INVESTIGATION OF FAST ELECTRONS IN POWERFUL PULSED DISCHARGES

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The properties of fast electrons (50 − 300 kev), which produce hard x rays in powerful pulsed discharges, are investigated. The dependence of the peak energy of the electron spectrum on the initial pressure and on the initial voltage is derived. The effect of an external longitudinal magnetic field on the electron energy is studied. The experiments were carried out in hydrogen, deuterium, and inert gases.

INTRODUCTION

IN 1952, hard x rays were observed during the course of investigations devoted to attempts at realizing controllable thermonuclear reactions in high-power gas discharges. In particular, a study was made[1,2] of the basic properties of hard x rays produced in discharges in cylindrical chambers. It was shown later on that the electrons responsible for this radiation are accelerated along the axis of the discharge chamber towards the electrode which is under positive potential at the initial instant of time ("anode"). The maximum energy of the fast electrons diverted from the discharge through the aperture in the "anode" was found to be (300 ± 20) kev at the initial voltage of 40 kv in the discharge chamber.[3]

It is well known[4] that a high-power pulsed discharge in deuterium is accompanied by the emission of neutrons. The neutron emission is due to a group of deuterons accelerated to energies of order 200 kev along the discharge axis towards the "cathode."[5,6] Thus, during the development of a powerful pulsed discharge, strong electric fields are produced and favorable conditions are created for acceleration of charged particles in the axial direction. The occurrence of a non-equilibrium group of fast particles in the plasma is not only of interest in itself, but may be significant in the explanation of the nature of bursts of cosmic radiation. The lack of sufficient experimental material and the complexity of the phenomenon have made it impossible until now to explain fully the mechanism of acceleration of charged particles.

In the present paper we report the results of an investigation of fast electrons produced in a powerful discharge.

EXPERIMENTAL SETUP AND MEASUREMENT PROCEDURE

The construction of the experimental setup is similar in its main outlines to the generators used previously in work on powerful pulsed discharges in cylindrical chambers. The capacitor bank consisted of 12 IM-3/50 capacitors, with a total capacity of 36 μf. The discharges were produced in a porcelain chamber 170 mm in diameter and 1,000 mm long. The discharge chamber was placed in a coaxial feeder. The parisitic inductance of the external circuit amounted to 0.5 microhenry. The capacitor bank could be charged with a high-voltage rectifier to 45 kev. The circuit was closed by applying an igniting pulse to a thyratron. After each discharge, the chamber was pumped out to a high vacuum and filled with a new batch of gas. When working with hydrogen and deuterium, the chamber was filled through a nickel gas-leak valve. In experiments with inert gases, the gases were spectrally pure. The time characteristics of the discharge were investigated by means of a type OK-17M double-beam pulse oscillograph. The current flowing in the main resonant circuit of the pulse generator was measured with a Rogovsky belt with an RL integrating network. In the case of hydrogen, the maximum in the discharge chamber was 200 kiloamp at a pressure of 6×10^{-2} mm Hg and 40 kv on the capacitor bank.

To divert the electron beam from the discharge, a hole was drilled through the center of the "anode." The energy of the electrons accelerated along the axis of the discharge was measured with a direct-deflection spectrograph, located directly behind the hole in the "anode." The electromagnet of the spectrograph was fed with direct current

from a storage battery. The electrons were registered with sensitive Agfa x-ray film, wrapped in aluminum foil 6 micron thick (to protect it against visible light). In the first experiment on the extraction of the fast-electron beam,[3] the exposure amounted to several tens of discharges. In order to reduce the exposure, we decreased considerably the distance from the hole in the electrode to the input slit of the spectrograph. To separate the vacuum volume of the spectrograph from the discharge chamber during the reloading of the film cassette, a special vacuum valve was used. After thorough adjustment of the spectrograph we succeeded in reducing the exposure to three or four discharges, and sometimes even to one discharge.

To determine the electron energy, the x-ray film was exposed without a magnetic field, and then, without changing the film, several discharges were made at 200 oe. This procedure produced on the same film both the energy spectrum of the electrons and a reference line corresponding to the undeflected beam. The density of the film was measured with a MF-4 microphotometer. The spectrograph dispersion curve was obtained by graphically plotting the electron trajectories. By using this curve and by measuring on the microphotogram the distance between the reference line and the boundary of the blackening due to the electrons deflected in the magnetic field, it is easy to obtain the maximum energy of the electron spectrum

The correctness of the plotted electron trajectories was verified with a 100-kev electron beam. In addition, the spectrograph was calibrated against the blackening of the film by the electrons ''shot through'' at the beginning of the discharge. At a pressure of 1.5×10^{-2} mm Hg and an exposure of one or two discharges, these electrons produce on the x-ray film a black sharp line. The energy of the electrons, obtained by measuring the difference in potentials, coincided within 3% or 4% with the energy obtained from the dispersion curve. In determining the end-point energy of the electron spectrum, an additional error of approximately 3% must be taken into account, due to the fact that the boundary of the blackened part of the x-ray film is somewhat smeared. The overall relative error in the determination of the end-point energy of the electron spectrum did not exceed 8%.

The instant at which the electron pulse occurs and its relative intensity under different initial discharge conditions was determined by a scintillation recorder feeding an oscillograph, the second beam of which recorded the discharge-current curve. In these experiments the hole in the
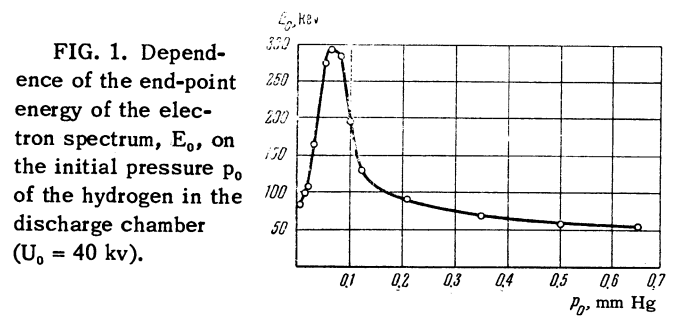

FIG. 1. Dependence of the end-point energy of the electron spectrum, E_0, on the initial pressure p_0 of the hydrogen in the discharge chamber ($U_0 = 40$ kv).

''anode'' was covered with a 6-micron aluminum foil. Located behind the foil was a luminescent stilbene crystal. To reduce the sensitivity to the hard x rays, a thin crystal (approximately 1 mm) was used. The optical connection between the crystal and the FÉU-19 photomultiplier was provided by a light pipe of organic glass.

MEASUREMENT RESULTS

1. The dependence of the end-point energy of the electron spectrum on the initial hydrogen pressure p_0 in the discharge chamber was determined with the direct-deflection magnetic spectrograph described above. The experiments were carried out with p_0 ranging from 4×10^{-3} to 6×10^{-1} mm Hg (the gas in the discharge chamber did not break down at $p_0 < 4 \times 10^{-3}$ mm Hg). A capacitor-bank voltage U_0 of 40 kv was used in these experiments. The dependence of the electron end-point energy E_0 on the pressure p_0 is shown in Fig. 1. The energy E_0 was determined by averaging the results of five individual experiments (the dispersion of the results of the individual experiments did not exceed 8% for each value of p_0). As can be seen from Fig. 1, when p_0 ranges from 2×10^{-2} to 1.3×10^{-1} mm Hg there is a sharply pronounced maximum, in which the electron energy reaches 295 kev.

The dependence obtained is similar to the dependence of the neutron yield on the initial pressure in discharges in deuterium, but differs somewhat from the corresponding dependence for the intensity of the hard x rays. This is apparently due to the fact that the electrons and deutrons, being accelerated in the same electric fields, acquire identical energies. The yield of neutrons depends exponentially on the energy of the deuterons accelerated along the discharge axis:[7]

$$\sigma_{dd} = (288/E_d)\exp[-45.8E_d^{-1/3}],$$

where σ_{dd} is the cross section of the (d,d) reaction in barns, while E_d is the deuteron energy in kev. At electron energies not greater than 500 kev the yield of x-ray quanta is, as is well known, di-

rectly proportional to the electron energy. As a result, with p_0 greater than 7×10^{-2} mm Hg, when the energy of the charged particles accelerated along the discharge axis diminishes rapidly, the neutron yield diminishes much more rapidly than the intensity of the hard x rays.
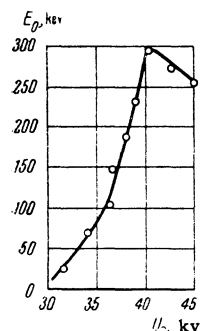

FIG. 2. Dependence of the end-point energy E_0 on the initial voltage U_0 ($p_0 = 7 \times 10^{-2}$ mm Hg).

FIG. 3. Dependence of the end-point energy E_0 on the intensity of the external longitudinal magnetic field H ($p_0 = 7 \times 10^{-2}$ mm Hg; $U_0 = 40$ kv).

2. We measured the dependence of the end-point energy E_0 on the initial voltage U_0 at an initial hydrogen pressure of 7×10^{-2} mm Hg (see Fig. 2). As in Fig. 1, the experimental points of Fig. 2 represent average values of several individual experiments. At initial voltages $U_0 < 30$ kv the intensity of the electron beam diminishes rapidly, since even an exposure of 15 or 20 discharges is insufficient for registration. The dependence considered here is also analogous to the dependence of the neutron yield on the initial voltage in discharges in deuterium. The reduction in the fast-electron energies at voltages $U_0 > 40$ kv can be attributed to the intense liberation of gas and evaporation of the wall material at the initial stages of very powerful discharges. Actually, the evaporation from the walls increases the mass of the gas-discharge column, slows down its compression, and consequently reduces the electric induction fields which can accelerate the charged particles.

3. In connection with the suggested possibility of accelerating the charged particles during the development of an unstable plasma pinch of the "neck-in" type, we investigated the dependence of the electron end-point energy E_0 on the intensity of the external longitudinal magnetic field.

For this purpose, the coaxial feeder surrounding the discharge chamber was placed in a solenoid. The solenoid winding consisted of 180 turns, uniformly distributed over the entire length of the discharge chamber. The solenoid was fed with direct current from a motor generator electronically stabilized to within 0.5% of the excitation current. The electron energies were measured with a direct-deflection magnetic spectrograph with the magnetic field intensity H on the solenoid axis ranging from 0 to 150 oe at the optimum initial discharge condi-
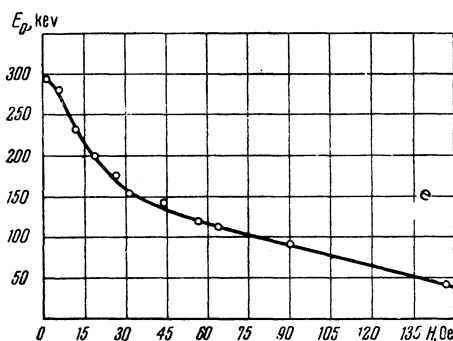
tions ($p_0 = 10^{-2}$ mm Hg, $U_0 = 40$ kv). The results obtained are shown in Fig. 3. When the current in the solenoid winding is reversed, the plot of E_0 vs. H remains the same. As can be seen from Fig. 3, the electron end-point energy diminishes sharply (from 300 to 150 kev) as the magnetic field intensity is increased from 0 to 25 or 30 oe. Further increase in the magnetic field causes the electron energy to diminish much more slowly.

If it is assumed that the plasma in the discharge has an infinite conductance and consequently the force lines of the magnetic field are "frozen-in" and completely entrained by the plasma, the longitudinal magnetic field H_z inside a pinch of radius r should increase as r^{-2} upon compression. The magnetic field H_φ of the discharge current increases as r^{-1} upon compression of the plasma pinch. At a radius r_m corresponding to the instant of maximum compression (approximately 1 to 2 cm) we have $H_\varphi \gg H_z$ (if $H_z = 30$ oe initially). It is therefore difficult to expect the presence of so weak an external magnetic field to influence noticeably the compression of the current column. However, the fields H_z and H_φ become comparable in magnitude when the plasma pinch radius becomes of order $0.2 - 0.5$ cm. Since the application of an external magnetic field H ~ 30 oe reduces the electron energy from 300 to 150 kev, it is obvious that the electrons acquire these high energies by acceleration in the electric field produced when the radius of the plasma pinch is reduced to 0.2 or 0.5 cm. A plasma pinch can have so small a radius where an instability of the "neck-in" type occurs.

4. The radial distribution of fast electrons accelerated along the discharge axis was investigated with a specially prepared collimator (see Fig. 4). The x-ray film was placed directly behind the collimator and could be covered with aluminum filters of different thickness. The experiments were
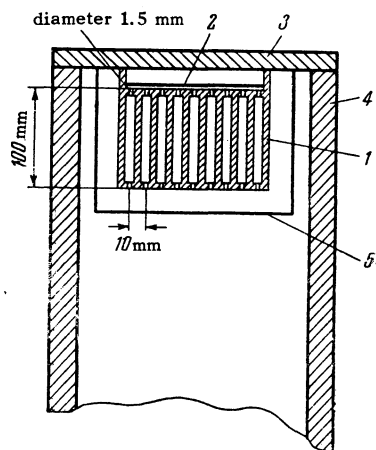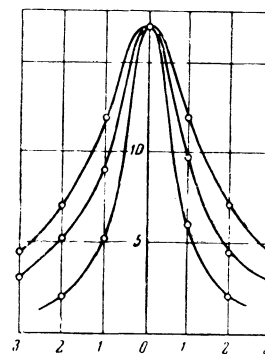
diameter 1.5 mm

FIG. 4. Arrange-
ment and placement of
the collimator. 1 — col-
limator, 2 — cassette
with x-ray film, 3 —
"anode" of discharge
chamber, 4 — side
walls of the chamber,
5 — protective cover.

FIG. 5. Radial distribution
of the intensity of the electron
beam at the outlet of the col-
limator. Ordinates — film density
(relative units), abscissas — dis-
tance from the tube axis (centi-
meters); the upper, middle, and
lower curves are for filter thick-
nesses of 30, 54, and 75 microns,
respectively.

carried out at $U_0 = 40$ kv. In the region of low
initial hydrogen pressures, approximately 7×10^{-3}
mm Hg, the intensity of the "shot through" elec-
trons produced at the start of the discharge ex-
ceeds considerably the intensity of the electrons
responsible for the hard x rays. Under these con-
ditions an exposure of ten discharges produced no
blackening of the film placed behind an aluminum
filter 30 microns thick. At the same initial pres-
sure and at a filter thickness of 12 microns, the
same blackening was obtained on x-ray films
placed opposite each opening of the collimator. It
follows therefore that the electrons, with energies
several times ten kev, produced at the start of the
discharge, are uniformly distributed over the
cross section of the discharge chamber.

The radial distribution of fast electrons respon-
sible for the hard x rays was investigated at p_0
$= 10^{-2}$ mm Hg. Figure 5 shows the film density
distribution after an exposure of 10 discharges with
aluminum filters 30, 54 and 75 microns thick. Ac-
cording to the experimental data, electrons with
energies 80, 110 and 140 kev have average ranges
of 30, 54 and 75 microns in aluminum, respectively.
As can be seen from Fig. 5, as the filter thickness
is increased the half-width of the radial distribu-
tion of the film density decreases. The results of
these experiments indicate that the non-equilibrium
group of fast electrons is accelerated in the immed-
iate vicinity of the axis of the discharge chamber.

Calibration experiments, in which the densities
of x-ray film exposed to electron beams of known

intensity were measured, made it possible to esti-
mate the number of fast electrons accelerated
along the discharge axis. At optimum initial con-
ditions ($p_0 = 7 \times 10^{-2}$ mm Hg, $U_0 = 40$ kv), the
total number of 140-kev electrons amounts to ap-
proximately 10^{13} electrons per discharge.

INVESTIGATION OF FAST ELECTRONS IN DEUTERIUM AND INERT GASES

For all the investigated gases, with the excep-
tion of krypton and xenon, there exists a minimum
pressure p_{min}, below which no electron pulses are
observed. These values of p_{min} are listed in the
second column of the table.

As the pressure increases above p_{min}, the am-
plitude of the electron pulse increases, reaches a
maximum value, and starts diminishing with fur-
ther increase in pressure. The third column of the
table lists the values of the pressure p_1 corre-
sponding to the maximum amplitude of the elec-
tron pulse. For krypton and xenon, the intensity of
the electron pulse increases down to 3×10^{-3} mm
Hg, below which these gases do not break down in
the discharge chamber. It must be noted that in
heavy gases the electron pulses appear both near
the first and near the second singularity of the
current oscillogram. On the other hand, in light
gases (hydrogen, deuterium, or helium) the elec-
tron-pulse time coincides as a rule, with the sec-
ond singularity of the discharge-current curve.
When the polarity of the voltage applied to the dis-
charge chamber is reversed, no electron pulses
are observed on the oscillogram even when the
sensitivity of the photomultiplier is increased by
two orders of magnitude.

Gas	Minimum pressure, p_{min} 10^{-2} mm Hg	Pressure p_1 at maximum electron energy, 10^{-2} mm Hg	Maximum electron energy registered, kev	Gas	Minimum pressure, p_{min} 10^{-2} mm Hg	Pressure p_1 at maximum electron energy, 10^{-2} mm Hg	Maximum electron energy registered, kev
H_2	2.5	7	295	Ar	0.4	4	105
D_2	2.0	6	290	Kr	0.3	0.5	50
He	1.5	5	290	Xe	0.3	—	<40
Ne	1.0	7	210				

The end-point energy E_0 of the electrons accelerated along the discharge axis was measured for each gas at initial pressures p_1 corresponding to the maximum intensity of the electron pulse. The results obtained are listed in the fourth column of the table.

The data listed in the table agree qualitatively with the assumption that inertial forces play a predominant role in the process of the constriction of the plasma pinch.[8] No accurate calculations can be made, however, because of the differences in the effective cross sections for the interactions between the ions and the electrons of the plasma with the neutral atoms.

CONCLUSION

Analyzing the dependence of the end-point energy of the electron spectrum on the intensity of the external magnetic field and on the initial pressure, as well as the radial distribution of the fast electrons, we can conclude that there exist two groups of nonequilibrium electrons in powerful pulsed discharges. The first group of fast electrons, with energies up to 100 kev, is apparently accelerated in the electric field produced when the current becomes redistributed during the constriction of the plasma pinch. The second group of fast electrons, with energies up to 300 kev, is apparently accelerated in the local electric field, due for example to the development of plasma pinch instabilities of the neck-in type. The corresponding estimates[5] lead to a voltage drop of approximately 50 kv for each "neck-in." Assuming a mechanism of successive acceleration of particles in several "neck-in" spots, one would expect a discrete spectrum of the fast electrons extracted along the discharge axis. Experiments have shown, however, that the electron spectrum has no such discrete nature.

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