ФІЗИКА ПЛАЗМИ
PLASMA PHYSICS

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STUDY OF LIGHT IONS ACCELERATION IN A DIODE WITH A SOLID TARGET AND REGISTRATION OF NUCLEAR PROTON-BORON REACTION PRODUCTS GENERATED IN THE PLASMA DIODE[a]

The results of proton fluxes registration and the nuclear reactions ($p + {}^{11}B \rightarrow 3\alpha$) they induce on boron-containing targets in a plasma diode pinch, generated by irradiation of the anode target with a relativistic electron beam, are presented. The dominance of protons as the fastest component of the explosive plasma fronts is observed, with energies exceeding those determined by the diode voltage. Alpha particles as products of nuclear reactions, are detected as emitted directly by the hot zone of the pinch when the anode target contains boron, as well as during the interaction of protons with the boron-containing screen behind the cathode, regardless of the anode target composition.

Keywords: self-magnetic pinch diode, plasma diode, micropinch, protons, alpha particles, collective acceleration, nuclear reaction.

1. Introduction

We present the results of experiments on the Shell Adamenko Driver (ShAD) apparatus, which realizes the breakdown of a vacuum diode of a special design with a solid-state target anode under the action of a voltage pulse with an amplitude of up to 1 MV. This facility is constructed using a high-voltage pulse generator based on a double-forming line [1] and a diode with a working pressure in the reaction chamber of $6 \cdot 10^{-2}$ Pa. The peculiarity of the processes at the ShAD facility is the combination of a micro-pinch discharge scenario and a plasma diode. Typically, a micropinch occurs in a vacuum diode as a result of electron self-focusing on the plasma formed by irradiation of the anode surface by the leading edge of the electron beam. Under certain diode parameters, a dense plasmoid, a "hot spot", is formed. At the ShAD facility, as well as at previously constructed facilities, in particular, the Impulse High Voltage Discharge (IHVD) facility [2], the anode target, which is a solid cylindrical rod, explodes as a result of focusing the electron beam directly on the target. The discharge takes the form of an intense plasma diode with a relatively dense plasma of the target material.

The micropinch hot spot was one of the centers of attention in the last century as an alternative project for inertial controlled fusion (ICF) [3 - 5]. Studies of the hot spot related to ICF were also performed at the Proton-21 Laboratory. At the IHVD facility with a diode voltage amplitude of 400 kV, protons with energies up to 1 MeV were recorded using a Thomson mass analyzer, in which a thin beam of explosive plasma in the diode's behind-anode space is split in crossed magnetic and electric fields according to M/Z ratio of the ions [2]. In separate experiments using boron-containing targets on the Thomson parabola M/Z = 2, groups of alpha particles were recorded. These data made it possible to declare the initiation of a certain number of nuclear reactions $p + {}^{11}B \rightarrow 3\alpha + 8.7$ MeV – "pB reactions" (proton-boron reactions) – and became the basis for studying and scaling up the effects of collective proton acceleration in plasma-diode discharges initiated in the Proton-21 Laboratory.

It should be noted that protons are observed in all discharges of the vacuum diode type and are a mandatory component of the anode plasma. This is due to the desorption and ionization of hydrogen-containing organic condensate, which typically forms on the anode surface as a result of pumping the working chamber and the adsorption of atomic layers of water condensate in the vacuum environment. The physics of modern megavolt diodes used for X-ray radiography at Sandia National Laboratories, USA (RITS-6 accelerator), CEG, France (ASTERIX generator), is largely explained by the presence of hydrogen ions generated from anode surface contamination "surface contaminants" [6 - 8]. Modeling of the contribution

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of anode-derived protons gives an estimate of the order of 10 monolayers and higher (1 ML = $= 10^{15}$ particles/cm²) [6]. It has been shown in [6 - 8] that the self-magnetic pinch impedance and current are largely determined by the anode plasma triggered by surface contamination of the anode in a hotspot-free regime, which is optimal for X-ray imaging purposes. Quantitative estimates of the anode plasma generated by the electron beam are given in [6, 8, 9] based on modeling with a code that takes into account the interaction of electrons with the plasma formed by the desorption of ions from the anode surface. In these calculations, plasma is considered as a single fluid, and the M/Z parameters are not present in the analysis at all. Therefore, the effect of the formation of the plasma component of accelerated protons is ignored. It should also be noted that the work [9] was performed on a super pinch diode, the parameters of which, as well as the method of pulse generation, are very close to those implemented at the IHVD facility.

Although the generation of protons with energies in the MeV range has been observed in the other plasma diodes (see e.g. [10]), the effect of the dominance of accelerated protons in explosive plasma fluxes was especially pronounced at the ShAD facility. The most complete theory of collective plasma acceleration processes is based on the concepts of the Hall electron MHD theory [11 - 14]. The plasma ions with the smallest M/Z ratio form the leading edge and carry the frozen magnetic field along with the accompanying electrons [14]. Thus, it can be implied that protons, as the lightest ions corresponding to the smallest value of M/Z = 1, provide the fastest evolution of plasma fronts, both during implosion and explosion. The subrelativistic protons are weakly thermalized and are controlled only by the Hall microfield of the fronts. At the same time, the heavy ions of the dense plasma are a target for non-thermalized proton fluxes.

The ShAD facility is characterized by significantly increased energy and pulse length (up to 100 ns) compared to the IHVD facility, and more massive anode targets with a working diameter of 3 - 8 mm. The number of protons in the anode plasma in experiments at the ShAD facility increases by orders of magnitude. The energy spectrum of protons is characterized by an increased value of the upper limit up to 2 MeV.

The aim of the work was to obtain and record accelerated proton fluxes with energies in the range where the effective cross-section of pB reactions is localized, and to initiate an increased number of these reactions in a plasma diode with boron-containing targets, compared to IHVD-type installations [2]. The obtained results indicate that these reactions produce alpha particles both within the explosive plasma – when boron-rich anode targets are used – and beyond the interelectrode gap, regardless of the target material, when secondary boron-containing screens are placed in the post-cathode region. Section 2 describes the design and electrical parameters of the ShAD experimental setup and diagnostic equipment; Section 3 describes the study of accelerated ions; Section 4 presents the results of recording the products of pB reactions; Section 5 concludes with remarks on the problems and prospects for continuing these experiments at the ShAD setup.

2. Description of the plant and equipment

A general view of the ShAD unit is shown in Fig. 1; a sketch of the reaction chamber together with the diode scheme is shown in Fig. 2. The unit accumulates energy of up to 35 kJ in the capacitors of the Marks oscillator, which is transferred to a double forming line of the triaxial Blumlein line type [1]. The output voltage pulse is close to rectangular. In the ShAD setup, the double shaping line is matched, in which up to 30 % of the energy of the storage device is transferred to the diode load.

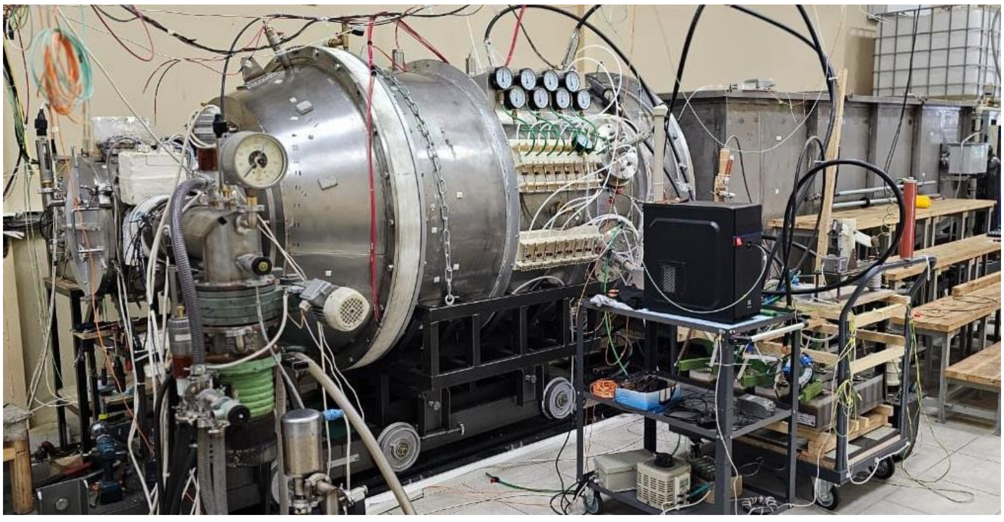

Fig. 1. Exterior of the “ShAD” installation. (See color Figure on the journal website.)

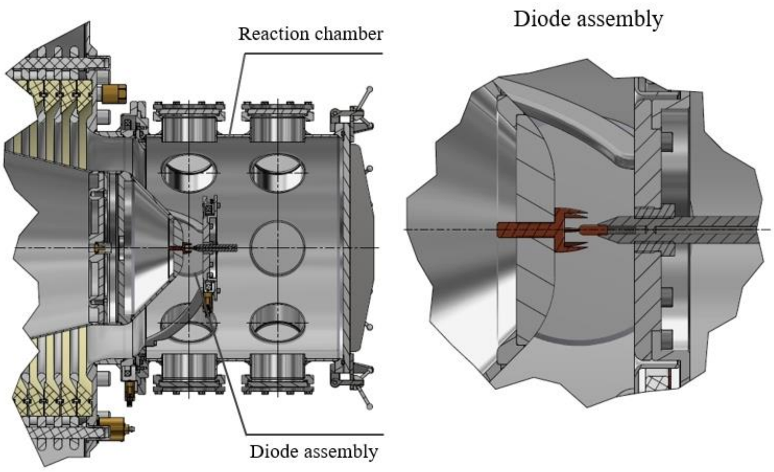

Fig. 2. Sketch of the reaction chamber and diode of the "ShAD". (See color Figure on the journal website.)

The anode target is positioned on the diode axis within the interelectrode gap, where it initiates plasmoid formation due to the self-focusing of the electron beam in the anode plasma. The evolution of the target proceeds explosively: the bulk material is vaporized and ionized. The resulting plasma-filled diode acts as the load for the ShAD shaping line over a duration of approximately 100 ns. Current and voltage pulses in the sub-microsecond range are measured using a Rogowski coil and a resistive voltage divider based on an aqueous $CuSO_4$ solution, respectively. A storage oscilloscope with a 500 MHz bandwidth is used to record the signals. The corresponding voltage and current waveforms are presented in Fig. 3.

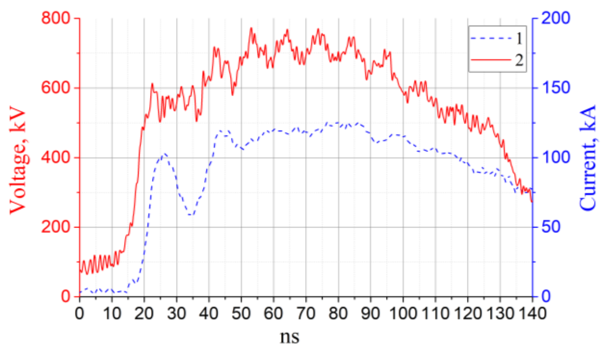

Fig. 3. Voltage and current waveforms. *1* – current (Rogowski coil); *2* – voltage (resistive voltage divider). (See color Figure on the journal website.)

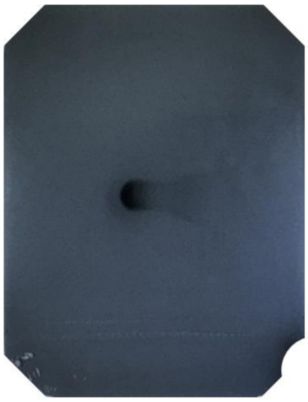

Fig. 4. Image of a 6.0 mm target anode in X-rays, using SD-Speedx film, class D, size 30 × 40 (experiment SH42944).

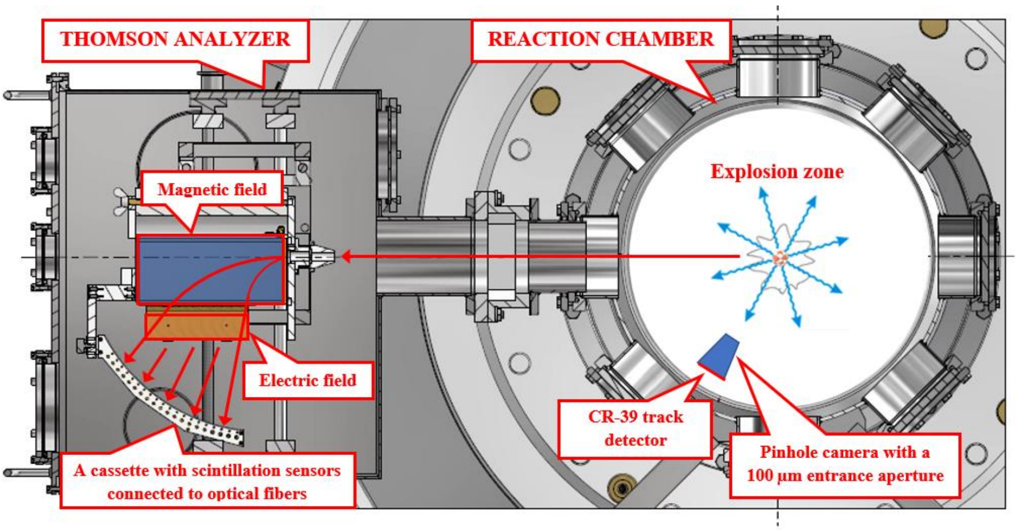

Fig. 5. Schematic view of the reaction chamber of the ShAD unit and diagnostic tools. (See color Figure on the journal website.)

Fig. 4 shows a photograph of the film exposed in an X-ray camera. The size of the image coincides with the size of the target in accordance with the aspect ratio and indicates the presence of focusing of the electron beam on the surface of the target anode.

The corpuscular radiation was recorded and diagnosed at the ShAD experimental setup using a Thomson mass analyzer and an ion obscura camera. Carbon-containing screens (graphite, polyethylene) were also used, which were activated by plasma flows during the experiment and then examined on a gamma spectrometer, where the annihilation gamma peak associated with the β^+ activity of the ^{13}N isotope was recorded. A schematic view of the Thomson mass analyzer assembled with the reaction chamber of the ShAD experimental setup, and the ion camera-obscura is shown in Fig. 5. Ion signals are recorded using CR-39 solid-state track detectors and scintillation sensors.

3. Research of accelerated ions

The study of accelerated particles with ion optics (camera obscura) makes it possible to capture images of the diode hot zone. Fig. 6 shows images for two experiments with different anode target materials: polyethylene and titanium, obtained with CR-39 solid-state track detectors. These images are formed mainly by proton tracks with energies of hundreds of kiloelectron volts, which are superimposed by bands produced by successive hot zone radiation fronts. This effect was called hot spot flickering in [2] and corresponds to the registration of proton signals in a Thomson mass analyzer. In the case of using polyethylene targets, an increased number of protons is observed, although their energy is characterized by a lower level. The upper part of the dense track image is formed by the fastest protons of the expanding plasma front. The continuation of the image to the lower part of the detector is formed by the deflection of slower protons in the magnetic field of the pinch.

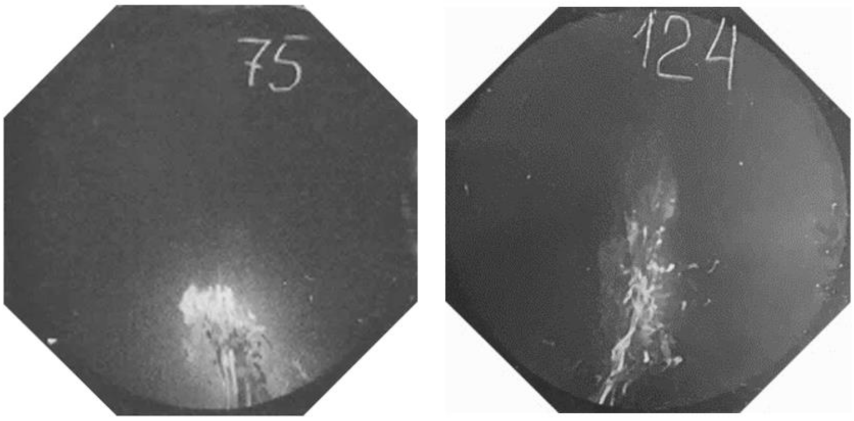

Fig. 6. Images of plasmoids on CR-39 track detectors No. 75 (experiment SH40767, target: polyethylene, Ø5.0 mm) and No. 124 (experiment SH42436, target: Ti, Ø5.0 mm).

To analyze the fluxes of fast ions of the expanding plasma, a Thomson mass analyzer is used, which is located outside the discharge chamber at a distance of 60 cm from the diode axis and analyzes a thin ion beam emitted in the equatorial plane of the diode (see Fig. 5). This beam successively passes a special collimation system, crossed magnetic and electric fields. The ion signals in the mass analyzer are recorded by scintillation detectors, which allow for time-of-flight measurements and identification of light ions. These measurements are periodically duplicated by track detectors. Fig. 7 shows an oscillogram of signals from scintillation detectors located within the basic parabola M/Z = 1. This parabola registers only proton signals and indicates the presence of a number of proton re-launches from the hot zone and a wide range of their energies from 100 keV to 2 MeV. The upper limit of the proton energy spectrum, which is an indicator of the efficiency of the acceleration process, is determined in the experimental cycle in the range from 1.00 ± 0.16 MeV to 2.00 ± 0.4 MeV. The measurement errors are primarily due to the limited resolution caused by the size of the scintillators, and more significantly, by the beam aperture at the collimator exit. The errors in proton energy values increase due to the decrease in the resolution of the analyzer's scintillator line in the high-energy region. Due to the difficulties of calibration and location of additional optical channels for recording signals from scintillation detectors at the positions M/Z > 1, the main part of the experiments was performed without turning on the electric field. In this configuration, all scintillation detectors were installed in the zero position without taking into account mass deviations. The presented oscillogram (Fig. 8) demonstrates the presence of a multicomponent ion component in the plasma process of this experiment, and due to the time-flight analysis, it makes it possible to identify proton signals.

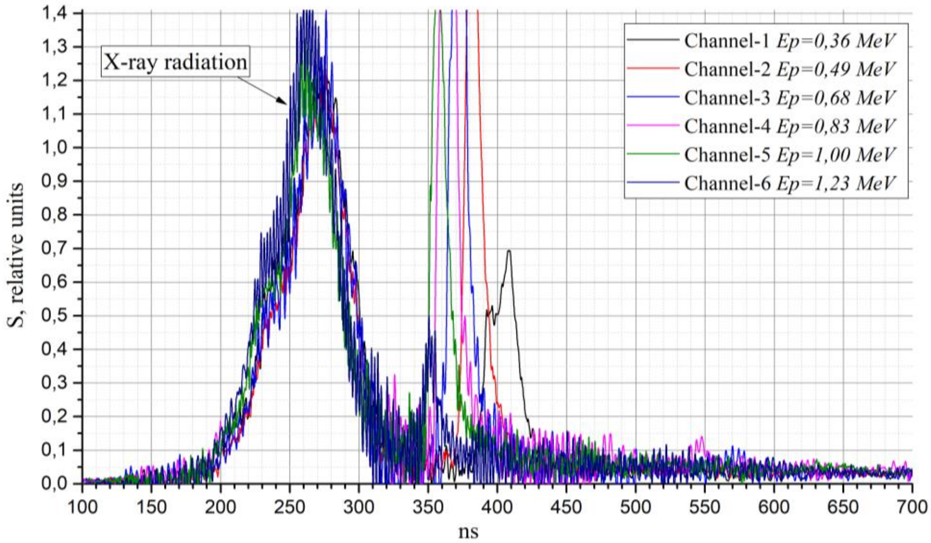

Fig. 7. Oscillogram of signals from scintillation detectors in the Thomson mass analyzer within the basic position M/Z = 1 (experiment SH42881). (See color Figure on the journal website.)

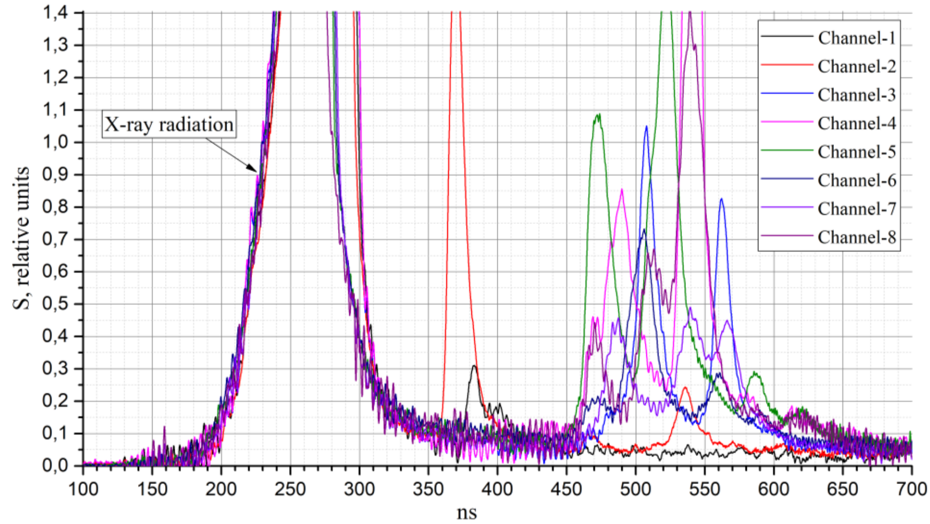

Fig. 8. Oscillogram of signals from scintillation detectors in a Thomson mass analyzer with the electric field turned off (experiment SH42918). Channel-1 – Ep = 0.36 MeV; channel-2 – Ep = 0.49 MeV. (See color Figure on the journal website.)

There is also a problem that during studies of plasma flows that expand after the target explosion, at considerable distances from the diode axis, a strict radial dispersion of particles is not ensured. This is influenced by many physical and design factors. As a result, the mass analyzer, which in this configuration is located in the equatorial plane, cannot always analyze the radial flux. Therefore, signal analysis in each experiment is not always possible. The influence of these factors is much less in the ion camera-obscura since they are located much closer to the diode axis.

In order to study the space distribution of fast proton flows, we measured the gamma activity of carbon-containing screens (graphite, polyethylene) irradiated by decay plasma. This technique is commonly used to diagnose accelerated protons in diode accelerators [10]. Under the action of accelerated protons, ^{13}N is produced by the reaction $^{12}C(p, \gamma)^{13}N$. The decay of ^{13}N is accompanied by the emission of positrons. A gamma spectrometer with a 63-mm NaI(Tl) scintillation detector records a 511 keV annihilation gamma peak. For the first time at the ShAD facility, we registered the presence of gamma activity on a structural element of the cathode assembly of our facility. Within 5 min after the experiment, this unit was dismantled and placed in a gamma spectrometer. During the measurement, a rather intense peak with an energy of 511 keV was registered in the spectrum (Fig. 9). To reliably identify the half-life of ^{13}N, up to 5 sets of spectra were taken for 600 s each. After the measurements and calculations, it was determined that the half-life of the source of this peak is 10 min with an error of ±30 s. Thus, we believe that this peak belongs to the nitrogen isotope ^{13}N.

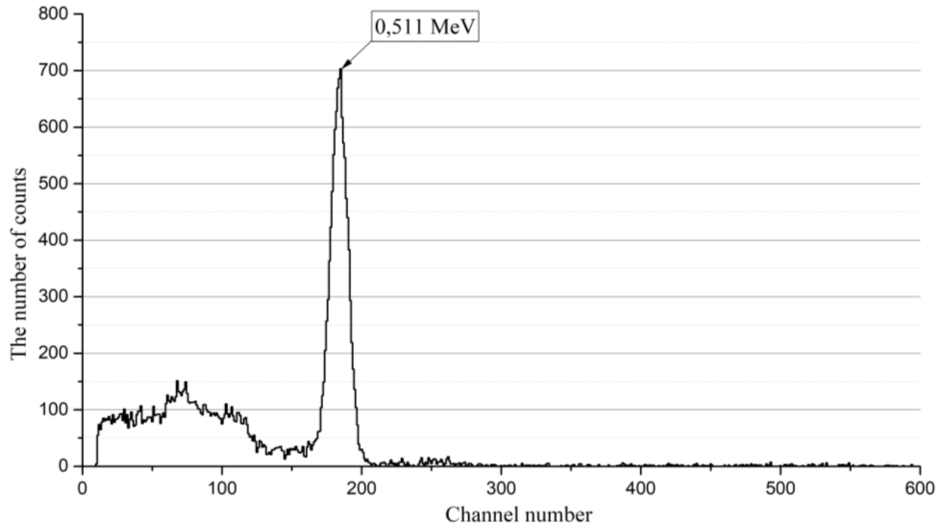

Fig. 9. An example of a gamma spectrum with an annihilation peak of 511 keV (experiment SH42522).

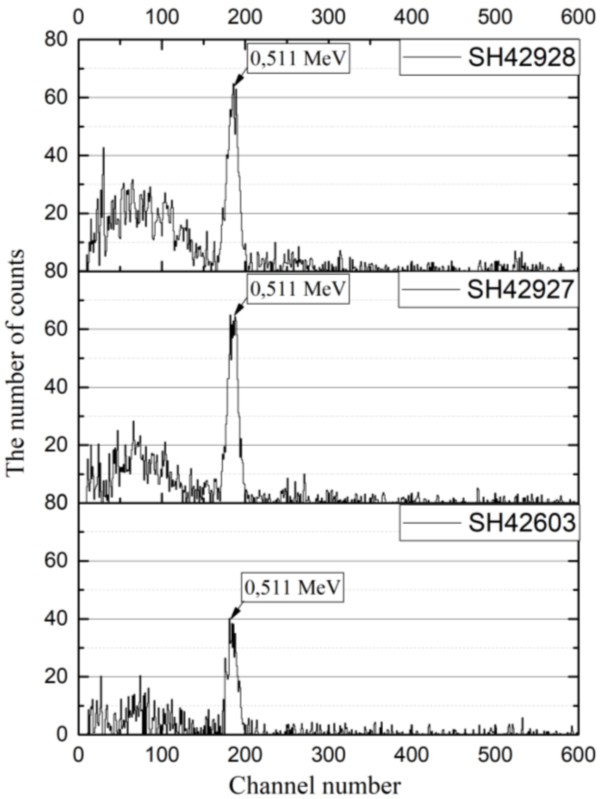

Fig. 10. Relative intensities of 511 keV annihilation gamma peaks recorded on carbon-containing films placed in different directions of plasma spread: SH42928 – post-anode region, SH42927 – post-cathode region, SH42603 – equatorial plane.

Subsequent investigations focused on the anisotropy of accelerated proton dispersal during the explosion of the target anode. Carbon-based films were employed as diagnostic screens. They were positioned in the post-cathode and post-anode regions, as well as in the equatorial zone of expanding plasma material. Gamma-ray activity measurements of these films, conducted following the experiment, confirmed that proton emission occurred in all directions from the explosion zone. The highest intensity of the accelerated proton flux was observed in the post-cathode and post-anode regions of the diode. Representative gamma spectra are presented in Fig. 10.

To avoid the problem of collimation of superfast proton signals in the Tomson analyzer, a directional channel was implemented along the diode axis within the cathode assembly. This channel separated a dense stream of accelerated ions directed toward the post-cathode area. Numerous measurements were conducted using CR-39 track detectors combined with various absorbing filters. Analysis of the tracks, following the methodology described in [2, 15], and accounting for proton energy losses in filters of specified thickness, indicated that proton energies reached up to 1.5 - 2.0 MeV. For example, Fig. 11 shows a track detector covered by a 20 μm aluminum filter.

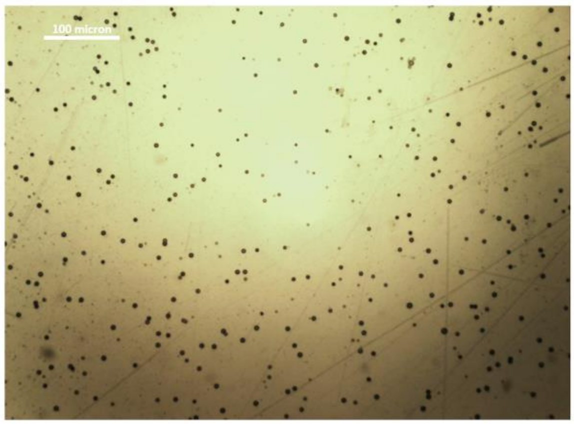

Fig. 11. Image of a fragment of the CR-39 track detector in the area covered by a 20 μm thick aluminum filter (experiment SH42942). (See color Figure on the journal website.)

The residual proton energy after passing through this 20 μm aluminum layer is approximately 600 keV.

Protons with 600 keV energy have a range of about 7 μm in aluminum. Therefore, prior to the aluminum filter, protons must have had sufficient energy to travel through an equivalent of 27 μm of aluminum. This corresponds to an initial proton energy of 1.5 ± 0.3 MeV.

4. Registration of pB reactions

The registration of pB reaction products, also known as the “3α reaction” with a total yield of 8.7 MeV, is the goal of many studies (for example, see [16, 17]). To maximize the yield of this reaction, protons should have an energy of 600 - 700 keV. Below are the results of recording the products of the pB reaction in an experiment with a primary anode target containing boron and secondary boron-containing substrate targets placed outside the diode gap. Fig. 12 shows the oscillogram of signals from scintillation detectors located within the M/Z = 2 parabola of the Thomson mass analyzer in the experiment with a composite boron-containing target Ø5.0 mm. In this experiment, the mass analyzer investigated the ion composition of the fast plasma flows from the target within the established parabola with eight discrete energy channels. The oscillogram shows that channels No. 7 and 8 registered two intense peaks corresponding to alpha particle energies in the energy range from 2.4 to 3.0 MeV with an error of ±0.2 MeV. The time-flight analysis for these channels is 74 and 84 ns, respectively, which corresponds to the presented oscillogram if the ion start occurs immediately after the X-ray flash. Thus, we conclude that the recorded signals belong to alpha particles, the products of pB reactions. At previous IHVD installations, the products of these reactions were confirmed using CR-39 track detectors, using the tracking technique – “the method of linear asymptotics of track lengths” [2, 15, 18].

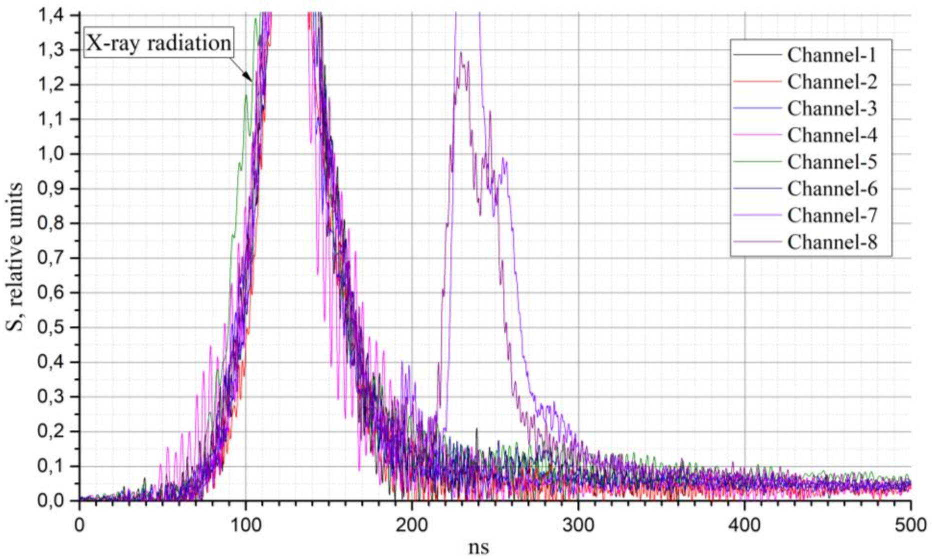

Fig. 12. Oscillogram of signals from scintillation detectors in the Thomson mass analyzer within the position M/Z = 2 (experiment SH41138). (See color Figure on the journal website.)

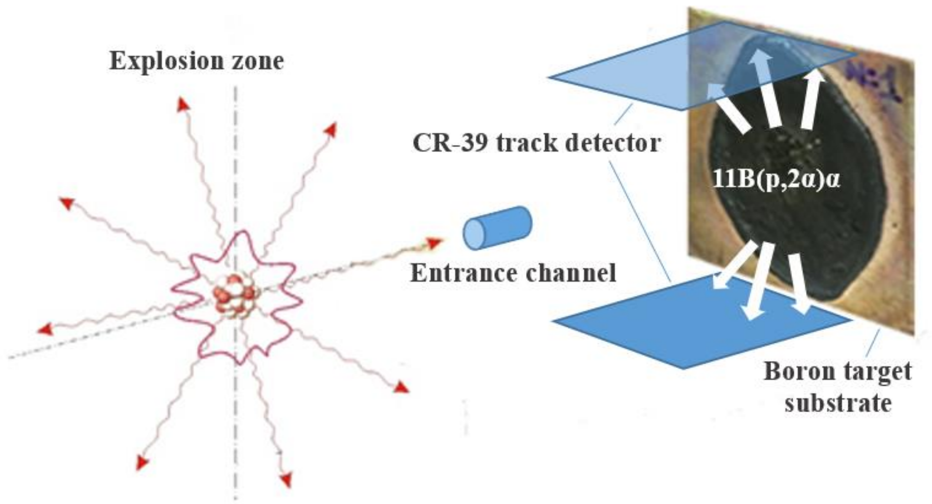

Fig. 13. Schematic of the experiment using a substrate containing boron. (See color Figure on the journal website.)

To investigate the effects on accelerated protons in the post-cathode region, an experiment was performed involving irradiation of a secondary boron-containing substrate target. The pB reaction was also realized on this target. The scheme of the experiment is shown in Fig. 13. Fig. 14 shows abundant alpha track deposits on CR-39 track detectors placed at right angles to this secondary target. Track analysis confirms the presence of alpha particles with energy close to 3 ±0.4 MeV. At the same time, the room background is exceeded by many orders of magnitude; the question of the origin of the tracks is resolved without reference to the alpha locus due to the incidence angle of the particles and the obvious beam-like character of the irradiation from the boron-containing substrate. In experiments where the same configuration was used but the substrate did not contain boron, the alpha particle beam track signal was absent.

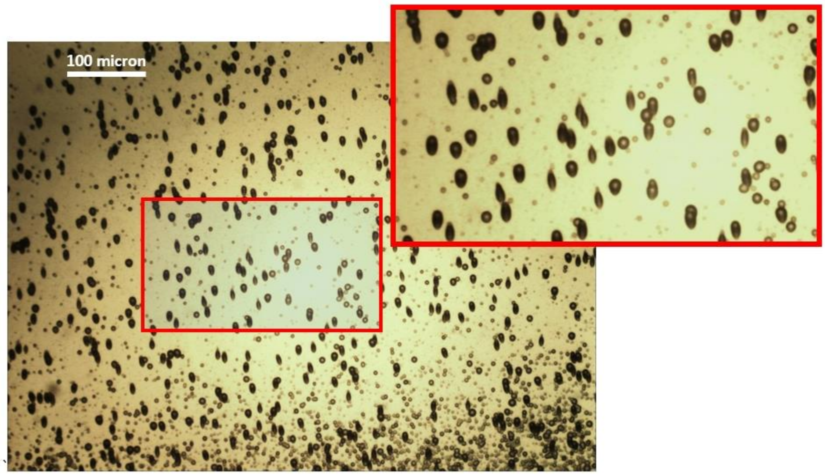

Fig. 14. An image of a fragment of the CR-39 track detector showing directional tracks of alpha particles generated on a boron target. (See color Figure on the journal website.)

It should be noted that the laboratory regularly performs background studies. For track measurements, we use CR-39 detectors of high purity and quality from the American company RTP, PSS-3000. The presence of the background is checked selectively for each batch. With the detectors used, the background is caused mainly by the radon activity of the air in the working room and the time within one hour spent on the preparation of the experiment. In the working room, we estimate the radon activity of the air to be 30 Bq/m^3.

5. Conclusions

The presented results indicate that the parameters of the ShAD facility allow the realization of collective proton acceleration effects. In this communication, we present evidence for the existence of accelerated protons with energies up to 2 MeV. The registered alpha particles are products of pB reactions caused by fast protons in the plasma of boron-containing anode targets, as well as outside the diode in the post-cathode region on secondary boron-containing screens without applying boron-containing anode targets. Intense alpha particle signals were recorded in all experiments involving successful damage of boron-containing targets, whereas only 7 % of experiments at the IHVD [2] were successful in this regard. These processes are characteristic of the self-organization of the plasma diode, which, however, do not occur under optimal conditions in our experiments. The quantitative proportions of the plasma components are not controlled but can be improved.

The use of boron-containing capsules as targets overload the plasma with carbon and heavy metal ions. An ideal scheme for initiating pB reactions would be to implement a diode with a pure boron-hydrogen plasma. The creation of lightweight relatively pure targets based on natural amorphous boron is not an unattainable goal and is envisaged in the program of further research at the ShAD facility. It is necessary to experiment with discharges in hydrogen as a working gas, to clarify the energy spectrum of accelerated ions. It is possible to implement the scheme of forming the plasma of the anode target by local pulsed hydrogen injection. The possibilities of improving the diode design, which can improve the alignment with the forming line of the installation, are far from being exhausted.

Various variants of the scheme for the hybrid realization of ionic inertial controlled nuclear fusion using various targets, both primary anode and secondary peripheral targets, are possible. The plasma diode ShAD can be realized with deuteride-lithium anode targets and in deuterium as a working gas. The basis for the realization of these tasks is the experience and technologies developed at the Proton-21 Electrodynamic Research Laboratory.

The high beam intensity in the plasma diode implemented in the ShAD facility makes it attractive for rapid compression of fusion fuel. The possibility of transporting the beam from the diode to the fuel through the anode target in the form of a cylindrical rod provides flexibility in the fuel compression technique. However, much more research is needed to understand the interaction of the beam with the fuel.

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ДОСЛІДЖЕННЯ ЛЕГКИХ ПРИСКОРЕНИХ ІОНІВ У ДІОДІ З ТВЕРДОТІЛЬНОЮ МІШЕННЮ ТА РЕЄСТРАЦІЯ ПРОДУКТІВ ЯДЕРНИХ pB-РЕАКЦІЙ, ГЕНЕРОВАНИХ У ПЛАЗМОВОМУ ДІОДІ

Наведено результати реєстрації потоків прискорених протонів, і спричинених ними на бормістких мішенях ядерних реакцій p + ^{11}B → 3α у плазмово-діодному пінчі, індукованому опроміненням релятивістським електронним пучком анодної мішені, що містить бор. Спостережено домінування протонів, як найшвидшої компоненти фронтів експлозивної плазми, прискорених до енергій, що перевищують значення, зумовлені напругою діода. Виявлено альфа-частинки – продукти ядерних реакцій, що випромінюються як безпосередньо гарячою зоною пінча, якщо анодна мішень містить бор, так і при взаємодії протонів з бормістким екраном за катодом, незалежно від складу анодної мішені.

Ключові слова: діод із самомагнітним пінчем, плазмовий діод, мікропінч, протони, альфа-частинки, колективне прискорення, ядерна реакція.

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