Journal of Applied Mechanics and Technical Physics, Vol. 36, No. 3, 1995

MC GENERATORS. SELECTION OF OPTIMAL EXPERIMENTAL CONDITIONS

A. M. Trubachev

UDC 537.639

Many experiments on generation of ultrahigh magnetic fields in the range 1–15 mG have been performed by rapid compression of a magnetic flux by a conducting shell. The experiments were arranged in various conditions. Different schemes of introduction of initial magnetic flux, techniques of acceleration of a liner, its materials and design, etc. have been tested [1–12].

It should be noted that conducting explosive experiments on magnetic cumulation (MC) is a rather labor-consuming problem which requires specific conditions; therefore, such experiments can be carried out only in a limited number of laboratories. At the same time there is no technique, apart from the experimenter's intuition, for unique selection of starting generator parameters that will provide maximum field using a particular device, which results in unproductive expenditures. The results obtained by different laboratories differ widely and are difficult to compare because of different experimental conditions .

In the present paper we systematize published results on generation of ultrahigh magnetic fields. A technique for selecting the initial magnetic field parameters is proposed, which allows one to choose optimal experimental conditions in a few steps.

The first attempt was made in [13] to find parameters that make it possible to integrate results obtained on magnetic cumulation. The following parameters were chosen: $b = B_m/B_0$ is the experimentally obtained field amplification; B_m and B_0 are the final and initial magnetic fields; ε is the ratio of the kinetic energy of the liner to the magnetic energy in the volume to be compressed at the beginning of the process. It is extremely easy to present experimental data in these variables, and the results appear to be rather interesting, so that their analysis must be continued.

Further, we shall compare the operational efficiency of a real MC generator with an ideal one, in which the field is compressed without flux losses by a conductive cylindrical shell. In this case, from the condition of conservation of flow and energy, it follows that the field amplification coefficient $b = B_m/B_0$ and the radius of the internal cavity of the liner $x = r/r_0$ to the stagnation moment are completely determined by the ratio of the kinetic energy of the liner to the magnetic energy at the beginning of compression:

$$b = \varepsilon + 1; \tag{1}$$

$$x = (\varepsilon + 1)^{-1/2}. \tag{2}$$

The straight line in Fig. 1 shows the dependence (1).

The field amplification b is completely determined by the power parameters of the generator and grows with ε only as long as the radius of the internal cavity of the liner x remains greater than the transverse size of the measuring unit or experimental device $x_d = r_d/r_0$ (r_d is the radius of the sensor) placed at the axis. Given $x = x_d$, the field amplification coefficient achieves the limiting value $b = x_d^{-2}$ and further remains invariant as ε grows. Consequently, amplification of the generator in this field of variation of ε is concerned with the possibility of geometrical rearrangement of the volume to be compressed up to the moment of sensor failure only.

Thus, the curve of amplification of the generator as a function of ε consists of two portions: inclined for small ε and horizontal for great ones. The level of arrival of the curve at the horizontal portion depends on the size x_d. In real conditions, due to the instability of the shell compression and other processes resulting

---

Institute of Hydrodynamics, Russian Academy of Sciences, Novosibirsk 630090. Translated from Prikladnaya Mekhanika i Tekhnicheskaya Fizika, Vol. 36, No. 3, pp. 18–23, May–June, 1995. Original article submitted May 10, 1994.

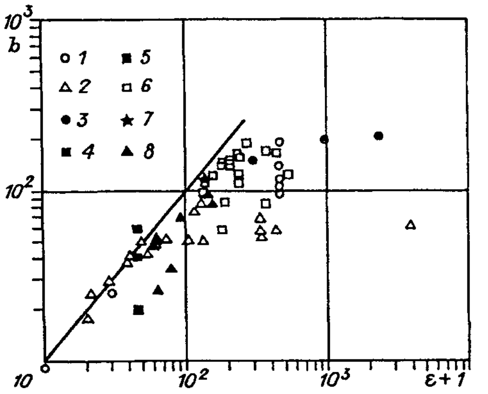

Fig. 1

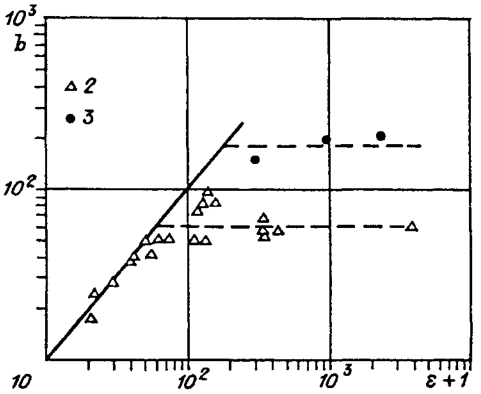

Fig. 2

in early destruction of the sensor, the size is not achieved, and a certain efficient size of the compressed region arises instead up to the moment when the signal registration terminates.

The results of data processing of the experiments on magnetic cumulation are presented in Fig. 1, where points correspond to the following experimental results: *1*, [7]; *2*, [2–6]; *3*, [1, 2]; *4*, [8]; *5*, [9]; *6*, [10]; *7*, [11]; *8*, [12]. We present the experimental results for which the value ε could be estimated.

In the processing, only two global parameters b and ε were used. Naturally, with this approach individual features of the experiments are lost. The diagram plotted does not contain direct information on the level of working fields and the devices themselves; however, it is noteworthy that, despite the wide variety of generator designs and different initial conditions of magnetic field and liner energy, the points in the diagram are arranged following a clearly pronounced pattern.

If we average the results for all experiments, the curve obtained for the amplification of the magnetic field will have a characteristic shape similar to that for amplification of an ideal generator. This similitude is particularly well expressed inside the groups of experiments (Fig. 2).

At the initial section (Fig. 1) up to $\varepsilon \cong 50$–60 the experimental points closely approach a straight line. In some cases they appear even higher than the straight line. Substantial losses (up to 80%) of magnetic flux from the compressed region were noted by all researchers. If during compression the symmetry of the liner is not distorted, its kinetic energy is used almost completely, while the minimum size of the compressed region due to the flux losses should be less than that given by relationship (2) but greater than the sizes of the sensing element. When working in this parameter range, one can obtain more or less reliable results, as well as observe the effect of the liner reflection from the magnetic field.

The position of several points significantly below the straight line in the above range of ε can be explained as follows. The statistics of published results is not complete. If reproducibility of results is not taken into account, then the best of them are reported, i.e., the data are filtered. It is known that negative results are frequently obtained in magnetic-cumulative experiments; therefore, all the stages below the straight line are accessible. The boundary of the accessible field amplification coefficients is the upper envelope going through the experimental points.

At $\varepsilon \geqslant 60$ the points depart from the straight line and are located in a wide horizontal strip $b \approx 60$–200. One notices that inside the strip the experiments conducted in different laboratories are joined in narrower stripes with different average levels. Thus, for points *2* $b \approx 60$, whereas for points *3* $b \approx 180$ (Fig. 1, 2, broken lines). This discrepancy is probably due to the features of the generators used.

Operation of the generators in the domain of high ε is characterized by a partial utilization of kinetic energy of the liner up to the moment when registration of the sensor signal terminates. The limiting amplification is connected not with the energy parameters of the generator, but with its physical state, i.e., the instability of the compression of the shell, overheating and evaporation of the shell, and the resulting

TABLE 1

Experiment	B_0, kG	B_m, MG	$b = B_m/B_0$	ε	B_0^0, kG	B^m, MG
LA1	90	14,3	158	300	127	20
LA2	20	4	205	2315	67	13,7
LA3	31	6,1	197	964	68	13,5

early destruction of the sensor. By the end of the signal recording, the effective size of the region occupied by the field mixed with the matter achieves its limiting value, which is greater than the size of the measuring element. Together with it, the field amplification coefficient, which is determined primarily by the feasibility of the geometrical rearrangement, achieves a maximum value independent of ε. Since at this section the main part is played by stochastic processes, the results are unstable. The improvement in sensor protection results in some cases in an increase of the maximum registered field, but it is easily seen that in all experiments the amplification does not exceed $b \approx 200$.

It follows from the behavior of the experimental amplification curve that to obtain the highest values of magnetic field using a particular system one should select the parameter ε so that the working point is placed in the transition region of the inclined portion of the amplification curve in the horizontal one. With the selection of ε, one may obtain high reproducibility of results and maximum amplification for a given explosive system and finite field. In this region the kinetic energy of the liner should be utilized completely by the moment the sensor is destroyed.

However, the majority of experiments do not satisfy the conditions formulated. By way of example, let us consider the experiments [1, 2] (points *3*, Fig. 1). Table 1 presents the parameters of the generators.

The large discrepancy in the values of b and ε attracted our attention, especially in the two last cases. If we accept that at the horizontal portion the coefficient b does not depend on the initial field or changes slightly, then following the aforesaid, one should change B_0 until the condition $\varepsilon \approx b$ is satisfied. Table 1 presents the initial field B_0^0 and the final field B_m expected in optimal conditions. It is obvious that the gain in field can be substantial even if one considers that b can be slightly reduced as the initial field increases.

The most representative is the series of experiments [8–10]. Its value consists in the fact that the same explosive system was employed in all experiments, i.e., the kinetic energy of the liner was the same, whereas the generator design and initial magnetic field were varied. The initial magnetic field was varied in a wide range ($B_0 \approx$ 50–160 kG), which makes it possible to estimate qualitatively the influence of the level of the working fields on the amplification coefficient.

With high levels of starting field, thermal processes accompanying the compression of the liner proceed more intensely and are triggered earlier than when the field is weak. Therefore, the registration of the signal ceases with the greater size of the compressed region and the lower field amplification coefficient. Thus, two experiments are presented in [9] (points *5*), and it is shown that for the given compression $\varepsilon \approx 46$ ($B_0 = 160$ kG) the amplification of the one-cascade generator equals $b \approx 20$ with relatively weak protection of the measuring element. One of the points *5* is way below the straight line and belongs to the horizontal portion of the amplification curve. This is confirmed by the reproducibility of the experiment and radiographs of the compressed shell presented in [9]. With the most reliable protection, the amplification of the generator is $b \approx 40$ (Fig. 1, second point *5*). The location of this point in the diagram shows that the amplification of the generator has achieved the limit, and further improvement of the protection by increasing its size can result in reduction of b again.

Under the same conditions the field amplification $b \approx 59$ is obtained (Fig. 1, point *4*) in a three-cascade generator [8]. The point lies way above the straight line of the generator amplification without losses. This fact, although unexpected at first glance, is explained by the presence of intermediate shields between the liner and the sensor zone. The possibility of this phenomenon, caused by the transfer of a part of the magnetic flux to the walls of the region being compressed, was described in [13, 14].

In the series of experiments with cascade generators [10] the initial magnetic field was varied within 50–100 kG, which corresponds to the change of the parameter ε in the range 130–500 (Fig. 1, points *6*). In approximately half of the experiments the average amplification of the field $b \approx 150$ was obtained. However, it is evident that the points leave the amplification straight line of an ideal generator and are widely spread along the horizontal straight line ($b \approx 150$), i.e., they do not lie in the optimal region of ε. If one takes into account that in the experiment [8] the point 4 is even somewhat above the straight line, then, having increased the initial field in these experiments, one can expect to attain the range of conditions necessary for achievement of the maximum field. According to our estimate, this corresponds to the range of initial and final fields 90–120 and 13–15 MG, respectively.

In the experiment [11] (point 7, Fig. 1) the liner was accelerated by a magnetic field instead of an explosive. Since at the starting moment the velocities of the liner and magnetic field in the region to be compressed are undetermined, to estimate ε an intermediate compression phase, when the liner velocity is stable, was selected. At the beginning of compression $\varepsilon \approx 137$, and the actually obtained field amplification $b \approx 116$. Unfortunately, this is thus far a single point, and it is difficult to predict the behavior of the amplification curve for this generator type with changes in the initial field; however, the experiment is likely to be carried out under almost optimal conditions.

The experimental points in Fig. 1 span a wide range of ε; however, one should bear in mind that these experiments were performed with different generators. Uniform experiments [8–10] cover the most interesting (from the viewpoint of obtaining maximum fields) region of ε (50–200) only fragmentarily. The exact course of the dependence of the feasible amplification coefficient on ε for a particular generator design is still unknown, but even the available scattered data allow one to select the optimal range of initial conditions.

When the generator design is selected, all its parameters (dimensions, kinetic energy of liner, etc.) are assigned and retained during the experiment. To choose the value of a single free parameter, i.e., the initial magnetic field, the following sequence of actions is proposed. The kinetic energy of the liner and the magnetic energy at the beginning of compression are determined in preliminary experiments with an arbitrary initial field, the field amplification coefficient b is found, and the parameter ε is calculated. It is evident from the diagram that the amplification $b \approx 200$ is limiting for all devices; therefore, in subsequent experiments the initial field should be selected so that the parameter ε does not exceed this value, which is its upper limit. Thereby the lower limit for the initial field is determined. The lower limit for the parameter ε and the upper limit for the initial field are determined from the condition $\varepsilon \approx b$, where b is the maximum among the amplification coefficients of the experiments.

Thus, in the preliminary experiments the range of ε is established ($b < \varepsilon < 200$), which should be used to achieve the maximum field. For example, it is evident from the diagram that the value $b \approx 100$ is rather typical; therefore, the upper and lower limits of the initial field differ by a factor of $\sqrt{2}$. This range is sufficiently narrow to be studied by a simple trial of initial fields or in a different way by monitoring the position of the working point in the diagram.

Thus, by analyzing the results on generation of ultrahigh magnetic fields, an empirical restriction on the field amplification coefficient in MC generators ($b \leqslant 200$) has been established. To select the optimal operation regime for an MC generator one should select the initial magnetic field so that the ratio of the kinetic energy of the liner to the magnetic energy at the inception of compression satisfies the condition $\varepsilon \approx b \leqslant 200$. Otherwise, the use of kinetic energy of the liner is inefficient. A significant part of the experimental results presented in Fig. 1 do not satisfy the condition formulated. This is partially explained by the problem of insertion of the initial magnetic flux into the closed metallic shell, which has been solved only recently by applying new principles in the design of generators [8, 15, 16]. In this connection the problem of correct selection of initial parameters of a MC generator arises.

The author is thankful to E. I. Bichenkov and S. D. Gilev for helpful remarks and advice.

This work was supported by the International Science Foundation (Grant RB0000) and by the Russian Foundation for Fundamental Research (Grant 94-02-04022).

REFERENCES

1. C. M. Fowler, W. B. Garn, and R. S. Caird, "Production of very high magnetic fields by implosion,"

J. Appl. Phys., **31**, No. 3 (1960).

2. F. Herlach, "Megagauss magnetic fields," Rep. Prog. Phys., **31**, No. 1 (1968).
3. F. Herlach and H. Knoepfel, "Megagauss fields generated in explosive-driven flux compression devices," Rev. Sci. Instrum., **36**, No. 8 (1965).
4. F. Herlach, "Flux loss on energy balance in magnetic flux compression experiments," J. Appl. Phys., **39**, No. 11 (1968).
5. F. Herlach and H. Knoepfel, "Results and limitations of cylindrical flux compression experiments," Proc. Conf. on Megagauss Magnetic Field Generation by Explosives and Related Experiments, Frascati, 1965, Brussels (1966).
6. C. di Gregorio, F. Herlach, and H. Knoepfel, "Simple flux compression devices with a small explosive charge," ibid.
7. A. Brin, J. Besancon, J. Champetier, et al., "Magnetic field compression," ibid.
8. A. I. Pavlovskii, N. P. Kolokol'chikov, O. M. Tatsenko, et al., "Reproducible generation of multimegagauss magnetic fields," Megagauss Physics and Technology: Proc. 2nd Intern. Conf. on Megagauss Magnetic Field Generation and Related Topics, Washington, 1979, New York (1980).
9. A. I. Pavlovskii, N. P. Kolokol'chikov, M. I. Dolotenko, et al., "Investigation of collapse dynamics of the shell of a magnetocumulative generator of ultrahigh magnetic fields," Ultrahigh Magnetic Fields. Physics. Engineering. Applications: Proc. 3rd Intern. Conf. on Generation of Megagauss Magnetic Fields and Related Experiments, Novosibirsk, 1983, Nauka, Moscow (1984).
10. A. I. Pavlovskii, A. I. Bykov, M. I. Dolotenko, et al., "Limiting value of reproducible magnetic field in cascade generator MC-1 ," Megagauss Technology and Pulsed Power Applications: Proc. 4th Intern. Conf. on Megagauss Magnetic Field Generation and Related Topics, Santa Fe, 1986. New York (1987).
11. T. Goto, N. Miura, K. Nakao, et al., "Megagauss field generation for application to solid state research," ibid.
12. T. Erber, H. G. Latal, J. E. Kennedy, et al., "Analysis of flux compression experiments," Acta Phys. Aust., **36**, Nos. 2–4 (1972).
13. A. M. Trubachev, "Effect of flux losses in MC generator," Megagauss Technology and Pulsed Power Applications: Proc. 4th Intern. Conf. on Megagauss Magnetic Field Generation and Related Topics, Santa Fe, 1986, New York (1987).
14. E. I. Bichenkov, S. D. Gilev, and A. M. Trubachev, "Shock-induced conduction waves in electrophysical experiment," Prikl. Mekh. Tekh. Fiz., No. 2, 132–145 (1989).
15. E. I. Bichenkov, S. D. Gilev, and A. M. Trubachev, "Shock-wave MC generators," Ultrahigh Magnetic Fields. Physics. Engineering. Applications: Proc. 3rd Intern. Conf. on Generation of Megagauss Magnetic Fields and Related Experiments, Novosibirsk, 1983. Nauka, Moscow (1984).
16. K. Nagayama and T. Mashimo, "Magnetohydrodynamic study of flux compression by the propagation of shock-compressed conductive region in semiconductors," ibid.