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Apple versus donut: How the shape of a tokamak impacts the limits of the edge of the plasma

May 28 2024, by Rachel Kremen

PPPL Staff Research Physicist Jason Parisi. Credit: Michael Livingston / PPPL Communications Department

Harnessing energy from plasma requires a precise understanding of its behavior during fusion to keep it hot, dense and stable. A new theoretical model about a plasma's edge, which can become unstable and bulge, brings the prospect of commercial fusion power closer to reality.

"The model refines the thinking on stabilizing the edge of the plasma for different tokamak shapes," said Jason Parisi, a staff research physicist at PPPL. Parisi is the lead author of three articles describing the model that were published in the journals *Nuclear Fusion* and *Physics of Plasma*. The primary paper focuses on a part of the plasma called the pedestal, which is located at the edge. The pedestal is prone to instabilities because the plasma's temperature and pressure often drop sharply across this area.

The new model is noteworthy because it is the first to match pedestal behaviors that were seen in the U.S. Department of Energy's (DOE) Princeton Plasma Physics Laboratory (PPPL) National Spherical Torus Experiment (NSTX). While conventional tokamaks are shaped like donuts, NSTX is one of several tokamaks that are shaped more like a cored apple. The difference in tokamak proportions impacts plasma and, as the model indicates, the pedestal.

Ballooning instabilities

Parisi, together with a team of scientists, explored the limits of pedestals and investigated how much pressure could be applied to plasma inside a fusion reactor before instabilities appeared. In particular, they studied disruptions in the pedestal called ballooning instabilities: bulges of plasma that jut out, like the end of a long balloon when squeezed.

"The model is an extension of a model that people have used in the field for maybe 10 years, but we made the ballooning stability calculation a lot more sophisticated," Parisi said.

To develop their model, the scientists looked at the relationship between pedestal measurements—height and width—and ballooning instabilities.

Parisi said the new model fit on the first try. "I was surprised by how well it works. We tried to break the model to ensure it was accurate, but it fits the data really well," he said.

Expanding the EPED model

The existing model, known as EPED, was known to work for donut-shaped tokamaks but not for the spherical variety. "We decided to give it a go, and just by changing one part of EPED, now it works really well," Parisi said. The results also give researchers a clearer picture of the contrast between the two tokamak designs.

"There is certainly a big difference between the stability boundary for the apple shape and the standard-shaped tokamak, and our model can now somewhat explain why that difference exists," he said. The findings could help minimize plasma disruptions.

Tokamaks are designed to intensify the pressure and temperature of plasma, but instabilities can thwart those efforts. If plasma bulges out and touches the walls of the reactor, for example, it can erode the walls over time.

Instabilities can also radiate energy away from the plasma. Knowing how steep a pedestal can be before instabilities occur could help researchers find ways to optimize plasmas for fusion reactions based on the proportions of the tokamak.

While he added that it's not yet clear which shape is more advantageous, the model suggests other experiments that would try to exploit the positive aspects of the apple shape and see how much benefit they could provide.

Fundamentally, the new model enhances our understanding of pedestals and brings scientists closer to achieving the greater goal of designing a fusion reactor that generates more power than it consumes.

Plasma shape and pedestal measurements

Parisi's second paper in the series explores how well the EPED model aligns with the height and width of the pedestal for different plasma shapes.

"Your core fusion pressure, and therefore your power, is so sensitive to how high your pedestal is. And so, if we were to explore different shapes for future fusion devices, we definitely want to make sure that our predictions work," he said.

Parisi started with old data from experimental discharges in NSTX and then modified the plasma's edge shape. He found that changing the shape had a very big effect on the width-to-height ratio of the pedestal. Additionally, Parisi found that some shapes could lead to several possible pedestals—particularly in tokamaks shaped like NSTX and its descendant, which is currently being upgraded, NSTX-U. This would give those running a fusion shot a choice between, for example, a steep or shallow pedestal.

"When people came up with these pedestal models, they were trying to predict the pedestal width and height because it can change the amount of fusion power generated by a lot, and we want to be accurate," Parisi said. "But the way that models are constructed at the moment, they only take into account plasma stability."

Heating, fueling and pedestals

Heating and fueling are other important factors and ones that Parisi's third paper explores. Specifically, Parisi looked at certain pedestals and determined the amount of heating and fueling required to achieve it given a particular plasma shape. A steep pedestal typically requires far more heating than a shallow pedestal, for example.

The paper also considers how a sheared flow, which occurs when adjacent particles move at different flow speeds, can impact the pedestal height and width. Past experiments in NSTX found that when part of the interior of the vessel was coated in lithium and the flow shear was strong, the pedestal became three to four times wider than when no lithium was added.

"It seems to be able to allow the pedestal to continue to grow," said Parisi. "If you could have a plasma in a tokamak that was all pedestal, and if the gradients were really steep, you would get a really high core pressure and a really high fusion power."

Understanding the variables involved in getting to a stable, high-power plasma brings researchers closer to their ultimate goal of commercializing fusion power.

"These three papers are really important for understanding the physics of spherical tokamaks and how the plasma pressure organizes into this structure where it increases sharply at the edge and maintains high pressure in the core. If we don't understand that process, we can't confidently project to future devices, and this work goes a long way toward achieving that confidence," said deputy director of research for NSTX-U and co-author of the papers Jack Berkery.

More information: J.F. Parisi et al, Kinetic-ballooning-limited pedestals in spherical tokamak plasmas, *Nuclear Fusion* (2024). DOI:

[10.1088/1741-4326/ad39fb](10.1088/1741-4326/ad39fb)

J. F. Parisi et al, Kinetic-ballooning-bifurcation in tokamak pedestals across shaping and aspect-ratio, *Physics of Plasmas* (2024). DOI: 10.1063/5.0190818

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Provided by Princeton Plasma Physics Laboratory

Citation: Apple versus donut: How the shape of a tokamak impacts the limits of the edge of the plasma (2024, May 28) retrieved 18 June 2024 from https://phys.org/news/2024-05-apple-donut-tokamak-impacts-limits.html