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Carbon as a flow-through, consumable PFC material

Tungsten PFCs may not be compatible with AT operation since AT may involve high plasma temperature at the edge, resulting in high sputtering rates from walls and targets. Concentrations of high-Z impurities in the confined plasma must be kept to very low levels. Much higher concentrations are permissible for the low-Z refractory carbon; however, graphite PFCs may not be compatible with the high neutron fluence of devices like FDF, DEMO and reactors due to swelling damage.

It has been recently reported that tungsten experiences a surface roughening effect due to He bombardment at energies below the threshold for physical sputtering (simultaneous D + T + 5-10% He, as will occur in burning plasmas), creating a surface "fuzz" (nanoscopic morphology) [1,2]. "Such structures are potentially large sources of high-*Z* dust, could harbour significant levels of retained hydrogen isotopes in the plethora of helium nanobubbles/voids within nanostructures and may have a dramatic influence on surface-thermal properties of W plasma facing components." [2]. The effect becomes significant over ~1000K and could be the most serious issue for W in DEMO [3]. A solution to the problem has been proposed [3,4]: coating the W with a low-Z material such as Be, B or C. Coating W with a low-Z material could also solve the problem of unacceptably high concentrations of W in the confined plasma. The low-Z coatings would be consumed and replenished continuously and so neutron damage would not be an issue. In a high duty cycle device plasma erosion also creates the most basic problem of loss of structure, requiring replacement of the substance of the PFC; continuous refurbishment of the plasma-facing surfaces with coatings could also solve this problem.

Reactors will operate with hot walls, ~500C-1000C, for reasons of thermal efficiency. At such high temperatures there is little tritium retention in any materials, including carbon. Low-Z coatings in hot wall devices will result in little tritium retention by the co-deposition process, which is a serious issue for cold (200-300C) wall devices like ITER. In devices with high wall temperatures the tritium problem is less likely to be one of retention than of permeation into the cooling system. Low-Z coatings on a W-substrate may also act as a permeation barrier, although if they reduce the surface recombination rate, that could increase tritium retention and permeation; R&D is required, including into finding the best substrate material.

The continual replenishing of the low-Z coatings will inevitably result in thick deposits accumulating at some locations inside the vessel which, even if they contain little tritium, will cause other problems, including dust formation. It will therefore be as important to be able to remove, *in situ*, the low-Z material as to be able to create, *in situ*, the coating in the first place. Carbon would appear to be unique in this regard since it is possible both to introduce it into the vessel as a gas, e.g. as methane, and to remove it as a gas, as CO and CO_2 using oxygen baking. Since little tritium would be contained in the carbon deposits, there would be little creation of tritiated water, which is problematic to handle and process. For a reactor having P_{heat} = 400 MW, and assuming P_{rad} = 75% P_{heat}, thus $0.25P_{heat} = \gamma k T_t \phi_t$, where γ = sheath heat transmission coefficient = 7; T_t = plasma average temperature in contact with surfaces = 10 eV assumed here; ϕ_t = total D/T-ion flux to all surfaces [ions/s], targets and walls; C physical sputtering due to D/T-ions and self-sputtering, Y_{eff} = 0.005 (Eckstein 2002 yields for maxwellian ions plus a 3kT-sheath); chemical sputtering and RES assumed to be not significant at assumed C surface temperature of 1100 ^{o}C; 80% duty cycle; then *gross* erosion rate = $\phi_t Y_{eff}$ = 23 tons/yr. *Net* erosion is far more difficult to calculate reliably; here, for concreteness, we assume net/gross = 0.1 thus net erosion rate ≡ carbon throughput rate = ~2 tons/yr, perhaps. O_2-baking at >700C is extremely rapid, such that even a graphite substrate, if present, would be removed quickly [5]. At 1100C, T/C <, ~ 0.003 in carbon codeposits, thus T-throughput via codeposition ~ 1.5 kgT/yr.

On the assumption that net erosion of the target is actually significant, then for locations experiencing low plasma fluxes the coatings might last long enough that their refurbishment could be carried out during non-operational periods. For other locations such as the divertor strike point region, however, the coatings might have to be continually refurbished, i.e. during the normal plasma operation. This might be done by puffing hydrocarbon gases or C-pellets + D_2 into the tile gaps in such regions during plasma operation. It is not possible to reliably predict what injection rate would be required to keep the coating in such locations at constant thickness. Experiments are required to provide an empirical basis for projection and, ultimately, much fine-tuning would be involved.

Coatings created during plasma operation will inevitably be non-uniform both toroidally and poloidally.

(a) Toroidal non-uniformity: 'plasma fire-polishing' of the carbon would selectively erode the regions where the carbon was 'proud', filling in the recessed, shadowed regions with deposition, tending to create toroidal uniformity. With carbon, the plasma tends to 'machine' the solid surface to match its own shape (metals behave oppositely). Carbon deposits formed on cold surfaces tend to adhere poorly, flake off, and create dust and UFOs, potentially causing disruptions; however, carbon deposits formed on hot surfaces tend to be graphitic and hard, adhering well [6].

(b) Poloidal non-uniformity: the carbon would gradually be transported poloidally away from the strike point regions, accumulating in deposits which would be removed periodically by O-baking. The carbon circuit would consist of continuous injection of fresh C from an external source, with accumulation of that material at locations away from the strike points; ideally, the carbon layer near the strike points would neither increase nor decrease with time.

For the above example, even simple estimates of net erosion indicate that there would be almost none at the targets. Net erosion will, however, occur at the walls, probably resulting in net deposition occurring throughout the divertor, as observed in DIII-D when both divertor legs are detached. Re-coating of the walls might be possible during maintenance periods, if the net erosion is not too concentrated.

A number of possibilities exist for increasing the plasma-wetted area near the strike points so as to reduce the peak deposited power flux density. Unfortunately the most natural way to do this, i.e. by making the angle of incidence between the field and the surface small, fails for angles less than a degree or two: the inevitable misalignments and other structural non-uniformities result in a plasma-wetted region which is 'spotty', with shadowed regions, such that the actual plasma-wetted area does not increase further with further decrease of the angle of incidence. If, however, carbon is used as the PFC material – whether as a coating on W or some other substrate, or as solid C – then 'plasma fire-polishing' will tend to create toroidal uniformity, making it possible to exploit smaller incidence angles to spread the power load better, reducing the peak power deposition density.

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