Attaining Tokamak level performance through plasma density profile shaping at Wendelstein 7-X

S. Bannmann[1], O. Ford[1], T. Stange[1], A. Langenberg[1], R. Lopez Cansino[2], R.C. Wolf[1], the W7-X Team

[1] Max-Planck-Institute for Plasma Physics, Greifswald
[2] Department of Atomic, Molecular and Nuclear Physics, University of Seville, Seville, Spain

Plasmas with a stable fusion triple product at a similar level to Tokamak plasmas have been achieved in the Wendelstein 7-X stellarator for the first time. By carefully balancing different heating and fueling systems and exploiting changes in the particle transport, peaked density profiles can be maintained in which the normally dominant turbulent heat transport is suppressed.

Background Reaching a high and stable plasma performance in the sense of a high triple product (nTτ) is key for a nuclear fusion reactor. Early stellarators suffered from prohibitively high neoclassical heat and particle losses due to the 3D structure of the magnetic field. The Wendelstein 7-X (W7-X) stellarator was successfully optimized to reduce the neoclassical heat and particle losses [1] [2] and the loss channels are now dominated in most cases by turbulence [3]. The turbulent heat transport caused by ion temperature gradient modes (ITG) limits the core ion temperature to a value of around 1.6 keV in all investigated magnetic configurations and under many heating scenarios [4] [5]. However, it was found experimentally, that in the presence of strong electron density gradients in the plasma core, ion temperatures above this limit can be reached by applying electron cyclotron resonance heating (ECRH), which implies that ITG modes are stabilized in these regimes [6] [7].

Methods Experimentally, two discharge scenarios lead to peaked density profiles in W7-X and therefore create the necessary density gradients: Pellet injection and pure, continuous neutral beam injection (NBI) heating. In the latter, to maximize performance, NBI is first used alone to create strong density gradients and then central ECR heating is applied to increase the ion temperature. However, two effects make the scenario development more intricate. Firstly, the creation and evolution of the core density gradient is not only driven by the NBI particle source but also by a transition in the anomalous particle transport after reaching a suspected critical normalized density gradient [8]. Secondly, the application of ECR heating has a so called 'pump-out' effect on the plasma core density, thereby reducing the density gradient which can ultimately lead to a return to the reduced confinement regime with a lower ion temperature. Consequently, in order to reach high plasma performance and keep it stable for several energy confinement times, the added ECRH power needs to be fine tuned to keep the core density gradient as stable as possible. To be able to compare different magnetic configurations, the experimental neoclassical and anomalous heat and particle transport are studied in detail before and during the high performance phases. Particle and power balance analysis combined with neoclassical transport modeling yield insights into the anomalous transport dynamics.

Results In this contribution a discharge with exceptional high plasma performance and the described NBI + ECRH heating scenario at W7-X is presented. The exact heating scenario and plasma profiles are shown in figure 1. A maximum ion temperature of 2.8 keV is attained for more than a second during the NBI+ECRH phase. The corresponding energy confinement time of $\tau_E = (260 \pm 10)$ms is about 20% higher than expected from the ISS04 scaling $\tau_{\mathrm{ISS04}} \approx 215$ms [10]. The maximum achieved triple product is $nT\tau_E$=(1.05±0.2) 10^{20} keV s m^{-3} and is kept stable for around 1.9 s, which puts the performance in line with tokamak plasmas, which are stable for several energy

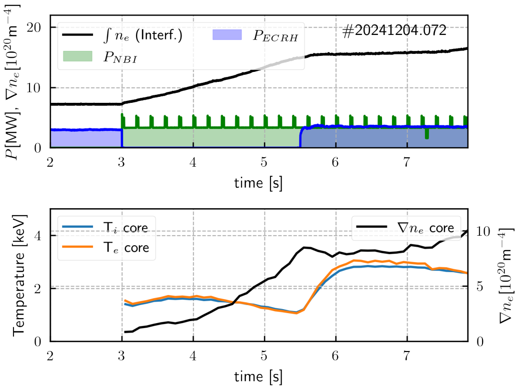

Figure 1: Record performance discharge. Top: Heating scenario and line integrated density trace. Bottom: Density gradient build up in pure NBI phase and strong temperature increase in NBI+ECRH phase.

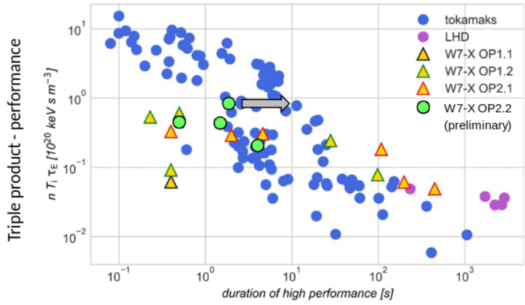

Figure 2: Triple product of recent high performance W7-X discharges (green dots) compared to tokamaks plasmas with a similar duration of multiple energy confinement times [9]. Grey arrow indicates the technically achievable duration in the next campaigns.

confinement times, as can be seen in figure 2. While reduced turbulent transport could be reached in several magnetic configurations (slightly changing ι-profile and ϵ_{eff}), it is found that a configuration with higher rotational transform $\iota = 1/q$ than the other two reference configurations performs best. However, this configuration exhibits large internal magnetic islands which must be reduced with the use of external control coils in order to obtain the improved confinement. It is found that the initial density gradient build up is mostly independent of the magnetic configuration. In contrary, the density pump out in the ECRH phase is different in configurations due to a combination of effects: a significant change in neoclassical transport, changes in core fueling and differing levels of core anomalous particle transport.

Conclusion A possible route to reach and sustain high energy confinement at W7-X is via creating and stabilizing core plasma density gradients. Careful fine tuning of plasma heating and fueling and exploring the magnetic configuration space led to a record plasma performance at W7-X. This marks an important step in proving the performance potential of stellarators. It also emphasizes the importance of having a profound understanding of the particle transport dynamics in a stellarator in order to model or extrapolate to an ignited stellarator fusion reactor. With the shown route to high performance, predicting and shaping the density profile is a necessity.

References

[1] C. D. Beidler et al. In: *Nature* 596.7871 (Aug. 2021), pp. 221–226. ISSN: 1476-4687.

[2] R. C. Wolf et al. In: *Physics of Plasmas* 26.8 (2019), p. 082504. DOI: 10.1063/1.5098761.

[3] D. Carralero et al. In: *Nuclear Fusion* 61.9 (Aug. 2021), p. 096015. DOI: 10.1088/1741-4326/ac112f.

[4] M.N.A. Beurskens et al. In: *Nuclear Fusion* 61.11 (Oct. 2021), p. 116072. DOI: 10.1088/1741-4326/ac1653.

[5] M.N.A. Beurskens et al. In: *Nuclear Fusion* 62.1 (Dec. 2021), p. 016015. DOI: 10.1088/1741-4326/ac36f1.

[6] S.A. Bozhenkov et al. In: *Nuclear Fusion* 60.6 (Apr. 2020), p. 066011. DOI: 10.1088/1741-4326/ab7867.

[7] O.P. Ford et al. In: *Nuclear Fusion* 64.8 (July 2024), p. 086067. DOI: 10.1088/1741-4326/ad5e99.

[8] S. Bannmann et al. In: *Nuclear Fusion* 64.10 (Aug. 2024), p. 106015. DOI: 10.1088/1741-4326/ad6b37.

[9] X. Litaudon et al. In: *Nuclear Fusion* 64.1 (Nov. 2023), p. 015001. DOI: 10.1088/1741-4326/ad0606.

[10] H. Yamada et al. In: *Nuclear Fusion* 45.12 (Nov. 2005), p. 1684. DOI: 10.1088/0029-5515/45/12/024.