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論 文 審 査 委 員	主　査　教　授　大藪 修義 教　授　岡本 正雄 教　授　佐藤 哲也 助 教 授　中島 徳嘉 教　授　若谷　誠宏（京都大学）

論文内容の要旨

Importance of the divertor plasma study has been emphasized in recent fusion programs since the divertor is the key ingredient in enhancing the plasma quality as well as handling the high heat flux in future reactor grade devices.

Recently a new divertor operational scenario, high temperature divertor plasma operation has been proposed to enhance the energy confinement. In this approach, the scrape-off layer (SOL) plasma is collisionless and the edge temperature is maintained to be very high by efficient pumping, leading to the enhancement of the energy confinement. It is planned to pursue this type of operation in the Large Helical Device. One of key physical issues here is the influence of secondary electrons emitted from the divertor plate, which tend to cool the SOL plasma. Maintaining a high edge temperature, however, is critical to achieve the improvement of the energy confinement. In many previous studies of the SOL plasma, electrons are assumed to be Maxwellian, and only ion dynamics are solved. This assumption is no more valid for collisionless SOL plasma of the high temperature operation. To understand a collisionless SOL plasma, a kinetic treatment for electrons is needed. Since the SOL plasma can be operated over a wide range of Coulomb collisionality, the dependence of the SOL plasma on the collisionality should be investigated.

In this thesis, a new Monte Carlo model with a kinetic treatment for electrons has been developed to study the global features of the SOL plasma in connection with main plasma parameters. The global features of the SOL plasma such as temperature, density, total potential drop, etc, are determined consistently with particle and energy flows from the confinement region to the SOL. By using the model, we have numerically investigated the characteristics of the SOL plasma such as potential formation, effects of secondary electron emission, dependence on collisionality, sheath energy transmission factor, etc. The simulations have been performed over a wide range of collisionality and much attention has been paid to collisionless SOL plasma related to the high temperature divertor operation.

First, for purpose of accurate modeling of Coulomb collision effects which are important in the SOL plasma, we have developed a nonlinear Fokker-Planck Monte Carlo collision model. Such a nonlinear collision model is especially useful in many important cases of edge plasma modeling where a significant deviation of the distribution function from Maxwellian makes a linearized collision operator not applicable. The presented nonlinear Monte Carlo operator collides all particles with each other via binary collisions so that non-Maxwellian effect is taken into account, improving previous linear operators. The operator puts emphasis both on accuracy and implementation efficiency. It conserves particle number, momentum,

and energy. Conservation of these quantities is important to maintain the correct balance of particle and energy in the SOL plasma. The operator is equivalent to the exact Fokker-Planck operator of Landau form in the sense that it can correctly reproduces the friction coefficient and diffusion tensor with the accuracy of order $O(\Delta t)$. Two highly vectorizable algorithms have been designed for the fast implementation of the nonlinear collisions. Drastic speedup is obtained by the algorithms on vector computers. The operator has been tested by various simulations regarding relaxation processes, electrical conductivity, etc. In all tests, the operator gives results in good agreement with these of theory. This nonlinear Monte Carlo operator, constructed in general case, is not limited for only the SOL plasma modeling, but can be widely useful for accurate simulations of collisional transport problems in magnetized and unmagnetized plasmas.

With the major goal being study collisionless SOL plasma related to the high temperature divertor operation, we have proposed velocity space model Fokker-Planck equations for both electrons and ions, taking essential physics processes into account. The cross-field plasma transport from the core into the SOL and secondary electron emission from the divertor plates are treated as sources, and particle and energy sink effects due to the absorbing plates are effectively modeled through the connection length L between two divertor plates. In the source terms, the conductive energy flux from the confinement region into the SOL is effectively modeled for the first time via randomly exchanging the source particles and the SOL particles. The conductive energy flux, which is independent of cross-field particle flux in determining the SOL structure, together with the convective energy flux introduced by the particle source term, ensures integrated balance of energy flowing to the SOL and energy lost to the plates. Coulomb collisions are incorporated by the nonlinear Monte Carlo operator mentioned above. The collision treatment using the nonlinear Monte Carlo operator is also extended on the secondary electrons. Instead of solving Possion's equation, the total potential drop between the SOL plasma and the plate is consistently determined by employing charge neutrality constraint. The model Fokker-Planck equations are solved via particle Monte Carlo simulation under charge neutrality constraint and zero-current condition. A steady state SOL plasma and total potential drop are obtained in terms of total particle flux and input power across the separatrix, the temperature of main plasma near the separatrix, secondary electron emission coefficient, and the SOL size. Within the present framework, the model can be extended to include other effects, such as neutral recycling and impurities, by introducing additional source terms.

The particle Monte Carlo model has been applied to study collisional, collisionless, and moderate collisional SOL plasma with focus on the issues relevant to the high temperature divertor operation. Essentially, a collisionless SOL plasma has been explored and the influence of secondary electrons has been clarified.

In collisional SOL plasma, the fundamental quantities such as total potential drop $e\Phi/T_e$ and electron sheath energy transmission factor γ_e obtained from the simulations agree close with predictions of the theory which assumes Maxwellian electrons. The validity of the proposed model has been confirmed.

A strong departure of the electron distribution function from Maxwellian has been shown for collisionless SOL plasma. The low collisionality and non-Maxwellian features affect the transport properties of the SOL plasma, and result in the total potential drop and electron energy transmission factor differing significantly from the analytical estimates. It has been found that in the presence of strong secondary emission the electron energy transmission factor γ_e in collisionless case is significantly smaller than that of collisional case. This fact indicates that the SOL plasma is not cooled by secondary electrons in collisionless case because the electron equilibrium temperature is inversely proportional to γ_e. The numerical study here provides a positive evidence that the high temperature divertor operation may be possible.

The potential drop $e|\Phi|/T_{e\|}$ has been found to increase with collisionality. For the same secondary emission coefficient the electron energy transmission factor γ_e has been found to decrease with decreasing collisionality, which indicates that the cooling effect of secondary emissions becomes weak in a collisionless SOL plasma.

The introduction of cross-field conductive energy flux plays a decisive role in power balance in the SOL. It is very interesting that in both collisional and collisionless SOL plasmas, the change in the conductive energy flux has little influence on $e\Phi/T_{e\|}$ and γ_e, while the electron temperature is raised as increasing the conductive energy flux.

It also has been demonstrated that, over a wide range of collisionality, as secondary emission is increased, the potential drop $e|\Phi|/T_{e\|}$ is reduced and γ_e is increased.

論文の審査結果の要旨

磁場閉じ込め核融合装置では、粒子処理・熱処理のために、ダイバータの開発が必要不可欠である。また、ダイバータは、周辺、あるいはスクレイプオフ層(SOL)における粒子リサイクリング等のプラズマ条件を制御し、主プラズマの閉じ込め性能向上に資することもできる。ダイバータ研究の進んでいるトカマクでは、通常、低温・高密度ダイバータ運転が行われる。しかしながら、エネルギー閉じ込め改善のために、最近、強力なポンピングにより粒子リサイクリングを低く抑え、高温プラズマをもつSOLを実現する高温ダイバータ運転が提案されている。ヘリカル系では、まだ、本格的なダイバータ実験は行われていないが、文部省核融合科学研究所において建設中の大型ヘリカル装置では、この高温ダイバータ運転が計画されている。高温ダイバータ、高温SOLでは、粒子の平均自由行程は長く、電子、イオンの分布関数はマックスウェル分布から大きくずれ、解析的取扱いがきわめて困難である。さらに、高温ダイバータ運転そのものが成立しなくなる危険性をもたらすダイバータ板からの２次電子の逆流という問題がある。しかし、このような問題は、これまでほとんど解明されてこなかった。

本論文では、高温ダイバータ運転に関連したSOLプラズマの特性に対する、SOLの密度や温度、ポテンシャル形成、および２次電子の効果を解明することを主目的としている。この目的のためには、SOLにおける粒子の分布関数を正確に取り扱い、主プラズマから流入する粒子束・熱流束とダイバータ板で処理される粒子束・熱流束、さらに２次電子をも含めて矛盾なく取り扱うことが要求される。そこで、先ず、粒子の分布関数を正確に取り扱うために、ランダウ型衝突積分に帰着する非線形衝突モデルを基にした粒子モンテカルロシミュレーションを開発し、さらに計算時間圧縮のための徹底したベクトル化プログラムを作成した。そして、主プラズマから流入する粒子束、粒子間衝突、ダイバータ板での損失、２次電子の効果すべてを含む、SOLに対する、粒子モンテカルロ・モデルの構築に成功した。このモデルでは、主プラズマとSOLプラズマとの間の熱交換が、実効的に取り入れられている。

この新しいモデルにより、本論文では、SOLプラズマの温度や電子熱伝導係数等、SOLプラズマのエネルギーバランスを正確に評価することができ、高く評価される成果を挙げた。２次電子に対しても衝突は正確に考慮され、この結果、電子熱伝導係数は衝突の少ない高温ダイバータでは比較的小さく、２次電子放出率が大きくても高温ダイバータ運転は可能であることが明らかになった。これらの成果は、これまで全く解明されていなかったものであり、本論文は、核融合研究において重要な貢献をするものである。また、本論文の手法は、SOLやダイバータの物理をさらに解明する発展性を有する。

以上より、本論文は、高温ダイバータに関連したスクレイプオフ層プラズマの特性を明確にする十分に独創的かつ発展性を有する研究であると認められた。また、出願者は、研究の動機と目的、問題解決法、新しく得た知見、独創性、研究の今後の発展性等を的確に理解していると認められた。核融合・プラズマ物理に対する知見も十分であると認められ、英語力、日本語力も十分であると判断された。

以上、出願者は、独立して研究を遂行するに十分な能力を有するものと認められるので、本試験は合格とした。