

Pellet particle-fueling experiments in the Wendelstein 7-X stellarator

During the last two experimental campaigns (OP1.2a and OP1.2b) at the advanced stellarator Wendelstein 7-X (W7-X), pellet fueling experiments were performed [1]. W7-X is situated at the Max Planck Institute for Plasma Physics in Greifswald, Germany. For the sake of deep and efficient particle fueling, series of pellets were injected into W7-X discharges. A blower-gun pellet injector [2] that was originally used at the Max Planck Institute in Garching, Germany, was loaned to W7-X, in order to investigate the fueling needs of a large stellarator.

For future campaigns, a steady-state pellet injector is presently under construction at Oak Ridge National Laboratory (ORNL), USA. The design of this new injector is derived from a former prototype that was developed for the tokamak ITER [3]. The new injector will be the result of a collaboration between ORNL, the Princeton Plasma Physics Laboratory (PPPL), the National Institute for Fusion Science (NIFS), Japan, and the Laboratorio Nacional de Fusión (CIEMAT), Spain. All activities are organized under the aegis of the European Atomic Energy Community (EURATOM) on the European side, and the US Department of Energy (USDOE) on the US side.

The Garching blower-gun injects hydrogen or deuterium ice pellets, with a maximum velocity of about 300 m/s. Each pellet is of cylindrical shape with a length and diameter of 2 mm; hence each hydrogen pellet contains nominally 3.3×10^{20} atoms. Helium is used as the propellant gas. Up to ≈ 40 pellets are frozen for one plasma discharge, which can then be injected with a variable repetition frequency between 2.5 Hz and 30 Hz. Previously this injector was used on ASDEX-Upgrade [4] with a single barrel; this design was changed for W7-X to a two-barrel injector. Consequently, pellets can be injected into the inboard port (AEL41) on the magnetic high-field side (HFS), and the outboard port (AEK41) on the magnetic

low-field side (LFS). Hence, both HFS and LFS pellet injection are possible into one discharge.

Figure 1 shows a sketch of the arrangement. Two pellet guide tubes connect the blower-gun with W7-X, with lengths of 14.5 m for the LFS pellets and 29 m for the HFS pellets. Microwave mass detectors [5] allow for the measurement of pellet mass and velocity in flight. A fast photodiode records the ablation light intensity, and a fast camera system (with a frame rate up to 350 kHz) observes the ablation clouds simultaneously from two sides [6]. A “burst-mode” Thomson scattering system [7] allows for the measurement of electron density and temperature profiles, with a time resolution $\approx 100 \mu\text{s}$. These fast data are rapidly evaluated, in order to investigate the final deposition of particles after radial drift of the ablated pellet.

In this issue . . .

Pellet particle-fueling experiments in the Wendelstein 7-X stellarator

Deep and efficient particle fueling experiments were performed in the stellarator Wendelstein 7-X (W7-X). Series of hydrogen ice pellets were injected by means of a blower-gun. The question was tackled, whether there is a difference in the fueling efficiency between the inboard and the outboard machine side. In addition, the injection of series of relatively small and slow pellets was tested, in preparation for a future steady-state pellet injector with faster and larger pellets. 1

PLADyS: Advanced Core-to-Core Network for High-Temperature PLAsma Dynamics and Structure Formation Based on Magnetic Field Diversity

This 5-year program is designed to elucidate the origin and the dynamical evolutions of the structural formations that are ubiquitously observed in nonlinear and/or nonequilibrium systems. The focus is on two key aspects to understand their mechanism: the dynamics of turbulence and energetic particles in high-temperature plasmas, and the resultant emergence of global spontaneous flow (structure, such as geodesic acoustic modes and zonal flows). 5

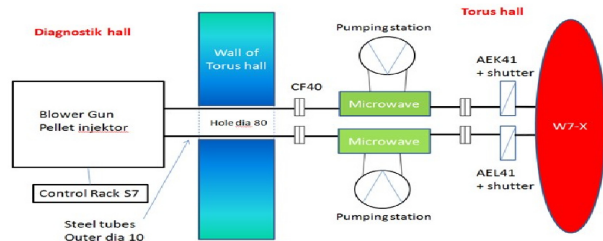


Fig. 1. Arrangement of the blower-gun in the diagnostic hall, which is separated from the torus hall by a radiation shield (the wall of the torus hall). Two steel tubes guide the pellets from the blower-gun to W7-X through a hole in the wall, the hole having a diameter of 80 mm. The guide tubes have an outer diameter of 10 mm. As the guide tubes are very long, they are built in shorter sections, which are connected by CF40 vacuum flanges. Halfway between the blower gun and W7-X, two pumping stations pump away the eroded hydrogen of the pellets. They also contain the microwave measurement systems. Shutters in front of the ports AEK41 (LFS pellets) and AEL41 (HFS pellets) separate W7-X from the guide tubes. Not to scale.

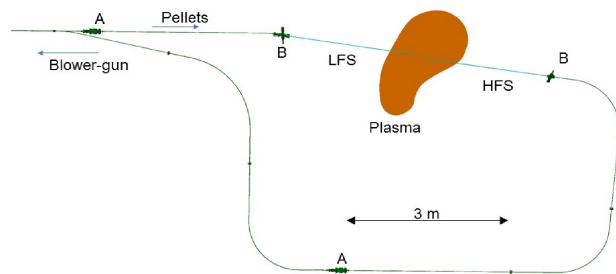


Fig. 2. Geometry of the HFS and LFS guide tubes in real space. The scale indicates the size of the arrangement. The blower-gun and W7-X are not shown. The labels A show the location of the microwave systems, the labels B the vacuum shutters.

Fig. 2 shows the shape and size of the two guide tubes.

Several motivations exist for the injection of pellets in W7-X. The most important is the mitigation of hollow density (or even pressure) profiles, for the case of dominating neoclassical particle transport in the core of W7-X. The off-diagonal term (thermo-diffusion) driven by the electron temperature gradient can induce a significant outward particle flux. Neoclassical transport calculations predict the requirement of a central particle-fueling rate in the range of $10 \times 21 \text{ s}^{-1}$ with a heating power of 10 MW. Only pellets can provide such a high central fueling rate.

Another motivation is the test of HFS pellet injection, in order to take advantage of the grad-B drift. This technique provided a considerably improved fueling efficiency in tokamaks [8]. Although the grad-B term in W7-X is smaller than in a tokamak, pellet code calculations predict

a favorable fueling efficiency for HFS pellets compared to LFS pellets.

In addition, the technique of injection of series of pellets was investigated, with comparably small and slow pellets. The use of small pellets is of particular interest in W7-X, because here electron cyclotron resonance heating (ECRH) is used, which exhibits a cut-off density of $1.2 \times 10^{20} \text{ m}^{-3}$ in the X2-mode polarization at 2.5 T main magnetic field strength. Only very large pellets offer the possibility of penetrating to the magnetic axis (as required for central fueling, see above). However, pellets of that size might violate the upper density boundary. A solution for this dilemma is, to some extent, the O2-mode polarization. However, large pellets will then reduce the single-path power absorption, which is a function of the electron temperature T_e . The lower the central T_e , the poorer the single-path absorption. Hence, unacceptably high stray radiation levels might be produced in the W7-X vessel.

Finally, pellets are known to induce modes of improved energy confinement, for instance by the formation of peaked density profiles, resulting from central particle fueling [9]. Such enhanced confinement modes could be demonstrated in W7-X with series of pellets.

The formation of hollow density profiles was not an issue during the first two experimental campaigns. Even without central particle fueling by pellets, the density profiles were always flat or slightly hollow. Therefore, enhanced central particle fueling was never required to avoid destabilization of deleterious MHD modes. Fast and efficient particle fueling could be demonstrated successfully nevertheless, as shown for instance in Fig. 3. A series of five pellets enhanced the central electron density faster than expected from a diffusive time scale. Within $<30 \text{ ms}$ about 80% of all pellet particles were deposited inside an effective minor plasma radius of 0.3 m. Such behavior was typical for most of the discharges.

In total, 147 discharges were fueled with series of pellets. Figure 4 is a photograph of the first HFS pellet ever injected into W7-X. In many cases, a distinct peaking of the density profile could be observed, as shown in Fig. 5. During a series of 15 pellets, the line density increases from $3 \times 10^{19} \text{ m}^{-2}$ to $9 \times 10^{19} \text{ m}^{-2}$ (corresponding to an averaged density of very roughly about $2 \times 10^{19} \text{ m}^{-3}$ to $7 \times 10^{19} \text{ m}^{-3}$). Each pellet can be seen as a sharp jump upward in the density signal. After the series of pellets, the line density decays on a time scale of about 1.3 s. The density profile peaking is defined as the ratio of the central to the average density. It increases considerably during the series of pellets, because of the enhanced central particle fueling.

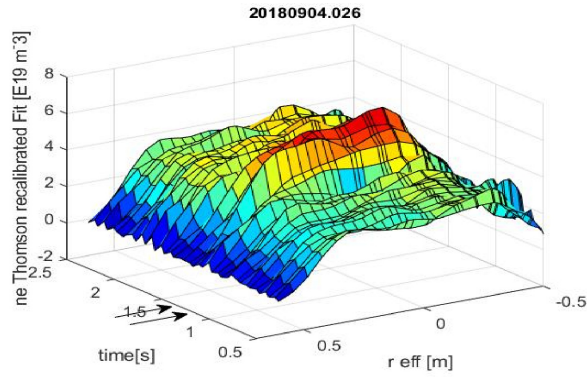


Fig. 3. Time development of the density profile, as measured by Thomson scattering. The two arrows indicate the time interval for the injection of the series of pellets. The Thomson data were recalibrated with respect to the interferometer line density measurement. The density value is color encoded (z-axis).

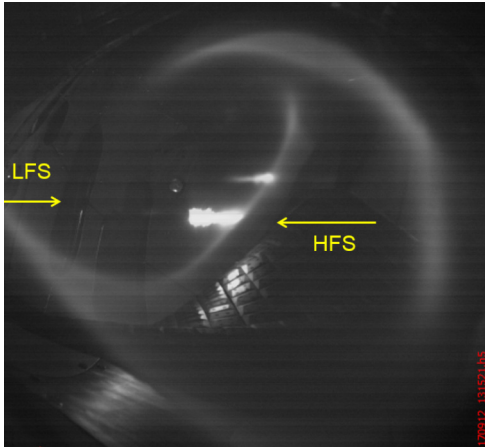


Fig. 4. Photograph of the first HFS pellet ever injected into W7-X. The HFS and LFS injection geometry are indicated by arrows. Some of the W7-X graphite tiles can also be seen, illuminated by the pellet ablation light. The second, weaker light trace above the ablation cloud is a reflection on the wall.

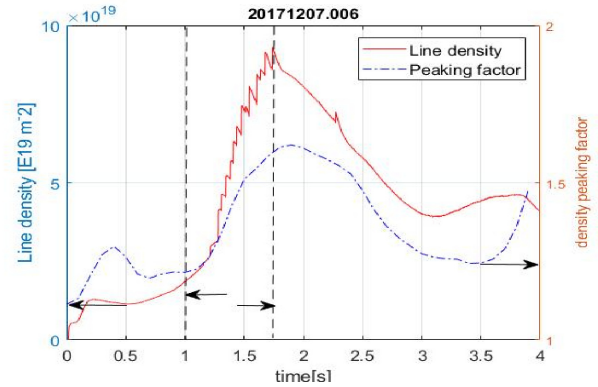


Fig. 5. Time traces of the plasma line density (left y-axis, solid line) and density peaking factor (right y-axis, dot-dashed line). The two dashed vertical lines indicate the time interval when the series of pellets was injected.

HFS pellets show a systematically higher fueling efficiency than LFS pellets. However, the difference is small and is, taking into account the measurement uncertainties, statistically not relevant. The measured pellet fueling efficiencies are $70\% \pm 31\%$ for LFS pellets and $88\% \pm 34\%$ for the HFS pellets. The uncertainties show the limited shot-to-shot and pellet-to-pellet reproducibility of the experiments. It is assumed that the rather small difference between HFS and LFS pellets is a result of the small grad-B term of about 0.8 T/m in the pellet injection plane.

These experimental results were compared to the outcome of HPI2 code calculations. HPI2 is a pellet deposition code [10] that calculates the deposition of pellet particles, taking into account the grad-B drift of the pellet plasmoid (the dense and cold high-beta cloud produced by the pellet particles). A deceleration of the plasmoid drift, which is caused by parallel currents inside and outside the plasmoid, is also considered by the calculation. The experimental findings are consistent with the calculations. Figure 6 shows the result of an HPI2 code calculation, performed for a single pellet. The measured density values from Thomson scattering (blue circles) are smoothed by a fit to a Gaussian process regression function (solid red curve), indicating the uncertainty of the measurement (dotted red curves). The dot-dashed black curve shows the result of the calculated particle deposition after the drift. The blue dashed curve shows the pellet ablation profile. As expected, the ablated material drifts away from the plasma center, as can be seen from the outward displacement of the deposited curve compared to the ablated one.

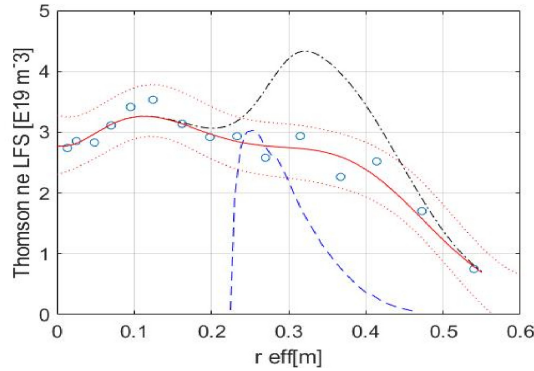


Fig. 6. Result of the HPI2 pellet code calculation. Shown is the measured Thomson density profile (circles) together with a smoothing regression to a Gaussian process function (solid red line) and the interval of reliability of the regression (dotted red lines). The HPI2 result for the pellet ablation is the dashed blue curve, and the final deposited particle density is indicated as the black dot-dashed line, being superposed on the density profile prior to pellet injection. The maximum of deposited particles is further outside the plasma compared to the maximum of the ablation, as a result of the grad-B drift.

The technique of injection of series of pellets works well, even with small and slow pellets. The experiments demonstrate that plasma cooling by the first pellets in a series supports the deeper penetration of the last pellets in the same series. Thus, the fueling efficiency is enhanced, and fast and efficient central particle fueling is facilitated. This was demonstrated for the first time in LHD [11].

A striking effect in W7-X was the strong transient enhancement of the energy confinement time that appeared a few 100 ms after the last pellet of a series. The experimental energy confinement time exceeded the expectation from the International Stellarator Scaling law ISS04 [12] by several 10%. It was, however, not possible to stabilize the phase of enhanced confinement to stationarity. Common for these discharges were a peaked electron density profile, reduced plasma radiation losses, strongly increased central ion temperatures, and a strong negative radial electric field. The highest fusion triple product, observed in a stellarator up to now, $6.5 \times 10^{19} \text{ keV m}^{-3} \text{ s}$, could be achieved, with central ion temperatures well above 3.5 keV, and energy confinement times above 200 ms. These findings could not be reproduced with gas puffing as a particle source. Figure 7 shows time traces of the energy confinement time τ_E for the experiment and the ISS04 expectation. After the series of pellets, the experimental τ_E transiently exceeds the ISS04 value.

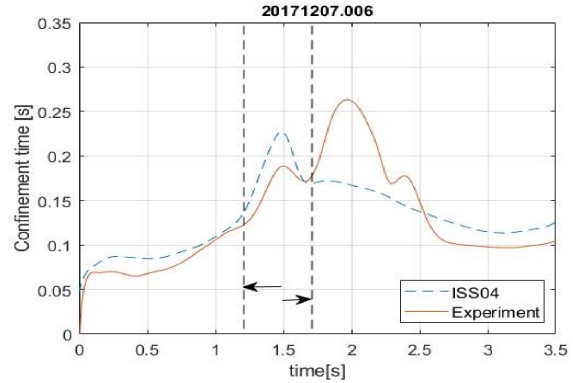


Fig. 7. Time traces of the energy confinement time for the experimental data (solid line) and the ISS04 expectation (dashed line). The two dashed vertical lines indicate the time interval of pellet injection.

It is assumed, as a working hypothesis, that the enhanced density gradients after pellet injection might help stabilize ion-temperature gradient (ITG) modes. This mechanism is supported by the advanced concept of W7-X including an approach to quasi-isodynamicity [13], reducing the W7-X sensitivity against electrostatic turbulence.

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Introduction to Stellarators

August 19–23, 2019

This summer school, which is supported jointly by the Princeton Plasma Physics Laboratory and the Simons Foundation Collaboration in Mathematical and Physical Science, will provide an introduction to Stellarators for graduate students and postdoctoral fellows in applied mathematics, computer science, fluid dynamics, and plasma physics. The course will be mostly self-contained, and no previous background in fusion or plasma physics is needed. The emphasis of the course will be on mathematical and physical foundations of Stellarators, and in addressing optimization methods for designing Stellarators. The lecturers of the course are drawn from members of the Simons Foundation Collaboration on “Hidden Symmetries and Fusion Energy.”

The lectures will be given at the Princeton Center for Theoretical Science. The lecture schedule includes problem-solving sessions by students and a computer lab at the Princeton Plasma Physics Laboratory. Students will have an opportunity to present and discuss their research in a poster session (optional).

The application deadline is July 1, 2019. Please apply on the website (<https://hiddensymmetries.princeton.edu/summer-school>).

PLADyS: Advanced Core-to-Core Network for High-Temperature PLAsma Dynamics and Structure Formation Based on Magnetic Field Diversity

The Institute of Advanced Energy (IAE) [1], Kyoto University, Japan (Prof. Kazunobu Nagasaki being the PI), has won the Core-to-Core Program implemented by the Japan Society for the Promotion of Science (JSPS) [2]. This program is designed to create world-class research centers that partner over the long term with other core research institutions around the world in advancing research in leading-edge fields on issues of high international priority. It also concentrates on fostering the next generation of trailblazing young researchers. (These two sentences are cited from the JSPS Website [2].) The program is approved for 5 years (April 2019–March 2024), with a rigorous interim evaluation. The approval rate for this fiscal year was 8 out of 52 applications (~15%) for all research fields, which demonstrates the competitiveness of this application.

The title of the approved program is *Advanced Core-to-Core Network for High-Temperature Plasma Dynamics and Structure Formation Based on Magnetic Field Diversity*. The objectives of this program are summarized as follows (translated mostly from the application form).

One of the largest scientific goals is to elucidate the trigger (or the origin) and the dynamical evolutions of the structural formations that are ubiquitously observed in nonlinear and/or nonequilibrium systems in physical, astronomical, biological, and social phenomena. In laboratory experiments on magnetically-confined high-temperature plasmas, the structural formations, which cause the transition to a new state with improved confinement, are not only observable, but also actively controllable through various means such as heating and magnetic configurations

This program will focus on two key aspects to understand the mechanism of these structural formations: the dynamics of turbulence and energetic particles in high-temperature plasmas, and the resultant emergence of global spontaneous flow (structure, such as geodesic acoustic modes and zonal flows). Recent research has demonstrated that such structural formations can be controlled by means of the three-dimensionality of the magnetic field configuration (magnetic field diversity).

This program aims to establish an international core-to-core network for emerging academic research on structural formation phenomena in nature by utilizing high-temperature plasmas in a variety of magnetic configurations. We have negotiated with partner institutions (abroad) since we started the application procedure, and have formed the core-to-core network shown in Fig. 1.

This program will facilitate international collaborations mainly through three activities: (1) research collaborations, (2) seminars, and (3) visiting research exchanges (younger generations).

In support of activity 1, we have set up three task forces (leading institutions designated), as summarized in Table 1.

In support of activity 2, annual seminars will be held in turn hosted by core institutions. The kick-off seminar is scheduled to be held in Kyoto (23–25 March 2020) jointly with the 20th Coordinated Working Group Meeting (CWGM).

Several young Japanese researchers have been already selected to be dispatched to collaborating institutions [long-term visit research exchanges (activity 3) for the 2019 Japanese fiscal year], and also we are ready to receive similar visitors from abroad with “matching funds” that they have received as part of their international collaboration budgets.

As mentioned, structural formation is a topic of broad common interest in many research fields. Thus, we will also foster interaction with other research fields and should be playing a leading role for emerging new academic research on structural formation through this program.

We have set up a website for this program [3] (mostly in Japanese at this moment) and created a logo (Fig. 2) reflecting images of flows and structure formation. We welcome expressions of interest in this program to pro-

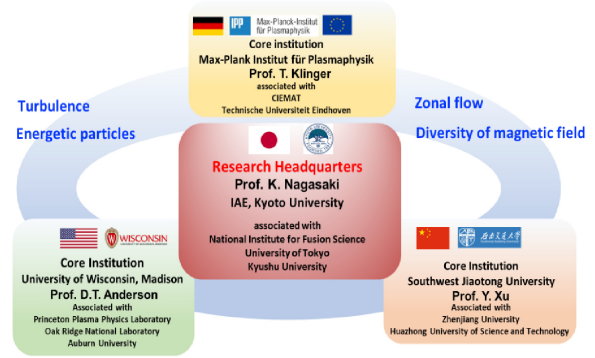


Fig. 1. Core-to-core network of this program.



Fig.2 PLADyS logo.

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- [4] K. Nagasaki and S. Kobayashi (Kyoto University); S. Inagaki (Kyushu University); M. Nakata, Y. Suzuki, and M. Yokoyama (National Institute for Fusion Science).

Table 1. Task Forces formed in this program.

Task Force Name	Focus area	Leading institution
1. Turbulence and spontaneous flow	Driving mechanisms of zonal flow and structural formation by high-resolution measurements and large-scale simulations	Kyoto University
2. Excitation of spontaneous flow by energetic particles	Driving mechanism of spontaneous flow and structural formation by nonlinear wave-particle interactions	Max Plank Institut für Plasmaphysik
3. Control of structural formation by means of three-dimensionality (3D) of magnetic field configurations	Controlling structural formation by diversity of 3D fields.	University of Wisconsin-Madison