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学位（専攻分野）	博士（理学）
学 位 記 番 号	総研大 1278 号
学位授与の日付	平成２１年９月３０日
学位授与の要件	物理科学研究科　核融合科学専攻 学位規則第６条第１項該当
学 位 論 文 題 目	Study of turbulence in a reversed field pinch plasma by microwave imaging reflectometry
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論文内容の要旨

The physics of turbulence is a key to understand the plasma confinement. In the reversed-field pinch (RFP) plasma, turbulence plays an important role to sustain the RFP configuration. However, the experimental study of the turbulence is not sufficient especially around the field reversal surface in the case of RFP plasma. Microwave imaging reflectometry (MIR) is expected to be a powerful tool for the turbulence measurement, because it provides the direct view of the 2D/3D image of the turbulence near the cutoff surface deeply into plasma. However, the turbulence study by using MIR has not been reported yet. This work presents the turbulence measurement around the reversal field surface in a large RFP device TPE-RX by using MIR.

In RFP, the reversed toroidal field in the edge region is sustained by the dynamo, which is driven by instabilities and turbulence. RFP also has an MHD turbulence suppression technique: the pulsed poloidal current drive (PPCD) operation. The MHD dynamo theory predicts that the fluctuations in the flow ($\tilde{v}$) and the magnetic field ($\tilde{B}$) form the equilibrium electromotive force (EMF) $<\tilde{v}\times\tilde{B}>_{\parallel}$, where || denotes parallel to the magnetic field (it is poloidal at the reversal surface). Without PPCD operation, the ohm's law is written as: $\eta J_{\parallel} =<\tilde{v}\times\tilde{B}>_{\parallel}$. The dynamo $<\tilde{v}\times\tilde{B}>_{\parallel}$ can drive the poloidal current, which generates the reversed toroidal field. The PPCD operation generates the external electric field $E_{\parallel}$. In this case, the ohm's law is written as $\eta J_{\parallel} = E_{\parallel} + <\tilde{v}\times\tilde{B}>_{\parallel}$. The poloidal current is directly driven by $E_{\parallel}$ without the help of the dynamo. As a result, the fluctuations in the PPCD plasma may be suppressed. So far various candidates for the RFP turbulence have been discussed: tearing instabilities, interchange instabilities and drift wave turbulence. Nevertheless, a definitive explanation still lacks. Therefore, comparison the turbulence around the field reversal surface between plasmas with PPCD and without PPCD may clarify the turbulence physics in the RFP plasma.

MIR is one of the new diagnostics to measure the 2D/3D density fluctuations. It is based on the microwave reflection at the density-dependent cutoff surface. MIR signal can be written as $Ae^{i\phi}$, where A is the amplitude and ϕ is the phase. The amplitude A is measured by a diode detector. The phase is measured by a quadrature (IQ) detector, as $\phi = \arctan(Q/I)$, where $I = \cos\phi$, and $Q = \sin\phi$. In order to investigate the principles of MIR measurement, comparison between the simulation and a laboratory test of the MIR system has been carried out. The numerical model based on the Huygens-Fresnel equation is used to simulate the MIR signal. In this test, we found that ϕ corresponds to the displacement of the cutoff surface in the radial direction, and A corresponds to the reflection power, which is modulated by the shape of the cutoff surface. From the simulation and laboratory test, MIR is valid with the condition *4k□L/D<1* to measure the motion of the cutoff surface. Here D is the diameter of the optical lens. L is the distance between the cutoff surface and the optical lens. k and □ are the perpendicular wavenumber and the radial displacement of the fluctuation, respectively. The measured fluctuations in TPE-RX plasmas mainly distribute in the range of *4k□L/D*<0.8 which suggests the present MIR system can make a clear image of the cutoff surface in plasma.

TPE-RX is one of the world largest RFP devices, which was built in National Institute of Advanced Industrial Science and Technology (AIST), Tsukuba, Japan, and it has the major and the minor radii of R=1.72m and a=0.45m, respectively. All discharges in this work have the plasma density in the range of (0.5~1.0)×10^{19} m^{-3} and the plasma current in the range of 200~300 kA. In order to measure the density fluctuations around the reversal surface (r/a=0.7~0.9) in TPE-RX, we have developed a MIR system with the microwave frequency of 20 GHz (O-mode, the cutoff density is 0.5×$10^{19}$$m^{-3}$) and a 4 × 4 Yagi-Uda antenna array. In this system, the spatial resolution is 3.7 cm and the temporal resolution is 1□s.

Analysis techniques, which have been developed to study the turbulence in this work, are as follows: (1) the cross correlation, (2) the wavelet, (3) the maximum entropy method (MEM), (4) the fluctuation distributions (skewness and kurtosis), and (5) the bicoherence. The skewness and kurtosis are used to quantify the distribution of the fluctuations. By using wavelet analysis, the short-lived turbulent structures can be observed. The wavelet bicoherence is used to quantify the nonlinear interaction. The maximum entropy method (MEM) is useful to estimate the high resolution 2D k spectrum.

The observed features of the RFP turbulence around the field reversal surface in this work are as follows:

(1) In the low k and the low frequency ranges, the MIR signal has a high correlation with the magnetic fluctuations. Without PPCD operation, the m=0 tearing modes (may be dynamo) are dominant. On the other hand, the m=1 tearing modes are dominant in the PPCD plasma.

(2) In the high k and the high frequency ranges, MIR signal has a high correlation with the electrostatic fluctuations measured by the Langmuir probe. The k spectrum is broad and is shifted in the electron drift direction in the plasma without PPCD. The high nonlinear coupling between the high k modes and the low k modes is observed. While in the PPCD plasma, the high k mode has not been observed.

(3) The intermittency is increased as the reversal parameter $|F|$ is increased in the case of without PPCD. (Note: the reversal parameter $F = B_t(a)/\langle B_t \rangle$ can be used to identify the strength of the dynamo as the reversed toroidal field $B_t(a)$ is mainly sustained by the dynamo. The deep F plasma corresponds to the strong dynamo.) The intermittency corresponds to the bursts of the negative spikes in MIR signal, which has a small-scale structure with high fluctuation amplitude. In the PPCD plasma, the intermittency is not observed and the confinement is improved as the soft-X-ray is increased by the factor of 100.

The fluctuations around the field reversal surface are probably caused by the resistive interchange instabilities, because the high frequency fluctuations have the features of electrostatic turbulence, while the low frequency fluctuations are dominated by the low k tearing modes. The high nonlinear coupling between the high k modes and the low k modes in the plasma without PPCD suggests that the dynamo and the electrostatic-like turbulence are correlated. The high intermittency at deep F plasma is expected to be partly driven by the nonlinear interaction between electrostatic-like turbulence. Simulation of MIR signal suggests that the intermittency in MIR signal is caused by the blob structure, which scatters the reflected wave and leads to the rapid decrease of the reflected power (negative spike). This enhances the transport and decreases the confinement.

In conclusion, this work is the first demonstration of MIR as the turbulence diagnostics. This is the fi rst observation of the turbulence around the field reversal surface in RFP plasma. This work demonstrat es how the dynamo and intermittent structures cause bad confinement.

博士論文の審査結果の要旨

近年，プラズマ内部の局所的乱流計測器としてマイクロ波イメージング反射計（MIR）が注目されている。これはマイクロ波をプラズマに照射し，プラズマのカットオフ現象により反射するマイクロ波を２次元検出器上に結像することで反射面の揺動（すなわち密度揺動）を観測するものである。他方，逆転磁場ピンチ（RFP）配位は乱流を駆動源とするダイナモ効果により維持されていると考えられているにもかかわらず，従来，プラズマ内部の乱流計測は不十分であった。本学位論文は，２次元 MIR 揺動計測法の開発を行い，これを用いて世界最大級の RFP 装置 TPE-RX（産業技術総合研究所）において揺動計測を行ない，磁場反転面近傍での乱流現象の解明に挑んだものである。

本論文では，はじめにプラズマでのカットオフ面の揺らぎを模擬する波状の金属反射面からのマイクロ波反射信号を，計算機でのシミュレーションとテストベンチでの実験を比較することにより，MIR 計測信号と揺動との関係を明確にしている。乱流は時間的にも空間的にも短い波の重ね合わせであるため通常のフーリエ解析では分解能が不十分であることから，ウェーブレット解析，バイスペクトル解析，最大エントロピー法（MEM），統計（Skewness/Kurtosis）解析などの乱流データ解析法を MIR 信号解析に取り入れている。とくに，振幅信号 A と位相信号 ϕ とを複素信号 $A\exp(i\phi)$ としてまとめて解析することの重要性を示したことは MIR 計測上有用な知見である。

TPE-RX では外部からのパルスポロイダル電流駆動（PPCD）により内部的なダイナモ効果なしで反転磁場配位を維持できる。PPCD を利用しない場合と比較してプラズマの閉じ込めが劇的に改善し，軟 X 線信号は２桁以上増加する。そこで本論文では外部的な配位維持の有無が RFP の乱流現象にどのような影響を与えるかを明らかにするために，20GHz の MIR 計測と上記の解析手法を駆使し，さらにプラズマ端部で測定した静電揺動や磁場揺動のデータとも相関解析を行うことで磁場反転面近傍での乱流現象を調べている。

その結果，PPCD 有り無しでは MIR 信号振幅は変わらないが，揺動のモード特性等が全く異なることが示された。PPCD 無しの RFP 運転では，頻繁に観測される間欠的信号がダイナモに起因すること，そして間欠的 MIR 信号波形が尖った反射面すなわち密度の吐き出し現象に対応することを見出した。更に，高周波（200－400kHz）・高波数（トロイダルモード数：n～70）の静電的不安定性がダイナモを駆動する低周波・低波数の MHD 揺動と強い非線形結合をおこすことも初めて見出した。これに対し PPCD 運転ではダイナモも静電的不安定性も抑制され，閉じ込め改善が達成されている。

これらの成果は，MIR 計測が乱流観測法として極めて有用であることを初めて実証し，これを用いて RFP プラズマにおける磁場反転面近傍での乱流構造を観測し，反転磁場配位の維持機構と乱流との関係を明確にしたものである。本論文はプラズマの乱流研究に新たな展望を開くものと高く評価できる。

よって，本審査委員会はこれらの成果と当該分野への貢献の程度から判断し，本論文が学位論文としてふさわしい学術内容を持っていると認めた。