THE RIGA DYNAMO EXPERIMENTS

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1. Introduction

Cosmic magnetic fields, including the magnetic fields of the Earth and the Sun, are produced by the hydromagnetic dynamo effect. This effect relies on the mechanism that the interaction of the fluid velocity with a given magnetic field produces an electric current which, in turn, induces exactly the original magnetic field. In mathematical terms, the self-excited magnetic field is an *eigenfield* of the dynamo operator. A necessary condition for the dynamo effect to occur is that the so-called magnetic Reynolds number $Rm = \mu\sigma LU$ (with μ denoting the permeability, σ the electrical conductivity, L a typical length scale and U a typical velocity scale of the fluid flow) exceeds a critical value which is typically in the order of 10-100. It turns out that, even for sodium as the best liquid conductor and for optimized flow helicity, the product LU must be greater than 1 m^2/s. It is this large number which had prevented laboratory dynamo experiments until the year 1999, when the dynamo effect was observed in two liquid sodium facilities in Riga [1] and Karlsruhe [2]. Since that time, a number of additional experiments have been conducted at either place [4]. This interim report is intended to summarize the main results of the Riga experiments. More details can be found in [3-7].

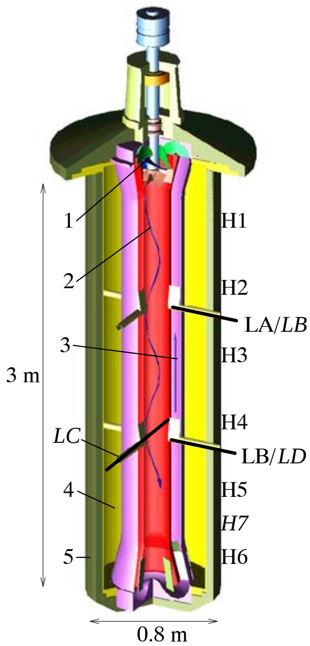

Fig. 1: The central module of the Riga dynamo experiment. 1 - Propeller, 2- Helical flow in central cylinder, 3 - Backflow in second cylinder, 4 - Outer cylinder with sodium at rest, 5 - Thermal insulation. H1-H7 – External Hall sensors. LA-LD – Internal Hall sensor lances.

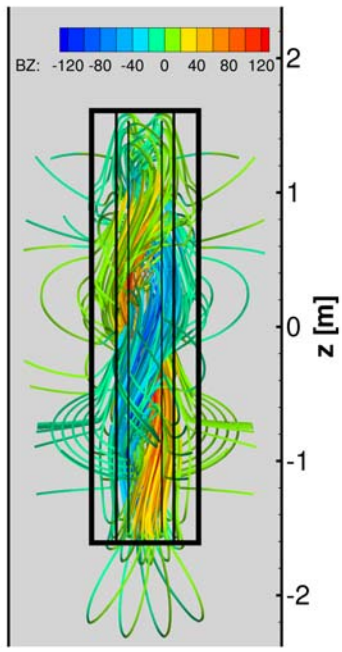

Fig. 2: Illustration of the magnetic eigenfield of the Riga dynamo experiment, as computed by a two-dimensional solver of the induction equation. The color coding reflects the axial component of the magnetic field in mT. The geometry and flow structure in the bending regions is slightly simplified.

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2. The Riga dynamo and its magnetic eigenfield

The central module of the Riga dynamo facility is sketched in Fig. 1. It comprises three concentric cylinders with different flow structures. The propeller in the upper part of the central cylinder drives a downward helical flow of liquid sodium with the ratio of axial to azimuthal velocity approximately close to one. The flow is bent at the bottom and goes upward in the second cylinder, after the rotation has been taken out by some guiding blades. The sodium in the third cylinder is at rest, at least at the beginning of the experiment. The propeller is driven by two electric motors with a maximum total power of about 200 kW. This enables sodium velocities up to 20 m/s, which is well above the critical point at which the dynamo effect occurs.

An impression of the field structure is given on the right hand side of Fig. 1. This field structure had been computed by means of a two-dimensional solver of the induction equation, which was also used for extensive computations for the optimization of the Riga dynamo experiment. Note the entangled helical structure of the magnetic field lines, which is typical for dynamos.

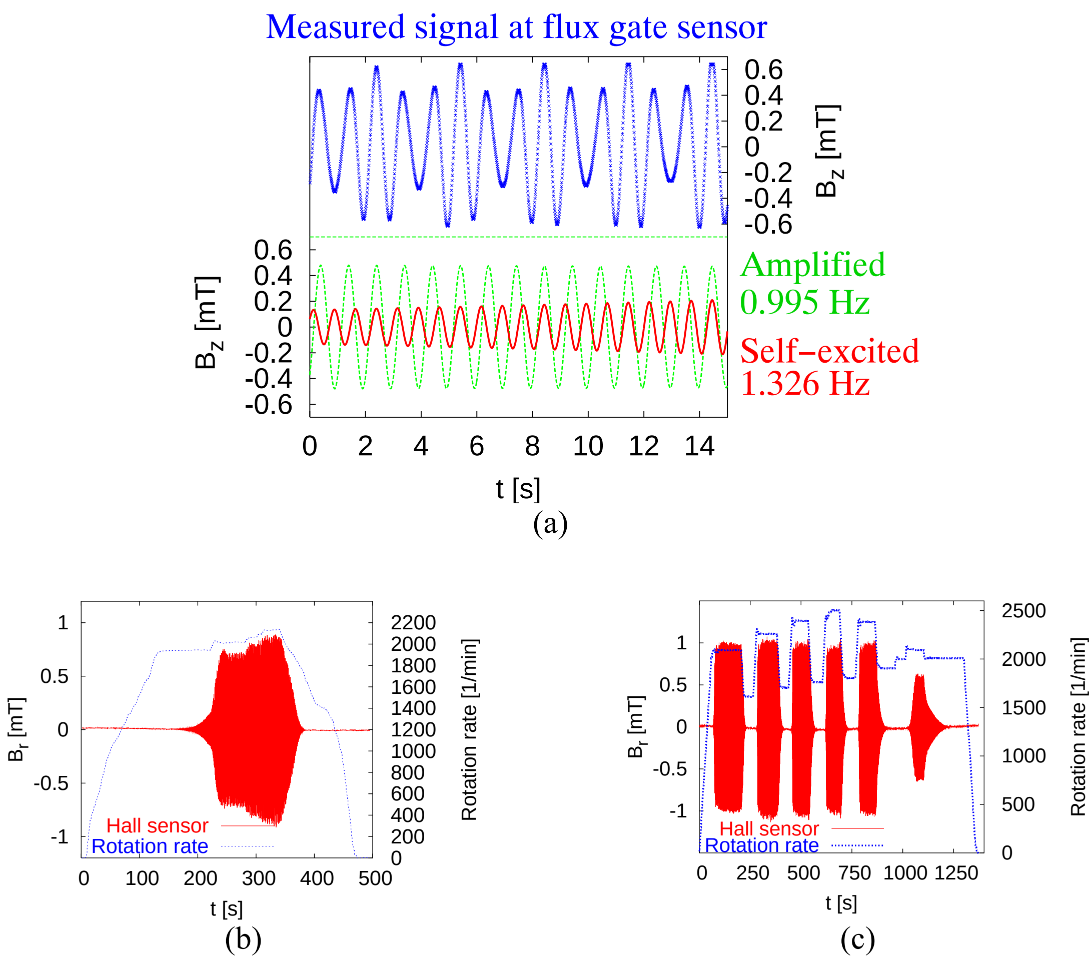


Fig. 3: Magnetic field data and propeller rotation rate during three different campaigns. (a) – First observation of an exponentially growing magnetic eigenfield in November 1999 (on the background of an amplified external signal). (b) - Exponential growth and saturation regime in July 2000. (c) - Switching the dynamo on and off during one run in the May 2004 campaign.

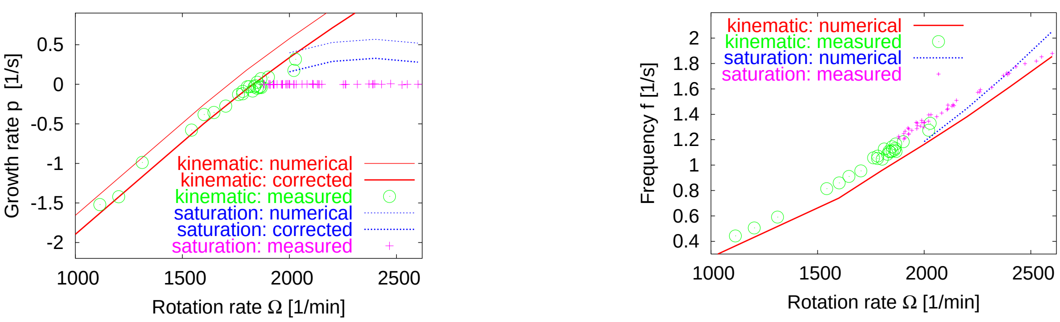
3. The experimental campaigns up to present

From November 1999 until May 2004, a total of six experimental campaigns have been conducted at the Riga dynamo experiment, with increasing complexity of the measurement system for magnetic fields, pressure and velocity.

The main achievement of the November 1999 campaign was the detection of a slowly growing eigenfield with a frequency clearly different from that of an amplified external signal (Fig. 3a). After the repair of a sodium seal, the next campaign took place in July 2000 [3]. It provided a wealth of data on the kinematic as well as on the saturated state of the dynamo. The growth rates and frequencies within the kinematic regime turned out to be in good agreement with the numerical predictions, with deviation of approximately 5 per cent. For the June 2002 campaign the magnetic field measurement had been significantly refined. At two heights, Hall sensor "lances" (LA-LD in Fig. 1) were inserted into the dynamo allowing the measurement of the radial dependence of the fields. The magnetic field measurements were also refined in the February 2003 and July 2003 campaigns, in particular with respect to the time resolution. First successful velocity measurements in the outer cylinder were carried out in the May 2004 campaign. These measurements confirmed the numerical result that the Lorentz force in the outer cylinder leads to a global azimuthal rotation and to two poloidal eddies. Another novelty of the May 2004 campaign was the measurement of the pressure in the inner cylinder by a pressure transducer which is flash mounted at the innermost wall.

4. The main results

In Fig. 4 we compile the growth rate and frequency data as recorded in the campaigns from November 1999 until July 2003. The first point to note is that the results are quite reproducible over the years, despite some slight changes in the facility (e.g. the insertion of tubes with sensor lances inside the innermost channel). The growth rates (Fig. 4a) in the kinematic regime increase with increasing rotation rate, whereas in the saturation regime they are zero by definition. In contrast to this sharp bend of the growth rate behaviour, the frequency (Fig. 4b) continues to increase after the transition from the kinematic to the saturation regime. The numerical predictions for the kinematic case are based on a 2D code for the solution of the induction equation [7]. This code does not include the effect of the lower conductivity of the stainless steel tubes between the different concentric cylinders. This effect of the finite wall thickness was determined by means of a simpler 1D code and is reflected in the corrected curves in Fig. 4a. This wall effect is negligible for the frequencies.



(a) (b)

Fig. 4: Computed and measured growth rates (a) and frequencies (b) in the kinematic and the saturation regime.

An interesting observation concerns the ratio of the fields at the upper and the lower lance. In Fig. 5 we observe an upward shift of the magnetic field with increasing propeller rotation rate. Another interesting quantity is the excess power, i.e. the motor power that is needed to feed the magnetic field (Fig. 6). The rather wide scatter of the data is due to the fact that it is not easy to determine the purely hydrodynamic power when the magnetic field is already present. Apart from this, the flatness of the fit curve is remarkable. For a propeller rotation rate that is 40 per cent overcritical, we have only 20 kW excess power, which is approximately 10 per cent of the total power there.

All these observations can be explained within a simple theoretical model [5,7] which gives a quite self-consistent picture of the flat power increase, the growth rate and frequency behaviour, and the axial field deformation. The self-exciting magnetic field produces a Lorentz force with all three components. The axial component acts against the axial flow, hence producing a pressure increase leading to a higher motor power consumption. However, if this were the only effect of the back-reaction, then the flow rate and the propeller rotation rate could not much increase above the critical value. Only the excess power would quadratically increase with the amplitude of the magnetic field. But this is in strict contrast to our observation. At 40 per cent overcritical propeller rotation rate we have only 10 per cent increase of the power consumption. The explanation is given by the action of the azimuthal component of the Lorentz force which leads to a reduction of the azimuthal velocity component. Since the azimuthal velocity is maintained only by inertia, its reduction accumulates downstream. Hence, in the lower part of the cylinder the velocity field looses its excitation capability which results in the change of the magnetic field pattern towards the upper part of the dynamo.

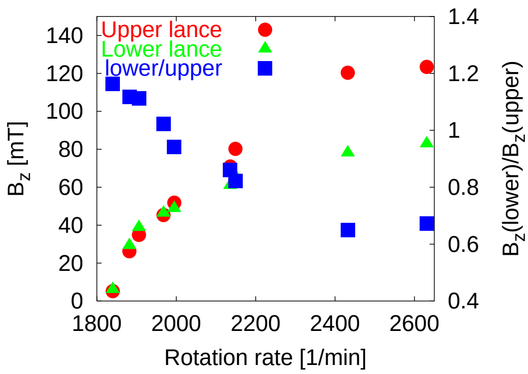


Fig. 5: Dependence of the axial magnetic fields measured close to the innermost wall on the lower and upper lance, and of their ratio, on the propeller rotation rate.

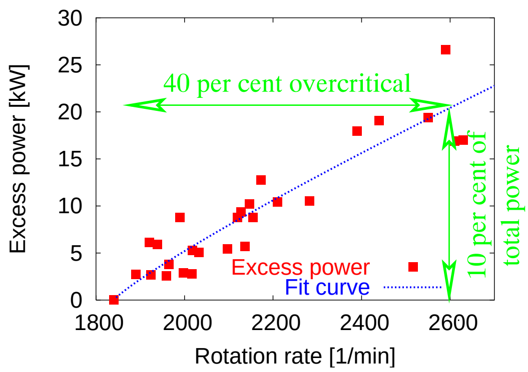


Fig. 6: Dependence of the excess power due to Joule losses on the (temperature corrected) rotation rate. The critical rotation rate is 1840 rpm.

Besides the back-reaction effects on the large scale flow structure, it is interesting to get some knowledge about fluctuations. In Fig. 7 we show two spectra, one from a Hall sensor which is located on the lower measurement level in the central cylinder, about 2 cm from the wall. The other spectrum results from the data of the pressure sensor, which is also mounted on the lower level. The main feature of the magnetic spectra is, of course, the peak at the eigenfrequency f. However, there is also a peak at the triple frequency, and even a small one at the fivefold frequency. Neither of these peaks is seen in the pressure spectrum. Instead we detect here a dominant peak at $2f$ and some smaller peak at $4f$. A common explanation of these peaks is that the magnetic eigenfield with the azimuthal mode number $m=1$ produces a

Lorentz force with a dominant $m=0$ part, but also with a $m=2$ part. The latter part influences the velocity and is also mirrored by the pressure peak at the double frequency. Now, this $m=2$ mode of the velocity induces, together with the dominant magnetic $m=1$ mode, a new contribution with $m = 3$ in the magnetic field. The product of $m=1$ and $m=3$ modes of the magnetic field produces the $m=4$ mode in the pressure. All the arguments for m transfer to the multiples of the frequency since the measurement is done at a fixed position. Concerning the inertial range of the spectrum, we have plotted the $f^{-11/3}$ law for the magnetic field in the inertial range and a $f^{-7/3}$ law for the pressure for comparison, without claiming a perfect coincidence. Between the main field frequency f and the propeller frequency f_{prop} there seems to be a region with f^{-1}, which has also been observed experimentally and numerically by other groups.

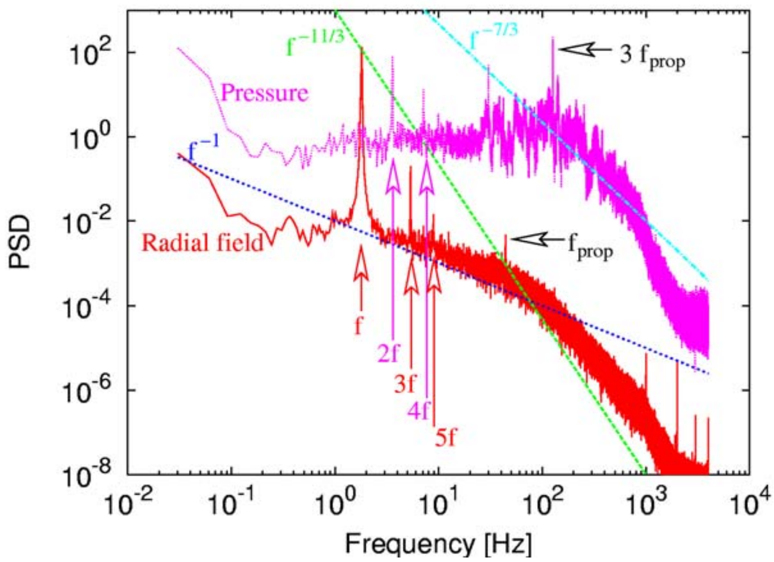


Fig. 7: Spectra of the radial magnetic field and the pressure, both measured on the lower level in the inner cylinder. The pressure sensor was flash mounted to the wall. The data are for a rotation rate of 2530 rpm. The peaks are multiples of the eigenfrequency f of the magnetic field.

4. Conclusions and prospects

With the nearly simultaneous sodium experiments in Riga and Karlsruhe the science of hydromagnetic dynamos has been pushed forward. Kinematic dynamo theory has been proven to be correct and robust with respect to low levels of turbulence and to complicated boundary conditions. The observed saturation effects are nontrivial as they concern not only the expected increase of motor power but also a spatial redistribution of the flow.

While the Karlsruhe facility has been disassembled, the Riga facility is ready for further experiments. The most important goal of the future experiments is to study in more detail the flow deformation under the influence of the self-excited magnetic field. Apart from the ultrasonic measurements in the outermost channel, no direct velocity measurements have been carried out in the sodium facility. Some effort is presently being spent to infer the velocity profile from the measured magnetic field data in the sense of an inverse problem using a new forward code based on the integral equation approach of dynamo theory and a simplex algorithm for the inversion. However, direct flow measurements seem unavoidable when it comes to confirm the results of the saturation model. Hence, such measurements with micro-magnet probes are envisioned for the next runs.

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