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Erosion of vanadium in lithium plasma

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Abstract

In this paper the results of first experimental study of the pulse discharges in lithium vapour with vanadium electrodes are presented. The goal of the investigation was modelling the conditions on divertor plates with the lithium protection during current disruptions. The electric current was about 2 ka with pulse duration of several milliseconds. The electron temperature estimated from plasma electrical conductivity was about 2.8 eV. The measured erosion rate of the vanadium anode was about 10^{-3} g/C. The dimensions of vanadium droplets scraped out from inner surfaces of the discharge tube have been measured. © 1999 Elsevier Science B.V. All rights reserved.

Keywords: Lithium; Plasma–material interaction

1. Introduction

Rapid decay of the radioactivity of vanadium irradiated by 14 MeV neutrons attracts an attention to vanadium as a perspective construction material for thermonuclear reactors. The interaction of a surface of vanadium with the plasma has been studied insufficiently. Different kinds of the erosion of vanadium irradiated by hydrogen and helium ions were investigated in Ref. [1,2]. To protect divertor plates against destruction during current disruption in tokamaks the using of liquid lithium was discussed in literature earlier (for example, [3]). The interaction of fully ionized lithium plasma with materials has some features affected by the record high potential energy of the lithium ions: metastable level $2s^3S$ of single ionized lithium atom has the energy of 59.02 eV and double ionized lithium atom has the energy of 75.64 eV in contrast with potential energy of proton 13.6 eV. The goal of the present study is the experimental investigation of the interaction of highly ionized lithium plasma with vanadium. For this purpose, the modeled high current discharge in a vapour-filled dielectric tube was used to produce highly ionized plasma.

2. The experimental set-up and diagnostics

The electric discharge was created in a quartz tube with inner diameter of 16 mm and outer diameter of 19 mm between vanadium electrodes (Fig. 1). The electrodes were spaced by 350 mm. The tube was placed in a vacuum chamber continuously pumped by means of a turbomolecular pump. The ambient pressure was $\leq 10^{-4}$ Pa. The vacuum chamber had a quartz window for an optical diagnostic of the plasma. Both the anode and the cathode were a truncated cone with the diameters $d_1 = 15$ mm, $d_2 = 10$ mm and height $h = 5$ mm. The surfaces of both the anode and cathode were mechanically polished. The anode was placed inside the discharge tube. The cathode closed opposite end of the tube.

To ignite the discharge, the lithium plasma jet was injected through the cylindrical channel with the diameter of 8 mm on the axis of the cathode. The cathode and coaxial central electrode formed the pulse plasma source. The plasma jet was formed by an electrical explosion of the two lithium wires of Ø 0.5 × 2 mm pressed out through the apertures in the central electrode.

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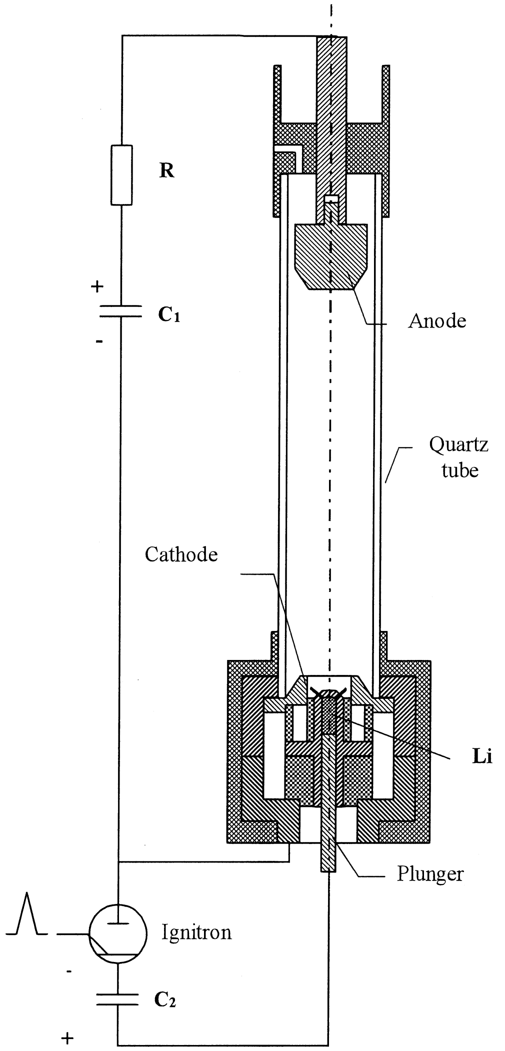

Fig. 1. Discharge tube with electrical circuit.

The capacitor banks of 2000 and 600 μF were used to supply respectively the main discharge and the pulse plasma source. The maximum voltage of the capacitors was 3 kV. The electrical circuit of the pulse plasma source had the ignitron to switch on the discharge. To restrict the discharge current, the ballast resistor of 0.42 Ω was used in the main discharge circuit. The discharge current and voltage drop were measured with help of the Rogowsky coil and the resistive divider respectively.

For spectroscopy of the discharge plasma, the optical system was used. The 500 mm lens collected a plasma light emitted along the chord passing through the axis of the discharge tube at the distance of 5 cm from the anode. The light was split by two mirrors and focused on the entrance slits of the monochromators. To analyse time integrated spectra of the plasma, a 0.5 m MDR-2 monochromator equipped with 600 grooves/mm grating was used. Photodetection was provided with a home-made multichannel analyser built around a linear 1024 pixel CCD array. This system enabled simultaneous measurement of a wavelength interval of 48 nm with a spectral resolution of approximately 0.2 nm. The CCD array exposure of 10 ms was greater than the discharge duration (about 3 ms). The time resolved measurements of the intensities of selected lines was performed by means of 0.4 mm SPM-2 monochromator having the inverse linear dispersion of 4 nm/mm with a FEU-79 photomultiplier behind the exit slit. The entrance slit and exit slit had respectively width of 30 μm and 1.5 mm so that the photomultiplier collects plasma light in wavelength range of about 6 nm. The height of both entrance slits was 4 mm. The computer controlled CAMAC acquisition system was used to record the experimental data. The signals were digitized with the time step of 10 μs. The optical system had been calibrated with help of standard tungsten ribbon lamp in the spectral range from 400 to 850 nm.

The discharge tube with electrodes has been cleaned up by glow discharge in argon with the pressure of about 10 Pa. Prior to the measurement an additional cleaning was performed by means of several lithium pulse discharges with the current of 4 kA. To produce the high current discharge the ballast resistor of 0.42 Ω was removed from the discharge circuit.

3. Experimental results

The charge voltage of both the capacitor banks was 2 kV. Typical voltage drop, current and spectral line intensities are shown in Fig. 2. The discharge in the tube started with 50 μs delay after beginning discharge in the pulse plasma source. The duration of the current in the pulse plasma source was about 300 μs. One can see that the discharge is 'noisy'. The increased level of fluctuations was observed during start up and before termination of the discharge. The current-voltage characteristic of the discharge for decreased current is shown in Fig. 3. The overview spectrum of the discharge shown in Fig. 4 was measured in the set of reproducible discharges. The lines of Li I (670.8 nm), Li I (610.3 nm), Li II (548.5 nm) and H_α can be seen on the spectrum [4]. Only these lines were seen on the spectra due to the drop of the CCD array sensitivity and low line intensities in blue wavelength region. The intensity of H_α line grew but Li I line intensities were unchanged when the voltage of the charge of the pulse plasma source capacitor bank increased. The Li I line intensities increased but H_α line intensity was reduced when the voltage of the charge of the main discharge capacitor bank increased. When the voltage of the charge exceed 2.5 kV the silicon ion lines appeared and its intensities grew with the rise of the

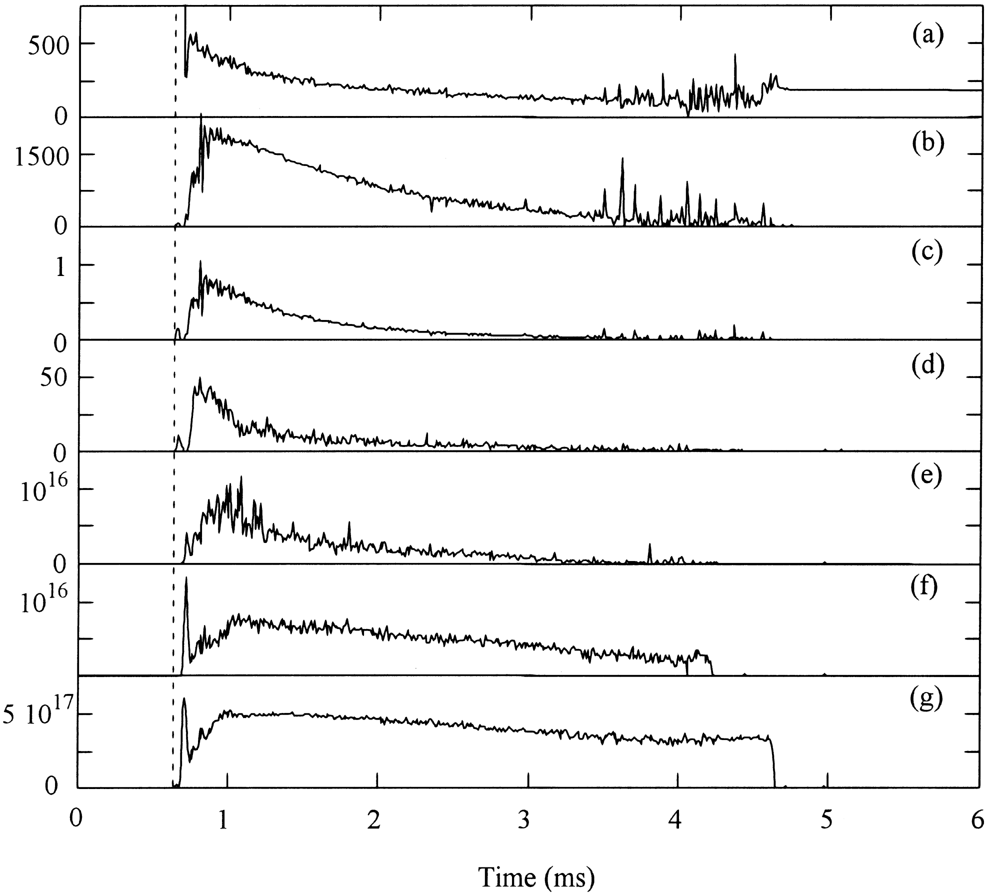

Fig. 2. The evolution of (a) discharge voltage V; (b) discharge current A; (c) discharge power MW; (d) neutral vanadium lines emission in the range of 434–440 nm a.u.; (e) LiII (548.5 nm) line intensity photon/cm^2 s sr; (f) LiI (610.3 nm) line intensity photon/cm^2 s sr; (g) LiI (670.8 nm) line intensity photon/cm^2 s sr. The dash line indicates the start of the pulse plasma source.

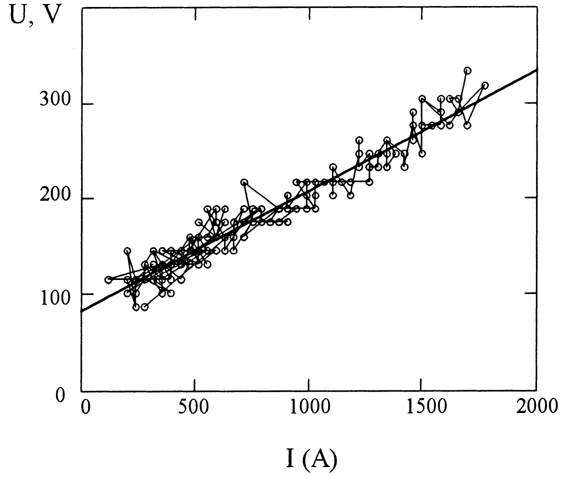

Fig. 3. Current-voltage characteristic of the discharge, straight line shows $U(I) = 0.125 \cdot I + 83$.

voltage. The very bright plasma column appeared during cleaning 4 kA-discharge. The spectra of the cleaning discharge have a bright continuum and numerous intense Si II lines additionally to the lithium lines.

After 140 shots the device was dismounted, and the discharge tube and electrodes were cleaned by flushing water to remove lithium and its compounds. The electrodes were made of small-grained vanadium alloy 98% V 2% Nb. The visual inspection of the cathode showed that the cathode top flat surface and a part of the neighbouring cone surface have tracks of an erosion, the rest surface being without changing. On the eroded surface a superposition of many melted crater areas can be seen by using an optical metalograph microscope. The craters were so close together that this surface looked liked sponge. Craters density on the top surface was about 10^5 cm^{-2}. Craters have nearly circular shape, its diameters vary in the range of 10–100 μm. The craters depth were approximately 1/3 of its diameter. The cra-

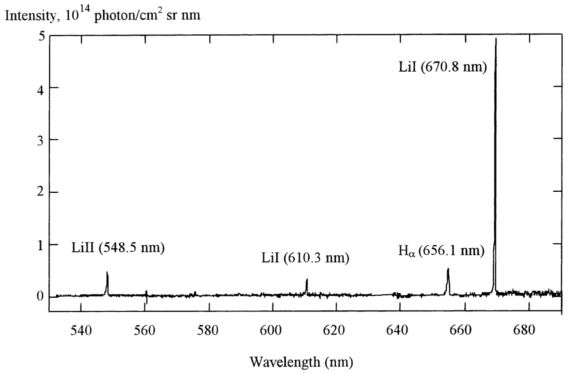

Fig. 4. Overview spectrum of the discharge.

ters become smaller in size on the edges and the cone surface with moving away from the center of the cathode. The 'sponge' on the top flat surface was destroyed. Upper surface layers of the sponge were nearly almost lost. Only fragments with size of several tens µm and the height in range of 50–70 µm were seen.

The erosion of the anode in comparison with the cathode one was not so local. The flat surface of the anode was melted and cracked. On this wavy surface irregularities were observed on the distance 1–3 mm from each other. Some irregularities have a oblong cone shape and the height varied in a range of 0.1–0.2 mm. Molten metal was also present in the form of large size droplets and flowed up on a curve surface located higher. On this part of the anode nearly circular spots with flat bottom were present. Its diameters ranged in the interval of 100–250 µm and the depth 10–50 µm, respectively. The amount of the anode weight loss was found to be 0.46 g after about 470 C charge transfer.

The inner surface of the quartz tube was covered by a dark deposit especially near the cathode. On it metal droplets as the result of arc erosion were observed along the all tube length. The droplets were scraped away from the tube surfaces with length of 4 cm in a vicinity of both electrodes separately and collected on photoplates surfaces to examine by the optical metalograph microscope. Droplets were slightly flattened and some of that were elongated due to a distortion of the molten droplets on impact. Its size and height above a substrate were measured to obtain the mean diameter. The relationship of the diameter to the height of the droplets above the substrate varied in the range of 1.5–2. The results of diameters measurements for both electrodes were plotted in the manner of a histograms with the step of 5 µm (Fig. 5). The minimum value for both electrodes was approximately the similar and has the value of 2 µm. The maximum diameter for the cathode and the anode was different: 115 and 165 µm respectively. For both cases 20 µm was the more frequently appeared value. The average diameter was approximately 30 µm, the anode droplets being slightly greater than the cathode droplets.

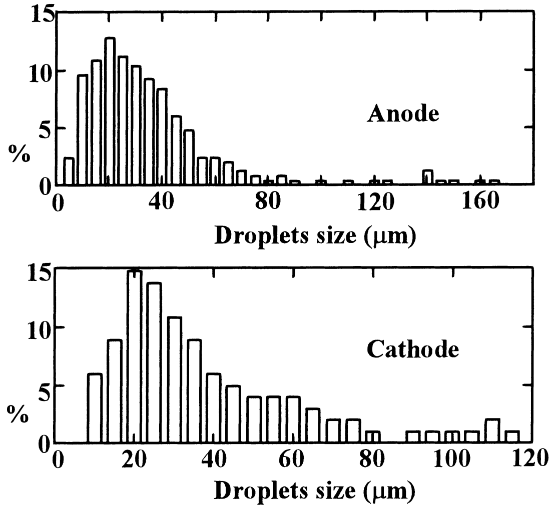

Fig. 5. Droplets size distribution in anode and cathode regions.

4. Discussion

The Ohms like current-voltage characteristic of the discharge confirms that the highly ionized plasma is produced. The slope of a current-voltage characteristic shown in Fig. 3 corresponds to the resistance of lithium plasma column of 0.125 Ω and the extrapolation of the characteristic to zero current provides the total electrodes voltage drop of 83 V. The electron temperature of 2.8 eV is estimated with help of Spitzer formula with using the current density averaged over the discharge tube cross section. The energy balance equation of electrons can be written as

$$\frac{j^2}{\sigma} = \frac{2m_e}{m_{\mathrm{Li}}}\delta\frac{3}{2}kT_e\frac{n_e}{\tau_e} \quad , \qquad (1)$$

where $j = en_e v_d$ is the density, $\sigma = 2e^2\, n_e\, \tau_e/m_e$ is the plasma conductivity, m_e and m_{Li} are respectively mass of electron and lithium atom, n_e is the electron density, T_e is the electron temperature, v_d is the drift velocity of electrons, τ_e is the electron-ion collision time and δ is the coefficient taking into account inelastic collisions which result in light emission [5]. The drift velocity of electron deduced from Eq. (1) is order of the ion sound speed

$$v_d = \sqrt{6\delta\frac{kT_e}{m_{\mathrm{Li}}}}. \qquad (2)$$

In our case the elastic collision dominates so that $\delta \approx 1$ and $v_d \approx 1.6 \times 10^6$ cm/s. Using this value and discharge current density of 1 kA/cm^2, the electron density

$n_e \approx 4 \times 10^{15}$ cm^{-3} has been estimated. For $\delta \approx 10$ the electron density $n_e \approx 10^{15}$ cm^{-3}.

Taking of the transition probability from [6] and measured Li 1 (670.8 nm) line intensity $I = 5 \times 10^{17}$ photon/cm^2 s srad from the Fig. 2, the average density of neutral lithium atoms in $2p^2P^0$ state is found $n_{2p} = 4\pi I/d_1 A_{21} \approx 10^{11}$ cm^{-3}. The ionization coefficient of lithium atoms from the $2p^2P^0$ state under the electron temperature of 2.8 eV is $\langle\sigma_{\text{ion}} v\rangle_2 \approx 1.6 \times 10^{-7}$ cm^3/s so that the frequency of ionization per one electron $\approx 1.6 \times 10^4$ s^{-1}. The total flux of atoms produced by evaporation of vanadium droplets is estimated as 2×10^{20} s^{-1}.

The mass loss of electrodes consists mainly of two components: vapour and liquid, and the intensity of a process of ejection of liquid metal depends on discharge conditions. The value of erosion rates measured in g/C is generally used for comparison of the erosion of electrodes by arcing for varying discharge conditions. In our experiment the loss of weight from the anode corresponds to an erosion rate of 10^{-3} g/C. This relatively large value may be caused by removing of molten material from the anode mainly in droplet form, the melting being caused by the shape of the anode.

Usually the size distribution of droplets emitted from the cathode shows a monotonously decreasing with increasing size (see, for example, [7]). Relatively small amount of small size droplets in our experiments may be caused by its evaporation during a movement through the plasma to the tube wall. Estimations for droplet evaporation in the plasma with the density of 3×10^{15} cm^{-3} and the temperature of 2.8 eV showed that the droplet with the diameter of 1 μm must be evaporated during approximately 0.3 ms.

It is known, that a turbulence occurs in the similar discharge due to some mechanisms of helical instabilities.

The observed 548.5 nm line corresponds to $2s^3S$–$2p^3P$ transition of LiII and the upper level energy is 61.28 eV [4]. Using the transition probability from [6] and the measured line intensity (Fig. 2) the density of the exited Li-ions is found to be in the range of 10^{10}–10^{11}cm^{-3}. Processes of the generation of such ions requires for special investigations, which are planned to made in the future.

5. Summary

The fully ionised pulse Li-plasma with the density of $\sim 5 \times 10^{15}$ cm^{-3} and the temperature of 2.5–2.8 eV was obtained.

The erosion rate for vanadium electrodes in such plasma for currents of 1–2 kA and the discharge duration of several milliseconds was estimated. The erosion rate of the anode was $\sim 10^{-3}$ g/C.

The excited Li-ions with level energy of 61.28 eV were observed in the discharge plasma.

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