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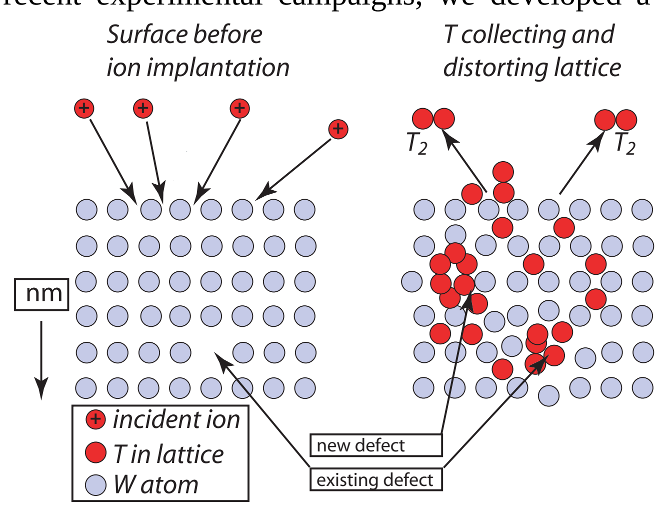
Understanding 'fuel economy' in a fusion reactor

New results from the Alcator C-Mod tokamak raise concerns about retention of tritium fuel in the metal walls of fusion reactors like ITER.

Recent experiments on Alcator C-Mod, the first diverted tokamak with all metal walls, showed that retention of hydrogen isotopes in the surface of those walls was much higher than expected from previous laboratory work. These studies bear on the tritium fuel cycle, a critical issue for ITER or any future fusion reactor, and highlight the need for better understanding of the underlying processes.

The flow of tritium, the radioactive isotope of hydrogen that would provide the fuel for a fusion reactor, must be tightly managed for reasons of economics and safety. Tritium is not a naturally occurring isotope and must be bred via nuclear reactions in "blankets" which would surround the fusing plasma. Only a small fraction of the fuel flowing through the reactor will be burned in each pass; most will impact on heat-bearing surfaces (plasma facing components or 'PFCs'). If any more than one part in 10 million of the impacting fuel ions become stuck in the PFC, then it will be stored faster than it can be bred. For ITER, a pulsed experiment, the requirement for low retention in the walls is eased slightly to about one part in a million.

High-Z refractory metals like tungsten and molybdenum (used for PFCs in C-Mod) are favored for reactors due to their resistance to degradation from interactions with the products of nuclear fusion as well as erosion by the plasma. Furthermore, the plasma characteristics at the plasma-PFC interface more closely approach those of ITER than any other existing experiment. Over recent experimental campaigns, we developed a new, accurate, method of measuring global retention of deuterium (a non-radioactive hydrogen isotope, which stands in for tritium in these experiments) during plasma discharges. Together, these characteristics allow for unprecedented investigations into hydrogen isotope retention.



T ions are implanted into the tungsten (W) lattice and diffuse through it until they are trapped at a defect (typically a missing or diplaced W atom). The pressure of T atoms in the lattice can also be so high that they displace W atoms creating more traps. Such high pressures are enhanced by the slow release of T from the surface as T_2.

Ex-situ, controlled laboratory experiments using deuterium ion beams (D^+) and carefully prepared samples have suggested that retention in tungsten and molybdenum can be very low [R. Causey, J. Nucl. Mat. 300, pg 91, 2002]. The undisturbed atomic lattice of these prepared metal surfaces contain few imperfections which can trap and store hydrogen However, the more realistic and reactor relevant experiments on Alcator suggest that unaccounted-for processes can lead to much higher levels of retention. This work suggests that “traps” are created or expanded in the metal as a direct result of the interaction with plasma.

It has been postulated that the high fluxes of ions implanted very short distances into the material (1 billionth of a meter) lead to local neutral densities approaching that of the lattice. As the tritium collects, the pressure becomes high enough to distort the lattice, creating and enlarging traps and allowing more tritium to be stored. Deuterium (and the other hydrogen isotopes) can only be released from a surface after recombining into molecules, a relatively slow process. For helium, an inert gas, release from a surface is not limited by recombination which suggested a test for the model. C-Mod experiments showed that retention is strongly reduced by the use of helium over deuterium, supporting the model that surface recombination is a rate-limiting process. One proposed solution to the retention problem is to operate the PFCs at an elevated temperature, an idea supported by experiments in Alcator with transiently heated walls. The Alcator C-Mod experiment is planning to test this in a steady-state, reactor-like solution over the next several years by longer pulse experiments with actively heated PFCs.

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