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Acceleration of protons in a Luce diode with a Teflon anode

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The number of protons collectively accelerated in a Luce diode with a Teflon anode was determined from the activity of the ^{13}N radionuclide formed in a graphite target by the nuclear reaction $^{12}C(p,\gamma)^{13}N$. It is shown that the average number of protons accelerated per shot at a chamber residual atmosphere pressure of $3 \cdot 10^{-5}$ and $2 \cdot 10^{-4}$ Torr is approximately the same within the error, and the efficiency of direct capture of protons into acceleration from the residual atmosphere does not exceed 0.25%. It is also shown that, due to the hydrophobicity of polytetrafluoroethylene, the number of protons captured in acceleration ($\sim 4 \cdot 10^{12}$) is on average an order of magnitude lower compared to the use of anodes made of polyethylene (10^{14}), BN ($5 \cdot 10^{13}$) and Al_2O_3 ($3 \cdot 10^{13}$).

Keywords: collective ion acceleration, polytetrafluoroethylene, adsorption, surface.

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Collective acceleration of ions was discovered in Plyutto's experiments with pulsed vacuum arcs [1]. Luce has proposed a special vacuum diode configuration [2] for collective acceleration of ions by a beam of relativistic electrons that passes through an aperture in a dielectric anode insert, induces partial evaporation of the anode surface, ionizes evaporated elements, and then captures and entrains ions, accelerating them to energies exceeding the potential applied to the diode by a factor of 2–3. This diode configuration has later become known as a „Luce diode," although certain authors [3] claim that the naming is incorrect, since the configuration used earlier by Plyutto closely resembles the one described above. The central problem arising in collective acceleration of ions heavier than protons in a Luce diode is the inevitable acceleration of a much greater number of protons produced from anode surface contaminants (water vapor and hydrocarbons of vacuum oils). Being the most lightweight of all ions, protons are the least inertial, and the efficiency of their entrainment from near-anode plasma into collective acceleration by a propelling agent is much higher. Specifically, it has been demonstrated in [4] that the number of protons accelerated collectively in a Luce diode with an anode insert made of hydrogen-free boron nitride was comparable to the number of protons accelerated with a polyethylene anode composed mainly of hydrogen. Since the number of collectively accelerated ions decreases exponentially with an increase in their energy in a bunch [5], the capture of much greater numbers of protons should lead to a reduction in the number and/or energy of heavier ions. This is the reason why the probability of capture of protons needs to be made as low as possible is the objective is to accelerate heavier ions. The contribution of protons may be suppressed by reducing the residual atmosphere pressure, which may be achieved through special measures: degassing of the surface of vacuum chamber walls and/or application of dry evacuation systems. However, it was decided that such measures are impractical in the conditions of the present study, since the process is too time-consuming.

A (3–4)-fold reduction in the fraction of protons captured into collective acceleration was achieved in experiments on acceleration of helium ions from the residual helium atmosphere in a Luce diode with a ceramic anode based on Al_2O_3 [6]. Polytetrafluorethylene (Teflon) features very low levels of surface tension and adhesion and is not wetted by water and vapors of vacuum chamber oils [7,8], suggesting that the fraction of protons captured into collective acceleration may possibly be reduced even further. Time t of formation of an adsorbate monolayer on the anode surface is inversely proportional to residual atmosphere pressure P in the working chamber; with an adsorbate sticking coefficient equal to unity (i.e., when each molecule reaching a surface attaches to it), this time may be estimated using the following well-known formula [9]:

$$t\,[\mathrm{s}] = 3 \cdot 10^{-4}/P\,[\mathrm{Pa}]. \quad (1)$$

According to formula (1), a surface with 100% adsorbate attachment under a pressure of $3 \cdot 10^{-5}$–$2 \cdot 10^{-4}$ Torr (4–27 mPa) is covered in just 0.75 and 0.11 s, respectively. This time is 7 and 45 times shorter than the interval between the shots (in most cases, approximately 5 s [5,6]) of an accelerator based on a Luce diode. The size of a water molecule may be estimated from the distance between neighboring molecules in ice, which is 0.267 nm. Thus, an individual surface area equal to the square of this distance (approximately 0.07 nm^2) may be assigned to a water molecule. It follows that the number of hydrogen atoms in a nominal water monolayer covering 1 cm^2 of the surface is $3.3 \cdot 10^{15}$, which yields 10^{16} hydrogen atoms available for capture into collective acceleration for an anode aperture area of 3 cm^2 (Ø1.2 × 0.8 cm). With the average number of protons accelerated collectively in a

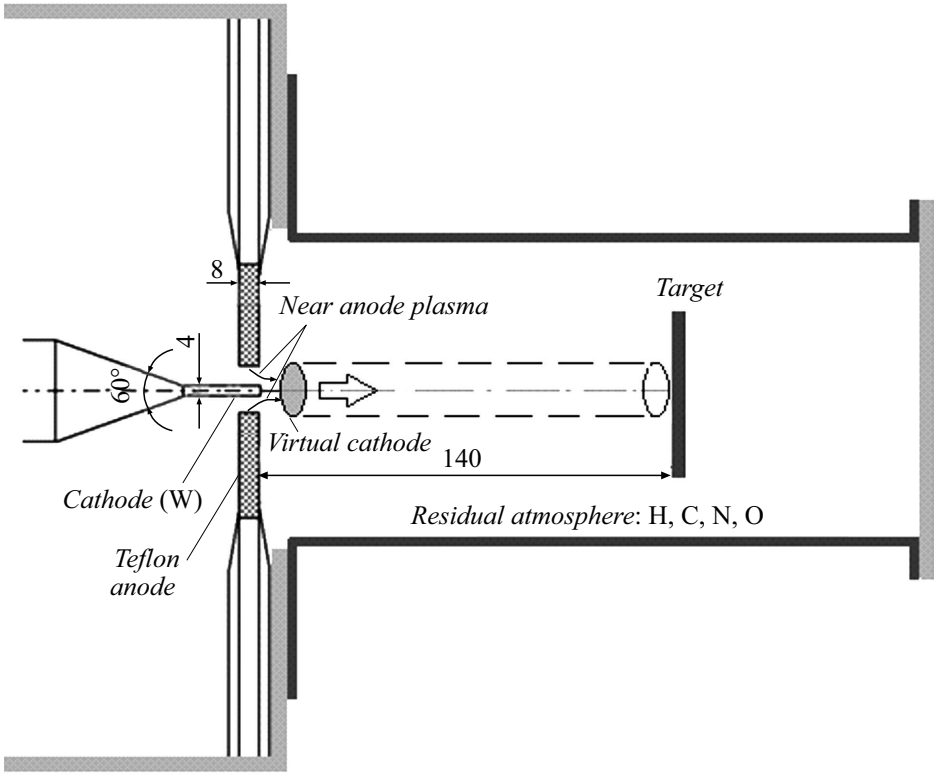

Diagram of the experiment: protons are captured into acceleration by a virtual cathode from near-anode plasma and residual atmosphere along the path from the anode to the target.

single shot being equal to 10^{14} [6], the efficiency of capture of protons from a water monolayer into acceleration is approximately 1%, while the probability of capture of protons into collective acceleration directly from residual atmosphere along the path from the anode to the target is, according to estimates made for deuterons accelerated from the residual deuterium atmosphere [10], below 0.1%. Thus, the use of a Teflon anode insert, which is hydrophobic (and should, consequently, reduce the number of protons in near-anode plasma), may help determine more accurately the efficiency of capture of protons into collective acceleration directly from residual atmosphere in a working chamber. In order to do that, one needs to find the average number of protons accelerated per shot with a Teflon anode insert in two experiments with the same geometry and substantially different residual atmosphere pressures in the working chamber.

The aim of the present study is to determine the average number of protons captured into collective acceleration in a Luce diode with a Teflon anode under two residual atmosphere pressures with a several-fold difference between them.

The experimental setup for collective acceleration of ions in a Luce diode based on a TEMP-4M accelerator (see the figure) was discussed in detail in [4,6,10]. Teflon anode inserts were fabricated in the form of 10-mm-thick washers with an aperture diameter of 14 mm. In a series of shots at the target, the residual atmosphere pressure in the working chamber was measured with a ZJ-52T/KF25 ionization sensor connected to a Meradat-VIT19IT2 controller (Russia). A stainless-steel tube with a diameter of 10 cm and a length of 22 cm (from the anode) was used as the working chamber. This configuration could be evacuated to a minimum pressure of $3 \cdot 10^{-5}$ Torr in 5 s after each shot. The upper pressure level ($2 \cdot 10^{-4}$ Torr) was chosen for the fact that the average number of protons accelerated in a Luce diode with a polyethylene anode was maximized under this pressure [11].

Targets made of MPG-6 reactor graphite had the form of Ø8 × 0.8 cm disks, were mounted at a distance of 14 cm from the anode, and were irradiated with accelerated protons in a series of ten accelerator shots. The chamber was then unsealed, and the irradiated sample was transferred to a high-purity Ge detector (Canberra) with a relative efficiency of 50% and lead shielding with a thickness of 5 cm. The activity of the ^{13}N radionuclide induced in nuclear reaction $^{12}C(p, \gamma)^{13}N$ was measured over a period of 550 s in the total absorption peak of annihilation γ-quanta with an energy of 511 keV three times with intervals of 10 min (in order to determine the contribution of the ^{13}N radionuclide with a half-life of 9.965 min). The efficiency of detection of γ-quanta with an energy of 511 keV was 6%, and the room background intensity in this peak was 0.02 counts/s.

Since the yield of ^{13}N in reaction $^{12}C(p, \gamma)^{13}N$ increases only weakly in the expected range of energies of accelerated protons (550–650 keV) [12], the num-

Average number of protons accelerated per shot (n_p)

Series number	P, mTorr	n_p, 10^{12}
1	0.2	3.5
2	0.2	4.2
3	0.2	3.9
4	0.03	4.6
5	0.03	2.0
6	0.03	4.3

ber of protons may be determined simply by finding radionuclide activity $A(^{13}\mathrm{N})$ at the end of irradiation with protons and using the obtained value to calculate number $N(^{13}\mathrm{N})$ of radionuclide nuclei formed in the target:

$$N(^{13}\mathrm{N}) = A(^{13}\mathrm{N})/\lambda(^{13}\mathrm{N}), \quad (2)$$

where $A(^{13}\mathrm{N})$ is expressed in Bq and decay constant $\lambda(^{13}\mathrm{N}) = 0.6932/T_{1/2} \approx 0.00116\,\mathrm{s}^{-1}$.

Number of protons n_p (with an expected energy within the 550–650 keV range) was determined as

$$n_p = N(^{13}\mathrm{N})/Y, \quad (3)$$

where $Y = 0.69 \cdot 10^{-9}$ nuclei/proton is the yield of reaction $^{12}\mathrm{C}(p,\gamma)^{13}\mathrm{N}$ at a proton energy of 600 keV; the yield of this reaction increases from $0.66 \cdot 10^{-9}$ at a proton energy of 550 keV to $0.705 \cdot 10^{-9}$ at 650 keV [12].

Aggregate data on six series of shots performed at a residual atmosphere pressure of $2 \cdot 10^{-4}$ and $3 \cdot 10^{-5}$ Torr are listed in the table.

It can be seen that the average numbers of protons accelerated in a single shot are approximately the same within the measurement accuracy for both residual atmosphere pressure levels and are equal to $(3.9 \pm 0.3) \cdot 10^{12}$ ($2 \cdot 10^{-4}$ Torr) and $(3.6 \pm 1.4) \cdot 10^{12}$ ($3 \cdot 10^{-5}$ Torr). With a low degree of confidence, the difference between these average values ($(0.3 \pm 1.4) \cdot 10^{12}$ protons per shot) may be attributed to the process of capture of protons into acceleration directly from the residual atmosphere under its pressure of $2 \cdot 10^{-4}$ Torr. As was demonstrated in [11], the number of protons along a 14-cm-long virtual cathode path from the anode to the target under this pressure may be estimated at $1.2 \cdot 10^{14}$ under the assumption that the residual atmosphere contains approximately equal numbers of hydrogen atoms and heavier ions (C, N, and O) and the average cross section of bunches is roughly equal to 1 cm^2. A rough estimate of efficiency of direct capture of protons into acceleration from the residual atmosphere is then $\sim 0.25 \pm 1.2\%$, which agrees in order of magnitude with the estimate [6] of efficiency of direct capture of deuterons into acceleration from the residual deuterium atmosphere (0.1%).

At the same time, the average number of protons $(3.6 \cdot 10^{12})$ accelerated in a single shot under a pressure of $3 \cdot 10^{-5}$ Torr should be associated with capture into acceleration from near-anode plasma; since the average efficiency of this capture was estimated above at 1% for a nominal water monolayer, $3.6 \cdot 10^{14}$ hydrogen atoms should be adsorbed by the surface of Teflon anode insert apertures. The resultant degree of coverage of Teflon inserts by nominal water monolayer islands may then be estimated at 2.5% for $1.45 \cdot 10^{16}$ hydrogen atoms in a nominal water monolayer with an area of 4.4 cm^2 (the surface area of apertures in the used Teflon inserts).

Thus, it was demonstrated that the average numbers of protons accelerated in a single shot in the process of collective ion acceleration in a Luce diode with a Teflon anode under a residual atmosphere pressure in the chamber of $3 \cdot 10^{-5}$ and $2 \cdot 10^{-4}$ Torr are approximately the same within the measurement accuracy, and the efficiency of direct capture of protons into acceleration from the residual atmosphere does not exceed 0.25%. It was also found that, owing to the hydrophobic properties of polytetrafluorethylene, the number of protons captured into acceleration ($\sim 4 \cdot 10^{12}$) is, on average, an order of magnitude lower than the one corresponding to polyethylene (10^{14}), BN ($5 \cdot 10^{13}$), and Al_2O_3 ($3 \cdot 10^{13}$) anodes. This suggests that polytetrafluorethylene is a promising material for anode inserts designed to be used for acceleration of ions heavier than protons.

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Conflict of interest

The authors declare that they have no conflict of interest.

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