Changes in the edge magnetic field of Wendelstein 7-X in high-beta plasmas

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The Wendelstein 7-X (W7-X) stellarator aims to demonstrate steady-state operation at high performance, including a volume-averaged plasma beta of about 5%. Due to pressure-gradient-driven magneto-hydrodynamic (MHD) currents, the structure of the magnetic field at high-performance operation can differ significantly from the vacuum field. W7-X relies on an island divertor for heat- and particle-exhaust, which has demonstrated good performance in the first two divertor campaigns [1]. The MHD-driven changes in the edge magnetic field can significantly change the structure of the divertor islands, which in turn impacts the performance and safe operation of the divertor.

Methodology: Anisotropic diffusion simulation for heat-load prediction

Divertor design research has to explore large configuration spaces, both concerning the magnetic configuration and the divertor geometry shape itself. Therefore, it relies on fast proxy models to estimate the heat-load distribution on plasma-facing components and to identify potential overload regions. For this work, we try to lessen the gap between fast simulations provided by single-directional field-line diffusion [2] and the full plasma simulation by codes such as EMC3-EIRENE (which require a grid generation process). We here use a Monte-Carlo model for anisotropic diffusion, made out of two alternating steps. The first step is a parallel field-line tracing step, with the tracing distance sampled from a Gaussian distribution centered at 0 (negative values mean reversed tracing direction). The second step is an isotropic displacement sampled from an isotrpic 3D Gaussian distribution. The ratio between the two distributions' variances corresponds to the ratio of parallel and isotropic diffusion coefficients.

Beta effects on heat-loads

To obtain changes in the edge magnetic topology, full-field MHD equilibria were simulated with the HINT code on the JURECA supercomputer. A particular focus of this study was the influence of the edge rotational transform ι on the heat-load patterns and their beta-dependence. Wendelstein 7-X features three distinct edge rotational transform configuration families, with the high-iota ($\iota = 5/4$) and the low-iota ($\iota = 5/6$) configurations marking the ends of its ι-range, and the standard configuration ($\iota = 5/5$) marking its center. The magnetic standard configuration is of particular importance, as it is one of the two major design configurations. The other major configuration is the high-mirror configuration, which also features an edge rotational transform of $\iota = 5/5$.

All three configurations show distinct responses to the transition to high plasma beta. The most benign response is exhibited by the standard magnetic configuration. Here, the dominant feature is the stochastization around the island separatrix (see figure 1), with the island surface structure remaining intact around the O-points. Additionally, due to a change of the outer flux surface shape, the incident angle of the island (along the toroidal cross-section) on the divertor planes is slightly modified, which leads to the appearance of an additional outboard strike-line on the horizontal divertor plate (see figure 2).

The high-iota configuration shows more substantial stochastization, likely due to the interaction of the island with the fully stochastic domain outside of the magnetic islands. On the divertor, the stochastization seems to mainly even out the heat-loads along the divertor plate. The impact of the stochastization on divertor operation (e.g. access to the high recycling regime), however, needs to be clarified in more detailed simulations.

The low-iota configuration shows the most peculiar response. In line with earlier analysis [3], the $\iota = 5/6$ islands shrink in diameter with increasing plasma beta, until at $\beta_{\text{ax}} = 5\%$ (volume-averaged beta of 2.5%) only the higher order $10/12$ islands remain. This leads to a transition away from a divertor configuration to a limiter-like edge topology, which is accompanied by with a transition in attached power loads from a line-like to a spot-like structure (which has substantially enhanced heat-loads).

Conclusions & Outlook

Based on the equilibrium and heat-load simulations, it seems that, from a view of island divertor stability, the $5/5$ family of magnetic configurations (which includes additional configurations like the bootstrap-optimized high-mirror configuration) is the most attractive for high-performance operation. The additional interaction of the beta-driven changes with the toroidal plasma currents present in the experiments, which have been studied separately and which have been neglected here, needs a joint assessment.

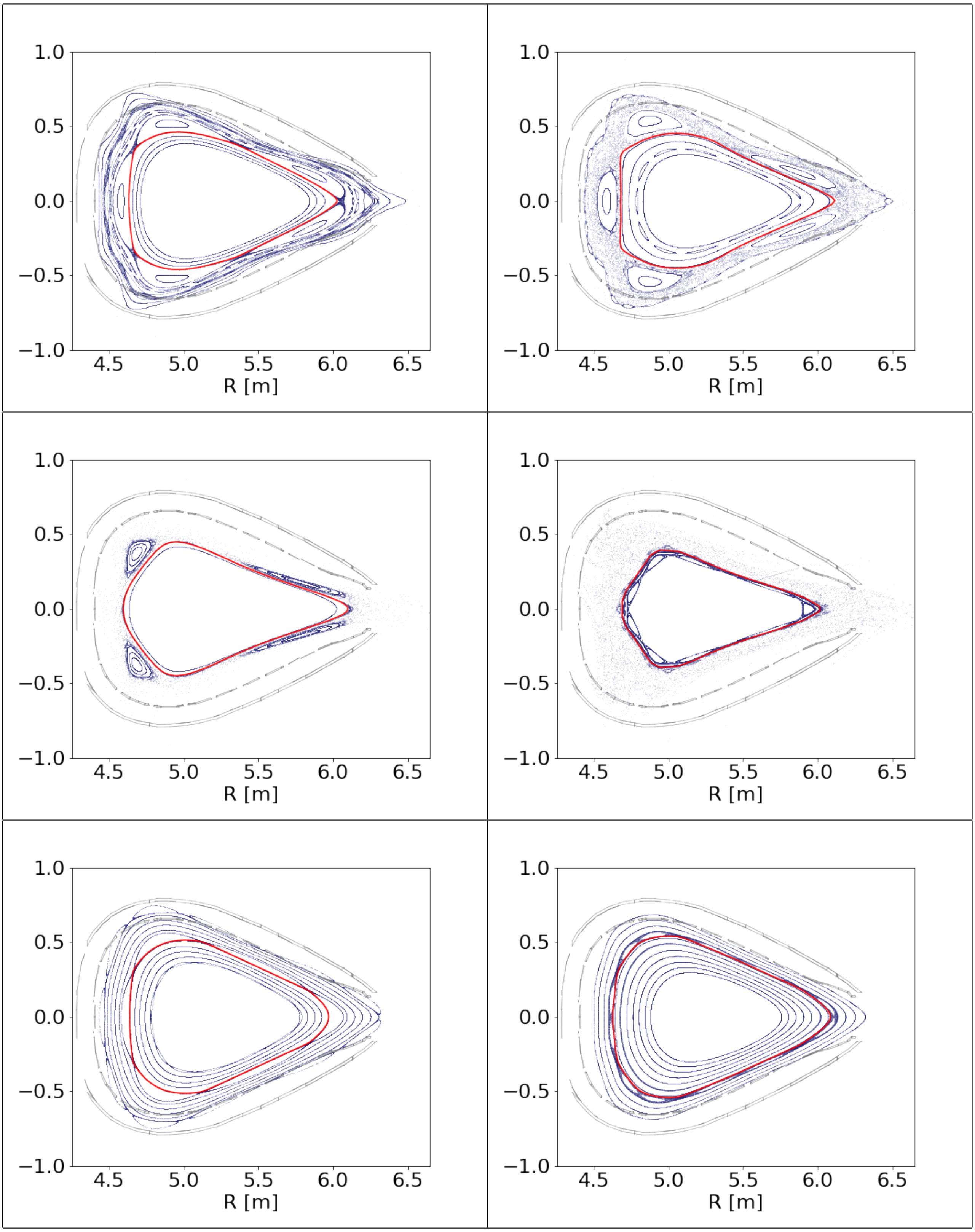

Figure 1: Magnetic topology for standard (top), high-iota (middle) and low-iota (bottom) configuration in vacuum (left) and 5% on-axis plasma beta (right). The red line indicates the flux-surfaces used to seed the heat-load test packets for the heat-load distributions in figure 2

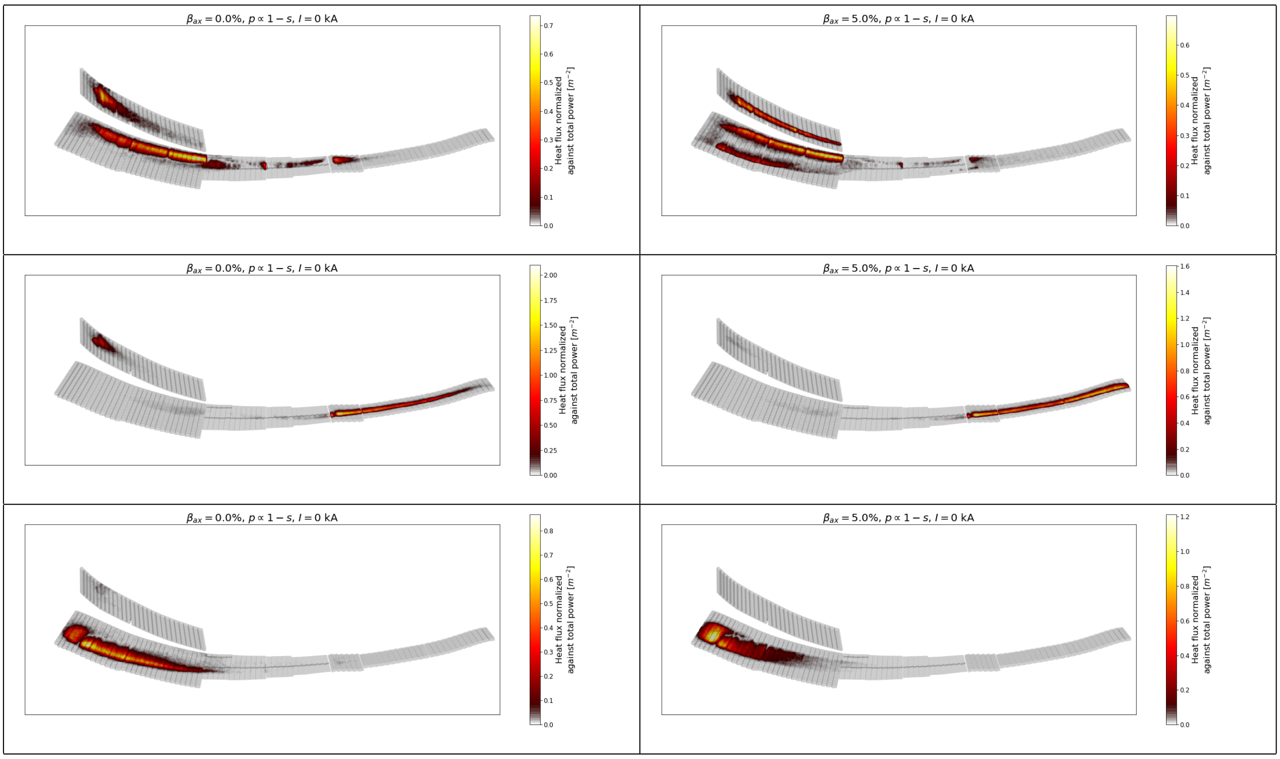

Figure 2: Simulated heat-loads normalized against the total power flow into the scrape-off layer (in unit m^{-2}) for standard (top), high-iota (middle) and low-iota (bottom) configuration in vacuum (left) and 5% on-axis plasma beta (right)

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References

[1] T.-S. Pedersen et al, First results from divertor operation in Wendelstein 7-X, Plasma Physics and Controlled Fusion **61** (2019)

[2] S. Bozhenkov et al, Service oriented architecture for scientific analysis at W7-X. An example of a field line tracer, Fusion Engineering and Design **88(11)** (2013)

[3] T. Hayashi et al, Formation and 'self-healing' of magnetic islands in finite-β Helias equilibria, Physics of Plasmas **10** (1994)

[4] Jülich Supercomputing Centre, JURECA: Modular supercomputer at Jülich Supercomputing Centre, Journal of large-scale research facilities **4**)(2018)