

What material is used to confine a 100 million degree fusion “star” on earth?

Fusion energy relies on confining a hot, burning plasma “star” in a magnetic field. The heat from the star replaces burning coal in a conventional steam-turbine electrical power plant. The hot core plasma is confined in a doughnut-shaped magnetic field that isolates most of the plasma from the “room temperature” metal walls of the device. The details of the transitional plasma that connects the hot core (10⁸° C) with the “room temperature” (300° C) material walls is one of the important challenges for a burning plasma experiment. Even if the hot burning core plasma is well confined by the closed magnetic field lines, a small leakage of particles or power from the core can damage the walls of the plasma device.

The plasma bombardment of the vessel walls causes erosion, much like concentrated thundershowers cause soil erosion. The eroded material (e.g. carbon or metals) may be transported to the core plasma where it adversely affects fusion performance by contaminating the (hydrogenic) core fusion fuel. It may also be re-deposited on the vessel walls, and can trap the fusion fuel. These deposited layers can act as a much larger reservoir for the hydrogen fuel than the plasma volume itself. From the standpoint of both safety and economics, minimizing the amount of fuel sequestered in the vessel wall in these deposited layers (and thereby unavailable for fusion reactions) is important. This is accomplished by a combination of careful choice of materials and wall cleaning techniques.

Several nations, including Europe, Japan, China, Korea, Russia, and the US are currently planning the construction of a large next-step burning plasma fusion experiment called ITER. The current design of the ITER experiment uses carbon in the area of the wall where the plasma interactions are concentrated, called the divertor. We have developed a large knowledge base of the plasma interactions with carbon walls. We know that carbon can absorb large amounts of heat, but it also can trap large amounts of the plasma fuel. Metal walls such as tungsten and molybdenum are being studied on machines such as the Alcator C-MOD at MIT, as it is predicted that these materials will have less fuel trapping, but they can melt with localized bursts of heat and contaminate the core plasma.

A recent experiment was completed on the DIII-D experiment to learn about the migration of carbon in the edge plasma and divertor. All of the surfaces in the DIII-D device, a doughnut-shaped tokamak research machine in San Diego, are made of carbon (graphite). These experiments focused on the measurement of the most likely locations of the deposited carbon layers. A special isotope of carbon, with mass 13 instead of the more naturally-abundant mass 12, was injected into the plasma star in the DIII-D tokamak to act as a tracer of the deposited carbon. The ¹³CH₄ methane was injected evenly around the top of the machine and was transported by the plasma.

A whole day of DIII-D pulses were used to build up measureable ¹³C deposits. After the experiment, several sections of the wall were removed and the surfaces were analyzed for ¹³C in a special surface analysis facility at Sandia National Labs, Albuquerque. This surface technique used an ion beam that reacted with the ¹³C on the surface so that we could selectively measure its concentration in the large background of ¹²C. Careful measurements were made from over 1000 locations.

As shown in the figure, we found that most of the carbon was deposited in one location, at the bottom of the tokamak in a region called the divertor. The divertor is where most of the leakage plasma interacts with the vessel wall, as it is a region of open magnetic field lines that connect the edge of the core plasma (closed field lines) with the wall. The carbon, when ionized, can flow either along the magnetic field lines or it is transported perpendicular to these lines by collisions with other ions. In these experiments, the most of the deposited carbon ¹³C was found near the inner “strike” point of the plasma in the divertor. These results are similar to those found earlier on the JET experiment in Culham, England.

The observation of localized deposition of carbon is important because removal and control techniques for the fuel that would be deposited with the carbon depend on whether the carbon surface is hot, cold, faces the plasma, or is hidden in corners. In a burning plasma experiment, if the fuel is sequestered in localized areas of the inner divertor, then specific, effective control techniques can be developed. These first experiments used a core plasma with lower confinement (L-mode) than ITER, and we will repeat them next year with a (H-mode) plasma more representative of ITER conditions. These and other experiments will guide the details of the vessel walls for the ITER experiment, which is planned to start construction next year.

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