Model predicts scenarios for power generation using nuclear fusion

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Nuclear fusion for the controlled and regular generation of electric power by converting hydrogen into helium and reproducing on a small scale what happens within stars is one of the foremost technological promises for coming decades. So far, only limited results have been achieved in laboratory experiments. Now, a prototype reactor called ITER is under construction in southern France. Its design capacity is for 500 megawatts, and the plan is to go live in 2025. The members of the ITER consortium are China, the European Union, India, Japan, Russia, South Korea and the United States. The cost of the megaproject is expected to surpass €20 billion.

ITER will not capture the energy it produces as electricity, but it will be the first tokamak to produce net energy, i.e., more power than the amount of thermal energy injected to heat the plasma. It will enable scientists to learn more about handling the multiple technical complexities of nuclear fusion, paving the way for machines that use it to supply electricity to the grid. The term tokamak comes from the Russian acronym for a toroidal chamber with magnetic coils.

It will be crucial to ensure that the nuclear fusion process can become self-sustaining and to prevent losses of energy via electromagnetic radiation and alpha particles,as these losses would allow the reactor to cool. Experimental results observed during the past 20 years have shown that the way in which fast ions (including alpha particles) are ejected from the plasma varies greatly from one tokamak to another. Until recently, no one understood which experimental conditions determined this behavior.

The problem has now been elucidated by Vinícius Njaim Duarte, a young Brazilian researcher. Duarte is currently engaged in postdoctoral research at the Princeton Plasma Physics Laboratory (PPPL) in the US. He is the lead author of the article, titled "Theory and observation of the onset of nonlinear structures due to eigenmode destabilization by fast ions in tokamaks," published in the *Journal Physics of Plasmas*.

Duarte's research drew so much attention that researchers at the largest U.S. tokamak, DIII-D, conducted experiments to test the model he proposed. The results confirmed the model's predictions.

Physicist Ricardo Magnus Osório Galvão said, "Electromagnetic waves excited by fast particles in tokamaks can display sudden variations in frequency, known as chirping. No one understood why this happened on some machines and not in others. Using complex numerical modeling and experimental data, Duarte showed that whether chirping occurs or not—and hence the nature of particle and energy losses—depends on the level of turbulence in the plasma confined in the tokamak. Nuclear fusion reactions take place in this plasma. Chirping occurs if it isn't highly turbulent. With severe turbulence, there's no chirping."

Nuclear fusion is distinct from nuclear fission, the process used in the world's existing nuclear power plants. In fission, the atomic nuclei of heavy elements such as uranium 235 split into nuclei of lighter elements—krypton and barium, in this case. This fission releases energy, electromagnetic radiation, and neutrons that in turn split in a chain reaction that keeps the process going.

In nuclear fusion, the atomic nuclei of lighter elements such as the hydrogen isotopes deuterium (one proton and one neutron) and tritium (one proton and two neutrons) fuse to form nuclei of heavier elements—in this case, helium (two protons and two neutrons)—and release energy.

"For nuclear fusion to be possible, it's necessary to overcome the electrostatic repulsion between positive ions," Galvão explained. "This only happens if the plasma formed by the nuclei of the light elements is heated to extremely high temperatures, on the order of tens to hundreds of millions of degrees Celsius."

At ITER, for example, 840 cubic meters of plasma are heated to 150 million degrees Celsius, over ten times the temperature of the sun's core. "At that kind of temperature, you reach energy break-even. The energy released by the fusion reactions is sufficient to equal the energy required to heat the plasma," Galvão said.

The process takes place in the toroidal chamber inside the tokamak. A torus is shaped like a doughnut. The solid contained by the surface is known as a toroid.

The nuclear fusion process develops as follows: A vacuum is produced in the chamber, which is then filled with gas. An electric discharge ionizes the gas, which is heated by high-frequency radio waves. An electrical field induced in the toroidal chamber subjects the gas to an extremely intense current (approximately 1 million amperes, in the case of DIII-D), which heats the gas even further via the Joule effect. Still more energy is injected by electromagnetic waves until the temperature required to trigger nuclear fusion is reached. Even a small tokamak, such as the one installed at the University of São Paulo, reaches temperatures on the order of 100 million degrees.

"At these extremely high temperatures, the ions vibrate so strongly that they collide and overcome electrostatic repulsion," Galvão said. "A powerful magnetic field confines the plasma flow and keeps it away from the vessel's walls. The highly energized alpha particles [helium nuclei] collide with other particles in the plasma, keeping it hot and sustaining the fusion reaction."

An analogy suggested by Galvão would be a bonfire made with damp wood, which will not catch fire easily at first but which flares up eventually after a certain temperature is reached, and the steadily more stable combustion produces enough energy to overcome the humidity. Plasma reaches the ignition point when alpha particles begin consistently feeding back into the process.

Among fusion's many advantages over fission is the fact that fusion involves a self-control mechanism: Once the ignition point is reached, if this temperature level is significantly exceeded—in other words, if the plasma overheats—the reaction automatically slows down. Thus, reactor meltdown, one of the most dangerous complications of accidents in power plants that use nuclear fission, could not happen in a nuclear fusion plant.

The problem is that resonant interaction between alpha particles and waves present in the plasma can excite electromagnetic oscillations, or even lead to the ejection of alpha particles. This can cause energy loss, plasma cooling and possible interruption of nuclear fusion. Understanding the causes of this problem and the factors that can prevent it is fundamental to ensuring the sustainability of the process and the use of nuclear fusion as a viable source of electricity.

"What Duarte found is that this outcome happens in a self-organized manner, with the production of chirping, if the plasma is not very turbulent. If turbulence is high, however, it doesn't," Galvão said [see below for an interview with Vinícius Njaim Duarte].

The crux of the problem is that in a highly turbulent fluid, there is no preferential direction, Galvão explained, offering another analogy to help illustrate his meaning.

"When you heat water slowly, you create a convection cell in the container. Hot water rises, and cold water sinks. This continues until all the water reaches boiling point," he said. "The medium then becomes turbulent, the convection cell is destroyed, and the energy spreads indiscriminately in all directions. This also happens in magnetically confined plasma. Its occurrence prevents the creation of a self-organized system that sustains an undesirable associated electromagnetic wave. There isn't enough coherence for waves to be generated. So the loss of energy that would end the fusion process doesn't occur.

"Duarte had already published a paper on this model during his Ph.D. research, but no one had performed an experiment to control the level of turbulence and see if the model applied or not. This has now been conducted by General Atomics at DIII-D, specifically in order to test the model, which was proven by the result."

Experimental physicists already knew empirically how to induce higher or lower turbulence, but they did not know this would affect the spectral nature of waves associated with the particle structure. Duarte's contribution consists of identifying the key control mechanism and explaining why. In terms of technological applications, this establishes optimal turbulence—enough to prevent self-organized particle and energy loss, but not enough to have other undesirable effects on overall plasma confinement.

Until now, tokamaks have been used on the laboratory scale. ITER will be the first prototype of a tokamak capable of generating electricity efficiently by nuclear fusion. The use of controlled nuclear fusion is not uncontroversial, but according to its advocates, it is safe, can produce a practically unlimited amount of power, and does not create radioactive waste, as do fission reactors.

More information: V. N. Duarte et al, Theory and observation of the onset of nonlinear structures due to eigenmode destabilization by fast ions in tokamaks, *Physics of Plasmas* (2017). DOI: 10.1063/1.5007811

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