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First-Principles–Based Divertor Optimization: A Unified MCF Divertor Framework Applied to Wendelstein 7-X

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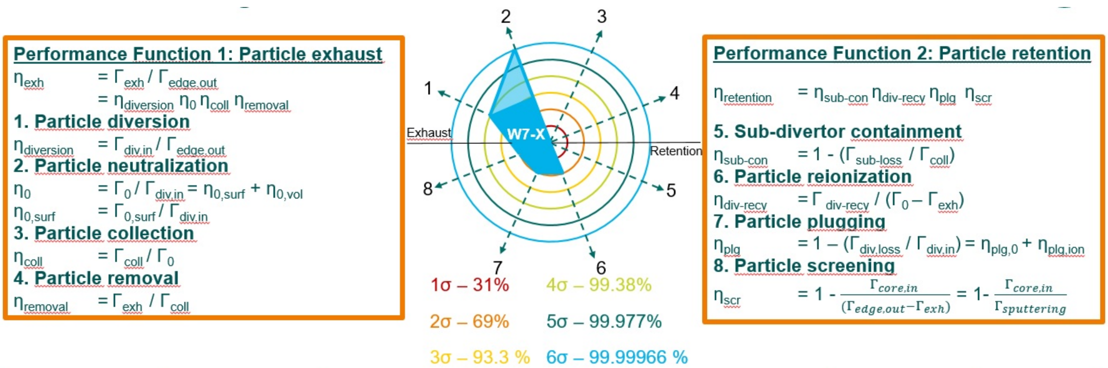
The stellarator's steady-state capability offers inherent advantages for fusion power plants (FPP), including disruption-free operation and access to higher densities beyond the Greenwald density limit. However, reconciling particle exhaust and retention while fulfilling mandatory requirements of divertor life-time survival remains a critical challenge for reactor-relevant divertor operation in stellarators and other magnetic confinement fusion (MCF) devices.

At Wendelstein 7-X (W7-X), we employ a six- σ design methodology [1]—a data-driven framework that optimizes processes by quantifying a priori performance metrics within six standard deviations (σ) of process yield —combined with the Kano model [2]. Following the principle of form follows function, we categorized divertor requirements into mandatory survival criteria (e.g., resistance to heat, sputtering, and mechanical stresses) and functional performance metrics (particle exhaust and retention). These performance metrics were further decomposed into eight a priori first principles. Statistical metrics derived for each principle enable quantitative assessment of the W7-X island divertor's current performance, shown in the table below, and facilitate direct comparisons with existing and future divertor concepts.



Requirement	Heat	Detachment	Sputtering	Mechanics	Neutrons	Cost/Time
Metric	$FOS = \frac{\dot{q}_{max}}{\dot{q}_{div}}$	f_{rad} & f_{v-rec}	$\eta_{sptr,resist} = 1 - Y$	$FOS = \frac{yield\ stress}{working\ stress}$	?	?
W7-X	1.67		?	> 1	?	?

Figure 1: W7-X divertor performance quantified based on a-priori first principles

A field-aligned, simple SOL density model is utilized, in which perpendicular transport processes are described by a single stochastic process with a uniform perpendicular diffusion coefficient. Based on the resulting normal distribution across common and private flux region, we present seven distinct target geometries applicable to any MCF device with diverted field lines. These designs employ distinct neutral-management strategies – prioritizing attached exhaust through the SOL or PFR, or re-ionization on the incident field line, the separatrix, or SOL density peak to drive volumetric ionization losses potentially leading to higher volume recombination ratios.

A rapid modelling cycle based on anisotropic SOL diffusion EMC3-Lite modelling [3], coupled with COMSOL [4], solving the neutral transport in the molecular flow regime via the angular coefficient method and the continuous flow regime via differential equations, was established to evaluate strike line positioning and quantify the 1st, 3rd, 4th, and 5th of the 8 a priori metrics. We benchmarked these metrics for W7-X's current divertor geometry with the 5/5, 5/4, and 5/6 resonant magnetic island configurations, and outline ongoing efforts in the W7-X divertor concept development, including the design and assessment of new divertor geometries.

This principle-driven framework bridges stellarator-tokamak divides, offering unified divertor criteria for current and next-step MCF devices. By balancing reactor demands for particle control, retention and component longevity, it advances the path toward feasible FPPs.

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[3] FENG, Y., et al. Review of magnetic islands from the divertor perspective and a simplified heat transport model for the island divertor. Plasma Physics and Controlled Fusion, 2022, 64. Jg., Nr. 12, S. 125012.
[4] MULTIPHYSICS, COMSOL. Introduction to comsol multiphysics®. COMSOL Multiphysics, Burlington, MA, accessed Feb, 1998, 9. Jg., Nr. 2018, S. 32.

Speaker's title

Mr

Speaker's Affiliation

Max Planck IPP, Greifswald

Member State or IGO

Germany

Author: Dr KREMEYER, Thierry (Max Planck Institut für Plasmaphysik)

Co-authors: Mr KHARWANDIKAR, Amit (Max Planck Institute for Plasma Physics); MENZEL-BARBARA, Antara (Max-Planck-Institut für Plasmaphysik); PANDEY, Arun (Max-Planck-Institute für Plasmaphysik, Greifswald); DHARD, Chandra Prakash (Max-Planck-Institut für Plasmaphysik, Greifswald); BOEYAERT, D. (University of Wisconsin-Madison); FELLINGER, Joris (Max-Planck-Institute für Plasmaphysik, Greifswald); JAKUBOWSKI, Marcin (Max-Planck-Institut für Plasmaphysik); Mr GRASSER, Markus (Max Planck IPP); Mr ENDLER, Michael (Max Planck IPP); W7-X TEAM (Max Planck Institute for Plasma Physics, Greifswald, Germany)

Presenter: Dr KREMEYER, Thierry (Max Planck Institut für Plasmaphysik)

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