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Liquid gallium jet–plasma interaction studies in ISTTOK tokamak

R.B. Gomes [a,*], H. Fernandes [a], C. Silva [a], A. Sarakovskis [b], T. Pereira [a], J. Figueiredo [a], B. Carvalho [a], A. Soares [a], P. Duarte [a], C. Varandas [a], O. Lielausis [b], A. Klyukin [b], E. Platacis [b], I. Tale [b], A. Alekseyv [c]

[a] *Associação EURATOM/IST, Instituto de Plasmas e Fusão Nuclear/IST, Av. Rovisco Pais, No. 1, 1049-001 Lisboa, Portugal*
[b] *Association EURATOM/University of Latvia, Institute of Solid State Physics, 8 Kengaraga Str., LV-1063 Riga, Latvia*
[c] *TRINITI Troitsk, Moscow reg. 142190, Russia*

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ABSTRACT

Liquid metals have been pointed out as a suitable solution to solve problems related to the use of solid walls submitted to high power loads allowing, simultaneously, an efficient heat exhaustion process from fusion devices. The most promising candidate materials are lithium and gallium. However, lithium has a short liquid state temperature range when compared with gallium. To explore further this property, ISTTOK tokamak is being used to test the interaction of a free flying liquid gallium jet with the plasma. ISTTOK has been successfully operated with this jet without noticeable discharge degradation and no severe effect on the main plasma parameters or a significant plasma contamination by liquid metal. Additionally the response of an infrared sensor, intended to measure the jet surface temperature increase during its interaction with the plasma, has been studied. The jet power extraction capability is extrapolated from the heat flux profiles measured in ISTTOK plasmas.

1. Introduction

The materials currently used in large size fusion devices are submitted to very high thermal loads (up to the GW/m^2 during off-normal events). Due to the high erosion levels and thermal stress produced by such power loads, the plasma facing components are likely 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 [1]. 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 allow a low recycling operation with the corresponding enhancement in plasma performance [2–4]. However, lithium remains in liquid state in a shorter temperature range than gallium which has essentially better thermal properties and lower vapor pressures (gallium reaches a 10^{-4} mbar vapor pressure at 890 °C, while the same value is achieved by lithium at 400 °C [5]). To explore further these properties, ISTTOK, a tokamak with main parameters: $R = 0.46$ m, $a = 0.085$ m, $B_T = 0.45$ T, $\tilde{n}_e(0) = 5 \times 10^{18}$ m^{-3}, $T_e(0) = 150$ eV, $I_P \sim 6$ kA an $V_{loop} \sim 3$ V, is being used to study the interaction of free flying, fully formed liquid gallium jets with the plasma. The main motivation for this work is based on the rather scarce number of studies on gallium interaction with tokamak plasmas. The only known other experiment was performed in T3-M device using a liquid metal droplet curtain as a limiter [6]. This paper presents some of the results obtained in ISTTOK, as well as the evaluation of the jet surface temperature increase expected for this interaction.

2. Experimental setup

A detailed description of the liquid metal loop installed on ISTTOK to inject gallium at the plasma edge has been done in [7]. Fig. 1 shows details of the implemented setup in the vicinity of the plasma–jet interaction region. The jets are generated by hydrostatic pressure, have a 2.3 mm diameter and a 2.5 m/s flow velocity. The liquid metal injector has been built from a ¼″ stainless steel pipe reduced to a suitable shaping nozzle 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. The setup parameters have been chosen to ensure a 13 cm break-up-length (continuous part of the jet, before its spontaneous decomposition into droplets, due to Rayleigh instability). A detailed characterization of the produced jets is presented in [8].

3. Influence of a gallium jet on ISTTOK plasmas

One of the objectives of this work was to assess the feasibility of tokamak discharges interacting with gallium jets and studying

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* Corresponding author.
E-mail address: gomes@ipfn.ist.utl.pt (R.B. Gomes).

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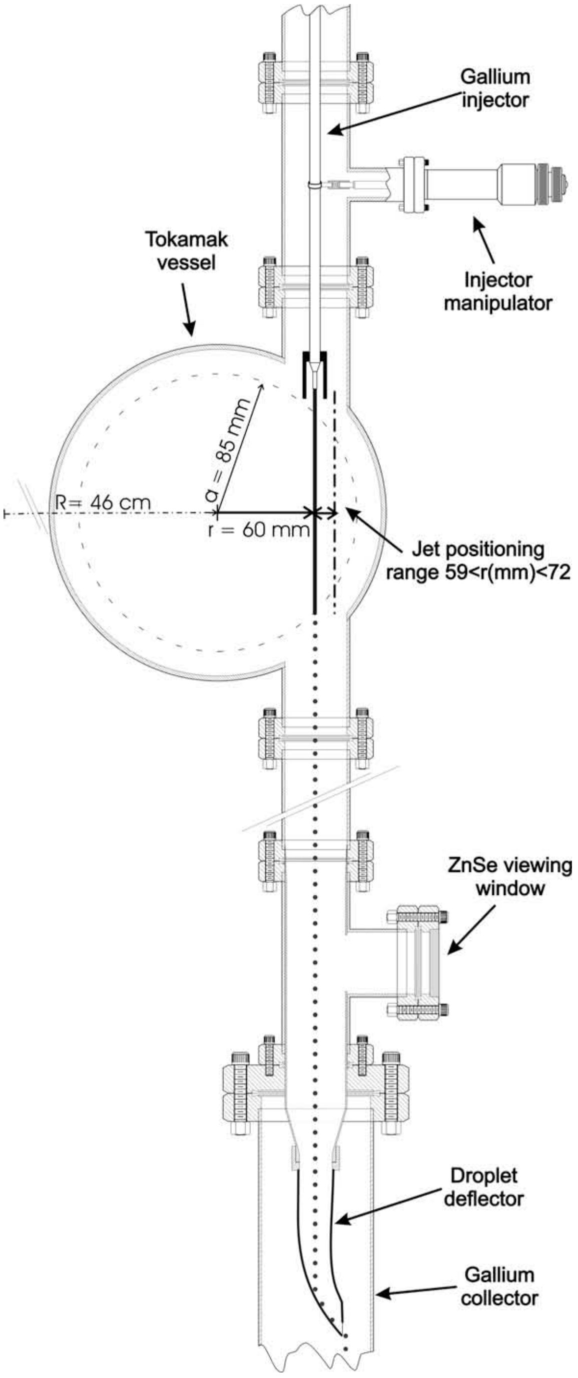

Fig. 1. Schematic cross-section of the implemented setup in the vicinity of the plasma–jet interaction region.

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_{loop}, I_p, $\tilde{n}_e$), 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 Fig. 2, for an injection position of $r = 65$ mm. In this figure radiation losses data was measured by silicon p–n bolometers (IRD Inc. AXUV100 bolometer, integrating light from 1 to 100 nm for UV band, and IRD Inc. UVG100 for the 300 to 900 nm range for visible) oriented along a vertical viewing cord looking towards the chamber center and located at a toroidal angle of $\phi = \phi_{\text{jet}} + 195°$. 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 does not 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 even in the presence of macroscopic size (~1 mm radius) gallium droplet in the discharge [9].

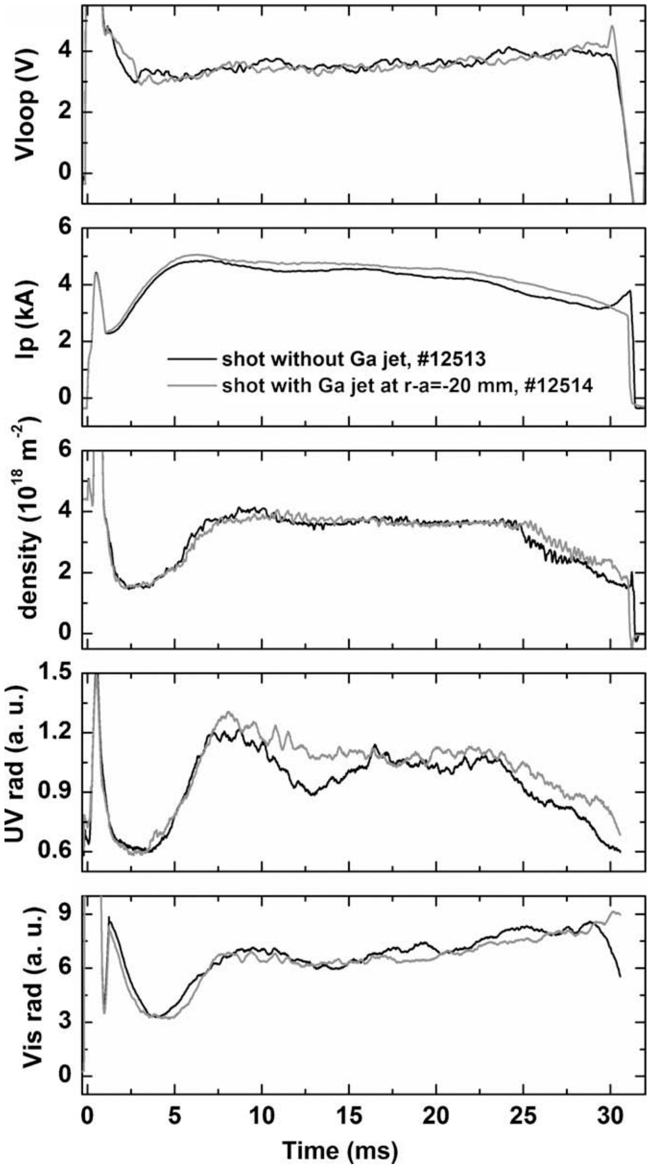

Fig. 2. Main plasma parameters and radiated power for discharges with and without gallium in the chamber.

In spite of these observations, the release of gallium due to the plasma–liquid metal jet interaction has been clearly identified looking at the plasma emission in the spectral region close to a characteristic wavelength of that element (Fig. 3). This spectrum was obtained using a ½ m imaging spectrograph. The collection optics for this diagnostic was based on a single lens objective that focused radiation into a multichannel fiber input and emitted from a region (~5×1 cm^2 effective area) of the poloidal plane where the

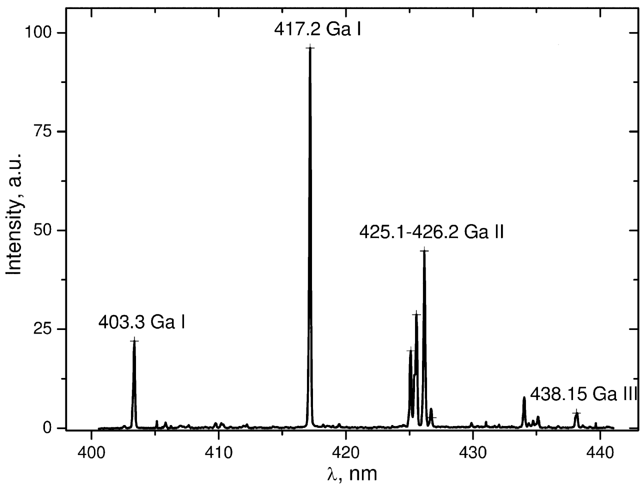

Fig. 3. Plasma emission spectrum around 420 nm.

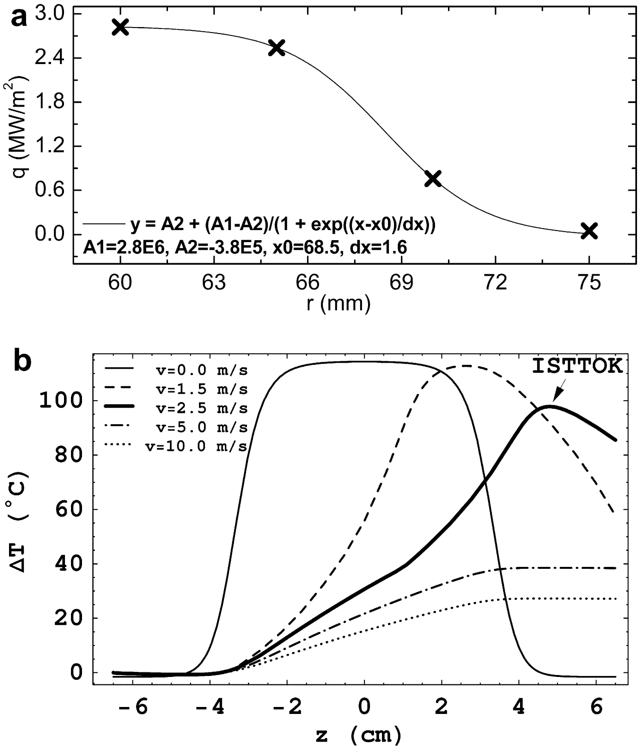

Fig. 4. (a) Measured plasma heat flux profile in a 9 kW ISTTOK discharge and (b) calculated temperature increase on the jet's surface, for several flow velocities, in a 16 kW discharge.

gallium injection was performed. In this measurement the observation was done along a viewing line tangent to the plasma, in the equatorial plane and directed towards the jet position. This diagnostic was able to provide additional information on the gallium and gallium ion species spatial distribution inside the plasma [7]. Fig. 3 shows that the presence of the jet in the chamber generates a pronounced increase in the spectral line emission. This increase is obviously due to the penetration of gallium in the plasma that is rapidly ionized, close to the jet surface, to higher ionization stages (Ga, Ga^+ and Ga^{2+} ionization potentials are respectively: 6.0, 20.5 and 30.7 eV). The attempts to acquire spectra like the one shown in Fig. 3, from a viewing window located at $\phi = \phi_{\text{jet}} + 135°$ have proven themselves to be unfruitful since the intensity of gallium (either neutral or ionized) lines were lower than the sensor detection limit. In any case the obtained results seem to indicate that the influence of the liquid metal jet on the plasma appears to be only a local perturbation since it is only observable at the jet position without any strong signals of plasma performance deterioration. The main reason for this observation is thought to be related to a reduced amount of gallium being released from the jet surface, either by evaporation or sputtering, during the plasma–jet interaction in ISTTOK, when compared to other impurity sources. This is indeed confirmed by the fact that there is no significant increase in the radiated power in UV band when the highest intensity gallium ions line emission occurs in this spectral region [10].

4. Gallium jet surface temperature increase analysis

4.1. Evaluation of the gallium jet surface temperature increase

The release of gallium from the jet surface can be due to both 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 [11]:

$$\Delta T(t) = \frac{1}{\sqrt{\pi \rho C_P \kappa}} \int_0^t \frac{q(t-t')}{\sqrt{t'}} \mathrm{d}t'; \tag{1}$$

where C_P is the material specific heat, ρ its density and κ its thermal conductivity. This equation is valid provided the heated object thickness is greater than the thermal penetration depth $\delta_{\text{skin}} = \sqrt{(\kappa t_{\text{heat}}/\rho C_P)}$ where t_{heat} is the heat deposition time. This condition is verified in our case since for a gallium jet in a 30 ms discharge, $\delta_{\text{skin}} = 0.64$ mm ($< r_{\text{jet}} = 1.15$ mm), assuming that $\rho_{\text{Ga}} = 6095$ kg/m^3, $\kappa_{\text{Ga}} = 31.7$ W/m K and $C_{P\text{Ga}} = 380$ 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. These parameters have been measured, in ISTTOK using a copper probe [7]. The heat flux profile shown in Fig. 4(a) was obtained for 9 kW power input ohmic discharges. It is possible to integrate Eq. (1) using the best fit function indicated in this figure and performing the variable transformation: $r \rightarrow \sqrt{(z^2 + 0.06^2)} \rightarrow \sqrt{((z_0 + v_{\text{jet}}t)^2 + 0.06^2)}$, 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. Since ISTTOK discharge is short duration the effect of the gravity acceleration has a small contribution to the change in the position of a gallium element of volume present in the chamber and, for simplicity, has been disregarded. The results of these calculations for 16 kW discharges and several flow velocities are presented in Fig. 4(b). It is seen from this figure that 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, for which gallium still has a low vapor pressure ($\sim 10^{-22}$ mbar!). It is also important to stress the behavior of the jet temperature as the flow velocity changes: as expected there is a clear decrease on the liquid metal surface temperature when velocity increases.

4.2. Gallium droplets surface temperature monitoring by infrared sensor

The emission of infrared radiation has been successfully used to measure the temperature of liquid lithium surfaces in FTU tokamak [12]. A HgCdTe infrared sensor, with a 6.7 µm cutoff wavelength, is being used in ISTTOK to monitor the radiation emitted by gallium droplets, after liquid metal interaction with the plasma, aiming at studying the power exhaustion capability of such thin jets.

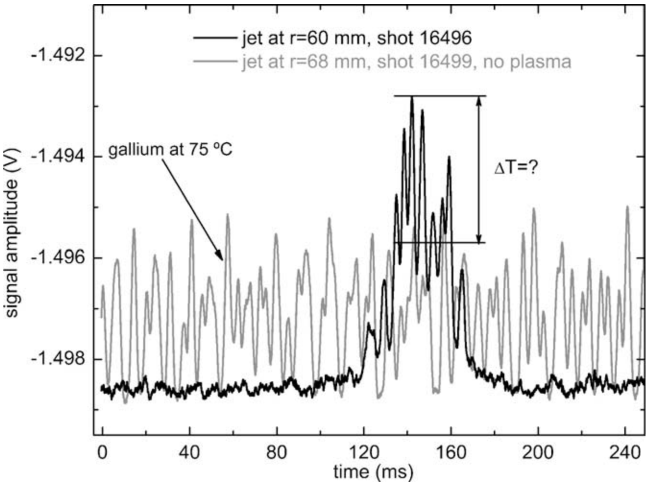

Fig. 5. Signal from the infrared sensor with and without plasma.

Measurements are performed at the viewing window schematically represented on the lower part of Fig. 1. The observation direction is perpendicular to the poloidal plane (in fact perpendicular to the direction represented in Fig. 1). At that distance from the chamber (∼48 cm from the equatorial plane) the gallium jet is already in droplet form and has reached thermal equilibrium since heat propagates about 3 mm (> droplet radius) before reaching that viewing cord. As such, the average power extracted by the gallium jet can be deduced from the specific heat definition by:

$$\bar{q} = \bar{m} C_{\mathrm{PGa}} \Delta T \tag{2}$$

where $\bar{q}$ is the average input power, $\bar{m}$ is the liquid metal mass flow rate and ΔT is the temperature rise, which is intended to be measured in this experiment. A germanium meniscus lens, with broadband antireflection coating, 25.4 mm focal length and 24 mm diameter was used to focus the radiation emitted by gallium droplets on a 1 mm core diameter silver halide optical fiber which, in turn, transmits the radiation to the cryogenically cooled (78 K) sensor.

Measurements with the mentioned device have provided the results shown in Fig. 5. These were obtained, with the collection lens 85 mm away from the droplets position. Each one of the spikes shown in the curves of Fig. 5 corresponds to single droplets. The gray curve in Fig. 5 is a reference shot (no gas) showing the droplet behavior without plasma. This has been obtained with gallium injector at $r = 68$ mm. This shows that there is a small tilt in the injector direction since it should be centered at $r = 60$ mm (Nonetheless it should be stressed that this corresponds to an angular shift less than 0.9°). Another important outcome of the measurements, obtained from the analysis of Fig. 5, is that the jet suffers a small (<10 mm) radial displacement due to the influence of the plasma. This is noticed since the droplets are not observed prior to the shot (black curve in Fig. 5, injector at $r = 60$ mm) and they appear in the collection optics FOV during the discharge time (with the corresponding delay). Previously acquired movies of the jet inside the chamber, during its interaction with the plasma, have not put this fact in evidence since at this location the shift is too small to be clearly identified. The observed increase in the signal amplitude, when compared to the shot without plasma, could only be related to an increase in the gallium jet temperature. It is not possible to provide a value for this parameter since its measurement requires a calibration procedure of the detector which is under development. But it is worthy to mention that for both curves, in Fig. 5, gallium at the injector output was at a temperature close to 75 °C. Unfortunately the sensor response is not linear [12] and this value is not enough to obtain the droplets temperature increase due to the plasma interaction. The low signal amplitude obtained for the data presented in Fig. 5 (a few mV) is related to two factors: (1) the low voltage output of the infrared sensor was connected directly to the tokamak data acquisition system, without being amplified and (2) the sensor response was not the most recommended for the temperature range under consideration. A new three-channel infrared sensor is planned for future measurements, using a more sensitive detector (suitable for lower temperature values, cutoff wavelength of 9 μm) and higher spatial resolution which will allow following the motion of the gallium droplets along the referred radial displacement.

5. Summary

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 time evolution of visible radiation from gallium characteristic spectral lines close to the jet and at one toroidally symmetric position shows that plasma-liquid metal interaction has only a local effect. This work proved the technical feasibility of gallium jets interacting with plasmas. Although the expected temperature increase of the jet surface had been estimated, the experimental measurements still require an ongoing calibration procedure to provide further insight in the jet power exhaustion capability.

Acknowledgments

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References

[1] M.A. Abdou, The APEX team, Fus. Eng. Des. 45 (1999) 145.
[2] R. Majeski, R. Doerner, T. Gray, R. Kaita, R. Maingi, D. Mansfield, et al., Phys. Rev. Lett. 97 (2006) 075002.
[3] V. Pericoli-Ridolfini, M.L. Apicella, G. Mazzitelli, O. Tudisco, R. Zagórski, The FTU team, Plasma Phys. Control. Fus. 49 (2007) S123.
[4] D.K. Mansfield, D.W. Johnson, B. Grek, H.W. Kugel, M.G. Bell, R.E. Bell, et al., Nucl. Fus. 41 (2001) 1823.
[5] R.E. Honig, D.A. Kramer, RCA Rev. 30 (2) (1969) 285.
[6] S.V. Mirnov, V.A. Evtikhin, Fus. Eng. Des. 81 (2006) 113.
[7] R.B. Gomes, H. Fernandes, C. Silva, et al., Fus. Eng. Des. 83 (2008) 102.
[8] R.B. Gomes, H. Fernandes, C. Silva, et al., AIP Conf. Proc. 875 (2006) 66.
[9] R.B. Gomes, H. Fernandes, C. Silva, A.C.A. Figueiredo, IEEE Trans. Plasma Sci. 36 (4) (2008) 1086.
[10] T. Shirai, J. Reader, A.E. Kramida, J. Sugar, J. Phys. Chem. Ref. Data 36 (2007) 509.
[11] H.S. Carslaw, J.C. Jaeger, Conduction of Heat in Solids, 2nd Ed., Oxford University, Oxford, 1959.
[12] A. Alekseev, V. Lazarev, Ya. Gorbunov, G. Mazzitelli, M.L. Apicella, G. Maddaluno, 33rd EPS Conference on Plasma Physics (Rome, Italy, 2006), p. 1.162.