Experiments on acceleration of deuterons and protons in an electron beam passing through a gas

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We have carried out experiments on acceleration of deuterons and protons on passage of a high-current electron beam through a low-pressure gas at $\nu/\gamma = 0.37$. For an electron energy of 700 keV the maximum energy of the accelerated deuterons and protons exceeds 2 MeV. The total number of accelerated particles in a pulse reaches $\sim 10^{12}$.

As was observed in some experiments by American workers, in passage of a high-current electron beam through a low-pressure gas, accelerated ions of this gas appear.[1-4] To investigate the causes of this effect and in particular to determine the threshold for its appearance, we have carried out experiments on the "Impul's" accelerator. Its design and the parameters of the beam produced have been discussed previously.[5,6] For an electron energy of 700 keV, a current of 15 kA, and a pulse duration of 50 nsec, the pulse power and beam energy in our case were about an order of magnitude lower than for the beams used in refs. 1–4. Nevertheless the ion acceleration effect was clearly observed. The basic arrangement of the apparatus used in the experiments is shown in Fig. 1. The beam was injected through a foil into a drift chamber filled either with deuterium or hydrogen at a pressure 0.05–1.0 Torr. In the course of the investigations we recorded the magnitude and duration of the current pulse and also the voltage on the diode gap. Detection of the accelerated particles was accomplished by various independent methods. A Faraday cup and collector grids were used to determine the ion current. The energy of the particles was estimated from the time of flight between grids (they were located ~23 cm apart). We also used independently the method of absorbers and threshold reactions of the type A(x, n)B, where A and B are the initial and final nuclei, x is the type of accelerated particle, and n are neutrons arising as the result of the reaction. The absolute neutron yield was determined by means of a radioactive indicator from the activity induced in it by slow neutrons. In the experiments we used the reactions $H_1^2(d, n)He_2^3$ and $C_6^{12}(d, n)N_7^{13}$. The reaction threshold in carbon for bombardment by deuterons is ~300 keV. This method in principle permits determination of the type of accelerated particles if the drift chamber is filled with a mixture of gases. A distinctive feature of the method is the possibility of its use in the presence of an intense electron flux under conditions of high x-ray background, since the detection of the induced activity is carried out approximately one second after the discharge. To determine the maximum energy of the ions from their range in matter (the absorber method) we used aluminum foils as a standard absorbing material. Detection of particles beyond the foils was accomplished either by a Faraday cup or by collector plates.

The investigations showed that ion acceleration is observed in a relatively narrow pressure range (Fig. 2). The maximum yield of deuterons per pulse is 8×10^{11}, and of protons $\sim 10^{12}$, and corresponds to a pressure $p \approx 0.12$ Torr. As evident from Fig. 2, for hydrogen a second maximum is observed at p = 0.3 Torr. The duration of the pulse of accelerated-particle current is 5–10 nsec. The maximum deuteron current is 8 A, and for protons 26 A. Measurements of the energy of the accelerated particles by the time of flight between collector grids and also by the absorber method showed that approximately half of the deuterons have an energy greater than 2 MeV. In the case where the experimental chamber is filled with hydrogen, protons, also with energy greater than 2 MeV, were observed. In Fig. 3 we have shown the experimentally determined maximum values of proton energy for various gas pressures in the drift chamber.

The efficiency of energy transmission from the electron beam to the ions for our case is

$$\eta = E_i N_i / E_e N_e = 2 \cdot 10^{-4}.$$

With the aid of the reaction $C_6^{12}(d, n)N_7^{13}$ for diagnostics, we found that the neutron yield rises sharply when a carbon target in the form of a cup is moved to a distance 50 cm from the anode foil, and is practically absent at

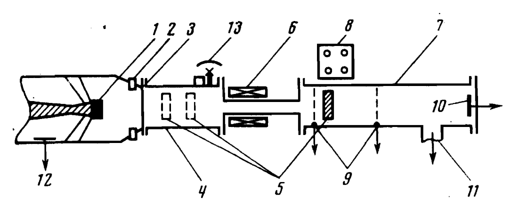

FIG. 1. Basic experimental arrangement: 1—plane graphite cathode, 2—shunt for current measurements, 3—titanium anode foil (50 μ), 4—acceleration section of drift chamber, 5—graphite target, 6—magnet for deflection of electrons, 7—measuring section of drift chamber, 8—paraffin block with counters for neutron detection, 9—collector grids, 10—Faraday cup, 11—pumping system, 12—capacitance probe for measurement of voltage on diode gap, 13—system for admission of gas and pressure measurement.

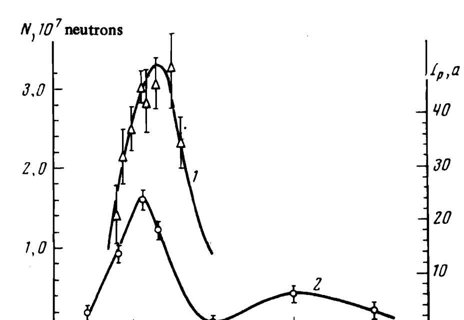

FIG. 2. Yield of neutrons in the reaction $C_6^{12}(d, n)N_7^{13}$ (curve 1) and value of proton current (curve 2) as a function of gas pressure in the drift chamber.

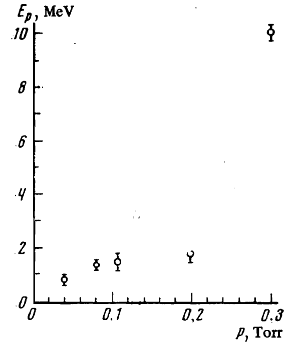

FIG. 3

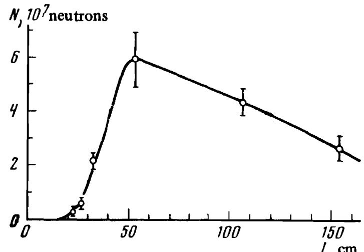

FIG. 4

FIG. 3. Experimental values of proton energy for various gas pressures in the drift chamber.

FIG. 4. Yield of neutrons in the reaction $C_6^{12}(d, n)N_7^{13}$ as a function of the length of the acceleration section.

distances less than 15 cm (see Fig. 4). Assuming that the main increase in energy occurs in a length $l < 30$ cm, we find for the effective value of the accelerating fields $\mathcal{E} > 0.1$ MV/cm. Here, in spite of the substantially different conditions (current, electron-beam energy), in the present experiments we can also trace the main features of ion acceleration observed previously [1-4] (see the table).

We note that the ion-acceleration effect appeared for the condition that the electron current I exceed a limiting value

$$I > I_{\lim} = I_0 \frac{\beta(\gamma^{2/3}-1)^{3/2}}{1+2\ln(b/a)}, \quad I_0 = \frac{mc^3}{e}$$

(I_0 = 17 kA), which corresponds to passage of a beam with radius a through a conducting tube with radius b [7] in a longitudinal magnetic field. In our case $I_{\lim}$ = 4 kA. At the same time the value of I was less than the Alfvén critical current $I_A = I_0\beta\gamma = 17\ \beta\gamma$ kA.

In our experiments the characteristic beam parameter ν/γ was comparatively small, amounting to $\nu/\gamma \approx 0.4$, where γ is the linear electron (the number of electrons in a length equal to the classical electron radius) and γ is the relativistic factor. For this value of ν/γ it is difficult to explain the experimentally observed maximum ion-energy values as the result of a localized pinch effect mechanism. [8] These data agree better with the model of a displaced virtual cathode, [9] if it is modified in accordance with ref. 10, which takes into account the effect of ionization carried out by newly formed ions. For calculation of the spectrum of accelerated ions, this and other models proposed so far must be generalized in order to take into account the consistency of the processes occurring and the efficiency for capture of ions produced in various stages of injection of the electron beam into the acceleration regime.

On the basis of the data obtained, we have begun work to increase the efficiency of the acceleration process for

Reference	V, MV	I, kA	τ, nsec	dI/dt, kA/nsec	Gas	p, Torr	τ_1, nsec	N_i	E_i, MeV	l, cm	$\mathcal{E}$, MV/cm
[1]	1 5	40	25(50)	1.6	H_2	0,05—0.2	3,0	10^{13}	5.0	30	0.2
					O_2	0.05—0.3	5,0	10^{13}	5.0		
[2]	1.0	160	35(80)	4.6	H_2	0.2	—	10^{12}	1.5	10	0.2—0.3
	1,0	110	—(50)	4.4		0.12	—	10^{12}	3		
[3]	1.5—2,0	100—50	70(90)	1.4—0.7	H_2, O_2	0.2	—	10^{11}—10^{12}	1—5	6,0	1
[4]	1,0	115	35(—)	7.5	H_2	0.15—0 6	—	$(0,5\div2)\cdot10^{12}$	12	10	1
Present work	0,65	20	30(50)	0,7	H_2	0.05—0.4	5—10	10^{12}	1—3	30	0,1
					O_2	0.05—0.3	10—15	10^{12}	1—4		

Note. τ is the current-pulse rise time to its maximum value; the numbers in parentheses in this column indicate the length of the current pulse; τ_1 is the duration of the ion burst.

ions of the gas. This work is directed in particular toward creation of conditions providing synchronization of the motion of the accelerated ions with the shifting of the potential well. For this purpose we have developed and prepared a sectionalized drift chamber, in the individual sections of which it is possible to have different pressures and also different gases.

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[1] S. Graybill and J. Uglum, J. Appl. Phys. **41**, 236 (1970).
[2] J. Rander, B. Ecker, and G. Yonas, and D. J. Drickey, Phys. Rev. Lett. **24**, 283 (1970).
[3] S. W. Kuswa, L. P. Bradley, and G. Yonas, IEEE Trans. Nucl. Sci. **NS-20**, 305 (1973).
[4] B. Ecker, S. Putnam, and D. Drickey, IEEE Trans. Nucl. Sci. **NS-20**, 301 (1973).
[5] L. N. Kazanskiĭ, A. A. Kolomenskiĭ, V. M. Likhachev, G. O. Meskhi, and B. N. Yablokov, Doklady simpoziuma po kollektivnym metodam uskoreniya (Reports at the Symposium on Collective Methods of Acceleration), Dubna, 1972, JINR, p. 161.
[6] A. A. Kolomenskiĭ, V. M. Likhachev, I. V. Sinil'shchikova, and O. A. Smit, ZhETF Pis. Red. **18**, 153 (1973) [JETP Lett. 18, 89 (1973)].
[7] L. S. Bogdankevich and A. A. Rukhadze, Usp. Fiz. Nauk **103**, 609 (1971) [Sov. Phys.-Uspekhi **14**, 163 (1971)].
[8] S. D. Putnam, IEEE Trans. Nucl. Sci. **NS-18**, 496 (1971); Phys. Rev. Lett. **25**, 1129 (1972).
[9] N. Rostoker, VII Intern. Conf. on High Energy Accel., Erevan, **2**, 509 (1969).
[10] K. F. Alexander, E. Hantzsche, and P. Siemroth, Preprint, Akademie der Wissenschaften der DDR Zentralinstitut für Electronenphysik, Berlin, 1973.

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