Magnetic cumulation

A. D. Sakharov, R. Z. Lyudaev, E. N. Smirnov, Yu. I. Plyushchev, A. I. Pavlovskiĭ,
V. K. Chernyshev, E. A. Feoktistova, E. A. Zharinov, and Yu. A. Zysin

(Submitted 23 August 1965)
Dokl. Akad. Nauk **165**, 65–68 (1965) [Sov. Phys. Dokl. **10**, 1045–1047 (1966). Also in S3, pp. 23–27].

Usp. Fiz. Nauk **161**, 47–51 (May 1991)

Any explosion is an abundant source of mechanical and thermal energy. In 1951 Sakharov proposed a possible way of converting this energy to magnetic form, together with the general design of devices for producing very strong fields and currents by the explosive deformation of current-carrying conductors. The process has been called magnetic cumulation. Here we describe briefly two typical generators of this type: The MK-1 (which employs compression of an axial magnetic field) and the MK-2 (ejection of the magnetic field from a solenoid and subsequent compression by the walls of a coaxial line).

Terletskii[2] published a short note on explosive compression of an axial field; a subsequent publication[1] later showed that similar experiments were done at about the same time at Los Alamos. No device resembling the MK-2 has previously been described.

I. The MK-1 is a metal tube surrounded by an explosive charge and containing an axial magnetic field. The charge produces rapid symmetrical compression and this induces a current in the tube which tends to maintain the field constant. For an ideally conducting tube

$$\Phi = \pi R^2 H = \pi R_0^2 H_0 = \text{const},$$

while the field strength and magnetic energy are inversely proportional to the square of the internal radius,

$$H = H_0 R_0^2/R^2, \quad W = W_0 R_0^2/R^2$$

where R_0, W_0, H_0 correspond to the initial values of the internal pipe radius, the magnetic energy, and the field strength, respectively.

The magnetic flux decreases if the conductivity is finite, the decisive parameter being $\eta = (4\pi\sigma R v/c^2)^{1/2}$, where σ is the conductivity and $v = -dR/dt$. The flux is conserved if $\eta \gg 1$. We have $\eta = \text{const}$ if $v \sim 1/R$. The flux follows $\Phi \sim R^{\alpha}$, where $\alpha = 2.26\eta^{-1}$ for η large.

Preliminary tests with aluminum tubes about 100 mm in diameter gave fields of 10^6 Oe; in one test with a stainless steel tube the field was 25×10^6 Oe for a final diameter of 4 mm (field pressure 25×10^6 atm). Figure 1 shows the oscillogram of the field in this test. The part corresponding to $H > 25 \times 10^6$ Oe lies outside the frame.

Figure 2 shows the general design of the generator. This test employed a charge giving very rapid and fairly symmetrical compression. The initial magnetic field was produced by a coil wound with aluminum foil on the tube; this coil was energized by a bank of condensers. The initial field penetrated into the free space, although the tube was not slotted, because stainless steel has a fairly low conductivity. The internal surface was coated with 20 μm of copper to provide better trapping of the field during compression.

Alternatively, the initial field may be provided by an MK-2 (see below), which can give strong fields over very large volumes; we recorded a field of 5×10^6 Oe in a volume of 100 cm^3 in a test with a copper tube 300 mm in diameter.

These fields clearly are not the strongest possible, for any desired H may, in principle, be provided by a tube compressed symmetrically at the appropriate speed, if, of course, the walls remain conducting in spite of the very large circulating currents.

II. The MK-2 consists of a central metal tube and a coaxial external spiral connected to a tube of the same diam-

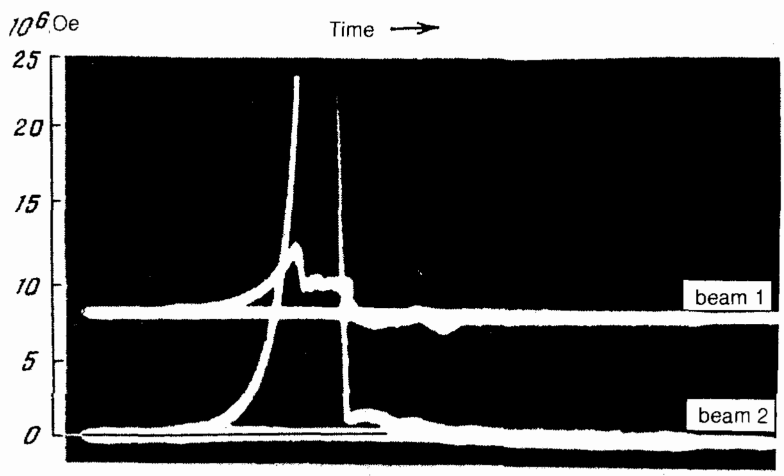

FIG. 1. Field oscillograms. Beam 1: background (signal from shorted leads); beam 2: signal from probe turn 1.5 mm in diameter (with RC integration).

 0038-5670/91/050385-02$01.00

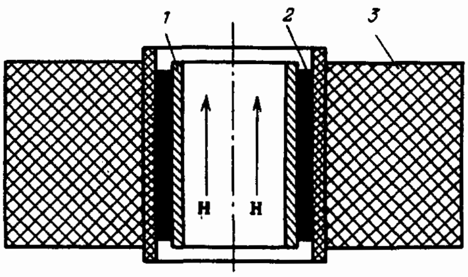

FIG. 2. The MK-1. 1: Stainless-steel tube; 2: winding of aluminum foil; 3: explosive.

eter (vessel) attached to the inner tube (Fig. 3). The latter contains a long cylindrical charge that is detonated from one end of the spiral. Another charge may be placed around the vessel and spiral. A bank of condensers is discharged through the circuit formed by spiral, vessel, and inner tube. The explosion causes the tube to diverge as a cone, which reaches the start of the spiral at the instant when the discharge current is maximal. The subsequent propagation along the tube gives rise to a pattern analogous to that from driving a metal cone along the spiral with the detonation velocity: the point of contact with the coil moves along a helix, the number of unshorted turns decreasing, and with it the inductance of the generator. The cone eventually reaches the start of the vessel to form a coaxial volume, whose length and inductance continue to decrease. The fall in the inductance leads to increase in the current I and magnetic energy W. Rapid deformation leads to conservation of the flux, i.e., $\Phi = LI \approx L_0 I_0$, so

$$I = \frac{\Phi}{L} \approx \frac{L_0}{L} I_0, \quad W = \frac{\Phi^2}{2L} \approx \frac{L_0}{L} W_0,$$

in which L_0, I_0, and W_0 are the initial values. The magnetic energy increases on account of the work done against the forces exerted by the field on the wall of the central tube.

The MK-2 has produced currents of 5×10^7 A with a final inductance of 0.01 μH; some tests have given a current amplification of over a thousandfold (to 10^8 A or more). The MK-2 has produced fields of 1 to 1.5×10^6 Oe in volumes of several liters, the stored energy being 1 to 2×10^7 J, or 10–20% of that produced by the explosive within the vessel (the flux is conserved during the deformation of the coaxial part).

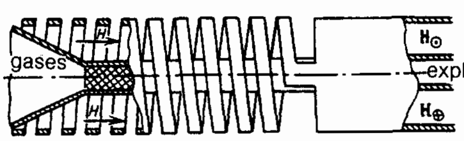

FIG. 3. The MK-2.

III. A load may be coupled to the MK-2 either directly (in which case the load inductance is the final one and must be kept small) or via a transformer (inductive coupling of the load to the generator).

A transformer allows one to transfer a substantial fraction of the explosion energy to the load; for example, 50% of the magnetic energy has been extracted from a small generator. This allows one to accumulate considerable energy in a load of substantial inductance and to place the load at some distance where it may be shielded from the explosion. In addition, a multistage generator may be based on this principle: the initial magnetic energy in the first generator is provided by a permanent magnet, and the energy produced in it is transferred via a transformer to a second generator, where it is further amplified and transferred to a third, and so on.

Another method of transferring the energy from the generator to the load is by interruption of the current-carrying circuit by means of an additional explosive charge, the magnetic flux being ejected from the MK-2 into the load (rupture method). This method allows one to transfer over 50% of the energy generated by the MK-2 to a load consisting of inductance and resistance. The transfer time has been 0.5×10^{-6} sec in some trials.

IV. These generators provide the basis for relatively small single-shot accelerators to produce 100–1000 BeV, as well as for plasma studies, acceleration of dense bodies to speeds around 1000 km/sec (production of stellar temperatures and pressures in the laboratory), shock-wave generation, research on the equation of state and properties of materials, and examination of effects on meteorite impact on spacecraft.

A generator of this type is under development for iron-free betatrons,[3] and trials have been made of remote supply of the electromagnet. Tests have also been done on coaxial electrodynamic accelerators; a velocity of 100 km/sec has been recorded for the metal vapor from aluminum foil of initial mass about 2 g.

These generators provide access to the very strong fields needed in the study of effects such as magnetoresistance in metals and semiconductors, magnetooptics, and so on.

[1] C. M. Fowler, W. B. Garn, and R. S. Caird, J. Appl. Phys. 31:588 (1960).
[2] Ya. P. Terletskii, ZhETF 32:387 (1957); Sov. Phys. JETP 5:301 (1957), trans.
[3] A. I. Pavlovskii, G. D. Kuleshov, G. V. Sklizkov, Yu. A. Zysin, and A. I. Gerasimov, DAN 160 1:68 (1965); Sov. Phys. Dokl. 10:30 (1965), trans.