GA–A26805

QUANTIFICATION OF CHEMICAL EROSION IN THE DIII-D DIVERTOR AND IMPLICATIONS FOR ITER

by

A.G. McLEAN, P.C. STANGEBY, B.D. BRAY, S. BREZINSEK, N.H. BROOKS, J.W. DAVIS, R.C. ISLER, A. KIRSCHNER, R. LAENGNER, C.J. LASNIER, Y. MU, J. MUNOZ, D.L. RUDAKOV, O. SCHMITZ, E.A. UNTERBERG, J.G. WATKINS, D.G.WHYTE, and C.P.C. WONG

JULY 2010

GENERAL ATOMICS

DISCLAIMER

GA–A26805

QUANTIFICATION OF CHEMICAL EROSION IN THE DIII-D DIVERTOR AND IMPLICATIONS FOR ITER

by
A.G. McLEAN,* P.C. STANGEBY,† B.D. BRAY, S. BREZINSEK,‡ N.H. BROOKS, J.W. DAVIS,† R.C. ISLER,* A. KIRSCHNER,‡ R. LAENGNER,‡ C.J. LASNIER,¶ Y. MU,† J. MUNOZ,§ D.L. RUDAKOV,# O. SCHMITZ,‡ E.A. UNTERBERG,* J.G. WATKINS,◊ D.G.WHYTE,◆ and C.P.C. WONG

This is a preprint of a paper to be submitted for publication in *J. Nucl. Mater.*

*Oak Ridge National Laboratory, Oak Ridge, Tennessee.
†University of Toronto Institute for Aerospace Studies, Toronto, Canada.
‡Institut fuer Plasmaphysik Forschungszentrum, Juelich, Germany.
¶Lawrence Livermore National Laboratory, Livermore, California.
§Oak Ridge Institute for Science and Education, Oak Ridge, Tennessee.
#University of California-San Diego, La Jolla, California.
◊Sandia National Laboratories, Albuquerque, New Mexico.
◆MIT Plasma Science and Fusion Center, Cambridge, Massachusetts.

Work supported by
the U.S. Department of Energy under
DE-AC05-00OR22725, DE-AC52-07NA27344,
DE-FG02-07ER54917,DE-FC02-04ER54698,
DE-AC04-94AL85000, and DE-FG02-04ER54767

GENERAL ATOMICS PROJECT 30200
JULY 2010

ABSTRACT

The Porous Plug Injector (PPI) has proven to be an invaluable diagnostic for *in situ* characterization and quantification of erosion phenomena in DIII-D. Previous work has led to derivation of three primary figures of merit for chemical erosion (CE) in attached and cold divertor conditions: relative intensity of C^+ impurities from chemical and physical sources, the CE yield (Y_{chem}), and effective photon efficiencies for chemically eroded products. Application of these figures of merit for accounting of observed absolutely calibrated CI and CII emission intensities is demonstrated to produce a self-consistent solution at the DIII-D targets. Reinterpretation of the CI (C^0) spectral lineshape profile supports the relative roles of local chemical versus physical sputtering as previously determined for CII (C^+). Finally, comparison of calculated *in situ* Y_{chem} to that measured *ex situ* suggests a tokamak-specific lower energy threshold for CE, and presents potentially major implications for prediction of tritium co-deposition near the divertor targets in ITER.

I. INTRODUCTION

Chemical erosion (CE) plays a fundamental role in tritium co-deposition, target lifetime, and flake and dust formation in present day fusion devices. Furthering understanding of the myriad of processes involved in CE and their complex parametric dependence is crucial for the successful operation of ITER with carbon divertor targets [1,2]. The porous plug injector (PPI) [3] was built for the DIII-D Divertor Materials Evaluation System (DiMES) for detailed *in situ* study of CE-related phenomena using spectroscopic and surface analysis techniques, and operating in a variety of plasma and plasma-facing surface conditions.

Artificial injection of both simple and complex hydrocarbons (CH_4 and C_2H_y/C_3H_y, respectively) from the PPI at known and controlled rates on the order of local natural CE into the outer strike point (OSP) (10^{17}–10^{18} molecules/s over a circular area 3 cm in diameter, for an injected particle flux density of 10^{20}–10^{21} $C/m^2/s$) provides direct comparison to intrinsic emission levels for calibration of spectroscopic signals, with minimized risk of local plasma perturbation. The PPI has made it possible to quantify ensemble figures of merit for CE including the relative intensity of C^+ from local chemical, local physical, and non-local sources, the gross CE yield (Y_{chem}) including the effects of re-erosion and re-deposition, and evaluation of effective photon efficiencies for chemically eroded products to relate spectral emissions to particle fluxes at specific plasma condition.

In the present work, past results acquired utilizing the PPI through experiment [4,5,6] and computer simulation using 3D DIVIMP-HC [7,8] are combined with reinterpreted analysis, and placed in context with measured *ex situ* laboratory data in order to draw conclusions about the nature of CE itself. Erosion yield data from the PPI are then compared to figures of merit which have been used to date for modelling of ITER, with implications for a significant reduction in the expected CE-produced carbon influx, and the associated amount of tritium co-deposition.

II. EXPERIMENT AND OBSERVATIONS

Geometry of the PPI DiMES sample with respect to adjacent tiles, and the orientation of the magnetic configuration are shown in Fig. 1. An L-mode deuterium plasma with a lower single-null (LSN) shape was developed for operation of the PPI with parameters of $I_p = 1.1$ MA, $B = 2.0$ T, $P_{NBI} \sim 0.23$ MW, $\Psi = 2.5°$, and $\langle n_e \rangle \sim 2.5\times10^{19}$ m^{-3} in attachment and $\langle n_e \rangle \sim 5.0\times10^{19}$ m^{-3} in a cold divertor condition. OSP plasma parameters were as follows: In plasma attachment, $\Gamma^{||}_{D^+,att} \sim 3.0\times10^{22}\,/m^2/s$, $n_e \sim 1.5\times10^{19}\,/m^3$ and $T_e \sim 25$ eV, and in a semi-detached cold divertor, $\Gamma^{||}_{D^+,cold} \sim 6.5\times10^{22}\,/m^2/s$ ($\sim 2\times$ higher than in attachment), $n_e \sim 6.0\times10^{19}\,/m^3$ and $T_e \sim$ 2–3 eV. The CH_4 injection rate from the PPI was in the range of $2\times10^{17} < \Gamma_{CH_4,PPI} < 8\times10^{17}$ mol/s.

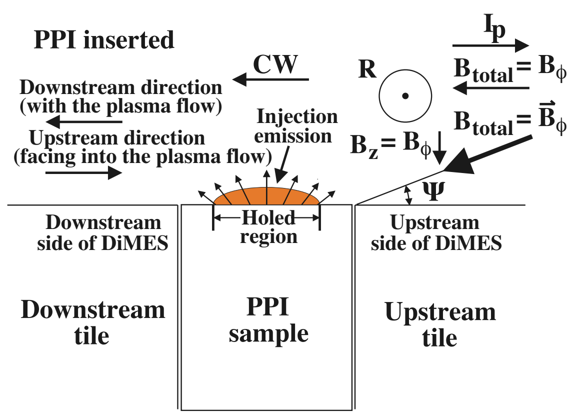

Fig. 1. Toroidal cross section of the PPI DiMES sample and adjacent tiles showing magnetic geometry and the location of measured spectral emissions.

Inverse photon efficiencies for CH_4 injection were found to vary as expected based on latest HYDKIN simulations [9]. Spectral emission of the CH-band emission (427-431.5 nm) as a consequence of the PPI puff is found to be from ~ equal to ~ 1/4 the strength to that of the CD-band (426-430.5 nm) from intrinsic chemical erosion.

Surface temperature of the PPI cap was measured by infrared (IR) camera to rise from room temperature to $T_{surf} \sim 450$ K in attachment, and $T_{surf} \sim 350$ K in the cold divertor; these temperatures are significantly greater than those of the surrounding graphite tiles due to the low thermal mass of the PPI cap. Temperature of the (1.6 mm) thin PPI cap was also measured from the back by an embedded type-E thermocouple, which collected data from 30-180 s beyond the end of each discharge in order to provide an accurate low-temperature calibration to the IR camera which also took data past its usual 10 s operating window.

In 2010, the PPI was also utilized in attached and detached plasmas in DIII-D during injection of both CH_4 and C_2H_4. The latter, ethylene, was chosen based on the *ex situ* measurement by Mech, *et al.* [10] which suggests that C_2H_4 is the most prominent HC produced in chemical erosion after CH_4 for typical OSP plasma conditions and T_{surf} ~ 350-450 K. As well, C_2H_4 is indicative of HCs containing a C=C double bond (145 kcal/mole bond energy compared to 80 kcal/mole for a C-C single bond such as in C_2H_6, and 98 kcal/mole for the C-H bond), thus it is expected to lead to significant C_2-dimer band emission after H atoms are initially stripped from the molecule by the plasma. These experiments expanded the operating envelope of the LSN L-mode plasma to include $2\times10^{19} < \langle n_e \rangle < 8\times10^{19}\ /\mathrm{m}^3$, and that of the OSP to include $20 < T_e < 40$ eV, $0.8\times10^{19} < n_e < 4\times10^{19}\ /\mathrm{m}^3$ and

$$\Gamma^{||}_{D^+,\mathrm{att}} \sim 3\times10^{22}\ /\mathrm{m}^2/\mathrm{s} \quad ,$$

in attachment, reducing to $T_e \sim 1$ eV with $\Gamma^{||}_{D^+,\mathrm{det}} \sim 5\times10^{21}\ /\mathrm{m}^2/\mathrm{s}$ in detached conditions. HC flow rates from the PPI were

$$5\times10^{17} < \Gamma_{CH_4,PPI} < 1\times10^{18}\ \mathrm{mol/s} \quad ,$$

and

$$4\times10^{17} < \Gamma_{C_2H_4,PPI} < 7\times10^{17}\ \mathrm{mol/s} \quad .$$

Preliminary spectral data from this experiment maintain a previous observation of extinguishment of the intrinsic CD-band emission in detached divertor operation [4]. Upon injection of C_2H_4, the magnitude of the integrated C_2-dimer from the PPI has been measured to be significantly greater (~ 3×) than that of the intrinsic source. This suggests that the role of C=C-containing HCs produced *in situ* by CE is significantly less than suggested by [10]. Detailed results of these experiments will be published and presented in the near future.

Finally, the operation of the PPI has also been applied to an innovative L-mode experiment which includes resonant magnetic perturbations (RMP) leading to creation of a 3D stochastic boundary and lobed strike point structure. In the experiment, individual lobes were passed slowly over the PPI cap to give sufficient time for spectral and digital video characterization. The CH_4 flow rate from the PPI was $4 \times 10^{17} < \Gamma_{CH_4,PPI} < 7 \times 10^{17}$ mol/s. Use of the PPI demonstrated a pronounced reduction in Y_{chem} within the lobed structure which, if it also leads to reduced hydrogenic co-deposition as would be expected, may be a significant positive result for ITER. Preliminary results from the PPI for this experiment may be found in [11].

III. DISCUSSION

The average chemical erosion yield over the MDS view chord at the OSP may be deduced by comparison of the integrated emission from intrinsic sources with that from the PPI for a known injection rate; see [5,6] for details. In attached conditions at the OSP, a yield of ~2.6% is found which is in agreement with laboratory measurements [12]. In the cold divertor, a yield of ~0.5% is found, accounting for ionized hydrogenic flux alone (i.e., no accounting for neutral hydrogenic flux, which may decrease the inferred erosion yield if considered). This latter value is significantly lower than that expected from laboratory measurements: for $E_{impact,D^+} = 10$ eV (where $E_{impact} \approx 5T_e$ after transit through the sheath [13]), $Y_{chem}^{C,\ 300\ K} \approx 0.7 \pm 0.2\%$, increasing to $Y_{chem}^{C,\ 400\ K} \approx 1.5 \pm 0.2\%$ [14]; see Fig. 2. Note, that the cause for this low yield cannot be a flux dependence which has been proposed by Roth [15,16] because the transition from attached to cold divertor plasma is also associated with an $\sim 2\times$ increase in flux simultaneously with a decrease in carbon influx.

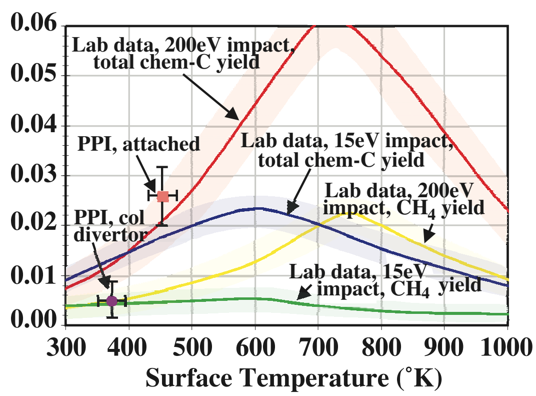

Fig. 2. Chemical erosion yield measured *ex situ* for $E_{impact} = 200$ eV and 15 eV indicative of electron impact energies of ~ 40 eV and 3 eV in attached and cold divertor plasmas, respectively [13]. Y_{chem} measured *in situ* in DIII-D using the PPI are also shown for both plasma conditions.

These observations of reduced CE yields appear to confirm other hints of a mechanism which leads to an energy dependence, and indeed, a low-temperature threshold for CE at the tokamak boundary [10,17]. The impact of such a threshold could be very positive for ITER which will operate with both targets in the semi-detached regime. Plasma parameters modeled at both targets are shown in Fig. 3 [18], as well as the estimated reduction in Y_{chem} near both targets (blue) in the cold divertor plasma region (i.e., $T_e <\sim 2$ eV, shown in yellow). Because this region is also where Γ_{D^+} is the greatest, it is estimated that the reduction in Y_{chem} would reduce the integrated Γ_C by $> 2\times$.

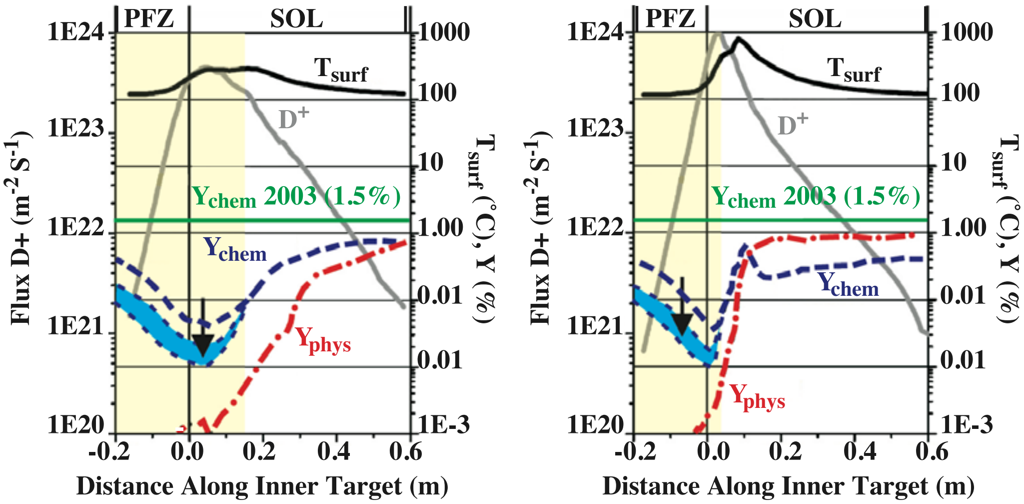

Fig. 3. Plasma and plasma-facing surface conditions expected at the ITER inner (left) and outer (right) strike points with resulting Y_{phys} and Y_{chem} radial profiles [18]. The impact of the current PPI data on the inferred Y_{chem} (with uncertainty) is also shown (by the arrow to the blue region). The drop in Y_{chem} is estimated to result in a 2-4 × reduction in total carbon influx.

It is also important to note that measured intrinsic (natural) and incremental (PPI) spectral emissions upon which the yield calculation is based is reflective of both erosion (i.e., primary C-release) and local re-erosion processes which are taking place in the view of the optical chord (i.e., at the OSP). If re-erosion were a significant process at the OSP, as has been shown for injection of HCs elsewhere [19], the resulting Y_{chem} should be skewed to a higher erosion yield.

A second figure of merit for CE to which data from the PPI is able to contribute significantly is the relative role of CE as it contributes to C^0 and C^+ impurity sources, especially those measured near the targets. In the previous work, [5,6], it was determined that, in attachment, intrinsic C^+ measured near the OSP was sourced almost equally from CE and physical sputtering (PS), and both were primarily local (i.e., not produced elsewhere and subject to long-distance transport/migration.) In cold plasma operation where T_e is below the threshold for PS (~ 3 eV), however, no contribution to C^+ at the OSP is expected from PS and the contribution from CE is determined to be ~ 10-15%. The remaining 85-90% of the measured C^+ is speculated to be non-locally produced (e.g., by CE at the main wall), then streaming into the divertor by fast SOL flows and recombining to lower charge states. For neutral C $\left(C^0\right)$, however, a measure of this figure of merit for CE has been made by lineshape analysis of the CI spectral profile by Isler [20] and Brooks [21] in a method developed originally by Bogen [22]. In this method, a single Gaussian profile is used to represent the emission profile produced by thermally-launched CE products, while a truncated Thompson distribution is used to represent the emission profile produced by energetic C^0 as a consequence of physical sputtering. A best fit of the two profiles is then acquired by a least-squares approach, and the integrated area beneath each contributing profile indicates what portion of the particle source is derived from each source. The result for attached divertor conditions at the OSP is an 80/20 split between CE and PS sources, respectively for C^0, significantly different from the conclusion based on C^+ as derived by data from the PPI (i.e., an ~ 50/50 split).

While there is no requirement for C^0 sources to match those of C^+, reanalysis of the original PPI data using a dual truncated Thompson, i.e., one for each of a low energy (100 eV, 37%) PS population and another for an energetic (500 eV, 30%) PS component representative of fast ions possible as a consequence of neutral beam injection, mixed with the traditional Gaussian function for the CE component (1.0 eV, 33%), the resulting profile is found to be as good a match to the CI emission lineshape data as the single Thompson fit performed by Brooks and Isler in which PS is found to be dominant in attached conditions (Fig. 4). This result presents the intriguing possibility of studying D^+ ion populations at the plasma-facing surface using future, higher resolution/lower dispersion spectrometer/camera combinations.

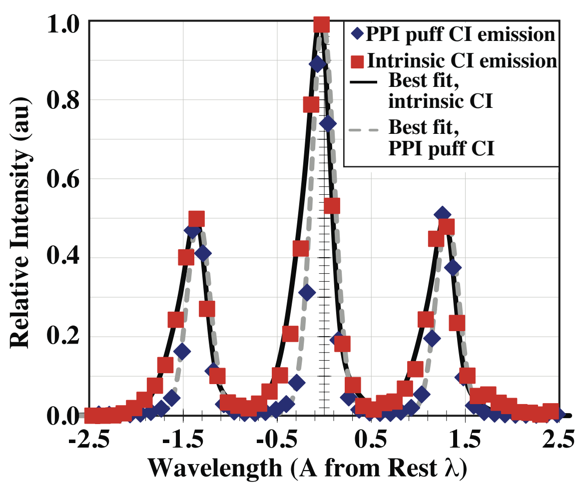

Fig. 4. Zeeman-split CI, 910 nm triplet as measured monitoring the PPI CH_4 puff, and that of the intrinsic, natural emission at the OSP [21]. Best-fit profiles are shown for both cases as discussed in the text.

Finally, application of all three figures of merit as measured with data from the PPI may be integrated into a model to attempt to fully account for spectral emissions at specific wavelengths as measured intrinsically. This is carried out for the CII, 514 nm emission line and shown in Table 1. Entries shown in red are taken from experimental results from operation of the PPI for CE, and from literature for PS. In the case shown, it is found that absolute, intrinsic CII, 514 emission at the OSP may be accounted for with an error of < 10%, well within the estimated error in the absolute calibration of the spectrometer used to make the measurement.

TABLE 1: CII, 514 nm emission intensity continuity results for PPI MkI SAPP shot 122197 with an attached divertor.

Measurement	**[Units]**	**Chemically sourced**	**Physically sourced**
Fractional contribution	-	0.5	0.5
Measured total CI intensity	CII, 514 nm/s/m^2/sr	**2.50x10^{18}**	
CII from each source	CII, 514 nm/s/m^2/sr	1.3x10^{18}	1.3x10^{18}
I_{sat} at OSP (Langmuir probes)	A/m^2	1.5x10^5	
	D$^+$/s/m^2	9.4x10^{23}	
B field angle to the floor	°	1.0	
Perpendicular D$^+$ flux	D$^+$/s/m^2	1.6x10^{22}	
Erosion yield	C/D$^+$	0.025	0.017
C release flux (form)	C/s/m^2	4.1x10^{20} (C_xD_y)	2.7x10^{20} (C)
D/XB (PPI) or S/XB (ADAS)	mol. or atom per ph	39	14
CII photon flux	CII, 514 nm/s/m^2	1.1x10^{19}	1.9x10^{19}
CII photon intensity	CII, 514 nm/s/m^2/sr	8.5x10^{19}	1.5x10^{18}
Factor, measured/expected	-	**1.48**	**0.82**
Total expected intensity	CII, 514 nm/s/m^2/sr	**2.37x10^{18}**	
Factor, measured/expected	-	1.06	

IV. CONCLUSIONS

The DiMES PPI continues to be a powerful *in situ* tool for characterization and quantification of chemical erosion at DIII-D. In this work, significant advancement in the analysis and interpretation of major figures of merit for quantification of chemical erosion are presented and discussed. While chemical erosion yield, Y_{chem}, in attached divertor operation is found to be in line or slightly higher than laboratory measurements, in cold divertor plasma it is determined to be significantly less than measured *ex situ*. This result, combined with an increasing ion flux, but decreasing carbon influx in the cold plasma condition, is highly suggestive of an energy dependence at low T_e, possibly even a threshold for chemical erosion akin to that for physical erosion. Such a dependence would be of significant benefit for the magnitude of hydrogenic (T) retention in carbon codeposits in ITER and is worthy of continued investigation. Re-erosion of HC fragments from the plasma-facing surface at the OSP of DIII-D is not believed to occur with significantly greater yield compared to that of erosion from virgin graphite. This is in contrast to the high re-erosion yield found for relatively large injections of HCs in the boundary of TEXTOR when enhanced Y_{chem} of 7-15% has been inferred by post-mortem analysis and modelling. Reinterpretation of CI lineshape profile analysis carried out on PPI data [20,21] using dual truncated Thompson distributions indicative of both a high and low temperature T_i distribution, resulting in a similar inferred contribution to the C^0 particle source in attached divertor operation as that found for C^+. Application of all three independent figures of merit measured by the PPI for the purpose of accounting for observed absolute emission intensity is found to lead to a self-consistent model C^0 and C^+; this represents a strong case for the validity of the analysis carried out using data from the PPI.

REFERENCES

[1] A. Loarte, *et al*., Nucl. Fusion **47** (2007) S203-S263.

[2] J. Roth, Physica Scripta **T124** (2006) 37.

[3] A.G. McLean, *et al*., Rev. Sci. Instrum. **80** (2009) 043501.

[4] A.G. McLean, *et al*., J. Nucl. Mater. **363-365** (2007) 86.

[5] A.G. McLean, "Quantification of chemical erosion in the divertor of the DIII-D tokamak." PhD thesis, University of Toronto, 2009.

[6] A.G. McLean, *et al*., J. Nucl. Mater. **390-391** (2009) 160.

[6] Y. Mu, *et al*., J. Nucl. Mater. **390-391** (2009) 220.

[7] Y. Mu, *et al*., J. Nucl. Mater., these Proceedings.

[8] J. Westerhout, *et al*., Appl. Phys. Letters. **95** (2009) 151501.

[9] A. Kirschner, *et al*., J. Nucl. Mater. **363-365** (2007) 91.

[10] B.V. Mech, A.A. Haasz, and J.W. Davis, J. Nucl. Mater. **255** (1998) 153.

[11] O. Schmitz, *et al*., J. Nucl. Mater., these Proceedings.

[12] J.W. Davis, and A.A. Haasz, J. Nucl. Mater. **241-243** (1997) 37.

[13] P.C. Stangeby, "The Plasma Boundary of Magnetic Fusion devices", Institute of Physics Publishing, Philadelphia, 2000.

[14] G.M. Wright, *et al*., J. Nucl. Mater. **337-339** (2005) 74.

[15] J. Roth, *et al*., Nucl. Fusion **44** (2004) L21.

[16] J. Roth, *et al*., J. Nucl. Mater. **337-339** (2005) 970.

[17] U. Wenzel, *et al*., J. Nucl. Mater. **290-293** (2001) 352.

[18] A. Kirschner, *et al*., J. Nucl. Mater. **363-365** (2007) 91.

[19] A. Kirschner, *et al*., J. Nucl. Mater., these Proceedings.

[20] R.C. Isler, *et al*., Phys. Plasmas **14** (2007) 012506.

[21] N.H. Brooks, *et al*., J. Nucl. Mater. **363-365** (2007) 131.

[22] P. Bogen and D. Rusbuldt, Nucl. Fusion **32** (1992) 1057.

ACKNOWLEDGMENTS

The authors would like to acknowledge the support of a Collaborative Research Opportunities Grant from the Natural Sciences and Engineering Research Council of Canada and the U.S. Department of Energy. This work supported by the U.S. Department of Energy under DE-AC05-00OR22725, DE-AC52-07NA27344, DE-FG02-07ER54917, DE-FC02-04ER54698, DE-AC04-94AL85000, and DE-FG02-04ER54767.