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NEW DESIGNS OF NEUTRON GENERATING TUBES

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Two new designs of neutron tubes are discussed: a neutron tube with a hot cathode placed in an ion source on the side of a tritium target and a neutron tube with an ion source with a hot cathode shielded by a grid joined with the ion source cylinder.

The systems used for the examination of tube characteristics are presented in the paper, together with a short discussion on the possibilities of practical application of the tubes.

1. Introduction

Neutron tubes generate neutrons from the nuclear reaction of deuterium with tritium $T(d, n)^4$He. The reaction energy Q equals 17.6 MeV and the maximum cross-section $\sigma_{max} = 5b$ occurs for a deuteron energy of 110 keV.

These tubes emit monoenergetic, 14 MeV neutrons with a mean efficiency about 10^8 n/s. Up till now most of the neutron tubes which have been designed [1], [2], have differed primarily in the kind of ion source used. The most frequently used ion sources are of the Penning type with heated or cold cathodes.

Two types of new designs of neutron tubes are presented in this work, both equipped with the Penning-type ion source with a heated cathode. The difference between the ion sources used in the types of tubes discussed lies mainly in the cathode position. In the first type the ion source used consists of a thin-walled, nickel cylinder provided with a metal grid dividing the inner space of the cylinder into two parts. The cathode is placed in the part situated on the side of the lamp socket.

The neutron tube equipped with such an ion source with a grid has a relatively great ion current at low supply voltages of the source.

The neutron current depending on the voltage of the ion source cylinder reaches a maximum value at comparatively low voltages, about 100–140 V. Owing to this fact the tube can be supplied with a relatively low amplitude signal *e. g.* from transistor sets.

In the other type of tube the cathode is placed on the side of the tritium target.

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The ion source of the latter type consists of three cylinders with equal diameters, situated on the same axis, similarly as in the triode electrode sequence. It has been proved experimentally that the ion current depending on the voltage of the middle cylinder has two ranges: the proportionality range in which the current depends linearly on the voltage, and the plateau range, in which the ion current is constant. This dependence makes possible the generation of a time-modulated neutron current. The tube can also be used as a pulse source with a constant neutron output in each pulse, independently of the pulse duration. It can also generate neutron pulses with intensity changing linearly in each pulse.

The arrangements used in examining the tube characteristics are presented in this work together with a short discussion of their possible practical use.

2. Neutron tube with ion source equipped with grid

The neutron tube [3] is a vacuum apparatus filled with deuterium under a pressure of about 0.1 N/m^2. In this pressure range the gap accelerating the ions is subjected to a voltage of ~ 100 kV, the ion source generates an ion current of ~ 100 μA, moreover, in special H. V. power supply circuits the neutron tube can function as an H. V. rectifier. In Fig. 1 the longitudinal cross-section of the tube with grid-mounted ion source is shown. The tube

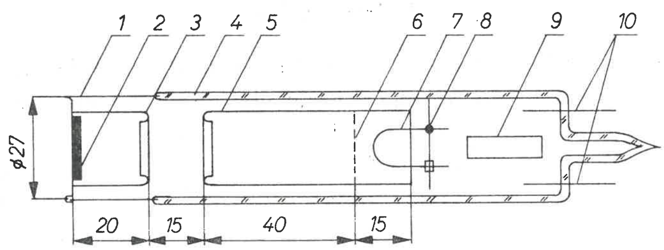

Fig. 1. Neutron tube with the ion source with a grid. *1* — Kovar cup, *2* — tritium target, *3* — tritium target shield, *4* — glass envelope, *5* — ion source cylinder, *6* — grid, *7* — cathode, *8* — cathode shield, *9* — deuterium container, *10* — bushings

parts are placed in a glass cylinder (*4*) with a diameter of about 30 mm and a length of about 150 mm. On one end the glass cylinder is provided with a metal cup (*1*) and on the other with a socle with bushings (*10*). A tritium target (*2*) covered with a shield (*3*) is fitted to the bottom of the metal cup (*1*). The ion source has a nickel cylinder (*5*) with the cathode (*7*) placed inside on the side of the socle. On the side of target the cathode is shielded with a grid (*6*) joined with the cylinder and on the side of socle with a round tantalium plate (*8*) joined to the cathode (*7*). The electrically heated deuterium container (*9*) made of nickel, contains about 1 g of powdered titanium saturated with deuterium up to a 0.5% atomic concentration.

The low voltage parts of the tube are supplied through eight bushings (*10*) placed symmetrically in the tube socle.

The tube works as a neutron source upon application of a suitable voltage.

The deuterium pressure in the tube is controlled by the current flowing through the heater of the deuterium container, (*9*) in Fig. 1. The admissible deuterium pressure depends primarily on the disruptive strength of the accelerating gap, which is placed between the shield (*3*) of the tritium target (*2*) and the ion source cylinder (*5*). It has been shown experi-

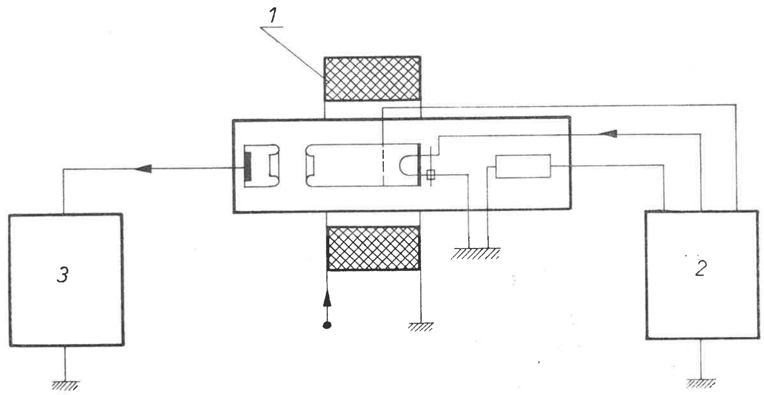

Fig. 2. Measuring apparatus for determining the characteristics of the neutron tube with a grid. *1* — magnetic lens, *2* — power unit, *3* — high tension unit

mentally that the electron current emitted by the cathode and the magnetic field intensity penetrating the accelerating gap and generated by a special magnetic lens, (Fig. 2), affect the disruptive strength of the accelerating gap. With a current of cathode emission of ~ 10 mA and a magnetic field intensity in the ion source of $\sim 10^4$ A/m the optimum value of the deuterium pressure can be estimated to be about 0.1 N/m^4.

If a magnetic lens made in the form of a coil is outwardly shielded with a ferromagnetic coat, the influence of the magnetic field intensity on the disruptive strength of the gap is decreased and the ion current efficiency is increased.

That is the reason why the magnetic lens is either supplied with direct current or is made of a permanent magnet and formed in such a way as to limit the magnetic field penetration into the accelerating gap, with a simultaneous increase of its inhomogeneity in the ion source space.

When a negative voltage of about 70 kV is applied to the tritium target and its shield, the difference of potential between the ion source cylinder and the cathode is about +100 V. The optimal value of the target voltage exceeds 100 kV.

The electrons emitted by the cathode are accelerated by the grid, after which they move along spiral trajectories in the coaxial magnetic field and ionize the deuterium particles.

The positive deuterium ions are extracted from the ion source in the direction of the gap, which accelerates them in proportion to the target voltage. They bombard the tritium target and as a result of the nuclear reaction of deuterium with tritium, fast neutrons of energy 14 MeV are emitted from the target. A measuring system for determining the characteristics of a neutron tube with a grid is presented in Fig. 2.

The neutron output obtained from the tube increases linearly with the ion current bombarding the target. This is the reason why the work parameters of the low-voltage tube parts should be chosen in such a way as to maximize the ion current.

The dependence of the ion current reaching the target upon the voltage of the ion source cylinder at different values of the magnetic lens current is presented in Fig. 3.

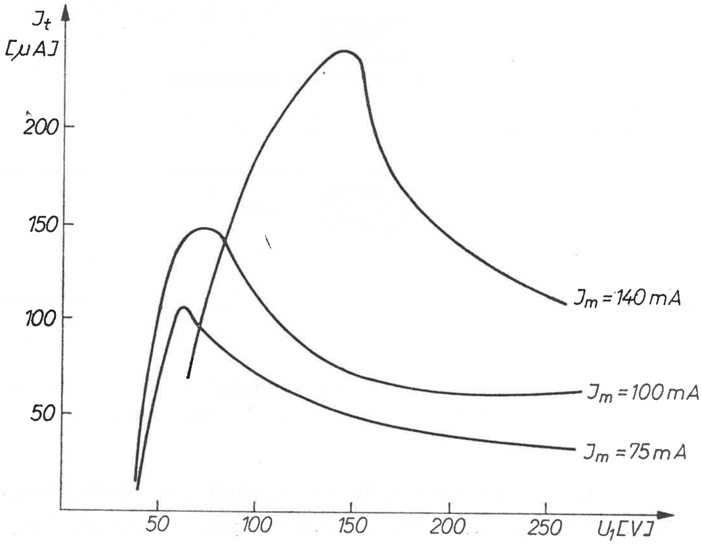

Fig. 3. Relation of the current flowing to the target to the voltage on the ion source cylinder at different values of the current flowing through the magnetic lens, I_m = 140 mA corresponds H_0 = 10^4 A/m

The use of the grid lowers the voltage necessary for the functioning of the source so much that the neutron tube in pulsed operations can be easily supplied by transistor systems. The neutron output obtained from this type of tube at voltages as great as 75 kV equals 10^7 n/s.

3. Neutron tube with the cathode on the side of the target

The main difference between the neutron tube described below and other tubes lies in the position of the cathode, which has been placed in the ion source on the side of the tritium target. The tube parts have been arranged as shown in Fig. 4. The ion source is placed in a glass envelope. The source is built of three cylinders: the anode (*2*), the control (*3*) and the cathode cylinder (*4*) which the cathode (*5*) is placed. The accelerating gap lies between the cathode cylinder (*4*) and the shield of the tritium target, which is mounted in the ring (*8*) soldered on the tube bottom (*10*). This bottom (*10*) is welded to the cylinder (*9*) in the presence of argon.

The deuterium pressure in the tube is regulated by means of the deuterium container (*11*) with powdered titanium saturated with deuterium (*11*), the temperature of which is regulated by the current of the heating coil. The low voltage parts of the tube are supplied by 8 molybdenum bushings (*12*), 1 mm in diameter. During vacuum processing the tube is joined to the vacuum system by means of the pump pipe. The ion source cylinders and the target shield have equal inner diameters of 20 mm. The cathode cylinder is 15 mm long. The anode and the control cylinders both have a length of 20 mm. The anode cylinder is cup-shaped. The target shield cylinder is 200 mm long. The ion beam is shaped between two cylinders: the cathode cylinder (*4*) and the target shield cylinder (*6*), both of them having identical openings, 10 mm diameter, placed on the same axis. The length of the

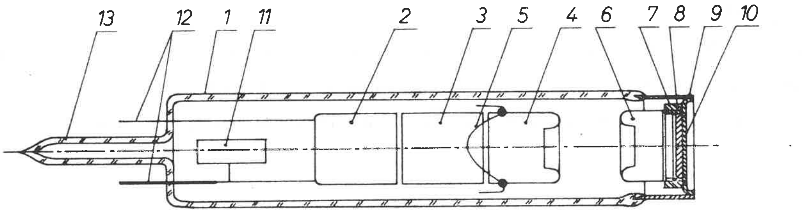

Fig. 4. Neutron tube with the cathode on the side of the tritium target. *1* — glass envelope, *2*, *3* and *4* — ion source cylinders: *2* — the anode one, *3* — control one, *4* — cathode one, *5* — cathode, *6* — target shield, *7* — tritium target, *8* — ring, *9* — cylinder joint, *10* — bottom, *11* — deuterium container, *12* — bushings, *13* — pump pipe

accelerating gap between the cathode (*4*) and the target shield cylinder (*6*) depends on the operating voltage of the tube. In the tube discussed the length of the accelerating gap is 15 mm.

A hot tungsten cathode placed on the plane running across the symmetry axis of the tube was used in the source, where the cathode is bent towards the control cylinder as shown in Fig. 4.

The total length of the tube including the bushings is about 140 mm. As has been mentioned before, the cylinder arrangement and the working principle of the ion source are analogous to those in the triode. The monotonic shaping of the potential along the tube axis was obtained by placement of the cathode on the side of the target. The difference between the ion sources of the existing tubes [1], [2] and the discussed ion source lies in the fact that the direction of ion movement in the latter is opposite to the direction of electron movement.

Due to this fact the movement of all the ions generated in the source is directed towards the tritium target of the tube. The voltage on the electrodes increases from the side of the target.

The tritium target is supplied by a negative voltage of about 70 kV, the cathode (*4*) and the anode (*2*) cylinders are supplied by a voltage of (0 — +20) V and +250 V, respectively, and the control cylinder (*3*) is operated by an intermediate voltage. During the process of neutron generation the pressure inside the tube ranges from 10^{-2} to 10^{-1} N/m^2.

The optimal pressure depends on the geometrical dimensions of the ion source. The maximal voltage of the pressure is determined by the development of avalanche discharge in the accelerating gap. To function, the neutron tube requires the presence of a magnetic field, of about 10^4 A/m, applied to the ion source. The optimal value of the field depends on the electron current emitted by the cathode, on the deuterium pressure in the tube, and on the voltage on the ion source cylinders.

These factors are determined by the electron and ion trajectories, by the potential distribution in the source, and by the dependence of the ionisation cross-section on the electron energy. The control of the ion current by means of the cathode emission current and pressure is characterised by great inertia and that is why these parameters are constant during the working of the tube [4]. It can be assumed as an approximation that the ionization cross-section of deuterium as a function of electron energy is a constant ranging from 30 to 250 eV.

In Fig. 5 the measuring circuit for determining static characteristics of the tube with the cathode on the side of the target is shown. The static characteristics of the ion source were measured under the following voltage conditions: the target (*1*) voltage $U_t = -3.75$ kV,

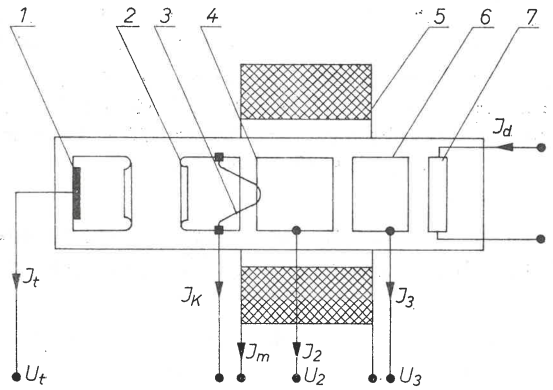

Fig. 5. Measuring circuit for determining the static characteristics of the neutron tube with cathode on the side of the target. *1* — tritium target with a shield, *2* — cathode cylinder, *3* — cathode, *4* — ionisation cylinder, *5* — magnetic lens, *6* — cup-shaped anode, *7* — deuterium container

the cathode cylinder (*2*) voltage $U_1 = 0$ V and the anode cylinder (*6*) voltage $U_3 = +250$ V. The cathode (*3*) filament current was $I_k = 2.15$ A, the magnetizing current of the magnetic lens by means of which the characteristics shown in Fig. 3 were measured was 125 mA and the heating current of the container (*7*) was 1.5 A which corresponds to a power of 6 W. The deuterium container contains 1 g of titanium saturated with a 0.3 % atomic concentration of deuterium. Under these conditions measurements were made of the currents supplied to separate cylinders of the ion source as a function of the voltage U_2 on the control cylinder (*4*).

The results shown in Fig. 6 indicate that the current I_t supplying the target is proportional to the electron current I_3 flowing towards the anode cylinder.

The analysis of the experiment data shows that:

1. At the magnetic field strength that is optimal for the working of the ion source the control cylinder current I_2 is negligible up to the moment when the control voltage U_2 is equal to the anode voltage U_3. A further increase in the control voltage causes a fast increase of I_2 current at the cost of I_3.

2. In the function $I_3(U_2)$ two characteristic ranges can be distinguished: the proportionality range in which

$$I_3 = k \cdot U_2 \qquad k > 0$$

and the plateau range in which the current I_3 is independent of U_2. Since the ion current flowing towards the target is proportional to the current I_3, the function $I_t(U_2)$ has the same proportionality range and plateau as the function $I_3(U_2)$.

3. The total length of the proportionality range and the plateau is equal to U_3. The length of the proportionality range does not exceed the voltage U_3 and is mainly dependent

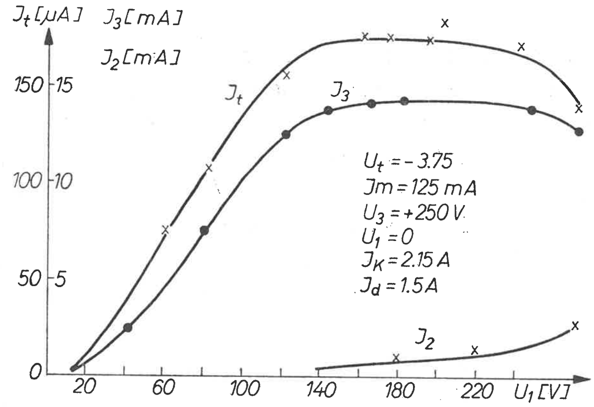

Fig. 6. Static characteristics of the neutron tube with a cathode on the side of the target

on the emission current of the cathode, the magnetic field strength and the pressure. Under certain circumstances the plateau range may vanish entirely.

In the plateau range the tube can work as a classical tube source of fast neutrons,

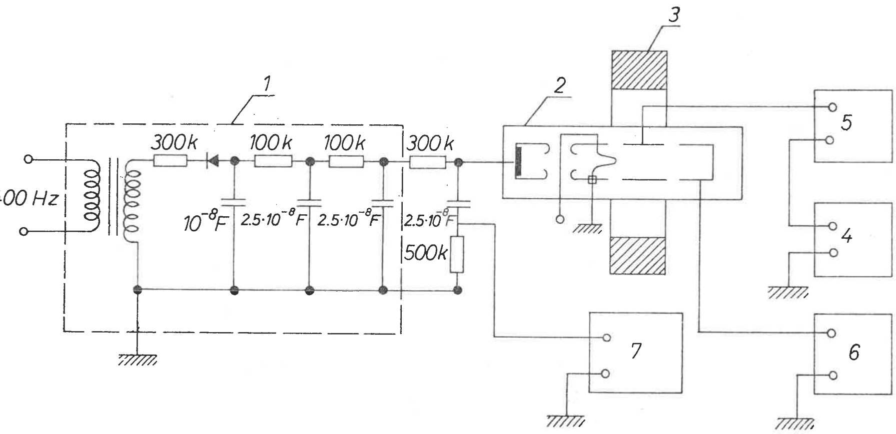

Fig. 7. System for examining the dynamic characteristics of the neutron tube. *1* — H.V. 20 kV supply unit with *RC* filter, *2*— neutron tube, *3* — magnetic lens, *4* — square-wave oscillator, *5* — constant voltage supply, *6* — anode power unit, *7* — oscillograph

and in the proportionality range the tube makes time modulation of the neutron flux possible. The tube also creates new possibilities in the control of pulsed neutron generation, *viz.* obtaining of constant neutron output in separate pulses irrespective of their duration, and the linear increase of the neutron flux during each pulse.

The examination of the dynamic characteristics of the neutron tube was carried out by means of the measuring apparatus presented in Fig. 7. The apparatus consists of a 20 kV H.V. power unit with an RC filter (*1*), the discussed neutron tube (*2*) with a magnetic lens (*3*), a square-wave oscillator (*4*) connected in series to a regulated voltage supply (*5*), an anode supply unit (*6*) and an oscillograph (*7*). The oscillograph serves as a recorder of the pulse shape of the ion current generated by the square pulse controlling the ion source.

Observations have proved that there are no discernible differences between the shape of the controlling voltage pulse and the shape of the corresponding pulse of the ion current. The pulse rise time of the ion current, in which the pulse rises from 10% to 90% of its full heigth, is shorter than 1 μs. Some observations of the ion current shape while the ion source was sinusoidally controlled were carried out. Accordingly the square-wave oscillator (*4*) in the circuit presented in Fig. 5 was replaced by an *RC* generator with regulated frequency and amplitude. It was observed that:

1. If the tube works on the linear part of the static characteristics and the control voltage amplitude does not exceed the proportionality range, the tube is able to transmit frequencies up to ~10 kHz without distinct nonlinear distortion.

2. A phase shift occurs between the ion current and the control voltage, resulting mainly from the ion flight time between the ion source and the target.

4. *Conclusions*

The above-described neutron tubes have some new exploitation characteristics. Accordingly, they have a much wider range of application. The neutron tube with a grid can be used in miniature transistor circuits, on the other hand, the neutron tube with the cathode on the side of the target can be used as a neutron source with a time modulated neutron flux, *e.g.* in reactor technology for determining kinetic parameters of the nuclear reactors.

These tubes can generate neutrons in the following four ways:

1. with time-modulated neutron output
2. in a pulsed current with constant neutron output in each pulse irrespective of its duration
3. in a pulsed current, with neutron output proportional to the duration of the neutron pulse
4. in constant output.

The construction of the neutron tubes presented was performed at the Experimental Tube Works in Piaseczno on the basis of a design made in the Institute of Nuclear Techniques at the Academy of Minning and Metallurgy in Cracow.

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