EQUILI module in ALYA: a free-boundary Grad-Shafranov equation solver using CutFEM

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The calculation of magnetohydrodynamic (MHD) equilibrium is a fundamental step in plasma modeling for magnetic confinement fusion devices such as tokamaks and stellarators. Accurate equilibrium calculations are essential for determining the magnetic configuration, which underpins all plasma simulations, particularly for integrated modeling efforts [1, 2]. This work represents a novel approach to solving magnetic equilibrium in fusion devices, with the long-term objective of building a comprehensive multiphysics simulation platform for plasma modeling within the ALYA framework. We introduce the EQUILI module, developed within the high-performance computing (HPC) multiphysics framework ALYA [3], to help address several key aspects of fusion reactor physics requiring a multiphysics approach.

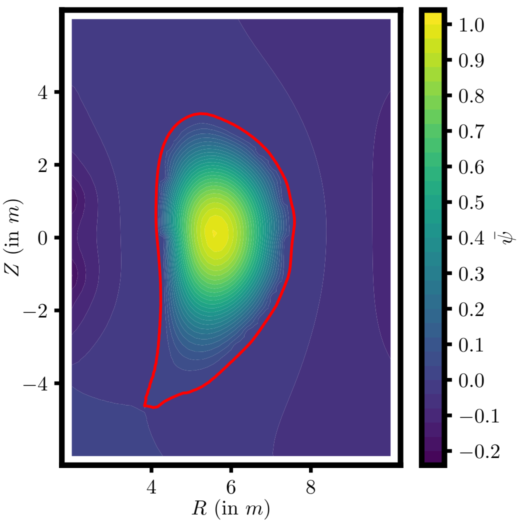

Figure 1: *ITER geometry simulation normalised poloidal magnetic flux $\bar{\Psi}$.*

EQUILI solves the Grad-Shafranov equation to obtain poloidal flux surfaces in axisymmetric geometries, such as tokamaks. Importantly, the plasma current and shape are coupled and can evolve over time, making fixed-boundary approaches for the last closed flux surface unsuitable. To address this, a novel Cut Finite Element Method (CutFEM) has been implemented for the first time to solve the magnetic equilibrium problem. CutFEM, a branch of finite element methods, uses an unfitted computational mesh where geometries and domains are embedded, and interfaces are tracked via level-set functions. This approach is especially suited to problems involving free boundaries and variable plasma shapes, as encountered in magnetic confinement. Initial validation of EQUILI has been conducted using the ITER magnetic configuration (Figure 1), with rigorous sensitivity tests exploring the impact of varying poloidal field coil currents on equilibrium states. Furthermore, the equilibrium computed by EQUILI has been successfully integrated with another ALYA module, MAXWEL, under development to simulate electromagnetic wave propagation in a plasma [4].

References

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