FLUX LOSSES DURING COMPRESSION OF A MAGNETIC FIELD BY FLAT STRIPS

E. I. Bichenkov and V. A. Lobanov

UDC 538.4

The compression of a magnetic field by a moving conductor – magnetic cumulation – is used to obtain powerful magnetic fields and large pulsed currents [1, 2]. The potentialities of magnetic cumulation are determined mainly by the flux losses due to diffusion of the magnetic field into the conductor and its capture in short-circuited cavities formed upon the joining of uneven conductor surfaces. Experiments on the compression of a magnetic field by flat strips of copper and Dural are described in the report, and a comparison is made with the calculation of diffusional flux losses. The possible role of a gutter instability of the copper conductors is evaluated for the explanation of the increase in flux losses when a critical linear current density, whose value in the experiments presented was 180-210 kA/cm, is exceeded in the strips.

1. The flux losses were measured in experiments on the compression of a magnetic field by flat strips (Fig. 1). A U-shaped circuit (1) 505 mm long was made from strips 40 mm wide. A flat welded cassette (2) 520 mm long was placed between the strips so that the end of the cassette stood off 10 mm from the bend in the strips. The cassette was filled with a charge (3) of fused TG 50/50 explosive. A bar of Plexiglas (4) 10 mm thick containing two channels (5) in which the induction pickups for measuring the current were located was placed between the end of the cassette and the strips. A capacitor battery with a capacitance of 10^{-2} F and a voltage of up to 4 kV was discharged on the strips. The explosive charge was set off at the moment of the current maximum. When this happened the walls of the cassette flew apart to the sides, joining with the strips and compressing the magnetic field, as shown by the dashed lines in Fig. 1. The current was measured by the oscillographic recording of the signals from the inductive pickups. In each of the experiments two independent measurements were made and the current and the derivative of the current were measured by the oscillograph. One of the oscillograms is presented in Fig. 2: the upper beam is dI/dt and the lower beam is I. The moment of joining of the cassette walls with the strips is recorded on the dI/dt oscillogram – the point 1. The moment of emergence of the detonation at the end of the cassette corresponded to the moment of the dI/dt maximum – the point 2. The time coordination of the two oscillograms was accomplished with respect to these points. The oscilligrams were calculated over the time t_1 between the points 1 and 2 on the oscillogram. Here it was assumed that the inductance of the circuit decreases linearly with time: $L_1(t)=L_0-L'Dt$, where L_0 is the inductance at the moment the strips are closed, L' is the linear inductance of the circuit, and D is the velocity of the detonation. At the moment the detonation emerged at the end of the cassette the inductance was $L_2=L_0-L'Dt_1$. In dimensionless form

$$L=\frac{L_1(t)}{L_0}=1-\frac{L_0-L_2}{L_0}\frac{t}{t_1}=1-\tau,$$

if the dimensionless time is

$$\tau=\frac{L_1-L_2}{L_0}\frac{t}{t_1}.$$

From the current oscillograms the dimensionless flux was determined as

$$F=\frac{L_1 I}{L_0 I_0}=(1-\tau)\frac{I}{I_0},$$

where I_0 is the initial current.

Novosibirsk. Translated from Zhurnal Prikladnoi Mekhaniki i Tekhnicheskoi Fiziki, No. 2, pp. 154-158, March-April, 1975. Original article submitted July 16, 1974.

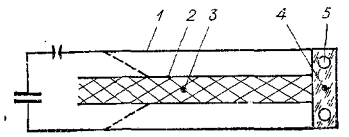

Fig. 1

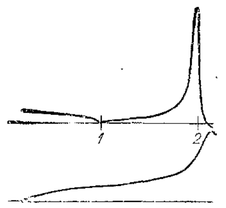

Fig. 2

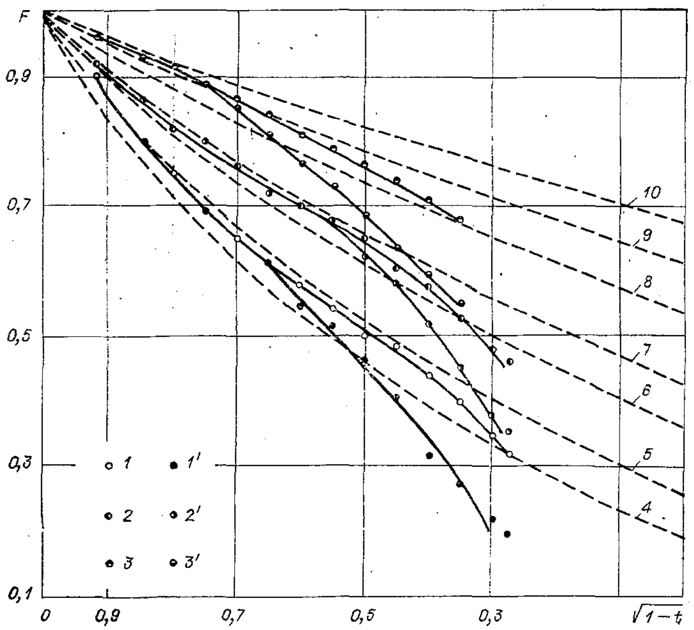

Fig. 3

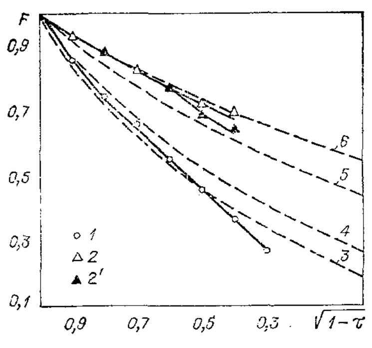

Fig. 4

Experiments were performed for different distances a between the strips and the walls of the cassette and different initial currents I_0. The experimental results for strips and cassette made of M1 copper are presented in Fig. 3: 1) $a=3$ mm, $I_0=240$ kA; 1') $a=3$ mm, $I_0=530$ kA; 2) $a=5$ mm, $I_0=260$ kA; 2') $a=5$ mm, $I_0=360$ kA; 3) $a=20$ mm, $I_0=100$ kA; 3') $a=20$ mm, $I_0=410$ kA. The results of experiments with Dural D16T are shown in Fig. 4: 1) $a=5$ mm, $I_0=120$–460 kA; 2) $a=20$ mm, $I_0=100$ kA; 2') $a=20$ mm, $I_0=400$ kA. Each curve was obtained by averaging over three to four experiments with two measurements in each. Despite this the experimental accuracy is not great because the current in each measurement varies by three to five times, which introduces a large error into the determination of I_0 from the oscillogram where the variation in the current during the entire experiment is recorded.

The calculated dependence $F(\tau)$ for the diffusion of a uniform field compressed in a flat slot made of a conductor with a constant conductivity is shown at the same time in Figs. 3 and 4 (by dashed lines). The calculations were made in accordance with the system presented in [3]. The initial field distribution was calculated on the assumption that the pumping current varies according to the law $\sqrt{t/t_0}$, where t_0 is the pumping time. As shown in [3], the diffusional losses during magnetic cumulation in flat slots depend weakly on the shape of the pumping current pulse and are determined mainly by the pumping time and the magnetic Reynolds number $\mu=4\pi\sigma a^2 D/c^2 l_0$, where l_0 is the initial length of the slot. This made it possible to approximate the quarter sinusoid of the pumping current by a parabola with good accuracy, which considerably simplified the calculations. In Fig. 3 curve 4 corresponds to $\mu=3$; 5) $\mu=5$; 6) $\mu=10$; 7) $\mu=15$; 8) $\mu=30$; 9) $\mu=50$; 10) $\mu=80$. In Fig. 4 curve 3 corresponds to $\mu=3$; 4) $\mu=5$; 5) $\mu=15$; 6) $\mu=30$.

2. It is not hard to see that the experiments for narrow slots with small initial currents (see Fig. 3, curves 1 and 2; Fig. 4, curve 1) basically correspond to the calculations. In this case the magnetic Reynolds

number is determined rather well by the equation

$$\mu=\frac{4\pi\sigma}{c^2t_1}\left(\frac{L_0h}{4\pi l_0}\right)^2\frac{L_0}{L_0-L_2}. \qquad 2)$$

Here h is the width of the strips. With $\sigma=5.3\cdot10^{17}$ cgs for a slot with $a=3$ mm this equation gives $\mu=4.15$; $a=5$ mm gives $\mu=12$; $a=20$ mm gives $\mu=87$.

The experiments with a wide slot (see Fig. 3, curve 3; Fig. 4, curve 2) at a small initial current correspond to the calculation only in the initial stage of compression. With the increase in the current toward the end of the compression the current losses become greater than the diffusional losses in all the experiments, this being especially noticeable for slots 20 mm wide.

The dependence of the flux losses on the initial current is clearly displayed for the copper conductors. With an increase in I_0 the flux losses at first proceed just as for small currents, but beginning with some critical current I_* they increase sharply: curves 1', 2', and 3' depart from curves 1, 2, and 3. For all three series of experiments I_* proved to be the same within the limits of accuracy of the flux loss measurements. The value of the critical current is $I_*=760$–840 kA, which corresponds to a magnetic field in the cavity of $B_*=230$–250 kG. The Dural conductors do not reveal the existence of a critical current I_*. Only for the slot 20 mm wide (see Fig. 4, curve 2) can one see some hint of an increase in flux losses at currents above $1.3\cdot10^6$ A (a field on the order of 400 kG).

3. It follows from Kidder's results presented in [4] that the surface layer of copper in a field of 250 kG is heated to a temperature no higher than 250°C. This does not allow one to explain the increase in flux losses in copper conductors by an increase in their resistance. On the other hand, the pressure of a 250 kG field on a conductor is 2.5 kbar and exceeds the tensile strength of copper. One can assume that in this case the surface of a conductor in a magnetic field begins to be curved – a gutter instability develops. When the irregular surfaces join the flux is captured in the cavities between them. If the average value of the surface irregularities is equal to δ then the flux losses in the uneven contact are described by the equation

$$\frac{dF}{dt}=-2\delta DB. \qquad (3.1)$$

The development of the irregularities occurs with a velocity on the order of the Alfvèn velocity $a=B/\sqrt{4\pi\rho}$, where ρ is the density. The time of development of the instabilities will be on the order of the time a/v_0 of movement of the plates up to the collision, where a is the width of the slot and v_0 is the velocity of the cassette wall. We assume that

$$\delta=\alpha a v_a/v_0, \qquad (3.2)$$

where α is some constant on the order of 1. By substituting (3.2) into (3.1) and integrating one can obtain in dimensionless form

$$F=\frac{1-\tau}{1-\tau+\frac{2\alpha v_{a*}}{v_0}\tau};\quad B=\frac{F}{1-\tau}=\frac{1}{1-\tau\frac{2\alpha v_{a*}}{v_0}\tau}.$$

Here the time is relative to the time of compression of the flux and the field is relative to the field at the initial time, taken as equal to the critical value B_*; the flux is relative to the initial flux F_*; v_{a*} is the Alfvèn velocity in the field B_*. The limiting compression corresponds to $\tau=1$ and the maximum field is

$$B^*=B_*\frac{v_0}{2\alpha v_{a*}}$$

or for the limiting current obtained in flat magnetic cumulation generators with a constant strip width we have

$$I^*=I_*\frac{v_0}{2\alpha v_{a*}}. \qquad (3.3)$$

To determine α in the experiments the limiting currents were measured. It was found that $I_*=2.4\cdot10^6$ A for $a=3$ mm; $I^*=2.6\cdot10^6$ A for $a=5$ mm; $I^*=2.7\cdot10^6$ A for $a=10$ mm. In these experiments $v_{a*}=250$–290 m/sec and $v_0=1.5$ km/sec and it follows from (3.3) that $\alpha=0.8$–1. One can also determine α from the behavior of the curve of flux losses at the critical point τ_*. With allowance for diffusion and the capture of flux at the site of contact of the strips we can write the dimensionless equation for the flux losses in the form

$$\frac{dF}{d\tau} = \frac{dF_g}{d\tau} - \frac{2\delta}{a} B. \quad (3.4)$$

The first term on the right side of this equation describes the diffusional losses and the second term, the contact losses. At the critical point $dF_g/d\tau$ is determined by the slope of the flux curve at small initial currents. The value of $dF/d\tau$ is determined from experiments with large currents. From curves 1-1', 2-2', and 3-3' (see Fig. 3) and from (3.2) and (3.4) one can now determine α. The calculations give α = 0.7-0.9, which agrees with the estimates based on the limiting currents.

The authors thank E. P. Matochkin for help in calculating the diffusional flux losses.

LITERATURE CITED

1. A. D. Sakharov, R. Z. Lyudaev, E. N. Smirnov, Yu. I. Plyushchev, A. I. Pavlovskii, V. K. Chernyshev, E. A. Feoktistova, E. I. Zharinov, and Yu. A. Zysin, "Magnetic cumulation," Dokl. Akad. Nauk SSSR, 165, No. 1, 65 (1965).
2. J. W. Shearer, F. F. Abraham, C. M. Aplin, B. P. Benham, J. E. Faulkner, F. C. Ford, M. M. Hill, C. A. McDonald, W. H. Stephens, D. J. Steinberg, and J. R. Wilson, "Explosive-driven magnetic-field compression generators," J. Appl. Phys., 39, 2102 (1968).
3. E. I. Bichenkov and E. P. Matochkin, "Flux diffusion during magnetic field compression in narrow slots," Zh. Prikl. Mekh. Tekh. Fiz., No. 4 (1974).
4. H. Knoepfel, Pulsed High Magnetic Fields, American Elsevier, New York (1970).