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# Theory-based models for the control of W7-X divertor plasmas

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Both the exploration of previously unattained plasma conditions in stellarators and high-reliability requirements (for safe, long-pulse operation at higher plasma performance) pose new challenges for plasma control in Wendelstein 7-X (W7-X). With upgrades being installed at present, the development of predictive tools for safe long-pulse operation of the optimized stellarator W7-X becomes more and more an urgent task. But the pace for the achievement of reliable plasma operation enjoying full benefit from inherent advantages of stellarators, i.e.~quiescent, stable steady-state operation will critically depend on control capabilities. This paper describes a novel approach for stellarators to develop theory-based, simplified models for control - tailored to stellarator specific requirements. A result of the proposed approach to control localized heat loads on the divertor shows the feasibility of the concept. Since the models originate from theory or scalings, it is expected that they can be applied to future experiments. Therefore, the validity range of the models are explored and result in a comprehensive characterization of physics regimes attained in W7-X so far. Both aspects of this study –validated physics models for operation and the characterization of physics regimes in optimized stellarators - contribute to the physics basis for potential future fusion power plant based on optimized stellarators.

Wendelstein 7-X (W7-X) is a superconducting magnetic confinement fusion device built as a proof-of-concept to assess the reactor potential of optimized stellarators. The plasma volume ($30m^{-3}$) is large enough to expect temperatures leading to low collision frequencies (also collisionalities $\nu^*$). In 3D-fields of classical stellarators, $\nu^*$ as low as for fusion leads to unacceptable losses. The optimized stellarator W7-X is built to demonstrate that detrimental low-$\nu^*$ effects can be mitigated by optimized magnetic fields. In its forthcoming campaigns ("OP2"), W7-X aims to demonstrate safe and reliable steady-state operation. Equally important, the plasma beta and collisionalities should meet requirements that allow one to examine the physics of fusion-grade plasmas. At present, the machine is being equipped with water-cooled plasma-facing components. Heating and fueling upgrades are being installed along with extended wall surveillance and measures to detect high, localized power loads.

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Results shown in this paper are based on systematic transport modelling of W7-X discharges from recent campaigns with an uncooled divertor ("OP1": limited in pulse lengths ($\nu^*$s) and heating power $\langle\beta\rangle$). The modelled discharges encompass a density range from $\tau_{pulse} < 100$ to $P < 7$MW. The plasmas were heated with electron cyclotron heating (ECH) in X2- and O2-polarization. Fig. 1 summarizes the analyzed data representatively covering discharges in the first campaigns. The representation is chosen to address electron-ion equilibration ($2 \times 10^{19}\mathrm{m}^{-3}$), long-mean-free-path conditions (collisionality $1.2 \times 10^{20}m^{-3}$) and plasma pressure ($T_e/T_i$) since those quantities are key for scenarios in the forthcoming campaigns of W7-X. The arrows indicate gaps from conducted experiments to target values for high performance in W7-X. Fig. 1 clearly reveals different stellarator-specific transport regimes. Core-electron-root-confinement (with positive radial electric fields and $\nu^*$ require low electron collisionalities and depend on the field ripples as predicted. Ion-root conditions were attained by density increase but not yet entering low-$\beta$ regimes due to a lack of ion heating. At high densities, divertor detachment shows up. Highest $T_e < T_i$ plasmas were obtained transiently with pellet injection.

Signatures for stellarator specific, long-mean-free-path transport is consistently found below a threshold of thermal collisionality in the plasma center of about $\nu^*$. Electron root conditions (size of the circles in Fig. 1 shows the extent of the positive radial electric fields in the plasma center) are obtained at high electron temperatures but lacking thermal equilibration. The transport modelling reveals that neoclassical energy losses are smaller than 40% of the total energy losses even in the core (electron-root: $\beta$). Anomalous transport, radiation and charge-exchange losses (showing up at the edge and SOL) dominate the energy transport otherwise. In ion-root conditions, neoclassical contributions to fluxes are small (as expected at higher $\nu^*(0) < 0.01$).

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In contrast to the radial energy flows, neoclassical mechanisms apparently dominate the parallel transport. The time response of the plasma current is modelled by an *L/R-response model* ($\rho < 1/3 \ldots 1/2$). While fits are frequently used to determine the stationary current $\nu^*$ and the L/R-response time $t_{ref} = 3.5$s from experimental data, the approach in this paper is different: theory and measurements are used to *forward model* (potentially in real time) $I(t) = I^\infty[1 - \exp(-t/\tau_{L/R})]$ and $I^\infty$ in order to *predict* the plasma current. To this end, stationary bootstrap current profiles were calculated (Fig. 2(e)) from measurements of densities and temperatures (Fig. 2(a) and (b)). The required neoclassical modelling included precalculated, theoretical transport coefficients and the (not intrinsically ambipolar) radial electric field (Fig. 2(c)). The resistivity was determined from the theoretical parallel transport coefficients (Fig. 2(d)), the plasma inductance was estimated from the mean major and minor radius, respectively. Errors (broken lines in Fig. 2) include uncertainties of the profile fit and $\tau_{L/R}$.

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Fig. 3 shows results of the *L/R-response model* with pre-calculated parameters from neoclassical theory. To demonstrate predictive capabilities, measurements (Fig. 2 (a) and (b)) at a reference time ($I^\infty$ early in the discharge) are used for predictive calculations. Good agreement of the model prediction (using information at $\tau_{L/R}$) with the plasma current is obtained for periods $Z_{eff}$. It is concluded that the *L/R-response model* using measured profiles provides a real-time prediction for plasma control. For discharge simulations (prior experiments), profiles of relevant quantities are reproducibly set by the heating power, the densities and the magnetic configuration. A parametrization of $t_{ref} = 3.5$s and $t_{ref}$ is therefore an option for pre-calculating the plasma current response or for simplified (but *life*) measurements of profile proxies.

Limitations of the model are found in transient phases of plasma current redistribution, e.g. during plasma start-up or changes of the heating power and current drive with minor effects on the long-term current evolution. Moreover, if magnetic islands are intentionally shifted inside the plasma, differences are found both in $t \gg t_{ref}$ and $I^\infty$ (in the order of a few tens of percent). The difference due to magnetic islands (even beyond the flattening of the pressure profiles) is investigated. For O2-heated, long-pulse discharges, systematic deviations in the predicted current occur. Differences may be due to electron cyclotron current drive (ECCD) from multi-pass reflections of strong microwave heating.

The findings demonstrate the potential of theory-based, but reasonably simple time response models to predict the plasma current. The presented results can be applied for *in-situ* control of changes in the edge rotational transform (affecting strike-line positions) being computationally much faster than full time-dependent modelling. Current seeding with ECCD could be used as an actuator. Further applications for the general approach lie in the prediction of stored energy and density control. Since the control scheme is proposed to rely on physics-based modelling or scalings, the approach can be extrapolated to upgraded heating capabilities expected in the next campaigns of W7-X. Ultimately, the models therefore contribute to the development of reliable plasma scenarios for next-step stellarators.

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