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Contributing to the Realization of a ‘Sun on Earth’ : Simulations of Burning Plasma

As energy demand continues to increase, research and development into fusion reactors, devices that can generate energy on Earth by producing nuclear fusion reactions similar to those in the sun, is gaining momentum. However, there are many challenges to overcome before a fusion reactor can be realized. One of the most fundamental challenges is the occurrence of various phenomena in the plasma during the fusion reaction that prevent the reaction from being sustained. Prof. Todo is contributing to the realization of fusion reactors by using simulations to elucidate the mechanisms by which these phenomena occur.

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Fusion Offers Many Advantages, but Realization is Difficult

Within the Sun, a huge amount of energy is produced by the nuclear fusion reaction in which four hydrogen (H) nuclei are transformed into one helium (He) nucleus. However, most of the fusion reactors currently being researched utilize the DT fusion reaction (Fig. 1), in which deuterium (D) and tritium (T) nuclei fuse to form a He nucleus and a neutron. This is because this reaction occurs in a fusion reactor more rapidly than other reactions, including those occurring in the Sun. It is anticipated that the large amount of energy generated by this reaction will be used for power generation and other purposes.

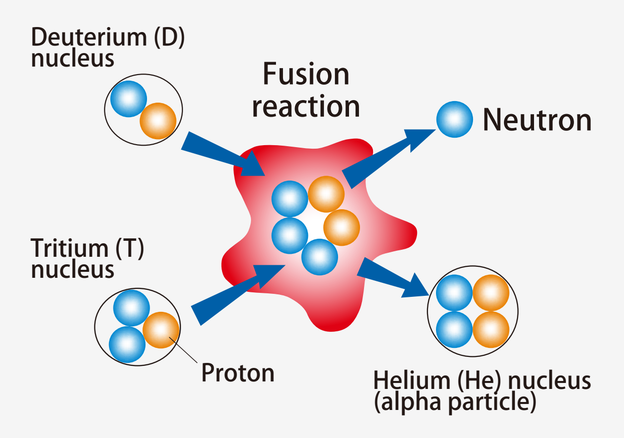

Fig. 1 : Reaction used in fusion reactors (DT fusion reaction)

In nuclear fusion, the mass after the reaction is smaller than before, and a large amount of energy is released by converting the lost mass into energy. In this reaction, 1g of D and T together can produce the same amount of energy as burning about 8 tons of oil. This figure is adapted from an illustration provided by NIFS.

The "fuel" for nuclear fusion, D, is obtained from seawater, and T is obtained by converting lithium (Li) found in seawater, so there is little concern about depletion. Furthermore, because the fusion reaction does not produce CO_2, it is considered an energy source with a low environmental impact.

However, to trigger a fusion reaction, D and T must be converted into extremely high-temperature plasma*[1], and atomic nuclei must be collided with each other at high speed. Furthermore, this plasma must be confined to a certain area and maintained at a high density for an extended period of time. To date, nuclear fusion reactions have been successfully induced by external heating. However, to use nuclear fusion as an energy source, the reaction must continue after initiation, powered solely by the heat generated by fusion, without external heating. Such a plasma is called "burning plasma," and to achieve this, it is calculated that the plasma temperature must be several hundred million degrees Celsius, and the ion density × confinement time at the plasma center must be at least 10^{20} ions/m^3·sec.

While various types of fusion reactors are being researched around the world with this goal in mind, the one expected to be the first to achieve nuclear burning plasma is ITER, which is being constructed in southeastern France with the cooperation of the seven Parties: Japan, the EU, the United States, Russia, South Korea, China, and India. ITER is a tokamak-type fusion reactor (Fig. 2), a type of reactor that confines plasma using a magnetic field.

Separating Particles of Interest from Others Enhances the Precision of Simulations

"In 2012, I used the K computer to perform the world's first realistic simulation of the phenomena caused by alpha particles (helium nuclei) in ITER plasma. Since then, I have continued to advance my research using the K computer and the supercomputer Fugaku," says Prof. Todo. He explains the significance of this work, saying, "Various phenomena occur in plasma confined by a magnetic field, and some of these can interfere with the maintenance of burning plasma. While these phenomena have been studied experimentally, only through simulations can the detailed mechanisms be clarified, which in turn enables the development of countermeasures for the phenomenon."

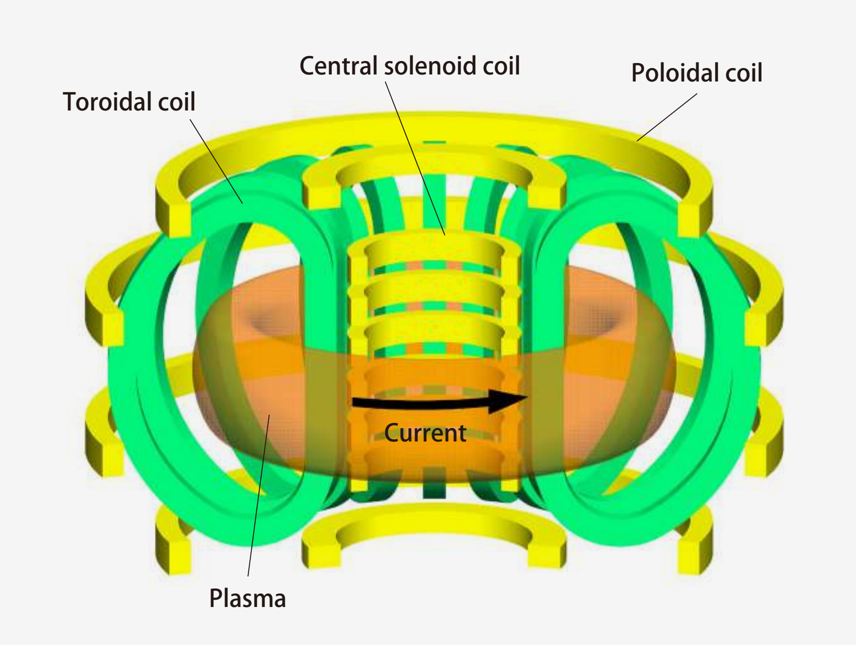

Fig. 2 : Basic structure of a tokamak-type fusion reactor

Although not shown in this diagram, the plasma is created in a vacuum vessel that is slightly larger than the plasma shown here, with three types of superconducting magnets (coils) installed around the vacuum vessel. By electromagnetic induction from the central solenoid, a large current flows in the plasma, and this current generates the magnetic field. This, together with the magnetic field of the toroidal coil, confines the plasma into a doughnut shape. The poloidal coil is used to adjust the position and shape of the plasma. In ITER, the plasma doughnut is about 7m high, has an outer diameter of about 16m, and a volume of about 800m^3, but the total mass of the plasma is only about 1g. This figure is adapted from an illustration provided by NIFS.

Phenomena that interfere with the maintenance of burning plasma include, first, degradation of confinement due to microscopic electromagnetic field disturbances, and second, sudden plasma collapse. Furthermore, high-energy alpha particles produced by nuclear fusion reactions play an important role in heating plasma, but there is also a third phenomenon in which these particles interact with plasma waves and escape from the plasma’s center. Prof. Todo and his collaborators have conducted simulations focusing on the second and third phenomena. The simulation uses a code called MEGA, which has been developed independently since 1995.

Traditionally, plasma simulations have been based on magnetohydrodynamics (MHD), which combines fluid equations with electromagnetic field equations. This method considers plasma to be an electrically conductive fluid, and assumes that this fluid obeys the MHD equations to calculate how the plasma changes over time (time evolution). MHD simulations have produced many successful results, but treating plasma, which consists of particles, as a fluid can result in significant deviations from actual physical phenomena. One approach to this problem is to calculate all plasma particles (ions and electrons) using the particle method, but this requires an enormous amount of computation and is therefore only possible for simulating very short intervals in small spaces. Prof. Todo has developed a “kinetic-MHD hybrid simulation,” which treats only the plasma particles of interest using the particle method, and the remaining particles and electromagnetic fields using MHD. The code for this is MEGA.

The Seriousness of the Problematic Phenomenon Has Become Clear

For many years, Prof. Todo has focused on a third phenomenon that impedes the maintenance of burning plasma. This phenomenon is quite complex, in that plasma waves called Alfvén eigenmodes become unstable when excited by alpha particles, which in turn causes changes in the distribution of alpha particles. The details of this phenomenon and the mechanism behind the changes in alpha particle distribution had not been fully elucidated.

In 2012, Prof. Todo simulated this complex phenomenon using the K computer (Fig. 3). This clarified the ebb and flow of Alfvén eigenmodes of various wavelengths, and predicted that the alpha particle pressure*[2] in the plasma core would decrease by 6% due to interactions with the Alfvén eigenmodes. “Previous research had not secured a sufficient wavelength range for the Alfvén eigenmodes, and there were concerns that the decrease in alpha particles would be even greater, but our simulations showed that this was not so serious,” Prof. Todo says. Using the K computer, it was possible to perform a full-scale simulation of ITER using MEGA, yielding important results that will contribute to the realization of burning plasma.

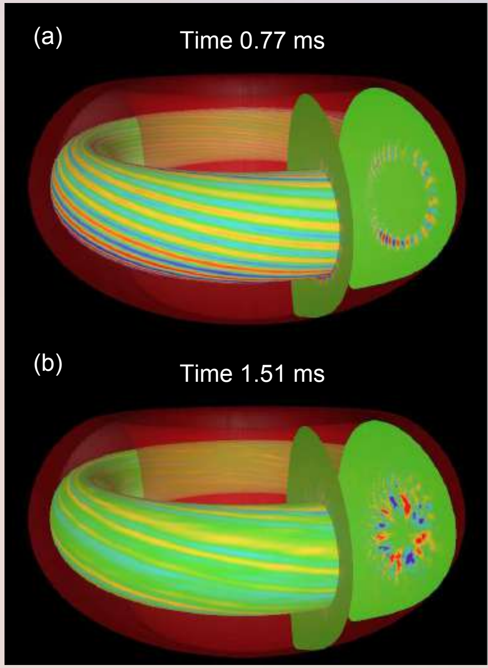

Fig. 3 : Simulation of the interaction of Alfvén eigenmodes and energetic alpha particles in ITER

In ITER, the plasma confined by the magnetic field is doughnut-shaped (represented in green in this figure). The magnetic field creates loose spiraling magnetic field lines within the doughnut, and ions and electrons move along these lines. Ions and electrons move to counteract the electric field generated by the charge density fluctuations, generating waves of charge density that travel along the magnetic field lines. These waves are called Alfvén waves (represented by the colorful lines moving like a barber’s pole within the green doughnut). These waves, like the strings of a musical instrument, vibrate at specific wavelengths. These are called Alfvén eigenmodes. In these figures, the yellow, red, and blue lines represent Alfvén eigenmodes of various wavelengths excited by alpha particles. Alfvén waves propagate both around the circumference of the doughnut and around the cross-section of the doughnut. However, they become unstable due to alpha particles. The Alfvén eigenmodes (the color distribution), which are relatively uniform at first (a) and become disordered over time as shown in (b), transport alpha particles away from the center of the plasma (the center of the circle in the cross section of the doughnut). Material from Prof. Todo, Yasushi TODO and Andreas BIERWAGE, Plasma Fusion Res. 9, 3403068 (2014), with permission from JSPF.

Increasing the Number of Particles Allows for a Detailed Depiction of the Phenomenon

In MEGA simulations, a doughnut-shaped plasma is divided into grids, and particles of a particular particle species are placed at each grid point, with their position and velocity changes calculated using the particle method. Meanwhile, changes in the electromagnetic field, including the remaining particle species, are calculated for each grid using MHD. However, because particles are charged, their motion is affected by the electromagnetic field, and conversely, particle motion changes the electromagnetic field. Therefore, particle calculations and electromagnetic field calculations are performed separately in short time steps, and the results are exchanged and reflected in the calculation of the next step, achieving a hybrid of the two.

In his simulations on the K computer, Prof. Todo used the particle method to treat energetic alpha particles and D ions injected from outside to heat the plasma. However, in a recent project on Fugaku, he also used the particle method to treat the “fuel” D and T ions*[3]. He developed the model to perform simulations closer to reality. Additionally, the number of particles placed at grid points was increased from one per particle type on the K computer to 8 or 64 on Fugaku.*[4]

“The changes in alpha particle distribution in the Fugaku simulation were similar to those on the K computer, confirming with greater certainty that there is not much outflow of alpha particles from the plasma core. Furthermore, by significantly increasing the number of particles, we were able to elucidate in detail the process by which the alpha particle distribution changes during the interaction between Alfvén eigenmodes and alpha particles (see Fig. 3).”

In this simulation, Prof. Todo analyzed the time evolution of the alpha particle distribution in phase space. Phase space is a virtual space that simultaneously represents the position and velocity of particles. It is a six-dimensional space consisting of the actual space (three dimensions) plus the velocity space (three dimensions). However, the results of this analysis can be displayed on a two-dimensional plane (Fig. 4). These analysis results provide a detailed depiction of the changes in alpha particle distribution and are expected to be useful in deepening the understanding of the interaction between Alfvén eigenmodes and alpha particles.

Simulating the Progress of Nuclear Fusion Reactions

Let us briefly introduce the results of the second phenomenon, "sudden plasma collapse." Regarding this phenomenon, Prof. Todo explains, "To maintain nuclear burning plasma, particles must be concentrated in the plasma's center and maintained at high temperature and density. But there is a limit to this. When the particle pressure reaches a certain level, plasma fluctuations develop rapidly, and the plasma can break down."

However, MHD simulations have not been able to accurately predict the pressure at which the collapse occurs. The National Institute for Fusion Science (NIFS) has the Large Helical Device (LHD, Fig. 5), a type of magnetic confinement device, where many important experiments have been conducted to clarify plasma behavior. Among these, high-pressure plasma experiments conducted in the early 2000s showed no plasma collapse, but MHD simulations predicted plasma collapse, resulting in a significant discrepancy between the experiments and the MHD simulations.

So in 2019, Prof. Todo and his collaborator, Masahiko Sato (Associate Professor, NIFS), used the K computer and other supercomputers to reproduce this experiment using the MEGA code. The results showed that plasma stability could be maintained up to pressures much higher than predicted by the MHD simulation, a result that closely matched the experimental results. "Accurately predicting the pressure limit is extremely important, as the pressure limit is one of the guidelines for determining the operating conditions of a fusion reactor," Prof. Todo says, emphasizing the significance of this result.

More recently, Prof. Todo and his colleagues used Fugaku to perform simulations of the National Institutes for Quantum Science and Technology's tokamak-type large-scale experimental device, demonstrating that the MEGA code can accurately evaluate the pressure limit. These results will likely be useful in research and development of ITER, another tokamak-type device.

In addition to the results introduced here, Prof. Todo has achieved many other results using MEGA. What kind of simulations does he plan to tackle in the future? "Simulations up until now have focused on a 'steady state' in which the number of particles of each particle type does not change. However, in reality, alpha particles are produced one after another in nuclear fusion reactions at the core of the plasma, and the distribution that has decreased due to interactions with Alfvén eigenmodes should return to normal. I would like to be able to clarify this process through simulation." To do this, a model that incorporates changes in the number of particles must be created, and the simulation time must be extended, but Prof. Todo, who has steadily improved MEGA up to now, will be able to do this quickly.

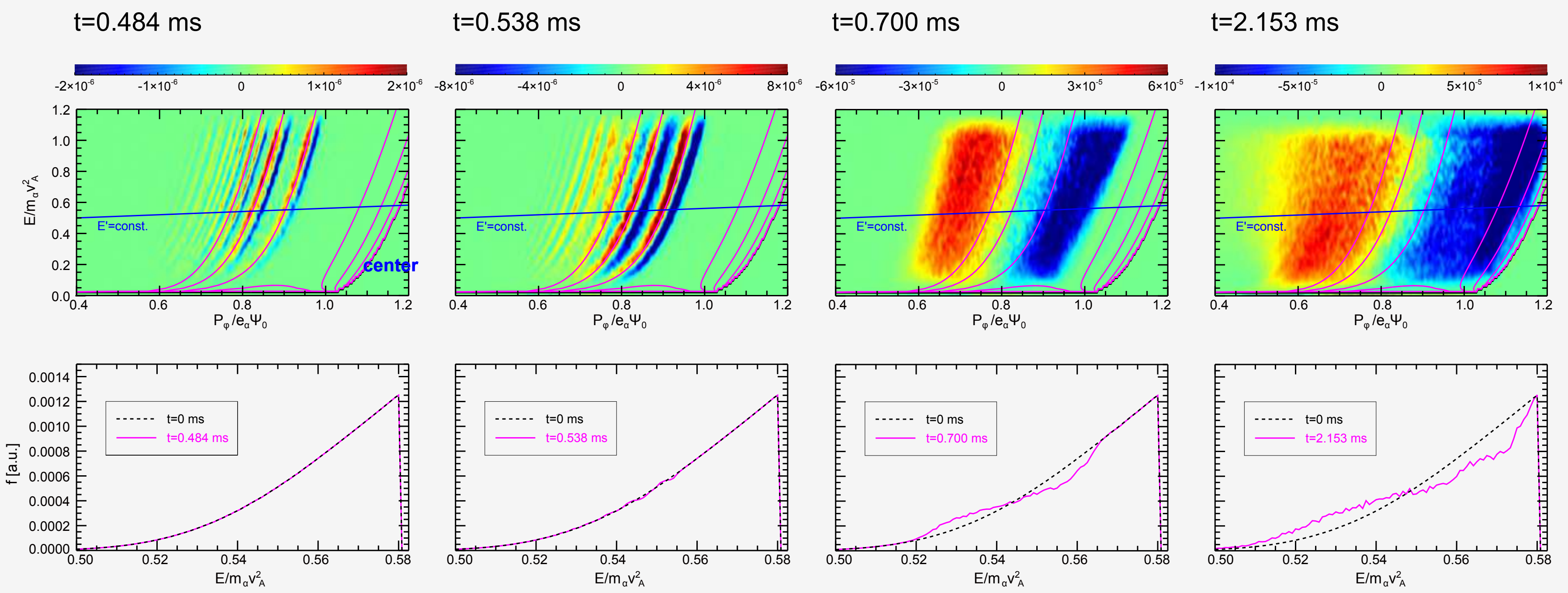

Fig. 4 : Alpha particle distribution analysis in phase space

The actual phase space is six-dimensional, but the result can be expressed in two dimensions. The top panel shows the evolution of the alpha particle distribution in a two-dimensional plane, with the alpha particle kinetic energy on the vertical axis and the momentum in the circumferential direction of the doughnut on the horizontal axis. The right edge of the panel corresponds to the center of the doughnut-shaped plasma cross section, while the left edge corresponds to the periphery. The magenta line represents the resonance conditions between alpha particles and Alfvén eigenmodes; red indicates the region where alpha particles increase, and blue indicates the region where alpha particles decrease. At the initial stage (t=0.484ms), a pair of red and blue stripes appears on both sides of the magenta line. Over time, as the amplitude of each Alfvén eigenmode increases, the stripes thicken and overlap, eventually forming a pair of thick red and blue bands.

The bottom panel shows the number of alpha particles in pink along the blue line shown in the top panel on which a physical quantity conserved during the interaction with the representative Alfvén eigenmode is constant. The dotted black line represents the distribution at the start of the simulation (t=0). In the initial stage, there are many alpha particles in the center (right edge of the figure) and fewer towards the periphery, but gradually the number of alpha particles in the center decreases and increases at the periphery. In other words, alpha particles are being transported from the center to the periphery.

Y. Todo et al., Nuclear Fusion 65, 102003 (2025).https://doi.org/10.1088/1741-4326/ae059f.

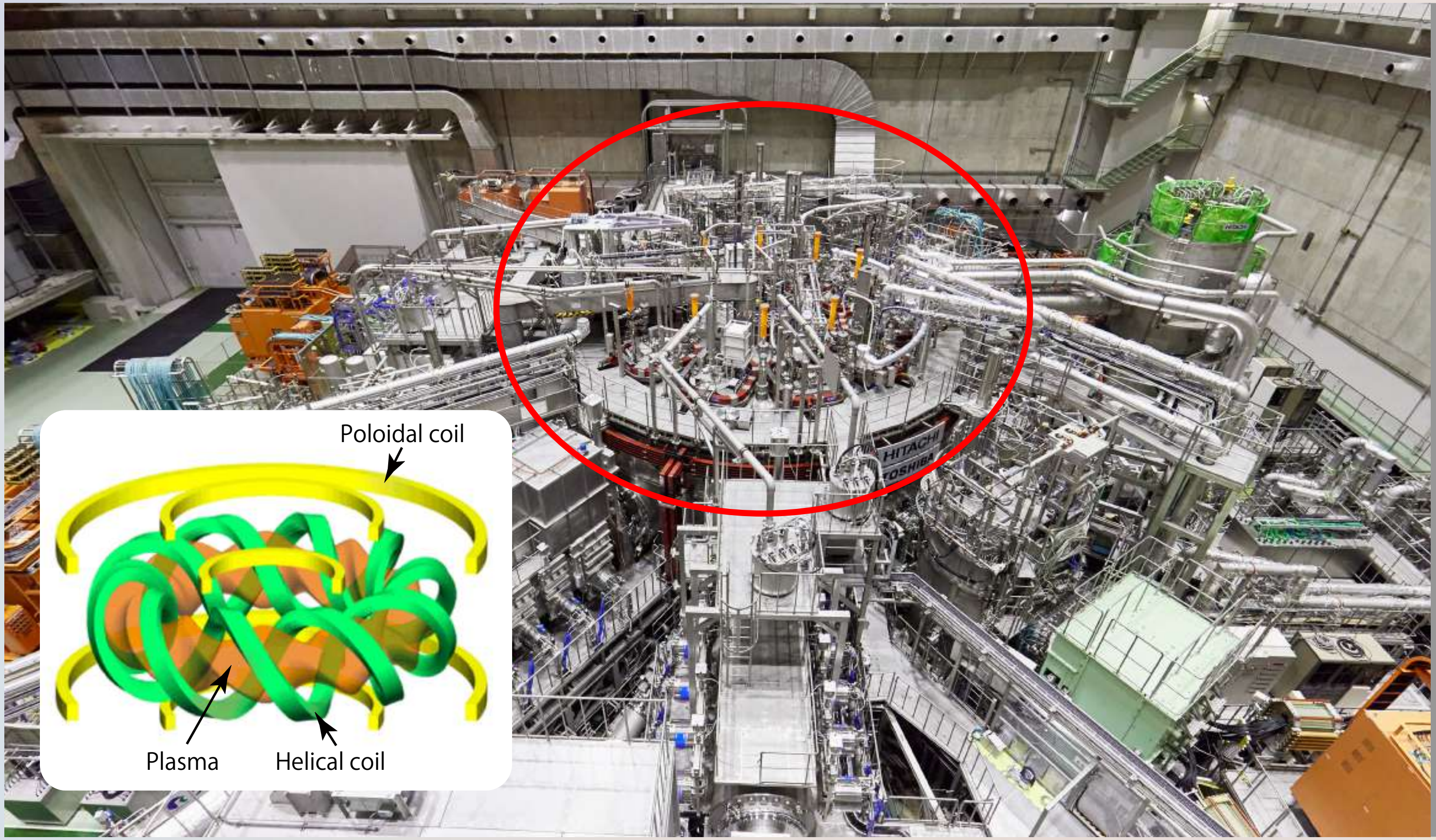

Fig.5 : The Large Helical Device at the National Institute for Fusion Science

The area circled in red is the main body of the LHD. Unlike the tokamak type, it uses two types of superconducting coils to create a spiral magnetic field and confine the plasma. While this device is not designed to produce DT fusion, it can generate high-temperature, high-density H and D plasmas for a variety of experiments. Since its launch in 1998, nearly 200,000 experiments have been conducted there, primarily by researchers at NIFS and domestic universities. It is scheduled to remain in operation until December 2025. Inserted figure is adapted from an illustration provided by NIFS.

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*1 As the temperature of a substance increases, it changes from solid to liquid to gas. Further increases in temperature cause electrons to separate from atoms (or molecules), forming ions, and these ions and electrons begin to fly around. This state is called plasma. Since D and T particles only have one electron, the ions that have lost their electrons become atomic nuclei.

*2 In plasma, not only the number of particles but also energy is important. For this reason, particle distribution is expressed not only in terms of density but also in terms of temperature and pressure. When the particle velocity distribution is direction-independent, the pressure is the sum of the energy of particles in a unit space multiplied by 2/3.

*3 The D ions injected for heating and the D ions used as fuel have significantly different energies (velocities). For this reason, they are considered separate types of plasma particles in simulations.

*4 The particle referred to here does not refer to a single actual plasma particle, but rather to a computational particle which represents a vast number of plasma particles. Increasing the number of computational particles placed at a lattice point reduces the number of plasma particles represented by a single computational particle, enabling more detailed simulations.

About the

Researcher

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Prof. Todo read Carl Sagan's book "Cosmos" when he was in high school and decided he wanted to become an astronomer. In graduate school, he worked on MHD simulations of astrophysical jets, but after graduating he got a job at his current research institute and embarked on the path of nuclear fusion. He didn't intend to continue for long, but he was fascinated by the process of developing hybrid simulation methods and how they could elucidate various physical phenomena.

His hobby is tennis. He started learning at a tennis school he attended about 15 years ago while accompanying his children, and he continues to play to this day. When he's on the court, he says, he concentrates fully on the game, which helps to clear his mind.

Interview date: August 1, 2025

Associated Research Projects:

Global transport of energetic particles and kinetic effect of thermal ions on magnetohydrodynamic instabilities in magnetically confined fusion plasmas (hp230113)
Impact of microscopic collective dynamics on pressure limit of magnetically confined fusion plasmas (hp240163)
Principal Investigator: Yasushi Todo, NIFS

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