Runaway of the front of a shock wave near a metallic surface, and mechanism of the destruction on the current sheath in a noncylindrical Z-pinch

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It is shown that heating the surface of an anode and of a gas layer adjacent to it by radiation of a current sheath is the cause of the runaway of part of the current-sheath front adjacent to the anode. The evolution of this process is also the cause of the destruction of the current sheath of the plasma focus.

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In a number of experiments (see[1,2]) on a noncylindrical Z pinch ("plasma focus") it was observed that when a small amount of a heavy impurity is added to the deuterium (D+1% Xe), runaway and destruction of the current sheath is observed near the surface of the anode. The runaway becomes noticeable after 2–2.5 μsec at distances of about 20 cm from the center of the anode. The destruction of the current sheath occurs after 4–4.5 μsec at a distance of about 10 cm from the center of the anode.

In the present article we propose the following mechanism for the runaway and the destruction of the current sheath of the Z pinch. In the course of the discharge, the shock-wave front, which is perpendicular to the surface of the anode, moves together with the sheath towards the axis of the Z pinch with increasing velocity.[1,2] The radiation coming from the hot gas behind the front is partially absorbed by the surface of the anode and heats the latter. The gas layer adjacent to the anode is isobarically heated in turn by the thermal conductivity of the gas, and its density decreases in inverse proportion to the temperature. The sections of the shock-wave front near the anode, propagating through the gas with lower density, begin to accelerate. In fact, if T, ρ, and u are respectively the temperature, the density of the heated gas, and the velocity of the shock-wave front in the heated gas, while T_0, ρ_0, and u_0 are these quantities far from the anode, then from the condition that the pressure is constant behind the shock-wave front (subsonic flow) we have

$$u = u_0\left(\frac{\rho_0}{\rho}\right)^{1/2} = u_0\left(\frac{T}{T_0}\right)^{1/2} > u_0 . \quad (1)$$

It is known[3] that the absorption coefficient of light in the ultraviolet region for D and Xe (and consequently also their emissivity) have a threshold. The short-wave absorption coefficient $\kappa(\lambda < \lambda_0)$ is larger by several orders than $\kappa(\lambda > \lambda_0)$, where λ_0 is the emission wavelength corresponding to an energy close to the ionization potential. Neglecting therefore the small radiation flux with $\lambda > \lambda_0$, we have for the energy flux radiated on account of the shock-wave front in the D+1% Xe mixture at a temperature T_c behind the front

$$J_c = 2\pi T_c\, c\, [(\lambda_D)^{-3}\exp(-E_D/T_c) + 0.11(\lambda_{Xe})^{-3}\exp(-E_{Xe}/T_c)], \quad (2)$$

where $\lambda_D = 860$ Å, $E_D = 14.7$ eV, $\lambda_{Xe} = 1022$ Å, $E_{Xe} = 12.1$ eV. The coefficient 0.11 in the second term of (2) is the optical thickness of Xe if the thickness of the Z-pinch shell is ~ 1 cm. For pure deuterium we have

$$J_D = 2\pi T_D\, c\,(\lambda_D)^{-3}\exp(-E_D/T_D). \quad (3)$$

The runaway of the shock-wave front, in the case of a gas mixture, is due to the fact that at the same shock-wave front velocity the temperature behind the front is proportional to the mass density of the gas ahead of the front, whence $T_c/T_D = 1.65$ for the considered D+1% Xe mixture. Since $T_D < T_c < E_D, E_{Xe}$, at the start of the motion of the shock-wave front, it follows that $J_c \gg J_D$. This explains the experimentally observed brighter glow of the mixture.

The temperature of the anode surface can be estimated at

$$T_a = a\frac{J}{c_a \rho_a}\left(\frac{t}{\chi_a}\right)^{1/2}, \quad (4)$$

where c_a, ρ_a, and χ_a are the specific heat density, and the thermal diffusivity of the anode material, t is the heating time, and $\alpha \approx 10^{-2}$ is the fraction of the incident radiation flux J observed by the anode surface.

Since at $t \gtrsim 1$ μsec we have $c_s^2(T_g)t \gg \chi_g(T_g)$, where $c_s(T_g)$ and $\chi_g(T_g)$ are respectively the speed of sound and the thermal diffusivity in the gas at $T = T_g$, the pressures near the surface of the anode have time to be equalized, and the density becomes inversely proportional to the temperature $\rho = \rho_0 T_0/T$, i.e., it changes noticeably over distances on the order of $\delta = (\chi_g t)^{1/2}$ from the anode, with $T_g \approx T_a$.

Calculating the temperature behind the shock-wave front from the experimentally measured front velocity and calculating J_c, J_D, and T_a in accordance with (2)–(4), we find that in D+1% Xe the runaway of the front becomes noticeable at $t = 2$ μsec at a height 0.2 cm above the anode for duraluminum and 0.1 cm for copper. At $t = 4$ μsec the relative velocity of the perturbed section of the front greatly exceeds the velocity of the unperturbed section even at a height 1 cm (duraluminum) and 0.5 cm (copper). The final destruction of the current sheath at $t \geqslant 4\ \mu$sec is apparently due to the development of Rayleigh-Taylor instability, since the scale of the perturbation of the front becomes of the order of thickness of the Z-pinch shell. In pure deuterium, analogous estimates show that at $t=4\ \mu$sec the runaway is noticeable at a height much smaller than the thickness of the shell, and the relative velocity of the different sections of the front is small. The Rayleigh-Taylor instability does not have time in this case to develop prior to the instant of the collapse of the pinch on the axis.

The foregoing estimates explain why it is easier to observe in experiment the destruction of the sheath in experiments with a duraluminum anode than with a copper anode.

A similar runaway effect along the wall was observed in the motion of an initially flat shock-wave front in experiments with shock tubes.[4]

It follows from the foregoing that the destruction of the current sheath in a noncylindrical Z pinch with pure deuterium can be due to pulsed ($t \approx 1$–$2\ \mu$sec) heating of the periphery of the anode surface. The break of the current sheath high above the anode, where it is usually not observed, can be initiated by placing and heating a grid in that position.

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