Magnetoic dipole discharges. I. Basic properties

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A simple discharge is described which uses a permanent magnet as a cold cathode and the metallic chamber wall as an anode. The magnet’s equator is biased strongly negative, which produces secondary electrons due to the impact of energetic ions. The emitted electrons are highly confined by the strong dipolar magnetic field and the negative potential in the equatorial plane of the magnet. The emitted electrons ionize near the sheath and produce further electrons, which drift across field lines to the anode while the nearly unmagnetized ions are accelerated back to the magnet. A steady state discharge is maintained at neutral pressures above $10^{-3}$ mbar. This is the principle of magnetron discharges, which commonly use cylindrical and planar cathodes rather than magnetic dipoles as cathodes. The discharge properties have been investigated in steady state and pulsed mode. Different magnets and geometries have been employed. The role of a background plasma has been investigated. Various types of instabilities have been observed such as sheath oscillations, current-driven turbulence, relaxation instabilities due to ionization, and high frequency oscillations created by sputtering impulses, which are described in more detail in companion papers. The discharge has also been operated in reactive gases and shown to be useful for sputtering applications. © 2013 AIP Publishing LLC. [http://dx.doi.org/10.1063/1.4817014]

I. INTRODUCTION

By applying a strong magnetic field transverse to the electric field between a cathode and anode, the electrons are confined, which increases the ionization efficiency. Such cross-field discharges have received much attention as efficient plasma sources for various applications such as Hall thrusters,1 magnetron sputtering devices,2 and hollow cathodes.3 Magnetron plasmas have been described by many authors in theory,4,6,7 simulations,7 experiments,8–12 and review articles.13–15 The present work describes perhaps the simplest cross-field discharge consisting of a permanent magnet as a cold cathode and the chamber wall as the anode. The ionizing electrons are produced by secondary emission from the magnet. They travel along the dipolar field lines, reflected by sheaths, ionize neutrals, and produce a dense plasma in the equatorial plane of the magnet. The work focuses on the physical properties of the plasma rather than on its applications. Space and time evolution of plasma parameters are measured and compared with similar observations on commercial planar and cylindrical magnetrons. Instabilities, pulsating discharges, and electromagnetic effects are treated in companion papers.16,17

This paper is organized as follows: After describing the experimental setup in Sec. II, the observations of basic discharge properties will be presented in Sec. III and the findings are summarized in the conclusion, Sec. IV.

II. EXPERIMENTAL ARRANGEMENT

The experiments have been performed at UCLA and reproduced in Innsbruck using similar plasma devices of approximately 40 cm in diameter and 100 cm in length, shown schematically in Fig. 1(a). In these chambers, a plasma of density $n_e \approx 10^5 \text{ cm}^{-3}$, electron temperature $kT_e \approx 2 \text{eV}$, in Argon gas at a pressure $10^{-5} < p < 10^{-2} \text{ mbar}$ can be created by a hot cathode dc discharge. This plasma helps to start the magnetron discharge at low neutral pressures ($p \approx 1 \times 10^{-3} \text{ mbar}$) where there is a lack of neutrals and electron density. It is not required for high gas pressures ($p \approx 5 \times 10^{-2} \text{ mbar}$) and large magnet voltages ($>500 \text{ V}$) where the cathode spots dominate and modify the $E \times B$ drifts as explained below and in Part II.16 The discharge can operate in rare gases as well as mixtures, such as air, and in reactive gases. For experimental convenience, Argon has been chosen.

As shown in Fig. 1(a), a strong cylindrical permanent magnet is supported inside the chamber and biased negatively with respect to the chamber wall. If the magnet is non-conducting (e.g., ferrite magnets), a metal (Ni, Al) electrode is placed around the magnet sidewalls. For conducting magnets (Nd, SmCo), the pole faces are covered by a mica sheet so as to draw current only from the cylindrical sidewalls. Conversely, when the poles are biased and the sidewalls are insulated, no discharge is produced. Different shapes have been used such as cylinders, long bar magnets, and a sphere. The peak field strength at the poles range from 1–9 kG.

Typical bias voltages of −200 to −800 V are applied relative to the grounded chamber wall. Series resistors of up to 1 kΩ are used to limit the current to 10 A in steady state operation. This is needed because much of the discharge power is converted into heating the cathode, which can raise the magnet temperature beyond the Curie temperature $T_{\text{Curie,Nd}} \approx 350 \text{ °C}$ and demagnetizes it. Operation at higher currents ($>10 \text{ A}$) is possible in pulsed mode at a low duty cycle. The pulse generator employs a high-voltage switching transistor and a capacitor charged by a dc-dc converter (12 to 800 V). Even higher current ($>200 \text{ A}$), short-duration ($\approx 1 \mu s$) discharge pulses are produced by relaxation.
instabilities triggered by cathode spots. The dc or pulsed magnet current is measured with a series resistor to ground or a calibrated Rogowski coil. The rf current to the magnet is obtained by inserting a broadband rf transformer in the line to the magnet.

The impact of energetic ions produces secondary electrons. In the present parameter regime, the yield (number of emitted electrons per ion impact) is well below unity such that the magnet current is dominated by ion collection.\textsuperscript{18,19} The electrons emitted from the magnet surface are energized in the sheath. They follow the magnetic field lines, which are nearly parallel to the side walls of the magnets whose permeability is near unity. The electron energy is largest in the mid-plane where a luminous plasma ring appears as shown in Fig. 1(b). The field lines end again on the magnet surface where the electrons are reflected by mirror forces and the sheath electric field.

For a large cylindrical Neodymium magnet (5 cm diam and 2.5 cm length), typical field lines in the region of interest are shown in Fig. 2(a). The radial field strength in the mid equatorial plane is shown in Fig. 2(b). The field lines are mapped by placing an electron source near the magnet and recording the light image. As shown in Fig. 2(c), the electron source can be a cold probe biased to $-500 \text{ V}$ emitting secondary electrons just like the magnet.

To first order, the electrons follow field lines, but to second order they are drifting across $\mathbf{B}$ due to $\nabla \mathbf{B}$, curvature and $\mathbf{E} \times \mathbf{B}$ drifts. Figure 2(d) shows that a single electron source can fill a plasma torus, depending on the electron mean free path. Collisions with neutrals and turbulent fields

\begin{figure}
\centering
\includegraphics[width=0.5\textwidth]{fig1}
\caption{Schematic diagram of (a) the experimental setup and (b) a photograph of the plasma ring in the equatorial plane of a cylindrical permanent dipole magnet biased at $-400 \text{ V}$ in Argon at pressure $p \approx 5 \times 10^{-3} \text{ mbar}$ (Nd magnet, 5 cm diam, 2.5 cm length, and 4 kG max).}
\end{figure}

\begin{figure}
\centering
\includegraphics[width=0.5\textwidth]{fig2}
\caption{Magnetic field and particle motions near a Neodymium permanent magnet (5 cm diam and 2.5 cm height). (a) Field lines. On the sidewalls, the field lines are nearly parallel to the wall. (b) Field strength vs radius in the mid plane. (c) Light from secondary electrons produced by the biased magnet and by a negatively biased electrode in the equatorial plane. (d) Electrons from an emissive probe drifting around the magnet.}
\end{figure}
cause cross-field electron transport. Current closure to the wall requires cross-field electron transport.

Langmuir probes are used to determine the plasma parameters. Probe perturbations can lead to unusual current-voltage \( (I-V) \) characteristics as discussed below. Coaxial probes are employed for fluctuation measurements, magnetic probes for electromagnetic signals, and light emission is detected with a movable photodiode with 0.1 \( \mu \text{s} \) time resolution and high spatial resolution transverse to the line-of-sight. The signals are acquired with a 400 MHz bandwidth 4-channel digital oscilloscope and up to \( 2.5 \times 10^6 \) samples are stored.

### III. EXPERIMENTAL RESULTS

#### A. Current, voltage, and light waveforms

We start by showing some basic properties of the magnetron discharge. When the magnet bias is below a certain threshold, it not only collects ions but begins to emit electrons. A glow discharge develops around the sides of the magnet. The threshold voltage depends on gas pressure, ambient plasma density, and magnet properties and typically lies in the range of \( -300 \) to \( -500 \) V.

In pulsed mode, there is a considerable time lag between the start of the discharge voltage and the discharge current, which is the current flowing from the magnet to ground [Fig. 3(a)]. The delay time decreases when an ambient background plasma is present. When the discharge begins to flow there is a voltage drop due to the series resistor \( (R = 100 \Omega) \). Furthermore, the discharge voltage decays since the supply capacitor \( (C = 2 \mu \text{F}) \) is discharged. The decay of the discharge voltage causes the current to drop and eventually to stop unless the supply capacitor is recharged. If a discharge power \( P_{\text{dis}} > 100 \) W is maintained in steady state, the cathode turns red hot [Fig. 3(b)] and the magnetic field and discharge disappear.

Prior to the onset of the discharge current, a low-density glow discharge forms, which provide ions for secondary electron emission on the magnet. The delay time can be shortened by providing an ambient background plasma with either a hot cathode discharge or a cold electrode biased to a high negative dc voltage.

Instead of supplying an external background plasma, two or more successive voltage pulses can be applied. Figures 4(a) and 4(b) show that the first current pulse exhibits a 200 \( \mu \text{s} \) delay with respect to the voltage pulse, while the second one starts with negligible delay due to the presence of the afterglow plasma of the first pulse. Each current pulse

![Graphs](image)

FIG. 3. Delay between turn-on of discharge voltage and current in the absence of a background plasma. (a) Magnet current and voltage which drop as the storage capacitor \( (2 \mu \text{F}) \) discharges. (b) Steady-state operation causes the cathode to glow and the magnet to demagnetize.

![Graphs](image)

FIG. 4. Discharge current, voltage, and light emission for double pulses. Without background plasma, the first pulse has a long delay time between start of discharge current (a) and applied voltage (b) while the second current pulse starts immediately in the afterglow plasma of the first pulse. The light intensity is not proportional to the discharge current. (c) Light and current for intense short duration discharge pulses. Except for the first pulse, the light pulses are delayed with respect to the current pulses. The peak light intensity decays relative to the peak current or density. Insert shows the time response of the photodiode.
produces a light pulse. While the magnet current scales linearly with ion saturation current to probes, i.e., density, the light intensity does not since it also depends on the electron energy. The highest electron energy arises during the rise of the first current pulse.

Short high current pulses are produced with a smaller charging capacitor (0.1 μF) and no current-limiting series resistor. The first current pulse (nearly 70 A maximum) in Fig. 4(c) is a regular magnetron discharge, while the subsequent pulses (>150 A, ≈1 μs halfwidth) are triggered by cathode spots, which are described in more detail in a companion paper. The light measurements show again differences in the current and light waveforms. During the first discharge, light rises faster than current, implying that energetic electrons are needed to start the discharge. Subsequently, the light drops at a constant current because the capacitor is discharged and the accelerating electric field decays. In the high current pulses, the light emission is delayed with respect to the current. The >0.5 μs delay is not instrumental since the photodiode has a time resolution of ≈0.1 μs as measured with a pulsed light emitting diode (see insert). Since the measured light intensity depends also on the volume of hot plasma, the delay is likely due to the expansion of hot plasma from a spot (arc) discharge. The peak light intensity drops in successive discharge pulses while the peak current, hence magnet voltage, remains constant.

The photodiode has a narrow angular sensitivity pattern transverse to the line of sight (3° halfwidth). It is mounted on a radially movable probe above the magnet and looks down at the plasma disk, and can thus resolve the radial light profile vs time. In order to avoid electrostatic interference, the probe is shielded and connected via a coaxial cable to the oscilloscope.

Figure 5 shows waveforms of the light emission at different radial distances from the magnet surface as well as the discharge voltage and current. Double pulses are used to show the effect of a background plasma. The first pulse exhibits an initial overshoot that propagates radially outward at a speed of \( v \approx 2.6 \times 10^6 \text{ cm/s} \), which indicates the cross-field transport of energetic electrons. The light intensity drops off radially since energetic electrons loose their energy by ionization and secondary electrons do not produce much light. When the discharge voltage is turned off, the afterglow light decays with \( e^{-}\)folding time \( \tau \approx 5 \mu s \), which is much faster than the density decay time. The light of the second pulse exhibits no radial propagation, hence is not produced by accelerated secondary electrons emitted from the magnet but by heated electrons in the entire afterglow plasma. The discharge voltage for the second pulse is comparable to that at the end of the first pulse and so is the light intensity.

Some properties of the discharge can be inferred from the relation between discharge current \( (I) \) and voltage \( (V) \). Pulsed discharge operation covers a wider range of \( I-V \) parameters than steady-state discharges. Since the power supply is a charged capacitor, the current waveform exhibits a peak while the voltage decays. We define the \( I-V \) characteristic for the peak current and its corresponding voltage.

Figure 6(a) shows a small family of \( I_{\text{magnet}}(t) \) and corresponding \( V_{\text{magnet}}(t) \) for different initial charging voltages. With increasing supply voltage, the current starts earlier, has
a larger peak value, and decays faster than for lower voltages. Figure 6(b) shows that the current starts at a high discharge voltage, reaches a maximum at an intermediate voltage, and vanishes at a low voltage.

Figure 6(c) shows that the peak discharge current rises rapidly with its corresponding discharge voltage. Thus, the plasma resistance, $V/I$, decreases with increasing current. At $I_{\text{max}} = 23 \text{ A}$ and $V_{\text{magnet}} = 340 \text{ V}$, one has $R = 15 \Omega$. For large currents (200 A) and short pulses, obtained without series resistor and smaller capacitors, the plasma resistance is observed to decrease to $<1 \Omega$. Thus, the discharge shows no current limitation within the present parameter regime. Unlike thermonic cathodes, the emission is not temperature or space charge limited but has an avalanche-like property: the secondary electron emission increases with increasing ion density, which in turn produces more ions collected again by the cathode.

As with most discharges, the present one also exhibits hysteresis: When raising the applied voltage, there is a high threshold for breakdown; while upon lowering the voltage, the discharge is extinguished at a low threshold. Such hysteresis can lead to relaxation oscillations with a capacitive power supply. This effect is used to produce high-current microsecond pulses requiring no fast switching circuits, as described in a companion paper.17

B. Density and potential profiles

The spatial distributions of plasma parameters have been mapped using a movable cylindrical (0.125 mm diam and 2.5 mm length) Langmuir probe. Figure 7 shows a typical profile of the ion saturation current in a plasma torus around a 5 cm diam Nd magnet. As expected from the visual images, the plasma density peaks in the mid plane of the magnet with a halfwidth comparable to the 2 cm height of the magnet. The plasma extends radially outward with a half-width of 10 cm, which exceeds that of the light emission since the electron energy drops with radius. The plasma disk is azimuthally uniform.

The plasma potential has been measured with an emissive probe. These measurements were restricted to steady-state conditions since the probe’s filament heater supply had a large stray capacitance to ground which limited the time response for pulsed experiments. Figure 8 shows the radial plasma potential for a relatively low $V_{\text{magnet, dc}} = -360 \text{ V}$,
and the radial electric field, $E = -\nabla \Phi$. Electrons which diffuse radially outward for a few cm gain enough energy to excite and ionize neutrals. Since the magnet voltage is far more negative than the plasma potential, there is an ion-rich sheath near the magnet surface where most of the particle acceleration takes place.

The floating potential of a cold Langmuir probe has been mapped radially and axially for a pulsed discharge. The plasma potential should be a few $kT_e$ positive with respect to the floating potential. Figure 9(a) shows the temporal behavior of $V_{\text{float}}$ near the magnet together with the discharge current, $I_{\text{magnet}}$. The potential is most negative at the start of the discharge ($t \approx 60 \mu$s). As the discharge current rises, the capacitor voltage drops which causes the potential to rise. The radial and axial potential profiles at the start of the discharge are shown in Figs. 9(b) and 9(c). The potential forms a deep well transverse to the plasma layer [Fig. 9(c)]. The electric field, $E_z$, is nearly parallel to the magnetic field, but this does not imply a net outflow of electrons. They are accelerated along $B$ and decelerated by magnetic ($-\mu \nabla B$) and electric forces where the field lines touch the negatively biased magnet. Electron bouncing enhances the ionization rate. Electrons created by ionization are also trapped and gradually drift away from the cathode due to collisions. Unmagnetized ions are collected in the channel and accelerated by the radial electric field toward the magnet. The potential profile indicates that the channel is ion-rich, $-\nabla^2 \Phi = (n_i - n_e) e / \epsilon_0 > 0$, and filled with plasma. Near the chamber wall, the plasma potential must be close to ground such that an electron current equal to $I_{\text{magnet}}$ is collected.

**C. Probe diagnostics**

Due to the confinement of electrons, Langmuir probes easily perturb the plasma when collecting electrons. Collecting ion currents with small cylindrical probes produces the least perturbation. In a pulsed plasma, the probe current is recorded for different dc probe voltages for repeated discharge pulses. A typical $I-V$ characteristics of a cylindrical probe ($0.125$ mm diam and 2 mm length) taken near the end of a weak magnetron discharge pulse is shown in the insert of Fig. 10(a). The electron retardation region yields an electron temperature $kT_e \approx 2.5$ eV; and together with the ion saturation current, a density $n_i \approx 8 \times 10^{11}$ cm$^{-3}$ is determined.

When the probe is at ground potential and placed into the plasma layer with negative floating potential, it draws electrons. The probe current exhibits large fluctuations [Fig. 10(a); $\delta I/I_{dc} \approx 50\%$], which are predominantly plasma potential fluctuations due to the steep rise of the $I-V$ curve. When the probe collects ions, as shown in Fig. 10(c), the fluctuations are relatively small. The plasma potential rises rapidly at the end of the discharge current, which causes a capacitive current spike. In the afterglow, the probe current decays gradually indicating a density decay with e-folding time constant $\tau \approx 0.65$ ms. In contrast, the electron current to the probe vanishes instantly, which is due to electron depletion by the probe and the rise in the plasma potential.

The $I-V$ probe characteristics has been extended to very negative voltages where secondary electron emission occurs,
as confirmed by light emission from the probe. A plane Langmuir probe (1 cm × 1 cm Ta) is used which produces a constant saturation current. It is biased in steady state and positioned near the magnet that creates the pulsed magnetron discharge. For \( j_{\text{probe}} > 400 \text{ V} \), light emission in the flux tube of the probe is observed [insert of Fig. 11(a)]. No significant enhancement in the \( I-V \) characteristics is found either in the magnetron discharge or the afterglow [Fig. 11(b)]. For the present ion energies, the secondary electron emission yield is well below unity. However, at still higher probe voltages, arcs develop on the probe, which increase the probe current by orders of magnitude. Since the negatively biased probe produces a steady-state plasma, it can be used to provide a background plasma for easy start of a pulsed magnetron discharge.

The mechanism of the perturbation by the probe on the trapped electrons is demonstrated in Fig. 12. The plane probe has been placed 3 mm in front of the magnet side wall so as to diagnose the dense plasma ring. Figure 12(a) shows the waveforms of the discharge current \( I_{\text{magnet}} \) and probe currents for positive and negative probe bias. The probe bias affects the duration of the discharge pulse and the decay time of the probe currents. By varying the dc probe voltage from pulse to pulse and recording the corresponding probe currents \( I_{\text{probe}}(t) \), the \( I-V \) characteristics can be constructed at different times of the discharge. As shown in Fig. 12(b), the floating potential is very negative in the early phase of the discharge \( (t = 3 \mu s) \) since the magnet voltage is large and electrons are energetic. In the steady-state part of the discharge \( (t = 15 \mu s) \), colder secondary electrons shift the floating potential to \( V_{\text{float}} \approx -60 \text{ V} \). A kink in the \( I-V \) curve develops, which becomes very pronounced in the early afterglow. As shown in Fig. 12(c), a region of negative differential conductance is formed which is due to probe depletion of trapped electrons. With increasing probe bias, the electrons are depleted faster, resulting in a decrease of current with voltage. The electron current drops faster than the ion current; and at \( t > 1 \mu s \) into the afterglow, the electron saturation current is as small as the ion saturation current. As shown in Fig. 12(d), the electron depletion can be minimized with a small cylindrical probe, which draws much smaller electron currents and exhibits a “normal” \( I-V \) characteristic.

A negative slope in the \( I-V \) curve has also been observed in gridded cavities with negative bias.\(^{20}\) There, the electron supply into the cavity is limited and a positive probe depletes the electron density causing the current to decrease with increased probe bias.

However, small probes can create other perturbations when biased positively. It is the formation of “fireballs,”\(^{21–25}\) which are small spherical discharges on positive electrodes in plasmas with sufficiently high neutral pressures.
These discharges are often unstable to relaxation oscillations as shown in the insert of Fig. 12(d). Fireballs increase the effective collection area of the probe such that large current spikes are produced. The probe has to be biased well above the ionization energy relative to the plasma potential. Since the plasma potential is negative in the magnetron discharge, fireballs arise even for low probe voltages above ground.

FIG. 12. $I$–$V$ characteristics of a 1 cm × 1 cm plane probe at 3 mm in front of cylindrical Nd magnet with pulsed voltage. Probe biased with dc voltage. (a) Waveforms of magnet current, probe electron, and ion saturation currents. Probe bias affects plasma: Collecting ions shortens the pulse width, drawing electrons depletes density in afterglow. (b) $I$–$V$ trace in the early discharge shows very energetic (>100 eV) electrons. Ionization during the discharge lowers the electron temperature. (c) Plasma potential is negative in discharge, positive in afterglow. Electron depletion increases with positive bias and creates a region with $dI/dV < 0$. (d) Small probe shows no negative slope in afterglow. For positive bias, pulsating fireballs are created around the probe which produce large current spikes (see insert).

($>5 \times 10^{-3}$ mbar). Fireballs increase the effective collection area of the probe such that large current spikes are produced. The probe has to be biased well above the ionization energy relative to the plasma potential. Since the plasma potential is negative in the magnetron discharge, fireballs arise even for low probe voltages above ground.

FIG. 13. Sputtering applications. (a) Steady-state discharge around a 2.5 cm diam SmCo magnet with insulated cylindrical cathode. Coating of a clean (bottom) ceramic rod with tungsten (top). (c) W wire cathode on the magnet. (d) Aluminum cathode which sputtered the exposed magnet surface with clean Al.
D. Sputtering

Although this paper mainly focused on the discharge physics, the applications of magnetrons for sputtering has stimulated the field. The impact of energetic ions on a surface not only releases secondary electrons but also ions and neutrals. The latter are unaffected by magnetic fields and scattered broadly away from the magnet. Any object, including the magnet, will be coated with neutrals of the sputtered cathode material.

Here, we show just one example for the effective coating of objects with films of tungsten and aluminum. The discharge is operated in steady state at low currents ($I_{\text{magnet}} = 0.1 \text{ A}$) to avoid heating of the magnet [Fig. 13(a)]. A Samarium-Cobalt magnet (2.5 cm diam and 3 cm length) has been used since its Curie temperature ($T_c \approx 750^\circ \text{C}$) is higher than that of Neodymium magnets ($\approx 320^\circ \text{C}$). A clean ceramic rod is suspended nearby [Fig. 13(b)]. A layer of thin fiberglass sleeving insulates a cylindrical Al cathode from the magnet. To form a W cathode, a layer of W wire is wound on the cathode [Fig. 13(c)]. After 2 h of operation, the ceramic rod was coated with tungsten [Fig. 13(d)] and so was the magnet surface. By unwinding the W wire, the Al cathode was sputtered. It created the white Al coating on the magnet shown in Fig. 13(d). A covered piece of the end face was not coated and shows the original magnet color.

Since no hot cathode is employed, the present discharge can also be operated in reactive gases. It has been run continuously or in pulsed mode in air, which cleans the cathode effectively.

IV. CONCLUSION

There are many types of cross-field discharges which differ in geometry and applications but have the same principle, i.e., electron confinement by transverse magnetic fields for improving the degree of ionization. The present device is perhaps the simplest configuration of such a discharge. It employs a permanent magnet as a cold cathode, which emits secondary electrons due to impact of energetic ions and also serves for confining the magnetized electrons although not the ions. Emitted electrons gain energy when they traverse the cathode sheath across the magnetic field. The energized electrons ionize the gas. Electrons produced outside the sheath are not only confined by the magnetic field but also reflected by the cathode sheath. The electron energy maximizes in the equatorial plane of the magnet where most of the plasma is produced and resides.

The properties of this discharge have been measured with probes and simple optical detectors. Many observations are in agreement with those found for planar magnetrons. The latter use a plane cathode on the pole face of a permanent magnet and observe a plasma ring (“racetrack”) in the $E \times B$ region. This geometry serves for sputtering on adjacent plane substrates. Sputtering discharges have an ignition threshold voltage, a steep $I$–$V$ characteristics with hysteresis, and develop cathode arcs with increasing currents. In the present experiment, very short high current pulses are produced by a relaxation instability between the voltage-dependent plasma resistance and a small charging capacitor. Cathode spots are nanosecond arcs which create localized discharges on the magnet that can support high plasma currents. They produce electromagnetic effects, instabilities, and transient oscillations, which are described in companion papers.

Although sputtering applications were not the objective of this experiment, it was shown that cathode material placed on the magnet can be deposited on surrounding objects. The cylindrical geometry may be best suited for etching and depositing material on cylindrical objects.

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