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MATTER AND RADIATION AT EXTREMES

Matter and Radiation at Extremes 1 (2016) 207–212

www.journals.elsevier.com/matter-and-radiation-at-extremes

Review article

Neutrons in a nanosecond low-pressure discharge in deuterium

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Received 17 May 2016; revised 12 July 2016; accepted 17 July 2016
Available online 23 August 2016

Abstract

Stable neutron generation with a yield of ~1.2×10^4 neutrons per pulse was obtained during d(d,n)^{3}He reaction initiated by the high-voltage nanosecond discharge in a gap with a potential tungsten cylinder (anode) and a grounded deuterated zirconium plate (cathode) filled with deuterium at a pressure of ~10^2 Pa. Estimated duration of the neutron pulse was ~1.5 ns. Less intensive neutron emission was registered without deuterated plate. Splashing of material of the tungsten electrode was observed during the high-voltage nanosecond discharge in the deuterium, hydrogen, helium and argon at pressures of 10^2–10^4 Pa.

PACS codes: 29.25.Dz; 52.38.Pn; 52.80.˙s

Keywords: Neutrons; Deuterium; High-voltage nanosecond discharge; Low-pressure; Thermonuclear reaction

1. Introduction

Creation of neutron sources with a pulse duration of several nanoseconds or less is a topical problem. Such sources can be used for solving various problems of applied nuclear physics and other areas, *e.g.*, radiography of fast processes, spectrometry at elemental analyses, studying of kinetics of nuclear reactions, testing of pulse detectors of neutrons, detection of explosives, drugs and fission materials, *etc.* [1–3] One way to obtain neutron pulses of short durations is via the impact of ultra-high-power laser pulse with pico- or femto-second duration on targets enriched with deuterium or tritium [1,3,4].

Also, neutron pulses with a duration of 10–10^3 μs can be obtained using the particle accelerators based on vacuum neutron tubes [2,5,6]. The neutron yield of such devices reaches ~10^{11} neutrons per pulse and they are widely used in practice, *e.g.* logging.

It is known about the possibility of neutron emission during high-voltage nanosecond discharge in a gap filled with deuterium at low pressure (hundreds of Pascal) [7–9]. Such neutron sources are simpler and cheaper than laser-based ones. In this case, potential electrode with small radius of curvature (anode) and grounded plate enriched with deuterium or tritium (cathode-target) are used. Emission of neutrons occurred due to d(d,n)^{3}He (DD-reaction) and t(d,n)^{4}He (DT-reaction) thermonuclear reactions described by Eqs. (1) and (2), respectively. These reactions are initiated by deuterium ions accelerated in the gap interacting with cathode-target.

$$D + D \rightarrow {}^3He + n + 3.269\ MeV \quad (1)$$

$$D + T \rightarrow {}^4He + n + 17.577\ MeV \quad (2)$$

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Peer review under responsibility of Science and Technology Information Center, China Academy of Engineering Physics.

http://dx.doi.org/10.1016/j.mre.2016.08.002

In Ref. [8,9], stable neutron emission due to DT-reaction initiated in high-voltage nanosecond discharge in deuterium at pressures of 10–100 Pa was registered. The maximal yield was ~1.5×10^6 neutrons per pulse.

For the first time, stable neutron emission provided by DD-reaction was demonstrated later, in Ref. [10]. It should be noted that the yield was several orders of magnitude smaller than the one of DT-reaction. This is conditioned by a lower value of DD-reaction cross-section at identical values of deuterium ions energy. Despite this, the DD-reaction-based neutron sources allow to form neutron pulses with durations of several nanoseconds or less, which are less harmful than DT-reaction-based ones. Wherein, such devices are promising for numbers of practical applications.

The objective of this paper is to study the possibility of stable neutron emission due to DD-reaction during the high-voltage nanosecond discharge in the gap filled with low-pressure deuterium with the electrode non-enriched with deuterium or tritium. Another objective is to obtain the maximum possible neutron yield at a discharge in the gap with a deuterated target.

2. Experimental equipment

The experiments were carried out on the setup which schematic is presented in Fig. 1. A discharge was ignited in the 56-mm-diameter gas-filled cylindrical metal chamber which was connected with a pulser (RADAN-220 [11]). A system consisting of a forevacuum pump, metal pipes, gas cylinders and pressure sensors was used for filling the chamber with gas, controlling its pressure and its evacuation. The pulser can form voltage pulses of both positive and negative polarities with an amplitude of ~220 kV at the high-resistance load. The duration of a voltage pulse at the matched load and its risetime in the transmission line is ~2 ns and ~0.5 ns, respectively. This pulser was operate in single-pulse mode. A voltage pulse from this pulser was applied across the interelectrode gap in the discharge chamber.

Since the experiments were carried out at low pressure of a gas medium, a lead shield with 7-cm-thickness walls was used to protect equipment and personnel from the influence of powerful X-ray pulses.

To measure the yield of neutrons appeared in d(d,n)^{3}He reaction, a ^{3}He-detector [12] with an efficiency of 0.0058 ± 15% was used. This detector consists of ten tubes filled with ^{3}He-Ar-CO_2 mixture surrounded by polyethylene. Each tube is a counter of thermal neutrons. The ^{3}He-detector was located at the side of the discharge chamber with a distance of 30 cm from it. The lifetime of a neutron in the detector is ~57 μs. Because the registration interval was 350 μs, the probability of the registration of a neutron was ~100%.

The neutron pulse duration was measured with a scintillation detector (SD) [13] consisting of a photomultiplier tube (PMT) XP-2020 (Philips) and a parallelepipedic plastic scintillator. The efficiency of this detector was 6×10^{-4}. The SD was located on the longitudinal axis of the discharge chamber with a distance of 100 cm from it. This detector was operated in one-neutron registration mode (neutron counting mode).

Signals from the ^{3}He-detector and SD were registered with the real-time digital oscilloscopes Tektronix TDS3054B (B_w = 500 MHz) and TDS3032B (B_w = 300 MHz), respectively. A sync pulse was a signal from the capacitive voltage divider (11 in Fig. 2). Acquisition and processing of experimental data were carried out with a personal computer.

The schematic of the discharge chamber is shown in Fig. 2. The chamber was made of steel in the geometry of a cylinder with an inner diameter of 54 mm. The potential electrode with small radius of curvature and the flat grounded electrode formed the interelectrode unit. The potential electrode with a cylindrical geometry was made of stainless steel or tungsten. The grounded electrode was made of aluminum plates. Deuterated zirconium (ZrD_2) and deuterated titanium (TiD_2) plates were mounted to the aluminum plate via brass ring (2 in Fig. 3(d) and (b)). Interelectrode distance and gas pressure in

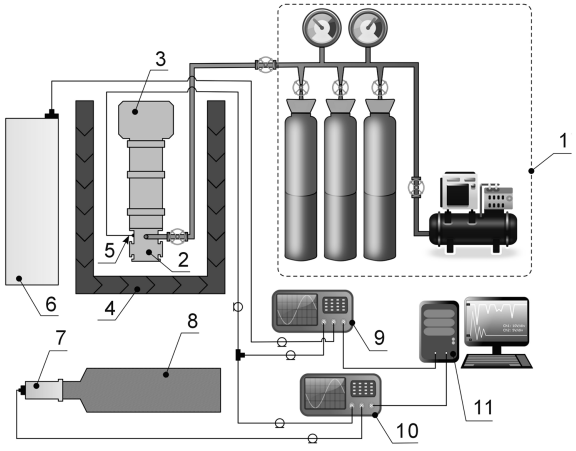

Fig. 1. Schematic of the experimental setup. 1 – gas system; 2 – discharge chamber; 3 – RADAN-220 pulser; 4 – lead shield; 5 – voltage sensor; 6 – ^{3}He-detector of thermal neutrons; 7 – photomultiplier tube XP-2020; 8 – plastic scintillator (scintillator detector); 9, 10 – digital real-time oscilloscopes; 11 – personal computer.

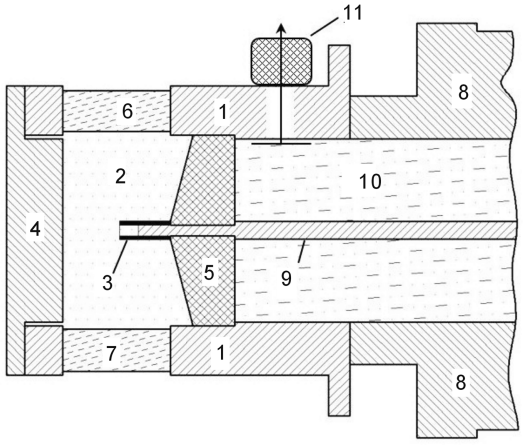

Fig. 2. Schematic of the discharge chamber. 1 – chamber housing; 2 – gas medium; 3 – potential electrode; 4 – grounded electrode; 5 – insulator; 6, 7 – quartz windows; 8 – transmission line of the RADAN-220 pulser; 9 – potential input; 10 – transformer oil; 11 – capacitive voltage divider.

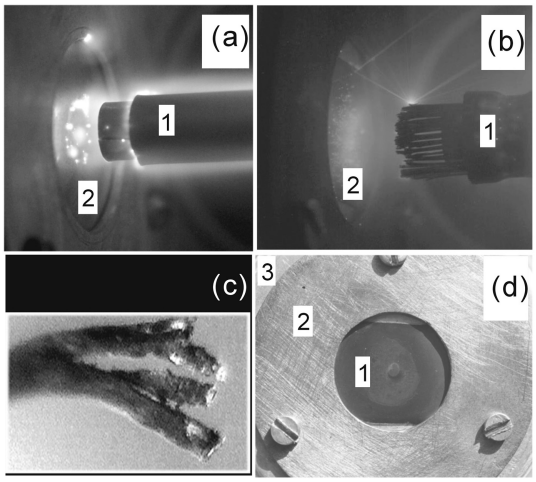

Fig. 3. (a) The image of glow of a plasma of the high-voltage nanosecond discharge in deuterium. 1 – cylindrical potential anode made of 100-μm-thickness steel foil, $\phi = 6$ mm, 2 – ZrD_2 plate (grounded cathode). (b) The image of glow of a plasma of the high-voltage nanosecond discharge in deuterium. 1 – cylindrical potential anode made 0.2-mm-diameter tungsten wires, $\phi = 8$ mm, 2 – ZrD_2 plate (grounded cathode). Deuterium pressure is ~100 Pa. Interelectrode distance is 5 mm. (c) The photo of the split end of a tungsten wire. (d) The photo of the grounded electrode. 1 – deuterated plate (ZrD_2), 2 – the compression brass ring, 3 – aluminum plate.

the chamber were varied from 1 mm to 10 mm and from 13.3 Pa to 10^5 Pa, respectively.

Images of the gap and discharge plasma glow were taken with digital camera SONY A100.

3. Experimental results

Due to the experiments carried out in Ref. [10], the optimal conditions providing stable neutron emission in DD-reaction are following:

- positive polarity of a voltage pulse;
- a potential anode with a cylindrical geometry (cylinder made of 100-μm-thickness steel foil, 1 in Fig. 3(a));
- grounded cathode-target as ZrD_2 plates;
- gas pressure p ~100 Pa;
- interelectrode distance d ~5 mm.

Under these conditions, a stable neutron yield of 3.1×10^3 neutrons per pulse into 4π sr angle was obtained.

To increase the neutron yield due to DD-reaction occurring at high-voltage nanosecond discharge in the gap with the electrode enriched with deuterium, the following was done. The steel cylindrical anode (1 in Fig. 3(a)) was replaced by 8-mm-diameter cylinder lateral surface of which consisted of 0.2-mm-diameter tungsten wires (1 in Fig. 3(b)). Each wire was split at the end on 3–5 strands (Fig. 3(c)). This provided additional amplification of electric field strength in the gap. The high-voltage nanosecond discharge was ignited in the gap with cylindrical tungsten potential anode and deuterated zirconium plate (grounded cathode) filled with deuterium at a pressure of ~100 Pa. The image of discharge plasma glow in the gap is presented in Fig. 3(b).

By using the tungsten potential anode (1 in Fig. 3(b)), the neutron yield was increased 4-fold compared with that in Ref. [10] and amounted to ~1.2×10^4 neutrons per pulse into 4π sr angle [14]. This value was determined on the basis of data obtained with the ^{3}He-detector taking into account the detector's efficiency. Typical signal from this detector is presented in Fig. 4 waveform 2. All peaks on this waveform except for the first one are corresponded to the detector response on neutron impact. The first peak is caused by X-ray generated under these conditions as a result of deceleration of fast electrons at the anode.

The fact of increasing of the neutron yield value can be explained as follows. The use of this cylindrical potential anode made of tungsten wires is provided with an increase of an amplitude of the voltage pulse compared with steel cylindrical electrode (Fig. 5). It is seen that the voltage pulse amplitude in Fig. 5(b) is 50 kV larger (375 kV) than one in Fig. 5(a) (325 kV). This leads to an increase of concentration and energy of deuterium ions which arrive at the deuterated cathode-target and initiate DD-reaction. Besides, the increase in the amplitude of the voltage pulse can be judged by the increase in the amplitude of the first peak on the waveform of a signal from the ^{3}He-detector. It was higher than the one with the use of the steel potential anode.

In addition, by using the data obtained with SD, an estimation of the neutron pulse duration τ_n was performed [14]. The typical signal from this detector located at a distance of 1 m from the discharge chamber is presented in Fig. 6(b). It is seen that the waveform consists of two peaks. It was established by means of time-of-flight technique where peak 1 is corresponded to X-ray and peak 2 is related to the detector response on neutron impact. The neutron pulse duration was determined by the following expression:

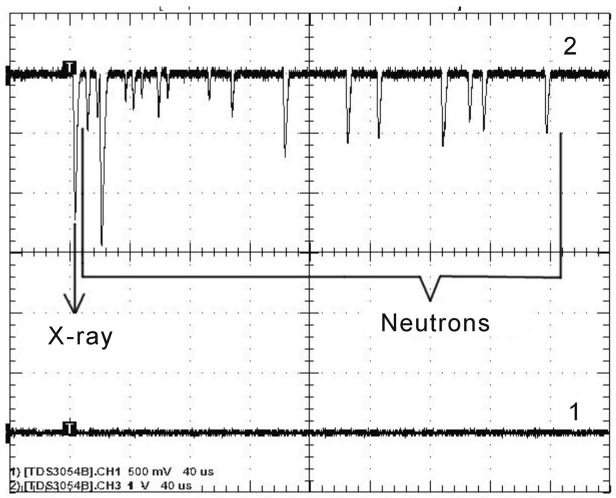

Fig. 4. Screenshot from digital oscilloscope Tektronix 3054B. 1 – waveform of signal from capacitive divider (sync pulse); vertical axis: 0.5 V/div; horizontal axis: 40 μs/div. 2 – waveform of the signal from ^{3}He-detector; vertical axis: 1 V/div; horizontal axis: 40 μs/div.

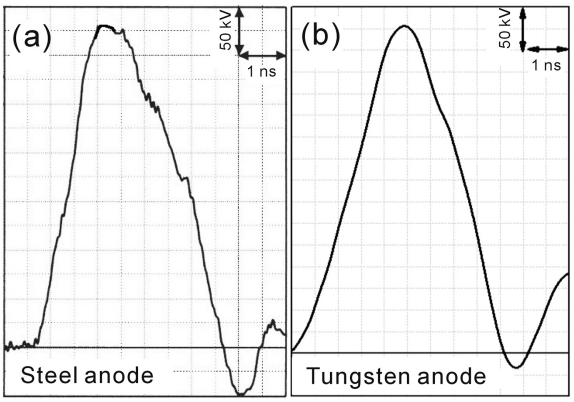

Fig. 5. Waveforms of the voltage pulses registered with the capacitive voltage divider during the high-voltage nanosecond discharge in the deuterium at pressure of ~100 Pa. (a) steel potential anode. (b) tungsten potential anode.

$$\tau_n \le 2.36\sqrt{\sigma^2(t_{ne})} = 2.36\sqrt{\sigma^2(t_n) - \sigma^2_{pmt}} \quad (3)$$

where $\sigma^2(t_{ne})$ is the dispersion of the distribution of time instants corresponding to the emission of a neutron from the deuterated target; $\sigma^2(t_n)$ is the dispersion of the distribution of time instants corresponding to the registration of a neutron with the detector; σ^2_{pmt} is the characteristic temporal resolution of the detector (equals 310 ps in experiments).

Determination of the value of σ^2 (t_n) was performed with the use of waveforms registered with SD. Preliminarily, peak 1 corresponding to the neutron signal was interpolated by a Gaussian curve. Then, a time instant $t_{1/2}$ on the leading edge corresponding to the half-maximum was chosen. Further, a distribution of these instants in relative to the voltage pulse onset time (reference point on the time axis) was plotted and the dispersion $\sigma^2(t_n)$ of this distribution was determined. The value of $\sigma(t_n)$ was 0.7 ns. So the estimated value of neutron pulse duration is $\tau_n \approx 1.5$ ns.

Using the data on the duration of a runaway electron beam generated at the same conditions [15], an estimation of the X-ray pulse duration was performed. Its value is ~0.8 ns.

It should be noted that inconsistency of the values of pulse durations received due to estimations and the ones presented on the waveform is explained by insufficient temporal resolution of the registration system.

Another important result was stable neutron generation during the high-voltage nanosecond discharge in the gap filled with deuterium of pressure of ~100 Pa in absence of electrode enriched by deuterium [10]. In this case, as it is seen from Fig. 7 waveform 2, less intensive neutron emission occurred. The measured value of the neutron yield was ~2×10^2 neutrons per pulse into 4π sr angle.

It was assumed that the neutron emission during the discharge without deuterium-enriched cathode-target occurred from the discharge volume. The hypothesis of the presence of the shock wave converging to the longitudinal axis of the gap has been proposed. As an argument of the shock wave presence can serve discharge autograph (Figs. 3(a) and 8) on the grounded cathode, which is, in fact, the "image" of the cylindrical electrode' butt end. A diameter of the ring in Fig. 8 is corresponded to the one of the steel cylindrical anode (~6 mm). This fact indicates that the discharge under these conditions has

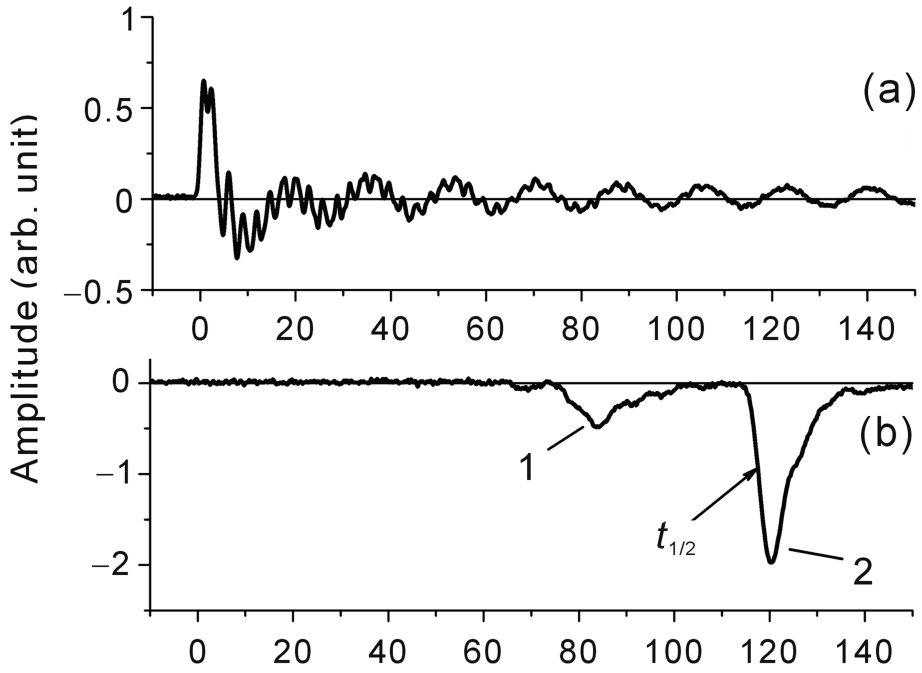

Fig. 6. (a) Waveform of the signal from the capacitive voltage divider. (b) Waveform of the signal from scintillation detector. 1 – the peak corresponding to the X-ray effect; 2 – the peak corresponding to the neutron impact; $t_{1/2}$ – time instant at the half-maximum.

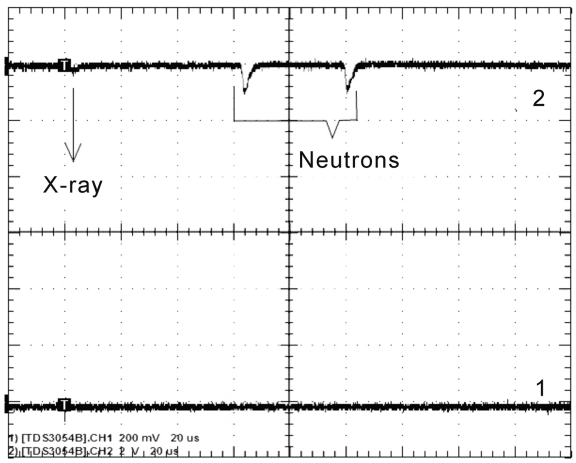

Fig. 7. Screenshot from digital oscilloscope Tektronix 3054B. 1 – waveform of the signal from the capacitive divider (sync pulse); vertical axis: 0.2 V/div; horizontal axis: 20 μs/div. 2 – waveform of the signal from the ^{3}He-detector; vertical axis: 2 V/div; horizontal axis: 20 μs/div.

a cylindrical geometry and the main part of the discharge current flows along the cylinder in the layer of a thickness of ~0.1 mm.

The calculations performed within one-fluid two-temperature model [16] showed that in the inner part of the cylindrical discharge, converging to the axis shock wave arises (more details in Ref. [10]). Due to the collapse of shock wave accompanied by a release of energy, a gas concentration on the longitudinal axis of the discharge gap increases eightfold and deuterium ions temperature reaches values of ~100 eV. This leads to an initiation of the DD-reaction in the discharge volume and neutron emission. According to the estimations performed within modeling presented in Ref. [10] it is possible to obtain a yield of ~10^2 neutrons per pulse during the high-voltage nanosecond discharge in the gap filled with low-pressure deuterium where electrodes are cylindrical potential anode with small radius of curvature and grounded flat deuterium- or tritium-free cathode.

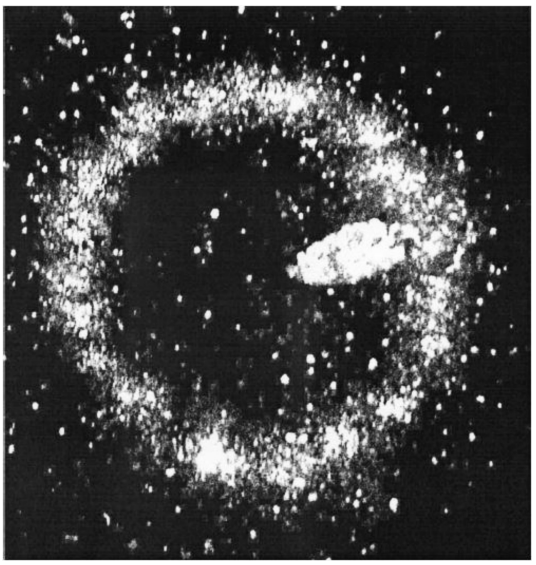

Fig. 8. The photo of the grounded cathode after several tens pulses. The ring's diameter is ~6 mm.

One more interesting result which was found during the experiments aimed at obtaining of neutrons is splashing of a material of the potential anode [17]. At the high-voltage nanosecond discharge in the gap with a tungsten potential anode of cylindrical geometry and grounded deuterated cathode-target filled with low-pressure deuterium, the bright tracks starting from bright spots on the electrodes were observed (shown in Fig. 9). It was established that this phenomenon occurs during the discharge in deuterium, hydrogen, helium and argon in the pressure range of 10^2–10^4 Pa at both polarities of the voltage pulse. The material splashing is observed predominantly from the tungsten potential electrode. It was found that pressure change in the gap affects the process. With increasing pressure from 10^2 to 10^4 Pa, the reducing of the tracks' length is observed. At a pressure more than 10^4 Pa, this phenomenon is no longer observed. This phenomenon is not observed using the steel potential electrode.

It can be assumed that under these conditions, the local release of a large amount of thermal energy on the electrode surface occurs (probably on microinhomogeneities). This can be caused by the high value of the flowing current. As a result, a splashing of hot bright drops consisting of electrode material occurs. The tracks' geometry (Fig. 9(d)) indicates that during motion a drop cools down and solidifies. This is manifested as an elastic interaction of particles with the surface of flat grounded electrode. Change in the track direction corresponds to the situation when a particle falling on the surface and reflecting from it at an angle equal to the incidence angle. This

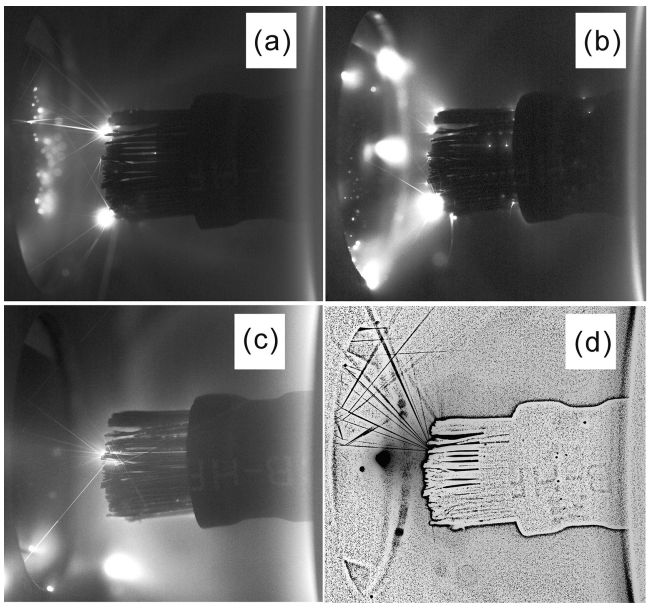

Fig. 9. Images of discharge plasma glow. Interelectrode distance is 5 mm. A potential electrode is an 8-mm-diameter tungsten cylinder. A grounded electrode is ZrD_2 plate. (a) deuterium, $p = 300$ Pa, negative polarity of voltage pulse (tungsten cylinder is the cathode). (b) deuterium, $p = 6000$ Pa, positive polarity of voltage pulse (tungsten cylinder is the anode). (c) argon, $p = 300$ Pa, positive polarity of voltage pulse (tungsten cylinder is the anode). (d) deuterium, $p = 300$ Pa, positive polarity of voltage pulse (tungsten cylinder is the anode).

situation takes place in most cases. However, this phenomenon needs a more detailed study.

4. Conclusion

During the high-voltage nanosecond discharge in the gap with the tungsten potential cylindrical anode and the flat grounded deuterated cathode-target filled with deuterium of pressure ~100 Pa, the stable neutron emission produced in $d(d,n)^3He$ reaction is observed. The maximal value of the neutron yield into 4π sr angle is $\sim 1.2 \times 10^4$ neutron per pulse. The duration of the neutron generated under these conditions is ≤ 1.5 ns, which is promising for the creation of a neutron source with a pulse duration of ~1 ns or less. It can be used to solve some problems in applied nuclear physics and not only.

The stable neutron emission was observed at the discharge in gap filled with low-pressure deuterium where none of electrodes was enriched with deuterium or tritium. The results of calculations show that in this case neutron emission occurs in the discharge volume due to collapse on the longitudinal axis of the discharge gap of the shock wave aroused there under these excitation conditions. The yield in this case is $\sim 2 \times 10^2$ neutron per pulse into 4π sr angle.

It was found that during the high-voltage nanosecond discharge in deuterium, hydrogen, helium and argon at pressures of 10^2−10^4 Pa in the gap with tungsten potential electrode and grounded deuterated cathode, the splashing of electrode material is observed. This phenomenon is observed predominantly from the potential tungsten electrode and at both polarities of the voltage pulse. At pressure higher than 10^4 Pa is terminated.

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