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Power Move: Cracking a 40-year-old Plasma Confinement Puzzle

Physicists can now accurately calculate the power required for a tokamak fusion reactor to achieve high-confinement mode.

CHICAGO—Fusion, the reaction that powers the sun and every other star in the universe, offers the prospect of virtually limitless clean energy. To recreate it on Earth, however, a gas must be superheated to more than 100 million degrees, about ten times hotter than the center of the sun. At that temperature its atoms break apart into charged particles, forming a plasma. For fusion reactions to take place, the plasma must then be trapped inside a magnetic cage, like the doughnut-shaped tokamak fusion device. This is immensely difficult, and the plasma's edge makes it harder still: it is constantly churning with turbulent eddies, swirls like those in boiling water, which carry particles and heat out of the machine too quickly for fusion to happen (see Figure 1).

In 1982, however, scientists in Germany discovered [1] that above a critical heating power, the turbulent eddies at the plasma edge suddenly die down, and the reactor's ability to retain heat, known as *confinement*, approximately doubles. This astounding discovery was at first met with disbelief in the fusion community. Since then, it has been reproduced in tokamaks around the world.

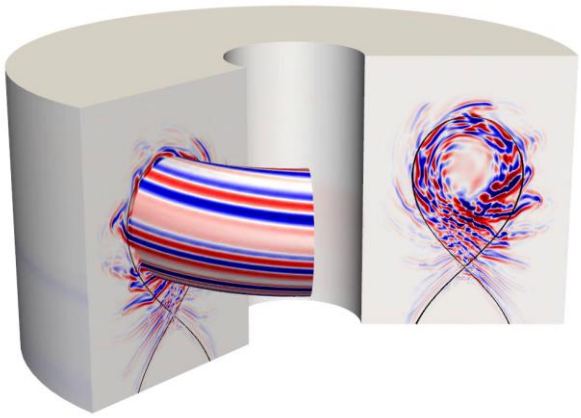


Figure 1: A supercomputer simulation of the turbulent plasma inside a tokamak, shown with part of the doughnut-shaped machine cut away. The two slices show turbulent eddies churning at the plasma's edge and carrying heat out of the machine. This is the leaky state, before the transition. Credit: B. De Lucca, Swiss Plasma Center, EPFL.

This "high-confinement mode" is now the planned way of running several of the multi-billion-dollar projects that aim to finally produce energy from fusion. Yet after more than 40 years of theory and experiments, no one had been able to calculate from the basic equations of physics how much power it takes to reach high-confinement mode. Reactor designers have instead relied on extrapolation from past experiments, an approach that becomes uncertain as machines grow to the size of power plants.

Using supercomputer simulations and pen-and-paper theory, researchers at the Swiss Plasma Center at EPFL, in Lausanne, Switzerland, have found an explanation for this transition: the turbulent eddies end up destroying themselves. As the plasma is heated, its edge reaches a regime that is unstable in a beneficial way: any rise in temperature makes the plasma edge spin faster, with neighboring layers moving at different speeds. This spinning shreds the turbulent eddies apart, letting less heat escape. The temperature climbs further, the spin grows faster still, and the cycle repeats until the edge locks into its high-confinement state. Having found the physical origin of the transition, the team could then calculate how much power is needed to trigger it.

The result is genuine predictive power: the team's formulas reproduce measurements on experiments worldwide, matching or surpassing in accuracy the experimental extrapolations used for decades. For ITER, under construction in France, they predict a minimum of about 43 megawatts, comfortably within its 73-megawatt heating budget. For SPARC, which plans to begin plasma operations in Massachusetts next year, the team predicts about 26 megawatts, very close to the 25 megawatts assumed in the machine's design.

These results are new and have been submitted for publication [2], building on earlier work on plasma-edge turbulence [3–5].

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Abstract

NI01/5 Power threshold of the L-H transition in tokamaks from first principles

Session NI01: Pedestal Physics, ELM Suppression, and Edge Transitions
9:30 AM–12:30 PM, Thursday, November 5, 2026
Room: Hilton Chicago, International North, Second Floor

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