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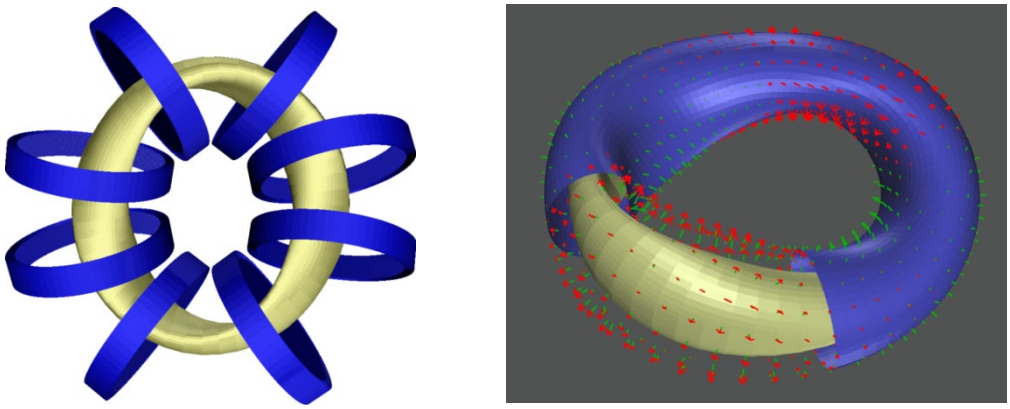
Permanent Magnets Can be Used to Simplify Stellarators

An array of permanent magnets can provide the shaping field in stellarators, and the electromagnets become very simple.



A simple set of circular electromagnets, shown on left. The shaping magnetic field is produced by an array of permanent magnets. Each magnet creates a dipole field, which is represented by an arrow. The total magnetic field created is designed for optimal plasma confinement.
Image courtesy of P. Helander, M. Drevlak, M. Zarnstorff, and S. C. Cowley, Phys. Rev. Lett. 124, 095001 (2020)

The Science

In the fusion-relevant magnetically confined plasma experiments, there are two possible ways to create the required closed “magnetic bottle”. The way used in tokamaks is for the plasma, which is a hot gas of charged particles, to carry the net current itself. This creates the required magnetic field in the short way around the torus, but the plasma current is pulsed which an impediment to steady-state operation, and relying on plasma currents can be a source of disruptive instabilities. The way used in “star machines” known as stellarators is to create plasmas with a complicated three-dimensional shape, as shown in the figure. This leads to more stable plasmas but requires the external electromagnets to have a complicated shape. Now, scientists have shown that the required shaping magnetic field can be produced by permanent magnets. This is potentially a revolution in stellarators that promises to greatly simplify the design of future stellarator fusion reactors.

The Impact

Stellarators, which can operate in steady state and relatively of disruptive instabilities, have some advantages over tokamaks as fusion reactors, but the coils needed for stellarators can be complicated. Fusion reactors that have a simple coil design are easier (and cheaper) to build. By using permanent magnets to create the required shaping field, the electromagnets in stellarators become simpler; in fact, they become much simpler, as shown in the figure.

Summary

In a multi-institutional collaboration involving scientists from Princeton University and the Max Planck Institute in Germany, potentially revolutionary designs for advanced stellarators have been produced. The

new designs exploit technological advances in the construction of permanent magnets, which are now much stronger. (Magnets made from neodymium, for example, can produce magnetic fields with a strength of 1.4 Tesla.)

Calculating where an array of thousands of these magnets should be placed to provide the required fields required solving a complicated inverse problem based on the equations that govern electricity and magnetism, namely Maxwell's equations. A particularly clever representation of this problem reduced the calculation to a problem that is routinely solved by existing stellarator optimization codes, so the mathematical problem turned out to be relatively easy. Previously unimagined stellarator designs are now possible. By simplifying the geometry of the electromagnets, the new designs allow easier access to the plasma for heating and diagnostics, for example.

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Publications

P. Helander *et al.*, "Stellarators with Permanent Magnets", *Physical Review Letters* **114,** 095001 (2020). [DOI: 10.1103/PhysRevLett.124.095001]