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論文内容の要旨

It is well known that magnetic field configurations in a variety of fusion devices evolve toward ordered states with well-organized structure. These states can be described only by a few global parameters, such as total current or magnetic flux and geometry of the device, but independent of the detailed initial condition and the dynamical process of the system. Similar phenomena are observed in many other natural systems. In general the phenomenon that a system with a disordered structure spontaneously relaxes to a state with an ordered structure is called "self-organization".

In the last two decades, Taylor's theory has attracted considerable attention of plasma physicists, because it has been able to predict a stable magnetic structure, for example, the field reversal structure of the reversed field pinch (RFP) and the spheromak configuration. Taylor conjectured that a weakly resistive magnetohydrodynamic (MHD) plasma would evolve toward a minimum magnetic energy state under the constraint of total magnetic helicity conservation, and predicted that a self-organized state (minimum magnetic energy state) is a force-free equilibrium.

It should be emphasized that the Taylor's theory can only be applied to a case where the plasma pressure is uniform throughout the whole system. In reality, however, an excess free magnetic energy is transformed into thermal energy. In general the released thermal pressure has a spatial structure because of the spatial dependence of current density (ohmic heating). In plasmas there are several mechanisms that can lead to redistribution of thermal energy, such as, convection, expansion and thermal conduction, it is not a natural consequence that the plasma pressure becomes spatially homogeneous. Many efforts have been made to extend the Taylor's theory to a finite pressure MHD plasma. However, most of the works have reached to the Taylor's force-free state.

In order to clarify the effect of the plasma pressure on the self-organization process of an MHD plasma, we have employed a three-dimensional MHD simulation code with a fourth-order accuracy both in time and space, and have carried out the simulation under the condition that the plasma is confined by the electrically conducting and thermally insulated vessel.

It is confirmed that driven magnetic reconnection plays a crucial role in the self-organization process. It is driven magnetic reconnection that actuates the selective dissipation of magnetic energy. The present study has revealed new features of the MHD self-organization. The value of $\mathbf{j} \cdot \mathbf{B}$ is negatively peaked in the vicinity of the reconnection points caused by kink flows, while that of $\mathbf{j} \cdot \mathbf{j}$ is sharply peaked at the same reconnection regions. The sharp peakings of $\mathbf{j} \cdot \mathbf{j}$ and the negative peakings of $\mathbf{j} \cdot \mathbf{B}$ at the reconnection points act to anomalously enhance the dissipation of magnetic energy and to critically reduce the dissipation rate of magnetic helicity, respectively. This implies that the helicity conservation is not a substantiated property for the MHD self-organization, though it has been widely believed so far. The present study has also revealed that the work done by the magnetic force $v \cdot (\mathbf{j} \times \mathbf{B})$ has an important contribution to the rapid dissipation of magnetic energy because a fast plasma flow is created by this force.

It is also found that the onset time of driven magnetic reconnection is almost independent of the electrical resistivity. For a case of an exceptionally large electrical resistivity, the magnetic reconnection process becomes not so conspicuous because most of the free magnetic energy dissipates before the first magnetic reconnection takes place and the process becomes almost diffusive. This indicates that a "weak electrical resistivity" condition, or a collisionless condition, is necessary for a clear-cut self-organization to take place.

We have demonstrated that a finite pressure MHD plasma system relaxes toward a state with a minimum magnetic energy in which the magnetic field configuration is similar to that for the pressureless case. This is because the most important physical process in self-organization is the driven magnetic reconnection process and the pressure is not the primary cause of reconnection. However, the magnetic field configuration is not described by the Taylor's force-free minimum energy state. The driven magnetic reconnection process produces an extremely heated plasma in the vicinity of a reconnection point. The locally heated plasma modifies the magnetic field through the pressure gradient force. Thus, the perpendicular electric current is generated to balance with the pressure gradient force. It is confirmed that the new self-organized state of a finite pressure MHD plasma is an MHD equilibrium $\mathbf{j} \times \mathbf{B} = \nabla p$, instead of the Taylor's minimum energy state.

We have also confirmed that the temporal evolution of magnetic energy and helicity is almost independent of the beta value of an initial uniform pressure and there are also no substantial effects of the initial plasma beta on the temporal evolutions of parallel (force-free) electric current and perpendicular electric current. Thus, there is no significant effect of the initial plasma beta on the self-organization of finite pressure MHD plasma. This suggests that, as far as the thermal energy released through the relaxation process is confined within a system where neither fast thermal conduction nor radiation cooling exist, the MHD plasma does not obey the Taylor relaxation process, but evolves on a non-Taylor relaxation process which leads to a force-balanced minimum energy state.

By introducing a heat conduction term into the energy conservation equation of the MHD equations, we have examined the effect of thermal conduction. The perpendicular electric current or equivalently the pressure gradient force in the self-organized state decreases as the thermal conductivity increases. It is concluded that the self-organized state of a finite pressure plasma approaches to a Taylor's force-free state in the presence of the thermal conduction. In this sense, the Taylor self-organized state is said to be only an approximate state.

We also discuss relaxation and self-organization of an MHD plasma under the influence of viscosity. We have found that viscous heating is an important process as well as the ohmic heating in the self-organization of an MHD plasma. For the case where the normalized viscosity has almost the same magnitude as the normalized electric resistivity, the energy conversion rate due to the viscous heating has the same order of magnitude as that due to the ohmic heating. For the case where the normalized value of viscosity is larger than that of electric resistivity, the rapid dissipation of magnetic energy takes place mainly through the viscous heating but not the ohmic heating. In this case the magnetic energy is converted to the thermal energy through two successive processes, i.e., the work done by the $\mathbf{j} \times \mathbf{B}$ force and the following viscous heating. This process can explain anomalous ion heating, which is observed in RFP experiment, because viscous heating is dominated by the ion viscosity.

論文の審査結果の要旨

核融合装置に磁気的に閉じ込められたプラズマが何らかの意味で不安定性であるがゆえに自分自身で進化し、最終的に何かある一つの状態に落ち着くことがある。この安定な最終状態は例えばプラズマの全磁束や全磁気エネルギーといったシステム全体の全力学量で特徴づけられており、系の初期値や細かい力学過程に依存しない。このように、非秩序的構造の物理系が自分自身で進化し一つの秩序的構造をもった物理系に緩和する現象は自然界でしばしば見られるもので、「自己組織化現象」と呼ばれている。

テイラーは弱抵抗性の磁化プラズマは全磁気ヘリシテイを保存しつつエネルギー極小の状態に進化するであろうと推測し、結果的にフォースフリーの状態に自己組織化されることを示した。テイラーの理論はシステムの進化を通じてプラズマ圧力が一様という場合にあてはまるものであるが、実際の場合は余分な磁気的フリーエネルギーはジュール加熱を通じて熱エネルギーとなり、一般にはプラズマ圧力の空間的な構造を持つようになると考えられる。これまでにテイラー理論にプラズマ圧力の影響を取り入れるべく幾多の試みがなされたが、その多くは、フォースフリーの状態に自己組織化されるというテイラーの結論を再現するに止まっていた。

本論文は磁化プラズマの自己組織化に対するプラズマ圧力の効果を明らかにする目的で、三次元のMHDシミュレーションコードを採用し、電気的には導体で熱的には絶縁性の容器で囲まれたプラズマ系の進化を時間・空間に関して四次の精度で計算した。シミュレーションの結果、幾つかの重要な物理現象が明らかにされた。すなわち：

○　磁気リコネクションの発生は、リコネクション点近傍に磁場と反対向きの局在化された電流を形成し、磁気ヘリシテイの散逸を遅くする。

○　この場合の自己組織化状態はプラズマの初期圧力に殆ど依存せず、磁場に平行な電流と同程度の垂直電流及び圧力勾配が存在し、磁気力と圧力勾配力とが釣り合うMHD平衡であることが確認された。

○　抵抗性散逸と電気抵抗に反比例する駆動型磁気リコネクションはともにプラズマ圧力の構造を作り出すが、自己組織化には後者の過程が重要となる。

○　プラズマの熱伝導は自己組織化の状態をフォースフリーの状態に近づけ、プラズマの粘性はイオン温度を上昇させる。等

以上、本論文は三次元のMHDシミュレーションによって、磁化プラズマの自己組織化に対するプラズマ圧力の効果を明らかにしたもので、プラズマ物理と自己組織化の本質にかかわる重要な結論が得られており、博士学位論文として十分の価値あるものと認められる。

論文審査委員会全員で出願者に口頭試問を行い、論文内容に関する質疑及び関連する基礎知識についての試験を行った。その結果、論文内容とその背景・展望などについて十分に理解していることが窺えた。関連する物理学の基礎的事項の理解も十分であると判断された。

論文は英語で書かれており、英語による討論も困難を感じない。また、論文説明を流暢な日本語で行った。

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。