Final Technical Report for DE-FG02-05ER54831
Laboratory Studies of Dynamos

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Executive Summary. The self-generation of magnetic fields by astrophysical bodies like planets, stars, accretion disks, galaxies, and even galaxy clusters arises due to a mechanism referred to as a homogeneous dynamo. It is quite simple to demonstrate the generation of a magnetic field from a rotating copper disk coupled with a coil of wire, a device known as the homopolar dynamo. The device works like a magnetic field amplifier with a feedback circuit: the differential rotation of a metal disk past an infinitessimally small seed magnetic field induces currents in the disk which, when coupled to a coil winding, can amplify the field until it becomes strong enough to slow the rotation of the disk. What is remarkable is that the same type of circuit may be achieved in a flowing conducting fluid such as a liquid metal in the case of planetary dynamos or a plasma in the case of astrophysical dynamos. The complexity of describing planetary and stellar dynamos despite their ubiquity and the plethora of observational data from the Earth and the Sun motivates the demonstration of a laboratory homogenous dynamo.

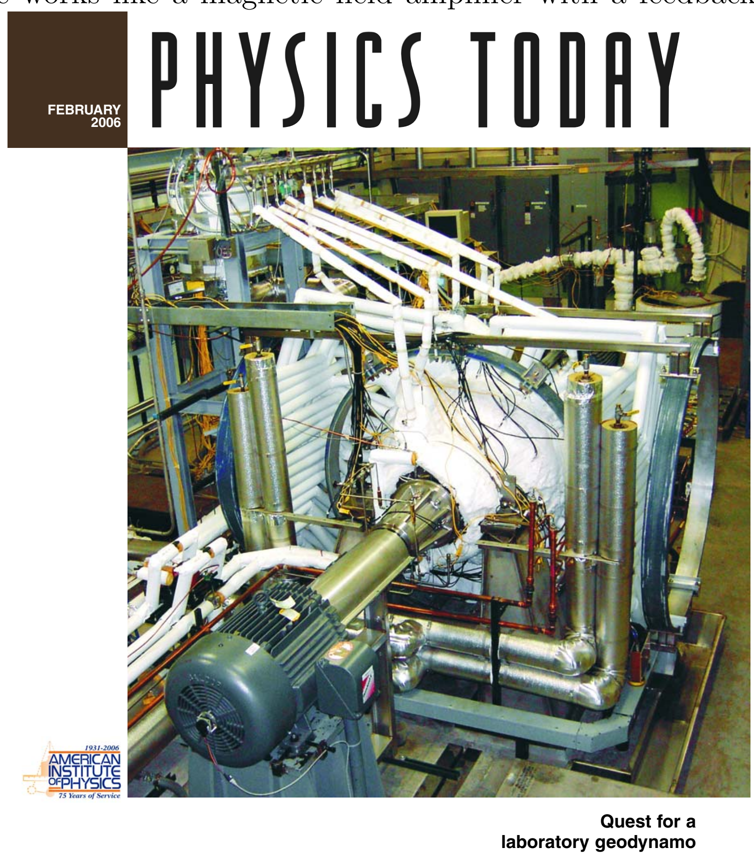

Figure 1: Photograph of the Madison Dynamo Experiment (located in a special liquid metal facility 10 miles south of the UW campus), taken from the cover of the Feb. 2006 issue of Physics Today. *The sphere is 1 meter in diameter and filled with $110^\circ C$ liquid sodium. High speed flows optimized for generating growing magnetic fields are created by two counter rotating impellers driven by 150 kW of mechanical power to create flow speeds on the order of 20 m/s.*

To create a homogenous dynamo, one first needs a sufficiently large, fast flow of a highly conducting fluid that the velocity shear in the fluid can bend magnetic field lines. This requirement is characterized by requiring a sufficiently large magnetic Reynolds number $Rm = LV/\eta$ where L is a characteristic length, V a flow speed, and $\eta = 1/\mu_0\sigma$ is the coefficient of resistive diffusion. With a high Rm-flow, the magnetic field can be amplified by the stretching action provided by differential rotation. The other critical ingredient is a flow geometry that provides feedback so that the amplified field reinforces the initial infinitesimal seed field—a mechanism that recreates the feedback provided by the coil of wire in the homopolar dynamo.

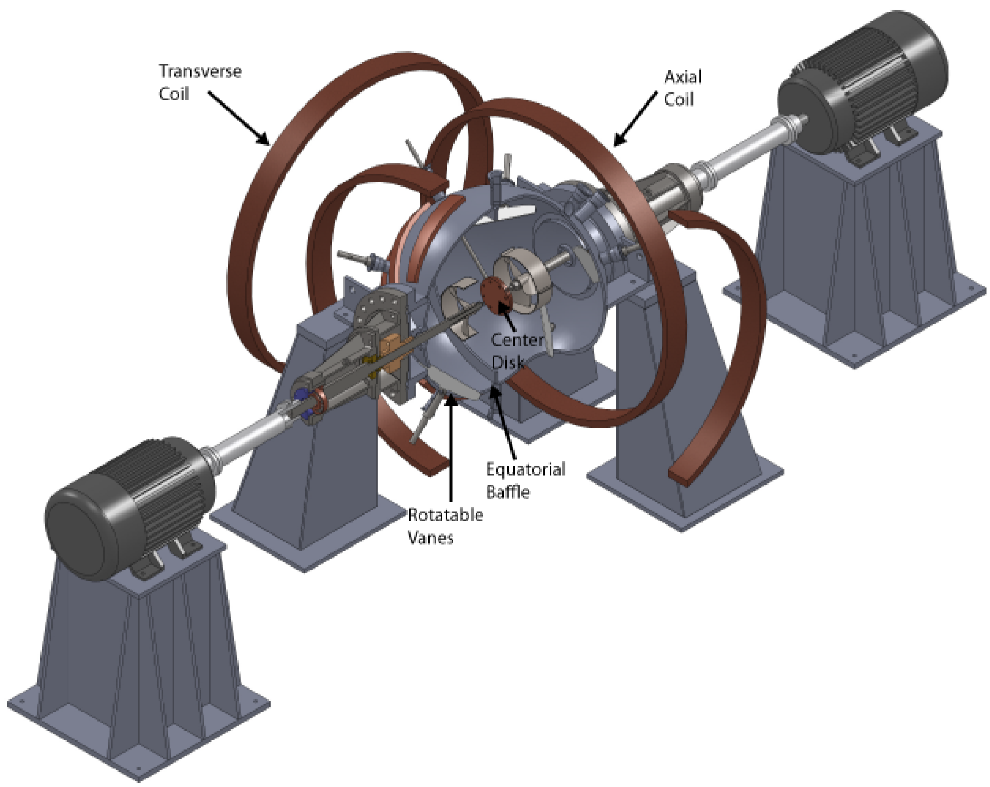

Figure 2: The Madison Dynamo Experiment. The experiment consists of a 1 meter diameter pressure vessel, 300 gallons of liquid sodium (stored, when not in use in a holding tank below the floor), and two 75 kW motors to stir the sodium. The baffles added to the experiment to tailor the large-scale flow are called out in the figure.

In the Madison Dynamo Experiment, this combination of magnetic amplification and feedback is feasible in the simple geometry of two counter-rotating helical vortices in a 1 meter-diameter spherical vessel filled with liquid sodium. For an optimal helical pitch of the flow the threshold for exciting a dynamo is predicted from laminar flow modeling to be at peak flow speeds of 5 m/s.

Liquid metals tend to have viscosities similar to that of water yielding inviscid flows. Whereas the timescale for the dynamo instability is on the resistive dissipation time $\tau_\eta \sim L^2/\eta$ which is necessarily long to sustain dynamo action, the timescale for hydrodynamic instability of the shear layer $\tau_\nu \sim L^2/\nu$ (where ν is the kinematic viscosity) is quite short meaning that the shear layer required to generate the magnetic field is broken up by Kelvin-

Helmholtz instabilities. The eddies generated by large-scale flow drive instabilities at progressively smaller scale giving rise to a cascade of turbulent eddies driven at the largest scale of the experiment.

The major contribution of the Madison Dynamo Experiment has been quantifying the role this turbulence plays in the generation of magnetic fields. Overall, the Madison Dynamo Experiment has now operated for about 1 decade and carried out experiments related to magnetic field generation by turbulent flows of liquid metal. The principle thrust of research and indeed the main scientific outcomes are related to how turbulent flows create and transport magnetic fields. The Primary results are well-documented in the scientific literature as outlined below:

- The stretch-twist-fold mechanism by which the large-scale flow can produce a self-generated and sustained magnetic field [1]
- The spectrum of turbulent fluctuations induced by large-scale instabilities in the flow [1].
- The presence of a turbulence-induced emf comparable to that which would be expected from the mean flow [2, 3]
- Implementation of the code Dynamo, a 3D incompressible MHD code in spherical geometry for simulating field evolution in the experiment. The code was subsequently used to show how turbulence can substantially increase the critical flow speed for dynamo onset [4, 5, 6, 7, 8].
- The consequent reduction of magnetic field amplification and suppression of the dynamo-generated magnetic field [9, 10].
- The dependence of this turbulent emf on the relative dissipation of the magnetic and velocity fields [11].
- Characterization of MHD turbulent spectra in the dissipation range [12].
- Direct measurement of the three-dimensional turbulent EMF and comparison with predictions from Mean Field Theory [13].

Education. Four PhD students received their doctorates from research on the dynamo experiment: Dr. Erik Spence, Dr. Mark Nornberg, Dr. Elliot Kaplan, and Dr. Zane Taylor. Dr. Kian Rahbarnia completed a postdoc with the group. In addition, approximately 5 undergraduate researchers began their careers as hourly employees working on the experiment.

Publications

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