GA–A25594

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OCTOBER 2006

GENERAL ATOMICS

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This is a preprint of a paper to be presented at the 21st IAEA Fusion Energy Conference, October 16-21, 2006, in Chengdu, China, and to be published in the Proceedings.

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Work supported by
the U.S. Department of Energy
under DE-FC02-04ER54698, W-7405-ENG-48,
DE-FG02-04ER54758, DE-AC04-94AL85000,
DE-FG02-04ER54235

GENERAL ATOMICS PROJECT 30200
OCTOBER 2006

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Abstract

We have studied carbon transport in both L- and H-mode plasmas in DIII-D by injecting $^{13}CH_4$ from a toroidally symmetric source into the top of lower single-null plasmas. The divertor plasma was well characterized by divertor diagnostics, including a 2-D tangential view of the upper half of the plasma. At the conclusion of each run campaign, carbon tiles were removed and analyzed by NRA and PIGE surface techniques. In both H- and L-mode plasmas, high ^{13}C coverage ($\sim 2-2.5\times10^{17}$ atoms cm^{-2}) was found just inboard of the inner divertor. In the H-mode case, the deposition extends into the private flux region between the divertor strike points. The divertor deposition accounts for about one-third of the injected ^{13}C. These experimental results are being compared with UEDGE and OEDGE models. These data, along with the modeling results, will contribute to the database required for estimating the ITER tritium inventory. Preliminary work on ^{13}C removal from these tiles is being explored with oxygen baking in a controlled side-lab experiment.

1. Introduction and Motivation for this Set of Experiments

The use of carbon as a plasma-facing material in fusion devices can lead to an accumulation of tritium that may be co-deposited with carbon that has been eroded from the wall, resulting in a potentially large reservoir for tritium which is undesirable. Estimates of the tritium inventory in ITER due to co-deposition with carbon vary widely, with large uncertainties [1]. In support of carbon as a plasma facing material, there is a wealth of information about carbon properties. It has been used extensively in tokamaks, it is very robust against disruptions and ELMs, and it does not melt. This paper is a description of experiments and modeling of carbon transport experiments in the DIII-D tokamak, which uses ATJ graphite as a plasma facing material. The goal of this work is to assess three aspects of the tritium co-deposition issue: (1) the location of the co-deposited carbon and, hence, the areas of tritium concentration; (2) plasma and surface modeling to help understand how the carbon is transported by the plasma to these locations; and (3) effectiveness of tritium removal techniques, such as oxygen baking.

To study the spatial distribution of carbon deposition, isotopically enriched methane as $^{13}CH_4$ was injected into a series of reproducible plasmas at the end of both the 2003 and 2004/5 DIII-D experimental campaigns. During the subsequent vessel entry, a representative set of carbon tiles was removed and analyzed for ^{13}C. The carbon tracer technique for carbon deposition was first used on JET [2]; the DIII-D experiments include toroidally symmetric injection, a well characterized background plasma, and an all-carbon plasma wall. Experimental results show that the highest concentration of ^{13}C is in the divertor in both L- and H-mode plasmas. This can be explained by an “ad hoc” carbon flow in the scrapeoff layer (SOL) plasma towards the divertor. As yet, this carbon flow has not been calculated by fluid codes such as UEDGE, which include calculations of the background deuterium ion flow in the SOL, but this work is ongoing. Section 2 summarizes experiments in L-mode, H-mode (Section 3), and progress in computational modeling (Section 4), followed by a discussion.

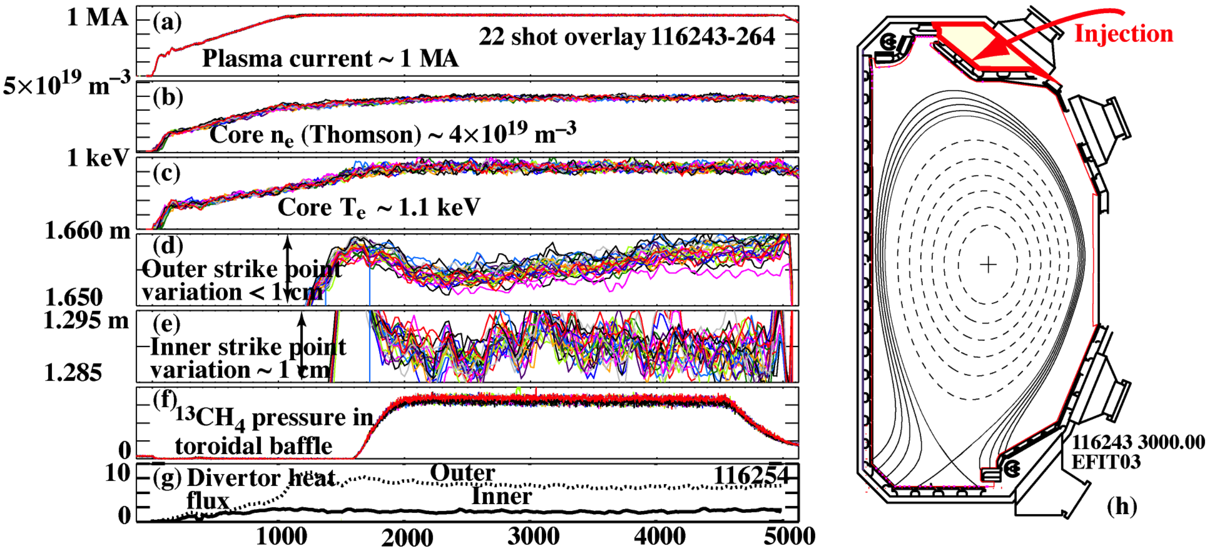

FIG. 1. Time histories of plasma conditions for L-mode studies, along with the lower single null plasma shape. $^{13}CH_4$ was injected from a toroidally symmetric plenum at the top of the machine. The highest ^{13}C concentration was found in the divertor region radially inward of the inner strike point.

2. ^{13}C Transport Experiments in L-mode Plasmas

The L-mode ^{13}C injection was preceded by a day of careful plasma characterization to document the plasma conditions and determine the required non-perturbative injection levels. We established that 4.4 T•L/s did not perturb the plasma, in that the divertor heat flux [Fig. 1(g)] did not change and SOL conditions were constant [charge exchange recombination (CER) and Thomson scattering] due to the injection. Short, low-power neutral beam pulses allowed core carbon measurements while maintaining the (primarily ohmic heating) L-mode conditions. As shown in Fig. 2, the divertor conditions were typical of L-mode operation in DIII-D at this density; the inner strike point (ISP) is detached and the outer is attached. The heat flux profile shows the absence of a well-defined peak at the ISP (detached), with a large peak in the heat flux and ion-saturation current at the outer strike point (attached).

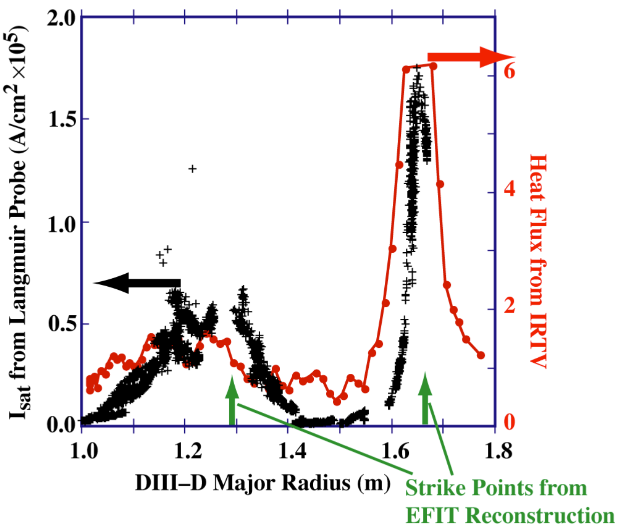

FIG. 2. Divertor plate plasma conditions for L-mode show an attached outer strike point, and a detached ISP, typical of DIII-D operation at this density. Heat flux from IRTV (red). I_{sat} from Langmuir probe (black).

As shown in Fig. 1, 22 identical shots were obtained with $^{13}CH_4$ injection, with a total of ~ 314 T•L or 1.0×10^{22} atoms of ^{13}C injected during the discharge. The strike point locations were maintained on all of these shots to within 1 cm, and the density and temperature time histories were constant. The normal post-campaign baking was not performed before 29 tiles were carefully removed from the vessel. Representative tiles were removed from the whole poloidal cross-section, with a selection at two toroidal locations to assess toroidal asymmetry.

The tiles were analyzed by two techniques: NRA and PIGE. The nuclear reaction analysis (NRA) technique [3] used a 2.5 MeV ^{3}He analysis beam and a special detector to measure the products from the $^{13}C(^{3}He,p)^{13}N$ reaction, with an uncertainty and detection limit of 2×10^{16} atoms cm^{-2}. Proton-induced gamma emission (PIGE) [4] was performed on selected tiles [3] using a 1.748 MeV proton beam resulting in a 9.17 MeV gamma. This measurement has higher depth resolution and a correspondingly lower detection limit for ^{13}C of about 10^{15} atoms cm^{-2}. Figure 3 shows the results of the NRA analysis of the L-mode data in the divertor region, analysis from other areas were below the detectability threshold of the technique. Each data point is the average of measurements at three toroidal locations on each tile, but the toroidal variation on each tile was small. Tiles 13 and 14 (red in Fig. 3) were located toroidally opposite from the other tiles and show a remarkable toroidal symmetry of the deposition profile. The NRA analysis shows the largest ^{13}C concentration inboard of the ISP in the lower divertor. The toroidal integral of the deposited ^{13}C from the NRA analysis is about ~35% of that injected. The PIGE analysis, as it is more sensitive, shows a level of about

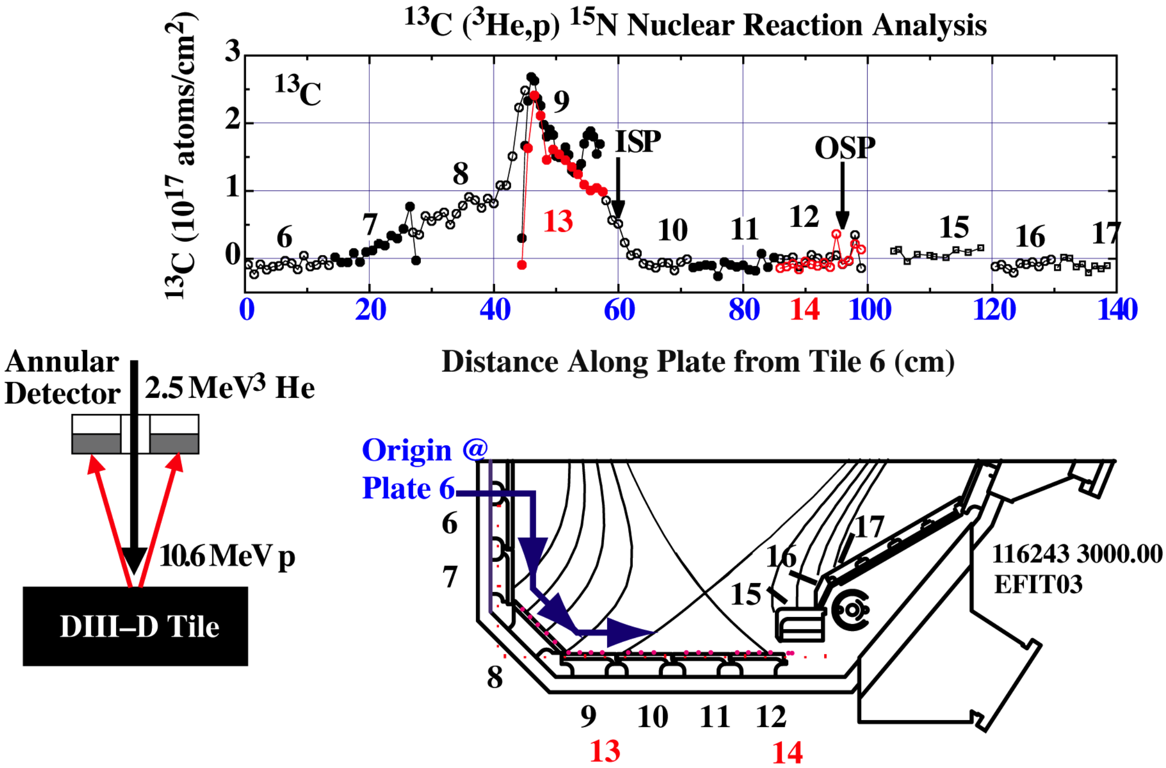

FIG. 3. Results from NRA analysis of DIII-D tiles exposed to L-mode plasmas, tiles not shown were below the delectability level of the measurement. The highest concentration is observed inboard of the ISP (detached divertor) in the lower divertor [5]. Naturally occurring ^{13}C has been subtracted.

2×10^{16} atoms cm^{-2} near the injection port at the top of the machine. More details of the PIGE results will be addressed in Section 4 in comparison with the H-mode results.

3. ^{13}C Transport Experiments in H-mode Plasmas

At the end of the next DIII-D campaign (2005), the ^{13}C injection experiments were repeated with ITER-like detached ELMy H-mode plasmas. Again, the first day was used to characterize the plasma and it was determined that roughly twice as much ^{13}C could be injected compared to the L-mode experiment. As shown in Fig. 4, $^{13}CH_4$ was puffed into 17 identical H-mode shots (123402-419) resulting in a total injection of ~ 690 T•L or 2.2×10^{22} carbon atoms. Neutral beam heating at 6.6 MW resulted in ELMing H-mode discharge conditions with a line-average electron density of 8×10^{19} cm^{-3} and an ELM frequency of 200 Hz. The strike point locations were maintained fixed within approximately 0.5 cm. The lower single-null plasma shape [Fig. 4(b)] was similar to that used in the L-mode case [Fig. 1(h)]. To maintain reproducible H-mode conditions, helium glow discharge cleaning (GDC) was performed for 5 min. between discharges. Detailed residual gas analysis (RGA) of the vessel was done throughout the 16 inter-shot GDC periods, and estimates from these data indicate that over 99% of the injected ^{13}C remained in the vessel after the GDC period. The divertor plasma conditions were typical of high density ELMing H-mode, in that both divertors were detached near the strike point, with the outer divertor reattaching at the outboard side of the outer strike point during each ELM. This is evidenced by the increase in the Langmuir probe ion-saturation current outboard of the outer strike point, and a reduced, broadened heat flux profile at the outer strike point measured by the Infrared TV (IRTV).

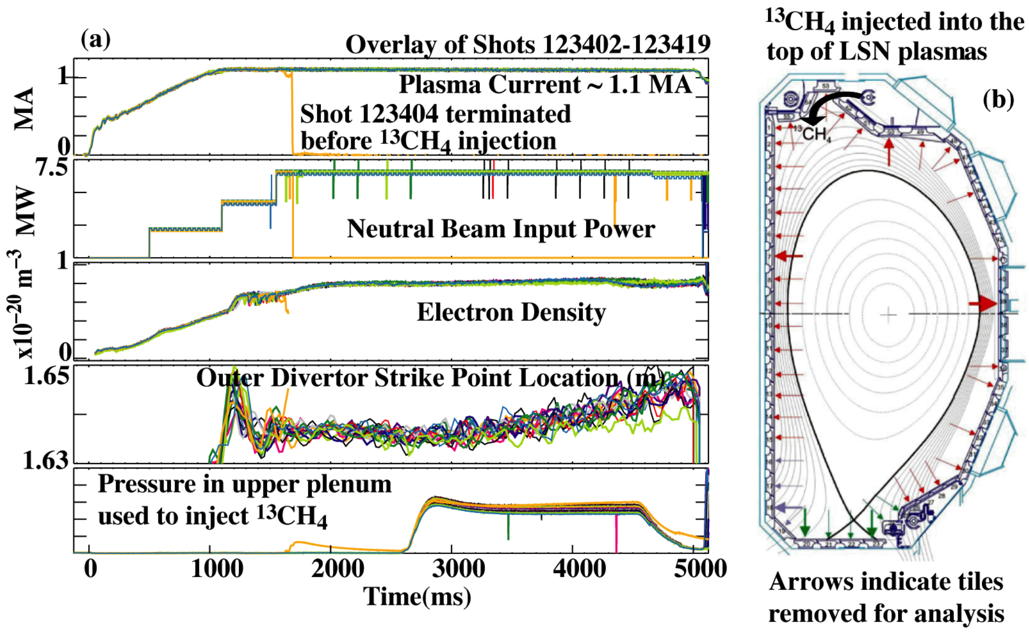

FIG. 4. The time history of the 17 repeatable shots used for the H-mode $^{13}CH_4$ experiment. The plasma shapes for the L- and H-mode experiments are compared at the right side of the figure.

On the plasma characterization day, sweeps of the divertor strike point were used to obtain 2-D profiles of the electron temperature and density with the divertor Thomson scattering (DTS) system. The T_e profile in Fig. 5 (averaged over ELMs) shows a low temperature region near the divertor, with $T_e < 5$ eV. Note that while the T_e is low throughout the lower divertor region, the density is large, even into the private flux region below the X-point. This is consistent with growing evidence that the private flux region of the divertor is important when determining divertor conditions, particularly when ELMs are present.

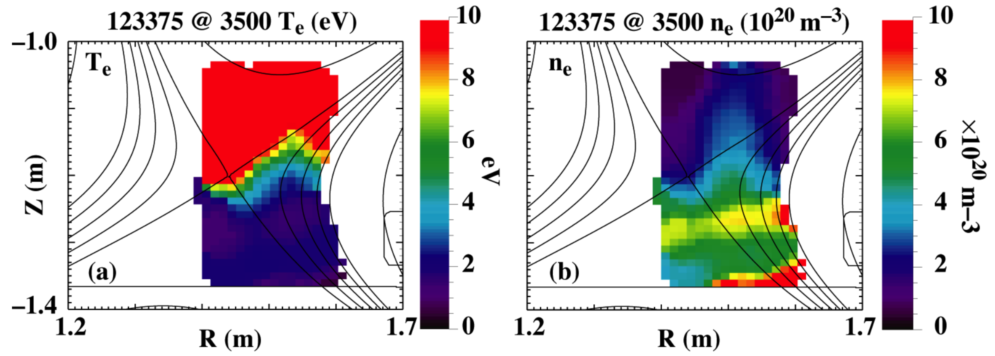

FIG. 5. 2-D measurements of the electron temperature (a) and density (b) from the DTS for the H-mode experiment. These data are typical of detached divertor ELMing H-mode operation on DIII-D.

Again, the ^{13}C experiment was on the last run day of the campaign and no baking of the vessel was done before venting the vessel. A total of 64 tiles were carefully removed, with 49 taken from a poloidal ring at one toroidal location, and the remainder from other toroidal locations to assess symmetry and to monitor other locations such as limiters. The NRA and PIGE analysis results for the upper divertor (left panel) and lower divertor (right panel) are shown in Fig. 6 for both L- and H-mode conditions [6]. In the lower divertor, the most striking feature is that the ^{13}C density is similar at the inner (detached) strike point for both L- and H-mode plasmas. For the H-mode case, there is substantial ^{13}C deposition in the private flux region extending nearly to the outer strike point, where the deposition drops to close to the detection limit. The (more sensitive) PIGE technique shows good agreement with the NRA data in H-mode, both at the high levels found in the private flux zone, and the low values outboard of the outer strike point.

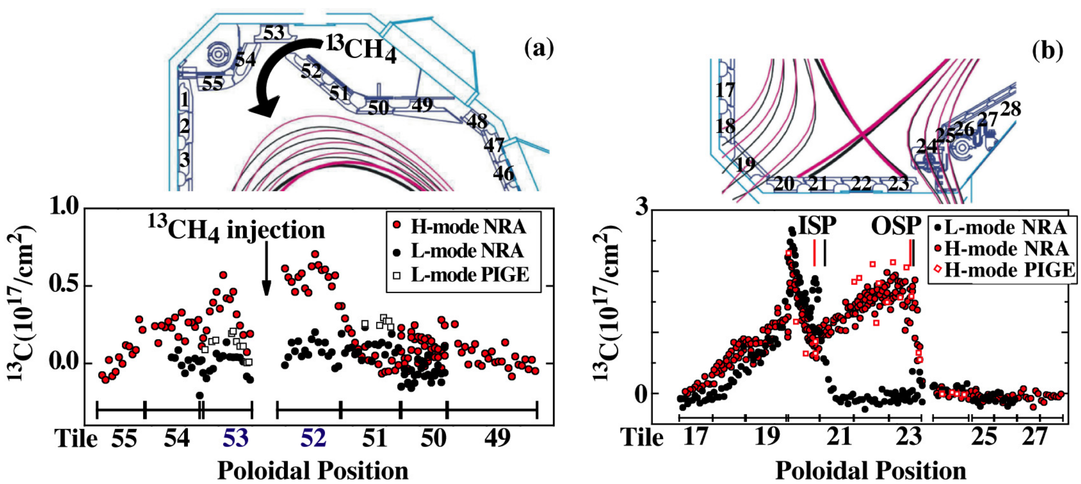

FIG. 6. NRA and PIGE data from the upper divertor (a) and lower divertor (b) for both L- and H-mode plasmas on DIII-D. Note there is more deposition in the private flux zone for the H-mode case.

In the upper divertor near the region of the ^{13}C puffing, there is a larger amount of ^{13}C for the H-mode case compared to the L-mode [Fig. 6(a)]. (As the PIGE technique is more sensitive, it is best to compare the NRA H-mode case with the L-mode PIGE case.) Recall that the H-mode case had nearly twice the amount of ^{13}C injected. Assuming toroidal symmetry, roughly 8-10% of the injected ^{13}C was deposited locally, presumably as part of the hydrocarbon break-up process. NRA measurements of tiles at other poloidal locations (such as the main chamber) were below the detection limit of the measurement. Preliminary PIGE analysis of five tiles at these locations for L-mode conditions — if they are representative, and assuming toroidal symmetry — indicate that a significant amount (~40%) injected ^{13}C could be in a low-level deposit over the rest of the plasma facing surfaces (L-mode).

Assuming toroidal symmetry, which appears justified because of the agreement of the NRA analysis at two different toroidal locations, an integral of the profiles in Fig. 6 shows that about 30% of the injected ^{13}C was found at the inner divertor for L-mode, and about 13% at the inner divertor and 24% in the private flux region for H-mode. With about 10% deposited near the injection, we have accounted for roughly 1/2 the total amount of ^{13}C injected by direct measurement. The PIGE samples suggest that the remainder is in low-level deposits or in tile gaps. This is undergoing further analysis, as this could be a key component in controlling the overall tritium inventory in a fusion device with carbon.

4. Carbon Transport in the DIII-D SOL: Data and Modeling

To understand these experimental results, and to ultimately estimate the carbon transport and deposition in future machines such as ITER, we have used 2-D measurements of carbon ionization states in both the upper and lower divertor, along with the OEDGE and UEDGE computational models. We also have (Langmuir and Mach) probe results from other DIII-D experiments in both L- and H-mode, both at the midplane and the divertor [7,8]. There is an emerging picture that a flow in the SOL can transport impurities in and out of the divertor, but the details have yet to be worked out. Shown in Fig. 7 are the 2-D reconstructed profiles of CII and CIII in the upper divertor during the ^{13}C injection period [9]. The fact that the CIII emission peaks farther away from the upper injection point than CII results in a carbon velocity flow of ~ 20 km/s in the SOL towards the inner divertor. However, this same signature was not as clear in H-modes, and the emission pattern was not influenced by changing the direction of the toroidal magnetic field, which would in turn change the direction of $E \times B$ and $\nabla B \times B$ drifts (if they are responsible for the flow).

OEDGE modeling has been used in the “interpretive” mode to prescribe plasma conditions that produce the measured patterns at the divertor plate [10-12]. Two features have emerged from this modeling effort: (1) a radial displacement of the carbon by ~ 2 cm, which was modeled by an inward velocity of 10 m/s, and (2) an ad-hoc *carbon* flow with a mach number of about M~0.4 (note this is the carbon velocity compared to *deuterium* sound speed) matches the deposition patterns at the divertor plate. In Fig. 8 are comparisons of the experimental data with different values of the defined Mach number, showing best agreement with M~0.4.

The UEDGE 2D fluid edge modeling code has not succeeded in obtaining ^{13}C deposition profiles consistent with those measured in DIII-D. The models indicate the existence of large parallel forces (parallel ion temperature gradients and parallel carbon pressure gradients) on the injected carbon (not included in the interpretive OEDGE model). The existence of these forces suggest even larger parallel flows would be required to be consistent with experimental deposition profile measurements. These flows are not found in the current fluid models. Including all the drift terms in the UEDGE code has not brought the results closer to the experimental results. As these are indicators of important underlying physics mechanisms, we are looking at the UEDGE cases in detail.

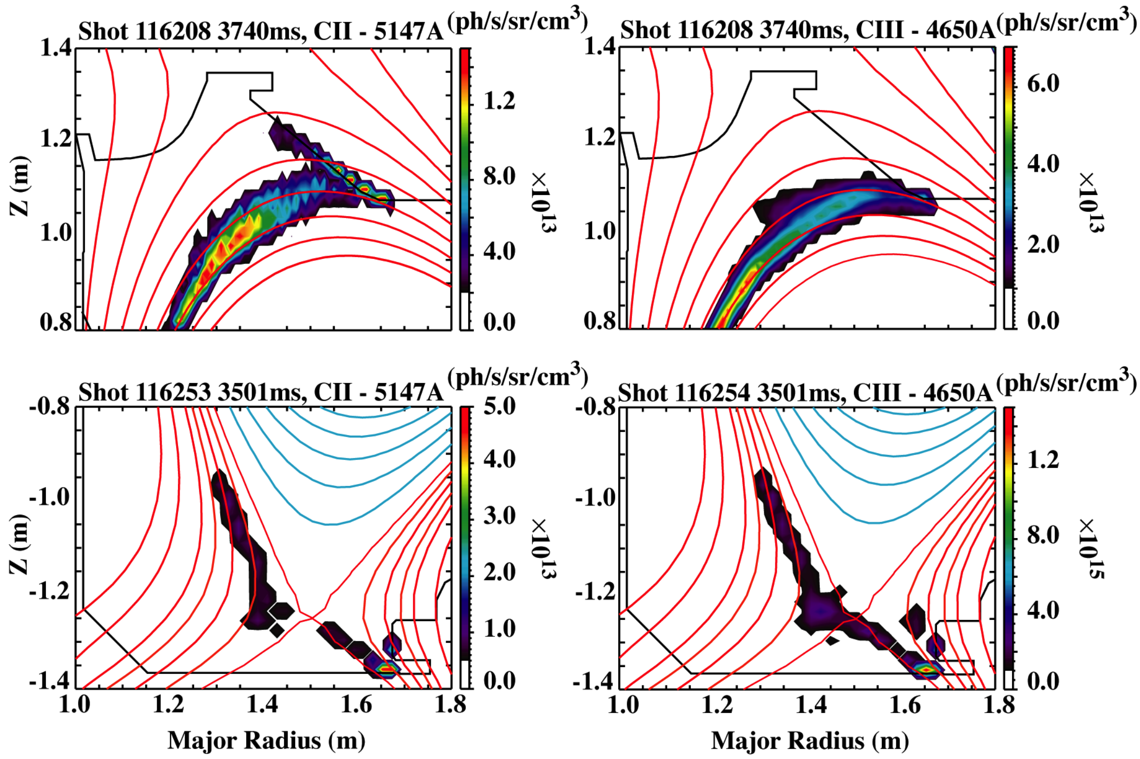

FIG. 7. 2-D profiles of CII and CIII emission in L-mode operation show flow away from the injection point.

The key difference between the L- and H-mode ^{13}C deposition profiles was the additional deposition in the private flux region. One obvious difference in L- and H-mode plasmas is that H-modes usually have some sort of ELMs which are known to transport particles and energy in the SOL. Recent 2-D measurements of carbon emission in the divertor, shown in Fig. 9, suggest that ELMs may also influence the carbon distribution in the divertor. On the right is the CI (neutral carbon) inverted profile before an ELM, and most of the neutral carbon emission is close to where the outer divertor. During the ELM, the emission peaks near the ISP, with some emission extending into the private flux region. While the details of deposition during an ELM are not yet clear, these data are suggestive that the ELM plays a role in the ^{13}C deposition in the private flux region of H-mode plasmas.

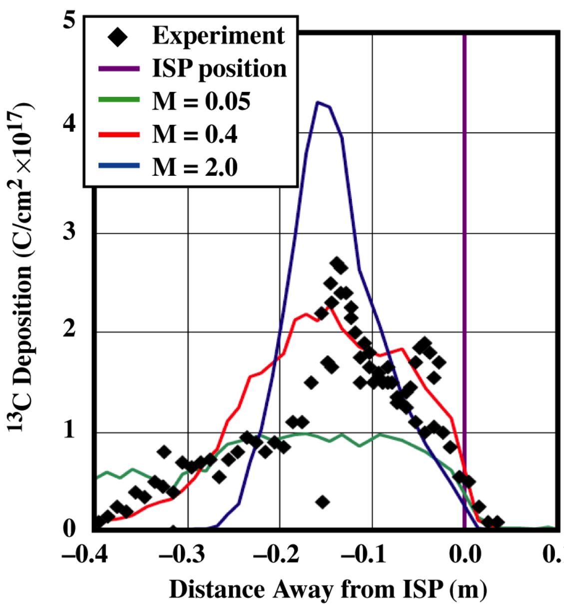

FIG. 8. OEDGE modeling of carbon flow shows a M~0.4 agrees best with the L-mode data.

Both L- and H-mode experiments support a lack of massive redistribution of deposited carbon [12]. PIGE analysis indicates that the tile surface still has approximately 80% ^{12}C (naturally occurring) coverage. This fact, coupled with the observation that over 1/2 of the carbon is directly measured in the divertor, with the remaining presumably in a low-concentration distributed layer, suggests that most of the deposited carbon stayed “close” to where it was originally deposited. This is important when designing tritium removal techniques.

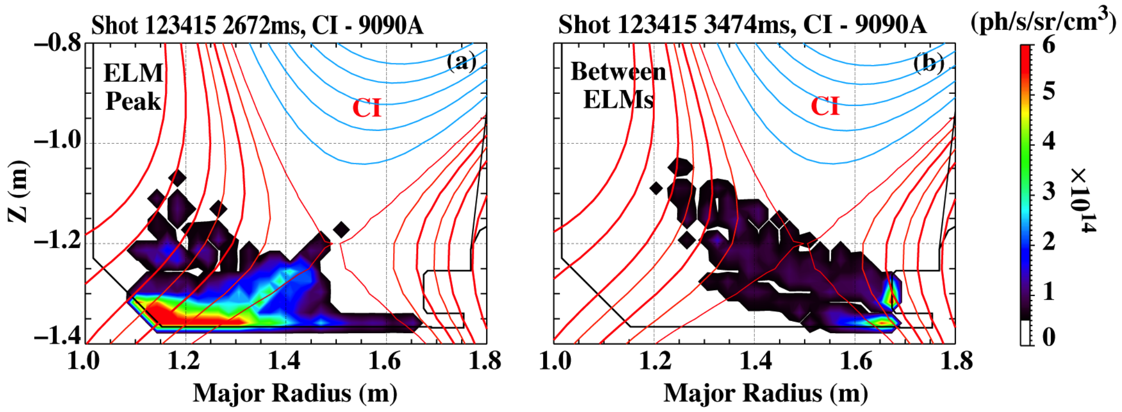

FIG. 9. 2-D reconstructions of neutral carbon emission at the ELM peak (left) and in between ELMs (right) show that the ELM redistributes carbon in the divertor.

To study the efficiency of tritium removal with oxygen baking, experiments are being carried out at the University of Toronto to estimate the efficiency of tritium removal with oxygen baking. The DIII-D ^{13}C tiles, as they are representative of tokamak surfaces, will be tested. If in-situ oxygen removal techniques continue to look promising, we are proposing an oxygen bake experiment on DIII-D, both to measure the removal of co-deposited layers, and to assess how quickly high performance plasma operation can be recovered.

This work supported by the U.S. Department of Energy under DE-FC02-04ER54698, W-7405-ENG-48, DE-FG02-04ER54758, DE-AC04-94AL85000, DE-FG02-04ER54235 and supported by the Collaborative Research Opportunities Grant from the Natural Sciences and Engineering Research Council of Canada.

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