Global energy confinement in the initial limiter configuration of Wendelstein 7-X

G. Fuchert, S.A. Bozhenkov, N. Pablant, K. Rahbarnia, Y. Turkin, A. Alonso, T. Andreeva, C.D. Beidler, M. Beurskens, A. Dinklage, J. Geiger, M. Hirsch, U. Höfel, J. Knauer, A. Langenberg, H.P. Laqua, H. Niemann, E. Pasch, T. Sunn Pedersen, T. Stange, J. Svensson, H. Trimino Mora, G.A. Wurden, D. Zhang, R.C. Wolf and W7-X Team

1 Max-Planck-Institut für Plasmaphysik, Greifswald, Germany
2 Princeton Plasma Physics Laboratory, Princeton, NJ, United States of America
3 CIEMAT, Madrid, Spain
4 Los Alamos National Laboratory, Los Alamos, NM, United States of America

E-mail: golo.fuchert@ipp.mpg.de

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Abstract

Global confinement properties of the limiter plasmas of the first operational campaign of W7-X are investigated with special focus on the energy confinement and possible operational limits. The energy confinement time was found to be close to expectations from the empirical ISS04 scaling for stellarators. Absolute values up to 160 ms were achieved. This can be considered as a great success for the initial operation of the device. However, a clear degradation of the performance was observed when radiative losses became significant, which was typically the case at low heating power. While a significant improvement of the plasma purity is expected during divertor operation, the presented results underline the importance of the impurity dynamics for the development of high-performance steady-state scenarios in W7-X.

Furthermore, comparisons of the global performance properties with neoclassical transport modeling are presented. These studies are not yet fully conclusive, which could indicate that anomalous transport may have played an essential role in the low-density OP1.1 plasmas.

Keywords: Wendelstein 7-X, energy confinement, stellarator

(Some figures may appear in colour only in the online journal)

1. Introduction

Wendelstein 7-X (W7-X) is the latest stellarator experiment of the Wendelstein line. Favorable results of confinement studies in the early Wendelstein stellarators [1] that were confirmed in the larger W7-A [2] led to a focus of the Wendelstein line on stellarators with low magnetic shear (to avoid low-order rations in the plasma) and low toroidal net current. Due to the mechanical and physical challenges of classical stellarators [3], the Wendelstein line was developed further by combining stellarator optimization with the concept of modular coils [4]. After successfully testing elements of this optimization process in W7-AS [5, 6], W7-X was realized as the first fully optimized stellarator. The optimization process of W7-X, described in [6, 7], aimed at finding a stellarator configuration which followed the basic philosophy of the Wendelstein line introduced above while at the same time having reduced neoclassical transport, sufficient MHD stability at fusion-relevant β values, minimized Shafranov shift, and good equilibrium properties (i.e. no larger islands or ergodic regions in the core, which would reduce the confinement quality by locally flattening the profiles or reducing the effective confinement volume). Furthermore, a mechanically
feasible set of modular coils had to exist to actually realize the optimized configuration. The result was a drift-optimized quasi-isodynamic configuration that has then become the design basis of W7-X [8]. Specifically concerning the global energy confinement, two main features of the W7-X configuration are the minimization of the neoclassical transport in the reactor-relevant $1/ν$ regime and the aforementioned good equilibrium properties at high $β$.

The mission of W7-X is to demonstrate the success of these measures in order to show that optimized stellarators are able to provide and sustain fusion relevant plasma conditions in steady state. For this, the density, temperature and energy confinement time have to be increased at the same time to maximize the triple product $nTτ$. It is expected that W7-X should be capable of concomitantly reaching central temperatures above 4 keV for both electrons and ions, densities above $10^{20}/m^3$ and global energy confinement times between 0.1 and 1.0 s. Finding a scenario which achieves these parameters in steady state is not straightforward and one of the main scientific goals of W7-X.

The first step of this demonstration, which follows a staged approach [9], was the integrated commissioning of the device and its control systems including plasma operation. This first operational phase, called OP1.1, featured three months of plasma operation from late December 2015–March 2016. The main goals and diagnostic capabilities of OP1.1 were described in [10] and an overview of first results was given in [11–14]. Since it was envisaged to test the magnet system as soon as possible [15], W7-X was operated in a limiter configuration and with unprotected wall components. Hence, only a cautious wall conditioning with short ECR-heated plasmas and carefully applied glow-discharge cleaning was conducted and, consequently, the plasmas in OP1.1 suffered from high impurity concentrations (preliminary spectroscopy analyses suggest a typical range of $Z_{eff}$ between 1.5 and 5) which led occasionally to radiative collapses. At the beginning of OP1.1 this limited the plasma operation to a few tens of milliseconds, which was shorter than estimates of the energy confinement time for these plasmas. The situation improved towards the end of the campaign, when plasma durations of more than ten times the energy confinement time were achieved. In these cases, plasma operation was not limited by radiative instabilities but an input-energy limit of initially 2 MJ, which was later raised to 4 MJ since the observed limiter loads indicated that damaging unprotected wall components was unlikely even with the increased limit [16]. While the integral demonstration of Stellarator optimization requires high plasma beta not achievable in the first phases of W7-X, the minimization of bootstrap current could be demonstrated even as early as in the first campaign [17].

It is believed that the special conditions of OP1.1 were detrimental for the plasma performance, since impurity-related losses (radiation and charge exchange processes) were significant and led to a reduction of the plasma volume capable of effectively storing energy. Nevertheless, promising energy confinement times have been observed, both in absolute numbers and compared to an empirical scaling for the energy confinement time in stellarators.

In this publication, investigations on the global energy confinement of the initial limiter plasmas in W7-X are presented. In order to put the experimental results into perspective, expectations concerning the energy confinement time in W7-X are discussed in section 2. In section 3, the diagnostics and procedures employed to determine the stored energy in OP1.1 are introduced together with their uncertainties. General observations concerning the stored energy in OP1.1 are presented in section 4 for centrally X2-heated hydrogen plasmas, focusing mainly on diagnostic agreement and the ratio of electron to ion energy. The resulting range of energy confinement times is shown in section 5 together with an initial analysis of the main influencing factors in OP1.1. Depending on the heating power, two regimes of different scaling behavior of the energy confinement time are found. A detailed discussion of the characteristics and relevance of these regimes is given in sections 6 (for medium and high power) and 7 (for low power). Furthermore, experimental values are compared to numerical results in section 8 in order to assess the predictive quality of the employed transport model and to get a preliminary understanding of the relative importance of different loss and transport mechanisms for the global energy confinement in OP1.1. Finally, the results are summarized in section 9.

2. Expected range of energy confinement times in W7-X

The energy confinement time $τ_E$ of a steady-state plasma can be defined as the ratio of the energy $W$ stored in the plasma and the heating power $P_{heat}$:

$$τ_E = \frac{W}{P_{heat}}.$$  \hspace{1cm} (1)

It is a figure of merit describing how fast energy is leaving the confined plasma due to losses and transport processes. In principle, the heating power refers to the sum of the external heating power and the fusion power provided by the plasma, even though for most experiments today the fusion power is negligible.

Maximizing the energy confinement time is of utmost importance for the realization of nuclear fusion as a viable energy source as it appears directly in the triple product of density, temperature and energy confinement time ($nTτ_E$) which has to be sufficiently high to reach ignition. For classical stellarators, however, the three-dimensional field geometry leads to an increased importance of neoclassical transport with strong temperature dependence. This is expected to lead to low energy confinement times especially at fusion-relevant conditions. This can be partly compensated by operating at higher densities, which is possible as the Greenwald density limit, known from tokamaks, seems not to exist in stellarators [18], and partly by increasing $τ_E$ directly by means of stellarator optimization.

The most extensive multi-machine study of the energy confinement time in stellarators has been done using data from the International Stellarator-Heliotron Database [19]. From this, two empirical scaling laws have been derived, first the ISS95 scaling [20] and later, with an updated experimental database,
the ISS04 scaling [21]. The empirical \( \tau_E \) scaling according to ISS04, parametrized by the minor radius \( a \), major radius \( R \), heating power \( P \) in megawatts, line-averaged density \( n_e \) in \( 10^{19} \text{m}^{-3} \), magnetic field strenght \( B \) in tesla, and \( \tau_{E/3} \) the rotational transform at two-thirds of the effective radius, reads as follows:

\[
\tau_{\text{ISS04}} = 0.134 \cdot a^{2.28} R^{0.64} P^{-0.61} n_e^{0.54} B^{0.84} \tau_{E/3}^{0.41}.
\] (2)

The parameter dependencies are basically the same for ISS04 and ISS95. The main difference is the numerical pre-factor, which is almost a factor of two higher in ISS04. The reason is the inclusion of data from LHD and W7-AS, which performed better than suggested by the ISS95 scaling. This can be seen as an indication for a hidden parameter, probably related to the different stellarator geometries. This issue is tackled in the ISS04 scaling (and partly also in the ISS95 scaling) by introducing an additional configuration factor, which is multiplied to the scaling law. This configuration factor, \( f_c \), describes the average deviation of \( \tau_E \) from the predicted \( \tau_{\text{ISS04}} \) (i.e. \( f_c = (\tau_E/\tau_{\text{ISS04}}) \)) for a particular device and configuration. The highest documented configuration factor of 1 (by definition) was found for the low-iota case in W7-AS [22].

Since empirical scaling laws are derived from existing experimental data, their parameter dependences are governed mainly by the physical effects most dominant in the existing experiments. Hence, they have a limited predictive capability if these dominating processes change. Furthermore, since the physics behind the configuration factor in ISS04 is not clear, it cannot be predicted easily. Hence, some effort was required to come to an expectation for the energy confinement time \( \tau_E \) of W7-X. Assuming that the neoclassical transport is dominant in high-performance plasmas, transport modeling has predicted that an improvement of \( \tau_E \) compared to ISS04 should be possible with a configuration factor of up to two. This value, however, should only be regarded as a rough estimate: On the one hand, it may be an optimistic upper bound if radiation or anomalous transport are contributing significantly to the power balance in high-performance plasmas of W7-X. On the other hand, alternative confinement regimes like H-mode may also lead to an unexpected improvement of the global energy confinement. Consequently, there is a large uncertainty in the exact value of the energy confinement time that will be achieved in W7-X. Considering both empirical scaling laws and transport modeling, a range for \( \tau_E \) of 0.1–1.0 s has been predicted [23]. In this context it is interesting to note that reactor studies based on the HELIAS concept suggest that ignition could be reached if \( \tau_E \) would scale like ISS04 to reactor-relevant plasma conditions [24, 25]. For the OP1.1 limiter configuration, which is different to later divertor operation, the following parameters are used to evaluate equation (2): \( a = 0.49 \text{m} \), \( R = 5.5 \text{m} \), \( B = 2.5 \text{T} \), and \( \varepsilon = 0.8 \). The volume enters the ISS04 scaling only implicitly through the major and minor radius. For the limiter configuration of OP1.1 the plasma volume confined within the last closed flux surface is approximately \( 26 \text{m}^3 \).

In order to compare these expected values to experimental data, the stored energy of the plasma has to be measured. Since W7-X is a new device with a set of diagnostics mostly untested before OP1.1, the determination of the stored energy and present uncertainties are discussed in detail in the following section before the actual results are shown.

3. Determination of the stored energy

The thermal energy can be calculated by integrating the electron and ion pressure \( (p_e,i) \) over the plasma volume \( V \). Since the pressure is constant on flux surfaces, radial profiles are sufficient to determine the kinetic energy \( W_{\text{kin}} \), also referred to as thermal energy) by evaluating

\[
W_{\text{kin}} = \frac{3}{2} \int_r \left( p_e(r) + p_i(r) \right) \frac{dV}{dr} dr.
\] (3)

The term \( dV/dr \) depends on the magnetic field configuration. Since no routine equilibrium reconstruction was available in OP1.1, the vacuum field was used to evaluate (3), which introduces a source of error due to incorrect mapping of the measured profiles to the flux surfaces. By comparing the resulting energy content to those calculated using an equilibrium reconstruction representing the highest \( \beta \) plasmas in OP1.1 it was found that this mapping error leads to an overestimation of the stored energy. However, since the volume averaged \( \beta \) was relatively low (around 0.2% in the best case), the effect causes deviations of only about 5%.

The available set of diagnostics [26–28] was suitable to determine reliable profiles of the electron density \( n_e \) (Thomson scattering, TS [29, 30], electron temperature \( T_e \) (TS, electron cyclotron emission spectroscopy, ECE [28, 31]), and x-ray imaging crystal spectroscopy, XICS [37]), and ion temperature \( T_i \) (XICS). Measurements of the ion density \( n_i \) were not available, also not indirectly from \( Z_{\text{eff}} \) profiles. This introduces another error to the kinetic energy, since impurity ions lead to unequal densities of ions and electrons. However, as will be shown below, the electron contribution to the total energy content of the low-density ECR-heated plasmas of OP1.1 was dominant, and, hence, the error introduced by uncertainties in the ion channel is rather low. In the appendix it is estimated that the impurities impose an uncertainty of about 10% on the stored energy.

A further source of error can arise from systematic uncertainties in the profile measurements. For the presented studies, the electron density and temperature profiles from TS are used together with the ion temperature from XICS to determine the kinetic energy. The main reason for this approach is that no further mapping between diagnostics is required to determine the electron pressure from the TS data only.

Cross-checks of the different diagnostics showed that typically the different \( T_e \) profiles agree within 10%. Possible systematic effects are investigated for the different diagnostics, but from the limited data set of OP1.1 there is no clear indication that the electron temperature would be systematically over- or underestimated. Concerning the electron density, comparisons of the line-averaged electron density measured by single-channel dispersion interferometry and calculated from Thomson scattering (absolutely calibrated by Raman
scattering [30]) also agree quite well. However, the ratio between these two density measurements is not a constant for all experiments and on average the density determined by TS is around 10% larger than the interferometry measurement. It can be concluded that the typical uncertainty in single \( n_e \) and \( T_e \) profiles is about 10% and the electron density measured by TS may be systematically overestimated by about 10%. A possible reason for the latter is an unstable alignment of the TS laser, which could only be adjusted manually and between experiment days. Remote alignment is planned to be realized for future experimental campaigns.

In order to measure the ion temperature by XICS, injection of argon as tracer impurity is required. For experiments where argon was injected for XICS, the \( T_i \) profiles are known with high accuracy within the core region of the plasma. For \( r/a > 0.6 \) the typical signal amplitude of the observed argon lines is too low to be reliably detected. In this region, a flat \( T_i \) profile is assumed up to the radius where \( T_e = T_i \) and for larger radii equal temperatures are assumed. This is in agreement with expectations from transport modeling (e.g. [32]) and imposes no significant error, since it will be shown later that in OP1.1 \( W_e > W_i \).

From all experiments with XICS measurements, the average electron to ion energy ratio, \( \langle W_e/W_i \rangle \), can be calculated to estimate the total thermal energy even for plasmas where \( T_i \) is not measured.

The determination of the thermal energy is straightforward, but suffers from the relatively large number of required diagnostics, each with characteristic errors and assumptions. A different approach is to measure the change of the toroidal flux with a diamagnetic loop from which the diamagnetic energy \( W_{\text{dia}} \) can be derived, which is physically equivalent to the thermal one (in the absence of fast particles). The flux change can be measured with high accuracy and reproducibility. A clear advantage is that the ion contribution is fully included in the measurement independently of the impurity content. However, compared to the kinetic energy, determining \( W_{\text{dia}} \) from the measured flux change is more complex: The magnetic field and coil geometry have to be known precisely and the flux change in the plasma induces currents in the main field coils and vessel components. Hence, it is useful to compare \( W_{\text{kin}} \) and \( W_{\text{dia}} \) to have an independent cross-check and to gain confidence in the OP1.1 diagnostics.

The diamagnetic energy is measured in W7-X by two independent diamagnetic loops at different toroidal positions (a third one will be added for later operational phases). One of the two loops in operation is equipped with an additional set of compensation coils to account for the reduction of the measured flux by induced currents. This compensated diamagnetic energy is used for the following analysis. Calibration measurements for the precise determination of the diamagnetic energy from the measured flux are work in progress. However, at the current stage these investigations suggest that in OP1.1 the measurements underestimated the diamagnetic energy by about 10% [33]. The experimental setup, compensation method, and data analysis to determine \( W_{\text{dia}} \) are explained in detail in [33, 34].

4. Energy content in OP1.1

Most plasmas in OP1.1 were too short to reach a full equilibrium (e.g. observed in a continuing rise in electron density or ion temperature). In order to systematically study the energy confinement in OP1.1 limiter plasmas without distorting the results by transient effects, quasi-stationary phases are defined: All relevant quantities are sampled with a time resolution of 100 ms and only those samples are analyzed for which the ECRH power (\( P_{\text{ECRH}} \)) and kinetic energy \( W_{\text{kin}} \) have changed less than 10% compared to the previous time slice. Only these quasi-stationary phases are considered in the following analysis. Furthermore, to ensure comparability of different plasmas, only hydrogen plasmas with on-axis X2-mode heating are analyzed (see [35] for a discussion of the different heating modes foreseen for W7-X). The measurements of the energy content are presented with special focus on the comparability of the kinetic and the diamagnetic energy and the distribution of the stored energy between electrons and ions.

As discussed in section 3 and the appendix, careful data analysis suggests that in OP1.1 the kinetic energy is overestimated and the diamagnetic one underestimated. Hence, in the following we compare \( W_{\text{kin}} \) and \( W_{\text{dia}} \) as well as \( W_{\text{kin}} = 0.8 \cdot W_{\text{kin}} \) and \( W_{\text{dia}} = 1.08 \cdot W_{\text{dia}} \). The correction factors represent the independent results of the error analysis, not fitted values to obtain agreement between the two methods.

It has been observed that the ratio \( W_{\text{kin}}/W_{\text{dia}} \) is fairly constant during one experiment, but can change from experiment to experiment. In figure 1 this ratio is displayed averaged for all quasi-stationary phases of constant \( P_{\text{ECRH}} \) for individual hydrogen experiments longer than 300 ms (i.e. an experiment with constant heating power results in one data point, every power step within an experiment results in another point) for which both \( W_{\text{kin}} \) and \( W_{\text{dia}} \) are available.

It is found that \( W_{\text{kin}} = (1.46 \pm 0.03) \cdot W_{\text{dia}} \) and \( W_{\text{kin}}^* = (1.08 \pm 0.02) \cdot W_{\text{dia}}^* \) (indicated in the graph by the dash-dotted lines). Hence, the uncorrected kinetic energy is considerably larger than the uncorrected diamagnetic energy. Using the corrected values the two agree within 10%.
This result underlines the presumptions arising from the current diagnostic understanding and the fact that in OP1.1 the stored energy is only known with an accuracy of about 20%.

Nevertheless, it is also a promising result that both ways to determine the stored energy qualitatively show similar results. It is, hence, expected that for the further analysis it plays no role whether \( W_{\text{in}} \) or \( W_{\text{kin}} \) is employed. The mismatch between the two will be systematically revisited in the next operation campaign OP1.2.

From figure 1 it can also be seen that in OP1.1 stored energies of more than 0.1 MJ were routinely achieved. Due to the dominant electron heating and low density operation in OP1.1, the energy transfer to the ions was relatively low and accordingly most of the energy resides in the electrons. Figure 2 shows a comparison of the energies stored by the electrons and ions, respectively. The gray points are calculated assuming \( n_e = n_i \), for the green points it is assumed that the total energy is reduced by 10% due to an ion density reduction by impurities. It is found that in OP1.1 the energy contribution of the electrons is clearly dominant, being typically between two to three times larger than its ion counterpart.

5. Energy confinement time in OP1.1

In this section, \( \tau_E \) data are presented for the quasi-stationary phases (as defined in section 4) of the hydrogen plasmas in OP1.1. The simple definition of \( \tau_E \) given in equation (1) has to be modified in case of slowly evolving plasmas:

\[
\tau_E = \frac{W}{P_{\text{heat}} - \dot{W}}. \tag{4}
\]

with \( \dot{W} \) the time derivative of the stored energy. Since ECRH was the only heating method applied in OP1.1, in the following \( P_{\text{heat}} = P_{\text{ECRH}} \) (note that the ongoing power calibration of \( P_{\text{ECRH}} \) leads to a systematic error of the heating power in OP1.1 of about 10%). Furthermore, since the database for measured kinetic energies is larger than for the diamagnetic ones, \( W_{\text{kin}} \) is used for the following analysis. According to the discussion in section 4 the qualitative results should be independent of this choice.

In view of the multi-machine scaling ISS04, introduced in section 2, the two main factors determining the energy confinement time should be the heating power and the density. As it is reflected in the scaling factors, typically in stellarators the energy confinement time increases with density and deteriorates with increasing heating power (referred to as power degradation). In view of these dependences, figure 3 displays \( \tau_E \) as a function of \( P_{\text{ECRH}} \) and \( \bar{n}_e \) as a function of the line-averaged electron density determined from TS profiles. In these plots, every data point represents 100 ms of quasi-stationary plasma operation. It can be seen that plasmas that reached quasi-stationary conditions had energy confinement times between 60 and 150 ms, with the majority of the data points between 100 and 150 ms.

The power degradation can clearly be seen in (a) for heating powers above 1 MW at roughly equal density. At lower heating powers, the energy confinement time drops quickly. A similar trend can be seen in (c), where \( \bar{n}_e \) is plotted as a function of the line-averaged electron temperature (calculated from TS profiles). The data with low temperatures and low energy confinement time are related to the low-power branch in (a). The reason for this peculiar low-power behavior will be discussed below. In (b) there seems to be no apparent density dependence of \( \tau_E \). This observation is caused by a strong correlation of density and heating power in OP1.1, as can be seen in figure 3(d), where \( \tau_E \) is shown color-coded as a function of \( \bar{n}_e \) and \( P_{\text{ECRH}} \). At constant heating power \( \tau_E \) indeed increases with the density.

Qualitatively the energy confinement time in OP1.1 behaves as expected by the ISS04 scaling. In order to quantify this statement, the configuration factor \( f_c \) is calculated and the scaling of \( \tau_E \) with power and density is investigated.

Figure 4 displays the ratio of \( \tau_E \) and \( \tau_{\text{ISS04}} \) as a function of \( P_{\text{ECRH}} \). An obvious observation is that there is a relatively large scatter in the data, indicating an influencing parameter not covered by ISS04. Most likely the changing machine conditions due to the cautious wall conditioning in OP1.1 play a major role here. Furthermore, there is a striking performance degradation (relative to ISS04), which is most prominent below 1 MW, but may already set in somewhere between 1 and 2 MW. At heating powers above 1 MW some experiments reached or even surpassed the ISS04 scaling. If \( f_E = \langle \tau_E / \tau_{\text{ISS04}} \rangle \) is calculated for experiments with \( P_{\text{ECRH}} > 1.0 \text{ MW} \), a value of

\[
f_E = 0.85 \pm 0.10_{(\text{stat})} \pm 0.15_{(\text{sys,W})} \pm 0.09_{(\text{sys,P})} \tag{5}
\]

is obtained. While the statistical error describes the scatter in the data (and may, hence, describe the influence of changing experimental conditions like, for instance, a varying impurity concentration), the two systematic errors account for the uncertainties in determining the stored energy and heating power (uncertainty in the power calibration of the gyrotrons of about 10%) in OP1.1. It is a promising results that such a high \( f_E \) could be reached after only a few weeks of

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**Figure 2.** Stored energy of the electrons and ions in OP1.1 limiter plasmas. The gray points are calculated using \( n_e = n_i \), the green points assume a reduced ion density to account for impurity effects such that the total energy decreases by 10%.
Figure 3. The energy confinement time $\tau_E$ is shown as a function of (a) the heating power, (b) the line-averaged electron density and (c) the line-averaged electron temperature. The density dependence of $\tau_E$ is masked by a correlation between density and heating power as can be seen in (d), where $\tau_E$ is shown as a color-coded function of density and heating power. Since $\tau_E$ depends on both density and power, the colors in (a) and (b) indicate different ranges of these quantities. In (a) three different density ranges are shown (blue: $\bar{n}_e < 1.25 \cdot 10^{19}$ m$^{-3}$, cyan: $1.25 \cdot 10^{19} < \bar{n}_e < 1.75 \cdot 10^{19}$ m$^{-3}$, purple: $\bar{n}_e > 1.75 \cdot 10^{19}$ m$^{-3}$) and in (b) three different heating power ranges (blue: $P_{\text{ECRH}} < 1.0$ MW, cyan: $1.0$ MW $< P_{\text{ECRH}} < 2.0$ MW, purple: $P_{\text{ECRH}} > 2.0$ MW).

In order to quantitatively compare the power and density scaling to the ISS04 scaling, the experimental $\tau_E$ data is fitted as $\tau_E \propto P_{\text{ECRH}} \bar{n}_e^\alpha$. Considering the clear confinement degradation at low heating power the fitting is done separately for heating powers above and below 1 MW. For $P_{\text{ECRH}} > 1$ MW, $\alpha = -0.64 \pm 0.03$ and $\beta = 0.75 \pm 0.05$ are obtained. While the power degradation is essentially found to be equal to the ISS04 scaling ($\alpha = -0.64 \pm 0.03$ compared to $-0.61$), the density dependence is somewhat stronger ($\beta = 0.75 \pm 0.05$ compared to 0.54). In [22], a stronger density dependence is also reported if only ECR-heated plasmas from the ISS04 data set are considered. However, the reported dependence ($\beta = 0.63 \pm 0.02$ [22]) is still weaker than the $\beta = 0.75 \pm 0.05$ found for OP1.1 W7-X plasmas. The reason for this different scaling behavior for ECRH plasma remains unknown.

Below 1 MW a clear deviation in the scaling behavior is observed: Here, the energy confinement time strongly increases with $P_{\text{ECRH}}$ ($\alpha = 0.51 \pm 0.14$) and the density dependence is found to be weaker ($\beta = 0.42 \pm 0.19$). While the latter finding may result from a relatively low density range at these low heating powers, (see figure 3(d), the improvement of $\tau_E$ with increasing power may point to an operational limit.

It is found that the experiments in OP1.1 with quasi-stationary hydrogen phases can be categorized in two groups: A standard confinement regime with $\tau_E$ comparable to the ISS04 scaling...
both regarding absolute $\tau_E$ values as well as the power and density dependence and a regime with degrading confinement at low heating power. In the following sections, these two regimes will be characterized in more detail.

6. OP1.1 plasmas with good energy confinement

In a few experiments with moderate ECR heating power around 2 MW, energy confinement times around 150 ms have been reached. In the experiment 20160310.029 around $t = 600$ ms, the energy confinement time is around 160 ms and slightly exceeds the ISS04 scaling with $\tau_{\text{ISS04}} \approx 150$ ms.

Figure 5 shows radial profiles of the $T_e$, $T_i$, $n_e$, and $E_r$. The $n_e$ and $T_e$ profiles were measured by Thomson scattering. The $T_i$ and $E_r$ profiles were measured by XICS. Note that in the plasma edge the density of ionized argon required for the XICS system in OP1.1 is low, which explains the large error bars for $\rho > 0.6$. The profiles display several features that have commonly been observed in almost all experiments:

- $T_e$ is larger than $T_i$ in the center of the plasma and its profile is generally more peaked.
- The $n_e$ profile is flat in the center and in particular flatter than the $T_e$ profile.
- The $E_r$ value is positive in the center part where the experimental error is small and shows a transition to negative values around roughly half the radius.

The positive $E_r$ and $T_e > T_i$ in the center are consistent with plasmas in the so-called core electron root confinement (CERC) regime [36], where the strong radial electrical fields are thought to reduce the neoclassical transport (details concerning the measurement of the radial electrical field and a comparison with neoclassical modeling are shown in [37] and the impact on the energy confinement is discussed in [17]). This means, however, that the OP1.1 plasmas may behave quite differently from the W7-X design plasmas. In these a

...
heating power. Fitting the energy confinement time data to 
\[ \tau_E \propto \bar{n}^{\alpha} T^{\beta} \]  
(\bar{T}_e being the line-averaged temperature calculated from TS profiles), \( \alpha = 0.045 \pm 0.059 \) (i.e. zero within the error) and \( \beta = -0.94 \pm 0.11 \) are obtained. While the relatively large and negative temperature dependence might explain the observed power degradation, \( \tau_E \) was basically independent of the density in OP1.1 (using temperature and density as scaling variables). In a plasma dominated by \( 1/\nu \) transport of the electrons, however, one would expect both a strong temperature and density dependence, since the energy confinement time can be related to the average heat diffusivity \( \chi \) as \( \tau_E \approx a^2/\chi \) and in the \( 1/\nu \) regime it is \( \chi_{1/\nu} \propto T^{7/2}/n \) \[38, 39\]. Of course this pure \( 1/\nu \) dependence is not expected to be found since the global energy confinement time depends on the average over all particle energies and radii and is influenced by different transport and loss mechanisms, yet it is indicative that no density dependence is found whatsoever.

7. OP1.1 plasmas at low heating power

At heating powers below 1 MW, a confinement degradation is observed relative to ISS04. A quantitative comparison with ISS04 revealed that the low density in these plasmas is not sufficient to explain the reduction in \( \tau_E \). Furthermore, the fact that in this regime \( \tau_E \) increases with the heating power indicates that these plasmas may be close to an operational limit.
Figure 9. Comparison of experimental $\tau_E/\tau_{\text{ISS04}}$ data with predicted results from transport modelling for three experimental reference cases (blue dots) at different heating powers.

Figure 6 shows profiles of a plasma heated with 600 kW of ECRH. Comparing these profiles to the ones shown in figure 5 for a 2 MW case, the following observations can be made:

- Even at low heating power, high $T_e$ values (several keV) are reached in the center, again with $T_e > T_i$.

- While the shape of the $n_e$ profile remains basically unchanged, extended flat edge profiles are observed in both $T_e$ and $T_i$, shifting the outer end of the gradient region further inwards.

- Within the diagnostic capabilities, no significant change in the $E_i$ profile is observed, again indicating a plasma in the CERC regime. However, no detailed information is available in the center and at the edge of the plasma.

Just from the profiles, it seems that the confinement degradation could mainly be explained by the extended flat region in the edge temperature profiles ($\rho > 0.6$). That this effect at least plays a significant role can be seen in figure 7. Displayed is the radius $R_{0.9W}$, within which $90\%$ of the electron energy $W_e$ is confined. While for mid to high heating power $R_{0.9W}$ is fairly constant, it starts to reduce below 1.5 MW and then quickly drops between 0.5 and 1.0 MW. This closely resembles the power dependence of $\tau_E/\tau_{\text{ISS04}}$ (see figure 4). Since $W_e > W_i$, the same qualitative trend is expected for the total stored energy.

The reason for this shrinkage of the plasma volume effectively confining the energy is believed to be radiation cooling in the edge by impurities. The radiation loss (measured by bolometry [40]) relative to the heating power is shown as a function of the heating power in figure 7(b). It can be seen that even at heating powers above 1 MW radiation is a significant loss channel with a radiated fraction $P_{\text{rad}}/P_{\text{ECRH}}$ between 20 and 30\%. Below 1 MW, however, the radiated fraction rises considerably and, at very low heating powers, becomes the dominant loss channel accounting for over 50\% of the heating power (it is interesting to recall that only quasi-stationary phases are analyzed which were stable over at least 100 ms $\approx \tau_E$).

Such a radiation-dominated regime is usually observed in stellarators at high densities, where an operational density limit is observed [41], while the plasmas analyzed here have particularly low densities. However, analytical models [42–44] as well as experiments, e.g. at W7-A [45], show that the same radiation-dominated regime occurs at low heating power and high impurity concentrations. In [46] these analytical models have been applied to the limiter configuration of OP1.1 and indeed are able to quantitatively predict this operational limit. An application to later divertor operation is work in progress. Hence, the observed operational limit can be understood as the low-power, high-impurity concentration branch of the radiative density limit known from stellarators. In that sense, the low-power regime is only relevant for the special conditions of the OP1.1 limiter configuration. Nevertheless, this phenomenon is likely to become relevant again at very-high densities and needs to be revisited during divertor operation.

8. Comparison with transport modelling

In this section experimental data of OP1.1 are compared to numerical results from transport modeling in order to assess the predictive quality of the transport model and to get an initial understanding for the main parameters determining the global energy confinement in OP1.1. However, since the low-density, low-power limiter plasmas analyzed here are expected to behave substantially different from the design scenarios of W7-X, the findings presented in the section will have to be revisited in the upcoming experimental campaigns.

For the transport modeling, NTSS [32] was employed which uses DKES [47, 48] for the neoclassical transport calculations (based on pre-calculated monoenergetic transport coefficients combined with an energy convolution) and a variable scaling law for anomalous transport. Losses like radiation or charge-exchange losses are not considered in these NTSS simulations.

For the comparison, three reference experiments with different heating powers have been chosen as examples. As input for the calculations, the experimental electron density profiles have been used, while the temperature profiles are determined self-consistently by the transport calculations and can be compared to the experimental ones to assess the agreement of the model and the experiment. In order to assess the sensitivity of the modeling results to the assumed anomalous transport and the impurity density (which can change the radial electrical field and, hence, affect the transport), the following input variations were analyzed: For every experiment, two different scalings for the anomalous contribution and two different values of $Z_{\text{eff}}$ are employed for the simulations: Based on experimental results from W7-AS [6], a scaling ansatz of $\chi_{\text{ano}} \propto 1/n$ with a fixed value at the boundary ($\rho = 1$) is assumed for the anomalous heat diffusivity. In one case, referred to as $\chi_{\text{edge}}$, in the following, a core plasma dominated by neoclassical transport is simulated by an exponential decay of $\chi_{\text{ano}}$ starting from $\rho = 0.8$ inwards. In a second case, $\chi_1/n$, the $1/n$ scaling of $\chi_{\text{ano}}$ is assumed over the entire radius. The difference is illustrated in figure 8. For $Z_{\text{eff}}$, a pure hydrogen plasma ($Z_{\text{eff}} = 1$) has been taken as one extreme and, for
the second case, a substantial impurity content is studied (assuming carbon as impurity and $Z_{\text{eff}} = 4$).

Besides the temperature profiles, one of the quantities that can be compared most easily with experimental results is the global energy confinement time $\tau_E$, or, equivalently, $\tau_E/\tau_{\text{SS04}}$. Figure 9 displays such a comparison for the three analyzed reference experiments (blue dots) with $P_{\text{ECRH}}$ of around 0.5, 1.9 and 2.7 MW. In all three cases the resulting energy confinement time is not very sensitive to the impurity content. The choice of the scaling ansatz to estimate the anomalous transport, however, has a significant impact on the calculated energy confinement time, changing it by roughly a factor of 1.5. The reason for this is that in the case of $\chi_{\text{edge}}$ the anomalous contribution in the core plasma is negligible to the neoclassical one, while in the case of $\chi_{\text{ano}}$ both contributions are of the same order of magnitude for roughly the inner half of the radius. This shows clearly that the predictive quality of transport modeling for W7-X is reduced in regimes where anomalous transport is comparable to the neoclassical one. It is planned for the future to find better anomalous transport scalings by analyzing experimental data and numerical simulations.

The best agreement is found for the medium power case, where a value of 1 is predicted for $\tau_E/\tau_{\text{SS04}}$ (using $\chi_{1/n}$), while in the reference experiment a value of 0.8 is found. At low heating power, the mismatch is stronger with again a predicted value of 1, but an experimental reference of 0.6. This underlines the important role of losses, especially radiation and possibly charge exchange losses, for the global energy confinement properties in OP1.1. In the high-power case, a drastic mismatch is found between the transport modeling (1.3) and the experiment (0.8). This is also reflected in the electron temperature, which is significantly overestimated ($T_e > 10\, \text{keV}$). Two possible reasons being discussed are that (1) not all assumptions of neoclassical theory may be satisfied in these plasmas (e.g. Maxwellian distribution, locality or linearity of the model) and (2) $\chi_{1/n}$ may still underestimate the anomalous contribution in these plasmas. In contrast to the other two cases the employed $\chi_{1/n}$ yields an anomalous transport which is small compared to the neoclassical contribution in this case. A comparison of the experimental electron temperature profiles with the best matching modeled ones (i.e. from the $\chi_{1/n}$, $Z_{\text{eff}} = 4$ case) is shown in figure 10.

In summary, despite the large variations in the modeling results a few important conclusions can be drawn from this analysis:

1. The global energy confinement in OP1.1 can only be understood as a combination of losses (radiation and possibly charge exchange losses) and neoclassical and anomalous transport. There is not one single dominant channel determining $\tau_E$.

2. The experimental data can only be understood from the applied transport modeling if the neoclassical and anomalous contribution in the simulation are comparable in the core. This agrees with preliminary local transport analyses where the experimental electron heat flux is roughly twice as high as neoclassical calculations [17]. As discussed above, possible reasons could be an underestimation of the neoclassical contribution in case not all assumptions of neoclassical theory are fulfilled, or a significant contribution by turbulent transport.

3. In order to improve the predictive capabilities of the transport model, a model for $\chi_{\text{ano}}$ suitable for W7-X is required. Determining such a model is work in progress and will be done by revisiting the empirical scaling as well as numerical turbulence simulations.

9. Summary and conclusion

In the first operation phase of Wendelstein 7-X, the kinetic energy of these initial limiter plasmas has been measured by integrating profile data ($n_e$, $T_e$ and $T_i$) and by analyzing flux measurements with a compensated diamagnetic loop. With the current diagnostic understanding, which has to be verified and improved in the next campaign, an agreement between the two methods within roughly 10% (relative error) could be achieved. A systematic tendency was observed that $W_{\text{kin}}$ is larger than $W_{\text{dia}}$, and it has been estimated that the stored energy is known with a systematic error of about 20%. The systematic error will be reduced with high likelihood in future campaigns.
Nevertheless, even using pessimistic assumptions concerning the systematic error, after three months of operation a global energy confinement time, $\tau_e$, of 150 ms was achieved in X2-heated hydrogen plasmas during the initial limiter phase. This was possible despite large radiation losses due to conservative wall conditioning.

An empirical benchmark for the energy confinement time in stellarators is the ISS04 scaling. As has been discussed in the introduction, the variety of stellarator geometries cannot be accounted for by one single scaling and, hence, the ISS04 scaling includes a configuration factor $f_c = (\tau_e/\tau_{ISS04})$. Here, $f_c = 1$ refers to the best confinement regime in Wendelstein 7-AS [22]. Hence, it is a promising result that the best performing plasmas in this initial limiter campaign could already exceed the ISS04 scaling. Averaging over all hydrogen plasmas that were performed in March 2016 in the OP1.1 standard field configuration with more than 1 MW of central X2 heating, a configuration factor $f_{c,\text{OP1.1}} \approx 0.85$ has been achieved. However, one has to keep in mind that the CERC plasmas in OP1.1 with low density and $T_e > T_i$ are very different from the high-performance plasmas W7-X has been designed for.

At lower heating power, a radiation-dominated regime has been observed, which seems to resemble the low-power, high-impurity-concentration branch of a radiative regime known in stellarators. Since it is expected that the next operation phases will feature cleaner divertor plasmas and an ECRH power of up to 9 MW, the radiation-dominated regime of OP1.1 is likely to play a less important role, but may be found again in future high-density experiments.

To understand the global confinement properties of the OP1.1 limiter plasmas transport modelling has been used. The analyses revealed that the global energy confinement was probably determined by neoclassical and anomalous transport as well as radiation losses, without one clearly dominating contribution. It is not clear, however, if this will also be true for the high-performance divertor plasmas.

All-in-all it can be concluded that within the three months of commissioning it was possible to achieve plasmas with pulse durations of several tens of $\tau_e$ and no sign of instabilities or increasing radiation before the pulses were ended due to a stipulated limit on the input energy of 4 MJ. These plasmas showed good confinement with respect to the empirical ISS04 scaling and a significant improvement is expected if it is possible in future divertor operation to sustain cleaner plasmas with reduced radiation losses and increased edge temperatures.

Since the confinement properties in these low-density CERC plasmas are expected to be different from those in plasmas W7-X is designed and optimized for (high $\beta$ with electrons in the $1/\nu$-regime), however, the OP1.1 results cannot be used directly to extrapolate the energy confinement time or configuration factor achievable in such a regime.

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**Appendix. Influence of impurities on the determination of the kinetic energy**

Since no experimental data is available for the ion density, $n_i = n_e$ is assumed when evaluating the stored energy. This is, of course, only correct for a pure hydrogen plasma with $Z_{\text{eff}} = 1$. First estimates of $Z_{\text{eff}}$ in OP1.1 result in values between 1.5 and 5, which are rather high. The reason is believed to be a combination of conservative wall conditioning to prevent damaging of the unprotected wall components and the direct contact of the plasma with the limiters.

As will be discussed below, this leads to an overestimation of the stored energy of about 10%. An individual correction for every experiment based on the appropriate $Z_{\text{eff}}$ is work in progress. Since, however, the relative impurity concentrations are not available for OP1.1, uncertainties will remain.

While $W_e$ can be determined precisely by integrating the electron pressure profile, the ion contribution $W_i$ is overestimated if the assumption $n_e = n_i$ is used. Hence, the error induced in $W_{\text{kin}}$ by assuming equal densities depends on the relative contribution of electrons and ions to the total energy and on the impurity concentration. However, due to the $Z^2$ dependence of $Z_{\text{eff}}$, the effect can only be quantified if the relative impurity concentration is known. Preliminary spectroscopic data suggest that the dominant impurity species were carbon and oxygen together with minor concentrations of high-Z impurities.

Assuming $n_i = n_e$ in typical OP1.1 plasmas, the stored electron energy seems to be twice as large as the ion energy (see figure 2). Now, from the experimental range of $Z_{\text{eff}}$, the reduction in $W_i$ is calculated assuming either carbon or oxygen composition.
oxygen as the only impurity species in a hydrogen plasma. Since for OP1.1 no profile information is available for $Z_{\text{eff}}$, a constant $Z_{\text{eff}}$ profile is assumed.

Figure A1 shows the ratio of the total stored energy $(W_e + W_i)$ obtained for $n_e = n_i$ ($W_{HI}$) and the corrected $W_{Z_{\text{eff}}}$ as a function of $Z_{\text{eff}}$ assuming either carbon or oxygen. The area shaded in gray shows the experimentally observed $Z_{\text{eff}}$ range. It can be seen that over a wide range of $Z_{\text{eff}}$, $W_{HI}$ overestimates $W_{Z_{\text{eff}}}$ by roughly 10%. Furthermore, adding higher-Z impurities at constant $Z_{\text{eff}}$ (here oxygen compared to carbon) improves the agreement of $W_{HI}$ and $W_{Z_{\text{eff}}}$. The fact that especially in the edge the impurities are not fully ionized, as assumed in this evaluation, improves the agreement further.

Hence, it is concluded for OP1.1 that employing $n_i = n_e$ leads to an overestimation of $W_{\text{kin}}$ on the order of 10%. Higher values than that are possible according to figure A1, but not very likely for reasons discussed above.

**ORCID iDs**

C.D. Beidler ✉️ https://orcid.org/0000-0002-4395-239X
A. Langenberg ✉️ https://orcid.org/0000-0002-2107-5488
G.A. Wurden ✉️ https://orcid.org/0000-0003-2991-1484
R.C. Wolf ✉️ https://orcid.org/0000-0002-2606-5289

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