Journal of Nuclear Materials 196–198 (1992) 686–691
North-Holland

journal of nuclear materials

Wall conditioning with impurity pellet injection on TFTR

J.A. Snipes, E.S. Marmar and J.L. Terry
MIT Plasma Fusion Center, 167 Albany Street NW 17-103, Cambridge, MA 02139, USA

M.G. Bell, R.V. Budny, K.W. Hill, D.L. Jassby, D.K. Mansfield, D.M. Meade, H.K. Park, J.D. Strachan, B.C. Stratton, E.J. Synakowski, G. Taylor and the TFTR Group
Princeton Plasma Physics Laboratory, P.O. Box 451, Princeton, NJ 08543, USA

D.N. Ruzic and M. Shaheen
University of Illinois, Nuclear Engineering Department, 103 S. Goodwin Avenue, Urbana, IL 61801, USA

Solid lithium and boron pellets have been injected into TFTR plasmas to improve plasma performance by coating the graphite inner wall bumper limiter with a small amount of lower Z pellet material, which reduces the influx of carbon from the walls and reduces the edge electron density. This new wall conditioning technique has been applied successfully when continued He conditioning discharges, which are normally used for wall conditioning, no longer significantly reduce the carbon and deuterium influxes. The results show that both Li and B pellets significantly improve wall conditioning and lead to 15–20% improvements in supershot plasma performance when injected ≥ 1 s prior to neutral beam injection in supershot target plasmas. Neutral beam penetration calculations indicate that the lower edge densities resulting from Li or B pellet wall conditioning lead to improved beam penetration. Sputtering yield calculations confirm that the addition of small amounts of Li on a graphite target can significantly reduce the C sputtering yield.

1. Introduction

Supershot plasma performance in TFTR is presently limited by several factors including the onset of MHD activity at high neutral beam (NB) power and the difficulty in reaching low target densities to achieve improved NB penetration [1]. Through various wall conditioning techniques [2–4], attempts have been made to remove adsorbed gases from the graphite limiter to reduce deuterium recycling and reduce the electron density. Boronisation has greatly reduced the oxygen levels in the plasma and standard ohmic He conditioning plasmas ($I_p = 1.4$ MA, $B_T = 4$ T) are routinely used to reduce the D influx.

Recently, a new wall conditioning technique using low Z impurity pellet injection has been discovered [5,6] that further enhances the plasma performance. Lithium, boron, and carbon (graphite) pellets were injected into standard He conditioning plasmas to test their wall conditioning properties. The parameters that are used to judge the quality of the wall conditioning are the electron density, edge carbon emission, and edge D_α emission. The injection of Li and B pellets significantly reduced the edge carbon emission (C^+), the edge electron density, and the total electron density. Discharges following Li pellet injection also tended to have lower D_α emission. By injecting Li pellets into a series of He conditioning discharges, the pre-pellet electron density and carbon content of the plasma decreased much more quickly than with He conditioning alone. The injection of carbon pellets, on the other hand, only slightly decreased the electron density and did not decrease the C^+ emission nor the D_α emission in the subsequent discharge.

Single Li or B pellets injected into supershot target plasmas about 1 s before neutral beam injection (NBI) reduced the carbon content during the supershots and increased the maximum neutron rates by 8–20% over similar discharges without impurity pellets. Li pellets were used in the discharge that achieved a record neutron rate ($S_n = 5 \times 10^{16}$ n/s), as well as in many of the discharges having the highest values of Q_{dd} ($1.5 \times 10^{-3} < Q_{dd} < 1.8 \times 10^{-3}$) for TFTR. Enhancements were also observed in the plasma stored energy, beta poloidal, energy confinement time, and central ion temperature.

An explanation for the observed improvements in plasma performance following Li or B pellet injection is that the Li or B coats the graphite limiter with a layer of lower Z pellet material, which then reduces both the chemical and physical sputtering of carbon from the limiter. Schemes to use Li alloys with higher

Z metals have been proposed to reduce plasma impurities and sputter erosion in future magnetic fusion devices [7,8]. Calculations have been done to determine what effect a small amount of Li would have on the sputtering yield of C from a graphite target. Assuming that the surface binding energy is changed in proportion to the amount of Li coverage of the graphite, the calculated sputtering yields of C from a graphite target by D, He, and C projectiles with energies of 100 and 300 eV are significantly reduced by a thin layer of Li.

2. Impurity pellet injection into He conditioning discharges

Lithium, boron, and carbon pellets were injected into a series of He conditioning discharges to test their effects on the wall conditioning of the subsequent discharges. In discharges after B pellet injection, both the electron density and the C^+ emission decreased significantly in comparison with similar discharges that were not preceded by impurity pellet injection. The D_α emission, however, showed no trends for the shots available. In discharges after Li pellet injection, the electron density and C^+ emission also decreased significantly compared to similar discharges that were not preceded by impurity pellet injection and the D_α emission typically decreased as well. Fig. 1 shows the line integrated central electron density and the C^+ emission measured at 3.0 s as a function of shot number throughout a series of He conditioning discharges. There is a clear change in slope of the electron density and C^+ emission versus shot number in the discharges with Li pellets. The change in slope indicates that the rate of reduction of the central electron density and carbon content is more than an order of magnitude greater with Li pellet injection than without. These

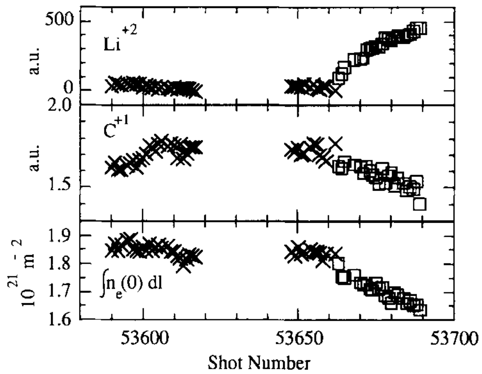

Fig. 1. The intensity of a Li^{2+} line, the edge carbon emission C^+, and the central line integrated electron density measured at 3.0 s in a series of ohmic He conditioning discharges. Squares indicate those discharges after a discharge in which a Li pellet was injected at 3.2 s.

results show that the wall conditioning process can be greatly accelerated by adding a single Li or B pellet to every discharge. In discharges after C pellet injection, the electron density decreased noticeably in comparison with similar discharges that were not preceded by impurity pellet injection. The C^+ emission and D_α emission, however, showed little change in the discharge following a discharge with a C pellet.

Fig. 1 also shows the intensity of the $n = 2$ to 1 transition in Li^{2+} measured just before the pellet injection time. It indicates that the amount of background Li increases (from zero) over this sequence of discharges. Detailed calculations based on spectroscopic measurements show that the concentration of background Li remains small, such that, at the end of this series of discharges $n_{Li}/n_C \approx 0.03$. Since the remainder of the plasma is almost entirely C (based on the measured Z_{eff}), the total number of Li ions in the plasma is $N_{Li} \lesssim 1.5 \times 10^{18}$, while the total number of C ions has decreased from the beginning to the end of this series of discharges by $\approx 5 \times 10^{18}$. So, the Li ions are not simply replacing the C ions. The Li coating apparently adheres to the wall and helps to retain C on the wall. While no absolute measurements of the total carbon content of the plasma were made, the reduced influx indicates that the overall content of carbon must also be reduced in the discharges following Li pellet injection. Note that the number of Li atoms in a single pellet ($\sim 3 \times 10^{20}$) is much larger than the number of Li ions in the plasma even after 23 successive discharges, each with a Li pellet. The number of atoms in a single pellet is calculated to cover 1–2 monolayers of the active surface of the inner wall bumper limiter, assuming uniform coverage on a smooth surface.

In the comparisons between Li, B, and C pellets, the number of electrons in each pellet was nearly the same, but the number of atoms varied substantially ($N_{Li} \approx 4.5$, $N_B \approx 2.9$, $N_C \approx 2.3 \times 10^{20}$ atoms). Thus, the amount of coating of the limiter is different for each pellet.

3. Supershot results

Lithium, boron, and carbon pellets were also injected into supershot target plasmas ≥ 1 s before the start of NBI to improve the supershot plasma performance. About 1 s after pellet injection, the density is less than or equal to the pre-pellet value. This 1 s interval is long compared to the particle confinement time. Thus, the pellet material has enough time to leave the plasma and be deposited on the limiter before NBI begins. The supershots with such Li or B pellet "preinjection" had improved performance over similar supershots without impurity pellet injection. Increases of 10–20% in the central ion temperature, plasma stored energy, neutron rate, and energy con-

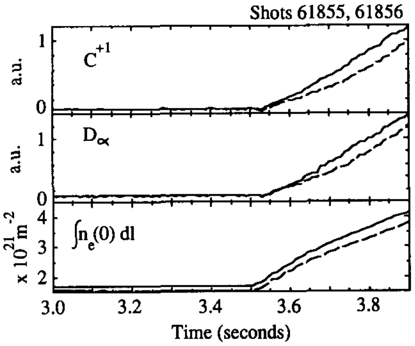

Fig. 2. Inboard edge line integrated electron density, C^+, and D_α emission versus time just before and during NBI for a pair of nearly identical supershots, one with a B pellet injected at 2.0 s (dashed line) and the other without a pellet (solid line). NBI occurs from 3.5 to 4.5 s at 23 MW.

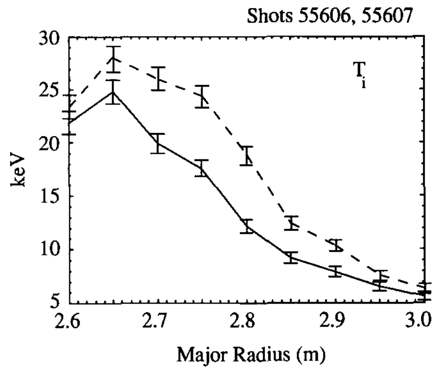

Fig. 3. Charge exchange ion temperature profiles at 3.32 s comparing similar supershots with (dashed line) and without (solid line) Li pellet preinjection at 2 s. Note that the profile does not include all of the plasma cross-section.

finement time were observed following Li or B pellet preinjection. One attempt was also made with a large C pellet ($N_C \approx 4.2 \times 10^{20}$ atoms) that resulted in an immediate disruption in the ohmic target plasma. As a result, no comparisons of supershot performance with C pellets were done.

3.1. Edge effects

As in the He conditioning discharges, the injection of Li or B pellets into deuterium supershot target plasmas reduced the target density and the C^+ emission ≈ 1 s after pellet injection compared to no pellet shots. Thus, at the start of NBI, more than 1 s after impurity pellet injection, the target density and carbon levels were lower than in discharges without impurity pellet preinjection. During NBI, the D_α emission was also reduced in discharges with Li or B pellet preinjection (fig. 2). The outermost measurement of the electron temperature from ECE, about 5 to 8 cm inside the last closed flux surface, shows little difference in the electron temperature near the edge during NBI with or without impurity pellet preinjection. Thus, the reduced carbon and deuterium influxes during NBI following impurity pellet injection appear not to be due to changes in the edge electron temperature.

3.2. Improved plasma performance

Improvements in the core region and global plasma parameters are also observed during supershots with Li or B pellet preinjection. The enhancements include higher peak neutron rate (5–20%), plasma stored energy (5–12%), energy confinement time (5–14%), and core ion temperature (8–20%) during supershots with impurity pellet preinjection.

Many of the profiles of the basic plasma parameters during NBI are also affected by Li or B pellet preinjection. Usually, the differences in the electron temperature profile during NBI between these pellet and no-pellet supershots are small, but the differences in the ion temperature profile can be significant. Fig. 3 shows a comparison of the charge exchange recombination spectroscopy (CHERS) ion temperature profiles during the rise of the neutron rate at 3.32 s for two similar supershots with and without a Li pellet injected at 2.0 s. The ion temperature in the discharge with the Li pellet is substantially higher over the central part of the profile and the difference is well outside the error bars of the measurements. Note that this is only a partial profile in that the plasma edge is at about 3.25 m.

The electron density profile also shows significant differences in the supershots with Li or B pellet preinjection. The profiles during NBI become significantly more peaked with the maximum profile peakedness ($F_{ne} = N_e(0)/\langle n_e \rangle$) increasing 8–15% in discharges with a Li or B pellet. Fig. 4 shows a comparison of the

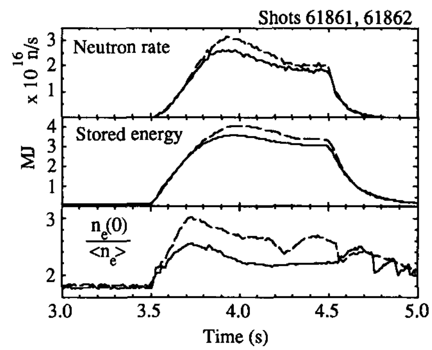

Fig. 4. Neutron rate, plasma stored energy, and density profile peakedness for a pair of similar supershots with (dashed line) and without (solid line) a boron pellet injected at 2.0 s. NBI is on from 3.5 to 4.5 s at the same power for both shots.

neutron rate, plasma stored energy, and F_{ne} for two similar supershots with and without a B pellet injected 1.5 s before NBI. Note that F_{ne} is the same for both discharges just before NBI. Then, the shot with B pellet preinjection becomes significantly more peaked and remains more peaked throughout the NB pulse. It appears that the wall conditioning effect of the B is responsible for substantially increasing the density profile peakedness during NBI.

3.3. Persistent effects

To determine for how many discharges the Li wall conditioning effects persist, several similar supershots were run without Li pellets after a series of 25 supershots with Li pellets. Plasma performance was slightly reduced in the first no-pellet discharge, but then degraded over the next three no-pellet discharges to a level only slightly above that achieved before any Li pellets had been injected. Thus, the effects of the Li persist for 3–4 shots. Further experiments were performed to determine if increasing the amount of Li in the plasma would further improve supershot performance. Since the Li effects apparently persist for a few shots, it was thought that additional Li deposition could be achieved by injecting a Li pellet near the end of one discharge, and then injecting another Li pellet 1 s before NBI in the following discharge. The idea was that the Li atoms from the first pellet would coat the limiter and not be buried nor burned away before the Li atoms from the pellet in the second discharge added another coat. Further enhancements in the peak neutron rate, plasma stored energy, and energy confinement time were observed in the discharges with a "double" Li pellet coating compared to discharges with only a "single" Li pellet coating. Double pellet sequences such as these produced 16–22% higher maximum neutron rates. In particular, the discharge that produced the highest neutron rate achieved to date in TFTR (5×10^{16} n/s) had such a "double" Li pellet coating. Fig. 5 shows the maximum neutron rate for a large number of TFTR supershots clearly demonstrating that the discharges with Li pellet preinjection (squares) generally have higher neutron rates than no-pellet discharges. These results suggest that additional deposition of Li or B may further improve plasma performance. It is clear that changes in the plasma wall interaction physics, which in this case are due to a small amount of Li or B atoms on the limiter, can also strongly affect the central plasma parameters in agreement with previous observations of supershots [9].

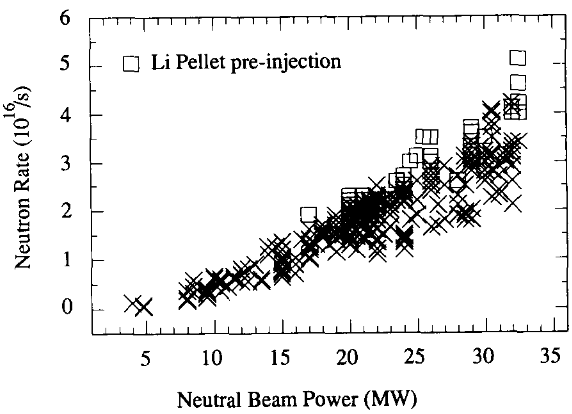

Fig. 5. Peak neutron rate for a large number of TFTR supershots with (squares) and without (crosses) Li pellet preinjection.

Table 1
Sputtering yields of carbon and lithium. See text for details

Projectiles	1	2	3	4	5	6
Carbon						
D, 100 eV	0.042 ± 0.003	0.018 ± 0.004	0.017 ± 0.004	0.034 ± 0.006	0.034 ± 0.006	0.000
300 eV	0.061 ± 0.003	0.033 ± 0.006	0.018 ± 0.004	0.048 ± 0.007	0.025 ± 0.005	0.000
He, 100 eV	0.109 ± 0.005	0.059 ± 0.008	0.028 ± 0.005	0.094 ± 0.010	0.046 ± 0.007	0.00
300 eV	0.231 ± 0.007	0.092 ± 0.010	0.104 ± 0.010	0.195 ± 0.014	0.115 ± 0.011	0.000
C, 100 eV	0.173 ± 0.006	0.106 ± 0.010	0.057 ± 0.008	0.137 ± 0.012	0.059 ± 0.008	0.000
300 eV	0.595 ± 0.011	0.374 ± 0.019	0.196 ± 0.014	0.447 ± 0.021	0.288 ± 0.017	0.000
Lithium						
D, 100 eV	0.000	0.062 ± 0.008	0.074 ± 0.009	0.006 ± 0.001	0.051 ± 0.007	0.159 ± 0.006
300 eV	0.000	0.050 ± 0.007	0.074 ± 0.009	0.006 ± 0.001	0.060 ± 0.008	0.145 ± 0.005
He, 100 eV	0.000	0.153 ± 0.012	0.188 ± 0.014	0.014 ± 0.002	0.145 ± 0.012	0.315 ± 0.008
300 eV	0.000	0.152 ± 0.012	0.236 ± 0.015	0.023 ± 0.002	0.157 ± 0.013	0.340 ± 0.008
C, 100 eV	0.000	0.277 ± 0.017	0.357 ± 0.019	0.020 ± 0.002	0.278 ± 0.017	0.741 ± 0.012
300 eV	0.000	0.376 ± 0.019	0.487 ± 0.022	0.059 ± 0.003	0.370 ± 0.019	0.991 ± 0.014

3.4. Time dependent transport code results

Comparisons of the neutron rate, beam penetration, and plasma confinement between similar supershots with and without Li or B pellet preinjection were also made through calculations with the TRANSP code [10]. The calculations indicate that the reduced edge density and carbon content of the discharge help to improve NB penetration in the first few hundred milliseconds of NBI. This leads to a more peaked density profile, which improves energy confinement. The peaked density profile also results in large increases in the thermonuclear neutron rate (50–100%) and in the beam–target neutron rate (15–30%), while the beam–beam component remains essentially unchanged during the first 400–500 ms of NBI.

4. Sputtering calculations

Calculations of the sputtering yield of Li and C from targets containing various mixtures of Li and C were done with VFTRIM [11,12], a vectorized fractal variation of TRIM [13]. The projectiles used were D, He, and C with energies of 100 and 300 eV. The angle of incidence was taken to be 45° with a fractal dimension of 2.05, which allows for roughness of the surface. The targets used were 1) 100% carbon, 2) 2 Å of Li on C, 3) 4 Å of Li on C, 4) 10% Li and 90% C throughout, 5) 50% Li and 50% C for the top 4 Å, then 10% Li and 90% C, and 6) 100% Li. The binding energy of C was taken as 3.8 eV at the lattice site with an additional surface term of 3.5 eV. The Li surface binding energy was taken as 1.6 eV. In the mixed surface layers, the surface binding energies were averaged by atomic concentration.

The results (table 1) show that a layer of Li on C (column 2) significantly reduces the C sputtering yield for all projectiles compared with a pure C target (column 1). By doubling the thickness of the layer, the sputtering yield is further reduced (column 3). With 10% Li imbedded in C, the C yields also dropped significantly (column 4). With 50% Li imbedded in the first 4 Å, the C yields decreased even more (column 5). Note, however, that the Li sputtering yields increase substantially with increased coverage of Li on the surface. The calculations can be compared with the experimental results from He conditioning plasmas given in section 2. Taking the ratio of the decrease in the number of C ions in the plasma to the increase in the number of Li ions in the plasma during the He conditioning sequence with Li pellets one obtains $\Delta N_C/\Delta N_{Li} = 4.5/1.5 = 3$. This can be compared with the ratio of the difference between the sputtering yields of C from column 1 and column 4 to the sputtering yields of Li from column 4 for He and C projectiles, which range from 0.94 to 1.8. The exact value depends on the relative amounts of He and C in the plasma. The other cases have C/Li yield ratios much lower than the experiment. Thus, the 10% Li case is closest to the experiment, but still falls somewhat lower in the C/Li yield ratios indicating that a coverage of 5–6% would give better agreement with experiment.

5. Conclusions

By injecting Li or B pellets into TFTR discharges, significant improvements in wall conditioning have been found. In He conditioning discharges, the addition of Li pellets significantly increases the rate of reduction of the target electron density and also significantly reduces the C emission from the plasma. Li or B pellets injected ≈ 1 s before NBI into supershot target plasmas lead to substantial enhancements in the neutron rate, plasma stored energy, ion temperature, and energy confinement time during NBI. Time dependent transport calculations indicate that the reductions in edge density resulting from Li or B pellet wall conditioning lead to improved NB penetration, which then peaks up the density profile and improves confinement. Sputtering yield calculations indicate that a layer of Li on C significantly reduces the C sputtering yield. The results suggest that increasing the coverage of Li or B on the limiter could substantially reduce C sputtering and lead to significant enhancements in plasma performance.

Acknowledgements

The authors would like to thank R. Hawryluk and K. Young for their continued support and to acknowledge the Max Planck Institut für Plasmaphysik for permission to use the TRIM code. The first author would also like to thank S. Cohen, D. Manos, S. Pitcher, and M. Zarnstorff for useful discussions.

References

[1] J.D. Strachan et al., Phys. Rev. Lett. 58 (1987) 1004.
[2] M. Ulrickson et al., Proc. 12th Int. Conf. on Plasma Physics and Controlled Nuclear Fusion Research, Nice, France, 1988, vol. 3 (IAEA, Vienna, 1989) p. 419.
[3] R.J. Hawryluk, et al., Proc. 11th Int. Conf. on Plasma Physics and Controlled Nuclear Fusion Research, Kyoto, Japan, 1986, vol. 1 (IAEA, Vienna, 1987) p. 51.
[4] H.F. Dylla et al., J. Nucl. Mater. 176 & 177 (1990) 337.
[5] J.L. Terry et al., Proc. 13th Int. Conf. on Plasma Physics and Controlled Nuclear Fusion Research, Washington, USA, 1990 (IAEA, Vienna 1991) A-V-5.
[6] J.A. Snipes et al., Proc. 18th Europ. Conf. on Controlled Fusion and Plasma Physics, Berlin, Germany, 1991, vol. III (EPS, Berlin, 1991) p. 141.

[7] A.R. Krauss and D.M. Gruen, J. Nucl. Mater. 103 & 104 (1981) 239.
[8] A.B. DeWald, P.A. Scott, J. Chu and A.R. Krauss, J. Nucl. Mater. 176 & 177 (1990) 848 and references therein.
[9] H.F. Dylla et al., J. Nucl. Mater. 162 & 164 (1989) 128.
[10] R.J. Hawryluk, in: Physics of Plasmas Close to Thermonuclear Conditions, vol. 1 (CEC, Brussels, 1980) p. 19.
[11] D.N. Ruzic, Nucl. Instr. and Meth. B47 (1990) 118.
[12] M. Shaheen and D.N. Ruzic, presented at this Conference (PSI-10).
[13] J P. Biersack and L.G. Haggmark, Nucl. Instr. and Meth. 174 (1980) 257.