様　式　Ｃ－１９、Ｆ－１９－１、Ｚ－１９　（共通）

科研費
KAKENHI

科学研究費助成事業　　研究成果報告書

令和　２ 年　 ６ 月 １１ 日現在

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研究種目：若手研究(B)
研究期間：2016～2019
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研究課題名（和文）First-principle simulation study of a novel self-heating channel for burning plasmas

研究課題名（英文）First-principle simulation study of a novel self-heating channel for burning plasmas

研究代表者
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研究者番号：１０５８４６９１

交付決定額（研究期間全体）：（直接経費）　　2,600,000円

研究成果の概要（和文）：この研究の目的は、最近発見された自己加熱チャンネルが核融合プラズマ性能にどう影響するかを明らかにすることである。これまで検討していた自己加熱チャンネルは、電磁流体として記述されたプラズマにおいてのみ存在することが判明した。ジャイロ運動論モデルによればとアルフベン波とイオン音波の結合は高周波数帯域で事実上消滅してしまう。一方、（１）高速イオン励起アルフベン波の新しい分枝の存在（２）大振幅アルフベン波がテアリングモードに対し、線形安定な配位にもかかわらず磁気島を生成するという2つの発見があり、未知の加熱チャンネルの探索を行う動機付けとなった。その物理機構に関しては現在、研究中である。

研究成果の学術的意義や社会的意義
核融合炉を実現するためには効果的な自己加熱機構の存在が重要である。この基礎研究は、以前発見した自己加熱機構の理解を深めるとともに２つの可能性を提示した。この研究成果は、Nature Communicationsに論文発表した。

研究成果の概要（英文）：The purpose of this research was to clarify how a recently discovered self-heating channel influences the performance of magnetically confined fusion plasmas. Using a more realistic numerical model of a tokamak plasma, we learned that the originally considered self-heating channel exists only in the magnetohydrodynamic (MHD) description of the plasma. When a more realistic gyrokinetic model is used, the coupling between Alfven waves and ion sound waves effectively vanishes in the high-frequency range of interest. Meanwhile, we have also made two discoveries that motivated us to search for unknown self-heating channels in other directions: (1) We found a new branch of Alvenic waves induced by fast ions. (2) We found that large-amplitude Alfven waves in an MHD-kinetic hybrid simulation give rise to magnetic islands even when the configuration is linearly stable with respect to conventional tearing modes. The underlying physics and practical implications are currently under investigation.

研究分野：トカマクプラズマ物理学

キーワード：突発的大事象　異常自己加熱　高エネルギー粒子　ハイブリッドシミュレーション　ジャイロ運動論的シミュレーション　トカマクプラズマ

１・研究開始当初の背景

One crucual condition for a tokamak power plant to become feasible is that the energetic alpha particles produced in deuterium-tritium fusion reactions will be able to transfer most of their kinetic energy (3.5 MeV) to the much cooler fuel ions (~30 keV). For this to be possible, the energetic alpha particles need to be sufficiently well confined for a sufficiently long time, and an efficient energy channels from the alphas to the fuel needs to exist. Collisional heating (alphas → electrons → fuel ions) is the most robust channel, but researchers are hoping that additional (noncollisional) energy channels will increase the self-heating efficiency of a fusion plasma. This would make it easier to access and maintain the fusion conditions.

This research was motivated by the discovery of a coupling between Alfvén waves and ion sound waves at unexpectedly high frequencies. Such Alfvén-acoustic coupling provides an additional self-heating channel, where alpha particles drive Alfvén waves, whose coupling to ion sound waves heats the fuel ions by a mechanism known as ion Landau damping: alphas → Alfvén waves → acoustic waves → fuel ions .

２・研究の目的

The purpose of this research was to evaluate the efficiency of the newly discovered Alfven-acoustic self-heating channel in comparison to other (possibly competing) mechanisms, and to obtain a better understanding of the underlying physics.

３・研究の方法

The previous simulations that motivated the present work were performed using a resistive magnetohydro-dynamic (MHD) model, which was implemented in a global 3-D nonlinear simulation code called MEGA. Although MEGA allows to treat energetic ions with a gyrokinetic model, the bulk (thermal) plasma was treated as a single MHD fluid. This captures the frequency spectrum of ion sound waves rather accurately, but misses their kinetic damping. Therefore, the first part of this project consisted of reevaluating the Alfvén-acoustic couplings with a more realistic model for the bulk plasma. The approach we have chosen was to collaborate with colleagues at Max Planck Institute for Plasmas Physics (IPP) in Garching/Germany, where a suitable linear gyrokinetic code called LIGKA had been developed. LIGKA is one of the codes approved to be used for ITER. A large portion of this KAKENHI grant was used by the PI to visit IPP each year. There, the PI received training in the use of LIGKA and participated in the resolution of various technical problems, which arose because we had to examine new parameter regimes.

Meanwhile, we also continued simulations using MEGA, with the goal of analyzing in more detail the Abrupt Large-amplitude Events (ALE) in JT-60U plasmas, where the Alfven-acoustic heating channel was first found. The simulations using MEGA are computationally very expensive and had to be performed in high-performance supercomputers; namely, Helios and its successor JFRS-1, as well as K computer and ICE-X. Altogether, on the order of 100 million core·hours were consumed.

All simulations were performed in realistic tokamak geometry. Most cases were based on JT-60U tokamak experiments where ALEs had been observed. In addition, a few cases were run for a tentative scenario for the current Japanese design of a DEMO power plant.

４・研究成果

(1) Our analyses of the JT-60U scenario using the LIGKA code revealed that clear signatures of Alfvén-acoustic couplings exist only in exotic parameter regimes, where the electron temperature T_e is several times higher than the bulk ion temperature T_i. As an example, Fig.1(a) shows the spectrogram of the fluctuations driven by an internal antenna (mimicking drive from resonant energetic ions) for a large value of the temperature ratio $T_e / T_i = 4.77$. The arrow indicates an excited ion sound wave branch. This signal is effectively absent in Fig.1(b), which shows the fluctuation spectra for a realistic temperature ratio $T_e / T_i = 1.68$. Moreover, our estimates of the energy transfer indicate that even in the exaggerated case in Fig.1(a) the Alfvén-acoustic channel cannot compete with direct damping of the Alfvén waves by several orders of magnitude, so we assume that this result is robust. (The gyrokinetic model in LIGKA relies on certain simplifying assumptions, but all corrections are expected to be of higher order.) Therefore, we conclude that this Alfvén-acoustic self-heating channel is unlikely to be relevant in practice. This result was published in [Bierwage et al., *Nucl. Fusion* **57** (2017) 116063] and the details can be found in that paper.

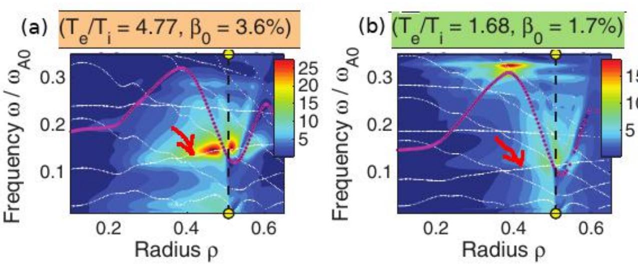

Fig.1: Spectrogram of antenna-driven fluctuations in LIGKA simulations with (a) increased and (b) normal electron temperature. The color contours represent the magnitude of the antenna response. The white and magenta curves indicate, respectively, the spectra of ion sound and Alfvén waves. The red arrow indicates the sound branch being driven. Here, a clear response is visible only in (a). [Adapted from Fig. 13 of Nucl. Fusion **57** *(2017) 116063.]*

Although a negative outcome was obtained for the Alfvén-acoustic self-heating channel, we have also made two discoveries during the course of this project that motivated us to search for unknown energy channels in other directions. These are described in the following items (2) and (3).

(2) When we included hot Maxwellian deuterons with temperature $T_h \geq 100$ keV >> $T_i = 1.3$ keV in LIGKA and examined damped local solutions of the dispersion relation, we discovered a previously unseen branch of waves, whose frequency varies with the hot ion temperature T_h. The example in Fig.2(a) shows results for $T_h = 100$ keV, where we dubbed this new wave branch "Energetic particle-induced Alfvén-acoustic Waves (EAAW)". In the presence of these waves, we also observe a disappearance of low-frequency Alfvén-acoustic couplings; in particular, the so-called Beta-induced Alfvén-Acoustic Eigenmode (BAAE) gap disappears, as shown in Fig.2(b). This observation suggests that the newly found wave branch affects energy channeling at very low frequencies, but it is not clear yet whether the effect of the energetic ions is beneficial or detrimental for self-heating. The correct physical interpretation also remains to be found.

The results shown in Fig.2 were obtained for a JT-60U tokamak scenario, and we found a similar effect in a case based on a tentative plasma scenario of the Japanese DEMO power plant design. Currently, we are investigating whether these new wave branches can be reproduced with more accurate models; for instance, including magnetic drift effects. If confirmed, we will prepare a paper reporting this finding.

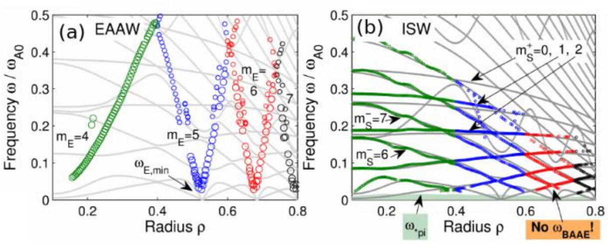

Fig.2: Frequency spectra computed with the LIGKA code showing (a) our newly discovered "Energetic particle-induced Alfvén-acoustic Waves (EAAW)" and (b) ion sound waves (ISW). The gray curves in the background show the Alfvén and acoustic wave spectra in the MHD limit, where a BAAE band gap exists at low frequencies (~ 0.05). This gap disappears in the presence of energetic ions and we speculate that this is due to the formation of the new EAAW branch. [Adapted from an invited talk given by the PI at the 21st MHD Stability Control Workshop held Nov. 7-9 2016 at General Atomics, San Diego/USA.]

(3) Our search for novel interaction channels between energetic ions and the thermal bulk plasma encompassed also a detailed examination of intense bursts of Alfvén wave activity that are known as Abrupt Large-amplitude Events (ALE) and that were first observed in beam-driven JT-60U plasmas. For this purpose, we performed detailed analyses of simulation results obtained with the MEGA code in our previous Wakate-B KAKENHI project (2013-2015), where we had successfully simulated ALEs for the first time. These data analyses included Poincaré plots of the magnetic field topology before, during and after an ALE. To our surprise, we found that ALEs leave behind multiple chains of magnetic islands as shown in Fig.3, in spite of the fact that the configuration at hand is linearly stable with respect to so-called tearing modes. (Indeed, after the ALE, these magnetic islands slowly disappear through resistive dissipation, which confirms the absence of tearing instabilities.) The actual mechanism producing the islands on the short time scale of the ALE burst is currently under investigation. We speculate that they emerge from the chaos that exists when Alfvén waves of different helicities are driven to large amplitudes and acquire non-wave-like components. This discovery of "reconnecting Alfvén waves" may have a significant impact on various branches of plasma physics and it was published along with other results of our ALE study in [Bierwage et al., *Nature Communications* **9** (2018) 3282].

Results of a sensitivity study and numerical convergence tests confirmed that the formation of magnetic islands during ALEs is a robust feature of the resistive MHD model used in the MEGA code. However, it is also clear that the resistive dissipation is a very rough approximation of the underlying kinetic processes that govern magnetic reconnection in real high-temperature plasmas, where particle-particle collisions are rare and various kinds of waves abound. A more realistic treatment of the "Alfvénic chaos" that we think is responsible for the observed magnetic reconnection will require a gyrokinetic treatment of the electrons and a fully kinetic treatment of all ions (both thermal and energetic). Therefore, some skepticism is appropriate until more evidence is found. Our results have been widely disseminated through papers, talks and press releases. They have attracted the attention of at least some experimentalists, theorists and computational physicists, who expressed interest in testing our findings. We will also continue to work on this subject, since it promises to yield new insights regarding plasma heating and the transport of both energy and particles.

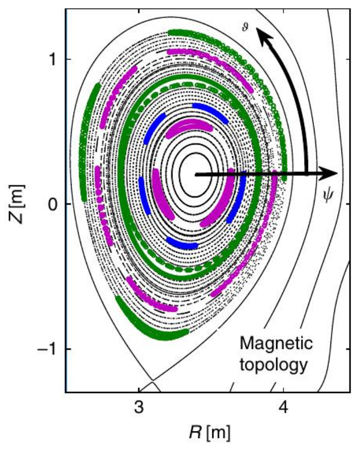

Fig.3: Poincaré plot of the magnetic field topology in a vertical cross-section of a JT-60U tokamak plasma after an Abrupt Large-amplitude Event (ALE) simulated with the MEGA code. The colored data points highlight magnetic islands, with each color representing a different toroidal wavelength. [Adapted from Fig.7 of Bierwage et al., Nature Communications **9** *(2018) 3282.]*

５．主な発表論文等

〔雑誌論文〕　計7件（うち査読付論文　5件／うち国際共著　6件／うちオープンアクセス　2件）

１．著者名 Andreas Bierwage, Kouji Shinohara, Yasushi Todo, Nobuyuki Aiba, Masao Ishikawa, Go Matsunaga, Manabu Takechi, Masatoshi Yagi	４．巻 9
２．論文標題 Simulations tackle abrupt massive migrations of energetic beam ions in a tokamak plasma	５．発行年 2018年
３．雑誌名 Nature Communications	６．最初と最後の頁 3282, 1-11
掲載論文のDOI（デジタルオブジェクト識別子） 10.1038/s41467-018-05779-0	査読の有無 有
オープンアクセス オープンアクセスとしている（また、その予定である）	国際共著 該当する

１．著者名 A. Bierwage, N. Aiba, A. Matsuyama, K. Shinohara, M. Yagi	４．巻 61
２．論文標題 Reconnecting instabilities in JT-60SA during current ramp-up with off-axis N-NB injection	５．発行年 2019年
３．雑誌名 Plasma Physics and Controlled Fusion	６．最初と最後の頁 014025, 1-17
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１．著者名 A. Bierwage and Y. Todo	４．巻 220
２．論文標題 Benchmark of multi-phase method for the computation of fast ion distributions in a tokamak plasma in the presence of low-amplitude resonant MHD activity	５．発行年 2017年
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掲載論文のDOI（デジタルオブジェクト識別子） http://dx.doi.org/10.1016/j.cpc.2017.07.022	査読の有無 有
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２．論文標題 Gyrokinetic analysis of low-n shear Alfven and ion sound wave spectra in a high-beta tokamak plasma	５．発行年 2017年
３．雑誌名 Nuclear Fusion	６．最初と最後の頁 116063, 1 -21
掲載論文のDOI（デジタルオブジェクト識別子） https://doi.org/10.1088/1741-4326/aa80fe	査読の有無 有
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1．著者名 A. Bierwage, K. Shinohara, Y. Todo, N. Aiba, M. Ishikawa, G. Matsunaga, M. Takechi and M. Yagi	4．巻 57
2．論文標題 Self-consistent long-time simulation of chirping and beating energetic particle modes in JT-60U plasmas	5．発行年 2017年
3．雑誌名 Nuclear Fusion	6．最初と最後の頁 016036, 1-19
掲載論文のDOI（デジタルオブジェクト識別子） 10.1088/1741-4326/57/1/016036	査読の有無 有
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1．著者名 A. Bierwage, K. Shinohara, Y. Todo, N. Aiba, M. Ishikawa, G. Matsunaga, M. Takechi, M. Toma and M. Yagi	4．巻 1
2．論文標題 First-Principle Simulations Reproduce Multiple Cycles of Abrupt Large Relaxation Events in Beam-Driven JT-60 Plasmas	5．発行年 2016年
3．雑誌名 Proceedings of the 26th IAEA Fusion Energy Conference, 2016, Kyoto, Japan, International Atomic Energy Agency, Vienna (Online)	6．最初と最後の頁 TH/4-3, 1-8
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1．著者名 A. Bierwage	4．巻 1
2．論文標題 Energetic-particle and MHD hybrid simulations	5．発行年 2016年
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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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2．発表標題 Energetic-ion-driven instabilities and transport in fusion plasmas: Multi-time-scale sim- ulations, validation, predictions and insights
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２．発表標題 Role of Reconnecting MHD Modes in Hybrid Simulations of Beam-Driven Tokamak Plasmas
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２．発表標題 Energetic Particle Dynamics in Tokamak Plasmas
３．学会等名 2017 JPSF Plasma Conference
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〔図書〕　計0件

〔産業財産権〕

〔その他〕

JT-60 Home Page
https://www.qst.go.jp/site/jt60-english/6636.html
Andreas Bierwage, Fusion Science
http://fusionofminds.org/FusionScience/index.html

６．研究組織

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