Towards a Stellarator Fusion Reactor: Achievements of the European Stellarator Program

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Within Europe, the EUROfusion Task on Stellarator Power Plant Studies (SPPS) has taken on the role to develop the engineering basis for future Stellarator fusion reactors. However, the complex 3D geometry of Stellarators poses a unique challenge in the analysis and design process requiring novel and flexible tools capable of handling such complex geometries. To tackle this challenge, this activity successfully developed a wide range of new tools such as parametric CAD models as well as advanced 3D engineering models, most notably in the area of neutronics and magnet assessment among others. These developments allow to shorten the time between high level design iterations on the way to a pre-conceptual Stellarator reactor design. In particular, with our toolchain it is now possible to start from a fresh magnetic field configuration, automatically generate a corresponding CAD model with blanket layers, on which multi-physics assessments can be directly carried out, i.e. neutronics, electromagnetics, thermo-hydraulics, etc. This process will be demonstrated on the example of a newly conceived, turbulence optimized quasi-isodynamic Stellarator configuration[1], but can be applied without restriction to any potential future magnetic field candidate.

Example of the newly developed toolchain, starting from a novel quasi-isodynamic Stellarator configuration (left), the automatic and parametrically generation of an accompanying CAD/FEM model (middle), and direct neutron transport simulations on that same geometry (right). (Note: the results are indicative as full simulations and optimization is still ongoing)

Neutronics: In the past, the neutronic analysis of complex 3D geometries like Stellarators was extremely cumbersome, in particular due to the difficulty of converting spline-based CAD models to the Monte Carlo native CSG format. With our new parametric tools, we can instead create triangular and tetrahedral meshes, which can be easily converted to the appropriate input formats for the Monte-Carlo codes. This process has been demonstrated for modern Monte Carlo neutron transport codes such as MCNP, Serpent2, and OpenMC, which have been benchmarked successfully in Stellarator geometry.

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[1]A.G. Goodman, et al., A quasi-isodynamic stellarator configuration towards a fusion power plant, J Plasma Phys, in preparation, 2025

Additionally, a new deterministic method was developed, that can bridge the gap between expensive Monte Carlo simulations and early, quick design iterations and due its speed can be used for design optimization. Key results show that while it seems easier to reach a high TBR in Stellarators, it is more challenging to fulfill the shielding requirements set by the magnets due to the space constraints. But thanks to the parametric models, blanket and shielding thicknesses can be automatically varied to address such issues. These findings demonstrate the importance of developing an appropriate tool chain helping to identify key design issues and in addressing them with quick design iterations thanks to their flexibility.

Magnets: The design of an appropriate winding pack layout for a Stellarator reactor magnet is an iterative process that involves the consideration of different aspects: electromagnetic analysis, mechanical structure, and thermal-hydraulic simulation. For the EM analysis a range of commercial software and in-house developed novel tools were tested and benchmarked, all showing similar results, but vary significantly in computational time. For the mechanical layout a parametric model was developed for the coil case and inter-coil support structure allowing to address issues related to high mechanical stress with low manual modification. Finally, well established 1D models have been employed for the thermal hydraulic analysis and the coil behaviour under quench conditions. This analysis highlighted the strong impact of the current decay time on the temperature evolution and emphasized that the original design has room for optimization. Thanks to the developed tool-chain such optimization, including the re-analysis of the entire process, can be done with minimal resources, an important aspect in the pre-conceptual design phase of a Stellarator reactor.

Divertor: The island divertor as employed by Wendelstein 7-X has demonstrated the capability of steady-state detachment making it a potential solution for a Stellarator reactor. While fundamental understanding and modelling is still underway, we focus on reduced heat load models that allows us to estimate divertor target placement, shaping, and size for the pre-conceptual engineering design. Compared to W7-X, a more closed divertor is under investigation that aims to improve on particle exhaust.

Apart from these early success stories, a number of activities have been initiated that are ongoing such as the 3D MHD simulation of liquid metal breeders to characterize the pressure drop and to optimize pipe pathing. Similarly, taking nuclear heating from neutronics simulations as input, the thermo-dynamic analysis of the blanket has been started. This also requires the knowledge of additional heat load on the wall, through e.g. fast particles, for which also simulation work has been started. Finally, remote maintenance poses a key design challenge, in particular in the space-constrained environment of a Stellarator. Several RM schemes are investigated in parallel and characterized with e.g. kinematic studies. However, further research and investment is required to advance these topics.

The reported work highlights the multi-disciplinary nature of reactor design activities, and the inherent need for tools that are able to handle the Stellarator-specific 3D geometry requirements. While success has been demonstrated in individual disciplines, ultimately, the various aspects need to be integrated into a coherent concept. For this purpose we aim to develop a Digital Twin framework, where appropriate models (inherently fast or surrogate) from the respective disciplines can combined to ensure feasibility and consistency, as well as to study the trade-offs between the various systems. Finally, we need to identify the Stellarator-specific key integration issues and work towards solving them, shaping the Stellarator Roadmap towards commercialization.

This presentation will highlight the key challenges and achievements of the European team for Stellarator reactor design and provides an outlook on initiated and planned tasks.

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