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Radiation losses of strongly ionized dense plasma

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Experimental research on a new type of low temperature discharges has been started in 1998 in the IVT RAS [1]. It is continued on the "Robotron" installation in Kiev [2-5]. Pulse discharges in quartz tubes supplied from a capacitor bank are used. A lithium plasma (more precisely lithium-vanadium) with a high degree of ionization is produced. Distinctive features of the discharges were the following: 1) the discharges are produced at continuous vacuum pumping and filling the tube by plasma from the special pulse source. The duration of the self-sustaining discharge exceeds the time of injection by one order of magnitude and more. 2) Such source in [1] was the electrical explosion of a lithium wire, in "Robotron", it is an arc discharge with a solid lithium cathode. Electrodes (the cathode of the main discharge and the anodes) have been made of fine-grain vanadium. 3) Plasma pressure exceeds pressure of saturated Li vapor at wall temperature. The chaotic flow of ions is much higher than their flow on walls. 4) Plasma was strongly turbulent with a wide spectrum of pressure and radiation oscillations. Measurements in "Robotron" [4] show that sign-variable longitudinal magnetic field up to 200 Gs is generated. 5) The power of 10-20 kW per cm of discharge column is dissipated. It corresponds to the power flux onto the tube wall of up to 2 kW/cm^{-2}.

The physical phenomena and the balance of energy in the experiments published in [1] are discussed. The main parameters of the discharges were as follows: the current up to 1.8 kA, the tube diameter of 1.6 cm, the value of the electric field in the column of about 7 V/cm, and the discharge duration of few milliseconds. Plasmas obtained in those discharges had for parameters: concentration $n_e \approx 10^{15}$ cm^2, plasma temperature T of several eV at the current density up to 1 kA/cm^2.

The foregoing discharge features can be explained by contracting of the discharge under the action of magnetic field produced by the current. In this case, the radial Hall field directed inside closes the ions flux on walls. The gradient of the density near the wall can be estimated by the formula

$$E(\omega\tau)_e \cong (T/en)(dn/dr), \tag{1}$$

with E – the longitudinal electric field, $(\omega\tau)_e$ - the Hall's parameter.

Estimations by means of this formula give a characteristic scale for the decrease of the ion density of approximately 0.2 cm. The plasma parameters correspond to values defined by the Bennet's formula:

$$3.2 \cdot 10^{-10}\ \bar{T}(N_e + N_i) = I^2, \qquad (2)$$

where $\bar{T}$ - average temperature eV, *I*- the current A and $N = 2\pi \int nr\,dr$ cm^{-1}.

Calculations by means of this formula give satisfactory agreement with the basic measured parameters. The estimation of temperature from the conductivity of a fully ionized plasma with effective charge $Z_{eff} = 2$ (by means of Spitzer's formula) gives a value of about 5 eV.

The flux of ions recombining on the wall was estimated using the line intensity of neutral lithium $\lambda = 670.8$ nm of $5 \cdot 10^{17}$ photon/cm$^2 \cdot$s$\cdot$sr. The flux of energy transferred to the wall by ions appears on several orders of magnitude less then the energy generated in the column.

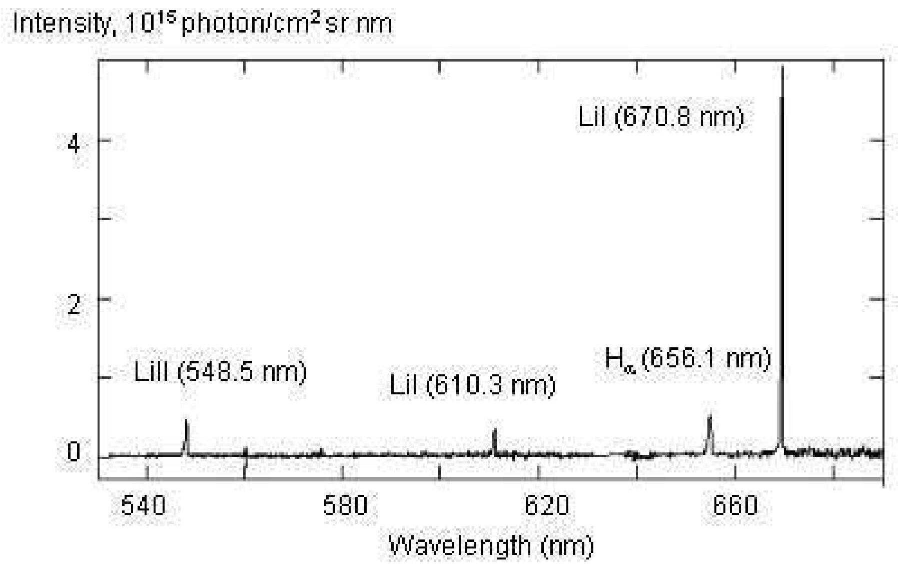

Fig. 1. Overview spectrum of the discharge.

The radiation of the discharge in the visible part of the spectrum is small (Fig.1) [1]. The main mechanism of losses of energy, apparently, is radiation in the far part of ultraviolet. Radiation with wavelength $\lambda = 548{,}5$ nm corresponding to transition $2p^3P_0$-$2s^3S$ of the ion of lithium was registered. Energy of the level 2p is 61.28 eV. Average concentration of excited ions at the level 2p corresponding to this radiation is about 10^9 cm^{-3}. Radiation of the transition $2p^1$-$1s^1$ is obviously closed. Under the conditions considered, the main broadening mechanism for the Li^+ 2p–1s resonance line $\lambda = 20.23$ nm is the Doppler effect. At T_e = 5 -10 eV the Doppler width equals $\Delta\lambda_D \approx 5.9\cdot10^{-4}\cdot(T_i)^{1/2}$ nm where T_i is the temperature of ions in eV. Even at very low ion temperature, the Doppler width is higher than the Stark width [6]. Then the absorption coefficient at the line center is

$$k_0 \approx \frac{\lambda^4}{8\pi c} n_1 \frac{g_2}{g_1} \frac{A_{21}}{\Delta\lambda_D}, \tag{3}$$

where n_1 is the population of the lower level of the line, g_1 and g_2 are the statistical weights of lover and upper levels, A_{21} is the transition probability.

For the lithium ion resonance line A_{21} = $2.56\cdot10^{10}$ s^{-1}, and at $n_1 \approx 10^{15}$ cm^{-3} we have $k_0 \approx 18/T_i^{1/2}$ cm^{-1}. Thus, the discharge plasma optical thickness for a photon at the line center is $\tau_0 \approx k_0R >> 1$ (R is the discharge column radius, R ~ 1 cm). Integrally over Doppler profile, the probability of the photon escape from the discharge column axis is [7]:

$$\Theta = \frac{1}{2\sqrt{\tau_0}} << 1. \tag{4}$$

Consequently, the lithium resonance line turns out to be trapped and energy escape by that is rather small.

Turbulence plays, apparently, a determinant role in energy losses. It is assumed in [5] that losses of energy are connected with three-body recombination of Li^{++} ions transported into the cold edge plasma due to plasma convection. The known formula according to which the constant of velocity of recombination for Z = 2, expressed by $\alpha \approx 5\cdot10^{-26}\cdot T_e^{-9/2}$ cm^6/s was used in work [5]. Such conceptions assume, that new Li^{++} ions are generated in the central zone. Radial convection results in an ion lifetime of about 0.5-1 μs. However, thermal electrons cannot generate Li^{++} ions with such a high frequency, superthermal (nonmaxwellian) are needed.

Existence of superthermal electrons with energy higher by one order of magnitude than their temperature can be caused by plasma turbulence. Generation of superthermal electrons and their heating in turbulent plasma is a general phenomenon in strongly ionized plasma. Detail study of the kinetics in turbulent lithium plasmas and of the mechanism of generation of UV radiation in it demands further researches. If thermodynamic relationships for calculations of parameters of Li-V plasma is used, then Li^{++} and V^{4+} ions would prevail in the case of 10% percentage of vanadium at $n_e \approx 10^{15}$ cm^{-3} and T = 5 eV.

Significant droplet erosion of the electrodes made of fine-grained vanadium was observed in [1]. For an explanation of the observed erosion in [8], the model has been proposed according to which the liquid film flows and leaves by pressure of vapor above the surface. The practical conclusion from this model is that drop erosion of porous anodes (with sizes of pores more than melting thickness) can be essentially reduced. It was confirmed experimentally in [2] where a decrease in erosion of porous anode of three orders of magnitude was observed.

Experiments in [1] have been connected to the problem of plasma-wall interaction in a thermonuclear reactor of the future. Researches on creation of lithium edge plasma layer where the most part of flux of energy to the walls is transferred by radiation instead of particles are carried on in several tokamaks. Such opportunity had been confirmed experimentally in works [1,5]. It is also seen that the problem of losses of energy from strong ionized dense lithium plasma in a discharge is not completely solved and demands further research.

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