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Until 7 a.m. MST, Monday, October 30, 2023

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The Contrarian: Counterintuitive methods improve fusion plasma performance

Kyle Callahan, Ph.D. student at UCLA, lead a project that showed the possibility of reducing heat losses and improving performance of fusion plasmas by injecting non-hydrogen elements like carbon or neon.

DENVER—Achieving a stable high-temperature plasma, the fuel for fusion reactions, is essential for efficient fusion energy production in devices that use powerful magnetic fields to contain the fuel, such as a tokamak. The plasma fuel in a tokamak needs to be heated until it reaches a specific operating mode, known as "high confinement mode" (H-mode), which is characterized by few energized plasma particles escaping the volume (high confinement) and few instabilities in the plasma (low turbulence). This approach was explored in recent work at the DIII-D National Fusion Facility led by Kyle Callahan, a Ph.D. student in the University of California, Los Angeles Physics program. H-mode will be an important part of initial operations of the international ITER experiment, what will be the world's largest fusion tokamak, currently under construction in France. H-mode will also be important in achieving efficient steady-state operations in fusion pilot plants, which is necessary for achieving commercially viable fusion energy production.

The ability to reach H-mode is often limited by power loss caused by turbulent conditions in the plasma. Different fuel isotopes, forms of a single element with different numbers of neutrons in the nucleus and therefore different masses, produce different levels of turbulence. As the atomic mass of the fuel ions becomes lighter, turbulence-induced power loss increases. This so-called "isotope effect" leads to more ions escaping the plasma and an inability to reach the power threshold needed to access H-mode. To date, the science underlying this isotope effect and solutions to address it have been elusive. Now, experiments led by Callahan at DIII-D have begun to answer these questions, showing that carbon impurities in plasma generated from a heavy isotope reduced power loss caused by turbulence and, thus, improved the ability to access H-mode (Figure 1).

To explore the physics driving the isotope effect, researchers at DIII-D studied heat loss and H-mode in plasmas generated from hydrogen (the lightest hydrogen isotope with a single proton in the nucleus) and deuterium (a heavier isotope with a proton and a neutron) under ITER-relevant conditions. In the experiments, deuterium plasmas were more stable, showing less turbulence and lower power loss, than hydrogen plasmas. These mass-based differences have important implications for fusion pilot plant efficiency, as these plants will use a mixture of deuterium and tritium (an even heavier hydrogen isotope with 1 proton and 2 neutrons) and therefore may benefit even more from reduced turbulence.

After examining numerous parameters, the researchers determined that the difference in power loss between the two isotopes could be attributed to differences in the plasma concentration of carbon atoms. These carbon atoms entered the plasma through erosion of the graphite tiles lining the interior of the tokamak (Figure 2).

The varying turbulence observed in the two types of plasma was modeled with two established physics codes, TGLF and CGYRO. The simulations showed that power loss was dependent on the carbon concentration. Notably, higher carbon concentrations weakened plasma instabilities that cause power loss.

Recognizing that lower concentrations of carbon are associated with needing more power to achieve H-mode, the researchers performed further experiments using a system in DIII-D known as the Impurity Powder Dropper (IPD) to increase the carbon concentration. With this dropper, they increased the carbon concentration in deuterium plasma above that caused by erosion from the tiles and confirmed that carbon addition can reduce the input power needed to access H-mode. Further studies to confirm this stabilizing effect in hydrogen plasma and evaluate the stabilizing potential of other impurities relevant to ITER and fusion pilot plants, such as neon, are ongoing.

These data and computer models provide key tools to improve plasma heating efficiency and H-mode access, which will help maximize efficiency for future fusion reactors. Furthermore, the IPD and similar systems could be important in the design of economically attractive fusion power plants, as impurity addition also distributes the heat load more evenly and thereby lessens stress on the device. Thus, the insights provided by this study offer proof-of-concept evidence and guidance for understanding and controlling real world isotope behavior to optimize tokamak-based fusion energy production.

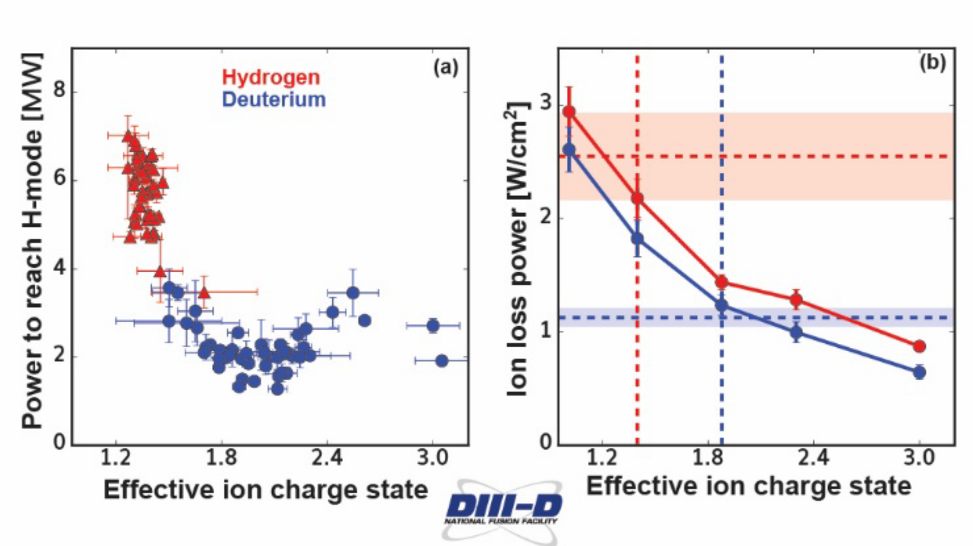

Figure 1. (a) Power needed to access high confinement mode (H-mode) in DIII-D plasmas based on the plasma composition, comparing hydrogen (light isotope, red) and deuterium (heavier isotope, blue). Due to the heavier mass, deuterium plasmas cause more carbon to be ejected from the vessel walls, and increasing carbon content tends to lower the power needed to access H-mode. (b) Calculation of how carbon content (effective ion charge state) affects turbulence in hydrogen (red) or deuterium (blue) plasma. Increasing the carbon content reduces turbulent ion power loss in both types of plasma. Physics code: CGYRO. Dashed lines: experimental values (vertical: Z_{eff}, horizontal: power loss).

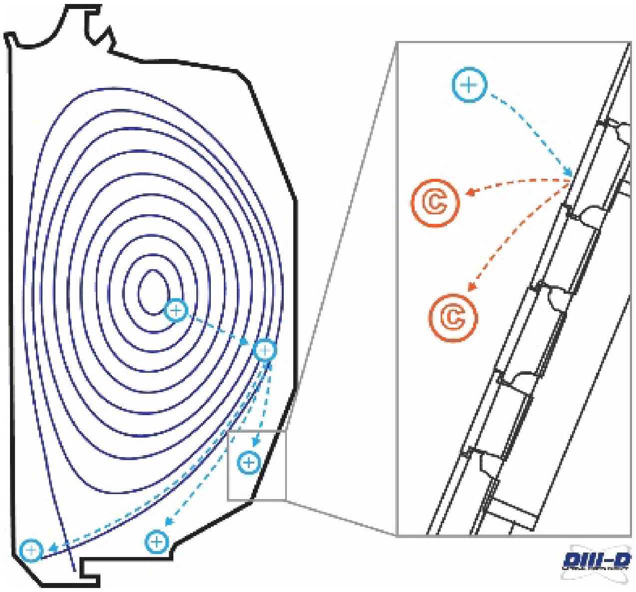

Figure 2. DIII-D vessel cross-section showing the plasma contained by the magnetic field (dark blue). The ions in the plasma (light blue circles) can experience turbulence that causes them to escape the core. When this happens, these high-energy particles can strike the vessel wall (inset), which is lined with graphite tiles. This collision causes carbon atoms to be ejected from the tiles, a process known as "sputtering." Then, these carbon atoms can enter the plasma as impurities, where they affect plasma behavior.

Contact

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Abstract

PI01.00006	Understanding the L-H transition isotope effect in DIII-D
Session	PI01: MFE: H-mode, Pedestal, and Fueling 2:00 PM–5:00 PM, Wednesday, November 1, 2023 Room: Plaza F