Subterrawatt ion beams in a plasma focus

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The amplitude-time characteristics of the deuteron beams were investigated in the plasma focus–type gas discharge. The diagnostic technique was based on the analysis of neutron and gamma radiation from the B^{11} $(d, n)C^{12}$ reaction produced as a result of interaction of the megavolt—energy deuterons with the boron carbide target. It is shown that the existence time of the deuteron–acceleration region is < 5 nsec and the total current reaches 1.5×10^5 A, which corresponds to a beam power of 0.15 TW for the average particle hardness of $\sim 10^6$ eV.

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Experimental study of accelerated particles produced as a result of the pinch effect in light gases was begun at the end of the 1950's[1] in order to explain satisfactorily the effects that produce a hard radiation and in particular neutrons in such discharges. Recent investigation of the noncylindrical *z*-pinch such as the plasma focus determined conditions under which the scale of this effect increased substantially (several orders of magnitude)— a number of particles equal to the total number of particles in the plasma compression zone was drawn in during the acceleration.[2,3]

The method of time-of-flight spectrometry for measurement of the energy distribution of accelerated deuterons generated in the plasma focus was described in Ref. 2. This method showed that the hard component of the ion flux has an average energy of

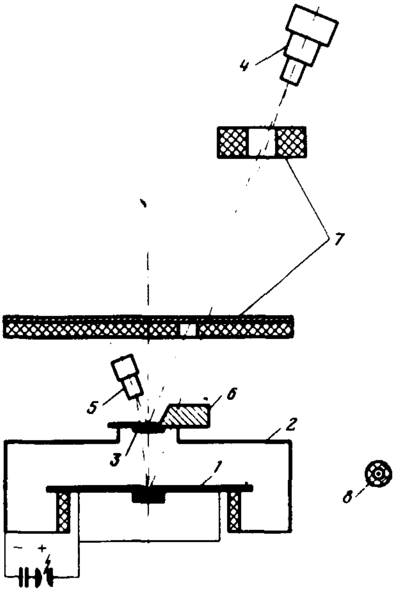

FIG. 1.

1 to 1.5 MeV with "tails" up to 5 MeV. Using an activation detector (a target made from a B_4C crystal) situated 25 cm from the plasma focus, we determined the total number of high-energy (in the MeV range) deuterons generated per unit discharge and measured the lifetime of the acceleration zone. At this position of the target the neutron pulse of the reaction $B^{11}(d, n)C^{12}$ was almost undistorted by the deuteron velocity spread. The experimental diagram is shown in Fig. 1. A 576-μF capacitor bank supplied a 16- to 18-kV charge to the chamber with a positive internal electrode (1). A baked boron carbide target (3) was mounted on the lid of the chamber (2) (cathode). The neutrons from the $B^{11}(d, n)$ reaction were recorded by the photoscintillation detector (4) situated 5.6 meters from the target. The scintillator in the pair with the coaxial photocell FEK-II (5) with a 2-mm lead shield recorded the hard x rays from the surface of the central part of the anode. A thick (up to 10 cm) lead shield (6) was used to reduce the effect of the x rays on the more sensitive detector-photomultiplier (4). The background of the scattered neutrons was reduced by using the intermediate polyethylene screens (7). The absolute neutron yield from the chamber was determined by the Ag^{109} silver isotope activation method using a beta-ray counter (8). By choosing this arrangement of the equipment and shielding with a 5.6-meter base, we were able to separate according to the time of flight the neutron radiation from the boron target from the plasma neutron radiation whose source is the plasma focus. For

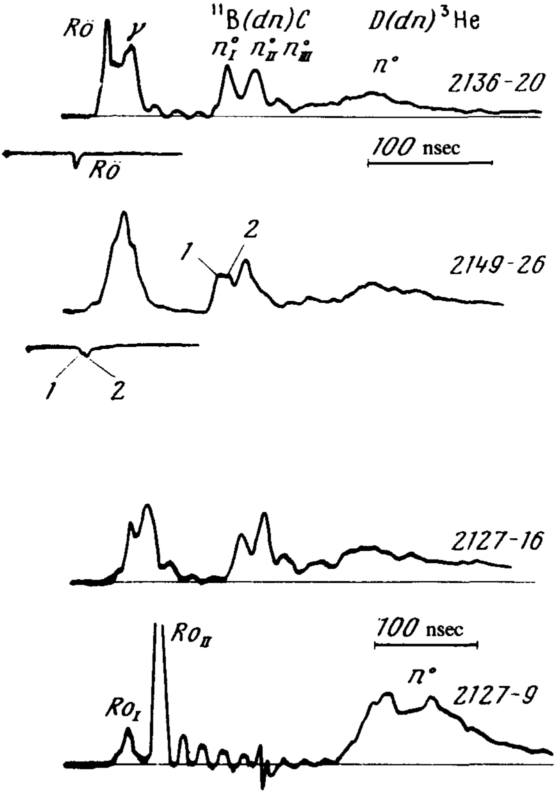

FIG. 2.

the ~1-MeV accelerated deuterons the discrete energies of the neutrons from the $B^{11}(d, n)C^{12}$ reaction are 13.6, 9.6, and 6.8 to 4.9 MeV,[4] which is attributable to several different excited states of C^{12}.

Figure 2 shows a number of oscillograms from the photographic detector (4), which were obtained by using the I2-7 oscillograph. Some of them contain signals from the detector (5), which were recorded simultaneously and in the same time scale. In analyzing the oscillograms, we assumed that the distance between the acceleration region and the target is equal to (25 ± 2) cm and that the acceleration of the electrons (to the anode) and of the ions (toward the cathode) occurs simultaneously. The oscillograms (Fig. 2) clearly show the signals from the neutrons of the first two or three energy groups, in good agreement with the values shown above. Their simultaneous appearance is a check of the correctness of the identification of the pulses from the $B^{11}(d, n)C^{12}$ reaction. The energy of the deuterons is indicated on the oscillograms in Fig. 2. The duration of the neutron pulse even for the selected distance between the source and the target (~25 cm) is somewhat higher because of the deuteron velocity distribution. Since the pulse expansion with respect to time was 11–13 nsec for the deuteron energy distribution (0.8–2.5 MeV) in the cluster obtained earlier.[2] Moreover, if we take into account the 2 to 3 nanoseconds the neutrons need to traverse the scintillator (~ 10 cm) and the frequency band of the photodetectors, then we can see from the given oscillograms that the $\leqslant$5-nsec duration of the deuterons in the acceleration region almost coincides with the duration of the megavolt-range hard x-ray radiation recorded by the FEK-II.

By using the reaction $B^{11}(d, n)C^{12}$ with formation of excited C^{12*} nuclei, we could independently check the time estimated above by analyzing the hard γ-ray peak (the second pulse on the 2136-20 and 2137-16 oscillograms in Fig. 2), which was produced as a result of the $C^{12*} \rightarrow C^{12}$ transition. The distance between this peak and that of the hard (MeV energy) x-ray pulse (~20 nsec) corresponds to the time of flight of the deuteron cluster from the acceleration region to the target and the width of the gamma-ray pulse as well as of the neutron pulse is associated with the generation time and pulse expansion due to the deuteron velocity distribution indicated above. The corresponding length (~5 cm) of the acceleration region can also contribute to the pulse broadening. The pair coincidence of the transit times and of the half widths of the pulses indicates that this region is very short along the pinch axis.

In a number of experiments the neutron and x-ray pulses were much more complicated than those examined above and to interpret the results we must assume the existence of several time-shifted acceleration zones. Thus, numbers 1 and 2 on the 2149-26 oscillograms denote the x-ray and neutron pulses associated with the two acceleration regions separated by 6 nanoseconds.

In specific cases the neutrons produced in the boron target increased the absolute neutron yield of the device by 30 to 150% relative to the average yield of 0.5×10^{10} of the (dd) reactions in the same series of experiments. We can see from the efficiency of the thick boron target close to 10^6 deuterons-neutrons for the MeV deuterons that the number of deuterons in the hard component of the cluster reaches 0.5×10^{16} deuterons, which is close to the results obtained in Ref. 3. Figure 3 shows a photograph of the surface of the boron target with traces of the damage caused by the ion clusters

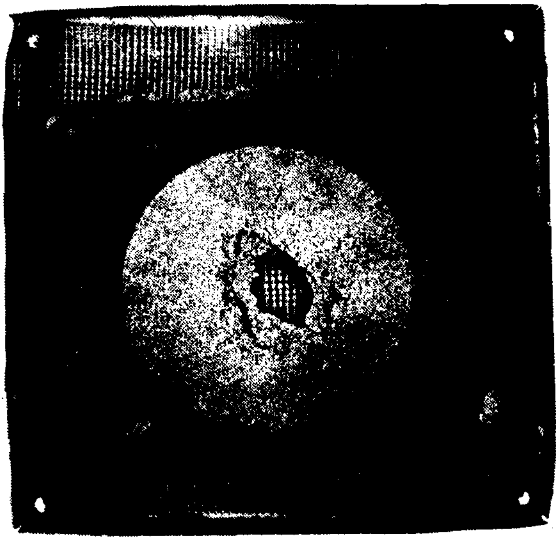

FIG. 3.

produced in two successful consecutive discharges. In one case the neutron yield of the $d\,(d,\,n)He^3$ reaction was 1×10^9 and in the other it was 0.5×10^{10} neutrons/discharge. The angular divergence of the ion flux, which for the given discharges is enclosed in the cone with an aperture angle of 3 and 6, respectively, was estimated from the size of the damaged area. The following sequence of processes occurring in the plasma focus can be obtained from an analysis of the pulses of hard x-rays and neutron emission. The 100-nsec time interval, which is determined by the generation of neutrons from the *dd*-reactions, has two clearly defined moments of time corresponding to two successive hard x-ray pulses.

The first pulse (first phase) is produced by slowing down at the anode a powerful, relatively soft electron beam with an average energy of up to 300 keV. The duration of this pulse is of the order of 20–30 nsec and its peak corresponds to the peak of the neutron (plasma) radiation. In the investigated modes the neutron emission from the *dd*-reactions is distinguished by very high stability of the absolute integral yield Y_n (up to 5%) at the average value $\overline{Y}_n = 0.5\times 10^{10}$ n/pulse. This phase of the plasma focus is accompanied by an outflow of matter from the compression zone, which is characteristic of discharges with noncylindrical geometry of the current sheath. The interaction of the electron beam with the plasma, on the one hand, and a decrease of the number of particles, on the other, create conditions for development of a large turbulence, which greatly decreases the electrical conductivity of the plasma. This can be further aided by the enhanced radiation cooling of the electronic component of plasma in the presence of heavy gas (Xe), which these modes require.

The first x-ray pulse and the neutron emission are almost independent of the intensity and hardness of the deuteron beams generated in this discharge.

The second x-ray pulse (second phase), which occurs 20 to 40 nsec after the first pulse, is associated with the production of a harder second electron beam in the megavolt energy range. This phase is much shorter than 10 nsec, and the amplitude-time characteristics depend directly on the parameters of the ion beams generated in this phase of the plasma focus. For an ordinary plasma diode the ion current should not exceed 1.5×10^4 A in the absence of magnetic fields at a full discharge current of 10^6 A. We can see from the measurements that the beam current reaches 1.5×10^5 A in individual discharges and the corresponding power is 0.15 TW. The observed peaking of the power as a result of generation of the ion beams is the most typical feature of the plasma focus type of gas discharge in the examined mode. It follows from the obtained results that more complex theoretical models than those used heretofore for the plasma focus must be developed to explain the observed effects. The generation of such beams of charged particles is probably described most adequately by Syrovatskiĭ,[4] who examined the mechanism of dynamic dissipation of energy of the magnetic field as a result of formation of current sheets due to filamentation of the pinch in the final stage of compression.

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[1] B.G. Brezhnev, Izv. Akad. Nauk SSSR, Énergetika i avtomatika **2**, 1960, p. 54.
[2] N.V. Filippov and T.I. Filippova, Pis'ma Zh. Eksp. Teor. Fiz. **25**, 262 (1977) [JETP Lett. 25, 241 (1977)].
[3] R.L. Gullickson and H.L. Sahlin, J. Appl. Phys. **49**, 1099 (1978).
[4] S.I. Syrovatskiĭ, Astronom. Zh. **43**, 340 (1966) [Sov. Astron. **10**, 270 (1966)].