しないと考えられていた境界層高調波振動に密度揺動の径方向伝播が存在することを明らかにし、ポロイダル方向及び径方向の伝播速度の比を評価した。DIII-Dトカマクにおいても同様の解析を行い、境界層高調波振動に伴う密度揺動の径方向伝播の存在を確かめた。磁場配位の異なるトカマクプラズマとヘリカルプラズマで同様の結果が得られたことは、境界層高調波振動の径方向伝播の普遍性を示唆している。

　さらにLHDで開発した解析手法を発展させて､DIII-Dトカマクでビーム放射分光計測による乱流揺動と境界層高調波振動との結合に関する研究を行った。乱流揺動強度が境界層高調波振動発生時に増大することを見出した後、密度揺動のポロイダル波数-周波数の2次元スペクトル解析において、空間方向に最大エントロピー法を採用し、伝播方向と周波数帯域が異なる二つの乱流揺動成分が同時に存在することを明らかにした。次に、同定した二つの乱流揺動成分のうち境界層高調波振動と帯域が大きくことなる成分についてバイコヒーレンス解析と包絡線解析を行い、１）有意なバイコヒーレンスが存在すること、２）乱流揺動成分の包絡線の「振幅と位相」と磁気面の移動による電子温度の時間変化の「振幅と位相」が異なることを見いだした。これらの結果は、乱流揺動と境界層高調波振動との有限バイコヒーレンスが､MHD的な振動による磁気面の振動ではなく､乱流揺動とMHD振動との間の非線形結合によって生じていることを示している。

　この研究成果は時空間スケールの異なる乱流揺動と MHD 振動の一種である境界層高調波振動との結合を実験的に初めて明らかにしたもので、その学術的意義は高い。境界層高調波振動は、核融合炉壁の損傷を引き起こす周辺局在モードを抑制する効果を持っている

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為に、将来の核融合炉において積極的に利用される MHD 振動と考えられる。従って、境界層高調波振動が乱流揺動と結合して、どの程度プラズマの輸送を変化させるかを評価することは極めて重要であることからも、本論文による知見は核融合研究の進展に貢献するものである。よって本論文の内容は学位（理学）の授与に十分値すると判断した。