NOTATION

τ, transfer of the target component; $y = Hz/K$, H, K, coefficient of the transfer equation $y_e = HL/K$; L, height of the column; $\varkappa_e = \sigma_e/H$, $\varkappa_i = \sigma_i/H$, σ_e, σ_i, samples at the positive and negative ends of the column; z, vertical coordinate; c', c", c_0, concentrations in the concentrating and stripping parts of the column and in the input flow, respectively; $\sigma_0 = \sigma_e + \sigma_i$; q_e, q_i, degrees of separation in the concentrating and stripping parts of the column; y_0, dimensionless coordinate of the feedpoint of the mixture being separated. Subscripts: opt, optimal; e, i, value of y at the positive and negative ends of the column.

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EMISSION OF AN EXPANDING PLASMOID

V. I. Derzhiev, V. S. Marchenko, and S. I. Yakovlenko

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The expansion of a radiating plasmoid into a vacuum is examined. It is shown that with an external energy input of $\sim 10^{12}$ W/cm^2 the bulk of the incident energy flux is lost as radiation.

In this paper we attempt an analytical investigation of the steady-state expansion of a plasmoid into a vacuum [1] with due regard to the loss from the plasma due to radiation. A relation between the emitted power and the plasma parameters is found. The dynamics of expansion of the plasmoid is considered. Approximate equations for estimation of the radiative loss and the plasma parameters in the case of a power-law time dependence of the energy input are obtained. Calculations show that the emission can greatly affect the expansion dynamics. A comparison is made with known experiments on the interaction of high-current electron beams with a target.

Emission of Plasmoid. We consider the bremsstrahlung, recombination, and line emission of the plasma. The assessment of reabsorption in the plasma is rather difficult and requires consideration of the contribution of many levels for different ions. In a rough approximation, we confine ourselves to estimates for an average ion $k \sim k_{av}$, and we will ignore reabsorption of bremsstrahlung and recombination radiation in the target plasma.

Bremsstrahlung. We evaluate the emission intensity from the equation [2]

$$Q_e^{\mathrm{brem}} = 1.54 \cdot 10^{-25} N_e T_e^{1/2} k_{\mathrm{eff}} N \ [\mathrm{erg/cm^3 \cdot sec}].$$

V. I. Vernadskii Institute of Geochemistry and Analytical Chemistry. Academy of Sciences of the USSR. I. V. Kurchatov Institute of Atomic Energy.

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Here $k_{eff} = n_0\sqrt{J_k/Ry}$ is the effective ion charge; Ry = 13.6 eV; n_0 is the principal quantum number of the ion. Using this relation and (5) [1], we have for the average ion

$$Q_e^{\text{brem}} \simeq 1.8\cdot 10^{-25} \sqrt{\frac{2}{A}}\, n_0^2 N^2 T_e^2 . \tag{1}$$

Photorecombination Emission. In the Kramers approximation, taking into account recombination of the average ion only to the ground state, we obtain [2]:

$$Q_e^{\text{p}} = 2.1\cdot 10^{-24} N_e T_e^{-1/2} N \frac{\mu_{n_0}}{n_0} \frac{J_k^2}{R_y^2} \;\; [\text{erg/cm}^3\cdot\text{sec}],$$

where μ_{n_0} is the number of vacancies in the main shell, and putting $\mu_{n_0} \sim n_0^2$, we have

$$Q_e^{\text{p}} = 1.46\cdot 10^{-24} \sqrt{\frac{2}{A}}\, n_0 N^2 T_e^2 \cdot \tag{2}$$

Line Emission. To evaluate its intensity we need to know the populations of the ion levels with $n > n_0$. We confine ourselves to a consideration of the average ion $k \sim k_{av}$.

Let n^* be the principal quantum number of the level for which radiative transitions are comparable with collisional transitions. To evaluate n^* we use the equation [3]

$$N_e \sim 1.68\cdot 10^{16} (T_e/k^2)^{1/3} (k/n^*)^7. \tag{3}$$

For the average ion, using $k_{av}^2 = 8T_e/A$, we obtain

$$n^* \sim 0.2\cdot 10^3 k_{av}/N_e^{1/7}. \tag{3a}$$

For $Z \sim 80$, $k_{av} \sim 10$, $N_e \sim 10^{21}$ all levels with $n > n^* \sim 2$ are collisionally mixed. When $k_{av} << Z$ practically all the excited levels are populated in accordance with the Boltzmann law, i.e.,

$$N_n \sim \frac{n^2}{n_0^2} N \exp\left(-\frac{E_{nn_0}}{T_e}\right) \sim N \exp\left(-\frac{E_{nn_0}}{T_e}\right). \tag{4}$$

Here E_{nn_0} is the energy of the $n_0 \to n$ transition and we put $n \sim n_0$. The excited levels are regarded as hydrogenlike

$$E_n = Ryk^2/\tilde{n}^2, \tag{5}$$

where $\tilde{n} = n - \Delta$ is the effective principal quantum number; Δ is the Rydberg correction, averaged over l, but weakly dependent on n [2, p. 43]. For the estimates we put $E_{n_0} = -J\cdot k_{av} = -Ryk^2/(n_0 - \Delta)^2$, i.e., $\Delta \approx n_0 - \sqrt{Ry/A}$, for the particular target material (e.g., gold) $A \sim 1.5$–2, $\Delta \approx n_0 - 3 = 2$ and $\tilde{n}_0 = n_0 - 2 = 3$, i.e., $\tilde{n}_0 > n^* \sim 2$, and (4) is valid when $k_{av} < 10$, $N_e > 10^{21}$ cm^{-3}.

We estimate the intensity of line emission to the state n from the equation $Q_n^{\text{line}} = A_{n+1,n} N \exp(-E_{n,n+1}/T_e) E_{n,n+1}$. Using the Kramers formulas for the radiative transition probability $A_{n+1,n}$ and evaluating the transition energy $E_{n+1,n}$ from (5) we obtain for a gold target

$$Q_{n_0}^{\text{line}} = 3.2\cdot 10^{-5} N T_e^3, \;\; Q_{n_0+1}^{\text{line}} = 9\cdot 10^{-7} \left(\frac{2}{A}\right)^2 N T_e^3 . \tag{6}$$

The reabsorption of line emission greatly reduces its flow from the target. Taking into account Holtsmark line broadening for a gold target, we obtain the reduction factor for the emission intensity of the line $n_0 + 1 \to n_0$

$$k_n = \varkappa_n x \sim 1.7\cdot 10^{-3} N_0^{1/3} x^{2/3} . \tag{7}$$

We note that this gives a significantly underestimated value for nonhydrogenlike lines. In view of (7), for the emission intensity of the line $n_0 + 1 \to n_0$ we have

$$Q_{n_0}^{\text{line}} = 1.9\cdot 10^{-2} N_0^{2/3} T^3 x^{-5/3} . \tag{8}$$

A comparison of the intensities of the bremsstrahlung, photorecombination, and line emission shows that when $N >> 4\cdot 10^{19}$ cm^{-3} line emission can be neglected.

Estimates of the bremsstrahlung absorption length $l \sim \varkappa^{-1}$ in a gold target [4] show that $\varkappa x \sim 1$ even at the end of expansion, and reabsorption must be taken into account. We note that photorecombination emission quanta are also effectively absorbed by free electrons.

Thus, the use of Eqs. (1) and (2) gives an upper estimate of the radiative loss. The lower estimate of the radiative loss in the expansion of a plasmoid is determined on the assumption that all kinds of radiation are reabsorbed. In this case

$$q_{\text{rad}} = \sigma T^4, \tag{9}$$

where $\sigma = 10^{12}$ erg/cm^2•sec•eV^4 is the Stefan–Boltzmann constant.

Model of Expansion with Radiative Loss. We consider the plane expansion of a target under the action of bulk heat release. For quantities averaged over the cross section the laws of conservation of mass, momentum, and energy have the form

$$\mu N x = M_0,\ M_0 \frac{dv}{dt} = P,$$
$$\frac{d}{dt}\left(M_0 \frac{v^2}{2} + \tilde{E}_{\text{in}}\right) = q - q_{\text{rad}}, \tag{10}$$

where μ is the mass of the heavy particle; $M = \mu N x$; $M_0 = \mu N_0 x_0$; $\tilde{E}_{in} = E_{in}x$, surface density of internal energy; N, density of the target material; $q_{rad} = Q_{rad}x$, flux density of emission from the plasma; Q_{rad}, total radiative loss from unit volume; x, space coordinate; here we also put $\partial P/\partial x \approx P/x$.

Expansion with Volume Emission. We will solve Eqs. (10) by using the results of solution of the system with $q_{rad} = 0$ and $q = q_s t^s$ (this case is thoroughly analyzed in [1]).

We express the total intensity of photorecombination and bremsstrahlung emission in terms of the energy $\tilde{E}_{in}$ and the coordinate x. From (1) and (2) we have

$$q_{\text{rad}} = Q_1 \tilde{E}_{\text{in}}^{4/3}/x;\quad Q_1 = 3.2\cdot 10^{-11}\left(\frac{2}{A}\right)^{-1/6} n_0\,(1.8\,n_0 + 14.6)\,N_0^{2/3}. \tag{11}$$

Then the initial equations, analogous to (4.3) in [1], take the form

$$M_0 x\ddot{x} = 6\tilde{E}_{\text{in}}/25,$$
$$\frac{d}{dt}\left(\frac{1}{2} M_0 \dot{x}^2 + \tilde{E}_{\text{in}}\right) = q_s t^s - Q_1 \tilde{E}_{\text{in}}^{4/3}/x. \tag{12}$$

Substituting in these equations

$$\tilde{E}_{\text{in}} = \varepsilon_s t^{s+1},\ x = y_s t^{\frac{s+3}{2}}, \tag{13}$$

we obtain the relation

$$M_0 (s+1)(s+3)\, y_s^2 = 24\,\varepsilon_s/25,$$
$$(28s+34)\,\varepsilon_s/25 = q_s - Q_1 \frac{5}{2}\sqrt{\frac{(s+1)(s+3)}{6}}\, M_0^{1/2}\varepsilon_s^{5/6} t^{-\frac{s+1}{6}}. \tag{14}$$

The time dependence disappears only when s = –1, but in this case, as was indicated in [1], there are no steady-state solutions. Nevertheless, in the two practically important cases s = 0 and s = 1 the variation of the second term on the right side of (14) with time is very slow (as $t^{-1/6}$ and $t^{-1/3}$, respectively). Regarding the time dependence parametrically in these cases, we find

$$\varepsilon_s = 25\,q_s\Big/\left(28s + 34 + Q_1 \frac{125}{2}\sqrt{\frac{(s+1)(s+3)}{6}}\, M_0^{1/2}\varepsilon_s^{-1/6} t^{-\frac{s+1}{6}}\right). \tag{15}$$

In estimations from this equation t on the right side must be replaced by the characteristic pulse time.

Expansion with Reabsorption of Emission. We evaluate the radiative loss in this case by using the relation

$$\tilde{q}_{\text{rad}} = \sigma T^4 = Q_2 \tilde{E}_{\text{in}}^{8/3},\ Q_2 = 10^{41}\,(A/2)^{4/3}/\tilde{N}_0^{8/3}. \tag{16}$$

If we seek the solution in the form of (13), the equation analogous to (14) has the form

$$\frac{28\,s + 34}{25}\,\varepsilon_s = q_s - Q_2 \varepsilon_s^{8/3} t^{\frac{5s+8}{3}}. \tag{17}$$

The time dependence disappears if s = −8/5. However, as was shown earlier [1], when the energy input varies with time in this way there is no steady-state mode of expansion. It is apparent from (17) that in the most interesting case ($s \geqslant 0$) the rate of increase of radiative loss is very high, more rapid than $t^{8/3}$. Hence, in this case use use another approximate method of estimation, which can be called "instantaneous" inclusion of emission. In fact, at the start of expansion the emission can be neglected and, then, in a certain, narrow interval of time $t_1 - \tau_1/2 < t < t_1 + \tau_1/2$ (the size of the region $\tau_1 \ll \tau$ — the characteristic pulse time) the emission becomes comparable with the energy input and when $t < t_1$ practically all the energy input into the plasma is converted to thermal emission of the target. Accordingly, at the start of expansion, when $t < t_1$, we put in the zeroth approximation

$$\varepsilon_s^{(0)} = 25\, q_s/(28\, s + 34). \tag{18}$$

Then the characteristic time t_1 is obtained from the equality

$$q_s = Q_2 \varepsilon_s^{(0)} t^{\frac{5s+8}{3}} \quad \text{or} \quad t_1 = Q_2^{-\frac{3}{5s+8}} q_s^{-\frac{5}{5s+8}} \left(\frac{28s+34}{25}\right)^{\frac{5s+8}{8}}.$$

In view of (16), we have

$$t_\perp = 10^{-\frac{123}{5s+8}} \left(\frac{2}{A}\right)^{\frac{4}{5s+8}} \tilde{N}_0^{\frac{8}{5s+8}} q_s^{-\frac{5}{5s+8}} \left(\frac{28s+34}{25}\right)^{\frac{5s+8}{8}}. \tag{19}$$

If we assume now that in the expansion $\tilde{E}_{in} = \varepsilon_s t^{s+1}$ $\varepsilon_s = \varepsilon_s(t)$ is a slow function of time, we again arrive at (17), neglecting the terms with $\dot{\varepsilon}_s(t)$. Then, in a first approximation for $t < t_1$ we have

$$\varepsilon_s^{(1)} = \varepsilon_s^{(0)}[1 - (t/t_1)^{\frac{5s+8}{3}}]. \tag{20}$$

We can neglect $\dot{\varepsilon}_s^{(1)}(t)$ because of the small parameter $(t/t_1)^{(5s+8)/3}$ when $t < t_1$. In fact, if it is necessary to take the derivative of the function $\varepsilon_s^{(1)}(t)t^{\alpha}$, the error arising in this case $\sim(5s + 8)/3\alpha\cdot(t/t_1)^{(5s+8)/3} \ll 1$.

Thus, when $t > t_1$ almost the entire energy input is converted to emission, i.e., neglecting the left side of Eq. (17), and taking emission into account in the form (16), we obtain

$$q_s = Q_2 \varepsilon_s^{8/3} t^{\frac{5s+8}{3}}$$

or

$$\varepsilon_s(t > t_1) = (q_s/Q_2)^{3/8} t^{-\frac{5s+8}{8}} = \varepsilon_s^{(0)} (t_1/t)^{\frac{5s+8}{8}}. \tag{21}$$

Expression (21) is valid in quasisteady conditions, since an energy input that is constant or increasing in time ($s \geqslant 0$) will lead to some heating of the plasma to ensure a constant or increasing radiative energy loss, which implies some violation of the parametric expressions (21). Since a detailed knowledge of the behavior of $\varepsilon_s(t)$ in the narrow region of τ_1 close to t_1 is not so important, then we can conveniently approximate $\varepsilon_s(t)$ by a single equation which has the same asymptotic forms (20) and (21):

$$\varepsilon_s(t) = \varepsilon_s^{(0)} [1 + (t/t_1)^{\frac{5}{8}\frac{5s+8}{3}}]/[1 + (t/t_1)^{\frac{5}{8}\frac{5s+8}{3}} + (t/t_\perp)^{\frac{5s+8}{3}}]. \tag{22}$$

In view of (14) we also obtain

$$y_s(t) = \sqrt{\varepsilon_s(t)\, 24/25\, (s+1)(s+3)\, \tilde{M}_0}. \tag{23}$$

Relations (22) and (23) completely solve the problem of estimating all the parameters of an expanding plasma with reabsorption of emission and a prescribed energy input. We find the radiative loss fraction $\delta = \int_0^\tau q_{rad} dt / \int_0^\tau q_s t^s dt$ by integrating the last of relations (10) and taking (22) and (23) into account:

$$\delta = 1 - \frac{(s+1)(\tilde{E}_{in} + \tilde{M}_0 v^2/2)}{q_s t^{s+1}} = 1 - \frac{s + 1 + \frac{3}{25}(s+3)}{q_s} \varepsilon_s(\tau), \tag{24}$$

$$\delta = 1 - (t_1/\tau)^{\frac{5s+8}{8}}, \ \tau > t_1.$$

For a constant energy input s = 0

$$t_1 = Q_2^{-3/8} \tilde{q}_0^{-5/8} \frac{34}{25} \simeq 5.7 \cdot 10^{-16} \left(\frac{2}{A}\right)^{1/2} \tilde{N}_0 \tilde{q}_0^{-5/8}. \tag{25}$$

Discussion of Results. We obtain numerical estimates of the parameters of an expanding plasma corresponding to the different limiting cases considered. Let the energy input be independent of time, $s = 0$, $\tilde{q} = \text{const}$. We take values close to those obtained experimentally [5-7]: $\tilde{q} = 10^{12}$ W/cm^2, $x_0 = 5 \cdot 10^{-4}$ cm, $\mu = 2 \cdot 10^{-22}$ g (gold), $N(x = x_0) = 5 \cdot 10^{22}$ cm^{-3} (density of solid). Then $\tilde{N}_0 = 2.5 \cdot 10^{19}$ cm^{-2}, $\tilde{M}_0 = 5.3 \cdot 10^{-3}$ g/cm^2. We first consider expansion, neglecting radiative loss. From (4.7) and (4.11) of [1] we have: $\varepsilon_0 \approx 0.735$, $q_0 = 7.35 \cdot 10^{18}$ erg/cm^2•sec, $y_0 = \sqrt{4/17} \cdot \sqrt{\tilde{q}_0/\tilde{M}_0} \approx 2.13 \cdot 10^{10}$ cm/sec$^{3/2}$, $t_0 = (x_0/y_0)^{2/3} = 0.82$ nsec. Since the pulse action time $\tau \sim 10^{-7}$ sec $\gg t_0 \sim 1$ nsec, the expansion can be regarded as forced practically all the time. We find the parameters of the expanding plasma at the end of the REB pulse. When $t \sim \tau = 10^{-7}$ sec the plasma expansion velocity $v = (3/2) y_0 \tau^{3/2} \approx 10^7$ cm/sec, $T_e = 170$ eV, $x(\tau) = 0.7$ cm.

In the case of expansion with radiative loss and no reabsorption we find ε_s from (15) by solving this equation by iteration. For s = 0 in a first approximation we replace ε_0 by its value when radiation is ignored: $\varepsilon_0^{(0)} = (25/34) q_0$. As a result of the first iteration we obtain $\varepsilon_0^{(1)} \approx 2.3 \cdot 10^{-2}$, $q_0 \approx 2.3 \cdot 10^{17}$ erg/cm^2•sec, $y_0^{(1)} \approx 0.4\sqrt{2\varepsilon_0/\tilde{M}_0} \approx 3.7 \cdot 10^9$ cm/sec$^{3/2}$. The second iteration alters the result by a factor of not more than $(\varepsilon_0^{(0)}/(25/34) q_0)^{1/6} < 2$. A further increase in accuracy has no sense in view of the roughness of the model. Thus, when emission is taken into account the fraction of energy expended on expansion and on accumulation of internal energy is $\tilde{E}_{in}/\tilde{q} + \tilde{E}_{kin}/\tilde{q} \approx 2.3 + 1 \approx 3\%$. In this limiting case the bulk of the energy is transformed into bremsstrahlung and photorecombination emission. For the discussed parameters at the end of the pulse of the external source we obtain $x = y_0 \tau^{3/2} \approx 0.1$ cm, $v \approx 1.7 \cdot 10^6$ cm/sec, $T_e \approx (7.5 \cdot 10^{10} \varepsilon_0/\tilde{N}_0)^{2/3} = 17$ eV. Thus, the velocity and temperature are approximately ten times less than in the absence of emission. We note that in this region of parameters emission depends practically linearly on the value of (15), whose accuracy is known only to order of magnitude. In the case of complete reabsorption (24) and (25) lead to $t_1 \sim 2 \cdot 10^{-8}$ sec, i.e., for pulse length $\tau \sim 10^{-7}$ sec the radiative loss is ~80% (s = 0). The plasma parameters at the end of the pulse are $x \approx y_0(\tau) \tau^{3/2} \sim 0.3$ cm, $v \sim 3 \cdot 10^6$ cm/sec, $T \sim 55$ eV.

It is clear from the obtained estimates that the dynamics of expansion is determined primarily by the absorbed (q_0) and emitted (q_{rad}) energy fluxes. In view of the unreliability of theoretical data the values of q_0 and q_{rad} have to be determined from direct measurements. Since we know of no such direct experiments, we confine ourselves to a preliminary discussion.

Experiments with gold foil [5-7] showed that with a flux $\tilde{q} \sim 10^{12}$ W/cm^2 ($I \approx 160$ kA, $j \approx 2 \cdot 10^6$ A/cm^2, $E \approx 1$ meV) and initial thickness $x_0 \approx 5$ μm at the end of the pulse ($\tau \approx 10^{-7}$ sec) the velocity of expansion and the temperature have values $v \approx 1.6 \cdot 10^6$ cm/sec, T = 10 eV. As the above estimates indicate, when radiation is taken into account close values ($v \approx 1.7 \cdot 10^6$ cm/sec, $T \approx 17$ eV) are obtained if we assume that an appreciable part of the energy $q\chi q_0$ is absorbed in the foil. We cannot, however, draw unambiguous conclusions from this agreement. The fact is that agreement with experimental results can be obtained by simultaneously reducing the energy input and the expenditure on radiation.

It would appear that this uncertainty can be eliminated in principle by considering in detail the problem of radiation transport during expansion. As already mentioned, however, the spatial and temporal characteristics of the energy input are practically unknown. Finally, the question of the stability of expansion has apparently not been investigated either. At the same time, we cannot rule out the possibility of production of plasma "spray" and similar collective effects. These questions cannot be clarified by theory alone and direct measurements are necessary.

APPENDIX

Test of Conditions of Applicability of Kinetic Models

The thermodynamic functions and methods of estimating radiative loss in this paper and in [1] are valid if 1) radiative transitions have no effect on the Boltzmann distribution of the populations of excited levels and 2) the rate of beam ionization of ions is small in comparison with the rate of ionization by plasma electrons.

The validity of the first condition during the action of an REB pulse on a target composed of heavy atoms (gold) ($\overline{n}^{\circ} > n^{*}$) for typical experimental beam parameters is indicated by the obtained solutions and (3a).

We now verify the applicability of the second condition. To estimate the cross section for ionization $\sigma_k^{ion}(\varepsilon_0)$ by relativistic electrons ($\gamma >> 1$) we can use the method of equivalent photons [8, p. 451], which connects $\sigma^{ion}(\varepsilon_0)$ with the photoionization cross section. A coarse estimate of the ionization cross section for the best represented ions gives $\sigma_{kav}^{ion} \sim \xi \cdot 10^{-19}/T_e$ (ξ is the number of equivalent electrons). Using this expression we find that when $q << 10^{-38}(8/A)^2(ZN_0^3/\xi T_e x^2)$ the contribution of beam ionization to the formation of the ion multiplicity distribution is small throughout the action of the REB pulse.

We also show that neglect of the loss due to line emission is justified. Although this loss increases with time $Q^{line}{}_{n_0}x \sim t$, $Q^{line}{}_{n_0+1}x \sim t^2$, at $\tau \sim 10^{-7}$ sec the flux of line emission $Q^{line} \approx (Q^{line}{}_{n_0} + Q^{line}{}_{n_0+1})x \approx 9 \cdot 10^{-2} N_0 T_e^3 (1 + 2 \cdot 10^4/N_0^{1/3} x^{2/3}) \approx 2 \cdot 10^{16}$ erg/cm²·sec is much less than the supplied flux $\tilde{q} \approx 10^{19}$ erg/cm²·sec.

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