



## Fast ion physics is heating up on Wendelstein 7-X

The goal of nuclear fusion is to create a self-sustaining fusion reaction whereby the kinetic energy of the fusion by-products is converted into heat both for energy generation and for sustainment of the temperatures necessary for the fusion reaction. The most likely candidate reaction is between isotopes of hydrogen (deuterium and tritium), producing 14.1 MeV neutrons and 4.3 MeV helium. The conditions under which this reaction occurs results in a plasma state, implying that the helium by-product is in a charged state. The goal of magnetic confinement fusion is to use magnetic fields to confine both the thermal hydrogen isotope plasma and the resulting energetic helium nuclei (alpha particles). Thereby the confined helium can collide with the deuterium and tritium, heating it and sustaining the reaction. Demonstration of the confinement of such energetic particles is a key goal of the Wendelstein 7-X (W7-X) project, as this is a necessary condition for bringing forward the Helias line of stellarators as a power plant.

The W7-X stellarator seeks to demonstrate reactor-relevant plasmas, including demonstration of good fast ion confinement. As the device will not be fueled with tritium, and is smaller and lower field than an equivalent power plant, proxy particles must be generated for demonstration of good alpha confinement. The neutral beam injection (NBI) and ion-cyclotron resonance heating (ICRH) systems serve this purpose, with 55 keV deuterium ions serving as proxy particles for fusion alphas in the larger reactor. In addition to simply demonstrating acceptable levels of fast ion confinement, the maximum- $J$  (the orbit bounce-averaged adiabatic invariant) nature of the W7-X magnetic field is predicted to improve fast ion confinement as the plasma beta is increased [1, 2].

In the previous experimental campaign on W7-X, the first neutral beam experiments were conducted. In these experiments, two of four ion sources were commissioned in neutral beam box NI21. A second neutral beam box (NI20) is being prepared for the future. The commission-

ing was smooth, achieving 5 s of continuous NBI, and no observed duct beam blocking. Discharges into the empty plasma torus provided a means to calibrate simulation model geometry [3], while spectroscopic measurements of the plasma-neutral beam interaction provided validation of neutral beam deposition simulations [4]. Such work highlights the neutral beam systems dual role as both heating system and plasma diagnostic [5].

### *In this issue . . .*

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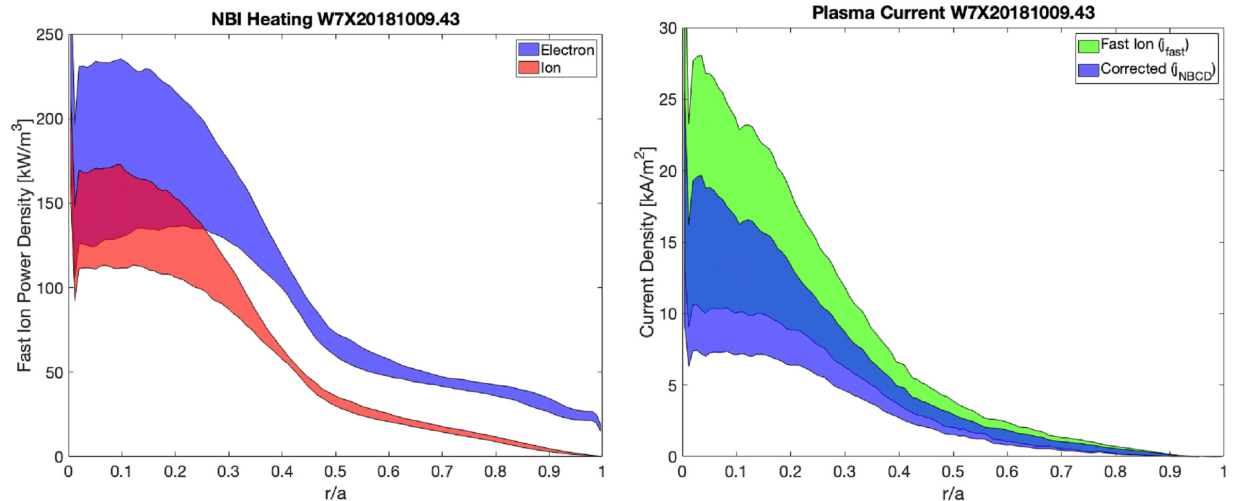
The Wendelstein 7-X (W7-X) stellarator commissioned the first of two neutral beam boxes during the previous experimental campaign. Data from these preliminary experiments is being used to validate simulations of neutral beam injection in stellarators. Predictive simulations are helping to inform future upgrades to and experiments on W7-X. . . . . 1

#### **Observation and prediction of the fast-ion distribution in the Large Helical Device using FIDASIM**

The National Institute for Fusion Science and University of California, Irvine have started an international research program for the observation and prediction of the fast-ion distribution in the Large Helical Device using fast-ion D alpha with FIDASIM since October 2018. The FIDA diagnostic is able to be a useful tool for understanding the fast-ion distribution in a three-dimensional magnetic field device. We describe the current status of the FIDA diagnostic and FIDASIM computer code on the LHD and show representative results. . . . . 3

#### **Online resources for learning about fusion research**

We provide an overview of freely available educational online resources relevant to plasma physics and fusion research. We hope that this list might constitute an entry point for young students, people in other fields, and teachers. . . . . 5



**Fig. 1.** Profiles of NBI in W7-X plasma heating (left) and current drive (right) as calculated from the BEAMS3D code for a pure NBI discharge in W7-X. Bounds indicate changes over 5 s.

Experiments scanning magnetic configuration, plasma density, and electron cyclotron resonant heating (ECRH) power were conducted. In general, plasmas in which the ECRH power was greater than the 3.6 MW of NBI power showed a consistent asymptotic density rise when the neutral beam was turned on with little response in plasma temperature. In contrast, discharges heated solely by NBI showed nearly constant plasma temperatures, a continual density rise, and strong density peaking in the core. These discharges reached the highest densities achieved in W7-X to date. Reintroduction of 1 MW of ECRH into these discharges arrested the density rise, flattened a region of density in the plasma core, and resulted in ion temperatures reaching 2 keV before dropping to 1.5 keV. These experiments are qualitatively in agreement with experiments conducted on W7-AS, and complementary experiments have been proposed for the Large Helical Device.

Data from these experiments is currently being simulated using the BEAMS3D [6], ASCOT [7] and VENUS-LEVIS [8] stellarator energetic particle codes. Analysis of these discharges is serving as a benchmarking activity for these codes, helping to validate their physics models and analysis workflows. Simulations such as these are an important part of the data analysis, as they provide the source terms in the radial transport equations and equilibrium calculations (current density). In Fig. 1, such terms for the heating and current drive are shown for a 5-s pure NBI discharge in W7-X. Work is underway to validate these simulation results against experimental data. And such simulations are already helping to guide future experiments in W7-X.

For the next experimental campaign, a second neutral beam box will be brought into operation and the ICRH antenna will begin operation. These upgrades will more

than double the ion heating capabilities of the experiment. The ICRH system will bring direct ion heating to W7-X and possibly produce higher energy fast ions than the NBI system. The second NBI beam line will not only double the heating power, but also allow for balanced beam injection. This allows for easy assessment of co- versus counter passing particle physics. Finally, efforts to improve the NBI pulse length, achieve higher neutralization efficiency and access high-density confinement modes will be explored.

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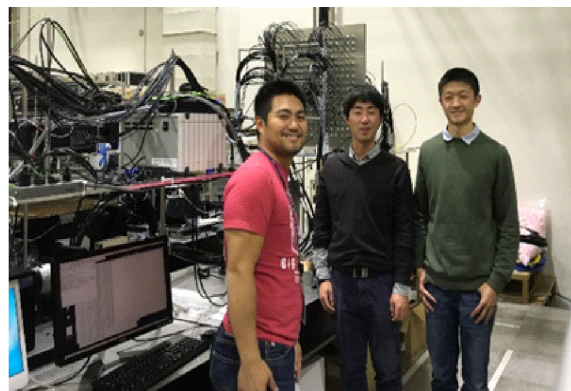
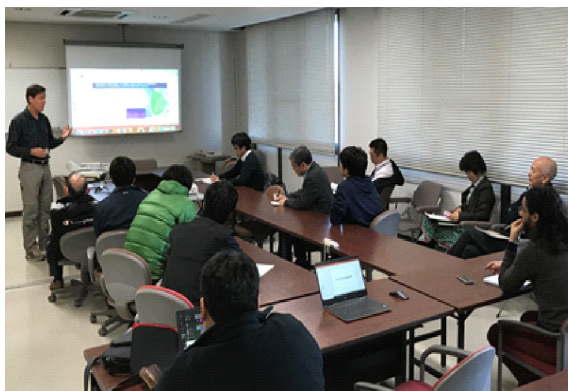
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## Observation and prediction of the fast-ion distribution in the Large Helical Device using FIDASIM

A magnetic confinement fusion reactor requires the sustainment of a high-temperature and high-density plasma by energetic alpha particles from fusion reactions. Therefore, it is important to understand the behavior of energetic particles in magnetic confinement devices. The study of energetic particle confinement has advanced in tokamak type devices [1] and is one of the main topics in ITER [2]. On the other hand, the study of energetic particle confinement in helical devices is rapidly developing. At the Large Helical Device (LHD), magnetohydrodynamics (MHD) mode-induced transport and loss of fast ions have been studied with high-power neutral beam injection (NBI) [3]. In the LHD, we have conducted only hydrogen experimental campaigns for several years. To understand the physics of fast-ions, deuterium experimental campaigns have been performed in the LHD since March 2017. The National Institute for Fusion Science (NIFS) and University of California, Irvine have started an international research program (Fig. 1) for the observation and prediction of the fast-ion distribution in the LHD, located in Toki, Japan, using fast-ion deuterium-produced alphas (FIDAs) with FIDASIM since October 2018.

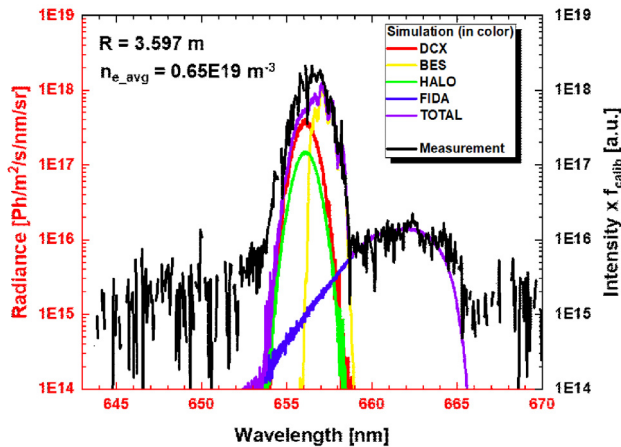
In the FIDA diagnostic, the Doppler-shifted D alpha light from fast-neutrals is utilized as a signal from the energetic particles. These fast neutrals are produced by the charge-exchange process between fast ions in plasmas and actively introduced neutrals from the NBI [4]. The advantages of the FIDA diagnostic are the velocity and spatially resolved measurement of fast ions at the crossing point between its line of sight and the incident line of the neutral beams.



**Fig. 1.** Photographs of a research meeting and preparation for experiments by researchers at the National Institute for Fusion Science and the University of California, Irvine.

Originally, the FIDASIM computer code predicted signals produced in two-dimensional (2D) axisymmetric devices. However, the effect of three-dimensional (3D) fields on fast-ion confinement is important. Therefore, FIDASIM has been enhanced to simulate signals produced in 3D geometry and is used here to predict FIDA signals at LHD. The code requires a distribution function, plasma profiles, magnetic equilibrium, and diagnostic geometry as inputs. GNET [5] solves a drift kinetic equation in five-dimensional phase space using a Monte Carlo technique, taking into account the guiding-center motion in the 3D magnetic configuration. It is used to calculate the distribution function. In order to validate FIDASIM, the radial profile of fast ions was measured using the FIDA diagnostic in MHD-quiet plasmas [6].

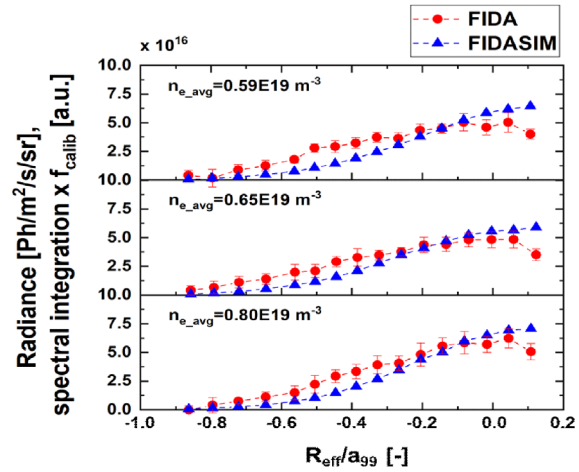
Figure 2 shows measured spectra from the FIDA diagnostic and various sources of light in the D alpha spectral band calculated by FIDASIM in the case of  $n_{e\_avg} = 0.65 \times 10^{19} \text{ m}^{-3}$  at  $R = 3.597 \text{ m}$ . The black solid line is measured spectra of the FIDA diagnostics with a calibration factor ( $f_{calib}$ ). The colored solid lines are calculated by FIDASIM. As a result of the comparison of the FIDA diagnostic data with FIDASIM results, they demonstrate good agreement.



**Fig. 2.** Measured spectra of FIDA diagnostic (black line) and various sources of light in the D alpha spectral band calculated by FIDASIM in the case of  $n_{e\_avg} = 0.65 \times 10^{19} \text{ m}^{-3}$  at  $R = 3.597 \text{ m}$ .

Figure 3 shows a comparison of the FIDA diagnostic radial profiles and the FIDASIM radial profiles for three different electron density discharges after integration over wavelength. The  $x$ -axis is the normalized minor radius of the LHD, and the  $y$ -axis is the radiance after spectral integration. The result indicates that, on average, the measurement and the simulation are consistent for these discharges at the center of the plasma ( $r_{eff}/a_{99} = -0.28 \sim 0.05$ ) when the line-averaged electron density is

$n_{e\_avg} \leq 0.805 \times 10^{19} \text{ m}^{-3}$ . Overall, the FIDA diagnostic results and the FIDASIM results are in good agreement in MHD-quiet plasmas at the center of the plasma for co-injection.



**Fig. 3.** Comparison of the FIDA diagnostic and FIDASIM radial profiles for three different discharges of spectral integration. The radiance and spectral integration profile are for Doppler shifts (660.05 nm ~ 665.30 nm).

This study indicates that the FIDA diagnostic can be a strong tool for understanding the fast-ion distribution in a 3D magnetic field device. For future work, we will endeavor to understand fast-ion behavior with the MHD instabilities using the FIDA diagnostic and the latest FIDASIM in the LHD.

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## Online resources for learning about fusion research

At the beginning of this year, lectures being taught online were still a minority in a typical student's schedule. While the concept of Massive Open Online Courses (MOOC) was a growing trend in higher education over the last years, these courses were often single courses given by educators and/or universities specializing in remote teaching. Now, almost a year (or two semesters) into a worldwide pandemic situation, basically all universities around the world have been forced to transit to online teaching. This has created a massive amount of educational resources that could in principle be available to everybody but are in reality often hidden behind a university-based teaching portal. Still, a few courses are free to access, but those are difficult to find. This fact motivated the idea to assemble an overview of freely available educational online resources relevant to plasma physics and fusion research. We hope that this list might constitute an entry point for young students to get interested in the field of nuclear fusion. It might also serve as an information source for people from other different fields to get an idea about what we are researching, or even serve as an inspiration for teachers for their own lectures. In no particular order, we have compiled the following list.

### Plasma physics: Introduction

This is an MOOC developed by EPFL and freely available at edX [1], EPFL courseware [2], or YouTube [3]. The course covers the basics about plasma physics and is an excellent starting point. It requires basic knowledge about electromagnetism, thermodynamics, and statistical physics (all topics covered by a typical physics bachelor's degree).

[1] <https://www.edx.org/course/plasma-physics-introduction>

[2] [https://courseware.epfl.ch/courses/course-v1:EPFL+PlasmaIntroduction+1T\\_2018/about](https://courseware.epfl.ch/courses/course-v1:EPFL+PlasmaIntroduction+1T_2018/about)

[3] <https://www.youtube.com/channel/UCM91JfbMX-vtwKYNQAVI0YuQ/playlists>

### Plasma physics: Applications

This course is the continuation of the previous course and covers plasma applications in industry, astrophysics, and nuclear fusion. It is available at edX [4], EPFL courseware [5], and YouTube [6].

[4] <https://www.edx.org/course/plasma-physics-applications>

[5] [https://courseware.epfl.ch/courses/course-v1:EPFL+PlasmaApplication+1T\\_2018/about](https://courseware.epfl.ch/courses/course-v1:EPFL+PlasmaApplication+1T_2018/about)

[6] <https://www.youtube.com/channel/UCM91JfbMX-vtwKYNQAVI0YuQ/playlists>

### Fusion research lecture

This lecture is usually given by the author of this article at the University of Stuttgart (Fig. 1). It requires basic plasma physics knowledge and covers various aspects of nuclear fusion research with a focus on magnetic confinement. It is available at YouTube [7].

[7] <https://www.youtube.com/playlist?list=PL9F2aQG5C-nOdw9MXqS309tojBUvChQ9jm>

### Summer school: Fusion Energy and Plasma Physics Course

The Summer Science Undergraduate Laboratory Internship (SULI) course is a summer school regularly given at Princeton Plasma Physics Laboratory (PPPL). It consists of a series of lectures ranging from an introductory level into plasma physics and nuclear fusion to specialized talks about turbulence in plasmas, plasma propulsion, and complex plasmas, to give just a few examples. The lectures are available at the PPPL website [8].

[8] <https://suli.pppl.gov/2020/course/index.html>

### Plasma fluid theory (magnetohydrodynamics)

This course requires basic undergraduate physics knowledge and starts with simple fluid mechanics, going then into a wide range of topics including 2-fluid treatment, magnetohydrodynamics (MHD), and more. It was originally taught at the National Research Foundation of Korea and is available on YouTube [9].

[9] [https://www.youtube.com/playlist?list=PLJnw7q\\_g-jMgmuGctIqL6crS7cmmALTZLe](https://www.youtube.com/playlist?list=PLJnw7q_g-jMgmuGctIqL6crS7cmmALTZLe)

### Introduction to Plasma Physics

Although the videos for this course were recorded 30 years ago, they are still relevant as they walk the audience through Francis Chen's book *Introduction to Plasma Physics and Controlled Fusion* which is considered a standard text book. This course was given at the University of Wisconsin–Madison by James D. Callen and is available on YouTube [10].

[10] <https://www.youtube.com/playlist?list=PL1FcfK-GHsyMhfKegznP0i7eO804Z5YBdm>

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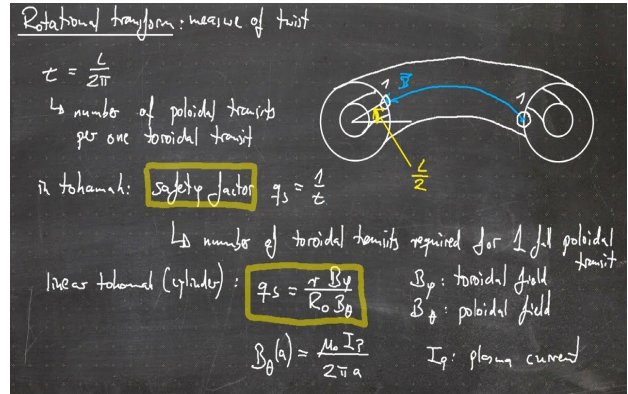


Fig. 1. Screenshot of the University of Stuttgart fusion research lecture [7].