氏　　　　　名	西 村　　伸
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学 位 論 文 題 目	Observation of the Non-uniform Poloidal Flow of Impurity Ion on Magnetic Surfaces using Bidirectional Charge Exchange Spectroscopy in CHS
論 文 審 査 委 員	主　査　教　授　松岡 啓介 教　授　藤原 正巳 教　授　須藤 滋 助教授　居田 克巳 教　授　近藤　克己（京都大学） 教　授　藤本　孝（京都大学）

論文内容の要旨

The radial electric fields in magnetically confined toroidal plasmas are considered to play an important role in plasma confinements. For example, they change the neoclassical ripple loss in the low collisionality regime in helical devices, and they are considered to be the important parameter to determine the L/H transition and the anomalous transport characteristics of L/H-modes in tokamak plasmas. Therefore many efforts to study the radial electric fields experimentally have been performed. One method for this study is the spectroscopic measurements of the rotations of impurity ions. However, toroidal effects on the plasma rotations have never been studied experimentally. The coupling of toroidal and poloidal rotations caused by the toroidal effect to satisfy the poloidal flow conservation condition is the most important basis of neoclassical transport theory and is also important for understanding the supersonic (with $Mp \sim 1$ where Mp is the poloidal Mach number) plasma flows in tokamak H-mode plasmas. Therefore many related theoretical studies have been made.

To study this problem experimentally is to compare poloidal flux on the inside and outside of the magnetic surfaces. In the poloidal rotation measurements in many tokamaks, the poloidal rotation velocities only on the outside were measured, since it is difficult to install the observation chords viewing vertically the inside of the torus. Another severe difficulty is the calibration of mechanical wavelength offset($\sim$0.5 Å) of spectrometers with the accuracy for the plasma rotation measurements. The study of the inside/outside asymmetry of poloidal rotation velocity requires the accuracy of absolute wavelength of $\sim$0.01 Å. To measure the absolute value of the rotation velocity canceling this offset, it needs the observation along opposite viewing directions. In past plasma rotation measurements using the observation from one direction only, some assumptions or approximations about the plasma rotation velocity profiles were used. For example, the average of the poloidal rotation velocities on the inside and the outside was used as poloidal rotation 'velocity' in Heliotron E.

In the present work, I have carried out the measurement of the profiles of the poloidal rotation velocity, the temperature and the density of impurity ions using bidirectional charge exchange spectroscopy(CXS) in the Compact Helical System(CHS). For the purpose mentioned above, this measurement system uses two fiber arrays to view vertically the beam line from up and down sides simultaneously at one vertically elongated section. In Heliotron/Torsatron devices like CHS, the strong parallel viscosity reduces the parallel ion flow velocity which is necessary for incompressible flow conservation when the perpendicular ion flow exists in low aspect ratio tori. This damping is strong in peripheral region where the helical ripple becomes large. However, the poloidal rotation of impurity ions mainly driven by radial electric field determined by the ambipolar condition of the electron and ion fluxes is also large in this peripheral region. Therefore the compensation of the asymmetry of inside and outside perpendicular flows by the parallel flows becomes difficult in this region. When the electrostatic potential is the surface quantity and the poloidal rotation of ions is mainly the $E \times B$ drift, the flow, especially of the impurity ions having low pressure, should be compressible. Otherwise the electrostatic potential is not the surface quantity or the poloidal rotation of impurity ions is not E×B drift. Investigating this problem is easier in low aspect ratio devices. Therefore this measurement in CHS with the lowest aspect ratio R_0/a=5 in helical devices will give the new information about the plasma rotations.

The preliminary measurements of plasma rotations using this system clarified some technical problems in multi-channel CXS. The most important problem was the apparent wavelength shift caused by the spectral fine structure of hydrogen-like ions used in CXS. This structure is the red-side/blue-side asymmetric splitting of the lines due to a relativistic effect and thus cause the red-side/blue-side asymmetry of the Doppler broadened spectral profile. Because of this asymmetry, the wavelength given by single Gaussian least square fitting shows the apparent shifts which depends on Doppler widths. The observed apparent shifts of CVI lines, not due to plasma rotation, in the plasma peripheral region (T_i ~100eV) and in the after-glow recombining phase (T_i ~30eV) are always red-shifts regardless the direction of plasma rotation. The magnitude corresponds to the velocity error of a few km/s. This direction and magnitude are consistent with the calculation using the collisional l-mixing model. This value is not negligible in CHS plasmas, and thus should be corrected.

The density profile of the fully ionized impurity ions can be measured using the intensity of the charge exchange spectral lines. For this purpose, the initial beam density profile without attenuation was also measured in the torus using Hα from the beam. The measured density profile was a broad and inside shifted profile compared with the calculated one. This result means the possibility to measure the parameters on inside of the torus with CXS. However, the calculation of the beam attenuation required that the average electron densities should be less than 2×10^{13}cm^{-3} to avoid the ambiguity of beam attenuation calculation and the degradation of signal level on the inside.

The measurements of the asymmetry of the poloidal flux of fully ionized carbon ions on the inside and outside of the torus were carried out for the magnetic surface configurations with different magnetic axis positions. In inward shifted configurations, the gradients of surface function (dΨ/dR) on the inside and outside of the section are almost symmetric. It becomes asymmetric in outward shifted configurations and the strength of the radial electric field will become asymmetric in these configuration.

The asymmetry of the Doppler shifts of the CVI line(Δn=8-7, λ=5290Å) on the inside and outside of the torus was successfully measured. In outward shifted configurations, the electrostatic potential calculated from this velocity using the momentum balance equation is the surface quantity. The measured density of impurity ions has a hollow profile and is higher on the inside of the magnetic surfaces compared with that on the outside. This inside/outside asymmetry of the density profile can be explained by the poloidal flow conservation on both sides under the damping of toroidal rotation.

In inward shifted configurations, the density has a flat or peaking profile and the inside/outside asymmetry is not clear. The quantitative comparison of the electrostatic potential and the poloidal flow on both sides is difficult in inward shifted configurations because of the intense background radiation at the inside of the magnetic axis. It causes the degradation of signal/noise ratio of spectrum after subtracting background spectrum. However, this change in the density asymmetry is consistent with the past measurement of the toroidal rotation damping and suggests the poloidal rotation accompanying the inside/outside asymmetric toroidal flow. Therefore the measurement of inside/outside asymmetry of the toroidal rotation velocity is an interesting future theme.

論文の審査結果の要旨

本学位論文は、ヘリカルプラズマに対して荷電交換分光を、世界で初めて上下双方向から行うことによりプラズマ断面全体にわたるポロイダル回転速度分布を決定したもので、それによりポロイダル方向のフローの保存が検証された。プラズマ回転のシアはエネルギー閉じ込めの改善を引き起こすので、重要な物理量と考えられている。

西村君は、６価炭素イオンのポロイダル回転速度（数km/s）を測定するに必要な測定器の較正を行った。多チャンネル荷電交換分光システムは、空間点に対応した多数の光ファイバーを入口スリット面上に並べることにより、１台の分光器、検出器で多チャンネル同時計測を行う。各ファイバーから１つの波長スペクトラムが得られ、各スペクトラムのドップラーシフトから回転速度が得られる。分光器固有の収差に加え、ファイバー列が直線から10 μm（波長にして0.04Å、回転速度にして２- ３km/s に対応）ずれているために生じるドップラーシフトの原点のずれ（オフセット）に対する補正を実行した。検出器の非線形性、光学系の絶対感度を較正した。それにより、イオンの回転速度のみならずイオン温度、中性粒子加熱ビームのプラズマ中での密度分布を精度よく決定した。

ポロイダル回転速度は一般には内外非一様性を示すが、速度の湧き出し＝ゼロを満たすための内外非対称なトロイダル回転速度が存在するかどうかを測定した。その結果、ヘリカルリップルによる新古典粘性のためにトロイダル回転が抑制されることを確認した。

これらによって得られた主な成果は以下の通りである。

１）炭素イオンの反磁性ドリフト速度とポロイダル回転速度から、径電場が得られた。

２）径電場の積分から得られたポテンシャルは磁気面上で一様である。

３）炭素イオン密度分布を発光強度とビームの密度から求めた。得られた分布は、磁気軸の外寄せ配位では、磁気面上内外非対称である。

４）炭素イオンの密度と速度の積の面積積分（トロイダル効果を考慮した）が磁気面上内外対称であり、ポロイダルフローの保存が示された。

本論文は、トロイダルプラズマの輸送に関連して重要な意味を持つ回転に対して新たな知見を与えるものであり、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。

西村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。荷電交換分光の原理、測定技術、トーラスプラズマの新古典理論、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。