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On Probe Measurements of Plasma Parameters in Ion Metal Vapor Lasers

by

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Summary. The specific features resulting from the presence of the electron-neutral and ion-neutral collisions in ion metal-vapor lasers are discussed in detail. The resulting criteria for the probe dimensions are presented. A method of interpretation of results is described which allows to calculate the electron density without the laborious iteration procedure.

List of regular symbols

D — discharge tube diameter,
e — electron charge,
I_i — ion current,
I_{io} — random thermal current,
k — Boltzmann constant,
l_p — probe length,
m_i, m_e — ion and electron mass,
n — electron number density,
p — neutral gas pressure,
r_p — probe radius,
$r_p x_0$ — sheath radius,
$s = r_p (x_0 - 1)$ — sheath thickness,
V_p — probe potential,
$V_e = \frac{kT_e}{e}$ — electron temperature,
x_0 — normalized sheath radius
λ_D — Debye length,
λ_i — ion mean free path,
μ_i — ion mobility.

Subscripts

1, 2 — numerical designation for double-probe electrodes,
e — electron,
i — ion,
p — probe.

1. Introduction. In recent years considerable amount of work has been done [1—6] in application of the cylindrical probe technique to measurements of plasma parameters in ion metal-vapor lasers (e.g. the $He\text{-}Cd^+$, $He\text{-}Se^+$, $He\text{-}J_2$ lasers). Nevertheless there is a lack of a general analysis of the factors involved. This concerns both the theoretical principles and the experimental technique of such measurements.

The conditions existing in ion metal-vapor lasers cause some difficulties in probe measurements. On the other hand, application of the probe technique is impelled by its indisputable advantages, first of all simplicity of the equipment and procedure.

In ion metal-vapor lasers the optimal conditions for laser operation are defined as

$$(pD)_{\text{opt}} = \text{const}. \tag{1}$$

The constant (1) depends on the kind of gas and of metal vapor used. Typical values of the total pressure p and the plasma diameter D are few torr and few millimetres, respectively. It means that the mean free parts of electrons and ions are comparable to the radius of cylindrical probe. Also the transversal dimensions of a plasma column are comparable to the probe length. These are the reasons that the electron-neutral and ion-neutral collisions and also the spatial nonuniformity of plasma have to be taken into account.

It is the purpose of the present work to discuss the specific features of probe measurements resulting from the factors mentioned above. The conclusions important for preparation of an experiment and for interpretation of its results are pointed out.

There exist additional difficulties in the probe measurements performed on plasma of ion metal-vapor lasers. They are connected mainly with the presence of metal vapors in the laser tube. These will not be discussed in this note.

2. Effect of ion collisions on probe measurements. The following measured data are required to determine an electron temperature and density from the probe measurements. For a single probe: the slope of the lin-log characteristic in the electron retarding region and the saturation ion current. For a floating double probe: the slope of lin-lin characteristic in the point of zero probe current and the value of saturation ion currents.

As shown by Talbot *et al.* [8, 9] the electron current to a probe is strongly affected by the presence of even scarce collisions in plasma. Therefore, the measurements with a single probe no longer yield the correct value of the electron temperature in our case. On the other hand, the value of the electron temperature determined from the double probe characteristic remains to all intentions and purposes unaffected by the presence of collisions.

The saturation ion current depends strongly on collisions. There exists a recognized theory of Talbot *et al.* [8] of the ion collection by probe in the presence of collisions. It covers the entire range of λ_i/λ_D and r_p/λ_D and predicts a monotonic decrease of probe current with growing r_p/λ_D or r_p/λ_i. However, the recent measurement by the authors [7] indicates an occurrence of a well pronounced resonance effect in ion collection by a probe when the thickness of the space charge sheath surrounding the probe is comparable with the mean free path of ions ($\lambda_i \sim s$). The dependence of dimensionless ion current on λ_D/λ_i and r_p/λ_D postulated in [7] is shown in Fig. 1.

It follows from the above that the understanding of the mechanisms involved in ion collection in the transition regime of pressure is still vague and in a primitive state and the corresponding theory requires further development. Up to date, only in the low pressure limit ($\lambda_i \gg r_p, \lambda_D$) and in the continuum limit ($\lambda_i \ll r_p$) the theory of ion collection has been worked out in detail. The low pressure conditions required

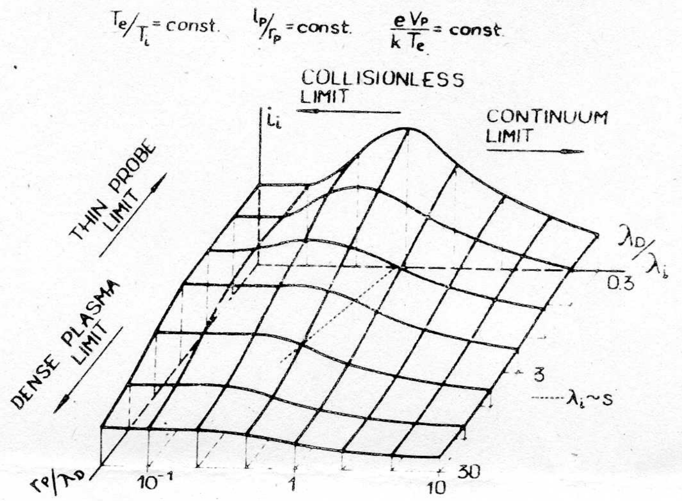

Fig. 1. The dimensionless ion saturation current as a function of r_p/λ_D and λ_D/λ_i

by the probe theory cannot be achieved in the plasma of ion metal-vapor lasers. Accordingly the only possibility of a reliable interpretation of probe measurements in such a plasma lies in the application of a floating double probe working in a continuum limit regime (i.e. "high pressure" limit $r_p \gg \lambda_i$) required by the probe theory).

3. Probe dimensions. In the conditions existing in the plasma of the laser discharge the continuum limit conditions may be achieved, if possible at all, only by a proper choice of the probe dimensions.

The probe in plasma is surrounded by a space charge sheath of external radius $x_0\, r_p$. Let us formulate the conditions for such a probe to have a cylindrical geometry and to work in the continuum limit regime, in the following form

(2)
$$l_p = k_1\, x_0\, r_p, \qquad k_1 \gg 1,$$
$$x_0\, r_p = k_2\, \lambda_i, \qquad k_2 \gg 1.$$

Another condition is required because of the nonuniformity of the radial distribution of the electron density:

(3)
$$\alpha \cdot l_p = D, \qquad \alpha \gtrsim 4.$$

Here the value of α has been limited taking into account that a substantial change of electron density along the probe can disturb the shape of the sheath and lead to a misinterpretation of the results.

Then the condition (1) can be written as

$$(pD)_{opt}=\frac{\lambda_{i1}}{\lambda_i}\cdot D, \tag{4}$$

where $\lambda_{i1}=p\lambda_i$ is the mean free path of ion at the pressure of 1 Torr, depending only on the kind of gas.

It follows from (2)—(4) that

$$k_1\cdot k_2=\frac{(pD)_{opt}}{\alpha\cdot\lambda_{i1}}=\frac{l_p}{\lambda_i}. \tag{5}$$

The value of the product $k_1\cdot k_2$ determines the field of possibilities in fulfiling the conditions (2). For example in the He-Cd^+ laser $(pD)_{opt}\sim 10$ Torr$\cdot$mm and $\lambda_{i1}\sim 5\cdot 10^{-2}$ mm. This corresponds to $k_1\cdot k_2$ not higher than 50.

The presented analysis shows how severely limited is the choice of the probe dimensions in most of the practical cases. It also indicates the necessity of extremely careful planning of the experimental arrangement. Worse still, the compromise in fulfilling simultaneously the two conditions (2) probably cannot be avoided in a typical case.

4. Interpretation of results. The formula for calculating the electron temperature from the double probe measurements obtained by Kirchhoff *et al.* [9] can be written in a more convenient form

$$V_e=\frac{kT_e}{e}=\frac{I_{i1}I_{i2}}{I_{i1}+I_{i2}}\left(\frac{dI_{12}}{dV_{12}}\right)^{-1}(1+\sigma)\Bigg|_{I_{12}=0}, \tag{6}$$

where I_{i1} and I_{i2} denote the saturation ion currents, I_{12} — current in the double probe circuit and V_{12} — potential difference between probes.

This formula differs from that used in collisionless regime only by the presence of $(1+\sigma)$. However, as shown in [9], the correction factor σ is small and a conventional double probe procedure can be used for determination of electron temperature in the ion metal-vapor laser plasmas. This procedure is identical as described for example in [10] and will not be discussed here.

The electron density can be calculated from the magnitude of the ion saturation current using the measured value of electron temperature.

The normalized continuum-limit ion current to a probe is [8, 9]:

$$\frac{I_i}{I_{i0}}=\lambda_i/r_p(1+\tau)\ln^{-1}(l_p/r_p x_0), \tag{7}$$

where $I_{i0}=2\pi en\,(eV_i/2\pi m_i)^{1/2}\,r_p\cdot l_p$ is the random thermal current and $\tau=V_e/V_i$.

The normalized sheath radius x_0 may be [9] determined from

$$|V_p/V_e|\cdot\beta^{-1/2}=f(x_0), \tag{8}$$

where

$$\beta=(1+\tau)/\tau(r_p/\lambda_D)^2\ln^{-1}(l_p/x_0 r_p)$$

and

(9) $$f(x_0)=x_0 \ln[(x_0^2-1)^{1/2}+x_0]-(x_0^2-1)^{1/2}.$$

If we take into account that $\lambda_i=\dfrac{4\mu_i V_i}{\bar{v}_i}$ and that in the laser plasma $V_e \gg V_i$ $(\tau \gg 1)$, the (7) and (8) become, respectively,

(10) $$I_i=2\pi e n l_p \mu_i V_e [\ln(l_p/x_0 r_p)]^{-1},$$

and

(11) $$|V_p/V_e|=r_p/\lambda_D \cdot [\ln(l_p/x_0 r_p)]^{-\frac{1}{2}} \cdot f(x_0).$$

Both I_i and x_0 are functions of electron density through their dependence on r_p/λ_D. Therefore in all hitherto published works on this subject, an iteration procedure was required to determine the electron density.

Here we will show, for the first time, that the laborious iteration procedure can be omitted. For this purpose (11) may be written as

(12) $$|V_p/V_e|=\gamma^{1/2} \cdot f(x_0),$$

where

(13) $$\gamma=\left(\frac{r_p}{\lambda_D}\right)^2 [\ln(l_p/x_0 r_p)]^{-1}.$$

It may be shown, using (10) and (13), that

(14) $$\gamma=I_i r_p^2 (2\pi\varepsilon_0 \mu_i l_p V_e^2)^{-1}$$

and it depends only on the parameters measured or known beforehand. Now, for a fixed probe to plasma potential V_p, Eq. (12) may be directly solved and x_0 calculated. An example of such a solution for $V_p=-15 V_e$ is shown in Fig. 2.

The procedure of the experiment and the interpretation of the results is as follows. First the double probe characteristic is measured and the electron temperature computed in the conventional way. Then the ion current to the highly negative probe ($|V_{12}| \gg V_e$) is determined. In this case the probe to plasma potential is approximately equal*) to $V_p \cong -|V_{12}|-5V_e$.

Next the γ is calculated and x_0 determined from a diagram as shown in Fig. 2. This makes it possible to calculate the electron density directly without iteration. It is convenient to use the formulas (10) and (14) in the following form

(15) $$\gamma=180 \cdot \frac{r_p^2 p I_i}{V_e^2 \mu_{io} l_p},$$

(16) $$n=10^{16} V_e^{-1} \frac{I_i p}{l_p \mu_{io}} \ln \frac{l_p}{r_p x_0},$$

where the units used are μm, V, Tr, cm² Tr/V sec mA/mm, cm^{-3}.

*) The other probe is nearly at the floating potential. For the present purposes the difference between the plasma and floating potential may by considered [9] as constant and equal to $(-5V_e)$.

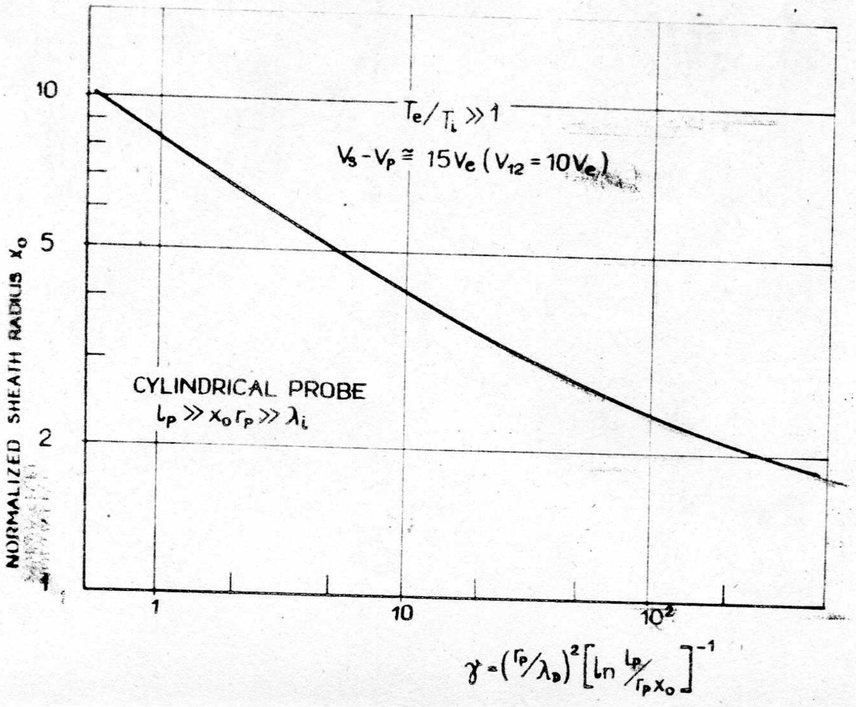

Fig. 2. Normalized sheath radius as a function of the parameter γ

5. Conclusions. The presence of collisions of the charged particles with the neutrals in the ion metal-vapor lasers imposes a certain critical limitation on the probe measurements of plasma parameters. These measurements may be carried out using only the floating double probe working in the continuum limit regime.

The proper choice of the dimensions of the probe is essential for meeting the above stated conditions. The appropriate criterium has been presented in the paper. Unfortunately, the possibility of an exact executing of this criterion is limited in practice. A compromise has to be sought for in a typical case.

A method of calculation of the electron density which does not require any kind of a laborious iteration procedure has been described in this note for the first time in the literature on the subject.

The results presented here have been applied by the authors [6] in the measurement of the parameters of a plasma in He-Cd^+ laser.

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Т. Копичыньски, Е. Мизерачик, З. Закшевски, **Об измерении параметров плазмы в лазере на парах металлов**

Содержание. В работе обсуждены специфижеские условия вытекающие из существования соударений электронов и ионов с неитральными частицами для случая зондовых измерений в лазере на смеси гелия и паров металлов. Определены критерии относительно размеров зондов. Описан метод истолкования результатов измерений позволяющий определить концентрацию электронов без применения трудоемкого итерационного приема.