Virtual Fusion Tokamak Structural Model Enabled by Supercomputing

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Determining the stress and strain fields in a fusion powerplant can help inform engineers how component design can be altered to improve the safety of operation of the device or optimise materials in components that are at higher risk of failure due to thermo-mechanical, electromagnetic or irradiation-induced loads. Attaining stress and strain values involves defining boundary conditions for the mechanical equilibrium equations, implying the availability of a full reactor model for defining those conditions. To address this fundamental challenge of reactor design, a finite element method (FEM) model for the Mega-Ampere Spherical Tokamak Upgrade (MAST-U) fusion tokamak has been developed and applied to assess mechanical deformations, strain, and stress in the full tokamak structure, taken as a proxy for a fusion power plant. The model, comprised of 127 million finite elements, illustrates the level of fidelity of structural simulations of a complex nuclear device made possible by the modern supercomputing systems.

In this contribution, we describe the necessary steps to create such a model before using a finite element representation to simulate the effects of various physical scenarios on the structure.

First, we investigate the stress and strain behavior of the tokamak under gravitational loading, to examine the impact on the structure of its own weight.

Second, we emulate the impact of operational conditions on the tokamak. In order to perform plasma experiments, the inside of a fusion reactor must operate under vacuum. We examine the stresses resulting from the pressure differential between the vacuum inside the tokamak and the atmospheric pressure on the outside.

Finally we investigate the behaviour of the tokamak under dynamic loads in the frequency domain. During a pulse, forces of electromagnetic origin can give rise to oscillatory motion. Forced sinusoidal displacement conditions are applied on the bottom face of the tokamak's four legs at varying frequencies enabling us to examine the resonant frequencies for certain components in the model.

The model enables defining computational requirements for simulating a whole operating fusion power plant, and provides a digital foundation for the assessment of reactor performance as well as for specifying the relevant materials testing program.