Nature of the hot local plasma formations in high-current pinches

Yu. A. Bykovskiĭ, V. B. Lagoda, and A. N. Oblizin
Moscow Engineering Physics Institute

(Submitted 24 November 1981)

Pis'ma Zh. Eksp. Teor. Fiz. **35**, No. 4, 139–141 (20 February 1982)

A model based on the fine structure of the current-carrying plasma can explain the basic features observed in high-current pinches.

PACS numbers: 52.55.Ez

The current-carrying plasma of high-current pinches has a fine structure consisting of current filaments. This fine structure has been detected in Θ pinches and Z pinches,[1] in the plasma focus in the Mather geometry and in the Filippov geometry,[3] in laser-initiated vacuum discharges,[4] and elsewhere. The structure of the current filaments which form the collapsing current shell has been studied experimentally and theoretically by Nardi[5] and Bostick *et al.*[6,7] It has been shown, in particular, that a) the current filaments self-stabilize because of the development of longitudinal internal magnetic fields B_Z, b) they arise in pairs, with oppositely directed fields B_Z, and c) the transverse dimension of a given filament is approximately equal to the Larmor diameter ($2\rho_Z$) of the ion in the field B_Z.

In Refs. 4 and 8-10, and also in further study by the present author, it was established that local hot plasma formations (Fig. 1) result from the linkup of several current filaments satisfying the condition

$$\sum_i B_Z^i = 0, \qquad (1)$$

where i is the index of a filament involved in the linkup. These hot plasma formations have the following properties: a) The electron temperature is on the order of a few keV; the electron density n_e is on the order of 10^{21} cm^{-3}; b) the transverse dimension of the hot region of the formation is approximately equal to the Larmor diameter ($2\rho_\Theta$) in the azimuthal magnetic field of the current, B_Θ; c) after the hot core of a formation arises, the formation expands comparatively slowly, and its decay time is comparable to the total duration of the pinch process; d) energy is supplied to the hot plasma formation by the Cerenkov pumping of plasma turbulence,

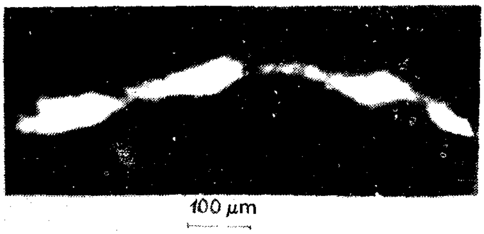

FIG. 1. Local hot plasma formations which arise along the line where several current filaments link up. The photograph was taken in x rays with an energy $\geqslant 2$ keV.

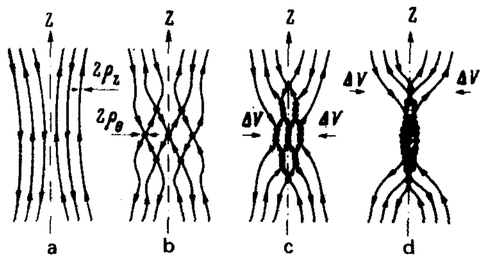

FIG. 2. Linkup of self-stabilized current filaments. The arrows show the directions of the fields B_Z.

and the effect is accompanied by microwave emission; e) the hot plasma formation is a source of fast ions, which are emitted along the axis in both directions (the most probable acceleration mechanism is acceleration by longitudinal plasma waves or ion sound).

In the present letter we wish to show that the events observed during the pinching of high-current discharges can be described by a set of processes, each of which occurs in the region in which several current filaments satisfying condition (1) link-up.

As an example, we consider a model for the closing of self-stabilized current filaments during collapse (Fig. 2a). We assume a deuterium plasma, and we assume that the scale times for the processes in which we are interested are much shorter than the discharge period. We assume that there is a certain critical current which can flow through a given filament (I^0_f). The number of filaments is then $N_f = I/I^0$, where I is the total discharge current. As the filaments close on each other, each experiences a force exerted by adjacent filaments. When a certain critical separation is reached, the filaments lose their stability with respect to the "firehouse" instability in their central region (Fig. 2b). The filaments come in contact at certain points; the fields B_Z are annihilated; and hot plasma formations appear. Each of these formations emits a beam of fast ions and a microwave pulse and dissipates a fraction W_{LHPF} of the discharge energy. The reconnected configurations of the B_Z fields which arise, and which tend to join together, cause an increment ΔV in the radial closing velocity of the filaments in their central region. This increment ΔV is provided by the energy released in the annihilation of the fields B_Z. The anomalously rapid contraction of the bound structure which results is accompanied by the formation of new local hot-plasma formations along the filament closure line (Fig. 2c). This process, accompanied by a dissipation of energy, propagates in both directions along the Z axis (Fig. 2d) until the current in each filament drops to the critical level $I^{\mathrm{cr}} = KI^0$, where K is a constant. Below this critical current, the appearance of local hot plasma formations ceases. The total number of formations which appear is

$$N_{LHPF} = \frac{CI^2 - C(N_f I_f^{cr})^2}{W_{LHPF}} = I^2 \frac{C(1-K^2)}{W_{LHPF}} \sim I^2 ,$$

where C is a constant of the discharge circuit. Assuming that the mechanism for the production of neutrons in this system is an interaction of accelerated deuterons from the hot plasma formation with thermal deuterons of other hot plasma formations, we find the neutron yield to be $N_n \sim 1/2 N_{\rm LHPF}^2 \sim I^4$.

In real high-current systems, the linkup of the filamentary structure of the current-carrying plasma during collapse is an irregular, stochastic process. Nevertheless, there is a good correspondence between the experimental results and the model outlined above. For example, this model gives an essentially complete description of certain aspects of the plasma of the focus: a) the independence of n_e from I over a broad range of discharge currents, $10\ \text{kJ} \leqslant CI^2 \leqslant 600\ \text{kJ}$ (according to the model, n_e should be approximately equal to the electron density of the "average" local hot plasma formation, multiplied by the packing density); b) the anomalously fast radial motion of the plasma in the region in which the current sheet closes; c) the dependence $\sim I^4$ for the neutron yield; d) the temporal coincidence of the beginning of neutron emission with the appearance of microwave emission from the pinch; e) the fact that the ion flux from the pinch region consists of discrete sets of highly collimated ion beams and the fact that the ion energy distribution is independent of I (each of the ion beams is accelerated in one of the local hot plasma formations); f) the fact that the current is not cut off completely during a pinch ($K \neq 0$).

According to these arguments, the pinch process may be thought of as a transition of a current-carrying plasma from a state with a scale dimension $2\rho_Z$ to a state with a scale dimension $2\rho_\Theta$. The selection of the parameters of high-current discharges may be interpreted as a search for the optimum set of parameters for the linkup of the filamentary current structure.

1. I. F. Kvartskava *et al.*, Proceedings of the First IAEA Conference on Plasma Physics and Conference on Nuclear Fusion Research, Salzburg, 1961, p. 533.
2. A. Bernard *et al.*, Phys. Fluids **18**, 180 (1975).
3. V. A. Gribkov *et al.*, Zh. Eksp. Teor. Fiz. **18**, 11 (1973).
4. U. A. Bykovsky and V. B. Lagoda, Proceedings of the Tenth European Conference on Plasma Physics, Moscow, 1981, Vol. 1, D9.
5. V. Nardi, Phys. Rev. Lett. **25**, 718 (1970).
6. W. H. Bostick, V. Nardi, and W. Prior J. Plasma Phys. **8**, 7 (1972).
7. W. H. Bostick, V. Nardi, and W. Prior, Ann. NY Acad. Sci. **251**, 2 (1975).
8. Yu. A. Bykovskiĭ, V. B. Lagoda, and G. A. Sheroziya, Pis'ma Zh. Eksp. Teor. Fiz. **30**, 489 (1979) [JETP Lett. **30**, 458 (1979)].
9. Yu. A. Bykovskiĭ, V. B. Lagoda, and G. A. Sheroziya, Pis'ma Zh. Eksp. Teor. Fiz. **30**, 489 (1980) [JETP Lett. **31**, 245 (1980)].
10. U. A. Bykovsky and V. B. Lagoda, Proceedings of the Fifteenth International Conference on Phenomena in Ionized Gases, Minsk, 1981, Vol. 2, p. 583.

Translated by Dave Parsons
Edited by S. J. Amoretty