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Susceptibility of States and Properties of Metallic Systems at a Threshold Breakdown of the through Holes under Power Laser Action

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I. Introduction

One of the promising parameter, allowing to describe in detail the states of the matter under laser action, is an exit diameter of threshold hole [1] in metallic foils resulting from threshold breakdown. The threshold breakdown corresponds to minimal laser fluence capable to produce through hole in a foil of a certain thickness. Minimum diameter of threshold exit hole can be considered as response of the system to an external action [2], and diameter *d* of this exit hole is a fluctuating value. This experimental approach gives possibility to connect properties of fluctuating magnitude with values characterizing behavior of matter under external action [2]. Formally, response *d* is expressed through susceptibility operator α [2]:

$$d = \hat{\alpha} f \qquad (1)$$

here *f* - is time function of generalized force.

II. Model

The incident electromagnetic field of laser radiation interacts with the electronic subsystem of metal and enlarges chemical potential μ_e of electrons in region of interaction. (Ponderomotivepotential $V = (q^2/4c \cdot m \cdot \omega^2) \cdot E^2$ is about $10^{-6} \div 10^{-4}$eV under experimental conditions λ = 694 nm and intensity $J \sim 10^6 \div 10^{10}$ W/cm^2[3]). As a result the electrons will start moving into area, in which the electron chemical potential is smaller or where the electron density is less. Into metal their density remains unchanged. Therefore, the excited electrons move into place, where their number is small, i.e. from a metal to the interface of "metal-gas". In particular, this sort of movement arises, when the initially solid matter is quickly heated up to high temperature [4]. Kinetic energy of motion of electrons and ions at these densities (densities of metals in solid and liquid states) turns out comparable with coulomb energy of their interaction. Electrons are concentrating at a "gas- metal" interface. It leads to original polarization at an "interface" which is expressed as difference of chemical potentials

$$(\mu_{e\_interface} - \mu_{e\_volume}) = e \cdot (\varphi_{interface} - \varphi_{volume}) \qquad (2)$$

here $\mu_{e\_interface}$ and μ_{e_volume} is the chemical potentials of electrons on interface and in volume. Therefore, the arising electric field of *E*, is determined as $(\partial\varphi/\partial r = (1/e) \cdot (\partial\mu_e/\partial r) = -E,\ \mu_e = \varepsilon_{Fermi}$. For cooper $\varepsilon_{Fermi} = 7eV$, so the order of magnitude of electric field strength corresponds to – $E \sim 7{\cdot}10^8$V/cm^2), which is enough to drag out positive ions from a warmed-up volume. Accelerated ions pass through the "gas-metal" interface. Due to comparable values of the kinetic energy of motion and the coulomb energy of interaction, the ions capture electrons, and abandon a metal.

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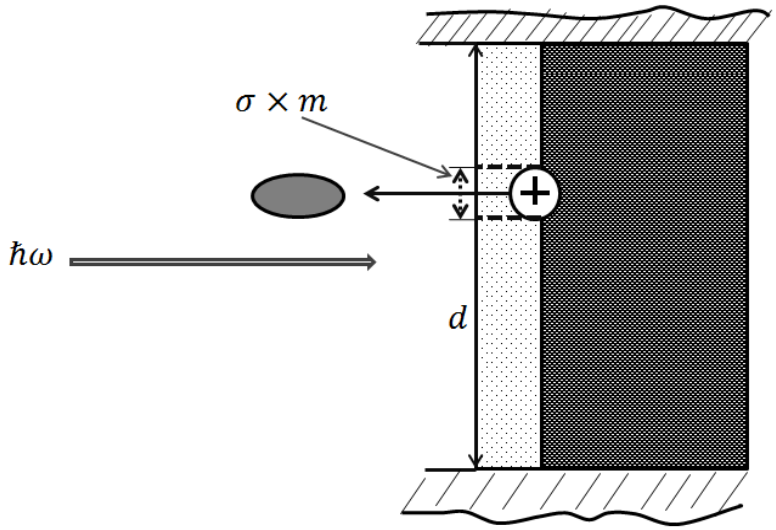

Fig. 1 : Creation (annihilation) of element of interface, σ, on leaving of ion from the volume of metal

Therefore, an ion, passing through an interface, participates in formation of surface, increasing (or decreasing) its area (Fig.1). Moreover, an ion, passing through an interface, transforms itself into an atom, and represents the same fluctuation part of the surface, which is the response of the system on the external field *f*, (Appendix A). Therefore, the elemental act of displacement (crossing of interface) can be considered as an act of moving away (or joining) of element of interface area per time. This element of area σ is approximately equal to the "area of surface» of shade of atom (Appendix A). Elemental area σ per time is connected with mass *m* of atom. Therefore, we can talk about moving away (formation) per time of area in the interface, by the characterized composition $N{\cdot}\sigma{\cdot}m$, where *N* is an amount of atoms in this region. Then the value *z* measureable in an experiment on the threshold breakdown of the through holes [1] is connected to the mean value of *d* (Appendix A)

$$N \cdot \sigma \cdot m = \pi(d/2)^2 \cdot m = (\pi/4) \cdot \left(z \cdot \sqrt{m}\right)^2 \qquad (3)$$

Effective diameter of the threshold exit, $d = z \cdot \sqrt{m}$, is the response of the system on external action *f*. In general, the threshold diameter *z*depends on time, and *d* is the function of time *t* :

$$d = d(t) \qquad (3a)$$

It is possible to construct generalized force *f* conjugated to the chosen response *d* [2]. In our case

$$f \sim (v \cdot \mathcal{E}/\omega)^{1/2}$$

here $\mathcal{E} = (1/c) \cdot \sqrt{\xi \cdot \mu} \cdot E \cdot H$ is electromagnetic energy density; E and $H \sim e^{+j\omega t}$ or $e^{-j\omega t}$ are tensions of the monochromatic field with cyclic frequency ω; v is volume accepting $\mathcal{E}$.

Dropping details of calculations [2]and taking into account that external perturbation is monochromatic, we will write down connection (1) between the response *d (t)* of the system and external perturbation *f* in Fourier components:

$$d_\omega = \alpha(\omega) \cdot f_\omega \qquad (4)$$

here *α(ω)* is generalized susceptibility. Symbol ω means Fourier component of value, for example:

$$d_\omega = \int_{-\infty}^{+\infty} d(t) e^{j\omega t}\, dt$$

Then, fluctuation-dissipative theorem [2] allows writing down Fourier component of square of diameter (areas) (3a) nascent hole in a form:

$$\langle d^2 \rangle_\omega = 2 \cdot \hbar\alpha_2 \cdot \left[\frac{1}{2} + \frac{1}{e^{\hbar\omega/kT} - 1}\right] \qquad (5)$$

here α_2 is imaginary part of generalized susceptibility (1) and (4):

$$\alpha(\omega) = \alpha_1 + j\alpha_2$$

$\hbar, k$ are Plank and Boltzmann constants, *T* is absolute temperature. The important feature of $\langle d^2 \rangle_\omega$ is that it consists of the composition area of the threshold hole, as functions of temperature, on a delta function *δ (ω)* (Appendix B).

III. Solution and Results

a) Determination of imaginary part of generalized susceptibility

Inverting expression (5), we will find the temperature of the electron-ion system depending on the "diameter" of the threshold hole

$$T = \frac{\frac{\hbar\omega}{k}}{\ln\left[\frac{1 + \hbar\cdot\alpha_2/d^2}{1 - \hbar\cdot\alpha_2/d^2}\right]} \qquad (6)$$

The expression (6) describes the dependences of imaginary part of generalized susceptibility for different diameters versus temperature (see Fig. 2). It is seen from Fig. 2 that these dependences intersect nowhere, and each one starts with the minimum of real value. Each of the curves corresponds only to a certain diameter of exit hole.

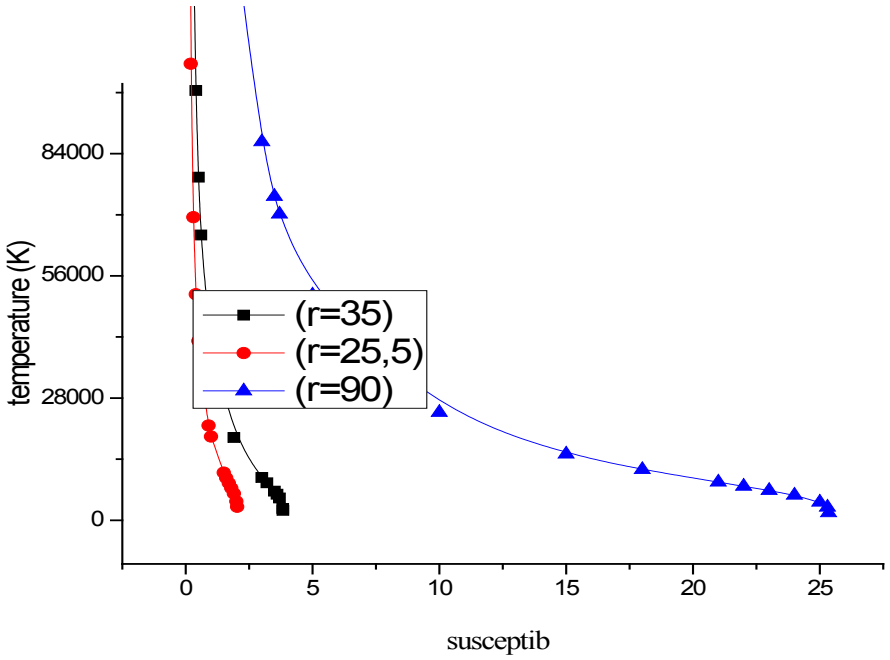

Fig. 2 : The temperature of the electron-ion system depending on α_2.
(Dimeter of exit hole $(\mu m) z = 2 \cdot r$)

The behavior of these curves allows finding of the values of imaginary part of generalized susceptibilityα_2 at different temperatures and also the real value of critical temperature (within the framework of the chosen approaching).

Each curve in Fig. 2 reveals the inflection point (see Fig. 3). An inflection point on dependence of $dT/d\alpha_2$ (to be more correct value, reciprocal to $dT/d\alpha_2$, i.e. $\frac{d\alpha_2}{dT} \sim \left(\frac{\hbar\omega}{kT}\right) \cdot \frac{1}{T}$) indicates the way how the energy of single quantum $\hbar\omega$ is adopted by the system at temperature of T.

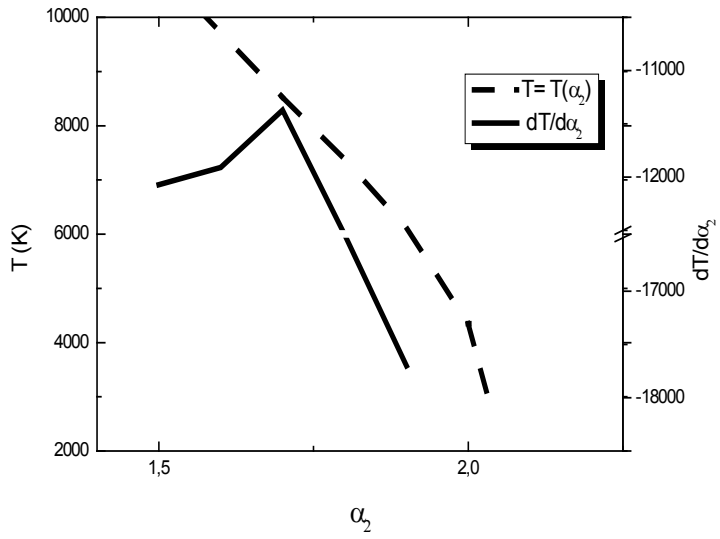

Fig. 3 : The inflection point of a derivative $dT/d\alpha_2$ (solid line), and temperature dependence $T(\alpha_2)$ for $r \sim 25{,}5\ \mu m$ (dashed line)

i. *State of the electro-ion system*

Imaginary part of susceptibility α_2 is fully determined by the state of electronic subsystem and its interaction with ionic subsystem. Behavior of two subsystems depends on the absorbed energy amount at interaction with laser field, which, in turn, depends on a reflectivity (absorptions) coefficient. From dependence (6) and Fig. 2, it is possible to specify behavior of the electron-ion system at critical temperature and around. Within the framework of Drude approaching [5-12] we can determine the reflectivity of metals [6, 7]. Note that the temperature range of research of reflectivity for metals is rather limited, both in a theoretical and in experimental way [9-11]. To calculate reflection coefficient we use (6) and take into account our experimental data of response fig.2. According to Drude approximation dielectric permittivity ε (ω) can be expressed through external field frequency ω plasma frequency ω_p and electron-ion collisions frequency of ν [3, 5-12]:

$$\varepsilon(\omega) = 1 - \frac{\omega_p^2}{\omega\cdot(\omega+j\nu)} = \varepsilon_1(\omega) + j\varepsilon_2(\omega) \qquad (7)$$

(value ν can be considered as relaxation time ν^{-1} of electronic distribution [10] or, as relaxation time of electrons interacting with both electrons and ions [6]). From another side, permittivity ε(ω) and susceptibility α(ω) are connected by relationships [5,6]:

$$\varepsilon(\omega) = 1 + 4\pi\cdot\alpha(\omega) = 1 + 4\pi(\alpha_1 + j\alpha_2) \qquad (8)$$

Expressions (7) and (8) yield α_1 and α_2:

$$\begin{cases}\varepsilon_1 = 4\pi\cdot\alpha_1(\omega)\\ \varepsilon_2 = 4\pi\cdot\alpha_2(\omega)\end{cases} \qquad (9)$$

Coming back to (7) we find:

$$\begin{cases}\varepsilon_1 = 1 - {\omega_p^2}/{(\omega^2+\nu^2)}\\ \varepsilon_2 = {\omega_p^2\cdot\nu}/{\omega(\omega^2+\nu^2)}\end{cases} \qquad (10)$$

here ω is frequency of the external field of radiation (for a ruby laser $27\cdot10^{14}s^{-1}$, ω_p is plasma frequency, ν is the frequency of electron-ion interaction.

In the threshold breakdown of the through hole conditions [1] temperatures exceeds few thousand Kelvin, so that $\hbar\omega\sim kT$, which result in ratio $|\varepsilon_1|\sim|\varepsilon_2|$. It means that calculations of conductivity and reflectivity, which are usually performed under conditions $|\varepsilon_1| \ll |\varepsilon_2|$,[12], cannot be carried out since this inequality is not fulfilled.

Electron-ion frequency νis expressed from second equation of (7a) system:

$$\nu^2 - \frac{\omega_p^2}{\varepsilon_2\cdot\omega}\cdot\nu + \omega^2 = 0 \qquad (11)$$

$$\nu_{(+),(-)} = \frac{\omega_p^2}{2\varepsilon_2\cdot\omega}\left(1 \pm \sqrt{1 - 4\cdot\left(\frac{\omega}{\omega_p}\right)^4\cdot(\varepsilon_2)^2}\right) \qquad (11a)$$

The equation (11a) shows that the frequency of electron-ion interaction has two roots. These two roots imply two different states of electronic subsystem. First root (+ sign) responds the case when electrons of conductivity with the increase of temperature more often collide with ions (mean free time of these electrons diminishes sharply). The system is kept in metallic state. The second one describe situation when frequency of collisions falls down. And it is possible (at temperatures below critical, when the volume, occupied by the system also below, than at a critical temperature) only at reduction of number of electrons participating in conductivity. Reduction of number of electrons of conductivity says that the electrons are localized on ions (or original ionic bubbles). Thus, a metal passes to the dielectric state.

Since both of these roots are interchangeable at identical temperatures, the matter represents itself coexistence liquid metal and dielectric. Thus, there is the only condition at which these two roots to coincide:

$$\nu_{(+)} = \nu_{(-)} \qquad (12)$$

It implies that square root in (10a) is equal to zero, i.e. $\omega_p^4 - (2\varepsilon_2\omega^2)^2 = 0$or

$$\varepsilon_2 = \frac{1}{2}\cdot\left(\frac{\omega_p}{\omega}\right)^2 \qquad (13)$$

The value $\varepsilon_2$can be found from imaginary part of susceptibility α_2(8), which corresponds to critical temperatureFig.3. From (11a), (12), and (13) the electron-ion colliding frequency at critical temperature is found$\nu_{(+)} = \nu_{(-)} = \nu$:

$$\nu = \frac{\omega_p^2}{\varepsilon_2\cdot\omega} = \omega \qquad (14)$$

Thus, at critical temperature the external perturbation distributes electrons and ions in such a way, that frequency of their interaction, ν, becomes equal frequency of the external field. Under laser irradiation ($\omega = 27\cdot10^{14}s^{-1}$) on a metal at a critical temperature, this frequency equals to $\nu = 27\cdot10^{14}s^{-1}$.

b) Temperature behavior of parameters of the electron-ion system

i. *Plasma frequency*

The temperature behavior plasma frequencyω_p (Fig. 4) is determined from the following consideration. In our approach we consider copper atoms, which are singly ionized (valence Z = 1) from melting temperature up to the critical one. We accept $\omega_p = 4\pi\cdot\frac{n^2}{m} = 31{,}80795\cdot10^{-8}$, where $n = 6{,}022\cdot10^{23}\cdot Z\cdot\frac{\rho}{A}$; $A = 64$. Temperature dependence of copper density ρ is

adopted from [15]. The metal density is taken into account in the temperature range from melting up to boiling. The value ω_p was determined from (12) at the critical temperature T_{cr} = 8522K, got from our results, Fig.3, preliminary defining ε_2 on α_2. In addition, experiment determined imaginary part of susceptibility and, accordingly, to the permittivity, and the value of critical temperature do not allow fluctuating of plasma frequency, due to correlation (11).

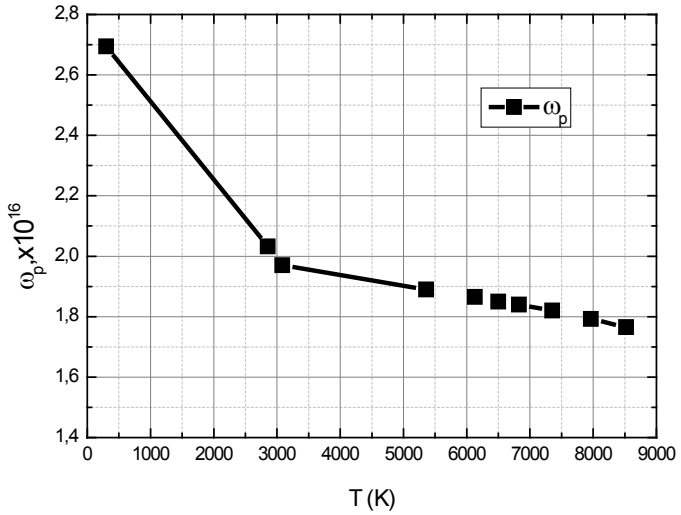

Fig. 4 : The temperature dependence of plasma frequency ω_p

ii. *Electron-ion interaction frequency*

Electron-ion interaction frequency ν consists of two branches $\nu(+)$ and $\nu(-)$ Fig.5. First of the branches corresponds to "metallic» part, and second - to "dielectric" part of the electron-ion system at the examined conditions. $\nu(+)$ demonstrates growth of frequency of electron-ion collisions, and $\nu(-)$ is shows reduction of frequency of electron-ion collisions due to localization of electrons by capture of them on ionic bubbles. It leads to growth of dielectric constituent of a metal.

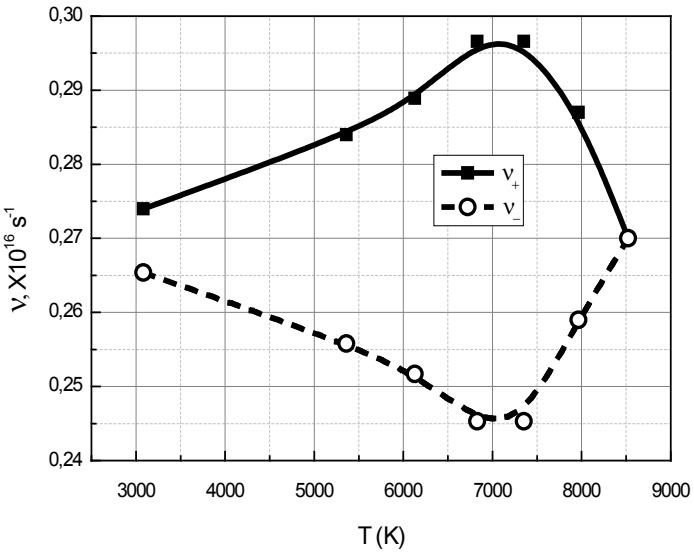

Fig. 5 : Frequency ν is temperature dependence of electron-ion interaction .Upper curve corresponds $\nu(+)$ metallic part of the electron-ion system, $\nu(-)$ corresponds to "dielectric" part of the electron-ion system

iii. *Reflectivity coefficient*

In order to determine reflectivity, *R*, and its temperature dependence has to know temperature behavior of permittivity, plasma frequency, and frequency of electro-ion interaction. These values are bound by the standard set of relationships (9) - (11a), which include imaginary part of susceptibility α (ω). Therefore the experimental dependence of temperature versus imaginary part of susceptibility, (Fig.2, and Fig.3), can be used to find temperature dependences ε_2, ω_p,

(Fig. 4), ν (Fig. 5) and reflectivity coefficient (Fig. 6). *R* calculated in accordance with the appendix C. Fig.6 demonstrates complicated behavior of reflectivity in the temperature range from boiling up to critical temperature of phase transition of liquid metal to gas state.

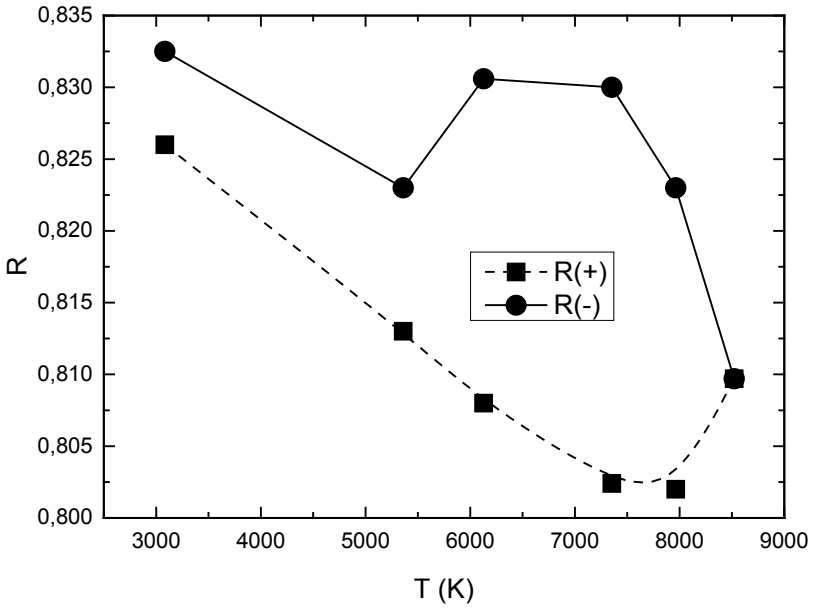

Fig. 6 : Reflectivity coefficients R (+) and R (-) for metallic and dielectric constituents of the electron-ion system

Dielectric constituent part of reflectivity R(-) plays substantial role. In a liquid metal near-by the critical temperature of R(-) is significantly lager than reflection of R(+) caused by a metallic constituent. Quite possible, that such situation is caused not only by appearance of the constrained localized states of electrons on ions or ionic bubbles, but also by origin of overlapping between such constrained states [21, 22] leading to generalization of the localized states. In such regions electrons work again as in a metal. Herein, presumably, and essence of the critical phenomenon at what distinction between a liquid metal and gas disappears.

iv. *Critical temperature*

Critical temperature, T_{cr}, arises from specific behavior of electron-ion system (fig. 5, 6). Thus, a critical temperature for a copper is approximately equal to $T_{cr} = 8522\ K$. In literature a few different values of critical temperatures for a copper are presented. A critical temperature was measured by method of explosion of thin wire by a large current [13]: $T_{cr} = 8390\ K$. In [14] a theoretical value $T_{cr} = 7800K$was obtained from calculations of modeling a phase diagram. But in such calculations, if reflectivity (absorptions) was used, then for such temperatures it would be obtained only by extrapolation on high temperatures, as a direct measuring of these coefficient at high temperatures, higher $3000K$ in literature are not presented. In [15] $T_{cr} = 9000\ K$ was found by extrapolation of density of the gas state of copper from the boiling temperature.

IV. Conclusion

The idea of threshold breakdown of the through holes and application of fluctuation-dissipative theorem allowed to find the value of critical temperature, and also temperature dependences of the generalized susceptibility of the system. This combination opens the prosperity of more thin and detailed high temperature measuring and possibilities of management by the electron-ion system at high temperatures.

V. Appendix A

To estimate the mean (quantum mechanical) value of *d* from (1) and (3), we will include next moments:

(1). At the densities of liquid metal and temperatures in thousands of Kelvin, coulomb energy of interaction of electrons and ions is comparable with their kinetic energy of motion [4]. In these conditions a liquid metal is the electron-ion system, being mixture of electron-ion gas (constrained electron-ion pairs) and electron-ion liquid. Such state is substantially heterogeneous and non-ideal. The last properties suppose a presence, both disconnected electrons and ions, providing the metallic state ("zone of conductivity" and level of Fermi in her), and appearing electron-ion pairs (atomic metallic gas) that can decompose in next moments. And at approaching of the liquid metallic state to the critical condition (critical temperature) frequency of origin of such virtual pairs grows (see for example, рис.5, behavior ν(-)).

(2). In this electron-ion system, electrons can be considered, as electrons of the strongly excited state of atom, at which peripheral electron of atom appear far remote from a positive ion [16]. The similar situation takes place when the electron being at long distance from a nucleus may attribute to the large main quantum number n (and orbital number $\ell = 0$. So the electron corresponds to excited S-state). Motion of such electron (or such ion in the field of electron) can be considered as mutual motion in the coulomb field of atomic remain (ion) with the effective charge of Z = 1 [16]: electric-field tension arising between the charges at that rate $\sim E_{n,l,m} \cdot (a \cdot e)^{-1}$, ($E_{n,l,m}$ is own energy of electron, *e* is an electron charge, *a* is a Bhor radius).

(3). The conduction band in a copper appears as a result of hybridization *4s* and *3d* shells of atom [17]. So that the wave function of electron in the conduction band can be decomposed on ball functions with certain quantum numbers [16, 17, 18] including those that correspond to the states of electrons participating in interaction with the external field. Part of them participates in dispersion of the external field, another part – in absorption (in optical transitions). For example optical transitions in cooper correspond transitions $3d^{10}5s - 3d^{10}4p$, $3d^{10}6s - 3d^{10}4p$,$3d^{10}5,6,7d - 3d^{10}4p$ [19].

Taking into account these facts, and (1) - (3), we can do the following estimations

(a) Remoteness of electron from a nucleus in approaching of hydrogen-like atom [16, 18] is determined by quantum mechanical mean distance of electron in an atom

$$\langle r\rangle_{n,l} = \frac{a}{2\cdot Z}\cdot[3n^2 - l\cdot(l+1)] \sim d/2$$

Then the distance of 5S -state (at Z = 1, looks higher, point (2)) equals to $\langle r\rangle_{5,l=0} = 19{,}838\cdot 10^{-8}cm$, i.e., an electron is remote from a nucleus on mean distance $19{,}838\cdot 10^{-8}cm$ (These distances are in Thomas-Fermi approaching [20]) Tension of electric-field of such electron operating on rest atom (ion) equaled to $\frac{E_{n,l,m}}{e\cdot\langle r\rangle_{5,0}}$ is the same, what $\frac{1}{e}\cdot\frac{\partial\mu_e}{\partial r} \approx 3{,}5\cdot 10^7\, {}^{V}/_{cm} = -E$

(b) The electromagnetic field of laser radiation interacting with target is changing slower than time of electron-electron τ_{e-e} interaction (period of oscillation for a ruby laser $\tau = 23\cdot 10^{-16}s$and $\omega_p^{-1}\sim\tau_{e-e} = 2.32\cdot 10^{-16}s$, where ω_p is plasma frequency). It implies that an electronic subsystem will have time to be tuned under external influence. Thus, electrical fields of interaction between charged particles will look like slowly changing. Atom of copper in exited state is considered in hydrogen-like atom approaching. Character (potential) of electric field allows to split up of wave function of atom $\Psi(x_\alpha, y_\alpha, z_\alpha; X, Y, Z) = \varphi_e(x,y,z)\cdot\Phi(X,Y,Z)$ in the adiabatic approaching on the wave function of electron $\varphi_e(x,y,z)$(here *a* numbered electrons in an atom; (x,y,z) are coordinates of relative motion of electron, (X,Y,Z) coordinates of center-of-mass of atom) and wave function of ion of atom $\Phi_n(X,Y,Z)$ so, that equalization of Schrodinger for the ion of atom will be written down, as

$$i\hbar\frac{\partial}{\partial t}\Phi_n = -\frac{\hbar^2}{2M}\Delta_{X,Y,Z}\Phi_n + [\mathcal{U}(X,Y,Z) + E_{n,l,m}(X,Y,Z)]\Phi_n \qquad \text{(A1)}$$

Because de Broglie wavelength of ion of atom is very small a wave function for wavelength is searched in a form [16]

$$\Phi_n = A\cdot exp\left(-{}^{iS}/_{\hbar}\right) \qquad \text{(A2)}$$

Where S, is an action [16], equals to

$$S = H\cdot t - P_X\cdot X - P_Y\cdot Y - P_Z\cdot Z \qquad \text{(A3)}$$

Substitution of (A2) in (A1) with an account (A3) yields to Hamiltonian

$$H = {}^{\vec{P}^2}/_{2M} + \mathcal{U}(X,Y,Z) + E_{n,l,m}(X,Y,Z) \qquad \text{(A4)}$$

It corresponds to classic behavior of ion of atom of copper, in the external field created by surroundings of ion, $\mathcal{U}(X,Y,Z)$ and by field $E_{n,l,m}(X,Y,Z)$created by remote valence electron.

We consider that $E_{n,l,m}(X,Y,Z)$ at moving of center-mass does not change. The external field for the ion of $\mathcal{U}(X,Y,Z)$is expressed through the difference of chemical potentials of electrons in the "interface" and in a "volume"

$$\mathcal{U}(X,Y,Z) = \left(\mu_{e_{interface}} - \mu_{e_{volume}}\right) = e\cdot\left(\varphi_{interface} - \varphi_{volume}\right)$$

It is accepted for simplicity the vector of tension of electric-field is directed on a normal to the "interface" Fig.1. Then equations of motion of center-of-mass of remain of copper atom take the following form

$$M\frac{d^2X}{dt^2} = 0$$

$$M\frac{d^2Y}{dt^2} = 0$$

$$M\frac{d^2Z}{dt^2} = -\frac{\partial}{\partial Z}\left(\mathcal{U}(X,Y,Z) + E_{n,l,m}(X,Y,Z) + \frac{q^2}{4mc\omega^2}J\right)$$

Value $|V| \ll |\mathcal{U}(X,Y,Z)|$, where $V = \frac{q^2}{4cm\omega^2}E^2$

It is accepted that the initial value of speed of remain in the moment of t = 0 is equal to zero $\left(\frac{dX}{dt},\frac{dY}{dt},\frac{dZ}{dt}\right) = 0$. It followes, the conserved values are $X - X_0, Y - Y_0 \sim\langle r\rangle_{n,l}$ and $(X - X_0)\cdot(Y - Y_0)$. In other words, an area $(X - X_0)\cdot(Y - Y_0) = \sigma$ is equal to the

area formed by the projection of atom on normal to moving of atom of plane, is conserved. Values of $M \cdot \sigma$ and $N \cdot M \cdot \sigma$ also are the invariants of motion during the process of transition of remained atom from one position in other. Distance overcame by the remain of atom is

$$Z - Z_0 = -\frac{1}{2M}\left[\frac{\partial}{\partial Z}\left(U(X,Y,Z) + E_{n,l,m}(X,Y,Z)\right)\right] \cdot \tau^2$$

Let us assume, that $Z - Z_0 = \langle r \rangle_{4,l=1} - \langle r \rangle_{5,l=0} = |7{,}671 \cdot 10^{-8}|\ cm$ then the remained of atom will overcome this distance after $\tau \sim 10^{-14} s$ before will go across from the state $|n = 5, l = 0\rangle$ in $\langle n = 4,\ l = 1|$. We note that the τ correspondsto creation time of new phase (or aggregate) state of substance [1].

VI. Appendix B

Calculation of spectral density of square of diameter of the threshold breakdown of the through hole $\langle d^2 \rangle_\omega$

Formation of hole is the temporal phenomenon. And the diameter of minimum exit hole depends on a diameter in the moment of time previous to the breakdown. So that it is possible to talk about temporal correlation function

$$\langle d(t) \cdot d(t') \rangle \qquad \text{(B1)}$$

in which t' is time moment of through breakdown of minimum exit hole by the diameter of d. $t = 0$ is the preceding moment of time is chosen as point of reference. It means an exit hole arises up at $t' - 0 = \tau$. Spectral density of square of diameter of the through breakdown of minimum exit hole with respect to [2] is written down

$$\langle d^2 \rangle_\omega = \int_{-\infty}^{+\infty} \langle d(0) \cdot d(\tau) \rangle e^{j\omega t}\, dt \qquad \text{(B2)}$$

It is assumed that diameter during τ is changed poorly the $d(\tau)$ is decomposed into row

$$d(\tau) = d(0) + \dot{d} \cdot \tau \qquad \text{(B3)}$$

(B2) is rewritten with taking into account (B3):

$$\langle d^2 \rangle_\omega = \int_{-\infty}^{+\infty} \langle d(0) \cdot (d(0) + \dot{d} \cdot \tau) \rangle e^{j\omega t}\, dt =$$

$$= \int_{-\infty}^{+\infty} \langle d(0) \cdot d(0) \rangle e^{j\omega t}\, dt + \int_{-\infty}^{+\infty} \langle d(0) \cdot \dot{d} \cdot \tau) \rangle e^{j\omega t}\, dt =$$

$$= \langle d(0) \cdot d(0) \rangle \int_{-\infty}^{+\infty} e^{j\omega t}\, dt + \tau \cdot \int_{-\infty}^{+\infty} (d(0)\dot{d}(0)) e^{j\omega t}\, dt = \qquad \text{(B4)}$$

one should notice

$$\int_{-\infty}^{+\infty} e^{j\omega t}\, dt = \delta(\omega) \qquad \text{(B5)}$$

$$\int_{-\infty}^{+\infty} (d(0) \cdot \dot{d}(0)) e^{j\omega t}\, dt = \langle d(0) \cdot \dot{d}(0) \rangle \qquad \text{(B6)}$$

Continuing equality (B4) and taking into account relations (B5) and (B6), then (B4) :

$$= \langle d(0) \cdot d(0) \rangle \cdot \delta(\omega) + \tau \cdot \langle d(0) \cdot \dot{d}(0) \rangle \qquad \text{(B7)}$$

It is assumed that change of diameter $\dot{d}$ versus time and size of diameter d in one and the same moment of time are not correlated. Then the second member in (B7) equals to the zero. So, finally

$$\langle d^2 \rangle_\omega = d^2(0) \cdot \delta(\omega)$$

VII. Appendix C

Reflectivity coefficient (relation of Fresnel of electromagnetic radiation for the normal incidence on interface)

$$R = \left|\frac{\sqrt{\varepsilon} - 1}{\sqrt{\varepsilon} + 1}\right|^2 = \left|\frac{n - j \cdot k - 1}{n + j \cdot k + 1}\right|^2 = \frac{(n-1)^2 + k^2}{(n+1)^2 + k^2}$$

$$\varepsilon^{\frac{1}{2}} = n - j \cdot k$$

$$n = \left\{\frac{1}{2} \cdot \left[\varepsilon_1 + (\varepsilon_1^2 + \varepsilon_2^2)^{\frac{1}{2}}\right]\right\}^{\frac{1}{2}}$$

$$k = \left\{\frac{1}{2}\cdot(\varepsilon_1^2+\varepsilon_2^2)^{\frac{1}{2}}-\varepsilon_1\right\}^{\frac{1}{2}}$$

$$\varepsilon = \varepsilon_1 + j\cdot\varepsilon_2 = 1-\frac{\omega_p^2}{\omega^2+\nu^2}+j\cdot\frac{\omega_p^2\nu}{(\omega^2+\nu^2)\cdot\omega} =$$

$$= 1-\frac{\omega_p^2\cdot\omega - j\omega_p^2\cdot\nu}{(\omega^2+\nu^2)\cdot\omega} = 1-\frac{\omega_p^2\cdot(\omega-j\nu)}{(\omega+j\nu)\cdot(\omega-j\nu)\cdot\omega} = 1-\frac{\omega_p^2}{\omega\cdot(\omega+j\nu)}$$

$$\varepsilon_2 = 4\pi\cdot\alpha_2$$

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