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論文内容の要旨

In magnetic confinement devices, it is required that fast ions, such as heating ions and alpha particles, are well confined until they transfer their energy to plasmas. In order to understand loss processes and loss mechanisms of fast ions in magnetic confinement devices, direct measurements of escaping fast ions are essential. These studies have been advanced on large tokamaks experimentally and theoretically. On heliotron/torsatron devices which are regarded as alternative devices of tokamaks, it is especially important to study loss processes and loss mechanisms because fast ion orbits in heliotron/torsatron devices are complicated due to the presence of helical ripples in addition to toroidal ripples.

In this study, a scintillator-type lost-fast-ion probe has been used for the first time to measure escaping fast ions originated from a tangentially injected neutral beam (NB) on the Compact Helical System (CHS) heliotron/torsatron. The probe detects escaping fast ions directly in the vacuum vessel and can provide the information on the pitch angle χ and the gyroradius ρ_i corresponding to the energy of detected ions. The probe mainly consists of a scintillator plate (ZnS(Ag)), an image-intensified CCD camera and a nine channel fiber array coupled each with a photomultiplier tube (PMT). The probe head (detection point) is placed at the distance of a few cm away from the last closed magnetic surface. Positions on the scintillator plate struck by incident escaping fast ions have the information on χ and ρ_i. The time behaviors of escaping fast ions with different ranges of χ and ρ_i are obtained by using the PMT array with the time resolution of 50 μs. A χ-ρ_i profile, light spots on the scintillator, are obtained by the CCD camera as a 2D image with the time resolution of 33.3 ms (30 Hz). The probe has a Faraday cup structure. The total absolute flux of ions incident on the scintillator can be measured as ion current. Prior to measurements, calibration works for the gain characteristic of instruments were made to compare the signal intensity among each of plasma discharges measured with different gain of these instruments or each of PMTs.

Loss orbits are identified by using an orbit following code with measured information on the pitch angle and the energy. Orbits are simply derived by solving the equation of motion with Lorentz force. Orbits start from the detector position and are calculated backwards in time.

The measurement was applied to NB heated plasmas on CHS. First of all, it was inspected that the probe signal does not arise from X-rays, the leakage of plasma lights and other noises, but from escaping beam ions. As a feature of the signal, the signal was observed just during NB injection and the signal intensity increased as the magnetic axis position R_{ax} moved outward (plasmas come close to the probe). Light spots on the scintillator moved to the position predicted from the magnetic field strength at the probe position with changes of the toroidal magnetic field strength B_T.

The fast measurement is essential for the investigation of time behaviors of escaping fast ions. Three kinds of losses were observed and were identified as losses from passing, transition and trapped orbits. The different time behaviors of escaping ions, which suggest different classical loss processes, were observed on signals corresponding to passing ions and trapped ions. The signal of passing ions started synchronously at the moment of NB injection, while the signal intensity of trapped ions rose gradually in time. To reveal these loss processes, the dependence of the rise time behavior for both signals on the electron density n_e was investigated. The signal intensity of passing ions always rapidly increased with NB injection, independently of n_e. On the other hand, the rise time of trapped ion signal was inversely proportional to n_e and showed similar tendency to that of the calculated deflection time. Therefore, it is thought that the former is due to the prompt loss and the latter is due to the collisional pitch angle scattering loss depending on n_e.

The fast measurement was applied to NB-heated plasmas with fishbone-like instabilities and toroidicity-induced Alfven eigenmode (TAE). In CHS, two types of the fishbone-like instabilities were observed on Mirnov coil array, soft-X ray array and a heavy ion beam probe. One is the m/n =3/2 (m/n =poloidal/toroidal mode number) fishbone-like instability, which is often observed in a discharge with an outward-shifted plasma ($R_{ax} \geq 0.949$ m). The other is the m/n=2/1 fishbone-like instability, which is often observed in a discharge with an inward-shifted plasma (R_{ax}=0.921 m). The low magnetic field (B_T~0.9 T), the co-injected NB and the low n_e (n_e~1.0x10^{19} m^{-3}) are characteristics of these two burst modes. No such instabilities were observed on electron cyclotron resonance heated plasmas without NB injection. The periodic beam ion losses correlating with MHD oscillation were observed on the signals of co-going passing boundary ions and counter (ctr.)-going trapped ions with the energy lower than injection energy during the m/n=3/2 fishbone like instability. There were thresholds in the mode amplitude for the ejection of fast ions. Above the threshold, losses were enhanced with increase of the mode amplitude. The excitation of the fishbone-like instability and the enhancement of MHD-induced losses strongly depend on the degree of the accumulation of beam ions in plasmas. Orbit calculations show that passing boundary ions which have large pitch angle and the toroidal velocity close to zero or close to the propagating velocity of magnetic fluctuation near the m/n=3/2 surface are ejected by the instability. No MHD-induced losses were seen in plasmas with the m/n=2/1 fishbone-like instability or TAE.

In conclusion, direct measurements of escaping fast ions have been carried out in CHS and the classical loss processes (the prompt loss and the collisional pitch angle scattering loss) and the loss mechanism of MHD-induced loss were studied. In classical losses, the signal intensity of passing boundary ions was most intense. With regard to the loss mechanism of MHD-induced losses, it was found that passing boundary ions moving excursively across magnetic surfaces between the outside and the inside of a plasma have resonance points near the m/n=3/2 surface, where their toroidal velocity is close to zero or close to the propagating velocity of magnetic fluctuation. Therefore, it is necessary for future large devices to control passing boundary ions.

論文の審査結果の要旨

本学位論文は、ヘリオトロン／トルサトロン型のヘリカル装置CHSにおける高エネルギーイオンの測定に関するものである。高エネルギーイオンは、CHSのプラズマ加熱用に用いられている40kV中性粒子入射加熱ビームの減速過程からのものである。CHSでは、その磁場構造にトーラス固有のトロイダルリップルに加えて、ヘリカルコイルに起因するヘリカルリップルが存在する。ヘリカルリップルの存在は新たな捕捉粒子を作り出す。捕捉粒子の軌道は概して磁気面から大きくずれてしまうので、損失粒子となりやすい。従って、ヘリカル型装置では、この粒子損失が重要な研究対象の一つとなっている。近藤君は、ヘリカル装置では世界で初めて高エネルギーの損失粒子の測定を行った。特に、MHD不安定性に同期して吐き出される損失粒子の測定結果は、MHD不安定性の理論との対比において貴重なデータを提供している。この測定は、CHSでの成功を受けて、ドイツのW7-ASヘリカル装置においても行われている。

近藤君は、米国のTFTRトカマクにおいて用いられていた損失粒子プローブに着目し、これにいくつかの改良を加えてCHSに導入した。同プローブは、高エネルギーイオンのラーマー半径が数cmと大きいことを利用し、プラズマの最外殻磁気面の外に出て来るこれらのイオンを、プローブに設けた2重のスリットを通して3.2cm×3.2cmの広さを持つZnSシンチレータ上に捕獲する。プローブには、粒子のエネルギーとピッチ角の情報がシンチレータ上に2次元の発光分布として現れることになる。従来は、シンチレータ全体の発光分布を観測していたが、近藤君は、新たに発光分布を約10の多チャンネルに分けて取り出し、50マイクロ秒の高時間分解での測定を行った。また、ヘリカル磁場中での粒子追跡コードを作成した。シンチレータに到着した損失イオンのエネルギーとピッチ角を初期条件として、粒子軌道を時間を逆に追跡することによって、損失イオンがプラズマ中でどのような種類の粒子であったかを調べた。これによって、トランジット粒子、遷移粒子、ヘリカルリップル捕捉粒子などについて、エネルギー毎に損失の様子が時間的に高時間分解で得られるようになった。トランジット粒子が損失する場合は、密度に関係なく中性粒子入射とともにすぐに増加し、イオン化したのち即時に損失すること、また、捕捉粒子の場合は、密度に逆比例して損失が増加し、減速過程のピッチ角散乱を経て損失すること、が分かった。

中性粒子入射ビームによって、CHSにおける最も強いMHD不安定性であるバースト状のビーム駆動型フィッシュボーン様不安定性が引き起こされる。従来、この現象には高エネルギーイオンが関与していると推測されていたが、この度の測定によって、この現象は不安定性が成長すると粒子が損失し、その損失とともに不安定性が抑制されるという繰り返しであることが、実験的に示された。不安定性に同期した損失粒子束の磁場強度、プラズマ密度に対する依存性が詳細に調べられ、蓄積されたビームの量が不安定性の誘起に大きな役割を果たしているものと考えられた。更に、この不安定性によって、トランジット領域と捕捉領域との境界付近の粒子が最も多く損失することが分かった。

本論文では、中性粒子入射加熱ビームの減速過程にある高エネルギー粒子に関する損失粒子計測をヘリカル装置において世界で初めて行うことにより、粒子損失に関するいくつかの新しい実験結果が示された。LHDを含む将来の核融合実験装置における高エネルギー粒子の振舞の解明に新たな展望を開くものであり、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。