The Madison plasma dynamo experiment: A facility for studying laboratory plasma astrophysics

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The Madison plasma dynamo experiment: A facility for studying laboratory plasma astrophysics


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The Madison plasma dynamo experiment (MPDX) is a novel, versatile, basic plasma research device designed to investigate flow driven magnetohydrodynamic instabilities and other high-β phenomena with astrophysically relevant parameters. A 3 m diameter vacuum vessel is lined with 36 rings of alternately oriented 4000 G samarium cobalt magnets, which create an axisymmetric multicusp that contains ∼14 m³ of nearly magnetic field free plasma that is well confined and highly ionized (>50%). At present, 8 lanthanum hexaboride (LaB₆) cathodes and 10 molybdenum anodes are inserted into the vessel and biased up to 500 V, drawing 40 A each cathode, ionizing a low pressure Ar or He fill gas and heating it. Up to 100 kW of electron cyclotron heating power is planned for additional electron heating. The LaB₆ cathodes are positioned in the magnetized edge to drive toroidal rotation through \( \mathbf{J} \times \mathbf{B} \) torques that propagate into the unmagnetized core plasma. Dynamo studies on MPDX require a high magnetic Reynolds number \( Rm > 1000 \), and an adjustable fluid Reynolds number \( 10 < Re < 1000 \), in the regime where the kinetic energy of the flow exceeds the magnetic energy (\( M_{A}^{2} = (v/v_{A})^{2} > 1 \)). Initial results from MPDX are presented along with a 0-dimensional power and particle balance model to predict the viscosity and resistivity to achieve dynamo action. © 2014 AIP Publishing LLC. [http://dx.doi.org/10.1063/1.4861609]

I. INTRODUCTION

The Madison plasma dynamo experiment (MPDX) is designed to create a steady-state, hot, weakly magnetized, flowing plasma in which the kinetic energy of the flow drives magnetohydrodynamic (MHD) instabilities. Such a device accesses a new regime relevant to astrophysical applications and never before achieved in a laboratory. This plasma is well-suited for studying astrophysical phenomena such as the dynamo process, the feasibility of which is the topic of several recent publications and is investigated in Sec. IV A. The magneto-rotational instability (MRI) could also be investigated using the tunable boundary driven flow or a supplemental central spinning post in conjunction with an external Helmholtz coil. In addition, many basic plasma physics experiments studying interactions and organization of flows and magnetic fields can be performed.

Previous and ongoing dynamo experiments use flowing liquid metals, which can be stirred mechanically and confined with a simple vessel. These interesting experiments suffer from several limitations, which can be avoided by using plasmas. First, the magnetic Reynolds number achieved in liquid metal experiments, which governs the transition to a dynamo, is too low. The magnetic Reynolds number \( Rm = vL/\eta \) (where \( L \) is the characteristic size, \( \eta \) is the resistivity, and \( v \) is the flow velocity) is the ratio of magnetic field advection by the flow to magnetic field diffusion from the resistivity. In liquid metal experiments, \( Rm \) is typically less than \( Rm_{crit} \) necessary for dynamo and MRI excitation. In addition, the fluid Reynolds number, which is the ratio of the momentum advection by the flow to the momentum diffusion by the viscosity \( Re = vL/\nu \) (where \( \nu \) is the viscosity), cannot be varied independently of \( Rm \) in liquid metals. The ratio of these quantities, the magnetic Prandtl number \( Pm = Rm/Re = v/\eta \) is a fixed, very small value \( \sim 10^{-5} \) in liquid metal; thus, the flows required to exceed \( Rm_{crit} \) are always turbulent. In plasmas, by contrast, \( Rm \) can be varied independently of \( Re \) by controlling the plasma resistivity and viscosity by changing the electron temperature, the plasma density, and the ion species. \( Pm \sim 1 \) is achievable in MPDX making these plasmas excellent candidates for dynamo action and comparison to simulations. In addition, laminar dynamo action (\( Rm > Rm_{crit}, Re < \sim 1000 \)) can be studied in the absence of fluid turbulence, which can suppress it.

To experimentally test theories about the dynamo mechanism in a plasma, the device operates in the flow-dominated regime as opposed to the magnetically dominated regime. Such an experiment requires not only that \( Rm \) be large but
also that the flow energy dominates over the magnetic energy. This is quantified by the Alfvén Mach number squared $M_A^2 = (v/v_A)^2$, which is the ratio of the inertial force to the magnetic force, where $v_A = B/\sqrt{\mu_n\mu_i}$ is the Alfvén velocity. When $M_A \gg 1$ and $Rm \gg 1$, flows can stretch and amplify the magnetic field. The feasibility of creating such a plasma in the lab has recently been demonstrated in a novel multi cusp confined plasma with electrostatic stirring, where unmagnetized plasmas with flows of $\sim 10$ km/s have been created.\(^{10}\) For MPDX class plasmas, a convenient set of formulae are

$$Re = 7.8 \frac{v_{km/s}}{L_m} n_{i,10^{18}m^{-3}} Z e^2 \sqrt{\mu/|T_s/eV|},$$

$$Rm = 1.6 T_s^{3/2} v_{km/s} L_m / Z,$$

$$M_A = 0.46 \frac{v_{km/s}}{\mu n_{i,10^{18}m^{-3}}/B_g},$$

where the Braginskii viscosity and the Spitzer resistivity for unmagnetized plasma are used for $\nu$ and $\eta$, respectively, $n_{i,10^{18}}$ is the ion density in $10^{18}/m^3$, $Z$ is the net charge of the ions, $T_s$ eV and $T_i$ eV are the electron and ion temperatures, respectively, in eV, $L_m$ is the characteristic size in meters, $v_{km/s}$ is the plasma velocity in units of km/s and $B_g$ is a characteristic strength of the background magnetic field in Gauss. The plasma parameters and relevant dimensionless parameters are adjusted by controlling the neutral fill pressure, input power, gas species, and torques imposed on the plasma edge.

The MPDX uses several well-established techniques to confine and stir a hot, unmagnetized plasma. First, an axisymmetric multipole magnetic ring cusp built from alternating rings of individual permanent magnets creates a strong magnetic field localized to the edge, forming a magnetic bucket to confine the plasma. Second, biased hot cathodes draw current to induce an $J \times B$ rotation to stir the edge of the plasma. The flow is driven at the boundary and momentum is viscously transported throughout the unmagnetized region. By controlling the spatial profile of these boundary-driven flows, arbitrary large scale helical flows can be established (Fig. 1).

The paper is organized as follows: Section II provides a description of the device, its construction and initial operation. Section II C describes the LaB$_6$ cathodes, which are used for producing plasma and controlling the boundary flow. Section II D describes the current state of diagnostics on MPDX. Section III presents initial measurements of plasma parameters in the MPDX operation that provides the basis for scaling to higher power. Section IV outlines simulations predicting machine confinement and operation as well as providing a plan for achieving several types of dynamo action in MPDX.

II. DESCRIPTION OF THE MPDX

New parameter regimes in laboratory plasmas can be reached due to recent breakthroughs in plasma physics technologies. This section describes the design of the facility, vacuum chamber, magnets, and plasma sources.

A. Vacuum chamber

The experimental vacuum chamber is comprised of two 3 m diameter hemispherical shells joined by equatorial flanges to create a spherical vessel. One hemisphere is mounted on a linear stage to provide easy opening and access to the chamber interior. The hemispherical shells are made of 0.03 m thick cast A356 aluminum (see Fig. 2). The wall thickness is determined by structural integrity and the need to provide sufficient material to machine flanges and other features into the walls.

Each hemisphere is cast as a single piece by Portage Casting and Molding, Inc., which provides many benefits over a traditional welded vacuum vessel. Casting not only eliminates the need for costly vacuum welds but also has allowed for a more complex and precise design at a greatly reduced cost. The design process resembled “3D Printing;” Solidworks computer aided design software was used by

![Image](image-url)
vacuum vessel and operate at temperatures up to 40 °C, far below their curie temperature of 350 °C. The magnets are covered by Kapton film and thin interlocking alumina ceramic tiles that protect and electrically isolate them.

The primary role of the magnets is to confine the large unmagnetized spherical volume of plasma for basic plasma experiments. The result from a Maxwell SV finite element modeling of the magnetic field used to design the magnet geometry is shown in Fig. 3. The magnetic field is < 1 G 0.25 m away from the magnet face. Residue marks on the tiles appeared after 10 h of integrated “plasma on” time and indicate the footprint of the plasma contact with the tiles. They are 0.0008 m wide, in good agreement with the width predicted by theory for our plasma parameters. The magnet ring spacing in the MPDX is 0.11 m, which implies that loss area is less than 1% of the surface area of the vessel. The MPDX confines ~14 m³ of plasma with a convective plasma loss surface area of ~0.2 m². Particle and energy confinement pertaining to achievable parameters in MPDX are further investigated in Sec. IV.

The cusp field also plays an important role in providing a surface for a 2.45 GHz electron-cyclotron resonance (where $B = 875$ G, approximately 0.05 m in front of the magnets as seen in Fig. 3). Five magnetrons manufactured by CoberMuegge, LLC, are being installed to provide up to 100 kW continuous power for ionizing and heating the plasma. Simple unternminated waveguide is used for antennas in either O-mode or X-mode polarization relative to the direction of the cusp magnetic field. Such sources are routinely used for heating overdense plasmas ($n_e$, greater than the critical density $7 \times 10^{16}$ m⁻³ for 2.45 GHz). This is speculated to be either be due to mode conversion to the electron Bernstein wave or by parallel propagation from the high field side of R-waves (whistler waves), neither of which suffers from the cutoff. Additionally, the magnetic fields are necessary for generating flows in conjunction with the LaB₆ cathodes and molybdenum anodes.

An external Helmholtz coil is now being installed for introducing a seed magnetic field and to probe the interactions between the driven flows and a scalable background magnetic field.

B. Magnets

Eighteen faceted rings are precisely machined into each hemisphere interior and used for mounting the 0.038 m × 0.025 m × 0.05 m samarium cobalt (SmCo) magnets. Unlike neodymium (NdFeB) magnets, SmCo magnets do not corrode in the presence of hydrogen gas. Each ring of magnets alternates in polarity, creating a 36 pole, axisymmetric magnetic field cusp for plasma confinement. The magnets are in good thermal contact with the water cooled vacuum vessel.

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C. LaB$_6$ stirring electrodes

Lanthanum Hexaboride has long been used as a high temperature ($T_e < 30$ eV), high density ($n_e < 2 \times 10^{19}$ m$^{-3}$) plasma source due to its high input power density and robust construction.$^{13-16}$ The ability to stir the MPDX plasma through LaB$_6$ cusp biasing is possible because LaB$_6$ can withstand high bias voltages ($V_d < 500$ V).

The LaB$_6$ stirring electrode design developed for MPDX is shown in Fig. 4. The cylindrical LaB$_6$ cathode (measuring 0.056 m in length, 0.0264 m in diameter, with 0.003 m thick walls) is radiatively heated up to 1600 °C by an internal graphite heater filament. This filament is precision machined with a five-fluted current path and threaded ends to ensure tight electrical connections. To prevent arcing, the heater filament is electrically isolated from the AC heater power supply with an isolation transformer and does not touch the LaB$_6$ cathode. A stainless steel tube allows for a sliding vacuum seal, a press-fitted plastic bushing provides structural support for the 12 kg electrode, and a large stainless steel “garage” allows the cathode to be completely retracted behind a gate-valve for periodic maintenance. The conductors for the heater circuit as well as the cathode discharge circuit are cylindrical copper tubes with a center molybdenum rod, coaxially nested inside the stainless steel tube and isolated from each other and the surrounding plasma by quartz tubing.

In anticipation of the large amounts of RF power provided by MPDX’s magnetrons, the three electrical feedthroughs per electrode are each paired with a copper clamp that fulfills three essential functions: electrical connection to power supply cables, water cooling to the cylindrical conductor bases, and transmission line chopping of RF waves.

Each LaB$_6$ stirring electrode is paired with one or more molybdenum anodes poloidally displaced one cusp. The current path between cathode and anode must cross a permanent anode-cathode pair in the cusp field. The torque is proportional to the anode-cathode bias voltage, current, and their location in the cusp, which determines $B$.

FIG. 4. LaB$_6$ stirring electrode design. The entire (1.1 m long) electrode is shown in (a), with detailed views of (b) the graphite heater filament and (c) the LaB$_6$ tip. Not shown: the linear vacuum feedthrough and garage/gate-valve assembly.

D. Diagnostics

The MPDX plasma is diagnosed by physical probes capable of making in situ measurements of local plasma parameters. These probes can all be pumped down and inserted into the machine via vacuum gate valves without interrupting operation. The plasma temperature and density are low enough for long probe lifetimes. The surface area of the probes and probe shafts is much smaller than the loss area on the cusp, and individual probes do not perturb the plasma.

A swept voltage bias is applied to the tip of planar Langmuir probes to create an “I-V” curve. This curve is analyzed to determine $T_e$, $n_e$, $\Phi_p$, and $\Phi_r$ using standard Langmuir probe techniques.$^{17}$ Plasma flows inside MPDX are measured using Mach probes. The probe tips are biased several times $T_e$ below the plasma potential to collect ion saturation current and the Mach number and absolute speed can be measured using standard techniques.$^{17}$ A triple probe is used to provide an additional measurement of $T_e$ and $\Phi_r$.

A phase locked set of 1 mm sources acquired from Virginia Diodes, along with two mixers and an Analog Devices phase detector provide a single channel interferometric measurement of the line-integral density. The 1 mm wavelength is optimal for normal MPDX densities of $\sim 10^{17}$–$10^{18}$ m$^{-3}$ when integrated along a 6 m pathlength twice the length of the MPDX plasma. These densities correspond to phase shifts from $\sim \frac{\pi}{4}$ to $\pi$, which are easily measurable. The upper bound for a measurable density is $n_e \sim 10^{21}$ m$^{-3}$ and the minimum detectable density set by the digitizer noise levels is $\sim 10^{15}$ m$^{-3}$, a sufficient resolution for MPDX densities. An example calibrated interferometer time trace is found in Fig. 6.
Plasma discharges every 45 s around the clock. Total plasma discharges are fully automated and create 3-5 s over 3000 discharges and nearly 3 h of “plasma on” time operation or in a steady-state mode. The MPDX has created a two dimensional movable probe drive mounted on the MDPX vessel with a gate valve and a rotatable vacuum wall. The bolometer is calibrated with a laser over a scaling of incident power. The machine can create steady state plasma discharges with a constant input power and fill pressure where plasma parameters stay constant over the length of the shot. However, the most interesting plasma regimes come where parameters stay constant over the length of the shot. The machine can create steady state plasma discharges with a constant input power and fill pressure where plasma parameters stay constant over the length of the shot. However, the most interesting plasma regimes come where parameters stay constant over the length of the shot.

**III. INITIAL MPDX RESULTS**

The first major result from MPDX is exhibiting confinement of an unmagnetized plasma using the edge localized magnetic multipole cusp. Eight LaB$_6$ cathodes ($\theta = 30^\circ$, 40$^\circ$, 50$^\circ$, 60$^\circ$, 125$^\circ$, 135$^\circ$, 145$^\circ$, 155$^\circ$, $\phi = 225^\circ$) and eight anodes, displaced one cusp poloidally and 90$^\circ$ toroidally ($\theta = 35^\circ$, 45$^\circ$, 55$^\circ$, 65$^\circ$, 120$^\circ$, 130$^\circ$, 140$^\circ$, 150$^\circ$, $\phi = 135^\circ$), were inserted radially into the unmagnetized region ($r = 1.25$ m). The cathodes were biased 200–500 V with respect to the anodes, with each cathode drawing 5–40 A for a discharge time of 3–10 s in order to characterize the breakdown and confinement in the MPDX. Electron heating was provided exclusively by the Ohmic heating of the anode-cathode circuit.

The machine can create steady state plasma discharges with a constant input power and fill pressure where plasma parameters stay constant over the length of the shot. However, the most interesting plasma regimes come where the neutral gas is puffed in, over a 20 ms time, 0.5 s before a discharge, achieving a neutral fill pressure high enough to achieve breakdown that is then pumped out to achieve high ionization fractions and electron temperatures. An example time trace for an 8 s discharge at 400 V drawing a total of 150 A for a helium gas puff is shown in Fig. 6. A Langmuir probe movement or the movement of an unmagnetized plasma using the edge localized magnetic potential $\log(\Psi)$ found from integrating the measured cusp field are plotted over the data. A radial cut of the data along the center of the plane is shown in (c) along with the measured value of the magnetic field. In the unmagnetized core of MPDX, $\beta = 100$ for $B = 1$ G and $P_m = 8$ for $T_e = 1$ eV. For $v_\phi = 5$ km/s, $Re = 35$, $Rm = 270$ in the MPDX core.
The values of $n_e$ and $T_e$ characteristic of the unmagnetized core ($r = 1.12$ m) were recorded for a scaling of input power 200–450 V, 20–300 A (4–135 kW) with a constant fill pressure $6.5 \times 10^{-5}$ Torr of helium ($n_e = 2 \times 10^{19}$ m$^{-3}$), as shown in Fig. 8. The ability to achieve a steady, chamber-filling breakdown with a discharge power as low as 4 kW is also indicative of a well confined plasma. The electron temperature saturates at higher input power as the ionization cross section climbs non-linearly and incrementally hotter electrons are required for large changes in density. Higher $T_e$ should be observed once the ionization percentage becomes sufficiently high. The total radiated power measured by the bolometer and integrated over the surface of MPDX is shown. Using the measured values of $T_e$, $n_e$, and the radiated power, a confinement model can be used to predict the equilibrium power as described in Sec. IV, plotted in the final panel. The experiment will eventually have up to 300 kW of heating power available.

The second major result is measuring the flow in MPDX. Only four cathodes and five anodes were used. The anodes and cathodes were retracted back into the magnetized edge cusp ($r = 1.40$ m) at the same toroidal and poloidal locations described above. In this setup, the only closure path for current is across the cusp field resulting in a $\mathbf{J} \times \mathbf{B}$ torque in the toroidal direction. A two-sided Mach probe was inserted into the plasma oriented to measure the toroidal flow $v_\phi$ in the vicinity of the cathode $r = 1.35$ m, $\theta = 55^\circ$, $\phi = 45^\circ$. An example time trace is shown in Fig. 9.
The volumetric ionization rate $S_e = \langle \sigma_e V_e \rangle n_e$ for an ionization cross section $\sigma_e$ is balanced by a boundary flux $\Gamma_e = 0.5n_e c_s$ such that $\int \int S_e \, dV = \int \int_{\text{edge}} \Gamma_e \, dA$. In the zero-dimensional limit, the volume integral can be replaced by the volume of the machine $V$ and the surface integral can be replaced with $A_e + A_l$ yielding

$$\langle \sigma_e V_e \rangle n_e n_i V = 0.5n_e c_s (A_e + A_l).$$

(4)

Equation (4) is transcendental in $T_e$ and independent of $n_e$. It determines the neutral density $n_i$ in the presence of the plasma in MPDX. This is related to the experimental fill density $n_f = n_e + n_i$.

The power balance in MPDX is similarly modeled by comparing the power added to the system by LaB$_6$ cathodes and magnetrons $Q_{tot}$ (in kW) to the power lost by volumetric radiation, ionization, and surface particle convection to the walls. In the 0D limit, this becomes

$$Q_{tot} = (\gamma_i k_B T_e + E_{iz})0.5n_e c_s (A_e + A_l) + Q_{rad} + Q_{zn}.$$  

(5)

The total radiation $Q_{rad}$ arises from electron-neutral collisions $Q_{en} = R_{en}(T_e)n_e n_i \nu_{en}$ and electron-ion collisions $Q_{ei} = R_{ei}(T_e)n_e n_i \nu_{ei}$. The radiation coefficients associated with these processes, $R_{en}(T_e)$ and $R_{ei}(T_e)$, were calculated from atomic data used in the KPRAD code.\(^{20}\) The heat lost to the neutral gas $Q_{zn}$ consists of electron neutral elastic collisions $Q_{zn} = 3(m_e/m_i)n_e k_B(T_e - T_n)\nu_{zn}$.\(^{9}\) Ion neutral elastic collisions $Q_{zn} = (3/2)n_e k_B(T_i - T_n)\nu_{zn}$, and charge exchange $Q_{cx} = n_e k_B(T_i - T_n)\nu_{cx}$. These depend on the elastic neutral gas collision rate for a species $\nu_{zn} = n_i \sigma_{en} \sqrt{k_B T_i}/m_i$ with $\sigma_{en} \sim 5 \times 10^{-19}$ m$^2$.

The total heat convected to a surface is modeled by the thermal transmission coefficient,\(^{21}\)

$$\gamma_i = \frac{Z}{1 - \delta_e} + \frac{2T_i}{Z T_e} - 0.5 \ln \left( \frac{2\pi m_i}{m_e} \right) \left( \frac{Z T_i}{T_e} \right) \left( \frac{1}{(1 - \delta_e)^2} \right),$$

(6)

which depends on the secondary electron emission coefficient $\delta_e$ and is only weakly dependent on the species via the mass ratio, for $T_e < 20$ eV, $\delta_e = 0$ and $\gamma_i = 5–8$.

A given $T_e$ and $n_e$ and $T_i$ uniquely determine neutral fill pressure and input power subject to particle and power conservation. Equation (4) is iteratively solved to find $n_i$. Equation (5) is iteratively solved using $T_e$ to calculate $Q_{tot}$. A more sophisticated model which self consistently calculates $T_i$ based on the ion power balance from collisions and viscous heating, as well as modeling the input beam power as a population of non-Maxwellian electrons will be presented in a future publication. However, the current model provides a reasonable prediction over much of the parameter ranges sought.

The model is benchmarked against MPDX data for $Q_{tot} < 150$ kW in Fig. 8. The measured values of $n_e$ and $T_e$ are used to calculate the radiated power flux. This rate is compared to the measured bolometer reading to give an
approximation for the additional loss area $A_l$. A value of $A_l = 0.25 \text{ m}^2$ fits the bolometer data best, which closely matches the surface area of the anodes, cathodes, and several probes in the machine. Using this additional loss area, the corresponding values of the equilibrium input power were calculated using Eq. (5). The result is plotted as a dashed line in Fig. 8(d). At high power, a fraction of the discharge electron beam is lost directly to the wall before it is thermalized and accounts for the difference between the measured input power (the total beam power) and the predicted equilibrium input power (just the thermalized beam). This fraction (as high as 25%) matches predictions based on the thermalization rate and the loss rate for a 450 eV electron. This loss fraction must be taken into account when designing the machine to operate at 300 kW coupled to the plasma, and an actual input power from LaB$_6$ may be higher.

The individual power loss mechanisms in the transport model are elucidated in Fig. 10. The total power $Q_{tot}$ is the sum of all the power losses and represents the equilibrium input power required to sustain a plasma with the corresponding plasma parameters $n_e$ and $T_e$. The power losses are dominated by ion radiation $Q_{ir}$ in argon due to the high number of emission lines. While the neutral radiation rate increases with $T_e$, the neutral density decreases from enhanced ionization and there is a net decrease in neutral radiation $Q_{ir}$ with increasing $T_e$. The plasma confinement decreases with increasing $T_e$ and the plasma ionization rate and ionization power $Q_{iz}$ increase with increasing $T_e$. The plasma power convected to the wall through the cusp $Q_c$ increases with the higher losses and the higher thermal heat coefficient $\gamma_t$. This model applies to singly ionized ions only.

When argon doubly ionizes, the radiation rate increases and the model predicts $Q_{tot}$ too low at high values of $T_e$. However, line radiation ceases for doubly ionized helium and $Q_{tot}$ should be lower than the model predicts at high values of $T_e$.

The confinement model predictions are used to calculate $Re$ and $Rm$ plotted in Fig. 11 for $v_\phi = 10 \text{ km/s}$ and $T_e = 1 \text{ eV}$, reasonable for the high input power and high ionization fractions. These predictions address the ability to achieve different types of dynamo action across a scaling of $Pm$ in MPDX. To generate this plot, the input power is fixed at 300 kW and the plasma density is varied by changing the neutral fill pressure. This creates a tradeoff between $Rm \propto T_e^{1/2}$ and $Re \propto n_e$.

The confinement model estimates when magnetic effects become important in MPDX by calculating the magnetic field required for various magnetic dimensionless parameter benchmarks (Fig. 12). The estimates assume $v_\phi = 10 \text{ km/s}$ for the same 300 kW discharge described above. MPDX will be unmagnetized (i.e., a flow-dominated regime) when the Alfvén Mach number $M_A > 1$ and when $\beta > 1$. This is satisfied for $B < 10 \text{ G}$.

The external Helmholtz coils can be adjusted from $1 \text{ G} < B < 350 \text{ G}$. The magnetic effects on the plasma during the transition to magnetically dominated regime, such as the effects on viscosity, can be studied. The MPDX can also be configured to probe magnetized plasma regimes relevant to laboratory plasma astrophysics. A Lundquist number $S > 5000$ is estimated in MPDX for $B > 100 \text{ G}$. The Lundquist number is the ratio of the $J \times \mathbf{B}$ torque to the resistive magnetic diffusion force $S = \mu_0 L N / \eta = Rm / M_A$. The
Hartmann number is the ratio of the magnetic force to the viscous force \( H_a = BL/\sqrt{\mu_0} = \sqrt{ReRm}/Ma \) and is important in determining boundary layers. A Hartmann number \( H_a = 100 \) in MPDX is predicted for \( B \sim 5 \text{ G} \).

### A. Dynamo scenarios

Kinematic dynamo simulations relevant to MPDX have been previously reported.\(^1\) The process for experimental design is briefly reviewed to both emphasize the connection between the dimensionless parameters used in the modeling but also to illustrate how the experiments are planned to operate. The essence of the stirring is that the axisymmetric multi-cusp magnetic field and cathode stirring allow the azimuthal velocity profile (rotation) \( v_\psi(0, t) \) to be controlled at the plasma boundary. Boundary driven flows are modeled by solving the incompressible Navier-Stokes equation

\[
\frac{\partial v}{\partial t} = \frac{1}{Re} \nabla^2 v - (v \cdot \nabla)v - \nabla p, \quad \nabla \cdot v = 0 \tag{7}
\]

to determine the velocity field subject to the boundary condition \( v_\psi(r = a, 0, t) = f(0) \). Then, the solution to the Navier-Stokes is tested for dynamo behavior by finding the eigenmodes of the induction equation

\[
\frac{\partial B}{\partial t} = \frac{1}{Rm} \nabla^2 B + \nabla \times (v \times B), \quad \nabla \cdot B = 0, \tag{8}
\]

which constitutes a kinematic dynamo problem.\(^3\) Note the Lorentz force is not included in Eq. (7) when linear dynamo stability is being addressed. An example of a resulting velocity field is shown in Fig. 13 for one of the most promising scenarios for which the transition to a self-excited magnetic field is \( Rm_{crit} \sim 300 \).

Table I provides a list of experimental parameters for achieving slow dynamo action based on the simulations described above. The values of \( Re \) and \( Rm \) are from predictions of the dynamo growth rate in the simulations. These uniquely determine \( n_e \) and \( T_e \) for a given gas \((\mu)\), \( T_e = 1 \text{ eV} \) based on possible flow velocities \( v_\psi \). The dynamo problem is reduced to a confinement problem in MPDX and the power balance code is used to predict the input power and fill density required to achieve the desired plasma parameters. The equipartition dynamo field that satisfies \( m_n v_\psi^2/2 = B_{eqp}^2/\mu_0 \) is used as an approximation for the observable saturation magnetic field for dynamo action. The predicted magnetic fields are large enough to be measured by Hall probes, as is done in liquid metal dynamo experiments. The input power required is available, the edge rotation velocities have been measured in similar devices, and the equipartition field is large enough to be easily measured.

### TABLE I. List of experimental parameters for achieving slow dynamos in MPDX.

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<th>Slow dynamo, ( Re = 150, Rm = 300 )</th>
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<td>Gas</td>
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<td>Power ( (\text{kJ}) )</td>
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<td>( v_\psi ) ( (\text{km/s}) )</td>
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<td>( B_{eqp} ) ( (\text{G}) )</td>
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V. CONCLUSIONS

A new experiment for rotating unmagnetized plasma using $\mathbf{J} \times \mathbf{B}$ forcing in a magnetic bucket configuration has been described. The apparatus is suitable for new astrophysically relevant experiments on flow-driven plasma instabilities. As in previous magnetic buckets, the arrangement of permanent magnets into a multicusp configuration results in a large volume of uniform, unmagnetized plasma. A power balance calculation has shown that there is a large range of accessible $Re$, $Rm$, and $Pm$.

The MPDX continues to upgrade its power systems and diagnostics to approach parameters necessary for exciting dynamo action. Additional diagnostics to measure the ion distribution function and additional two-dimensional probe drives are planned for use.

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