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Energy confinement in W7-X, more than just a scaling law

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Scaling laws for the energy confinement time using engineering parameters as input are of great importance for fusion research. While they provide only limited insight in the actual physics determining the energy confinement, they are necessary tools for system studies and control schemes. It has become clear for both tokamaks and stellarators, however, that the scaling behavior is fundamentally different in various operation regimes. It is, hence, important to distinguish and characterize regions in the operational space according to their scaling behavior.
For stellarators, there are two almost identical cross-machine scalings available, called ISS95 and ISS04. In early low-density experiments of the optimized stellarator Wendelstein 7-X (W7-X), the energy confinement time scaling was well described by those scalings. W7-X has been designed and optimized to demonstrate fusion-relevant plasma performance during in stellarators during long-pulse operation. A positive density dependence of the energy confinement time would have favorable consequences to achieve this goal, since it is believed that fusion reactors would operate at densities between 1 and $2 \cdot 10^{20}\,\mathrm{m}^{-3}$. Recent W7-X experiments at higher densities, however, show clear deviations from these scalings, especially concerning the density dependence, which is found to be weaker than suggested by the empirical scalings. This is visualized in Fig. 1, where the scaling exponent of the density (α) is shown as a function of line-averaged density and ECRH power. The scaling exponent α is highest below $4 \cdot 10^{19}\,\mathrm{m}^{-3}$ and then remains relatively constant up until 6 to $8 \cdot 10^{19}\,\mathrm{m}^{-3}$, depending on the heating power.

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Both the plasmas used to derive the ISS04 scaling and the early plasmas of W7-X are relatively far away from fusion-relevant conditions. Hence, without understanding the exact origin of the favorable density scaling in stellarators, it cannot be assessed whether it extrapolates to fusion-relevant plasmas or not. Understanding the difference in the scaling behavior between the low-density and high-density plasmas in W7-X will help to elucidate this question. One issue with present energy confinement time scalings is that during the data selection process, plasmas with high radiation losses are excluded. This is done in order to scale as accurately as possible the energy transport with engineering or physics quantities without other influences that cannot be expected to scale accordingly. While this approach in principle makes sense, it introduces a bias towards low densities, since commonly the relative importance of radiation losses also increases with density. This is not only an issue because it is expected that power exhaust concepts of future fusion reactors include high levels of edge radiation but also because it potentially masks other effects that could occur while raising the density in today's experiments. Up until now, two effects have been identified that likely contribute to the weaker scaling at higher densities: The characteristics of the turbulent transport in W7-X and a pressure drop in the edge, likely caused by the increasing impurity radiation and charge-exchange losses.

The first effect is a change in the relative importance of the electron and ion transport channel as Ti approaches Te. There are indications that in the standard ECRH plasmas of W7-X, turbulent ion-transport is stronger than the electron one (see M. Beurskens et al. at this conference) and, hence, a larger transfer of energy from the electrons to ions at higher densities leads to an increase of the overall losses. In W7-X this effect starts to play a role at densities between α and 3, coinciding with the first decrease of the density-scaling exponent seen in Fig. 1. The second effect is a pressure loss in the plasma edge, affecting the stored energy by effectively reducing the volume contributing to the total pressure. This pressure drop is visualized in Fig. 2 and includes the effect of the radiation losses. There are, however, indications that interactions with neutrals due to the increased fueling required for higher densities may play a role as well. Regarding fusion relevance, a pressure drop exclusively in the edge is less harmful than in the core. Yet, due to the larger volume in the edge it has a stronger impact on the stored energy. As can also be seen in Fig. 2, the core pressure is indeed not affected in the analyzed experiments and illustrates that profile effects also play a role in determining the density scaling of the stored energy. This has to be kept in mind for extrapolations to fusion plasmas and is currently not reflected in the simple scaling laws for the energy confinement time.

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Since the radiation losses occur predominantly in the edge of the plasma, simply correcting the heating power, entering the scaling, by the radiation losses is not feasible and, hence, it is not easy to quantify how strong the impact of these losses on the energy confinement is. Hence, quantifying the relative importance of the aforementioned effects (radiation losses, charge-exchange losses and changes in transport behavior) is challenging and work in progress. It is clear, however, that simply excluding plasmas with high levels of radiation systematically removes effects from energy confinement time databases which are important when increasing the density towards fusion-relevant plasma conditions. Accordingly, the empirical scalings derived from such databases have to be revisited and new tools have to be developed to deal with this issue.

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