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学位論文題目 Heavy Ion Beam Diagnostic of MHD Instabilities

in the Compact Helical System

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## 論文内容の要旨

The heliotron/torsatron devices are regarded as an attractive candidate for a fusion reactor because of their steady state operation without inductive plasma currents. In these devices, major disruptions induced by current driven instabilities can be avoided. However, they are susceptible to pressure driven instabilities such as interchange modes and ballooning modes, which limit high- $\beta$  operation. Recent theoretical study suggests that such instabilities also contribute to enhance anomalous transport and deteriorate the confinement. In the Compact Helical System (CHS), magnetic fluctuations have been studied by the use of poloidal and toroidal arrays of magnetic probes. It has been found that the fluctuation modes depend on magnetic configuration, beta value, direction of beam induced current during NBI heating (which can change the magnetic shear), and so on. Among these fluctuations, periodic, burst type  $m/n=2/1$  ( $m$ : poloidal mode number,  $n$ : toroidal mode number) modes observed in a low- $\beta$ , NBI (co-injected) plasma have shown the strongest activity.

The oscillations appear periodically, typically every 4 milliseconds, and their frequency generally decreases from 40kHz to 15kHz during a growing phase. The mode is considered to be an interchange instability. However, the mode, propagating initially in the ion diamagnetic drift direction, reverses the direction (to the electron diamagnetic drift direction) in the decaying phase. In addition, the role of the magnetic fluctuations on confinement has not been clarified yet. Local and direct measurements of the internal structure is necessary for further investigation.

We have applied the heavy ion beam probe (HIBP) for the first time to measure MHD instabilities in helical systems. The HIBP is a unique and powerful technique which can directly measure the electric potential and its fluctuations in high temperature plasmas. It has been successfully applied to tokamaks, mirrors and bumpy tori in which toroidal field component is dominant on the beam path and the beam trajectories are basically two dimensional in the same poloidal plane. First application of HIBP to a helical device was done in the ATF torsatron, but only preliminary data have been reported. HIBP measurements in helical devices are not so simple as in tokamaks because of its three dimensional beam trajectories.

The CHS HIBP has two sets of beam deflectors to control the primary and secondary ion beams independently so that the injection angle of the secondary beam into the energy analyzer is kept constant during a radial scan. This method makes the observation area wider and improve accuracy in determining a plasma potential. Because an observation point is determined by the combination of four deflector voltages, it is inevitably sensitive to the accuracy of beam line alignment and fringing field of the deflectors. Experimental calibration is necessary to verify the accuracy of the total system. A movable detector and a gas ionization method have been applied to calibrate the beam trajectory and observation points. Sets of deflector voltages to observe locations along a radial scan line were experimentally obtained. The results agree well with the calculation. The movable detector is also used to optimize the focusing condition of the primary beam in the plasma region. Total calibration procedures with these methods have been successfully carried out.

In applying HIBP to measure the local space potential and its fluctuations during MHD activities, various non local effects (path integral effects along the beam trajectories) have to be examined. The effects of beam deflection and acceleration (or deceleration), which are caused by the fluctuating vector potential, on local potential fluctuation measurements are evaluated using the experimental data from HIBP and magnetic probes. By taking those effects into account, the radial structures of the  $m/n = 2/1$  burst type MHD oscillation have been derived. The potential fluctuation has a strong peak around the  $q = 2$  surface in the growing phase and its amplitude is about 40 volts at maximum. The oscillation frequency decreases from 20 kHz to 10 kHz and the phase difference between the potential fluctuation and the Mirnov coil signal varies about 90 degree during the growing phase. The mode is propagating in the ion diamagnetic direction. At the end of the growing phase, the mode structure abruptly changes and the potential fluctuation is suppressed everywhere. The magnetic perturbation decays slowly at the constant frequency of 5 kHz (decaying phase). The maximum amplitude is larger than that in the growing phase. The propagation is in the electron diamagnetic direction and the mode appears to be fixed to the  $E_r \times B_t$  plasma rotation ( $E_r$ : radial electric field,  $B_t$ : toroidal magnetic field) determined by the electrostatic potential. By considering those characteristics, the mode is considered to be an  $m/n = 2/1$  interchange mode in the growing phase, although the propagation velocity and the growth rate are not fully explained. The mode structure in the decaying phase is completely different and is suggesting an  $m = 2$  island formation at the  $q = 2$  rational surface.

In conclusion, the application of HIBP for studying MHD instabilities in a helical plasma has been successfully carried out. Radial structure of the potential fluctuation associated with the  $m/n = 2/1$  burst type interchange instability is experimentally clarified. The result demonstrates a new diagnostic approach to MHD fluctuation studies in helical plasmas.

## 論文の審査結果の要旨

本学位論文は、重イオンビームプローブ(HIBP)によるヘリカルプラズマのMHD不安定性の測定に関するものである。HIBPは、トカマクでは実績があるが、ヘリカル型装置では、ビーム軌道が3次元であるためトカマクよりもその適用は困難であり、本格的な実績はなかった。李君は、HIBPの測定手法を確立するために、先ず、ビーム軌道の較正を行った。次いで、ヘリカルプラズマでは主たるMHD不安定性である圧力駆動型の交換型不安定性の内部構造を初めてHIBPによって測定した。この不安定性はCHSプラズマでは最大の振幅を持つもので、比較的lowベータのNBIプラズマ中に周期的に発生するバースト状の揺動である。モードはポロイダルモード数  $m=2$ 、トロイダルモード数  $n=1$  である。主な結果は、以下の通りである。

1) CHSのHIBPは1次ビーム側と2次ビーム側の両方にビーム軌道偏向装置を持っており、それによって観測位置を制御しているのが特長である。可動検出器とヘリウムガスによる電離法によって、観測位置の較正を行い、ビーム軌道偏向装置による制御が計算通りであることを確認した。

2) 測定された静電ポテンシャルの揺動が局所的な値であることを立証した。即ち、MHD不安定性に伴うベクトルポテンシャルの揺動を磁気プローブ、HIBPのデータと理論モデルに基づいて評価し、その経路積分がビーム軌道に与える影響の小さいことを示した。

3) その結果、バーストの成長期における静電ポテンシャルの揺動は、回転変換角  $\epsilon=1/2$  ( $m=2/n=1$ )の有理面において最大値  $37 \pm 4V$ を持つことが実験的に示された。また、揺動の周波数は約20kHzであり、回転方向はイオンの反磁性ドリフト方向である。

4) 一方、バーストの減衰期には、静電ポテンシャルの揺動自身は抑制され、NBIプラズマ中の負の電場による  $E \times B$  ドリフト (電子の反磁性ドリフト) 方向に回転する。本論文によって、ヘリカルプラズマのMHD不安定性に伴う静電ポテンシャル揺動の内部構造を調べるのが初めて可能になった。従って、本論文は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られる。

李君の学位論文に関して、専門分野、基礎分野について口述により学力を確認した。HIBPの原理、測定技術、MHD不安定性、CHSプラズマの諸特性などについて広範囲の質問に的確に答えた。これにより、学位を与える上で十分な知識を有するものと判断できた。また、英文論文(top author)を1編発表している。本論文は英語で書かれており、英語についての学力も十分であると認められた。