



---

Soviet-era science, translated into English

# Physics

S. R. Kholev and D. S. Poltavchenko

1960

SovietRxiv

---

View the original and related papers at <https://sovietrxiv.org/items/ru-196001.47218>

Source: Math-Net.Ru and CyberLeninka. Machine translation. Verify with the original.

Fig. 1

Figure 1: Fig. 1

**Abstract****Full Text***Physics***S. R. Kholev and D. S. Poltavchenko****ACCELERATION OF DISCHARGE PLASMA  
AND THE PRODUCTION OF STRONG  
SHOCK WAVES IN A CHAMBER WITH  
COAXIAL ELECTRODES***(Presented by Academician Ya. B. Zel'dovich on 9 XI 1959)*

1. In a number of experimental works ((<sup>1-8</sup>) and others), various methods of accelerating plasma during its interaction with an electromagnetic field have been investigated. The idea of the plasma-acceleration method considered below consists in a comparatively long-lasting (for example, over one or several periods of the current) interaction of the radial discharge current with a concentric magnetic field. The aim of the work was not only to investigate the method of plasma acceleration, but also to obtain strong shock waves. In this case a peculiar redistribution of energy can take place: gas compressed by the accelerated plasma can itself be transformed into plasma with an even higher temperature.

**Fig. 1.**  $E$  –accelerating electrodes;  $P$  and  $P_1$  –spark gaps;  $C_1$  –initiating capacitor;  $T$  –pulse transformer;  $a-a$  –point of connection of the transformer to the spark gap  $P$

The accelerating device was made in the form of two coaxial cylindrical electrodes (Fig. 1A): a central rod and a tube. When the capacitor bank  $C$  is discharged, a current flows in the circuit, the direction of which is shown in Fig. 1A by arrows. The radial discharge current  $\mathbf{I}$  interacts with the concentric magnetic field  $\mathbf{H}$  of the central electrode. The ponderomotive force that arises as a result,  $\mathbf{F} = [\mathbf{I}\mathbf{H}]$ , regardless of the direction of the current, is always directed toward the outlet from the accelerating electrodes. Thus, the magnetic field must act on the discharge plasma like a piston.

Without clarifying the concrete picture of the interaction of the magnetic field of the accelerating electrodes with the current flowing in the gas, one can determine the force acting on the plasma when the inductance of the discharge circuit  $L$

increases with the simultaneous increase in the mass of the moving portion of the circuit. In this case the equation of motion can be written as:

$$\frac{d}{dt}(mv) = \frac{1}{2}I^2(t)\frac{dL}{dx}, \quad (1)$$

where  $m$  is the mass of the accelerated gas (in Fig. 1);  $v$  is its velocity;  $dL/dx = b$  is the inductance of the accelerating electrodes per unit length. The oscillogram of the discharge current can, with good accuracy, be approximated by the expression

$$i = Ae^{-Bt} \sin \omega t. \quad (2)$$

The constants  $A$ ,  $B$ , and the angular frequency  $\omega$  are determined from the oscillograms.

Let

$$m = m_0 + kx, \quad (3)$$

where  $m_0$  and  $k$  are constants. Then from (1) and (2) we have

$$\frac{d}{d\tau} \left[ (m_0 + kx) \frac{dx}{d\tau} \right] = \frac{bA^2}{2\omega^2} e^{a\tau} \sin^2 \tau, \quad (4)$$

where  $\tau = \omega t$ ;  $a = -2B/\omega$ . Integration of (4), taking into account the initial conditions ( $x = 0$ ,  $v = 0$  at  $t = 0$ ), gives:

$$(m_0 + kx) \frac{dx}{d\tau} = \varphi(\tau); \quad (5)$$

$$v = \omega \frac{dx}{d\tau} = \frac{\omega \varphi(\tau)}{\sqrt{m_0^2 + 2k \left[ \int \varphi(\tau) d\tau - C \right]}}. \quad (6)$$

Here

$$\varphi(\tau) = \frac{A^2 b}{2\omega^2(a^2 + 4)} \left[ e^{a\tau} \left( a \sin^2 \tau - \sin 2\tau + \frac{2}{a} \right) - \frac{2}{a} \right];$$

$$C = \frac{A^2 b(3a^2 + 4)}{a^2 \omega^2 (a^2 + 4)^2}. \quad (7)$$

Fig. 2

Figure 2: Fig. 2

Fig. 3

Figure 3: Fig. 3

2. In the experiments, Plexiglas cylindrical chambers with an internal diameter from 2 to 5 cm and a length from 50 to 90 cm were used. The accelerating electrodes were made of brass, steel, or duralumin. The capacitance of the banks in different series of experiments was 150, 600, and 2400  $\mu\text{F}$  at an initial voltage of 5-6 kV. The circuit for initiating the discharge is clear from Fig. 1.

**Fig. 2.**  $V = 5 \text{ kV}$ ,  $C = 150 \mu\text{F}$ ,  $D = 36.4 \text{ km/sec}$ ,  $p_1 = 0.08 \text{ mm Hg}$ .

The experiments were carried out with air in the pressure range 0.02-0.75 mm Hg under continuous pumping. The accuracy of the pressure measurement was of the order of 10%. Streak photography of the process of plasma propagation in the chamber and measurement of the velocity were performed with an SFR-2M photochronograph. The error in the velocity measurement was no more than 5%.

To record current oscillograms, the voltage from a low-inductance resistor ( $1.5 \cdot 10^{-3} \Omega$ ,  $1.5 \cdot 10^{-11} \text{ H}$ ), connected into the discharge circuit, was applied to the plates of an OK-17M oscilloscope.

3. Figure 2 shows a typical streak photograph of the self-luminosity of the process in a small chamber (diameter 2 cm). Next to it is shown a diagram of the arrangement of the chamber and the accelerating electrodes. The conical expansion in the lower part of the chamber was made to facilitate breakdown conditions at low pressures.

The most characteristic feature of the streak photographs with accelerating electrodes is the ejection of discharge plasma from the interelectrode region and its acceleration during motion between the electrodes. The experimental conditions are given in the figure. The leading front of the luminous flow under these conditions is a shock wave. The cause of the appearance of such a powerful shock wave ( $M = 110$  at the exit from the accelerating electrodes) is

**Fig. 3**

**Fig. 4.**  $V = 5 \text{ kV}$ ,  $C = 2400 \mu\text{F}$ ,  $I = 560 \text{ kA}$ .  
1- $p = 0.43 \text{ mm Hg}$ ; 2- $p = 0.19 \text{ mm Hg}$ .

Fig. 4

Figure 4: Fig. 4

the accelerated motion of the discharge plasma, clearly visible in the photographs. The existence of a rear boundary of the accelerating plasma is essential. The acceleration of this rear boundary apparently occurs owing to the existence of a strong magnetic field, which acts on the plasma like a piston. Between 12 and 13  $\mu\text{sec}$  the current reaches a maximum ( $\sim 70$  kA for the experiment under consideration); the magnitude of the magnetic field at this time in the region behind the plasma is  $\sim 20$  kG. A sharp acceleration of the rear boundary of the plasma at this time is clearly visible.

In Fig. 3, 1 shows the effect of plasma acceleration in a chamber of diameter 5 cm at  $C = 600 \mu\text{F}$ . The heavy portions of curves *I* and *III* denote the period of motion of the shock-wave front between the electrodes. Curve *II* represents the result of an experiment under the same conditions but without the external accelerating electrode (instead of it, a ring remained at the base of the electrodes), when the described mechanism of plasma acceleration does not operate. Also shown is the current dependence  $I(t)$ , phased with the velocity curves, for 5 kV (curve *IV*). Curve *III* was calculated by formula (6) for values of the constants determined from current oscillograms:  $A = 1.97 \cdot 10^3$  A,  $a = -0.139$ ,  $\omega = 1.26 \cdot 10^5 \text{ s}^{-1}$ , and the known value  $b = 3.4 \cdot 10^{-9}$  H/cm. The constants  $m_0$  and  $k$  entering this formula were determined as follows. Directly from equation (5), using the known value of the velocity for a given instant of time, the value  $m = m_0 + kx$  was determined. The instant of time was chosen so that the plasma was still moving between the electrodes, but the acceleration was equal to zero. For the case shown in Fig. 3 this condition was satisfied by the point  $t = 10 \mu\text{s}$  ( $\tau = 1.26$ ). For this point ( $d^2x/dt^2 = 0$ ), from (4) we have

$$k = \frac{bA^2}{2v^2} e^{a\tau} \sin^2 \tau. \quad (8)$$

Knowing  $k$  and  $m$ , from (3) we determine the value of the initial mass  $m_0$ . The constants thus determined in the case under consideration are:  $m_0 = 2.2 \cdot 10^{-5}$  g,  $k = 2.84 \cdot 10^{-5}$  g/cm. For comparison we note that under these conditions (initial pressure 0.18 mm Hg) the mass of air corresponding to 1 cm (of the order of the breakdown width) of chamber length ( $\sim m_0$ ) is  $2.16 \cdot 10^{-6}$  g. If it is assumed that the accelerated mass increases only through the inflow of gas through the shock-wave front, then  $k = 2.16 \cdot 10^{-6}$  g/cm. The large value of the experimentally determined values of  $m_0$  and  $k$  is apparently explained by a considerable inflow of material from the electrodes (<sup>9</sup>).

In experiments with a capacitor bank of 2400  $\mu\text{F}$ , somewhat higher velocities were obtained at a comparatively high pressure. The results of these experiments are presented in Fig. 4. Here it should be noted that there is a significant acceleration of the plasma as it moves between the accelerating electrodes, along with noticeable attenuation after it emerges from them.

### Table 1

$D$ , km/sec	$M$	$p_1$ , mm Hg	$T_2$ , °K	$p_2$ , atm	$\rho_2/\rho_1$	$n_e$ , cm <sup>-3</sup>
<b>I.</b>	<b>I.</b>	<b>I.</b>	<b>I.</b>	<b>I.</b>	<b>I.</b>	<b>I.</b>
$C = 600$	$C = 600$	$C = 600$	$C = 600$	$C = 600$	$C = 600$	$C = 600$
$\mu\mathbf{F}$ ,	$\mu\mathbf{F}$ ,	$\mu\mathbf{F}$ ,	$\mu\mathbf{F}$ ,	$\mu\mathbf{F}$ ,	$\mu\mathbf{F}$ ,	$\mu\mathbf{F}$ ,
$V = 5$	$V = 5$	$V = 5$	$V = 5$	$V = 5$	$V = 5$	$V = 5$
<b>kV</b> ,	<b>kV</b> ,	<b>kV</b> ,	<b>kV</b> ,	<b>kV</b> ,	<b>kV</b> ,	<b>kV</b> ,
$I = 158$	$I = 158$	$I = 158$	$I = 158$	$I = 158$	$I = 158$	$I = 158$
<b>kA</b>	<b>kA</b>	<b>kA</b>	<b>kA</b>	<b>kA</b>	<b>kA</b>	<b>kA</b>
<b>A.</b>	<b>A.</b>	<b>A.</b>	<b>A.</b>	<b>A.</b>	<b>A.</b>	<b>A.</b>
<b>With</b>	<b>With</b>	<b>With</b>	<b>With</b>	<b>With</b>	<b>With</b>	<b>With</b>
<b>acceler-</b>	<b>acceler-</b>	<b>acceler-</b>	<b>acceler-</b>	<b>acceler-</b>	<b>acceler-</b>	<b>acceler-</b>
<b>ation</b>	<b>ation</b>	<b>ation</b>	<b>ation</b>	<b>ation</b>	<b>ation</b>	<b>ation</b>
32	97.5	0.75	40 000	14	12.4	10 <sup>17</sup>
43	130	0.18	55 000	5.4	~ 13	~ 10 <sup>16</sup>
46	140	0.07	50 000	~ 2	~ 14	~ 10 <sup>16</sup>
49	148	0.02	~ 50000	~ 1	~ 14-15	~ 10 <sup>15</sup> -10 <sup>16</sup>
55 (6 kV)	167	0.02	~ 55000	~ 1	~ 14-15	~ 10 <sup>15</sup> -10 <sup>16</sup>
<b>B.</b>	<b>B.</b>	<b>B.</b>	<b>B.</b>	<b>B.</b>	<b>B.</b>	<b>B.</b>
<b>With-</b>	<b>With-</b>	<b>With-</b>	<b>With-</b>	<b>With-</b>	<b>With-</b>	<b>With-</b>
<b>out</b>	<b>out</b>	<b>out</b>	<b>out</b>	<b>out</b>	<b>out</b>	<b>out</b>
<b>acceler-</b>	<b>acceler-</b>	<b>acceler-</b>	<b>acceler-</b>	<b>acceler-</b>	<b>acceler-</b>	<b>acceler-</b>
<b>ation</b>	<b>ation</b>	<b>ation</b>	<b>ation</b>	<b>ation</b>	<b>ation</b>	<b>ation</b>
20	61	0.70	25 000	5	13	5 · 10 <sup>16</sup>
21	64	0.18	~ 25000	~ 1	~ 14.5	~ 6 · 10 <sup>15</sup>
28	85	0.03	~ 30000	~ 1	~ 14	~ 10 <sup>14</sup>
<b>II. <math>C =</math></b>	<b>II. <math>C =</math></b>	<b>II. <math>C =</math></b>	<b>II. <math>C =</math></b>	<b>II. <math>C =</math></b>	<b>II. <math>C =</math></b>	<b>II. <math>C =</math></b>
2400	2400	2400	2400	2400	2400	2400
$\mu\mathbf{F}$ ,	$\mu\mathbf{F}$ ,	$\mu\mathbf{F}$ ,	$\mu\mathbf{F}$ ,	$\mu\mathbf{F}$ ,	$\mu\mathbf{F}$ ,	$\mu\mathbf{F}$ ,
$V = 5$	$V = 5$	$V = 5$	$V = 5$	$V = 5$	$V = 5$	$V = 5$
<b>kV</b> ,	<b>kV</b> ,	<b>kV</b> ,	<b>kV</b> ,	<b>kV</b> ,	<b>kV</b> ,	<b>kV</b> ,
$I = 560$	$I = 560$	$I = 560$	$I = 560$	$I = 560$	$I = 560$	$I = 560$
<b>kA</b>	<b>kA</b>	<b>kA</b>	<b>kA</b>	<b>kA</b>	<b>kA</b>	<b>kA</b>
<b>With</b>	<b>With</b>	<b>With</b>	<b>With</b>	<b>With</b>	<b>With</b>	<b>With</b>
<b>acceler-</b>	<b>acceler-</b>	<b>acceler-</b>	<b>acceler-</b>	<b>acceler-</b>	<b>acceler-</b>	<b>acceler-</b>
<b>ation</b>	<b>ation</b>	<b>ation</b>	<b>ation</b>	<b>ation</b>	<b>ation</b>	<b>ation</b>
54	164	0.43	75 000	20	12	2 · 10 <sup>17</sup>
82	248	0.19	130 000	19	~ 13	~ 10 <sup>16</sup>

Table 1 gives the equilibrium parameters of the air behind the shock wave for several typical experiments.  $D$  is the velocity of the shock-wave front at the exit from the accelerating electrodes;  $M$  is the Mach number, equal to  $D/a$ ,

where  $a = 0.33$  km/sec;  $p$  is pressure;  $T$  is temperature;  $\rho$  is density; subscript 1 refers to the undisturbed gas, 2 to the gas behind the shock-wave front;  $n_e$  is the electron concentration.

The calculation was made from the measured velocity of the shock wave at the exit from the accelerating electrodes, using the data of Ref. <sup>10</sup> for our experimental conditions. The sign  $\sim$  indicates that the given quantity has been estimated with an accuracy of  $\pm 50\%$ . We emphasize that the question of the equilibrium of the gas parameters behind the shock wave under our conditions has not yet been resolved, and the data in Table 1 are given only for estimation.

4. Thus, the results of the experiments confirmed the effectiveness of the proposed method of plasma acceleration. The velocities of the shock waves and of the plasma increased by a factor of 1.5-2 in comparison with those obtained under the same conditions without accelerating coaxial electrodes, and reached 30-80 km/sec at initial air pressures of 0.7-0.02 mm Hg and an initial voltage of 5 kV. It should be noted, however, that hydrodynamic forces, as is evident from the experiments without accelerating electrodes, also play a significant role.

The use of hydrogen as the accelerated gas should lead to an increase in the velocities of plasma motion both because of the decrease in molecular weight and as a result of the reduction of ionization losses.

The authors express their gratitude to A. S. Predvoditelev for his attention to the work and to Ya. B. Zel' dovich for valuable comments during preparation of the article for publication.

Moscow State University  
named after M. V. Lomonosov

Received  
6 XI 1959

## References

1. W. H. Bostick, Phys. Rev., **104**, 292, 1191 (1956).
2. L. A. Artsimovich, S. Yu. Luk' yanov, I. M. Podgorny, S. A. Chuvatin, ZhETF, **33**, 3 (1957).
3. A. Kolb, Phys. Rev., **107**, 345, 1197 (1957).
4. A. Kolb, Phys. Rev., **112**, 291 (1958).
5. S. Kesh, Collection *Magnetohydrodynamics*, 1958, p. 98, 105.
6. V. J. Josephson, J. Appl. Phys., **29**, 30 (1958).

7. I. S. Shpigel, ZhETF, **35**, 411 (1959).
8. N. A. Borzunov, D. V. Orlinskii, S. M. Osovets, ZhETF, **36**, 717 (1959).
9. I. G. Nekrashevich, I. A. Bakuto, *Engineering Physics Journal*, No. 8, 59 (1959).
10. V. V. Selivanov, I. Ya. Shlyapintokh, ZhFKh, **32**, 670 (1958).

*Note: Figure translations are in progress. See original paper for figures.*

*Source: Math-Net.Ru and CyberLeninka. Machine translation. Verify with the original.*