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Bottling the Sun

BY EVAN DAVIS

A metallic feminine voice rings out through the control room: … *Three. Two. One. Zero. Entering pulse.* Dozens of scientists and engineers hold their breath and fix their eyes on the large computer display at the front of the room. A warm, guttural hum fills the air, the ground softly vibrates, and a flash of light appears on monitors throughout the room.

In fractions of a second, millions of watts of power heat dilute gas to 200 million degrees Fahrenheit, 10 times the temperature of the sun's core. At this temperature, the gas atoms are stripped of their electrons and their positively charged nuclei whiz by at 1 million miles per hour. Some of these nuclei smash into each other with just the right orientation and speed to fuse, forming an altogether different nucleus and releasing an enormous amount of energy.

The pulse ends almost as soon as it began. The gas cools, the glow fades from the monitors, and scientists scramble to analyze the data. *Ten minutes until next shot*, the voice states, reminding the researchers they must work quickly so they're ready to coax every last bit of performance out of their machine in the next experiment.

It's a typical day of operation at the Massachusetts Institute of Technology's Alcator C-Mod reactor, located down a humble side street in urban Cambridge, Mass. C-Mod is a compact nuclear fusion reactor designed to study the scientific and engineering challenges that must be overcome to make this technology a viable energy source.

Fusion is the energy of the sun and stars. Many scientists and engineers, including my MIT colleagues and me, want to bottle the sun for power generation on Earth. When fully developed, fusion will provide continuous power from abundant, virtually inexhaustible fuels, such as deuterium, a hydrogen isotope harvested from seawater. Fusion power plants will not directly produce any greenhouse gases. They also would produce no long-lived nuclear waste, and there is no risk of a meltdown or nuclear materials spreading for use in weapons.

Tokamaks like C-Mod are the leading candidates for successful fusion reactor designs. These doughnut-shaped vacuum vessels use powerful magnetic fields (2 to 3 Tesla, about the strength used in typical magnetic resonance imaging (MRI) medical devices) to suspend a plasma in space, preventing the hot core from touching any material walls. To prevent melting the walls, the plasma temperature must drop from hundreds of millions of degrees in the core to a few thousand at the reactor wall, creating one of the largest thermal gradients in the universe.

Unfortunately, small-scale turbulence allows the plasma to leak through the tokamak's magnetic fields. Indeed, Nobel laureate Richard Feynman once described confining plasma within a tokamak as trying to hold Jell-O with rubber bands: it's possible, but it's taxing and you'll probably lose at least part of the Jell-O. A dozen or so scientists work on C-Mod with the express purpose of understanding and controlling this turbulence.

Researchers at C-Mod and several other tokamaks over the past two decades have identified several desirable operating modes that suppress these detrimental turbulent fluctuations. In particular, we've discovered that the potential fusion gain in tokamaks is strongly controlled by parameters in the last inch or so of the plasma's edge.

My colleagues and I are working to develop and test a first-principles computer model of this edge turbulence so that we can predict and optimize a device's performance before it's even built. Developing such a model requires a strong coupling between experiment, computation, and theory. That means you'll find me scrambling to set-up C-Mod's phase contrast interferometer before the day's experiments begin and fervently analyzing the measured turbulent density fluctuations between shots. In the evenings, I run edge turbulence simulations on the world's most powerful supercomputers, aiming to validate the code by comparing it with my experimental measurements. It's a long, arduous process, but this crucial element of physics must be understood if we're to advance to a viable reactor.

Fusion science has progressed exponentially since its inception, and we now stand poised to make a viable reactor for the first time. An international collaboration is constructing ITER, the first device expected to reach and exceed fusion breakeven – the point at which energy put into the reaction equals the energy it produces.

C-Mod is the only tokamak that operates at the same densities and heat fluxes as those expected in ITER, so it's thrilling to be here – and extremely important that our research continue.

The author is a third-year fellow at the Massachusetts Institute of Technology and this his winning entry in the 2013 SSGF Essay Slam.