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# OVERVIEW OF ADVANCES IN THE APPLICATION OF LIQUID METAL DROPLETS IN TOKAMAKS AND PLASMA INSTALLATIONS

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**Abstract**

The use of liquid-metal in-vessel components (IVCs) in thermonuclear reactors is a promising approach to addressing plasma–wall interaction, particularly where plasma exposure risks material erosion. In tokamaks and other fusion devices, these IVCs can take the form of capillary-porous systems (CPS), droplet/jet injection systems, or thin liquid-metal films. Injection of droplets into plasma avoids the formation of short circuit of the current through the stream, distinguishing this configuration from alternative schemes. This report presents results of experimental study demonstrating the feasibility of a droplet flow arrangement, in which galinstan droplets are injected into a steady-state magnetized plasma in the PLM device, focusing on the electric charge acquired by droplets within a magnetic field.

## 1. INTRODUCTION

The use of liquid metals (lithium Li, tin Sn, gallium Ga, and their alloys) as materials for in-vessel components (IVCs) of fusion reactors is considered a promising solution to the problem of plasma–wall interaction, where high-energy plasma can erode and damage structural materials, including tungsten [1]. Compared to solid materials, liquid-metal components offer higher resistance to surface degradation under plasma exposure and can positively influence the near-surface plasma in a fusion reactor.

Liquid-metal IVCs can take several forms: capillary-porous systems (CPS) [2, 3], liquid-metal droplet or jet injection systems [4], and thin liquid-metal films on walls [5]. Among these, lithium-based CPS have been most extensively tested in experiments on tokamaks (T-11M [6], T-10 [7], FTU [8]), stellarators (NSTX [9], TJ-II [10]), and other plasma devices such as PLM [11]. CPS can be installed on manipulators with adjustable immersion into peripheral plasma, which presents challenges in maintaining the CPS temperature within a narrow range (~220 °C–450 °C) under high plasma-thermal loads to prevent local overheating or solidification of the liquid metal.

Lithium circulation schemes (evaporation from CPS into plasma followed by deposition on lithium collectors) [12–14, 3] require extremely high purity of the structural elements in contact with lithium to minimize the formation of lithium carbonate compounds. Such compounds, which can form irregular layered coatings on walls during prolonged CPS operation, have reduced electrical and thermal conductivity, negatively affecting plasma-surface interaction and peripheral plasma parameters [12]. The use of tin in CPS is also being studied, with experimental tests on the PLM device showing promising results [11].

Experiments with a droplet curtain enable the assessment of factors critically affecting the hydrodynamic stability of a jet-droplet flux in plasma, including droplet size and initial injection velocity. These studies help identify key challenges for the further development of the method and the design of injectors, aiming to minimize potential limitations of the jet-droplet flow concept compared to other approaches for implementing liquid-metal components.

The present work focuses on the experimental investigation and demonstration of the feasibility of a droplet flow scheme in which liquid metal is injected into a stationary magnetized plasma. In addition, it examines the electric charge acquired by the droplets as they move through the plasma under the influence of a magnetic field. The experiment, conducted with galinstan droplets injected into a stationary plasma discharge, was carried out in the PLM plasma device at the National Research University "MPEI".

## 2. REVIEW OF STUDIES ON LIQUID METAL DROPLETS IN TOKAMAKS AND PLASMA DEVICES

The first challenge in using liquid metals in a fusion device is the selection of the appropriate material. From the outset, lithium was regarded as the natural candidate for use in blankets, as it enables the realization of a self-cooled blanket concept [13]. At first glance, such a design appears relatively straightforward, since the same liquid metal simultaneously functions as a neutron moderator, tritium breeder, and coolant. In this configuration, the majority of fusion power is released directly into the coolant, simplifying a heat transfer. Circulation of the liquid breeder for tritium extraction is inherently ensured by coolant circulation. In terms of compatibility with structural materials, it is relatively easy to achieve sufficiently high operating temperatures and efficient thermal-to-electric conversion. Lithium's high thermal conductivity and heat capacity, combined with its large blanket mass and low residual heating, provide favourable passive safety characteristics in the circulation loss. Furthermore, appropriate structural materials, such as vanadium-based alloys, can be selected to ensure relatively low residual radioactivity [14].

The practical feasibility of a liquid-metal limiter was demonstrated in [15]. In this experiment, the limiter consisted of a stream of droplets, 2–4 mm in diameter, arranged in two rows of discrete jets with a total width of approximately 4 cm. The droplet velocity ranged from 2–5 m/s, determined by the pressure head of an MHD pump. Droplet formation was achieved by modulating the liquid metal flow with a magnetic vibrator that induced Rayleigh instability. Plasma parameters obtained using the liquid gallium limiter were compared with those observed when employing a graphite limiter of similar geometry.

The resulting droplet streams exhibited good regularity. Their effect on plasma behaviour was contrasted with that of the graphite reference limiter. Analysis of the experimental data shows that the gallium limiter produced higher radiative losses during the initial discharge phase, but these losses were significantly reduced in the middle phase compared to the graphite analogue, indicating potential performance benefits. Plasma conductivity remained comparable in both cases. These findings confirm the fundamental feasibility of employing liquid-metal limiters in tokamak devices.

The authors' theoretical calculations showed that, as gallium droplets move through the plasma, their surface temperature rises by only 100–200 °C, which is negligible compared to the metal's boiling point (2400 °C). Therefore, the contribution of gallium evaporation to plasma contamination can be considered negligible. However, the mechanisms of gallium sputtering and self-sputtering under plasma bombardment remain unresolved.

Additional measurements did not detect any increase in electron density during the discharge, indicating that the self-sputtering coefficient of gallium was, at least, not greater than unity. Nevertheless, subsequent analysis of the vacuum chamber surface revealed the presence of liquid metal droplets (<1 mm) even in regions far from the limiter. This may suggest the development of gallium droplet erosion, which requires further investigation.

The article [16] describes the design of a lithium injector using an ultrasonic vibration generation method. The developed lithium ultrasonic injector for the T-11M tokamak is based on a Langevin-type resonant oscillatory system. At the core of the design is the resonant oscillatory unit, which is hermetically secured to the main injector body on the port cover of the tokamak vacuum chamber using a clamping flange and gasket. Heating and maintaining the lithium temperature above its melting point is achieved with an electric heater. The reservoir of liquid lithium required for the experimental campaign is located within the internal feeding cavity of the oscillatory system and is delivered to the spraying end surface inside the tokamak vacuum chamber.

During injector tests on the tokamak, it was installed in the equatorial port from the outside. Injection was recorded using a high-speed video camera synchronized with the tokamak discharge. Based on the sequence of recorded frames and the observation angle, the authors analyzed the velocity distribution in the plasma flow. According to their data, droplet velocities before cleaning the injector with a glow discharge ranged from 2.8 m/s to 6.4 m/s. After cleaning, velocity analysis was complicated due to higher droplet speeds and insufficient frame rate, so the analysis focused on the speed of droplet clusters.

In addition, the authors determined the injector flow rate by measuring the lithium inventory in the injector at the end of each experimental day. The estimated flow rate for this injector was 12–15 mg/s.

## 3. INJECTION OF LIQUID METAL DROPLETS IN THE PLC INSTALLATION

The PLM plasma device [17] is designed for the study of plasma–surface interactions and the testing of fusion materials with steady-state plasma, simulating the edge and divertor plasma of a tokamak. Fig. 1 shows a top view schematic of the PLM device.

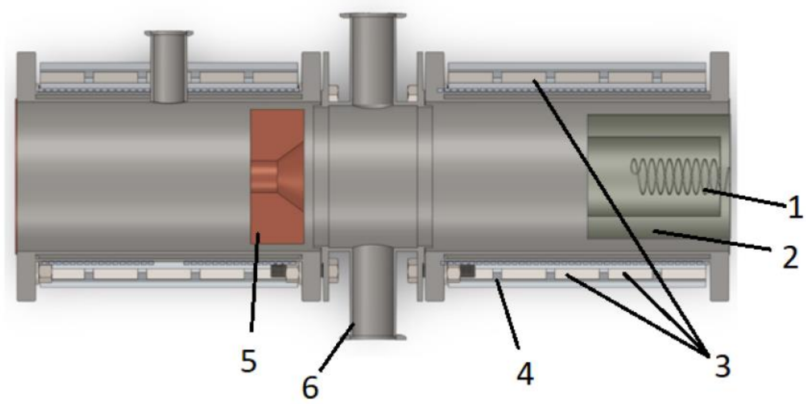



*Fig. 1 Discharge chamber and magnetic system of the PLM installation: 1 — cathode; 2 — cathode shield; 3 — permanent neodymium magnets; 4 — solenoid of the longitudinal magnetic field; 5 — copper anode with a 3.5 cm diameter aperture; 6 — vertical diagnostic window*

The magnetic system of PLM has a linear geometry with a longitudinal magnetic field created by a solenoid and a multicusp system of radial magnetic fields generated by permanent neodymium magnets. These magnets are arranged in eight assemblies along the discharge chamber above the solenoid winding, evenly spaced in the azimuthal direction with alternating magnetic poles. This configuration forms a multicusp magnetic field – the 8-pole multicusp (octupole). The cusps are regions where the radial component of the magnetic field strength exceeds the longitudinal component; the magnetic induction in the cusps reaches 0.2 T, providing a magnetic barrier at the periphery of the cylindrical magnetic trap.

The water-cooled discharge chamber contains the cathode and the anode. The working gas was helium supplied from a regulated injection system to the cathode region. Plasma was generated by electron-impact ionization of helium, with a negative potential (-180 to -300 V) applied to the heated (from 2000 K to 2500 K) tantalum cathode.

The falling liquid metal droplets were recorded using a video camera with a frame rate of 120 $s^{-1}$ and an exposure time of 1/400 s. For the droplet curtain experiments, the Galinstan alloy (68.5 % gallium, 21.5 % indium, 10 % tin) was used, which has a melting point of -19 °C, low saturated vapor pressure ($10^{-6}$ Pa at 500 °C), and a viscosity of 0.0024 Pa·s [18]. Galinstan's physicochemical properties make it suitable for studying liquid-metal dynamics in plasma [18–20].

In vacuum, the droplets initially had an elongated cylindrical shape due to the breakup of a continuous metal stream (Fig. 2a). This shape cannot be attributed to motion blur, which is limited to under 1 mm by the exposure time. When moving through plasma, the droplets transformed into a spherical shape and their trajectories deviated from vertical under the influence of the electric field between the cathode and anode, indicating that they acquired an electric charge (Fig. 2b).

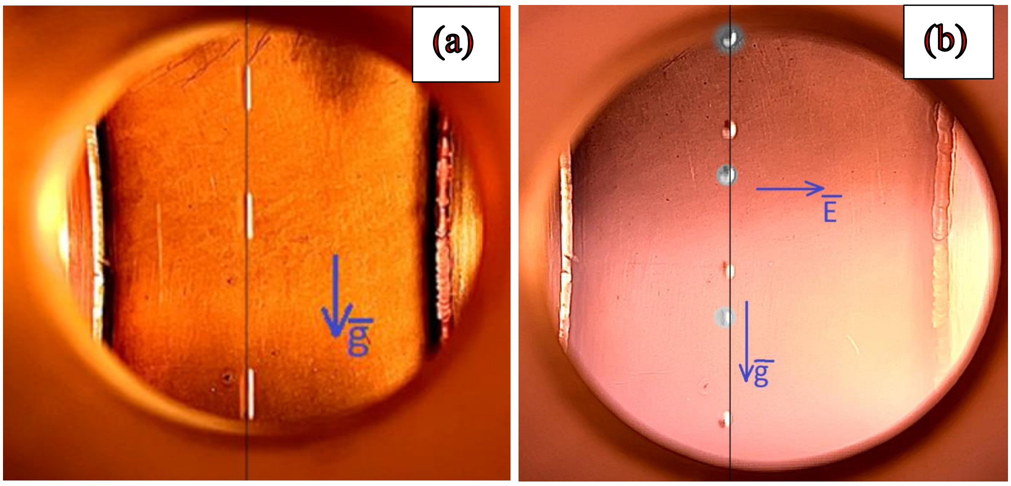
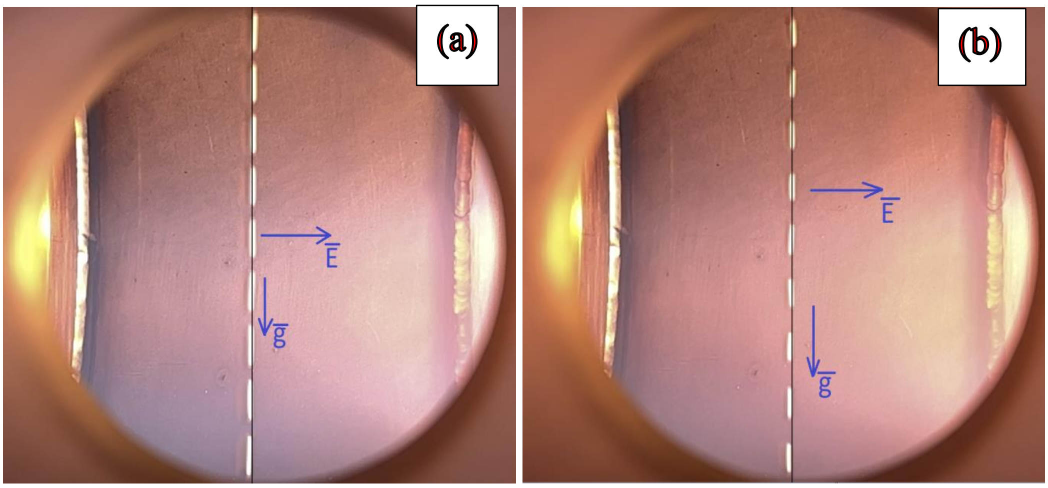



*Fig. 2. Optical image of the droplet flow in the PLM chamber, observed through the horizontal diagnostic window: (a) – in vacuum without plasma; (b) – in plasma during the first series of experiments. The vertical is marked as a dark line along the direction of the gravitational acceleration vector g, E – the vector of the electric field intensity in the plasma.*

Images obtained during the second series of experiments are shown in Fig. 3 (a–d). In this series, a deviation of the droplet trajectory from the vertical axis (z-axis) was observed too. In addition, the interaction of droplets with the plasma was accompanied by shape transformations. As the discharge current (and consequently the plasma density) increased, the initially cylindrical droplets entering the plasma exhibited a reduction in length, gradually transforming into a nearly spherical shape in the lower region of the discharge.

Using the photographs obtained during the second series of experiments, the droplet coordinates at fixed points along their trajectories were determined and analysed. For each experiment (at a fixed plasma current, see Table 1), a droplet charge corresponding to the calculated trajectory that most closely matched the experimentally measured trajectory was selected. Since the comparison between experimental and calculated trajectories was performed with a charge increment of $10^{-7}$ C, the uncertainty of the determined charge in this procedure was $0.5 \times 10^{-7}$ C.

The second evaluation method involved analyzing the droplet shape and size. For this purpose, the extremities of the droplet images were digitized, and the dimensions of the liquid metal droplets were estimated assuming a cylindrical shape.



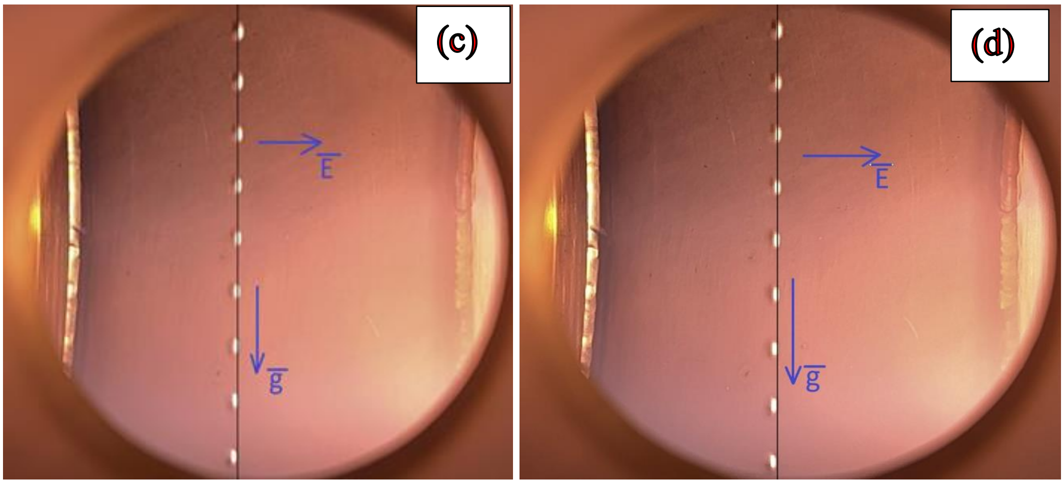



*Fig. 3. Optical images of the droplet flow in the PLM plasma, observed through the horizontal diagnostic window, discharge current: (a) Ip = 1 A; (b) Ip = 3 A; (c) Ip = 10 A; (d) Ip = 13.9 A.*

The estimated droplet charges, as well as those estimated from trajectory analysis, are presented in Table 1. Differences between the charges obtained via droplet shape analysis and trajectory analysis can be attributed to the neglect of reactive forces caused by uneven droplet evaporation in the plasma and the temperature dependence of the surface tension coefficient of Galinstan.

TABLE 1. CALCULATED DROPLET CHARGES AT VARIOUS PLASMA DISCHARGE CURRENT IN THE PLM.

| Plasma current, A | Charge estmated from the shape analysis, $10^{-7}$ C | Charge estimated from the trajectory analysis, $10^{-7}$ C |
|---|---|---|
| 1 | 1.5 | 1.5 |
| 2 | 1.5 | 2.0 |
| 3 | 2.3 | 2.0 |
| 5 | 3.1 | 3.0 |
| 10 | 3.1 | 5.0 |
| 13.9 | 3.2 | 5.0 |

The obtained data can be used to evaluate droplet dynamics during the injection of a droplet flow into the peripherial plasma of a tokamak with plasma parameters: electron density $10^{18}$ cm$^{-3}$ and electron temperature 1–10 eV, corresponding to the far SOL (scrape-off layer) plasma or the divertor plasma.

## 4. CONCLUSION

The advantages of using liquid metal droplets finjected in plasma were demonstrated in plasma experiments. Numerical simulations and experimental results confirm that droplet injection allows control parameters, such as droplet size and velocity, without significantly affecting vacuum conditions or contaminating the plasma. Experiments with a Galinstan liquid droplet flow in the PLM plasma device show interaction with plasma, including trajectory deviations due to droplet charging and shape transformations under plasma impact. The results highlight the potential of droplet-based liquid metal systems to improve plasma performance and protect material surfaces in fusion devices. For fusion reactor relevant conditions, the approach provides a promising pathway to address erosion and material lifetime challenges. Further experimental studies are necessary to investigate droplet dynamics, interactions with plasma and solid surface, and to optimize injection and collection systems for practical tokamak applications.

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