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Edge Turbulence Velocity Changes with Lithium Coating on NSTX

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Abstract

Lithium coating improves energy confinement and eliminates edge localized modes in NSTX, but the mechanism of this improvement is not yet well understood. We used the gas-puff-imaging (GPI) diagnostic on NSTX to measure the changes in edge turbulence which occurred during a scan with variable lithium wall coating, in order to help understand the reason for the confinement improvement with lithium. There was a small increase in the edge turbulence poloidal velocity and a decrease in the poloidal velocity fluctuation level with increased lithium. The possible effect of varying edge neutral density on turbulence damping was evaluated for these cases in NSTX.

1. Introduction

Lithium coating is a very effective method for wall conditioning in tokamaks. It was recently used both on the National Spherical Torus Experiment (NSTX) and the Experimental Advanced Superconducting Tokamak (EAST), and both have achieved very good results; for example, the first H-mode plasma appeared after wall conditioning by lithium on EAST [1]. On NSTX lithium wall coating has been shown to reduce recycling, improve energy confinement, and suppress edge localized modes (ELMs) [2-5]. The underlying cause of this improvement in confinement with increased lithium is not yet well understood in terms of the microscopic transport physics, although some correlated decreases in edge turbulence measured using reflectometry and high-k scattering have been reported [3]. The present paper describes measurements made using the GPI diagnostic of edge turbulence during a scan of lithium coating in NSTX, and analysis done in order to help determine if changes in edge turbulence velocity are correlated with the improvement in confinement. These measurements are made within ±2 cm of the separatrix, so are somewhat farther out in radius than the profile and turbulence changes reported near r/a=0.8 in [2,3].

It is widely believed that the transition from low confinement (L-mode) to high confinement (H-mode) in tokamaks involves turbulence stabilization by shear flow [6]. Earlier theoretical and experimental work also suggested that charge-exchange (CX) collisions might have an important role in modifying the ion flow in the edge plasma where neutral concentration is high [7-12], and in affecting the L-H translation threshold power [13-17]. Thus because lithium coating reduces recycling, this should change the edge neutral density and charge-exchange collision rate, and so might cause a decrease in turbulence and improvement in confinement. This possible mechanism is evaluated in this paper using GPI measurements of edge turbulence, turbulence flow velocity, and neutral density modeling to estimate the CX damping rate.

This paper is organized as follows: Section 2 describes the parameters for the shots used in this lithium scan. The GPI data analysis techniques and results with varying lithium coatings are described in Sec. 3, and an evaluation of the change exchange damping effects with varying lithium is in Sec. 4. Finally, in Sec. 5 we summarize and discuss the results.

2. Database for this analysis

The discharges used in this paper were all standard NSTX near-double-null, neutral beam heated, deuterium divertor plasmas taken on Oct. 21, 2010. The main parameters of the 8 shots used in this paper are shown in Table 1. The GPI data for these 8 shots was analyzed over a 10 ms period between the "start" and "end" times in this table, which were during the steady-state H-mode of these discharges during times without any ELMs. At these times the shots had a toroidal magnetic field 4.3 KG, plasma currents of 650-700 KA and neutral beam injection (NBI) powers of 2.9-4.8 MW. Note that the two shots with the highest lithium also had the lowest NBI power, in order to keep the normalized beta $\beta_N = \beta_T/(I/aB)$ constant at about 5.

The last two columns in Table 1 shows the lithium deposited just before this shot and the total lithium deposited during this day before this shot. The lithium deposited before each shot increased from about 20 mg to 300 mg over this sequence of 8 shots. The maximum lithium ever deposited in between shots in NSTX was 900 mg in 2008 [2], i.e. about 3 times the lithium deposited in the present paper; however, no GPI data was available from those shots in [2]. The shots in Table 1 were a subset of the shots taken on the same run day used in [3] when GPI data was available and when there were no ELMs during the GPI measurements.

Figure 1 shows the variation of the some plasma parameters during the scan of Table 1 during the GPI puffing time. Figure 1(a) shows the normalized beta β_N, which was approximately constant for these 8 shots. Figures 1(b) shows the injected NBI power, in which there was a decrease for the two highest lithium coating shots in order to keep β_N constant. Figure 2(c) shows the $H_{98(y,2)}$ empirical thermal confinement scaling coefficient [18], which was generally increased with increasing lithium deposited, as observed previously [2-4]. This suggests that a slightly better energy confinement time was obtained with more lithium deposited before these shots (at constant β_N). Fig. 1(d) shows the total lower divertor D_α emission, which indicates the recycling decreased for the highest lithium shots, similar to the injected NBI power. Fig. 1(e) shows the evolution of the edge pressure as measured by an ion gauge at vessel wall near outer mid-plane. The edge pressure also decreased with more lithium coating prior to the shot, implying fewer neutral particles in the outer mid-plane edge as a result of reduced outgassing and recycling from the wall, consistent with previous observations [4].

3. GPI Data analysis

A brief review of the gas-puff-imaging (GPI) diagnostic on NSTX is included here, more details can be found in these papers [19,20]. The GPI measurement on NSTX is a two dimensional diagnostic of the edge turbulence near the outer midplane. A gas puffing manifold located at the outer wall provides a deuterium gas puff into the plasma, and the visible D_α emission from this gas cloud is then imaged by a fast camera. Since the turbulence is highly elongated along the magnetic field, the D_α light from GPI gas puff cloud was viewed along the local magnetic field to resolve the radial versus poloidal structure of turbulence.

The edge turbulence measured by GPI near the separatrix in this experiment had a typical radial correlation length of ~4-7 cm, a typical poloidal correlation length ~5-10 cm, and an autocorrelation time of ~20-60 μsec, which are similar to previous GPI measurements in NSTX [19,20]. This is a much higher size scale than electron temperature gradient modes, but perhaps comparable to edge ion temperature gradient or microtearing instabilities.

To evaluate the poloidal flow speed of the turbulence, for every pixel for each frame during the 10 msec of interest we evaluated time delay of the peaks of the poloidal cross-correlation functions of nearby pixels as a function of poloidal separation, using a time-averaging for each cross-correlation of ±10 frames (i.e. over ~25 μs), similar to the procedure in [20]. We then fit these time delays to get a local poloidal turbulence velocity for each pixel for each time, which results in a time-resolved poloidal velocity with a frequency response of ~ 40 kHz. We then averaged these poloidal velocities over the poloidal range of the GPI data at each radius. Figure 2 shows the resulting average poloidal velocity as a function of the pre-discharge lithium level, along with the RMS fluctuation levels in poloidal velocity shown as error bars. There is systematic trend for an increase in the poloidal velocity with more lithium, i.e. V_{pol} = 2 km/s to 3 km/s, independent of radius over $R\text{-}R_{sep}$ =-2, 0 and 2 cm. This velocity is in the electron diamagnetic drift direction. Although there is an unknown level of uncertainty in the evaluation of the separatrix position in by EFIT (which may be up to ~2 cm), we assume that this uncertainty does not depend on the amount of lithium, so the trend of increasing poloidal velocity with increased lithium should be fairly reliable. Note that the error bars are not experimental errors in the estimate of V_{pol}, but the time-dependent RMS fluctuation levels of V_{pol} estimated using this technique. Note that passive or active spectroscopic measurements of the carbon ion poloidal rotation on NSTX are not be directly related to these turbulence velocity measurements, since the turbulence is presumably affected by the the main ion fluid ExB motion (see Sec. 5).

Figure 4 shows the fluctuating part of poloidal velocity δV_{pol} divided the time-averaged poloidal velocity V_{pol} vs. the amount of lithium coating before shot for the same data as in Fig. 2. The relative fluctuations in the turbulence poloidal velocity are decreasing by a factor of x2-3 with increased lithium at each radius, in part from the increase in V_{pol} with increased lithium (Fig. 2). These fluctuations are in the range up to ~40 kHz, and since they are averaged over the poloidal range of the GPI data, might be associated with “zonal flows”, similar to the analysis of GPI data for Alcator C-Mod [21].

4. Evaluation of charge-exchange vs. lithium deposition

As mentioned in the Introduction, it is not yet clear why coating the wall surfaces with lithium should affect the plasma energy confinement time. One potential mechanism for this is that the lithium coating reduces the outgassing and recycling from deuterium from the wall, and this in turn reduces the neutral deuterium density in the plasma edge. The edge neutral density can in theory affect the E×B flow and flow shear in the edge, which can in principal affect the edge turbulence and its resulting transport. A correlation between increased energy confinement and decreased edge turbulence was described previously in the context of lithium coating experiments on NSTX [3]. Previous work on DIII-D [15-16] and NSTX [17] also showed that the charge exchange damping introduced by neutrals could play an important role in L-H translation.

Here we evaluate effect of charge exchange (CX) collisions during the NSTX lithium scan described in this paper. Such collisions can introduce a damping of ion flow in both the parallel (along B) and poloidal directions [7-12], which could then potentially affect edge E×B flow and edge turbulence. Generic theoretical estimates [11] indicated that the modification of ion flow due to CX can be significant when the ratio of neutral density to electron density was $n_n/n_e > 10^{-3}$. Results from the 2D fluid turbulence simulation code SOLT also suggested that edge turbulence and radial transport decreased as the E×B flow damping parameter increased [22]. As mentioned in Ref. [23], the time-averaged transport coefficient has a maximum value when the mean E×B flow equals the oscillatory part of E×B flow. So it is possible that the increase in H factor with lithium as shown in Figure 2 could be due to changes in either the mean or fluctuating E×B flow.

Figure 5 shows the simulated midplane neutral density profiles from a KN1D code analysis [24] using the plasma electron density and temperature profiles from Thomson Scattering diagnostic and the edge pressures from ion gauge shown in Table 1. The uncertainty in these neutral profiles depends mainly on the uncertainty in the Thomson profiles since the charge exchange cross-sections are well known. Figure 5 shows the charge-exchange rate for ions calculated from Figure 4. The lithium coating increased with shot number. At 2 cm inside the separatrix both the neutral density and CX rate decreased with more lithium coating, except shot #141322 in which the high edge density makes the neutral density decrease unusually low in the SOL.

5. Summary and discussion

This paper presented the results of GPI measurements in NSTX with increasing lithium coating. During the scan of lithium deposition in the 8 shots in this database, we observed a slight increase in H factor (Fig. 2), which was also seen in previous lithium deposition scans on NSTX [2-4]. For the same scan we found with increasing pre-discharge lithium deposition a slight decreased edge pressure (Fig. 1) and a slight increase in the poloidal flow speed both inside and outside the EFIT separatrix (Fig. 2).

There is not yet a clear interpretation of these results in terms of edge turbulence physics. The observed increased poloidal flow of the turbulence could simply be due to the increase in the edge density gradient with increased lithium, which could cause the observed increase in the phase speed of the turbulence speed in the electron diamagnetic direction. The increased poloidal turbulence speed could also be affected by changes in the toroidal plasma rotation, which were not measured during this scan. There might be an increase in poloidal flow shear associated with the increase in poloidal turbulence rotation, but the magnitude of the local flow shear could not be evaluated accurately enough in this data set to show any systematic trend with lithium. In this sense the present results are similar to those discussed previously [2, 3], in which a correlation was observed between edge turbulence, lithium coating, and the effects on confinement, but a causal relationship was not proven.

As discussed in the Introduction, one possible causal connection between the lithium wall coating and the plasma energy confinement time could be through the decrease in edge neutral density with increased lithium. Assuming that the global energy confinement time depends on the edge turbulence transport, if the edge neutral density reduced the edge turbulent transport, then it could also cause an increase the global energy confinement time. One possible mechanism for the edge neutrals to affect the edge turbulence is through charge exchange collision, where a decrease in CX collision with increased lithium could cause a viscosity and modification of ion distribution function in the parallel flow and flow shear of the turbulence [7-11], according to [6].

Two new pieces of evidence for a possible causal connection were described in this paper; namely, a slight increase in the mean poloidal flow speed with increasing lithium (Fig. 2), and a decrease in the relative poloidal flow fluctuations (Fig. 3). These point to a possible change in edge shear or zonal flow with increasing lithium. An attempt to directly evaluate the charge exchange damping effect showed that the CX collision frequency (calculated from neutral density and ion density and temperature, assume the ions have the same density and temperature as electrons, shown on Fig. 5) was small compared with ion transit frequency (about 10^4 Hz) inside the separatrix, but the effect of CX on the poloidal flow speed was not directly evaluated. Note that Ref. [12] suggested that the CX damping can play a very important role in this region.

There were certainly limitations and uncertainties in the present data and analysis. The main limitations came from the relatively few shots available with GPI data for these NSTX lithium scans, and in particular the decrease in NBI power for the two shots with the highest lithium coating. Although this decrease in NBI power was done intentionally to keep the plasma beta constant, a previous study indicated that edge turbulence in NSTX was correlated with the NBI power [25]. Therefore the relative effects of NBI power and lithium coating on the edge turbulence are still undetermined.

Further work on the confinement effects of lithium could focus on direct measurements of the neutral density profile, the edge poloidal flow profile, and the transport effects of the edge turbulence as a function of lithium coating. Ideally, these measurements should be done at multiple poloidal locations, and should be used to compare with computational simulations of edge turbulence and transport.

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Table 1 Shot list of database

shot	Start time (ms)	End time (ms)	P_{NBI} (MW)	W_{MHD} (J)	P_{loss} (MW)	$\tau_{E<MHD>}$ (s)	$H_{98(y,2)}$	n_e ($10^{15} cm^{-2}$)	I_p (KA)	B (kG)	β_N	Edge pressure (10^{-5}Torr)	Li dep'n (mg)	Li accum (mg)
141307	480	490	3.8	1.37E+05	4.2	0.032	0.893	7.5	700	4.43	4.45	5.82	22	1497
141309	480	490	4.8	1.60E+05	5.2	0.031	0.837	7.8	700	4.43	4.90	6.76	22	1540
141319	530	540	3.9	1.42E+05	4.0	0.035	0.877	7.9	650	4.43	4.87	4.7	90	2041
141320	530	540	4.0	1.42E+05	4.0	0.035	0.952	8	650	4.43	4.98	4.66	90	2131
141321	530	540	3.9	1.41E+05	4.8	0.029	0.809	7	650	4.43	4.27	5.42	89	2220
141322	530	540	4.0	1.48E+05	4.2	0.035	1.02	8	650	4.43	5.02	4.8	151	2371
141324	530	540	2.9	1.26E+05	2.8	0.045	1.22	6	650	4.43	4.96	3.1	246	2845
141326	530	540	2.9	1.57E+05	2.9	0.054	1.33	5.6	650	4.43	5.62	3.06	314	3396

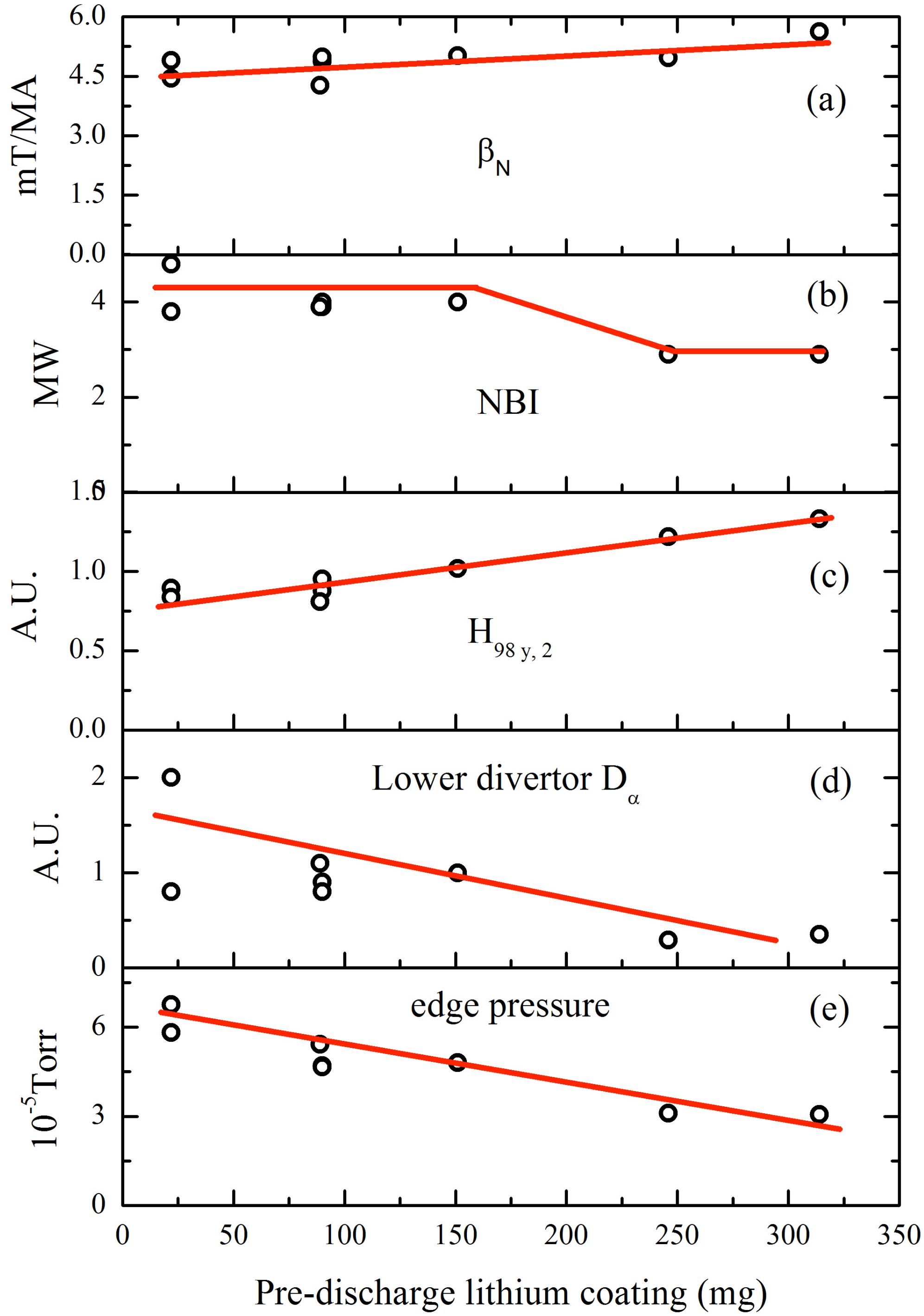

Fig. 1 Main parameter changes with lithium: (a) shows the β_N, (b) shows the injected NBI power, (c) shows the empirical scaling coefficient $H_{98y,2}$, (d) shows the divertor D_α light, (e) shows the edge pressure. The red lines are linear fits of these points, except for (b).

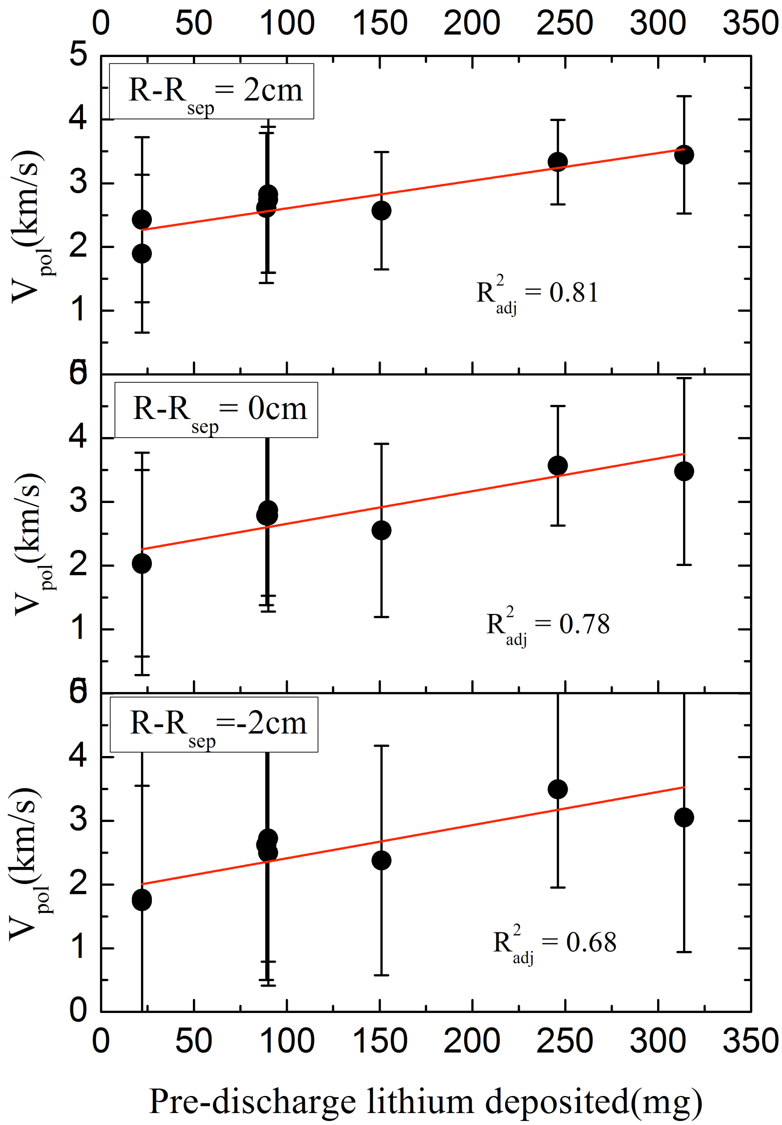

Fig. 2 Poloidal turbulence velocities vs. lithium at different radial locations ($R\text{-}R_{sep}$ =-2, 0, 2 cm). The error bars are the RMS variations of V_{pol} at each point. The average poloidal velocity increases from ~2 km/s to ~3 km/s with more lithium for all radii.

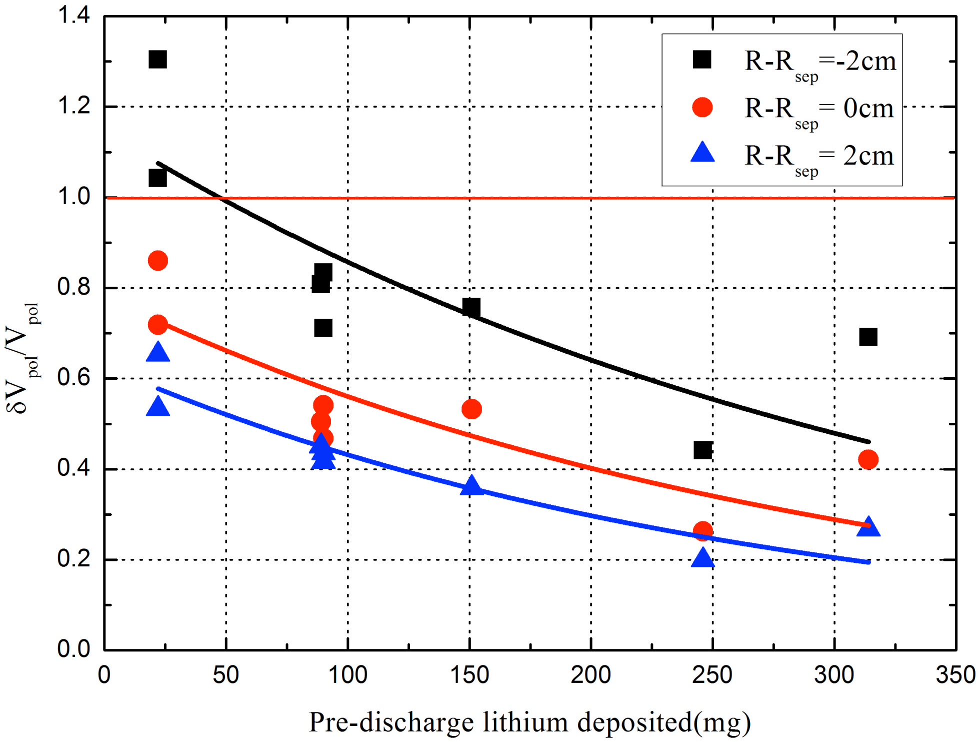

Fig. 3 Fluctuating part of the poloidal velocity (δV_{pol}) divided the mean poloidal velocity (V_{pol}) at different radial locations vs. the amount of lithium coating before shot. The $\delta V_{pol} / V_{pol}$ decreased with increased lithium coating.

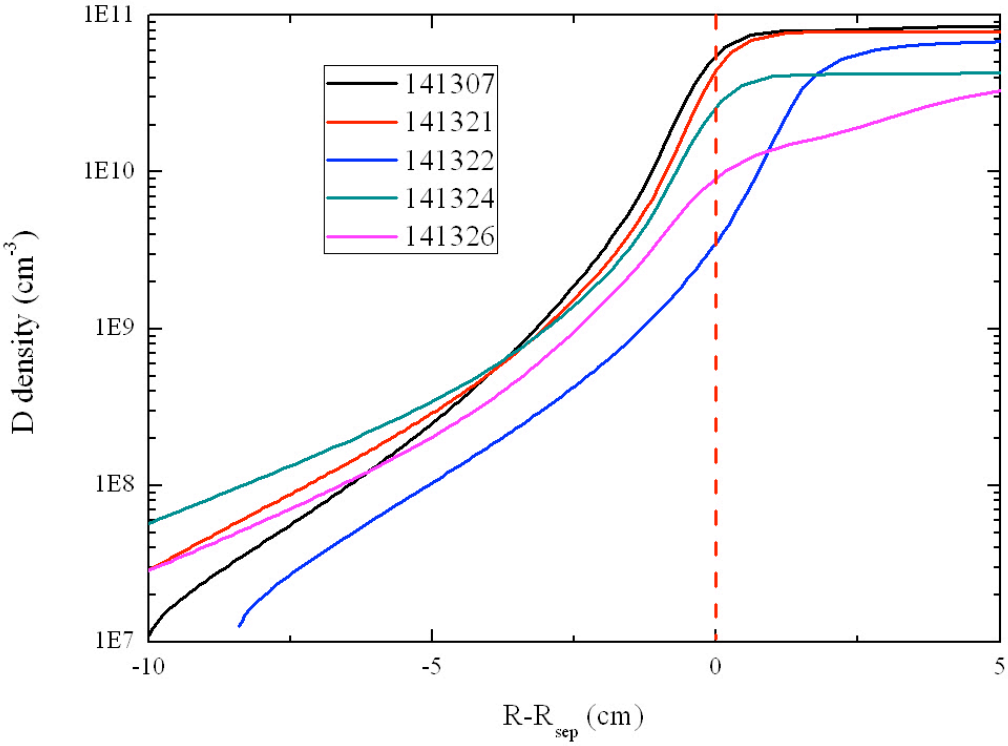

Fig. 4 Edge neutral density profiles from neutral particle simulation codes of KN1D, using the plasma electron density and temperature profiles from Thomson Scattering diagnostic and the edge pressures from ion gauge shown in Table 1. The lithium coating increased with shot number.

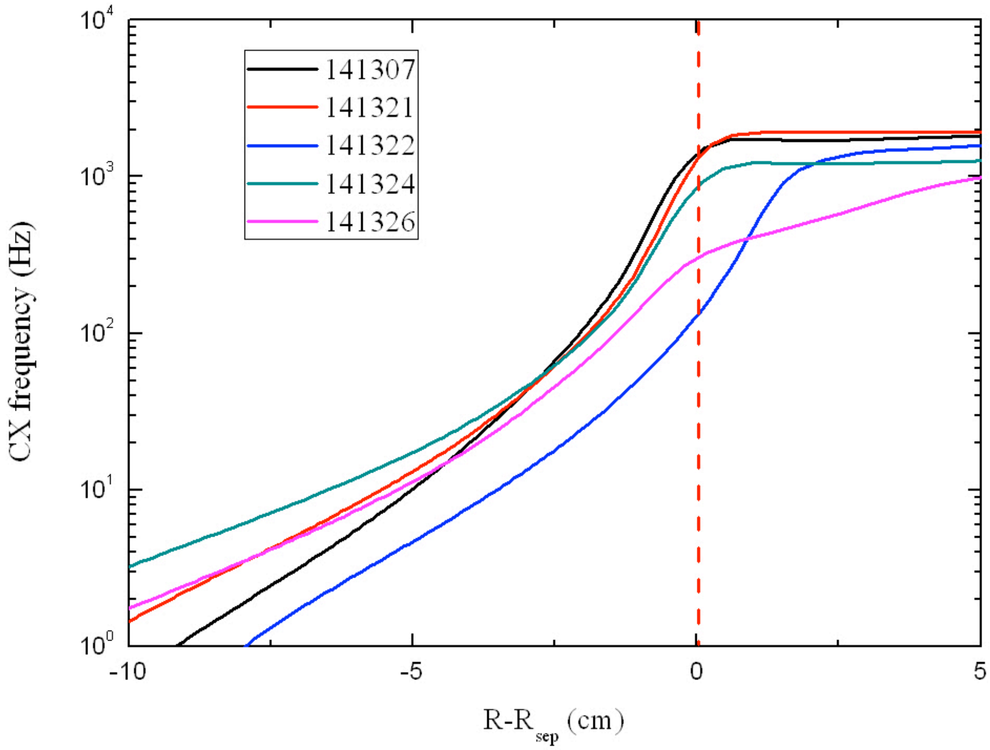

Fig. 5 Ion charge exchange collision frequency profiles from neutral particles simulation results with the same labels as for Fig. 4. The lithium coating increased with shot number.

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