MEASUREMENTS OF NET VERSUS GROSS EROSION OF MOLYBDENUM DIVERTOR SURFACE IN DIII-D

by
D.L. RUDAKOV, P.C. STANGEBY, N.H. BROOKS, W.R. WAMPLER,
J.N. BROOKS, D.A. BUCHENAUER, J.D. ELDER,
M.E. FENSTERMACHER, A. HASSANEIN, C.J. LASNIER,
A.W. LEONARD, A.G. McLEAN, R.A. MOYER, A. OKAMOTO,
T. SIZYUK, J.G. WATKINS and C.P.C. WONG

OCTOBER 2012

GENERAL ATOMICS

DISCLAIMER

GA–A27410

MEASUREMENTS OF NET VERSUS GROSS EROSION OF MOLYBDENUM DIVERTOR SURFACE IN DIII-D

by

D.L. RUDAKOV,[1] P.C. STANGEBY,[2] N.H. BROOKS, W.R. WAMPLER,[3]
J.N. BROOKS,[4] D.A. BUCHENAUER,[5] J.D. ELDER,[2]
M.E. FENSTERMACHER,[6] A. HASSANEIN,[4] C.J. LASNIER,[6]
A.W. LEONARD, A.G. McLEAN,[6] R.A. MOYER,[1] A. OKAMOTO,[7]
T. SIZYUK,[4] J.G. WATKINS[3] and C.P.C. WONG

[1]University of California San Diego, La Jolla, California USA
[2]University of Toronto Institute for Aerospace Studies, Toronto, Canada
[3]Sandia National Laboratories, Albuquerque, New Mexico USA
[4]Purdue University, West Lafayette, Indiana, USA
[5]Sandia National Laboratories, Livermore, California USA
[6]Lawrence Livermore National Laboratory, Livermore, California USA
[7]Tohoku University, Sendai, Japan

GENERAL ATOMICS PROJECT 30200
OCTOBER 2012

GENERAL ATOMICS

ABSTRACT

A substantial reduction of the net compared to gross erosion of molybdenum was observed in a series of experiments conducted in the lower divertor of DIII-D using the Divertor Material Evaluation System (DiMES). Post-exposure net erosion of Mo films deposited on Si substrate was measured by ion beam analysis (IBA) for samples exposed to well-controlled plasma conditions in three consecutive experiments, yielding net erosion rates of 0.4 – 0.7 nm/s. Gross erosion was estimated in-situ using a filtered camera, and also post-mortem using IBA on a very small sample, where re-deposition is negligible. Net erosion on a Mo sample 1 cm in diameter was reduced by about a factor of 2 compared to gross erosion. The experiment was modeled with the REDEP/WBC erosion/redeposition code package coupled to the ITMC-DYN mixed-material code, with plasma conditions supplied by the OEDGE code using Langmuir probe data input. The code-calculated net/gross erosion rate ratio of 0.46 is in a good agreement with the experiment.

1. INTRODUCTION

Net erosion of high-Z plasma-facing surfaces in a tokamak is expected to be reduced by local redeposition due to sputtered atom collisions with the impinging plasma [1]. In earlier experiments on ASDEX Upgrade [2] and DIII-D [3,4], samples of tungsten, molybdenum and vanadium were exposed to divertor plasma, and post-experiment analysis found redeposited material mostly within a few mm from the samples, supporting the local redeposition picture. Reduction of net compared to gross erosion has been demonstrated for tungsten in ASDEX Upgrade [5]. However, in Alcator C-Mod the measured campaign-integrated peak net erosion of Mo divertor tiles was found to be ~10X higher than that computed using the REDEP/WBC code, while the gross erosion predicted by the code was a reasonable match to MoI influx data [6]. The recent experiments at DIII-D [7] reported here were aimed at measuring both net and gross erosion of Mo under stable well-diagnosed plasma conditions allowing more accurate comparison with the modeling.

Gross erosion rates in tokamaks are usually measured spectroscopically: the intensity of an atomic line of the sputtered impurity is measured and converted to a particle influx rate using an inverse photon efficiency value, $S/XB(T_e)$, obtained from atomic theory or calibrated experiment. This method contains a number of uncertainties. Here we report a novel non-spectroscopic method for measuring the gross erosion rate. It is based on post-experiment IBA analysis of the net erosion of a sample that is smaller than the mean free pass of the sputtered atoms for the plasma conditions involved. Thus local redeposition on the sample is unlikely and gross erosion is expected to be close to net erosion. The latter assumption was verified by modeling (see Sections 2 and 3).

2. EXPERIMENTAL ARRANGEMENT AND RESULTS

Three experiments were conducted in the lower divertor of the DIII-D tokamak [8]. Molybdenum was chosen over tungsten for better known S/XB coefficients, and also for better comparison with Alcator C-Mod results. In order for net erosion to be measurable by ion bean analysis (IBA), thin coatings of Mo on silicon substrate were used. All samples featured a 1 cm diameter Mo-coated spot [Fig. 1(a)], while in the latest experiment there was also a 1 mm spot for gross erosion measurement [Fig. 1(c)]. The samples were installed in graphite casings and inserted flush with the divertor tiles using the Divertor Material Evaluation System (DiMES) manipulator [9]. All experiments were performed in L-mode deuterium discharges, in Lower Single Null (LSN) magnetic configuration, with the attached outer strike point (OSP) dwelling near the inboard edge of the samples for 3–4 s in each exposure discharge.
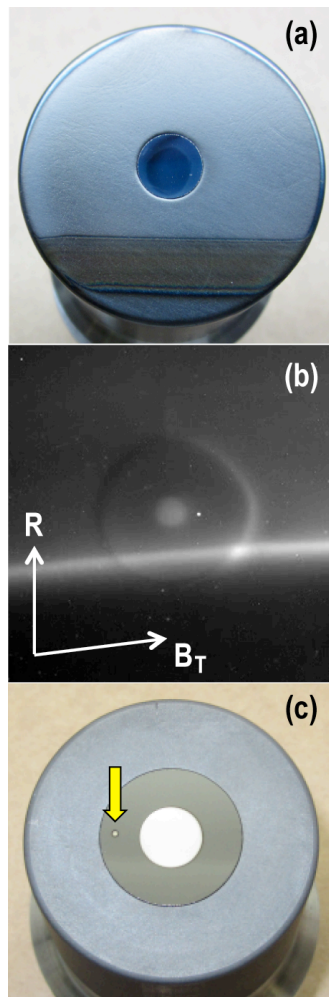

FIG. 1. (a) Post-exposure photograph of the DiMES holder with Mo sample in first experiment; (b) image of the sample taken during the first experiment by a CCD camera with MoI 390 nm filter; (c) sample with additional 1 mm Mo spot used in third experiment.
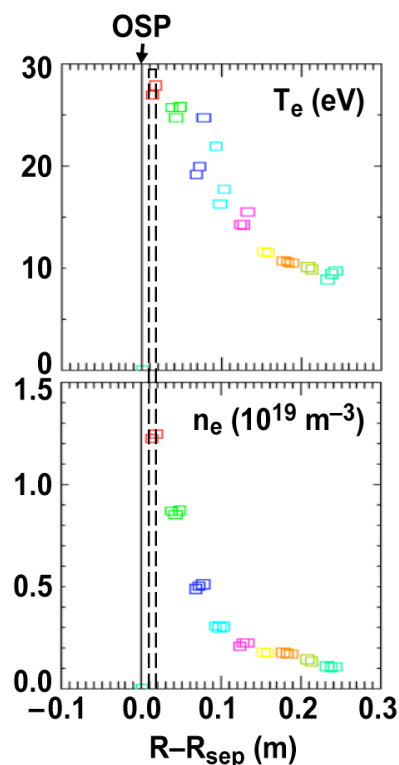

FIG. 2. Langmuir probe profiles of electron temperature and density across the lower outer divertor in the first experiment. Location of the 1 cm Mo sample is showed by dashed lines.

In the first experiment a silicon disk 1 cm in diameter coated with a 24 nm thick film of Mo was exposed in a series of 7 reproducible discharges for a total plasma exposure time of ~28 s. The plasma density and temperature near the OSP were measured by the divertor Langmuir probes [Fig. 2]. The gross erosion rate of Mo, essentially completely due to a ~1% plasma carbon background, was measured spectroscopically, using an absolutely calibrated CCD camera with MoI filter centered around 390 nm and having a bandwidth of ~10 nm. A sample image from the camera is shown in Fig. 1(b). The 10 nm bandwidth passed several non-MoI lines and also a few CII lines identified using a high resolution MDS spectrometer [10] which

was not, however, intensity calibrated for this wavelength, [Fig. 3]. The bright strip in Fig. 1(b) corresponds to the location of the OSP, as determined by magnetic equilibrium reconstruction, and is due to CII, while the illuminated circle is MoI light plus emission of several other lines in the passband. By correcting for contributions of the non-MoI lines passed by the filter, a first estimate of 0.68 nm/s for the gross erosion rate was made using the inverse photon efficiency, S/XB, for the MoI line measured on PISCES by Nishijima et al. [11]. Allowance was also made for (i) the transmission of the 10 nm filter, (ii) the transmission of a second filter used to block the intense D_α line, (iii) the transmission of the vacuum window, (iv) reflection from the Mo surface and (v) the fact that only part of the MoI triplet near 390 nm was passed by the filter. The combined uncertainty was estimated to be a factor of ~ 4X. Therefore in the second and third experiments, a 1 nm bandwidth filter centered on the MoI line at 386 nm was used. The high resolution spectrometer measured no emission in this 1 nm passband other than the MoI line and the camera view no longer registered the bright CII band along the strike point location. The resulting uncertainty estimate for the further experiments was reduced by an estimated factor of 2.

Net erosion of Mo was measured by comparing the Mo layer thickness measured by Rutherford backscattering (RBS) before and after the exposure [12]. Measured toroidal and poloidal profiles of the net Mo erosion across the sample are shown in Fig. 4(a). The reduction of Mo thickness in the first experiment was 11±1 nm on the average, corresponding to an average net erosion rate of 0.42 ± 0.03 nm/s for the first experiment.
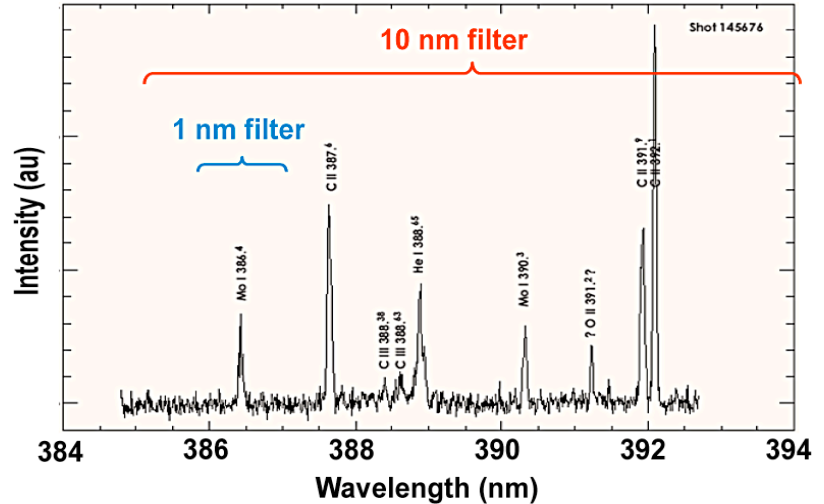

FIG. 3. Spectrum measured by MDS spectrometer view centered on DiMES during the first experiment. Pass bands of the 10 nm filter used in the first experiment and of the 1 nm filter used in second and third experiments are shown schematically.
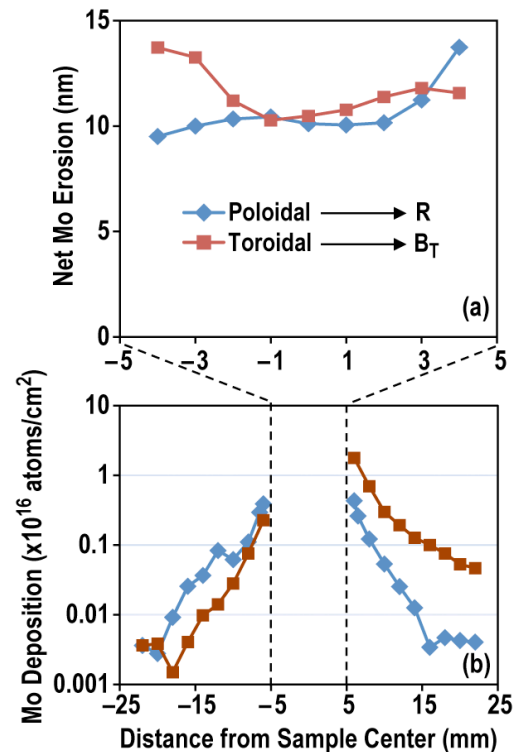

FIG. 4. (a) RBS measurements of net erosion of Mo from the sample (b) and Mo deposition on the graphite holder for the first experiment.
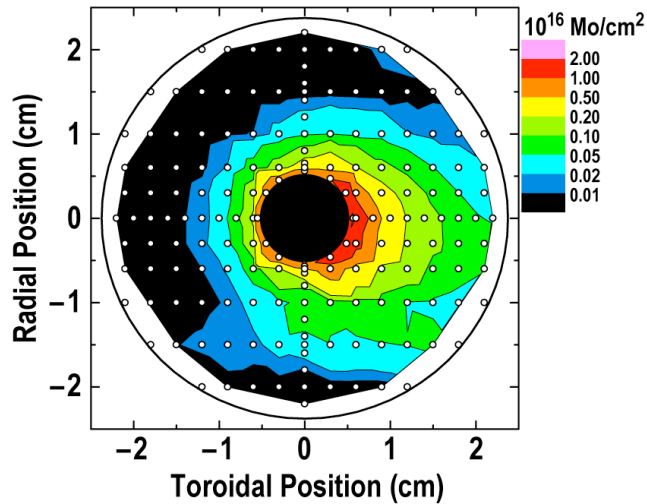
FIG. 5. 2D map of Mo deposited on the complete 5 cm diameter graphite surface in the first experiment.

The distribution of Mo redeposited on the graphite holder was also measured by RBS. Figure 4(b) shows poloidal and toroidal areal density profiles of deposited Mo. A complete 2D map is shown in Fig. 5. As expected by our understanding of the dominant redeposition process, Mo deposits were concentrated near the Mo-coated sample edge, with an e-folding length of ~2 mm. Concentration of the deposited Mo was a factor of 8–10 larger on the downstream side of the sample compared to the upstream side. The total amount of Mo found on the holder was only ~20% of the net amount of Mo eroded from the sample.

[3]He nuclear reaction analysis was used to measure the coverage of carbon on the Mo/Si sample, which was low, and deuterium on the sample and adjacent graphite [12]. Deuterium coverage was low, consistent with net erosion, over most of the probe except for a narrow band just inside the OSP [see Fig. 1(a)], where net deposition occurred at a rate of 1.8×10^{17} carbon atoms/cm^2/s with a relatively high deuterium content of D/C=0.8 atom ratio.

The second experiment was used to establish that (i) the 1 nm filter passed enough light to provide an adequate spectroscopic measurement and (ii) a single discharge exposure of 4 s is sufficient to give an adequate IBA measurement. Accordingly, both were employed for the third experiment where the Langmuir probe measurements indicated that the plasma was somewhat different than in the first experiment: the peak T_e was 40 eV instead of 30 eV and the peak density was 1.2×10^{19} m^{-3} instead of 1.5×10^{19} m^{-3}. For the third experiment a 1 mm diameter Mo sample was included on the graphite head, 0.5 cm upstream of the 1 cm diameter Mo sample where it would receive negligible Mo deposition from the 1 cm sample, Figs. 1(c) and 4(b). For such a small sample and these plasma conditions, simple estimates indicate that very few of the Mo particles sputtered from the 1 mm spot would be expected to return to and deposit back on the 1 mm spot. This was confirmed by detailed REDEP-ITMC code package modeling, Section 3, which found only ~5% redeposited. Thus gross erosion ~ net erosion and so by measuring the net erosion of the 1 mm Mo sample using IBA, a non-spectroscopic method for measuring gross erosion can be carried out.

For the third experiment IBA showed that the thickness of the 1 cm Mo spot reduced from 16.1 nm by 2.93 nm (average values over the spot) for the 4 s plasma exposure, for a net erosion rate of 0.74 ± 0.08 nm/s. The 1 mm Mo spot was reduced from 12.9 nm by 5.26 nm, for a gross erosion rate of 1.38 nm/s after correcting for the 5% deposition on the 1 mm spot. The resulting net/gross erosion ratio measurement of 0.54±12% was close to the code calculated result of 0.46,

Section 3. For the same experiment the spectroscopic method yielded a gross erosion rate of 2.45 nm/s, with uncertainty about a factor of 2, therefore in reasonable agreement with the non-spectroscopic method. The increase in net erosion rate (averaged over the spot) from 0.42 + 0.02 nm/s in the first experiment to 0.74 ± 0.08 nm/s in the third is qualitatively expected from the increased T_e. A quantitative assessment of this difference is being carried out.

3. MODELING

Molybdenum sputtering and transport from DiMES was modeled with the REDEP/WBC [13,14] erosion/redeposition code package coupled to the ITMC-DYN [15-17] mixed-material evolution/response code, part of the HEIGHTS package [18], and with plasma conditions supplied by the OEDGE code with Langmuir probe data input [19]. As described in e.g. [13,14] WBC computes the 3-D, sub-gyro-orbit, full-kinetic motion of sputtered atoms/ions, subject to the Lorentz force motion, and velocity-changing and charge-changing collisions with the plasma. Major new simulation capability involves the Mo/C mixed-material evolution and re-sputtering of Mo deposited in the carbon divertor surface, per coupled REDEP/ITMC-DYN calculations, as described in [20]. Focus of the modeling was on the first experiment.

Modeling inputs include a D plasma with 1% carbon, with nominal at-probe sheath/ plasma boundary conditions for the first experiment, $T_e = T_i = 30$ eV, $n_e = 1.5 \times 10^{19}$ m^{-3} (essentially uniform over the Mo sample surface), sound speed flow at the solid surface, and with measured magnetic field components. The BHI-3D sheath code [21] was used to verify WBC models for the dual structure, magnetic + Debye sheath, including incident carbon ion impingement energy/angle for the studied DIII-D conditions.

The REDEP simulations show a high Mo redeposition fraction (54%) on the 1 cm Mo spot and a consequent ratio of ~2 to 1 for gross/net erosion. The predicted Mo content in the carbon portion of the DiMES head is 13%, which compares well with the IBA measured 19%. Other modeling predictions include a ~100% overall Mo redeposition on the divertor (including the DiMES head) with essentially zero core plasma Mo contamination. The initially surprising result that only 19% of the Mo removed from the 1 cm sample was found on the 5 cm DiMES graphite head is seen in ITMC-DYN modeling to be due to fast saturation of the Mo in C and subsequent re-sputtering. Although experiments 2 and 3 were not simulated in as much detail, initial modeling indicates similar trends. Mo erosion from DiMES is being modeled with the ITMC-DYN/REDEP/WBC sputtering erosion/redeposition code package, with plasma conditions supplied by the OEDGE code using Langmuir probe data input. REDEP simulations show a high Mo redeposition fraction (~50%) on the small Mo spot in good apparent agreement with the post-exposure RBS data, and essentially complete (~100%) redeposition on the divertor generally. Such high-Z sputtered material transport behavior has positive implications for the ITER tungsten divertor; tending to support predictions of low net erosion and core plasma contamination.

4. DISCUSSION AND CONCLUSIONS

For a specific divertor plasma condition (attached L-mode, low density, relatively high T_e) the measured ratio of net to gross erosion was found to agree well with code modeling, i.e. is in accord with the 'standard' model of prompt, local re-deposition. The large model/data discrepancy in the Alcator C-Mod (gross erosion to net erosion measurement of ~3–10 versus a model prediction of > 30) stands in contrast with the experiments reported here. While the discrepancy is not yet understood it must be pointed out that the C-Mod observation was based on campaign-integrated conditions (1300 s) where plasma conditions can vary greatly through the course of a campaign. (The higher gross/net C-Mod ratio, whether measured or modeled, is due to both the much higher density and the use of a full Mo divertor instead of just a small sample as used in this report). On the other hand, for the plasma conditions used here there is not a great difference between net erosion and gross erosion, only a factor of 2, and therefore to be more conclusive, these studies should be extended to include higher density and/or larger samples where, according to the standard model, a lower ratio of net erosion to gross erosion is expected.

The sputtered Mo that does not promptly redeposit on the 1 cm sample apparently travels only a short distance before redeposition adjacent to the edge of the Mo sample, as evidenced by the rapidly decaying profiles of Mo on the C surface, Figs. 4(b) and 5. However, there is also longer range transport of some ions, as expected by the relatively low density and the near-oblique magnetic field angle to the surface. Longer range transport is caused by re-sputtering from the DiMES carbon surface, involving mixed materials effects including a high sputtering rate due to shallow Mo deposition and reduced binding energy of Mo/C relative to Mo/Mo.

A new, non-spectroscopic method for measuring gross erosion rates has been demonstrated, based on post-experiment surface analysis measurement of the net erosion experienced by a very small sample where gross erosion will be close to net erosion. Such a method makes optimum use of the removable DiMES facility, and provides confirmation of the spectroscopic method which is subject to a number of uncertainties, including the values of the S/XB ratio. The non-spectroscopic method provides a means of calibrating S/XB for general tokamak use.

Future studies will examine tungsten, and also aluminum as proxy for Be. As noted above, for the plasma used here, net erosion was only somewhat less than gross erosion, owing to the rather long ionization mean-free-path for the sputtered Mo atoms. In these future studies it is planned to use plasmas with higher densities and thus shorter mean-free-paths and thus lower ratios of net erosion to gross erosion.

REFERENCES

[1]   BROOKS, J.N., Nuclear Tech./Fus. **4** (1983) 33.

[2]   NAUJOKS, D., *et al*., J. Nucl. Mater. **210** (1994) 43.

[3]   BASTASZ, R., *et al*., J. Nucl. Mater. **220-222** (1995) 310.

[4]   WAMPLER, W.R., *et al*., J. Nucl. Mater. **233-237** (1996) 791.

[5]   KRIEGER, K., *et al*., J. Nucl. Mater. **266-269** (1999) 207.

[6]   BROOKS, J.N., *et al*., J. Nucl. Mater. **415** (2011) S112.

[7]   STANGEBY, P.C., *et al*., "An experimental comparison of gross and net erosion of Mo in the DIII-D divertor," 20th Intl. Conf. on Plasma-Surface Interactions in Controlled Fusion Devices, Aachen, Germany, 2012 to be published in the J. Nucl. Mater.

[8]   LUXON, J.L., Nucl. Fusion **42** (2002) 614.

[9]   WONG, C.P.C., *et al*., J. Nucl. Mater. **258–263** (1998) 433.

[10] BROOKS, N.H., *et al.,* Rev. Sci. Instrum. **63** (1992) 5167.

[11] NISHIJIMA, D., *et al*., J. Phys. B: At. Mol. Opt. Phys. **43** (2010) 225701.

[12] WAMPLER, W.R., *et al*., "Measurements of net erosion and redeposition of molybdenum in DIII-D," 20th Intl. Conf. on Plasma-Surface Interactions in Controlled Fusion Devices, Aachen, Germany, 2012 to be published in the J. Nucl. Mater.

[13] BROOKS, J.N., Phys. Fluids **8** (1990) 1858.

[14] BROOKS, J.N., WHYTE, D.G., Nucl. Fusion **39** (1999) 525.

[15] HASSANEIN, A., SMITH, D.L., Nucl. Instr. and Meth. B **13** (1986) 225.

[16] SIZYUK, T., HASSANEIN, A., J. Nucl. Mater. **404** (2010) 60-67.

[17] SIZYUK, T., HASSANEIN, A., "Dynamic evolution of plasma facing surfaces in NSTX: impact of impurities and substrate composition on fuel recycling," 20th Intl. Conf. on Plasma-Surface Interactions in Controlled Fusion Devices, Aachen, Germany, 2012 to be published in the J. Nucl. Mater.

[18] HASSANEIN, A., SIZYUK, V., MILOSHEVSKY, G., SIZYUK, T., "Can tokamaks PFC survive a single event of any plasma instabilities?," 20th Intl. Conf. on Plasma-Surface Interactions in Controlled Fusion Devices, Aachen, Germany, 2012 to be published in the J. Nucl. Mater.

[19] STANGEBY, P.C., *et al*., J. Nucl. Mater. **313–316** (2003) 883.

[20] BROOKS, J.N., *et al*., "Advanced simulation of mixed-material erosion/evolution and application to Mo, C, Be, W containing plasma facing components," 20th Intl. Conf. on Plasma-Surface Interactions in Controlled Fusion Devices, Aachen, Germany, 2012 to be published in the J. Nucl. Mater.

[21] BROOKS, J.N., NAJUOKS, D., Phys. Plasmas **7** (2000) 2565.

ACKNOWLEDGMENT