GA–A25482

^{13}C-TRACER EXPERIMENTS IN DIII-D PRELIMINARY IN THERMAL OXIDATION EXPERIMENTS TO UNDERSTAND TRITIUM RECOVERY IN DIII-D, JET, C-MOD, AND MAST

by

P.C. STANGEBY, S.L. ALLEN, N. BEKRIS, N.H. BROOKS, K. CHRISTIE, C. CHROBAK, J.P. COAD, G.F. COUNSELL, J.W. DAVIS, J.D. ELDER, M.E. FENSTERMACHER, M. GROTH, A.A. HAASZ, J. LIKONEN, B. LIPSCHULTZ, A.G. McLEAN, V. PHILIPPS, G.D. PORTER, D.L. RUDAKOV, J. SHEA, W.R. WAMPLER, J.G. WATKINS, W.P. WEST, AND D.G. WHYTE

JUNE 2006

GENERAL ATOMICS

DISCLAIMER

GA–A25482

^{13}C-TRACER EXPERIMENTS IN DIII-D PRELIMINARY IN THERMAL OXIDATION EXPERIMENTS TO UNDERSTAND TRITIUM RECOVERY IN DIII-D, JET, C-MOD, AND MAST

by

P.C. STANGEBY,* S.L. ALLEN,† N. BEKRIS,‡ N.H. BROOKS, K. CHRISTIE,¶ C. CHROBAK,¶ J.P. COAD,§ G.F. COUNSELL,# J.W. DAVIS,* J.D. ELDER,* M.E. FENSTERMACHER,† M. GROTH,† A.A. HAASZ,* J. LIKONEN,∆ B. LIPSCHULTZ,∞ A.G. McLEAN,* V. PHILIPPS,◊ G.D. PORTER,† D.L. RUDAKOV,° J. SHEA,¶ W.R. WAMPLER,◆ J.G. WATKINS,◆ W.P. WEST, AND D.G. WHYTE¶

This is a preprint of a paper to be presented at the 33rd EPS Conf. on Plasma Physics, June 19-23, 2006, Roma, Italy, and to be published in the *Proceedings.*

*University of Toronto Institute for Aerospace Studies, Toronto, Canada
†Lawrence Livermore National Laboratory, Livermore, California
‡Forschungszentrum Karlsruhe, Eggenstein-Leopoldshafen, Germany
¶University of Wisconsin-Madison, Madison, Wisconsin
§EFDA-JET, Culham Science Center, Abingdon, United Kingdom
#EURATOM/UKAEA, Culham Science Center, Abingdon, United Kingdom
∆EURATOM-Tekes, Helsinki, Finland
∞Massachusetts Institute of Technology, Cambridge, Massachusetts
◊Forschungszentrum Jülich GmbH EURATOM-Association, Jülich, Germany
°University of California-San Diego, La Jolla, California.
◆Sandia National Laboratories, Albuquerque, New Mexico.

Work supported by
the U.S. Department of Energy
under W-7405-ENG-48, DE-FC02-01ER54698, DE-FG02-04ER54762, DE-FG02-04ER54758, and DE-AC04-94AL85000

GENERAL ATOMICS PROJECT 30200
JUNE 2006

^{13}C-Tracer Experiments in DIII-D Preliminary to Thermal Oxidation Experiments to Understand Tritium Recovery in DIII-D, JET, C-Mod, and MAST

P.C. Stangeby[1], S.L. Allen[2], N. Bekris[3], N.H. Brooks[4], K. Christie[5], C. Chrobak[5], J.P. Coad[6], G.F. Counsell[7], J.W. Davis[1], J.D. Elder[1], M.E. Fenstermacher[2], M. Groth[2], A.A. Haasz[1], J. Likonen[8], B. Lipschultz[9], A.G. McLean[1], V. Philipps[10], G.D. Porter[2], D.L. Rudakov[11], J. Shea[5], W.R. Wampler[12], J.G. Watkins[12], W.P. West[4], and D.G. Whyte[5]

[1]*University of Toronto Institute for Aerospace Studies, Toronto, Canada*
[2]*Lawrence Livermore National Laboratory, Livermore, California 94550, USA*
[3]*Forschungszentrum Karlsruhe, Eggenstein-Leopoldshafen, Germany*
[4]*General Atomics, P.O. Box 85608, San Diego, California 92186-5608, USA*
[5]*University of Wisconsin-Madison, Madison, Wisconsin, USA*
[6]*EFDA-JET, Culham Science Center, Abingdon, United Kingdom*
[7]*EURATOM/UKAEA, Culham Science Center, Abingdon, United Kingdom*
[8]*EURATOM-Tekes, Helsinki, Finland*
[9]*Massachusetts Institute of Technology, Cambridge, Massachusetts, USA*
[10]*Forschungszentrum Jülich GmbH EURATOM-Association, Jülich, Germany*
[11]*University of California-San Diego, La Jolla, California, USA*
[12]*Sandia National Laboratories, Albuquerque, New Mexico, USA*

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 [1]. 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. In DIII-D and JET, $^{13}CH_4$ has been (and in C-Mod and MAST, will be) injected toroidally symmetrically, facilitating quantification and interpretation of the results. Tiles have been removed, analyzed for ^{13}C content and will next be evaluated in a thermal oxidation test facility in Toronto 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 (6.5 MW), high density, detached, ELMy H-mode discharges [2]. The puff was toroidally symmetric and at a rate which did not significantly perturb the local plasma conditions. The puff rate averaged 18.8 torr *l*/s lasting 2 s during each of 17 repeat discharges. Immediately after the experiment, DIII-D was vented and a total of 77 tiles were removed. The ^{13}C content of 48 of the tiles was measured using nuclear reaction analysis (NRA) and proton-induced gamma-ray emission (PIGE). 37% of the ^{13}C was found on front faces of tiles in the inner divertor region and the private flux zone, PFZ, Fig. 1, and ~10% near the puff. Fig. 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 [3]. 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 2.5 MeV ^{3}He [3]. The ^{13}C deposits were also measured on a sub-set of the tiles at the University of Madison-Wisconsin, using the more sensitive PIGE technique [4], Fig. 1. Protons have a resonant nuclear reaction with ^{13}C at 1748 keV, very narrow in energy ~0.075 keV. The excited nucleus emits a 9.2 MeV gamma ray, which is detected by a scintillator. 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 higher depth resolution than NRA and hence lower detection limit for ^{13}C deposited on graphite of about 10^{15} atoms/cm^{2}, compared with $\sim 2 \times 10^{16}$ atoms/cm^{2} for NRA.

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 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 in the divertor. 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 ^{13}C enrichment is ~0.1-0.2 microns, indicating that the intrinsic deposition rate was ~1-4 nm/s over the ~50-100 s of total injection time. The constant ^{13}C count rate seen deep into the sample is a result of the intrinsic 1.1% ^{13}C.

Almost half the injected ^{13}C is accounted for on the front faces of 7 tile-rows in the divertor and 3 tile-rows near the injection point. Although the inner wall tiles have not been measured yet using PIGE, the detection of ~40% (with large uncertainties) of the injected ^{13}C at that location in the earlier L-mode ^{13}C experiment in DIII-D suggests that much of the remaining ^{13}C in the current H-mode experiment may be accounted for on the surfaces of tiles. It is hypothesized that the ^{13}C-deposits in the divertor were not significantly disturbed by ongoing plasma exposure, including ELMs, although ELM-related changes in divertor carbon emissions remain to be explained. Any disturbance, if present, certainly did not cause the sort of massive migration of co-deposits to remote regions that occurred in the JET DTE1 experiment [5] and it appears that the ^{13}C that entered the divertor remained on the divertor tiles. The JET results were for an entire campaign that included a variety of discharge conditions and configurations, in contrast with the single (detached) condition used here. That the co-deposits seem to stay approximately where they are initially formed — at least for detached divertor conditions – could have important implications for tritium retention, namely the absence of migration of the tritium to remote locations that may be less accessible for tritium recovery. Deposition in tile gaps remains to be measured. The results from the outer baffle ring tile No. 24, (poloidal position >310 cm) contrast sharply with the other divertor (floor) tiles: the surface ^{13}C is that expected for natural carbon, indicating that enriched ^{13}C fluence was probably never present to these surfaces, since deposition and re-erosion would still leave some signs of an equilibrium ^{13}C layer near the surface, particularly at locations toward the outer walls. 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 10-20 m/s (in +R-direction, acting in the inner SOL, above the X-point) [6]. The existence of neither of these transport features has been predicted by standard edge codes, but fast parallel flows toward the inside have been directly measured on a number of tokamaks, and Kirnev [7] 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 to replicate the observed deposition; some form of radial pinch is needed to move the ^{13}C-ions toward the separatrix 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 >20 m/s, on the other hand, pushes too much of the deposition outward and onto the PFZ wall. A radial pinch of ~10 m/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 at all 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.

ITER operation is based on divertor detachment to control peak heat loads. DIII-D ^{13}C-tracer experiments in detached H-mode suggests that it might be possible to arrange for a significant amount 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. If hot enough, 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 H/D/T more easily than “hard” deposits formed by ionic deposition, and are more readily removed by thermal oxidation [1]. For detached divertor conditions, co-deposits may stay where first formed — much of it on relatively accessible locations — and not experience migration of the tritium by erosion-redeposition to inaccessible regions.

This work was supported in part by the US Department of Energy under W-7405-ENG-48, DE-FC02-04ER54698, DE-FG03-96ER54373, DE-FG02-04ER54758, and DE-AC04-94AL85000 and by a Collaborative Research Opportunities Grant from the Natural Sciences and Engineering Research Council of Canada.

[1]G. Federici, C.H. Skinner, J.N. Brooks, et al, Nucl. Fusion **41** (2001) 1967.
[2]W.R. Wampler, A.G. McLean, S.L. et al., 17th Int. Conf. on Plasma Surface Interactions, Hefei, China (2006).
[3]W.R. Wampler, S.L. Allen, A.G. McLean, et al., J. Nucl. Mater. **337-339** (2005) 134.
[4]W.G. Whyte, Proc. of 5th ITPA Divertor and Scrape-Off Layer Group Meeting, Lisbon (2004).
[5]M. Keilhacker, M.L. Watkins, JET Team, J. Nucl. Mater. **266-269** (1999) 1.
[6]J.D. Elder, A.G. McLean, P.C. Stangeby, et al., ibid Ref. 1.
[7]Kirnev, et al., J. Nucl. Mater. **337–339** (2005) 271.

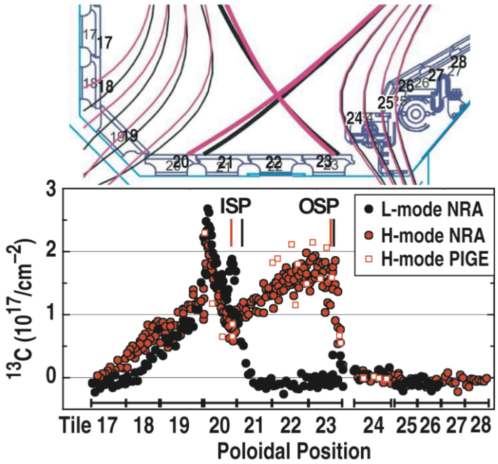

Fig 1. ^{13}C measured in divertor by NRA and PIGE.

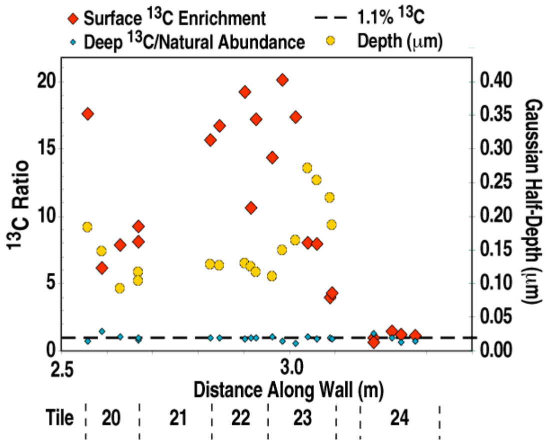

Fig. 2. Fitting parameters from PIGE analysis.

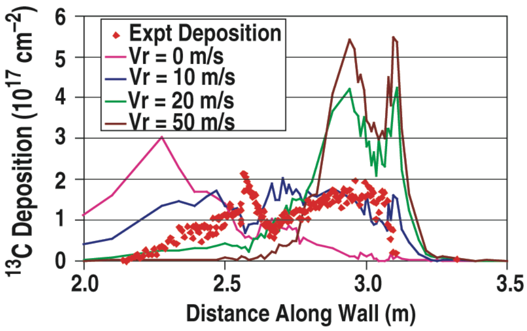

Fig. 3. OEDGE code analysis showing the influence of a radial pinch on the ^{13}C deposition pattern. Fast parallel plasma flow along the inner SOL has also been included here, at M = 0.3 (Fig. 4). Modeling assumes time-invariant plasma conditions; see [4].

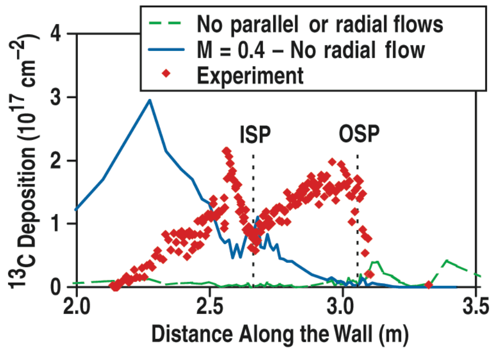

Fig. 4. OEDGE code analysis showing the dependence of deposition on the assumption of a radial pinch and a fast parallel flow in the inner SOL. For no parallel flow or radial pinch, the code-simulated deposition pattern is completely unlike that measured.