Contraction of Z-pinch as a result of losses to radiation

V. V. Vikhrev

I. V. Kurchatov Atomic Energy Institute
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The dynamics of contraction of a Z-pinch in deuterium with appreciable energy loss to radiation is considered. It is shown with an actual example that the pinch contraction turns in this case into a collapse, as a result of which the plasma density in the pinch and the neutron emission from the pinch increase substantially.

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An attempt to assess the role of radiation during the concluding stage of plasma contraction in a Z-pinch was made in[1], where it was shown that in the case when the current in the pinch exceeds the Braginskiĭ current[2], then the radiation increases the contraction of the plasma in it. In[1] and[2], however, principal attention was paid to quasi-equilibrium states of the Z-pinch, whereas the radiation influences primarily the dynamics of the pinch contraction.

To describe the dynamics of a Z-pinch when it is contracted as the result of radiation losses, we use a model developed in[3], in which we take in addition the following effects into account: 1) the inertia of the radial motion of the matter, 2) the decrease of the current as a result of the increased inductance and resistance of the plasma pinch, 3) the heat dissipated by the anomalous resistance, 4) the viscous heat release, 5) the plasma bremmstrahlung and its transition into absolute black-body surface radiation from the plasma pinch, 6) the pressure of the degenerate electron gas, and 7) the thermonuclear heat released in the plasma.

The results of numerical simulation of the development of the discharge in the Z-pinch, with allowance for the foregoing effects, are shown in Fig. 1, which illustrates the variation of the plasma parameters in the coordinates n (the concentration of the medium) and T (the plasma temperature). Curve 1 in Fig. 1 pertains to discharges with current of 1 MA. Currents of the size are reached in plasma-focus installations.[4]

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The temperature rise (curve 1) is due initially to impact heating of the plasma without a substantial increase of the density. At temperatures from 300 eV to 8×10^3 eV, adiabatic heating of the plasma takes place, and in this region we have $n\sim T^{3/2}$, which corresponds to the simple model of plasma-focus development.[3] At a temperature $\sim$10 keV, the dense plasma in the pinch breaks up as a result of the anomalous Joule heat release in the pinch.[5] The plasma density at 10 keV reaches a maximum value $\sim10^{20}$ cm^{-3} and then decreases. At the instant of the maximum compression we have $n\tau=2\times10^{11}$ cm^{-3} sec. The neutron yield from the d-d reaction during the entire discharge is 2×10^{10}, in agreement with the experimentally observed data.

Curves 2–5 in Fig. 1 correspond to discharges in deuterium with 1% xenon added, using an installation of energy 2×10^6 J under the following initial conditions plasma column radius 4 cm, column length 1 cm, and system inductance 40 nH. The initial current in such a distance is 10 MA. Curves 2–5 correspond to different initial numbers N_1 of the particles in the plasma-column section. At $N_1=2\times10^{20}$ cm^{-1} (curve 2) the radiative cooling by the impurities does not influence the dynamics of the Z-pinch, and the plasma parameters vary in the same manner as when the current is 1 MA (curve 1). Turbulent disintegration of the dense plasma is observed in this case a a temperature higher than 10^5 eV, and the density is able to grow to a value $\sim10^2$ cm^{-3}. The current decreases during the course of the compression of the plasma column as a result of the increase of the inductance, and is equal to 7 MA at the instant o maximum compression. The value of $n\tau$ of the high-temperature plasma reaches 10^1 cm^{-3} sec, and the neutron yield during the entire discharge is 10^{14}.

The substantial increase of the plasma density in the Z-pinch, and by the same token in the $n\tau$ of the high-temperature of the plasma, is due to the losses to radiation in the case when the rate of energy loss to radiation exceeds the rate of energy loss du to plasma outflow,[3] i.e., at

$$Q_{\rm rad} > \frac{5NT}{\tau}, \qquad (1$$

where $Q_{\rm rad}$ is the power radiated from a unit length of the plasma pinch, N is th number of ions in the pinch cross section, and τ is the characteristic time of outflow c matter from the plasma pinch. Just as in[3], we have

$$\frac{1}{\tau} = \frac{1}{\tau_l} + \frac{1}{\tau_r}, \qquad (2$$

where the time of outflow of the plasma through the ends of the plasma pinch $\tau_l=l/2v_T$ (l is the pinch length and v_T is the thermal velocity of the ions), while τ_r the time of outflow in the radial direction, $\tau_r=\alpha r/v_T$ (r is the average pinch radi and α is the factor by which the time of plasma containment in the radial directi exceeds the ion radial transit time, $\alpha\sim10$).

The straight lines "a" and "A" in Fig. 1 correspond to condition (1) frc bremmstrahlung of deuterium with 1% xenon admixture is a fully ionized plasma at current 10^7 A, the line "a" being drawn for $\tau=\tau_l$ at $l=1$ cm, while line "A" line drawn for $\tau = \tau_r$ at $\alpha = 10$. If the values of n and T of the plasma fall in the region above the lines "a" and "A," then radiative cooling of the plasma becomes significant. The plasma pressure in the pinch decreases in this case, and the plasma pinch is compresed by the pressure of the magnetic field, and the pinch plasma density increases appreciably. This phenomenon can be called radiative collapse of the Z-pinch. Curves 3, 4, and 5 describe the behavior of the discharges in which such a collapse is realized.

Plasma contraction without a temperature rise is hindered primarily by the conversion of the volume radiation of the plasma into absolute-black-body surface radiation of the plasma pinch. The boundary of the transition is shown by line "D" in Fig. 1. At the plasma parameters above the line "D," the plasma radiation is trapped and surface radiation of the plasma pinch sets in. In the case of absolute-black-body radiation, the plasma contraction can be accompanied only by a rise in the temperature, as is indeed observed on curves 3, 4, and 5 after the boundary "D" is crossed.

The line "B" corresponds to the condition

$$\frac{5NT}{\tau_r} = 2\pi r \sigma T^4 \tag{3}$$

at $\alpha = 10$, i.e., the energy outflow from the pinch becomes comparable with the absolute-black-body emission from the plasma pinch. Above this line, pinch contraction due to radiative losses is impossible. Therefore the calculated curves 4 and 5 in Fig. 1 are tangent from below to the line "B," but do not cross the line.

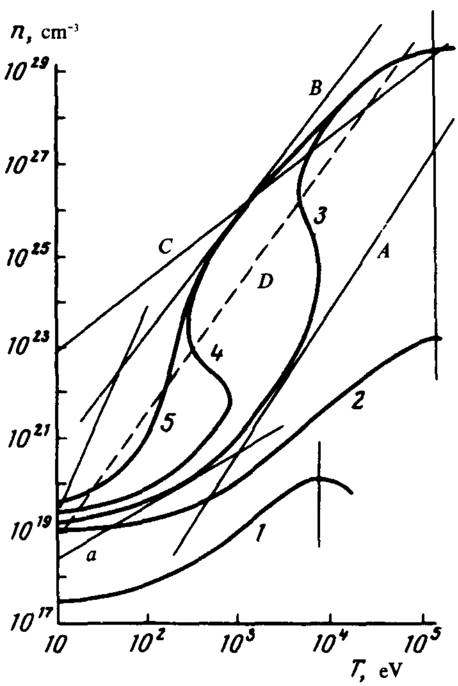

FIG. 1. Plots of the density against temperature in a Z-pinch: 1) initial current 1 MA, 2–5) initial current 10 MA in a discharge of deuterium with 1% xenon added, for different initial amounts of particles in the plasma-pinch cross section: 2—$N_1 = 5\times10^{20}$, 3—10^{21} 4—2×10^{21}, 5—5×10^{21} cm^{-1}.

The line "C" corresponds to degeneracy of the electron gas. Above this line, the pressure of the degenerate electron gas exceeds the pressure nT. Curves 3, 4, and 5 penetrate slightly into the degeneracy region, but the Joule and Nuclear heat released at this instant leads to heating of the plasma in the pinch and the plasma parameters go outside this region.

At a temperature above 10^5 eV, the pinch is destroyed as a result of the appearance in it of anomalous plasma resistance; the temperature then increases and the plasma density decreases. Calculation shows that the radius of the plasma pinch in radiative collapse, at the instant of maximum contraction, is $\sim 10^{-5}$ cm, the current at this instant is 4 mA, the density reaches a value $> 10^{27}$ cm^{-3}, the temperature exceeds 10 keV, $n\tau \sim 10^{16}$ cm^{-3} sec, and the neutron yields during the entire time of the discharge 8×10^{14} (curves 4 and 5) or 1.5×10^{16} (curve 3).

In radiative collapse of a Z-pinch in a mixture of deuterium with tritium, the thermonuclear yield reaches 10^{18} neutrons per discharge. This means that in a deuterium-tritium mixture it is possible to obtain in the neutron radiation an energy equal to the initially stored energy in the current source (2×10^6 J). Thus, a thermonuclear reactor based on a Z-pinch is possible in principle in the energy range of several megajoules.

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[1]J.W. Shearer, Phys. Fluids **19**, 1426 (1976).
[2]S.I. Braginskiĭ, Zh. Eksp. Teor. Fiz. **33**, 645 (1957) [Sov. Phys. JETP **6**, 494 (1958)].
[3]V.V. Vikhrev, Fiz. Plazmy 3, 981 (1977) [Sov. J. Plasma Phys. **3**, 539 (1977)].
[4]V.I. Agafonov *et al.*, Plasma Phys. and Contr. Nucl. Fus. Res., IAEA, Vienna **2**, 21 (1969).
[5]V.V. Vikhrev *et al.*, Plasma Phys. and Contr. Nucl. Fus. Res. IAEA, Vienna **3**, 455 (1977).