7th Asia-Pacific Conference on Plasma Physics, 12-17 Nov, 2023 at Port Messe Nagoya

Innovations in high-fidelity magnetohydrodynamic modelling for advanced stellarators

A. M. Wright[1,2], N. M. Ferraro[2]
[1] Department of Nuclear Engineering and Engineering Physics, University of Wisconsin – Madison
[2] Princeton Plasma Physics Laboratory
e-mail (speaker): adelle.wright@wisc.edu

The advent of high-fidelity magnetohydrodynamic (MHD) simulations of advanced stellarator configurations has opened a new frontier in understanding the nonlinear, macroscopic characteristics of stellarator plasmas. A new capability of the extended-MHD code, M3D-C1 [1,2], has been applied to model strongly shaped stellarators, providing new insight on equilibrium, stability, and macroscopic dynamics, that informs on-going stellarator fusion pilot plant design and development activities.

All stellarator optimization and design activities rely on certain assumptions, such as the existence of magnetic surfaces, MHD stability, pressure profiles, and the dynamical accessibility of equilibria. The M3D-C1 code uses a high-fidelity, macroscopic physics model and provides a unique way of assessing the veracity of these assumptions. This enables high-fidelity validation of optimized equilibria, which has not previously been possible. Specifically, the magnetohydrodynamic evolution of the magnetic field and pressure profiles are simulated subject to anisotropic thermal transport and realistic heating sources, without imposing any constraints on the geometry of the plasma or the existence of magnetic surfaces. This includes the calculation of transport due to MHD instabilities which may saturate at finite amplitude without imposing stiff constraints on the plasma profiles. These activities have contributed towards substantiating the physics basis of stellarators as a fusion pilot plant concept and understanding and explaining experimental observations. The latter serves the dual purpose of stringent code validation.

The new M3D-C1 capability has been applied to assess the macroscopic stability properties of next-generation optimized stellarators, which exploit various symmetries of the magnetic field (including axisymmetry and helical symmetry) as the basis for improved fusion plasma performance. It was applied, for example, to assess the nonlinear stability properties of a recently developed 2-field-period quasi-axisymmetric stellarator configuration, optimized at 2.5% plasma beta for good energetic particle confinement and self-consistent bootstrap current [3].

Overall, the configuration was found to be unstable to fast-growing magnetohydrodynamic (MHD) modes with moderate to high poloidal and toroidal mode numbers. Strong toroidal mode coupling, arising due to the absence of axisymmetry, led to rapid destabilization of other modes in the n=0 mode family (modes with even toroidal mode number, n). Nonlinearly, these modes were found to generate radially elongated perturbations of the pressure profile and led to rapid destruction of nearly all flux surfaces present in the initial equilibrium (see Figure 1). Simulations were performed for realistic Lundquist numbers and both uniform and Spitzer resistivity profiles. The qualitative stability characteristics were found to be insensitive to these parameters, indicating that the configuration is robustly unstable.

This first-of-a-kind M3D-C1 analysis demonstrates that MHD stability must remain a critical consideration when designing stellarator plasmas, especially for high-performance applications such as fusion pilot plants. This motivates the on-going development of new tools and reduced models which allow nonlinear MHD stability to be incorporated directly into stellarator optimization.

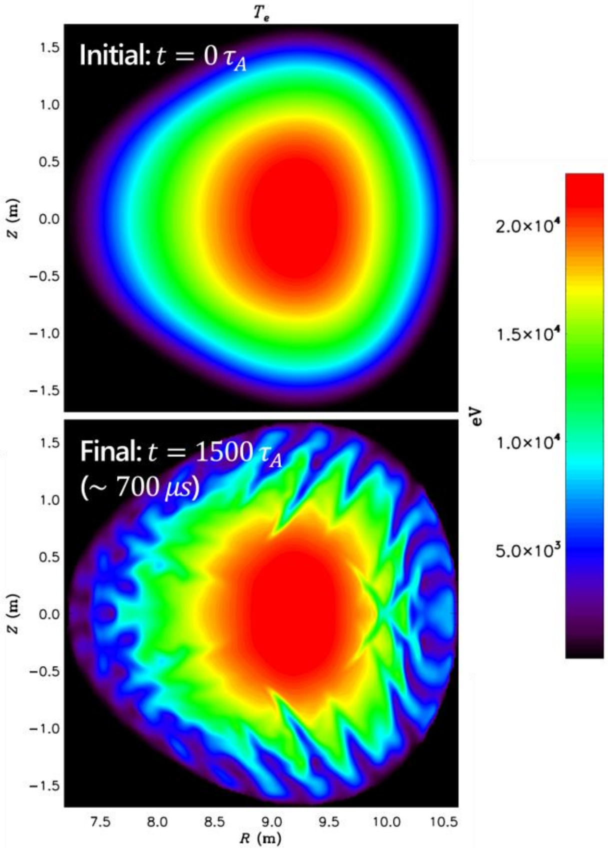

Figure 1: *The electron temperature profile ($\phi = 45°$) at the initial (top) and final (bottom) time slice of an M3D-C1 simulation of a 2-field-period quasi-axisymmetric stellarator equilibrium, optimized at 2.5% plasma beta. The simulation shows rapid growth of moderate toroidal and poloidal mode number MHD modes, with elongated mode structure, leading to rapid destruction of the initial flux surfaces.*

References

[1] Jardin et al., Comput. Sci. Discov., 5.1 (2012).
[2] Zhou et al., Nuclear Fusion 61.8 (2021).
[3] Landreman et al., Phys. Plasmas 29, 082501 (2022).