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論文内容の要旨

The concept of a field-reversed configuration (FRC) is attractive for fusion plasmas because the magnetic configuration is very simple and a high beta plasma is confined inside the magnetic separatrix. The physics of FRC's has so far been studied from both theoretical and experimental points of view. An ideal MHD theory predicts that compact tori become unstable against an internal tilt mode. On the other hand, many experimental observations show that FRC plasmas remain stable for many growth times.

Until now, theoretical and numerical studies have examined various physical effects which have not been taken into account in an ideal MHD theory. They are roughly classified into the following three effects: (A) the finite ion Larmor radius effect, (B) the profile control effect, and (C) the ion beam effect. However, this contradiction remains unsolved up to the present. For example, the kinetic simulations with the particle orbit effect have disclosed that the tilt mode can be stabilized for a kinetic plasma of $\bar{s} \sim 1$, but it tends to be unstable for a moderately kinetic plasma of $2 \leq \bar{s} \leq 5$. On the other hand, in experiments, it is reported that the tilt mode is stable over a wide range of $\bar{s}$ $(1 < \bar{s} < 8)$. This fact means that the tilt stability is not determined only by a single parameter $\bar{s}$. The numerical simulation by using an extended MHD model with Hall terms was carried out to verify the profile control effect and found that a FRC with a hollow current profile becomes stable for a high enough separatrix beta value. In this model, however, $\bar{s}$ decreases as the current profile becomes hollow and the stable configuration is realized in kinetic plasmas of $\bar{s} \sim 1$. Therefore, this model cannot distinguish the profile control effect from the finite ion Larmor radius effect. In considering which of various effects is a key process leading to the tilt stabilization of FRC plasmas, it is important to develop the physical model which can control each effect independently and deal with them simultaneously. We carry out the three-dimensional macroscale electromagnetic particle simulation based on such a physical model.

We consider a FRC plasma confined by a uniform external magnetic field within a cylindrical conducting vessel. The plasma consists of thermal ions, thermal electrons, and cold beam ions which are treated as superparticles. The simulation starts from two-dimensional equilibrium. The temporal evolution of the system is given by solving both the equations of motion and the Maxwell equations in a self-consistent manner. In the present model, three kinds of parameters can be controlled independently. The first is the kinetic parameter $\bar{s}$ which controls the finite ion Larmor radius effect. The second are the profile control parameters β_{sp} and D which determine the pressure at the separatrix, and the hollowness of the current profile, respectively. The third are the number ratio of the beam ions to the thermal ions N_b/N_i, and the current ratio of the beam ions to the thermal plasma I_b/I_p, which control the ion beam effect. We carry out several simulation runs for a moderately kinetic plasma of $2 \leq \bar{s} \leq 5$ to clarify the tilt stabilization mechanism in this region.

In the first place, we examine the dependences of tilt instability on both the finite ion Larmor radius effect and the profile control effect by carrying out several simulation runs with different values of β_{sp}, $\bar{s}$, and D. The result is that it is effective against the tilt instability to increase the separatrix beta value (β_{sp}) and the tilt mode can be stabilized for a high β_{sp} (≥ 0.2). On the other hand, the stabilization of tilt mode can be scarcely altered by changing the $\bar{s}$ value and the current profile for low β_{sp} (≤ 0.1) and moderately kinetic plasmas. The detailed analysis reveals that the number flux of the ions crossing the magnetic separatrix repeatedly ("cycling ions") increases in proportion to β_{sp} and the tilt stability is realized for a large number flux of cycling ions.

The stabilization mechanism by cycling ions is as follows. Tilt instability is triggered by the internal mode, i.e., the collective motion of plasma is generated inside the magnetic separatrix. The typical cycling ions execute a gradient-$\boldsymbol{B}$ drift in the vicinity of the separatrix, and so they exist outside the separatrix as long as they do inside the separatrix on the average. The ions which make a cyclic motion across the separatrix are not able to follow the collective motion when they are moving outside the separatrix. The phase difference between the collective motions of cycling ions and non-cycling ions is created in proportion to the period during which cycling ions exist outside the separatrix. When cycling ions come back inside the separatrix, the internal tilting motion is disturbed by the motion of cycling ions. In other words, they play a role to suppress the tilting motion because their motion is out of phase with the tilting motion. The number of cycling ions increase as β_{sp} increase and thus the tilt mode is stabilized for a high β_{sp}. One can speculate that the cycling ions executing a gradient-$\boldsymbol{B}$ drift play a role as "chain" to connect the internal plasma with the external plasma and stabilize the tilting motion through their "chain" effect.

In the second place, we examine the dependences of tilt instability on the ion beam effect by carrying out two types of simulation runs. The first type is the case when the beam velocity varies while keeping the total number of beam ions for each run. The second type is the case when the total number of beam ion varies while keeping the beam velocity for each run. For both cases, the growth rate remains almost unchanged until the current ratio I_b/I_p reaches the critical value of 0.03. However, the growth rate gradually decreases as the ratio exceeds the critical value. The detailed examination reveals that this phenomena can be explained in terms of the effective $\bar{s}$ value, $\bar{s}_{eff}$, which is obtained by using the average velocity of all ions in place of the ion thermal velocity. The $\bar{s}_{eff}$ value is almost the same as $\bar{s}$ when $I_b/I_p < 0.03$. However, the derivation of $\bar{s}_{eff}$ from $\bar{s}$ becomes distinct for $I_b/I_p > 0.03$ and $\bar{s}_{eff}$ becomes smaller as I_b/I_p increases. We have the relation $\bar{s}_{eff} \sim 1$ for $I_b/I_p \sim 0.5$.

It is concluded that the tilt stabilization by the energetic ion beam is realized for the small value of $\bar{s}_{eff}$.

By comparing the above two cases, we examine the relation between the tilt growth rate and the kinetic energy ratio of total beam ions to total thermal plasma. In the case the velocity of beam ions varies, the ion beam needs 40% of the kinetic energy of thermal ions to reduce the growth rate below a half of that for the case without beam ions. On the other hand, in the case the total number of beam ions varies, only 10% of the kinetic energy of thermal ions is needed for the beam ions to get the same growth rate. Thus, the tilt mode can be suppressed more effectively by increasing the number ratio N_b/N_i.

論文の審査結果の要旨

単純な磁場配位と高ベータ値により、ＦＲＣプラズマは魅力的な核融合装置として現在まで多くの研究がなされてきた。理想ＭＨＤ理論から不安定となることが予測される傾斜モードが実験では予測に比べ遥かに安定であることが、ＦＲＣプラズマに関する謎として知られている。この謎を解くため、本論文は、運動方程式とマクスウェル方程式をセルフコンシステントに解く電磁粒子シミュレーションを行い、ＦＲＣプラズマの傾斜モード安定化の物理機構を明らかにした。まず、本研究は、シミュレーションにより、有限ラーマー半径や電流分布の効果に比べ、セパラトリクスのベータ値の増加が、傾斜モードの安定化に最も有効であることを見出した。さらにその安定化の物理機構を明らかにするため、セパラトリクスの内外を往来する粒子（アンカリング・イオン）の挙動を綿密に調べ、セパラトリクスベータ値の増加に伴うアンカリング・イオンのフラックスの増大が集団運動としての傾斜モードの位相を乱し、安定化をもたらすことを示した。また、本論文では、全電流に対するビーム電流の比がある閾値を超えるとビームエネルギーの大小に関わらず傾斜モードが安定化されることが確かめられた。従って、ビーム速度の増大よりもビーム粒子数の増加によって、より低エネルギーで安定化が可能となり、熱的イオンエネルギーに比べて僅かなビームエネルギーでも傾斜モードの安定化が実現できることが示された。以上のように、本論文は、電磁粒子シミュレーションに基づくＦＲＣプラズマの傾斜モードの精密な解析により、その安定化機構に対する新しい知見と物理的描像を示した。よって、本論文は博士論文としての価値を十分に有し、合格であると判断した。

次に面接試験において、まず出願者が博士論文の内容について説明を行い、その後審査委員全員による論文内容およびプラズマ物理学・シミュレーション手法に関する様々な質問に対して返答を行った。その結果、出願者は、研究の動機、目的、方法および研究成果を的確に述べ、これまでのＦＲＣプラズマに関する他の研究成果との関連性およびこの博士論文で得た新しい知見の意義を十分に理解していることが認められた。博士論文における精密な研究方法とその独創的な研究成果からプラズマ物理学・シミュレーション手法を十分に修得し優れた理論解析能力を有すると判断された。また、その他の関連分野についての豊富な知識を備えていることが質疑応答を通して明らかになった。さらに、提出された博士論文から、出願者は英文による十分な記述能力を有していることが認められた。従って、審査委員会は、出願者が試験に合格であると判断した。

以上の審査の結果、博士論文審査委員会は、本論文が博士論文として合格であり、出願者が学位を授与されるに十分な能力を有していると結論した。