

Wendelstein 7-X status update

First divertor operation: higher plasma densities, longer discharges

Shortly before Christmas, the 2017 experimental campaign on Wendelstein 7-X (W7-X) was completed as planned. Starting in early September, fifteen weeks of operation were conducted and major machine components worked without failures, allowing the scientists an efficient use of the machine time. The W7-X team currently comprises about 150 scientific staff members based in Greifswald and more than 60 scientists from EUROfusion laboratories, the United States, Japan, and Australia.

Expectations for the experiments were high: after the first campaign, ending in March 2016, W7-X was equipped with a new component for plasma exhaust – the so-called island divertor. The divertor takes up heat loads conducted along magnetic field lines onto its special targets that interact with magnetic islands external to the confinement volume in which nested magnetic surfaces exist (see Fig. 1).

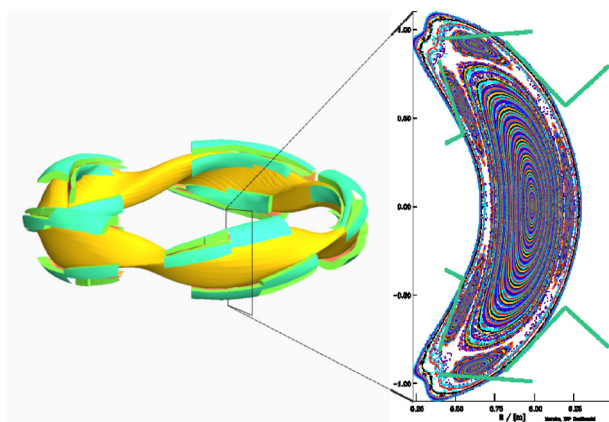


Fig. 1. Wendelstein 7-X plasma (yellow) with divertor (green); plasma cross-section with magnetic islands cut by divertor targets (green).

The test divertor was installed for the recently conducted campaign and experiments to be carried out in 2018, and is part of a long-term strategy to extend plasma pulse length. Prior to this experimental campaign, ten divertor units had been installed. Even without water cooling, the test divertor units are more tolerant to unexpected loads and thus an ideal tool for first divertor tests. Consequently, the goals of this divertor phase were to gain experience with the magnetic field in the presence of the divertor and to develop safe and reliable operation. This will form the basis for experiments that will ultimately extend pulse lengths from seconds to several minutes.

Figure 2 shows how the plasma acts on the divertor. The figure shows thermography data indicating the location of the heat loads. During the campaign the maximum surface temperature on the divertor approached 900 °C after a few seconds of the discharge. A first analysis indicates that the observed temperatures match theoretical predictions. Having gained confidence that the heat loads can be controlled, longer discharges of up to 30 s became routine by the end of the campaign. With the longer discharges, the divertor allowed deposit of up to 75 MJ of heating energy in W7-X – more than 18 times the energy limit of the first campaign.

In this issue . . .

Wendelstein 7-X First divertor operation: higher plasma densities, longer discharges

With the new (as yet uncooled) divertor installed, discharges up to 30 s became routine, and 75 MJ of energy could be absorbed by the ten divertors. The magnetic field was tweaked to equalize the power load on all the divertors. Pellet injection was used to raise core plasma densities to $1.4 \times 10^{20} \text{ m}^{-3}$ 1

2017 International Stellarator–Heliotron Workshop

The 2017 International Stellarator–Heliotron Workshop (ISHW-2017), hosted by the Heliotron J group [Institute of Advanced Energy at Kyoto University], was held at Kyoto University 2–6 October 2017.

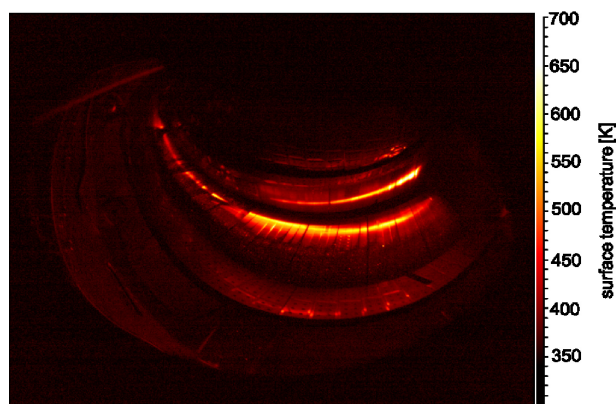


Fig. 2. Infrared image of one of ten divertor units during a plasma discharge in W7-X. Two bright stripes indicate the most highly loaded areas, called strike lines. These strike lines are typically a few centimeters wide and reach a temperature of up to more than 400 °C in this example.

However, in order to successively extend the heating power and pulse lengths, small deviations from the ideal magnetic fields leading to asymmetric power loads needed to be overcome. These deviations are due to small inaccuracies in the construction of the superconducting coils of Wendelstein 7-X, but small magnetic field errors can be corrected with a set of supplementary trim coils. Using these coils, we successfully equalized the heat load to each divertor unit as confirmed by the infrared cameras.

With these symmetrized power loads it was possible to extend the heating energy. With correspondingly extended heating power, the plasma density could also be increased. Core plasma densities up to $1.4 \times 10^{20} \text{ m}^{-3}$ were achieved — more than four times as much as in the previous campaign. Two developments made this achievement possible:

1. A new system for efficient fueling of Wendelstein 7-X plasmas (the pellet injection system) was successfully brought into operation. The injector shoots tiny frozen hydrogen pellets into the plasma, as illustrated in Fig. 3. As the pellets propagate through the plasma, they are ablated and finally ionized, thereby fueling the plasma.
2. A new heating scheme is required at high densities. A special polarization of the microwave beams allows them to penetrate into the plasma center beyond regions of high plasma density, where the beam would otherwise be reflected. The microwave beam polarization is changed during the initial 2 s of plasma operation, when densities are lower. This heating scheme creates plasmas with excellent energy confinement and high ion temperatures.

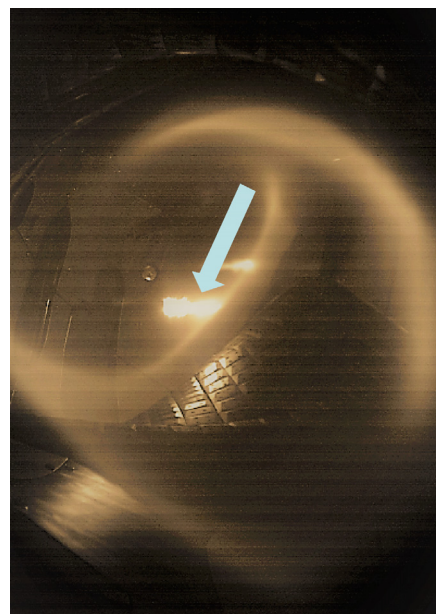


Fig. 3. View into the plasma vessel of W7-X during pellet injection. Tiles of the structured wall protection are seen in the lower central region illuminated by the visible plasma light (blurry regions). The pellet is indicated by the arrow.

Finally, the capability of plasma operation at high plasma density appears to be a key ingredient to operate the divertor under favorable conditions — the so-called detachment regime. This is the state of the divertor plasma in which the divertor target plates are well isolated, preventing higher heat fluxes from reaching the target plates. Divertor detachment may be a requirement for future fusion power plants, because it significantly minimizes the power loads to the divertor surface. In this campaign, we could reach stable, complete detachment for several seconds. This achievement results in a reduction of the power loads by a factor of 10 on all ten divertors.

Additional physics aspects also benefited from the extension of achievable plasma densities at different heating power. Crucial aspects of stellarator optimization such as the control of internal plasma currents and the stellarator specific heat transport could be addressed. New and exciting insights into plasma turbulence and the flows of impurities were possible with new and upgraded diagnostics systems. All experiments performed included variations of the magnetic field configuration, which is an important parameter influencing the plasma transport and stability properties.

In summary, the 2017 experimental campaign has been successfully completed. The time until summer 2018 will be used for completing and commissioning new installations including new plasma diagnostics, a specially designed divertor element (the so-called scraper element),

and new heating systems. The present plan foresees that plasma operation will be commenced in July 2018.

Dr. Andreas Dinklage for the W7-X Team
Max-Planck-Institut für Plasmaphysik Greifswald
Wendelsteinstraße 1
17491 Greifswald, GERMANY
E-mail: w7xnewsletter@ipp.mpg.de

2017 International Stellarator–Heliotron Workshop

The 2017 International Stellarator–Heliotron Workshop (ISHW-2017), hosted by the Heliotron J group [Institute of Advanced Energy at Kyoto University], was held at Kyoto University from October 2 to October 6, 2017. The conference was locally organized by a team from Kyoto University coordinated by Prof. Mizuuchi (chair) and Prof. Nagasaki (secretary). The conference attracted nearly 200 delegates from the stellarator-heliotron community, as well as invited speakers from the tokamak community. Our Japanese hosts provided an excellent and unique atmosphere for the conference.

The international scientific program committee, chaired by C. Hidalgo, played a key role in the development of the scientific program [<http://www.center.iae.kyoto-u.ac.jp/ishw2017/program.html>]. The objective of the conference was to assemble contributions with depth and high quality from the entire stellarator-heliotron community, including a special session on the physics of decoupling transport channels to promote synergies between tokamaks and stellarators.

There were four important highlights since the previous workshop held in Europe [Greifswald, October 2015]:

- The first experimental campaign on W7-X has been conducted (with an uncooled limiter in the OP1.1 campaign) with a program dedicated to the investigation of neoclassical physics and the effect of correction coils on the limiter loads [Lazerson et al.] followed by (during fall 2017 and on-going when the conference was held) operation using an inertially cooled graphite divertor (OP1.2a campaign). The successful W7-X start confirmed that a complex magnetic topology can be achieved with an accuracy better than 1:100,000 [Otte et al.]. Among the achievements were the first demonstration in W7-X of a reduced bootstrap current in optimized magnetic field configurations, and global confinement that matched well with the ISS04 scaling. These findings provide the first experimental evidence that the basic elements of stellarator optimization work as predicted [Sunn Pedersen et al.; Dinklage et al.].
- LHD isotope effect studies have successfully started in 2017 after several years of preparation [Morisaki et al., ISHW-2017]. There are some indications of improvements in electron confinement [Tanaka et al.], whereas gyrokinetic analysis predicts improved confinement due to zonal flow stabilization of trapped electron modes (TEM) in deuterium plasma [Nakata et al.]. The ion temperature could be extended, reaching 10 keV. The LHD isotope effect program has boosted a dedicated program on iso-

tope physics in mid-size devices such as Heliotron-J (H-J) [Ohshima et al.] and TJ-II [Losada et al.].

- A potential threat to the performance of stellarators and heliotrons is the problem of impurity accumulation. Results presented during the conference have shown that temperature screening of impurities and moderation of neoclassical impurity accumulation are possible in relevant operating regimes and that flux-surface variations of electrostatic potential can have a significant impact on high-Z impurity radial fluxes [Mollén et al.; García-Regaña et al.; Velasco et al.].

- With the advent of neoclassically optimized stellarators, optimizing them for turbulent transport is a key next step. Mechanisms to reduce turbulent transport [Hegna et al.] and validation of gyrokinetic calculations [Anderson et al.; Sánchez et al.] were presented during the workshop.

The conference offered a keynote talk by O. Motojima on “Development of Fusion Energy Research in the Context of Stellarator and Heliotron” and two poster sessions and contributed papers covering a wide range of topics in the fields of core transport [Morisaki et al., Dinklage et al.], plasma-wall and limiter/divertor physics [Bader et al.; Motojima et al.; Masuzaki et al.; Wenzel et al.; Winter et al.], impurity [Kawamura et al.; Nunami et al.] and particle transport [Panadero et al.], fast particle dynamics [Ogawa et al.; Yamamoto et al.], operational limits [Volpe et al.], magnetic topology effects [Mizuuchi et al.; Michael et al.], coil design and error field prediction [Zhu et al.], 3-D field effects [Prebeton et al.] and equilibrium reconstruction [Cianciosa et al.], plasma transitions [Dreval et al.; Takahashi et al.], heating scenarios [Grekov et al.; Wolf et al.], neoclassical modeling of flows and electric fields [Kumar et al.], and integration [Goto et al.]. Contributed papers and posters covered both the engineering approach to control and improve performance of magnetic confinement, as well as the physics approach, oriented at providing basic understanding in order to predict the behavior of burning plasmas with confidence.

The special scientific session on transport decoupling mechanisms included contributions from stellarators [Ida, Helander] and tokamaks [Hubbard, Kamada], followed by a general discussion led by Hidalgo. There are some conflicts in the optimization criteria for fuel, energy, and impurity control since the desire is fuel peaking and an increase in energy confinement, together with lack of accumulation and peaking of impurities (including He with a strong core source). Then, validation of mechanisms that might decouple energy/particle/impurity transport channels is an important open question in which synergies between tokamaks and stellarators should be explored. The present state of theoretical research on transport decoupling mechanisms was presented by Helander. The phenomenology and physics of I-mode trans-

port decoupling in tokamaks were reported by Hubbard. Kamada presented an overview of research regimes and status of JT-60SA. Impurity transport in various stellarator/heliotron devices was reviewed by Ida from the viewpoint of ion particle transport decoupled from the electron transport. Strategies to study the importance of kinetic (e.g., quantifying particle and energy transport driven by fluctuations at different energies) and fluid (e.g., phase relation between density and temperature fluctuations) effects were addressed during the discussion session.

The local organizing committee gave two awards to (not invited) PhD students: to Dorothea Gradic (Max Planck Institute for Plasma Physics, Greifswald, Germany) for her contribution on “Doppler Coherence Imaging of Divertor and SOL flows in W7-X and ASDEX-Upgrade” and to Caoxiang Zhu (University of Science and Technology of China) for “Hessian Matrix Used for Stellarator Coil Design and Error Fields Prediction.”

C. Hidalgo,¹ D. Gates,² R. König,³ S. Kubo,⁴ C. Michael,⁵ T. Mizuuchi,⁶ K. Nagasaki,⁶ V. Pustovitov,⁷ and V. Voitsenya⁸

¹CIEMAT, Spain

²PPPL, USA

³IPP, Germany

⁴NIFS, Japan

⁵ANU, Australia

⁶Kyoto University, Japan

⁷NRCKI, Russia

⁸Kharkov, Ukraine.