

CONFERENCE PRE-PRINT

TESTS OF ULTRASONIC LITHIUM INJECTOR
WITH EXTERNAL LITHIUM SUPPLY ON
TOKAMAK T-11M

A.N. SHCHERBAK, S.V. MIRNOV, V.B. LAZAREV, YA.A. VASINA, A.S. DZHURIK, A.V. AGEEV,
A.V. ZORIN
JSC "SRC RF TRINITI"
Moscow, Troitsk, Russian Federation
Email: shcherbak@triniti.ru

Abstract

Using liquid lithium to protect the first wall of the tokamak is a promising idea, and it has found wide application at many fusion devices. In 2021 at T-11M tokamak the injector for real-time lithization was developed. It showed excellent results, but change of the lithium in the lithium reservoir required opening the vacuum chamber to atmosphere. Therefore, in 2023 a new device (lithium injector) with possibility to refilling without depressurization of the vacuum chamber was developed, and then the first tests have been carried out. This paper presents the results of testing a finely dispersed lithium injector with an external lithium supply system in plasma discharges at the T-11M tokamak. Its efficiency was demonstrated experimentally, and seven refilling of the injector were performed without depressurizing the vacuum chamber of the tokamak. The characteristic operating parameters of the lithium injector were calculated: the velocity of lithium microdroplets ranged from 1.5 to 7 m/s, and the injected lithium flow varied from 10 to 70 mg/s.

1. INTRODUCTION

The use of liquid lithium to protect the first wall and divertor plates of the tokamak from the effects of high-temperature plasma is being actively studied at many fusion devices, and seems to be the most promising idea for use in future tokamak-reactors [1]. The main effect of using lithium is a decrease of impurities in plasma and, accordingly, a decrease in the effective charge of the plasma column Z_{eff} . There are various methods of using lithium to protect the first wall of the tokamak, such as preliminary lithization, lithium limiters of various designs, and lithium injectors. One of the methods for introducing lithium to the periphery of the plasma column is the method of lithium injection. Outstanding results had already been achieved using such devices at tokamaks, for example, in the TFTR using DOLLOP technology (supershot discharge; more than 10 MW of thermonuclear power [2]), and in the EAST using the lithium dropper (the record plasma discharge duration of 1056 s [3]). However, one of the disadvantages of the latter method was the introduction of additional impurities into the plasma column, which are present in the shell of lithium pellets to protect lithium from atmospheric gases, which ultimately resulted in Z_{eff} reaching a level of 2 [4], which is obviously insufficient for the operation of future tokamak-reactors.

Since 2021, in addition to lithium limiters used to organize a closed lithium circulation loop to protect the first wall of the tokamak, an ultrasonic injector of finely dispersed lithium has been tested at the T-11M tokamak to introduce lithium into the plasma. The main operating principle of this injector is to generate droplets on the surface of a thin liquid layer under the influence of ultrasonic vibrations. One of the advantages of this injector is the direct introduction of lithium droplets into the tokamak chamber without any impurities.

Tests of such an injector [5] have demonstrated a decrease in the level of impurities in the tokamak chamber, an increase in the discharge duration, suppression of accelerated electron beams, and an increase in the power of radiation losses at the periphery of the plasma column. To use such injectors in tokamaks operating in stationary and quasi-stationary modes, for example, T-15MD and TRT, a prototype of a finely dispersed lithium injector with an external lithium refilling system without breaking vacuum conditions was developed and manufactured. Additional advantages of such an injector include the ability to regulate the parameters of liquid lithium injection and control the start of the lithium particle injection process relative to the moment of discharge ignition.

Since 2024, a prototype of a finely dispersed lithium injector with an external lithium supply system, developed for the T-15MD tokamak (NRC "Kurchatov Institute"), has been tested. The results of the lithium injector tests, as well as its impact on the plasma discharge, are presented in the report.

2. EXPERIMENT

Tests of lithium injector with external lithium supply system, as well as study of lithium injection influence on plasma parameters, were carried out on T-11M tokamak. T-11M tokamak is a limiter tokamak of circular cross-section, where lithium limiters based on CPS (capillary porous systems) of various designs usually work in emitter-collector system to organize close lithium circulation loop. Main parameters of tokamak: $R/a = 0.7 \text{ m}/0.2 \text{ m}$; toroidal magnetic field $B_T = 1.2 \text{ T}$; plasma current $I_p = 60\text{--}70 \text{ kA}$; the average duration of discharge $\Delta t = 150\text{--}200 \text{ ms}$; the line averaged electron density $n_e = 2\text{--}5 \cdot 10^{19} \text{ m}^{-3}$, the electron temperature in the plasma column center $T_e = 450 \text{ eV}$, working gas – deuterium. In experimental series with lithium injector the graphite limiter was used as the main limiter.

Figure 1 shows a three-dimensional model of the T-11M tokamak vacuum chamber in one of its configurations. There are shown the lithium injector (1), the horizontal collector target (with the ability to remove lithium from the vacuum chamber without breaking the vacuum conditions) (2), and the graphite limiter (3), used as the main limiter. The red arrows indicate the viewing angles of the intrachamber components using a high-speed video camera.

Figure 2 shows a typical plasma discharge from the T-11M tokamak with lithium injection with the typical plasma parameters. There are presented the time dependences of the lithium Li I line intensity, the neutral hydrogen H α line intensity, the loop voltage, the electron density, and the plasma current from top to bottom.

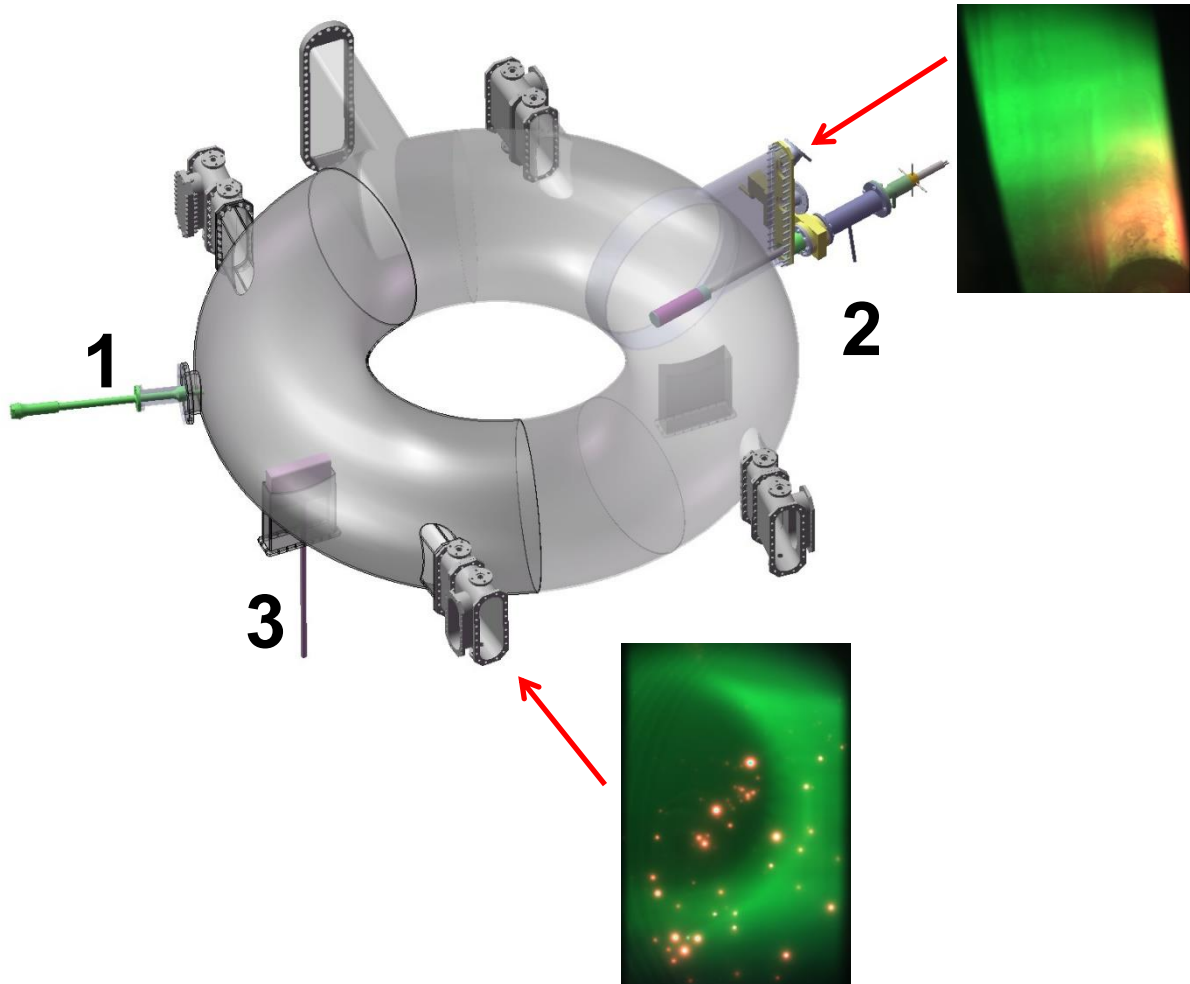


FIG. 1. Three-dimensional model of the T-11M tokamak vacuum chamber and the relative position of the intrachamber elements: 1 – lithium injector, 2 – horizontal lithium collector, 3 – graphite limiter; red arrows – viewing angles of the intrachamber elements using a high-speed video camera.

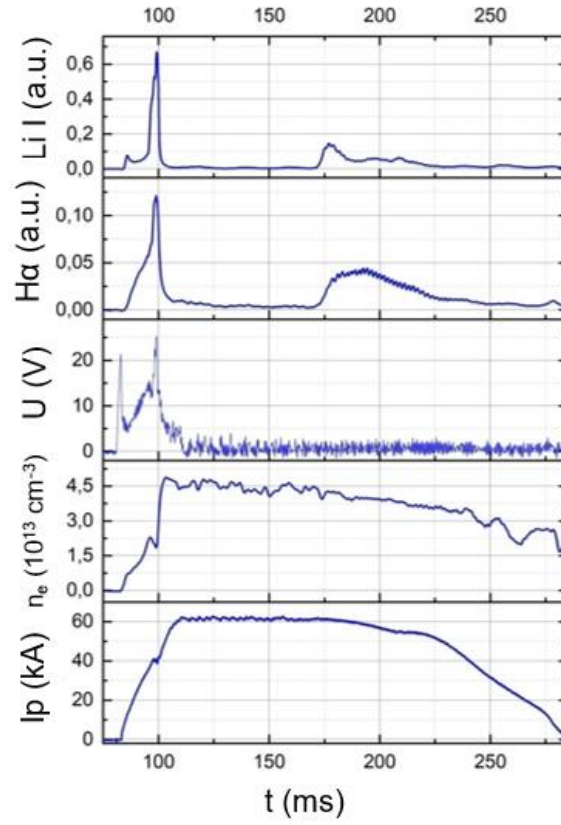


FIG. 2. The main parameters of the typical plasma discharge with lithium injection: from top to bottom – the intensity of the lithium Li I line, the intensity of the neutral hydrogen H α line, the loop voltage, the line averaged electron density, the plasma current.

The photo of the lithium injector in the tokamak vacuum chamber with a graphite limiter restricting the plasma column, is shown in Figure 3.

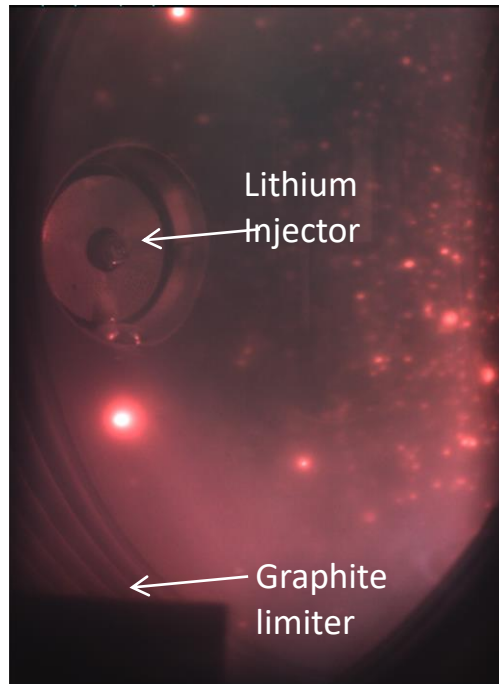


FIG. 3. Relative arrangement of the graphite limiter and lithium injector in the vacuum chamber of the T-11M tokamak.

3. RESULTS

Lithium injection using the lithium injector with an external lithium supply system was performed through the equatorial port of the T-11M tokamak. Figure 4 shows video frames of the interaction of the injected lithium droplet flow with the plasma at different discharge phases, as well as the lithium flow dynamics during injection, where red color corresponds to the light emission intensity of neutral lithium Li I ($\lambda=671$ nm), and green color corresponds to the light emission intensity of singly ionized lithium Li II ($\lambda=549$ nm). Lithium influx from the injector was estimated using data from Baumer HXG 20C high-speed video camera during the discharge. The operating temperature of the injector was 200-350°C. The characteristic size of lithium microdroplets is 50 μm . The high-speed video camera was also used to calculate the characteristic velocities of the injected microdroplets, which ranged from 1.5 to 7 m/s. Figure 5 shows several video frames used to calculate the microdroplet velocity.

The lithium injector was equipped with an ultrasonic oscillator with adjustable power. A distinctive feature of this type of generator is that before each start, the piezoelectric transducer, located in the ultrasonic oscillator system, is tuned and the operating resonant frequency is found to generate mechanical vibrations. Therefore, the injection start time was directly dependent on the generator tuning time. The ultrasonic oscillator tuning time, and therefore the resonant frequency, depended on the temperature of the working substance (liquid lithium) and its volume. Adjusting the ultrasonic generator's power allowed for varying the injector's throughput and, consequently, the number of lithium droplets. The injected lithium flow rate during the experiment ranged from 10 to 70 mg/s, depending on the ultrasonic generator power.

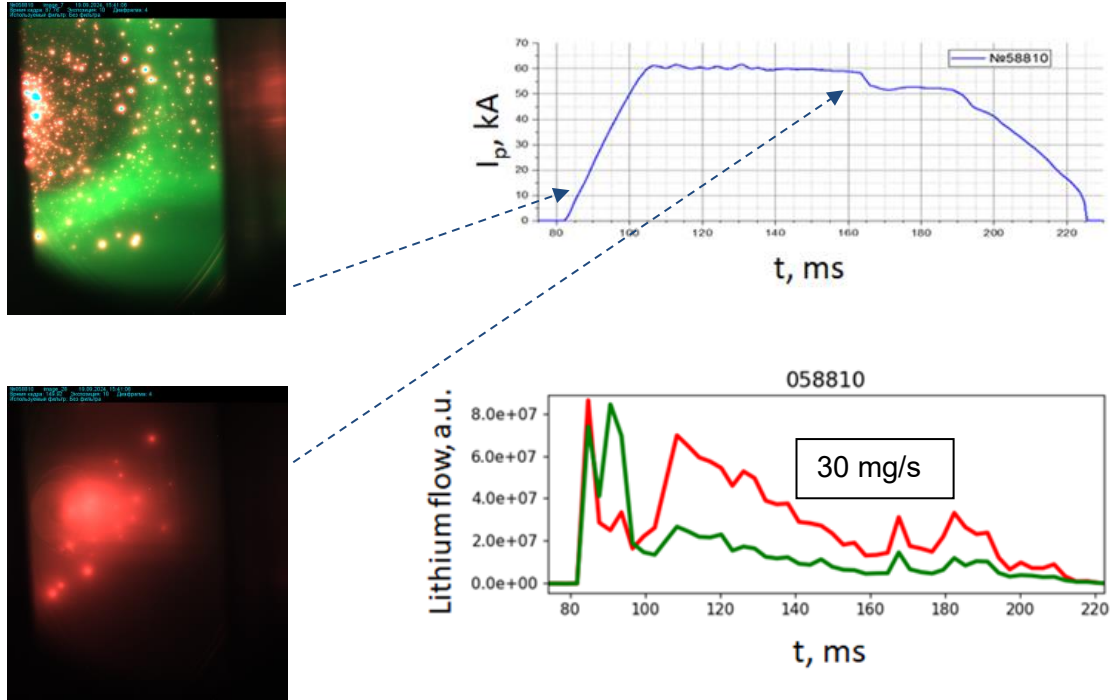


FIG. 4. Evolution of plasma current during discharge and lithium flow dynamics during lithium injector operation. Video frames of the interaction of the flow of injected lithium droplets with plasma at different discharge phases.

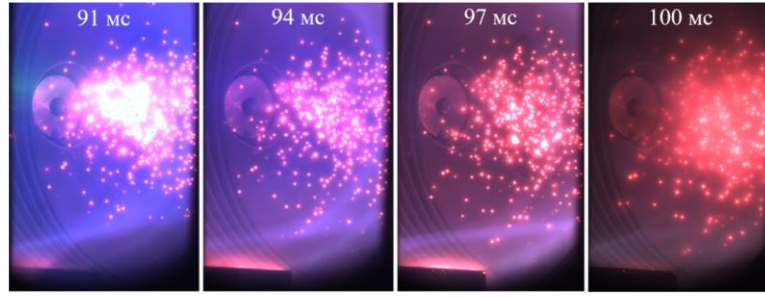


FIG. 5. Video frames of the lithium injection process, from which the microdroplet velocities were calculated

The Figure 6 (on the left) shows an infrared image of the lithium injector. The maximum surface temperature was approximately 267°C. The dynamics of the lithium injector temperature during the discharge is shown in the Figure 6 on the right.

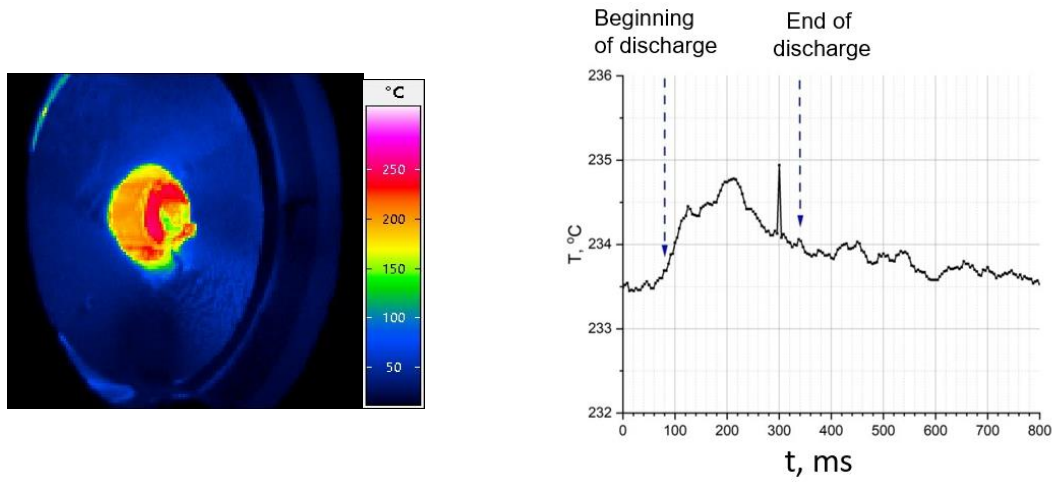


FIG. 6. Dynamics of heating of the injector surface during the plasma discharge of the T-11M.

The lithization effect of the lithium injector can be demonstrated using a residual gas spectrum obtained with a quadrupole mass spectrometer. The Figure 7 shows the evolution of partial pressures of some residual gases (hydrogen, water, and nitrogen, accordingly, $m/e=2, 18, 28$ amu) during seven experimental days. A decrease in the partial pressures of residual gases is observed after starting work with the lithium injector.

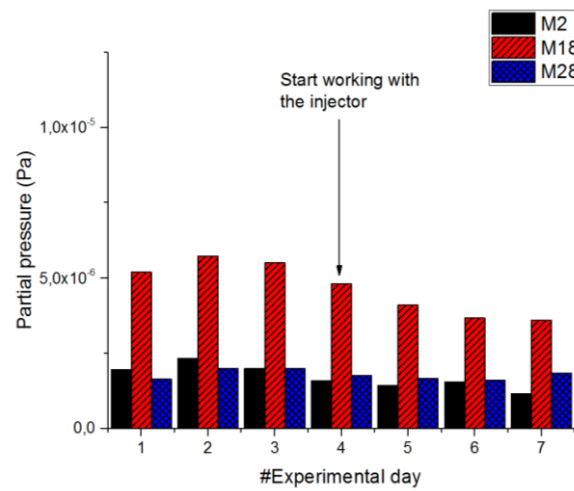


FIG. 7. Evolution of partial pressures of residual gases in the vacuum chamber of the T-11M tokamak before starting work with the injector and during operation.

During the two-year experimental campaign with the lithium injector, seven refills were performed without depressurization of the vacuum chamber: the first refill included completely filling the entire lithium path and the main tank of the lithium injector, then six more additional refills were carried out. Testing of the injector with an external lithium supply under plasma conditions at the T-11M tokamak demonstrated trouble-free operation without refilling for at least 193 plasma discharges, with a total injection time of approximately 203 s.

In some discharges an increase in electron density was observed in process of lithium injection. This can be due to a decrease in recycling given by the deposition of lithium on the walls of the vacuum chamber. Figure 8 shows the behavior of plasma parameters over time for two discharges: with lithium injection (No. 59075) and without it (No. 59073). The figure, from top to bottom, shows the intensity of neutral lithium near the wall, the plasma density, and the plasma current. On average, during the discharge, an increase in density along the central chord of $\Delta N = 1 \cdot 10^{13} \text{ cm}^{-3}$ was observed. The lithium ion flux was $\Gamma_{\text{Li}} = 1.45 \cdot 10^{20} \text{ atoms/s}$, which is equivalent to a lithium mass flow rate of 1.7 mg/s.

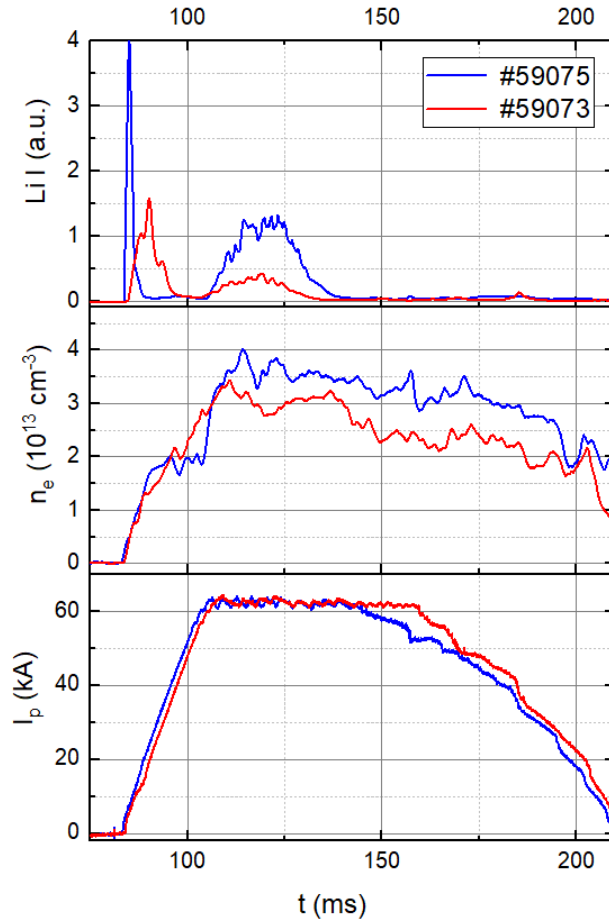


FIG. 8. Comparison of plasma characteristics in a discharge with lithium injection (No. 59075) and without lithium injection (No. 59073). From top to bottom - neutral lithium intensity, plasma density, plasma current.

4. CONCLUSION

The new lithium injector with an external lithium refilling system was tested in the plasma discharges of the T-11M tokamak. The key features of this injector, such as, the real-time lithization, and the possibility of the lithium injector refilling without breaking of vacuum conditions were experimentally demonstrated. Seven injector refilling were performed without depressurizing the tokamak chamber. It was found that one refill enough for at least 193 plasma discharges, with a total injection time of approximately 203 s. Lithium fluxes from the injector were estimated based on Li I light emission, and were found to be approximately 10 to 70 mg/s. The velocity distribution of lithium microdroplets was calculated using data of the high-speed video camera. The velocity of the injected lithium microdroplets was determined from 1 to 7 m/s. The lithium injector and its support system have demonstrated stable and reliable operation during plasma discharges at the T-11M tokamak.

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