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論文内容の要旨

Concepts of deuterium-tritium (D-T) fueled tokamaks have been studied mainly to realize the commercial fusion reactors. However, certain engineering problems for a commercial D-T fusion reactor which are attributed to 14-MeV neutrons have never been resolved. Deuterium-^{3}He fusion fuels are considered to mitigate the engineering problems associated with 14-MeV neutrons. To reduce the synchrotron radiation losses in a D-^{3}He burning plasma, a use of a high beta field-reversed configuration (FRC) is a proper choice. Moreover, an FRC is surrounded by open lines of force and is thus suitable for the application of highly efficient direct energy converters (DEC). However, it still remains to investigate some issues, such as the particle transport and the experimental confirmation of the DECs. In the present work, the particle transport and the particle loss in an FRC due to the randomization of particle motion at x-points are studied.

Particle motion near the separatrix of an FRC has been considered as stochastic, because the particle is accessible to the vicinity of the field-null x-points. Nevertheless, no quantitative investigation on the property of the randomization of particle motion associated with the x-points has been so far carried out. In addition, since particles which go through near the x-points might travel to the points where the magnetic mirror coils are arranged, these are closely related to the axial mirror loss. Hence, the investigation on the statistical property of the particle motion near the x-points is of consequence. The radial action integral J is introduced to reveal the characteristic of the particle motion near the x-points. This action integral preserves its value as a particle moves in relatively uniform field, and is proportinal to the magnetic moment in this case. On the other hand, an abrupt change of the action integral is observed, when a particle approaches the x-points. The property of this sudden change referred to as the collisionless scattering is investigated numerically using the particle tracing routine. The correlation coefficient of the action integral between before and after the collisionless scattering is approximately 0.1 which is much smaller than the one for the regular particles. Therefore, the collisionless scattering can be understood as a stochastic process. A series of the successive collisionless scatterings is found to be an isotropic process, because the numerically calculated histogram in J-space approaches the isotropic distribution function in the velocity space. Larger changes in the action integral due to the collisionless scattering are observed for the particles with smaller action integral as well as smaller absolute value of canonical angular momentum. Moreover, it is found that larger changes in the action integral due to the collisionless scattering are observed for the particles with higher kinetic energy. By the present numerical studies, the fitting curve of the ensemble square average of the changes in the action integral due to the collisionless scattering is obtained, and will be the useful data for the axial mirror loss of particles in an FRC.

The particles which move near the separatrix are trapped around the x-points where the magnetic field is a minimum along the guiding center of their axial motion. However, certain works have neglected the effect of the mirror trap because of the high bounce

frequency compared with the collision frequency which relates to the classical cross-field particle transport. Recently, the electrostatic potential associated with the kinetic effect has been proposed to play an important role of the loss mechanism, which can not be explained unless the particle axial motion is considered. Moreover, the density gradient around the separatrix is dependent on the axial mirror confinement of plasma particles, and it affects the transverse particle transport. Thus the overall particle confinement time will be modified due to the collisionless stochastic scattering which the mirror-trapped particles suffer. In the present paper, a combination process of axial and radial transport considered the collisionless stochastic scattering has been investigated. The distribution function for the particles near the separatrix is derived from the transport equation which is expressed in terms of the Hamiltonian, the canonical angular momentum, the radial action, the magnetic flux function, and the stream function. Without collisions or turbulences, it is found that the distribution function is independent of the stream function and also found that the dependence on the canonical angular momentum and the flux function are degenerated in our case. The cross-field and the axial diffusion due to collision and collisionless scattering determine the dependence of the distribution function on the Hamiltonian, the canonical angular momentum and the action integral. Since the axial and the radial diffusion coefficie nts for electrons and ions are different from each other, the electrostatic potential is formed at the mirror points and at the midplane on the separatrix to keep the charge neutrality and the ambipolar particle loss flux. This ambipolar potential at the mirror is found to be in the range from -0.4 T to -T. Here, the quantity T denotes the plasma temperature. The consequent potential at the midplane on the separatrix is found to be identical to the one at the mirror points. This result is attributed to the fact that the collisionless scattering ions at the separatrix are large enough to enhance ion loss upto the mirror loss of electrons without any electrstatic potential. The sharp density gradient at the separatrix due to the collisionless stochastic scattering is obtained, which enhances the cross-field diffusion. Contrary, the density gradient becomes gentle without this scattering. The overall particle confinement time is predicted from the continuity of the radial density profile near the separatrix. It appears that in the high temperature plasmas the calculated confinement time approaches the one predicted without the mirror confinement effects. High temperature will be required for the fusion reactor, thus the mirror confinement effects will be safely neglected in this case.

論文の審査結果の要旨

本博士論文は、ＦＲＣ（逆転磁場配位）における粒子軌道のストキャスティック無衝突散乱に関する理論的研究及びこれに関連した粒子の輸送と閉じ込め時間を理論的に考察したものである。

ＦＲＣ配位のセパラトリックスは磁場が零になるＸ点を含むので、セパラトリックス近傍を運動する粒子はストキャスティックになると考えられるが、これまでこれに関しては定量的研究はなかった。本論分では、先ず、Ｘ点近傍に近接し得る粒子の運動可能領域を求め、それが正準角運動量の大きさによりカスプ型とミラー型に分類できることを明らかにした。次いでＸ点に近接できる粒子の運動を、ハミルトニアンと正準角運動量及び作用積分Ｊで記述し、Ｘ点近傍を通過するときのＪの急激な変化を計算し、通過前後のＪの相関を取ることにより、粒子はＸ点近傍でストキャスティックに振る舞い、無衝突散乱されることを明らかにした。この無衝突散乱は速度空間で等方的であることも明らかにした。この結果、次のような粒子閉じ込めの描像を導いた。すなわち、閉じ込め領域を衝突拡散してセパラトリックスを横切った粒子は、セパラトリックス近傍の磁力線に沿って断熱運動をし、Ｘ点近傍でストキャスティック無衝突散乱を受け、ミラー点に向かって軸方向に速やかに失われる。このとき、軸方向損失率は閉じ込め領域を拡散する径方向損失率よりも十分大きいので、セパラトリックス近傍に急峻な密度勾配が形成される。この新しい軸方向損失機構は、実験で観測されているセパラトリックス近傍の急峻な密度勾配と大きな粒子損失を説明する可能性を秘めている点で注目に値する。

また、径方向粒子輸送と軸方向粒子輸送を同時に取り扱い、さらに、両極性ポテンシャルを求めるため、セパラトリックス近傍における粒子の位相空間における分布関数を衝突項も含め解析的に求めた。得られた分布関数から電子とイオンの粒子束を求め、これから計算された両極性ポテンシャルはミラー点でプラズマ温度程度であり、高温で衝突の効果が少なくＸ点でストキャスティック無衝突散乱が支配的なときは、イオンの軸方向損失が電子のそれと同程度になるため、セパラトリックス中央点におけるポテンシャルはミラー点でのポテンシャルと同程度になることを見いだした。大域的粒子閉じ込め時間も評価され、閉じ込め時間はセパラトリックス半径の自乗とセパラトリックス上の磁場の大きさの積に比例することが分かった。ＦＲＸ－ＣやＴＲＸ－１，ＬＳＸ等のＦＲＣ実験結果との比較は、理論的予測と良い一致を示した。

ＦＲＣ配位において、特異点（Ｘ点）における粒子のストキャスティックな振る舞いに着目し、粒子輸送を大域的に論じたのは本研究が始めてであり、学術面・応用面から高く評価できる。