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Positively Biased Probes in Magnetized Plasmas

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Positively biased probes in magnetized plasmas can create several phenomena which are not described by standard probe theories. These include transient currents for pulsed electrodes in the regime of Electron MHD, relaxation oscillations induced by large probes and high frequency instabilities at the sheath-plasma frequency. Although they may limit the use of probes for diagnostic purposes they also offer new applications and belong to the general knowledge of probes in plasmas.

1 Introduction

According to Langmuir probe theory [1–5] a plane probe biased positively with respect to the plasma potential collects an electron saturation current due to the random thermal motion of electrons entering the sheath. This steady-state model assumes that the potential between the probe and the plasma drops off in a stable, electron-rich sheath of a few Debye lengths, that the plasma is unperturbed by the collection of electrons and that collisions are negligible. Probe theory has been extended to include magnetized plasmas but does not consider the perturbations by the probe on the plasma. Time-dependent current collection by probes is another unresolved topic which falls between probe and antenna theories. The present work summarizes a few experimental observations which may stimulate further theoretical work or simulations. The effects include large transient electron currents, relaxation instabilities, sheath-plasma instabilities and fireballs.

2 Transient probe currents

In order to resolve time-dependent plasma parameters it is necessary to acquire the current-voltage (I-V) characteristics of a probe on a fast time scale. This is accomplished by either a fast voltage ramp applied to the probe or a voltage step function whose value is incremented in time, recording the probe current vs time at each voltage step and reconstructing the I-V characteristic from repeated measurements. Alternatively, multi-channel probes have been used for non-repetitive events [6].

When such measurements are performed with plane probes in a weakly magnetized afterglow plasma in the parameter regime of magnetized electrons and unmagnetized ions (Electron MHD) one observes the effects shown in Fig. 1 [7, 8]. Related phenomena have also been studied in Q-machines [9]. The applied voltage waveform is a step-function (50 ns rise time) starting from the floating potential. For voltages below the plasma potential ($V_{probe} < 5$ V) the probe current displays also a step function. But with increasing amplitude an initial current overshoot and subsequent current pulses develop. First we focus on the current overshoot, in the next section on

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the current relaxation instability. The insert shows no saturation in the dependence of the overshoot current on probe voltage, $I_{max}(V)$. It can far exceed the electron saturation current and is only limited by the maximum ion current collected at the chamber wall. The duration of the current overshoot ($\simeq 2\ \mu$s) well exceeds the ion transit time through the sheath excluding the frequently quoted explanation by Bills [10]. The pulse width is proportional to the probe diameter. For probes smaller than the electron cyclotron radius the relaxation oscillations disappear. When the probe is rotated such that the magnetic field is tangential to the surface the overshoot current is nearly unchanged while the relaxation oscillations disappear, implying no magnetic "insulation" due to the small electron Larmor radius. Light measurements show no ionization effects which become visible at higher neutral gas pressures [7, 11].

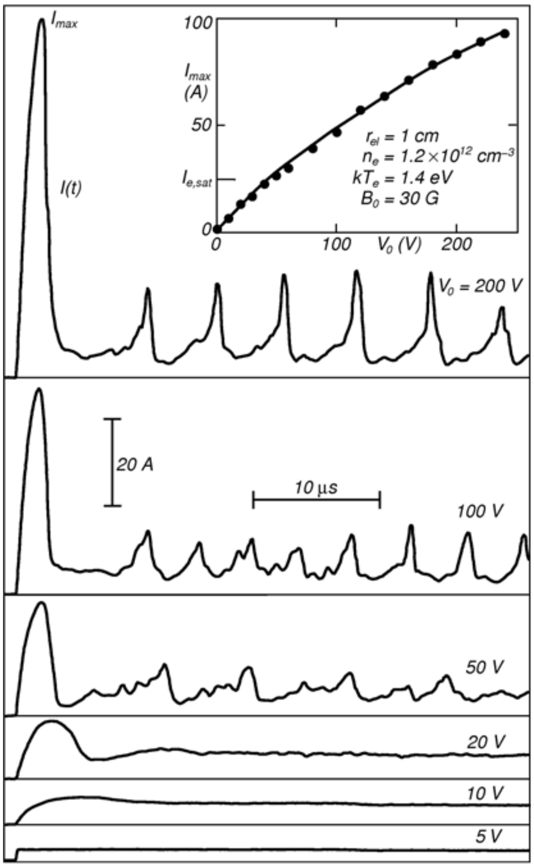

Fig. 1 Current to a disk electrode in response to a positive voltage step of different amplitudes. For voltages above the plasma potential a large current overshoot and subsequent relaxation oscillations develop. Insert shows peak overshoot current vs applied voltage, which exhibits no saturation at $I_{e,sat}$ as predicted by probe theories.

The duration of the overshoot current decreases with probe size. When the diameter is smaller than the electron Larmor radius the relaxation oscillations disappear. Such a small probe has been used to diagnose the plasma around a large probe. During the overshoot current a strong radial electric field is observed on the sides of the extended flux tube of the large electrode. Thus ions are accelerated radially out of the flux tube leading to a density depletion, particularly in front of the electrode, which triggers the current collapse. A smaller parallel electric field, pointing away from the electrode for distances large compared to the Debye length ($\lambda_D \simeq 50\ \mu$m), accounts for the acceleration of electrons toward the electrode.

Using magnetic probes the time-varying field $\mathbf{B}(\mathbf{r}, \mathbf{t})$ has been measured so as to obtain the current flow and closure within the plasma. Figure 2 displays selected lines of the current density $\mathbf{J}(\mathbf{r}, \mathbf{t}) = \nabla \times \mathbf{B}/\mu_0$ during the probe current overshoot. The current density lines form field-aligned helices. The positive helicity is due to the azimuthal $\mathbf{E} \times \mathbf{B}$ electron drift. Time resolution shows that the helix front propagates at the whistler speed along $\mathbf{B_0}$. Prior to reaching the end of the chamber the return current flows in an outer coaxial helix to the chamber wall through which the electrode shaft is inserted. The front of the current propagates with the speed of an electromagnetic wave, the whistler mode in EMHD [7, 8, 12–17]. The wave electric field penetrates far outside the Debye sheath. The probe current increases with electric field or probe voltage and is *not* determined by the electron thermal flux. In EMHD the current is carried by electron displacements which includes cross-field Hall currents. Only at the electrode surfaces the current is due to particle collection, electrons at the positive electrode, ions at the return electrode. There is no ”single” probe but a closed current system.

These concepts are of course not contained in any steady-state probe theory, yet are of fundamental importance to the understanding of transient probe currents. Even in an unmagnetized plasma where electromagnetic modes are evanescent the transient electric field extends beyond the Debye sheath to at least the inertial scale c/ω_{pe}. Explaining the observed overshoot phenomena in terms of ion inertial effects in a dc sheath ignores the currents [10, 18–20].

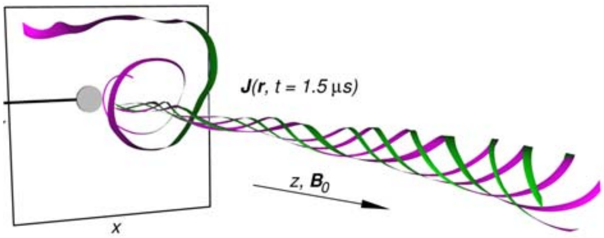

Fig. 2 Lines of the current density $\mathbf{J}$ during the current overshoot of a positively pulsed electrode in a dense magnetoplasma. The current spirals due to an electron Hall current. The current front propagates in the whistler mode. The return current to the end wall forms an outer spiral. (Color figure: www.cpp-journal.org).

When a negative voltage step is applied to the probe the transient current is due to the sheath and stray capacitances since its sign depends on dV/dt. No relaxation instabilities exist. The probe I-V characteristic is not time-dependent and the ion saturation current does not depend on the probe area. Thus, negatively biased probes are not perturbing but do not yield the plasma potential and bulk electron temperature. Positively biased probes should remain smaller than an electron Larmor radius, which minimizes plasma perturbations, shortens the current overshoot and provides the correct ratio of electron to ion saturation currents.

While the present observations were made with rapidly rising probe voltage in a quiescent plasma, they also apply to situations where the probe is constant while the plasma potential drops rapidly. In rf discharges the plasma potential oscillates rapidly at a fixed frequency such that the time-averaged I-V characteristics is strongly distorted. However, if the probe potential oscillates with the plasma potential the dc-like I-V characteristics is recovered [21, 22].

3 Current relaxation oscillations

The recurrent spikes in the probe current at large probe voltages, shown in Fig. 1, are not a transient phenomenon but a relaxation instability which exists irrespective of the voltage rise time, i.e., also for dc bias. Sampling field and plasma properties with a small probe it is found that each current spike leads to a radial ion expulsion. After current collapse the ions diffuse back into the current flux tube and the process repeats. However, the density fluctuations alone cannot explain the large current fluctuations. Axial potential measurements reveal that a potential minimum of several kT_e forms in front of the electrode. Such a potential well reflects electrons and stops the current to the electrode. The potential structures develop when the electron drift velocity approaches the electron thermal velocity which is triggered by the density loss in the current carrying flux tube. Strong turbulence is also observed and associated with the onset of the Buneman instability [23].

The present relaxation instability has similarities and differences to previously studied relaxation instabilities in Q-machines [24, 25]. Experiments on the current-driven ion cyclotron instability, using ”button” electrodes also showed radial ion expulsions from the button flux tube, but the ions returned at the ion cyclotron frequency which determined the relaxation frequency of the instability. In the present case of unmagnetized ions the relaxation time is an ion sound transit time across the perturbed channel, hence depends on probe dimensions. In potential relaxation oscillations the axial propagation of a double layer was observed which does not occur in the present case. The current-limiting potential structure builds up near the electrode but does not propagate axially making the relaxation time independent of the machine length [26, 27]. In the low-beta Q-machine plasmas electromagnetic phenomena are negligible but in the present EMHD regime the transient current pulses excite whistler wave packets which propagate along $\mathbf{B_0}$ but do not determine the pulse repetition time.

4 Fireballs

When an electrode is biased above the plasma potential by more than the ionization potential the electrons can ionize neutrals in the sheath. Sheath ionization deposits ions in the normally electron-rich sheath which leads to sheath broadening [28–30]. Sheath expansion enhances the probability of ionization such that the sheath expands into the typically spherical shape of a fireball [31–36]. However, there are a great variety of fireball formations in magnetized and unmagnetized plasmas as shown in Fig. 3.

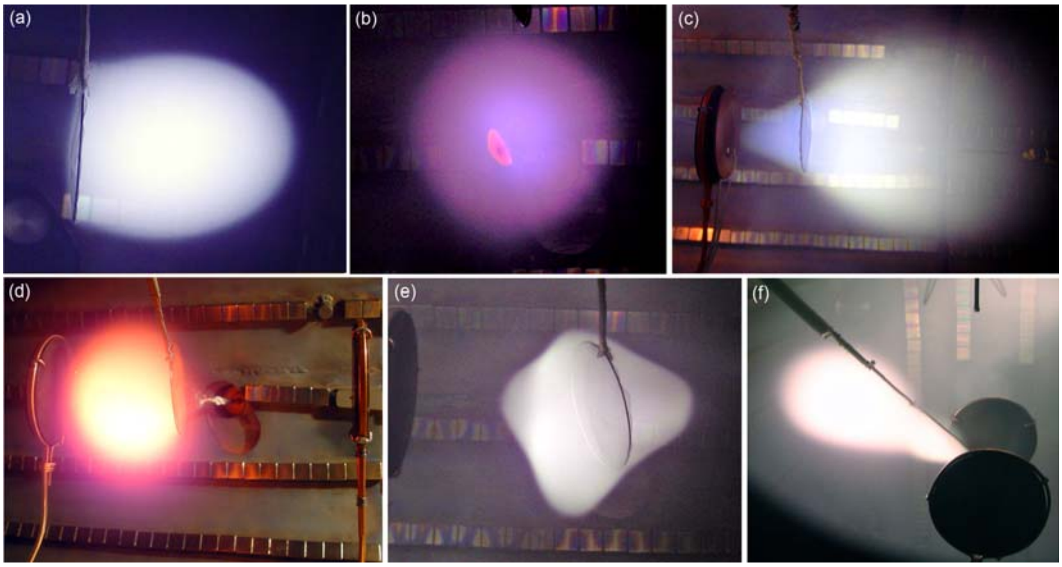

Fig. 3 Images of fireballs on positively biased electrodes. (a) One-sided fireball in an unmagnetized Ar plasma. (b) Spherical fireball concentric with small gridded electrode, B=0. (c) Fireball to a gridded electrode in the diverging magnetic field of a permanent magnet. (d) Neon fireball to a gridded electrode in the center of a mirror magnetic field between two permanent magnets. (e)Asymmetric fireball in a cusp magnetic field between two opposing permanent magnets. (e) Fireball elongated along the radial magnetic field lines of a cusp field topology. (Color figure: www.cpp-journal.org).

A double layer separates the fireball from the surrounding plasma. The double layer potential drop is slightly above the ionization potential [37, 38]. The growth of the fireball greatly enhances the collected current for the following reasons: The surface area of the fireball exceeds that of the electrode. Ionization takes place inside the fireball since the electrons gain energy above the ionization energy at the double layer. The plasma potential in the discharge is raised since enhanced electron collection at the electrode requires increased ion collection at the wall. The rise of the plasma potential to $V_{electrode} - V_{double-layer}$ enhances the space-charge limited electron emission and ionization probability which in Argon increases with electron energy.

A stable fireball requires a stable double layer, i.e., momentum balance between accelerated electrons and ions across the potential drop. The accelerated ions are produced by ionization in the fireball. If the ionization rate does not produce the required outflow of ions or if the electron collection is inhibited the fireball will collapse. Without the fireball the initial conditions are reestablished and the process repeats. The repetition rate depends on the initial density and density decay. The threshold is reached when the sheath has widened and sheath ionization reoccurs. Since the electrode voltage controls the density, the repetition time increases with electrode voltage, gas pressure and cathode current. The entire I-V characteristics includes ranges of stable and unstable fireballs.

These observations show that an electrode with fireball cannot be treated as an isolated single-probe problem. The probe ”perturbation” on the entire discharge is so profound that the entire system has to be investigated as a nonlinear system. Selected models have made such attempts but a complete theory for fireball electrodes in magnetoplasmas have not yet emerged [39].

5 Sheath-plasma instability.

At high frequencies ($\omega \simeq \omega_{pe}$) an ion-rich sheath can be considered to form a capacitance between an electrode and the plasma. For $\omega < \omega_{pe}$ a plasma has an $\epsilon = \epsilon_0(1\text{-}\omega/\omega_{pe}) < 0$. The series impedance between a capacitive sheath and an inductive plasma forms a resonance, the sheath-plasma resonance [40]. It is proportional to the electron plasma frequency to within a factor <1 which depends on the sheath thickness and electrode geometry.

When the probe bias is positive the electron-rich sheath is still capacitive since the electron density is lower than in the ambient plasma due to the electron acceleration. The electron current through the sheath adds a resistive component to the sheath impedance. At high frequencies the electron inertia creates a phase shift between ac current and electric field. When the normalized phase shift $\omega_{res}\tau > 2\pi$, where τ is the electron transit time through the sheath, the rf resistance becomes negative and the sheath oscillates spontaneously [41]. This effect is the plasma analogue to the monotron oscillator in vacuum diodes [42, 43].

High frequency oscillations have been observed in the current to a positively biased electrode which produced pulsating fireballs. The rf signal is observed between the fireball pulses when there are no electron beams and the sheath potential drop is large compared to kT_e, a precondition for exciting the sheath-plasma instability. The oscillations are also observed on rf probes in the plasma. Spatial scans show an amplitude decay without significant phase shifts. Thus, the signal is an evanescent rf field originating from the electrode and not a short-wavelength electron plasma wave.

The rf signals are bursty and have many interesting spectral features. Some examples of waveforms and spectra are shown and explained in Fig. 4. There are periods in time where the instability is highly monochromatic [(a),(d)]. At other times the waveform displays beats due to two frequencies separated by more than the ion plasma frequency [(b),(e)]. The gridded electrode (5 cm diam) has sheaths on both sides which can resonate at different frequencies if there is a density gradient across the grid (c). This is supported by measuring the field with an rf probe on one side of the grid. It displays dominantly one of the two lines. The lower frequency/density occurs on the side where the fireball is formed. The lower density creates a wider sheath where ionization is easier than in a thinner sheath. On the other hand unstable fireballs eject ions rapidly such that the remnant density is low and the next fireball is reproduced on the same side as the previous one. Visually, pulsating fireballs appear stationary but fuzzy compared to stable fireballs.

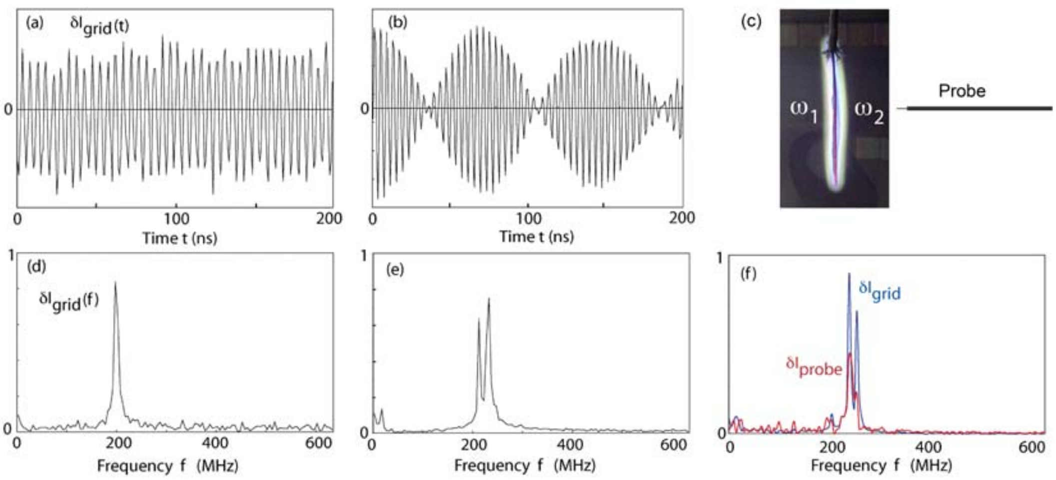

Fig. 4 Sheath-plasma instability in time and frequency domains. (a,d) Monochromatic oscillation in time, (b,e) beat between two single oscillation frequencies, (c) visible sheaths on a circular grid electrode oscillating at different frequencies and producing a beat waveform. (f) Beat spectra of the grid current and of a probe signal, which identifies which sheath oscillates at the lower frequency.(Color figure: www.cpp-journal.org).

When the two sheath oscillations interfere destructively they produce the nodes in the beat waveform. For monochromatic sheath oscillations a phase shift between the two sheath oscillations has been observed. When the phase shift approaches 180^0 the oscillations stop explaining the bursty nature of the rf signal. When the time waveform is broken up into sequential time intervals each of which is Fourier or wavelet transformed the resultant frequency-time diagram reveals the density decay between fireball pulses. However, the decay is not smooth as inferred from the beat effect. The beat frequency can increase in time, indicating different density decay rates on both sides of the grid. The beat can also go through a null, indicating that the higher frequency decays faster and becomes the lower frequency mode, again caused by different density decays across the grid. Mode competition among three frequency modes have also been observed, possibly due to two-dimensional modes of oscillations on an extended grid. The sheath plasma resonance is only the cutoff of sheath-plasma waves on extended conductors in plasmas [44]. Sheath-plasma oscillations also exhibit nonlinear effects. Amplitude clipping has been observed for one polarity of the rf waveform. In the frequency domain clipping results in a dc component and a spectrum of harmonics. While the fundamental frequency is below cutoff the harmonics should excite propagating electromagnetic waves and be detectable in the far zone of the electrode.

Sheath plasma oscillation prior to onset of a fireball show that the oscillation frequency drops precipitously and the instability disappears at the start of the fireball. The frequency drop is not due to a density decrease because the beginning ionization increases the density and frequency. However, sheath ionization increases the sheath thickness and electron transit time. The transit time also decreases since the potential drop across the sheath decreases as the fireball grows. Since the instability occurs only when $\omega_{res}\tau > 2\pi$ the increase in τ requires a decrease in ω_{res}. With further decreasing sheath potential drop the instability falls below threshold and disappears.

In an earlier study the sheath-plasma oscillation occurred in bursts due to periodic ion ejection which modulated the sheath thickness [41]. Thus, the high frequency instability can provide useful information about the ion dynamics and ionization phenomena at a positively biased probe.

6 Conclusions

Positively biased electrodes show a variety of effects which are usually neglected in probe theories. For rapidly varying potential differences between a probe and plasma the excited currents and fields cannot be understood in terms of sheath physics but are wave phenomena.

In magnetized plasmas positively biased probes can excite relaxation instabilities due to the ion dynamics across the flux tube of the electrode. For unmagnetized ions the relaxation time is given by the probe size and the sound speed, for magnetized ions it is the ion cyclotron period. In order to minimize such instabilities the probe size should be less than an electron Larmor radius.

In the presence of neutral gas a positively biased electrode can produce ionization in the electron-rich sheath which further expands into a fireball. The fireball phenomenon affects the entire discharge such that the probe I-V characteristics is not suited for plasma diagnostics.

An electron-rich sheath can be unstable and excite oscillations at the sheath-plasma resonance. These oscillations are useful for inferring the properties of the sheath and adjacent density with minimum perturbations.

All these phenomena belong to the general knowledge of probes in plasmas.

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