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SOME PROBLEMS AND POSSIBILITIES OF THE UTILIZATION OF NEUTRON GENERATORS IN NUCLEAR PHYSICS[1]

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Some possibilities and technological problems of the utilization of neutron generators in nuclear physics are discussed here. Especially the limitations in receiving high yields of fast neutrons, the unstability of the produced neutron yield, the spectrum of the obtained neutrons from special types of neutron generators and the basic features of the pulse fast neutron production are the main topics of this paper.

I. INTRODUCTION

Small charged particle accelerators have been frequently used for the fast neutron production also in nuclear physics for a long time. Many groups of physicists using neutron generators as the main tool of experimental research have performed many interesting experiments and obtained many valuable results [1]. During this long period of time most of the simple and immediate experiment have been performed. In spite of this fact many laboratories continue doing the research with neutron generators. In order to achieve new original results with such experimental technique a great deal of imagination and ingenuity for the formulation of scientific programs is required. Such program necessitates usually an improved quality auxiliary equipment and also a high quality neutron generator. That is why the development of neutron generators in many laboratories are still topical in spite of the available commercial neutron generators which are designed, first of all, for a lot of applications.

In the following I would like to draw your attention to some basic technical and technological problems in the development of neutron generators, and to show what is new and what experimentalists, in principle, can expect from neutron generators. Because experimentalists are interested mainly

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in parameters of neutron generators we shall focus in the following mainly on them. After a brief review of the basic principles and main features of neutron generators we shall discuss technical and technological facilities, as well as the limitations in receiving high yields of fast neutrons; then we shall talk about the problem of unstability of the neutron yield and how this can be solved. The neutron spectrum from the sealed neutron generator tube will also be mentioned in this respect. Finally we shall deal with some of the main properties and designs of pulse neutron generators.

II. FUNCTION AND BASIC PROPERTIES OF NEUTRON GENERATORS

The basic properties of the neutron generator result from the properties of its main parts (ion source, accelerating and focusing system and target) which are the following:

Ion source. Here the beam of deuterons is extracted from the deuterium plasma. There are three types of the ion sources convenient for the neutron generator according to the required properties: The radiofrequency ion source, the penning type one and duoplasmatron. In Table 1. there are presented their more important output characteristics as the ion beam intensity, the percentage fraction of D^+ ions in the beam, the operating pressure, the gas efficiency, defined as the ratio of the number of ions emerging from the ion source to the number of all particles leaving the ion source during one time unit.

Table 1

Ion source	Ion beam current [A]	Fraction of D^+ ions [%]	Operating pressure [Pa]	Gas efficiency [%]
Radiofrequency	up to 0,01	80—95	1 —0,1	5— 10
Penning type	up to 0,03	5—10	0,1—0,01	30— 50
Duoplasmatron	up to 1	60—90	1	90—100

Accelerating and focusing system. Here the deuteron beam is focused and accelerated. The acceleration and the focusing of the beam are not a complicated problem in the neutron generators if the current density of the beam is not too high. The strong repulsive force act on the charged particles in a high density current beam, and the beam is defocused [2]. Fortunately, the space charge is partially compensated by two factors: the secondary electron emission from the target and the ionisation of the residual gas by the beam [3]. Besides the focusing of the high current beam to the small diameter at the target is usually not desirable because of the target overheating problem, which will be discussed later.

Target. The accelerated beam of deuterons strikes the target containing tritium (or deuterium) atoms. The most advantageous target are tritium or deuterium absorbed in titanium or zirconium layers [1]. These metals, as well as Er, Sc, Y and U, create hydrides with hydrogen isotopes which withstand temperatures up to several hundred °C in vacuum without losing a significant amount of gas. To produce a target several mg/cm² thick, a layer of absorber is evaporated or soldered on a 0.25—1 mm thick backing metal having good mechanical properties and a high transfer heat koefficient. This layer of absorber is loaded with tritium or deuterium to an atomic ratio of tritium to absorber equal up to 1.5—1.8. The disintegration of the hydride layer occurs at a temperature of several hundred °C for example Ti—T at 230 °C, Er—T at about 500 °C. The target must therefore be intensively cooled in order to avoid overheating the hydride layer and its disintegration.

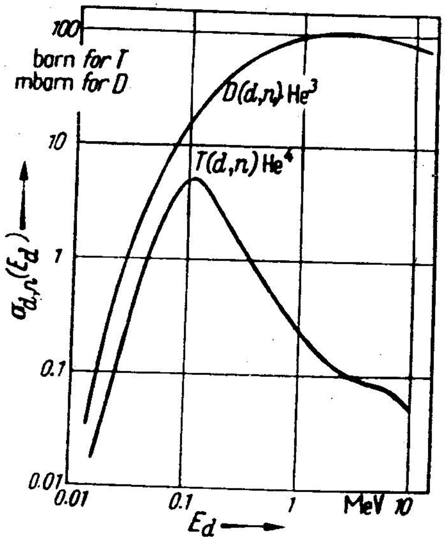

Fig. 1. The cross section of the D-D and the T-D reactions as a function of deuteron energy.

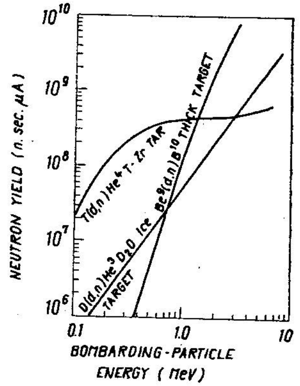

Fig. 2. The thick target total neutron yield from various (d, n) reactions as a function of deuteron energy.

III. NEUTRON YIELD

The number Y of neutrons produced in a target per second is

$$Y = Nn \int_{E_D-\varepsilon_D}^{E_D} \frac{\sigma(E)}{\mathrm{d}E/\mathrm{d}x}\,\mathrm{d}E. \qquad (1)$$

Here n is the concentration of the target atoms (T or D) in the active target layer, N is the number of particles (deuterons) striking the target per second; $\sigma(E)$ is the cross section for the neutron producing the nuclear reaction. As it can be seen from Fig. 1. $\sigma(E)$ varies rapidly with the energy of the initiated particles. $\mathrm{d}E/\mathrm{d}x$ is the stopping cross section of the deuterons in the active layer of the target; E_D is the incident energy of deuterons; ε_D is the „thickness" of the target expressed by the energy losses of particles passing through the active layer of the target. For the thick target we have $\varepsilon_D = E_D$, of course.

Fig. 2. shows the thick target neutron yield dependence on the energy of the incident deuteron for the reaction D – T and D – D, respectively.

IV. THE NEUTRON GENERATORS WITH A HIGH NEUTRON YIELD

The success and the quality of the physical experiment depends often on the neutron yield. Therefore several original neutron generators have been developed in order to achieve a high neutron yield and a lot of technological problems has been solved.

It follows from the relation (1) that the neutron yield from a target can be practically influenced only by the intensity and the energy of the deuteron beam. The concentration of the target atoms and the stopping cross section $\mathrm{d}E/\mathrm{d}x$ are practically constant given by the technology of the manufacturing of the target. Duoplasmatrons are able to produce beams of deuterons with the intensity of 1 A and the high voltage sources are able to produce sufficient power which is necessary for the acceleration of such beams to the required energy. If we suppose the specific yield of neutrons to be $y = 10^8$ n/s μA at the deuteron energy of 200 keV, the resulting yield would be 10^{14} n/s. Such neutron yields however, have not been achieved by the neutron generators so far, because the maximum of the neutron yield from the neutron generator is determined by the heat removal possibilities of the target cooling systems.

V. COOLING OF THE TARGET

The heat developed by the impinging deuterons on the active surface of the target is conducted into the cooling medium through the backing metal, Fig. 3. The active layer, as well as the backing of the target are thin layers and they have a relatively good heat conductivity. Therefore the main gradient of temperature occurs at the backing metal — cooling medium boundary, as shown in Fig. 4.

The quantity Q of the heat transferred through this boundary is determined by Newton's equation:

$$Q = \alpha S(T_s - T_m), \qquad (2)$$

where α is the transfer heat coefficient, S is the surface, T_s is the temperature of the cooled surface of the target, and T_m is the temperature of the cooling medium.

The quantity Q may be affected in different ways, because the transfer heat coefficient α depends on different factors, as for instance the quality of the cooled surface, the cooling medium and the way and the speed of its flow. Different kinds of the cooling medium have been tested in order to achieve a high value of α or to achieve a great difference $(T_s - T_m)$. As cooling media liquid nitrogen, freon, alcohol and even mercury have been used.

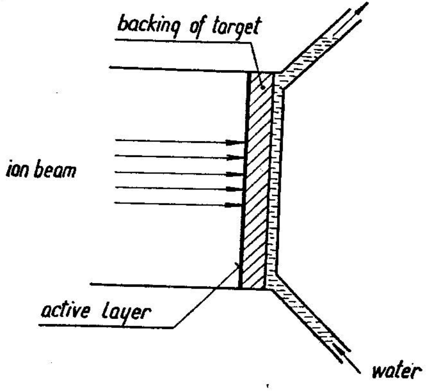

Fig. 3. Target cooling system.

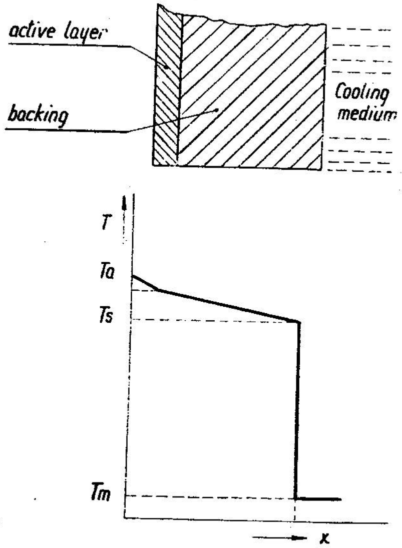

Fig. 4. Distribution of temperature in a target cooling system.

However, for cooling the targets water has proved to be the best medium, also because of practical reasons. The measurements of the transfer heat coefficient at the boundary between the smooth surface of the target and water flowing in different directions by different velocities in a system shown in Fig. 3, give the optimum result $\alpha \doteq 3$ W/cm² °C [4, 5].

J. **Rethmeier** and D. R. **Van der Meulen** [5] have achieved a significant extension of the effective cooling capacity using a silver backing of the target with fins. The boundary surface has benn enlarged $\sim$13 times and the efficiency of cooling was 43 W/cm² °C. If such a cooling system is used it will allow to produce theoretically 10^{12} n/s from 1 cm² of the target at the temperature gradient $T_s - T_m = 100$ °C by a deuteron beam current of 20 mA and the energy of 200 keV.

The aforementioned calculations have been done with the assumption of a homogeneous load of the target by the deuteron beam. In reality, however, the current density distribution is not homogeneous and therefore the resulting heat load of the target is also nonhomogeneous. It is evident from the results of **Petrov** and **Oparin** [6]. Fig. 5 shows the current density distribution and Fig. 6 shows the corresponding temperature distribution of the target. The curves „*a*“ represent the temperature distribution close under the active surface of the target ZrT at the deuteron beam intensity equal to 1, 2 and 3 mA. The curves „*b*“ represent the corresponding temperature distribution on the cooled surface of the backing metal. From these results the large temperature gradient in the vicinity of the axis of the beam is evident.

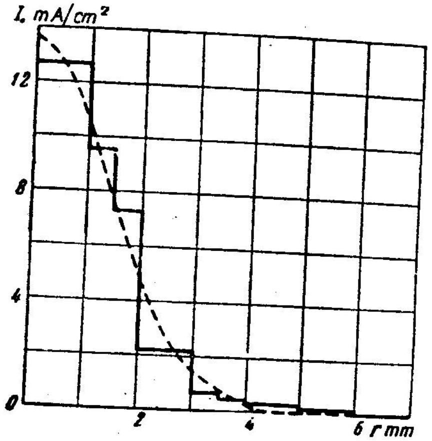

Fig. 5. Radial current density distribution in a beam.

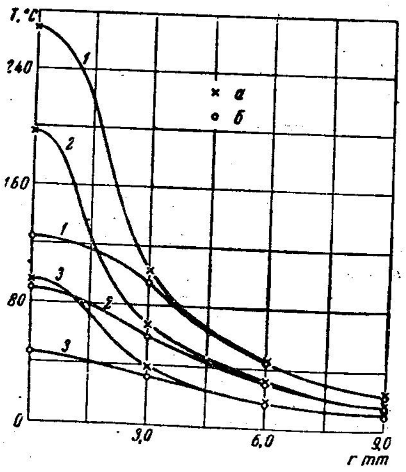

Fig. 6. Radial temperature distribution in the target.

That means, the active layer of the target can be overheated in this area above the desintegration temperature of the hydride already by a small intensity of the deuteron beam.

In order to avoid the local overheating of the target, the deuteron beam is deflected in such a manner that the same place of the target is loaded only for a very short time. The same result can be achieved by rotating the target or by the combination of both ways. The homogeneous load of the target is guaranteed if the spot of the deflecting beam describes a spiral on the target [4] given by the following equations:

$$\varphi = \omega t \qquad (3)$$

$$r = k \sqrt{t}$$

Here φ and r are evident from Fig. 7; ω is the circular frequency; t is the time and k the constant.

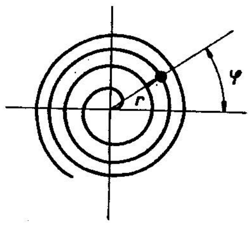

Fig. 7. The spiral according to eq. (3).

If the diameter of the beam is much greater than the distance between the neighbouring threads of the spiral and if the velocity of the spot on the target is sufficiently high, then the target is practically homogeneously loaded. Using the intensive cooling system described above it should be possible to achieve a yield of neutrons as high as 10^{12} n/s from 1 cm² of the target. In order to avoid the local overheating of the target a sufficiently large cross section of the beam is used. By doing this, the current density in the axis of the beam can be reduced to a resonable value.

The greatest yields of 14 MeV neutrons have been achieved by neutron generators with fast revolving targets. The rotating target of such a neutron generator was described by R. **Booth** et al. [7]. The diameter of this target is 22 cm and the speed of rotation is 1 100 r/min. The target is cooled by water. The diameter of the beam spot on the target is not greater than 1.6 cm. The yield of neutrons was 3×10^{12} n/s at a 12 mA beam intensity and the energy 400 keV. J. B. **Hourst** and M. **Roche** [8] have described a similar construction of the rotating target. The diameter of the beam of the intensity 100—500 mA is 4 cm at the target. The mean diameter of the target ring containing tritium is 35 cm. The rotation speed of the target is 1200 r/min. The energy of the deuterons is 150—250 keV. That means that the huge power of 15—125 kW dissipates at the target. The maximum neutron yield was 3×10^{13} n/s.

From the presented examples it is possible to get a general idea about the ways and possibilities of obtaining high neutron yields. It is obvious that with an increasing neutron yield the heat output dissipates at the target also increases. In order to receive 10^8 n/s, it is necessary to conduct the dissipated power of about 0.1—0.3 W off the target.

VI. THE NEUTRON YIELD STABILITY

It is known that since the cross section of the T — D reaction is extremely small only a fraction of the deuterium bombarding and penetrating the target is used for the production of neutrons. The remaining and larger portion of the deuterium entering the target remains there. However, since the target is already saturated by tritium and since in addition, during the deuterium beam bombardement, deuterium is constantly introduced, it is necessary for the hydrogen to escape from the target. This loss of hydrogen is a mixture of tritium and deuterium and leads to the fact, that the target becomes poor in tritium and consequently, the neutron yield is continuously decreasing in such a way as shown in Fig. 8. The decrease of the neutron yield to half of its initial value is the main characteristic of the target lifetime which is defined as follows [1]:

$$\text{Target lifetime} = \frac{\text{Ion current [mA]. Hours to the half yield}}{\text{Target area [cm}^2\text{]}}$$

The target lifetime for common TiT targets is in the region of 2—4 mAh/cm².

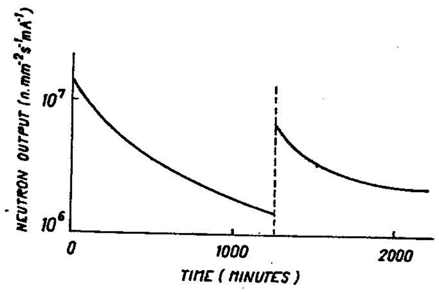

Fig. 8. Neutron output from target before and after heat treatment.

It is evident that the neutron yield decrease does not take place for the D — D neutron production.

The decrease of the neutron yield can be reduced by increasing the working target area, for instance by means of a rotaring target. The whole active surface of the target can be effectively utilized, when the target executes the spiral movement discussed above.

It can be expected that tritium from the deeper layers of the thick target absorber with a high tritium concentration diffuses to the depleted surface layers. The tritium diffusion rate is temperature dependent so that the higher the temperature, the more rapidly the redistribution occurs. D. M. Bibby et al. [9] have shown it achieving by thermal treatment of the depleted target a remarkable increase of the neutron yield.

H. Fabian [10, 11] has suggested a continual completion of tritium into the depleted layer of the target. His target is obtained, in the most simple case, by using two hydrides for instance titanium hydride and erbium hydride, with different disintegration temperatures, mounted on a backing which is impermeable to hydrogen, shown in Fig. 8. The target is held at the temperature of 300 °C. It is a higher temperature than the disintegration one of the TiT hydride. Therefore the TiT layer tends very hard to give off tritium. Since the copper backing is practically completely impermeable to hydrogen, it is possible for the tritium to diffuse only into the erbium hydride layer, which is at 300 °C completely disintegration resistant. By suitably varying the cooling of this target it is possible to control the tritium diffusion in such a way that the tritium continuously takes the place of the deuterium penetrating by bombardment into the erbium layer.

The fluent completion of tritium in the target is simply solved in the sealed neutron generator tube [12]. A mixture of deuterons and tritons is accelerated towards the target and the equilibrium concentration of the tritium and deuterium is held in the active target layer because of it. Such neutron generators produce constant neutron yields within several hundred hours.

From the point of view of the basic research the serious disadvantage of the just mentioned type of neutron generators is the rather complicated energy spectrum of the neutrons leaving the target.

VII. NEUTRON ENERGY DISTRIBUTION OF A SEALED NEUTRON GENERATOR TUBE

The beam containing D^+, D_2^+, T^+, T_2^+ and $(DT)^+$ ions strikes the target having an equal amount of deuterium and tritium. In such a target the following neutron producing reactions occur:

$$D + D \rightarrow {}^3He + n + 3.27\ MeV \quad (En = 2.5\ MeV) \qquad (4)$$

$$T + T \rightarrow {}^4He + 2n + 11.33\ MeV \quad (En_{max} = 9.5\ MeV) \qquad (5)$$

$$D + T \rightarrow {}^4He + n + 17.59\ MeV \quad (En = 14.1\ MeV) \qquad (6)$$

The neutron energy *En* given in parentheses for each reaction is calculated from the energy of the reaction without taking into account the energy of the incident particles. The effective cross sections of the D — D and T — T reactions are two orders of magnitude lower than the cross section of D — T reaction therefore in the produced neutron flux there are only a few percents of the D — D and the T — T neutrons, respectively. In spite of this fact the presence of these neutron groups in the total yield can cause various difficulties in precise physical measurements. Since the energies of the D and the T particles in the beam during the 14 MeV neutron production are different, the spectrum of the D — T neutrons is rather complicated as shown in [13].

VIII. PRODUCTION OF NEUTRON PULSES

The pulse neutron generators are useful in several fields of nuclear and neutron physics. They are used for the study of short lived nuclei, for neutron spectrometry, for the study of many problems of reactor physics and so on. The bursts of neutrons from the neutron generator can be simply achieved by the interruption of the deuteron beam impinging on the target. This can be achieved by a mere deflection of the beam through the limiting aperture as schematically shown in Fig. 10. Using an appropriate voltage it is possible to make the deuteron beam pulse lasting for ns. The ion source operates during that time continously.

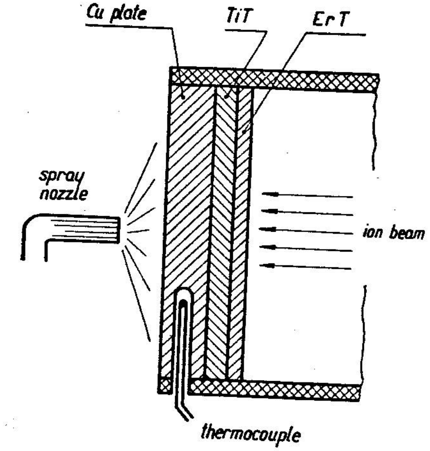

Fig. 9. Target for a continual completion of tritium into the loaded layer.

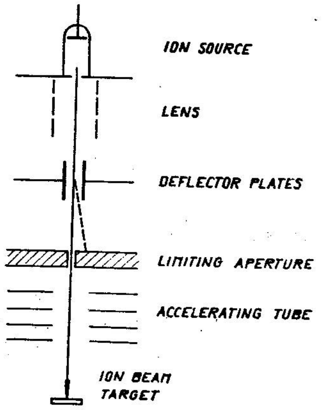

Fig. 10. Deuteron beam pulse system.

Deuterium pulses with a duration of several μs and longer can be obtained more successfully by a pulse operation of the ion source. The ion source can produce a more intensive beam in short periods with comparing to the continuous work. The pulse neutron generator based on the pulse operation of the ion source has been developed also in our laboratory. Plasma is generated in the high frequency electromagnetic field of the resonance solenoid circuit in which the discharge vessel is placed as shown in Fig. 11. The high frequency energy is supplied to this resonance circuit from the r. f. generator, placed on an earth potential, through the isolating transformer. The amplitude of the output high frequency voltage of the r. f. generator is modulated by a rectangular signal. From the plasma excited by the pulses of the high frequency voltage the deuteron beam is extracted by a constant extraction voltage. The maximum density of the plasma is achieved in 10—20 μs after the high frequency voltage pulse has been switched. The rise and the fall time of the deuteron pulse corresponds to this delay, as shown in Fig. 12.

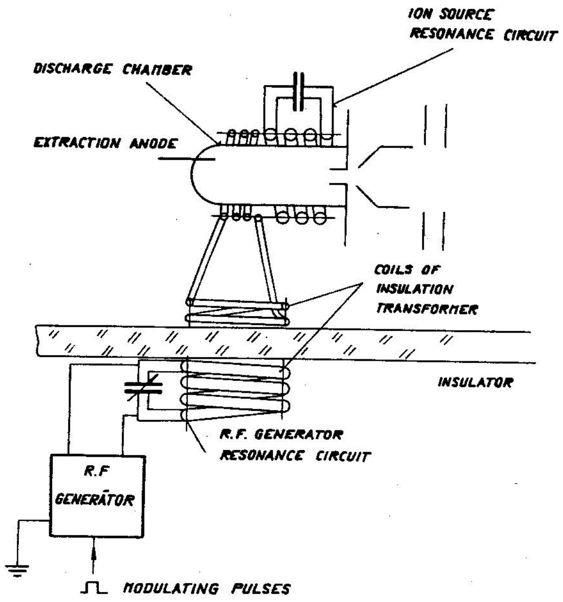

Fig. 11. The arrangement for pulse modulation of plasma density in ion source.

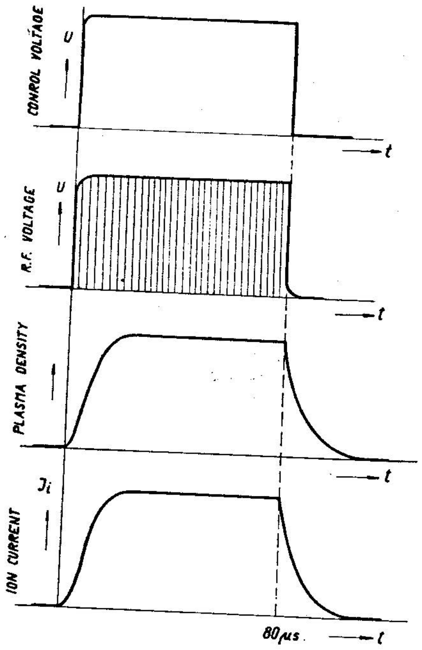

Fig. 12. Time diagram of the beam pulse production by modulation of plasma density.

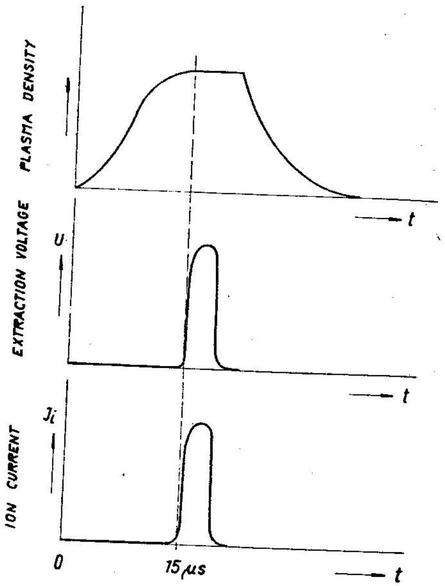

Fig. 13. Time diagram of the μs beam pulse production.

The aforementioned principle of generating the deuteron beam pulse is suitable for the production of beam pulses lasting for 0.1 ms and longer. The shorter pulses in the range of μs are obtained in this generator by a combination of the pulse plasma modulation and the pulsation of the extraction voltage. When the density of the plasma reaches its maximum, that is 10—20 μs after the r. f. generator has been switched on, the pulse of the extraction voltage of the required length and amplitude is attached to the anode of the ion source. The time diagram of the production of such pulses is in Fig. 13.

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