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学位論文題目　Simulation Study of Self-Consistent Potential Formation in Edge Plasmas

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Summary of Doctoral Thesis

Name in full: LE THI QUYNH TRANG

Title: Simulation Study of Self-Consistent Potential Formation in Edge Plasmas

In the magnetically confined fusion, high-energy ions and electrons are confined by the magnetic field because charged particles move along the magnetic field lines with the gyro motion. Usually, in the edge of the fusion plasma the magnetic field lines are opened. Because, if the fusion plasma on the closed magnetic field line directly touches the first wall of the device, many impurities and neutrals from materials of the first wall come into the fusion plasma. The radiation between fusion plasma and impurities cools down the temperature of the fusion plasma. That means the fusion reaction rate is reduced. To avoid that, the magnetic field should be diverted from the first wall. Therefore, the physics in the plasma edge is very complicated because the magnetic topology changes from the closed field line to the open field lines with small spatial scale. To understand the physics in the plasma edge, sophisticated experimental and theoretical studies are necessary.

Since the mass of the electron is much less than the ion mass and the electron is lost faster than the ion on the open field line, the electric potential structure appears self-consistently in the edge plasma by breaking the charge neutrality. In the edge plasma region where the L-H transition occurs, the radial electric field, Er, affects ion losses and E×B shear flow, which is necessary for suppression of the turbulence. Understanding the radial electric field is necessary task to enable better control of edge transport and to improve core plasma confinement. There is strong relationship between magnetic field and potential profile because particles move along the magnetic field line in magnetized plasma. Magnetic field affects to the orbit of particle, in other words affects to particle transport, thereafter, influences on formation of potential. If the magnetic topology is externally changed for example stochastic field, a responded electric field must be presented. Therefore, the electric potential structure is a key issue to know the magnetic structure. Recently, in many fusion plasma experiment devices, probes are used to measure the potential profile or radial electric field in the presence of magnetic field. In these experiments, the relation between the magnetic field and electric field is summarized [1-4]. However, theoretical and modeling works are not many. In those cases, the radial electric field is computed in the presence of RMPs using fluid descriptions or reduced kinetic models [5-8]. However, those models cannot resolve very small spatial and time scale because their models deal with macroquantities. Due to this limitation, the relationship between stochastic field and formation of potential is not clear given in these studies. To understand this relation, we need develop new theory and numerical code based on the fully kinetic description.

Understanding the importance of the relationship between magnetic field, particle transport, and potential formation, we aimed to develop a model which can clearly show this relation. In our work, we developed a numerical code based on the Particle-in-Cell (PIC) methods. The PIC model is a method using fully kinetic model description to model the electrical potential structure self-consistently [9]. PIC simulation can deal with drift explicitly in comparison with the fluid model. The two spatial dimensions and three velocity coordinates (2D3V) PIC is necessary to study the effects of magnetic island on potential formation. To do that, we developed a completely new PIC code step-by-step, starting with 1D3V PIC model. Then, the 2D3V code is extended based on the 1D model. Because of the extension to the 2D, the parallelization of the code is required to study the whole edge region.

It has been suggested that the magnetic field can affect the flux to the wall [10-11]. The magnetic field changes particle transport which, therefore, influences the fluxes to the wall. We applied our PIC model to study the effects of external magnetic field on particle and heat fluxes to the wall targets. The plasma which consists of ion and electron is produced from the source region and is absorbed at the conductor wall. The wall is assumed to satisfy the floating potential condition. In one dimensional consideration, the external magnetic field is modified by applying the change of the magnetic field in the direction perpendicular to the plasma flow. This magnetic field is localized and switched from strong negative values to strong positive values at several locations in the simulation region. By performing the simulation using one spatial dimension and three coordinates for velocities (1D3V) PIC model, we found that this localized reversed magnetic field traps the particles in the simulation domain, and then reduces the particle and heat fluxes to the wall targets. The reduction of fluxes comes from particle reflection at the locations of strongly localized magnetic field. Based on the modeling results, external localized-reversed magnetic fields can control the particle and heat fluxes to the wall in one dimensional consideration [12]. There is a perspective of heat transferring along the wall. This localized magnetic field profile can be generated by injecting current filaments in experimental or in two dimensional numerical studies. To understand more qualitatively the effects of the external localized magnetic field, in other words, the current filaments, we performed the simulation using two spatial dimensions and three coordinates for velocities (2D3V) PIC model. Localized plasma flow enters the simulation box at the source region and is fully absorbed at the wall. We inject current filaments in the direction which is perpendicular to the simulation plane to change the magnetic field structure. The magnetic mirror forms in between current filaments. In comparison with the case of without injecting the current filaments, we obtained that trapped electrons and ions in the magnetic mirror change the particle and heat transport. Therefore, the high particle and heat fluxes to the wall are reduced and transferred along the wall. Consequently, injecting current filaments is a good candidate for reducing the high heat flux to the material. The mechanism of heat fluxes reduction comes from the reflection of particles in the magnetic mirrors and the expansion caused by the diffuse magnetic structure regardless of the boundary condition at the wall. Each device has different condition for the wall which may not be the floating potential condition. These boundaries do not affect to the tendency of flux reduction by the current filaments. These results can be applied for shielding high energy ion and electron fluxes to divertor tokamak, the satellite or spacecraft in the space.

To study the relationship between magnetic field and potential formation in the edge plasma, we model a flow of plasma consisting of ions and electrons on a boundary between closed and opened field lines using two spatial, three velocity coordinates (2D3V) PIC. We consider a small region inside and outside the Last Closed Flux Surface (LCFS) to study the formation of potential. In the Scrape-off Layer (SOL) region, the magnetic field line is opened. For simplicity, the SOL has been straightened out; the torus geometry is transferred to a small two-dimensional slab geometry. For verifications of the code and boundary conditions, two dimensional magnetic fields including poloidal and toroidal magnetic field are added initially. The magnetic field used in the slab geometry for modeling the magnetic field in torus geometry contains the curvature and toroidal gradient. The potential is self-consistently formed in the simulation; therefore, the radial electric field is presented. The profile of given radial electric field helps to get deeper understanding on physical phenomenon of plasma transport in the SOL region. We obtained that the radial electric field has a similar tendency with experimental results and theoretical prediction which is negative and localized in the edge region and increases from the edge to the SOL region. By changing particle temperatures, their Larmor radii changes. Consequently, it reflects in the change of particle fluxes near the LCFS. The higher temperature particles have, the deeper negative potential at the closed magnetic field line region is. We also obtained that the asymmetry of potential profiles depends on the values of inverse aspect ratio. Staring from the system with symmetric magnetic field, potential structure becomes asymmetry by larger inverse aspect ratio. These results give a better understanding on the potential formation by using PIC simulation method in comparison with other numerical model, and this is the advantage by using PIC model in comparison with fluid model. After verifying the code, the radial magnetic field is added to include the magnetic island in the simulation domain. In slab geometry, it is hard to make the magnetic island as exactly as in the torus. For simplicity, we add the current filaments into the simulation system to form the island. Magnetic islands change the transport of particle in the simulation. Changes in particle transport affect changes in particle fluxes, then, cause change in the formation of potential. The size and shape of the magnetic island are adjusted by the strength of current filaments. Strengthen current forms clearer magnetic island, causing bigger changes of particle transport and fluxes near the island. Therefore, potential structure gets deeper effects. Apart from that, more details on the stochastic boundary are studied, which mean some separatrices are overlapped. By injecting some nearby current filaments near the main island to created overlap, we studied the effects of stochastic field in potential formation. Particle transport near these overlap regions is changed. Particles are trapped in the magnetic island. Their movements are changed in both radial and poloidal directions. The magnetic island, finally, changes the potential in two dimensions.

In summary, we developed the PIC simulation to study the self-consistent formation of potential in edge plasmas. We applied the PIC simulation in the study of heat flux reduction to the material. We proposed the methods using localized-reversed magnetic field or the current filaments which is a good candidate to reducing the burden of high heat fluxes to the wall. The relationship between potential formation and magnetic field is presented. This is the prior work for study of potential formation in the edge plasma using PIC simulation. This is an important result which gives a deeper understanding of relationship of potential formation and magnetic field in the edge plasmas.

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Results of the doctoral thesis defense

博士論文審査結果

LE THI QUYNH TRANG

Simulation Study of Self-Consistent Potential Formation in Edge Plasmas

磁場閉じ込めプラズマの周辺部では磁場のトポロジーが閉構造から開構造へ変わる。もしプラズマを閉構造の磁場のみで閉じ込めると装置の壁にプラズマが直接触れることになり，壁から大量の不純物や中性粒子がプラズマへ流入して，定常運転実現の妨げとなる。これを避けるため，閉じ込め磁場は壁から離すように形成し，周辺で閉構造から開構造へ変える。この磁場トポロジーの変化のため，周辺部における輸送の物理は複雑である。

電子温度とイオン温度がほぼ等しい場合，電子質量がイオン質量と比べて極めて小さいため，開構造の磁場では電子がイオンより速く流出し，周辺部で電気的中性が破れ，静電ポテンシャルが形成される。このとき，動径方向の電場が生成されるため，イオン流出と$E \times B$シアフローが影響を受ける。このように，周辺部での輸送の物理を理解するためには磁場構造及び静電ポテンシャル形成，輸送の関係を自己無撞着に調べる必要がある。

これまで多くの磁場閉じ込め実験装置で静電ポテンシャルや電場の計測が行われ，磁場と電場の構造の関係が調べられた。また，流体モデルを使った理論シミュレーション研究では共鳴磁場摂動を加えた場合の電場構造が調べられた。さらに，電子を案内中心粒子モデルで解き，イオンは運動方程式を解く粒子モデルによるシミュレーション研究も行われ，スクレイプオフ層でのプラズマフロー形成が研究されたが，輸送に対する電場の効果は調べられなかった。このように，先行研究では，プラズマ周辺部における磁場構造と静電ポテンシャル形成，輸送の関係は十分に理解されていない。

そこで，電場もしくは静電ポテンシャル構造を自己無撞着に計算して，磁場構造と静電ポテンシャル形成の関係を明らかにして，粒子運動，さらには輸送に対するそれらの影響を調べるために，出願者は，第一原理に従って，電子・イオンの運動方程式を直接解く静電 Particle-in-Cell(PIC)コードを独自で開発して研究を進めた。コード開発は空間１次元・速度３成分(1D3V)から空間２次元・速度３成分(2D3V)へ順次かつ着実に進められ，また，シミュレーション規模を大規模にするためにコードの分散並列化も進めた。開発したコードを使い，それぞれの特徴を活かして，以下のような研究成果を挙げた。

まず，1D3V-PIC コードによる輸送研究により，並列に並ぶ電流フィラメントによるミラー磁場構造とその磁場構造により自発的に形成された静電ポテンシャルによって壁へ向かう粒子及び熱フラックスが低減されることを見出した。このフラックス低減は，フラックスの空間的広がりを考慮できる 2D3V-PIC コードにおいても確認され，壁に沿った方向にフラックスが輸送されることにより，そのピーク値が低減されることを明らかにした。これらの結果について電流フィラメントの個数や強度に対する依存性も調べられ，個数及び強度の増加により，フラックス低減効果が強まることも示され，電流フィラメントによる磁場構造とフラックス低減の関係を明確にした。ここで示されたフラックス低減法は磁場閉じ込めプラズマだけでなく，宇宙機や人工衛星への応用も示唆された。

また，2D3V-PIC コードによるトロイダルリミターを模擬する２次元スラブモデルで，南部モデルによる衝突効果を組み込んで新古典的な輸送を模擬し，また，トーラスプラズマの磁場構造を模擬する磁場を導入して計算を行った。このモデル磁場ではトーラスプラズマの主半径と副半径の比を変更することで磁場勾配ドリフトの大きさを制御することができる。計算の結果，磁場勾配ドリフトが大きくなることによりポロイダル方向の中心線を挟んで非対称な静電ポテンシャルが形成されることが示された。次に，主半径を十分に大きくとることで磁場勾配ドリフトの効果を小さくする磁場構造を取り，プラズマ温度を変化させることでラーマー半径を変化させる計算を行った。計算の結果，ラーマー半径が大きくなることで動径方向の輸送が強まること，周辺部の内側で負の静電ポテンシャルが形成されることを示した。このように，磁場勾配ドリフトの効果とラーマー半径の効果を分離することで，それぞれの効果による静電ポテンシャル形成への影響を明確にすることができた。

さらに，２次元スラブモデルに電流フィラメントを配置して磁気島を模擬して，磁気島が静電ポテンシャル形成及び輸送に与える影響を調べた。電流フィラメントの強度や個数を増加することで，

形成される静電ポテンシャル構造が変わること，イオンのラーマー半径と磁気島の大きさの比が増加すると動径方向のフラックスが増加することが示された。最後に，トカマクにおける磁気島を２次元スラブモデルで模擬するため，ポロイダル方向に周期境界条件を課してファデーエフ平衡による磁気島構造を導入した。この磁気島モデルでは磁気島を挟んでポロイダル磁場の向きが異なるため，トカマクとは異なる磁場構造である。しかし，磁気島を巧みに表現することができるため，磁気島における粒子輸送を調べることができる。磁気島の大きさに対してイオンのラーマー半径が大きくなると，イオンのラーマー運動によりイオンは磁気島の外へ移動することができ，小さい場合は磁気島内にイオンが捕らわれていることが示され，磁気島によるイオン輸送の影響を定量的に調べることができた。

本研究で用いた静電 PIC シミュレーション法は典型的な手法であるが，磁場構造や境界条件，シミュレーションボックスなど，ち密なシミュレーションモデルを設定することにより，磁場構造と静電ポテンシャル形成，輸送の関係を第一原理に基づいて系統的かつ定量的に調べた。開構造の磁場構造をもつ周辺プラズマではいくつかの物理が絡まることで輸送現象が複雑になるのに対して，磁場勾配ドリフト・ラーマー半径・磁気島の大きさのように，問題を基礎的な物理過程へと切り分けることで，それぞれの物理過程と，静電ポテンシャル形成及び輸送の関係を初めて明確にすることができた。本研究は磁場閉じ込め核融合プラズマの周辺部における基礎研究として，学術的に高く評価される。

以上ついて出願者は博士論文を執筆し、研究成果は主著者として１編が国際学術雑誌に掲載され，２編が投稿中である。また，出願者は国際会議で４回のポスター発表を行っている。出願者による研究成果は，博士論文の内容に十分値するものであり，本審査委員会は，本論文が博士学位論文として十分な価値を有するものと判断した。