Increasing the density in W7-X: Benefits and limitations

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Both in tokamaks and stellarators high-density operation is mandatory for achieving high fusion performance. As the first comprehensively optimized stellarator, Wendelstein 7-X (W7-X) is an essential experiment to study the benefits and limits in this kind of device. This contribution presents first experiments on the density dependence of the energy confinement in W7-X and limitations of the achievable density. Theoretical predictions and empirical scaling laws for the energy confinement time in stellarators (e.g. the ISS04 scaling [1]) predict a positive correlation between the plasma density and the energy confinement time. This suggests that higher densities in fusion plasmas could be beneficial for the triple product $nT\tau$, since a decreasing temperature should be overcompensated by the increase of the energy confinement time and the density itself. However, this line of argument might not be valid for plasma operation close to operational limits or changing confinement regimes. This leads to the rather obvious conclusion that the energy confinement time scaling and the presence of operational limits and different confinement regimes have to be understood and studied as an intertwined system. While this is already a common approach in tokamak research, it is still an open issue for stellarators. The reasons are the lack of an extensive set of large experimental devices (with only LHD being comparable in size to W7-X) and the fact that different field configurations may show substantial differences.

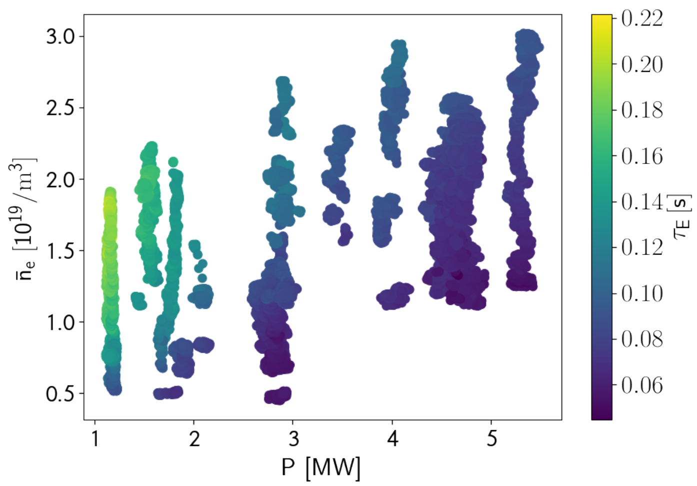

Fig. 1: Energy confinement time (color-coded) as a function of heating power and line-averaged density for quasi-stationary phases of purely gas-fueled hydrogen plasmas in the first test divertor campaign (OP1.2a) of W7-X.

The experimental exploitation of W7-X has only started, however, the gradual completion of the machine capabilities (especially concerning the installation of the high-heatflux divertor and the completion of heating capabilities) are an ideal opportunity to map out the configuration space accessible in the current configuration and to identify key issues on the route to high-performance long-pulse operation.

In the first two experimental campaigns, featuring a limiter (OP1.1) and a test divertor (OP1.2a) configuration, the energy confinement time has been analyzed under quasi-stationary conditions. A positive density and negative power dependence (*power degradation*) have been found for hydrogen plasmas (see fig. 1) and the scaling coefficients are close to the expectations from ISS04. Moreover, the positive density dependence has been confirmed in density ramps during plasma operation. Such density-ramp experiments are important to exclude the possibility of spurious correlations in the database for the scaling analysis and to identify regimes in which the energy confinement time scaling might differ from the empirical scaling laws.

During these experiments, however, radiative collapses have been observed, where a further increase of the density led to a fast increase of the radiation power and a drop in the diamagnetic energy. The detailed mechanism of these collapses is still under investigation, but the density at which they occur seems to follow a Sudo-like power scaling [2] (i.e. close to a square-root power dependence). Such a *radiative density limit* is predicted by simplified analytical models [3]. Such a model has been applied to W7-X [4] in order to estimate a critical density, n_c. In purely gas-fueled hydrogen plasmas, no stable plasma operation has been achieved above this critical density in OP1.2a (see fig. 2) and radiative collapses have been observed at densities above $0.5 \cdot n_c$ at different n/n_c. These variations of n/n_c could be caused by changing machine conditions, since n_c depends on the impurity density, which is not yet routinely measured and, hence, assumed constant. If impurity radiation indeed plays a major role, additional measures to improve the plasma purity like, for instance, boronization (planned for the next campaign) should further increase the critical density. It has been observed that the critical density also depends on the magnetic configuration, which directly relates this issue to scenario development and shows the importance to understand the underlying physics in detail. Furthermore, first experiments with pellet-fueling showed line-averaged densities well above the critical density, which indicates that the role of profile and fueling effects need to be investigated in detail. This might be related to fueling-issues predicted for the island divertor geometry of W7-X [5], but it might also point to a more general radiative instability, since a Sudo-like density limit is also known from LHD [6], which does not feature a similar divertor geometry.

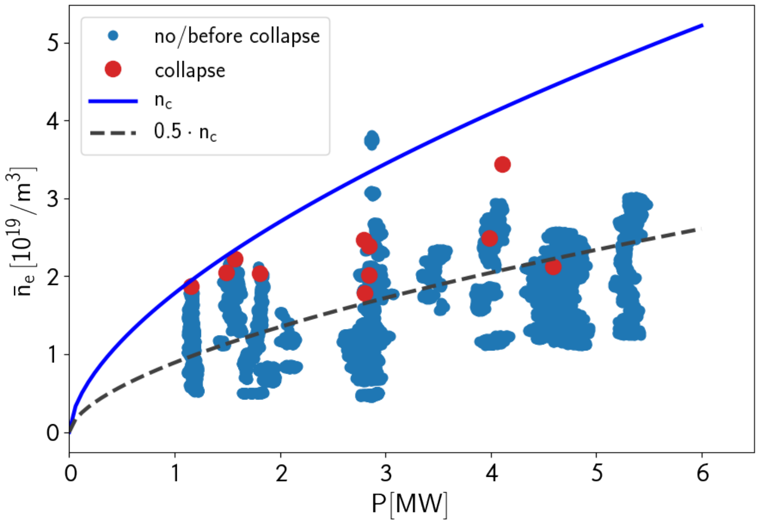

Fig. 2: Comparison of densities achieved in purely gas-fueled hydrogen plasmas in OP1.2a with a model for a critical density for radiative collapses.

In summary, first experiments in W7-X confirm that an increasing density is indeed beneficial for the energy confinement, at least in the currently accessible density range. It remains to be shown that this trend extrapolates to the high-performance plasmas W7-X was designed for. The experiments have also shown, however, that high-density operation involves a careful scenario development, as fueling issues and radiative instabilities limit the currently accessible operational space of W7-X in its current state of completion. It is clear, that measures to ensure a lower impurity content have to be investigated, as the obtained scaling for the critical density (depending on the impurity density), a density of $1.2 \cdot 10^{20}/m^3$ would require 25 MW of ECRH power.

References

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