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Alcator C-mod bows out with a new world record

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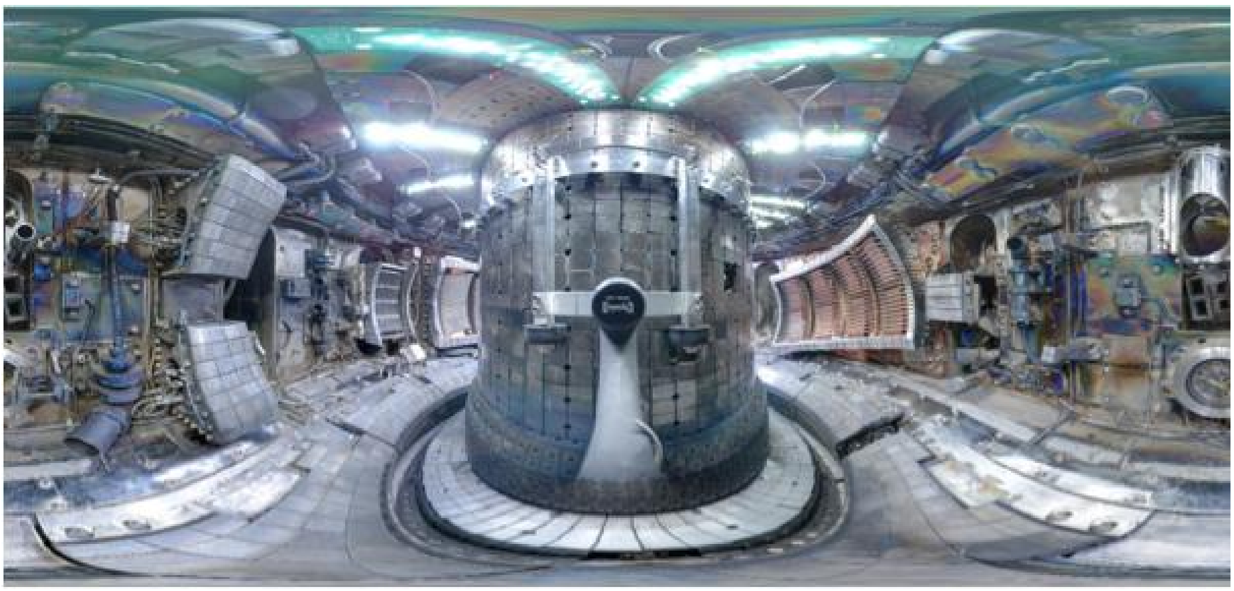

Fish-eye view of the interior of the C-Mod tokamak experiment. Credit: Massachusetts Institute of Technology's Plasma Science & Fusion Center

On its final day of operation, the Alcator C-Mod tokamak at the Massachusetts Institute of Technology's Plasma Science & Fusion Center set a new record for plasma pressure in a magnetic confinement device. These results help validate the high-field approach to fusion energy, which could lead to smaller, cheaper fusion power plants.

Fusion energy requires that the product of three factors—a plasma's particle density, its confinement time, and its temperature (the so-called "triple product")—exceed a certain threshold value. Above this value, the energy released by the fusion process exceeds the energy required to keep the reaction going.

Pressure, which is the product of density and temperature, accounts for about two-thirds of that challenge. Fusion power density increases with the square of the pressure—so doubling the pressure leads to a fourfold increase in energy production. And since the economics of fusion energy will be dominated by the capital costs, high power densities will be essential.

C-Mod is a compact, high-field tokamak, which has produced a wealth of new and important results since it began operation in 1993, contributing data that extends tests of critical physical models into new parameter ranges and into new regimes. The research team includes scientists, engineers, technicians and students from MIT and a large number of national and international collaborating institutions. Its unique and record-breaking capabilities flow directly from the powerful electromagnet at the heart of its design.

During the 23 years Alcator C-Mod has been in operation, it has repeatedly advanced the record for plasma pressure in a magnetic confinement device. The previous value of 1.77 atmospheres, set at C-Mod in 2005, was eclipsed by the new record of 2.05 atmospheres (in other units 2.1 Bar or 0.21 MPa). These latest values were attained by employing over 4 megawatts of radio frequency heating, raising the temperature inside C-Mod to over 35 million degrees Celsius or approximately twice as hot as the center of the sun. The machine was operated with a central magnetic field strength of 5.7 Tesla and 1.4 million amps of electrical current.

In these new experiments, the C-Mod results exceeded the next highest pressure, achieved in other devices, by approximately 70 percent. Unless a new experiment is announced and constructed, the pressure record just set in C-Mod will likely stand for at least the next 15 years. ITER, a tokamak currently under construction in France, will be approximately 800 times larger in plasma volume than C-Mod, but it will operate at a lower magnetic field. ITER is expected to reach 2.6 atmospheres when in full operation by 2032, according to a recent U.S. Department of Energy report.

In 2012, the DOE decided to end funding to C-Mod due to budget pressures from the construction of ITER. Following that decision, the U.S. Congress restored funding to C-Mod for a three-year period, which ended on Sept. 30.

Throughout its life, results from C-Mod have directly supported design decisions and operational planning for ITER. At the same time, they point the way toward a fusion development path that would feature more compact, higher field devices.

As noted above, fusion power density increases with the square of the plasma pressure, which in turn scales as the square of the magnetic field. Thus fusion power density increases as the fourth power of the magnetic field. Energy gain scales with the third power of the field. From these arguments, it is clear that the most cost effective fusion devices would operate with the highest fields that can be reliably engineered. On several previous occasions when the United States was planning to build its own burning plasma devices, for example, the proposed CIT, BPX and FIRE devices, the price to performance argument led to compact high-field designs. Looking forward and considering the substantial costs and extended construction schedule for ITER, which was designed with moderate-field superconducting magnet technology, a development path that features higher field seems attractive.

Until recently, the high-field option was only open for pulsed experiments since conventional niobium based superconductors have critical currents and fields that would limit large volume fusion magnets to about 6 Tesla. However, the industrial maturity of so-called high-temperature superconductors (HTS) based on rare earth compounds like yttrium-barium-copper-oxide (YBCO) is a game changer. A fusion pilot plant concept, called ARC, has been developed at MIT to explore the capabilities enabled by the new superconducting technology. This study showed that a machine the size of the JET tokamak, running with HTS magnets at 9 Tesla and with normalized plasma parameters already achieved in current day experiments, could produce 500 megawatts of fusion power and 200 megawatts of net electricity.

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