

Interaction of a liquid Gallium jet with ISTTOK edge plasmas

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1. Introduction

The materials currently used in large size fusion devices are submitted to very high thermal loads (up to the GW/m² 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 on the research of liquid metals that 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 exhaustion 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 a remarkable hydrogen retention properties which allows a low recycling operation with the corresponding enhancement in plasma performance [1,2]. 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, 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 and $V_{loop} \sim 3$ 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.

2. Experimental Setup

Fig. 1 presents a schematic 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 buildings materials had to be carefully chosen (only SS and Nickel were used); 2) gallium expands 3% when it freezes. To overcome that issue the lower part of the loop (where liquid metal is stored) had to be permanently heated; 3) A special system had to be implemented to introduce oxide-free gallium in the main loop; 4) To avoid

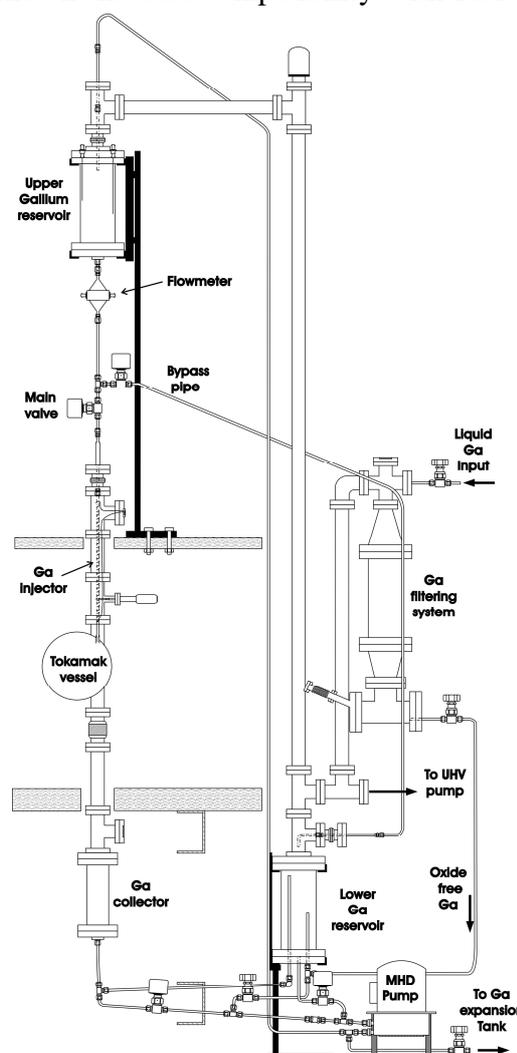


Fig.1 Schematic representation of the LML implemented in ISTTOK

currents in the jet that would lead to perturbation owing to $\mathbf{j} \times \mathbf{B}$ forces, the entire injector part of the setup 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 the jet decomposes into droplets due to Rayleigh instability after a certain length (L). 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 (at the nozzle). The liquid metal injector has been build from a 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). 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].

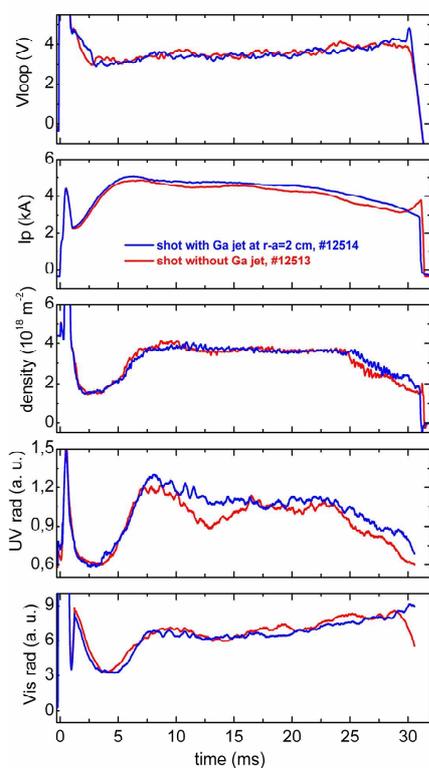


Fig. 2 Main plasma parameters and radiated power for discharges with and without gallium in the chamber.

the 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 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

3. Interaction of gallium jet with ISTTOK plasmas

One of the main objectives of this work was to assess the feasibility of tokamak discharges contacting with gallium jets and studying its 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_{loop} , I_p , \bar{n}_e) for consecutive discharges with and without liquid metal jets in the chamber has been performed at several radial positions ($r=60, 65$ and 70 mm). Typical result, including the radiated power in the UV and visible range, is shown in Fig 2, for an injection position of $r=65$ mm. Those measurements clearly show

no significant changes in the discharge parameters, particularly in the radiated power demonstrating only a weak interaction of

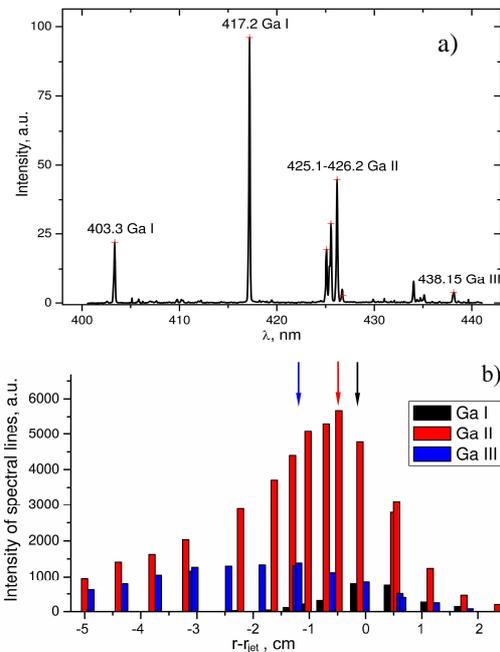


Fig. 3 a) Characteristic spectrum of gallium and b) distribution in ISTTOK plasma with the arrows indicating the peak emission position.

a $\frac{1}{2}$ m imaging monochromator (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 a radial direction (~ 1.2 cm span). The analysis of the mentioned spectra, acquired during a shot by shot spatial scan of the plasma, granted 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 H_{α} (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 $\phi = \phi_{\text{jet}} + 165^{\circ}$, 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 and electron density (due to ionization of neutral gallium) with the corresponding increase in H_{α} 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.

4. Gallium jet temperature increase.

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 evaporation rate. One expression that can be used to roughly estimate the peak increase in this factor is:

$$\Delta T_{\text{max}} = \xi \frac{P_{\text{dis}}}{\pi C_p V_{\text{jet}} \rho r_{\text{jet}}^2} \quad (1)$$

Where ξ is a coefficient that defines the fraction of discharge power that is deposited on the jet, C_p is gallium specific heat (0.38 J/g °K), ρ its density in liquid state (6095 kg/m³), P_{dis} is the total power in the discharge and the other symbols are obvious. In order to experimentally measure ξ 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 36 mm exposed to the plasma and the rest protected inside a boron nitride holder where its surface temperature is measured by a thermocouple. This setup 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 due to plasma exposition has been obtained by energy balance. Since all the 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.

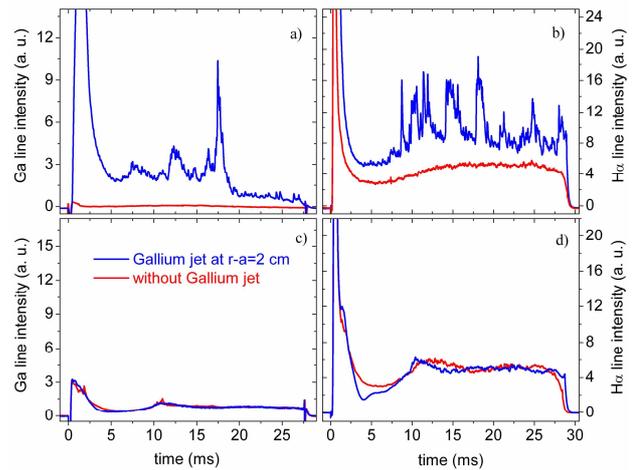


Fig. 4 Emission line intensity from filtered photodiodes during plasma discharges with and without gallium jet interacting with the plasma. a) gallium and b) H_{α} line at $\phi = \phi_{\text{jet}}$, and c) gallium and d) H_{α} line at $\phi = \phi_{\text{jet}} + 165^{\circ}$.

In these conditions, the average power deposited in the copper wire can be obtained simply from:

$$P_w = \frac{C_{PCu} m_w \Delta T_{meas.}}{t_{shot}} \quad (2)$$

where m_w is the wire weight (2.06 g) and C_{PCu} its specific heat (0.385 J/g °K). The curves depicted in Fig. 5 have been obtained for low power discharge (~9 kW) and 30 ms pulse time. From eq. (2) and the information in Fig. 5 it was possible to obtain the following values for ξ : $\xi_{70}=1.2\%$, $\xi_{65}=4.6\%$ and $\xi_{60}=5.2\%$. The area for the part of the copper wire exposed to plasma is 2.2 cm^2 . For the duration of the plasma the jet travels 7.5 cm (assuming a typical 30 ms pulse) so the effective area has to be replaced by

5.4 cm^2 which provides a value of 12% for the ξ_{60} factor. In these conditions, a 16 kW discharge would be expected to produce an 85 °C increase in the jet temperature at $r=60\text{ mm}$. Since at the input the LM is at 75 °C, the maximum temperature it will reach will be 160 °C, at which gallium still has a very low vapor pressure ($\sim 10^{-24}$ Torr!). Although this value seems to indicate that the evaporation process should not be the dominant one, with regards to material loss from jet surface, it is necessary to take into account that eq. (1) assumes fast heat propagation to the center of the jet which is not the case (the heat diffusion coefficient for gallium is $D_{Ga}=17\text{ mm}^2/\text{s}$). In practice, since most part of the heat is deposited on a thin layer on the surface (the thermal skin depth, $\sqrt{D_{Ga} t_{shot}}$, is only 0.7 mm), the maximum temperature increase could be significantly higher. In any case it is readily understood that, in our specific case, ion sputtering or even runaways electron could have a much more pronounced effect on the release of LM from the jet to the plasma than the evaporation process.

5. Conclusions.

The interaction of the liquid gallium jet with ISTTOK plasmas has been shown not to significantly affect the discharge behavior, with no severe effect on the main plasma parameters. The measurements of visible radiation from gallium and hydrogen characteristic spectral lines close to the jet and at one toroidally symmetric position shows that plasma-LM 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 exhaustion 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 was not assessed.

Acknowledgments

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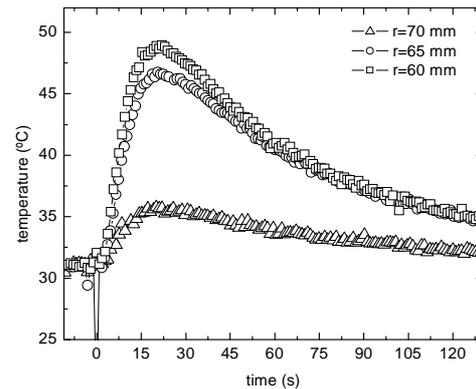


Fig. 5 Temperature evolution on the Copper wire due to plasma exposure at several radial positions