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PLASMA HEATING AT CONSTANT IMPEDANCE

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UDC 533.9 +537.52 +539.893

It is well known that the plasma conductivity σ depends strongly on the temperature T [1], $\sigma \sim T^{3/2}$, which leads to breakdown in plasma matching during heating with an energy source and to a drop in heating efficiency. Constancy of impedance facilitates broadband matching of an energy source with a target [2, 3]. This paper demonstrates that the impedance changes little during pulsed heating of a solid plasma through propagation of an ionization wave [4].

We consider a solid dielectric between the two conductors S_1 and S_2 of a transmission line (Fig. 1). A thin wire or film AB is within the dielectric. We limit ourselves to the simplest case where the conductors S_1 and S_2 are plane-parallel plates. A powerful radio or video pulse is fed into the line [5, 6], the film explodes [7, 8], and an ionization wave is propagated from the film with the field and current pattern shown in Fig. 2. The ionization front is propagated to the left, $E_1 \neq 0$ on the left ahead of the front, $\sigma_1 = 0$ in the dielectric, and $\sigma = \sigma_2$ on the right behind the front. The uhf field or short pulse does not penetrate within the conducting plasma behind the ionization front ($E_2 = 0$) so that the pulsed current j is zero everywhere except for a thin skin layer in which energy is deposited, and the propagation of the discharge, as noted in [4], is completely analogous to the detonation process [4, 9]. In the system shown in Fig. 1, propagation of both a breakdown wave and an ionization wave is possible with the wave having the greater velocity being the one propagated [4].

The propagation of ionization waves in gases was discussed in detail in [4] and the propagation of ionization waves was first discussed in [10, 11]. The present paper studies the features of ionization-wave propagation at condensed-state densities.

For the velocity D of a plane detonation wave and the specific internal energy ε of the material behind the front, the relations [4, 9]

$$D = [2(\gamma^2 - 1)(S/\rho)]^{1/3}, \tag{1}$$

$$\varepsilon = \frac{2^{2/3}}{(\gamma^2 - 1)^{1/3}(\gamma + 1)}(S/\rho)^{2/3} = \frac{\gamma}{(\gamma^2 - 1)(\gamma + 1)} D^2 \tag{2}$$

are valid, where S is the flux of absorbed energy, erg/(sec · cm^2); ρ is the density of the material; γ is the effective adiabatic index [9].

For example [7], let the pulse energy be 10 kJ = 10^{11} ergs, the duration $\tau = 10^{-9}$ sec, which corresponds to a power of $\sim 10^{13}$ W = 10^{20} erg/sec, let the heated sample be a cylinder of radius $r_0 = 1$ mm and length 2 mm with the lateral surface of the cylinder ~10 mm^2 or ~0.1 cm^2, and $S \simeq 10^{14}$ W/cm^2 = 10^{21} erg/(sec · cm^2). One can set $\rho \sim 1$ g/cm^3 for a solid dielectric.

Moscow. Translated from Zhurnal Prikladnoi Mekhaniki i Tekhnicheskoi Fiziki, No. 6, pp. 6–10, November–December, 1977. Original article submitted October 25, 1976.

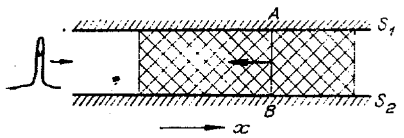

Fig. 1

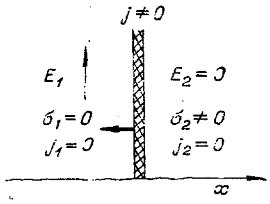

Fig. 2

The question of the effective adiabatic index is considerably more complicated since the material is not an ideal gas at high densities with multiple ionization taken into consideration [9]. For rough estimates we set $\gamma = 1.33$; the result depends weakly on γ as in a multiply ionized gas. Then

$$D = 1.23\cdot 10^7\ \mathrm{cm/sec} \sim 10^7\ \mathrm{cm/sec},\ \varepsilon = 1.14\cdot 10^{14}\ \mathrm{cm^2/sec}.$$

Therefore, the ionization front travels a total of 10^{-2} cm = 0.1 mm during the time of heating. One can see that $D \sim r_0^{-2/3}$, $\varepsilon_0 \sim r_0^{-4/3}$ for such targets. In the ideal gas approximation, we have for the pressure

$$p \simeq (\gamma - 1)\,\rho\varepsilon = \frac{2^{2/3}(\gamma-1)^{1/3}}{\gamma+1}\,\rho^{1/3}S^{2/3}. \tag{3}$$

For the example discussed above, $p \sim 0.38\cdot 10^8$ tech. atm. The pressure of the electric and magnetic fields was not taken into account in the derivation of Eqs. (1) and (2). Such neglect is justified in this case because the pressure of the field is considerably less than the pressure of the material. Therefore, instabilities typical of plasma confinement by a magnetic field will not appear.

In the coordinate system fixed in the propagating plane wave, the phenomenon is stationary and therefore the complex impedance is constant in that system. In the conversion to the laboratory system of coordinates, the impedance will remain constant if

$$D\tau \ll \lambda,\ \lambda = c/\omega_m \sim c\tau/\pi, \tag{4}$$

where ω_m is the upper limiting frequency of the video pulse spectrum. This inequality is equivalent to the condition

$$D \ll c/\pi, \tag{5}$$

which is amply satisfied when $S \sim 10^{14}$–10^{16} W/cm^2. The supplementary condition $D\tau < L$, where L is a characteristic transverse dimension, is necessary for waves of arbitrary configuration. For a radio pulse, λ in Eq. (4) corresponds to the length of the carrier wave. For a video pulse, Eq. (5) is amply satisfied, but for a radio pulse, Eq. (4) imposes a limitation on either the working frequency or the pulse duration. The condition (4) is certainly not satisfied for laser heating of a plasma [12].

According to Eq. (3), pressure depends weakly on the degree of ionization z and we have for a Boltzmann gas

$$p = nkT = n_+(1+\tilde{z})kT,\ T \sim 1/(1+\tilde{z}).$$

The width of the ionization wave front is determined by the following factors: the finite ionization time and the finite time for exchange of energy between electrons and heavy ions; electron and radiative thermal conductivity; the finite thickness of the skin layer.

The maximum range for radiation in air is 0.6 cm [9]; conversion yields a value of 3 μ for the range. The electric field heats the electrons, the ratio of electron and ion heat capacities in a Boltzmann gas is equal to the ratio of particle number and z so that the electron temperature is insignificantly higher than the final temperature behind the front, and the electrons lead the front by a distance of the order of the Debye radius d,

$$d \sim v_0/\omega_0 = (c/\omega_0)(v_0/c),\ v_0 \sim \sqrt{2kT/m};$$

even for single ionization, ω_0 corresponds to the ultraviolet region so that $d < 10^{-5}$ cm = 0.1 μ. Ionization by electron collision can be roughly considered as a collision between heated and atomic electrons. Exchange of energy between particles of equal mass occurs rapidly in contrast to the exchange between electrons and ions. With an ionization cross section of 10^{-16} cm^2 at the maximum [9], the time is short. Note that all calculations must be carried out rigorously for condensed media, which is not a simple problem because of the specific properties of different materials [9, 13]. We estimate the plasma conductivity and the thickness of the skin layer. For a completely ionized gas,

$$\sigma = \frac{e^2 n_-}{m\nu} \sim \frac{1}{4\pi}\frac{\omega_0^2}{\nu} \cong \frac{n_-}{n_0 z^2} T^{3/2} \sim \frac{1}{z} T^{3/2}.$$

For a hydrogen plasma ($z=1$) at $T=1.4$ keV, the conductivity is close to the conductivity of copper [1]. For an incompletely ionized gas, it is also necessary to consider the loss of directed velocity for the free electrons during collisions with bound electrons (we neglect this situation). For an incompletely ionized gas $z^2 \sim I_n \sim T$, so that $\sigma \sim T$ when there is a change in temperature and simultaneous change in ionization. The depth s of the skin layer is determined by the conductivity σ and the signal frequency: $s \sim 1/\sqrt{\sigma}$, $s \sim 1/\sqrt{f}$, where $f \sim 1/\pi\tau$ for a pulse and τ is the pulse length. For copper at $f=100$ MHz, $s \cong 6\ \mu$, the field is $\sim e^{-x/s}$, and the heat release, which is quadratic with respect to the field, occurs mainly at a depth $s/2 \sim 3$-$4\ \mu$. For example, if $T=1.4$ keV, Na or Mg will be completely ionized and the conductivity will be poorer than in copper by somewhat more than an order of magnitude ($s \sim 18\ \mu$, $s/2 \sim 9\ \mu$). For a temperature $T=140$ eV, the drop in conductivity, according to Eq. (5), amounts to yet another order of magnitude so that $s/2 \sim 30\ \mu$. Since the temperature and conductivity are small at the leading edge of the ionization wave, the values given above must be increased somewhat.

Thus, as with uhf heating [4], the width of the ionization front is mainly determined by the thickness of the skin layer. Because of high plasma conductivity, the resistance of the sample is small (fractions of an ohm), $\xi = H/E \gg 1$ near the sample, and a broadband resistance transformer is necessary for matching the target to the transmission line [2, 3]. Breakdown fields for polymers at pulse lengths of 5-100 nsec are 10^7 V/cm [14, 15]. A rigorous theory of pulse breakdown of dielectrics does not exist for polymers [16, 17], a strong increase in electrical stability for very short pulses is observed in gases [18, 19], but there are no reliable data for dielectrics. We therefore take the field value $E=10^7$ V/cm. In the practical system of units, we have for the energy flux

$$S \cong [EH] = (\xi E^2/\eta)\sqrt{\varepsilon};\ \eta = \sqrt{\mu_0/\varepsilon_0} = 377\Omega.$$

When $\xi=30$ and $\varepsilon=4$, we find $S = 2\cdot 10^{13}$ W/cm^2.

For an ionization wave to exist, it is necessary that its velocity exceed the velocity of the breakdown wave; this condition is not the same as the condition for absence of a breakdown. In a case where the maximum field exceeds the value of the breakdown field by a factor of three, we arrive at a flux value $S \sim 10^{14}$ W/cm^2.

What has been said indicates that high temperatures and pressures with high heating efficiency can be obtained in ionization waves in condensed media excited by a video pulse; this is of interest in the physics of high energy densities [12].

The authors thank S. A. Regirer and A. A. Barmin for their interest and valuable advice.

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ELECTRON TEMPERATURE DIFFERENCE IN FLOW CORE OF AN MHD ACCELERATOR CHANNEL

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UDC 537.529

The operating characteristics of MHD devices depend on the electrical conductivity of the plasma. Accordingly, it is important to know how it can be increased, taking into account the design properties of the materials used.

Generally speaking, as a result of the interaction of the plasma with the electric field the electron temperature is different from that of the ions and neutrals, and since the electrical conductivity of the plasma depends on the electron temperature, the question of nonequilibrium ionization has aroused considerable interest. In [1-3] an attempt was made to demonstrate, theoretically and experimentally, the presence of nonequilibrium ionization in an argon plasma seeded with potassium. The nonequilibrium ionization of noble gases seeded with alkali metal was also investigated in [4, 5].

In [6, 7] the effect of an elevated electron temperature near the surface of an insulator wall was investigated on the assumption of equilibrium electron concentration across the boundary layer. The equilibrium concentration was determined from the Saha equation. A similar assumption can be made in relation to the flow core, i.e., in the undisturbed region of the plasma.

We have investigated the undisturbed region of the plasma with allowance for diffusion and ionization of the charged particles at various concentrations of the potassium seed in nitrogen. We considered a dense plasma at a pressure p ~0.1 tech. atm, so that the ion temperature and the temperature of the basic gas may be taken to be the same.

The following assumptions are made: 1) The plasma is quasineutral; 2) all the plasma components, except for the electrons, are in thermal equilibrium; 3) there is no magnetic field; the electron temperature depends on the electric field strength and the current density.

Under these assumptions, the electric field strength, the particle fluxes, and the electron temperature are related as follows:

$$j=(D_e/\tau_e+D_i/\tau_i)G,\quad G=-j_e\tau_e/D_e,\ j_i=-j_e\tau_eD_i/\tau_iD_e,\ j=j_i-j_e,$$
$$\tau_e=\tau_i+c\sigma_0G^2/\nu, \tag{1}$$

where τ_e, τ_i, j_e, j_i, D_e, D_i are the temperatures, fluxes, and diffusion coefficients of the electrons and ions, respectively,

$$D_e=\frac{\tau_e^{1/2}}{\sum\limits_{s\neq e}N_sQ_{es}}\left(\frac{m_i}{m_e}\right)^{1/2},\quad D_i=\frac{\tau_i^{1/2}}{\sum\limits_{s\neq i}N_sQ_{is}}$$

and G, σ_0, and ν are the electric field strength, the electrical conductivity, and the electron collision frequency [8].

We will use the collision cross sections obtained for nitrogen seeded with potassium [9]. The charged particle concentration is found from the Saha equation using the electron temperature:

Zhukovskii. Translated from Zhurnal Prikladnoi Mekhaniki i Tekhnicheskoi Fiziki, No. 6, pp. 10-12, November-December, 1977. Original article submitted October 25, 1976.

