Toward a theory of plasma opening switches

P. V. Sasorov
Institute of Theoretical and Experimental Physics, 117259, Moscow

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A mechanism is proposed for the operation of plasma opening switches in high-current, high-voltage inductive storage banks. This mechanism is based on an explosive burst of plasma from the switch onto "cold" electrodes under conditions such that the (anomalous) resistance of the plasma increases with decreasing density. A relatively new mechanism for an anomalous resistance of a hot plasma is used.

An opening switch is a necessary part of any inductive bank for the storage of electromagnetic energy. The rate at which this switch opens determines the voltage which arises and the power which is dissipated in the load. In high-current (100-kA to 10-MA), high-voltage (100-kV to 10-MV) storage banks, a plasma bridge is often used as the opening switch:[1–4] a plasma opening switch. Inductive storage banks of this type are usually lengths of coaxial line; the plasma opening switch is a "sleeve" which closes the circuit between the outer and inner electrodes.1) The operation of the plasma opening switch can be summarized by saying that the plasma bridge conducts a current for ~100 ns to 1 μs, making possible an accumulation of energy. The resistance of the switch then increases spontaneously and sharply, becoming greater than the load impedance over a time ~10–100 ns. Our purpose in the present letter is to identify the physical reason for these properties of the plasma opening switch.

Although plasma opening switches have frequently been used successfully in practice, there is nothing approaching a consensus of opinion regarding the operating mechanism for these devices. This situation is obviously a hindrance to the rational use of these switches, although relationships[4] found experimentally are of some assistance in filling this void. Two factors have contributed to this state of affairs. First, before the appearance of the paper by Hinshelwood *et al.*,[5] there was no reliable experimental information on the dynamics of the plasma in the switch. The door was thus left open to a variety of (sometimes interesting) hypotheses. The second problem is that until just recently we did not have an adequate theory for the resistance of a plasma under the pertinent conditions. The resistance of the switch, we might note, is what determines its operation.

In a plasma opening switch, the relations

$$\omega_{pi0}a/c \lesssim 1 \text{ and } eHa > m_ec^2 \tag{1}$$

typically hold. Here ω_{pi0} is the ion plasma frequency corresponding to the initial electron density n_0, and H is the magnetic field in the inductive bank near the switch. After the publication of the paper by Sasorov,[6] it became clear that under these conditions, with a smooth current distribution along the switch, the plasma has an anomalous resistance which corresponds to an effective electron-ion collision rate ν_{eff}

on the order of the gyrofrequency of the cold electrons in the self-consistent magnetic field: $\nu_{\text{eff}} \simeq \omega_{\text{He}} = eH/m_e c$. By definition we have $\nu_{\text{eff}} = \eta_{\text{eff}} e^2 n/m_e$, where η_{eff} is the effective resistivity of the plasma, n is the electron density, and m_e is the mass of an electron. The second condition in (1) can be rewritten as $I > 17(2\pi r/a)$ kA, where $r \gtrsim a$ is the radius of the inner conductor of the coaxial line, and I is the total current in the bank. This resistance arises from the joint excitation of long-wave drift helicons and fluctuations in the ion density.[6] A resistance of the same magnitude arises when other, related mechanisms[7,8] operate, so our estimate of ν_{eff} is extremely reliable.[2)]

We would particularly like to stress that under conditions (1), which are typical of plasma opening switches, the well-known anomalous-resistance mechanisms involving the excitation of an ion acoustic turbulence or a turbulence of lower hybrid drift waves make a much smaller contribution to ν_{eff}. They alone would be insufficient to cause an anomalous plasma heating to significantly affect the dynamics of the plasma if the current distribution along the switch is smooth. Certain researchers[5,9] who have taken up the interpretation of experimental data have mentioned that it is desirable to introduce an anomalous resistance with a ν_{eff} comparable to ω_{He}.

Another recent step forward has been the experimental confirmation[5] of the basic hypothesis of Ref. 10 regarding the mechanism for the operation of a plasma opening switch. According to this hypothesis, the increase in the resistance of the switch is associated with a decrease in the plasma density. It has also been determined that the plasma density decreases everywhere throughout the plasma volume, except near the electrodes, where it probably increases rather than decreases. Hinshelwood *et al.*[5] attribute the decrease in the plasma density to a macroscopic motion of the plasma.

Now let us look at this new mechanism for the operation of a plasma opening switch.

The plasma of the switch is in direct contact with "cold" electrodes. No measures are taken to establish a stable, equilibrium plasma configuration or to thermally insulate the plasma. In a case of this sort the plasma must strike the walls and be destroyed there over a time scale $\tau_d \simeq a/c_s$, where c_s is the sound velocity in the plasma; it must also lose heat over a time scale $\tau_t \simeq a/u$, where u is the average electron current velocity. Correspondingly, we can write the following model equations for the average density and the average electron temperature of the plasma:

$$\frac{d}{dt} n = -n/\tau_d, \quad \eta_{\text{eff}} j^2 \approx n T_e/\tau_t. \tag{2}$$

The second of these equations assumes that the rate of Joule heating of the electrons is approximately equal to the rate at which the electrons are cooled at the cold walls, so that an amount of energy much greater than the internal energy of the plasma is "pumped" through the switch over the hydrodynamic time scale. Assuming that the impedances of the inductive storage bank (Z_s), of the load (Z_L), and of various types of leakage (Z_l) are much larger than the resistance of the switch, so the current flowing through the storage bank remains constant during the stage in which the switch resistance increases, and solving system of equations (2), we find

$$n(t) = n_0(\Delta t/t_c)^2, \quad U(t) = U_{h0}(t_c/\Delta t)^2, \tag{3}$$

$$R_m=(\omega_{pi0}a/c)(\Delta t/t_c), \quad nT_e\simeq H^2/8\pi, \tag{4}$$

where $\Delta t=t_c-t$, $t_c\simeq a/c_{A0}$ is the duration of the stage in which the switch has a good conductivity, $U(t)$ is the voltage across the switch, $U_{h0}=H^2/4\pi n_0 e$ is the initial so-called Hall voltage, $c_{A0} = H/\sqrt{4\pi n_0 m_i}$ is the initial Alfvén velocity, and R_m is an effective magnetic Reynolds number. We see that the plasma strikes the walls in an explosive fashion and that the plasma density vanishes (in this model) over a finite time, while the voltage becomes infinite. The duration of the conducting stage of the switch is determined by the hydrodynamic time scale. Since the condition $v_{\text{eff}}\sim\omega_{\text{He}}$ holds, the plasma rushes primarily toward the cathode, by virtue of the Hall effect. The equations written here do not depend on the relation between T_e and m_ec^2, provided that the condition $u\ll c$ holds, where u is the average current velocity. The limiting resistance of the switch in this model, with $u\sim c$, would be $\sim a/2\pi rc=30(a/2\pi r)\,\Omega$. The plasma is quasineutral throughout the range of parameter values which we are considering.

Noting that all the impedances (Z_s, Z_L, and Z_l) are finite, matching the current acceleration time in the storage bank with the duration of the conducting stage of the switch (t_c), and adopting the natural conditions $Z_s\lesssim Z_L<Z_l\ll 30(a/2\pi r)\,\Omega$ (in order to achieve the maximum voltage), we find that the increase in the voltage across the switch is bounded and that the maximum voltage, U_m, corresponds to the estimate

$$U_mU_{h0}\simeq U_0^2, \quad t_m\simeq t_c(U_0/U_m). \tag{5}$$

Here U_0 is the emf of the source powering the bank, and t_m is the length of the voltage pulse. Equation (5) imposes conditions on the parameters: n, a, and H. These conditions, along with the condition of a matching in terms of t_c, must be satisfied in order to reach the voltage U_m.

If $\omega_{pi0}a>c$, the explosion of the bridge precedes the wave in which the plasma detaches from the anode,[11] in which the resistance is determined by the drift-helicon mechanism,[6] under the condition $eU_{h0}>(m_e/m_i)m_ec^2\sim 100-200$ eV.

The mechanism proposed here for the operation of a plasma opening switch agrees with the basic relations found experimentally.[4] Used along with the known parameters of the storage bank and the opening switch, this mechanism makes it possible to calculate the duration of the conduction stage, the voltage across the switch at this time, the maximum voltage, and its duration, all of which are in agreement with experimental data. (We will not actually go through this comparison in this letter.) This mechanism is fairly simple and in a sense very crude in comparison with some other mechanisms which have been proposed (some of which are described in Refs. 7 and 10–13, for example), which are based on some extremely subtle properties of the plasma near the electrodes—properties which are difficult to verify.

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1) We assume for simplicity that the thickness of the bridge (i.e., the dimension of the plasma along the direction of the electric field **E**), which we denote by a, is approximately equal to the length of the bridge (i.e., the dimension of the plasma along the direction of $\mathbf{E}\times\mathbf{H}$), while the dimension of the plasma along **H** (the magnetic field) is left arbitrary.

2) Chukbar and Yan'kov[7] were the first to emphasize the basic physical processes (other than, perhaps, the

destruction of the plasma at the electrodes) which (in our opinion) govern the operation of the plasma opening switch.

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