Development of instability and the neutron emission by a Z-pinch

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(Submitted November 4, 1972)
Zh. Eksp. Teor. Fiz. **64**, 1222-1227 (April 1973)

High-current pulsed discharges in hydrogen and deuterium are studied with apparatus possessing high time and space resolution. It is shown that instabilities of the neck type begin to develop at early stages of compression of the plasma column, long before the plasma concentration at the axis is maximal. These instabilities are characterized by a very pronounced spatial periodicity. The time dependence of neutron emission is investigated. A correlation between the beginning of the neutron pulse and phase of the discharge current is established. The results are compared with the theoretical predictions.

1. INTRODUCTION

The Z-pinch is a classical object of research in hot-plasma physics. It is here that the macroscopic instabilities were first observed, the superthermal particles were revealed, and hard plasma radiation (neutrons and x-rays) were discovered. Yet many details of the processes remain unclear. During the initial stages of the research, 15—20 years ago, there was no adequate experimental technique; later the interests of the physicists actively working on hot plasma and controlled fusion shifted to the study of quasistationary systems, namely open and closed magnetic traps.

In this paper we attempt to fill some blank spots in the general picture of the development of a pulsed discharge in hydrogen at large current strength. It should be noted that the characteristic times of the investigated process run to several dozen nanoseconds, and it is this fact which dictated our use of specially constructed apparatus with high temporal and spatial resolution.

2. EXPERIMENTAL SETUP

The vacuum chamber was a ceramic tube with inside diameter 200 mm and length 700 mm. The distance between the copper electrodes placed at the ends was 600 mm. In the central plane of the tube, on two mutually perpendicular diameters, four holes of 40 mm diameter were drilled to serve for diagnostic purposes. The pulsed discharge was fed from a capacitor bank with a total capacitance of 60 μF. The working voltage ranged from 15 to 40 kV. The maximum discharge current was 400 kA; the time required for the current to rise to its maximum was 4.5 μsec. The working gases were hydrogen and deuterium, and the initial pressure ranged from 3×10^{-2} to 3×10^{-1} Torr.

The placement of the measuring apparatus is shown in the schematic figure 1. Opposite window 1 is placed an optical system that projects a section of the plasma pinch 10 mm high on the input slit of an MDR-2 monochromator. An optical shutter (Kerr cell) was placed in the path of the light beam. The radiation separated by the monochromator is transported from the exit slit of the spectral instrument to six photomultipliers via a six-channel fiber-optics system. The described system is used to measure the contours of the spectral lines at a given instant of time (the exposure time is determined by the duration of the voltage pulse applied to the electrodes of the Kerr cell, and amounted as a rule to 20 nsec). Opposite windows 2—4 we placed electrooptical shutters and photographic cameras intended to photograph the plasma pinch for the purpose of determining the dimensions and shapes of the radiating volume during different stages of the discharge. A special optical system made it possible to photograph on film discharge regions with linear dimensions on the order of 80 mm. A detailed description of the six-channel polychromator, the photographic recording devices, and the synchronization system is contained in[1]. In each experiment, oscillograms were obtained of the discharge current and of the discharge-chamber voltage.

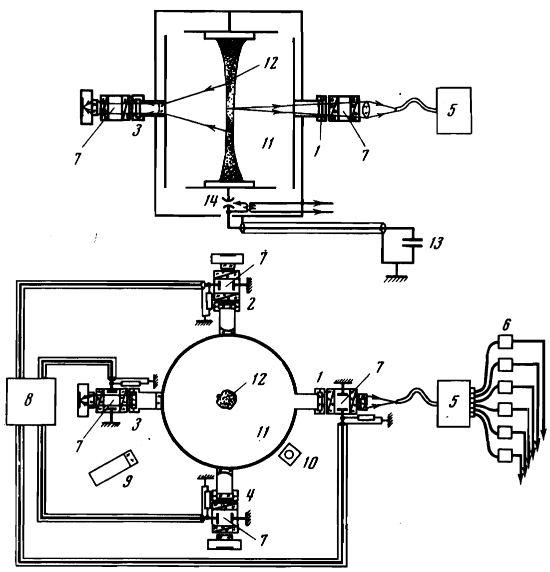

FIG. 1. Diagram of setup and arrangement of measuring apparatus: 1-4—Viewing windows, 5—MDR-2 monochromator, 6—type FEU-52 photomultipliers; 7—Kerr cells, 8—power supply for Kerr cells, 9—type ELU-FK photomultiplier with scintillator, 10—integral neutron counter, 11—vacuum chamber, 12—plasma pinch, 13—capacitor bank (C = 60 μF, U_0 = 15-40 kV), 14—discharge gap.

To register the time variation of the neutron radiation we used a scintillation counter located in the central plane of the discharge tube, 70 cm away from its axis. A plastic scintillator in the form of a cylinder 30 mm high and 50 mm in diameter was mounted to make optical contact with the end face of the glass bulb of an ÉLU-FK photomultiplier opposite the photocathode. The signals from the photomultiplier output were fed through a matched coaxial cable directly to the plates of a two-beam oscilloscope. The second beam of the oscilloscope was used to record the discharge current. The time resolution of the neutron registration system was ~20 nsec. The neutron-radiation intensity was determined by a standard procedure from the artificial radioactivity induced in a silver target. A PoBe source was used for the absolute calibration.

3. MACROSCOPIC INSTABILITIES

Ultrahigh-speed photography is one of the simplest and most illustrative methods of recording macroscopic plasma instabilities. If the exposure time amounts to a few dozen nanoseconds, then even if the plasma boundary moves at a speed $\sim 10^7$ cm/sec, the blurring of the boundary in the photograph will not exceed several millimeters, and the structure of the plasma configuration is reproduced with the required sharpness. The reduction of the exposure is accompanied, however, by a decrease in the light energy reaching the photographic film. Therefore the ordinary photographic technique in conjunction with a fast shutter can trace the variation of the shape of the plasma pinch only in a relatively narrow time interval. The start of the registration is determined by the instant of time when the plasma pinch, detached from the chamber wall, is dense and bright enough, while the end of the registration is determined by the stage of plasma disintegration after the first contraction. Under the experimental conditions, the duration of this interval was 1.5 μsec. The exposure duration was chosen to be 20 nsec. An analysis of the structures in the region of the second singularity calls for the use not only of very short exposures, but also for optical amplifiers.

Figure 2 shows a series of photographs pertaining to different discharges. The initial conditions were maintained constant and were strictly controlled. If it is assumed that the distribution of the glow intensity duplicates the distribution of the population of the charged particles, then we can draw the following conclusions:

1. The instant of maximum compression, in contrast to the customary point of view, does not coincide with the instant of the first singularity on the current curve; the compression occurs approximately 300 nsec before the instant of singularity.

2. The observed instabilities are characterized by distinctly pronounced spatial periodicity. Reduction of a large number of photographs leads to the conclusion that the characteristic wave length of the perturbation is

$$\lambda_{\mathrm{exp}} = 18.0 \pm 2.0 \text{ mm}.$$

It is interesting to note that this value remains constant, within the limits of measurement accuracy, during the entire period of the observations. We call attention also to the fact that the development of necks on the plasma pinch is noticeable even in the earlier stages of compression, long before the instant corresponding to the maximum plasma concentration on the discharge axis.

3. The results are in good agreement with the notions developed by Osovets et al.[2]. Indeed, within the framework of the model used by them, instabilities of the Rayleigh-Taylor type should appear starting with the instant of plasma detachment from the walls of the discharge chamber, and should be characterized by a definite periodicity. More accurately speaking, the wavelength of the perturbations is connected with the discharge parameters by the relation

$$\lambda = \frac{5.5 \cdot 10^9}{(dI/dt)_0^{1/2}} \frac{a_0}{N^{1/4}} \text{ [cm]}. \tag{1}$$

Here $(dI/dt)_0$ is the rate of current growth at the start of the discharge (in A/sec), a_0 is the inside radius of the chamber (in cm), and N is the number of particles per cm of plasma-column length.

The quantity $(dI/dt)_0$ can easily be determined from the oscillogram of the discharge current and amounts to $\sim 2 \times 10^{11}$ A/sec in this series of experiments. The value of N can be obtained from the initial pressure of the gas filling the chamber. The correctness of the assumed value of N can be additionally checked by spectroscopic measurements. Figure 3 shows the contour of the spectral H_α line obtained with an exposure of 20 nsec at the instant of the first maximum plasma compression. This contour was obtained with the polychromator referred to in Sec. 2 of the present paper. The value of N determined from the measured half-width of the H_α line contour (the Stark effect) turned out to be 3.5×10^{18} cm^{-1}, which practically coincides with the estimate obtained for N from the value of the initial pressure (2.5×10^{-1} Torr) and from the degree of compression. Substituting the numerical values of $(dI/dt)_0$, N, and a_0 in formula (1), we obtain

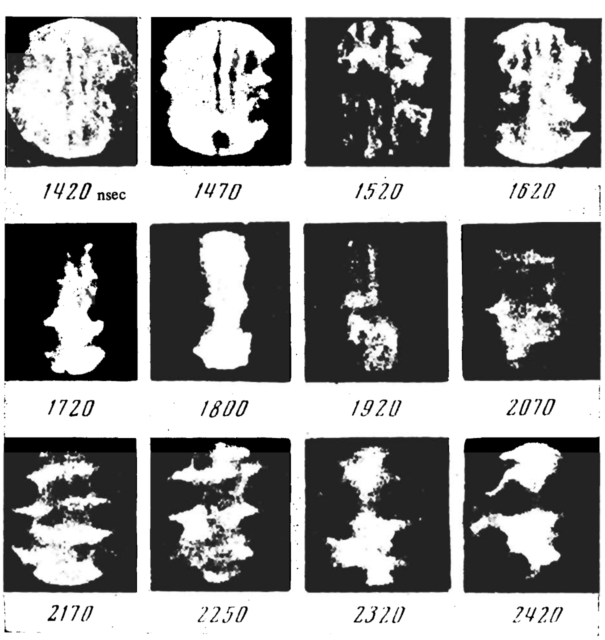

FIG. 2. Photographs of the Z-pinch (working gas — hydrogen, p_0 = 2.5×10^{-1} mm Hg; U_0 = 20 kV), obtained at different instants of time relative to the start of the discharge. The plasma pinch was photographed in light of the H_α line. The exposure of each frame was 20 nsec; the time (in nsec) elapsed from the start of the discharge is indicated under the photographs. The first singularity (kink) on the current curve is observed at ~ 2100 nsec after the start.

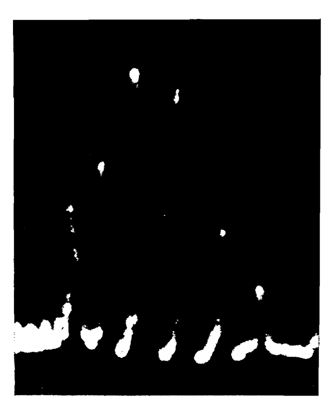

FIG. 3. Contour of H_α spectral line, obtained with an exposure of 20 nsec at the instant of the first maximum plasma contraction. The amplitudes of the successive six signals are proportional to the radiation intensities in the adjacent spectral intervals. The width of each interval is 16 Å, the working gas is hydrogen, p_0 = 2.5×10^{-1} mm Hg, U_0 = 20 kV.

$\lambda_{theor} = 25$ mm.

The agreement between experiment and theory on this point calls for no further comment.

4. NEUTRON RADIATION

In the experiments reported in this section, the working gas was deuterium. The initial pressure was 6×10^{-2} mm Hg, and the voltage to which the capacitor bank was charged was 30 kV. As is well known,[3,4], the intensity of the neutron radiation varies by several orders of magnitude when the pressure is varied in the range from 10^{-3} to 1 mm Hg. A distinct maximum is observed near $p_0 = 6 \times 10^{-2}$ mm Hg. A characteristic feature of the neutron effect is the considerable spread in the number of neutrons observed in each individual discharge even at formally identical initial parameters. Under our conditions, the total neutron yield determined by measuring the induced radioactivity was 10^7–10^8 neutrons per discharge. The presented figures were obtained by analyzing a large amount of experimental material (several hundred pulses). Each experimental run was preceded by thorough preconditioning of the vacuum chamber by means of discharges.

Figure 4 shows typical oscillograms of the neutron pulse and of the discharge current. Reliable phasing was attained by applying time markers from one and the same generator to both oscilloscope beams. The high time resolution of the scintillation counter employed ensured the necessary accuracy of neutron-emission measurement and made it possible to establish, within a 20-nsec interval, the current phase at which the neutron emission from the plasma begins. It should be noted that the half-width of the neutron pulse is practically independent of its intensity. This made it possible to determine the duration Δt of neutron emission by averaging the data pertaining to different discharges. Under the investigated conditions we obtained $\Delta t = 180 \pm 20$ nsec. In all cases, the start of the neutron radiation coincides with the start of the rise of the discharge current after the second (or third) singularity. The neutron emission is accompanied, as a rule, by high-frequency oscillations (several dozen MHz) in the discharge circuit.

Returning to the theoretical model of Osovets et al.[2], the conclusions of which with respect to the development of the macroscopic instabilities turned out to agree well with the experimental data, we can state that the measured duration of the neutron pulse agrees with the general picture of the process of deuteron acceleration in the strong electric fields that are produced during the final stage of instabilities such as necks. The absence of neutron emission near the first singularity (necks are clearly observed even at earlier instants of time!) is due to the fact that the conditions necessary to accelerate the particles are not yet satisfied in this case[5].

FIG. 4. Oscillograms of discharge current (upper trace) and of neutron pulse (lower trace). The interval between the start of the current rise following the second singularity and the start of the neutron pulse is equal to the time of flight of the neutrons (~ 30 nsec) and to the delay of the signal in the photomultiplier (~ 15 nsec). The working gas is deuterium, $p_0 = 6 \times 10^{-2}$ mm Hg, $U_0 = 30$ kV.

The authors consider it their pleasant duty to thank S. A. Chuvatin and A. I. Gorlanov for help with the experiments.

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Translated by J. G. Adashko
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