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Prompt γ and neutron spectrometry of intense nanosecond ion bunches collectively accelerated in a Luce diode

V.A. Ryzhkov[*], *I.N. Pyatkov*

Tomsk Polytechnic University, Tomsk, Russia
[*]*ryzhkov@tpu.ru*

Abstract. Instantaneous time-of-flight spectrometry of neutrons (nToF) and γ-spectrometry from nuclear reactions generated by nanosecond proton and ^{12}C ion bunches collectively accelerated in a Luce diode at a voltage across the diode of 200–300 kV has been thoroughly researched. A two-channel γ-spectrometer with time resolution of 2.5 ns enables a prompt control of number and energy of collectively accelerated protons in their separate bunches dumped into a sustainable and refractory B_4C target. Combination of nuclear reactions $^{10}B(p,\alpha\gamma)^7Be$, $^{12}C(p,\gamma)^{13}N$, and $^{11}B(p,\gamma)^{12}C$ was used to characterize the intense nanosecond proton bunches with energy and number per shot in excess of 500–750 keV and $6\cdot10^{14}$, respectively. The radioactivity of ^7Be and ^{13}N radionuclides was measured with a conventional HP Ge detector to calibrate the prompt technique. The threshold nuclear reaction $^{11}B(p,n)^{11}C$ was used to perform nToF spectrometry of high-energy protons bunches with energy higher than 3.02 MeV, while $^{12}C(d,n)^{13}N$ and $^2H(^{12}C,n)^{13}N$ reactions were used to control deuteron and ^{12}C ion bunches.

Keywords: collective ion acceleration, virtual cathode, prompt nuclear spectrometry.

1. Introduction

Collective ion acceleration was discovered by Plyutto in experiments exploiting pulsed vacuum arcs as early as in 1960 [1]. Luce proposed a distinct configuration of vacuum diode to collectively accelerate ions by a beam of relativistic electrons which passes through an aperture in the dielectric anode insert, vaporizes partially the anode surface, and atomizes and ionizes the evaporated insert elements, mostly hydrogen and carbon, then captures and finally drives the protons (and possibly the heavy ions) in some way, accelerating them to energies that are usually multiples of the initial potential applied to the diode U_d [2]. Such a configuration later received the common name “Luce diode”, although some workers argue that the configuration was principally similar to the one used by Plyutto [3]. Our approach to studying the model of collective ion acceleration is to use nuclear analysis methods to diagnose ion bunches accelerated by a Luce diode operated in the same configuration of electrodes at moderate voltage values of about 250 kV [4–10]. At such voltages, on the one hand, accelerated ions are already capable of generating nuclear reactions in targets made of light elements, but, on the other hand, it is still possible to selectively excite the required analytical reactions and generate selective signals that can be unambiguously attributed to one or another group of accelerated protons and heavy ions (mainly ^{12}C ions).

2. Experimental

Here we report our recent results on a selective γ- and ToF spectrometry of neutrons generated by ions collectively accelerated with a Luce diode mode of TEMP-4M accelerator which was mostly described in [4–10]. Usually, two types of dielectric anode inserts with a hole diameter of 12 mm were used: polyethylene 8 mm thick and h-BN 2–4 mm thick. The end of a cylindrical tungsten cathode 20 mm long and 4 mm in diameter was aligned with the outer end of the anode insert. Several series of shots were carried out at different pressures of the residual atmosphere of the drift chamber. Pressure of the residual atmosphere was controlled from 10^{-5} to $2.5\cdot10^{-3}$ Torr with a use of Russian made device MERADAT-VIT19IT2. The voltage across the diode was controlled by changing the voltage of the double forming line (Blumlein). Fig.1 shows a typical scheme of registration of prompt electrons emitted by virtual cathode (VC), Bremsstrahlung, γ-rays and neutrons from nuclear reactions.

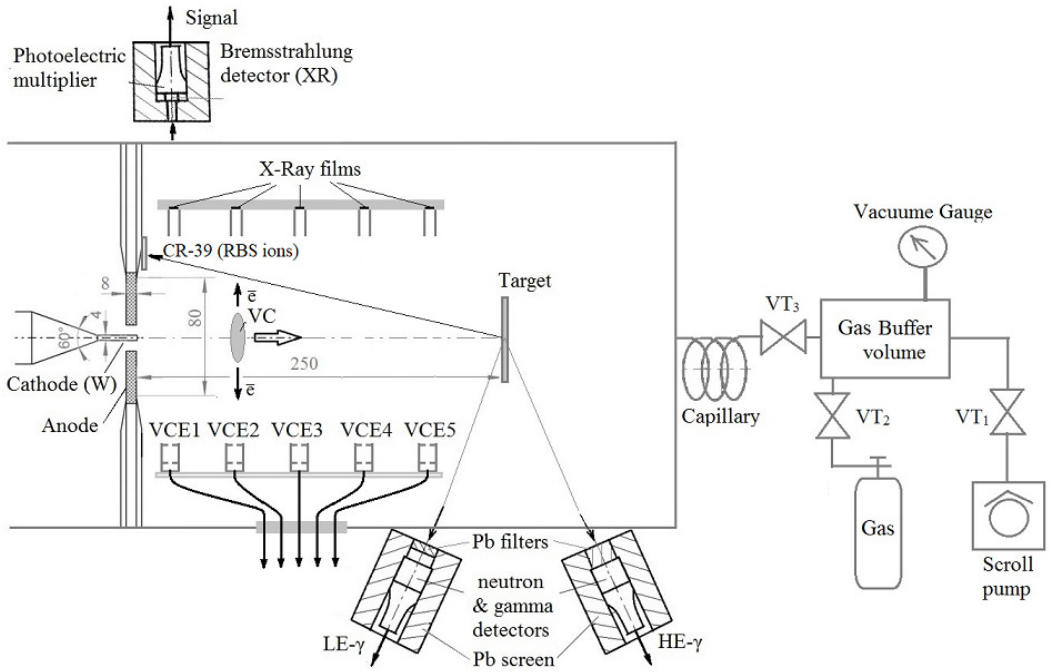

Fig.1. A typical scheme of registration of electrons emitted by virtual cathode (sensors VCE1-VCE5), prompt Bremsstrahlung (XR), γ-rays and neutrons from nuclear reactions.

Typically, three organic scintillation detectors of SP101 type (Hangzhou Shalom Electro-optics Technology Co., Ltd, China), axially oriented towards objects under interest like the target center or the diode electrodes, were used to register the prompt neutrons, γ-rays and Bremsstrahlung. Detectors destined to register Bremsstrahlung, low energy and high-energy γ-rays are further referred as XR (X-Ray), LE-γ and HE-γ, respectively. All the detectors more effectively register low-energy neutrons (up to 0.5–0.7 MeV) rather than γ-rays. The time resolution for a single cosmic γ-ray at the FWHM was about 2.5 ns for all three detectors coupled with Philips Photomultiplier tubes XP2020. Signals from the detectors were registered by Tektronix TDS224 digital oscilloscope. The cables were matched in length to provide the same signal delay as it was for the voltage and electric current signals. All the intrinsic signal delays of the detectors were measured and taken into consideration when time of arrival of ion and/or neutron bunches was estimated. In all the following temporal graphs, the zero point for time is matched at the start of voltage applied to the diode (U_d). The distance between the irradiated target and the anode was controlled within the interval from 3 to 60 cm. To estimate the contributions of protons and ^{12}C ions in ion bunches collectively accelerated in the Luce diode, we used the detection of Rutherford backscattered (RBS) ions by CR-39 track detectors places at the anode holder and observing angles of 150°–160°.

3. Results and discussion

3.1. Prompt γ-spectrometry

For instantaneous control of the number and energy of protons in individual bunches collectively accelerated in a Luce diode, a two-channel γ-spectrometer was proposed and experimentally studied [4], in which time-resolved determination of the energy and number of protons in different proton bunches in each shot is possible due to selective measurement by two fast organic detectors (with a resolution time of about 2.5 ns and better) of different sizes, placed in lead shielding of different thicknesses (2 and 7 cm) of signals from instantaneous γ quanta with an energy of 429 keV (LE-γ detector) from the nuclear reaction $^{10}B(p,\alpha\gamma)^{7}Be$ and γ quanta with $E_\gamma \geq 2366$ keV (HE-γ detector) from the $^{12}C(p,\gamma)^{13}N$ and $^{11}B(p,\gamma)^{12}C$ reactions excited in the B_4C

target. The ratio of the signals and their absolute values at the instants of time corresponding to the discharge of bunches of collectively accelerated protons onto the target determine the energy and number of protons in these bunches, respectively [4]. The calibration of the instantaneous γ-spectrometer of proton bunches is carried out by the radioactivity ^{7}Be and ^{13}N induced in the B_4C plates [5]. The use of the γ-spectrometer in combination with a virtual cathode (VC) time-of-flight spectrometer emitting electrons along the normal to the axis of its motion, recorded by VCE1–VCE5 sensors, made it possible to prove that the VC and the main group of ions arrive at the target simultaneously.

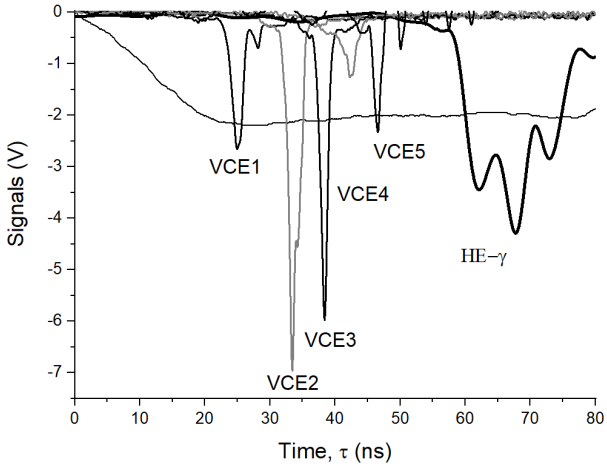

Fig.2. Signals from VCE detectors, HE-γ-detector and diode voltage signal for a typical shot done at at CF_2 target placed at Z = 25 cm from anode.

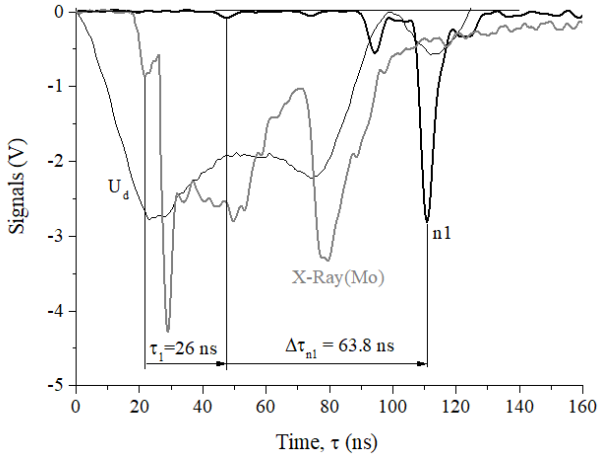

Fig.3. Signals of shot at $Ca(OD)_2$/Mo: τ_1 = 26 ns is ToF of the ion bunch from anode to target , $\Delta\tau_{n1}$ = 63.8 ns is ToF of the neutron bunch from target to detector n1 [10].

3.2 ToF of neutrons from threshold nuclear reactions

Time-of-flight spectrometry of neutrons (nToF) from threshold nuclear reactions is based on a sharp increase in the yield of the (ion,n) reaction and, accordingly, neutrons with energies of ~0.5 MeV with an increase in ion energy of at least 0.5 MeV above the threshold. Neutrons with this energy can be detected with high efficiency by organic scintillators. With a further increase in the energy of the ion, the energy of the neutrons produced in the threshold reaction also increases, which sharply reduces the efficiency of detection of such neutrons. As a result, neutron spectrometry from each selected threshold reaction is selective with respect to the ion energy exceeding the threshold value by a certain value, which is determined by the rate of growth of the reaction cross section with increasing ion energy from the threshold value.

Thus, to estimate number and energy of high-energy protons collectively accelerated in a Luce diode, we studied the threshold reaction $^{11}B(p,n)^{11}C$ (3.02 MeV), which make it possible to estimate the number of protons with an energy of higher than 3.1 MeV in a single shot [6]. The nToF spectrometer is calibrated by measuring the ^{11}C radioactivity induced in the refractory B_4C targets. In this case, the energy and number of protons of the main group (450–800 keV) are also controlled by the induced activity of ^{7}Be and ^{13}N, and the number of ^{12}C [7] ions is also controlled by the activity of ^{18}F. The fractions of high-energy protons with energies of ~3.4 MeV during collective acceleration in the Luce diode vary quite widely from shot to shot, and on average over a series of 10 shots they were about $5\cdot10^{-5}$ part of the main group of protons (on average ~10^{14} per shot). In the future, of interest for refining the spectrum of protons with energies above 1 MeV is the use of threshold reactions $^{55}Mn(p,n)^{55}Fe$ (E_{th} = 1.03 MeV), $^{93}Nb(p,n)^{93m}Mo$ (1.2 MeV), $^{51}V(p,n)^{51}Cr$ (1.565 MeV)) and $^{7}Li(p,n)^{7}Be$ (1.88 MeV).

There are only a few threshold (d,n) reactions, of which two are of practical interest: $^{12}C(d,n)^{13}N$ (0.328 MeV) and $^{16}O(d,n)^{17}F$ (1.83 MeV), which proceed in good , targets made of these elements can be refractory (graphite, carbides, and oxides), which makes it possible to perform radioactivation calibration of nToF spectrometers. The first reaction was used in this work for the nToF spectrometry of the main group of collectively accelerated deuterons bumped on graphite targets. It is shown that the main group of deuterons is accelerated in the Luce diode to the same speed as protons, but their number ($5\cdot10^{12}$ per shot on average) is an order of magnitude smaller than the number of protons ($5\cdot10^{13}$ per shot on average), even when using an anode insert made of deuterated polyethylene [8]. When deuterons are accelerated from the residual atmosphere of deuterium, their energy is the same, but the number was still an order of magnitude lower ($5\cdot10^{11}$ per shot on average) even at the maximum tested pressure of 1.34 mTorr. Nevertheless, the number of accelerated deuterons increased exponentially with increasing pressure in the investigated range of 0.22–1.34 mTorr [9]. In the near future, it is planned to use targets made of refractory oxides for spectrometry of the high-energy group of deuterons with an energy of about 2 MeV/amu by using the $^{16}O(d,n)^{17}F$ reaction.

As regards the spectrometry of collectively accelerated ^{12}C ions, the best possibilities for the main group of ions are nToF spectrometry based on the threshold reaction $^{2}H(^{12}C,n)^{13}N$ (E_{th} = 2.3 MeV) implemented in [10]. In this case, $Ca(OD)_2$ layers deposited from CaO suspensions in heavy water onto molybdenum foils 250 μm thick were used as accessible deuterium-containing targets – see typical signals from such a target in Fig.3. The following facts were established for the collective acceleration of ^{12}C ions in a Luce diode with anode inserts made of polyethylene and h-BN: the speed of ^{12}C ions is equal to the speed of the main group of protons, which indicates the joint acceleration of protons and carbon ions by one mover (virtual cathode); the number of ^{12}C ions captured in the collective acceleration is proportional to the pressure of the residual atmosphere of the working chamber and does not depend on the material and geometry of the anode insert, i.e. does not depend on the conditions of near-anode plasma formation, which means that they are captured into acceleration from the residual atmosphere on the way from the anode to the target. As for the high-energy groups of collectively accelerated ^{12}C ions, for these purposes it is planned to use selective nuclear reactions, e.g. like $^{27}Al(^{12}C,\alpha n\gamma)^{34m}Cl$ reaction.

3.3 Detection of Rutherford backscattered ions

Fig.4 and 5 show typical images of developed tracks of protons and ^{12}C ions backscattered at an angle of 150° by a layer of Pb smeared on a B_4C target with a thickness of ~400 nm, given by the target roughness. The side of the square in the optical image in Fig.4 is 100 μm.

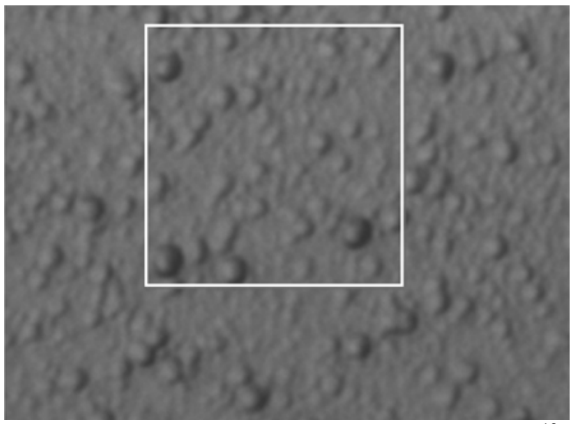

Fig.4. Optical image of tracks of RBS protons and ^{12}C ions from 400 nm Pb layer.

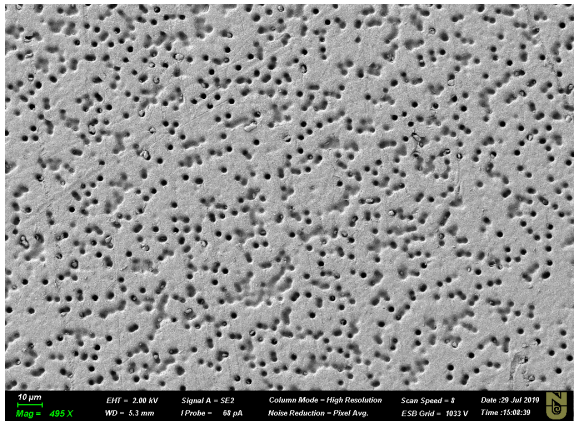

Fig.5. SEM image of RBS protons from 400 nm Pb layer. (the bar is 10 μm).

The energy of the RBS ions is predetermined by the kinematics of the elastic interaction and the initial energy of the ions, while the number of the RBS ions that hit the detector is calculated analytically by the absolute method. An analysis of the size distribution of tracks in Fig. 4 assigns them to protons (~82% of the smaller tracks) and ^{12}C ions with specific energy of ~650 keV/amu. Such a technique provides the missing information in the case of instantaneous analysis of complex ion bunches.

4. Conclusion

The combination of instantaneous nToF and γ-spectrometry has proved to be a very productive tool for studying the mechanism of collective ion acceleration in the Luce diode and controlling parameters in given acceleration modes, such as selective acceleration of ^{12}C ions or protons, or their joint acceleration with a given energy balance of each of these ionic components. The ability of this complex spectrometry to selectively determine the number and energy of high-energy protons, which are poorly represented in the total beam, turned out to be especially valuable. The approaches studied require further development in terms of spectrometry of high-energy deuterons and ^{12}C ions. Detection of RBS ions, protons and ^{12}C, with CR-39 track detectors aids these instantaneous methods for diagnosing nanosecond bunches of collectively accelerated ions.

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5. References

[1] Plyutto A.A., Suladze K.V., Temchin S.M., *At. Energy*, **27,** 1197, 1969; doi: 10.1007/BF01164972
[2] Luce J.S., Sahlin H.L., Crites T.R., *IEEE Trans. Nucl. Sci.*, **20**(3), 336, 1973; doi: 10.1109/tns.1973.4327115
[3] Belensov P.E., *Phys. Usp.*, **47**/2, 209, 2004; doi: 10.1070/PU2004v047n02ABEH001715
[4] Ryzhkov V.A., Pyatkov I.N., Remnev G.E., *NIM A*, **998**, 165190, 2021; doi: 10.1016/j.nima.2021.165190
[5] Ryzhkov V.A., Remnev G.E., Zhuravlev M.V., Pyatkov I.N., Lopatin V.S., *Techn. Phys. Letters*, **45**(7), 718, 2019; doi: 10.1134/S1063785019070265
[6] Ryzhkov V.A., Pyatkov I.N., Remnev G.E., *NIM A*, **1016**, 166274, 2022; doi: doi.org/10.1016/j.nima.2021.166274
[7] Ryzhkov V.A., Remnev G.E., Pyatkov I.N., Zhuravlev M.V., *Vacuum*, **187**, 110081, 2021; doi: 10.1016/j.vacuum.2021.110081
[8] Ryzhkov V.A., Pyatkov I.N., Kibler I.N., Zhuravlev M.V., Remnev G.E., *Russ. Phys. J.*, **63**(13), 151, 2021; doi: 10.1007/s11182-021-02311-8
[9] Ryzhkov V.A., Pyatkov I.N., Remnev G.E., *Vacuum*, **202**, 111212, 2022; doi: 10.1016/j.vacuum.2022.111212
[10] Ryzhkov V.A., Pyatkov I.N., Remnev G.E., *NIM A*, **1036**, 166871, 2022; doi: doi.org/10.1016/j.nima.2022.166871