

Complex Plasma Systems Research Section

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1. Introduction

Nuclear fusion energy possesses several attractive features as a promising option for future base-load power generation, and research on magnetic confinement fusion is therefore being actively pursued worldwide. However, several critical issues remain to be resolved for the realization of a fusion reactor. To address these challenges, experiments on Heliotron J are being carried out. The main objectives include (1) identification of the effects of waves excited by energetic particles on plasma confinement, (2) Elucidation of the mechanism of confinement improvement in high-density plasmas, and (3) optimization of the Heliotron J magnetic configuration for improved particle confinement.

The FY2025 results presented in this report include the observation of intermittent behavior of energetic particle-driven waves, the development of advanced diagnostics, and studies on methods for magnetic configuration optimization.

2. Observation of Bursty MHD mode

In NBI-heated plasmas in Heliotron J, coherent magnetic fluctuations in the frequency range of several tens of kHz to 200 kHz are excited as shown in Fig. 1. The amplitudes of these modes are not stationary, but exhibit bursty behavior on a timescale of 0.2–1 ms. Such bursty behavior can be described in terms of a carrier wave and its envelope. The carrier wave is considered to correspond to linearly excited modes in the frequency range of 10–200 kHz, and energetic particle-driven Alfvén waves have been identified. The carrier wave has finite poloidal and toroidal mode numbers (m/n), with typical values of $m = 6-8$ and $n = 1$. On the other hand, the envelope has a frequency of 1–5 kHz and is characterized by $m/n = 0/0$. These observations suggest that the bursty behavior arises from nonlinear coupling between the carrier wave and modes with spatial structures similar to zonal flows.

In Heliotron J plasmas, these bursts occur in temporally clustered events. Two types of clustering have been observed: (I) a single, sporadic occurrence of burst clustering on a timescale of ~ 10 ms, and (II) quasi-periodic, intermittently repeating burst clustering on a timescale of ~ 5 ms. While both types exhibit unpredictability in terms of their impulsive and intermittent nature, they are considered to originate from different underlying physical mechanisms.

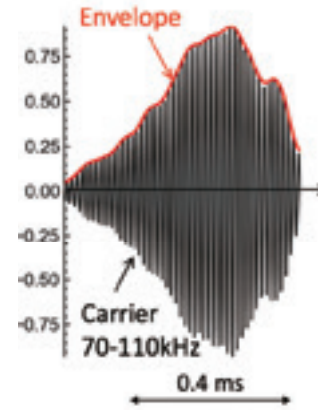


Fig. 1 Radial profile of time-averaged flow velocity.

Furthermore, instantaneous frequency analysis using the Hilbert transform has revealed that the frequency varies during amplitude bursts as shown in Fig. 2. The observation of frequency chirping-down suggests nonlinear interactions between energetic particles and Alfvén waves. In this process, energy is transferred from particles to waves, leading to wave growth, while the energetic particles are transported toward the plasma periphery. The decrease in frequency is consistent with a scenario in which the resonant frequency shifts downward as energetic particles move outward in the plasma.

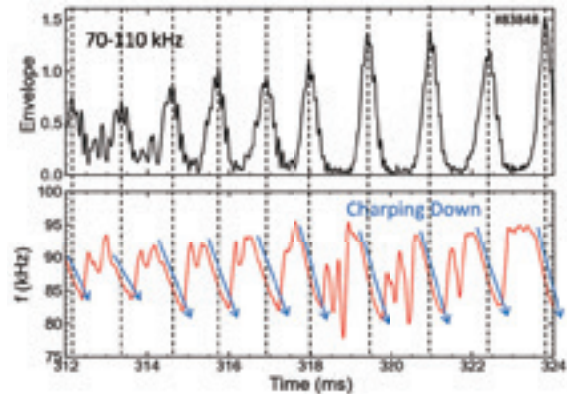


Fig. 2 Frequency chirping-down during MHD bursts

3. Dynamics of plasma reconfiguration after pellet injection in Heliotron J

In magnetically confined fusion reactors, the fusion

power is proportional to the product of the fuel ion densities (i.e., approximately to the square of the electron density). In addition, in tokamaks and Heliotron J, it is well known that the energy confinement time increases with increasing electron density. Therefore, achieving and sustaining high-density plasmas is essential for realizing ignition and steady-state burning, and extensive efforts have been devoted over many years to the production of high-density plasmas. In particular, with the establishment of pellet injection techniques, high-density plasmas with electron densities exceeding 10^{20} m^{-3} have been achieved in many devices, where steep electron density profiles and the associated improvement in confinement have been observed. However, the physical origin—namely, why confinement improves in high-density plasmas and how it can be sustained—remains unclear.

Because of the many degrees of freedom in magnetized plasmas, the plasma is largely reconfigured when the plasma achieves a non-equilibrium steady state in response to changes in the internal environment. We observed a plasma reconfiguration process when the density is increased by pellet injection in Heliotron J. The plasma exhibited no adiabatic response to pellet injection and achieved an improved confinement during the reconfiguration process, as shown in Fig. 3. This has sometimes been referred to as "reheat mode". The onset of re-excitation of the magnetic fluctuations was delayed from the onset of the reheat phase. The re-excitation of magnetic fluctuations may be caused by an increase in the peripheral pressure gradient, i.e. plasma expansion. It was found that the magnetic field line structure in the divertor region also changed in the plasma reconfiguration process. [K. Ogihara *et al*, Sci. Rep. 15, 16503 (2025)]

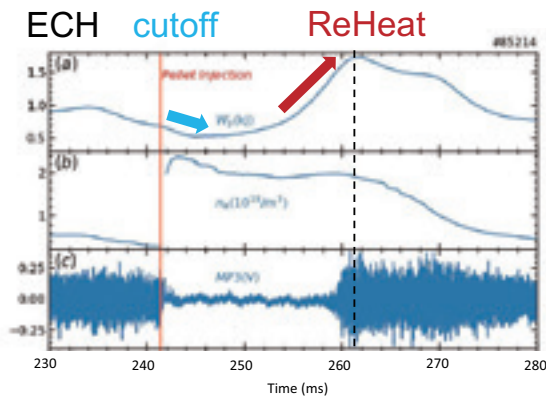


Fig. 3 Typical temporal evolution of pellet discharge: (a) stored energy, (b) averaged electron density, (c) magnetic fluctuation. A pellet was injected at 241.4 ms.

4. Exploration of optimized magnetic configurations in Heliotron J

Three-dimensional magnetic fields are widely recognized to influence plasma confinement; however, systematic experimental verification remains limited. The Heliotron J device can generate a wide variety of magnetic configurations by independently controlling the currents in its five coil groups. Nevertheless, the possible combinations of coil currents exceed ten billion, making an exhaustive search impractical.

In this study, we have developed a noble exploration method of required magnetic configurations in Heliotron J. In this study, we performed a systematic exploration of magnetic configurations in Heliotron J by applying an optimization method that combines magnetic field-line tracing calculations with Bayesian inference. To improve particle confinement, we focused on the ripple structure of the magnetic field strength, following the concept of Omnigenity, in which the magnetic-well depth and width, as well as the maxima and minima of $|B|$ along magnetic field lines, are uniformly distributed. Specifically, we defined an objective function that minimizes the standard deviations of the magnetic-well depth, width, and the maxima and minima of $|B|$ along magnetic field lines. The result is shown in Fig. 4, where several new magnetic configurations were identified. These include configurations in which the ripple bottoms are aligned, those in which the ripple tops are aligned, and those in which both are aligned. Calculations of the effective ripple coefficient for these configurations reveal cases where the ripple is either reduced or increased compared with the standard configuration. These results provide a basis for experimentally investigating the dependence of confinement properties on magnetic field structure.

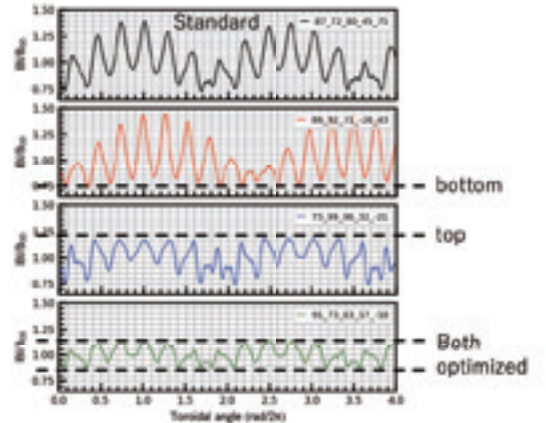


Fig. 4 Magnetic field strength along the field line for four different configurations. From top to bottom: the standard configuration, the bottom-ripple aligned configuration, the top-ripple aligned configuration, and the both-ripple aligned configuration, respectively. Note that the last configuration is most close to the condition of omnigenity.

Collaboration Works

長崎百伸, 小林進二, 稲垣泰一郎, 稲垣滋, 門信一郎, 金史良, Univ. Wisconsin (アメリカ), Oak Ridge National Laboratory (アメリカ), Max Plank Institute (ドイツ), 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), 先進ヘリカルシステムにおける周辺プラズマ・ダイバータ研究

長崎百伸, 小林進二, 稲垣泰一郎, 稲垣滋, 門信一郎, 金史良, Wisconsin University (アメリカ), CIEMAT (スペイン), Max-Planck Institute (ドイツ), 先進ヘリカルシステムにおける周辺揺動解析

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金史良, 若手研究, 磁場閉じ込めプラズマにおける雪崩輸送の計測法の開発

2. Others

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