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Remote participation in the LHD experiments

International collaboration is essential for fusion plasma research. However, due to the spreading of the COVID-19 virus, it is not easy to join collaboration experiments directly, especially in foreign countries. To stimulate collaboration for the Large Helical Device (LHD) experiments, activities to support remote participation have been started. The purpose of the effort is to extend and to improve the present services [1] and to make remote participation as comfortable as possible. Towards those goals, two actions are being taken: (1) to provide data handling capabilities similar to those available when you are in the control room, and (2) to update the documents to make them easier to use by newcomers. Available network resources are listed on a Web page [2].

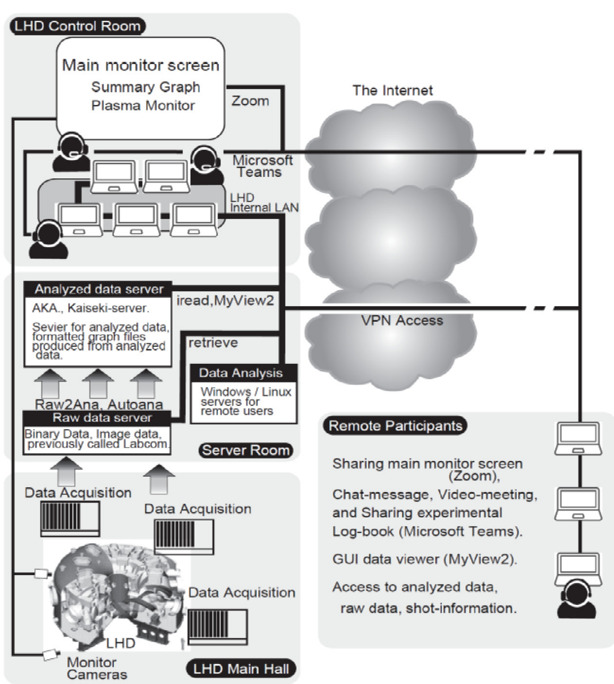

Fig. 1. Conceptual diagram of the data flow of the LHD experiment and network resources for remote participants.

The data flow for LHD experiments is shown in the left part of Fig. 1 [3]. Experimental data are acquired by the distributed data acquisition system. Acquired binary data are stored in the "raw data server." Physical values are automatically calculated using the so-called auto-ana system [4] and stored in the "analyzed data" servers in the "Kaiseki-data format" [5]. Two supporting libraries for handling raw data and analyzed data are provided. Because these libraries have interfaces to user-friendly languages such as PV-WAVE (https://www.perforce.com/products/pv-wave) and Python (https://www.python.org), it is quite easy to access both raw and analzed data. Remote access is available to users with a VPN connection. An easy-to-use GUI data viewer for Kaiseki-data, MyView2 [6], has been developed by NIFS and is widely used in LHD experiments. MyView2 can be operated remotely with a VPN connection as well. There are Windows/Linux servers directly connected to the LHD internal LAN. For those who need to handle large amounts of data, using those servers can be a good solution.

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In the control room, the summary graph and camera monitor images of the LHD plasma are shown continuously on the main monitor screen. These images are broadcast via a Zoom (https://zoom.us/) connection. For chatting, messaging researchers, video meetings, and sharing documents, services based on Microsoft Teams (https://www.microsoft.com/en-us/microsoft-teams/group-chat-software) can be used (Fig. 1). If you join the LHD topical experimental group, you can be a member of a Team. Tutorial documents (https://www-lhd.nifs.ac.jp/LHD/pdf/LHD_Guide/Tutorial_for_beginners_v1.pdf) are also available for detailed information.

In summary, network services for remote participants have been significantly improved. Many international collaboration experiments are already being performed in the present experimental campaign. We hope many new collaborators join the LHD experiment and enjoy experiments remotely in a comfortable manner.

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Plasma filaments in the scrape-off layer of Wendelstein 7-X

Large, coherent, field-aligned plasma filaments (or blobs) are universal phenomena at the edge of magnetic plasma devices. They have been measured in stellarators, linear devices, and tokamaks, where they can provide a significant source of heat and particle transport. A recent publication co-first-authored by C. Killer and B. Shanahan [1] has coordinated experimental measurements and numerical simulations to characterize filaments in the Wendelstein 7-X (W7-X) scrape off-layer (SOL).

Filaments were observed by probes that measured the ion saturation current and floating potential. From these measurements, the size of the density perturbation and radial velocity of the filaments were calculated. A comparison with target probes indicated that these filaments extend to the plasma-facing components. Two-dimensional (drift-plane) seeded filament simulations were then performed using a cold-ion, full-profile fluid turbulence model in the BOUT++ framework, an open-source framework for solving partial differential equations in curvilinear geometry. Initial conditions characteristic of those measured by the reciprocating probes were then used to seed the filaments. As the simulations were two dimensional, parallel sheath closures were implemented in order to incorporate parallel dynamics. Furthermore, the nonaxisymmetric nature of the W7-X SOL was ignored and an average curvature was assumed. Despite this strong approximation, the scaling of the experimental filament velocity with perpendicular size was reflected in simulations with remarkable agreement (Fig. 1).

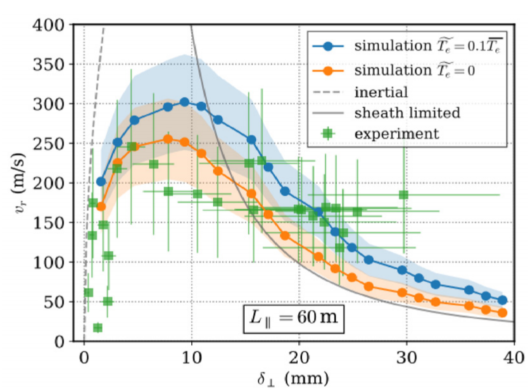

Fig. 1. Two-dimensional numerical simulations (orange and blue circles) recover experimental measurements (green) of plasma filament velocity scaling as a function of perpendicular size in the W7-X SOL [1].

Aside from the agreement between theory and experiment, it was determined that the filaments in this work have a small radial velocity due to the low ballooning drive of W7-X and therefore do not stray far from the flux surface at which they originate.

This work, which emphasizes collaboration between theory and experiment, also indicates that the macroscopic characteristics of filament transport in a stellarator might be independent of the three-dimensional magnetic field.

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Hydrogen isotope effects in confinement structure formation in LHD

One of the biggest challenges for plasma physicists is to clarify the background physics of the hydrogen isotope effect. The hydrogen isotope effect is the phenomenon in which the heavier the mass of the fuel gas, the better the plasma confinement becomes. Since heavier ions are expected to have a larger excursion length in a transport event, intuitively it is difficult to accept the hydrogen isotope effect. As future thermonuclear fusion plants are planned to be operated with a tritium-deuterium fuel mixture, whether the confinement scaling follows the simple scaling model—the so-called gyro-Bohm scaling—is a crucial issue for projecting reactor plasma performance. From an academic aspect, the hydrogen isotope effect is also an attractive theme in assessing how the basic properties of a medium in an open non-equilibrium system determine the eventual steady-state structure of the system.

In addition to the well-known hydrogen isotope effect widely observed in the energy confinement time scaling, the fuel mass dependence of the threshold power necessary for the edge transport barrier to form across the low- to high-confinement mode transition is experimentally revealed. That is, the threshold power is approximately halved in the deuterium plasma case compared to the hydrogen plasma case [1]. Such an observation is routinely obtained in different tokamak devices, but knowledge concerning stellarators is scant due to the lack of experimental cases. Since the confinement mode transition is attractive both for fusion reactor operation and for the study of nonlinear structure formation, the isotope effect at the confinement mode transition event needs to be characterized experimentally. In the Large Helical Device (LHD), the deuterium experimental campaign was started in 2017, and direct comparison in plasmas with different deuterium content is being performed. This contribution is focused on the production of internal transport barriers (ITBs), and their relationship to the hydrogen isotope effect. ITBs are spontaneously formed confinement structures observed in many tokamaks and stellarators. In LHD, they are produced typically at low density and high heating power. Depending on the plasma species being subjected to the intense heating, the ITB appears either in the ion temperature profile or in the electron temperature profile. These structures are called the ion-ITB and the electron-ITB, respectively, and are investigated separately for possible hydrogen isotope effects.

The study of the hydrogen isotope effect in the ion-ITB case is begun by defining the ITB intensity. In LHD, the typical non-ITB ion temperature profile features a domeshaped profile. An indicator of the ITB intensity is defined based on how much the ion temperature surpasses the typical L-mode profile shape, which we call the profile gain factor [2]. Figure 1 presents the typical ion-ITB profiles in the deuterium case and the hydrogen case. The dashed curves show the reference L-mode profile for each case. At first glance, a higher central ion temperature is achieved in the deuterium case owing to the stronger ITB, which is evident by the larger deviation of the ion temperature from the reference L-mode profile. The hydrogen isotope effect in the ion-ITB strength is systematically examined by plotting the profile gain factor with respect to the line-averaged density, as shown in Fig. 1(c). As the line-averaged density decreases, the profile gain factor gradually rises due to the ion-ITB formation. The ITB intensity in deuterium plasmas is consistently higher than that in hydrogen plasmas in a lower density range. To explore the underlying physics of the hydrogen isotope effect in the ion-ITB intensity, a principal component analysis is performed in a multidimensional parameter space. It is found that a stronger ion-ITB is formed not only when the line-averaged density is low enough, but also if the electron density tends to peak, [3].

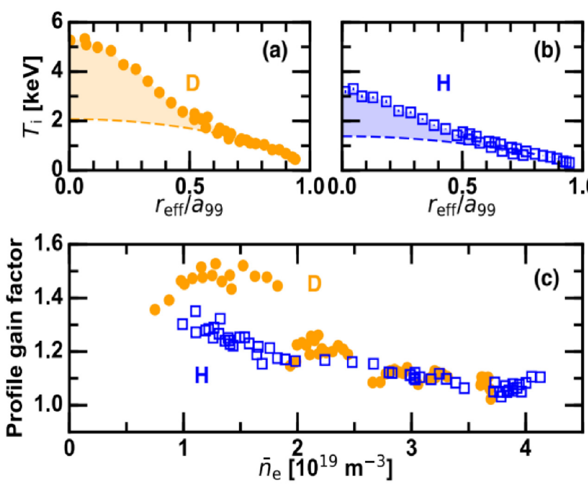

Fig. 1. Radial profiles of the ion temperature with the ion-ITB in (a) deuterium and (b) hydrogen plasmas, and (c) line-averaged density dependence of the profile gain factor.

The hydrogen isotope effect in the electron-ITB is assessed based on a perturbative experiment. In a steady-state plasma discharge, the ECH power is modulated and the response in the electron temperature gradient is observed. Figure 2 shows the line-averaged density dependence of the modulation amplitude in the electron temperature gradient. When the base electron density is sufficiently high, the modulation amplitude in the electron temperature gradient does not depend on the line-averaged density. However, it monotonically rises as the line-averaged density is decreased in the lower density range due to the transient electron-ITB formation/deformation synchronized with the modulating ECH. The threshold density for the electron-ITB transition is higher in the deuterium case; i.e., the electron-ITB is easily formed in the heavier hydrogen isotope fuel. This isotope effect is predominantly caused by the branch transition in the local electron thermal diffusivity shown in Fig. 2(b). In the higher density range, the local electron thermal diffusivity follows the $\bar{n}_e^{-1.2}$ scaling, likely due to the density stabilization effect in the global confinement scaling. Once the density crosses the electron-ITB threshold, the local electron thermal diffusivity drops off from the $\bar{n}_e^{-1.2}$ trend [4]. Unlike the local transport property, the nonlocal contribution scarcely has any meaningful impact on deuterium plasmas and hydrogen plasmas [4,5] (not shown in this contribution).

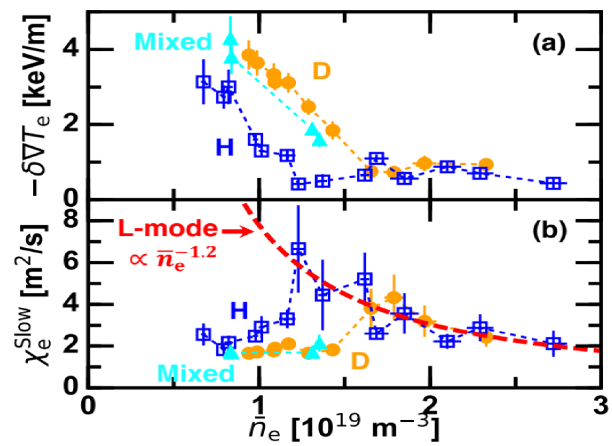

Fig. 2. Line-averaged density dependence of (a) the modulation amplitude in the electron temperature gradient, and (b) the classical diffusion coefficient in deuterium, hydrogen, and mixed deuterium-hydrogen plasmas.

To reveal the underlying physics of the isotope effects in the ITB plasmas, multiscale turbulent fluctuation diagnostics play a key role in examining the turbulence transport contribution. In addition to routinely operated density fluctuation diagnostics in LHD, such as Doppler back scattering (DBS) and phase contrast imaging (PCI), a new beam emission spectroscopy (BES) system is being developed [6]. The new BES system covers the low-frequency and low-wavenumber domain that neither the DBS nor the PCI can access. The new BES system has a large-diameter narrowband interference filter for selectively sensing either the hydrogen beam emission or the deuterium beam emission for the hydrogen isotope experiment. By combining all of these density fluctuation diagnostics, a wide parameter range of turbulence is obtained.

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