NON-SELF-SUSTAINED DISCHARGE WITH RECOVERY OF IONIZING BEAM

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Ionization of a gas by the beam from an electron accelerator can be used to instigate a spatial discharge at high gas pressures [1] and thereby attain a high specific energy of excitation of the gas, which is exploited in electrically excited preionization lasers [2].

It has also been proposed to utilize an electron-beam-controlled spatial non-self-sustained discharge in plasma chemistry, to effect the chemical reactions involved in the synthesis of ozone and oxides of nitrogen [3]. The use of a non-self-sustained discharge to stimulate chemical reactions is based on the existence in this sort of discharge of a large difference between the vibrational and translational temperatures of the gas molecules. Accordingly, the chemical reactions proceed under thermodynamically nonequilibrium conditions, as a result of which the reaction yields can be greater than under equilibrium conditions. In molecular gases only the first few vibrational levels are efficiently excited, the characteristic energy of the vibrational quantum being $\sim$0.1 eV. Thus, taking the vibrational temperature of the molecules to be $\sim$1 eV, we find that the specific energy Q that has to be injected into the gas must be no less than 5 J/cm^3 • atm. Also, the efficiency of the chemical reactions increases as the specific energy injected into the gas increases.

As shown in [2], for example, the energy evolved in an electrically excited preionization discharge depends on the conductivity of the positive column of the discharge and on the density n of current carriers (electrons), which is determined by the competing processes of ionization and recombination:

$$n = (\psi/\beta)^{1/2}, \tag{1}$$

where ψ is the rate of ionization of the gas; β is the electron–ion volume recombination coefficient. Setting the rate of ionization of the gas by an electron beam of current density J_B equal to $\psi = J_B\alpha p/e$, where α is the coefficient of specific ionization of the gas by the beam (pairs/cm • atm), we obtain the following expression for the specific energy injected into the gas in the active stage of the discharge:

$$Q = \int_0^{\tau_B} \left(\frac{E}{p}\right)^2 e\mu \left(\frac{J_B \alpha p}{e\beta}\right)^{1/2} dt, \tag{2}$$

where E is the electric field intensity in the gas; μ is the electron mobility in the gas; and τ_B is the duration of the beam pulse. The derivation of (2) neglects Townsend multiplication and electron attachment, which is valid for nitrogen for $E/p \leqslant 10$ kV/cm • atm.

The vibrational levels of the gas molecules are excited most efficiently by the electron beam at ratios $E/p \sim 10$ kV/cm • atm; at larger values of E/p, excitation of the electronic levels prevails [4]. Accordingly, electric field intensities corresponding to $E/p \sim 10$ kV/cm • atm are utilized for excitation of the gas of electrically excited preionization lasers operating on vibrational transitions. Also, the static field intensity must to be raised above the breakdown value. At low values of E/p (up to 30 kV/cm • atm) and typical values of beam current of $I_B \sim 10$ kA and pulse duration $\tau_B \sim 10^{-8}$ sec, values of Q of the order of 1 J/cm^3 • atm can be attained experimentally.

It can be shown that values of Q of $\sim$1 J/cm^3 • atm correspond to a concentration of active particles in the gas of 10^{16}–10^{17} cm^{-3} • atm^{-1}. The concentration of the products of chemical reactions involving active particles is of this same order, i.e., does not exceed 1%. Such a low concentration of reaction products cannot satisfy the demands of the chemical industry, and the question of further increasing Q is accordingly acute.

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However, further increase of the specific energy injected into the gas for excitation of the vibrational levels of the molecules is connected with fundamental difficulties. At high values of Q the superheated-ionization instability results in the development of a spark discharge in the gas in a time $\sim 10^{-6}$ sec [5]. It is shown in [6] that the ultimate energy density that can be evolved in a stable discharge amounts to 0.8 J/cm^3 • atm.

On account of the above difficulties, the possibilities of further increasing Q while maintaining a stable spatial discharge are almost exhausted at the present time. The possibility remains, however, of increasing Q by using pulses of duration shorter than the time required for the spark discharge to develop, although the spatial discharge produced in this manner will be unstable and nonuniform. While such a discharge may not be very suitable for pumping the working gas of a laser, nonuniformity is not important as far as plasma chemistry is concerned.

In such a discharge Q can be increased by increasing the ionization of the gas and the current density of the discharge. It is known, however, that at large current densities electron-impact quenching of the vibrationally excited states of molecules begins to become important.

Fears have been expressed [6] that this phenomenon will also limit the energy density of a spatial discharge. However (by the estimates of [7]), the electron density n at which electron-impact de-excitation begins to have a significant effect is $\sim 10^{15}$-10^{16} cm^{-3} for a pumping pulse duration of $\sim 10^{-6}$ sec. In the electrically excited preionization laser the electron density reaches $\sim 10^{12}$-10^{14} cm^{-3}. Large reserves of increasing the discharge current density exist accordingly.

Increasing the ionization of the gas by increasing the beam current density J_B is, however, impracticable, as J_B appears in expression (2) to the power of 1/2; attainment of large values of Q would require too high beam-current densities and very powerful accelerators.

In known devices for producing an electrically excited preionization discharge, the gas is ionized with the aid of high-power electron accelerators. Only a small part of the beam energy goes on ionizing the gas in the discharge gap, as a result of which the mean free path of high-energy electrons in the gas is usually much greater than the electrode spacing l. To reduce the energy of the beam electrons with a view to increasing the cross section for interaction of the electrons with the gas molecules is not possible, as the beam from the accelerator is extracted through a foil that is opaque to electrons of low energy.

The beam utilization coefficient K was introduced in [8] as the ratio of the energy injected by the discharge into the gas to the energy carried by the beam (kinetic energy of the beam):

$$K = l\int_0^{\tau_D} J_D E dt \Big/ \int_0^{\tau_B} \frac{U_B}{e} J_B dt, \qquad (3)$$

where U_B is the energy of the beam electrons and τ_D is the duration of the discharge pulse. The coefficient K increases with increasing electrode spacing l. However, with increasing l, the breakdown intensity of the electric field in the gas decreases due to the total-voltage effect, so that one has to go over to a mode of operation with smaller E/p. As a result, the specific energy Q injected into the gas decreases.

The ratio E/p can be increased by using a pulsed voltage and creating an overvoltage across the discharge gap. At high values of E/p it is not the vibrational levels of the molecules that are excited efficiently, but their electronic levels. However, for the purposes of plasma chemistry, the creation of a nonequilibrium state by exciting electronic levels is of no less interest than by exciting vibrational levels. For instance, it is shown in [9] that the synthesis of ammonia in a glow discharge occurs mainly in the negative glow region, in which, as is well known, the electronic levels of the gas molecules are efficiently excited.

The use of a pulsed voltage gives rise to difficulties connected with the synchronization of the voltage pulses applied to the electrodes of the discharge gap and the beam pulses of electrons. The method proposed in [10] avoids these difficulties by pulsing the discharge gap from the same pulsed voltage source that is used to power the accelerator tube.

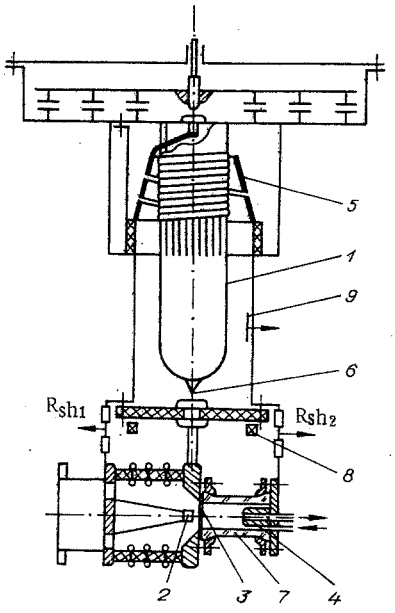

Fig. 1

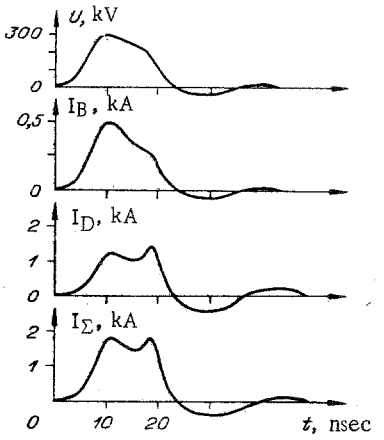

Fig. 2

A diagram of the setup on which the experiments using this method were performed is shown in Fig. 1. A pulse of high voltage from storage device 1 is fed simultaneously to the discharge chamber and to the accelerator tube with explosive-emission cathode 2. The accelerator tube and the discharge chamber have a common anode 3, which is transparent to the electron beam. After traversing the anode, the beam enters the gas of the discharge gap and is decelerated by the retarding electric field between the anode and cathode 4; part of the beam energy is lost in ionizing the gas, and part returns to the storage device (i.e., some of the energy of the electron beam is recovered). The ionization of the gas between the electrodes results in the formation of a spatial non-self-sustained discharge, the current density of which is determined by the density and mobility of the secondary electrons. The source of the current of the spatial discharge is the storage device, and in the long run most of the energy stored in the storage device (including the recovered energy) is injected into the discharge between the electrodes.

As the ionization cross section σ for small electron energies is much greater than for high energies (for example, in nitrogen, $\sigma = 3 \cdot 10^{-16}$ cm^2 for $U_B = 100$ eV, while $\sigma = 10^{-19}$ cm^2 for $U_B = 1$ MeV), the beam decelerated by the retarding electric field causes enormously more ionization in the gas than a conventional high-energy beam. Accordingly, we can expect larger discharge current densities than in conventional setups.

The secondary electrons move under the action of the electric field toward the anode, exciting the gas molecules in the process and determining the magnitude of the discharge current. Beam electrons that have given up their kinetic energy drift in the same direction. Most of the beam electrons are unable to reach the cathode, so that the part of the discharge gap immediately in front of the cathode remains initially weakly ionized. However, as a result of the redistribution of the electric field in the discharge gap, the field intensity in the cathode region increases and subsequently exceeds the ionization threshold of the gas; the latter breaks down, becoming in effect an unlimited emitter of electrons, as in the case of the conventional electrically excited preionization discharge [2]. The magnitude of the electric field intensity in the discharge gap is determined by the electrode spacing l. By varying l, it is possible to vary E/p over a wide range. At low values of E/p the vibrational levels of the gas molecules will be efficiently excited; at high values of E/p, the electronic levels will be efficiently excited.

In the setup shown in Fig. 1, the coaxial storage device, which was filled with transformer oil, was charged to 300 kV at a stored energy of 10 J. The storage device was charged from a pulse transformer 5 using coupled circuits. When the voltage across the storage device was at its positive peak, an oil spark gap 6 of needle-and-plane type operating on self-breakdown was triggered. The triggering voltage jitter did not exceed 10%, which is very important for reproducibility of the experiments.

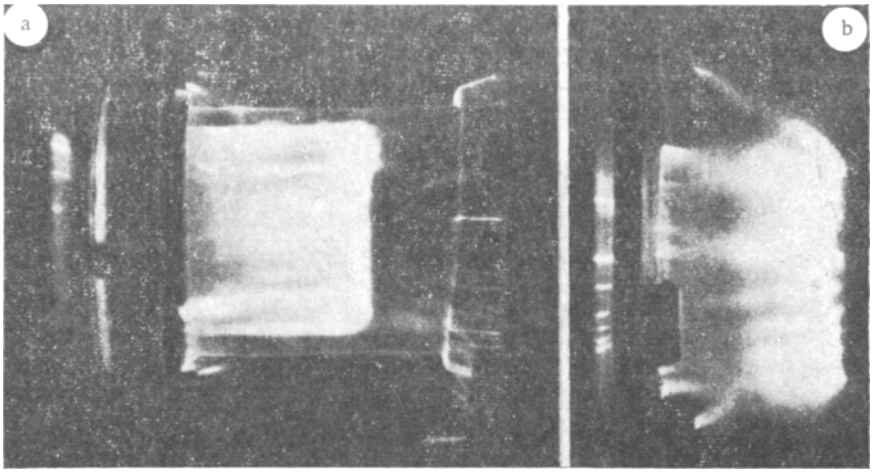

Fig. 3

The vacuum in the accelerator tube was $\sim 10^{-4}$ mm Hg. The tubular cathode is made from niobium foil of thickness 10 μ and diameter 10 mm; the anode is made from titanium foil of thickness 50 μ and diameter 50 mm. The length of the accelerating gap is ∿1 cm.

The discharge chamber is a 60-mm-diameter glass tube 7. The cathode of the discharge chamber has the form of a Rogowski electrode made from stainless steel. The length l of the discharge gap can be varied from 2 to 10 cm. The discharge chamber is supplied with air at atmospheric pressure.

The cathodes of the accelerator tube and the discharge chamber are connected by low-inductance low-resistance shunts R_{sh} with the grounded chassis of the storage device. The signals from the shunts are recorded by oscilloscopes. The discharge current of the storage device I_Σ is measured by the pulse current transformer 8 described in [11]. The voltage across the storage device U_S is measured by a capacitance divider 9. The voltage on the anode U_D is measured by a resistive divider, the high-voltage arm of which is made from a rubber tube filled with a solution of copper sulfate.

Typical oscillograms of the anode voltage U_D and of the currents in the system are shown in Fig. 2. The beam current I_B, measured by shunt R_{sh_1}, did not exceed 0.5 kA. The discharge current I_D, measured by shunt R_{sh_2}, reached 1.5 kA. The total discharge current of the storage device, measured by the pulse current transformer, reached 2 kA.

In the present method, the electron-beam utilization coefficient can no longer be defined as the ratio of the energy injected into the gas by the discharge to the energy carried by the beam, as the latter, on account of recovery, is returned to the storage device and, in the long run, is also injected into the gas. When recovery is taken into account, the electron-beam utilization coefficient K defined by (3) reduces to infinity. If we introduce K as the ratio of the energy injected into the gas to the difference between the energy expended on producing the beam and the energy given up by the beam in the discharge chamber as a result of recovery and interaction with the gas, then this definition will duplicate the concept of the efficiency of an accelerator tube. In addition to the energy losses in the accelerator tube, energy losses also exist in the other elements of the system. Accordingly, it is meaningful to talk about the efficiency of the entire system, defining it as the ratio of the energy injected into the gas to the energy stored in the storage device. This quantity can be expressed approximately in the form

$$K = \int_0^{\tau_D} I_D U_D dt \Big/ \frac{1}{2} C U_s^2, \tag{4}$$

where C is the capacitance of the storage device; U_S is the voltage to which the storage device is charged. Graphical integration of the oscillograms and calculations via formula (4) showed that the efficiency of the entire system reached 50%.

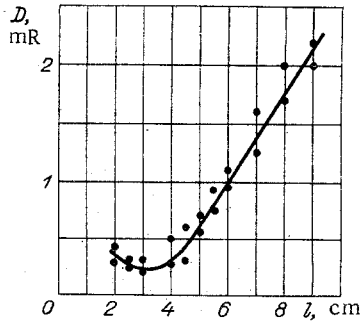

Fig. 4

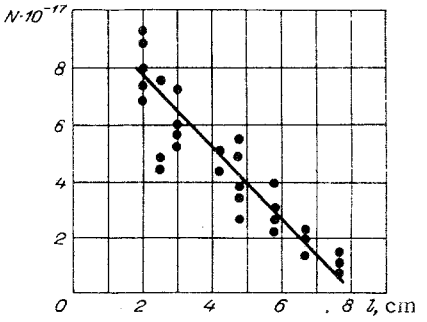

Fig. 5

The discharge in the discharge chamber was observed visually and was photographed. A thin brightly glowing layer was located directly at the cathode. After it there was a diffuse (thickness up to 2 cm) glowing layer, clearly visible on the photographs of the discharge glow (Fig. 3a, discharge in glass tube; Fig. 3b, discharge in air without glass tube; length of discharge gap, 6 cm). The rest of the region between the electrodes gave off a weak violet glow. Weak streamers are evident on the background of the glow from the spatial discharge; they did not, however, go over into a spark discharge. The brightness of the glow from the gap was much less than the brightness of the spark of a self-sustained discharge struck in the same gap (this was done for purposes of comparison with the explosive-emission cathode removed and with no electron beam).

The glow picture described above can be interpreted in the following manner. The thin brightly glowing layer at the cathode is an unlimited emitter of electrons. The ionic conductivity in the rest of the volume of the system, and the magnitude of the emission is automatically maintained at a level prescribed by the conductivity of the remaining volume of gas [2]. The layer of thickness up to 2 cm following the layer at the cathode is probably of the same nature as the negative glow of a glow discharge. The nonuniform ionization of the gas by the electron beam from the accelerator tube gives rise to large gradients of electron density in the gas, and a redistribution of potential along the discharge gap occurs. A considerable drop of voltage results across the near-cathode region of thickness $\sim$1 cm that is weakly ionized by the electron beam. Electrons emitted by the near-cathode layer are accelerated in this region. The accelerated electrons are responsible both for exciting the electronic levels of the gas molecules and for ionizing the gas. The glow that is observed from the layer of thickness up to 2 cm is in fact due to the interaction of the accelerated electrons with the gas. In the weakly glowing region near the anode it would appear that the field intensity is not so high, and the energies of the discharge electrons are sufficient here only for exciting the vibrational levels of the molecules. This region is the positive column of the discharge.

The extent of the region of weak violet glow decreased with increasing length l of the discharge gap, while the thickness of the glowing cathode layer remained almost unchanged, only slightly increasing. At small values of l, a mean electric field intensity of above 100 kV/cm was achieved without the spatial discharge going over into a spark discharge.

Figure 4 shows the dependence on l of the integrated dose of x-ray emission recorded by a DK-0.2 dosimeter located at a distance of 0.5 m from the discharge chamber. The source of the emission, the target in this experiment, was the air of the discharge gap and the anode foil. The x-ray emission is generated due to the deceleration of the electron beam from the accelerator tube as a result of collisions with air molecules. However, some of the energy of the electron beam is removed by the opposing electric field, which also decelerates the beam. Evidently, if electrode 4 of the discharge chamber is removed to infinity, the opposing field will equal zero, and all the energy of the beam will go on ionizing the gas.

In this case the dose of x-ray emission will be at its greatest. With decreasing l the intensity of the opposing field increases, more and more beam energy is removed by the field, and a steadily decreasing proportion of the energy goes on ionizing the gas. The dose of x-ray emission decreases correspondingly. Although the total ionization on the entire length of the electron mean free path in the gas actually decreases with increasing opposing field, the specific ionization per unit length of the mean free path increases substantially due to the increase in the ionization cross section with decreasing electron energy. Accordingly,

the decrease in the dose of emission with decreasing l does not contradict what has been said above. The minimum in the emission dose at $l \approx 3$ cm probably comes about because at $l < 3$ cm the field intensity exceeds 100 kV/cm, an intense "running away" of the electrons in the field occurs, and they bombard the anode foil from the discharge chamber side, so giving rise to additional x-ray emission for $l < 3$ cm [12].

A chemical analysis was made of the gas in the discharge chamber. Ozone and oxides of nitrogen (NO and NO_2) were detected. The analysis was performed on a chromatograph and also by the photocalorimetric method.

Also, the formed oxides of nitrogen were dissolved in hydrogen peroxide and the resultant solution titrate. Figure 5 shows the dependence on l determined by titration of the number of molecules of oxides of nitrogen formed per discharge. It can be seen that the yield of nitrogen oxides probably increases linearly with decreasing discharge gap l. The quantity of energy injected into the gas is probably little dependent on the length of the discharge gap l, since in the long run all the energy of the storage device, except for losses dependent on the efficiency of the system, is injected into the discharge.

Accordingly, as l is reduced for a fixed energy in the storage device, the specific energy injected into the gas increases linearly, although the power of the discharge increases as $1/l^2$. This means that with decreasing l the duration of the discharge decreases. At the minimum gap $l = 2$ cm the quantity Q did not exceed 0.2 J/cm^3 • atm, the mean field intensity amounted to 150 kV/cm, and the energy yield of the reactions of oxidizing nitrogen was 3 molecules at 100 eV. At a gap of $l = 8$ cm, Q did not exceed 0.05 J/cm^3 • atm, and the energy yield of nitrogen oxides amounted to 0.37 molecules at 100 eV at a mean electric field intensity of 37.5 kV/cm.

In this manner, the energy yield of nitrogen oxides is observed to increase with increasing Q and E/p.

The obtained yields of nitrogen oxides are no worse than the yields obtained in the oxidation of nitrogen in a normal non-self-sustained discharge with excitation of the vibrational levels of the gas molecules (see [3], for example). At values of E/p > 30 kV/cm • atm it is the electronic levels of the molecules that are excited and not the vibrational levels. We may thus conclude that the oxidation of nitrogen in a spatial discharge which excites the electronic levels of the molecules occurs no less efficiently than in discharges which excite the vibrational levels. In the method described above, however, there is the possibility of increasing the specific energy injected by the discharge into the gas over and above the values obtained in the normal electrically excited preionization discharge.

High values of the specific energy injected into the gas were not obtained in the experiments described above as the energy stored in the storage device was inadequate. The experiments demonstrated, however, the capabilities and prospects of the system.

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EVOLUTION OF A ONE-DIMENSIONAL MAGNETOSONIC SOLITON

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It is well known that the hydrodynamic equations for cold electrons and ions ($nmc^2 \gg H^2/8\pi \gg nT$) have a solution in the form of a steady-state solitary wave (soliton) [1].

In the present work we investigate the stability of a flow of this sort with respect to electron perturbations of helicon type [2]. The stability of solitons in the Korteweg–de Vries approximation has been investigated by Kadomtsev and Petviashvili [3], who showed that a weak MHD soliton is stable against negative-dispersion perturbations.

We start from the equations of two-fluid hydrodynamics in the quasineutrality approximation $n_e = n_i$:

$$m_e \frac{d\mathbf{v}_e}{dt} = -e\mathbf{E} - \frac{e}{c}[\mathbf{v}_e\mathbf{H}]; \tag{1}$$

$$m_i \frac{d\mathbf{v}_i}{dt} = e\mathbf{E} + \frac{e}{c}[\mathbf{v}_i\mathbf{H}]; \tag{2}$$

$$\operatorname{rot}\mathbf{H} = \frac{4\pi en}{c}(\mathbf{v}_i - \mathbf{v}_e); \tag{3}$$

$$\operatorname{rot}\mathbf{E} = -\frac{1}{c}\frac{\partial \mathbf{H}}{\partial t}; \tag{4}$$

$$\frac{\partial n}{\partial t} + \operatorname{div}(n\mathbf{v}) = 0. \tag{5}$$

Allowing for electron inertia in the lowest order in the parameter $m_e/m_i \ll 1$, Eqs. (1)–(5) can be used to construct a one-dimensional magnetosonic soliton whose magnetic field $H_z = H_0[1 + h(x - ut)]$ is described by the equation [1]:

$$\pm a\frac{dh}{dx} = \frac{h}{1 - \dfrac{h + h^2/2}{M^2}}\sqrt{1 - \frac{(2+h)^2}{4M^2}},$$

where

$$a^2 = \frac{m_e c^2}{4\pi e^2 n_0}; \quad M^2 = \frac{u^2}{H_0^2/4\pi n_0 m_i}; \quad u^2 = \frac{(H_0 + H_{\max})^2}{16\,\pi n_0 m_i}.$$

The density n and longitudinal velocity of the soliton v_x are then given by

$$n = \frac{n_0 u}{u - v_x}, \quad v_x = u\frac{h + h^2/2}{M^2}.$$

We now investigate the stability of the soliton with respect to perturbations, the frequency of which is large: $\omega_{He} > \omega \gg u/a$.

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