Pushing the plasma density limit

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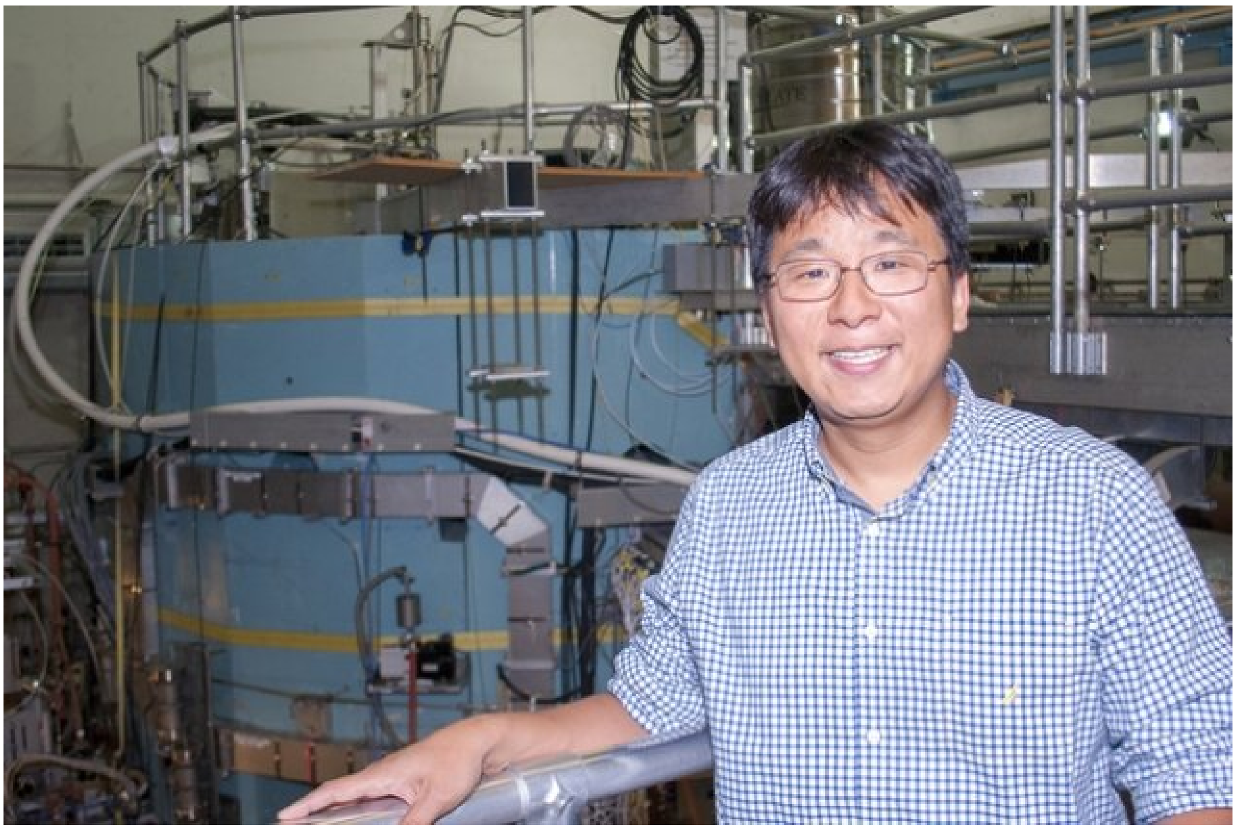

Seung Gyou Baek and his colleagues performed experiments on the Alcator C-Mod tokamak to demonstrate how microwaves can be used to overcome barriers to steady-state fusion reactor operation. Credit: Paul Rivenberg/PSFC

For decades, researchers have been exploring ways to replicate on Earth the physical process of fusion that occurs naturally in the sun and other stars. Confined by its own strong gravitational field, the sun's burning plasma is a sphere of fusing particles, producing the heat and light that makes life possible on earth. But the path to a creating a commercially viable fusion reactor, which would provide the world with a virtually endless source of clean energy, is filled with challenges.

Researchers have focused on the tokamak, a device that heats and confines turbulent plasma fuel in a donut-shaped chamber long enough to create fusion. Because plasma responds to magnetic fields, the torus is wrapped in magnets, which guide the fusing plasma particles around the toroidal chamber and away from the walls. Tokamaks have been able to sustain these reactions only in short pulses. To be a practical source of energy, they will need to operate in a steady state, around the clock.

Researchers at MIT's Plasma Science and Fusion Center (PSFC) have now demonstrated how microwaves can be used to overcome barriers to steady-state tokamak operation. In experiments performed on MIT's Alcator C-Mod tokamak before it ended operation in September 2016, research scientist Seung Gyou Baek and his colleagues studied a method of driving current to heat the plasma called Lower Hybrid Current Drive (LHCD). The technique generates plasma current by launching microwaves into the tokamak, pushing the electrons in one direction—a prerequisite for steady-state operation.

Furthermore, the strength of the Alcator magnets has allowed researchers to investigate LHCD at a plasma density high enough to be relevant for a fusion reactor. The encouraging results of their experiments have been published in *Physical Review Letters*.

Pioneering LHCD

"The conventional way of running a tokamak uses a central solenoid to drive the current inductively," Baek says, referring to the magnetic coil that fills the center of the torus. "But that inherently restricts the duration of the tokamak pulse, which in turn limits the ability to scale the tokamak into a steady-state power reactor."

Baek and his colleagues believe LHCD is the solution to this problem.

MIT scientists have pioneered LHCD since the 1970s, using a series of "Alcator" tokamaks known for their compact size and high magnetic fields. On Alcator C-Mod, LHCD was found to be efficient for driving currents at low density, demonstrating plasma current could be sustained non-inductively. However, researchers discovered that as they raised the density in these experiments to the higher levels necessary for steady-state operation, the effectiveness of LHCD to generate plasma current disappeared.

This fall-off in effectiveness as density increased was first studied on Alcator C-Mod by research scientist Gregory Wallace.

"He measured the fall-off to be much faster than expected, which was not predicted by theory," Baek explains. "The last decade people have been trying to understand this, because unless this problem is solved you can't really use this in a reactor."

Researchers needed to find a way to boost effectiveness and overcome the LHCD density limit. Finding the answer would require a close examination of how lower hybrid (LH) waves respond to the tokamak environment.

Driving the current

Lower hybrid waves drive plasma current by transferring their momentum and energy to electrons in the plasma.

Head of the PSFC's Physics Theory and Computation Division, senior research scientist Paul Bonoli compares the process to surfing.

"You are on a surf board and you have a wave come by. If you just sit there the wave will kind of go by you," Bonoli says. "But if you start paddling, and you get near the same speed as the wave, the wave picks you up and starts transferring energy to the surf board. Well, if you inject radio waves, like LH waves, that are moving at velocities near the speed of the particles in the plasma, the waves start to give up their energy to these particles."

Temperatures in today's tokamaks—including C-Mod—are not high enough to provide good matching conditions for the wave to transfer all its momentum to the plasma particles on the first pass from the antenna, which launches the waves to the core plasma. Consequently, researchers noticed, the injected microwave travels through the core of the plasma and beyond, eventually interacting multiple times with the edge, where its power dissipates, particularly when the density is high.

Exploring the scrape-off layer

Baek describes this edge as a boundary area outside the main core of the plasma where, in order to control the plasma, researchers can drain—or "scrape-off"—heat, particles, and impurities through a divertor. This edge has turbulence, which, at higher densities, interacts with the injected microwaves, scattering them, and dissipating their energy.

"The scrape-off layer is a very thin region. In the past RF scientists didn't really pay attention to it," Baek says. "Our experiments have shown in the last several years that interaction there can be really important in understanding the problem, and by controlling it properly you can overcome the density limit problem."

Baek credits extensive simulations by Wallace and PSFC research scientist Syun'ichi Shiraiwa for indicating that the scrape-off layer was most likely the location where LH wave power was being lost.

Detailed research on the edge and scrape-off-layer conducted on Alcator C-Mod in the last two decades has documented that raising the total electrical current in the plasma narrows the width of the scrape-off-layer and reduces the level of turbulence there, suggesting that it may reduce or eliminate its deleterious effects on the microwaves.

Motivated by this, PSFC researchers devised an LHCD experiment to push the total current by from 500,000 Amps to 1,400,000 Amps, enabled by C-Mod's high-field tokamak operation. They found that the effectiveness of LCHD to generate plasma current, which had been lost at high density, reappeared. Making the width of the turbulent scrape-off layer very narrow prevents it from dissipating the microwaves, allowing higher densities to be reached beyond the LHCD density limit.

The results from these experiments suggest a path to a steady-state fusion reactor. Baek believes they also provide additional experimental support to proposals by the PSFC to place the LHCD antenna at the high-field (inboard) side of a tokamak, near the central solenoid. Research suggests that placing it in this quiet area, as opposed to the turbulent outer midplane, would minimize destructive wave interactions in the plasma edge, while protecting the antenna and increasing its effectiveness. Principal Research scientist Steven Wukitch is currently pursuing new LHCD research in this area through PSFCs' collaboration with the DIII-D tokamak in San Diego.

Although existing tokamaks with LHCD are not operating at the high densities of C-Mod, Baek feels that the relationship between the current drive and the scrape-off layer could be investigated on any tokamak.

"I hope our recipe for improving LHCD performance will be explored on other machines, and that these results invigorate further research toward steady-state tokamak operation," he says.

More information: S. G. Baek et al. Observation of Efficient Lower Hybrid Current Drive at High Density in Diverted Plasmas on the Alcator C-Mod Tokamak, *Physical Review Letters* (2018). DOI: 10.1103/PhysRevLett.121.055001

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