PHYSICS

Yu. K. ZEMTSOV, V. D. PISMENNYI, and I. M. PODGORNYI

1964

SovietRxiv

Abstract

Full Text

PHYSICS

Yu. K. ZEMTSOV, V. D. PISMENNYI, and I. M. PODGORNYI

ON THE QUESTION OF THE ELECTRON TEMPERATURE IN A POWERFUL PULSED DISCHARGE

(Presented by Academician L. A. Artsimovich, 12 XI 1963)

The results of previously published experimental studies of the radiation from a powerful pulsed discharge indicate a relatively low electron temperature (^1): the ion temperature T_i, determined from the Doppler broadening of lines of impurity ions, is 200-250 eV, while the electron temperature T_e, obtained from measurements of the relative intensities of the spectral lines of the same ions, lies in the range from 20 to 30 eV. It should be noted that the indicated temperature values are averaged over the time interval corresponding to the intense emission of highly ionized ions at the stage of maximum compression, when the electron concentration is $\sim 10^{17}$ cm^{-3} (^2).

Since a considerable part of the energy accumulated by the plasma in the compression process is concentrated in the ions, at the moment of maximum compression $T_i \gg T_e$. At the subsequent stage, equalization of the electron and ion temperatures occurs.

The principal processes determining the rate of temperature equalization are:

1. Coulomb collisions of ions with electrons.
2. Spontaneous radiation of excited states of impurity ions.
3. Ionization.
4. Bremsstrahlung and recombination radiation.

Estimates of the relative role of the last three processes show that even with a population of levels strongly differing from the Boltzmann distribution, the principal process responsible for the loss of energy by electrons is line radiation. Therefore, to calculate the time behavior of the electron and ion temperatures, the equation used was

$$\frac{dT_e}{dt} = \frac{4}{3}\sqrt{2\pi m}\,\frac{e^4 L n_p}{M k^{3/2}}\,\frac{T_i - T_e}{\left(T_e + \frac{m}{M}T_i\right)^{3/2}} - \frac{2}{3k}\sum_{r,s}\frac{n_r^*}{n_e}\,h\nu_{rs}A_{rs}, \qquad (1)$$

where T_e and T_i are the electron and ion temperatures in degrees; m and M are the masses of the electron and proton; e is the electron charge, L is the Coulomb logarithm ($L \simeq 15$); n_p, n_e, n_r^* are the concentrations of protons, electrons, and impurity ions in the r-th excited state; A_{rs} is the probability of a spontaneous transition from state r to state s, and $h\nu_{rs}$ is the energy of the emitted quantum; k is Boltzmann' s constant.

The calculations were carried out under the assumption that all radiative losses are determined by transitions of the OVI ion. In reality, besides the OVI lines, bright lines of the ions OV, NV, and NIV are observed. However, the conditions for their excitation differ little from the conditions for excitation of the OVI lines. Therefore, to simplify the calculations of radiative losses, it is assumed that the impurities consist only of OVI ions. The calculations were carried out for two cases: 1 and 10% concentration of impurity ions. The total concentration of nitrogen and oxygen impurities, obtained from the processing of the available-

of the experimental material is $\sim 5\%$*. Thus, the data presented here correspond respectively to underestimated and overestimated radiation losses.

Losses due to line radiation were calculated by summing over all possible transitions between the levels of the OVI ion. The transition probabilities A_{rs} were calculated by the Bates-Damgaard method (^{3}) and by the quantum-defect method (^{4}). In the case where r and s correspond to large values of n and l, one may use tables compiled for hydrogen-like ions (^{5}). The upper limit of the summation was determined from the condition of lowering of the ionization potential due to the Stark effect (^{6}).

Losses to line radiation depend substantially on the character of the distribution of ions over excitation states. If the level populations are determined by the Boltzmann formula, the radiation losses as a function of the electron temperature are approximated with sufficient accuracy by the curve

$$\frac{2}{3k}\sum_{r,s}\frac{n_r^*}{n_e}h\nu_{rs}A_{rs} = \begin{cases} 2.8\cdot 10^5\cdot\theta_e^{9/2}\dfrac{n_{\mathrm{OVI}}}{n_e}\ \dfrac{\mathrm{eV}}{\mathrm{s}}, & \text{if } 1\text{ eV} \ll \theta_e \ll 20\text{ eV},\\ 2.0\cdot 10^{11}\dfrac{n_{\mathrm{OVI}}}{n_e}\ \dfrac{\mathrm{eV}}{\mathrm{s}}, & \text{if } \theta_e \gg 20\text{ eV}. \end{cases} \tag{2}$$

where θ_e is the electron temperature in electronvolts; n_{OVI} is the total concentration of impurities; $n_{\mathrm{OVI}} = \sum_r n_r^*$. In the case where the radiation losses are determined only by the resonant transition $2s - 2p$, the loss rate, under the condition of Boltzmann population of the $2p$ level, is

$$\frac{2}{3k}\sum_{r,s}\frac{n_r^*}{n_e}h\nu_{rs}A_{rs} = \begin{cases} 2.5\cdot 10^5\cdot\theta_e^{4}\dfrac{n_{\mathrm{OVI}}}{n_e}\ \dfrac{\mathrm{eV}}{\mathrm{s}}, & \text{if } 1\text{ eV} \ll \theta_e \ll 10\text{ eV},\\ 2.5\cdot 10^{9}\dfrac{n_{\mathrm{OVI}}}{n_e}\ \dfrac{\mathrm{eV}}{\mathrm{s}}, & \text{if } \theta_e \gg 10\text{ eV}. \end{cases} \tag{3}$$

Fig. 1

Figure 1: Fig. 1

Fig. 2

Figure 2: Fig. 2

Under actually existing conditions, Boltzmann population occurs only for the lower levels, while the population of the higher levels proves to be considerably smaller. Therefore the true value of the loss rate lies within the limits determined by formulas (2) and (3).

Fig. 1. Variation with time of T_e (I and II) and T_i (III), taking account of losses to line radiation. Curves 1 and 2 were calculated from formulas (2), curves 3 and 4 from formulas (3). $\eta = \frac{n_{\mathrm{OVI}}}{n_e} 100\%$ is the percentage impurity content. 1 and 3 $-\eta = 10\%$; 2 and 4 $-\eta = 1\%$; 5 $-\eta = 0$. $n_e = 10^{17}$ cm^{-3}, $T_{i0} = 300$ eV.

Figure 1 presents the time dependence of the electron and ion temperatures, taking account of radiation losses at different impurity concentrations and with different populations of excited levels. It is seen from the graphs that the electron and ion temperatures practically equalize in a time shorter than the lifetime of the compressed state, which lasts about 1 μs. The subsequent change in T_i and T_e is determined by radiation losses, and the relation $T_i \gtrsim T_e$ is satisfied. Thus, the observed on in the experiment, the difference between T_i and T_e cannot be satisfactorily explained by insufficiently rapid equalization of the electron and ion temperatures.

This difference becomes understandable if one considers the lifetime of ions under compressed-state conditions. Figure 2 presents the dependence of the lifetime τ_i of OV, OVI, NIV, and NV ions on the electron temperature T_e, under the assumption of ionization by electron impact ($n_e = 10^{17}$ cm^{-3}). The lifetimes τ_i were calculated for three cases: a—ionization only from the ground state (7); b—ionization from states corresponding to the ground and first excited configurations, in the presence of a Boltzmann population; c—ionization with allowance for all excited states in the presence of a Boltzmann population (8).

Fig. 2. Dependence of T_e on time t and τ_i for oxygen and nitrogen ions on T_e. I—T_e as a function of t without allowance for energy losses; II—T_e as a function of t with allowance for radiative losses; III—ion lifetime τ_i as a function of T_e. The designations of curves 1-5 are the same as in Fig. 1.

In Fig. 2, curves I show the course of the electron temperature in time for different initial values of the ion temperature T_{i0} ($T_{e0} = 0$), without allowance

---

* L. Cher, Diploma thesis, Moscow State University.

for radiation losses. Lines II represent the change of T_e with time for $T_{i0} =$ 300 eV, with allowance for radiative losses at the same concentrations η of impurity ions as in Fig. 1. The intersection of the curves $T_e(t)$ and $\tau_i(T_e)$ occurs at the electron temperature T_{v}, the time required to reach which is equal to the burn-out time of the corresponding ion at this temperature. The value of T_{v}, and therefore also the ion burn-out time, depend on the type of ion and on the character of the population of its levels. For example, with a Boltzmann population, $T_{\text{v}} = 10.5$ eV for NIV and $T_{\text{v}} = 14$ eV for NV (see Fig. 2 for nitrogen, curves c). This means that by the time when the electron temperature is equal to 10.5 eV, practically all NIV ions will have burned out, and the line radiation of impurities in the time interval corresponding to $10.5 \div 14$ eV is due mainly to NV ions. Beginning at 14 eV, NV ions are absent. Therefore, in the case when a Boltzmann population is realized, measurements of the electron temperature from NV lines should give values of T_e in the interval from 10.5 to 14 eV. If the character of the population is such that all ions may be considered to be in the ground state (see Fig. 2 for nitrogen, curves a), the temperature interval corresponding to the radiation of the NV ion is $47 \div 60$ eV for a 10% impurity concentration and $48 \div 65$ eV for a 1% impurity concentration.

An analogous consideration for the OVI ion (Fig. 2, oxygen) gives, for T_{e} in the case of a Boltzmann distribution, values of 14 and 18 eV for $\eta = 10\%$, 14 and 19 eV for $\eta = 1\%$, and in the other limiting case (curves a)—60 and 72 eV for $\eta = 10\%$; 63 and 82 eV for $\eta = 1\%$.

The actually existing distribution is an intermediate one; therefore the experimental values of T_{e} must lie between the indicated limits. Indeed, the electron temperature obtained from processing the experimental results is 20–30 eV; moreover, this value may have been somewhat underestimated because of the deviation of the true distribution from the Boltzmann distribution.

Beginning with values of T_{e} corresponding to burnup of the OVI ion (see Fig. 1, II), the time course of the electron temperature is determined by losses associated with radiation from OVII ions. The line radiation of the OVII ion is less intense than the radiation of OVI, since the first excitation potential of OVII is 574 eV. For this reason the electron temperature can reach high values.

To determine the maximum value of T_{e}, it is necessary to carry out measurements using the OVII and OVIII lines, the principal ones of which lie in the x-ray region.

Moscow State University
named after M. V. Lomonosov

Received
31 X 1963

CITED LITERATURE

1. V. D. Pis' mennyi, I. M. Podgornyi, Sh. Sukever, ZhETF, **43**, 2008 (1962).

2. S. Yu. Luk' yanov, V. I. Sinitsyn, ZhETF, **34**, 849 (1958).

3. V. Bates, Phil. Trans. Roy. Soc. London, A **242**, 101 (1950).

4. A. Burgess, M. J. Seaton, Rev. Mod. Phys., **30**, 992 (1958).

5. L. C. Green, P. P. Rush, C. D. Chandler, Astrophys. J., Suppl., **3**, 37 (1957).

6. D. C. Inglis, E. Teller, Astrophys. J., **90**, 439 (1939).

7. R. W. P. McWhirter, Proc. Phys. Soc., **75**, 3, 520 (1960).

8. L. N. Biberman, Yu. N. Toropkin, K. N. Ul' yanov, ZhTF, **32**, 7, 827 (1962).

Note: Figure translations are in progress. See original paper for figures.