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Unexpected Peculiarities of Ignition of a Self-Sustained Discharge in Crossed Electric and Magnetic Fields

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It is reported about the discovery of a double current structure upon ignition of a self-sustaining glow discharge in crossed electric and magnetic fields — in an ExB discharge. The initial state for the first current jump is neutral gas; for the second — plasma. The measured ignition curves and time characteristics of the process are given. The ion current was used as a parameter that made it possible to register two modes of the E × B discharge. For the first time, a different character of discharge ignition for Penning pairs is shown.

Keywords: discharge, crossed electric and magnetic fields.

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The electric discharge in gases in zero external magnetic field was studied thoroughly [1]. Its current–voltage curve incorporates currents induced by natural radiation and features the so-called dark discharge region, which is followed by different types of glow discharge and an arc discharge. Plasma sources with plasma flows and particles extracted from the E × B discharge region (discharge in crossed electric and magnetic fields) are used widely at present. It is hard to imagine engineering processes in nanoelectronics [2], spacecraft orbit adjustment [3], and medicine [4] without them. Specifically, plasma accelerators with an anode layer (AALs) and an extended acceleration region (stationary plasma thrusters, SPTs) are used. The E × B discharge ignition conditions have been studied since the 1980s [5]. The ignition of a self-sustained non-sustained (in the presence of a source of external electrons) glow E × B discharge was understood as electrical breakdown in [5]; other researchers did not see. In this case, the electrical current of the discharge was measured as an indicator of ignition The results of experiments on igniting a self-sustained E × B discharge in argon, xenon, and nitrogen were presented in [6,7]. Dependences of ignition voltage U_{ig} on Pd (P is the gas pressure and d is the distance between electrodes) were similar in shape to Paschen curves in zero magnetic field, but the U_{ig} values were lower at the same Pd. At the moment of ignition of a discharge in an SPT, the net current is 10−20 times higher than the current in steady-state operation; minimum $U_{ig} \approx 220\,\mathrm{V}$ was determined for the $U_{ig} = f(B_{ig})$ curve at $B \approx 190\,\mathrm{G}$ [8]. A discharge is produced in an SPT $7\,\mu$s after the voltage is switched on. The current density reaches its peak at $t \approx 25\,\mu$s, and the transition to steady-state operation is completed within approximately $50\,\mu$s [9].

Integral dependences $U_{ig} = f(B_{ig})$ for neon, argon, and krypton for an anomalous glow discharge in an AAL used in the described experiments (see a detailed description in [10]) are similar to the ones provided in [6–8]. In determining these dependences, the radial component of induction at the cathode B_{ig} was calculated based on the current measured in the circuit of a coil, which produces the AAL magnetic field, at the moment of breakdown. A Rogowski coil encircling the anode−cathode AAL supply line was used as a sensor. This Rogowski coil had the following parameters:$L \approx 35\,\mu\mathrm{H}$, $C \approx 100\,\mu\mathrm{F}$, $R \approx 0.7\,\Omega$; and integrating RC circuit was not used. The typical oscilloscope signal record is shown in Fig. 1, *a*. A peak of induction current at the moment of discharge ignition, which is followed by the transition to steady-state operation, stands out. Since the attempts at identifying probable precursors of a glow discharge with a Rogowski coil failed, we decided to use the current of ions leaving the AAL through a circular aperture in the cathode as an indicator of discharge ignition. The collector of a retarding field analyzer (RFA) with a control and measurement system capable of monitoring the signal for 100 s [11] was used as an ion current sensor.

The AAL anode voltage was set first. A voltage increasing in steps at different rates $dU_{\mathrm{RFA}}/dt \leqslant 10\,\mathrm{V}/30\,\mathrm{ms}$ was then applied to the RFA analyzer grid to monitor the temporal dynamics of the ion signal. In conjunction with the U_{RFA} growth, the magnetic field in the AAL increased slowly (upon variation of current in its coil) up to the moment of breakdown (ion current jump at the RFA collector). These measurements revealed a double current structure of the ion signal (Figs. 1, *b*, *c*), which is equivalent to a double structure of the electron and discharge-current density in a E × B discharge. The value of B_{ig} (induction at the site of production of primary electrons at the cathode) was used as a quantitative characteristic of the magnetic field. The calculated (in FEMM) B_{ig} value was determined based on the measured current in an axial coil generating the AAL magnetic field. Figures 1, *b* and *c* show the typical oscilloscope records of ion current (time is counted from

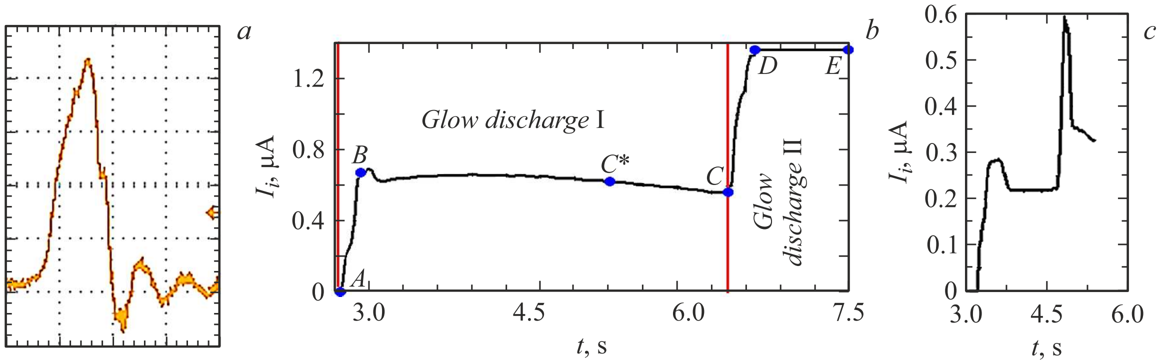

Figure 1. Oscilloscope records of ignition of a E × B discharge. *a* — Neon, signal from the Rogowski coil, inflow rate $q = 50\,\mathrm{cm}^3/\mathrm{min}$, $U_{ig} = 1140\,\mathrm{V}$, $B_{ig,\mathrm{I}} = 2400\,\mathrm{G}$, 5 μs/div sweep, 100 mV/div sensitivity; *b* — neon, $dU_{\mathrm{RFA}}/dt = 2\,\mathrm{V}/30\,\mathrm{ms}$, $q = 80\,\mathrm{cm}^3/\mathrm{min}$, $U_{ig} = 1150\,\mathrm{V}$, $B_{ig,\mathrm{I}} = 1480\,\mathrm{G}$, $B_{ig,\mathrm{II}} = 2150\,\mathrm{G}$; *c* — argon, $dU_{\mathrm{RFA}}/dt = 2\,\mathrm{V}/30\,\mathrm{ms}$, $q = 5\,\mathrm{cm}^3/\mathrm{min}$, $U_{ig} = 1040\,\mathrm{V}$, $B_{ig,\mathrm{I}} = 1430\,\mathrm{G}$, $B_{ig,\mathrm{II}} = 1630\,\mathrm{G}$.

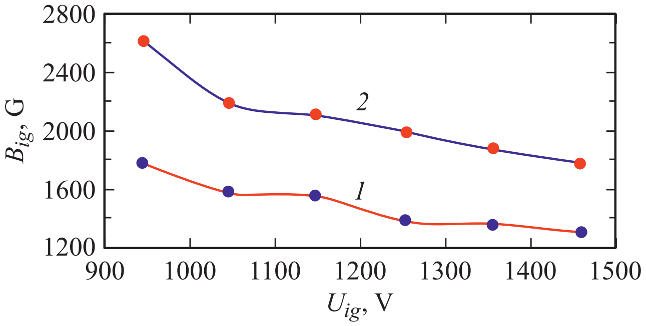

Figure 2. Ignition curves for neon. *1* — Mode I, *2* — mode II. $q = 70\,\mathrm{cm}^3/\mathrm{min}$.

the moment of RFA initiation) corresponding to the curve of ignition of a E × B discharge „in ion light.“Two current jumps (sections *AB* and *CD* in Fig. 1, *b*) followed by two steady anomalous glow discharge states (sections *BC* and *DE* in Fig. 1, *b*) are evident. The transition from mode I to mode II is initiated by an increase in the magnetic field induction. Sections BC^* and *DE* in Fig. 1, *b* correspond to the state when the magnetic field remained unchanged; it increased up to point *A* and within the C^*C section.

Figure 2 shows the ignition curves of E × B discharges, which were initiated by a magnetic field, obtained „in a single frame.“It should be stressed that neutral gas and plasma are the initial states for the first and the second current jumps, respectively. The measured ratios of amplitudes of jumps for different ignition conditions are $I_{\mathrm{II}}/I_{\mathrm{I}} \approx 2{-}11$.

Varying dU_{RFA}/dt in the process of ignition, we could observe ions with energies $50\,\mathrm{eV} \leqslant W_i \leqslant eU_A$ at the collector, where U_A is the AAL anode voltage at the moment of ignition ($U_A = U_{ig}$). Ions were produced in collisions between electrons and neutral particles of the working gas at different sites within the discharge gap and were thus accelerated to different energies. The ion current depended on the range of energies in which it was measured. Specifically, ions with energies $W \leqslant 150\,\mathrm{eV}$ and $W \geqslant 700\,\mathrm{eV}$ were detected at $dU_{\mathrm{RFA}}/dt = 2\,\mathrm{V}/50\,\mathrm{ms}$ and $dU_{\mathrm{RFA}}/dt = 4\,\mathrm{V}/10\,\mathrm{ms}$, respectively. The highest current was measured at energies close to the maximum of the energy spectrum of ions.

Working with mixtures of inert gases, we could not pass over experiments with „Penning pairs“ [12,13] (in the present case, the studied mixtures were those of neon with argon or krypton, wherein the potential of excitation of neon to a metastable state is around 16.7 eV and exceeds the ionization potentials of argon (15.7 eV) and krypton (14 eV)). The natural „Penning“behavior of ignition curve $B_{ig} = f(q)$ (reduction of the energy input from the magnetic field required for ignition) was observed when argon or krypton were admixed as impurities into neon (Fig. 3, *a*). However, when neon itself was admixed into argon or krypton, the ignition induction increased to $q_{\mathrm{Ne}} \approx 30\,\mathrm{cm}^3/\mathrm{min}$ and then decreased monotonically, but did not reach the starting value at $q_{\mathrm{Ne}} \leqslant 90\,\mathrm{cm}^3/\mathrm{min}$ (Fig. 3, *b*); the Penning effect in its explicit form is not observed here. The results presented in Fig. 3 were obtained using an induction sensor (Rogowski coil).

Realizing that a flow of ions leaving the E × B discharge region may be an indicator of ignition (emergence of electrons and plasma in the AAL anode–cathode gap), we performed an experiment on measuring the values of U_{ig} and B_{ig} at the moment when a signal is detected at the ion collector. This „ion monitoring“ had an additional advantage in that it provided an opportunity to demonstrate explicitly that a self-sustained E × B discharge did indeed spread over the entire anode–cathode gap, since the RFA signal at the moment of ignition corresponds to ions with energies $50\,\mathrm{eV} \leqslant W_i \leqslant eU_A$. Two steady-state E × B discharge modes extending from zero (neutral gas) to I_1 (point *B* in Fig. 1, *b*) and approximately from I_1 (steady-state plasma E × B discharge mode — point *C* in Fig. 1, *b*) to I_2 (point *D* in Fig. 1, *b*) were found as a result. The „plasma“ jump cannot be induced without a cathode potential jump. Two current jumps (to the glow discharge mode and at the glow discharge stage) constitute a fundamental difference

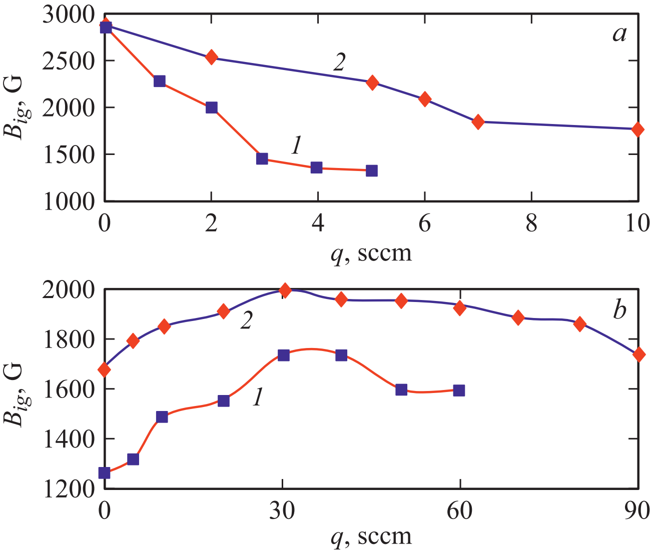

Figure 3. Ignition curves at ignition voltage $U_{ig} \approx 830\,\mathrm{V}$ measured *a* when krypton (*1*) and argon (*2*) were admixed into neon ($q_{\mathrm{Ne}} = 60\,\mathrm{cm}^3/\,\mathrm{min} = \mathrm{const}$) and *b* when neon was admixed into krypton ($q_{\mathrm{Kr}} = 5\,\mathrm{cm}^3/\mathrm{min} = \mathrm{const}$) (*1*) and argon ($q_{\mathrm{Ar}} = 8\,\mathrm{cm}^3/\mathrm{min} = \mathrm{const}$) (*2*).

between a E × B discharge and a discharge in zero magnetic field. The following sequence of E × B discharge generation may then be formulated: mode I of an anomalous glow discharge–mode II of an anomalous glow discharge–arc discharge.

The difference in behavior of Penning pairs corresponding to different roles of gases (primary gas or impurity) is attributable to variations of the degree of influence of a discharge on the potential distribution in the cathode region. When neon is the primary gas, a discharge is ignited at $B_{ig} \geqslant 2800\,\mathrm{G}$. A cathode potential layer with thickness $\Delta < 3\,\mathrm{mm}$ and magnitude $\Delta\varphi \geqslant 30\,\mathrm{V}$ forms in this case. If easily ionized components (Ar, Kr) are the primary gas, a discharge is ignited at $B_{ig} \leqslant 1700\,\mathrm{G}$, and $\Delta\varphi$ does not exceed15–20 V, thus making the ionization of neon and its excitation into a metastable state unlikely.

Conflict of interest

The authors declare that they have no conflict of interest.

References

[1] Y.P. Raizer, *Gas discharge physics* (Springer, 1991), p. 128.

[2] W. Liu, G. Zhang, C. Jin, Y. Xu, Y. Nie, X. Shi, J. Sun, J. Yang, Appl. Phys. Lett., **121**, 073301 (2022). DOI: 10.1063/5.0092988

[3] I.D. Kaganovich, A. Smolyakov, Y. Raitses, E. Ahedo, I.G. Mikellides, B. Jorns, F. Taccogna, R. Gueroult, S. Tsikata, A. Bourdon, J.-P. Boeuf, M. Keidar, A.T. Powis, M. Merino, M. Cappelli, K. Hara, J.A. Carlsson, N.J. Fisch, P. Chabert, I. Schweigert, T. Lafleur, K. Matyash, A.V. Khrabrov, R.W. Boswell, A. Fruchtman, Phys. Plasmas, **27**, 120601 (2020). DOI: 10.1063/5.0010135

[4] M. Keidar, Plasma Sources Sci. Technol., **24**, 033001 (2015). DOI: 10.1088/0963-0252/24/3/033001

[5] A.E.D. Heylen, IEE Proc. A, **127**, 221 (1980). DOI: 10.1049/ip-a-1.1980.0034

[6] G. Petraconi, H.S. Maciel, R.S. Pessoa, G. Murakami, M. Massi, C. Otani, W.M.I. Uruchi, B.N. Sismanoglu, Braz. J. Phys. **34**, 1662 (2004). DOI: 10.1590/S0103-97332004000800028

[7] S.-Z. Li, H.S. Uhm, Phys. Plasmas, **11**, 3443 (2004). DOI: 10.1063/1.1737743

[8] A.N. Ermilov, V.F. Eroshenkov, D.N. Novichkov, Yu.A. Kovalenko, T.M. Sapronova, S.V. Korolev, T.V. Chernyshov, A.P. Shumilin, High Temp., **51**, 443 (2013). DOI: 10.1134/S0018151X13040081.

[9] C.L. Ellison, Y. Raitses, N.J. Fisch, IEEE Trans. Plasma Sci., **39**, 2950 (2011). DOI: 10.1109/TPS.2011.2121925

[10] V.M. Bardakov, S.D. Ivanov, N.A. Strokin, Phys. Plasmas, **21**, 033505 (2014). DOI: 10.1063/1.4846898

[11] V.M. Bardakov, S.D. Ivanov, A.V. Kazantsev, N.A. Strokin, Rev. Sci. Instr., **86**, 053501 (2015). DOI: 10.1063/1.4920998

[12] F.M. Penning, Naturwissenschaften, **15**, 818 (1927). DOI: 10.1007/BF01505431

[13] B. Ohayon, G. Ron, E. Wahlin, J. Instrum., **10**, 03009 (2014). DOI: 10.1088/1748-0221/10/03/P03009