stellarator news

Published by Oak Ridge National Laboratory
Building CR 5600 P.O. Box 2008 Oak Ridge, TN 37831-6169, USA

Editor: James A. Rome Issue 145 October 2014
E-Mail: jamesrome@gmail.com Phone (865) 482-5643
On the Web at *http://www.ornl.gov/sci/fed/stelnews*

Plans for first plasma operation of W7-X

Present status of the commissioning of W7-X

Wendelstein 7-X (W7-X) has now started its commissioning in preparation for first plasma operation. A recent picture of W7-X is shown in Fig. 1. The cryostat is closed, and has been under vacuum for several months. It is pumped by five turbomolecular pumps with a total pumping speed of about 6000 L/s. Leak checking of the cryostat was initially done with ultrasonic detection, but is now performed with helium, nitrogen, and neon leak checking. A number of leaks have been identified and repaired, and the neutral pressure status as of mid-September was in the low 10^{-3} mbar range, now dominated by water outgassing from the large surface area of the multilayer insulation. The plasma vacuum vessel remains under air, since a number of in-vessel components are still being installed. This also helps with leak finding from the inside (between plasma vacuum vessel and cryostat vacuum).

The focus on the machine assembly is at the moment transitioning to peripheral components and commissioning of key subsystems, such as the helium refrigeration plant, water-cooling circuits, and the main magnet systems.

Fig. 1. Recent overview shot of W7-X. (Photo by Beate Kemnitz)

A new startup plan: OP1.1, OP1.2, OP2

It was decided in 2013 to perform the first plasma operation phase, in 2015 with a reduced set of in-vessel components. Most importantly, the uncooled test divertor unit (TDU) will not be installed until after this first phase; instead a limiter configuration will be used. Because of this, the plan for the operational phases of W7-X was revised, as shown in Fig. 2. The plan now has three distinct operational phases, defined primarily through the status of the in-vessel components and the associated pulse length and heating power restrictions.

The first plasma operation phase with the limiter is referred to as OP1.1, the second phase with the TDU is now referred to as OP1.2, and the steady-state-capable phase with the high heat flux (HHF) divertor is still referred to as OP2. OP1.1 was introduced to allow for an accelerated, fully integrated commissioning of the main systems on W7-X, and to gain the first physics results from the device. This mitigates risk and stabilizes the schedule, since many upgrades and improvements can be

In this issue . . .

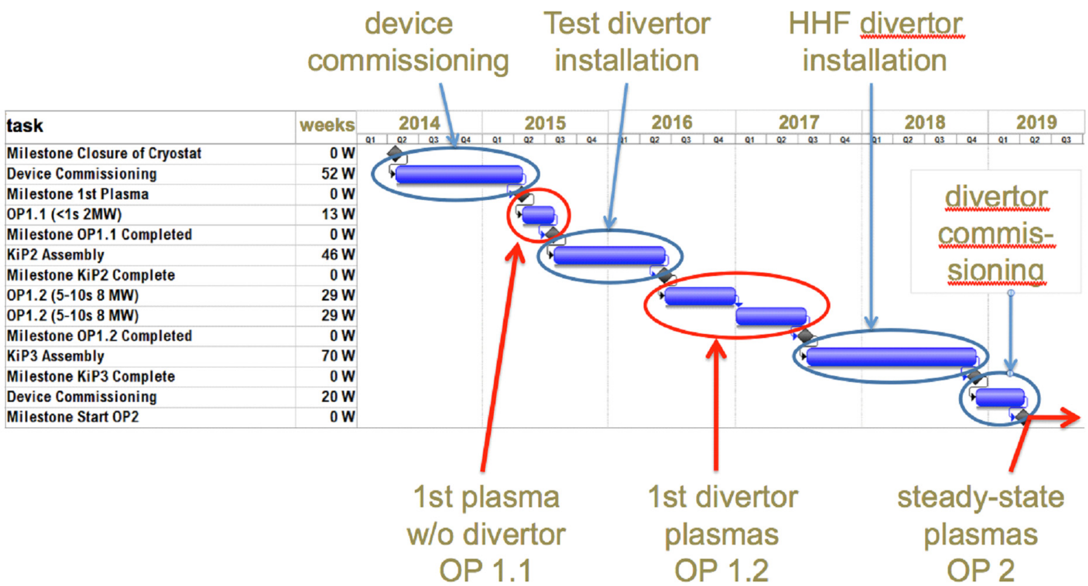


Fig. 2. A recent (tentative) plan for W7-X operation is shown here, with plasma operation phases marked with red, and hardware installation and commissioning periods in cyan. (Of course, these time lines are always in a state of flux.)

done in parallel with the TDU installation in the roughly one year experimental pause between OP1.1 and OP1.2. In the following, we will present some of the physics elements that can be addressed in OP1.1.

OP1.1: Limiter operation

In preparation for OP1.1, five uncooled graphite limiter stripes have been installed symmetrically in the five bean-shaped planes on the inboard side, one of which is shown in Fig. 3.

The limiters were designed with a three-dimensional (3D) machined surface optimized to spread the heat loads over a large surface area. If the five limiters can be loaded symmetrically, plasma pulses with an integral heat input of 2 MJ should be achievable. The heating will be exclusively electron cyclotron resonance heating (ECRH), with heating power of at least 2 MW (up to 5 MW might be installed).

An asymmetry of the heat loads on the limiters is expected due to a combination of magnetic field asymmetry and asymmetry in the actual installation locations of the limiters. The symmetry of the magnetic field will be measured by flux surface mapping (see next section) at the end of OP1.1, since this is important for the future operation of the divertor. For OP1.1, symmetry of the heat load on the five limiter stripes will allow the goal of 2 MJ per discharge to be reached, since each limiter can only absorb 0.4 MJ per discharge. This symmetry can be achieved by use of the trim coils even without explicitly measuring the cause of the asymmetric loading. Postponing the field error measurement saves time on the path towards first plasma.

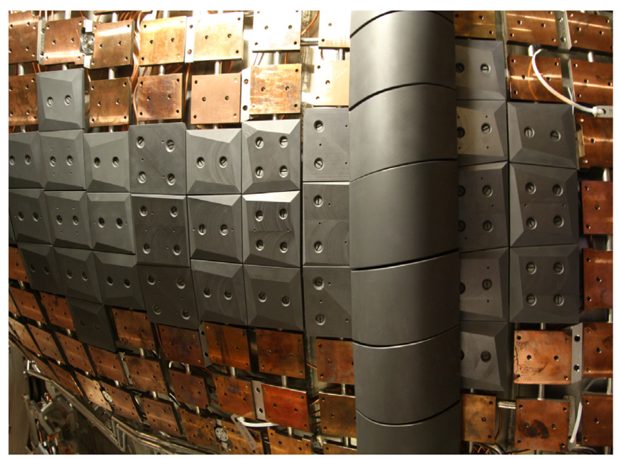
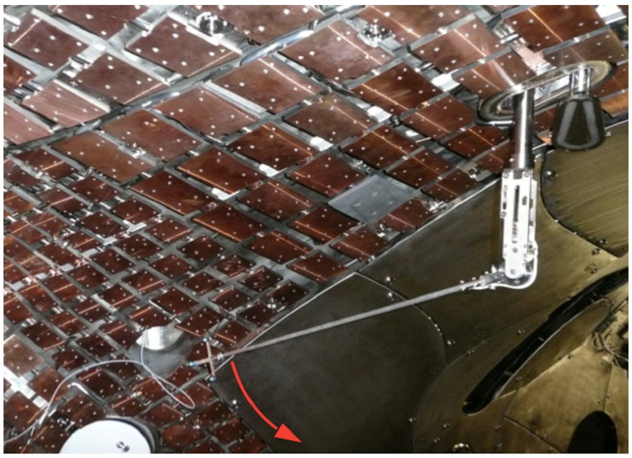


Fig. 3. One of the five limiters is shown here, installed on the heat shields, which are only partly covered with graphite in OP1.1.

Flux surface mapping

The first important physics results on W7-X will be from flux-surface mapping. The flux-surface mapping will be done with the standard electron-beam phosphorescent-rod technique. Two movable phosphorescent rods, each with an integrated electron gun, have been manufactured and installed. They will work in unison, with one system used to place the electron gun on a particular magnetic surface and emit the electron beam, and the other performing a sweeping motion of the phosphorescent rod through the flux surface at a different toroidal location. Figure 4 (top) shows one of the two systems during motion tests after installation.

The goal of the first flux-surface mapping campaign is to confirm that nested flux surfaces exist all the way out to the limiter, and that the expected value of the rotational transform has been achieved, so that no large island chains exist near the last closed flux surface. A Poincaré plot of the limiter configuration is shown in Fig. 4 (bottom).



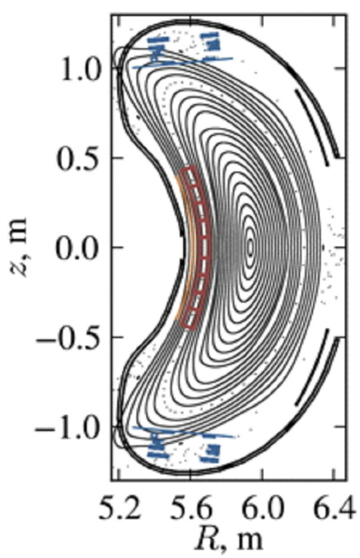


Fig. 4. Top: One of the installed flux surface measurement rods during a motion and metrology measurement inside W7-X under atmospheric pressure. The rotation direction of the rod is indicated by the red arrow. The electron gun will be installed at the tip of the rod, where the four-way cross holds corner cubes in this photo. Bottom: A Poincaré plot of the limiter configuration showing the location of the limiter (in red), and other components in black and blue, well in the shadow of the limiter.

The trained eye will notice the flux surface deformations that indicate a moderately sized internal, natural $n/m = 5/6$ island chain in the Poincaré plot. This island chain should be clearly detectable in the flux-surface mapping pictures, and will therefore measure and verify the location of the iota = 5/6 surface. This then ensures that no low order rational values can create islands in the near scrape-off layer (SOL) behind the limiters. Thus, parallel transport will not cause any radial widening of the near SOL, and the convective plasma loads will be effectively absorbed by the limiters. Therefore, only small convective heat loads will reach the other plasma-facing components, most of which are bare metal surfaces in OP1.1.

The second goal of the flux-surface measurement campaigns in OP1.1 will be to measure and eliminate resonant low-order magnetic field errors. The so-called standard configuration of W7-X has iota = 1 and a natural resonant $n/m = 5/5$ island chain at the edge. This configuration is sensitive to $n = m$ resonant field components, where m and n are poloidal and toroidal mode numbers respectively, especially to $n/m = 1/1$ and, to a lesser degree, $n/m = 2/2$ field errors.

The 1/1 field error can be measured very accurately with flux-surface mapping of a special magnetic configuration designed for that purpose. The configuration has iota just barely above 1 on the magnetic axis, and therefore the axis itself will shift measurably for a resonant 1/1 field error as low as $B_{11}/B_0 = 2 \times 10^{-5}$. The flux surfaces for this configuration are shown in Fig. 5 for a field error of $B_{11} = 1 \times 10^{-4}$ T on the right and no field error on the left. The direction of the shift of the axis is directly related to the phase of the 1/1 field error, and the magnitude of the shift allows a direct measurement of the 1/1 field error amplitude. The trim coils will then be used to eliminate the measured field errors and to create well-defined error fields in order to verify the accuracy of this method.

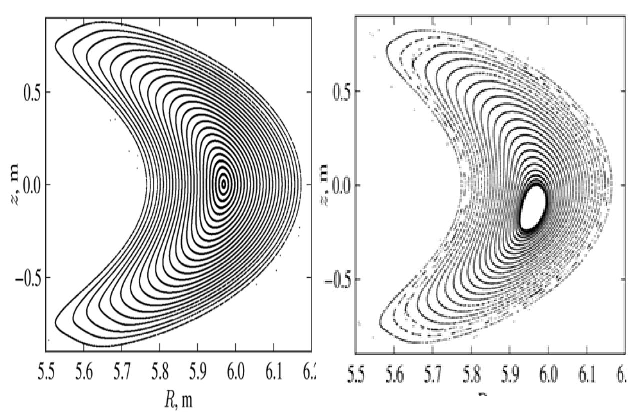


Fig. 5. Flux surfaces for a configuration with iota = 1.01 on axis are shown. Left: Without field errors. Right: With a 1/1 field error of 10^{-4} T.

SOL physics in a limiter configuration

The limiter plasmas actually provide a unique opportunity to study SOL transport processes in a helical configuration with comparably short connection length compared to the island divertor geometry. Hence, comparative studies between the limiter and the island divertor operational phases are most informative for generic edge transport effects such as the capability of heat flux deposition widening due to long parallel connection lengths. In the limiter phase (OP1.1), the parallel connection length will be very well defined and short due to the five well-localized limiters and the absence of edge islands. Due to shadowing effects from one limiter onto another, each limiter will have two distinctly loaded regions, one region with a short connection length (about 30 m), and another with a longer connection length (about 80 m), as shown in Fig. 6. The limiters will be diagnosed with thermocouples, as well as infrared (IR) cameras and embedded Langmuir probes. While the thermocouples serve primarily to monitor the temperature of the holding structures of the limiters, the IR cameras and Langmuir probes will together be able to diagnose the heat load patterns and the SOL plasma parameters. Together they will provide the first SOL physics measurements. Here, one outstanding challenge for stellarators and tokamaks alike is to be able to predict and control the width of the wetted area, λ_q. Recent publications [1, 2] assuming that λ_q scales linearly with the connection length L_c agree with observations from a number of tokamak experiments. In a stellarator island divertor, one has a large amount of freedom in choosing L_c and should therefore be able to design for a desired λ_q, assuming that the same proportionality holds in stellarator island divertors. The limiter configuration therefore gives valuable data points for the SOL width at the aforementioned relatively short L_c values, to be compared with L_c values of 100–500 m in later island divertor operation.

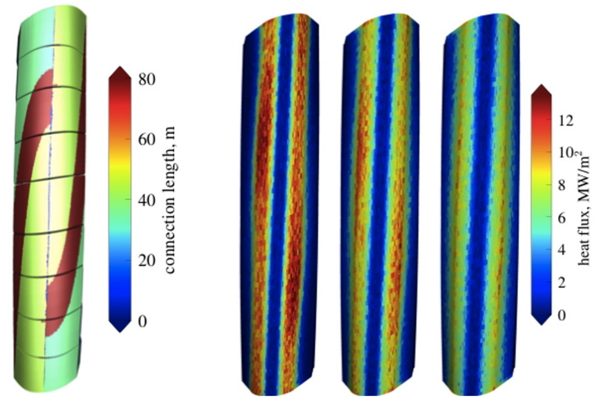


Fig. 6. Left: The limiter configuration will create a SOL which has two regions with distinctly different connection lengths (L_c). Right: The SOL transport diffusion coefficient *D* can be determined by measuring the heat load deposition patterns on the limiters. Shown, left to right, are heat load patterns calculated for three distinctly different values of *D*: 0.5, 1.0, and 2.0 m^2/s.

Plasma startup and wall conditioning plasmas

The OP1.1 plasma operation phase will be done with helium as the primary working gas, even though the primary working gases for the future operation phases will be hydrogen and deuterium. A smaller number of hydrogen plasma discharges will be attempted in the last couple of weeks of OP1.1, in order to gain first experience with these plasmas. Initial plasma pulses will be short and at moderate power. For the very first plasmas, heating pulses at 500 kW with about 100 ms duration will be used, i.e., the injected energy will be on the order of 50 kJ. Even for such short-lived plasmas, significant temperatures should be reachable. Figure 7 shows predictions for an early discharge with 60 kJ of absorbed energy from a transport simulation that includes neoclassical transport and an ad hoc model for the anomalous transport [3]. It is seen that the electron temperature should reach several kiloelectron volts and ion temperatures approach 1 keV. The electron root feature in the core is also clearly seen.

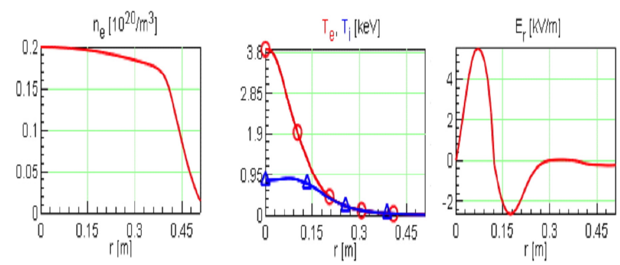


Fig. 7: Assumed density profile and calculated temperature and radial electric field profiles for a plasma heated with 500 kW for 100 ms after being fully ionized.

As operational experience is gained, the energy per pulse will be increased with the aforementioned goal of reaching 2 MJ per discharge.

There are several reasons for starting with helium plasmas. In several other stellarator/heliotrons, including WEGA and Heliotron-J, ECRH breakdown is significantly easier in helium. Helium can be used for wall conditioning, so the first plasma discharges in OP1.1 will be wall (or limiter) conditioning discharges, as well as serving to commission the first diagnostics and the ECRH heating system. However, it is expected that as the limiter and the walls are conditioned, relatively clean helium plasmas can be achieved, with significant electron temperatures (several keV), and an interesting first plasma physics program can be performed.

ECRH and helium beam gas inlets as feed-forward discharge control tools

Since ECRH will be the only heating method in OP1.1, the ion temperatures will depend on our success in extending pulse lengths and increasing density in an at least somewhat controlled way. The fast actuators for discharge control in OP1.1 will be the preprogrammed segment control of the ECRH, allowing on- and off-axis heating with complex time evolution of the heating profiles, as well as the high-pressure fast piezo-valve gas boxes that will later be used for the helium beam diagnostic and active divertor gas fueling. Both of these systems have submillisecond response times, and will be used in a feed-forward sense. Feedback loops for density and temperature control are not expected to be operational in OP1.1.

Heat pulse propagation studies

The fast programming of the ECRH combined with the electron cyclotron emission (ECE) diagnostic will allow for first studies of electron thermal transport through heat pulse propagation studies. This is of interest, in particular since the plasmas — owing to the ECRH heating and the relatively low densities to be achieved — are likely to be in the electron root with outward-pointing electric fields. The electron root feature should help keep the plasma discharges relatively clean from impurities. Modeling shows that if relatively long-lived, high-density discharges are achieved, the core plasma will change from electron root confinement to ion root confinement later in the discharges. Thus, a comparison between ion and electron root confinement appears reachable, both for the plasma fluid and for the impurities.

Diagnostics in OP1.1

The amount of physics that can be learnt in this phase will depend on many factors. One of these is which diagnostics are available. More than 20 diagnostics are under development and are on track for being available for first plasma operation. However, it is not clear if there will be enough time and resources to bring all of them into operation for OP1.1. The resources are being allocated according to a priority list. The following diagnostics are deemed necessary in order to start OP1.1:

- ⇨ Flux surface measurements (verify the quality of the magnetic field and its topology)
- ⇨ Neutron counters (needed for operation allowance)
- ⇨ ECE (T_e measurements)
- ⇨ Interferometer (line-averaged n_e measurements)
- ⇨ Video diagnostic (safety diagnostic, also used for flux surface measurements)
- ⇨ Limiter IR and visible observation system (heat load patterns and symmetry, SOL studies)
- ⇨ Limiter Langmuir probes (SOL studies)
- ⇨ Limiter thermocouples (determine discharge duration and dwell time)

These diagnostics receive special priority and are consequently all far advanced.

Summary

W7-X has started its commissioning phase in preparation for the first plasma operation campaign, OP1.1, in 2015. The cryostat is under vacuum and is being actively leak tested, in parallel with in-vessel and peripheral completion work. The main goals of the first operation phase are to do an integral commissioning of all main systems — cryostat vacuum, cryoplant, superconducting magnets, plasma vessel vacuum, the ECRH system, and a first basic set of diagnostics. The high-priority physics goals of this campaign are to obtain first results concerning magnetic field quality, plasma breakdown behavior, confinement, and edge transport aspects in a helical limiter plasma; dynamics should also be achievable.

References

[1] T. Eich et al., Phys. Rev. Lett. **107**, 215001 (2011).

[2] R. J. Goldston, Nucl. Fusion **52**, 013009 (2012).

[3] Y. Turkin et al., Phys. Plasmas **18**, 022505 (2011).

Thomas Sunn Pedersen, on behalf of the W7-X team and the topical working group "OP1.1 physics":
Tamara Andreeva, Hans-Stephan Bosch, Sergey Bozhenkov, Andreas Dinklage, Yühe Feng, Joachim Geiger, Dirk Hartmann, Ralf König, Hauke Hölbe, Marcin Jakubowski, Heinrich Laqua, Matthias Otte, Thomas Sunn Pedersen, Mélanie Preynas, Torsten Stange, Yuriy Turkin, Max Planck Institute for Plasma Physics, Greifswald, Germany
Monika Kubkowska, Institute of Plasma Physics and Laser Microfusion, Warsaw, Poland
Florian Effenberg, Oliver Schmitz, U. Wisconsin-Madison, WI, USA
David A. Gates, Samuel Lazerson, Princeton Plasma Physics Laboratory, Princeton, NJ, USA

A new review of stellarator theory

Newcomers to the field can find it difficult to learn stellarator theory. Only one book [1] has been published on the subject, and although there are a number of review papers about stellarators, these either do not go into mathematical details or do not describe modern developments. To obtain an overview of the field, the student must find and read research articles scattered over several decades in the literature.

To somewhat alleviate the situation, a review paper has recently been published in the journal *Reports on Progress in Physics* [2]. This journal may not be on the radar screen of most plasma physicists, but it has published review papers for a general physics audience since 1934. The text is primarily meant for students and others entering the field, but could be of interest also to established stellarator physicists. The emphasis is on basic theory—no experimental results are mentioned—and the following topics covered are:

- ⇨ MHD equilibrium. Magnetic field, magnetic coordinates, plasma current, origin of the rotational transform, equilibrium variational principle, rational surfaces
- ⇨ Single-particle motion. Guiding-centre Lagrangian, precession, quasisymmetry, omnigeneity and quasi-isodynamicity, maximum-*J* configurations
- ⇨ Kinetic theory. Neoclassical transport, intrinsic ambipolarity, plasma rotation, bootstrap current

References

[1] M. Wakatani, Stellarator and heliotron devices (Oxford University Press, 1998).

[2] P. Helander, Theory of plasma confinement in non-axisymmetric magnetic fields, Rep. Prog. Phys. **77**, 087001 (2014).

P. Helander
Max-Planck-Institut für Plasmaphysik
Greifswald, Germany

20th International Stellarator-Heliotron Workshop (ISHW)

The 20th International Stellarator-Heliotron Workshop will take place in Greifswald, 5–9 October 2015.

The Max Planck Institute for Plasma Physics is pleased to host this workshop, which is planned to take place against the background of the first experiments in Wendelstein 7-X. The workshop will be held at the Alfried Krupp Wissenschaftskolleg, which is located in the medieval city center of Greifswald, next to the 14th-century cathedral.

Head of the International Programme Committee: Prof. Hiroshi Yamada, National Institute for Fusion Science, Toki, Japan.

Head of the Local Organizing Committee: Prof. Per Helander, IPP, Greifswald, Germany.

http://www.ipp.mpg.de/3523924/ishw_2015

Preliminary ISHW schedule:

1 May 2015	Start of conference registration
15 May 2015	Abstract submission deadline
30 June 2015	Accommodation booking deadline
30 June 2015	Conference registration deadline
5–9 October 2015	ISHW