DRESDYN - A new facility for MHD experiments with liquid sodium

F. Stefani, S. Eckert, G. Gerbeth, A. Giesecke, Th. Gundrum, C. Steglich, T. Weier, B. Wustmann

Helmholtz-Zentrum Dresden-Rossendorf, P.O. Box 510119, D-01314 Dresden, Germany

The DREsden Sodium facility for DYnamo and thermohydraulic studies (DRESDYN) is intended as a platform both for large scale experiments related to geo- and astrophysics as well as for experiments related to thermohydraulic and safety aspects of liquid metal batteries and liquid metal fast reactors. The most ambitious projects in the framework of DRESDYN are a homogeneous hydromagnetic dynamo driven solely by precession and a large Taylor-Couette type experiment for the combined investigation of the magnetorotational instability and the Tayler instability. In this paper we give a short summary about the ongoing preparations and delineate the next steps for the realization of DRESDYN.

Introduction

Beginning with the early considerations of Bevir [1], Pierson [2], and Steenbeck [3], there has always been a tight connection between experimental dynamo studies and research related to liquid metal fast reactors (LMFR), in particular to sodium fast reactors (SFR). For example, a precursor of the Riga dynamo experiment [4] had been carried out in 1987 at a test facility for SFR pumps in Leningrad [5]. Later, Alemany et al. [6] studied the possibility of self-excitation in the pumps and cores of the French Phénix and Superphénix reactors. With the DRESDYN project we intend to resume this tradition by setting-up a new research infrastructure for liquid sodium experiments related both to the origin and action of cosmic magnetic fields (with possible applications for the construction of large-scale liquid metal batteries) as well as to safety aspects of LMFR’s. First, we present the plans for a precession driven dynamo experiment and a Taylor-Couette type experiment for the combined investigation of the magnetorotational instability (MRI) and the Tayler instability (TI). The destructive effect of the TI on the layered stratification in envisioned large-scale liquid metal batteries, and a possible provision to avoid this effect, will then be discussed. The paper closes with delineating further experiments related to In-Service-Inspection problems for LMFR’s.

1. Experiments with geo- and astrophysical background

1.1. Precession driven dynamo

The most ambitious project within the framework of DRESDYN is a large scale precession dynamo experiment. Precession has been discussed since long as an, at least complementary, energy source of the geodynamo [7, 8, 9, 10, 11, 12]. This idea is supported by paleomagnetic measurements that have revealed a modulation of the geomagnetic field intensity by the 100 kyr Milanković cycle of the Earth’s orbit eccentricity and by the corresponding 41 kyr cycle of the Earth’s axis obliquity [13]. The 100 kyr cycle is also known to influence the reversal statistics of the geomagnetic field, an effect that is very probably being enhanced by stochastic resonance [14, 15]. In this
context there is an interesting correlation of geomagnetic field variations with climate changes, clearly demonstrated for the last 5000 years [16], and perhaps also existing for the sequence of ice ages [17], although the causal mechanism of how exactly the Milanković cycles affect both the climate and the magnetic field is far from being settled. In an early paper, Doake had speculated that the increasing ice sheets would change the moment of the inertia of the Earth, thereby influencing the geodynamo by a modified rotation period [18]. However it could be worthwhile to investigate also the reverse causal chain that changing Earth’s orbit parameters lead, in the first instance, to a modified geodynamo field which, in turn, could then influence the climate by modifying the shield against cosmic ray flux (which was recently discussed as a key climate driver through cloud formation [19, 20]).

Apart from this general geophysical motivation, a precession driven dynamo experiment is also interesting from the narrower magnetohydrodynamic point of view. In comparison with the previous experiments in Riga [4], Karlsruhe [21], and Cadarache [22], a precession experiment would represent a homogeneous dynamo par excellence. Containing only a homogeneous fluid rotating around two axes, it would neither contain any propeller, as in Riga, nor any assembly of guiding tubes, as in Karlsruhe, nor any soft-iron material (which is crucial for the low critical magnetic Reynolds number and the close to axisymmetric eigenmode in the Cadarache experiment [23]).

The central part of the envisioned precession dynamo experiment (see Fig. 1 for a preliminary draft) will be a cylindrical vessel of approximately 2 m diameter.

Figure 1: Sketch of the planned large scale precession driven dynamo experiment with the envisioned sizes and rotation rates.
and length, rotating with up to 10 Hz around its symmetry axis, and with up to 1 Hz around another axis whose angle to the first axis can be varied between 90° and 45°. The inner cylindrical shell (made of copper) is immersed into a larger cylindrical stainless container with conical end parts that can later also be used to house alternative inner shells, e.g. in the form of ellipsoids.

The mechanical and safety demands for such a large scale sodium experiment are tremendous. With a total mass of approximately 20 tons (including the sodium in the conical end parts and the stainless steel walls) the sodium filled cylinder will have a moment of inertia of around $10^4$ kg m$^2$. With a rotation rate of 10 Hz and a precession rate of 1 Hz, this amounts to a gyroscopic moment of $5 \times 10^6$ Nm which requires an extremely massive basement and a careful avoidance of resonances. Further, the experiment must be fenced by a containment which can be quickly flooded with Argon in case of a sodium accident.

In order to determine various crucial parameters for the design of this large-scale sodium experiment, we have started a series of experiments at a smaller (scale 1:6) water precession experiment which is shown in Fig. 2. This small water experiment is similar to the ATER experiment guided by J. Léorat [23], but comprises some special measuring devices. Most important for the later sodium experiment is the determination of the torques and motor powers needed to drive the rotation of the cylinder and the turntable, and of the gyroscopic torques acting on the basement. Those measurements have already confirmed the expected sharp transition between a laminar flow and a turbulent flow which in our case occurs at a precession ratio of around 0.07. At this point, the needed motor power increases sharply, as indicated in Fig. 3a.

Concerning the flow field determination, up to present we have only installed a number of ultrasonic sensors for the determination of the axial velocity component. For a (rather low) rotation rate of 0.2 Hz and a precession rate of 0.01 Hz, Fig. 3b shows first results of the axial velocity measured by Ultrasonic Doppler...
Figure 3: First results obtained with the water precession experiment. (a) Motor power (electrical and mechanical) in dependence on the precession rate. Note the sudden jump of the power for a precession ratio of approximately 0.07 which indicates the transition between the laminar and the turbulent flow regime. (b) Axial velocity component for half a rotation, measured by 6 Ultrasound sensors at a rotation rate of 0.2 Hz and a precession rate 0.01 Hz. The sign change indicates the typical Kelvin mode (m=1) structure.

Velocimetry (UDV).

1.2. MRI/TI experiment The second liquid sodium experiment with geo-and astrophysical motivation will be a large-scale Taylor-Couette-Experiment (Fig. 4) with a diameter of approximately 1 m and a height of 2.5 m, wrapped by a coil that produces a strong vertical magnetic field, and supplemented by technical means to guide independent electrical currents through a bore in the center and through the liquid sodium between the inner and outer cylinder.

In the following this experiment will be called the "MRI/TI experiment", indicating its astrophysical background in terms of the Magnetorotational instability (MRI) and the Tayler instability (TI). The MRI had been discussed, for the first time, by Velikhov in 1959 [25], and was then rediscovered and applied to accretion disk physics by Balbus and Hawley in 1991 [26]. Nowadays, MRI is thought to play a crucial role in enabling angular momentum transport by destabilizing the Keplerian rotation profiles of accretion disks that would otherwise be hydrodynamically stable.

With this large-scale MRI/TI experiment we plan to extend our previous investigations [27, 28] on the helical version of MRI (HMRI) to the realm of the standard MRI (SMRI). A particular focus will be on the interesting mode transitions between the HMRI and the SMRI, as discussed recently in [29, 30].

In addition to this, the experiment will also allow to study the kink-type Tayler instability (TI) [31, 32] and its transitions to the azimuthal MRI (AMRI) [33]. Recent experimental work on TI with the eutectic alloy GaInSn has revealed a complicated interplay of the very TI with large scale convection effects due to Joule heating [34]. With the envisioned sodium experiment we intend to suppress those convection effects significantly. On this basis, we see a much better chance to study the numerically predicted intrinsic saturation effects of TI by means of an increased turbulent resistivity [35].
2. TI and liquid metal batteries  Tightly connected with the research on TI, we will also investigate liquid metal batteries that have recently been proposed as cheap devices for the storage of the highly fluctuating renewable energies.

Typically, such a battery would consist of a self-assembling stratification of a heavy liquid half-metal (e.g. Bi, Sb) at the bottom, an appropriate molten salt as electrolyte in the middle, and a light alkaline or earth alkaline metal (e.g. Na, Mg) at the top. The functioning of a small version of this type of battery has already been verified [36]. However, for large-scale batteries (which are the only interesting ones in terms of economic competitiveness) the occurrence of TI can be easily imagined to represent a serious problem for the integrity of the stratification (see Fig. 5a).

In our experiments, we will focus on various ways to avoid TI in such configurations, e.g. by using a return current through the center of the battery (see Fig. 5b), as it was proposed in a recent paper [37].

3. Experiments related to liquid metal fast reactors (LMFR)  The safe and reliable operation of liquid metal systems in innovative reactor concepts like sodium fast reactors (SFR) or transmutation systems based on lead-bismuth cooled reactors (LBFR) requires appropriate measuring systems and control units, both for the liquid metal single-phase flow as well as for gas bubble liquid metal two-phase flows. Hence, there is a growing need for small and medium sized liquid sodium experiments to study various thermo-hydraulic and safety aspects of SFR’s, comprising sodium boiling, argon entrainment, bubble detection, sodium flow metering and many more [38].

A significant portion of the LMFR-related experiments in the framework of
Figure 5: Liquid metal batteries. (a) Illustration of the expected action of TI on the self-assembled stratification in a liquid metal battery. (b) A simple provision to avoid TI by returning the charging/discharging current through a bore in the center.

DRESDYN will be conducted at an In-Service-Inspection (ISI) facility the principle sketch of which is shown in Fig 6. Basically, it will consist of a heated stainless steel vessel with a diameter of approximately 1 m that is filled with liquid sodium covered by argon. The internal components will comprise a simple mock-up of a reactor core and a primary pump. The main goal of this facility is to test a variety of measurement techniques for the position of internal components, for flow velocities and argon bubble detection. The latter will also include experiments on Argon entrainment on the free surface. Particular attention will be paid to the application of the Contactless Inductive Flow Tomography (CIFT) for the flow reconstruction in LMFR’s. This technique has been developed at HZDR during the last decade [39, 40], and it was recently deployed for visualizing the flow structure in a physical model of the continuous casting of steel [41]. CIFT could be of particular value for Lead-Bismuth cooled transmutation systems, such as MYRRHA [42]. The lower “cold pool” of MYRRHA is characterized by a rather free velocity field which is very likely prone to flow instabilities that could easily be detected by CIFT.

DRESDYN will also comprise a liquid sodium loop which will replace the presently existing one. This loop will contain various test sections, among them one section for the study of smart heat exchangers with intermediate heat transfer media. The deployment of such smart heat exchangers in future SFR’s could reduce significantly the risk of energetic sodium-water reactions. Another suite of experiments will be devoted to the important problem of sodium boiling which is a key safety issue for SFR’s due to their positive reactivity coefficient. Starting with very small experiments at a flat wall, we plan to go over later to boiling experiments at rods or rod bundles. For the visualization of the boiling we plan to use the Mutual Inductance Tomography [43], as well as X-ray radiography [44] and, in collaboration with another group at HZDR, the ultrafast X-ray tomography [45].

Finally, with the advent of Oxide Dispersion Strengthened (ODS) steels as new promising nuclear reactor materials (because of their superior swelling resistance and excellent high temperature strength) [46], we come back to our starting
point of considering the possibility of magnetic-field self-excitations in SFR’s. It has been shown that the use of ferritic or martensitic steels in the core of large SFR’s could indeed foster magnetic field self-excitation [47, 48]. This is consistent with the key role of high magnetic permeability material for the dynamo process in the Cadarache experiment [23]. Hence, it is certainly necessary to reconsider this point before new steel sorts can be utilized in large scale SFR’s. Related experiments on this topic are also envisaged in the framework of DRESDYN.

4. Conclusions In this paper, we have discussed the motivation behind, and the concrete plans for a number of experiments to be set-up in the framework of DRESDYN. The new building and the essential parts of the experiments are expected to be ready in 2015. Apart from hosting the discussed experiments, DRESDYN is also meant as a general platform for further large-scale experiments, basically but not exclusively with liquid sodium. Proposals for such experiments are, therefore, highly welcome.

Acknowledgments This research was supported by Deutsche Forschungsgemeinschaft (DFG) under grant STE 991/1-1 and in frame of the SFB 609 "Electromagnetic Flow Control in Metallurgy, Crystal Growth and Electrochemistry". We thank Jacques Léorat for his proposal and his insistence to build a precession driven dynamo, and Canlong Ma for assistance in the processing of data from the
water precession experiment.

REFERENCES

1. M.K. Bevir. Possibility of electromagnetic self-excitation in liquid-metal flows in fast reactors. *J. Br. Nucl. Energy Soc.*, vol. 12 (1973), pp. 455–458.

2. E. S. Pierson. Electromagnetic self-excitation in liquid-metal fast breeder reactors. *Nucl. Sci. Eng.*, vol. 57 (1975), pp. 155–163.

3. M. Steenbeck. Letter to H. Klare, President of the Academy of Sciences of the GDR (1975).

4. A. Gailitis et al. Detection of a flow induced magnetic field eigenmode in the Riga dynamo facility. *Phys. Rev. Lett.*, vol. 84 (2000), pp. 4365-4368.

5. A. Gailitis et al. Experiment with a liquid-metal model of an MHD dynamo. *Magnetohydrodynamics*, vol. 23 (1987), pp. 349–353.

6. A. Alemamy, P. Marty, F. Plunian, and J. Soto. Experimental investigation of dynamo effect in the secondary pumps of the fast breeder reactor Superphenix. *J. Fluid Mech.*, vol. 403 (2000), pp. 262–276.

7. W.V.R. Malkus. Precession of Earth as cause of geomagnetism. *Science*, vol. 160 (1968), pp. 259–264.

8. R.F. Gans. On hydromagnetic precession in a cylinder. *J. Fluid Mech.*, vol. 45 (1970), pp. 111–130.

9. J.P. Vanyo. Core-mantle relative motion and coupling. *Geophys. J. Int.*, vol. 158 (2004), pp. 470–478.

10. A. Tilgner. Precession driven dynamo. *Phys. Fluids*, vol. 17 (2005), Art. No. 034104.

11. S.L. Shalimov. On the precession driven geodynamo. *Izvestiya, Phys. Sol. Earth*, vol. 42 (2005), pp. 460–466.

12. C. Nore, J. Léorat, J.L. Guermond, and F. Luddens. Nonlinear dynamo action in a precessing cylindrical container. *Phys. Rev. E*, vol. 84 (2011), Art. No. 016317.

13. J.E.T. Channell, D.A. Hodel, J. McManus, and B. Lehman. Orbital modulation of the Earth’s magnetic field intensity. *Nature*, vol. 394 (1998), pp. 464-468.

14. G. Consolini and P. De Michielis. Stochastic resonance in geomagnetic polarity reversals. *Phys. Rev. Lett.*, vol. 90 (2003), Art. No. 058501.

15. M. Fischer, F. Stefani, and G. Gerbeth. Coexisting stochastic and coherence resonance in a mean-field dynamo model for Earth’s magnetic field reversals. *Eur. Phys. J. B*, vol. 65 (2008), pp. 547-554.

16. M.F. Knudsen and P. Rihager. Is there a link between Earth’s magnetic field and low-latitude precipitation? *Geology*, vol. 37 (2009), pp. 71-74.

17. V. Courtillot, Y. Gallet, J.L. Le Mouel, F. Fluteau, and A. Genevey. Are there connections between Earth’s magnetic field and climate?. *Earth Planet. Sci. Lett.*, vol. 253 (2007), pp. 328–339.

18. C.S.M. Doake. Possible effect of ice ages on Earth’s magnetic field. *Nature*, vol. 267 (2007), pp. 415-417.

19. K. Scherer et al. Interstellar-terrestrial relations: Variable cosmic environments, the dynamic heliosphere, and their imprints on terrestrial archives and climate. *Space Sci. Rev.*, vol. 127 (2006), pp. 327–465.

20. H. Svensmark. Cosmoclimatology: a new theory emerges. *Astron. Geophys.*, vol. 48 (2007), pp. 18-24

21. R. Stieglitz and U Müller. Experimental demonstration of an homogeneous two-scale dynamo. *Phys. Fluids*, vol. 13 (2001), pp. 561–564.
22. R. Monchaux et al. Generation of a magnetic field by dynamo action in a turbulent flow of liquid sodium. Phys. Rev. Lett., vol. 98 (2007), Art. No. 044502.
23. A. Giesecke, F. Stefani, and G. Gerbeth. Role of soft-iron impellers on the mode selection in the von Kármán-sodium dynamo experiment, Phys. Rev. Lett., vol. 104 (2010), Art. No. 044503.
24. J. Léorat. Large scales features of a flow driven by precession, Magnetohydrodynamics, vol. 42 (2006), pp. 143-151.
25. E.P. Velikhov. Stability of an ideally conducting liquid fluid between cylinders rotating in a magnetic field. Sov. Phys. JETP, vol. 9 (1959), pp. 995–998.
26. S.A. Balbus and J.F. Hawley. A powerful local shear instability in weakly magnetized disks. I. Linear analysis. Astrophys. J., vol. 376 (1991), pp. 214–222.
27. F. Stefani et al. Experimental evidence for magnetorotational instability in a Taylor-Couette flow under the influence of a helical magnetic field. Phys. Rev. Lett., vol. 97 (2006), Art. No. 184502.
28. F. Stefani et al. Helical magnetorotational instability in a Taylor-Couette flow with strongly reduced Ekman pumping. Phys. Rev. E vol. 97 (2006), Art. No. 184502.
29. O.N. Kirillov and F. Stefani. On the relation of standard and helical magnetorotational instability. Astrophys. J. vol. 712 (2010), pp. 52–68.
30. O.N. Kirillov and F. Stefani. Paradoxes of magnetorotational instability and their geometrical resolution. Phys. Rev. E vol. 84 (2011), Art. No. 036304.
31. R.J. Tayler. Adiabatic stability of stars containing magnetic fields. 1 Toroidal fields. Mon. Not. R. Astron. Soc. vol. 161 (1973), pp. 365–380.
32. H.C. Spruit. Dynamo action by differential rotation in a stably stratified stellar interior. Astron. Astrophys. vol. 381 (2002), pp. 923-932.
33. R. Hollerbach, V. Teeluck, and G. Rüdiger. Nonaxisymmetric magnetorotational instabilities in cylindrical Taylor-Couette flow. Phys. Rev. Lett. vol. 104 (2010), Art. No. 044502.
34. M. Seilmayer et al. Experimental evidence for Taylor instability in a liquid metal column. Phys. Rev. Lett. submitted (2011); arXiv:1112.2103.
35. M. Gellert and G. Rüdiger. Eddy diffusivity from hydromagnetic Taylor-Couette flow experiments. Phys. Rev. E vol. 80 (2009), Art. No. 046314.
36. D.J. Bradwell, H. Kim, A.H.C. Sirk, and D. Sadoway. Magnesium-Antimony liquid metal battery for stationary energy storage. J. Am. Chem. Soc. (2012), dx.doi.org/10.1021/ja209759s
37. F. Stefani, T. Weier, Th. Gundrum, and G. Gerbeth. How to circumvent the size limitation of liquid metal batteries due to the Taylor instability. Energy Conv. Manag. vol. 52 (2011), pp. 2982-2986.
38. D. Tenchine. Some thermal hydraulic challenges in sodium cooled fast reactors. Nucl. Eng. Des. vol. 240 (2010), pp. 1195–1217.
39. F. Stefani and G. Gerbeth. A contactless method for velocity reconstruction in electrically conducting fluids. Meas. Sci. Techn. vol. 11 (2000), pp. 758–765.
40. F. Stefani, Th. Gundrum, and G. Gerbeth. Contactless inductive flow tomography. Phys. Rev. E vol. 70 (2004), Art. No. 056306.
41. T. Wondrak et al. Combined electromagnetic tomography for determining two-phase flow characteristics in the submerged entry nozzle and in the mold of a continuous casting model. Met. Mat. Trans. B vol. 42 (2011), pp. 1201–1210.
42. H.A. Abderrahim and P. D’Hondt. MYRRHA: A European Experimental ADS for R&D Applications. J. Nucl. Sci. Techn. vol. 44 (2007), pp. 491–498.
43. N. Terzić et al. Use of electromagnetic induction tomography for monitoring liquid metal/gas flow regimes on a model of an industrial steel caster. Meas. Sci. Techn. vol. 22 (2011), Art. No. 015501.
44. S. Boden, S. Eckert, and G. Gerbeth. Visualization of freckle formation induced by forced melt convection in solidifying GaIn alloys. *Mat. Lett.* vol. 64 (2010), pp. 1340–1343.

45. F. Fischer and U. Hampel. Ultra-fast electron beam X-ray computed tomography for two-phase flow measurements. *Nucl. Eng. Des.* vol. 240 (2010), pp. 2254–2259.

46. T. Kaito, S. Ukai, A.V. Povstyanko, and V.N. Efimov. Fuel pin irradiation test at up to 5 at% burnup in BOR-60 for Oxide-Dispersion-Strengthened ferritic steel claddings. *J. Nucl. Sci. Techn.* vol. 46 (2009), pp. 529-533.

47. F. Plunian, A. Alemany, and P. Marty. Influence of magnetohydrodynamic parameters on electromagnetic self-excitation in the core of a fast breeder reactor. *Magnetohydrodynamics* vol. 31 (1995), pp. 421-429.

48. J. Soto. A Finite Element-Spectral formulation for the kinematic MHD Dynamo problem. Application to the Fast Breeder Reactors Phénix and Super-Phénix. *PhD Thesis* Grenoble (1999)