Automated Design of Field-Reversed Configurations via Genetic Algorithms and Free-Boundary MHD Modeling

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A new computational framework has been developed for the magnetic configuration design and equilibrium optimization of Field-Reversed Configurations (FRCs) [1], leveraging the combined capabilities of genetic algorithms (GA) [2,3] and advanced magnetohydrodynamic (MHD) modeling [4]. Genetic algorithms are stochastic population-based optimization methods particularly well suited for highly nonlinear problems where the search space may contain numerous local minima and the objective function is not amenable to gradient-based optimization techniques. Genetic algorithms enable efficient global exploration of complex design spaces and, through years of successful applications, have proven particularly effective for non-convex and multi-modal optimization problems such as those arising in plasma equilibrium and magnetic configuration design [5]. The proposed method integrates a GA-based optimizer with the ASTRA (Axisymmetric Simulation Tool for Reversed-field plasma Analysis) free-boundary equilibrium code developed in ENEA Frascati [6] which solves the Grad–Shafranov equation for FRC plasmas in the presence of external magnetic fields generated by a set of independently powered coils. Within this framework, the GA iteratively adjusts the currents in the external coil array to find a MHD equilibrium with a target magnetic separatrix shape, representing a desired equilibrium configuration. This work will study the possibility of modeling the plasma current density profile according to the Rigid Rotor Model (RRM) [7,8]. The RRM is a well-established, experimentally validated approach that accurately captures the self-consistent balance between magnetic pressure and plasma rotation in FRCs. Extending the optimization domain to include the parameters that define the rigid rotor current density allows the algorithm to identify the optimal coil current distribution necessary to achieve the prescribed equilibrium. It can also potentially determine the frequency of the rotating magnetic field (RMF) necessary to sustain the steady-state azimuthal plasma equilibrium current. This self-consistent coupling of equilibrium reconstruction, external magnetic field design, and RMF current drive characterization could be a powerful tool for exploring advanced steady-state FRC regimes. The developed framework could enable the automation of equilibrium synthesis, multi-parameter optimization, and parametric studies of FRC magnetic topologies under realistic engineering constraints. Its flexible and extensible design makes it suitable for application to both tuning experimental configurations and for conceptual, reactor-scale design studies, supporting the systematic advancement of compact, magnetically confined fusion systems based on the FRC concept [9].

References

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