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Exploring improved PFC heat load distributions on Wendelstein 7-X using multi-objective optimization

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One of the major milestones of the Wendelstein 7-X experiment is the achievement of high-performance long-pulse discharges. Therefore, it is of paramount importance to restrict the heat loads on its divertor to values it can tolerate in steady-state conditions.

While configurations can be analyzed for their heat load distributions ahead of time, it becomes challenging to adjust the configuration when deviations between experiment and theory become apparent. Similarly, when not all optimization criteria can be simultaneously fulfilled, classical optimization techniques require the tradeoff between them to be defined before the optimization, limiting their usefulness for explorative studies.

Multi-objective (MO) optimization addresses the above concerns. Instead of trying to maximize a single function, MO optimizers attempt to build a front of Pareto-optimal configurations - configurations that can not be further improved in any aspect without making sacrifices somewhere else.

To find out about the available tradeoffs, we defined a multi-objective study to directly optimize the heat load predictions in different divertor sections against each other, using coil currents as input parameters. This study allows us to study how much heat loads in one specific divertor region could be reduced at the expense of additional loads in other places.

The heat load distribution was calculated using the FusionSC [1] field line tracing library using an anisotropic diffusion approximation for the heat transport [2]. Candidate configurations for evaluation were obtained by sampling coil currents directly from the Multi-Objective Tree of Parzen Estimators implemented in the Optuna optimization library [3].

The target objective functions used included the heat loads on 4 different regions (namely baffles, divertor, middle divertor section and outer port) and an objective function to fix the required magnetic field strength for the electron cyclotron heating resonance. Additionally, penalty constraints were added that would make the optimizer prioritize preferentially address individual objective functions if their values were grossly exceeding tolerance limits. These limit the exploration of the Pareto front to approximately feasible configurations.

During optimization, the optimizer discovered a configuration family with low divertor peak loads, that could potentially form a baseline for scenarios requiring safe high-power exhaust.

Additionally, parameter importance analysis showed some of the optimization functions to disproportionately respond directly to some of the input coil currents. This presents us with simplified heuristics to address overloads by tuning individual coil currents.

Currently, this approach has only been used for direct predictive modeling, which is restricted by the accuracy of the heat load model. We plan to generate a more finely meshed database so that we can also directly predict adjustments to be made during experiment to the target configurations based on observed overloads.

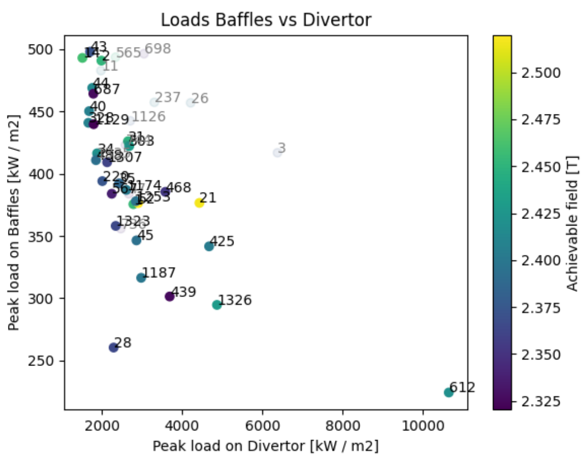

Figure 1: View of the most relevant region of the analyzed configuration space, indicating the 3-way tradeoff between divertor, baffles, and magnetic field. Points with black labels correspond to Pareto-optimal configurations, while trials with grey label are dominated in all aspects by at least one other configuration in the picture.

References

[1] Github https://github.com/alexrobomind/fusionsc
[2] A. Knieps et al, Plasma Physics and Controlled Fusion (2022)
[3] https://doi.org/10.48550/arXiv.1907.10902