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Particle Orbit Analysis under Equilibrium Configuration for Evaluating the Orbit Current Distribution driven by Electron Cyclotron Heating on QUEST

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論 文 名　：Particle Orbit Analysis under Equilibrium Configuration for Evaluating the Orbit Current Distribution driven by Electron Cyclotron Heating on QUEST
Title　　　（QUEST における電子サイクロトロン加熱による駆動プラズマ電流分布評価のための平衡配位での粒子軌道解析）

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Category

論 文 内 容 の 要 旨

Thesis Summary

Radio frequency (RF) waves have been widely used for the non-inductive plasma current drive. Among all the RFs, the electron cyclotron heating and current drive (ECH/CD) is one of the intense methods of non-inductive plasma current drive. The plasma sustainment with RF or ECH waves is a key issue for the steady state operation in the tokamak configuration. The plasma was sustained for more than 2 hours by the ECH/CD non-inductive method in the Q-shu university experiment with steady-state spherical tokamak (QUEST). The ECH waves accelerated the electrons with the Doppler-shifted electron cyclotron resonance (ECR) interactions, and effectively ramped and sustained the plasma current non-inductively for long discharge duration.

In the QUEST, 28 GHz and 8.2 GHz ECH waves have been used to attain the plasma current start-up and sustainment. The plasma current was generated with the abundant high-energetic electrons in the ECH/CD plasmas. The plasma current generation is strongly related to the ECR conditions and confinements of the electrons in the magnetic field. The plasma current fitting analyses for the ECH/CD plasmas showed that the plasma current existed in the open magnetic fields outside the last closed flux surface (LCFS). In this thesis, the guiding center orbits of the ECR electrons were calculated and analyzed under equilibrium magnetic configuration to consider the current distribution outside the LCFS. A framework with several sets of calculation codes accordingly for various theoretical models was developed with EFIT (Equilibrium Fitting) plasma equilibrium to calculate and analyses guiding center orbits as well as to evaluate orbit current distribution. The plasma equilibrium and shaping were properly taken into account for the orbit analyses and the current evaluation, but the evaluated current was not included in the plasma equilibrium and shaping self-consistently.

Chapter 3 described how to obtain the equilibrium magnetic configuration from the plasma equilibrium solution of a discharge. The plasma equilibrium and shaping as well as magnetic configuration were evaluated by solving the Grad-Shafranov equation with the external magnetics for constraint of a discharge using EFIT code.

Chapter 4 described about the guiding center orbits calculations of the ECR electrons and the characteristics of the obtained orbits. The guiding center orbits of the resonant electrons were calculated and analyzed for the 8.2 GHz ECH waves in non-relativistic and relativistic Doppler-shifted ECR. The down-shifted and up-shifted fundamental and second (2^{nd}) harmonic resonances were considered separately. Various parallel and perpendicular velocities to the magnetic field, $v_{\parallel}$ and $v_{\perp}$, were considered from the Doppler-shifted ECR condition for the electrons to be resonant with the ECH waves. Orbit trajectories of the resonant electrons were obtained for various positions of the coordinates (R, Z), pitch angles and refractive indexes in a direction parallel to the magnetic field $N_{\parallel}$ in the multiple-wall reflection model. The number of the stepped parameters was more than 5,200000. A number of orbit trajectories of ECR electrons were plotted as contour plots of the resonant electrons' energy on the equilibrium magnetic configuration. The energy was expressed in terms of magnetic moment and toroidal angular momentum. The energy, magnetic moment, and toroidal angular momentum were conserved in the orbit trajectories. A large number of passing resonant electrons with initial positive $v_{\parallel}$ starting from the high field side were maintained their orbits at the outside of the LCFS, while all the passing resonant electrons with initial negative $v_{\parallel}$ starting from the high field side were maintained their orbits inside the LCFS. The trapped resonant electrons only being the 2^{nd} harmonic ECR were maintained banana orbits at the low field side of the torus where most of the portions of the banana orbits of positive $v_{\parallel}$ were placed outside the LCFS.

Chapter 5 described the orbit current distribution evaluation processes as well as the obtained results. The orbit current distributions were evaluated from the electrons' orbital distributions along with the drift toroidal velocities, v_{φ} throughout the orbit. The electrons with initial positive $v_{\parallel}$ were contributed positive current while the electrons with initial negative $v_{\parallel}$ were contributed negative current. The trapped electrons with initial positive and negative $v_{\parallel}$ were contributed both the positive and negative currents. The direction of the positive current was opposite to the toroidal magnetic field i.e. co-current direction of QUEST plasma current while the direction of the negative current was parallel to the toroidal magnetic field i.e. counter-current direction of QUEST plasma current. A significant amount of the positive current by the passing resonant electrons with initial positive $v_{\parallel}$ appeared outside the LCFS, while the entire negative current by the passing resonant electrons with initial negative $v_{\parallel}$ appeared inside the LCFS. The trapped electrons contributed both the positive and negative currents. The positive current portion was distributed outside the LCFS while the negative current portion was evaluated inside the LCFS.

In the summary, several codes required to evaluate the orbits have been developed with the EFIT code. Various criteria of non-relativistic and relativistic ECR conditions for fundamental and 2nd harmonic ECR electrons were properly taken into consideration for the orbit analysis. The current contribution appeared outside the LCFS could be qualitatively explained by the developed codes.