# Lithization effects on density control and plasma performance in RFX-mod experiment

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**Abstract**. Plasma-wall interaction is one of the most important issues that present magnetic confinement devices have to face. In the RFX-mod experiment density profile control has recently become even a more crucial point due to the observation that single-helical-axis states (SHAx), and their consequent improved confinement regime obtained at high plasma current ($I_p$>1.2 MA) and low density ($n/n_G \approx 0.15$), spontaneously disappear when operating at medium plasma density ($n/n_G \geq 0.25$). It is believed that reducing hydrogen influx from the wall and controlling density profile will allow operating at higher density improving in such way the energy confinement time. Different techniques have been tested to reduce hydrogen wall influx: He glow discharges cleaning, He discharges at high plasma current, wall boronization and baking. All such techniques were able to improve the situation but none allowed a complete and stationary hydrogen influx reduction. At high plasma current their effect lasts only few discharges, characterized by a lower hydrogen influx and low density equilibrium with a recycling factor still equal to one; furthermore, the wall sometimes responds in an uncontrollable way providing very high influxes during the discharges. Given the good results obtained on Tokamak and Stellarator experiments, in order to improve this situation we tested the effect of wall conditioning by Lithium. As a first lithization method to deposit on the wall a controllable amount of Lithium we used a room temperature pellet injector (max pellet diameter of 1.8 mm and max length of 5). Lithization was applied both directly to the graphite tiles and over a fresh boronization. The technique of depositing Lithium by pellet injection has been found effective in maintaining Hydrogen wall recycling very low. A good effect has benn observed also on edge density providing more peaked density profiles. Preliminary tests have been performed also by a Liquid Lithium Limiter with a capillary porous system on loan from FTU experiment of ENEA laboratories in Frascati.

## 1. Introduction

In the experiments of magnetically confined plasmas first wall play a crucial role for the attainment of good plasma performance. The choice of the first wall involves important physical and technological issues such as: (1) avoiding plasma contamination; (2) reducing recycling; (3) withstanding high thermal loads from plasma interaction without surface damage; (4) allowing an easy removal of retained gas. Till now no tested first wall material proved to be able to face all previous issues: low Z materials are reliable in terms of contamination but not of recycling control and gas retentions, on the contrary high Z materials are not suitable to keep at low value the plasma $Z_{eff}$. On tokamak experiments [2,3] (and recently on stellarators too [4]) to improve the situation two solutions have been developed: wall conditioning and divertor configuration. The first one proved to be very effective particularly for high Z wall materials, since low Z coatings can reduce in plasma the high Z impurity content, while the divertor proved to be a must for the achievement in tokamaks of the H mode improved confinement.

Less effort on wall optimization has been spent for the Reversed Field Pinch (RFP) configuration; typically to decrease the device costs the RFPs typically use stainless steel or aluminium vacuum vessel also as first wall, sometimes adding some localized high or low Z limiters [5,6]. Divertor solution is difficult (but non impossible) to be implemented in the RFP configuration because it send away from plasma the conductive shell, whose closeness to the plasma boundary is crucial for stability and edge error magnetic field reduction.

Greater effort has been spent in wall optimization in the RFX-mod RFP experiment (R/a=2.0/0.46 m, $I_p \leq 2.0$ MA) [7]. Since RFX-mod has been designed for very high plasma current, its first wall is entirely covered by graphite tiles. Graphite was chosen because it is a good solution in terms of allowable power load to the wall and impurity control. Allowable power load is a very important aspect to be accounted for because RFX-mod can operate with input power over 40 MW for about half of second. Graphite drawback is the retained gas and consequent hydrogen recycling. Since at room temperature hydrogen desorption from graphite is very low, in the inter-discharge time interval hydrogen trapped during discharges is not pumped out. In a few discharges the plasma facing side of tiles becomes completely hydrogen saturated, after that graphite acts as a big hydrogen reserve resulting in a hydrogen influx that depends only on the power load on the wall. The lack of influx control provides both operation and performance effects. It denies operation at a desired density particularly at high plasma current ($I_p > 1.5$ MA) when power load is very high, but, even worse, it affects plasma performance preventing density profile control by external refuelling; in particular high density becomes associates to hollow density profiles characterized by a high density but cold plasma edge. This seems to affect plasma performance making impossible the attainment of the improved confinement regime associated to the single-helical-axis states (SHAx) [1] at intermediate plasma density ($n/n_G \geq 0.25$).

To overcome the described limitations hot wall operation and inner shots wall conditioning treatments have been tested but neither of them proved to be able to simultaneously control hydrogen influx and providing good performance. In the RFX device (in operation from 1992 to 1999) it was possible to operate at a wall temperature of about 350 °C, providing in this way an empty wall at the beginning of each discharge since in the inter-discharge time interval the Hydrogen trapped in the wall was desorbed by graphite and pumped away. This avoided wall saturation but introduced new problems: large density variation during the discharge and high density driven fast terminations. Indeed empty graphite requires a high filling pressure to set-up the discharge and a high puffing flux to sustain the density, in this way in a short time during the discharge the wall became filled by a high amount of gas that (probably) operating a 350 °C was easily and suddenly released in presence of the localized plasma wall interaction (PWI). Probably the situation could be better in the new RFX-mod because the feedback system of edge radial field is able to strongly reduce the localized PWI but unfortunately the hot wall operation is not compatible with the new internal magnetic probes (maximum wall temperature is limited to 100 °C in RFX-mod). Regarding wall conditioning treatments, sessions of He discharges, Glow Discharge Cleanings (GDCs), wall boronization [8] and wall baking were tested but none of them provided a solution stationary over many discharges. Boronization coating was the most effective in controlling hydrogen influx over about 100 discharges [9] (the exact number depends on discharges characteristics: plasma current, duration, density value) but it wasn't effective in improving significantly plasma performance. In RFX-mod boronization lowers only slightly $Z_{eff}$, because as expected it effectively reduces oxygen content but carbon reduction is only partial and balanced by boron increases. Since in RFX-mod oxygen contribution to $Z_{eff}$ is small, the final result is a small reduction of $Z_{eff}$ value that does not produce a significant energy confinement improvement since in RFX-mod at low/medium density energy loss associated to radiation is a small fraction (≈10%) of total losses.

To improve density control and plasma performance over those of boronization, recently we tested on RFX-mod the lithization technique, aiming to match the good results obtained on many tokamaks [10-13] and stellarators [14] experiments with a lithium coating limiter. This is the first time that this technique has been applied to a RFP device. In this paper we describe the optimization of lithization method and its effect in RFX-mod on plasma profiles and performance comparing it to the boronization method.

## 2. Lithium wall conditioning techniques

On RFX-mod two techniques have been implemented for lithium wall conditioning: lithium pellet injection and Liquid Lithium Limiter (LLL), the first one has been used for wall conditioning before two high current plasma performance campaigns, while the second one has been tested on medium plasma current discharges for commissioning purpose only. We describe here the two techniques while in the paper we will present the results obtained with lithium pellet experiments only.

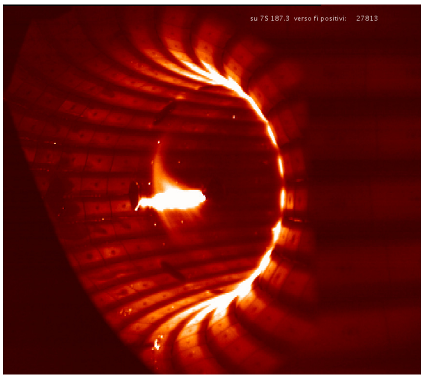

*Fig. 1 Image of an injected lithium pellet.*

### 2.1 Lithium wall conditioning by pellet injection

For lithium pellet injection we take advantage of a room temperature pellet injector (RTPI) able to launch any material made room temperature solid pellets of variable sizes. In RTPI injector solid pellets are inserted in the frontal hole of cylindrical sabots. Sabots are accelerated by a driver gas till they hit a bumper, they are stopped by the bumper while pellets can fly to the plasma through a central hole in the bumper. This allows the RTPI to inject pellets with a size up to a cylinder Ø1.8x5 mm with a maximum speed of 200 m/s. A sabots loader provides a reserve of about 25 pellets for a full day operation [15].

For wall conditioning purpose the largest pellets have been used to maximize lithium injection. To get a complete pellet ablation we injected them at a speed of about 100 m/s into discharges with a plasma current of ≈1 MA, plasma density of $\approx 2 \div 3 \cdot 10^{19}$ $m^{-3}$ and a corresponding temperature of ≈600 eV. In such plasma conditions, pellets are ablated in about 5 ms and arrive close to the plasma centre (fig. 1). Deep pellets penetration was selected to provide a uniform toroidal and poloidal Li deposition over the wall, indeed during the 5 ms of pellet ablation and the following 20 ms of density diffusion the localized PWI moves toroidally and poloidally providing a distributed lithium deposition. Since localized PWI position is uniformly distributed over discharges injecting pellet on many discharges provides a nearly uniform deposition of lithium over the wall.

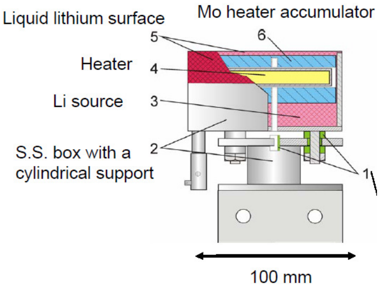

*Fig. 2: LLL schematic section.*

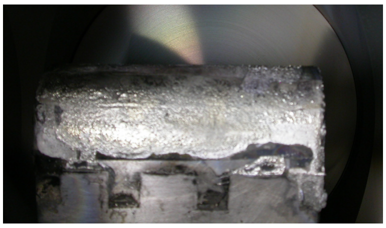

*Fig. 3: LLL after exposure to 0.5 MA plasma.*

### 2.1 Liquid Lithium limiter

An apparatus for wall conditioning with a Liquid Lithium limiter (LLL), obtained with capillary porous system (CPS) configuration [16] (see fig.2), has been tested in RFX-mod. The LLL proved to be a good candidate to overcome the problems of heat load and erosion on the first wall, keeping a very low recycling regimes and improved energy confinement time [11,12]. This is the first time a CPS head is exposed to RFP plasma and the absence of previous experience requires gradual approach. The techniques has been applied for wall conditioning before the target hydrogen RFP plasma of 1.2MA: a run of RFPs plasma at low current (0.5 MA with He discharges) has been done setting the LLL at 3 mm inside the internal convolution of the full cover graphite wall (fig. 3).

The application of LLL on RFP plasmas in the range 1.5 to 2 MA will be pursued next year, aiming at operations with significant increase of the quantity of Lithium.

## 3. Lithium wall conditioning experiments

To study the effect of the wall status below Li coating, lithium pellets have been injected both in the case of clean graphite wall and in the case of graphite previously coated by boron but with few hydrogen shots performed before lithization. On each conditions a maximum of about 50 lithium pellets have been injected corresponding to about $2\cdot10^{22}$ atoms for a theoretical coating thickness of about 10 nm.

First experiments of lithium wall conditioning have been devoted to optimize the technique, to such purpose to qualify the pellet effectiveness in conditioning graphite wall we have used Li influx measured during plasma discharges. Initially we injected Li pellets on H (fig. 4a) discharges and later on He discharges. The highest Li influxes have been obtained with He discharges, but a further increase has been possible by reducing the discharge length (fig. 4b).

We can wonder why we obtained these behaviours; apparently the easiest to explain is the dependence on pulse length. From figure 4b we see that when there is no pellet injection Li influx decreases with about a constant rate, which is about one half of the increasing rate observed with pellet injection. This mean that on each conditioning discharge there is simultaneously lithium deposition and lithium “removal” and reducing pulse length we shorten the “removal” phase. Previous explanation can be applied to the difference observed between H and He discharges saying that H “removal” efficiency is higher than He. The problem is what could be the physical “removal” mechanism. We can think to a true physical removal or to the formation of chemical bound that make lithium inert. In the first case Li is removed from the wall by physical and chemical sputtering, being the first one the only one available in He discharge case and both available in H discharges case explains the higher H removing effectiveness. Measured lithium influx shows that Li is removed from the wall during the discharges but there are no indications that a fraction of it does not return to the wall. As expected residual gas analysis (RGA) does not show the presence of Li or Lithium Hydride (LiH) on extracted gas, since at room temperature Li is a solid and so it can not pumped out. The final position of Li nor returning to graphite surface could only be as a dust at the vessel bottom on the graphite tiles shadow, but there it can not be measured. About the formation of chemical bounds that make lithium inert we can consider the formation of (LiH) at the graphite surface [17] or Li-C-H bounds inside the graphite (we will discuss in sec. 3.1 this point). This is confirmed from the observation that on each H discharge most of hydrogen is not desorbed after the discharge. This does not seem to apply to He discharges: He can not bind with Li, but in our experiments H was present in He discharges too. From spectroscopic ann density measurements we estimate a fraction of H between 20÷50% on He discharges, hydrogen was not filled-in but extracted from graphite during the discharges. It is the extracted H that recycling to the wall bound to lithium. An indication that Li is not truly “removed” from the wall is obtained from graphite samples [18] exposed during wall conditioning campaigns. After lithization campaigns, depth profiles

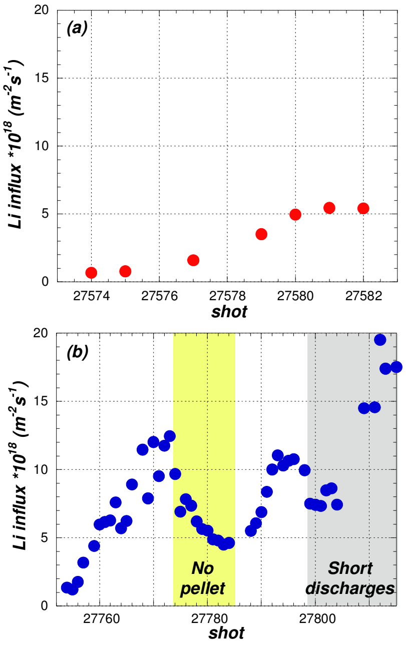

*Fig. 4: Lithium influx measured injecting pellet on H discharges (a), He Discharges (b).*

measurements of the present species performed by SIMS (Secondary Ions Mass Spectrometry) show the presence of lithium on samples inserted after standard H discharges when lithium influx measured was small; furthermore lithium on samples increases with the number of lithization campaigns.

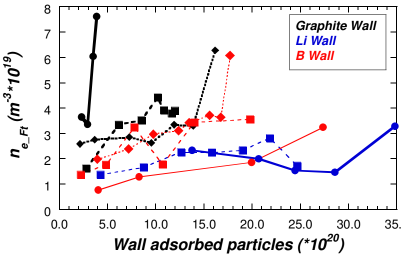

*Fig. 5: Plasma flat-top density versus total filled/puffed particles between two He-GDC: each point correspond to a discharge and particles are summed over discharges.*

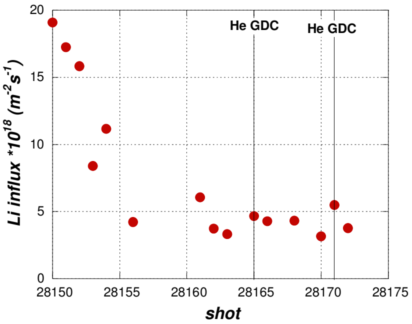

*Fig. 6: Time history of Lithium influx on some high plasma current H discharges.*

## 3. Lithization effects on plasma behaviour

### 3.1. Gas absorbing capacity and lithium saturation

Lithium wall conditioning increases wall capability to adsorb hydrogen. This has been seen in discharges with similar density by comparing the particles adsorbed on each discharge by the wall before and after Li conditioning. It has been also confirmed by comparing the total number of hydrogen particles absorbed between two He glow discharge cleaning operations (He-GDC) required for recovering the plasma density. As written in the introduction in RFX-mod, when the amount of hydrogen in the wall becomes high, density depends only on wall saturation level and input power; density increases on discharges basis, up to a value at which plasma current cannot be sustained and a He-GDC is required to empty the wall. Comparing to the clean graphite case, after lithization density increas is lower for the same amount of gas, furthermore the final He-GDC is required after a higher quantity of wall trapped particles when plasma density is still low (fig. 5). Li absorbing effect is similar to those of boronized wall.

The increased absorbing capacity of lithium coating allows a better control of plasma density. On clean graphite strong gas puffing or pellet injection can be used to control density immediately after He-GDCs only, after the first discharge density control is demanded to a gentle trimming of filling pressure and wall status. This is not the case of Li wall conditioning where strong gas puffing and pellets require more discharges to saturate the wall, and operation at high densities are possible without losing density control. The situation is similar to the boronization case but with the lithium absorbing effect disappearing faster than in boronization case.

Loosing of lithium adsorbing capacity could be related to the lithium saturation by hydrogen binding discussed in previous section. Indeed we observe a progressive reduction of lithium influx on a shot to shot basis (fig. 6) that reduction is faster than in the lithization phase probably because of the higher quantity of filled/puffed hydrogen. Comparing from figure 5 the number ($\approx 3 \cdot 10^{21}$) of hydrogen atoms adsorbed on the wall before He-GDC to the lithium atoms in the coating, we see that it is about a factor of 10 lower, this could indicate that at room temperature lithium loose its adsorbing capacity well before reaching 1:1 ratio with hydrogen (as observed in ref. 9). From fig. 6 we can have an indication on the He-GDC ability on recovering a slightly higher lithium influx, this could

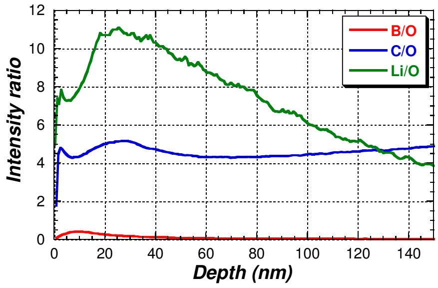

*Fig. 7: Deposition profiles on one samples exposed to lithization discharges.*

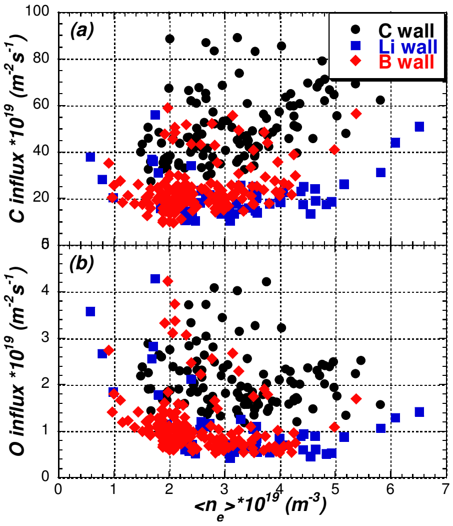

*Fig. 8: Variation of influx (a) C and (b) O with ne for 3 sets of discharges.*

be related to the extraction of some of hydrogen bounded to lithium. To reduce lithium adsorbing capacity could also contribute its depth distribution on graphite. Preliminary measurements with SIMS (which has some uncertainty related to the porous nature of RFX-mod graphite) show that lithium is not deposited on graphite surface but it diffuses into the graphite up to about 100 nm. (see fig. 7). We do not know if such diffusion is specific to the lithization pellet technique or if it is a spontaneous diffusion [19], but it could affect lithium ability in adsorbing hydrogen.

### 3.2. Impurities reduction

To analyze impurity behavior we measured carbon and oxygen influxes, because C and O are the main source of impurity in RFX-mod. For carbon influxes we measured the CII line at 6578Å while for oxygen the OII line at 4415Å. In figure 8 we drawn carbon and oxygen influx versus average density for high plasma current discharges performed on clean graphite, after boronization and after lithization. It is apparent that at similar average density both boronization and lithization are very effective in reducing carbon and oxygen content; but lithization is slightly more effective in reducing carbon than boronization. The improved carbon screening of lithium coating can surprise considering that its theoretical thickness is much smaller than boron thickness (about 100 nm) and that based on SIMS measurements Li is mixed with carbon. A possible explanation could be related to recent observation of the non-toroidal uniformity of boron coating in RFX-mod [18] with probably some region of graphite wall not covered by boron coating.

### 3.3 Edge density and temperature variation

Lithium wall conditioning has a strong effect on edge plasma properties both on time averaged quantities than on fluctuations.

Thermal Helium Beam diagnostic shows that after lithization edge temperature increases and electron density decreases; temperature increases more than compensates density decrease and provides a higher edge pressure compared to discharges performed with graphite (fig. 9). Reduction on edge density has been confirmed by reflectometer measurements, the single wavelength measurement shows that at the same average density the position of the $10^{19}$ $m^{-3}$ cut-off layer move inward of about 1 cm after lithization (fig. 10). The edge density variation affects also global density profile as can be inferred from density profiles measured by a multi-chords interferometer. This can be verified analysing the density peaking factor $P_n=n(0)/<n>$. Since on RFX-mod there is a high variation of density profiles, mostly related to

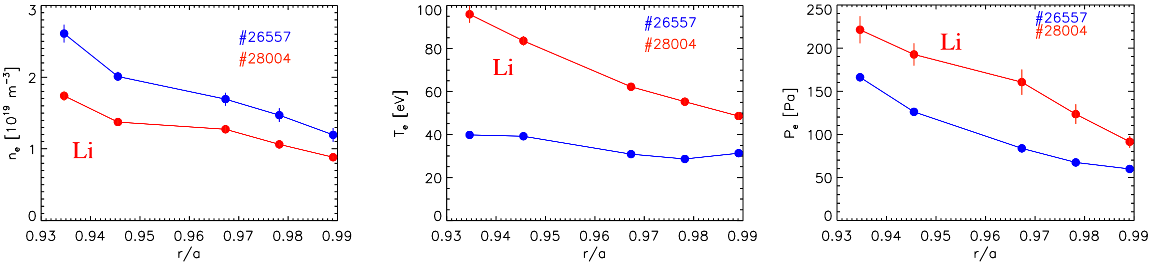

*Fig. 9: Edge density, temperature and pressure measured by Thermal Helium Beam diagnostic on similar discharges before #26557 and after lithization #28004.*

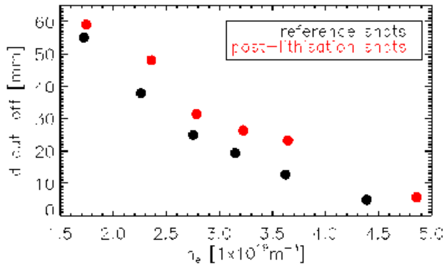

*Fig. 10: Single wavelength reflectometer cut-off layer distance: for discharges with clean graphite (black) or after lithization (red). Each point is an average over some discharges with the same density.*

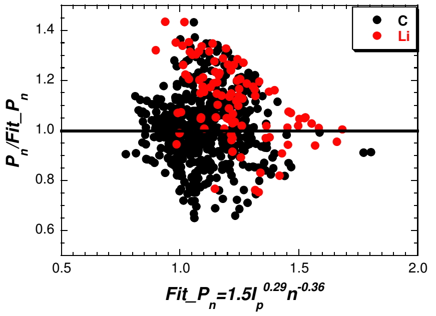

*Fig. 10: Electron density profile peaking factor. Comparison between discharges with and without lithium conditioning.*

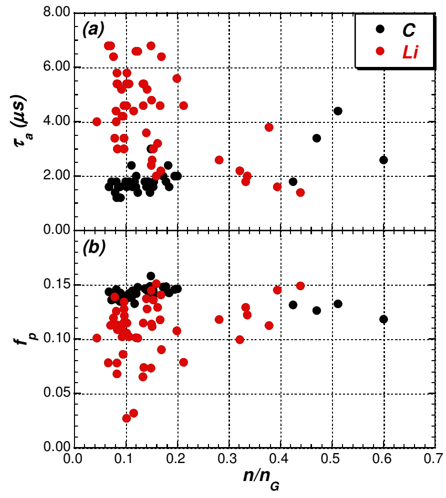

*Fig. 12: GPI measurements: a) autocorrelation, b) frequency; for discharges with clean graphite (black points) or after lithization (red points).*

mean density and plasma current, we compared $P_n$ with a fit ($Fit\_P_n$) on it calculated on clean graphite discharges as a function of $I_p$ and <n>, see fig. 11. After lithization the ratio $P_n/Fit\_P_n$ is typically higher than one. Analogous effect of lithization can not be point out on global temperature profiles measured by Thomson scatering. These effects are specific of lithium conditioning and are not observed after boronization.

We can wonder about the reason of the observed edge differences, they could be a simple effect of a different impurity content in Li case than in graphite case or they could be the results of a different transport at the edge. To get some indication about the reason of the observed difference we analyses density fluctuations measured at the edge by the Gas Puff Imaging (GPI) diagnostic [20]. The raw signals show a big difference between discharges before and after lithium wall conditioning. To quantify this difference in figure 12 we compared the autocorrelation ($\tau_a$) of the edge fluctuations, and the packing fraction ($f_p$), which measures the percentage of GPI signal occupied by strong bursts [21], associated with coherent blobs presents in the plasma edge. The autocorrelation shows that for all the discharges with clean graphite the autocorrelation time is less than 2 μs, instead for the discharges after lithization there is a spread in autocorrelation time, but all greater than 2 μs, with a slight scaling with the normalized density. Since the propagation velocity of the edge fluctuations is the same for the two sets of discharges, this means that the edge blobs are larger after lithization. Edge blobs, though larger, after lithization occupy less plasma volume: indeed packing fraction is about 15% for standard discharges while it is smaller for lithisated ones. The different behavior of the edge density structures means a different particle transport associate to them, even if a direct measurement of the total particle flux in the edge is not available in RFX-mod yet. In fact if we consider the particle flux due to edge bursts we find a lower flux after the lithization than before. This give us that lithization is able to effectively modify edge particle transport.

### 3. 4. Particle and energy confinement time

The significant edge effects we previously describe only slightly affect global plasma performance. Lithization provides a particle confinement time increase both over clean graphite case and over boronization as can be see from fig. 13 where particle confinement is

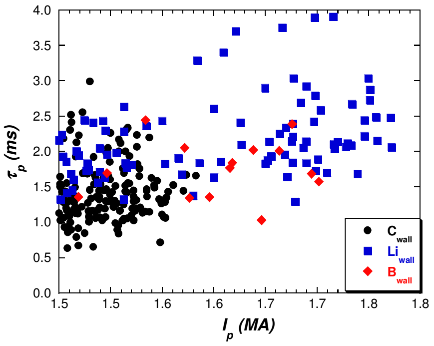

*Fig. 13: Particle confinement time versus plasma current of discharges with an average density of about 3 · $10^{19}$ $m^{-3}$ with and without Lithium or Boron conditioning.*

plotted versus plasma current for the three wall cases. However particle confinement time improvement is not accompanied by a global energy confinement time improvement.

## 4. Conclusions

Wall conditioning by means of lithium proved to be an effective tool in controlling wall recycling. The technique provides or improves all the features of boronization wall conditioning: increases hydrogen wall absorbing capacity and reduces the impurity content. It seem also able improve the edge particle behaviour providing a higher particle confinement time. The absorbing wall capacity allowed for the first time operating RFX-mod close to its 2 MA target plasma current.

Though up to now the beneficial effect of lithium wall conditioning does not seem to extend to the plasma core the differences observed on density and temperature at plasma edge, suggests that improving the lithization technique could be a valuable solution to improve also plasma core. Some beneficial eefects can still be obtained by improving the lithization technique: performing lithization over a better conditioned wall for example removing all stored hydrogen by baking or intense He-GDC; makeing a stronger lithium deposition injecting a much higher number of pellet (by a centrifugal injector able to inject many pellet on each discharge) or by using the LLL as planned for the next year.

## Acknowledgment

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## References

[1] LORENZINI, R. et al, Nature Phys. **5**, (2009) 570.
[2] WINTER, J., et al., J. Nucl. Mater. **162-164** (1989) 713.
[3] JACKSON , G.L., et al., J. Nucl. Mater. **196-198** (1992) 236.
[4] TABARÉS, F.L., et al., J. Nucl. Mater. **313–316** (2003) 839.
[5] DEXTER , R. N., et al., Fusion Tech. **19** (1991) 131.
[6] BRUNSELL, P.R., et al., Plasma Phys. Control. Fusion **43** (2001) 1457.
[7] GNESOTTO , F., et al, Fusion Eng. Des. **25** (1995) 335.
[8] SONATO , P., et al., J. Nucl. Mater. **227** (1996) 259.
[9] TRAMONTIN, L., et al., J. Nucl. Mater. **266-269** (1999) 709.
[10] MANSFIELD, D. K., et al., Phys. Plasmas **3**, (1996) 1892.
[11] MIRNOV, S.V., et al., Plasma Phys. Control. Fusion **48** (2006) 821.
[12] APICELLA, M.L., et al., J. Nucl. Mater. **363–365**, (2007) 1346.
[13] DING, S., et al., Plasma Phys. Control. Fusion **52**, (2010) 015001.
[14] SANCHEZ, J., et al., Nucl. Fusion **49**, (2009) 104018.
[15] GARZOTTI, L., et al., Rev. Sci. Instrum. **70**, (1999) 939.
[16] ALFIER, A, et al. *"Liquid Lithium Limiter on the RFX-mod experiment"*, accepted for J. Nucl. Mater.
[17] BALDWIN, M. J., et. al., Nucl. Fusion. **42**, (2002) 1318.
[18] BARISON, S., et al. *"Analysis of the interaction between plasmas and the graphite first wall in RFX-mod*", accepted for J. Nucl. Mater.
[19] ITOU, N, et al., Journal of Nuclear Materials **290-293**, (2001) 281.
[20] AGOSTINI , M. et al. *"Optical measurements for Turbulence Characterization in RFX-mod edge"* accepted for Rev. Sci. Instrument..
[21] SPOLAORE , M., et al., Phys. Rev. Letter **93** (2004) 215003.