Magnetic dipole discharges. III. Instabilities

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Instabilities in a cross-field discharge around a permanent magnet have been investigated. The permanent magnet serves as a cold cathode and the chamber wall as an anode. The magnet is biased strongly negative and emits secondary electrons due to impact of energetic ions. The electrons outside the sheath are confined by the strong dipolar magnetic field and by the ion-rich sheath surrounding the magnet. The electron energy peaks in the equatorial plane where most ionization occurs and the ions are trapped in a negative potential well. The discharge mechanism is the same as that of cylindrical and planar magnetrons, but here extended to a 3-D cathode geometry using a single dipole magnet. While the basic properties of the discharge are presented in a companion paper, the present focus is on various observed instabilities. The first is an ion sheath instability which oscillates the plasma potential outside the sheath below the ion plasma frequency. It arises in ion-rich sheaths with low electron supply, which is the case for low secondary emission yields. Sheath oscillations modulate the discharge current creating oscillating magnetic fields. The second instability is current-driven ion sound turbulence due to counter-streaming electrons and ions. The fluctuations have a broad spectrum and short correlation lengths in all directions. The third type of fluctuations is spiky potential and current oscillations in high density discharges. These appear to be due to unstable emission properties of the magnetron cathode.

I. INTRODUCTION

Cross-field discharges such as Hall discharges,1,2 magnetron discharges,3–6 and surface magnetic field devices7 have attracted much attention since they produce plasmas more efficiently than field-free discharges. The magnetic field partially confines the ionizing electrons which enhances the ionization rate. Magnetrons have the added advantage that no heated cathodes are required since ion impact provides for secondary electron emission.

In most cross-field devices, the electron transport across the field is not classical. Since these plasmas are not quiet, it is natural to suspect anomalous transport due to turbulence. Instabilities in magnetrons have been predicted theoretically5 and investigated experimentally.9 However, not all fluctuations are due to plasma wave instabilities. Discharge “instabilities” like short-duration arcs, called cathode spots or anode fireballs10–13 can drastically alter the transport and thereby the discharge properties.

The present experiment employs the simplest magnetron using a permanent magnet as cathode and the vacuum chamber as anode. It does not focus on applications14 but on the discharge physics whose basic characteristics are described in a companion paper.15 The present paper focuses on different types of instabilities that have not yet been described. First, a cathode sheath instability is described which arises when an ion-rich sheath is formed in a plasma with a restricted supply of electrons. The sheath oscillates near the ion plasma frequency causing global plasma potential oscillations in the surrounding plasma. Potential oscillations also modulate the discharge current and produce magnetic oscillations as well as oscillating inductive electric fields. The ion sheath instability has been studied in double plasma devices16–21 and gridded plasma bubbles22–25 but without electromagnetic effects. Observationally, ion-rich sheaths with a small population of electrons create copious harmonics.

Second, broadband turbulence is observed for stronger discharge currents. Its spectrum falls into the ion acoustic regime. Sound waves are weakly damped since the electron to ion temperature ratio is large. Since the instability is seen only during the discharge, it can be described as current-driven ion sound turbulence.

Spiky potential and current fluctuations are observed and explained by the emission properties of the cathode. The cathode current increases progressively as the potential drop across the cathode sheath increases. Thus, a plasma potential rise increases the cathode current and vice versa. Potential fluctuations can in turn arise from ionization in the cathode sheath which increases the space charge density when the electron mobility exceeds that of the ions. Hence, the mechanism of the spiky discharge current can be described as a sheath ionization relaxation instability.

The present paper is organized as follows: After reviewing the experimental setup and diagnostics in Sec. II, the observations of instabilities will be presented in Sec. III and its various subsections. The findings are summarized in Sec. IV.

II. EXPERIMENTAL ARRANGEMENT

The experimental setup shown schematically in Fig. 1 has already been described in companion papers15,26 and will only be summarized here. It is a deceptively simple discharge consisting of a permanent magnet as the cathode and the chamber wall as anode. A negative voltage of order
500 V is applied to the cathode in dc or pulsed mode. Plasma ions impacting the magnet release secondary electrons which turns the cold magnet into an electron emitting cathode. The electrons are energized as they traverse the cathode sheath. The magnet partially confines electrons, which results in a much higher ionization probability than in a field-free discharge.

Permanent magnets of different geometries (cylinders, spheres, bars) and materials (Nd, SmCo, Fe$_3$O$_4$) are used. DC operation of magnetrons usually requires a current-limiting series resistor so as to limit heating and demagnetizing the permanent magnets. Higher currents are obtained in pulsed operation at a low duty cycle. The pulse generator employs a fast high voltage switching transistor and a capacitor charged by a dc-dc converter of up to −800 V. The magnet current is obtained from a Rogowski coil or a shunt to ground. The rf component of the magnet current is obtained from a broadband rf transformer inserted in the line to the magnet.

Langmuir probes are used to determine the plasma parameters. These consist of cylindrical probes (0.125 mm diam, 2 mm length, Ta) and a plane probe (1 cm × 1 cm, Ta). A pair of cylindrical probes, movable in radial and vertical direction is used for cross-correlation measurements. RF oscillations are usually detected with coaxially fed cylindrical Langmuir probes. The grounded coaxial outer conductor has to be carefully insulated so as to avoid drawing electrons in regions of negative plasma potential. Alternatively, differential RF probes have been used which consist of two 1 mm diameter semirigid coaxial cables connected to a balanced broadband rF transformer (0.2 – 350 MHz). The insulated transformer avoids ground currents and the differential arrangement measures electric or magnetic wave fields while canceling large common-mode potential variations in pulsed discharges. Magnetic RF probes are made of 1 mm diameter coaxial cables, bent into an 8 mm loop with a break in the outer shield. By rotating the probe, two field components can be measured or the proper probe response $V_{probe} \propto \cos \phi$ verified.

Special attention has been paid to the interpretation of probe signals in a pulsed plasma. Fast current fluctuations can be displacement currents due to plasma potential variations and the sheath capacitance, $I = C dV/dt$. Electrons and ion conduction currents also depend on plasma potential variations because cylindrical Langmuir probes do not have constant saturation currents.

All signals are acquired with a 4-channel digital oscilloscope with bandwidth up to 400 MHz and up to $2.5 \times 10^6$ samples are stored.

III. EXPERIMENTAL RESULTS

Discharges are subject to various instabilities, particularly when a magnetic field is transverse to the cathode-anode direction. Commonly discussed are current driven plasma instabilities but cross-field discharges also exhibit sheath and ionization instabilities due to secondary electron emission, sputtering, and arc formation. Observations of several types of instabilities will be discussed below.

A. Ion sheath instability

An ion rich sheath can become unstable when the electron supply is limited and cannot balance the expansion of the ion sheath. An ion sheath instability has been observed in double plasma devices but cross-field discharges also exhibit plasma bubbles formed by spherical grids with negative bias in an ambient plasma. The sheath oscillates near the ion plasma frequency.

Such a situation also arises at the cathode of the present magnetron discharge. Secondary electrons emitted from the cathode by impact of Ar ions of <1 keV have a yield of typically 0.1. Electrons from the ambient plasma are prevented from approaching the sheath due to a strong transverse magnetic field and an opposing electric force. Thus, the ion charge density in the cathode sheath leads to a sheath expansion which is not balanced by electrons. The inertia of ions provides a positive feedback for an oscillation of the sheath near the ion plasma frequency where the ion transit time corresponds to an rf plasma period, $f_{\nu i} = 1$. A similar transit time instability exists at the electron plasma frequency in electron-rich sheaths. Oscillations of the sheath charge density affect the potential drop across the sheath which creates an oscillating plasma potential in the ambient plasma for a constant electrode potential.

In the present experiment, the shear oscillation instability is observed for low dc discharge voltages or in the early phase of pulsed discharges. The latter is displayed in Fig. 2(a) showing the pulsed discharge current, $I_{magnet,dc}$, and coherent oscillations in the magnet current, $I_{magnet,rf}$, as well as in two rf probes, $I_{probe,rf}$, located at different radial and axial positions. All signals oscillate at the same frequency, $f \approx 1.5$ MHz, which is close to the ion plasma frequency in Argon at a density $n \approx 2 \times 10^6$ cm$^{-3}$. The magnet voltage (−600 V) is applied at $t = 0$ which produces a low density discharge plasma followed by the delayed onset of the magnetron discharge. Prior to the rise of $I_{magnet,dc}$, there may be a positive space charge layer which reflects the ions. Such a “virtual anode” is unstable and oscillates near the ion plasma frequency.

Figure 2(b) shows waveforms of $I_{magnet,rf}$ and $I_{probe,rf}$ for two different vertical positions $z$. The signals are conditionally averaged, i.e., the oscilloscope is triggered from $I_{magnet,rf}$ and both signals are averaged over many repeated
discharges. The same oscillations in both traces indicate that they have a long temporal coherence.

One obtains the spatial coherence by moving the probe. No phase shift is observed in the $z$-direction ($\parallel \mathbf{B}$), nor in $r$-direction ($\perp \mathbf{B}$). Thus, the plasma potential oscillates globally, supporting the conclusion that the sheath is the source of the instability. The oscillations are not due to propagating ion acoustic waves. The oscillation amplitude decays outside the plasma layer, implying that there is a rf electric field. The movement of the probe perturbs the electron confinement causing small frequency shifts. Since the plasma potential oscillates at a high frequency ($\approx f_{pi}$), the oscillating magnet current is predominately a displacement current rather than an ion current.

Sheath oscillations can become strongly nonlinear as demonstrated in Fig. 3(a) where the Fast Fourier Transform of $I_{\text{magnet}}$ is shown. The spectrum displays multiple harmonics. The second harmonic amplitude exceeds that of the fundamental, which suggests that the first line is a subharmonic of the second. Similar effects have been observed in earlier sheath instability investigations. The frequency increases with $|V_{\text{magnet}}|$ since the discharge current, hence density and ion plasma frequency, increases with $|V_{\text{magnet}}|$ [Fig. 3(b)]. Close inspection of Fig. 3(a) also shows that the frequency increases as the discharge current grows in time. The harmonics are above the ion plasma frequency and cannot excite ion acoustic waves.

A magnetron discharge has a threshold voltage for the onset of $I_{\text{magnet}}$. The sheath oscillations arise just below the threshold for ignition of the magnetron discharge. It shows that a background plasma is needed to ignite the magnetron magnetron discharge. Figure 4(a) shows the fluctuations and net current to the magnet for a pulsed voltage below threshold. The magnet current exhibits a capacitive transient at $t \approx 0.02 \text{ ms}$ when the magnet voltage is switched on, but a negligibly small discharge current develops, $I_{\text{magnet,dc}} \approx 1 \text{ mA}$. However, due to the oscillating plasma potential there is a rf displacement.
current flowing from the magnet to ground, $I_{\text{magnet rf}}$. Its amplitude and frequency exhibit a peak, caused by density variations since the magnet voltage is constant. The time resolved spectrum displayed in Fig. 4(b) shows that the oscillation has a pronounced second harmonic. If $V_{\text{magnet}}$ is raised, the onset of $I_{\text{magnet}}$ occurs at the peak of the oscillation.

When the magnetron discharge occurs, the instability changes its character. Figure 4(c) shows magnet current and voltage waveforms, the oscillation from the rf probe and their spectra in several inserts. Prior to the onset and after the end of $I_{\text{magnet}}$, the oscillations are again sheath-plasma instabilities with narrowband lines and a harmonic. Broadband turbulence is created during the magnet current pulse and its properties are described below.

**B. Current-driven turbulence**

When a strong discharge current of several Amperes flows, the plasma exhibits broadband turbulence in the ion acoustic frequency range. Typical waveforms of the discharge current and the probe signal are displayed in Fig. 5(a). The oscillations exhibit random waveforms which occur only in the presence of the discharge current. Thus, cross-field electron drifts ($E \times B$, $\nabla B$), which also exist in the afterglow plasma, are not the cause for the noise, as speculated in Ref. 8. The time-resolved spectrum of the probe signal [Fig. 5(b)] shows that the center frequency of the broadband noise and the noise amplitude decrease as the discharge current decays in time.

The spatial and temporal coherencies of the turbulent oscillations are obtained by conditionally averaging two movable probe signals. For this case, the trigger level "condition" is typically chosen at half the peak oscillation amplitude of the stationary probe signal. An ensemble average is formed over many repeated discharges of both probe signals. The temporal coherence is judged by the decay of the average in time, the spatial coherence is given by the decay with probe separation. Coherent signals are sinusoidal, incoherent signals decay rapidly in space and time. The latter is observed in the present case.

Figure 6 shows conditional averages of $I_{\text{probe rf}}$ vs time in the azimuthal (a) and radial direction (b). The temporal coherence has a halfwidth of $\Delta t \approx 0.5 \mu s$ corresponding to the inverse bandwidth of the broadband signal. The spatial coherence in both azimuthal and radial directions has similar half-widths of $\Delta r \approx 7 \text{ mm}$. A small shift of the contours indicates a preferential propagation in the $E \times B$ direction and radially inward direction, the direction of the ion drift. The propagation speed is $v_{\text{phase}} \approx (0.7 \text{ cm}/0.5 \mu \text{s})/\sqrt{2} \approx 1 \text{ cm}/\mu \text{s}$, while the sound speed is $c_s \approx 0.5 \text{ cm}/\mu \text{s}$ in Ar for 10 eV electrons.
The above observations are consistent with properties of current-driven ion sound turbulence. The current is due to counter-streaming electron and ion drifts. Magnetized electrons drift azimuthally around the equator of the magnet except when scattered radially away from the magnet in the radial electric field. Unmagnetized ions are accelerated toward the magnet. Sound waves drift with the ions and grow along the electron drift. No turbulence arises without discharge current. After the end of the discharge, there remains an afterglow plasma with cross-field electron drifts but these are insufficient to maintain the broadband turbulence.

Other investigators have studied instabilities in planar magnetrons and concluded that they are drift waves in the $\mathbf{E} \times \mathbf{B}$ direction. Since both $\mathbf{E}$ and $\mathbf{B}$ are spatially varying, it is not obvious why eigenmodes with discrete frequencies are formed. In the present experiment, the instability exhibits no discrete spectral lines and the spatial coherence length is much shorter than the azimuthal circumference, hence forms no drift wave eigenmodes. To our knowledge, the present observation of ion sound turbulence in magnetrons is novel.

C. Magnetic oscillations

For large discharge currents, the sheath instability modulates the discharge current leading to magnetic oscillations. These have been detected with magnetic probes and shown not to be propagating electromagnetic waves but instabilities of the cathode emission.

Figure 7(a) displays the waveform of a short but strong discharge current pulse produced with a 2 $\mu$F charged capacitor and a small series resistor ($R = 1 \, \Omega$). As the magnet current rises, it exhibits small oscillations whose frequency increases with current ($f = 40$–$90 \, \text{MHz}$), hence are not transient ringing effects. The same oscillations are observed with a magnetic probe near the magnet [Fig. 7(b)]. Since the amplitude and phase fluctuate from pulse to pulse, the probe signal has been conditionally averaged [Fig. 7(c)]. The probe signal is gated to a desired time, then the oscilloscope is triggered at a chosen amplitude level (the “condition”) and the signal is averaged over typically 100 repeated discharge pulses. The temporal coherence extends only over a few cycles. Together with the magnetic probe signal, the fluctuations in the magnet current are averaged [Fig. 7(d)]. The “dc” current is subtracted so as to display only the fluctuations. Not surprisingly, the current and magnetic oscillations correlate. The magnetic probe signal increases as the probe is moved closer to the feed wire of the magnet but exhibits no phase shift with distance inside the plasma. Thus, although the oscillation frequency falls into the whistler mode regime, it is not a plasma eigenmode but an electromagnetic oscillation of the discharge current.

In order to confirm that the high frequency probe signal is a magnetic oscillation, the angular probe response has been checked. Figure 7(e) shows conditionally averaged traces of two identical magnetic probes, one movable and the other stationary. The latter provides the trigger for conditional averaging, i.e., a reference phase. The movable probe is then rotated around its axis by an angle $\Delta \phi$ and exhibits a sign change when $\Delta \phi = \frac{180}{\pi}$ [Fig. 7(f)]. The rotation...
indicates that the magnetic field is azimuthal to the wire connected to the magnet. Initially, the frequency of the magnetic oscillations increases with discharge current. The latter has been raised to its limits by discharging the capacitor without a series resistor for a few shots, reaching currents up to 400 A in 2 s pulses. Figure 8(a) shows the oscillations in the current waveform and magnetic probe signal. The time-resolved frequency spectrum of the probe signal [Fig. 8(b)] shows the frequency increase during the rise of \( I_{\text{magnet}} \) up to 200 MHz followed by an abrupt drop to 20 MHz approaching the current peak. The initial oscillation is consistent with the ion plasma frequency of a dense plasma \( (n \approx 4 \times 10^{13} \text{ cm}^{-3}) \). However, the sudden frequency drop with rising current indicates a different mechanism such as a ringing effect due to a cathode spot as described in the previous companion paper. All frequencies are well below the electron cyclotron frequency of the strong Nd magnet \( (B_{\text{max}} \approx 4 \text{ kG}, f_{ce} = 11 \text{ GHz}) \).

D. Probe displacement currents

The signal of rf probes is frequently found to consist of pulses rather than sinusoidal oscillations. In order to interpret these features, the probe response has been first investigated.

When the discharge is turned on, the floating potential of Langmuir probes drops rapidly to a large negative value and subsequently decays gradually. Figure 9(a) displays the discharge current, Fig. 9(b) the rf probe signal, and Fig. 9(c) the floating potential on a Langmuir probe attached to a high impedance oscilloscope probe. The rf probe is a cylindrical probe connected to a grounded broadband rf transformer and a matched 50 \( \Omega \) coaxial cable to the oscilloscope. Its signal is a negative pulse closely resembling the derivative of the floating potential waveform. Since the probe is grounded and the floating potential is negative, the probe should also collect electrons. However, the probe current peaks prior to the most negative floating potential, after which it reverses sign, rather than decay slowly with the floating potential, all inconsistent with an electron current to a probe. The rf transformer can transform a pulse of 5 \( \mu s \) duration, albeit with some droop. Thus, the probe current is best explained by a displacement current due to the time varying plasma potential and the sheath capacitance, \( I = C_{\text{sheath}}dV_{\text{plasma}}/dt \). When the probe current is integrated, its waveform is proportional to the floating potential and can be fitted by a constant factor [Fig. 9(c)]. Since the electron temperature is small compared to the potential drop \( (KT_e \ll e|V_{\text{float}}|) \), it is not unreasonable to assume that the plasma potential behaves like the floating potential. From the scaling factor (1.66) and the probe
The potential oscillations have been explored. Figure 8 shows the simultaneously recorded probe signals for two different probe separations along the electron drift direction of a bar magnet. The probe signals are in phase irrespective of the probe position, implying that the signal is not due to a propagating wave but to a global potential oscillation of the plasma layer with respect to ground or the constant cathode potential.

**E. Spiky discharge fluctuations**

Ionization instabilities can produce fluctuations in a discharge which are far stronger than microinstabilities in the plasma. One of these effects was shown in a companion paper\textsuperscript{26} which described the formation of pulsating “fireball” discharges on a positively biased probe. It modulates the discharge current, the plasma potential, and most probe signals. Another example is the unstable current-voltage characteristic of a cold cathode with secondary electron emission.

Figure 10 presents examples of spiky potential and current oscillations in a magnetron discharge. The discharge current has an initial pulse due to the capacitive power supply, followed by a low current, slowly decaying discharge [Fig. 10(a)]. In the low-current regime, the potential exhibits repetitive sub-microsecond pulses [Fig. 10(b)]. These are not plasma waves but global plasma potential fluctuations. The potential is obtained by integrating the displacement current of the rf probe. It is positively correlated with fluctuations in the discharge current, i.e., the current increases when the potential increases [Fig. 10(c)].

When the discharge voltage is increased, the discharge current is increased [Fig. 10(d)]. The frequency of the rf probe pulses increases and their spacing becomes so close that the spikes go over into a continuous oscillation [Fig. 10(e)]. Still, the signal remains a global potential oscillation but it is not a sound wave. During the current decay, the frequency decreases as shown in the time resolved FFT of $V_{\text{probe,rf}}$ [Fig. 10(f)].

Spikes are also observed in the discharge current [Fig. 10(g)]. Since they correlate with the potential oscillations, their frequency also decreases when the magnet current decreases. Note that while the peak current increases the low level current may decrease. The current spikes of the middle trace are shown on an expanded time scale in Fig. 10(h). The spikes are all positive, very short, and reach a significant fraction of the dc discharge current $(\delta I/I \simeq 0.3)$. The magnetic probe signal confirms that the current spikes create magnetic field spikes inside the plasma. When the discharge voltage is further increased, the discharge develops cathode spots, i.e., short duration arcs which produce high current discharge pulses but little subsequent spikes. The high current discharge mode has been described in more detail in a companion paper.\textsuperscript{26}

One cannot distinguish between cause and effect of the phenomenon from the simultaneity of current and potential spikes alone. However, the steep current-voltage characteristics of the magnetron discharge provide additional information. As the cathode voltage is increased, the ion energy increases which raises the secondary electron emission yield. The increased electron current and energy increase ionization and ion collection, hence the discharge current rises.

![FIG. 8. Oscillations in the magnet current of a strong discharge.](image_url)

(a) Discharge current waveform and magnetic probe signal. (b) Time-resolved frequency spectrum of the magnetic oscillations. The frequency rises rapidly which confirms that it is an instability and not a transient ringing effect. A sheath instability modulates the cathode current at the ion plasma frequency which yields an estimate of the ion density near the cathode ($n \approx 4 \times 10^{13}$ cm$^{-3}$). The abrupt frequency drop near the peak current suggests a transient oscillation triggered by a cathode spot. (5 cm diameter Nd magnet, 2 $\mu$F capacitor charged to 800 V, $R_{\text{series}} = 1$ $\Omega$, 5 mbar Ar).

![FIG. 10.](image_url)

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progressively. The ions acquire their energy mainly from the potential drop of the cathode sheath. For a constant magnet voltage, the plasma potential rises, the sheath potential drop increases, and the same feedback arises as when the magnet voltage is made more negative. Thus, a potential rise produces a current increase. However, the positive feedback between potential and current is limited by the requirement that the return current to the chamber wall has to vary exactly as the cathode current. Since the wall collects electrons, a potential rise decreases the electron collection, unless compensated by a density increase. Thus, the potential and current spikes are limited in amplitude and duration. The spacing of spikes increases when the ionization rate decreases, i.e., for low discharge voltages and currents. At high discharge voltages, a spike may trigger the short-duration arcs (spots) which alter the discharge physics dramatically.

The feedback between potential and current is independent of pulse polarity. Thus, a decrease in potential causes a loss of current or a negative current spike, an example of which is displayed in Fig. 11. The rf probe signal starts with a negative pulse followed by a positive polarity which upon integration yields a negative potential pulse [Fig. 11(a)]. The magnet current also exhibits negative spikes, consistent with the integrated magnetic probe trace [Fig. 11(b)]. The magnet
current is not a displacement current since its waveform differs from that of the rf probe. The rf probe current is not differentiated by the rf transformer which passes microsecond pulses without distortions. When negative and positive spikes are closely spaced such as in Fig. 10(e) they are difficult to distinguish from wave signals, unless spatial cross-correlations are performed.

IV. CONCLUSION

Instabilities in a cross-field discharge of the magnetron type have been investigated. The cathode sheath was found to be a primary source of the instabilities. For low secondary electron emission, the ion-rich sheath is unstable to ion transit time effects which cause oscillations near the ion plasma frequency. The space charge in the sheath, \( \frac{n_i}{C_0} = \frac{n_e}{C_1} e^{-r^2 U} \), determines the sheath thickness and potential drop \( U \) and the latter is observed to oscillate. The oscillations are detected with a rf probe whose current is shown to be a displacement current due to the sheath capacitance and potential oscillation. The ion density near the sheath has been estimated from the oscillation frequency. Correlation measurements reveal global potential oscillations and no wave propagation.

The sheath oscillations affect the ion current collected by the cathode. Significant electromagnetic effects arise at high discharge currents. Magnetic probes detect oscillating fields below the electron cyclotron frequency but no whistler waves. Periodic current and potential bursts have been

FIG. 10. Properties of spiky discharges. (a) Magnet current waveform. (b) Rf probe waveform with spikes. (c) Expanded time scale with rf probe signal, magnet current spikes, and potential spikes obtained by integrating the probe displacement current. (d) Magnet current waveform for larger charging voltage than in (a). (e) Rf probe waveform with higher spike frequency compared to (b). (f) Time resolved spectrum of the oscillations in (e), showing a frequency decrease as the discharge current decays in time. (g) Three magnet current waveforms with different levels of spikes. The bottom waveform (saturated) shows very high discharge current pulses due to the formation of cathode spots. (h) Current spikes of the middle trace on an expanded scales. Magnetic probe signal correlates with the derivative of the current or magnetic field spikes. (27 cm long bar magnet, 9 mbar Ar).

FIG. 11. Example of spikes with negative polarity. (a) Rf probe current is a displacement current whose integral is proportional to the plasma potential. (b) Negative spikes in the magnet current and magnetic field which correlate with the potential spikes. (27 cm long bar magnet, \( V_{\text{charge}} = -500 \text{ V} \), no cathode spots).
observed which may arise from ionization events in the sheath. Potential and discharge current are positively correlated which results from the cathode current-voltage characteristics. The current rises steeply with the potential drop across the cathode sheath, i.e., the difference between cathode and plasma potential.

Current-driven ion sound turbulence, which can produce anomalous cross-field electron transport, has also been observed. It exhibits short correlation times and lengths which distinguish it from sheath oscillations. Very large discharge currents, triggered by impulsive arcs (cathode spots), produce high frequency transient ringing in probes and the discharge circuit.

Thus, the cross-field discharge is not a quiescent plasma but its afterglow eliminates most of the instabilities. Knowledge of the instabilities is important for applications of plasma-surface interactions.

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