**A study of parameters useful
 for describing plasma-opening switches**
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INTRODUCTION

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Plasma opening switches (POS) have been used continually and studied since their introduction in 1975.¹ During that period they have performed well for prepulse suppression and sharpening the front of the power pulse.^{1,2} Their use for long conduction time and rapid opening to stand off high voltage in the same POS has met with very limited success. There has been a large theoretical effort involving models and particle-in-cell simulations (PICS), but the connection between theory and experiment has been tenuous at best, and convincing agreement with experiment has been minimal.

The authors believe progress toward long conduction and rapid opening would be faster if macroscopic physical parameters describing the physics of the switch were used to compare experiment to simulation. One of these parameters (electron flow impedance^{3,4}) has been used to describe the electrical characteristics of the POS. This parameter provides a good description of both the standard POS (SPOS) and the magnetically controlled POS (MCPOS) because its value is sensibly independent of load current. An additional parameter, the effective mass of the plasma, was measured in one MCPOS experiment.³ In this article we will describe other parameters important to operation of the SPOS and the MCPOS, and parameters important in designing PICS used to study these devices.

EFFECTIVE GAP AND FLOW IMPEDANCE

Metal surfaces in devices of interest are space-charge-limited electron emitters. Therefore the only electric field on the boundaries are at anode surfaces. The net charge on such surfaces is small compared to the plasma electron or ion charge in any POS. A POS plasma is always quasi-neutral on the global scale. It will be shown later that large voltage drops must occur across sheaths in regions that are not quasi-neutral, where the electron density is small compared the bulk of the plasma. Electrons flow in a direction normal to the electric field, and ions flow along the electric field in these sheaths.

We define effective sheath thicknesses for these sheaths. Consider sheaths with only electrons for the moment, and define the effective gap, g_e , as the ratio of the voltage across the sheath to the electric field at the anode surface. Using pressure balance across the current sheet, and replacing magnetic field by current and electric field by charge per unit length⁴ we get $(I_a^2 - I_c^2)(1+P^2) = c^2 Q_a^2 = c^2 [2\pi r_c V/g_e]^2 = (1+P^2)V^2/Z_f^2$ where the subscripts refer to values at the anode and cathode and Z_f the flow impedance. P is the pitch of the magnetic field, i.e. $P=B_z/B_\theta$. For the SPOS $P=0$. We will neglect the difference between the radii of the anode and cathode electrodes, and use the cathode radius, r_c for both. The flow impedance is equal to the TEM wave impedance for a transmission line with radius r_c and gap g_e , so effective gap and flow impedance are alternative measures of the same effect.⁴ For electrical measurements flow impedance is more convenient.

Using pressure balance across a sheath with only ions, and defining the effective gap by $g_e = V/E_c$, $I_i = \pi r_c L_e [q_i \epsilon_0 / (2m_i)]^{1/2} V^{3/2} / g_i^2$ where L_e is the length of the plasma, or an effective length if the gap is a function of axial position.

We used the same symbol, g_e , for both cases because they have the same value. This is because electron current is normal to the electric field, and therefore flows along equipotentials. Thus there is a function $f(\phi/V)$ such that $I^2 = I_c^2 + (I_a^2 - I_c^2)f(\phi/V)$ where $f(0)=0$ and $f(1)=1$. Again using pressure balance

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$$(I^2 - I_c^2)(1 + P^2) - \frac{2(2\pi r_c)^2 J_i}{\mu_0} \left(\left[\frac{2m_i V}{q_i} \right]^{1/2} - \left[\frac{2m_i (V - \Phi)}{q_i} \right]^{1/2} \right) = c^2 Q^2.$$

Using $Q=0$, $I=I_a$ and $\phi=V$ at the anode side of the sheath shows that the values of g_e defined by ion and electron flow above, are equivalent. Replacing I by $f(\phi/V)$ with the above expression, this can be integrated to get $g/g_e = \int_0^1 [(1-\eta)^{1/2} - (1-f(\eta))]^{-1/2} d\eta$ where g is the actual gap between the radii where Q (and E) are zero. If gap varies with axial position, then g is the minimum gap, and the effective length is given by $L_e = \int g^{-2}(z) dz$ integrated over the length of the plasma.

The equivalence of these gaps was tested using PICS where the plasma was modeled as a conducting block with ion emission at its surface (Fig. 1 inset). The load was an electron diode. The POS gap and the load gap were varied between PICS. Protons were used to increase the ion current relative to the electron current. Figure 1 shows a plot of effective gap measured with ion current plotted versus that measured with electron current. The gap is shown both as a distance and as an impedance. There are three POS gaps at three load gaps represented in the plot. The bars on the points represent the spatial noise in the data. The point with the large variation came from a simulation where the electron flow broke into vortices. The data fall on a line of slope one as expected. In all cases the flow impedance is 0.6 times the vacuum impedance of the POS gap.

We concluded that only one parameter is needed to model both electron and ion current in a circuit model of a POS if the ion species is known. The flow impedance needs to be an appreciable fraction of the vacuum impedance (i.e. the effective gap needs to be an appreciable fraction of the actual gap) for efficient power transfer to a load.

VOLTAGE AVERAGED ELECTRON CHARGE DENSITY IN A CURRENT SHEET

Due to the small mass of the electrons, the rate of change of momentum of the electron cloud is small when compared to the electric and the magnetic force on the cloud over most of the POS. The exceptions to this are generally in regions near the electrodes where electrons are emitted or lost. Using $\rho_e = n_e e$, $\rho_i = n_i q_i$, $-\rho_e \vec{E} + \vec{j} \times \vec{B} = d(m_e \rho_e \vec{v}/e)/dt \equiv 0$ where we neglect the contribution of ion flow to the current. Using Ampere's law and neglecting displacement current $\rho_e \vec{E} = -\nabla B^2/(2\mu_0)$ where we neglect curvature of field lines in comparison to the thinness of current sheets. This expression has been used in several forms^{5,6,4} in areas of plasma physics and magnetically-insulated electron flow. It is valid in non-neutral and quasi-neutral plasmas. Integrating from cathode to anode along a path that passes through the plasma and avoiding regions where electrons are emitted or lost, $(1 + P^2)(I_a^2 - I_c^2) = 2(2\pi r_c)^2 \langle \rho_e \rangle V/\mu_0$ or $\langle \rho_e \rangle = \mu_0(1 + P^2)V/[2(2\pi r_c)^2 Z_f^2] = \epsilon_0 V/[2g_e^2]$. $\langle \rho_e \rangle$ is voltage-averaged charge density, i.e., the field-weighted average of ρ_e , $\langle \rho_e \rangle = \int_c^a \rho_e d\Phi/V = \int_c^a \rho_e \vec{E} \cdot d\vec{s}/V = \overline{\rho_e E}/E$.

Figure 1. Ion effective gap plotted versus electron effective gap. All of these gaps are 0.6 of the actual gap.

Because of the high charge density of a POS plasma, we can write $(\rho_e g^2)/(2\epsilon_0) \gg V$ so $\langle \rho_e \rangle \ll \rho_e g^2/g_e^2$. Thus when the POS is open (so g_e is comparable to g) the electron charge density in the current sheet must be small compared to that in the plasma for efficient power transfer to the load.

Figure 2 is a plot of electron charge density, ion charge density, and potential versus radius for a PIC simulation of an open POS. In this case there are slow and fast fields. It is seen that the charge density is low where the potential is changing rapidly as predicted. Using the expression above for $\langle \rho \rangle$, with $V=0.65$ MV, $Z_f=3.0$ Ω , and $P=1.77$ taken from the simulation data, we get $\langle \rho \rangle = 0.063$ C/m², which is also plotted in Fig. 2. Clearly the value is calculated correctly, since it agrees with the value of ρ_e where the electric field is large. This can be used to get the electron charge density in the sheath of an experimental POS.

Figure 2. ρ_e , ρ_i , and ϕ plotted versus radius for an open MCPOS. Notice that in the region of strong electric field that $\rho_e = \langle \rho_e \rangle$.

IMPORTANT PARAMETERS FOR PIC SIMULATIONS

It is impractical to simulate POS with experimental densities and conduction times. Moreover, it is desirable to run many simulations with run times of no more than a few hours, which requires plasma parameters to be even further from experimental values. When a magnetic field pushes on a POS plasma, the electron density in the current sheet is roughly the same as the plasma electron density, so there is a voltage drop^{5,6} of about $\mu_0 I_a^2 / [2(2\pi r_c)^2 \rho_p]$. This value is of order of kilovolts in experiments, and should be small compared to $mc^2/e=511$ KV in a simulation, or else the current sheet will not be quasi-neutral as it is in an experiment, and the cathode sheath will not form properly.

The current sheet in the plasma will be c/ω_{pe} thick, so the spatial cell size, δ , must be smaller than this value. In addition, numerical heating will give an artificial thermal velocity of $\omega_{pe}\delta$. The plasma pressure due to this "numerical heat" must be small in comparison to the magnetic pressure, thus $I_a / (2\pi r_c \rho_p c) \gg \delta$. This criterion is more stringent than the first for a POS plasma. In a group of 25 PICS when the parameter to cell size ratio was >2 the error was $<5\%$, when ~ 1 the error $\sim 10\%$, and when $\sim 1/3$ the error was $\sim 50\%$.

MAGNETIC VELOCITY AND ELECTRON REPLACEMENT VELOCITY

The sub-microsecond time scale of POS is too short for momentum transfer between the ion cloud and the electron cloud by collisions or turbulence. Because of this there can be no appreciable magnetic field penetration of the plasma electron cloud. However, if electrons are replaced by emitted electrons, momentum is transferred to the electrodes and flux penetrates the ion cloud. The original plasma electrons are replaced by electrons emitted from the cathode in regions of high magnetic field. This occurs if there is an azimuthal magnetic field since the current will involve cathode emission, as is always the case for a POS. If there is a radial and axial field, as in the MCPOS, the transfer of angular momentum to the anode necessary for these fields to penetrate involves the radial current as a mechanism to carry the electrons with their angular momentum to the anode.

Consider the simple case of a radial washer of current replacing the electrons in the plasma with emitted electrons. The plasma electrons, of charge density ρ_p , are in a region of zero magnetic field ahead of the washer. As the washer moves through the plasma these electrons are lost, and replaced by a like charge of emitted electrons. If the current through the POS is I , and the

current of plasma electrons to the anode is I_p , then the washer moves through the plasma with a velocity u given by $\rho_p g u = I_p$ and the remainder of the current to the anode is in emitted electrons with current $I - I_p$. This can be rewritten as $u = u_r I_p / I$ where $u_r = I / \rho_p g$ is the maximum possible replacement velocity.

The plasma behind the washer (consisting of ions and emitted electrons) is moving with a velocity v due to the impulse of the magnetic field. From electron charge conservation $\rho_p u = \rho_e (u - v)$ where ρ_e is the electron density behind the washer, and from momentum balance $u v = v_m^2$ where $v_m = (\mu_0 q_i / 2 \rho_p m_i)^{1/2} I / 2 \pi r_c$. The change in velocity of the ions is due to a potential drop, $(u v - v^2 / 2) m_i / q_i$, across the washer. If $u = v_m$, then also $v = v_m$, and the ions reside in a zero-thickness layer. u_r is the velocity sometimes called the "Hall penetration velocity", but is derived here from charge conservation without the reference to the Hall current term.

Although this model has assumed a radial current sheet and azimuthal magnetic field, the magnetic velocity, v_m , could include fields due to other currents. The actual replacement velocity, u , is not known because the ratio I_p / I is not known, but the maximum value, u_r , is known, and u should be comparable. Figure 3 shows a measured value of u from a PIC simulation of a SPOS. The current sheet is not radial at all radii, but does tend to move uniformly in the z direction. For this case $u_r = 0.53$ cm/ns and $u = 0.40$ cm/ns (Fig. 3). From the current, $v_m = 0.053$ cm/ns we can calculate the plasma velocity $v = 0.0070$ cm/ns behind the current sheet. The voltage drop across the current sheet should be 35 KV, which agrees with the simulation.

The velocity parameters u_r and v_m , and the relationship between them, are important in how a POS behaves. It is important to preserve the relationship in scaling a PICS of a POS. If the replacement velocity is appreciably faster than the magnetic velocity, the magnetic field will penetrate the ion cloud, and will not be able to move it to generate the low-density sheath needed for efficient operation. Erosion of the ions by the electric field will still occur, but if the density is high enough to keep the plasma in place for long conduction time the POS will not open rapidly.

In the case of an MCPOS the replacement velocity must be smaller than the magnetic velocity when the control magnetic field (due to the fast coil) is energized to be confident that the fast field will not be able to penetrate the ion cloud.

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Figure 3. Axial penetration of magnetic field into a SPOS versus time. The slope is 0.4 cm/ns compared

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