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Can we sustain a high ion temperature with low T_e/T_i ratio in a burning plasma?

Among the crucial issues in a burning plasma are how to heat ions using alpha particles and whether a high ion temperature plasma can be sustained using electron heating. A high core-ion temperature is usually associated with the ion transport barrier, and the electron temperature is lower than the ion temperature ($T_e/T_i < 1$). However, most of the energy of the alpha particles produced by the nuclear fusion reaction contributes to electron heating rather than ion heating because the energy of the alphas is extremely high compared to the plasma temperature. An important question is whether the ion transport barrier can be achieved in the plasmas in which $T_e/T_i \geq 1$. The threshold value of T_e/T_i is a key parameter for predicting the feasibility of an ion transport barrier and an ion temperature high enough to sustain nuclear fusion reactions in a burning plasma with alpha particle electron heating.

A recent LHD experiment shows the disappearance of the ion transport barrier (a drop of normalized ion temperature gradient) with $T_e/T_i > 0.75$, as seen in Fig. 1 [1]. This experimental result implies that the formation of an ion transport barrier is impossible with electron heating by alpha particles, where the T_e/T_i ratio cannot be lower than unity through the electron-ion collision process, which can take several hundred milliseconds or more. Therefore, direct ion heating without the electron-ion collision process is desirable to achieve a low T_e/T_i ratio and good ion confinement (due to the ion transport barrier) as a step towards realizing a compact fusion reactor.

The MHD wave excited by alpha particles enhances the energetic particle loss and degrades the confinement. However, it is speculated that the wave energy could instead be passed on to fuel ions, through a process known as alpha-channeling. The key question is to what extent these effects (energetic particle loss and alpha-channeling) can be achieved simultaneously.

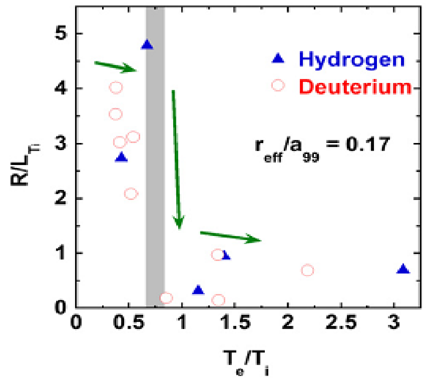

Fig. 1. The normalized ion temperature gradient as a function of the ratio of electron temperature (T_e) to ion temperature (T_i). Here R is major radius, and L_{Ti} is the scale length of the ion temperature gradient. (Adapted from Fig.1(b) in Ref. [1].)

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Alpha-channeling is collisionless energy transport from alpha particles to bulk ions through wave-particle interactions, known as Landau and inverse Landau damping. The alpha-channeling can be a solution to achieve plasmas with lower T_e/T_i and high ion temperature with an ion transport barrier in the burning plasma. The question is: How much Landau damping and inverse Landau damping? These well-known basic physics processes have been observed in magnetosphere and laboratory plasmas. However, collisionless energy transfer from energetic particle to bulk ions through these processes has not been directly observed in a laboratory plasma. Very recently, the deformation of the ion velocity distribution from Maxwellian associated with MHD burst events have been observed via measurements of the ion velocity distribution function with fast charge-exchange spectroscopy in LHD, as seen in Fig. 2 [2].

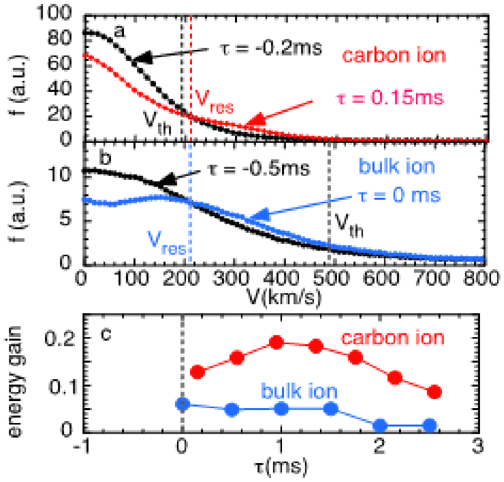

Fig. 2. Ion velocity distribution function before and after the onset of an MHD burst event for (a) carbon impurity ions and (b) bulk ions dominated by deuterium. Here $\tau = 0$ is the onset time of the MHD burst. (c) Increase of kinetic energy (energy gain) during the MHD burst for carbon impurity ions and bulk ions. (Adapted from Fig. 6 in Ref. [2].)

The energy gain due to the collisionless energy transfer is a 7% increase for bulk ions and a 20% increase for carbon impurity ions. The energy gain for carbon impurity ions is three times that for bulk ions. The higher energy gain is obtained when the thermal velocity is close to the resonance velocity due to the larger gradient in velocity space. This observation implies that a significant amount of neutral beam injection energy can be transferred to the bulk and impurity ions associated with the MHD burst. Mass-dependent collisionless energy transfer from energetic particles to bulk ions and impurity ions is thus directly observed for the first time. One-third of the beam energy loss is transferred to the bulk ions, while two-thirds of the beam energy loss is due to enhanced particle diffusion associated with the MHD burst. This experiment suggests that alpha-channeling is comparable to the particle diffusion loss and can be a possible scenario for ion heating in the burning plasma.

Reference

[1] M.Osakabe et. al., Nucl. Fusion **62** (2022) 042019.

[2] K.Ida et. al., Commun. Phys. **5** (2022) 228.

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And I welcome the submission of new articles. Please sign up for the Stellarator mailing list on our home page and check the contributor check box.

The 24th LHD experiment campaign in JFY2022 was finished successfully

The 24th Large Helical Device (LHD) experiment campaign in JFY2022 was successfully finished in December 2022. Due to a dramatical increase in fuel costs in Japan, the 24th experiment campaign, originally scheduled from the end of September 2022 until the beginning of February 2023, was substantially shortened. However, during the 14 weeks of the campaign until the end of December 2022, LHD operated for 53 days, and 8,091 discharges were accomplished. No significant trouble with LHD, heating or diagnostics occurred during the campaign. During the past two years, we have learned how to deal with COVID-19. Consequently, overseas visits to Japan were again available, albeit with restrictions, so many overseas collaborators could participate in LHD experiments. And we continued to conduct remote experiments utilizing the Zoom and Microsoft Teams applications to expand opportunities for participation in LHD experiments.

We continued our mission of acquiring scientific knowledge that will deepen our understanding of magnetically confined toroidal plasmas. One of the significant outcomes of this campaign was the first observation of the process of waves carrying plasma heat, which was published in *Communications Physics* (also see preceding article). Plasma heating via the interaction with the electromagnetic waves generated in the plasma is a critical process to maintain ignited fusion plasmas and also causes particle acceleration in the Earth's magnetosphere.

And, of course, the LHD experiment contributed to fusion plasma research. For example, A. Matsuyama (QST) published a paper in *Physical Review Letters* describing how deeper penetration of the hydrogen pellets into the high-temperature plasmas can be achieved. This result will contribute to the establishment of plasma control technologies for future fusion reactors, including ITER in France. More information on these and other significant scientific results obtained in the LHD experiment campaign can be found here. LHD/NIFS has also made significant contributions to open science. For example, any researcher can access LHD experimental data through the LHD Experiment Data Repository. We very much hope that researchers unable to participate in the 24th LHD experiment campaign can use this repository and publish exciting papers based on their original ideas.

The 24th LHD experimental campaign was the last experiment campaign in which deuterium could be used. With this experimental campaign, the LHD project also ended. Fortunately, however, we were allowed to continue the operation of the LHD, as an academic research platform, for the next three fiscal years. We will continue to conduct experiments that do not use deuterium and do not produce neutrons in LHD. We hope that people in various research fields, not only those in plasma and fusion research, will use this fortunate three-year opportunity. The next LHD experiment campaign will start in the spring of 2024, and thus experimental proposals will be collected through the website in 2023.

We look forward to receiving your interesting and meaningful proposals for the next campaign.

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