where $\lambda = 1/\tau_0 = 7 \times 10^6$ sec^{-1}, τ is the time interval within which the Mossbauer spectrum is measured (60 nsec or ∞ in our experiments), $P_{(\tau)}$ is the fraction of the Co decay in the Fe^{2+} state and decreases from $P_{(0)}$ to $P_{(0)}\lambda(\lambda + K)^{-1}$ in the time τ. It is natural to assume $P_{(0)}$ equal either to unity, since the initial form of the Co^{57} isotope is taken in the form Co^{2+}, or to the fraction ($\sim$0.5) of the Fe^{2+} doublet in the emission GR spectrum of $Co^{2+}[Fe^{II}(CN)_6]^{4-}$ (see Fig. a), i.e., for a compound in which there is no transfer of the electron to the intraspherical iron. Experiments yielded P(60 nsec) = 0.37 ± 0.10 and $P_{(\infty)} = 0.07 \pm 0.014$. We obtain $K \simeq 10^8$ sec^{-1} or $K \simeq 5.5 \times 10^7$ sec^{-1} (T = 80°K) for $P_{(0)} = 1$ and $P_{(0)} = 0.5$, respectively.

The intramolecular electron transfer times are of the order of 10 - 20 nsec and are too short to be attributed to a simple tunnel transition without realignment of the forms of the two potential wells, i.e., to a random superposition of two very narrow ($\sim 10^{-7}$ eV) electronic levels. A more natural assumption is that the transition of the electron from an excited level in a narrow well (Fe^{2+}) to various levels in a deeper well ($[Fe^{III}(CN)_6]^{3-}$) is of the activation-tunneling type. A rough estimate of the activation energy of such a process (if the pre-exponential factor is $10^{13} - 10^{15}$ sec^{-1} and T = 80°K) yields E $\simeq$ 0.08 - 0.1 eV, which agrees with the estimate given in [6].

Additional information on the intramolecular transfer of electrons can be obtained from GRS studies, with the delayed $\gamma\gamma$ coincidence technique, of similar compounds at temperatures both above 80°K and, most importantly, below 80°K.

[1] C.S. Wu, Y.K. Lee, N. Benczer-Koller, and P.C. Simms. Phys. Rev. Lett. 5, 432 (1960).
[2] R.E. Holland, F.J. Lynch, C.J. Perlow, and S.S. Hanna, Phys. Rev. Lett. 4, 181 (1960).
[3] B.M. Chadwick and A.G. Sharpe, Advances in Inorg. Chem. and Radiochem., 8, 83 (1966).
[4] W. Triftshauser and D. Schroeer, Phys. Rev. 187, 491 (1969).
[5] W. Triftshauser and P.P. Craig, Phys. Rev. 162, 274 (1967).
[6] D.S. Chernavskii, Usp. Fiz. Nauk 107, 157 (1972) [Sov. Phys.-Usp. 15, No. 3 (1972)].

RADIAL DISTRIBUTION OF FAST ELECTRON IN A Z PINCH

I.G. Presiantsev, V.D. Pis'mennyi, A.T. Rakhimov, and A.N. Starostin
Nuclear Physics Institute of the Moscow State University
Submitted 2 June 1972
ZhETF Pis. Red. 16, No. 2, 68 - 72 (20 July 1972)

Two decades after the observation of hard radiation [1] there is still no convincing explanation of the mechanism whereby charged particles are accelerated in powerful pulsed discharges in rarefied gases. Numerous attempts to offer such an explanation (cf., e.g., [2]) were based on the results of experimental research 10 - 15 years old, when the diagnostic methods for fast processes in a hot plasma did not yield information on the plasma parameters with high temporal and spatial resolution. It is therefore advisable to verify the main features of the phenomenon by modern diagnostic means and to accumulate additional experimental facts.

One of the important premises of the phenomenon in question, one regarded in the literature to be unequivocally established, concerns the localization of the region of acceleration: it is customarily assumed that it occurs near the

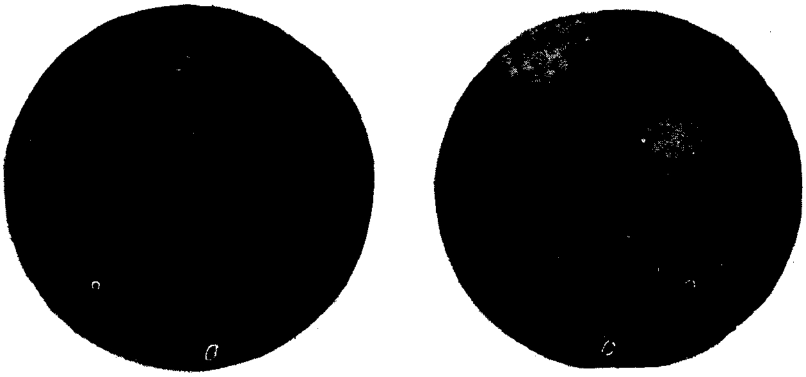


Fig. 1. Photographs of "perforated" anode in light of fast electrons.

axis of the discharge, within a radius of only a few millimeters [3]. The bases of this conclusion were, in particular, measurements of the fluxes of fast electrons extracted from the discharge through collimators placed in the anode along the radius of the discharge tube [4]. Owing to the low sensitivity of the detectors (x-ray film sheathed in aluminum foil), such measurements were inevitably averaged (exposures to 10 discharges).

We used in our experiments a setup analogous to that of [4]. The operating conditions were $C = 60\ \mu F$, $V_0 = 40$ kV, $I_{max} = 500$ kA, period $\sim 20\ \mu sec$. The working gas was hydrogen at an initial pressure 3×10^{-2} mm Hg, purified by passage through a palladium filter. The inside diameter of the alundum chamber was 20 cm and its length was 80 cm.

In the first half-period, the anode is a copper electrode 1.5 mm thick, the central part of which, of 80 mm diameter, is a "sieve" made up of densely and regularly disposed holes of 1.5 mm diameter. Directly behind the anode is an organic-glass screen of 1 mm thickness, coated with a thin terphenyl film and shielded against the visible radiation of the plasma and against electrons of energy lower than 100 keV by an aluminum foil 45 μ thick. The glow of screen was recorded simultaneously with a photographic camera and with an LV-01 electron optical converter, so that multiple-frame photography at a minimum exposure of 50 nsec was possible. The use of a fiber optics system capable of transforming a plane picture into a line and reconstructing the initial picture, has made it possible to employ the LV-01 converter for a photographic study of the time variation of the screen glow, with a resolution not worse than 10 nsec.

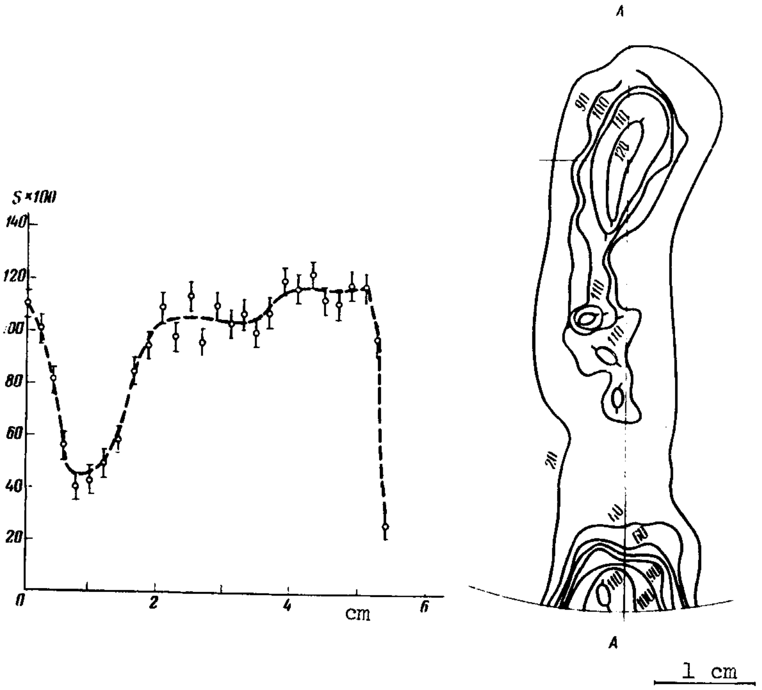
The experiments have demonstrated the following:

1. The generation of fast electrons (above 100 keV); (a) is observed only after a series of "preconditioning" discharges and is not observed if the gas is even slightly contaminated, (b) occurs at the instant of the last of the series of "singularities" in the current (their total number is 3 - 4), (c) lasts from 60 to 150 nsec, and (d) appears and disappears simultaneously (within $\sim$10 nsec) in all the emission regions.

2. The distribution of the fact electrons over the cross section of the discharge chamber: (a) is highly varied and is different for each discharge (Fig. 1), (b) occupies an area from a fraction to several cm^2, (c) has as a rule approximately the same intensity within the limits of each clearly distinguished injection zone.

The last conclusion is illustrated in Fig. 2, which shows the result of a microphotometric reduction of Fig. 1a.

Fig. 2. Micrograms along the line AA and maps of equal-density lines for cases a and b of Fig. 1.



Thus, the fast electrons of the Z pinch have a complicated radial distribution that apparently reflects the instability of the current filament at the instant of the last "singularity," which sets in under the conditions of our experiments some 2.0 - 2.3 μsec after the start of the discharge. This distribution is difficult to understand from the point of view of the acceleration mechanisms discussed in the literature, including the mechanism recently proposed in [5].

As a possible explanation of the described phenomena, let us consider a mechanism of super heat instability, analogous to that developed in [6]. Under the pinch conditions the instability increment is maximal at the instant when the temperatures of the electrons and ions become approximately equal (∿100 eV), which occurs apparently at the last "singularity" of the current. This instability can break up the pinch into current filaments, a fact accompanied by the formation of a large number of neutral magnetic-field lines. For estimating purposes, we write down the nonstationary energy balance equations and continuity equations for the electrons and ions during the cumulation stage (in this stage the pressure of the magnetic field does not exceed the gas-kinetic pressure and can be neglected in the first-order approximation):

$$\frac{\partial}{\partial t}\left(\frac{3}{2}n_kT_k+\frac{n_km_kv_k^2}{2}\right)+\operatorname{div} v_k\left(\frac{5}{2}n_kT_k+\frac{n_km_kv_k^2}{2}\right)=Q_k, \qquad (1)$$

where k = e, i stands for the electrons or ions, respectively,

$$Q_e=\sigma E^2-\frac{2m}{M}\,\frac{n_e(T_e-T_i)}{\tau_{ei}};\quad Q_i=\frac{2m}{M}\,\frac{n_e(T_e-T_i)}{\tau_{ei}};\quad n_e=n_i=n$$

σ is the Coulomb conductivity, τ_{ei} is the time between the electron-ion collisions, $\sim 10^{-10}$ sec, and

$$\frac{\partial n}{\partial t} + \operatorname{div} n\mathbf{v} = 0 . \qquad (2)$$

It is assumed in (1) that the dimension of the current filament is larger than the characteristic dimension of the Coulomb thermal conductivity, $L \gg [\chi(\Omega\tau)^{-2}\gamma^{-1}(M/m)^{1/2}]^{1/2}$; $\chi \sim \ell v_{Te}$, ℓ is the mean free path, v_{Te} is the thermal velocity of the electrons, Ω is their cyclotron frequency, and γ is the increment of the instability under consideration. Estimates show that the energy lost to radiation can be neglected in the case of a pure hydrogen plasma. In the presence of contaminations, the superheat instability may not develop, since the power of the impurity emission line increases with temperature. In addition we shall consider perturbations whose dimension satisfies the condition $L \ll (1/\gamma)\sqrt{T_e/M}$, owing to which the summary pressure of the plasma in the filament remains constant. As a result, in analogy with [6], we obtain the equation

$$\frac{\partial n}{\partial t} = - \frac{2}{5}\frac{n}{p}\sigma E^2 \qquad (3)$$

where $\sigma = \sigma_1 T^{3/2}$ and $p = 2TN$. The solution of this equation is

$$T(t) = T(0)\left(1 - \frac{3}{5}\frac{\sigma_0 E^2}{p} t\right)^{-2/3} \qquad (4)$$

It follows from (4) that $\gamma \sim \sigma_0 E^2/p$, and its order of magnitude for the experimental conditions is $\gamma \sim 10^7 - 10^8$ sec^{-1}, while the characteristic current-filament dimension satisfying the imposed limitations is $L \sim 10^{-2}$ cm. The time of realignment of the magnetic field is $\tau \sim (4\pi\sigma L^2/c^2) \sim (1/\gamma)$.

Estimating the induced electric field connected with the formation of the current filaments and with the appearance of neutral lines of the magnetic field, $E \sim \gamma(Hr/c)$, where r satisfies the condition $L \ll r \lesssim R_0$ (R_0 is the radius of the pinch, $\sim$1 cm), and $H \sim 10^5$ Oe, we obtain $E \sim 10^4 - 10^5$ V/cm. The occurrence of induction fields of this order of magnitude and the formation of a large number of superheated filaments and neutral lines of the magnetic field may explain the experimental data described above.

The authors thank L.A. Artsimovich, A.A. Vedenov, and E.P. Velikhov for supporting the work and numerous discussions, and also A.A. Semenov and M.A. Timofeev for help with the experiments.

[1] L.A. Artsimovich, A.M. Andrianov, E.I. Dobrokhotov, S.Yu. Luk'yanov, I.M. Podgornyi, V.I. Sinitsyn, and N.V. Filippov, Atomnaya Energiya 3, 84 (1956).
[2] M.D. Raizer and V.N. Tsytovich, ibid. 14, 249 (1963).
[3] L.A. Artsimovich, Upravlyaemye termoyadernye reaktsii (Controlled Thermonuclear Reactions), Fizmatgiz, 1963.
[4] N.G. Koval'skii, I.M. Podgornyi, and M.M. Stepanenko, Zh. Eksp. Teor. Fiz. 38, 1439 (1960) [Sov. Phys.-JETP 11, 1040 (1960)].
[5] I.F. Kvartskhava, Yu.V. Matveev, and N.G. Reshetnyak, ZhETF Pis. Red. 15, 619 (1972) [JETP Lett. 15, 437 (1972)].
[6] E.P. Velikhov, I.V. Novobrantsev, V.D. Pis'mennyi, A.T. Rakhimov, and A.N. Starostin, Dokl. Akad. Nauk SSSR 205 (1972).