Sheath Propagation Along the Cathode of a Plasma Opening Switch

Amnon Fruchtman, John M. Grossmann, Stephen B. Swanekamp, and Paul F. Ottinger, *Member, IEEE*

***Abstract*— A model is proposed for sheath propagation along the cathode of a plasma opening switch that is valid for switch conditions intermediate to the erosion-dominated and MHD-dominated regimes. The model assumes that the sheath propagates due to erosion of the plasma that conducts the current. The calculated velocity of propagation agrees with particle-in-cell simulation results much better than do velocities calculated by previous models that assumed magnetic pressure opens a vacuum gap along the cathode.**

***Index Terms*— Hall effect, opening switch, pulsed power, sheath, vacuum gap.**

I. Introduction

THE PLASMA opening switch (POS) consists of a plasma injected into the vacuum gap between the electrodes of the power feed of a pulsed power generator [1]. The POS conducts current while energy is stored inductively and then opens quickly to deliver energy to a downstream load. Opening is achieved by formation of a vacuum gap in the plasma. The evolution of the sheath, a nonneutral region near the electron emitting cathode, is very important to POS performance. It affects the gap evolution that may determine the load power delivery of the POS. Plasma erosion, plasma pushing by the magnetic field pressure, and magnetic insulation of the electrons govern the sheath evolution. Because of the complexity of the phenomena, the evolution in time of the two-dimensional (2-D) sheath is not well understood.

Most analytical treatments of sheath evolution are either one-dimensional (1-D) and dynamic [2]–[5] or 2-D but static [6], [7]. Mendel [8] analyzed this 2-D evolution at the stage at which the current is so large that the electrons are magnetically insulated. In that model, the switch current returns along the plasma surface above the vacuum gap allowing the gap to open by magnetic pushing. The velocity of the sheath was predicted to be $(c^2 v_A)^{1/3}$, where c is the velocity of light in vacuum, $v_A = B/\sqrt{4\pi n_i M}$ is the Alfven velocity, B is the magnetic field, and n_i and M are the ion density and mass. As could be intuitively anticipated, for a larger v_A the sheath propagates with a higher velocity because of a higher magnetic pressure. Recently, Fruchtman [9] has extended Mendel's model by including the effect of electrons slowing down in the return current layer above the vacuum gap. This model predicts that when v_A is larger than $(3/2)c\epsilon^{3/4}$, the velocity of the sheath decreases for larger v_A. Here, $\epsilon \equiv Zm_e/M$ where Z is the ion charge state and m_e is the electron mass. This counterintuitive prediction of a decrease of the sheath velocity with the current increase is a result of the model for the physical mechanism by which the plasma carries a current.

Recent particle-in-cell simulations by Grossmann *et al.* [10], investigated sheath propagation and gap formation. In these simulations, a localized potential hill develops which accelerates ions toward the cathode. Thus, the gap forms predominantly by ion erosion toward the cathode rather than magnetic pushing of ions toward the anode. The density of the plasma begins to decrease in the region along the cathode in which the current and magnetic field have penetrated, but only behind the propagating current sheath does the plasma density decrease so much that a vacuum gap forms and the emitted electrons are magnetically insulated. Electrons emitted in the gap flow axially until they reach the sheath where they can begin to turn radially into the current sheet. This picture is illustrated in Fig. 1. Even in the plasma sheath, however, ion motion and density modification are crucial to axial sheath propagation. Indeed, if the ions in the simulations are made immobile, the sheath does not propagate along the cathode at all. However, relatively small ion motion is sufficient for sheath propagation and, unlike the assumption of the previous models, the formation of a vacuum gap is not essential for the propagation.

Motivated by these simulations, an approximate analytical description of the sheath propagation is derived here. This description is based on an erosion model rather than the magnetic pressure model used previously. After the model is presented in Section II, the results of the model are compared to the results of the simulations [10]. The present model appears to agree with the results of the simulations better than do the models of Mendel [8] and Fruchtman [9], in which magnetically controlled gap formation dictates the sheath propagation. Thus, it can be concluded that ion erosion toward the cathode is responsible for sheath propagation but formation of a vacuum gap (i.e., complete removal of the plasma) is not necessary.

II. The Model

For a collisionless plasma where current is carried by $E\times B$ drifting electrons, the voltage between the vacuum (v) and the

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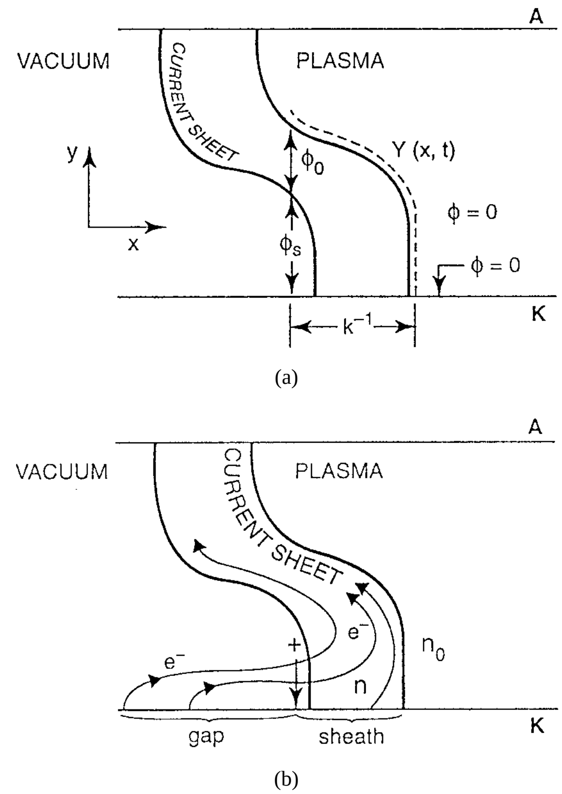

Fig. 1. (a) A schematic of the current sheet. The voltage ϕ_0 across the current sheet is described by (1) while the voltage ϕ_s across the sheath is described by (2). The width of the sheath is denoted by k^{-1}, while the region penetrated by the magnetic field is below and to the left of the dashed line denoted by $Y(x, t)$. The sizes of the current sheet, the sheath, and $Y(x, t)$ have been exaggerated. The width of the current sheet is smaller than k^{-1}. (b) Electron flow in the current sheet. The average electron density in the sheath is n. Ions are accelerated toward the cathode in the sheath region.

plasma (p) is [11]

$$\varphi_0 = -\int_p^v E\,ds \simeq \int_p^v \frac{v_e B}{c}\,ds = -\int_p^v \frac{j_e B}{e n_0 c}\,ds = \frac{B^2}{8\pi n_0 e}. \tag{1}$$

Here B is the value of the magnetic field at the plasma-vacuum boundary, and n_0 is the plasma electron density in the current layer and in the body of the plasma, and j_e is the electron current density. The ion density is related to the electron density via $Zn_i = n_0$, where Z is the charge state of the ions. In the case of a coaxial POS experiment with the inner electrode charged negatively ("negative polarity"), the B in (1) is negative because the current flows toward the generator (i.e., to the left in Fig. 1) in the center conductor (i.e., $y = 0$). In either polarity, the potential in the unmagnetized plasma is lower than it is in the current layer and in the magnetized vacuum.

The dynamics of the electrons in the region where they are emitted from the cathode and move into the $E \times B$ drifting electron layer is described next. In previous models [8], [9] the electrons were assumed to accelerate while they move across a vacuum gap according to the Child–Langmuir law. Recently, Grossmann *et al.* [10] have proposed a different model where the emitted electrons accelerate while they move across a positive ion background. As was shown in [10], the voltage between the cathode and the plasma is of a form similar to that in (1)

$$\varphi_s = \frac{B^2}{8\pi n e} \tag{2}$$

where n is an average density of the electrons in the sheath. In this paper, the model of [10] is adopted for the voltage across the emitting layer, in contrast to the models employed in previous papers [8], [9], in which the emitted electrons moved across a vacuum gap.

The difference in the behavior of the sheath predicted by this paper and that predicted by previous papers is mostly due to this different form of voltage across the electron emitting layer expressed in (2). Referring again to Fig. 1, the voltage in the present model first rises in the direction from the cathode (K) to the plasma, according to (2), and then decreases according to (1). Because of plasma erosion, the density n is smaller than n_0, and an inductive voltage is formed that accounts for the difference between φ_0 and φ_s. This induced voltage allows the propagation of the potential hill associated with the sheath along the cathode, as observed in the simulations described in [10]. Note that this propagation is due to electron motion from a region of a low density plasma (n) to a region of a higher density plasma (n_0). Such motion results in a penetration of a magnetic field into a plasma due to the Hall field [12], [13].

Faraday's law can be written in the form

$$-\frac{1}{c}\frac{\partial}{\partial t}\int_x^{\infty} B(x', t)Y(x', t)\,dx' = \varphi_s - \varphi_0. \tag{3}$$

Here x is the coordinate along the cathode and y is in the direction normal to the cathode. $Y(x, t)$ represents the height in y into which the magnetic field has penetrated at time t and at position x. A quasi-1-D picture is assumed in which the magnetic field is uniform in y at a given x position for distances smaller than $Y(x, t)$. This value of the magnetic field is denoted by $B(x, t)$. The inductive loop voltage here is the voltage between the cathode and the bulk of the plasma. It is assumed that in the bulk of the plasma, as well as at $x = \infty$, the electric field and voltage are zero. The cathode is also assumed to be at zero voltage.

As was done in [8] and [9], the sheath at the cathode is assumed to propagate in the x direction with a constant velocity u. Using the approximation $\partial/\partial t = -u(\partial/\partial x)$, and substituting (1) and (2) into (3) yields

$$-\frac{u}{c}Y = \frac{B}{8\pi e}\left(\frac{1}{n} - \frac{1}{n_0}\right). \tag{4}$$

Next the density change due to erosion is estimated. Using the continuity equation for the ions

$$\frac{\partial n_i}{\partial t} + \nabla \cdot (n_i \boldsymbol{v}) = 0 \tag{5}$$

and the previous approximation with $\partial/\partial x \simeq k$ yields the approximate form

$$-ku(n_0 - n) - \frac{2nv_y}{Y} \simeq 0. \tag{6}$$

Here v_y is the y component of the ion velocity $\boldsymbol{v}$, and electron densities have been substituted for the ion densities. The spatial derivative in y is written somewhat loosely as a ratio in which the denominator is the height $Y/2$ of the sheath, and $\partial(nv_x)/\partial x$ is assumed negligible. This last assumption is reasonable because ions are predominantly accelerated toward the cathode. Note that the term k^{-1} as used in (6) is a measure of the width of the current channel in the x direction.

In order to estimate the velocity v_y of ions in the sheath at the cathode, the momentum equation is used

$$\frac{dv_y}{dt} = \frac{qE}{M}. \tag{7}$$

Since the current sheet passes quickly [i.e., in a time $\sim (ku)^{-1}$] over the ions in this model, we assume that their inertia prevents them from being accelerated in the y direction to the full voltage associated with the sheath. This assumption is described further in Section III. Consequently, using the approximations $d/dt \simeq -ku$ and $E \simeq -2\varphi_s/Y$, with φ_s given by (2), provides

$$-kuv_y = \frac{ZB^2}{4\pi nMY}. \tag{8}$$

Note that the electric field points in opposite directions on the two sides of the potential hill. In (8) we have used the average electric field on the cathode side of the potential hill, an electric field that points toward the cathode.

There are now three equations [(4), (6), and (8)] with five unknowns u, k, Y, v_y, and n. Guided by the simulations [10], Y and k are chosen as

$$Y = \frac{-\alpha_1 B}{4\pi n_0 e} \tag{9}$$

and

$$k = \frac{\omega_{pe}}{c\alpha_2} \tag{10}$$

where α_1 and α_2 are constants found in the simulations [10] to be about 16 and 4, respectively, and $\omega_{pe} \equiv (4\pi n_0 e^2/m_e)^{1/2}$ is the electron plasma frequency. Equation (9) states that the sheath height scales as the Debye length with an effective temperature given by $e\varphi_0$ [see (1)]. Equation (10) states that the current sheet width scales as the collisionless skin depth. A more complete discussion of the derivations and implications of (9) and (10) is given in [10]. Substituting these expressions [(9) and (10)] into (4), (6), and (8) yields

$$\frac{2\alpha_1 u}{c} = \frac{n_0}{n} - 1 \tag{11}$$

$$\frac{\alpha_1 u}{c}\left(\frac{n_0}{n} - 1\right) = 2\alpha_2 \frac{v_y}{v_A}\left(\frac{Zm_e}{M}\right)^{1/2} \tag{12}$$

and

$$uv_y = \frac{\alpha_2}{\alpha_1} cv_A \frac{n_0}{n}\left(\frac{Zm_e}{M}\right)^{1/2}. \tag{13}$$

There are now three equations in three unknowns: u, n, and v_y.

Equations (11)–(13) can now be solved. Substituting for v_y from (13) and for n from (11) yields a transcendental equation for the sheath velocity

$$u = c\left[\frac{\alpha_2^2}{\alpha_1^3}\,\frac{Zm_e}{M}\left(1 + \frac{2\alpha_1 u}{c}\right)\right]^{1/3}. \tag{14}$$

Assuming $\alpha_1 u/c \ll 1$ gives the approximate result

$$u = c\left(\frac{Zm_e}{M}\,\frac{\alpha_2^2}{\alpha_1^3}\right)^{1/3}. \tag{15}$$

In this limit

$$n = \frac{n_0}{1 + 2(\alpha_2^2 Zm_e/M)^{1/3}} \tag{16}$$

and

$$v_y = v_A\left(\alpha_2^2 \frac{m_e Z}{M}\right)^{1/6}. \tag{17}$$

These results provide the desired solution.

III. Discussion

For a C^{++} plasma with $\alpha_1 = 15.7$ and $\alpha_2 = 4.2$ (as found in [10]), (15)–(17) predict that $u = 2.2 \times 10^8$ cm/s, $n = 0.81n_0$, and $v_y = 0.34v_A$. The ratio $\alpha_1 u/c \simeq 0.12 < 1.0$, as assumed. The predicted value of u is in reasonable agreement with the sheath velocity of about 3×10^8 cm/s seen in simulation results [10]. This value of the sheath velocity holds over an even broader range of simulations than that reported in [10] for densities large enough that the sheath structure remains local to the cathode [14], [15]. An underlying premise used to justify (2) and (8) is that ions, because of their inertia, do not have time to move far during the passage of the sheath. Using $Y/2v_y$ as a measure of the ion transit time and $(ku)^{-1}$ as a measure of the dwell time of the sheath, this assumption can be written as

$$v_y \ll kuY/2. \tag{18}$$

Using (9), (10), and (17), this expression can be written as

$$1 < \left(\frac{M}{8\alpha_2^2 Zm_e}\right)^{1/3}. \tag{19}$$

For the example above, the right-hand side of (19) is $\simeq$4.3. As expected, this result is consistent with (16) for a small change from n_0 to n.

Fig. 2 shows the sheath velocity u as a function of the current according to the various models. A C^{++} plasma of density 10^{15} cm^{-3} is assumed, as in [10]. As calculated previously, the present model predicts a constant velocity of 2.2×10^8 cm/s. A nearly constant sheath velocity is seen in simulations described in [10]. For currents of 0.6, 1.2, and 2.4 MA and a cathode radius of 4.5 cm, the sheath velocity is about 3×10^8 cm/s with an uncertainty of about $\pm 1 \times 10^8$ cm/s. These simulation results are shown as points on Fig. 2. Since this model was normalized to the simulations by using α_1 and α_2 derived from these simulations, agreement is expected. In contrast, the velocity predicted by [8] for 1.2 MA is about 40 times larger than the velocity in the simulation. The velocity predicted by [9] is about five times larger.

The results presented here need to be put in context with previous POS work. At low density, (2) indicates that the sheath voltage will be large. Hence, ions in the sheath would be accelerated to high velocity and the assumptions of a nearly unperturbed ion background in the sheath would be incorrect.

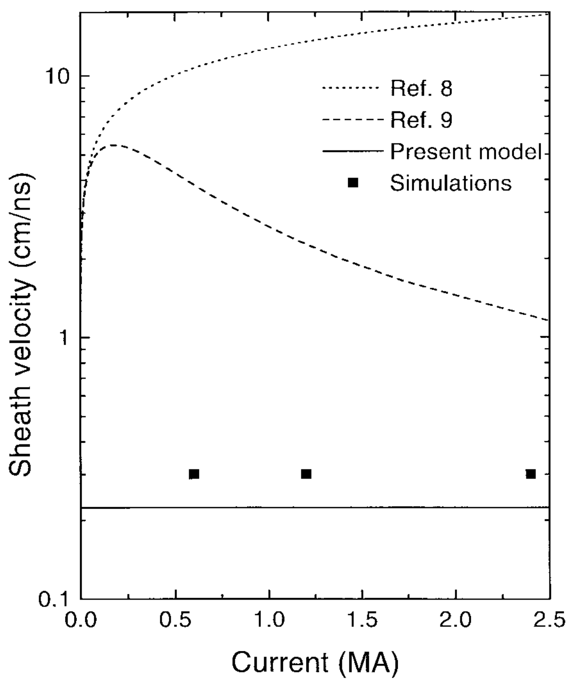

Fig. 2. The sheath velocity as a function of the current according to models of vacuum gap formation [8], [9], and according to the present model for a C^{++} plasma with an electron density of 10^{15} cm^{-3}. Also denoted is the value of the sheath velocity 3 $\times 10^8$ cm/s, found in simulations [10].

The ion erosion model [3] may then be a better model of this situation. It predicts a sheath velocity of

$$u_E = \frac{cB}{4\pi n_0 e V_D \tau}\left(\frac{Zm_e}{M}\right)^{1/2} \tag{20}$$

where a linearly rising current is assumed with a risetime τ and V_D is the velocity associated with the ion flux to the cathode. When $u_E \geq u$, the sheath propagates along the cathode with the erosion rate given in (20). Using (15) and (20), this condition can be written as

$$n_0 < \frac{\alpha_1 B}{4\pi e V_D \tau}\left(\frac{8m_e Z}{\alpha_2^4 M}\right)^{1/6}. \tag{21}$$

At densities higher than that given in (21), the sheath propagates at the speed u given in (15). An example where the erosion mechanism is thought to apply is the short-conduction-time POS used on Gamble I at NRL. Typical parameters for Gamble I POS experiments were $B \simeq 20$ kG, $\tau \simeq 50$ ns, and $V_D \simeq 5 \times 10^6$ cm/s [16]. Substituting these values for a C^{++} plasma into (21) yields $n_0 < 1.7 \times 10^{13}$ cm^{-3}. The electron density in the POS region was measured on Gamble I using interferometry. Results indicate an average density on the order of 10^{13} cm^{-3} for long switch geometries ($l = 30$ cm) and 4 $\times$ 10^{13} cm^{-3} for short switch geometries ($l = 10$ cm). Thus, these results suggest that the Gamble I POS operated in a transition region between these two regimes.

Long-conduction-time ($\simeq\mu$s) plasma opening switches require much higher plasma densities. The conduction time has been shown in many cases to be controlled by MHD displacement and redistribution of the POS plasma. In this case the model presented here may fail if the electrons are not magnetically insulated on the generator side of the sheath. This condition can be written as

$$Y/2 \leq \rho_e \tag{22}$$

where $\rho_e = m_e C N_e / eB$ is the electron gyroradius. Assuming $v_e = (2e\phi_s/m_e)^{1/2}$ and using (2) and (9) yields

$$n \geq \frac{\alpha_1^2 B^2}{16\pi m_e c^2}. \tag{23}$$

For densities greater than that specified in (23), the sheath would not propagate. An example of where MHD conduction time scaling is thought to apply is the long-conduction-time POS on HAWK at NRL [16]. Typical parameters for HAWK are $B = 28$ kG and $\tau = 1$ μs. Equation (23) predicts that sheath propagation and opening will not occur until the plasma is thinned by MHD redistribution below a density of $\simeq$1.0 $\times$ 10^{15} cm^{-3}. The maximum measured density during the conduction phase of the HAWK POS is $\simeq 10^{16}$ cm^{-3} [16].

Despite the agreement between the simulation and the model, it should be emphasized that this model is a great simplification of the physics. The assumption of a quasi-1-D evolution is not a very good assumption, as can be seen in the simulation. On the other hand it does provide insight into the approximate range of validity of the erosion model for short conduction time switching and where MHD pushing of the plasma dominates sheath propagation for long conduction time switching. It is also found to agree well with simulation results over a broad range of plasma densities and magnetic fields in the POS plasma.

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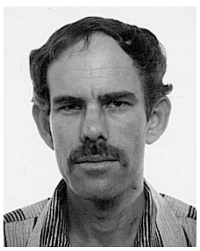

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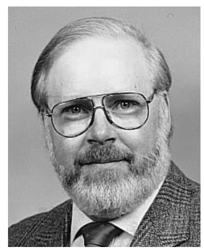

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