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SHOCK-WAVE METHOD OF GENERATING MEGAGAUSS MAGNETIC FIELDS

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UDC 537.639

Relatively recently, we and Japanese investigators proposed a new method of generating superstrong magnetic fields through the compression of magnetic flux by a system of shock waves (SW) converging in a substance capable of converting from a nonconducting to a conducting state during compression [1-4]. In the present paper we study the possibilities of generators using this principle.

1. Compression of Magnetic Flux in a Perfectly Packable Substance with an Unlimited Electrical Conductivity Behind the SW Front

A fundamental property of the method of magnetic cumulation under consideration consists in the unavoidable losses of a certain (most often considerable) fraction of the magnetic flux. These losses are connected with the compressibility of the substance and occur even when the electrical conductivity of the material in the conducting state is unlimited. The mechanism of this kind of loss is simplest to understand on the model of a porous substance with an initial density ρ_0, which acquires electrical conductivity upon compression to a density ρ. In this case the magnetic flux initially penetrating a nonconducting granule of the substance remains frozen into the granule material after the phase transition, and only that part of the flux which was initially in the pores between granules of the substance is displaced into the region filled with uncompressed and nonconducting substance. If we designate the change in the area occupied strictly by particles of the substance as dS_c and consider that in compression this quantity is negative, and we also assume that the sizes of individual particles ahead of the SW front are small enough to establish equilibrium between the fields in the pores and the particles, then the equation for the flux losses from the compression region can be written in the form

$$d\Phi = BdS_c. \tag{1.1}$$

Using the equation of conservation of the mass flux at the SW,

$$\rho_0 dS = \rho dS_c, \tag{1.2}$$

we rewrite (1.1) for a uniform field:

$$d\Phi = \frac{\rho_0}{\rho}\frac{\Phi}{S}dS. \tag{1.3}$$

There are many reasons to assume that in the compression of metal powders coated with a film of nonconducting oxides, electrical conduction develops when a certain density ρ_c is reached, which is lower than the density of the crystalline state of the substance, of course, but which can prove to be a constant quantity for the same material and for initial grains of about the same shape. Under such an assumption, Eq. (1.3) is easily integrated and yields relations for the flux

$$\varphi = \frac{\Phi}{\Phi_0} = \left(\frac{S}{S_0}\right)^{\rho_0/\rho_c}$$

Novosibirsk. Translated from Zhurnal Prikladnoi Mekhaniki i Tekhnicheskoi Fiziki, No. 3, pp. 15-24, May-June, 1987. Original article submitted July 25, 1986.

and for the field

$$\beta = \frac{B}{B_0} = \left(\frac{S_0}{S}\right)^{1-\rho_0/\rho_c}. \tag{1.4}$$

In this case, (1.2) in the kinematic aspect leads to

$$\rho_0/\rho_c = 1 - u_c/D = 1 - \alpha,$$

while the assumption made means that the transition of the substance to the conducting state occurs at that phase of compression in the SW front when the ratio of the mass velocity u of the substance to the wave velocity D proves to equal a certain constant value α. It is clear that if the SW is strong enough and compresses the substance above the density ρ_c, the field frozen into the substance will increase in proportion to the degree of compression, but this says practically nothing about the field ahead of the SW front.

Individual specific features of the shock-wave compression of magnetic flux can be analyzed on the example of the problem of the compression of a perfectly packable substance by a cylindrical liner moving at a velocity u_0. We assume that the substance has a density ρ_0 ahead of the SW front, while behind the front it has a density ρ which does not depend on the intensity of the SW. At the initial time the substance occupies a cylindrical region with a radius R_0 and a field B_0 in it. So as not to complicate the problem, we assume that the liner compressing the substance is thin with a mass M per unit length along the axis. The formulated problem is characterized by the set of dimensionless parameters

$$\alpha = \frac{u}{D} = 1 - \rho_0/\rho; \tag{1.5}$$

$$p_0 = \frac{B_0^2}{8\pi}\frac{2}{\rho u_0^2}; \tag{1.6}$$

$$m = \frac{M}{\pi R_0^2 \rho}. \tag{1.7}$$

Instead of p_0 of (1.6), in a number of cases it is more convenient to introduce the initial magnetic energy, normalized to the kinetic energy of the liner:

$$e_0 = \frac{B_0^2}{8\pi}\pi R_0^2 \frac{2}{M u_0^2} = \frac{p_0}{m}.$$

The presumed incompressibility of the substance after the transition to the conducting state and the known law of variation (1.4) of the magnetic field frozen into the substance allow one to calculate the energy of the magnetic field during compression,

$$e = \frac{e_0}{1-2\alpha}\left(1 - \alpha - \alpha x^{2(1-2\alpha)}\right), \tag{1.8}$$

where $x = r/R_0$; r is the position of the SW front moving toward the axis. An analysis of this formula shows that for highly compressible substances ($\rho_0/\rho \ll 1$, $\alpha \approx 1$) the magnetic energy grows without limit as the wave converges toward the axis. Strictly speaking, for this it is sufficient that $\alpha > 1/2$. For $\alpha = 1/2$, from (1.8) we get $e = e_0(1 - \ln x)$, i.e., a similar phenomenon is observed. In return, for moderately and poorly compressible substances ($\alpha < 1/2$), the magnetic energy is always finite and

$$e \xrightarrow[x\to 0]{} e_0 \frac{1-\alpha}{1-2\alpha}.$$

This means that in such a case the SW can arrive at the axis of symmetry, if dissipative processes of the viscous type [5] do not prevent this.

More detailed information about the dynamics of SW cumulation can be obtained by solving the equation

$$\frac{dy}{dx} = \frac{2y}{x}\left(\frac{2 - \alpha - \frac{\alpha x^2}{\zeta^2}\left(1 - \frac{m}{\zeta^2}\right)}{\ln\frac{\zeta^2}{x^2} + \frac{m}{\zeta^2}} - 1\right) + \frac{2\alpha p_0}{x^{4\alpha+1}}\frac{1}{\ln\frac{\zeta^2}{x^2} + \frac{m}{\zeta^2}}, \tag{1.9}$$

to which the equations of motion of the liner and the medium are reduced. Here $y = D^2/D_0^2$; $\zeta^2 = R^2/R_0^2 = 1 - \alpha + \alpha x^2$; $x = r/R_0$; D is the SW velocity; r is the position of the SW front; R is the position of the outer boundary of the compressed material; the zero index pertains to initial values.

The change of variables

$$y = \frac{1}{u}\frac{\alpha p_0}{1-2\alpha}\frac{1}{x^{4\alpha}}\frac{1}{\ln\frac{\zeta^2}{x^2}+\frac{m}{\zeta^2}}, \quad \xi = x^2$$

reduces (1.9) to

$$\frac{du}{d\xi} = (1-2\alpha)\frac{u}{\xi}(u_* - u), \tag{1.10}$$

where

$$u_* = 1 - \frac{1-\alpha}{1-2\alpha}\frac{1}{\ln\frac{\zeta^2}{\xi}+\frac{m}{\zeta^2}},$$

with the initial condition

$$u(1) = u_1 = \frac{\alpha p_0}{1-2\alpha}\frac{1}{m} \text{ for } \xi = 1.$$

It is easy to establish that in the region of compression $0 \leq \xi \leq 1$ there are two singular points of Eq. (1.10): $\xi = 0$, $u = 0$, with asymptotic behavior $u \approx C\xi^{1-2\alpha}$ of the solution in its vicinity, and $\xi = 0$, $u = 1$, with asymptotic behavior $u \approx 1 + C\xi^{2\alpha-1}$. In the case of high compressibility ($\alpha > 1/2$), the point $\xi = 0$, $u = 0$ consists of a pole with trajectories diverging in its vicinity, because of which $u \to \infty$ and $y \to 0$ as $\xi \to 0$, i.e., the falling SW stops and it is reflected from the "magnetic wall" at a finite value of the compression radius $x_* = (\xi_*)^{1/2}$. And the point $\xi = 0$, $u = 1$ consists of a node with trajectories converging to it in this case, but these solutions are nonphysical, since for $\alpha > 1/2$ they correspond to negative values of $y = D^2/D_0^2$.

For moderate and poor compressibility ($\alpha < 1/2$) the situation changes: The point $\xi = 0$, $u = 0$ becomes a node to which trajectories contract, while the point $\xi = 0$, $u = 1$ is converted into a pole with trajectories diverging in its vicinity. This means that for integral curves of the first type cumulation ends with the arrival of the SW at the axis, while for those of the second type it ends with reflection from the "magnetic wall." To which of the singular points a solution belongs depends on the initial conditions, while the separation of the solutions into two types depends on whether or not they intersect the curve

$$u = u_*(\xi). \tag{1.11}$$

It is easy to see that if $\xi = 1$, $u = u_1$, $u_1 \leq u_*(1)$ at the initial time, then the integral curve of Eq. (1.10) falls immediately below the critical curve (1.11) and, at the end of compression, arrives at the node $\xi = 0$, $u = 0$, i.e., the SW arrives at the axis upon an unlimited increase in velocity. For this it is sufficient that the initial magnetic energy be small,

$$e_0 \leqslant 1 - 2\alpha - (1-\alpha)/m. \tag{1.12}$$

On the other hand, if $u_1 \geq 1$, the trajectories $u(\xi)$ depart to infinity as $\xi \to \xi_*$, i.e., the SW stops at a certain finite distance from the axis and is reflected, for which it is sufficient to satisfy the condition

$$e_0 \geqslant (1-2\alpha)/\alpha. \tag{1.13}$$

The estimates (1.12) and (1.13) are useful, but rather coarse. More precise critical values e_0^* can be found by a numerical solution of Eq. (1.10) in the segment $\delta \leq \xi \leq 1$ with the initial condition $u(\delta) = u_*(\delta)$ for an unlimited decrease in δ. Calculations of this kind were made numerically, and their results are shown in Fig. 1, where the dependence $e_0^*(\alpha)$ is plotted for $m = 10$, 1, and 0.2 (lines 1-3). If $e_0 > e_0^*$, the SW decelerates and stops. Otherwise, the compression proceeds up to the axis. In this case the finite electrical conductivity and compressibility of the now conducting material can be a limitation on the magnitude of the field.

In the case when the energy restrictions prove to be dominant (a high initial magnetic pressure, a light liner), it is interesting to compare the degree of magnetic field compression attainable (β_*) with the limiting value β_{cl} attainable in classical magnetic cumulation by an incompressible, perfectly conducting liner: $\beta_{cl} = 1/e_0 + 1$.

Calculations of this kind were made for the problem formulated above, and their results, in the form of the dependence of the ratio $r = \beta_*/\beta_{cl}$ on the initial field energy, are shown in Fig. 2a-d for $\alpha = 0.2$, 0.4, 0.6, and 0.9, respectively, with $m = 0.2$, 1, and 10 (lines 1-3). We note that for a heavy liner ($m \geq 1$), the limiting field is always somewhat higher than in the classical case, while for a light liner the dependence is more com-

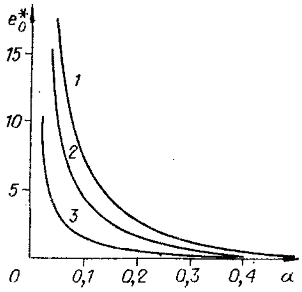

Fig. 1

plicated: In a wide range of initial field energy the field strengthening is lower than the classical value, but with a decrease in e_0 to the critical value e_0^* it increases sharply. This occurs because of a strong decrease in the stopping radius in comparison with its value in the ideal problem of classical magnetic cumulation. With an increase in α to ~ 1 this problem approaches the classical one, and for $\alpha = 1$ changes into it.

2. Compression of Magnetic Flux by a Perfectly Packable Substance with a Finite Electrical Conductivity in the Compressed State

Choosing the simplest subject for analyzing the influence of finite conductivity, we consider the plane problem of compression of a magnetic field by two plane SW moving toward each other with a velocity D. At the initial time the region containing a uniform magnetic field B_0 is filled with a nonconducting substance having a density ρ_0 and a transverse size $2x_0$. As a result of compression, the density of the substance grows to ρ and a conductivity σ develops in it. For simplicity, we take ρ and σ as constants, as well as the SW velocity. Then the mass velocity u of the substance behind the wave front also proves to be constant. By virtue of the symmetry of the problem, we can consider half of the compression region, placing a perfectly conducting plane in the middle of it. In the frame of reference connected with the SW front, the field in the compressed substance is determined by the equation

$$\frac{\partial B}{\partial t} = \frac{c^2}{4\pi\sigma}\frac{\partial^2 B}{\partial x^2} - (D - u)\frac{\partial B}{\partial x},$$

in which the well-known diffusional term, described by the first term on the right side, is supplemented by a second, convective term, describing the removal of field by the conducting substance moving relative to the front with a velocity $(D - u)$.

The condition of continuity of the tangential component of the electric field at the SW front ($x = 0$) leads to the relation

$$\frac{c^2}{4\pi\sigma}\frac{\partial B}{\partial x} = (x_0 - Dt)\frac{\partial B}{\partial t} - uB.$$

The formulated problem is a generalization of the simplest problem of magnetic cumulation between two conducting plane plates [6, 7] and changes into it for $u = D$.

Normalizing the size to x_0, the time to the compression time x_0/D, and the field to B_0 and introducing the magnetic Reynolds number $\mu = 4\pi\sigma D x_0/c^2$ and the kinematic compression parameter α, we reduce the problem of the field in the conductor to the solution of the equation

$$\frac{\partial^2 b}{\partial x^2} - \mu(1 - \alpha)\frac{\partial b}{\partial x} = \mu\frac{\partial b}{\partial t}, \quad x \geqslant 0 \tag{2.1}$$

with the condition at the boundary

$$\frac{\partial b}{\partial x} = \mu(1 - t)\frac{\partial b}{\partial t} - \alpha\mu b, \quad x = 0 \tag{2.2}$$

and the initial condition $b(x, 0) = 1$, $x \geq -1$. In the region not yet reached by the SW ($t - 1 \leq x < 0$), the field is uniform and equal to the field b(t) at the boundary of the conductor.

We find that Eq. (2.1) and the assigned initial conditions are satisfied by the expression

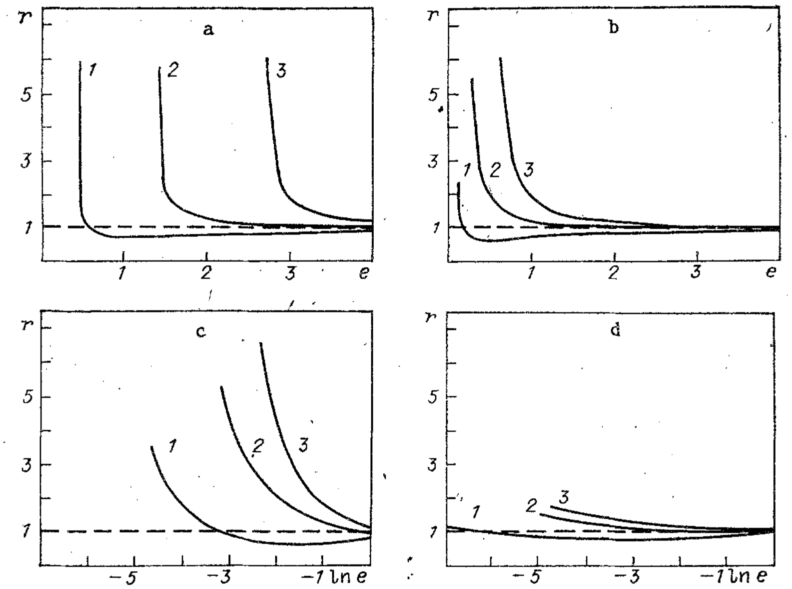

Fig. 2

$$b(x,t)=1+e^{\frac{1-\alpha}{2}\mu x-\frac{(1-\alpha)^2}{4}\mu t}\int_0^t \operatorname{erfc}\left(\frac{\sqrt{\mu}\,x}{2\sqrt{t-\tau}}\right)\frac{d}{d\tau}\left[(b(\tau)-1)\,e^{\frac{(1-\alpha)^2}{4}\mu\tau}\right]d\tau, \tag{2.3}$$

which takes the value b(t) at the boundary x = 0. From the solution (2.3) it is simple to calculate the value of $\partial b/\partial x|_{x=0}$ and, after substitution into the condition (2.2), to obtain an integrodifferential equation for the field ahead of the SW front:

$$\mu(1-t)\frac{db}{dt}-\alpha\mu b=\frac{1-\alpha}{2}\mu(b-1)-\sqrt{\frac{\mu}{\pi}}\,e^{-\frac{(1-\alpha)^2}{4}\mu t}\int_0^t \frac{d}{d\tau}\left[(b(\tau)-1)\;e^{\frac{(1-\alpha)^2}{4}\mu\tau}\right]\frac{d\tau}{\sqrt{t-\tau}}.$$

By methods similar to those of [6, 7] we can reduce this equation to the ordinary differential equation

$$(1-t)\frac{d^3b}{dt^3}=\left[\frac{1}{\mu}+\left(\frac{3}{2}+\alpha\right)(1-t)-\frac{(1-\alpha)^2}{4}\mu(1-t)^2\right]\frac{d^2b}{dt^2}+$$
$$+\left[-4-\alpha+\frac{(1-\alpha)^2}{4}+\frac{(1-\alpha)^2(2+\alpha)}{4}(1-t)\right]\frac{db}{dt}-\frac{\mu\alpha(1-\alpha)^2}{4}b+f(t), \tag{2.4}$$

where

$$f(t)=e^{-\frac{(1-\alpha)^2}{4}\mu t}\sqrt{\frac{\mu}{\pi}}\frac{\alpha}{\sqrt{t}}\left(\frac{1}{2\mu t}-\frac{(1-\alpha)^2}{4}\right)+\frac{\alpha\mu(1-\alpha)^3}{8}\operatorname{erfc}\left(\frac{(1-\alpha)}{2}\sqrt{\mu t}\right).$$

The initial conditions are determined in the process of derivation of (2.4) and have the form

$$b(0)=1,\quad \frac{db}{dt}=\alpha,\quad \frac{d^2b}{dt^2}\to\alpha\left(\frac{1}{\mu}+\frac{3+\alpha}{2}\right)-\frac{\alpha}{\sqrt{\pi\mu}}\frac{1}{\sqrt{t}}\quad \text{at}\quad t=0. \tag{2.5}$$

Integration of Eq. (2.4) is connected with a number of difficulties, chief of which is that the point t = 1, corresponding to the end of compression, is an irregular singular point. The fundamental system of this equation consists of two solutions that can be represented, at least asymptotically, in the series form

$$g_j\approx\sum c_k^j(1-t)^k,\quad j=1,2, \tag{2.6}$$

while a third has the form

$$g_3\approx\left[\Sigma d_k(1-t)^k\right]\exp\frac{1}{\mu(1-t)}.$$

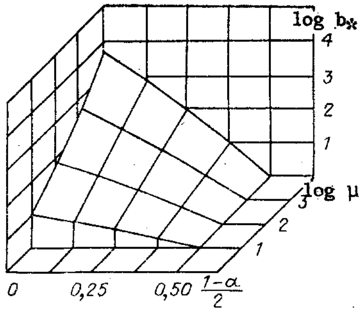

Fig. 3

The presence of such a physically unnatural solution as part of the fundamental system leads to divergence of the numerical calculation in time as t approaches one. Such difficulties were encountered in problems analyzed earlier [8, 9] and were bypassed by starting the integration from the point $t = 1$. But this complicates the problem, since the initial conditions on the function b(t) and its derivatives at the point $t = 1$ are unknown. This problem is solved as follows. First two independent solutions of the homogeneous equation (2.4) are sought in the series form (2.6), and by substituting them into (2.4), a system of equations determining the coefficients c_k is obtained. To solve this system it is sufficient to assign only the values of c_0 and c_1. For the first of the solutions sought for the homogeneous equation we take $c_0 = 1$, $c_1 = 0$, and for the second $c_0 = 0$, $c_1 = 1$. Having determined the next three coefficients using recurrent relations, we can move over a certain small segment δ from the singular point and enter into a standard procedure of computer integration of the homogeneous equation (2.4) up to $t = 0$. The value of δ was chosen in successive calculations such that its variation did not affect the final result.

After the calculation of two linearly independent solutions of the homogeneous equation, a solution of the inhomogeneous equation was sought in the same way. For this the function f(t) was expanded in a series in powers of $(1 - t)$, while in the solution sought, which had the form (2.6), the series coefficients c_0 and c_1 were taken as zero.

After the three auxiliary calculations described, the general solution of the problem was sought in the form of a linear combination of two solutions g_1 and g_2 of the homogeneous equation and a particular solution $\bar{g}$ of the inhomogeneous equation: $b = a_1 g_1 + a_2 g_2 + \bar{g}$.

The unknown coefficients a_1 and a_2 were determined from the first two conditions (2.5) at the point $t = 0$ and the third was used to monitor the accuracy of the solution obtained. As a rule, it was satisfied to within the fifth place. In the numerical integration of Eq. (2.4) it was found that with an increase in the magnetic Reynolds number μ and a decrease in the compressibility of the material $(\alpha \to 0)$, the calculation also becomes unstable in the described procedure for solving the problem backwards in time. In such cases the calculation procedure became more complicated: Integration was carried out from the points $t = 1 - \delta$ and $t = 0$ to a certain internal point of the segment $[0, 1 - \delta]$, where splicing was done.

The results of calculations of the extreme field strengthening b_* are given in Fig. 3. With an increase in the compressibility and the magnetic Reynolds number, b_* increases. For infinitely compressible material $(\alpha \to 1)$, the extreme strengthening coincides with the analytical result of [6], corresponding to field compression in a plane slot between two conductors, $\beta_* = \mu/8 + (\mu/\pi)^{1/2} + 1$. In the case of finite compressibility, b_* is less than β_* for the same value of μ, and in an incompressible material it is entirely absent.

The growth of the field with time is shown in Fig. 4, where we give the results of calculations for $\mu = 1000$ and $\alpha = 1$, 0.75, 0.5, and 0.25 (lines 1-4). It is seen that 99% of the time, the compression is well described by a straight line in log–log coordinates, which corresponds to the power law (1.4), allowing only for convective removal of flux from the compression region. The finite electrical conductivity is felt only at the last instant of compression, bringing the field strengthening to the final value b_*.

The relative role of diffusional flux losses is small in the initial stages of compression, but it becomes decisive by the end of compression. This is indicated by the results of calculations of the relative decrease in the coefficient of field strengthening due to the finite conductivity of the compressed substance, $\Delta b/b = (\beta - b)/b$ [$\beta(t)$ and b(t) are the coefficients of field strengthening in the substance for ideal conductivity in the compressed state and for finite electrical conductivity, taken at a certain time]. The time dependence of this quantity is shown in Fig. 5 for the same values of μ and α as in Fig. 4.

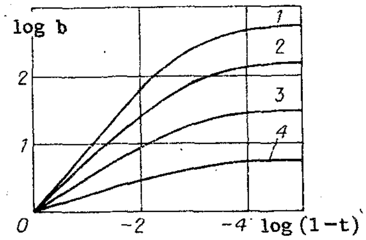

Fig. 4

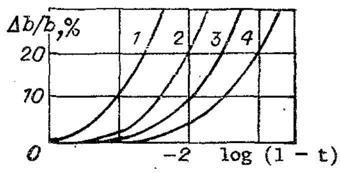

Fig. 5

3. Experimental Results

To determine the influence of the compressibility of the material on the field strengthening and to obtain magnetic fields in the megagauss range, we set up two series of experiments. The first series was carried out jointly with K. Nagayama in a laboratory at Kumamoto University (Japan). We used a very compact generator of a converging cylindrical wave, described in [4], that he developed. As the working substance we used aluminum powder with well calibrated grains of a certain size. The compression region consisted of a polyvinyl chloride plastic cylindrical can with an inside diameter of 44 mm; the fitting for the pressure sensor had an outside diameter of ~5 mm. A cylindrical tubular charge of plastic explosive was placed outside the can containing the aluminum powder. Using auxiliary charges and spacers of inert substance, simultaneous initiation along the middle of the main charge was accomplished and a good axisymmetric, converging SW was created. The time and the readings from the sensors were recorded by an instrument with digital storage, which simplified the further treatment of the results obtained.

The conditions and some results of the experiments are given in Table 1. The tests differed in the grain size of the aluminum powder and the initial density. In order to compact the fine aluminum powder, in test 2 it had to be wetted with acetone and pressed in this form, bringing its density approximately to the density of the coarser powder. The test was made after exposing the pressed and wetted powder for about 12 h, resulting in the evaporation of a considerable amount of acetone. The powder still remained moist immediately before the explosion, however. A decrease in the initial density (transition from test 1 to 3) considerably increased the degree of field strengthening and hardly affected the recording time. On the other hand, the decrease in α upon wetting of the material (compare test 2 with tests 3 and 1) shows that the coefficient of field strengthening decreases catastrophically.

It is interesting to depict the results of these three experiments in log−log coordinates, $\ln(B/B_0)$ and $\ln[(t_f - t_0)/(t_f - t)]$, where B_0 and t_0 are the initial field and the time of the start of compression and t_f is the conditional time of arrival of the SW at the axis of the system. If the SW velocity is taken as constant, then the value of $(t_f - t_0)/(t_f - t)$ equals the ratio of the initial size of the compression region to the size of the region bounded by the converging SW at the time t; such a construction allows one to judge the applicability of the assumptions of Sec. 1 to these experiments. Unfortunately, the low accuracy in determining B_0 and t_0 from a recording of the experimental results and a certain arbitrariness in the choice of the value of t_f hinder the execution of this attractive scheme, while the assumption that the compression velocity is constant seems extremely bold and can be adopted at all only for a considerable mass of explosive charge and strong stemming, which occurred, fortunately, in our experiments. With allowance for these reservations, let us consider the experimental results treated in this way, which are shown in Fig. 6, where the points are experimental readings while the straight lines are constructed by the method of least squares. The numbers by the lines correspond to the experiment number. It is seen that the experimental points can be arranged fairly well on the corresponding straight line, and the assumption that the compression velocity and amount of compaction are constant proves to be not so bad. The results of certain calculations based on these constructions are summarized in Table 2.

Thus, our experiments showed that the decisive factor for obtaining high magnetic field strengthenings is the choice of the initial state of the material, while the degree of its compressibility in the transition to the conducting state is the determining indicator for success of the experiment.

A second series of experiments was carried out at Novosibirsk [10] with the aim of obtaining magnetic fields in the megagauss range, for which we improved the shock-wave generator described in [3], in which PAP-1 aluminum powder with an initial density of 0.33 g/cm³ was used, as before. The changes introduced into the generator (Fig. 7) consist in the introduction into it of a copper liner 2 with a slit for the penetration

TABLE 1

Test number	Material	Grain size, μm	ρ_0, g/cm³	Field strengthening	Compression time, μsec
1	Powder	100	1,14	3,5	9,1
2	Powder + acetone	10	1,1	2,3	7,4
3	Powder	10	~0,5	18,9	9,2

TABLE 2

Test number	$\langle\alpha\rangle$	$\langle\delta\alpha\rangle/\langle\alpha\rangle$	ρ/ρ_0	ρ, g/cm³	D, km/sec	p, GPa
1	0,28	0,1	1,4	1,59	2,42	1,9
2	0,18	0,19	1,22	1,35	2,97	1,8
3	0,66	0,22	2,95	1,5	2,39	1,9

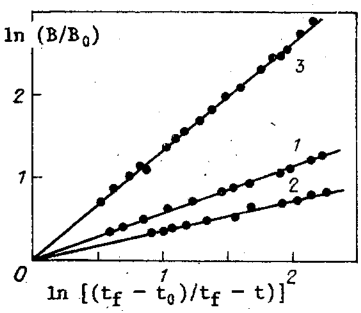

Fig. 6

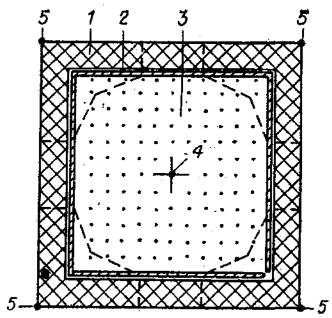

Fig. 7

of magnetic flux into the compression region. Besides the liner, the complete assembly contained a charge of TG 50/50 explosive 1 with a weight of 500 g, the working substance 3, and an inductive sensor 4. The dimensions of the working region were 130 × 130 × 50 mm. The initial magnetic field was produced in the substance using busbars mounted at the top and bottom, forming a Helmholtz pair of coils. The explosive charge was initiated at the four corners 5 of the generator over the entire height at once. After the charge is fired, a nearly cylindrical system of converging SW is organized in the working region (shown by dashed lines in Fig. 7). In the generator being described, the liner fills several functions at once:

it serves for the more efficient transfer of the explosive energy into the SW;

it permits the use of practically all the magnetic flux created in the working region for compression;

it fills the role of a kind of concentrator of magnetic flux, somewhat increasing the initial field in the generator.

In the experiments we were able to achieve the following results: The initial field B_0 = 40 kG was strengthened about 90-fold and reached 3.5 MG. An oscillogram of one of the tests is given in Fig. 8. The field in the generator is given by both channels, the sensitivities of which differ by a factor of 10. The time markings are 10 μsec.

Estimates show that in the process of compression, the pressure behind the SW front in the powder does not exceed several gigapascals, while the magnetic pressure is ~50 times higher by the end of the operation of the generator. Despite this, no peculiarities are observed on the oscillograms indicating a slowing of the rate of rise of the magnetic field. It seems that the initial magnetic field in the generator can be increased considerably without significant detriment to the magnetic field strengthening.

Our experiments also showed that sufficiently precise focusing of the SW onto the sensor, 3 mm in diameter, is accomplished in the generator, since the scatter of the results of several experiments proved to be small. If one considers that the size of the linear region of compression varies by a factor of about 40 in this case, it must be acknowledged that effects connected with instability and mixing of the field with the substance, which complicate experiments with classical generators of the MK-1 type [11], are greatly suppressed in the generator described.

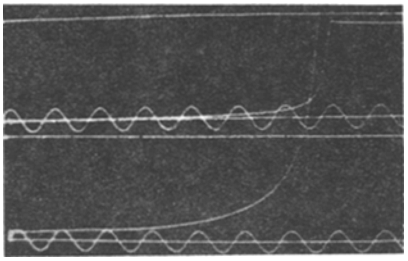

Fig. 8

The authors see future prospects for the shock-wave method of obtaining megagauss magnetic fields in the rational choice of the working substance with a low density and a rather high compressibility, as well as in an increase in the scale of the experiment. On the whole, shock-wave magnetic-cumulation generators of megagauss magnetic fields represent, in our opinion, a rather simple to build and inexpensive source for physics experiments.

In conclusion, the authors thank K. Nagayama for making it possible to conduct and use the results of the series of experiments.

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