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A POS HALL MODEL

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The model explains POS operation on the basis of internal processes in the plasma: cathode plasma creation, double layer formation, field penetration of the plasma and current switching.

The large number experiments performed to date has not clarified the physics of POS [1]. The simple 1D model [2] can not explain field and current penetration of plasma. This model proposes four successive phases of POS action: conductivity, erosion, enhanced erosion and magnetic insulation of electron flow. But opening after the current maximum [1] and switching on a too high-impedance load do not provide magnetic insulation in vacuum [3]. These facts and the practical independence of rate of impedance rise on the load indicate, in our opinion, the presence of an internal mechanism of POS action [4].

1. Cathode plasma creation. Our assumption for plasma injection in the POS gap are the following [5]:
a) plasma velocity v_p provides delay of neutrals from the ei-component during plasma gun pulse time τ_p of not less than the gap width d. This gives $v_p \approx d/\tau_p = 10^7$ cm/s for τ_p = 1 μs and d = 10 cm;
b) plasma volume is large for total erosion in the gap during generator pulse time τ_g. This means (Fig.1) $2\pi r_C l d > \mu I_m \tau_g / e n_p$, where $\mu = \sqrt{m_e/m_i}$, I_m is the maximum current, n_p – the plasma density;
c) I_m is sufficiently large for plasma erosion: $I_m > I_s = 2\pi r_C l j_s$ ($j_s = e n_p v_p/\mu$), or $\tau_g < \tau_p$ (from a) and b));
d) n_p is sufficiently low and not influenced by the electron work function from the cathode.

Requirements a) and d) lead to DL creation. The low voltage $V = m_e v_p^2/2e$ reflects the electrons in the injected plasma and an ion sheath of dimension $\approx v_p/\omega_{pe}$ (current density = $e n_p v_p$) is formed near the cathode. It extends along the not emitting cathode to the depth of collisionless skin layer $\delta_s = c/\omega_{pe}$. With increasing voltage to $V_s = m_i v_p^2/2e$ = 0.6 kV (C^+), the sheath expands to $\approx v_p/\omega_{pi}$. The cathode electric field reaches the value $E \approx \omega_{pi} V_s / v_p$. If E ≈ 0.1 MV/cm, a dense cathode plasma can be created. This gives $n_p \approx 10^{13}$ cm^{-3} (δ_s = 2 mm, v_p/ω_{pi} = 0.1 mm). The actual n_p may differ from this value. We shall consider a somewhat denser injected plasma when the cathode explodes at $V < V_s$.

2. DL formation and plasma erosion. The dense plasma front moves with a velocity ≈ 10^6 cm/s. DL formation is described in [5] as the quasi-stationary evolution of potential distribution in the plasma-filled gap. The voltage and current density reaches the values V_s and j_s for $t = t_s$. DL size slowly rises to $\approx v_p/\omega_{pi} \ll \delta_s$ with an almost constant velocity $\approx \partial_t j / e n_p v_p$ (≈10^5 cm/s for the μs installation [3] and ≈ 10^6 cm/s for ns generators). Saturation at V_s and I_s leads to erosion. The simple 1D model [6] (see [5] too) shows that the magnetic field acts on the electrons during an erosion time $\approx \omega_{pi}^{-1} \approx 1$ ns, when its Larmor radius $r_{ce} = \delta_s$.

3. Field penetration of the plasma. This action forces electrons accelerated in DL to be displaced towards the load and slow injected electrons towards the generator. This is the Hall effect. It forms two regions of fast-electron ExB-drift. The first is the cathode layer (CL), where the emission area extends along the cathode. Magnetic insulation of the electron flow, neutralized by ions, is realized in CL. Using Ampere's law, we can write the insulation condition $\delta = r_{ce}$ in the form

$$eV = B^2/8\pi n \qquad (B \approx 2I/cr_C), \qquad (1)$$

where n is the average CL density. CL growth follows a $\delta \sim 1/\sqrt{n}$ law in this erosion phase.

The second layer is the magnetic insulation front moving along the POS axis as the radial current sheath (CS; Fig.2). Its dynamics was discussed in [1].

The emission current density is about j_s for any $t > t_s$, and the current rise is supported by the CS movement through the plasma. The rise stops when CS reaches the load POS boundary ($t = t_c$). The critical values I_c and V_c can be determined from the LC-circuit equation, where the POS voltage (1) is included. We can use the simple law $n \sim I^{-2}$ for CL density. Then, the analysis of the Airy equation gives us I_c and V_c. For example, for L= 0.5 μH, C = 0.5 μF, U_o= 20 kV, r_C= 3 cm (Fig.1), we obtain I_c= 15 kA, V_c= 3 kV when t_c= 0.6 μs, t_s= 0.3 μs.

The CS dynamics equations are

$$m_i (Nv)^{\cdot} = B^2/8\pi, \qquad \dot{N} = n_p v - v_p N/d, \qquad (2)$$

which include the snow-plough effect as well as the

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plasma loss to CL. The loss is small for $t \ll d/v_p = 1\ \mu s$, when (2) is the snow-plough model. For $I = \dot{I}t$, constant acceleration $w = \dot{I}/cr_C\sqrt{3\pi m_i n_p}$ satisfies the model. The loss is considerable for $t \gtrsim d/2v_p = 1/\alpha$. The exact solution is

$$Nv = \int_{t_s}^{t} \frac{B^2 dt}{8\pi m_i}, \qquad N^2 = 2n_p \int_{t_s}^{t} e^{-\alpha(t-t')}\cdot(Nv)(t')dt'. \quad (3)$$

It gives $v \approx wt\sqrt{\alpha t/2}$ for $\alpha t \gg 1$ and $I \sim t$. We can find from (3) the velocity $v_c \approx 10^7$ cm/s and the axial dimension of the injected plasma region $l \approx 10$ cm in our example.

4. Switching. Plasma absorption by the moving CS changes the process. This was noted in our experiments [3] by the appearance of anode plasma, the position of which testified to current flow curvature and enhanced e-bombardment of the anode for $\tau = t - t_c > 0$.

Rapid current decay occurs after t_c. There arises an inductive voltage $-c^{-2}L\dot{I}$. Simultaneously, magnetic field and its pressure weaken and can not accelerate CS in this phase. The anomalous heating (possibly type [7]) leads to rapid CS expansion. These equations can be written as

$$m_i\ddot{b} = 2\varepsilon/3b, \qquad \dot{\varepsilon} + 2\dot{b}\cdot\varepsilon/3b = IV/N_p \quad (4)$$

in the frame of reference moving with velocity v_c. Here, b is CS width (Fig. 3), ε the internal energy for one ion, N_p the number of ions in CS. We take $N_p \approx 2\pi r_C l d n_p$, CS losses as < 1/3 of plasma in our example. System (4) has the law of conservation $m_i N_p \dot{b}^2/2 + N_p\varepsilon = L(I_C^2 - I^2)/2c^2$. We see that a limit value $v_m = I_C\cdot\sqrt{L/m_i c^2 N_p} \approx 10^8$ cm/s exists. The maximum temperature ≈ 10 eV allows us to explain the observated spreading of the axial glow [8], the brightness of which increases in the direction of load.

A part of heated plasma diffuses backward across the magnetic field, losing average movement towards the cathode due to turbulence and forms a wake after CS. Its density is $n \approx n_p l/a$, where a is the wake length; $a \approx \sqrt{(cT/eB)\tau}$ for Bohm diffusion. The retardation of diffusion allows us to fix the value n_* for a current decay time τ_* (see definition below; $a(\tau_*) \approx 1$ cm).

CL develops in this plasma as a result of its erosion. Ion balance analysis gives the dependence $n_*/n = \sqrt{\omega_{ce}\omega_{ci}}\cdot\delta/\dot{\delta}$ for CL density. From (1) and the circuit equation, we obtain

$$\ddot{I} + 2(c^2U/L - \dot{I})\dot{I}/I + (\Omega^2 + I^2/\tau_*^2 I_C^2)I = 0;$$
$$I = I_C, \qquad \dot{I} = 0 \quad (\tau = 0). \quad (5)$$

Here, $\tau_* = c\sqrt{\pi r_C^3 L\mu m_i n_*}/I_C$ (≈ 0.1 μs in our example), $\Omega = c/\sqrt{LC}$ (≈ $2\cdot10^6\ s^{-1}$). The solution of (5) leads to

$$\frac{\tau}{\tau_*} = \int_1^{I_C/I} \frac{du}{\sqrt{2\ln u}}, \qquad V \approx -\frac{L\dot{I}}{c^2} = \frac{LI^2}{c^2\tau_* I_C}\cdot\sqrt{2\ln\frac{I_C}{I}} \quad (6)$$

for optimal charging of the inductor ($t_C \approx \pi/2\Omega$). The voltage maximum $V_m = LI_C/\tau_* c^2\sqrt{2e}$ (≈30 kV in the example; e = 2.71...) is reached in time $\tau \approx \tau_*$. The POS impedance has a sharp peak too, but its maximum appears later. The CL size and its density vary as

$$n/n_p = (\delta_B/\delta)^2 = (\delta_B/\sqrt{\mu L r_C})\cdot\sqrt{(n_*/n_p)/2\ln(I_C/I)}.$$

It is diffusive initially, when $\delta \approx \sqrt{2D\tau}$ with $D = r_C L/2\omega_{ce}(I_C)\tau_*^2$. Then, the increase in CL size slows down.

The model (4) does not include plasma loss from CS to wake. Besides, there are C^+, C^{2+}, H^+ ions in the actual plasma and they are separated according to mass as acceleration proceeds. This promotes further acceleration. Magnetic field diffusion in CS is considerable too. Its diffusivity is determined from the anomalous resistivity (of ion acoustic type, where "collisional" frequency $\nu_{ef} \approx \omega_{pe}\cdot\sqrt{l/b}$, for example). Therefore, the field penetrates the entire CS in time $t_B - t_C \approx c^2\delta_B v_m^{-2}\cdot\sqrt{b(t_B)/l} \approx 0.2$ μs. Its penetration into the vacuum electron layer on the plasma front weakens the image force on these electrons. The anomalous resistivity rise leads to an increase of electrons moving along the plasma boundary to the anode. Ions (H^+ preferentially) are drawn from the plasma and form an almost charge neutral ep-beam before the plasma. Its propagation ($v \approx 10^8$ cm/s) towards the load gives voltage stabilization at the level $V \approx Bdv/c$ (≈ 3-4 kV) instead of the decay (6). Beam's arrival at the load switches on current.

Our model is valid if $I < \mu I_B c/v_p$ (160 kA in the example), when the space-charge layer is not thicker than r_{ce}. Otherwise, one must add the contribution of the ion sheath voltage to (1).

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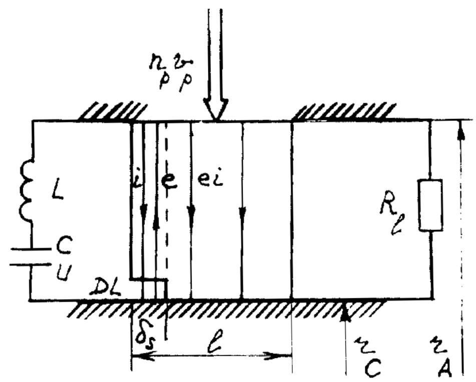

Fig.1

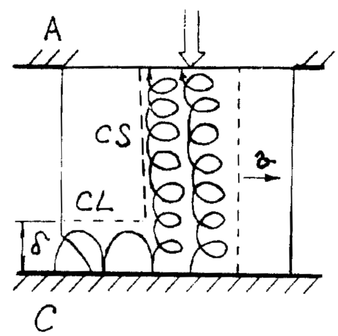

Fig.2

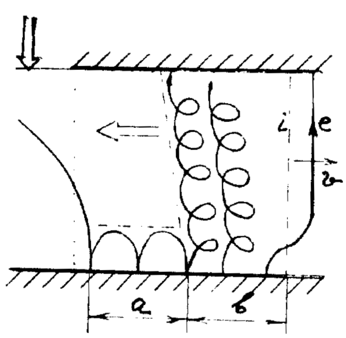

Fig.3

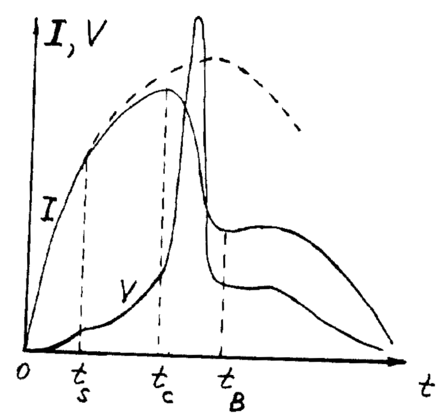

Fig.4