PRODUCTION OF STRONG TOROIDAL FIELDS BY MAGNETIC FLUX COMPRESSION

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Experiments conducted to produce megaGauss toroidal magnetic fields by flux compression are described. The possibility of intensifying the field by more than 20 times is shown experimentally. The experimental results are compared with theory. It has been shown previously experimentally that when compressing a longitudinal magnetic field by a liner which is also accelerated by magnetic pressure it is possible to obtain stable motion and good symmetry of the collapse [1-3]. These conditions are necessary for effective field intensification. However a configuration with closed lines of force is necessary from the viewpoint of the possibility of plasma containment and heating by a magnetic field. With this objective we examined the possibility of intensifying a toroidal field by magnetic flux compression.

The operating principle of the system is easily seen from the schematic shown in Fig. 1. The metal ring 6 travels with the velocity v between two coaxial cylinders so that in the process of the motion reliable electrical contact is provided between the ring and the cylinder at the point of sliding. In this case the magnetic field H_φ will be in a closed contracting volume. If we assume that the condition LI = const (for the contracting contour) is satisfied in the compression process, then the magnetic field intensity will increase in the compression process

$$H = L_0 H_0 / L$$

Hence we see that in the case of ring motion between cylinders it is necessary that the length l_0 of the compression segment be $\sim$5-10 cm in order to obtain a sufficiently large compression ratio for a final length on the order of a few millimeters.

The ring was accelerated by an azimuthal magnetic field. As a result of the long diffusion time in comparison with the compression time, the penetration of the accelerating magnetic field into the compression volume can be neglected. In view of the fact that the accelerating and retarding magnetic pressure depends on the radius

$$p_H \sim r^{-2}$$

to obtain uniformity of the motion it is necessary to ensure uniformity of the ring mass distribution.

However, it is not possible in practice to satisfy the uniform acceleration condition in the region near the wall because of the existence of friction. Therefore it is possible that unbalanced forces may develop which will lead to overturning of the ring. This phenomenon was actually observed in experiments with small ring thickness ($\sim$1.5 mm) and large travel. Therefore the ring thickness was made quite large in order to stabilize the motion. In this case the motion is stabilized as a result of the mechanical forces developed in the ring material.

Bimetallic rings (copper and aluminum, diffusion bonded together) were used in the experiments. Typical ring dimensions were: outside diameter 77 mm, inside diameter 63 mm, thickness 7 mm, mass 40 g.

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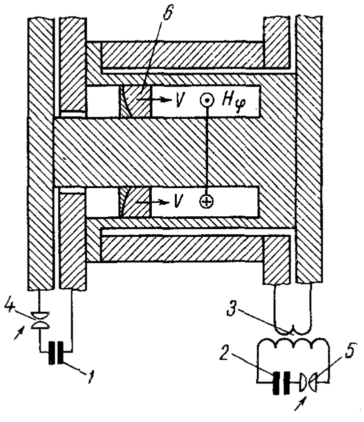

Fig. 1

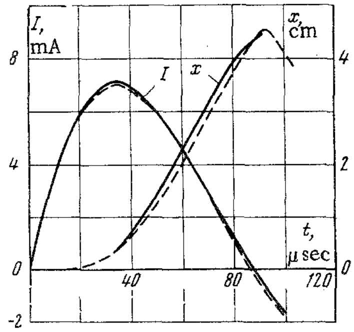

Fig. 2

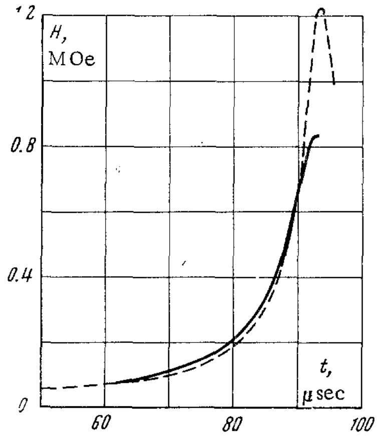

Fig. 3

The accelerating magnetic field is created by the discharge of the condenser bank 1 of capacity $42 \cdot 10^{-3}$ ef with voltage 5-5.5 kV through the system of discharge gaps 4. The design of the condenser bank and the switching system is analogous to that described in [2]. The initial discharge circuit inductance $L_0 = 1.4\text{-}10^{-8}$ H, the resistance $R = 2 \cdot 10^{-4}$ Ohms.

It was found experimentally that the motion between the cylindrical surfaces did not ensure good electrical contact with the ring, therefore in the subsequent experiments the cylinders were replaced by cones with taper $\sim 1°$ to the axis. In the experiments we used a 5-cm-long cone, with a 10-cm-long cone being used in some of the tests, but because of the doubled energy losses in friction the maximal magnitude of the fields obtained in this case was somewhat lower. To reduce the friction coefficient the cone surfaces were covered with a thin layer of tin ($\tau \sim 10^{-2}$mm). The initial magnetic field was created by the discharge current of the additional condenser bank 2 of capacity $5 \cdot 10^{-3}$ ef. The field penetrated into the closed compression volume because of the considerably shorter diffusion time ($\tau \sim 300$ msec) in comparison with the discharge period. Matching of the low-resistance load with the discharge circuit was accomplished by the current transformer 3.

The transformer was made structurally in the form of a coil (length 35 cm, diameter 26 cm, inductance $5 \cdot 10^{-4}$ H) wound from 50 turns of copper busbar of section 4×10 mm^2. The winding was baked in epoxy resin to increase the mechanical strength. The secondary, wound from 8-mm-thick copper sheet, was placed around the coil. The transformer leakage inductance was 10^{-4} H and together with the lead inductance provided a bank discharge period T = 5 msec.

With a voltage of 10 kV on the supply condenser bank the transformer provided a current of up to $1.2 \cdot 10^6$ A into the $R \sim 5 \cdot 10^{-5}$ Ohm resistive load. The initial magnetic field, measured in the compression volume in the different experiments, varied from 20 to 50 kG.

Inductive probes were used to measure the field in the compression process. The probe was made from two turns of 0.15-mm-diam PÉV-1 wire, wound on a 1.0-1.5 mm diameter frame. The four probes, spaced 90° apart, were mounted in the end of the compression volume so that the probes were destroyed as the moving ring reached full travel. This positioning of the probes made it possible to evaluate the uniformity of the motion of the entire ring in the field compression process. The probe leads passed through holes in the outer frame. One of the probes was also used to measure the initial field immediately prior to initiation of the compression process.

The experimental results were compared with numerical calculations made on a Minsk-22 computer. The calculations were made for the case of ring motion between cylindrical surfaces. We examined a system consisting of the capacitance C, inductance $L = L_0 + L(x)$, and resistance R. At the time t = 0 the capacitor was charged to the voltage U_0, $L = L_0$. The equations describing the electrical processes in the circuit may be written as follows after simple transformations:

$$\frac{dI}{dt} = \frac{U_0 - q/C - RI - 2\cdot 10^{-7} Ix^{\cdot} \ln(r_2/r_1)}{L_0 + 2\cdot 10^{-7} x \ln(r_2/r_1)}, \qquad \frac{dq}{dt} = I \tag{1}$$

Here I is the current in the circuit, x is the distance traveled by the ring, r_1, r_2 are the radii of the inner and outer cylinders, q is the charge.

We combine with these equations the equation of motion of the ring under the action of magnetic pressure

$$\frac{d^2x}{dt^2} = \frac{\ln(r_2/r_1)}{m}\left[I^2 - \frac{I_0^2 l_0^2}{(l_0 - x)^2}\right] - \frac{F}{m} \tag{2}$$

Here I_0 is the initial current, l_0 is the compression chamber length, m is the ring mass, F is the friction force.

The friction force was found from the equation

$$F = k\sigma_b S$$

Here k is the friction coefficient, σ_b is the ultimate strength, S is the friction surface area; all quantities were assumed to be constant in time. In the calculation the friction coefficient $k = 0.2$, $\sigma_b = 15$ kgf/mm^2 (for aluminum).

Figure 2 shows curves of the accelerating current I and the distance x traveled by the ring. The distance versus time curve was obtained after analyzing the magnetic probe signals under the assumption Φ = const. Also shown for comparison are the calculated curves (dashed). The approximately identical nature of the theoretical and experimental curves up to $t = 80\ \mu$sec ($H = 250$ kG) suggests that up to these fields the condition Φ = const is satisfied quite well in this experiment. The slight difference between the curves at this stage is obviously explained by the inaccuracy in determining the parameters affecting the velocity, and also the error in measuring the magnitude of the magnetic field, which amounts to $\sim 5\%$. The comparatively marked difference in the behavior of the curves in the final stage of the motion can be explained by increase of the losses resulting from strong current heating of the contact surfaces and walls of the compression chamber.

Comparison of the signals from the four probes shows that the ring retains its flat form throughout the motion to within ~ 1 mm. In certain experiments with high initial fields the ring was brought to a stop by the magnetic forces. In this case no reverse motion was observed thanks to the relatively low magnitude of the field ($H \simeq 250$ kG) and the presence of considerable friction. Therefore it appears that the ring retained the same form it had at the moment it stopped. Stopping of the ring is indicated by the existence of a maximum of the field and the partially undamaged condition of the magnetic probes. In examining the ring we found that the portion which traveled opposite the holes for the probe leads protrudes ahead somewhat, since because of field nonuniformity in this location the retarding force is less than on the remaining segments.

Figure 3 shows the experimental curve of magnetic field intensity as a function of time; here again the theoretical curve is shown for comparison. The maximal value of the field recorded in the experiment was N = 840 kG. In the volume of about 4 cm^3 the ring velocity reaches $\sim 10^5$ cm/sec. The studies made showed the possibility of producing a strong magnetic field in such a system. In the experiments we were able to obtain more than 20-fold field intensification. It was also shown that stable motion with good uniformity can be obtained.

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