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A Comprehensive Study of Energetic Particle Transport Due to Energetic Particle Driven MHD Instabilities in LHD Deuterium Plasmas

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The transport of energetic particles induced by the toroidal Alfvén eigenmode (TAE) excited by multiple super-Alfvénic particles was for the first time in stellarator/helical devices studied using comprehensive neutron and energetic particle diagnostics in Large Helical Device (LHD). It was clearly shown that both super-Alfvénic hydrogen and deuterium beam ions are transported to the outer region of the plasma owing to TAE. The total neutron emission rate (S_n) and stored energy (W_p) show that the degradation of global energetic particle confinement due to TAE is less than 5%. In addition, a study of energetic particle transport owing to the energetic particle mode (EPM) excited by the helically-trapped energetic particle pressure coupled with bulk plasma pressure (i.e., EIC) was performed. The neutron emission profile, S_n, and orbit following simulation show that the global confinement of helically-trapped energetic particles degrades by up to 50% due to EIC.

In a tokamak fusion reactor, two types of super-Alfvénic ions exist, e.g., fusion-born α particles for self-heating and beam ions for driving the current. Therefore, the combination of energetic particle pressure can excite TAE. Then, TAE can cause the transport of α particles and beam ions. In addition, energetic particle transport owing to EPM (e.g., off-axis fishbone/energetic particle-driven wall mode) is of considerable interest [A]. The understanding of energetic particle transport induced not only by TAE under multi super-Alfvénic particle condition but also by EPM in LHD is extremely helpful to clarify the fundamentals of energetic particle driven mode physics not only in stellarators/helical devices but also in tokamaks.

TAE excitation experiments were performed using intensive super Alfvénic hydrogen ($v_{bH} \sim 1.5v_A$ where v_A represents the Alfvén velocity) and deuterium ($v_{bD} \sim v_A$) beams in the relatively low field ($B_t = 0.6$ T) and high energetic particle beta (~1%) conditions (Fig. 1). The excited TAE composed of poloidal mode number/toroidal mode number of 1+2/1 has a relatively wide radial structure whose peak is at a normalized minor radius of ~0.6 [B]. A neutron flux detector, vertical neutron cameras, a tangential E||B neutral particle analyzer (NPA), and a fast ion loss detector (FILD) were employed at the same time to measure confined and escaping energetic particles. The TAE burst induces a slight decrease in S_n, a decrease in W_p owing to the loss of heating source, an increase in the co-going transit fast hydrogen/deuterium flux, and an increase in the escaping fast ion flux corresponding to co-going (40° pitch angle) and transition orbits (60° pitch angle) near the injection energy. The short decay time of transition particles compared with co-going particles may result in shorter confinement time of transition particles. Although we observed a considerable increase in the fast neutral flux and escaping fast ion flux, S_n and W_p showed that the degradation of global energetic particle confinement due to TAE was less than 5%. In this experiment, the TAE amplitude decreased with an increase in the plasma density, and the considerable transport or loss of energetic particles were not observed at the line-averaged density of 2×10^{19} m^{-3}.

By the intensive perpendicular neutral beam injection into the relatively low-density plasma ($\sim 1\times10^{19}$ m^{-3}), the steep pressure gradient of helically-trapped energetic particles excites EIC classified as EPM. EIC located at the plasma edge (r/a ~0.85) induced a decrease in S_n by ~50%, a decrease in W_p, and a change in the neutron emission profile. The orbit following simulation using the DELTA5D code [C] that included EIC fluctuation was performed to understand the energetic particle transport. A change in the neutron emission profile owing to EIC was successfully reproduced (Fig. 2). We determined that a change in the line-integrated neutron emission profile due to EIC indicated the considerable loss of helically-trapped beam ions, which excited EIC. The steep pressure gradient of beam ion immediately excites EIC by overcoming strong damping, whereas the pressure gradient of beam ion gradually excites TAE under weak damping conditions [D]. Therefore, the energetic ion transport owing to EIC is probably larger compared to the transport due to TAE. With an increase in the plasma density ($\sim 1.5\times10^{19}$ m^{-3}), EIC became weaker, and no significant energetic particle transport was observed.

The effect of TAE and EIC on global energetic particle confinement in the high-density region in LHD is weak because the energetic particle pressure became lower due to the shorter slowing down time. This result showed the possibility of TAE and EIC control by a slight increase in the plasma density. This approach allows to us achieve the high-density operation of a helical-type fusion reactor.

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Country or International Organization

Japan

Affiliation

National Institute for Fusion Science

Primary author: Dr OGAWA, Kunihiro (National Institute for Fusion Science, National Institutes for Natural Sciences)

Co-authors: Prof. ISOBE, Mitsutaka (National Institute for Fusion Science, National Institutes for Natural Sciences); Dr KAMIO, Shuji (National Institute for Fusion Science, National Institutes for Natural Sciences); Dr FUJIWARA, Yutaka (National Institute for Fusion Science, National Institutes for Natural Sciences); Dr SIRIYAPORN, Sangaroon (National Institute for Fusion Science, National Institutes for Natural Sciences); Dr SEKI, Ryosuke (National Institute for Fusion Science, National Institutes for Natural Sciences); Dr NUGA, Hideo (National Institute for Fusion Science, National Institutes for Natural Sciences); Dr YAMAGUCHI, Hiroyuki (National Institute for Fusion Science, National Institutes for Natural Sciences); Dr KOBAYASHI, Makoto (National Institute for Fusion Science, National Institutes for Natural Sciences); Prof. OSAKABE, Masaki (National Institute for Fusion Science, National Institutes for Natural Sciences)

Presenter: Dr OGAWA, Kunihiro (National Institute for Fusion Science, National Institutes for Natural Sciences)

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