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Higher Plasma Densities, More Efficient Tokamaks

The efficiency of magnetic confinement fusion devices known as tokamaks is limited by the maximum operational density. A new model shows how this limit may be overcome.

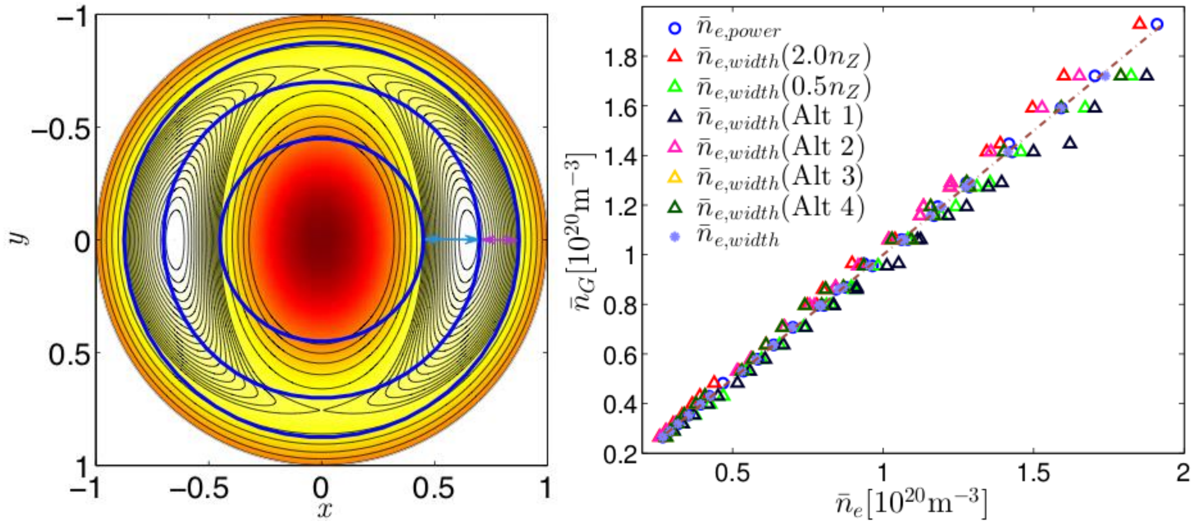

Image courtesy of Qian Teng, Princeton Plasma Physics Laboratory.
The left figure shows a large, *asymmetric* magnetic island, which bulges on the inside (i.e., the blue arrow is longer than the red), that can lead to a disruption and end a plasma discharge. The right figure shows the empirical scaling law of the density limit derived from experimental observations compared to the theoretical prediction, where the different symbols indicate different parameter assumptions (e.g., different impurity concentrations). For all parameters, the predicted density limit agrees almost perfectly with the experimental scaling, i.e. $\overline{n}_e \approx \overline{n}_G$.

The Science

When the density of the hot, ionized gas (known as a plasma) inside the tokamak class of fusion experiments exceeds a certain limit, the plasma discharge becomes unstable. This usually leads to rapid loss of both the thermal (heat) energy and the plasma currents, the latter of which are required to complete the “magnetic bottle” that confines the plasma. Such events are called disruptions. Disruptions lead to an abrupt termination of the plasma discharge and can cause serious damage to the inner wall of the experiment.

Before the final disruption, large magnetic islands, or tearing modes, are often observed. This gives an important insight into the formation of disruptions, and a possible control mechanism. Magnetic islands, shown in the figure above (left), are thermally isolated, small “bubbles” of plasma created by magnetic reconnection.

Recent investigations have confirmed that the thermo-resistive tearing-mode model correctly predicts the density limit. The magnetic island will grow when the “cooling” power flowing out of the island exceeds the “heating” power flowing in. The heating comes from the small-but-significant electrical resistance to plasma currents. The cooling comes from radiation emitted by impurities in the magnetic island.

When the plasma density is increased, the plasma currents shrink, and so the heating is reduced. The impurity radiation, on the other hand, is proportional to the square of plasma density; and so as the density doubles the cooling quadruples. The net effect is that the island grows in size. When the island becomes large enough, the hot plasma core mixes with the cool plasma, and this causes the disruption.

The Impact

The density limit in tokamaks has been an experimental obstacle for decades. It's crucial to understand the density limit, because the fusion power produced by tokamaks is proportional to the square of plasma density; so the higher the plasma density the more power. This work correctly explains the density limit, and this has led to suggestions that that the density limit can be exceeded by carefully heating the magnetic island using external heating sources, or by reducing the impurity density.

Summary

In this work, the classical expression for the growth of the size of the magnetic island is extended to include the effect of island asymmetry (shown in above figure) and the effect of thermal perturbations inside the island. These corrections are crucial for understanding the dynamics of magnetic island growth and therefore disruptions.

Not only does the island change in time, so does the background plasma equilibrium. This effect must be taken into account to get an accurate, self-consistent solution. An internal inductance model is used to calculate the equilibrium evolution with increasing plasma density, and the impurity radiation is calculated with corona equilibrium cooling rates.

The increased density limit predicted by the new model agrees almost perfectly, as shown in above figure (right), with the scaling laws derived from an experimental database of disruptions for the world's most important tokamaks.

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Publications

Q. Teng, D. P. Brennan, L. Delgado-Aparicio, D. A. Gates, J. Swerdlow, and R. B. White, "A predictive model for the tokamak density limit", *Nuclear Fusion* **56**, 106001 (2016), [DOI: 10.1088/0029-5515/56/10/106001]

D. A. Gates and L. Delgado-Aparicio, "Origin of tokamak density limit scalings", *Physical Review Letters* **108**, 165004 (2012), [DOI: 10.1103/PhysRevLett.108.165004]

R. B. White, D. A. Gates, and D. P. Brennan, "Thermal island destabilization and the Greenwald limit", *Physics of Plasmas* **22**, 022514 (2015), [DOI: 10.1063/1.4913433]

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