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Experimental confirmation of efficient island divertor operation and successful neoclassical transport optimization in Wendelstein 7-X

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We present here recent highlights from Wendelstein 7-X (W7-X), the most advanced and largest stellarator in the world, in particular stable detachment with good particle exhaust, low impurity content, and energy confinement times exceeding 100 ms, maintained for tens of seconds, as well as proof that the reduction of neoclassical transport through magnetic field optimization is successful. W7-X, which has a magnetic field strength of 2.5 T and a plasma volume of 30 m^3, started operation in 2015 [1-5]. Following the installation of a full set of in-vessel components, in particular 10 passively cooled fine-grain graphite test divertor units, it was operated again in 2017 and 2018. Plasma pulses up to 100 s were successfully sustained [6], despite the lack of active cooling. Stable and complete detachment was achieved routinely. The pumping efficiency was initially relatively low [7-9] but it significantly improved later. Detachment with high pumping efficiency was achieved for up to 28 seconds at a heating power of 5 MW with a very low impurity content [10] (Figure 1), indicating control of divertor-heat-flux, plasma density, and impurity content, and giving confidence for reaching the foreseen high-performance, quasi-steady-state (30 minutes) discharges in the future [11]. The performance of the W7-X divertor, and the behavior and parameters of the edge- and scrape-off-layer plasma are now understood in quite some detail [eg. 12], thanks to measurements from a suite of diagnostics [eg. 13-17].

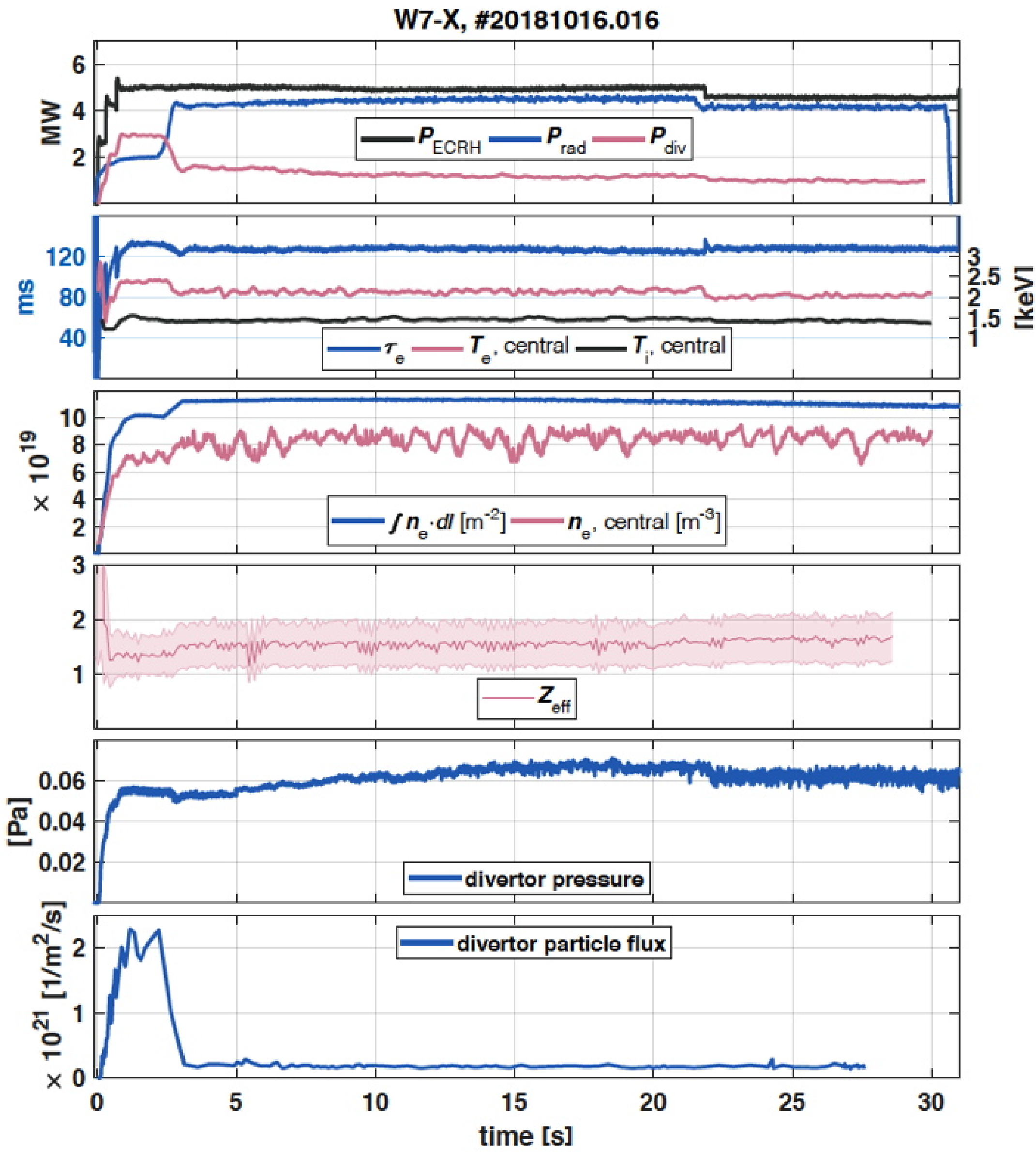

Figure 1: Main parameters for the discharge that was stably detached with good particle exhaust, low impurity content, stable density and stored energy for more than 28 s, until the pre-programmed discharge end [10].

The earlier-reported stellarator triple-product record discharge [18] has now been shown to provide proof that the optimization for reduced neoclassical transport in W7-X was successful, Figure 2 [19]: The high temperature (appr. 3.5 keV for both ions and electrons in the center) and high hydrogen ion density (appr. 7x1019 m-3 in the core) were achieved with 5 MW of heating, and an energy confinement time of 0.22 s corresponding to about 1.4 times the energy confinement time expected from the ISS04 stellarator scaling [20]. For other, less optimized stellarators scaled to the W7-X size and magnetic field strength, similar plasma temperature and density profiles would have required significantly higher heating power to balance neoclassical transport, in particular in the mid-radius (strong gradient) region.

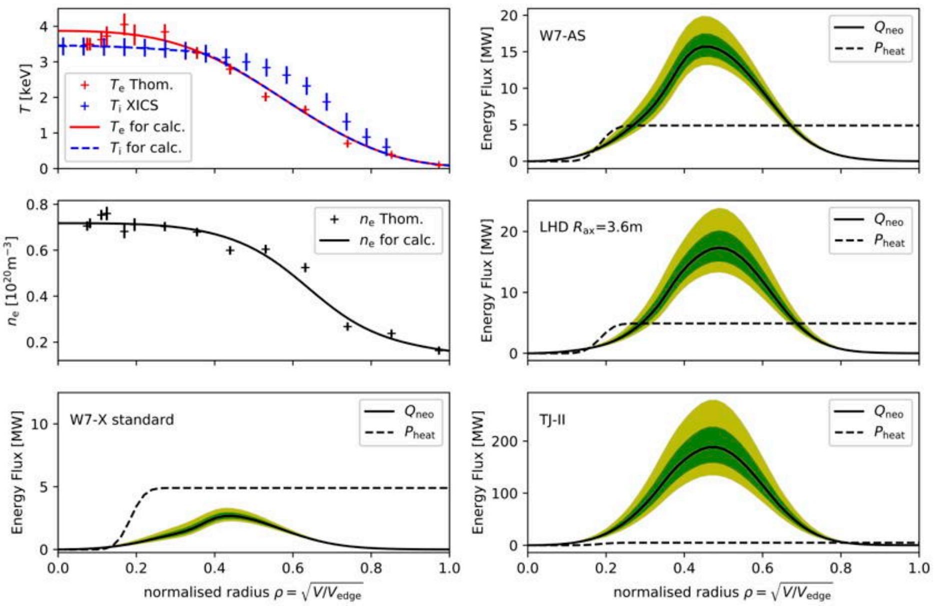

Figure 2: Proof of successful reduction of neoclassical transport in W7-X: Left: The temperature (top) and density profiles (middle) in discharge 20171207.006 for the time window around t~2 s where the triple-product record was achieved: For W7-X (bottom left), calculations show that neoclassical transport accounted for about half the losses at mid-radius, and less at outer radii. Right panels: Less optimized configurations with the same plasma- and machine-parameters would have needed significantly higher heating power than what was available in the W7-X discharge to overcome their neoclassical transport losses at mid-radius. Solid black lines with green error bars: Total calculated radial neoclassical heat transport for the discharge. Dotted lines: The heating power density integrated up to the given normalized radius (total heating 5 MW of ECRH, absorbed in the central region of the plasma).

A number of discharges with similar performance to the triple-product-record discharge have since been achieved. These are generally characterized by core density peaking, and a reduction of turbulent density fluctuations. Without such turbulence reduction, the central ion temperature appears to be clamped to appr. 2 keV [21]. These findings are consistent with W7-X transport usually being dominated by ITG turbulence, but stabilized by strong density gradients in a so-called stability valley [22], as exemplified in Figure 3 for the W7-X standard configuration.

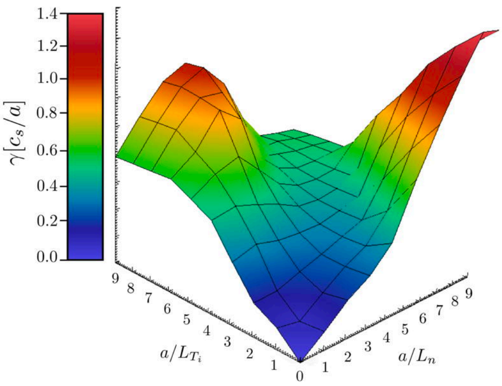

Figure 3: The normalized linear growth rate of ITG modes, calculated by the GENE code for the W7-X standard configuration, shows a reduced growth rate in a "valley"where the temperature- and density gradient scale lengths are comparable, suggesting that a significant temperature gradient can be sustained without causing strong turbulence, if the density gradient is also significant. This was indeed the case for the transient high-performance phase of the triple-product record shot. This calculation was done assuming Te=Ti. See also [22].

During turbulence-dominated phases, impurity confinement times are low (of order the energy confinement time) and no impurity accumulation is seen, but they can be very large if the turbulence is suppressed, and this then leads to impurity accumulation [23]. Recent findings from the Large Helical Device (LHD) show that ITG-dominated discharges readily mix hydrogen isotopes, whereas electron-scale (trapped-electron mode) turbulence does not [24]. It is tentatively concluded that a non-negligible amount of ITG turbulence is beneficial for impurity control as well as for fuel (isotope) exchange and helium exhaust in a stellarator fusion reactor, whereas too much ITG turbulence could potentially clamp the ion temperature below the burn point. These and other recent results [see eg. 25-31] will be put into the context of future goals for the W7-X, the world stellarator program, and the magnetic confinement fusion program in general.

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Country or International Organization

Germany

Affiliation

Max Planck Institute for Plasma Physics, University of Greifswald

Author: Prof. PEDERSEN, Thomas Sunn (Max Planck Institute for Plasma Physics)

Co-author: W7-X TEAM

Presenter: Prof. PEDERSEN, Thomas Sunn (Max Planck Institute for Plasma Physics)

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