Exascale Simulations for Fusion Blankets

Misun Min[1]

[1]*Argonne National Laboratory, Lemont, U.S.A.*

Accurate modeling of fusion blanket flows requires resolving the strong coupling between turbulence, heat transfer, and magnetohydrodynamics in complex, reactor-scale geometries. In this keynote, I will present recent high-fidelity simulations of lead–lithium and water flows in ITER fusion blanket systems using the NekRS spectral-element solver on exascale platforms, including Frontier and Aurora.

NekRS, developed at Argonne National Laboratory, is a high-performance, open-source code for incompressible and low-Mach-number flows that employs rapidly convergent high-order spectral-element methods to minimize numerical dissipation and dispersion. These properties are critical for resolving MHD-driven flow modifications, Hartmann layers, and pressure losses in electrically conducting blanket components. The code incorporates multilevel preconditioners, high-order time integration, and communication-efficient solvers implemented through OCCA, enabling portable execution across CUDA, HIP, and DPC++ backends.

A central focus of this work is the recent introduction of magnetohydrodynamics capabilities in NekRS [1, 2]. I will discuss the formulation, verification, and performance of both the full incompressible MHD equations and reduced inductionless models relevant to low magnetic Reynolds number regimes. Emphasis will be placed on their applicability to liquid-metal fusion blankets, verification against analytical and benchmark results, and scalability to extreme concurrency. These results demonstrate a significant step toward predictive simulation of fusion blanket thermal–hydraulic and electromagnetic behavior under reactor-relevant conditions.

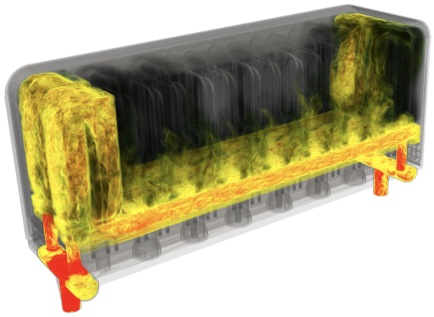

Figure 1: *Velocity throughout the Water-Cooled Lithium Lead Test Blanket Module.*

References

[1] M. Min, Y.H. Lan, P. Fischer, E. Merzari, T. Nguyen, Y. Guo, H. Yuan, P. Shriwise, S. Kerkemeier, A. Davis, A. Dubas, R. Eardley-Brunt, N. Bhatia, R. Akers, V. Mateevitsi, K. Rowe, R. Balakrishnan, Exascale MHD Simulations for Liquid Metal Fusion Blankets, Int. J. High Perform. Comput. Appl., under review, 2025.

[2] Yichen Guo, Paul Fischer, Misun Min, Development of MHD for NekRS, Argonne National Laboratory, ANL-23/62, 2024.