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Retention of tritium in carbon co-deposits is a serious concern for ITER. Developing a reliable in-situ removal method of the co-deposited tritium would allow the use of carbon plasma-facing components which have proven reliable in high heat flux conditions and compatible with high performance plasmas. Thermal oxidation is a potential solution, capable of reaching even hidden locations. It is necessary to establish the least severe conditions to achieve adequate tritium recovery, minimizing damage and reconditioning time. The first step in this multi-machine project is ^{13}C-tracer experiments in DIII-D, JET, C-Mod and MAST. $^{13}CH_4$ is injected toroidally symmetrically, facilitating quantification and interpretation of the results. Tiles are then removed, analyzed for ^{13}C content and subsequently evaluated in a thermal oxidation test facility with regard to the ability of different severities of oxidation exposure to remove the different types of (known and measured) ^{13}C co-deposit. Removal of D/T from B on Mo tiles from C-Mod will also be tested. OEDGE interpretive code analysis of the ^{13}C deposition patterns is used to generate the understanding needed to apply findings to ITER. First results are reported here for the ^{13}C injection experiments in DIII-D.

$^{13}CH_4$ was puffed through the upper pumping plenum of DIII-D (pump off) into lower single-null (LSN), neutral beam heated (6.5MW), high density, detached, ELMy H-mode discharges [1]. The puff was toroidally symmetric and at a rate which did not significantly perturb the local plasma conditions. The puff rate averaged 18.8 torrl/s lasting 2 s during each of 18 consecutive discharges. Immediately after the experiment, DIII-D was vented and a total of 77 tiles were removed. The ^{13}C content of 64 of the tiles was measured using Nuclear Reaction Analysis (NRA) and Particle-Induced Gamma-ray Emission (PIGE). ^{13}C deposition was found primarily on tiles in the inner divertor region and the private flux zone, PFZ, Fig.1, with some measurable deposition near the puff region. Figure 1 also shows results from an earlier, similar experiment which used low density L-mode discharges where in total half as much ^{13}C was injected. The most significant difference in the ^{13}C deposition pattern was that in the detached H-mode experiment there was substantial deposition on the PFZ wall. The NRA measurements were made at Sandia National Laboratories using the $^{13}C(^{3}He,p)^{15}N$ reaction with an analysis beam of 2.5MeV ^{3}He [2]. Background counts including those from the 1.1% natural abundance of ^{13}C in graphite, were subtracted as described in [2]. The lowest detectable ^{13}C deposition is about 2×10^{16} atoms/cm^2. The ^{13}C deposits were also measured on a sub-set of the tiles from the divertor region at the University of Madison-Wisconsin, using the more sensitive PIGE technique, Fig.1. Protons at 1750keV are incident on the graphite tiles. Protons have a resonant nuclear reaction with ^{13}C at 1748keV, very narrow in energy ~0.075keV. The excited nucleus emits a 9.2MeV gamma ray, which is detected by a scintillator. The protons are continuously reduced in energy passing through the graphite. Therefore, the protons can only produce the gamma emission when they match the resonance energy of the reaction. In theory this is from an extremely narrow depth range, ~2nm. By scanning the initial beam energy a highly resolved depth profile of ^{13}C can be measured. PIGE measures the concentration of ^{13}C versus depth with a smaller depth resolution than NRA and hence lower detection limit for ^{13}C deposited on graphite of about 10^{15} atoms/cm^2.

In the PIGE analysis, the depth profile of the ^{13}C count rate peaks at the surface, and has a

Gaussian “tail” which levels off at a depth ~0.5 microns into the tile. The constant ^{13}C count rate seen deep into the sample is a result of the intrinsic 1.1% ^{13}C. The Gaussian shape is fit to the raw data using a nonlinear least-squares fitting routine. Three parameters are fit at each analysis point: the surface ^{13}C concentration (i.e. count rate, shown in Fig.1), the 1/e half width of the Gaussian (i.e. the depth of the ^{13}C) and the offset count rate which represents the “deep” natural ^{13}C. From these parameters, plotted in Fig.2, one can deduce important aspects of the ^{13}C deposition. First, the isotope enrichment at the surface is typically a factor of ~5-20. Since the natural ^{13}C abundance is 1.1%, this indicates that the surface still has >80% ^{12}C deposition. This is significant as it indicates that the ^{13}C injection did not appreciably perturb the intrinsic deposition process, i.e. that the experiment was genuinely a tracer experiment, providing information on the natural co-deposition process. Second, the typical depth scale of the 13C enrichment is ~0.1-0.2 microns, indicating that the intrinsic deposition rate was ~1-4 nm/s over the ~50-100s of total injection time. Third, the relatively smooth poloidal variations in 13C depth indicates the absence of any major deposition and re-erosion process of these tiles; it appears that the ^{13}C remained on the first surface it deposited on, and the ongoing plasma exposure, including the effect of ELMs, did not disturb the deposits by eroding and re-depositing the ^{13}C. If the latter process had, in fact, occurred, it would likely manifest itself as poloidal variations of the depth of deposition, which were not found. The fact that the co-deposits appear to stay where they are formed — at least for detached divertor conditions — has important implications for tritium retention, namely the absence of migration of the tritium to other locations which may be less accessible for tritium recovery. The results from the outer baffle ring tile No. 24, (poloidal position >310 cm) contrast starkly to the other divertor (floor) tiles: the surface ^{13}C is that expected for natural carbon, i.e. no obvious ^{13}C enrichment, indicating that enriched ^{13}C fluence was never present to these surfaces, since deposition and re-erosion would still leave some signs of an equilibrium ^{13}C layer near the surface. This implies that transport of the ^{13}C occurred essentially entirely via the inner SOL, resulting in a more concentrated co-deposition pattern than might be expected if significant quantities of the ^{13}C were transported along both inner and outer SOL, or entered the confined plasma.

The interpretive Onion-Skin-Model Eirene Divimp edge (OEDGE) code was able to approximately reproduce the measured ^{13}C deposition pattern, by making two key assumptions: (a) the existence of a fast parallel flow along the SOL toward the inner divertor, (b) a radial pinch of 10-20m/s (in +R-direction, acting in the inner SOL, above the X-point) [3]. Neither of these transport features have been successfully replicated by predictive edge codes, but fast parallel flows toward the inside have been directly measured on a number of tokamaks, and Kirnev [4] assumed the existence of a similar radial pinch in his EDGE2D modeling of JET, in order to reproduce the fast parallel SOL flow, where the pinch was needed to close the particle recirculation loop. The detailed breakup kinetics of the $^{13}CH_4$ was included in the OEDGE modeling and showed that the ^{13}C-ions are produced too far out in the SOL to be able replicate the observed deposition; some form of radial pinch is needed to move the ^{13}C-ions far into the SOL for deposition to occur where measured.

Figure 3 illustrates the effect of assuming different radial pinches in the OEDGE analysis. With no radial pinch, too much of the deposition occurs well to the inside of the inner strike point. A radial pinch >20m/s, on the other hand, pushes too much of the deposition outward and onto the PFZ wall. A radial pinch of ~10m/s approximately replicates the measured deposition pattern of the ^{13}C. Figure 4 shows that both a parallel flow and a radial pinch are required in order to replicate anything similar to the deposition pattern measured. The OEDGE modeling showed that most of the ^{13}C deposited as neutrals formed by volume recombination in the cold, dense detached plasma in the inner divertor and the PFZ.

The ITER design is based on divertor detachment. The DIII-D ^{13}C-tracer experiment in detached H-mode indicates that it may be possible to arrange for much of the tritium co-deposition to occur on the PFZ wall. This could be advantageous since that surface need not possess significant heat-removal capability and so could be engineered to permit its being heated to high temperatures, even continuously. If hot enough, the carbon deposition will occur without co-deposition trapping of tritium. Intermittent heating to release the tritium, with or without simultaneous thermal oxidation, could be achieved in various ways, including flash heating by mitigated disruptions, since this surface is in direct view of the main plasma. Deposition of carbon as neutrals will also create “soft” co-deposits which release hydrogenic content more easily than ‘hard’ deposits formed by ionic deposition. For detached divertor conditions, co-deposits may stay where first formed — much of it on relatively accessible locations — and not experiencing migration of the tritium by erosion-redeposition to inaccessible regions.

ACKNOWLEDGEMENTS

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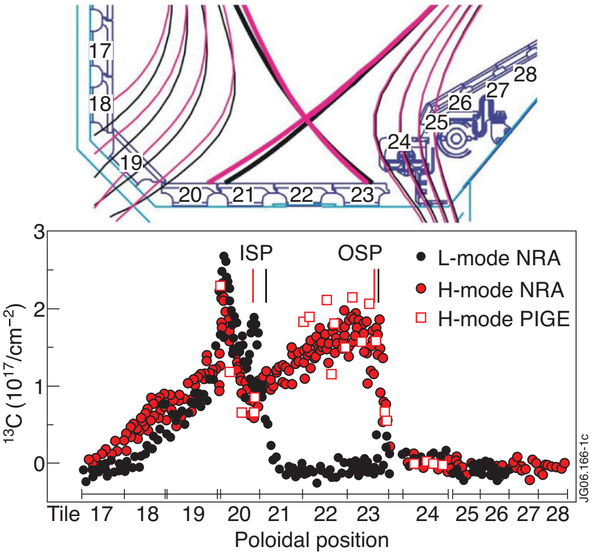

Figure 1: ^{13}C deposits measured in divertor region using NRA and PIGE.

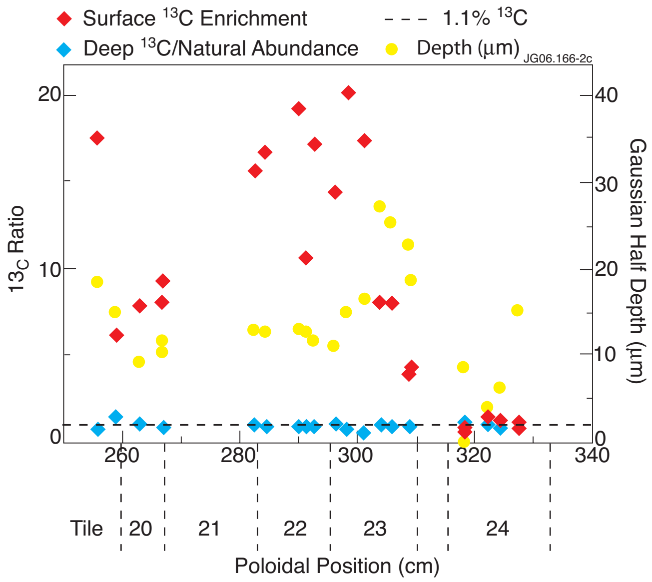

Figure 2: Spatial variations of the fitted parameters from the PIGE analysis.

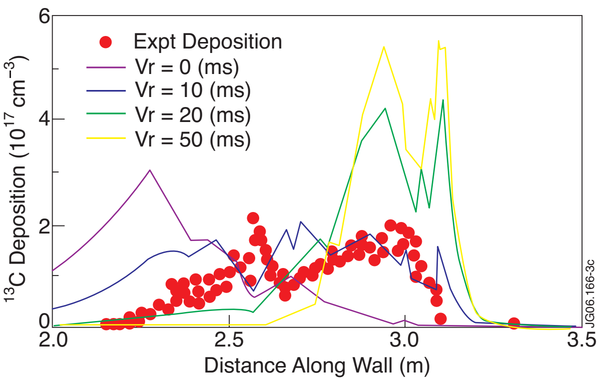

Figure 3: OEDGE code analysis showing the influence of a radial pinch on the ^{13}C deposition pattern. Fast parallel plasma flow along the inner SOL has also been included here, at $M_{//} = 0.3$ (Fig.4).

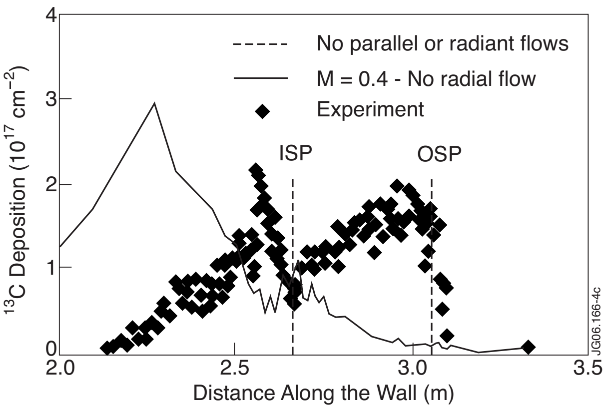

Figure 4: OEDGE code analysis showing the dependence of deposition on the assumption of a radial pinch and a fast parallel flow in the inner SOL. For no parallel flow or radial pinch, the code-simulated deposition pattern is completely unlike that measured.