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Balancing the Macroscopic Pressure and Magnetic Force in Stellarators

Faster, more-accurate calculations of macroscopic force balance opens new possibilities for stellarator design calculations

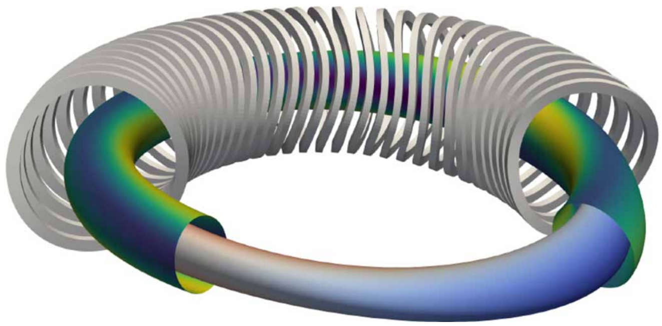

Image courtesy of S. R. Hudson et al., Plasma Physics and Controlled Fusion, 62:08402 (2020)

A set of electromagnets (coils) shown in gray, the computational boundary and the plasma boundary are shown.

The Science

The class of magnetically confined plasma experiments known as stellarators, or “star machines”, necessarily have a complicated, so-called three-dimensional geometry. A set of electromagnets, more commonly known as “coils” and shown in gray in the figure, that carry electrical current produce a magnetic field specially designed to confine the hot charged particles that comprise the plasma. But, the plasma, being electrically conducting, produces its own magnetic field. So where exactly will the plasma be? To calculate the equilibrium position of the plasma, it is required to compute all of the macroscopic forces acting on the plasma. To enable this, an international collaboration between Princeton Plasma Physics Laboratory (PPPL) and the Max-Planck Society in Germany have implemented a novel approach for computing the so-called free-boundary equilibrium in strongly shaped stellarators.

The Impact

Computing the equilibrium state of the plasma is the foundation of most theoretical analyses of plasma behavior in stellarators The magnetic field produced by the electrical currents flowing the plasma opposes the magnetic field produced by the coils. And, as the gas pressure in the plasma increases, the plasma expands. Holding everything in place is the external magnetic field. When the total magnetic forces balance the pressure forces, the plasma is in an equilibrium state. The new approach for computing the position of the plasma has been implemented in the stepped-pressure equilibrium code. This approach provides new insights into plasma phenomena and opens new directions in the design of future stellarators by combining the search for plasmas that give optimal fusion performance with the search for simpler, and cheaper, coil designs.

Summary

This code uses a somewhat esoteric representation to describe the plasma and the magnetic field, what mathematicians call a “weak” representation. The pressure and magnetic field are represented by discontinuous “stepped” functions that accurately describe the volume-averaged properties of macroscopic force balance. This code self-consistently calculates the magnetic field produced by the plasma currents and adds this and the plasma pressure force to the magnetic forces provided by the external coils. An advantage of the new approach over existing methods is that the mathematical description of the external field is particularly efficient. Information regarding the field produced by the

external set of coils is only required on the boundary of the computational domain, rather than in the entire computational domain. So, when then geometry of the coils change, it is much faster than existing methods to recompute the free-boundary plasma equilibrium. (By “free-boundary”, we mean that the plasma boundary is allowed to move to find the lowest energy state, i.e. to find the equilibrium.) The new capability enables mathematically efficient algorithms to solve the combined plasma + coil design optimization problem, in which the plasma properties and the coil geometry are simultaneously varied to find new stellarator designs.

Contact

S. R. Hudson, C. Zhu, J. Loizu, S. Henneberg, P. Helander
Princeton Plasma Physics Laboratory, Max Planck Institute for Plasma Physics

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Publications

S. R. Hudson et al., “Free-boundary MRxMHD equilibrium calculations using the stepped-pressure equilibrium code”, Plasma Phys. Control. Fusion 62 (2020) 084002, https://doi.org/10.1088/1361-6587/ab9a61