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# USE OF A CHARGE-EXCHANGE PROCESS IN SPECTRAL DIAGNOSTICS OF PLASMA STREAMS

**Yu. P. Zakharov, O. M. Orishich,
V. N. Snytnikov, and I. F. Shaikhislamov**

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Currently both in actual experiments for injection of plasma into space around the earth [1] and in the corresponding model laboratory tests [2, 3] there is extensive use of optical diagnostics.

However known optical methods based on recording the natural luminescence of a plasma are used in these experiments only for qualitative analysis and sometimes they may lead to erroneous conclusions (see below). This is connected with the fact that in a nonsteady-state plasma excitation of ions is not in equilibrium and it is governed by processes of recombination or electron shock and it depends strongly on a parameter which is difficult to determine such as electron temperature.

In [4] a study was made by experiment under conditions typical for modelling explosive astrophysical processes of a charge-exchange mechanism for exciting the luminescence of individual lines of multicharged laser plasma ions. Charge-exchange excitation was accomplished in a neutral gas admitted into a vacuum chamber.

In the present work on the basis of the results of these studies a new method is suggested for measuring the distribution of plasma stream ion concentration by recording the luminescence of lines excited during charge-exchange. Use of the new method is described in experiments for modelling the interaction of a rapidly expanding plasma cloud with a magnetic field. For comparison data are provided which were obtained in recording the natural luminescence of a plasma excited during recombination.

The experimental data presented are given from the point of view of demonstrating the possibility of the new optical diagnostic method. More complete description of the results from a physical point of view and their analysis is not the aim of the present work.

**Theoretical Model.** We consider for simplicity a freely expanding spherical plasma cloud created for example by action of laser radiation on a small target [4]. As will be seen, the results are easily generalized for the case of plasma streams with other geometry.

It is well known that the bright-line luminescence of this plasma expanding in a vacuum has a purely recombination character. With admission of the background gas (on condition that the length of the elastic collision between the plasma and the gas is much greater than the size of the region observed) due to the charge-exchange reaction luminescence develops connected with charge-exchange excitation of ions:

$$C^{i+1} + H_2 \to C^i_{\text{air}} + H_2^+ \to C^i + H_2^+ + \gamma.$$

Here i is ion charge; $H_2$ (molecular hydrogen) is background gas used in the experiments; $\gamma$ is light quantum.

Lines of ion i with a principal quantum number n = 1 + 1 show the greatest sensitivity of the charge-exchange [5, 6]. The dependence of luminescence for these lines on gas pressure was studied in [4]. Shown in Fig. 1 as an example is this dependence for line 580.1 nm of ion $C^{+3}$ with a distance to the target of 2 cm. Areas are marked for predominance of recombination luminescence 1 and charge-exchange luminescence 2.

The equations which describe the charge-exchange interaction and luminescence of a laser plasma with background gas have the form

$$\partial n_i/\partial t + \operatorname{div} n_i \mathbf{v} = -n_i(n_* \sigma_i v + 1/\tau_r^i) + n_{i+1}(n_* \sigma_{i+1} v + 1/\tau_r^{i+1}),$$

$$\partial n_*/\partial t = -n_* \sum_i n_i \sigma_i v, \quad J_i \sim n_{i+1}(n_* \sigma_{i+1} v + 1/\tau_r^{i+1}),$$

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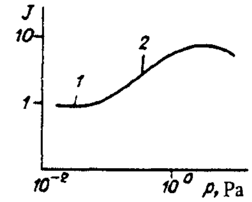


Fig. 1

where $n_*$ is background concentration; $n_i$ is the concentration of ions of charge i; $\sigma_i$ is charge-exchange luminescence; $\tau_r^i$ is recombination time for an ion of charge i into 1 − 1; v is local velocity of cloud ions; $J_i$ is luminescence intensity for ion lines. It is assumed that the luminescence for excited ions is much less than other characteristic times.

We shall assume that $n_*\sigma_i v \gg 1/\tau_r'$ and recombination may be ignored. We also assume that $n_i \gg n_{i+1}$, which is true for highly charged ions. Then the equations have the form of solutions:

$$n_i = n_i^0(R, t) \exp[-X_i],\ X_i = \int_0^t n_*(R(t),t)\sigma_i v dt,$$

$$n_* = n_*^0 \exp[-Y],\ Y = \int_0^t \sum_i n_i(R, t)\sigma_i v dt,$$

$$J_{i-1} \sim n_*^0 n_i^0(R, t)\sigma_i v \exp[-Y - X_i].$$

Here $n_i^0(R, t)$ is the distribution of the concentration of ions in the absence of background (values sought); $n_*^0$ is concentration of the background in the absence of a cloud; the integral for $X_i$ is taken along the trajectory for movement of a cloud element; R is distance from the point of explosion; t is observation time.

For the indices of exponents $X_i$ and Y it is possible to provide limiting estimates: $X_i \leq n_*^0\sigma_i R \equiv R/\lambda_i$ ($\lambda_i$ is charge-exchange length for ion i), $Y \leq (R_c/R)^2$, $R_c = \sqrt{\sum_i N_i^0\sigma_i}$ ($N_i^0$ is the total number of ions i of the cloud flying through the point of observation in a single solid angle).

As can be seen, excitation of cloud ions due to charge-exchange occurs at distances $R \gtrsim \lambda_i$ and excitation of the background occurs at $R \lesssim R_c$. Therefore with $R_c \ll \lambda_i$ these inequalities for $X_i$ and Y tend towards equality.

Thus, in approximating $R_c \ll \lambda$ for luminescence we have

$$J_{i-1}(R, t) \sim n_i^0(R, t)\sigma_i v \exp[-(R_c/R)^2 - R/\lambda_i].$$

As a result of this for the ion concentration sought we obtain

$$n_i^0(R, t) \sim (J_{i-1}(R, t)/\sigma_i v) \exp[(R_c/R)^2 + R/\lambda_i]. \tag{1}$$

In the space interval $R_c < R \ll \lambda_i$ a simple relationship is fulfilled

$$n_i^0(R, t) \sim J_{i-1}(R, t)/\sigma_i v.$$

Thus, luminescence of a plasma in lines excited predominantly during charge-exchange give the relative spatial distribution of ion concentration. A change-over to absolute requires calibration of luminescence by comparison with data by comparison with data obtained by other measurement methods.

In addition comparison of recombination and charge-exchange luminescence of an ion line makes it possible to obtain the relative distribution of the value $f = n_e^2/T_e^{0/2}$ in a plasma. For the ion $C^{+4}$ used in this work recombination will be three-piece with recombination time $\tau_r^i \sim T_e^{0/2}/n_e^2$. Assuming that with admission of the gas charge-exchange excitation of the line is much greater than recombination excitation, we obtain

$$f \sim J_0/J_r, \tag{2}$$

where $J_0$ is the luminescence without admitting gas; $J_g$ is luminescent with gas.

**Experimental Scheme.** Tests were performed in a KI-1 unit in a chamber with length 5 m and diameter 1.2 m [7] in a uniform magnetic field $B_0 \leq 0.06$ T. In order to generate a plasma cloud a $CO_2$-amplifier was used generating a bell-shaped

TABLE 1

| Fig. No. | Gas | Filter | $B_0$, T | Scale | $t$, μsec |
|---|---|---|---|---|---|
| 3, a | – | – | 0 | 1 : 24 | 1,65 |
| 3, b | + | + | 0 | 1 : 24 | 1,65 |
| 3, c | – | – | 0,01 | 1 : 24 | 1,65 |
| 3, d | + | + | 0,01 | 1 : 24 | 1,65 |
| 4, a | – | – | 0,01 | 1 : 48 | 3,2 |
| 4, b | + | + | 0,01 | 1 : 48 | 3,2 |
| 5, a | – | – | 0,062 | 1 : 10 | 3 |
| 5, b | + | – | 0,062 | 1 : 10 | 3 |
| 5, c | + | + | 0,062 | 1 : 10 | 3 |

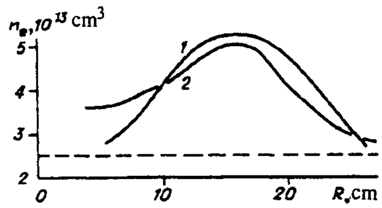


Fig. 2

pulse with a half-height width of 100 nsec. A caprolon ($C_6H_{11}ON$) spherical tablet 5 mm in diameter was used as the target. With excitation of the target from two opposite directions by radiation beams focused on a spot 7 mm in diameter a plasma cloud close to spherical was created with a total number of particles N in the range $(0.8\text{-}2)\cdot 10^{17}$ and with a characteristic front expansion velocity $v = (1\text{-}2)\cdot 10^7$ cm/sec [8].

According to ion flight-time mass analyzer data [9] the laser plasma consisted of protons ($\approx 50\%$), carbon ions $C^{+4}$ ($\approx 40\%$), and ions $C^{+1}$, $C^{+2}$, $C^{+3}$ ($\approx 10\%$). The main energy of the cloud ($\approx 80\%$) and discharge was concentrated in a layer of $C^{+4}$ ions and low-discharge ions formed a slowly moving stream ($v \leq (3\text{-}6)\cdot 10^6$ cm/sec). About 20% of the cloud energy arrived in the proton precursor ($v = 2\cdot 10^7$ cm/sec).

In order to record plasma luminescence an electron-optical converter was used operating in a frame mode with an exposure duration of 50 nsec and with a special resolution of 0.5 cm. The required spectral interval was separated by an interference filter. The conformity of the filter transmission range for the plasma luminescence line observed was studied in a separate test using a monochromator with photoelectric recording.

Control measurements of plasma concentration were performed by Langmuir double electric probes and the structure of the magnetic field excited was studied by screened magnetic probes [10].

Plasma luminescence was recorded either in the spectral range $\Delta\lambda = 300\text{-}690$ nm determined by the sensitivity of the image converter tube photocathode or by using a filter for line 580.1 nm ($\Delta\lambda = 5$ nm) for ion $C^{+3}$. This line is excited to the maximum with charge-exchange of ion $C^{+4}$ by $H_2$ with a charge-exchange section $\sigma = (3\text{-}6)\cdot 10^{-15}$ cm$^2$ [6]. The residual gas pressure in the chamber is $3\cdot 10^{-4}$ Pa. For charge-exchange excitation hydrogen was admitted to a pressure of $p = (1\text{-}3)\cdot 10^{-2}$ Pa.

From the experimental parameters it follows that $R_c = \sqrt{N\sigma/4\pi} \lesssim 5$ cm, $\lambda = 1/n_*\sigma \gtrsim 25$ cm, i.e. the condition $R_c \ll \lambda$ is fulfilled. Four types of plasma luminescence were recorded: $J_0$ is luminescence without admitting gas and using a filter, i.e. plasma recombination luminescence, $J_f$ is luminescence without gas and with a filter, i.e. recombination luminescence of ion $C^{+3}$ line, $J_g$ is luminescence with admission of gas and without a filter, $J_{g.f}$ is luminescence with gas and a filter, i.e., charge-exchange luminescence of the $C^{+3}$ ion line.

Gas pressure was selected in order to fulfil the condition

$$J_{g.f}/J_f \gg 1. \tag{3}$$

In the experiments performed this relationship was not less than ten. It is necessary to note that close to the target recombination always predominates. In the data provided this region had the dimensions $R \leq 3\text{-}4$ cm and it comprised a negligibly small part of the total plasma volume.

**Procedure for Treating Experimental Data.** From the photographs obtained it is necessary to restore the true spatial distribution of plasma luminescence. An Abelization procedure was used for objects close to axisymmetrical.

Absolute calibration of Eq. (1) was carried out for the integral characteristic, i.e. the total number N of $C^{+4}$ ions in the cloud which was found from probe and mass spectroscopic measurements.

Shown for comparison in Fig. 2 is the distribution over the radius of the concentration of electron $n_e$ in the cloud measured by a probe (curve 1) and calculated by the method described above from photographic data (curve 2). The cloud expands in a background hydrogen plasma with addition of a neutral component and in an external uniform magnetic field of 0.01 T. The concentration of the background plasma is shown by a broken line. The measurement time was 2 $\mu$sec.

Measurement errors inherent for this method are determined by the extent that inequality (3) and Eq. (1) are fulfilled. The relative error may be written as

$$\delta = O(J_f / J_{g\,f}) + O(R_c/\lambda).$$

In these experiments this value was 15-20%. The condition of quanta self-absorption for line 580.1 nm of ion $C^{+3}$ has the form $n_c{}^{+3} \geq 3 \cdot 10^{15}$ cm, 1/cm$^3$ [11]. In our case the expanding plasma became optically thin in time 0.2-0.25 $\mu$sec.

**Experimental Results.** Experimental conditions are given in Table 1 with which the photographs in Figs. 3-5 were obtained. The presence or absence of a neutral gas and filter, the magnitude of the magnetic field in the chamber, the photographic scale, and photography time are given.

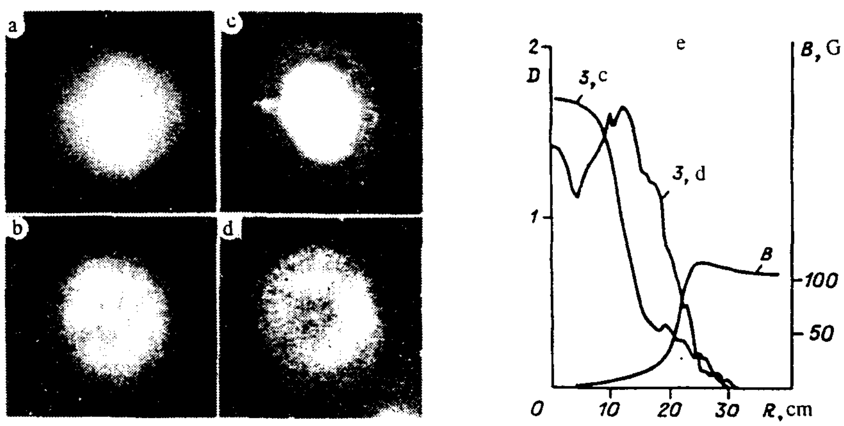


Fig. 3

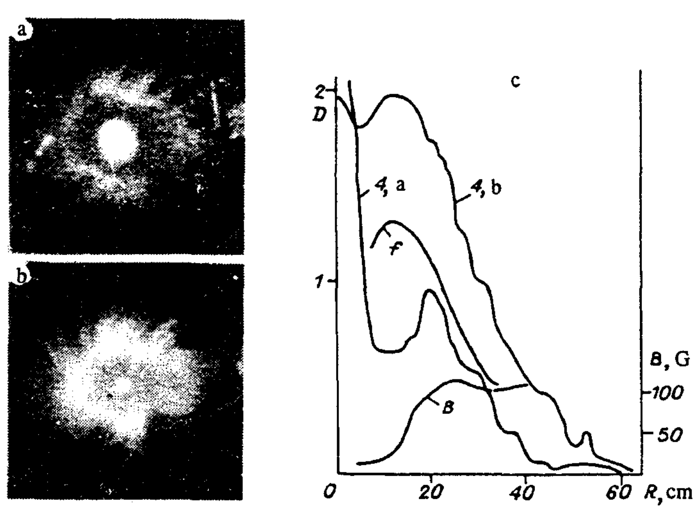


Fig. 4

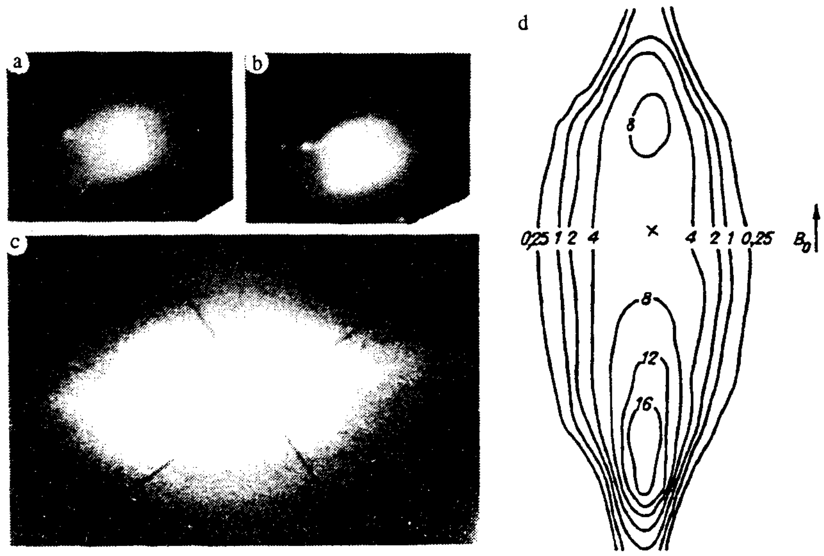


Fig. 5

In Figs. 3 and 4 the magnetic field is directed perpendicular to the plane of the picture, and in Fig. 5 it is in parallel. Given for comparison in Figs. 3e and 4c are curves for the density D of photographic films in one direction from the target. Curves are labelled with the numbers of photographs corresponding to them. Profiles of the magnetic field at the same instant of time are also shown.

**Discussion of Results.** In preceding experiments [2, 12] it was established that the main parameter governing the interaction regime for a spherical cloud with a uniform magnetic field $B_0$ is $\varepsilon_B = R_H/R_B$, where $R_H = v_0Mc/ZeB_0$ is the Larmor radius of ions with mass M, charge Z, and velocity $v_0$, and $R_B = (3E_0/B_0^2)^{1/3}$ is the classical radius [13] for a cloud with initial energy $E_0$ retarded by a field.

The effect of a magnetic field on the natural luminescence of a plasma has been studied by experiment in [4, 14]. It was shown in [4] that recombination luminescence of a plasma decreases on switching on a field. This is connected with the fact that due to plasma interaction with the field in the current layer there is heating of electrons which leads to a reduction in recombination rate.

The nature of plasma cloud interaction with a magnetic field with $\varepsilon_B \gtrsim 1$ is illustrated in Figs. 3 and 4. In this experiment $R_B \approx 30$ cm, $R_H \approx 45$ cm, and the characteristic time $t_B = R_B/v_0 = 2$ $\mu$sec. In this regime [15] in the initial stage of expansion the cloud expels the field from its volume and forms a magnetic cavern with radius $R_B/2$. Then as expansion proceeds there is development of channelled instability for the cloud boundary and anomalously rapid penetration of the field into the plasma. Here the plasma by not experiencing marked retardation spreads perpendicular to $B_0$ in the form of a jet up to the extent $R_H$.

The early stage of cloud expansion is illustrated in Fig. 3. Figure 3b and d show that the distribution of charge-exchange luminescence, which reflects plasma concentration, is almost unaffected by a magnetic field with $t = 1.65$ $\mu$sec $< t_B$. In contrast to this the natural luminescence of a plasma changes sharply on switching on the field (Fig. 3a, b). It can be seen from Fig. 3e that this luminescence decreases markedly in a cloud of gradient B, i.e. in the region of current passage.

The latter stage of interaction is shown in Fig. 4 where a developed channelled structure is shown. It can be seen from Fig. 4c that natural recombination luminescence of a plasma the same as with small t is caused by the temperature of electrons in the cloud, i.e. luminescence is suppressed at the front and has a minimum in the region of current passage. In contrast, charge-exchange luminescence shows weak retardation of the front and has a maximum at the boundary of the cavern, which points to contraction of the plasma by a magnetic field with $t \gtrsim t_B$. The profile of the relative electron temperature calculated by Eq. (2) is also plotted in Fig. 4c.

With $\varepsilon_B \lesssim 1$ the plasma experiences marked retardation [2, 12] and in times $t \geq r_B$ close to gas dynamic flow forms with preferred spreading along the magnetic field [16]. Results of an experiment under these conditions ($R_H \approx 7.3$ cm, $R_B \approx 8.9$ cm and $t_B \approx 0.6$ $\mu$sec) are presented in Fig. 5. It is clear that the plasma luminescence integral over the spectrum both without a gas and with it does not reflect the structure of the plasma since it is predominantly recombination in nature. Similar photographs of a plasma under analogous conditions were also obtained in [17]. Only charge-exchange luminescence obtained with admission of gas and use of a filter clearly show the detailed picture of flow in the form of a "bottle' with a narrow neck of the size of the order of $R_H$ directed along the magnetic field.

The structure of flow makes it possible to carry out the quantitative treatment procedure described above. Given in Fig. 5d are isolines for the concentration of $C^{+4}$ ions (in units of $10^{12}$ $cm^{-3}$) obtained from Fig. 5c. The cross shows the position of the target. The scale of the figure 1:10.

Thus, the experiments carried out showed that use of charge-exchange for exciting ions makes it possible to measure the distribution of ion concentration in plasma streams. The new procedure permits quantitative use of optical diagnostics for studying the dynamics of plasma streams in magnetic fields.

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## REFERENCES

1. P. A. Bernhardt, R. S. Roussel-Dupre, M. B. Pongratz, et al., "Observations and theory of the AMPTE magnetotail barium releases," J. Geophys. Res., **92**, No. A6, 5777-5795 (1987).
2. Yu. P. Zakharov, A. M. Orishich, and A. G. Ponamerenko, Laser Plasma and Laboratory Modelling of Non-Steady State Cosmic Processes [in Russian], ITPM SO AN SSSR, Novosibirsk (1988).
3. B. N. Ripin, C. K. Manka, T. A. Peyser, et al., "Laboratory laser-produced astrophysical-like plasmas," Laser and Particle Beams, **8**, No. 1/2, 183-190 (1990).
4. A. M. Orishich and I. F. Shaikhislamov, "Spectral diagnostics of a plasma spreading in a background gas and a magnetic field," Prikl. Mekh. Tekh. Fiz., No. 3, 13-19 (1992).
5. F. Bruiar and D. Mak-Gowen, Physics of Ion–Ion and Electron–Ion Collisions [Russian translation], Mir, Moscow (1986).
6. S. Takagi, S. Ohtani, K. Kadota, and J. Fugita, "Cross-section for one-electron capture by highly stripped ions of Be, B, C from $H_2$ and Ar below 10 keV," J. Phys. Soc. Jpn., **52**, No. 11 (1983).
7. L. B. Gevorkyan, A. M. Orishich, A. G. Ponamerenko, et al., "Development of methods for modelling some astrophysical phenomena in a laboratory experiment," in: Physical Gas Dynamics: Aerophysical Studies, No. 6 [in Russian], ITPM SO AN SSSR, Novosibirsk (1976), pp. 192-196.
8. A. A. Avdyeva, Yu. P. Zakharov, V. V. Maksimov, et al., "Creation of spherical clouds of a laser plasma by two-sided radiation," Prikl. Mekh. Tekh. Fiz., No. 6, 62-66 (1989).
9. V. M. Antonov, "Features of the diagnostics of the corpuscular composition parameters of intense laser plasma streams in a KI-1 unit," in: Powerful $CO_2$-Lasers for Plasma Experiments and Technology, A. G. Ponamerenko (ed.), ITPM SO AN SSSR, Novosibirsk (1986), pp. 117-124.
10. Yu. P. Zakharov, "Features of probe methods for studying the interaction of laser plasma streams with a magnetized background medium," in: Powerful $CO_2$-Lasers for Plasma Experiments and Technology, A. G. Ponamerenko (ed.), ITPM SO AN SSSR, Novosibirsk (1986), pp. 125-132.
11. S. Yu. Luk'yanov, Plasma Diagnostics, No. 3 [in Russian], Atomizdat, Moscow (1973).
12. Yu. P. Zakharov, A. M. Orishich, A. G. Ponamerenko, and V. G. Posukh, "Experimental study of the effectiveness of retarding and expanding diamagnetic plasma cloud by a magnetic field," Fizika, Plazmy, **12**, No. 10, 1170-1177 (1986).
13. Yu. P. Raizer, "Expansion and changes of the energy of a plasma expanding in empty space in which there is a magnetic field," Prikl. Mekh. Tekh. Fiz., No. 6, 19-28 (1963).
14. K. D. Bonin and T. G. Mason, "Changing fluorescence in a streaming barium plasma due to an axial magnetic field," Phys. Rev. A, **43**, No. 6, 3005-3014 (1991).
15. Yu. P. Zakharov, A. M. Orishich, A. G. Ponamerenko, and I. F. Shaikhislamov, "Electron heating under conditions of anomalous penetration of the magnetic field into expanding plasma blobs," 10th Europe School on Plasma Physics, Tbilisi (1990); Paper Singapore: World Sci., **8**, 184-202 (1991).
16. S. Sudo, K. N. Sato, and T. Sekiguchi, "Re-thermalization and flow of laser-produced plasmas in a uniform magnetic field," J. Phys. D: Appl. Phys., **11**, 389-407 (1978).
17. R. G. Tuckfield and F. Schwirzke, "Dynamics of a laser created plasma expanding in a magnetic field," Plasma Phys., **11**, No. 1, 11-18 (1969).