$$|f_1^+(\zeta - 2n)| < |\zeta - 2n|^\alpha,$$

is valid for sufficiently large n, where $\alpha < 1$; therefore, for $\mathrm{Re}\,\zeta \leqslant 1$,

$$\left|(\Delta_{12}\Delta_{13})^n\left(\frac{\zeta-1}{\zeta-2n-1}\right)^2 f_1^+(\zeta-2n)\right| < |\Delta_{12}\Delta_{13}|^n\frac{|\zeta-1|^2|\zeta-2n|^\alpha}{|\zeta-1-2n|^2}\to 0$$

as $n \to \infty$ for any finite value of ζ. Consequently, Eq. (A.14) tends to

$$f_1^+(\zeta) = E_0(\zeta-1)^2\sum_{k=1}^{\infty}\frac{(\Delta_{12}\Delta_{13})^k}{(\zeta-2k-1)^2}, \qquad \mathrm{Re}\,z \leqslant 1 \tag{A.15}$$

in the limit as $n \to \infty$. Therefore, for these values of ζ, the series (A.15) is bounded by the converging numerical series

$$\sum_{k=1}^{\infty}\frac{(\Delta_{12}\Delta_{13})^k}{(2k)^2},$$

which thus provides one of the two desired functions.

The second unknown function $f_1^-(\zeta)$ is determined from the second Eq. (A.12). Substituting Eq. (A.15) into this equation gives

$$f_1^-(\zeta) = E_0 - \frac{E_0}{\Delta_{13}}(\zeta-1)^2\sum_{k=1}^{\infty}\frac{(\Delta_{12}\Delta_{13})^k}{(\zeta+2k-1)^2}, \qquad \mathrm{Re}\,z \geqslant 1. \tag{A.16}$$

Equations (A.15), (A.16), and (A.10) make it possible to write explicit expressions for the functions $f_p(\zeta)$, p = 1, 2, 3. Then, reverse mapping of (A.2) is used in Sec. 3 to find Eqs. (3.1) for the electric field.

LITERATURE CITED

1. I. E. Tamm, Basic Theory of Electricity [Russian translation], Nauka, Moscow (1976).
2. E. Duran, Electrostatics, Methods for Calculating Dielectrics [in French], Vol. 3, Masson, Paris (1966).

GENERATION OF ELECTRICAL PULSES DURING FORMATION AND DEVELOPMENT OF CURRENT-DRIVEN INSTABILITIES IN PLASMAS

P. I. Zubkov

UDC 533.952

In a current-carrying circuit left to itself, the electromagnetic forces act to increase the inductance. This is a consequence of the general principle that a system evolves in the direction of reduced potential energy. Initially stored in the electromagnetic field, the potential energy is converted into internal and kinetic energy of moving conductors. A current-carrying circuit is unstable with respect to increasing inductance.

Convincing examples of practical devices that operate on this principle include z- and θ-pinches, rail guns, electrodynamic accelerators of plasmas and solids, plasma dynamic opening switches, etc. As will be shown below, instabilities with respect to increasing inductance are of considerable importance in plasma opening switches.

When a current-driven instability develops, an inductive emf that is controlled by the currents and voltages in the circuit appears on the portions of the circuit with increasing inductance. The possible generation of electrical pulses by changes in the inductance under the action of intrinsic currents has been discussed from this point of view [1]. This analysis was carried out for motion in specified plane and cylindrical geometries. It was shown that in a formal mathematical sense, the emf increases without bound in a z-pinch under these assumptions [1]. This method may be useful for generating voltages and interrupting currents.

Novosibirsk. Translated from Prikladnaya Mekhanika i Tekhnicheskaya Fizika, No. 4, pp. 24-31, July-August, 1993. Original article submitted June 23, 1992.

0021-8944/93/3404-0473$12.50

© 1994 Plenum Publishing Corporation

Circuits in which the deformable element is a plasma are often used in experimental devices and are of special interest from this standpoint. With its high compressibility and low inertia, a plasma is subject to a wide range of instabilities, particularly current-driven instabilities that cause the inductance to increase.

In practical applications, plasma instabilities must usually be stabilized. On the other hand, current-driven instabilities may be useful for generating voltages and interrupting currents. In addition, by removing factors which stabilize a plasma and creating destabilizing factors by various technical means, it is possible to control the formation and development of instabilities that raise the inductance, to control the rise in the inductance, and thereby, to control the processes of voltage generation and current interruption.

Possible ways of using plasma instabilities for current switching have been proposed [2, 3]. However, no practical analysis of the prospects for these methods has been made. The author is unaware of any work on voltage generation and control by means of instabilities.

This paper examines the feasibility of generating electrical pulses during the formation and development of plasma instabilities from the standpoint described above and estimates the inductive emf produced under these circumstances. Because no theory of large amplitude current-driven instabilities has been developed, we shall examine a simplified model of these processes in which the plasma is usually an ideal conductor and an electrical circuit approximation is used.

For the purpose of estimates, let us consider a circuit containing a capacitance C plus a rigid inductor L_0 in series with a plasma column whose inductance varies under the influence of the current flowing through it. Various technical means can always be used to induce an instability at a current $I_0 \approx V_0\sqrt{C/L_0}$ close to the maximum in order to achieve maximum utilization of the stored energy. At this time the voltage on the capacitor is much lower than V_0 and can be neglected. Since we are most interested in instabilities with characteristic formation times $\tau \ll T = 2\pi\sqrt{L_0C}$, we can also neglect the variation in the voltage on the capacitor. Assuming flux conservation and neglecting the mutual inductance, we find the emf $\mathscr{E}$ across the rigid inductance L_0 ($L_0\dot{I} = -(L\dot{I})$) to be

$$\mathscr{E} = -L_0\dot{I} = L_0I_0\,\frac{(L_0+L_i)\,\dot{L}}{(L_0+L)^2}, \tag{1}$$

where L_i and L are the initial and instantaneous inductances of the plasma column and $\dot{L}$ is the rate of change of the inductance. This formula will also be valid for inductive energy storage.

In many problems involving a physical experiment it is necessary to specify the time variation of $\mathscr{E}$ in advance. Equation (1) can then be used to find the variation in the inductance L when it is forced to increase by an external interaction. In particular, for $\mathscr{E}$ = const ($L_i \ll L_0$) we have

$$L = L_0\,\frac{t/\tau}{1-t/\tau}$$

(τ = const is the risetime of the inductance). In this case $\mathscr{E} = L_0I_0/\tau = V_0T/2\pi\tau$ and for $\tau \ll T$ the emf $\mathscr{E}$ is much greater than V_0, the initial voltage on the capacitor.

The energy initially stored in the capacitor bank has "spilled out" into the circuit inductance. Its further conversion by the external interaction is unrelated to the storage process and may be independent of the storage unit. Thus, arbitrary emfs are possible, especially those such that $\mathscr{E} \gg V_0$.

When the inductance L changes under the action of a flowing current, the conservation of energy can be used to rewrite Eq. (1) in the form

$$\mathscr{E} = -L_0\dot{I} = \frac{2\dot{W}}{I_0}$$

($\dot{W}$ is the rate of change of the energy in the plasma column). It also follows from the conservation of energy that even when $L = L_0$ ($L_i \ll L_0$) half the electromagnetic energy goes into kinetic and internal plasma energy. Thus, to estimate $\dot{W}$ we can set $\dot{W} \approx L_0I_0^2/4\tau$, which yields a characteristic $\mathscr{E}_0$ of

$$\mathscr{E}_0 \approx \frac{L_0I_0}{2\tau} = V_0\frac{T}{4\pi\tau}, \tag{2}$$

which implies that $\mathscr{E}$ can attain values considerably higher than V_0 for $\tau \ll T$.

The resulting power

$$N = \frac{I_0 \mathscr{E}}{2} \approx I_0 V_0 \frac{T}{8\pi\tau} = \frac{CV_0^2}{2T}\frac{T}{2\tau}$$

is also much greater than the average power in a rigid circuit. Note that the characteristic times for development of an instability can be varied over a wide range by technical means.

The above estimates show that electrical pulses can be generated during the formation of discharges in cases where the magnetic pressure is much higher than the gas kinetic pressure.

We now consider the most typical current-driven instabilities.

Kink (m = 1) Instability. The inductance during the kink instability varies as $L = \mathscr{L}^2/l$ (where $\mathscr{L}$ is the length of the helical spiral of the plasma column and ℓ is the initial size or interelectrode distance). For a helical spiral with radius r and wavelength λ we obtain

$$L = l\left(1 + \left(\frac{2\pi r}{\lambda}\right)^2\right).$$

We shall assume that the instability develops linearly with a characteristic time τ. In this approximation (made in order to obtain an estimate) with $r^2 = \lambda^2(L_0 + \ell)/4\pi^2\ell$ the maximum emf $\mathscr{E}$ is

$$\mathscr{E}_{\max} = \frac{L_0 I_0}{2\tau} = V_0 \frac{T}{4\pi\tau},$$

which agrees with the previous estimate (2). The characteristic time for development of the kink instability is [4] $\tau \approx \lambda/(2\sqrt{2}\pi v)$ and $\mathscr{E}_{\max} \approx V_0 T v/\lambda$ (where v is the isothermal sound speed in the plasma). This implies that for $\lambda \ll Tv$, we have $\mathscr{E}_{\max} \gg V_0$.

Sausage (Constriction) Instability. The sausage instability is one of the most dangerous from the standpoint of the stability of a plasma column. For simplicity of calculating the inductance of a plasma column subject to the sausage instability, we represent the perturbation of its surface as a step. Let the radius of the constriction be $r - \delta$ (where r is the equilibrium radius and δ is the perturbation in the radius) for length $\lambda/2$ of the column and $r + \delta$ for the other half of the wavelength. In this approximation the external inductance of a plasma column of length ℓ is $L = \ell \ln R^2/(r^2 - \delta^2)$ (where R is the radius of the outer current conductor). Equation (1) yields an inductive emf of

$$\mathscr{E} = \frac{2I_0(L_0 + L_i) L_0 l \delta\dot{\delta}}{\left(L_0 + l \ln \frac{R^2}{r^2 - \delta^2}\right)^2 (r^2 - \delta^2)},$$

from which it follows that when the instability is strong ($\dot{\delta} \neq 0$) $\mathscr{E}$ increases without bound when $\delta \to r$. This is clearly impossible physically. However, various techniques can be used to obtain ever higher values of $\mathscr{E}$.

When the process evolves in this way, the current in the circuit approaches zero. This is evidently one of the reasons the current is cut off. The current becomes so small that it cannot overcome the processes leading to recombination and decay of the plasma.

This expression for $\mathscr{E}$ does not assume that the instability develops linearly. If we consider an instability that develops linearly, then it seems that $\mathscr{E}$ will increase without bound for $L_0 > 2l \ln\left(\frac{R}{r}\right)$. Otherwise $\mathscr{E}$ has a maximum, which means that the compression is slowed down and may cease for some value of δ. After compression ceases the constriction of the plasma column begins to expand owing to the gas kinetic pressure. The inductance L begins to decrease. Part of the energy goes into L_0. A series of voltage pulses can be generated in this way. The generation of a series of pulses is especially characteristic of cylindrical z-pinches and it can even occur when $L_0 > 2l \ln\left(\frac{R}{r}\right)$. In oscilloscope traces of the current, three features are observed experimentally [5] to accompany the voltage spikes.

The termination of compression when $L_0 < 2\ell \ln(R/r)$ is one of the factors preventing collapse of the constrictions.

The preceding discussion suggests that the inductive emf should behave similarly during nonlinear constrictions under conditions like those described above.

An unlimited growth in $\mathcal{E}$ when the inductance of the plasma column increases under the action of a flowing current is characteristic for a finite change in the dimensions of the circuit. The growth in the circuit inductance as the circuit dimensions increase does not lead, even formally, to an unlimited increase in the inductive emf. In this case $\mathcal{E}$ has a limit, as is confirmed by the behavior of the emf during development of the kink instability.

Overheating-Type Instabilities. An overheating instability, resulting from the temperature dependence of the conductivity and low heat conductance, leads to a redistribution of the current through a conducting material. Besides the current, the magnetic field is also redistributed and this creates an inductive electric field in accordance with the Maxwell equation

$$\mathrm{rot}\,\mathbf{E} = -\frac{1}{c}\frac{\partial \mathbf{B}}{\partial t}. \qquad (3)$$

A similar picture occurs when magnetohydrodynamic instabilities develop, e.g., during constrictions. The difference is that in the first case the realignment of the current is not accompanied by motion of the material, but in the second it is caused precisely by this motion. The inertial properties of the material are not involved in the development of an overheating-type instability, so it may develop over times much shorter than the time for current-driven instabilities to develop [4].

In the following we examine an ideal model which applies to real conditions or can be created specially by technical means and estimate some typical parameters.

Consider a cylinder of radius R with conductivity σ and a uniformly distributed current I_0 flowing along the cylinder. At some time t a superconducting cylinder of radius $r \ll R$ is formed in the center and the current and magnetic field begin to realign themselves. A wave will propagate radially. When $\sigma \gg \varepsilon c/(4\pi R)$ the propagation of this wave obeys an equation similar to the heat conduction equation with a characteristic time $\tau \sim 4\pi\sigma R^2/c^2$ for changes in the magnetic field [6].

For simplicity we shall assume that the current I_0 in the circuit is constant. The redistribution of the current and magnetic field tend to steady-state values. In the final state the magnetic field on the surface of the inner cylinder is $B_0 = 2I_0/cr$. Given the cylindrical symmetry of the problem, Eq. (3) takes the form

$$\frac{\partial E_z}{\partial r} = \frac{1}{c}\frac{\partial B_\varphi}{\partial t}.$$

After this equation is reduced to dimensionless form we obtain

$$\frac{\partial e}{\partial x} = \frac{2I_0 R}{E_0 c^2 \tau r}\frac{\partial b}{\partial y}, \qquad (4)$$

where $e = E/E_0$ and $b = B/B_0$ are the dimensionless electric field and magnetic induction, $x = r/R$ is the dimensionless coordinate, and $y = t/\tau$ is the dimensionless time for readjustment of the current. Equation (4) implies that the characteristic electric field is $E_* = 2I_0R/(c^2\tau r) = I_0R/(2\pi\sigma R^2 r)$. The characteristic voltage, given by $E_*\ell$, is

$$V_* = V_0\frac{R}{2r}$$

(where V_0 is the initial voltage on the conducting cylinder). Formally the characteristic voltage goes to infinity when the radius of the superconducting cylinder approaches zero. Physically it is clear that its radius may be determined by the techniques used and by the processes that occur as the current density rises.

High voltages can also be obtained when the conductivity is low, but these estimates are no longer valid if $\sigma < \varepsilon c/(4\pi R)$. As for the conductivity of the inner cylinder, it is sufficient to make it much greater than the initial value.

When sausage-type instabilities develop, constriction of the plasma column may proceed to the point that the current is interrupted at a constriction. Then the readjustment of the current and field proceeds in a form similar to a thermal wave propagating through the residual gas which has not been "swept up" during compression. The formulas given above for E_* and V_* remain valid here. Redistribution of the current and magnetic field can begin when the degree of ionization of the residual gas owing to radiation from the compressed plasma is high enough. Typically the polarities of electrical pulses generated by constriction and by overheating instabilities are opposite. In the case of constrictions, the polarity of the pulse is the same as that of the initial voltage. In plasma opening switches the polarities of the applied and generated pulses are also the same.

A similar problem has been considered [7] to explain the neutron yield from constrictions. There it was assumed, without adequate physical justification, that an Alfvén wave propagates through the residual gas at a velocity determined by the plasma density and magnetic field. The model proposed here may be useful for explaining the appearance of bunches of charged particles in z-pinches and plasma opening switches.

Plasma Opening Switches. The method discussed above for generating electrical voltages by means of current-generated instabilities is also applicable to the operation of plasma opening switches. Previous models of plasma opening switches [8-10] are generally extensions of a model [8] based on a deficiency of current carriers. The main shortcoming of this model, in our opinion, is that it neglects the plasma dynamics. The inability of this model to explain a number of operating features of plasma opening switches has been pointed out elsewhere [9, 11].

The model proposed below is based on the formation and development of current-driven instabilities in a plasma injected by plasma guns along the radius of the coaxial storage device of a plasma opening switch. This plasma is an analog of a plane layer and is unstable with respect to pinching and constrictions [4]. The formation and development of pinches are promoted by the inhomogeneity of the plasma, which is injected in the form of discrete beams, reflected from the electrodes, and expands into a vacuum, as well as by the nonuniform current and magnetic pressure.

Estimates of the characteristic magnitudes of the plasma parameters in a plasma opening switch suggest that a hydrodynamic description of the motion transverse to the magnetic field [12], which is all we shall consider, will suffice.

When it is injected into the storage device the plasma expands toward the electrodes and along them at a velocity of $\sim 5\cdot 10^6$ cm/sec. Turning on a current creates a magnetic field which accelerates the plasma along the electrodes. The magnetic pressures at the inner and outer electrodes can differ by an order of magnitude, and this will lead to significant spreading of the plasma layer along the storage device.

If we treat the magnetic field as a piston which "scoops up" the plasma, then its velocity can be as high as $\sim 10^8$ cm/sec. The magnetic field propagates along the storage unit at the same velocity. Its propagation velocity is considerably higher than the field penetration rate ($\sim 10^6$ cm/sec) is a stationary plasma, which can also explain the disagreement between measured and calculated values of the velocity [13].

According to our scheme the plasma moves along the storage unit and is compressed in pinches (with respect to which the nonuniform layer is unstable). Assuming that pinches are formed and develop in plasma opening switches makes it possible to explain qualitatively most of the characteristic features of their operation and to obtain quantitative estimates in agreement with experiment.

The expansion and compression of the plasma can begin to slow down when

$$\frac{B^2}{8\pi} \geqslant p + \rho v^2,$$

where B is the magnetic induction at the boundary of the inhomogeneity and p, ρ, and v are the pressure, density, and expansion velocity of the plasma. Expressing the magnetic induction in terms of the current I, we obtain

$$I \geqslant \sqrt{2\pi}cR\sqrt{p + \rho v^2} \qquad (5)$$

(where R is the characteristic size of the inhomogeneity). Equation (5) provides a qualitative explanation of the operating dynamics of plasma opening switches.

Equation (5) implies that the operation of a plasma opening switch does not depend on the direction of current flow or, therefore, on the electrode polarity. According to [14], a plasma opening switch operates with any combination of electrode polarity and plasma injection; the polarity effect is apparently caused by specific technical features of the design. According to the model of [8], a plasma opening switch operates only with one polarity of the electrodes. We shall not attempt to explain all the operating features, but only consider a few of them.

Equation (5) indicates that there is a critical current I_{cr}, known as the cutoff current. The cutoff current and its dependence on various factors have been studied experimentally by many authors [11, 13]. The operating conditions are chosen so that $I_{cr} \approx I_0$ in order to ensure more complete utilization of the stored energy. It has been shown experimentally that when the delay between the time of plasma injection and turning on the supply current is increased, the cutoff current becomes greater; then the plasma opening switch enters a short circuit regime and the switch operates again after a long (~100 μsec [15]) time.

According to the model proposed here, increasing the delay time leads to increases in R and ρ. R increases because expansion of the injected plasma, while ρ and p increase because of the continuous operation of the plasma gun (the operating time of the plasma gun usually is considerably longer than the supply pulse). Equation (5) implies that this requires an increase in the cutoff current.

When R and ρ reach values corresponding to $I_{cr} > I_0$, the switch ceases to operate. The short circuit regime sets in. When the delay time is long the plasma fills a large volume and stabilizes, which is favored by continuous operation of the plasma gun. The switch does not operate. After the plasma gun finishes operating, recombination and decay of the plasma cause the conducting region to shrink and the switch again begins to operate. This explains the striking dependence of I_{cr} on the shape of the plasma gun current pulse [11].

The plasma may begin to expand less rapidly and pinches begin to appear with a rising current near I_0. This leads to a reduction in R which ensures further compression even when $I < I_0$, i.e., in the falling portion of the current. This experimentally observed fact [11] finds a natural explanation in the model proposed here but cannot be explained at all by the model of [8].

Because of the plasma inhomogeneity, the cylindrical geometry, and the spreading out of the plasma along the storage unit by the nonuniform magnetic field, Eq. (5) cannot be satisfied simultaneously over the entire length of the inhomogeneity. This leads to the development of a noncylindrical z-pinch terminated by constrictions [16]. The strong localized electric fields observed in the plasmas of plasma opening switches [17] may be caused by the formation of constrictions and may confirm their existence.

z-Pinches develop in this model after the plasma expansion has been slowed down. This suggests that the magnetic pressure is greater than the gas dynamic pressure when the current rises rapidly. In this case the characteristic compression time [4] is $\tau = c\rho^{1/2}/j$. According to [16, 18], $j \approx 20$ kA/cm², so that $\tau \approx 10^{-8}$ sec, which is in good agreement with experiment.

We now use Eq. (2) to estimate the characteristic voltages that develop. For the plasma opening switch of [18] at $T \approx 2.5\cdot10^{-7}$ sec we have $\mathcal{E}_0 \approx 3V_0$ and for microsecond plasma opening switches [11] at $T \approx 1.5\cdot10^{-6}$ sec we have $\mathcal{E}_0 \approx 10V_0$. During operation with a diode as the load the maximum voltages are limited by breakdown of the diode and do not reach the calculated values. With an inductive load [11] they are determined by the load inductance L_i and given by $L_i\dot{I}_i \approx [L_i/(L_0 + L_i)](L_0I_0/\tau) \approx 2V_0$, which is also in good agreement with experiment [11].

In the proposed model the question of whether the compression of the parallel pinches is stable arises naturally. This problem can be resolved positively assuming a high plasma conductivity and low initial inductance of the z-pinches.

In conclusion, we note that the stability of plasma configurations is usually studied for equilibrium steady states under the assumption of small perturbations. In these cases the characteristic velocity for MHD flows is the sound speed v. Hence, the time for instabilities to develop is $\sim\lambda/v$, where λ is the characteristic size of the plasma formation for a given type of instability. When an instability is excited by different technical means one must expect that the characteristic times for them to develop will be determined either by the Alfvén speed or by shock waves. In this case $\tau \sim \lambda\rho^{1/2}/B \sim cx_0\lambda\rho^{1/2}/I$, where x_0 is the characteristic size. Increasing the parameters of the problem (x_0, I, ρ) greatly extends the prospects of controlling the time for the instabilities to develop. When $x_0 = \lambda = a$ (where a is the initial radius of the plasma column), the expression for τ coincides with the characteristic time to form the discharge [4] when the gas kinetic pressure is low compared to the magnetic pressure.

The author thanks L. A. Luk'yanchikov for continuing interest in this work and for support and S. M. Ishchenko and K. A. Ten for helpful discussions and comments.

LITERATURE CITED

1. P. I. Zubkov "Generation of pulsed voltages by an inductance that varies under the influence of intrinsic currents," Zh. Tekh. Fiz., 61, No. 11 (1991).
2. K. Schoenbach, K. Kristiansen, and G. Scheffer, "A review of opening switch technology for inductive energy storage," IEEE Trans., 72, No. 8 (1984).
3. K. Kristiansen, K. H. Schoenbach, E. E. Kunhardt, et al., Report of the Workshop on, "Repetitive Opening Switches," in: Proc. Third IEEE International Pulsed Power Conf., Albuquerque (1981).
4. A. F. Aleksandrov and A. A. Rukhadze, Physics of High Current Electric Discharge Light Sources [in Russian], Atomizdat, Moscow (1976).
5. V. S. Komel'kov, T. I. Morozov, and Yu. V. Skvortsov, "High-power discharges in deuterium," in: Plasma Physics and the Problem of Controlled Thermonuclear Reactions [in Russian], Vol. 2, Izd. Akad. Nauk SSSR, Moscow (1958).
6. L. D. Landau and E. M. Lifshitz, Electrodynamics of Continuous Media [in Russian], GITTL, Moscow (1957).
7. B. A. Trubnikov, "Particle acceleration and neutron production in the constrictions of plasma pinches," Fiz. Plazmy, 12, No. 4 (1986).
8. P. F. Ottinger, S. A. Goldstein, and R. A. Meger, "Theoretical modelling of the plasma erosion opening switch for inductive storage applications," J. Appl. Phys., 53, No. 3 (1984).
9. G. V. Ivanenkov, "Model of the dynamics of a high-current plasma erosion opening switch," Zh. Tekh. Fiz., 61, No. 5 (1991).
10. A. V. Gordeev, A. V. Grechikha, A. V. Gulin, and O. M. Drozdov, "Hall effect in plasma opening switches," Fiz. Plazmy, 17, No. 6 (1991).
11. É. N. Abdullin, G. P. Bazhenov, A. A. Kim, et al., "Plasma opening switch with microsecond energy input times into an inductive storage system," Fiz. Plazmy, 12, No. 10 (1986).
12. L. A. Artsimovich and R. Z. Sagdeev, Plasma Physics for Physicists [in Russian], Atomizdat, Moscow (1979).
13. D. D. Hinshelwood, J. R. Boller, R. J. Commisso, et al., "Plasma erosion opening switch operation at long conduction times," IEEE Trans. Plasma Sci., PS-15, No. 5 (1987).
14. B. M. Koval'chuk, V. A. Kokshenev, and F. I. Fursov, "High-power pulse generator with an intermediate inductive storage system," in: Abstracts of talks at the 6th All-Union Symp. on High-Current Electronics [in Russian], Tomsk (1986).
15. É. N. Abdullin, G. P. Bazhenov, A. N. Bastrikov, et al., "High-current plasma-filled diode in the current opening switch regime," Fiz. Plazmy, 11, No. 1 (1985).
16. V. F. D'yachenko and V. S. Imshennik, "Two-dimensional magnetohydrodynamic model of a plasma focus z-pinch," Reviews of Plasma Physics, Vol. 8 (Russian original, 1974).
17. Yu. P. Golovanov, G. I. Dolgachev, L. P. Zakatov, et al., "Study of electric fields in a plasma opening switch by means of Stark broadening of hydrogen spectrum lines," Fiz. Plazmy, 17, No. 7 (1991).
18. R. A. Meger, R. J. Commisso, G. Cooperstein, A. Shyke, and S. A. Goldstein, "Vacuum inductive store/pulse compression experiments on a high power accelerator using plasma opening switches," Appl. Phys. Lett., 42, No. 11 (1983).