MAGNETIC FIELD IN NON-STATIONRY TOROIDAL SCREW FLOWS OF LIQUID METAL

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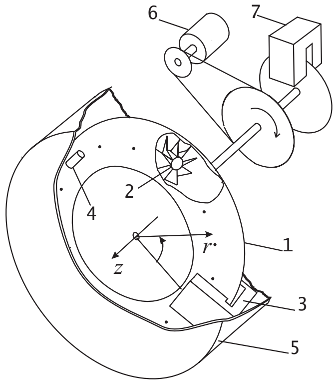
Introduction. The Perm dynamo project suggests to study the dynamo action in a non-stationary screw flow in an abruptly braked toroidal channel filled with liquid sodium. The experiment intends to implement a Ponomarenko like dynamo, and differs from the Riga experiment by the toroidal geometry and non-stationary character of the flow. The experimental scheme developed in Perm allows to avoid the use of large masses of liquid sodium and high power consumption, but leads to complex mechanical problems which concern the rotating channel and the braking system construction. Two kinds of experimental studies are planned to be performed at the sodium dynamo set-up. First, the peculiarities of Ponomarenko dynamo in toroidal geometry should be examined. Second, we plan to perform an extended study of dynamo actions, provided by essentially non-stationary processes.

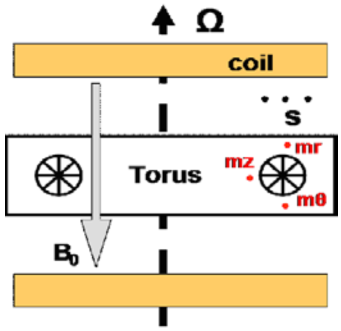
At the beginning of this project we have studied the non-stationary screw flow in water experiments. The results of these measurements were used for extended numerical simulations of induction processes in the toroidal channel, which allowed to optimize the characteristics of the experimental set-up. As the first stage of experimental studies of nonstationary induction processes in turbulent screw flows of liquid metals, we performed a number of experiments, in which the magnetic field of simplest toroidal and poloidal configurations was imposed on the turbulent screw flow of liquid gallium, driven in the smaller toroidal channel, and the magnetic field induced by the flow was measured. In spite of the fact that the flow is characterized by strong turbulence (hydrodynamic Reynolds number $\mathrm{Re} \approx 10^6$ and magnetic Reynolds number $\mathrm{Rm} \approx 1$), our measurements do not provide clear evidence of the small-scale turbulent effects (all results can be interpreted in terms of the mean velocity field only). We show that during the transition to the screw flow the poloidal magnetic field gets a burst of energy from the imposed toroidal field.

Gallium set-up. A schematic diagram of the gallium set-up is presented in Fig. 1a. The set-up consists of a toroidal channel (1) made of insulator (textolite), in which two oppositely located diverters (2) are fixed. The channel is fastened to a horizontal axle rotated by electromotor (6). A disc braking system (7) is fixed on the same axle.

Initially, the fluid together with the toroidal channel is in solid body rotation at a frequency up to 45 Hz. After braking, the model stops and, under the action of inertia, the diverters convert the toroidal motion of liquid gallium into a decaying turbulent screw flow. Some Hall probes are placed outside the gallium and measure the deformation of the imposed magnetic field B_0 under the action of the decaying motion.



(a)



(b)

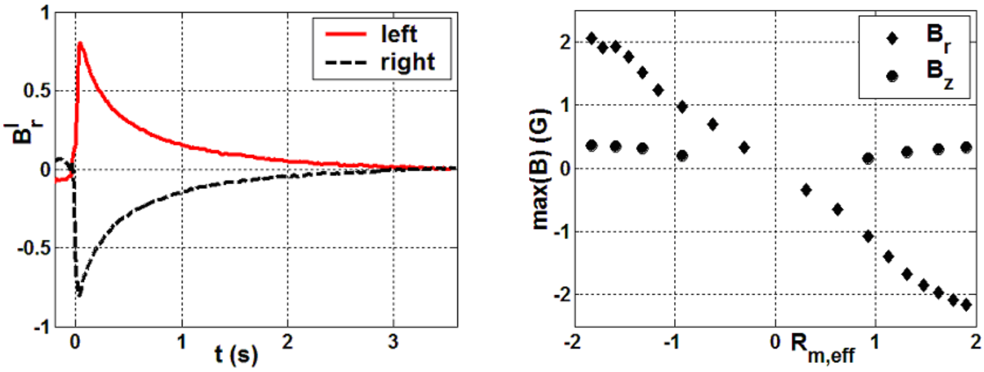
Fig. 1. (a) Scheme of the set-up: 1 – toroidal channel, 2 – diverter with left-hand or right-hand rotation fixed in the channel, 4 – magnetic sensor, 5 – steel cover, 6 – electromotor, 7 – brake, 8 – electromagnets; (b) Scheme of the experiment with a uniform transverse field.

The significance of the induced magnetic field B is characterized by the magnetic Reynolds number $\mathrm{Rm} = 2\pi R f r_0/\lambda$, calculated in terms of the large radius of the torus R, the small radius of the torus r_0, the frequency of rotation f and the magnetic diffusivity λ. In all experiments, Rm is less than 2, so only weak nonlinear phenomena can be expected. We have analyzed the symmetries of the induced field with respect to the flow reversals. The cylindrical coordinates (r, θ, z) (as shown in Fig. 1) are defined in the laboratory reference system, in which the z-axis is the revolution axis. Reversing the direction of rotation changes the signs of both the poloidal (V_r,V_z) and the toroidal V_θ velocity components, but keeps the sign of helicity. Replacing the right diverter by the left diverter changes the sign of the poloidal component only, which changes the sign of the large-scale helicity.

Magnetic Field in Nonstationary Toroidal Screw Flow of Gallium. First, we have applied the transverse field B_0 (Fig. 1*b*. The induced magnetic field generated by the flow of gallium was investigated in three experiments (with right diverters, with left diverters, without diverters) and at different Reynolds numbers. Fig. 2*a* shows the typical time evolution of the radial component B_r measured by the 3D static probe. The induction process starts with the beginning of braking ($t = 0$), quickly reaches a maximum and then decreases as the flow does. The curves were obtained in experiments with left (solid line) and right (dashed line) diverters for $f = -45Hz$ ($\mathrm{Rm} = -1.9$). Fig. 2*b* shows the maximum of B_r (location m_r, diamonds) and B_z (location m_z, dots) as a function of the magnetic Reynolds number. The results indicate a satisfactory axisymmetry of the induced magnetic field. The B_r component is an odd (almost linear) function of the magnetic Reynolds number, and B_z is even. When the left diverters are replaced by the right ones, the B_r component reverses its sign, while at location m_z the B_z component keeps its sign.

The induced poloidal magnetic field is produced by stretching of the transverse field lines by the poloidal velocity gradients and, since the poloidal velocity must be antisymmetric with respect to the plane $z = 0$, such linear effect must be zero at location m_z. At this location, the non-linear action of the poloidal velocity is measured. This effect expels the field lines from the vortex and, therefore, increases the magnetic field outside the flow. This expulsion mechanism does not depend on the rotation direction and is even in Rm. The obtained results indicate that one should not neglect this mechanism even under weak nonlinearity.

In order to investigate the possible induction effects induced by the small-scale



(a) (b)

Fig. 2. (a) Time evolution of B_r for $f = -45Hz$ and different diverters. (b) Maximal values of B_r (m_r probe, diamonds) and B_z (m_z probe, dots) versus Rm (left diverters).

helical vortices that could be responsible for conversion of the toroidal magnetic field into the poloidal one (α-effect), we have used the setup shown in Fig. 3. The imposed toroidal magnetic field of amplitude 35 G is created by a strong axial current, $I_0 = 1.5\,\mathrm{kA}$, passing along the axis of rotation.

The large-scale (mean) screw flow can produce only the toroidal mode from the imposed (toroidal) magnetic field. We expect that the small-scale turbulent pulsations are also helical and could support the α-effect. The latter is thought to generate a toroidal electrical current parallel to the imposed field, which results in a time-dependent axisymmetric poloidal (dipolar) magnetic field. The polarity of this dipole should be defined by the direction of the imposed field and the sign of helicity (i.e., by the kind of diverter, but not by the direction of rotation). We have recorded the flux of the induced field passing through the coil perpendicularly to the z-axis (Fig. 3) and consisting of 10000 loops of radius 0.05 m. The signal is amplified by the factor $A = 200$ before acquisition and then integrated and corrected by the geometrical factors to obtain an averaged value of the transverse magnetic field B_z on the surface of the coil.

Fig. 4 presents the averaged data of the measured magnetic field for two types of diverters and $\mathrm{Rm} = 1.9$. To separate the contribution of the α-effect, the signal is split into even and the odd parts with respect to the direction of rotation. The even part $B_{\mathrm{even}} = (B_z(\mathrm{Rm}) + B_z(-\mathrm{Rm}))/2$, which has to reflect the α-effect, shows a short strong burst, which changes the sign together with the helicity. The odd part $B_{\mathrm{odd}} = (B_z(\mathrm{Rm}) - B_z(-\mathrm{Rm}))/2$, which reflects the dependence of the induced field on the direction of rotation, is a smoothly decaying signal, which follows the decay of the flow. The strong burst in the even part corresponds

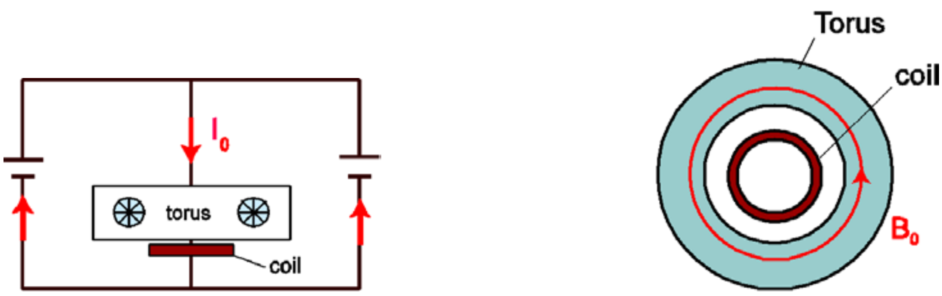
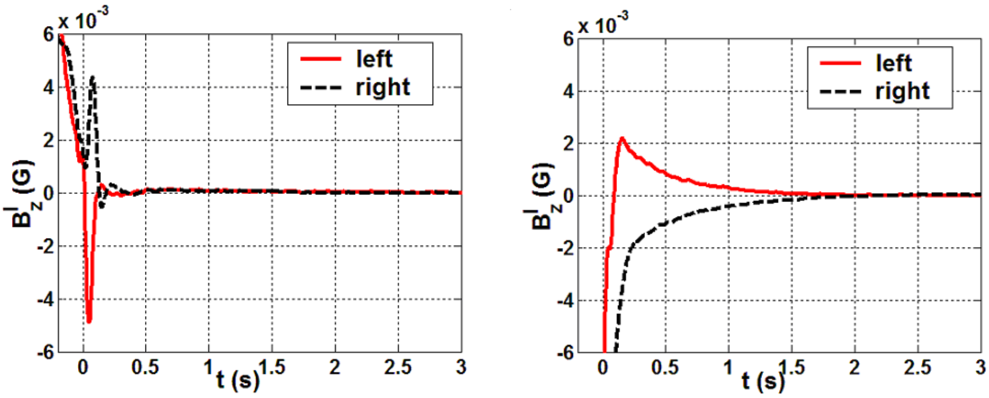


Fig. 3. Scheme of the experiment with the imposed toroidal field.

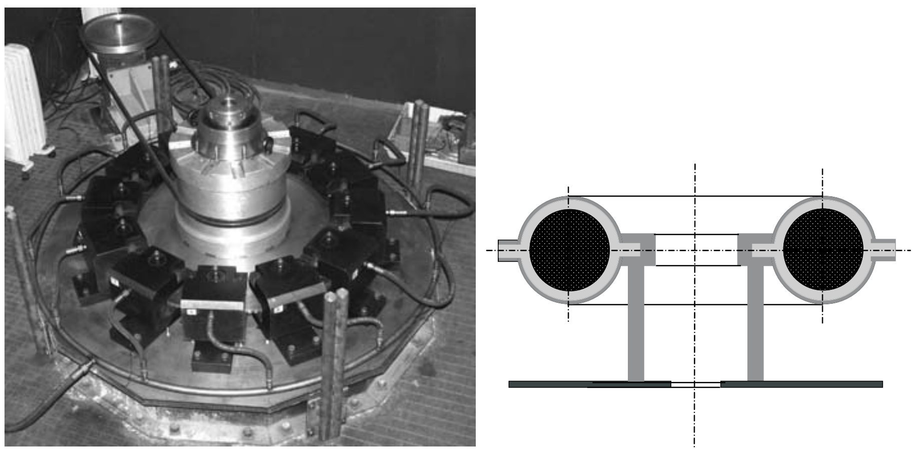


(*a*) (*b*)

Fig. 4. (*a*) Time evolution of the even part of the induced magnetic field measured by the coil (for left and right diverters). (*b*) Corresponding curves for the odd part.

to the transient regime, when the front of the screw flow propagates along the channel, producing a strong toroidal gradient of the poloidal velocity mode. The absence of the even part during the main stage of flow evolution ($0.1 < t < 1\,\mathrm{s}$) means that the possible contribution of the α-effect to the induced field is smaller than $B_z/B_0 \le 10^{-4}$. The odd part of the induced magnetic field (Fig. 3b) can be explained by weak transverse magnetic fields generated by supply wires (the symmetry plane of the torus is not that of wires).

The sodium set-up which should allow to achieve the dynamo threshold, is under construction. In contrast to the gallium set-up, the sodium one has a vertical axle of rotation. The set-up, which consist of a braking system, a hub and a toroidal channel itself, is fixed on a massive foundation in a concrete underground box. The setup without the channel is shown in Fig.5a, where 12 braking devices around the hub can be seen. The channel made of chromium copper ($R_0 = 0.4$m, $r_0 = 0.12$m) filled with 115 kg of sodium will be installed on the top of the hub (Fig.5b) and covered by a thermo-insulating shell. The final stage of construction works is expected to be performed in the spring of 2005.



(*a*) (*b*)

Fig. 5. (*a*) The hub with the braking system; (*b*) toroidal channel with sodium, the hub and the braking disc (scheme).