

Scientists Double Fuel Density by Inverting Fusion Plasmas

New approach could provide a path to more powerful fusion power plants.

LONG BEACH, Calif. — Fusion energy has the potential to provide nearly limitless clean power by replicating the same process that powers the sun — fusing light atoms together to release energy. To make this happen on Earth, scientists use powerful magnetic fields to contain super-hot plasma (a state of matter where atoms break apart into charged particles) inside donut-shaped devices called tokamaks.

A major challenge in tokamak research has been a phenomenon known as the "Greenwald limit." This long-standing barrier limits the amount of fusion fuel that can be packed into a plasma. For decades, researchers believed there was a hard limit to how dense a plasma could become before it grows unstable and allows its energy to escape. The formula behind the Greenwald limit has shaped the design of fusion reactors worldwide.

Because plasma density is a factor in determining how much power a fusion reactor can generate, it has major implications for future power plant designs. Higher plasma density means more fusion reactions in the same amount of space, potentially leading to smaller, more economical power plants that could deliver clean energy to more communities at lower cost. For that reason, scientists have looked for ways to surpass the Greenwald limit.

Researchers at the DIII-D National Fusion Facility in San Diego have explored an approach called "negative triangularity" (NT). Unlike typical tokamak plasmas, NT plasmas have an inverted "D"-shaped cross-section that naturally avoids certain large instabilities at the outside edge of the plasma. These instabilities, known as edge-localized modes (ELMs), are a common problem with conventional tokamak shaping. However, NT plasmas are difficult for most tokamaks to create and maintain due to hardware constraints.

The unique design of DIII-D allowed scientists to create and maintain NT plasmas, which inherently avoid producing ELMs that can confuse experiment results in standard approaches. Using NT plasmas at DIII-D, the researchers were able to exceed the Greenwald limit, demonstrating stable operation at up to 1.8 times higher density. In the process, they discovered that the Greenwald limit is not a single barrier as previously thought but rather two separate limitations, one at the plasma edge and one in the core.

At the edge, a cooling effect caused by radiation limits plasma density, which creates a natural ceiling for how dense the outer region can become (Figure 1). In the core, density continues to rise beyond the traditional limit until it reaches a point where turbulent fluctuations change the plasma character. The core plasma evolves from small, random movement to large, avalanche-like bursts of activity that prevent further density increases. The researchers also found that increased plasma heating power affects the edge and core density limits differently, with the edge responding more strongly to additional power than the core.

The DIII-D National Fusion Facility is a U.S.

Department of Energy, Office of Science scientific user facility operated under the Fusion Energy Sciences program. This work was supported under award DE-FC02-04ER54698, DE-SC0019352, DE-SC0019004, DE-FG02-97ER54415, DE-AC52-07NA27344, DE-FG02-08ER54999, DE-SC0016154, and the awards of contributing collaborators.

Contact:

Rongjie Hong, University of California, Los Angeles, hongrongjie@fusion.gat.com

Abstract

[CI03.4](#)

Session

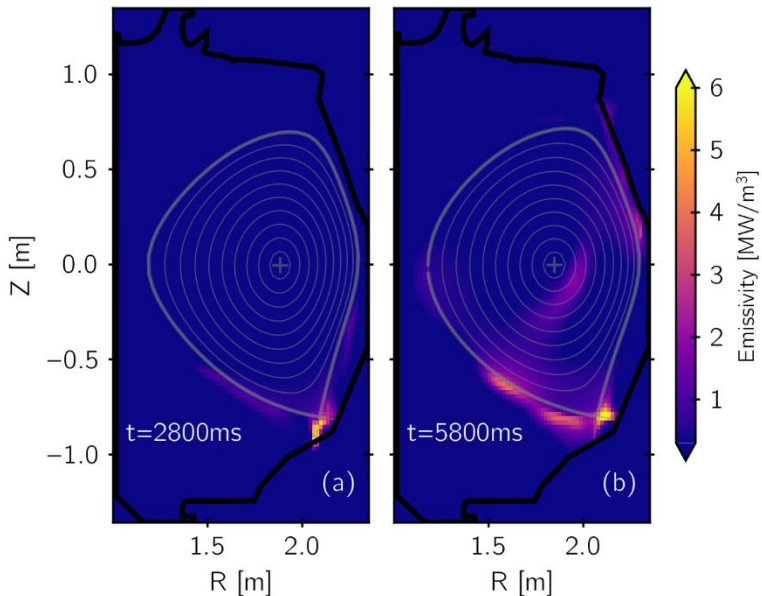


Figure 1: This sequence shows how a cooling effect develops at the edge of the fusion plasma, similar to how mist cools the air on a hot day. The colorful images reveal how radiation (shown in warm colors from yellow to red) moves through the plasma during an experiment, with the tokamak wall indicated by the thick black line. Starting as concentrated radiation at the bottom (a), it grows into an intense zone near the inner curve of the plasma (b). This visual evidence shows why there's a natural limit to how dense the outer region of the plasma can become, which scientists have traditionally seen as a hard barrier to fusion energy. The discovery that this cooling effect only limits the plasma's edge — not its entire structure — allowed researchers to safely operate plasma at nearly twice the density previously thought possible.

[Disentangling Core and Edge Mechanisms of the Density Limit in DIII-D Negative Triangularity Plasmas](#)

[CI03: Invited Session MFE: Weimar Award and Pedestal and Transport](#)

2:00 PM–5:00 PM, Monday, November 17, 2025

Room: Grand Ballroom II