Interaction of a Liquid Gallium Jet with ISTTOK Edge Plasmas

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Abstract. The use of liquid metals as plasma facing components in tokamaks has recently experienced a renewed interest stimulated by their advantages in the development of a fusion reactor. Liquid metals have been proposed to solve problems related to the erosion and neutronic activation of solid walls submitted to high power loads allowing an efficient heat exhaust from fusion devices. Presently the most promising candidate materials are lithium and gallium. However, lithium has a short liquid state range when compared, for example, with gallium that has essentially better thermal properties and lower vapor pressure. To explore further these properties, ISTTOK tokamak is being used to test the interaction of a free flying, fully formed liquid gallium jet with the plasma. The interacting, 2.3 mm diameter, jet is generated by hydrostatic pressure and has a 2.5 m/s flow velocity. The liquid metal injector has been build to allow the positioning of the jet inside the tokamak chamber, within a 13 mm range. This paper presents the first obtained experimental results concerning the liquid gallium jet-plasma interaction. A stable jet has been obtained, which was not noticeably affected by the magnetic field transients. ISTTOK has been successfully operated with the gallium jet without degradation of the discharge or a significant plasma contamination by liquid metal. This observation is supported by spectroscopic measurements showing that gallium radiation is limited to the region around the jet. Furthermore, the power deposited on the jet has been evaluated at different radial locations and the surface temperature increase estimated.

Keywords: Liquid metals; Plasma-surface interaction; Gallium; Liquid metal jet; Limiter.

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INTRODUCTION

The materials currently used in large size fusion devices are submitted to very high thermal loads (up to the GW/m\textsuperscript{2} during off-normal events). Due to the high erosion levels and thermal stress produced by such power loads, the plasma facing components are expected to require frequent replacement. This question has recently boosted the interest in the research of liquid metals which could be successfully used to overcome these problems. The possibility to perform a permanent renewal of liquid surfaces has been pointed out as one adequate solution for both the protection of solid walls and an efficient power exhaust process from fusion plasmas. Among a set of several liquid metals, lithium has shown the best compatibility with fusion plasmas (due to its low Z) as well as remarkable hydrogen retention properties which allow a
low recycling operation with the corresponding enhancement in plasma performance [1, 2]. However, lithium remains in liquid state in a small temperature range when compared, for example, with gallium that has essentially better thermal properties and lower vapor pressures. To explore further these properties, ISTTOK, a tokamak with main parameters: $R = 0.46$ m, $a = 0.085$ m, $B_T = 0.45$ T, $n_e(0) = 5 \times 10^{18}$ m$^{-3}$, $T_e(0) = 150$ eV, $I_p \sim 6$ kA an $V_{\text{loop}} \sim 3$ V, is being used to test the interaction of a free flying, fully formed liquid gallium jet with the plasma. This paper presents the first achieved experimental results concerning the liquid gallium jet-plasma interaction.

**EXPERIMENTAL SETUP**

Figure 1 presents a scheme of the Liquid Metal Loop (LML) that has been installed in ISTTOK to perform the injection of liquid gallium jets at the plasma edge. The design of the setup had to obey to some restrictions due to gallium specific physical properties and compatibility with tokamak operation: 1) since gallium corrodes most metals the building materials had to be carefully chosen (only SS and Nickel were used); 2) gallium expands by 3% when it freezes. To overcome that issue the lower part of the loop (where liquid metal is stored) is permanently heated; 3) Since gallium oxidizes easily while submitted to air, a special system was implemented to introduce oxide-free gallium in the main loop; 4) To avoid currents in the jet that would lead to perturbation owing to Lorentz forces, the entire injector part of the set-up has been allowed to be floating at the plasma potential. The insulation from tokamak vessel and other grounds is ensured by 3 kV ceramic insulators located at suitable places in the LML. Electrical insulation on the collector side (Fig. 1) occurs spontaneously since, after a certain length (L), the jet decomposes into droplets due to Rayleigh instability. The jet interacting with the plasmas is generated by hydrostatic pressure, has a 2.3 mm diameter and a 2.5 m/s flow velocity. The liquid metal injector has been built from a $\frac{1}{4}$" stainless steel pipe reduced to a suitable shaping nozzle at the output and allows the positioning of the jet inside the tokamak chamber, within a 13 mm range ($59 < r < 72$ mm in the plasma). The pressure required to generate a stable vertical jet is generated by a 1.3 m height liquid metal column. This is obtained by pumping (using a homemade MHD pump) a suitable amount of gallium from the lower to the upper tank (Fig. 1). A more detailed description of the LML and a characterization of the produced jets are presented in [3].

**INTERACTION OF A GALLIUM JET WITH ISTTOK PLASMAS**

One of the main objectives of this work was to assess the feasibility of tokamak discharges interacting with gallium jets and studying their influence on the plasma parameters. ISTTOK tokamak is equipped with one fully poloidal graphite limiter (FPL) placed at $r = 85$ mm radius which acts as the main limiting surface during the operation with the gallium jet. A comparison of the main plasma parameters ($V_{\text{loop}}, I_p, \bar{n}_e$) for consecutive discharges with and without liquid metal jets in the chamber has been performed with injection at several radial positions ($r=60, 65$ and $70$ mm). Typical results, including the radiated power in the UV and visible range, are shown in
FIGURE 1. Schematic representation of the LML implemented in ISTTOK.
FIGURE 2. Main plasma parameters and radiated power for discharges with and without gallium in the chamber.

Fig 2, for an injection position of r=65 mm. Those measurements clearly show that there are no significant changes in the discharge parameters, particularly in the radiated power demonstrating only a weak interaction between plasma and gallium. The good reproducibility observed from discharge to discharge doesn’t seem to indicate a significant increase in the plasma impurity content or a contamination of the

FIGURE 3. (a) Characteristic spectrum of gallium and (b) distribution in ISTTOK plasma with the arrows indicating the peak emission position.
ISTTOK chamber. No evidences of disruption induced by liquid metal had been noticed during the experiments. In spite of these observations, the release of gallium due to the plasma-liquid metal jet interaction has been clearly identified looking at the characteristic spectra of that element (Fig 3 (a)) using a ½ m imaging spectrograph (CVI laser DK480). The relaying of the radiation collected from the interaction region has been performed by a multi-channel optical fiber that allows the simultaneous measurement at 7 viewing points in radial direction (~1.2 cm span). The analysis of the mentioned spectra, acquired during a shot by shot spatial scan of the plasma, provided additional information on the neutral and ions relative distribution in the radial direction. The results are presented in Fig. 3 (b). As expected, the maximum emission for neutral gallium is seen in the vicinity of the jet position while species of higher degrees of ionization penetrate deeper inside the plasmas owing to radial diffusion. Another evidence of the interaction of the liquid metal jets with ISTTOK plasmas is shown in Fig 4. There, it is possible to observe the time evolution of both the gallium (at 417.2 nm) and the Hα (656.3 nm) line emission at two opposite toroidal positions. The analysis of the curves presented in Fig 4 (c) and (d) shows clearly that there is no significant change in the line intensities, for discharges at the φ= φjet+165º, either when the jet is present or not in the tokamak vessel, and this is observed either at the gallium or hydrogen line wavelengths. On the contrary from Fig. 4 (a) and (b) it could be inferred that there is a strong influence in light emission when the observation is done close to the jet position. In this case the presence of gallium in the chamber generates a pronounced increase in the lines emission. This increase is clearly due to the penetration of gallium in the plasma, leading to a local increase in recycling.

![FIGURE 4. Emission line intensity from filtered photodiodes during plasma discharges with and without gallium jet interacting with the plasma. (a) gallium and (b) Hα line at φ= φjet, and (c) gallium and (d) Hα line at φ= φjet+165 º.](image-url)
and electron density (due to ionization of neutral gallium) with the corresponding increase in Hα emission. In any case the influence of the liquid metal jet on the plasma appears to be a local effect since it is only observable at the jet position.

**GALLIUM JET TEMPERATURE INCREASE ESTIMATE**

The main issue in ISTTOK’s plasma-LM interaction experiment is related to the moderate power available and consequently an expectedly low power flux at the jet position. The release of gallium from the jet surface can be due both to particle sputtering and evaporation. The jet is heated during its exposure to plasma and this increase in temperature is the main aspect that influences the evaporation rate. The temperature rise in a planar surface submitted to a power flux density \( q(t) \) can be written using the well known expression [4]:

\[
\Delta T(t) = \frac{1}{\sqrt{\pi \rho C_p \kappa}} \int_0^t \frac{q(t - t')}{\sqrt{t'}} \, dt' 
\]

\( C_p \) is the surface material specific heat, \( \rho \) its density and \( \kappa \) its thermal conductivity. This equation is valid provided the heated object thickness is greater than the thermal penetration depth \( \delta_{\text{skin}} = \sqrt{\frac{\kappa t_{\text{heat}}}{\rho C_p}} \), where \( t_{\text{heat}} \) is the heat deposition time. This condition is verified in our case since for a gallium jet in a 30 ms discharge, \( \delta_{\text{skin}} = 0.64 \, \text{mm} \) (< \( r_{\text{jet}} = 1.15 \, \text{mm} \)), taking into account that \( \rho_{\text{Ga}} = 6095 \, \text{kg/m}^3 \), \( \kappa_{\text{Ga}} = 31.7 \, \text{W/m K} \) (at 75 ºC) and \( C_{\text{PGa}} = 380 \, \text{J/kg K} \). It is possible to obtain the expected temperature increase of the gallium jet surface, while passing through the chamber, provided the heat fluxes along its path are known. In order to experimentally measure this parameter we have used a 2.0 mm diameter copper wire inserted vertically into the plasma to simulate the gallium jet. The wire is 81 mm long, having 26 mm exposed to the main plasma and the rest protected inside a boron nitride holder where its surface temperature is measured by a thermocouple. This set-up was placed on a moveable arm that allows a precise positioning of the probe inside the plasma. The extrapolation of the increase in temperature of the probe tip due to plasma exposure has been obtained by energy balance. Since the whole system is under vacuum the heat losses in the wire are essentially radiative and, due to their low value, can be disregarded since the peak temperature is a good representation of the equilibrium conditions. In these conditions, the average power deposited in the copper wire can be obtained simply from:

\[
P_w = \frac{C_{\text{PCu}} m_w \Delta T_{\text{meas}}}{t_{\text{shot}}} 
\]

where \( m_w \) is the wire weight (2.06 g) and \( C_{\text{PCu}} \) its specific heat (0.385 J/g ºK), \( t_{\text{shot}} \) is the pulse duration (~30 ms in ISTTOK). The effective area for the part of the copper wire exposed to plasma is 1.6 cm². Taking into account the performed measurements.
we were able to obtain the heat flux profile shown in Fig. 5, for 9 kW power input discharges. It is possible to integrate equation (1) using the best fit function indicated in Fig. 5, and performing the following variable transformation: $r \rightarrow \sqrt{(z^2+0.06^2)} \rightarrow \sqrt{((z_0+v_{jet}t)^2+0.06^2)}$, where $z$ is a coordinate along the jet, $z_0$ the position of an element of fluid, at $t = 0$ s, and it is assumed that the injector is at a $r = 60$ mm position. The results of these calculations for 16 kW discharges and several flow velocities are presented in Fig. 6. From this figure we see than the maximum expected temperature increase on the jet surface in ISTTOK experiment is about 98 °C. Since at the input the liquid metal is at 75 °C, the maximum temperature it could reach would be 173 °C, at which gallium still has a very low vapor pressure ($\sim 10^{-22}$ Torr!). It is also interesting to observe the behavior of the jet temperature as the flow velocity changes: as expected there is a clear decrease on the liquid metal surface when velocity increases.

FIGURE 5. Average heat flux profile in a 9 kW ISTTOK discharges.

FIGURE 6. Temperature increase on the jet surface for different flow velocities.
In any case it is readily understood that, in our specific case, ion sputtering or even runaway electrons could have a much more pronounced effect on the release of liquid metal from the jet to the plasma than the evaporation process.

CONCLUSIONS

It has been shown that the interaction of the liquid gallium jet with ISTTOK plasmas has no significant effect on the discharge behavior and no severe effects on the main plasma parameters. The measurements the time evolution of visible radiation from gallium and hydrogen characteristic spectral lines close to the jet and at one toroidally symmetric position shows that plasma-liquid metal interaction has, in our case, only a local effect although the transport of gallium ions towards the center of the plasma has been detected. In order to estimate the expected increase in jet temperature and its power exhaust capability, a probe has been immersed in the plasma to measure heat flux densities at relevant radial positions. This work proved the technical feasibility of gallium jets interacting with plasmas. However, due to the low power densities of ISTTOK plasmas and the small area of the jet used, the ability of liquid gallium to handle high heat loads could not be assessed.

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