Study of the Impact of Pre- and Real-Time Depositions of Lithium on Plasma Performance on NSTX

Gustavo Paganini Canal, Rajesh Maingi, Todd E. Evans, Stanley M. Kaye, and Dennis K. Mansfield

***Abstract*— The efficiency of two lithium (Li) injection methods used on the National Spherical Torus Experiment (NSTX) are compared in terms of the amount of Li used to produce equivalent plasma performance improvements, namely, Li evaporation over the divertor plates, prior to the initiation of the discharge, and real-time Li injection directly into the plasma scrape-off layer during the discharge. The measurements show that the real-time method can affect the energy confinement and the edge stability of NSTX plasmas in a more efficient way than the Li evaporation method, as it requires only a fraction of the amount of Li used by the evaporation method to produce similar improvements.**

***Index Terms*— Lithium, plasma confinement, tokamaks.**

I. Introduction

EXPERIMENTS conducted in several machines have shown improvements on the plasma confinement and edge stability when elemental lithium (Li) is used to coat the plasma-facing components (PFCs) [1]–[20]. While some technologies have been developed to apply thin-film Li coatings onto PFCs prior to the initiation of the discharge [12], [13], other technologies have been designed to deposit Li into the plasma scrape-off layer (SOL) during the discharge, i.e., in real time [1], [6]–[8].

On the National Spherical Torus Experiment (NSTX), three methods of introducing Li into the plasma were used in the past, namely, the pre-deposition via Li evaporation [12], [13], [15], the real-time Li injection [16], and the liquid Li divertor [18]. In this paper, the impact of pre- and real-time Li depositions on the performance of NSTX plasmas is compared in terms of the amount of Li used.

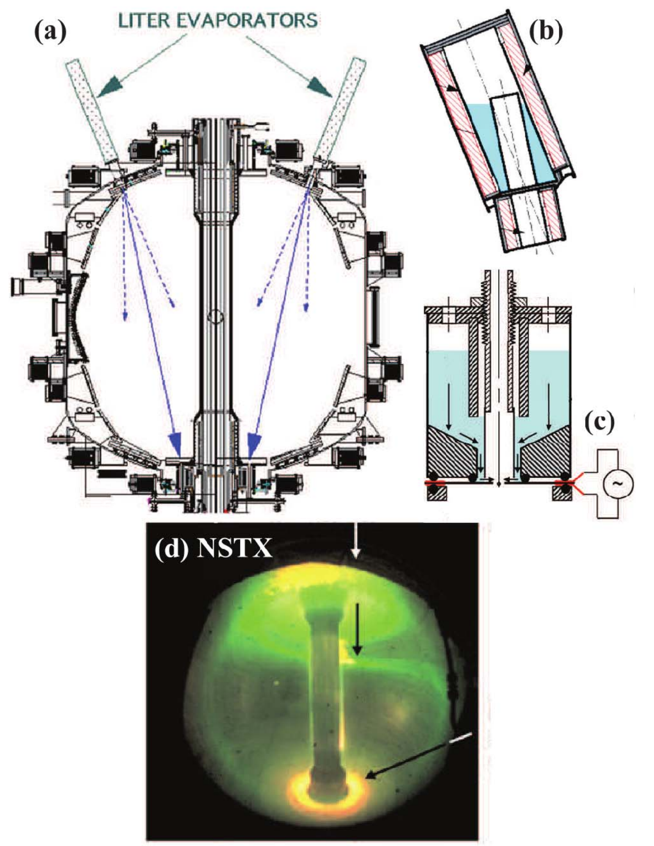

Fig. 1. (a) NSTX cross section showing two LITER units. Schematic of (b) LITER and (c) Dropper. (d) Visible light image of an NSTX plasma with the Dropper in operation.

In the first method, a Li thin film is deposited over the lower divertor targets by evaporation, before the discharge, using a device termed LIThium EvaporatoR (LITER) [12], [13], which consists a reservoir oven with an output duct inserted into a gap of the NSTX upper divertor [see Fig. 1(a) and (b)]. To provide liquid Li, the reservoir oven operates at temperatures between 550 °C and 650 °C, with the output duct operated about 50 °C–100 °C hotter to reduce the Li condensation. The evaporation rates obtained with this method are in the range of 1–40 mg/min, per LITER unit, with the rate being controlled by the reservoir oven temperature. The LITER central axis aims at the lower divertor, and the Gaussian half-angle at $1/e$ of the measured evaporated Li angular distribution is about 11.5°, with the angular distribution of the evaporated Li being independent of the Li reservoir oven temperature. In the second method, a Li aerosol is injected into

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G. P. Canal is with General Atomics, San Diego, CA 92186-5608 USA, also with Oak Ridge Associated Universities, Oak Ridge, TN 37831 USA, and also with Institute of Physics, University of São Paulo, São Paulo 05508-090, Brazil (e-mail: canal@if.usp.br).

R. Maingi, S. M. Kaye, and D. K. Mansfield are with the Princeton Plasma Physics Laboratory, Princeton, NJ 08543-0451 USA.

T. E. Evans is with General Atomics, San Diego, CA 92186-5608 USA.

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the plasma SOL during the discharge using a device termed "Li Dropper" [16], or simply "Dropper," which drops spherical Li powder into the plasma SOL by gravitational acceleration in a controllable manner using a vibrating piezoelectric disk with a central aperture [see Fig. 1(c)]. In these studies, a powder of spherical Li particles of 44 μm of average diameter were used. To avoid the uncontrolled chemical reaction with air, the Li particles were coated with a 30-nm mantle of microcrystalline Li_2CO_3, such that the particles are 99.9% Li and 0.1% Li_2CO_3 in composition. The injection rates obtained with this method are in the range 1–120 mg/s, per Dropper unit, with the rate depending on the amplitude of the ac voltage applied to the opposite sides of the vibrating piezoelectric disk. The Dropper has been used to inject Li in three machines: NSTX [16], Experimental Advanced Superconducting Tokamak (EAST) [19], and DIII-D [20]. Fig. 1(d) shows a visible light image of an NSTX plasma with the Dropper in operation. The dominant green light emission in this image comes from singly ionized Li (LiII, 548.5 nm). Light emission from the neutral Li is also visible in the lower divertor region (LiI, 670.8 nm). Compared to the Li thin-film pre-deposition method, the real-time injection of Li aerosol has the advantage of replacing, in real time, the Li thin-film removed from the PFCs by the plasma. In the NSTX discharges described in this paper, the LITER evaporated Li for several minutes prior to the initiation of the discharges, while the Li Dropper operated for only about 1 s, which is the typical duration of an NSTX discharge. Therefore, given their respective injection rates, the total amount of Li used during a full discharge by these two methods are comparable.

II. Description of the Experiments

To compare the impact of pre-deposition and real-time injection of Li on plasma performance, three NSTX H-mode discharges with similar global plasma parameters were selected: 1) the reference discharge that had no Li injected, #132549; 2) a discharge that used the LITER to evaporate 100 mg of Li prior to the initiation of the discharge, #139045; and 3) a discharge that used the Li Dropper with 110 mg/s of injection rate, #135058. The reference discharge had 5 min of He glow wall conditioning and gas fueling rate of 44 Torr-l/s. During the LITER discharge, two LITER units, installed 150° apart, were used on NSTX to increase the evaporation rate [see Fig. 1(a)]. During the Dropper discharge, the injection rate was kept constant with the starting time set prior to the initiation of the discharge, such that the Li powder could arrive at the plasma SOL, by gravitational acceleration, at the beginning of the discharge. In both the LITER and Dropper discharges, the gas fueling rate was 33 Torr-l/s. In these three NSTX discharges, the ion ∇B-drift direction pointed toward the x-point and the global plasma parameters were minor radius $a = 0.61$ m, elongation $\kappa = 2.3$, top triangularity $\delta_{\rm top} = 0.42$, bottom triangularity $\delta_{\rm bot} = 0.75$, safety factor at 95% of the normalized poloidal flux $q_{95} = 8.5$, toroidal magnetic field $B_0 = 0.45$ T, plasma current $I_P = 1.0$ MA [see Fig. 2(a)], and neutral beam injected power $P_{\rm NBI} = 4.0$ MW for the reference and Dropper discharges and $P_{\rm NBI} = 6.0$ MW for the LITER discharge [see Fig. 2(b)].

III. Results

The first indication of changes in particle recycling and plasma edge stability due to the Li injection method can be seen in the D_α light emission measured by a filterscope located at the top of NSTX viewing the lower divertor region [see Fig. 2(c)]. When Li is injected into the machine, the measurements show a significant reduction in the D_α light emission. A reduction in the baseline D_α emission is usually observed when Li is injected in NSTX and other machines, such as EAST [21]–[23]. Note that, as shown in [24], the small difference in gas fueling rate between the reference and Li discharges is not expected to cause any significant change in the D_α light emission. Furthermore, the D_α light emission in the reference and Li discharges differ by at least a factor of 3, while the plasma density in these discharges differs by only about 30%. Therefore, the different plasma densities and a small difference in gas fueling rates alone cannot explain the reduction in the D_α light emission observed when Li is injected. The measurements also show that the LITER causes a stronger reduction in the D_α light emission compared to the Dropper. This could be caused by the fact that the location, where Li is dropped into the SOL during the Dropper discharge inside the field of view of the D_α light detector. Since this would increase the D_α light emission, the measurement shown in Fig. 2(c) must be regarded as an upper limit for the D_α light emission. Unfortunately, the field of view of other NSTX D_α light detectors is such that they cannot be used to decouple these effects. The D_α light emission indicates that edge localized modes (ELMs) were strongly mitigated in the LITER discharge, while in the Dropper discharge, ELMs appear to have been completely suppressed. Note that ELM suppression was achieved in several NSTX discharges using the LITER but with larger amounts of evaporated Li (>200–300 mg) [12]–[16], [18], [25]. Here, in this specific discharge, 100 mg of evaporated Li prior to the discharge was insufficient to achieve ELM suppression. Nonetheless, the fact that the Dropper reduced recycling and eliminated ELMs with about 100 mg of Li, i.e., much less than 200–300 mg usually required by the LITER, by itself, is evidence that the Dropper is more efficient.

Another important effect associated with the injection of Li is the control of core fueling. The Thomson scattering measurements in the plasma center show a significant reduction of the electron density, n_{e0}, and its rate of change, dn_{e0}/dt, when Li is injected [see Fig. 2(d)], but no significant difference is found between the LITER and the Dropper. Note that if the lower D_α light emission measured during the LITER discharge is caused by lower recycling and, therefore, due to an associated lower particle source, then a lower dn_{e0}/dt should also be observed. Since no significant difference in dn_{e0}/dt was found between the LITER and the Dropper discharges, an extra electron source could be responsible for fueling the LITER discharge. Another possibility, as already pointed out, is that the recycling is about the same in both the LITER and the Dropper discharges, but the measured D_α light emission in the Dropper discharge is being affected by the location of the Dropper. The latter seems to be a better explanation, as an extra electron source should be a consequence of a

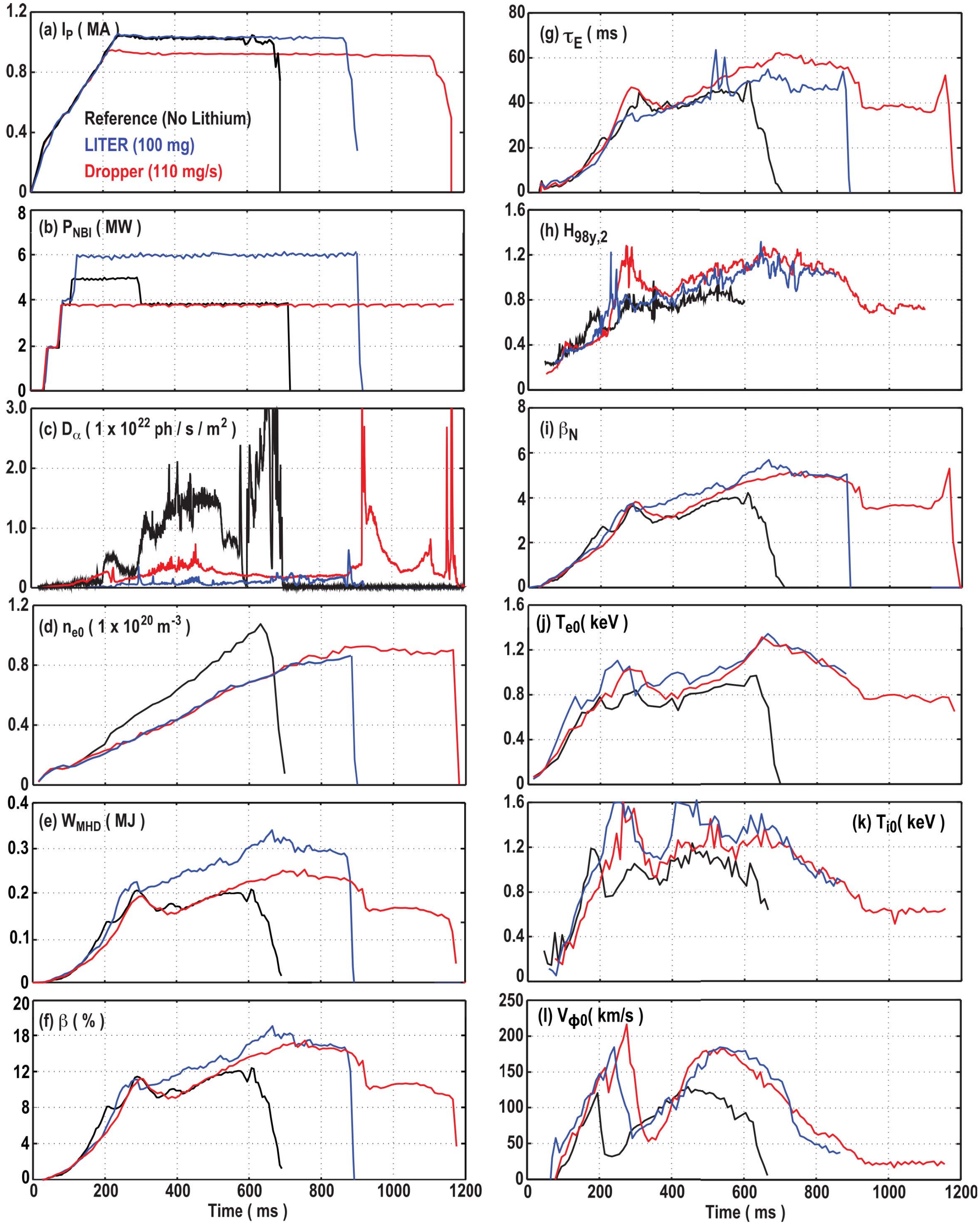


Fig. 2. Time traces of (a) plasma current, (b) neutral beam injected power, (c) D_α light emission intensity, (d) central electron density, (e) plasma stored energy, (f) normalized plasma pressure, (g) energy confinement time, (h) energy confinement enhancement factor, (i) normalized β, central, (j) electron and (k) ion temperatures, and (l) central plasma rotation for three NSTX discharges: #132549 (No lithium), #139045 (LITER with 100 mg), and #135058 (Dropper with 110 mg/s).

higher effective ion charge, Z_{eff} (considering carbon as the main plasma impurity), which, as presented in the following, is opposite to the observation.

The measurements show an increased plasma stored energy, W_{MHD}, and normalized plasma pressure, β, in the LITER discharge [see Fig. 2(e) and (f)], which can be explained by

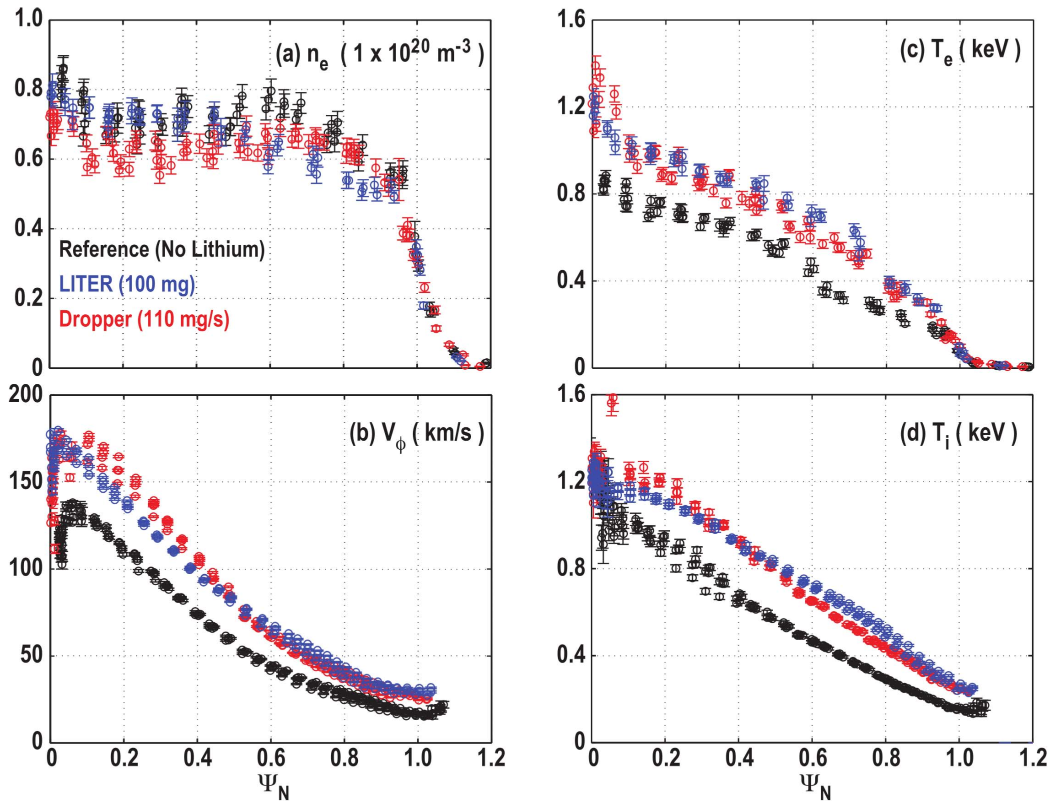


Fig. 3. Radial profiles of (a) electron number density, (b) plasma rotation, and (c) electron and (d) ion temperatures for three NSTX discharges: #132549 (No lithium), #139045 (LITER with 100 mg), and #135058 (Dropper with 110 mg/s).

the higher NBI power than in both the reference and the Dropper discharges. The energy confinement time, τ_E, and the energy confinement enhancement factor, $H_{98y,2}$, however, are found to be somewhat larger when the Dropper is used [see Fig. 2(g) and (h)]. Although the measurements show just a modest improvement in energy confinement when the Dropper is used, note that this improvement is obtained with just a fraction of the amount of Li used by the LITER as the improvement can be seen as early as 400 ms. For a Li injection rate of 110 mg/s, it is estimated that at about 400 ms, only about 40% of the amount of Li used in the LITER discharge was used by the Dropper. It is, therefore, notable that a significantly smaller amount of Li can cause a significant change in the energy confinement when the Dropper was used.

The maximum value of the normalized β, β_N, in both the LITER and Dropper discharges, is about 25% higher than in the reference discharge [see Fig. 2(i)]. Here, $\beta_N = \beta[\%]a[m]B_0[T]/I_P[\text{MA}]$ and the normalized plasma pressure $\beta = 2\mu_0\langle p\rangle/\bar{B}^2$, with $\langle p\rangle = (1/V)\int p dV$ being the volume averaged plasma pressure, $\bar{B}$ being the mean magnetic field at the plasma boundary, and μ_0 being the vacuum magnetic permeability. The central electron, T_{e0}, and ion, T_{i0}, temperatures in both the LITER and the Dropper discharges are found to be very similar [see Fig. 2(j) and (k)] even though the energy confinement time is higher in the Dropper discharge. This occurs because of the inverse dependence of energy confinement time with input power [26]. Since the LITER discharge needs more external heating power to maintain T_{e0} and T_{i0} as high as in the Dropper discharge, the energy confinement time in the LITER discharge must be lower than in the Dropper discharge. The results also show that the plasma rotates faster in the center when Li is injected, but the evolution of the central plasma rotation, $V_{\phi 0}$, in the Dropper discharge is not significantly different from that in the LITER discharge [see Fig. 2(l)].

To compare the plasma kinetic radial profiles with these NSTX discharges, the profiles were taken from slightly different times in each discharge due to the observed difference in the evolution of n_{e0}, namely, 0.47–0.52 s for the reference discharge and 0.63–0.67 s for both the LITER and Dropper discharges. With these selected time windows, the electron density, n_e, profiles from the three discharges overlay reasonably well [see Fig. 3(a)]. The measurements show that the plasma rotation, V_ϕ, increases across the plasma radius when Li is injected, but no significant difference is observed between the two Li injection methods [see Fig. 3(b)]. The fact that the plasma rotates faster when Li is injected might result from a reduced drag caused by the lower number of charge exchange processes due to the lower recycling. However, to explain the very similar effect of both Li injection methods on the V_ϕ profile, the amount of Li injected in these discharges must be large enough to cause the contribution of charge exchange processes to the torque balance to be negligible, causing V_ϕ to be independent of the Li injection method. The electron, T_e, and ion, T_i, temperature profiles are higher than in the reference discharge, but no significant difference between

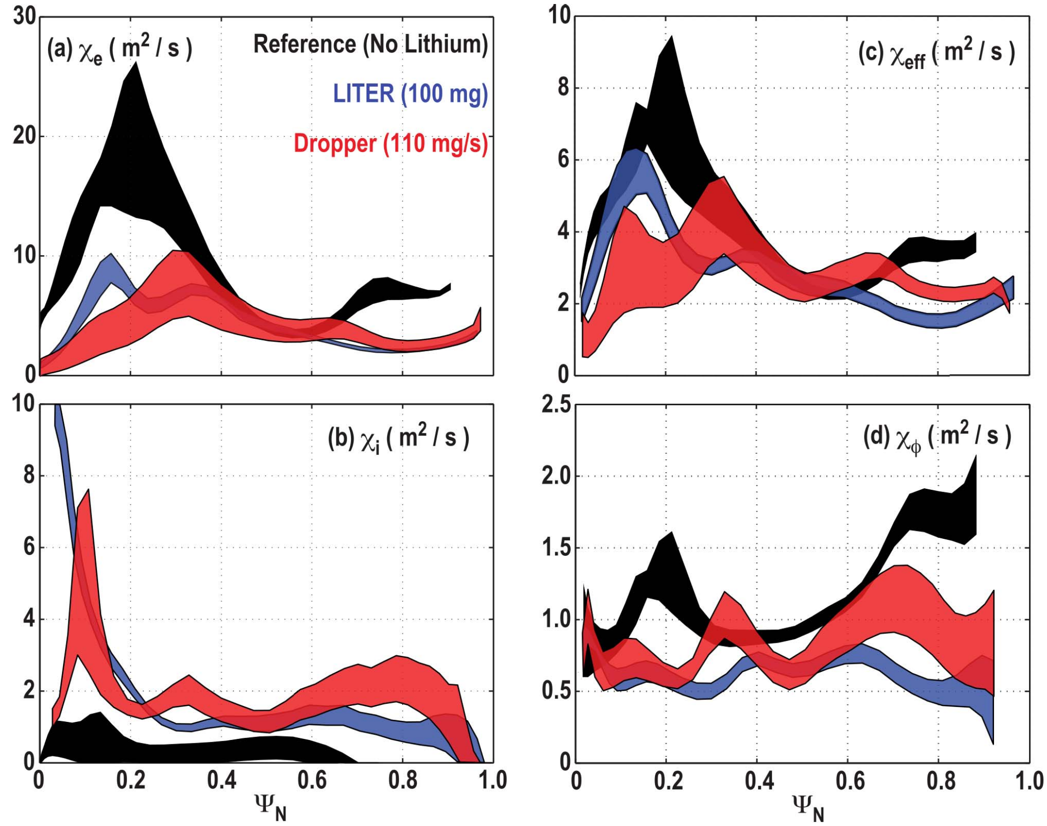


Fig. 4. Radial profiles of (a) electron and (b) ion thermal diffusivities, (c) effective (single-fluid) thermal diffusivity, and (d) momentum diffusivity for three NSTX discharges: #132549 (No lithium), #139045 (LITER with 100 mg), and #135058 (Dropper with 110 mg/s).

the two Li injection methods is observed [see Fig. 3(c) and (d)] even though the larger neutral beam injected the power during the LITER discharge.

To better understand the effect of the Li injection method on the plasma confinement, diffusive cross-field transport coefficients were estimated for these three NSTX discharges using the plasma transport code TRANSP [27]. The calculations show, for both Li injection methods, a strong and similar reduction in the electron thermal diffusivity, χ_e [see Fig. 4(a)]. The ion thermal diffusivity, χ_i, however, is found to increase when Li is injected [see Fig. 4(b)] with an increase of χ_i in the plasma edge during the Dropper discharge being slightly larger. To explain the modest improvement in the energy confinement when Li is injected into the plasma, the reduction of the electron heat transport channel must compensate for the increase of the ion heat transport channel. In the plasma edge, the two-fluid thermal diffusivities χ_e and χ_i can sometimes be dominated by the electron–ion energy exchange (equipartition) term, which usually has a larger uncertainty in the edge region. To avoid this issue, one can calculate the effective thermal diffusivity, χ_{eff}, which combines the two species into a single-fluid thermal diffusivity, thereby canceling the energy exchange term. χ_{eff} is, therefore, a more reliable indicator of the overall change in the plasma energy transport in the edge region. As shown in Fig. 4(c), the calculations show a significant reduction in χ_{eff} when Li is injected. While the LITER has a stronger effect on χ_{eff} in the plasma edge ($\Psi_N \geq 0.6$), the Dropper is found to have a stronger effect in the plasma core ($\Psi_N \leq 0.3$). The momentum confinement is also affected by the injection of Li. The toroidal momentum diffusivity, χ_ϕ, is found to reduce significantly when Li is injected [see Fig. 4(d)] with χ_ϕ being somewhat lower in the LITER discharge.

The impact of the Li injection method on the impurity accumulation and radiated power was also addressed. High-Z impurity concentrations were estimated using a steady-state coronal-equilibrium model [28] to determine the exact value of the impurity concentration needed to match the central radiated power density. This calculation assumed that iron is the only radiating impurity in the plasma center and that all low-Z radiators are fully stripped in the 1-keV core region. The measurements show that the radiated power, P_{rad}, in the reference discharge is significantly higher than in the LITER and Dropper discharges [see Fig. 5(a)]. This is a consequence of the higher values of n_e and lower values of T_e and T_i in the reference discharge. The measurements show slightly higher values of P_{rad} during the LITER discharge than in the Dropper discharge, which can be explained by the larger neutral beam injected power. The high-Z impurity density, n_Z, is found to be higher in the reference and LITER discharges than in the Dropper discharge [see Fig. 5(b)]. However, since n_e in the reference discharge is higher than in both the LITER and Dropper discharges, the high-Z impurity concentration in the plasma center, n_Z/n_e, is lower in the Dropper discharge than in the LITER discharge [see Fig. 5(c)].

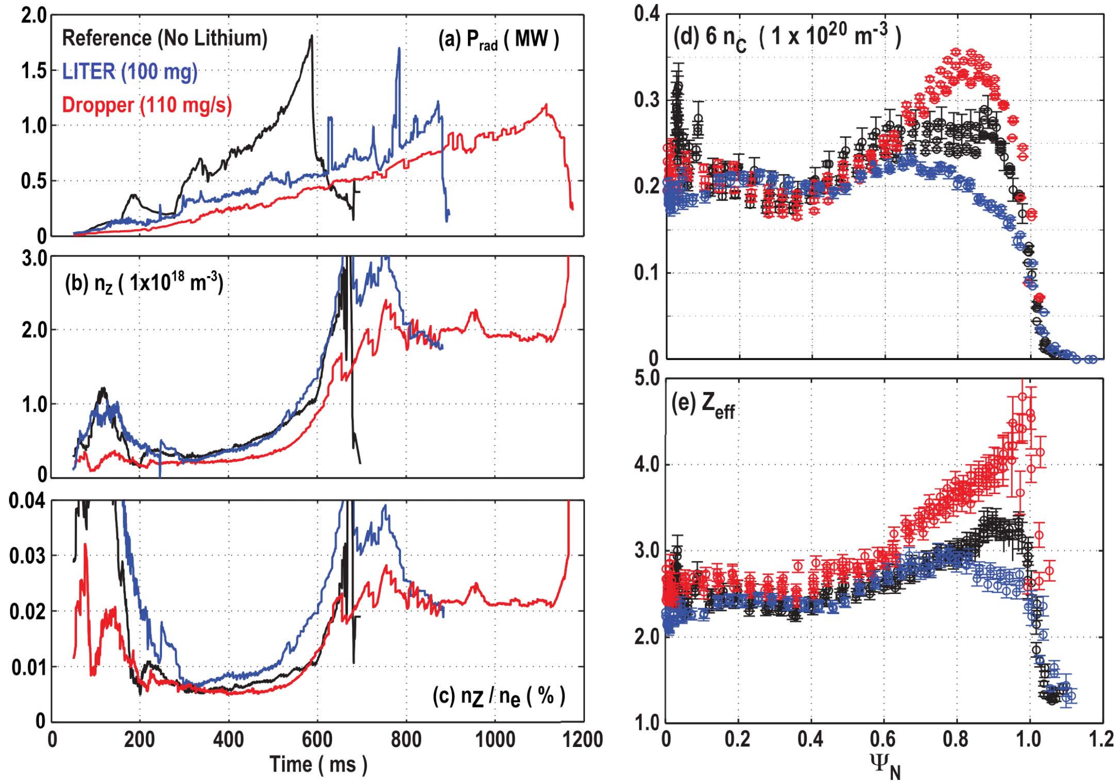


Fig. 5. Time traces of (a) radiated power and high-Z impurity, (b) density, and (c) concentration in the plasma core for three NSTX discharges: #132549 (No lithium), #139045 (LITER with 100 mg), and #135058 (Dropper with 110 mg/s). Radial profiles of (d) carbon density and (e) effective ion charge for the same three NSTX discharges.

Measurements of the carbon density, n_C, profiles in the three discharges are very similar in the plasma core region [see Fig. 5(d)]. The measurements show differences only in the plasma edge, where higher values of n_C were measured in the Dropper discharge compared to both the reference and LITER discharges. Furthermore, lower values of n_C were measured in the LITER discharge compared to the reference discharge. This could be explained by the lower carbon sputtering expected when the graphite PFCs are coated with Li prior to the discharge, while a somewhat higher carbon sputtering due to the Li recycling flux is expected when Li is injected during the discharge. The same behavior is observed in Z_{eff}, which is higher in the Dropper discharge than in the LITER discharge [see Fig. 5(e)]. A more detailed description of the carbon transport in the NSTX discharges with Li can be found in [29] and [30].

IV. Summary

Improvements in the plasma confinement and the edge stability have been observed in several machines when elemental Li is used to coat the PFCs. On NSTX, such improvements were observed when Li was evaporated into the machine and pre-deposited on the divertor targets prior to the initiation of the discharge and also during real-time injection, where Li was injected directly into the plasma SOL. In this paper, the efficiency of these two Li injection methods is compared in terms of the amount of Li used to produce equivalent plasma performance improvements.

When Li is injected into the machine, a significant reduction in the D_α light emission is observed with a stronger reduction observed during the LITER discharge. However, no significant differences in dn_{e0}/dt are observed. If the lower D_α light emission measured during the LITER discharge is due to lower recycling and, therefore, due to an associated lower particle source, then a lower dn_{e0}/dt should also be observed. Since no significant differences in dn_{e0}/dt were found between the LITER and the Dropper discharges, an extra electron source could be responsible for fueling the LITER discharge. Another possibility is that the recycling in both the LITER and the Dropper discharges is about the same, but the measured D_α light emission in the Dropper discharge is being affected by the location of the Dropper. The latter seems to be a better explanation, as an extra electron source should be a consequence of a higher Z_{eff} (considering carbon as the main plasma impurity), which is opposite to the observation.

In addition, ELMs were strongly mitigated in the LITER discharge, while ELM suppression was achieved with the Dropper using just a fraction of the amount of Li used by the LITER. Note that ELM suppression was achieved in several NSTX discharges using the LITER but with larger amounts of evaporated Li (>200–300 mg). In this specific discharge, 100 mg of evaporated Li were insufficient to achieve the ELM suppression. Therefore, the fact that the Dropper reduced the recycling and eliminated the ELMs with about 100 mg of Li, i.e., much less than 200–300 mg usually required by the LITER, by itself, is evidence that the Dropper is more efficient.

The results also show a somewhat higher energy confinement in the Dropper discharge than the LITER discharge. All these observations show that the Dropper can affect the energy confinement and the edge stability of NSTX plasmas in a more efficient way than the LITER, as it requires only a fraction of the amount of Li used by the LITER to produce similar improvements. When the Dropper is used, the Li that is directly injected into the plasma SOL during the discharge is transported by the plasma to the targets. This method has, therefore, the advantage of replacing, in real time, the Li thin film removed from the PFCs by the plasma, which is thought to be the cause of the observed higher efficiency of the Dropper in improving the plasma performance to a level equivalent to that obtained with the LITER.

REFERENCES

[1] B. Terreault *et al.*, "Effect of lithium wall conditioning on deuterium in-vessel retention in the TdeV tokamak," *J. Nucl. Mater.*, vol. 220, pp. 1130–1134, Apr. 1995.

[2] D. K. Mansfield *et al.*, "Enhanced performance of deuterium–tritium-fueled supershots using extensive lithium conditioning in the tokamak fusion test reactor," *Phys. Plasmas*, vol. 2, pp. 4252–4256, Nov. 1995.

[3] H. Sugai *et al.*, "Wall conditioning with lithium evaporation," *J. Nucl. Mater.*, vol. 220, pp. 254–258, Apr. 1995.

[4] D. K. Mansfield *et al.*, "Observations concerning the injection of a lithium aerosol into the edge of TFTR discharges," *Nucl. Fusion*, vol. 41, p. 1823, Dec. 2001.

[5] S. I. Krasheninnikov, L. E. Zakharov, and G. V. Pereverzev, "On lithium walls and the performance of magnetic fusion devices," *Phys. Plasmas*, vol. 10, pp. 1678–1682, May 2003.

[6] V. A. Evtikhin *et al.*, "Lithium divertor concept and results of supporting experiments," *Plasma Phys. Controlled Fusion*, vol. 44, no. 6, p. 955, 2002.

[7] S. V. Mirnov *et al.*, "Li-CPS limiter in tokamak T-11M," *Fusion Eng. Des.*, vol. 65, pp. 455–465, Apr. 2003.

[8] S. V. Mirnov *et al.*, "Experiments with lithium limiter on T-11M tokamak and applications of the lithium capillary-pore system in future fusion reactor devices," *Plasma Phys. Controlled Fusion*, vol. 48, no. 6, pp. 821–837, May 2006. doi: 10.1088/0741-3335/48/6/009.

[9] R. Majeski *et al.*, "Enhanced energy confinement and performance in a low-recycling tokamak," *Phys. Rev. Lett.*, vol. 97, no. 7, 2006, Art. no. 075002.

[10] F. L. Tabarés *et al.*, "Plasma performance and confinement in the TJ-II stellarator with lithium-coated walls," *Plasma Phys. Controlled Fusion*, vol. 50, no. 12, 2008, Art. no. 124051.

[11] G. Mazzitelli *et al.*, "Status and perspectives of the liquid material experiments in FTU and ISTTOK," in *Proc. 22nd IAEA Fusion Energy Conf.*, Geneva, Switzerland, Oct. 2008, pp. 1–8. http://www-pub.iaea.org/MTCD/Meetings/FEC2008/ex_p4-6.pdf

[12] H. W. Kugel *et al.*, "The effect of lithium surface coatings on plasma performance in the national spherical torus experiment," *Phys. Plasmas*, vol. 15, no. 5, 2008, p. 056118.

[13] H. W. Kugel *et al.*, "Evaporated lithium surface coatings in NSTX," *J. Nucl. Mater.*, vol. 390, pp. 1000–1004, Jun. 2009.

[14] Y. Hirooka *et al.*, "Active particle control in the CPD compact spherical tokamak by a lithium-gettered rotating drum limiter," *J. Nucl. Mater.*, vol. 390, pp. 502–506, Jun. 2009.

[15] R. Maingi *et al.*, "Edge-localized-mode suppression through density-profile modification with lithium-wall coatings in the national spherical torus experiment," *Phys. Rev. Lett.*, vol. 103, Aug. 2009, Art. no. 075001.

[16] D. K. Mansfield *et al.*, "A simple apparatus for the injection of lithium aerosol into the scrape-off layer of fusion research devices," *Fusion Eng. Des.*, vol. 85, pp. 890–895, Nov. 2010.

[17] R. Maingi *et al.*, "The effect of progressively increasing lithium coatings on plasma discharge characteristics, transport, edge profiles and ELM stability in the national spherical torus experiment," *Nucl. Fusion*, vol. 52, no. 8, 2012, Art. no. 083001.

[18] M. A. Jaworski *et al.*, "Liquid lithium divertor characteristics and plasma–material interactions in NSTX high-performance plasmas," *Nucl. Fusion*, vol. 53, Jul. 2013, Art. no. 083032.

[19] J. S. Hu *et al.*, "New steady-state quiescent high-confinement plasma in an experimental advanced superconducting tokamak," *Phys. Rev. Lett.*, vol. 114, Feb. 2015, Art. no. 055001.

[20] T. H. Osborne *et al.*, "Enhanced H-mode pedestals with lithium injection in DIII-D," *Nucl. Fusion*, vol. 55, May 2015, Art. no. 063018.

[21] D. P. Boyle *et al.*, "The relationships between edge localized modes suppression, pedestal profiles and lithium wall coatings in NSTX," *Plasma Phys. Controlled Fusion*, vol. 53, no. 10, 2011, Art. no. 105011.

[22] R. Maingi *et al.*, "Continuous improvement of H-mode discharge performance with progressively increasing lithium coatings in the national spherical torus experiment," *Phys. Rev. Lett.*, vol. 107, no. 14, 2011, Art. no. 145004.

[23] R. Maingi *et al.*, "ELM elimination with Li powder injection in EAST discharges using the tungsten upper divertor," *Nucl. Fusion*, vol. 58, Jan. 2018, Art. no. 024003.

[24] R. Maingi *et al.*, "ELMs and the H-mode pedestal in NSTX," *J. Nucl. Mater.*, vols. 337–339, pp. 727–731, Mar. 2005.

[25] R. Maingi *et al.*, "Dependence of recycling and edge profiles on lithium evaporation in high triangularity, high performance NSTX H-mode discharges," *J. Nucl. Mater.*, vol. 463, pp. 1134–1137, Aug. 2015.

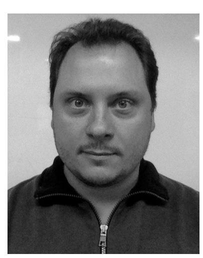
[26] M. Wakatani *et al.*, "Chapter 2: Plasma confinement and transport," *Nucl. Fusion*, vol. 39, no. 12, pp. 2175–2249, 1999.

[27] J. Breslau, M. Gorelenkova, F. Poli, J. Sachdev, and X. Yuan, *Transp*. Jun. 2018. doi: 10.11578/dc.20180627.4.

[28] D. E. Post, R. V. Jensen, C. B. Tarter, W. H. Grasberger, and W. A. Lokke, "Steady-state radiative cooling rates for low-density, high-temperature plasmas," *At. Data Nucl. Data Tables*, vol. 20, no. 5, pp. 397–439, 1977.

[29] M. Podestà, R. E. Bell, A. Diallo, B. P. LeBlanc, F. Scotti, and NSTX Team, "Measurements of core lithium concentration in a Li-conditioned tokamak with carbon walls," *Nucl. Fusion*, vol. 52, no. 3, 2012, Art. no. 033008.

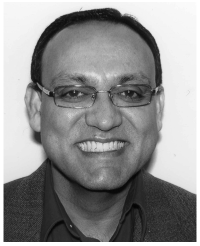
[30] F. Scotti *et al.*, "Core transport of lithium and carbon in ELM-free discharges with lithium wall conditioning in NSTX," *Nucl. Fusion*, vol. 53, no. 8, 2013, Art. no. 083001.



Gustavo Paganini Canal received the B.S. degree from the Federal University of Espírito Santo, Vitoria, Brazil, in 2007, the M.S. degree from the Brazilian Center for Physics Research, Rio de Janeiro, Brazil, in 2009, and the Ph.D. degree from the École Polytechnique Fédérale de Lausanne, Lausanne, Switzerland, in 2014, all in physics.

He was with General Atomics, San Diego, CA, USA, and the Princeton Plasma Physics Laboratory, Princeton, NJ, USA, from 2014 to 2017. He has been a Visiting Professor with the University of São Paulo, São Paulo, Brazil, since 2018. His current research interests include high-temperature plasma stability and transport in toroidal magnetic confinement devices.

Dr. Canal received the European Fusion Doctorate Certificate from FuseNet as a stamp for high-quality education in Europe in the field of nuclear fusion research and development in 2015.



Rajesh Maingi received the Ph.D. degree in nuclear engineering from North Carolina State University, Raleigh, NC, USA, in 1992.

He performed his post-doctoral research at DIII-D from 1992 to 1997. In 1997, he joined Oak Ridge National Laboratory (ORNL) as a Research Staff, still at DIII-D, until moving to National Spherical Torus Experiment (NSTX) in 1999. He became a Distinguished R&D Staff at ORNL. He is currently the Deputy Department Head of the ITER and Tokamaks Department and the Head of Boundary Science on NSTX-U with the Princeton Plasma Physics Laboratory (PPPL), Princeton, NJ, USA. In 2012, he joined PPPL Staff as a Principal Research Physicist. He has conducted experiments on many of the world's fusion facilities, including Alcator C-Mod, ASDEX-Upgrade, DIII-D, EAST, KSTAR, MAST, NSTX, and TdeV. He is also the Lead Principal Investigator of an international collaboration on plasma-material interactions on the EAST, ASDE-Upgrade, and KSTAR devices. His current research interests include edge physics, including L–H transitions, H-mode pedestal and edge localized mode research, scrape-off layer and divertor physics, plasma-material interactions, and liquid metal plasma-facing components.

Dr. Maingi was elected as a fellow of the American Physical Society in 2009 and the American Nuclear Society in 2019 and a Distinguished Research Fellow at PPPL in 2014. He has served in several national committee leadership roles, including the 2008–2009 ReNeW Strategic Planning Exercise (as the Vice-Chair of the Plasma-Materials Interface Group), the 2010 DoE Multi-Machine Joint Research Target on Thermal Transport in the Scrape-Off Layer (as the Chair), the 2015 Fusion Energy Sciences Community Workshop on Plasma-Materials Interaction (as the Chair), the 2018 FESAC Transformative Enabling Capabilities Panel (as the Chair), and the 2018 International Plasma-Surface Interactions Conference, Princeton, NJ, USA (as the Chair).

Todd E. Evans received the B.S. degree in physics and engineering physics from Wright State University, Dayton, OH, USA, in 1978, the M.S. degree in physics from The University of Texas at Dallas, Richardson, TX, USA, in 1979, and the Ph.D. degree in physics from The University of Texas at Austin, Austin, TX, USA, in 1984.

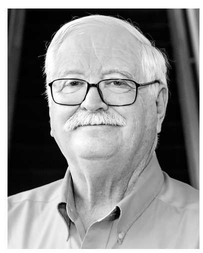
He is currently a Senior Technical Advisor, Scientist IX, with General Atomics, San Diego, CA, USA. His current research interests include high-temperature plasma stability and transport in toroidal magnetic confinement devices.

Dr. Evans is a fellow of the American Physical Society. He was a recipient of the 2008 IAEA Nuclear Fusion Prize, the 2018 APS-DPP John Dawson Award for Excellence in Plasma Physics, and the 2018 U.S. Congressional Certificate of Special Recognition for Exceptional Scientific Research in Fusion and Plasma Physics.

Stanley M. Kaye received the Ph.D. degree in geophysics and space physics in 1979.

From 1979 to 1980, he was with the Lockheed Research Laboratory, Palo Alto, CA, USA, where he was involved in magnetospheric research. He is currently the Interim Director of Research for NSTX-U at the Princeton Plasma Physics Laboratory (PPPL), Princeton, NJ, USA. In 1980, he joined as a Research Staff at PPPL, where he has been involved in PDX, PBX, PBX-M, and TFTR tokamaks. He coordinated the physics design of National Spherical Torus Experiment (NSTX) starting in 1991, and he has been associated with the project ever since, serving as the Head of physics analysis and the Deputy Director of Research before becoming Interim Director of Research. His current research interests include core transport and confinement.

Dr. Kaye was elected as a fellow of the American Physical Society in 2002. He was the winner of the PPPL Kaul Prize for Excellence in Plasma Physics in 2009. He has served in several national committee roles, including as a member of the 2017–2018 National Academy of Sciences Study on Burning Plasmas and the Executive Committee of the U.S. Burning Plasma Organization and in leadership roles as the Chair of the Transport and Confinement ITPA Group and the U.S. Transport Task Force. He has served on the DIII-D and CCFE Program Advisory Committees and the DIII-D Theory and Five-Year Plan Review Committees.



Dennis K. Mansfield received the B.A. degree in physics from Rutgers University, New Brunswick, NJ, USA, in 1970, the M.A. degree in physics from the Washington University in St. Louis, St. Louis, MO, USA, in 1972, and the Ph.D. degree in solid state physics from Rutgers University in 1977.

In 1977, he joined the Princeton Plasma Physics laboratory, Princeton, NJ, USA, as a Post-Doctoral Research Fellow, where he is currently a Principal Research Physicist. His current research interests include developing systems and techniques for real-time wall conditioning of fusion plasma devices. These devices have been used on fusion research facilities all over the globe, including the National Spherical Torus Experiment (NSTX) tokamak at Princeton, and are currently being used on the EAST tokamak in China, the DIII-D tokamak in San Diego, and the KSTAR tokamak in South Korea, among others. He has served as an International Visiting Professor of physics with the Chinese Academy of Physics from 2012 to 2013.

Dr. Mansfield received the Kaul Foundation Prize for his contributions to real-time wall conditioning (along with co-author R. Maingi) in 2018.