Hydrogen Inverse Z-Pinch at the High-Current Generator MIG

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Abstract – The paper describes an experimental setup created for the study of the pd reaction ($p + d \rightarrow {}^3He + \gamma$ (5.5 MeV)) in the region of ultralow energies (~ keV) of proton-deuteron collisions using a pulsed plasma accelerator. It is shown that the formation process of the hydrogen inverse Z-pinch is fairly well modelled by zero-dimensional calculations of the liner motion dynamics. Equipment for diagnostics of the liner flow formation is designed and created. Conditions for conducting experiments at the high-current generator MIG of the Institute of High-Current Electronics (Tomsk, Russia) are investigated.

In the papers [1, 2], a method to study the pd, dd and d^{3}He reactions at ultralow particle collision energies using pulsed plasma accelerators was suggested. By now investigations of the dd reaction in the inverse Z-pinch configuration have been conducted using the pulsed plasma generator SGM at the IHCE ($I = 950$ kA, $t = 80$ ns).

As a result of the investigations [4–6], the cross section of the dd reaction $d + d \rightarrow {}^3He + n$(2.5 MeV) for deuteron collision energies in the range 1.8–3.7 keV was measured for the first time.

The ion acceleration in the inverse Z-pinch configuration (the liner expands from the axis) has a number of advantages over the direct Z-pinch (the ion acceleration is performed in the course of the liner compression to the axis). These advantages are chiefly connected with the possibility of separating in time the liner plasma electrodynamics acceleration and the plasma interaction with the target.

Exactly this circumstance provided sufficient reason to carry out an experiment on the study of the dd reaction

$$p + d \rightarrow {}^3He + \gamma \text{ (5.5 MeV)} \qquad (1)$$

using the high-current generator MIG [7, 8].

In the present paper an experimental setup for the study of reactions (1) in the region of ultralow energy (~ keV) of proton-deuteron collisions is described. The setup consists of the next main parts: the pulsed high-current generator MIG, a load module, detectors for diagnostics of the hydrogen liner formation in the inverse Z-pinch configuration, ion collectors, optic detectors of plasma radiation, a deuterium target based on deuterated polyethylene, γ-quantum plastic scintillation detectors.

A general scheme of the location of the equipment in the experiment at the pulsed high-current generator MIG (the duration of the voltage pulse is $t \sim 100$ ns, the amplitude of the pulse is $U \sim 1$ MV, the maximum current through the load is $I \sim 2.5$ MA) is presented in Fig. 1.

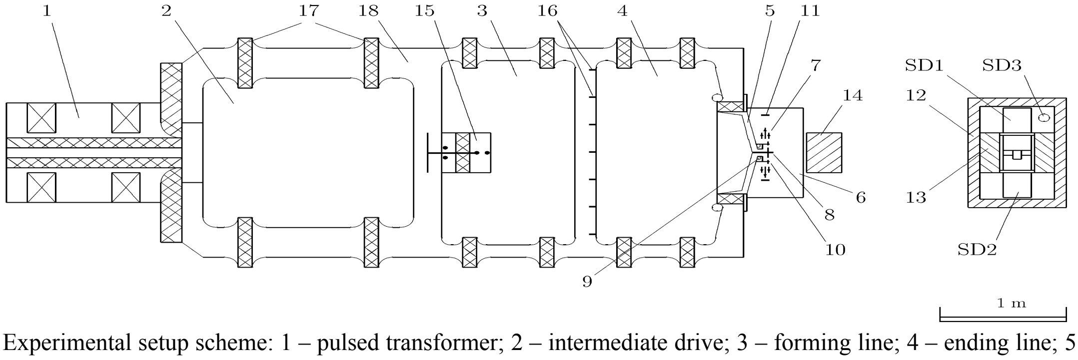

Fig. 1. Experimental setup scheme: 1 – pulsed transformer; 2 – intermediate drive; 3 – forming line; 4 – ending line; 5 – load module; 6 – diagnostic chamber; 7 – liner; 8 – return conductor; 9 – Rogovski belt; 10 – current-intercepting rods; 11 – target; 12 – leaden box; 13 – leaden container; 14 – additional leaden shielding; 15 – controlled commutator; 16 – uncontrolled commutator; 17 – insulators; 18 – water gap; SD1, SD2 and SD3 – scintillation detectors

The load module of the generator is intended for shaping a supersonic cylindrical gas stream injected in a spark gap, as well as for creating conditions for plasma liner formation and for plasma ion acceleration under the action of the current through the liner.

The location of the instruments and devices in the diagnostic chamber is shown in Fig. 2. Gaseous hydrogen was placed in a forechamber under a pressure of $P \sim 4.5$ atm. The hydrogen entered the spark gap by means of a high-speed electromagnetic valve through the supersonic Laval nozzle 1. The nozzle was made in the form of a circular slot with an internal diameter of 20 mm and an external one of 24 mm.

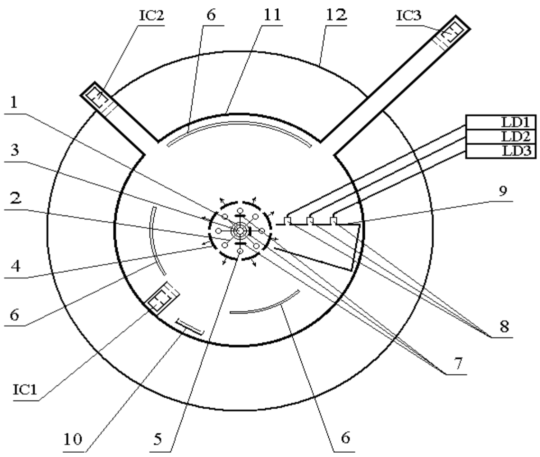

Fig. 2. Diagnostic chamber: 1 – supersonic Laval nozzle; 2 – wire cathode; 3 – return conductor; 4 – liner; 5 – current-intercepting rods; 6 – targets; 7 – dB/dt probes; 8 – collimators of the optic detectors; 9 – light-protecting cone; 10 – bolometer; 11 – diagnostic chamber; 12 – shell of the generator MIG; IC1, IC2 and IC3 – ion collectors; LD1, LD2 and LD3 – optic detectors

The electromagnetic valve and supersonic nozzle were installed at the anode electrode of the load module, which was at the ground potential. The amount of the entering gas was defined by the critical section of the supersonic nozzle and by the pressure of the hydrogen in the forechamber. By means of the wire cathode 2 and return conductor 3, conditions for accelerating the liner 4 in the inverse Z-pinch configuration were created.

The current through the liner was measured by means of the Rogovski belt 9 (see Fig. 1).

Twenty current-intercepting rods 5 were located on circumferences with a diameter of 90 mm, each metallic rod being 1 mm in diameter. The rods were used for interruption of the liner acceleration.

Three magnetic d*B*/d*t* probes 7 were located at the distances 22, 28 and 37.5 mm from the load module axis. The probes were used for registering the moment of the passing of the liner current shell through the d*B*/d*t* probes.

Figure 3 shows the time dependence of the current through the liner in one of the shots and the curve of the liner moving. The curve was calculated using the zero-dimensional model for a liner mass of 14 μg (~ $8.4 \cdot 10^{18}$ protons).

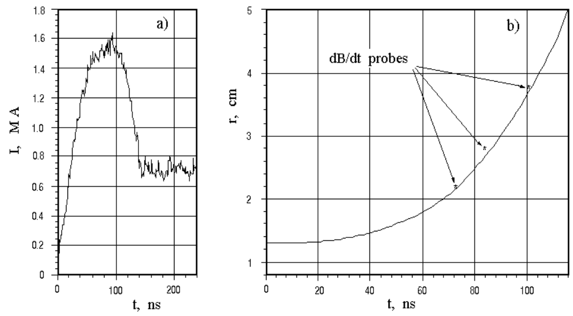

Fig. 3. Time dependence of the current through the liner (a); calculated curve of the liner moving (b)

As is seen, there is a satisfactory agreement of the calculation with the moments of d*B*/d*t* probe signal appearances indicated in Fig. 3.

Distribution of the liner ions in the velocity of their motion in the radial direction was measured using two types of detectors: ion collectors [9] and optic detectors of liner radiation [5].

Three ion collectors were installed on the way of the expanding liner: the IC1 at a distance of 30 cm from the load module axis, the IC2 – 129 cm, and IC3 – 157 cm, consequently (see Fig. 2).

For separation of the plasma ions (protons) and electrons a metallic mesh was placed between the collimator and collector, the collector being at the negative potential to the mesh.

The current of the collector is defined by the current of the entering liner ions as well as by the current of the escaping electrons from the collector as a result of secondary electron emission, caused by the collector ion bombardment.

Thus, there exists a possibility of defining the ion speed distribution by measuring the time dependence of the full current of the collector.

It is necessary to note that the hit of the ultraviolet radiation of the liner plasma on the collector also causes secondary electron emission as a result of the photoeffect due to the γ-quanta collisions with the atoms of the collector material. Although the intensity of the collector irradiation decreases during the liner expansion, this imposes restrictions on the accuracy of measurements for the high-energy ions of the plasma.

The detector of optical radiation [5] consists of a collimator connected with the entrance window of the photomultiplier FEU-115 by a flexible light guide.

Three optic detectors, LD1, LD2, and LD3, were used in the investigation. The detector collimators were placed at the distances 13, 18, and 23 cm from the load module axis, correspondingly (see Fig. 2). To protect the optic detectors against the stray radiation from the liner, the detector collimators 8 were placed in the light-protecting cover 9 having the form of a truncated cone.

The optic detectors measured the intensity of the hydrogen characteristic radiation (H_α-line, the wavelength equal to 656 nm) resulting from the charge exchange reactions of the liner ions (protons) with the atoms of the residual gas in the diagnostic chamber. Light glass filters were used to extract the hydrogen radiation. In more detail the optic detector arrangement and methods of processing the time dependencies of the radiation are presented in papers [5, 6].

The liner energy gained during the liner acceleration was checked by means of the bolometer 10 installed on the way of the moving liner at a distance of 36 cm from the liner axis. The bolometer 10 was made from copper foil 4.5 cm in length, 2 mm in width, and 17.5 μm in thickness.

The liner energy density was measured by the change in the foil electric resistance as a result of the foil heating at the collision with the liner. The procedure of the measurement and calibration of the bolometer is described in detail in paper [6].

To measure the γ-quantum yield from reaction (1), the scintillation detectors SD1, SD2, and SD3 were used. These detectors were made up of plastic scintillator 160 mm in diameter and 210 mm in length, as well as a photomultiplier.

In order to reduce the influence of the x-ray radiation from the generator on the detectors SD1, SD2, and SD3, the latter were placed in the leaden box 12 (see to Fig. 1). The Pb layer was 5 cm thick. The photomultiplying tubes were placed in the leaden container 13, its wall being 10 cm in thickness.

The additional leaden shielding 14 was placed between the generator MIG and the box 12 to overlap the main stream of the x-ray radiation from the generator MIG. This shielding was located near the wall of the diagnostic chamber 6 of the load module. The shielding was 20 cm in thickness.

Four-channel digital oscilloscopes were to detect signals from all detectors.

The targets were made of deuterated polyethylene in the form of a disk with a diameter of 40 mm and a thickness of 0.2 mm. The total area of the target was 250 cm^2.

Upon completing the investigations on the optimization of the conditions for the hydrogen inverse Z-pinch formation, 10 shots were made.

As an example, the oscillograms of the signals from the optic detectors LD1, LD2, and LD3 for one of the shots is presented in Fig. 4. The oscillograms of the signals from the ion collectors IC1, IC2, and IC3 is presented in Fig. 5.

According to the preliminary estimations, the maximum of the energy distribution of the accelerated protons is within the range of 3–10 keV.

It should be noted that one of the most important features of the experiments at the accelerator MIG is the deposition of different materials on the CD_2 target surface.

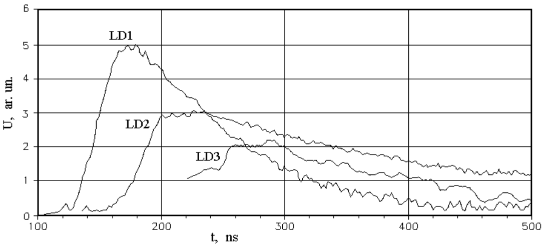

Fig. 4. Oscillograms of the signals from the optic detectors LD1, LD2, and LD3

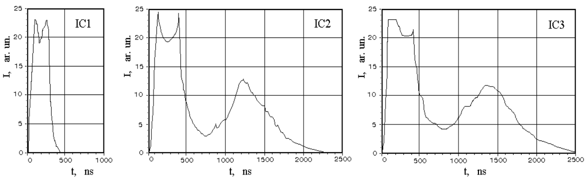

Fig. 5. Oscillograms of the signals from the ion collectors IC1, IC2, and IC3

Under the generator's powerful electromagnetic pulse (irradiation, skin effect, pressure of the magnetic field) the materials inside the diagnostic chamber partly evaporate and are deposited on the inner surface of the chamber.

The thickness of the deposit layer and its element composition were measured in several shots. With this aim glass disks of diameter 20 mm with plates of polished silicon on their surface were fixed on the targets. The thickness of the deposit film on the glass disk in the shot was measured by means of a profilometer, the silicon plate being used as a mask. The element composition in the thickness of the deposit film on the silicon plate was defined by the Auge spectrometry.

As an example, the results of the measurement of the element distribution in the thickness of the films deposited on the silicon plates 1 and 2 are presented in Fig. 6.

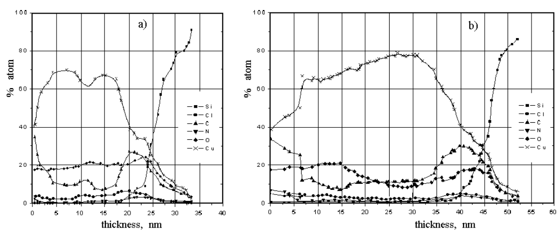

Fig. 6. Distribution of the elements in the thickness of the deposit layer: a) – for plate 1, b) – for plate 2

Plate 1 was placed in the middle of the target, where the maximum of the ion liner flow was expected. Plate 2 was displaced from the centre of the target by 4 cm to the diagnostic chamber cover.

It is seen from this distribution that in spite of the difference in the thickness of the deposition, 27 nm for plate 1 and 47 nm for plate 2, the element composition of the deposit film practically does not depend on the location of the used sample. The copper presence in the composition of the deposit film is basically connected with the evaporation of the copper wires, which are used as the cathode to maintain the galvanic contact of the liner current layer with the return conductor during the liner acceleration.

It should be mentioned that the absence of hydrogen in the element composition of the deposit film is connected with the fact the Auge spectrometry defines the presence of the elements starting from Li.

According to the 3-profilometry measurement, the thickness of the deposit film reaches 70 nm. It is approximately equal to the range of a proton with the energy 2 keV in copper [10].

However, this situation is not critical as the liner proton interaction with the target and the film formation of the deposit materials on the target surface are separated in time. The deposit film on the target surface appears substantially later in comparison with the time of the pd reaction.

Nevertheless, it is necessary to change the target or clean the deposit materials off the target surface after each shot.

The main results of the investigations are as follows:

1) the load module of the pulsed generator MIG for forming the hydrogen plasma flow in the inverse Z-pinch configuration is designed and created;

2) acceleration of the liner is realized in the energy interval 3–10 keV with an intensity of $\sim 10^{19}$ particles/pulse;

3) equipment for diagnostics of the formation of the liner plasma flow is designed and created;

4) experimental conditions for conducting investigations using the high-current generator MIG are examined.

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