様　式　Ｃ－１９、Ｆ－１９－１、Ｚ－１９　（共通）

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研究課題名（和文）Simulation study of the energy channel and the particle radial transport due to the energetic particle driven geodesic acoustic mode

研究課題名（英文）Simulation study of the energy channel and the particle radial transport due to the energetic particle driven geodesic acoustic mode

研究代表者

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研究成果の概要（和文）：エネルギー粒子駆動測地線音響モード（EGAM）は、エネルギー粒子からバルクプラズマにエネルギーを伝達することにより、プラズマ加熱効率に大きく影響します。 研究代表者はこの現象を調査し、以下の3つの側面で良好な成果を上げました。 (1) EGAM活動中の異常なバルクイオン加熱を初めてシミュレーションで再現し、そのメカニズムを確かな証拠で明らかにした。 (2) EGAMチャネリングのバルクイオン加熱効率を初めて体系的に調査した。 (3) 研究代表者は、CFQSという名前の準軸対称ステラレーターで、研究分野を拡大し、エネルギー粒子による不安定性を調査しました。

研究成果の学術的意義や社会的意義
本研究の学術的意義は、EGAMのエネルギーチャネルの物理機構を初めて解明したことにあります。これは、EGAMの理解を深めるだけでなく、磁場閉じ込め核融合の閉じ込めレベルのさらなる向上に貢献するものです。さらに、本研究の成果は、従来のステラレータだけでなく、トカマクや先進的なステラレータなど、他のタイプの磁気閉じ込め核融合装置にも適用可能であることがわかった。磁場閉じ込め核融合は、人類の将来のエネルギー問題を解決する鍵であるため、この研究の社会的意義は、人類の将来のエネルギー問題を解決するための新しいアイデアを提供することであると言えます。

研究成果の概要（英文）：The energetic particle driven geodesic acoustic mode (EGAM) strongly affects the plasma heating efficiency by transferring energy from energetic particles to bulk plasma. The principal investigator investigated this phenomenon and obtained good achievements in the following 3 aspects. (1) For the first time, the anomalous bulk ion heating during EGAM activity is reproduced in simulation, and the mechanism is clarified with solid evidence. It is found that sideband resonance is dominant during the energy transfer from EGAM to the bulk ions, and the transit frequencies of resonant bulk ions are one-half of the EGAM frequency. (2) For the first time, the bulk ion heating efficiency of EGAM channeling is systematically investigated. These investigations are helpful for improving heating efficiency in the experiment. (3) The principal investigator extended his research field and investigated energetic particle driven instabilities in a quasi-axisymmetric stellarator named CFQS.

研究分野：プラズマ閉じ込め

キーワード：EGAMチャネリング　測地線音響モード　バルクイオン加熱

１．研究開始当初の背景

Nuclear fusion may solve the energy crisis of human beings. For the magnetic confinement fusion, one of the most important issues is the plasma heating, because we are not able to create burning fusion plasma without effective heating. Also, there are many plasma activities, and one of them is the energetic particle driven geodesic acoustic mode (EGAM). EGAM strongly affects the plasma heating efficiency. On the one hand, the EGAM has advantage for plasma heating, because it establishes an energy channel from energetic particles to bulk ions via EGAM, and thus the energy of energetic particles can easily transfer to the bulk ions. In LHD, the effective bulk ion temperature can be increased from 0.4 keV to 0.7 keV during EGAM activities. On the other hand, the EGAM has disadvantage for plasma heating, because it enhances particle radial transport. In DIII-D, the neutron emission drops during the EGAM activities, this suggests the particles are transported outward from the core region. Similar phenomenon is also observed in LHD.

２．研究の目的

The applicant has carried out research for the following three purposes. (1) To understand the physical mechanism of anomalous bulk ion heating during EGAM activities. (2) To investigate the effect of different experimental parameters on the efficiency of anomalous bulk ion heating. (3) To expand the present research to understand the properties of other instability (for example Alfvén eigenmode), and to understand the properties of instabilities on other fusion devices (for example ASDEX-Upgrade Tokamak and CFQS Stellarator).

３．研究の方法

A hybrid simulation code for energetic particles interacting with a magneto-hydrodynamic (MHD) fluid, MEGA, is used for the simulations of EGAMs. Both the energetic particles and the thermal ions are described kinetically. The kinetic thermal ions are very important for EGAM channeling simulation because the Landau damping process is a kind of wave-particle interaction process, and this process can be simulated only by the kinetic thermal ions model. In past EGAM simulations by MEGA, the EGAM channeling was not found because of the MHD description of thermal ions.

The δf method is applied for the energetic particles. Before the δf method was developed, usual particle simulations were based on the importance sampling Monte Carlo technique, where the computational particles are assumed to have the same distribution in phase space as the physical particles in the problem being investigated. This technique suffered from noise problems. The δf method is based on the control variates Monte Carlo technique. In the δf method, the noise can be low if a good control variate f0 is chosen, while the high accuracy can be realized with large number of particles.

The spatial derivatives in equations are approximately calculated by using the finite difference method. To obtain higher accuracy, the higher order of the finite difference approximation is required, and more computational resources are consumed. In order to keep balance between accuracy and computational resources consumption, the 4th order finite difference approximation is applied in the present research. The Runge-Kutta method is applied for time integration. Similar with the cases of finite difference, the 4th order Runge-Kutta method is used in the present research to keep balance between accuracy and resources consumption.

A realistic 3-dimensional equilibrium generated by the HINT code is used for the simulation. This equilibrium data is based on the LHD shot #109031 at time t = 4.94 s. At this moment, the EGAM activity is very strong, thus it is a good dataset for reproducing the EGAM phenomenon. The following six parameters for the EGAM simulation are based on an LHD experiment: (1) The plasma major radius. (2) The magnetic field strength on the magnetic axis. (3) The electron density profile. (4) The safety factor profile. (5) The injected neutral beam energy. And finally, (6) a Gaussian-type pitch angle distribution function of energetic particles.

４．研究成果

The applicant obtained good achievements in 3 aspects.

(1) The mechanism of EGAM channeling is clarified for the first time

The phenomenon of EGAM channeling was reproduced in the simulation, as shown in Figure 1. Figure 1(a) shows the frequency spectrum of the simulated EGAM. The mode frequency in the linear stage is 50 kHz and then the frequency chirps up in the nonlinear stage. At t = 0.5 ms, the frequency has already exceeded 60 kHz. The frequency chirping rate $d\omega/dt$ gradually decreases with time. Figure 1(b) shows the time evolution of EGAM amplitude v_θ. The linear stage is from t=0 to about t=0.1ms. At t = 0.1 ms, the mode amplitude reaches the maximum value, and then steps into the nonlinear stage. Figure 1(c) shows the energy transfer of various species. In the present work, from t = 0 to t = 0.36 ms, the energy transferred from energetic particles is 63 J. About one-half of this energy (51%) is transferred to bulk ions (34%) and electrons(17%), while the other half is dissipated. The heating power to bulk ions around t = 0.1 ms is 3.4kWm^{-3}.

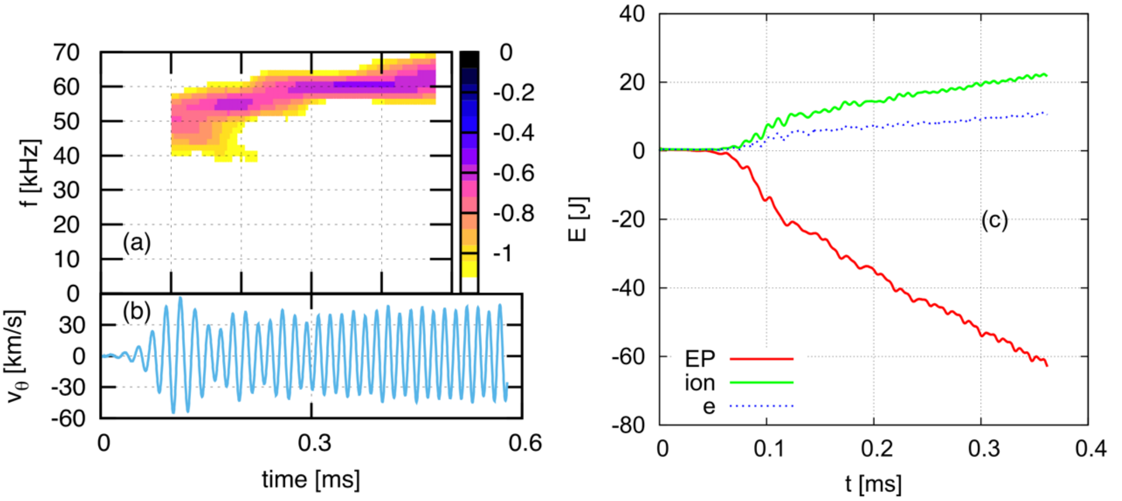

Figure 1. (a) The frequency spectrum of EGAM. (b) The time evolution of EGAM amplutude. (c) Energy transfer of various species during EGAM activity.

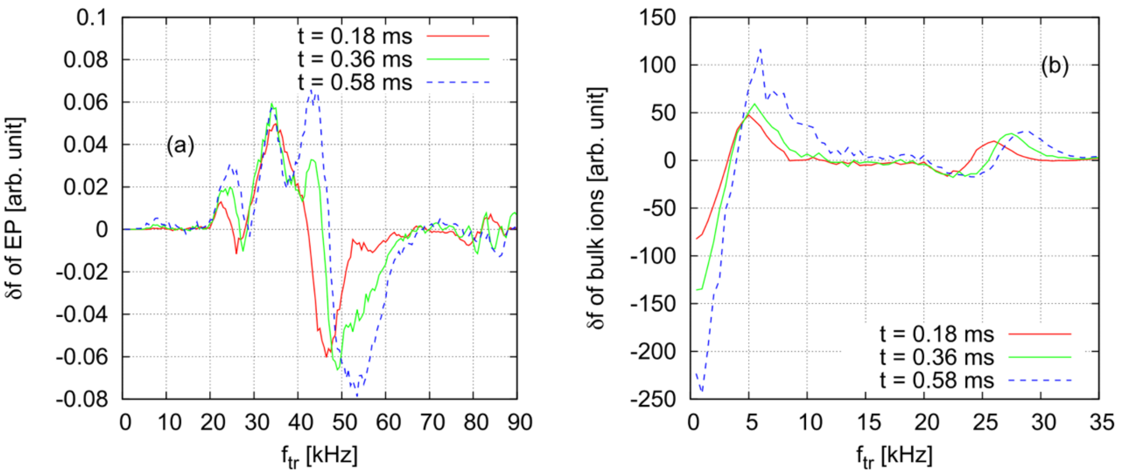

Figure 2. The δf distributions of (a) energetic particles and (b) bulk ions in f_{tr} phase space at t = 0.18 ms (red), t = 0.36 ms (green), and t = 0.58 ms (blue).

In order to identify the dominant resonant particles, the δf distribution of both energetic particles and bulk ions at different times are analyzed in the particle transit frequency space, as shown in figure 2. The EGAM obtains energy from energetic particles via inverse Landau damping, and EGAM transfers energy to bulk ions via Landau damping. These processes modify the distribution function of both energetic particles and bulk ions, and thus, δf values change with mode evolution. The particles with negative δf values form the hole structure in phase space, and the particles with positive δf values form the clump structure. Large absolute δf values indicate strong interactions between EGAM and resonant particles. Figure 2(a) shows the δf of energetic particles. A hole around f_{tr} = 50 kHz is formed. The bottom of this hole moves rightward. This indicates that the transit frequencies of particles in the hole increase with time and this increase of frequency is kept consistent with the chirping up of the

EGAM frequency. The resonance condition between EGAM and energetic particles is given by $f_{EGAM} = f_{tr,EP}$. Figure 2(b) shows the δf of bulk ions. Two clumps around f_{tr} = 25 kHz and ftr = 5 kHz are formed. The peaks of these clumps move rightward. This indicates that the transit frequencies of bulk ions in these clumps increase with time and these transit frequencies are kept at half of the EGAM frequency (and one-tenth of the EGAM frequency). Sideband resonance is important for the interaction between the EGAM and the bulk ions. This is the first time the resonance condition between EGAM and bulk ions during the establishment of EGAM channeling has been quantitatively revealed.

（2）The plasma parameters of EGAM channeling are systematically investigated for the first time

The properties of EGAM channeling are systematically investigated for the first time, and mode profiles in three-dimensional form are presented. Six conclusions are found as follows. First, during the EGAM activities without frequency chirping, EGAM channeling occurs in the linear growth stage but terminates in the decay stage after saturation. During the EGAM activities with frequency chirping, EGAM channeling occurs continuously in both linear growth stage and nonlinear saturated stage. Second, during the existence of the EGAM energy channel, the bulk ion heating power increases with time, but the energy transfer efficiency (E_{ion}/E_{EP}) does not change because both the energy absorption of bulk ions and the energy loss of energetic particles change together. Third, lower frequency EGAMs make energy transfer efficiency higher because the interactions between lower frequency mode and bulk ions are stronger. This is confirmed by changing the parameters of energetic particle pressure, energetic particle beam energy, and energetic particle pitch angle. Fourth, higher bulk ion temperature makes energy transfer efficiency higher because the transit frequency of bulk ions $f_{tr,ion}$ is higher, and thus, more bulk ions are resonant with mode and absorb energy. Fifth, the energy transfer efficiency increases with the decrease of dissipation coefficients. Less energy dissipates by decreasing the dissipation coefficients, and thus, more energy can be transferred to the bulk ions. Last, the isotope effect is analyzed with a hydrogen plasma configuration and with the hydrogen plasma density and temperature profiles. Under these conditions, the energy transfer efficiency in the deuterium plasma is lower than in the hydrogen plasma.

In experiment, the higher NBI power, the lower NBI velocity, the higher number of perpendicular injected particles, the higher bulk ion temperature, and the wider bulk ion temperature profile are probably applicable strategies for improving observation of EGAM channeling. Also, it is possible that EGAM channeling can be more easily observed in hydrogen plasma than that in deuterium plasma.

（3）Nonlinear properties of Alfvén eigenmodes in CFQS are investigated for the first time

A nonlinear simulation of the Alfvén eigenmode (AE) in the Chinese First Quasi-Axisymmetric Stellarator (CFQS) has been conducted for the first time. Both the m/n = 3/1 global Alfvén eigenmode (GAE) and the m/n = 5/2 toroidal Alfvén eigenmode (TAE) were found, where m is the poloidal mode number and n is the toroidal mode number. Four important results were obtained as follows. First, the instability in the CFQS in three-dimensional form was shown for the first time. Second, strong toroidal mode coupling was found for the spatial profiles of AEs, and it is consistent with the theoretical prediction. Third, the resonant condition caused by the absence of axial symmetry in CFQS was demonstrated for the first time. The general resonant condition is $f_{mode} = Nf_{\phi} - Lf_{\theta}$, where f_{mode}, f_{ϕ}, and f_{θ} are mode frequency, particle toroidal transit frequency, and particle poloidal transit frequency, respectively; N and L are arbitrary integers, represent toroidal and poloidal resonance numbers. For GAE, the dominant and subdominant resonant conditions are $f_{GAE} = 3f_{\phi} - 7f_{\theta}$ and $f_{GAE} = f_{\phi} - f_{\theta}$, respectively. For TAE, the dominant and subdominant resonant conditions are $f_{TAE} = 4f_{\phi} - 9f_{\theta}$ and $f_{TAE} = 2f_{\phi} - 3f_{\theta}$, respectively. The toroidal resonance numbers are different from the toroidal mode numbers by 2. This indicates that the 2-fold rotational symmetry affects the resonance condition. On the other hand, the subdominant resonances satisfy N = n, which is expected for the axisymmetric plasmas and most of the toroidal plasmas including stellarators. Fourth, the nonlinear frequency chirpings of AEs in CFQS were demonstrated for the first time. Hole and clump structures were formed in the pitch angle and energy phase space, and the particles comprising the hole and clump were kept resonant with the GAE or TAE during the mode frequency chirping.

５．主な発表論文等

〔雑誌論文〕　計2件（うち査読付論文　2件／うち国際共著　0件／うちオープンアクセス　0件）

１．著者名 Wang Hao、Todo Yasushi、Osakabe Masaki、Ido Takeshi、Suzuki Yasuhiro	４．巻 60
２．論文標題 The systematic investigation of energetic-particle-driven geodesic acoustic mode channeling using MEGA code	５．発行年 2020年
３．雑誌名 Nuclear Fusion	６．最初と最後の頁 112007～112007
掲載論文のDOI（デジタルオブジェクト識別子） 10.1088/1741-4326/ab8a04	査読の有無 有
オープンアクセス オープンアクセスではない、又はオープンアクセスが困難	国際共著 －

１．著者名 Wang Hao、Todo Yasushi、Oasakabe Masaki、Ido Takeshi、Suzuki Yasuhiro	４．巻 59
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掲載論文のDOI（デジタルオブジェクト識別子） 10.1088/1741-4326/ab26e5	査読の有無 有
オープンアクセス オープンアクセスではない、又はオープンアクセスが困難	国際共著 －

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〔図書〕　計0件

〔産業財産権〕

〔その他〕

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6．研究組織

	氏名 （ローマ字氏名） （研究者番号）	所属研究機関・部局・職 （機関番号）	備考

7．科研費を使用して開催した国際研究集会

〔国際研究集会〕　計0件

8．本研究に関連して実施した国際共同研究の実施状況

共同研究相手国	相手方研究機関