Taking Control of Fusion Reactor Instabilities

A mechanism for preventing destructive instabilities in magnetically confined plasmas provides a new way for scientists to operate future nuclear-fusion reactors.

By **Saskia Mordijck**

All magnetically confined plasmas naturally develop instabilities, regions where small perturbations grow rapidly [**1**]. Scientists have been looking for ways to prevent instabilities in a tokamak—a leading candidate for a fusion reactor—because the instabilities can cause substantial damage to the tokamak's walls. Now Georg Harrer at the Vienna University of Technology and his colleagues have shown how these destructive instabilities can be avoided by adjusting the properties of the plasma and its confining magnetic field [**2**]. The researchers' findings offer a fresh approach to running future fusion reactors.

A tokamak uses a powerful magnetic field to confine fusion fuel in the form of a plasma (a highly ionized gas) that is shaped like a ring donut. Instabilities that originate at the plasma edge (the "glaze" of the donut) are called edge-localized modes (ELMs) [**3**]. ELMs transport heat and particles along magnetic-field lines, moving them from the well-confined plasma core (the "filling" of the donut) to the divertor—a region of the tokamak's walls. ELMs come in various sizes and frequencies (repetition rates). Their size, expressed as a percentage of the energy stored in the plasma core, strongly influences how much heat and how many particles will be deposited by each ELM in the divertor.

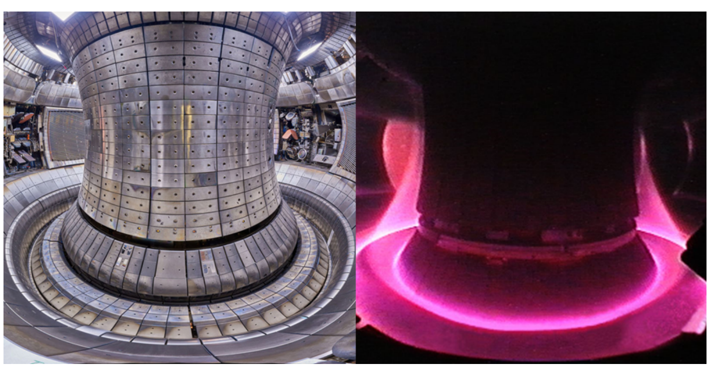

Figure 1: The plasma vessel of the ASDEX Upgrade tokamak (left). View of the donut-shaped plasma (pink) confined in this vessel (right). The plasma's edge is directed onto divertor plates located at the vessel's base.
Credit: Max Planck Institute for Plasma Physics (IPP)

In the largest operating tokamak, the UK-based Joint European Torus, large ELMs have contributed to the melting of the tungsten tiles used in the device's divertor [**4**]. In a fusion reactor, these ELMs could be even more destructive because the plasma core's stored energy—whose magnitude determines the energy deposited per ELM in the divertor—will be hundreds to thousands of times higher than that in current devices. For this reason, researchers are actively working on ways to avoid or mitigate large ELMs in tokamaks [**5**]. Fundamental advances in the understanding of plasma dynamics are required to extrapolate findings from current devices to fusion reactors because reactor-relevant conditions cannot be replicated in present-day setups.

Harrer and colleagues performed experiments on the ASDEX Upgrade tokamak (Fig. **1**), located at the Max Planck Institute for Plasma Physics in Garching, Germany. The researchers investigated how the topology of the confining magnetic field influenced the size and frequency of the resulting ELMs. They measured these ELM properties using a filterscope—an optical device that detects the visible light produced when a plasma interacts with gas in the divertor. Using additional diagnostics, the team compared the observed ELM onset with theoretical predictions.

The researchers show that large ELMs can be avoided by first increasing the plasma density and then tailoring the magnetic topology. The density increase reduces the local plasma current, such that the pressure gradient at the plasma edge is the dominant instability driver. The result is a reduction in the size of the ELMs and an increase in their frequency. These smaller ELMs lack the destructive impact of their larger counterparts. Moreover, predictions indicate that smaller ELMs could remove spent fusion fuel (helium ash) from the plasma core, preventing the core from being contaminated with nonfusible particles.

When the pressure gradient becomes the main instability driver, Harrer and colleagues demonstrate that the instability threshold (the magnitude of the pressure gradient needed to produce ELMs) can then be changed by adjusting the system's magnetic topology. In a tokamak, magnetic-field lines wind helically around the plasma. In doing so, they cross back and forth between a region of "good curvature" and a region of "bad curvature." Good curvature means that the vector representing the curvature of the field lines points in the same direction as the positive pressure gradient, reducing instability. Conversely, bad curvature means that this vector points in the opposite direction to the positive gradient, increasing instability. The researchers find that increased helical winding of the field lines strengthens the impact of the good curvature, raising the instability threshold. Increased magnetic shear (the relative angle between two crossing field lines) at the plasma edge also raises this threshold.

Harrer and colleagues show that at low magnetic shear, large ELMs are constantly present and intermixed with smaller ELMs. By contrast, at the highest shear studied, independent of the contribution of the good curvature, small ELMs are constantly present. The researchers' modeling of the plasma edge confirms that the instability threshold is directly affected by both the magnetic shear and the relative contribution of good and bad curvature. This modeling also verifies that small ELMs are driven by the pressure gradient at the plasma edge.

Expanding understanding of the plasma edge in tokamaks is crucial for designing and operating a fusion reactor. This region represents the interface between the hot fusing core and the plasma-wall interactions. The pressure gradient in this region greatly affects the fusion energy gain, but it cannot be too steep because that would lead to destructive instabilities. Moreover, this region needs to efficiently expel burned fuel while also allowing new fuel to reach the core because it is impossible to fuel the core directly [**6**].

In present-day devices, instabilities can be avoided, and ELMs even eliminated [**7**], by altering the plasma conditions using external actuators—such as heating power, momentum injection, current drive, and special magnetic-field coils. In a fusion reactor, these actuators will be unavailable. Therefore, the development of regimes, such as the one found by Harrer and colleagues, that require no external active actuators is crucial. However, as the researchers caution, no present-day device can fully replicate all the conditions of a reactor. Fortunately, with the current construction of multiple tokamaks designed to operate for the first time using self-heated plasmas (that is, as fusion reactors), we will soon be able to test all these theories as well as discover and explore new frontiers in the study of magnetically confined plasmas.

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