

Complex Plasma Systems Research Section

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1. Introduction

Magnetic nuclear fusion energy has some attractive features as a future option for the base-load electrical power source: (1) inherent safety features, (2) no long-life nuclear waste emission, (3) no greenhouse gas emission during the energy production, (4) huge energy density stored in the fuel source (~90 MWh/g for D-T fuel), (5) abundant source availability spreading all over the Earth, and (6) high nuclear proliferation resistance, in terms of both resources and weapons technologies.

Among various issues to be overcome in physics and engineering fields, we have focused on the problems related to the plasma transport and magneto-hydrodynamics. Specifically, determination of a magnetic configuration that can efficiently confine high-density plasma at high temperature with a sufficiently long confinement time and developing diagnostics and control schemes for the high-temperature plasmas in such magnetic fields are regarded as crucial. In these respects, our research section investigates about heating and fueling, confinement and diffusion mechanisms and their diagnostics in a magnetic plasma confinement device, named Heliotron J.

Results in FY2020 featured in this report are about the comparison between the experiments and theory/simulation in turbulent and MHD phenomena.

2. Study of Turbulence Properties against Isotope Ratio and Zonal Flow Activity in Heliotron J

Confinement improvement in deuterium (D) plasmas, compared to the hydrogen (H) plasmas, called “isotope effect”, has been a long-standing issue in the study of magnetic confinement fusion. The isotope effect contradicts a fundamental model of transport, in which an increase of characteristic scale (ion Larmor radius or turbulence scale size here) simply gives the increase of transport, in other words, D plasmas should exhibit poorer performance than the H plasmas do, although experimental observations show the opposite result. A possible mechanism to explain the isotope effect is a favourable impact of a zonal flow, a type of coherent structure induced by turbulence itself,

on the plasma transport. Several theoretical and experimental works also support the hypothesis. However, turbulence responses behind the isotope dependence of zonal flows, have not yet been studied in detail so far.

The frequency spectra of floating potential and ion saturation current indicate that the turbulence level gradually increases against the H/D ratio, as hydrogen is more dominated, as shown in Fig. 1(a) and (b). Interestingly, the small different characteristics can be seen by comparing two spectra; higher frequency components of > 100 kHz emerge in the case of floating potential, and fluctuation level in all the frequency range increases in ion saturation current, as hydrogen

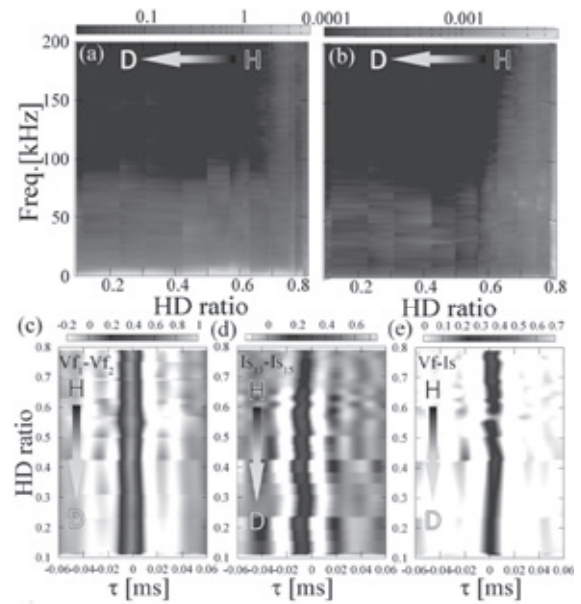


Fig. 1 (a) Dependence of frequency spectra on hydrogen/deuterium (H/D) ratio ($\sim n_H/(n_D + n_H)$) for potential fluctuation and (b) density fluctuation. (c) Isotope dependence of two-point correlation between adjacent probe signals with the distance of 5mm for floating potential (d) density fluctuations, and (e) between potential and density fluctuations and double-path measurement using two forward backward scattered lights (chain line).

becomes dominant. This observation suggests that turbulence-induced transport increases in H plasmas.

Furthermore, the decorrelation of density and potential is also demonstrated from a statistical viewpoint using a joint probability density function (joint-PDF) technique. The observed decoupling of fluctuation has been revealed to be attributed to the enhancement of the zonal flow observed in this experiment.

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3. Simulation Study of Energetic Particle-driven MHD Modes and Energetic Particle Redistribution in Heliotron J

Sufficiently long energetic particle (EP) confinement time is important for realizing self-sustainable plasma; however, these EPs can resonate with the shear Alfvén waves (SAW) through fundamental and sideband resonances in the magnetic confinement fusion devices (e.g. tokamak and stellarator/heliotron).

The interaction between energetic particles (EPs) and EP-driven magnetohydrodynamic (MHD) instabilities in Heliotron J has been investigated by MEGA¹⁻²⁾, a hybrid MHD-EP simulation code.

The three-dimensional magnetic field of Heliotron J is mainly composed of the helicity, toroidicity, and bumpy Fourier components. This creates additional interactions between EP and SAW³⁾.

It has been shown in Ref.4) that the free MHD boundary condition can have a significant impact on the stability of the low-n mode in the strongly shaped plasma. Then, we have recently made a success in improving the application of the MEGA simulation to free-boundary condition on the last closed flux surface (LCFS).

In this study, we analyzed the stability of the EP-driven MHD instabilities and their effects on the EPs confinement in Heliotron J. Both the fixed and free MHD boundary conditions are utilized. The simulation is conducted on the low ($\epsilon_{01}=0.01$) bumpiness configurations.

The fixed boundary simulation results show that the $n/m=2/4$ mode is dominant while the $n/m=1/2$ mode is observed as a recessive component (Fig.2a). The time evolution of the $n/m=1/2$ mode is obscured due to the large difference in the amplitude between $n/m=1/2$ and $n/m=2/4$ modes. This contradicts with the experiments where the $n/m=1/2$ mode is dominant.

In the free boundary simulation, much higher linear growth rates are predicted for both the $n/m=1/2$ and $2/4$ modes (Fig.2a). The change is much higher for the $n/m=1/2$ mode such that the $n/m=1/2$ mode emerges as the dominant mode, although both the

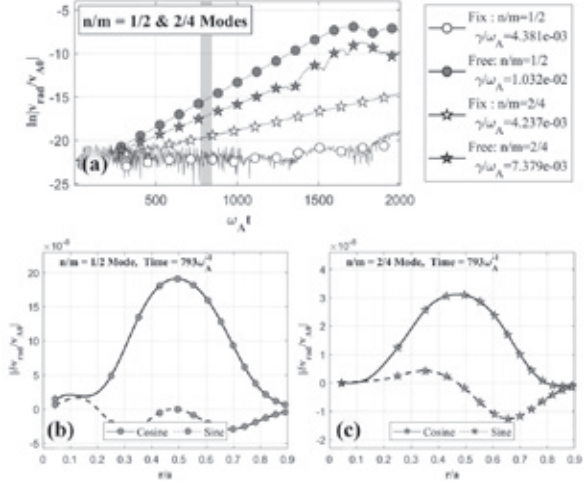


Fig.2 (a) The comparison of the logarithmic time evolution of the radial MHD velocity for $n/m=1/2$ and $2/4$ modes between the fixed and free boundary simulations. The spatial profile of the $n/m=1/2$ and $2/4$ modes at $793\omega_A^{-1}$ are shown in panels (b-c), respectively. $793\omega_A^{-1}$ is indicated by the vertical transparent gray bar in panel (a).

$n/m=1/2$ and $2/4$ modes are located at the same radial location. The spatial profiles of the $n/m=1/2$ and $2/4$ modes are shown in Figs.2b-c, respectively. In contrast to the fixed boundary case²⁾, the mode profiles are broadened and radially shift toward the edge. By analyzing the changes in the EP driving rate (γ_h) and MHD dissipation rate (γ_d), it shows γ_h is higher in the free boundary simulation while γ_d remains the same. The stronger EP-SAW interactions are brought about by the broadening of the mode profile. From the analysis of the EP redistribution in velocity space, the majority of the interactions are brought about by the high velocity co-passing EPs interact with the SAWs through high velocity toroidicity-induced resonance. These EPs have large orbit widths such that they can interact with the mode in the edge region.

This study shows that the boundary condition has a significant role in Heliotron J, a low shear helical-axis stellarator/heliotron. The boundary condition at the LCFS can significantly affect the linear properties of the low-n EP-driven mode, even if the mode's radial location is at $r/a \approx 0.5$. The prospective cause is the low magnetic shear of Heliotron J. This shall be verified in other low shear stellarators.

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Collaboration Works

大島慎介, 西南物理研究所 (中国), 非線形結合
定のための新しい揺動解析手法に関する共同研究

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Max-Planck Institute (ドイツ), ヘリカル磁場配
位における周辺揺動研究

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Stuttgart Univ (ドイツ), CIEMAT (スペイン),
Australian National Univ., (オーストラリア),
Kharkov Institute (ウクライナ), Southwest Institute of
Physics (中華人民共和国), ヘリカル型装置におけ
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長崎百伸, 大島慎介, 岡田浩之, 南貴司, 小林進二,
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