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# Milestone achieved in predicting turbulence in fusion plasmas

**In a comprehensive experimental study, an international team of researchers has confirmed the calculations of a leading turbulence simulation code to an unprecedented degree. This marks a major breakthrough in understanding turbulent transport processes in nuclear fusion devices. The study has now been published in the scientific journal Nature Communications and lays a crucial foundation for predicting the performance of fusion power plants.**

Future fusion power plants aim to generate usable energy efficiently by fusing light atomic nuclei. The most advanced approach—magnetic confinement fusion—confines a plasma, a gas heated to millions of degrees Celsius, within a magnetic field. This plasma is suspended without wall contact inside a donut-shaped vacuum chamber. The energy released from the nuclear fusion reaction is intended not only for electricity generation but also for maintaining the plasma temperature. To sustain the process, the plasma must retain as much energy as possible—what researchers refer to as achieving a high energy confinement time.

Strong Turbulence Negatively Affects Plasma Properties

To achieve this goal, physicists must first understand the extremely complex turbulent processes in plasmas and, ideally, find ways to regulate them. To some extent, turbulence is actually beneficial, as it helps transport the helium nuclei—byproducts of the fusion reaction—out of the plasma while bringing fresh fuel into the core. However, excessive turbulence reduces the energy confinement time because the energy escapes from the plasma centre too quickly.

“You can compare this to a drop of milk in a cup of coffee: if you stir with a spoon, turbulent eddies form, and the liquids mix much faster than without stirring,” explains physicist Dr. Klara Höfler, who studied this phenomenon at the Max Planck Institute for Plasma Physics (IPP) in Garching near Munich.

Together with colleagues from IPP and five other research institutions in Europe and the United States, she has made a significant breakthrough in understanding turbulence in fusion plasmas. For the first time, the team achieved a comprehensive agreement between experimental results and computer simulations. The researchers simultaneously compared seven key plasma turbulence parameters—significantly more than in previous studies.

For the new study, now published in the scientific journal Nature Communications, Klara Höfler utilized the world’s unique diagnostic equipment at the IPP fusion device ASDEX Upgrade. This allowed her to precisely measure the properties of the multi-million-degree plasma during two discharges with different settings.

Microwaves Provide a Detailed Image of the Plasma

If you want to determine the temperature of a lake, you simply place a thermometer in the water. In fusion research, plasma temperature is typically measured using microwaves emitted by the plasma itself. From these emissions, fluctuations in the electron temperature can also be derived. Additionally, by launching microwaves into the plasma, researchers can analyse the backscattered radiation to extract information about fluctuations in the electron density—that is, the number of electrons per unit volume. Using this approach, Klara Höfler and her team were able to characterize fluctuations in both plasma temperature and plasma density.

Two diagnostic methods played a central role:
· Doppler reflectometers for measuring fluctuations in the plasma density. Using three reflectometers from ASDEX Upgrade's diagnostic suite, the team analysed vortices of various sizes at different locations.
· A Correlation-Electron-Cyclotron-Emission (CECE) radiometer from the Massachusetts Institute of Technology (MIT) in the USA for very precise measurements of electron temperature fluctuations.
The comparative plasma simulations in five-dimensional phase space were conducted using the GENE code, developed at IPP and globally recognized as a leading tool for numerically modelling turbulent processes inside plasmas. The complexity of these phenomena is so immense that the supercomputers used for this study required a total of two months of computing time to model the observed turbulence over just a few milliseconds.

Close collaboration between experimental and theoretical physicists was important here. It is not enough for GENE calculations to reproduce the turbulence correctly. They also have to simulate the elaborate measurement process, which the researchers have now achieved after years of work. Only in this way can comparability between experiment and numerical calculation be established at all.

GENE Also Reproduces Unexpected Experimental Results

"When I received the simulation results, I was genuinely surprised by how well they matched all the experimental data," recalls Klara Höfler. Even phenomena that were not intuitively expected were accurately predicted by GENE. One example: The research team set different temperature profiles for the two plasma discharges studied at ASDEX Upgrade. In Discharge 1, steeper temperature gradients were applied compared to Discharge 2. As expected, Discharge 1 exhibited larger temperature fluctuations than Discharge 2. However, completely unexpectedly, the density fluctuations behaved in the opposite way—a result that initially seemed inexplicable. Yet, the GENE simulations reproduced this behaviour precisely.
"We have proven that GENE reliably predicts the real behaviour of the two plasma discharges," Klara Höfler summarises. For fusion research, this means that simulations can be used to optimize plasma scenarios to achieve the highest possible energy confinement time. The concept of a digital twin of a fusion device is now more tangible, allowing for improved predictions of reactor plasma performance.

Original publication:

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This core team from IPP in Garching compared plasma measurement data from two discharges at ASDEX Upgrade with the results of GENE simulations: Dr Tim Happel, Dr Tobias Görler, Prof. Dr Frank Jenko, Dr Klara Höfler, Prof. Dr Ulrich Stroth (from left to
Frank Fleschner
MPI for Plasma Physics


Dr. Pedro Molina from EPFL in Lausanne (left) was responsible for integrating the Correlation Electron Cyclotron Emission Radiometer (CECE) from MIT into the measurements. Dr. Carsten Lechte from the University of Stuttgart (right) carried out importan
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