**Chasing Fast Dynamos in the Plasma Lab**

**Final Technical Report**

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**Overview:**

Self-generating magnetic field research is performed through the operation of the newly built Madison Plasma Dynamo Experiment (MPDX). MPDX is designed to explore a hitherto unexplored part of parameter space where dynamos operate in nature. Dynamos are systems which continuously transform kinetic energy from plasma flow into magnetic energy. Before this project, MPDX had demonstrated the ability to create steady-state, unmagnetized high conductivity, low viscosity plasmas in the lab and shown that sheared flows can be driven from the plasma boundary using an electrostatic stirring technique; the resulting Reynolds numbers and Alfvén Mach numbers easily match those required for our dynamo scenarios. The research activities included: (1) systematic undertaking of a set of plasma hydrodynamics experiments, exploring several different flow geometries, measuring plasma viscosity, how toroidal and poloidal flows self-consistently interact, observing the transition to turbulence and experimentally understanding the boundary conditions (on flow and magnetic field) that make this system unique, (2) searching for slow, laminar dynamos, and (3) searching for fast, turbulent dynamos. Discovering the conditions under which dynamos self-generate magnetic fields and then understanding how this field changes plasma dynamics is one of the most compelling questions in all of plasma astrophysics.

We have explored an alternative plasma flow drive method, Volumetric Flow Drive (VFD), that produces self-organized plasma Couette flow. VFD uses a weak externally applied magnetic field and injected cross-field currents to create global-scale body forces on the plasma. This scheme has been shown to create high-Alfven Mach number, centrally peaked flow profiles in a Couette geometry. The advantage of VFD over edge-driven flow as we have previously used is that it removes the need for strong viscous coupling of momentum from the magnetized edge of the plasma to the core. In previous edge-driven flows, neutral charge exchange collisions dramatically lowered the maximum achieved flow speeds and prevented fast flows need to study the dynamo.

The VFD experiments not only produced strong Couette flow, but also highlighted a unique Hall effect feature in the MPDX plasmas. For the densities of plasmas in MPDX, the ion inertial scale is on the order of 1m, so ions are not inertially coupled to magnetic fields on the system scale. This means that magnetic fields in MPDX are advected with the fast, light electron fluid solely. The VFD experiments we preformed confirmed this by observing massive magnetic field amplification caused by electron current injection. This affect is similar to the omega effect found throughout the dynamo literature, except it is fueled by current injection from our array of high-power emissive cathodes.

Measurements of the magnetic fields associated with the VFD scheme were made using a multi-position 3-axis Hall probe array as well as a partial set of surface array sensors used to map global magnetic modes. While the Hall probe array was instrumental in characterizing the amplification of the magnetic field, the surface array confirmed that the global mode was axisymmetric, which was necessary for understanding this unique Hall equilibrium.

Another major instrumentation achievement made under this award was the optimization of a Fabry-Perot spectrometer for high-resolution ion temperature and velocity measurements. This system was developed and tested using VFD on a MPDX prototype experiment. We were able to measure ion temperature and flow profiles with precision of 0.05eV and 10m/s, respectively. As far as we are aware, this is unprecedented in the field. The Fabry-Perot is distinct from laser induced fluorescence (LIF) due to its optical simplicity (entirely passive light collection) and its comparatively short integration times (~10-100ms).

In the last year, we have prototyped magnetic sensor arrays for global field measurements of a dynamo system, developed a state-of-the-art low temperature ion spectrometer and produced strongly sheared, Hall dominated plasma flows that show unique magnetic characteristics.

**Publications Detail:**

Milhone, J., Flanagan, K., Nornberg, M. D., Tabbutt, M., & Forest, C. B. (2019). A spectrometer for high-precision ion temperature and velocity measurements in low-temperature plasmas. *Review of Scientific Instruments*, 90(6), 063502.

Flanagan, K., Milhone, J., Egedal, J., Endrizzi, D., Olson, J., Peterson, E. E., Sassella, R. & Forest, C. B. (2020). Weakly magnetized, Hall dominated plasma Couette flow. *Physical Review Letters*, 125(13), 135001.

Intellectual Properties Detail:
There are no intellectual properties to report.

Technologies and techniques detail:
There are no technologies to report.

**Other Products:**

Conference:

(invited talk)
Flanagan, K. (2020). High-β, Weakly Magnetized and Hall Dominated Plasma Couette Flow. *Bulletin of the American Physical Society*.

Forest, C. (2020). Overview of Experiments from the Wisconsin Plasma Physics Laboratory (WiPPL). *Bulletin of the American Physical Society*.

Poster Session:

Flanagan, K., Milhone, J., Nornberg, M., & Forest, C. (2018). Strong magnetic field amplification in quasi-Keplerian high-β plasma flows. In *APS Division of Plasma Physics Meeting Abstracts* (Vol. 2018, pp. CP11-008).

Forest, C. (2018). Overview of Experiments at the Wisconsin Plasma Physics Laboratory. In *APS Division of Plasma Physics Meeting Abstracts* (Vol. 2018, pp. CP11-007).

Milhone, J., Flanagan, K., Nornberg, M., & Forest, C. (2018). Measuring Plasma Viscosity with a Fabry-Perot Spectrometer. In *APS Division of Plasma Physics Meeting Abstracts* (Vol. 2018, pp. CP11-010).

Flanagan, K., Milhone, J., & Forest, C. (2019). Magnetic flux amplification via the Hall effect high-β plasmas. In *APS Division of Plasma Physics Meeting Abstracts* (Vol. 2019, pp. PP10-040).

Training and professional opportunities:

Three graduate students and an undergraduate student were supported in part by this grant during this reporting period. Doug Endrizzi, Ethan Peterson, Jason Milhone, and Amanda Ready.

Doug Endrizzi attended the Geophysical Union's Fall Meeting 2018, presented a poster and participated in Shock focused session.

Amanda Ready participated in the APS Conference for Undergraduate Women in Physics, University of Minnesota 2020.

Samuel Grees presented his results and interacted with his colleagues at the American Geophysical Union's Fall Meeting 2018. He attended the Student and Early Career Scientist Conference for networking, exchanging ideas, and learning about early-career issues.

Ethan Peterson attended the Geophysical Union's Fall Meeting 2018. He presented his experimental work on rotating magnetospheres and the creation of a Parker Spiral.

Doug Endrizzi attended the 2018 APS Division of Plasma Physics Meeting and presented a poster.

Ethan Peterson attended the 2018 American Physical Society Division of Plasma Physics annual meeting. He presented his experimental work on rotating magnetospheres and the creation of a Hall-MHD Parker Spiral in the lab.

Jason Milhone attended the American Physical Society (APS) Division of Plasma Physics (DPP) 2018 conference to present his research conducted on the Big Red Ball at the Wisconsin Plasma Physics Laboratory.