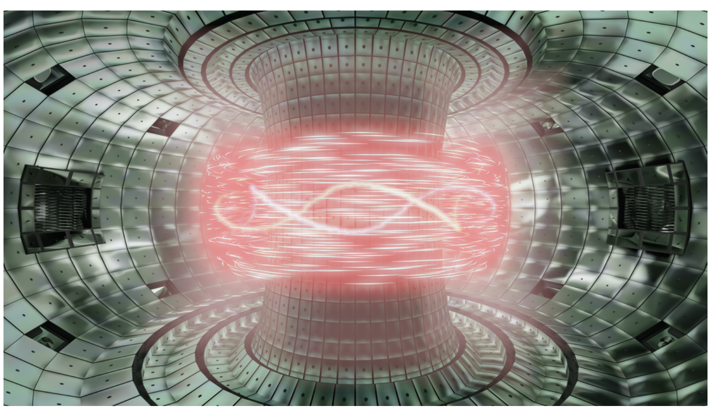
Gauging Edge Instabilities in Future Fusion Reactors

Researchers are unraveling the influence of energetic particles on the stability of plasmas in fusion reactors.

By **Katherine Wright**

A popular format for future fusion devices is the so-called tokamak reactor, a device that confines a burning plasma in a doughnut shape. However, experiments and simulations have shown that the edges of this doughnut can develop waves and destabilize, which has ramifications for the integrity of the tokamak reactor. Such destabilizations are "a serious threat to future fusion devices," says Jesús Dominguez-Palacios from the University of Seville, Spain. Now he and his colleagues have simulated the effect that high-energy particles—which are injected into the plasma in certain fusion schemes—have on edge-localized instabilities [**1**]. The findings have implications for the design of destabilization-mitigating methods in future tokamaks.



Simulations of edge-localized modes interacting with highly energetic particles indicate that the presence of the particles increases the likelihood that the plasma will "crash" into the tokamak's walls and erode the device.
Credit: Peter Hansen/stock.adobe.com

In an ideal tokamak plasma, magnetic fields confine a million-degree plasma to a doughnut-shaped region, preventing it from touching (and thus damaging) the device's walls. However, disturbances, such as so-called edge-localized modes, can develop along the plasma's edge, creating a risk that some of the plasma will "crash" into the tokamak's walls and erode the device's components. This degradation limits the tokamak's ability to operate correctly. Edge-localized modes can also trigger other instabilities that similarly attack the tokamak structure.

Because of these issues, researchers would like to eliminate the appearance of edge-localized modes, but first they need to understand how these modes come about. To that end, Dominguez-Palacios and his colleagues simulated what happens to edge-localized modes when they interact with highly energetic particles. In certain reactor scenarios, such particles are injected into the plasma to help kickstart the nuclear reactions. High-energy particle injection is being studied for the International Thermonuclear Experimental Reactor (ITER) that should come online within the next decade. "In future burning plasmas, we will have a large energetic particle population, so we need to learn how [edge-localized modes] behave in the presence of energetic particles," says team member Manuel Garcia-Muñoz from the University of Seville.

In the team's simulations, a beam of neutral energetic particles is injected into a tokamak plasma, one modeled after the ASDEX Upgrade tokamak in Germany. The neutrality of the particles is important, as it lets them pass through the magnetic fields confining the plasma. Once inside the doughnut the beam particles collide with particles in the plasma, creating high-energy ions that help to heat the plasma to the fusion-burning temperature.

Without accounting for any high-energy ions, the simulations show a stable plasma doughnut. A long-period wave can form on the plasma's outer edge, but the magnitude of the wave is too small for the plasma to touch the tokamak's walls. Factoring in high-energy ions, the simulations indicate that both the frequency of the edge-localized modes and their maximum magnitude increase, making crash events more likely. Crash events start occurring with regularity once the energy of the ions goes above 20,000 eV, about 4 times the average energy of particles in the background plasma. The properties of these crash events, as well as those of the edge-localized modes, match those seen in experiments.

"We see that highly energetic ions can have a significant impact on the properties of edge-localized modes," Dominguez-Palacios says. "That suggests that if we want to develop proper mitigation strategies, we need to factor in controlling these energetic ions." These strategies include updating the confining magnetic fields of the plasma or tinkering with the injection timing or geometry. "The results show that highly energetic particles that are born inside the plasma can move to the edge and significantly impact edge-localized physics," says Chang Liu, a plasma physicist at Princeton Plasma Physics Laboratory, New Jersey, who was not involved in this study.

Liu notes that researchers had previously thought that the inside and outside of the plasma were independent and could be studied separately. The findings of Dominguez-Palacios, Garcia-Muñoz, and their colleagues turn that belief on its head. "We need to do whole device modeling that connects the core and the edge," Liu says. "The population of these highly energetic particles may be small, but here we see they can have a very big effect on the edge modes and how the plasma behaves."

Katherine Wright is the Deputy Editor of ***Physics Magazine***.

REFERENCES

1. J. Dominguez-Palacios *et al.*, "Effect of energetic ions on edge-localized modes in tokamak plasmas," **Nat. Phys. 21, 43 (2025).**