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Core V_ϕ and T_i Profiles and Transport in TFTR DD and DT Plasmas with Lithium Conditioning

C. E. Bush[a], R. E. Bell[b], B. LeBlanc[b], D. K. Mansfield[b], E.J. Synakowski[b],
R. V. Budny[b], K. W. Hill[b], W. Houlberg[a], E. Mazzucato[b], P. Mioduszewski[a],
H. Park[b], C. H. Skinner[b], and M.C. Zarnstorff[b]

[a]Oak Ridge National Laboratory, P.O. Box 2009, Oak Ridge, TN 37831, USA
[b] Plasma Physics Laboratory, Princeton University, Princeton, NJ 08543, USA

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Abstract

High performance DT plasmas have been obtained using neutral beam heating with lithium (Li) conditioned graphite walls in TFTR. Values of $\tau_E > 300$ ms have been obtained with neutron source rates of $> 10^{18}$ n/s and $n\tau T \approx 10^{21}$. Also, ion temperature (T_i) > 40 keV and toroidal velocity (V_ϕ) > 800 km/s have been obtained. The $T_i(R,t)$ and $V_\phi(R,t)$ profiles show strong gradients near the plasma core with $\nabla V_\phi > 3.5 \times 10^6$/s and E×B shearing rate $> 2\times10^5$/s realized. This strong E×B flow shear is consistent with formation of a "transport barrier" in the plasma core. Measured V_ϕ , T_i, and carbon density, n_C, profiles from charge-exchange recombination spectroscopy (CHERS) and neoclassical calculations of poloidal velocity, V_θ, are used to assess the roles of the pressure and velocity contributions to E_r (or E×B) with varying Li conditioning. The profiles and gradients and resulting confinement and transport are found to vary with the amount of Li applied and the Li deposition technique. Correlations between the V_ϕ and T_i profiles and recycling and impurity behavior as implied from edge carbon and D_α light and Li deposition are also observed.

Introduction

A number of confinement regimes can be studied in TFTR. These include: L-mode, supershot, high beta poloidal H-mode [1], reversed current shear (RS), and enhanced reversed shear (ERS) [2]. Studies in this report are being carried out in both DD and DT plasmas with well-degassed and conditioned walls. Here DD means neutral beam injection heating (NBI) using D^o beams into D^+ plasma and DT means $T^o + D^o$ beams into D^+ plasmas. The main input of tritium is through T^o beam injection. Neutral beam power, P_b, of species mixes from all D^o (up to 32 MW) to all T^o (up to 40 MW) can be injected. One of the main reasons for this versatility in confinement experiments is the use of a variety of techniques to condition the walls and limiters including glow (GDC), pulsed discharge cleaning (PDC), and wall coating techniques. Since the beginning of DT experiments in 1993, the most striking of these has been the use of lithium pellet injection [3,4]. Lithium conditioning has been a factor in obtaining most of the high performance plasmas and some of the key advances in improved confinement on TFTR. Li deposition on the walls of TFTR is observed to have two main confinement results. First, a dramatic increase in performance can occur in some confinement regimes and, second, Li may play a role in lowering the power threshold for transition from the RS to the high density ERS regime. An extensive lithium conditioning sequence allowed the achievement of the record 10 MW fusion power, P_{fus}, for the DT campaign. The TFTR results with lithium conditioning are important for ITER and advanced tokamaks not only because they allow operation at reactor relevant parameters, but also because they provide a dramatic indication of the important role of plasma/wall interactions relative to performance of advanced tokamaks.

The effects of lithium on plasma performance were discussed in an earlier report [4]. These include higher energy confinement time, τ_E, higher and broader T_i profiles, and high $n\tau T$ product resulting in higher P_{fus}. With Li conditioning, the high performance (high τ_E and reduced core transport, χ_i) is maintained for a longer duration and often improves throughout the beam pulse rather than suffering the early “rollover” in τ_E, and neutron rate, S_{DT}, as often seen in other plasmas. In this paper, we investigate the effect of Li conditioning on the plasma profiles and how this conditioning may be affecting core transport and confinement.

Experimental Arrangement and Technique

DT/DD experiments with lithium conditioning on TFTR have been carried out over a wide range of operating parameters. These include $I_p > 2.5$ MA, $B_\phi \sim 5.6$ T, and P_b up to 40 MW. Nearly full bore circular plasmas, minor radius ~ 95 cm, have been run, limited mainly by a circular inner graphite belt limiter. This limiter is extensively degassed and cleaned using a regimen of techniques starting with GDC and culminating in a long series of higher power pulses (including both ohmic and beam heated conditioning plasmas) [5]. After recycling has been reduced using these techniques, lithium is applied through pellet injection. The pellets (size ~ 2 mm) are injected into the plasma at the midplane at speeds of 0.4 to 0.6 km/s. Pellets are usually injected into the preceding OH plasma or the OH pre-beam phase of the beam heated discharge of interest so as to be available as a fresh Li "coating." The terms "coating," "layer," or "painting" imply the simple picture of a pure film of one material on top of the surface of another. More likely, and what is intended in this report, is a surface modification, including a resulting complex plasma facing matrix or mixture of mainly carbon, lithium, and their compounds along with isotopes of hydrogen and small amounts of other impurities.

Increased lithium deposition is obtained using what is referred to as a "painting" technique [4]. Essentially this involves injecting Li pellets into several OH plasmas (5 or 6) so as to build up a thicker layer of lithium. Depletion of the effective Li in the surface layer of the limiter by OH discharges is negligible when compared to depletion during high power NBI. The painting process includes Li pellet injection into OH plasmas with several different major radii, which presumably yields Li deposition over a wider area of the inner bumper limiter. The painting process with the OH plasmas is followed immediately by the high power NBI shot of interest; the highest TFTR performance and P_{fus} were obtained with this technique.

Spectroscopy is used to measure the amount of Li and carbon in the plasma core and edge and also to measure the V_{ϕ}, T_i and n_C profiles. Li II (199.5 Å) and C III (977 Å) line emissions are monitored, and a maximum Li/C fraction (ratio of line brightness) of 0.17 to 0.4 has been found in the Ohmic target conditioning plasmas. The charge-exchange recombination spectroscopy system (CHERS) [6] is used to measure V_{ϕ} (R, t), T_i (R, t), and n_C (R, t). Information about the poloidal variation of carbon and deuterium influx is obtained from arrays of D_{α} and C II detectors.

At present, a clear model for how the Li affects the walls and edge plasma has not been determined. But, there are indications that a thin layer of Li deposited in the surface layers of the graphite can reduce the chemical [7] and physical sputtering of carbon by incident carbon and hydrogenic ions. The reduced recycling is correlated with improved performance. For a comprehensive model, the data obtained as indicated above await extensive modeling using codes which include proper treatment of both edge transport and plasma/wall interactions.

Core profiles: Li conditioning

The main effects on the plasma edge and wall recycling can be seen from Figure 1, which shows the time evolution of the plasma edge line density, $n_e l$, D_α, and other parameters for a sequence of four shots. The first shot had no lithium conditioning and the next three had pellets injected into the OH pre-beam phase with 1, 2, and 3 lithium pellets injected into each successive shot respectively. As seen from Fig. 1 for the one pellet case, there is an immediate reduction in $n_e l$ and also D_α and CII light. The differences in magnitude of these signals remained for the duration of the NBI pulse. The D_α light decreased by a factor of 2 and the C II by ~ 70%; the Li 199A° VUV line intensity increased by > 2 times and the Li II/CII ratio by more than a factor of 5 in going from no Li to 3 Li pellets. Usually the ratio of Li to C light is ~ 50% (C concentrtion ~ 6 to 7%) at beam turnon and decreases with a time constant of 0.4 to 0.6s during the NBI pulse [see Fig. 1(f)]. The global confinement time increase was especially significant, going from ~ 150 ms (at t = 4.0 secs.) with no Li to ~ 200 ms with 3 Li pellets. The effects on the plasma profiles were more dramatic, especially the V_ϕ and T_i profiles. This can be seen in Fig. 2, which shows V_ϕ (R, t), T_i (R, t) and their gradients ∇V_ϕ and ∇Ti, respectively. The n_c and n_e (not shown) profiles also show strong central peaking as the number of pellets is increased.

The radiated power profile, Q_{rad}(R,t), also showed changes as the Li was increased, but mainly in shape, with essentially no change in the total fraction of power radiated, 20%. The Q_{rad} profile, obtained from image reconstruction of data from two orthogonal bolometer arrays, showed an interesting effect; the outboard half profile increased with increasing Li deposition, while the inner side, where the plasma is in contact with the inner bumper limiter, decreased. There is usually a strong in/out asymmetry during high power NBI, with intense localized impurity radiation coming from the inner bumper. However, as the Li was increased in the shot sequence of Fig. 1, the magnitude at the inner edge went from > 0.7 W/cm^3 with no Li conditioning to ~ 0.25 W/cm^3 with 3 Li pellets, with the profile becoming in/out symmetric. Thus, the bolometer data also supports the model of Li conditioning as a process for reducing plasma/inner wall interaction.

A Paradigm for Enhanced Core Confinement in TFTR

As indicated earlier, the density profile becomes more peaked as the Li conditioning is increased. Analysis of the data using the TRANSP [8] code shows the plasma pressure profile p (R,t) also becomes more peaked, indicating improved core confinement. Here, we examine improvements in core confinement in the framework already established for Hmodes, where shear in E×B flow leads to formation of an edge transport barrier. Peaked density and pressure profiles in supershot and other enhanced confinement regimes on TFTR also support this as a likely scenario in the core of these plasmas.

The electric field for the E×B flow is obtained from the zeroth order force balance equation:

$$E_r = l/Z_i e\,(T_i/n_i\; dn_i/dR + dT_i/dR) + V_\theta B_\phi - V_\phi B_\theta. \qquad (1)$$

All of the parameters in the equation can be determined experimentally except V_θ, the poloidal rotation velocity. The equation holds for each plasma ion species; hydrogen or impurity. n_i, T_i, and V_ϕ are measured using CHERS, and the motional Stark effect (MSE)[2] technique is used to measure B_θ. Using this collection of experimental data, neoclassical calculations [9] are carried out to determine V_θ. From Fig. 2, we see that as the Li increases, the gradients, ∇T_i and ∇V_ϕ, also increase near R ~ 284 cm. This radial position is typically in the vicinity of the location of the maximum gradients in T_i and V_ϕ for many supershots. Maxima in the gradients of n_e and total plasma pressure, p_i, also occur between R ~ 283 to 290 cm for the plasmas of Fig. 2. These profile characteristics described here are similar to those reported for JT-60U which were taken to be indicative of a core "transport barrier" [10]. As can be seen in Fig. 2, the maximum in ∇V_ϕ is observed, consistently for a variety of enhanced τ_E plasmas, to be inside (by 6 to 10 cm) the position for the maximum in ∇T_i. This is an interesting observation; however, the implications of this feature for the physics of the core transport have not been determined.

Neoclassical calculations of E_r for the four plasmas of Fig.2 have been performed and the peak value for each is ~ 60 kV/m. The contributions of the p_i and V_ϕ terms in Eq. (1) change significantly as the number of Li pellets (Li conditioning) increases, whereas the contribution by V_θ remains small. The shearing rate [11], $\omega_{E\times B} \equiv \frac{B_\theta}{B} \times \frac{d}{dr}\frac{E_r}{B_\theta}$ of the E×B flow is a maximum at the position of ∇V_ϕ(peak), and it increased from ~ 0.5×10^5/s with no Li conditioning to a magnitude of ~ 1.5×10^5/s for the plasma conditioned using 3 lithium pellets. This result suggests that the model of suppression of turbulent fluctuations in the core of high performance supershots, obtained with Li conditioning, by E×B flow shear could explain the resulting reduced core transport.

Significant gains in τ_E are obtained when the Li conditioning process is optimized by ensuring deposition of Li over a wider surface area. The time-evolutions of τ_E and the D_α light for a high performance supershot obtained in such a way are shown in Fig. 3. Values are plotted for two DT plasmas, one with extensive Li conditioning and the other without Li. A 50/50 D/T beam species mix was used for beam heating in both cases. Results from this particular extensive Li conditioning case are some of the most impressive for the technique. τ_E > 300 ms was obtained with a neutron source rate of > 10^{18} n/s and $n\tau T > 10^{21}$ achieved. A T_i > 40 keV, V_ϕ > 800 km/s, and ∇V_ϕ >3.5×10^6/s were obtained for the high performance case [4,12]. Reduced recycling and thus edge density may play major roles in obtaining such impressive performance since, among other factors, better core deposition is obtained. This would allow greater influence of the beam on the core profiles. From Fig. 3, the large differences in D_α for the two cases is evidence of the strong decrease in wall recycling using the Li painting technique. For the Li conditioned case, there is a much smaller increase in D_α during the beam pulse, with almost no increase during the first ~ 300 ms after beam turn on at t = 4.0 s. The values of $n_e l$ and CII line emission (not shown) also remained low during the initial 300 ms (~ the longest observed duration of effectiveness of the Li coating for high power NBI pulses). Results from the neoclassical calculation of $\omega_{E\times B}$ for the plasma of Fig. 3 are shown in Fig. 4. The peak in the magnitude of $\omega_{E\times B}$ occurs at ~ 290 cm and is > 2.3×10^5/s. The peak value of E_r (not shown) at t = 4.5 s was ~ 250 kV/m, with the V_ϕ contribution dominant.

The magnitude of ∇V_ϕ is a good measure of the shape of the V_ϕ profile in the core and possibly correllates with the decrease in core transport; a plot of τ_E vs ∇V_ϕ is shown in Fig. 5(a) for a wide variety of DD and DT beam heated plasmas with and without Li conditioning. The higher values are obtained for the Li conditioned DT plasmas, with τ_E increasing with the magnitude of ∇V_ϕ . Core transport for the optimized Li conditioned plasmas is also reduced as can be seen from Fig. 5(b), which is a plot of χ_i vs r/a for the no-Li and the 3-Li-pellet cases of Figs. 1 and 2 along with similar data for the plasma of Fig. 3 (solid curves) which had more aggressive Li conditioning. The values of χ_i are from the TRANSP analysis of the experimental data.

Li Pellets and RS/ERS Transitions

The reversed magnetic shear regime is also being studied in TFTR [2]. Reversed shear is expected to add stability and allow better plasma performance. On TFTR a bifurcation in core confinement can occur, which results in a transition from the RS to the ERS regime. The ERS regime is characterized by reduced turbulent fluctuations and transport and highly peaked density and plasma pressure profiles. Short scale turbulent fluctuations have been studied using microwave reflectometry [13]. In ERS plasmas, reflectometry shows the level of fluctuations to be very small throughout most of the plasma region with negative magnetic shear, and to increase near the point in the plasma where q reaches its minimum value (q_{min}), often near r/a ~ 0.35. Inside the q_{min} radius $\tilde{n}_e/n_e$ is usually < 0.2%. By contrast, RS plasmas are characterized by large fluctuations which appear as a series of bursts.

Lithium pellet injection is not necessary to obtain RS to ERS transitions; however, transitions are found to be reliably triggered when the pellets are injected prior to the beginning of the high power phase of RS plasmas. The net effect apparently is reduction of the threshold for the transition. A possible scenario is that the Li pellet is vaporized by the plasma and, subsequently, coats the wall and reduces recycling, allowing better beam penetration, thus, permitting establishment of a region of strong E×B shear.

RS to ERS transitions with and without Li pellet injection were obtained for a series of plasmas with P_b ~ 27.5 MW over a two day period. Out of 22 such cases with Li pellets injected into the pre-heat phase of the RS target, 500 ms before the high power phase, 20 resulted in RS/ERS transitions (the two exceptions had large amplitude MHD fluctuations). It is not clear if the beneficial effects of Li are the result of changes in wall conditioning as opposed to changes in the background core plasma profiles brought about by the pellet injection itself. However, some interesting observations are as follows. Without Li pellet injection, a much larger fraction of non-transition cases resulted. At the beginning of the high power phase, the n_e profile was the same with and without Li pellet injection. However, T_e near the plasma edge was ~ 200 eV lower with Li pellet injection and T_i/T_e ~ 3.5 compared to 2.5 without. T_i and T_e near the "transport barrier" at the time of RS to ERS transition were lower by 1.5 keV and 0.25 keV, respectively, with Li pellet injection. This was also the radial position at which the turbulent fluctuations were negligibly small, i.e., $r/a < 0.3$, and the position of peak dV_ϕ/dR and $\omega_{E\times B}$ for the ERS plasmas.

In summary, the results presented are consistent with Li conditioning of a clean degassed limiter as a beneficial contributor to improvement of core confinement and reduction of core transport in TFTR. This conclusion is supported by correlations between the amount of Li deposited and features in the core profiles.

Acknowledgments

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Figure Captions

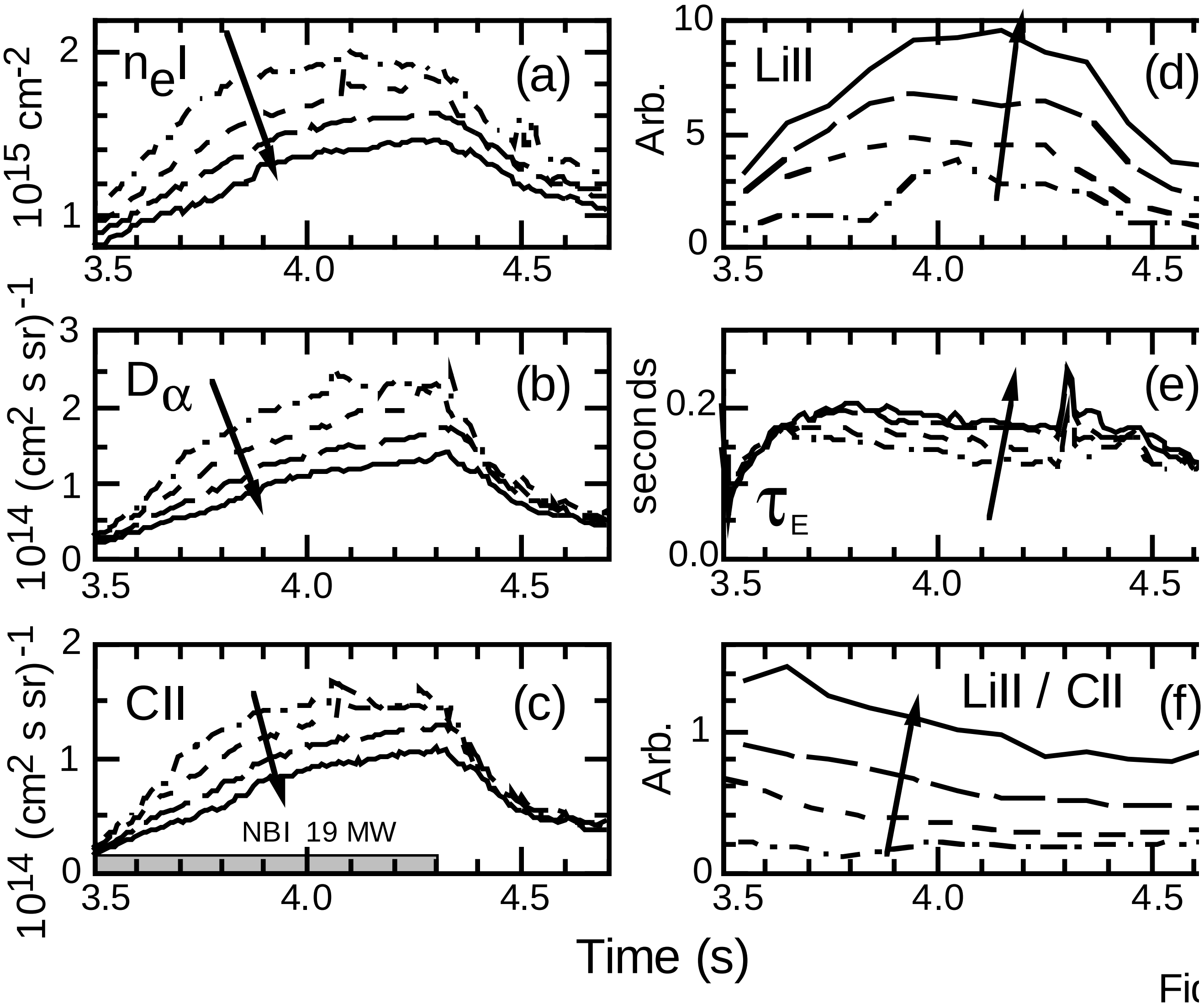
Fig. 1. Time variation of n_el, D_α, CII, LiII, τ_E, and the ratio of LiII/CII for different levels of conditioning. Some operating parameters for the four shots: P_b = 19.5 MW, Ip = 2.48 MA, B_ϕ = 5.1T, and R_p = 2.52 m. Pellets injected at t $\leq$ 2.7 s. No-Li (dot-dash), 1-pellet (short-dash), 2-pellet (long-dash), 3-pellet (solid).

Fig. 2. Variation of V_ϕ, T_i, ∇V_ϕ and ∇T_i with Li conditioning, from no Li to 3 Li pellets.

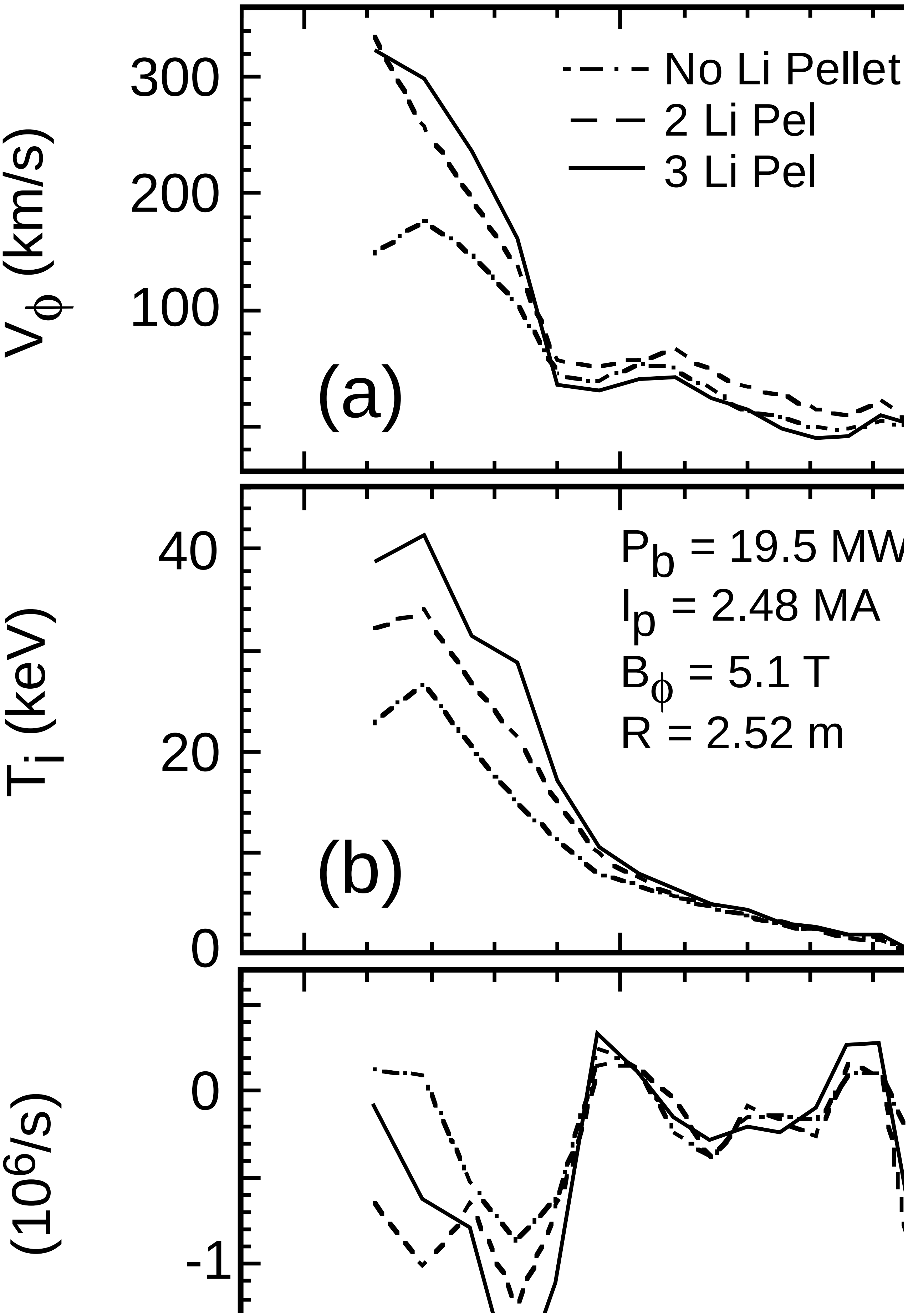
Fig. 3. τ_E and D_α signals for a high performance plasma obtained using the Li painting (solid curve) technique compared to signals without Li (dashed curve).

Fig. 4. Shearing rate, ω_{EXB}, for the Li conditioned case of Fig.3 (solid) and the no-Li case of Fig.2.

Fig. 5. (a) τ_E vs ∇V_ϕ for a wide variety of Li conditioned and no Li plasmas.
(b) χi for the no Li, 3 pellet Li conditioned and Li painted plasmas.


$n_e l$
(a)
10^{15} cm^{-2}
1
2
3.5
4.0
4.5
LiII
(d)
Arb.
0
5
10
3.5
4.0
4.5
D_α
(b)
10^{14} (cm^2 s sr)$^{-1}$
0
1
2
3
3.5
4.0
4.5
(e)
seconds
τ_E
0.0
0.2
3.5
4.0
4.5
CII
(c)
10^{14} (cm^2 s sr)$^{-1}$
0
1
2
NBI 19 MW
3.5
4.0
4.5
LiII / CII
(f)
Arb.
0
1
3.5
4.0
4.5
Time (s)

Fi


No Li Pellet
2 Li Pel
3 Li Pel
300
200
100
V_ϕ (km/s)
(a)
P_b = 19.5 MW
I_p = 2.48 MA
B_ϕ = 5.1 T
R = 2.52 m
40
20
0
T_i (keV)
(b)
0
-1
(10^6/s)

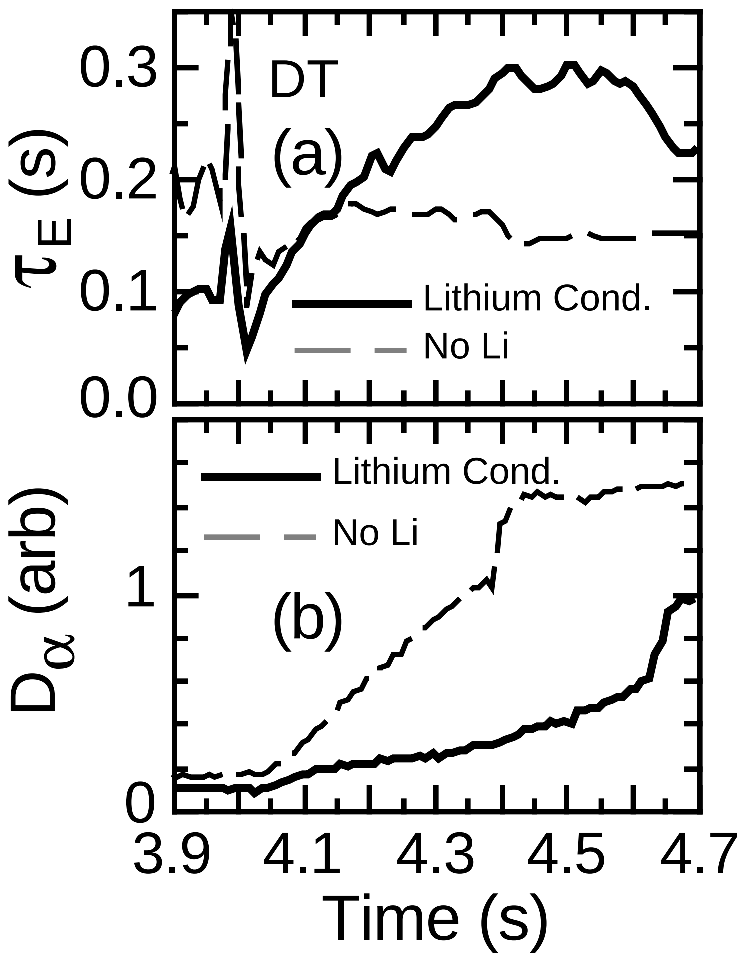

DT
(a)
τ_E (s)
0.0
0.1
0.2
0.3
Lithium Cond.
No Li
(b)
D_α (arb)
0
1
Lithium Cond.
No Li
3.9
4.1
4.3
4.5
4.7
Time (s)

Fig. 3

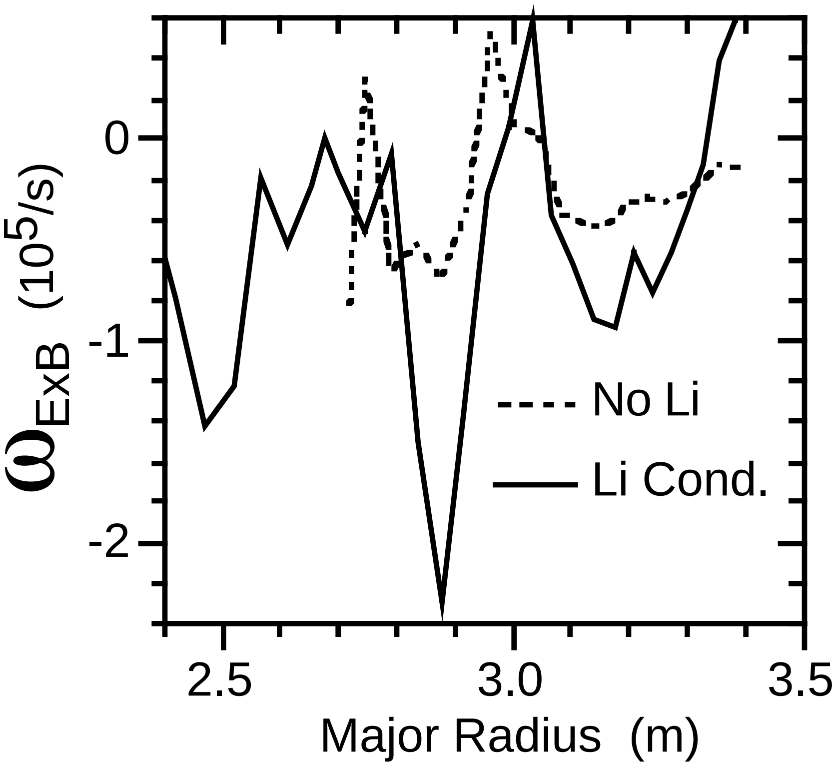


Fig. 4

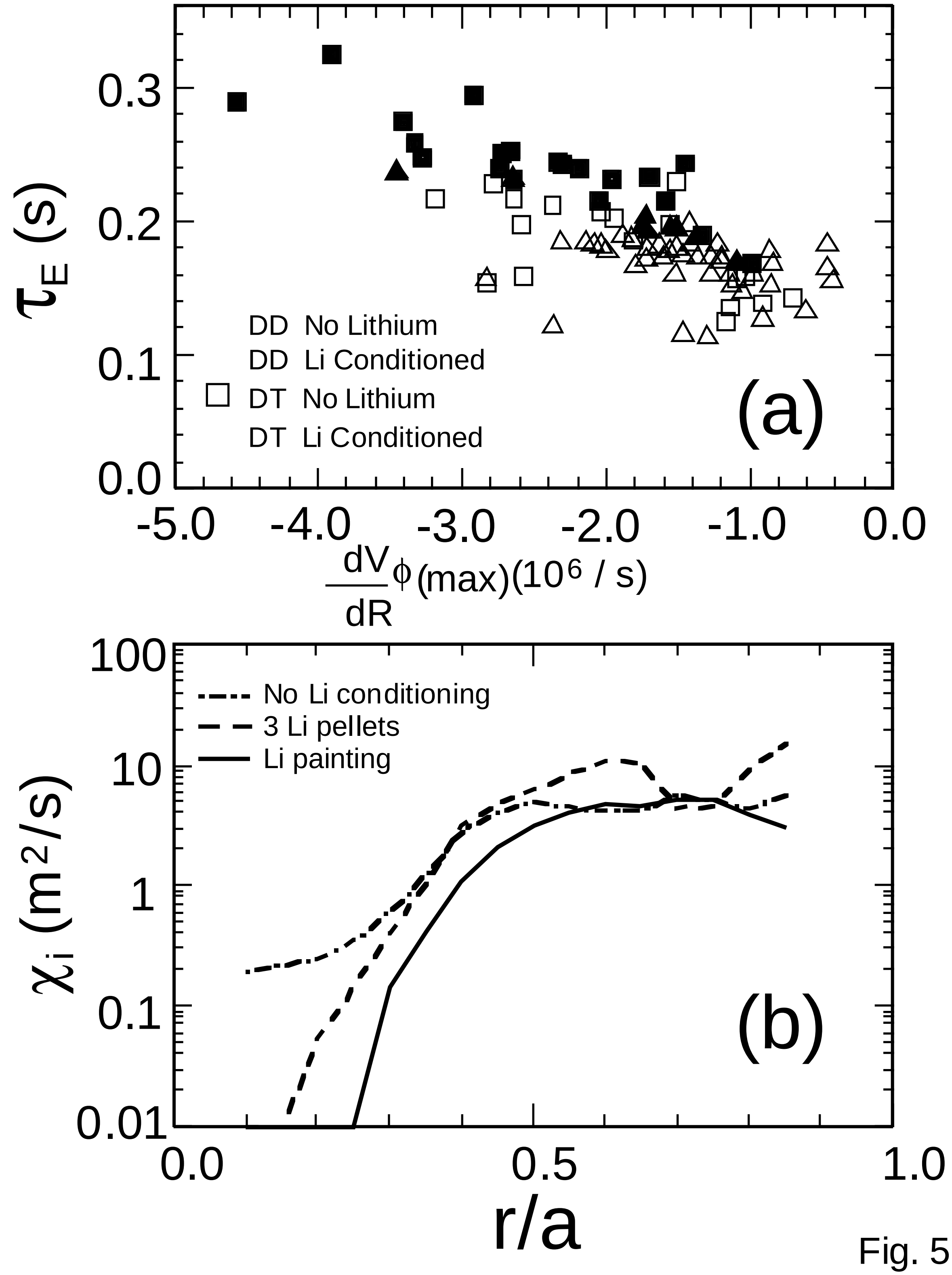

0.3
0.2
0.1
0.0
τ_E (s)
DD No Lithium
DD Li Conditioned
□ DT No Lithium
DT Li Conditioned
(a)
-5.0
-4.0
-3.0
-2.0
-1.0
0.0
$\frac{dV_\phi}{dR}$(max)(10^6 / s)
100
10
1
0.1
0.01
χ_i (m^2/s)
No Li conditioning
3 Li pellets
Li painting
(b)
0.0
0.5
1.0
r/a

Fig. 5