OBTAINING STRONG MAGNETIC FIELDS WITH MAGNETOCUMULATIVE GENERATORS BASED ON A POROUS MATERIAL

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In magnetocumulative (MC) generators, intended for obtaining strong magnetic fields, trapping of the initial magnetic flux and its subsequent compression are realized by a closed metallic shell, accelerated by the products of the detonation of an explosive charge. The strongest magnetic fields were obtained with a MC-1 scheme [1-3].

High-quality and stable operation of such a generator requires that the cylindrical symmetry of the compressing shell be retained. For this reason, quite strict requirements are imposed on the preparation of both the shell itself and the generator of the cylindrical detonation wave.

The process of compressing the field is also complicated by the development of a Taylor instability, whose amplitude increases with time, on the inner surface of the cumulating shell. This effect breaks down the symmetry of compression of the shell and leads to catastrophic losses of flux during the last stage of operation of the generator.

High reproducibility of results are obtained in [3], where the problem of introducing the initial flux into the working region by combining the function of the solenoid and of the cumulating shell were originally resolved. However, the MK-1 generator, as before, is a complicated setup, and its construction and operation are beyond the means of individual laboratories. A dynamic method of forming the moving conducting shell was used for the first time in [4, 5] in order to amplify the current in flat and coaxial generators. For this purpose, the cumulating region was filled with a porous material, which, under the shock, acquires a high conductivity. If a closed configuration of shock waves, converging to a single axis, is formed in such a material, then the conducting layer forming behind these fronts can be used to compress the magnetic flux. An analogous method is proposed in [6].

In this paper, we present the results of experiments on obtaining magnetic fields in the megagauss range and we estimate the limiting possibilities of the method.

1. A diagram of the generator used in our experiments is presented in Fig. 1. The explosive charge 2 and the working substance 3, separated by a interlayer 4, are arranged in a square 1, prepared from an insulating material. The field at the center of the generator was measured with an induction meter 5. To create the initial magnetic flux in the region of compression, the generator was placed inside a solenoid, fed from a capacitor bank (not shown in Fig. 1).

The charge was detonated simultaneously at points 6 at the corners of the square at one-half the height of the charge with the help of four segments of a detonation fuse, which were initiated by a single detonator.

Two series of experiments were performed with the generators, differing by the size of the region of compression (50×50 mm^2 and 92×92 mm^2). The height of the working part of all generators was 30 mm. The explosive charge was hexogen with a density close to the bulk value. The mass of the explosive was about 70 g in the first series and 200 g in the second series.

PAP-1 aluminum powder with a starting density of 0.33 g$\cdot$cm^{-3} was primarily used as the working substance. In the starting state, the particles in the powder are usually covered with an oxide film, so that the powder has a satisfactory insulation strength. Under a shock load, due to the mechanical breakdown of the oxide layer and the sharp increase in its electrical conductivity with temperature, the powder acquires a high conductivity. These processes proceed on the average at lower pressures than the semiconductor–metal phase transition [4] and, therefore, the energy of the shock wave can be converted more completely into magnetic field energy. The results of the experiments are presented in Table 1.

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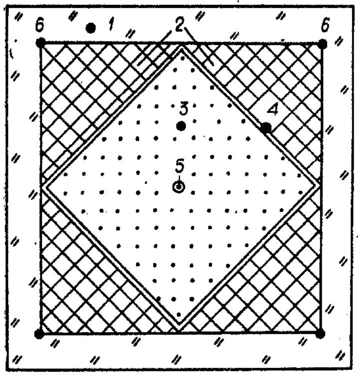

Fig. 1

In experiment 4, PA-4 aluminum powder with a density of 1.6 $g \cdot cm^{-3}$ was used as the working substance. Comparison of this experiment with the other experiments demonstrates explicitly the advantage of aluminum powder, so that it was used in all other experiments.

Comparison of experiments 1 and 2, as well as experiments 5 and 6, shows that the increase in pressure in the shock wave does not lead to an increase in the coefficient of amplification of the magnetic field $k = B_*/B_0$. Moreover, for generators with more powerful explosive charges, the coefficient k turned out to be smaller.

To estimate the size of the region of compression toward the end of the operation of the generator and the accuracy of the arrival of shock waves at the meter, experiment 8 was performed. The difference between this experiment and experiment 6 consisted of the fact that the meter was placed inside a textolite tube with an outer diameter of 10 mm. The considerably lower amplification factor of the field in this case indicates that the region is compressed quite symmetrically and its area in experiment 6 at the end of operation of the generator was less than 0.2 cm^2. The same experiment permitted estimating the average, over the time of operation of the generator, magnitude of the ratio of the mass velocity to the shock wave velocity, which turned out to equal 0.7.

Experiments 6 and 7 were performed under identical conditions, but the coefficients of amplification recorded in these experiments differ by 20%. This difference is explained by the breakdown in the symmetry of compression due to the nonsimultaneity of the emergence of the shock waves in the powder, as well as the errors in preparing and assembling the generator. The resulting possible spread in the results is also estimated to be about 20%.

Experiment 9, in which the maximum amplification factor was obtained, demonstrates the effect of the initial form of the working region on the quality of operation of the generator. The interlayer separating the explosive charge and the powder was slightly bent toward the explosive charge (R = 153 mm). This change in shape permitted increasing the initial magnetic flux, trapped by the cumulating shell, and simultaneously decreasing somewhat the weight of the explosive. An oscillogram of this experiment is presented in Fig. 2. Here, the field at the center of the generator is recorded in both beams and the sensitivity of the channels differs by a factor of 15. The time marks equal 10 μsec.

We note that in our experiments, the behavior of the magnetic field and its derivative during compression do not exhibit any peculiarities or tendencies to saturation up to the moment of breakdown of the sensor. In addition, the velocities of the shock waves in the generators of the two series, estimated from their times of operation, are practically identical. This indicates the weak damping of shock waves in the powder. Therefore, by selecting a more favorable form of the working region and by increasing the transverse size of the generator, it is possible to achieve even higher values of the amplification factor and of the final magnetic field.

2. To estimate the limiting field, which can be obtained by compressing with shock waves, we shall examine the problem in a two-dimensional formulation (Fig. 3).

A starting magnetic field B_0 is present in a region $0 < x \leqslant x_0$ filled with a porous medium with density ρ_0. A wall with infinite conductivity is located on the left side of the region. At time t = 0, a plate with mass M per unit area is incident on the right boundary of the region with velocity v. In the starting state, the medium does not conduct. Behind the shock wave front, the conductivity is σ. For our estimate, we shall assume that

TABLE 1.

Series	Number y of experiment	Hexogen density, g/cm^3	B_0, kG	$k=B_*/B_0$	B_*, kG
I	1	1,13	6,8	10	68
	2	0,9	6,4	18	115
	3	0,9	22	20	440
II	4	0,9	4,9	3,5	17,2
	5	1,13	3,8	20	76
	6	0,9	18,9	33,5	630
	7	0,9	19,4	26	500
	8	0,9	18,7	18	340
	9	0,9	19,6	46	900
	10	0,9	38,6	26	1000

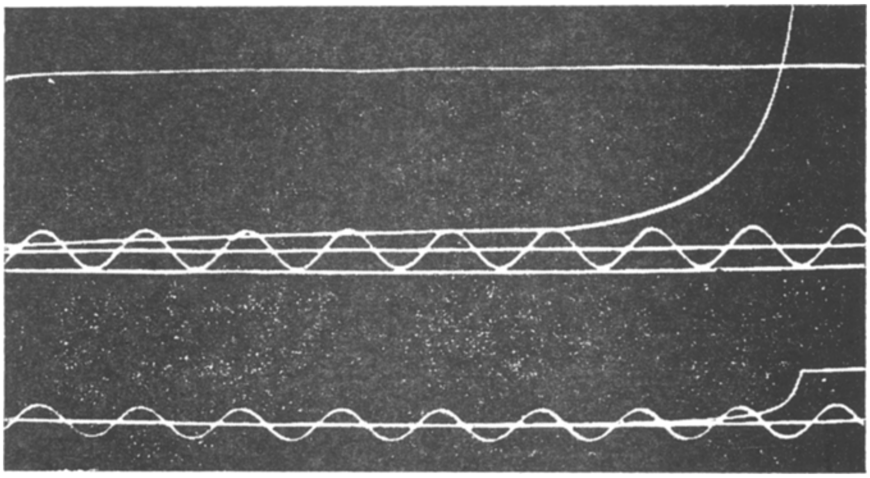

Fig. 2

the porous medium consists of rigid particles, which are packed by the shock wave from density ρ_0 to a density ρ. This model of the medium leads to a constant ratio of the mass velocity to shock velocity, i.e., u/D = const.

In this formulation, the process of compression of the field is described by the equation

$$-\frac{B^2}{2\mu_0} = \rho_0 uD + [\rho(x_2 - x_1) + M]\frac{du}{dt}, \tag{2.1}$$

where x_1 and x_2 are the coordinates of the shock front and of the impactor, respectively; B is the field between the wall and the shock front.

Since the ratio u/D is constant, the law governing the variation of the field in the region of compression $0 < x \leqslant x_1$ can be obtained from the equation of electromagnetic induction:

$$B = B_0(x_0/x_1)^{u/D}. \tag{2.2}$$

This relation is valid when diffusive losses of flux from the compression region can be neglected compared with convective losses. The region of applicability of this approximation will be indicated below.

Integrating Eq. (2.1), substituting (2.2), it is easy to obtain the velocity of the shock front as a function of its coordinate:

$$D^2(x_1) = \left(\frac{dx_1}{dt}\right)^2 = \left(1 + \frac{m}{\beta-2} - \frac{x_1}{x_0}\right)^{-2}\frac{4p_0}{\rho_0\beta}\left\{\left[\left(\frac{x_0}{x_1}\right)^{\beta-2} - 1\right]\frac{1}{\beta-2} + \frac{1+\frac{m}{\beta-2}}{\beta-1}\left[\left(\frac{x_0}{x_1}\right)^{\beta-1} - 1\right] + \frac{\varepsilon m}{\beta(\beta-2)}\right\},$$

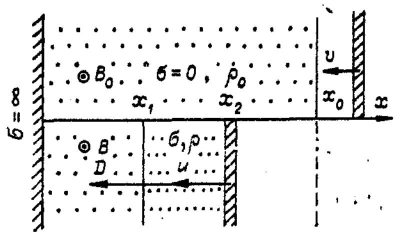

Fig. 3

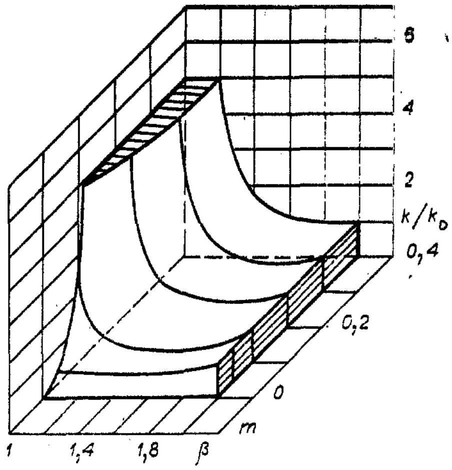

Fig. 4

where $m = 2M/\rho x_0$ is the dimensionless mass; $\varepsilon = Mv^2/p_0 x_0$ is the dimensionless energy; $p_0 = B_0^2/2\mu_0$ is the initial magnetic energy density; and $\beta = 2u/D$.

The field in the region of compression $0 < x \leqslant x_1$ reaches its maximum value at the time the medium and the impactor stop, i.e., when $dx_1/dt = 0$. From this condition, substituting (2.2), we obtain the equation for the limiting field B*

$$\frac{2-\beta+m}{\beta-1}\left[\left(\frac{B^*}{B_0}\right)^{\frac{2(\beta-1)}{\beta}}-1\right]+\left(\frac{B^*}{B_0}\right)^{\frac{2(\beta-2)}{\beta}}-1=\frac{\varepsilon m}{\beta}. \tag{2.3}$$

From here, we obtain two limiting regimes for amplifying the field:

a) $\beta \to 2$, i.e., $u \to D$, a flat MC generator with superconducting liner

$$B^*/B_0 = 1 + \varepsilon/2; \tag{2.4}$$

b) $\beta \to 1$, i.e., $u/D \to 0.5$. In this case, the maximum field depends exponentially on the energy ε:

$$B^*/B_0 = \exp\left[(\varepsilon m + 1)/2(m + 1)\right]. \tag{2.5}$$

Comparison of relations (2.4) and (2.5) shows that by selecting the parameters ε and m as $u/D \to 0.5$, it is possible to attain larger field amplification factors than in the classical case.

Figure 4 shows the solution of Eq. (2,3), obtained numerically. Here, the field amplification factor $k = B^*/B_0$, scaled to the amplification factor for $\beta = 2$, is presented for $\varepsilon = 100$ as a function of the parameters β and m.

The behavior of the field compressed by a cylindrical shock wave qualitatively retains the same character as in the two-dimensional geometry, i.e., the field is related linearly with ε as $\beta \to 2$ and depends exponentially on ε as $\beta \to 1$.

3. In the estimate of the limiting field presented above, we neglected diffusion losses of flux out of the cumulating region. Indeed, diffusion flux losses are large for large gradients of the magnetic field and, for compression of the field by a shock wave, the gradients are smoothed out due to the convective removal of flux by the matter from the region of compression. From the equation of electromagnetic induction, we can estimate the size of the region of compression, for which diffusion losses of flux equal convective losses: $x_1/x_0 \sim (u + D)D/[\mu(D - u)^2]$, where $\mu = \mu_0\sigma D x_0$ is the magnetic Reynolds number.

Substitution of the characteristic values, realized in experiments with aluminum powder, into this relation leads to the estimate $x_1 \sim 10^{-4}$ m. Since, in reality, sensors or the specimen being studied, whose sizes exceed our estimates, are placed in the region of compression, diffusive losses of flux can practically always be neglected when working with MC generators based on a porous material.

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INVESTIGATION OF THE INITIAL STAGE OF SEPARATION FLOW AROUND A CIRCULAR CYLINDER

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The model of potential flow of an ideal incompressible fluid is used extensively in theoretical investigation of nonstationary separation flow around bodies (see [1, 2], for instance). However, within the framework of this model a number of important questions have not yet been solved. Among them is the construction of the asymptotics for the solution in the neighborhood of the initial time. This paper is devoted to an investigation of this question for plane separation flow around a circular cylinder that starts to move from a state of rest.

Let us consider the plane fluid flow around a circular cylinder that occurs as it moves from a state of rest. We assume that the flow occurs with stream separation, which we model by one vortex wake converging with the cylinder outline. We consider the fluid ideal and incompressible, and the flow outside the cylinder and the vortex wake potential.

Let us formulate the problem of determining the kinematic flow parameters in a small neighborhood of the initial time $t = 0$ for certain constraints on the cylinder motion and the vortex wake parameters. Let us introduce a rectangular $O_1x_1y_1$ coordinate system at whose infinite point the fluid is at rest. Let a cylinder L_0 of radius R move at a velocity $-U(t)$ along the O_1x_1 axis (see Fig. 1).

We shall assume that the curvature of the vortex wake contour L_1 is continuous in the direction from A to B_1 while the intensity of the vortex wake $\gamma_1(\tau_1, t)$ has a derivative with respect to τ on L_1 that belongs to the class H^* in the neighborhood of the end B_1 and to the class H on the remaining part [3] (τ is the complex coordinate of a point of the contour L_1 in the complex plane $z_1 = x_1 + iy_1$, and t is the time). We also assume that the fluid velocities are finite everywhere. Consequently, the vortex wake will converge with the streamlined contour along the tangent [4], and its intensity at the point B_1 will be zero.

At a fixed time t in the complex plane z_1 a boundary value problem can be formulated for the complex velocity $\bar{v}(z_1, t)$ analogously to how it is done in [5, 6], on the construction of an analytic function $\bar{v}(z_1, t)$ outside the contours L_0 and L_1 which would satisfy the condition of nonpenetration on L_0, have a given jump on L_1, disappear at infinity, be finite everywhere and satisfy the Thomson theorem on constancy of the circulation of velocity over a closed fluid contour. This problem is a Reimann-Hilbert problem and allows of a unique solution that can be written in the form

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