OVERVIEW OF STELLARATOR PHYSICS AND ENGINEERING SIMULATION AND MODELING FOR FUSION PILOT PLANT DESIGN AND OPTIMIZATION

R.M. Churchill[1], A. Anandkumar[2], P. Balaprakash[3], D. Bindel[20], A. Boozer[7], A. Coelho[12], B. Faber[5], R. Hager[1], S. Henneberg[17], J. Hidalgo-Salaverri[1], D. Iliescu11, B. Kinch[9], A. Khodak[1], E. Kolemen[1], S. Klasky[3], J. Larson[6], M. Landreman[4], S. Lazerson[12], J. Lion[19], , N. Mandell[15], J. Merson[8], E. Miralles-Dolz[1], A. Mollén[1], C. Moreno[5], T. Munson[6], S. Murakami[13], X. Navarro-Gonzalez[5], N. Pablant[1], D. Panici[1], E. Paul[7], T. Qian[1], P. Romano[6], J. Sachdev[1], A. Scheinberg[10], J. Schwartz[1], M.S. Shephard[8], D. Spong[3], D. Steward[11], Y. Suzuki[14], C. Swanson[18], E. Toler[6], N. Trask[9], P. Wilson[5], A. Wright[5], M. Zarnstorff[1], C. Zhu[16]

[1]Princeton Plasma Physics Laboratory, Princeton, NJ, USA
[2]California Institute of Technology, Pasadena, CA, USA
[3]Oak Ridge National Laboratory, Oak Ridge, TN, USA
[4]University of Maryland, College Park, MD, USA
[5]University of Wisconsin, Madison, WI, USA
[6]Argonne National Laboratory ,Lemont, IL, USA
[7]Columbia University, New York, NY, USA
[8]Rensselaer Polytechnic Institute, Troy, NY, USA
[9]University of Pennsylvania, Philadelphia, PA, USA
[10]Jubilee Development, Cambridge, MA, USA
[11]ANSYS, Canonsburg, PA, USA
[12] Gauss Fusion, Munich, Germany
[13] University of Kyoto, Kyoto, Japan
[14] Hiroshima University, Hiroshima, Japan
[15] Type One Energy, Madison, WI, USA
[16] University of Science and Technology of China, Hefei, Anhui, China
[17] Max-Planck-Institut für Plasmaphysik, Greifswald, Germany
[18] Thea Energy Inc., Kearny, NJ, USA
[19] Proxima Fusion, Munich, Germany
[20] Cornell University, Ithaca, NY, USA

Email: rchurchi@pppl.gov

1.INTRODUCTION

Achieving the ambitious goal of completing an initial Fusion Pilot Plant (FPP) design by 2028 will require integrating many tools to aid in optimizing and verifying the design. Stellarator design by nature demands a closer integration of physics and engineering analyses, as coil shaping decisions strongly dictate the achievable plasma performance. This challenge is also a strength of stellarators, since the dominant external control allows innovations in design to be reliably made using theory and computation at minimal cost and time.

This overview presentation will discuss the current state of stellarator simulation and modeling, and multiple efforts to firmly establish tools and metrics for stellarator digital models, useful for physics and engineering design validation and optimization. There are many formal stellarator computational projects worldwide [1-4] with work at both public institutions and private companies. This overview will highlight the tremendous progress that has been made in stellarator computational tools, and current areas of research and development, focusing on U.S. efforts and tying to the larger international stellarator community. This includes better integrating simulation codes across multiple fidelities, leveraging advanced optimization and Artificial Intelligence (AI) methods for robust design optimization, and including more detailed engineering analyses in stellarator optimization.

2. STELLARATOR PLASMA PHYSICS SIMULATION

The level of fidelity in describing and predicting stellarator plasma physics has matured significantly since current stellarator machines were designed and optimized, reflecting a progression in physics, numerical algorithms, and computational power. Examples include MHD stability, fast ion loss, energetic particle modes, and microturbulence calculations [5-8]. Tradeoffs between fidelity and compute time have led to a range of simulation codes focused on different tasks from optimization to design validation. Higher-fidelity codes are being used to derive better proxies for direct computation, for use in automated optimization. Artificial Intelligence (AI) is likewise being used to create code surrogates across a range of geometries for direct inclusion of higher fidelity physics calculations in optimization loops (see Fig. 1) [9]. Further opportunities are to be found in integrating codes to create a truly multi-physics, integrated modeling capability for the stellarator fusion plasma.

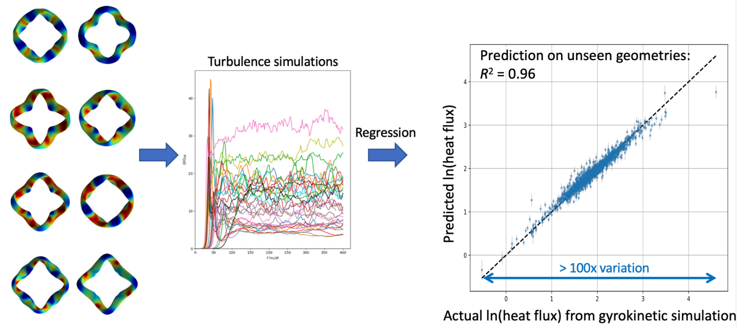

Fig 2: Results of neural network predictions of stellarator turbulent energy flux, based on ~70k gyrokinetic turbulence simulations with GX [10]

3. STELLARATOR ENGINEERING

Engineering design of stellarators requires various calculations ensuring e.g. magnets that create desired plasmas, sufficient tritium breeding in the blanket, minimization of nuclear heating to superconducting magnets, and building support structures for magnets. Computational tools for engineering tasks such as these are being streamlined and automated, from targeted plasma and coil optimization packages [11-12] to parametric generation of full 3-D stellarator CAD designs[13]. Simulation tools for detailed neutronics calculations at the CAD-level are now routinely available [14], critical for the 3-D nature of stellarators. Coupling neutronics calculations with additional engineering simulation for conjugate heat transfer with liquid lithium and MHD flow provides a holistic breeder blanket simulation capability [15]. Additional engineering analysis workflows have been developed to perform structural optimization (for example magnet support structure placement between modular coils), utilizing detailed finite-element level calculations (multi-physics from electromagnetics, structural, thermal-hydraulic, etc.).

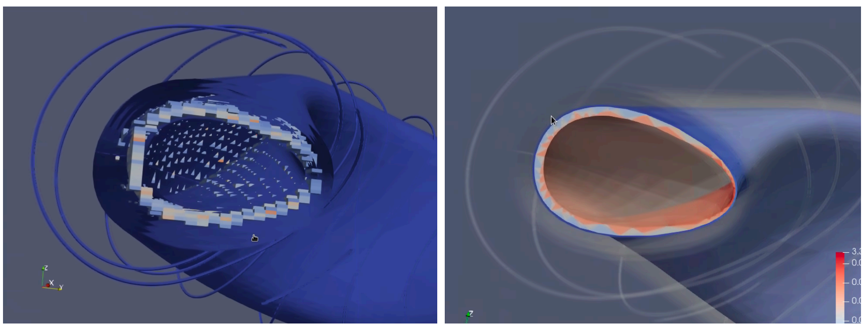

Fig. 2 Neutronics calculations with OpenMC in a model reactor level stellarator, showing improvement CAD-level modeling results gives to local nuclear heating measurements.

ACKNOWLEDGEMENTS

This work was supported by the US Department of Energy under DE-AC02-09CH11466, and DE-SC0024548; the Simons Foundation (No. 560651, D B); JSPS KAKENHI Grant Number JP24K00609; Strategic Priority Research Program of the Chinese Academy of Sciences with Grant No. XDB0790302; European Union via the Euratom Research and Training Programme (Grant Agreement No 101052200 - Euro fusion). Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or the European Commission. Neither the European Union nor the European Commission can be held responsible for them. This research used resources of the National Energy Research Scientific Computing Center (NERSC), a Department of Energy Office of Science User Facility using NERSC award FES-ERCAP0032722.

References

[1] https://hiddensymmetries.princeton.edu/
[2] https://hifistell.plasma.princeton.edu/
[3] https://www.scidac.gov/projects/2023/fusion-energy-sciences/project_2023_010.html
[4] https://princetonuniversity.github.io/STELLOPT/STELLOPT.html
[5] Wright, A., et. al., Phys. Plasmas 31, 082509 (2024)
[6] Spong, D.A., et. al. Nuclear Fusion 57, no. 8 (June 2017): 086018. https://doi.org/10.1088/1741-4326/aa7601.
[7] Maurer, M., et. al. J. Comp. Phys. 420 (November 1, 2020): 109694. https://doi.org/10.1016/j.jcp.2020.109694.
[8] Cole, M. et. al.. Physics of Plasmas 27, no. 4 (April 2020): 044501. https://doi.org/10.1063/1.5140232.
[9] Landreman, M., et. al. arXiv, February 17, 2025. https://doi.org/10.48550/arXiv.2502.11657
[10] N.R. Mandell, et. al. 2024. J. Plasma Phys. 90, 905900402. https://doi.org/10.1017/S0022377824000631
[11] Landreman, M., et. al., J. Open Source Soft., 6, no. 65 (September 10, 2021): 3525. https://doi.org/10.21105/joss.03525.
[12] Dudt, D. W., et. al. Phys. Plasmas 27, no. 10 (October 2020): 102513. https://doi.org/10.1063/5.0020743.
[13] Moreno, Connor, et al. Frontiers in Nuclear Engineering 3 (2024): 1384788.
[14] Romano, Paul K., et al. Annals of Nuclear Energy 82 (2015): 90-97.
[15] Khodak, A., et. al. SOFE 2025
[16] Churchill, R.M., et. al. SOFE 2025