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50 mm Diameter digital DC/pulse neutron generator for subcritical reactor test

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ABSTRACT

A 50 mm diameter digital DC/pulse neutron generator was developed with 25 mm ceramic drive-in target neutron tube. It was applied in the subcritical reactor test of China Institute of Atomic Energy (CIAE). The generator can produce neutron in three modes: DC, pulse and multiple pulse. The maximum neutron yield of the generator is 1×10^8 n/s, while the maximum pulse frequency is 10 kHz, and the minimum pulse width is 10 μs. As a remote controlled generator, it is small in volume, easy to be connected and controlled. The tested results indicate that penning ion source has the feature of delay time in glow discharge, and it is easier for glow discharge to happen when switching the DC voltage of penning ion source into pulse. According to these two characteristics, the generator has been modified. This improved generator can be used in many other areas including Prompt Gamma Neutron Activation Analysis (PGNAA), neutron testing and experiment.

1. Introduction

The pulsed neutron source technique can be used to solve many physics problems of reactor. In most applications, it is superior to other methods since it offers more insight into the physics of a particular problem and gives more accurate results. For example, it can be applied in reactivity measurements on reactor systems and measurements of neutron spectra from moderator and reactor systems by the time-of-flight method [1]. This technique is suitable for measurements on reactors operating in the subcritical or zero power regions. The reactivity measurement is made by injecting a burst of neutrons into the reactor core and at some later time measuring the decay rate of the neutron flux in the reactor. The decay rate is directly related to the reactivity of the core [2]. In these measurements, the neutron output should be modulated over a wide range of pulse lengths and repetition frequencies [3]. In some case, due to the limitation of the inside volume of reactor, the volume of pulsed neutron source has to be small enough to be placed into the test hole.

Sealed-tube neutron generator is a portable and on–off neutron source. It is smaller in volume and easier to be controlled. The sealed-tube neutron generator is highly suitable for reactor testing, because it has higher neutron yield and can output a wide variety of pulsed neutron. The 50 mm diameter digital DC/pulse neutron generator described in this paper is a sealed-tube neutron generator, and it was developed according to the request for subcritical reactor from China Institute of Atomic Energy (CIAE). The large accelerator-based neutron source is inconvenient to install and operate [4], so they wanted to use a portable pulsed neutron generator for dynamic characteristics testing [5]. In this subcritical reactor, the hole for neutron generator is only 50 mm in diameter and the neutron generator has to be inserted into the reactor for 700 mm in depth. At the same time, CIAE makes four main requisitions as below:

(1) The generator can produce the pulsed neutron with frequency ranging from 500 Hz to 10 kHz.
(2) The rising and falling edge of the ion source pulsed voltage cannot exceed 3 μs.
(3) The generator has the function of synchronized signal output and remote control.
(4) The neutron generator can satisfy the need for experiments besides reactor testing.

Due to these requirements, the generator was designed for two considerations:

First, the neutron tube must be smaller in diameter, and the generator must be well-insulated inside. Therefore, we designed the generator with the newly-developed 25 mm diameter ceramic drive-in target neutron tube designed by Institution of Radiation Technology (IRT) in Northeast Normal University. In order to develop a generator of 700 mm in length, the encapsulated module was improved and redesigned with a stainless steel shell, small size high voltage film capacitors and high voltage diodes, insulation paper and silicone oil insulation material.

Second, the pulsed neutron is generated by supplying pulsed voltage into ion source anode [6]. For this reason the controller

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needs to achieve the 2 kV pulse voltage with wider frequency range, steeper rising and falling edge. Therefore, the controller is improved by utilizing advanced power electronic devices, microcontroller and embedded system.

2. 25 mm Diameter ceramic drive-in target neutron tube

As shown in Fig. 1, the neutron tube, which is designed for logging, is a small diameter neutron tube based on drive-in target technology [7–10]. The neutron tube is loaded with a mixture of deuterium and tritium according to a 1:1 ratio, and makes use of D–T and D–D fusion reaction to produce fast neutron as shown in formulae (1) and (2). The cross section of D (T, n) is over 100 times more than that of D (D, n) under the used energy range (100–120 keV). Therefore, the average energy of produced neutron is approximately 14 MeV.

$$D + D \rightarrow {}^{3}He\,(0.82\ MeV) + n\,(2.45\ MeV) \quad (1)$$

$$D + T \rightarrow {}^{4}He\,(3.5\ MeV) + n\,(14.1\ MeV) \quad (2)$$

Thin-film titanium is deposited on a ceramic substrate which is joined onto kovar alloy. Multi-hole of the ceramic increases the surface area of thin-film titanium. The target is not loaded with the mixture of deuterium and tritium before it is sealed into the neutron tube. The D and T atom bombard into the target after the tube is vacuumed under high temperature in the process of neutron tube manufacture. During the operation of neutron tube, gas can replenish by itself in the target, which causes a longer lifetime of neutron tube (more than 500 h) without deterioration (with neutron yield of 1×10^{8} n/s). Diameter of neutron tube is decreased into 25 mm by utilizing the optimized penning (PIG) ion source, acceleration electrode and ceramic drive-in target. Ceramic insulation shell is used for improving the electrical insulation and mechanical strength of the neutron tube. The maximum accelerator voltage can be as high as 120 kV.

Generation and yield of neutron can be controlled by adjusting gas reservoir current, anode voltage and acceleration voltage. The anode current of ion source is from 0 to 450 μA at 2 kV anode voltage, and a 0–120 μA ion beam can be extracted at 0–120 kV acceleration voltage. This neutron tube is currently being used by Daqing Logging of China with a maximum yield of 1×10^{8} n/s. This tube can also be utilized in oxygen activated logging and C/O logging.

3. Neutron generator design

The 50 mm diameter DC/pulse neutron generator incorporates two subassemblies which are connected by a 30 m electric cable.

(1) An encapsulated module consists of a 25 mm diameter neutron tube, a high voltage transformer, and a voltage-multiplier. In addition, an ion source drive circuit (supply DC or pulse voltage) is installed inside it.

(2) A controller consists of three power supplies, a digital controller, a LCD screen, buttons and rotary knobs.

3.1. Encapsulated module design

The structure of encapsulated module is shown in Fig. 2. The shell is made by welding a square-shaped stainless steel case onto a stainless steel cylinder. The cylinder is 50 mm in diameter and 930 mm in length. Since the cylinder wall is made of stainless steel, the thin and long shell is firm enough. The square-shaped case is divided into upper and lower layers and the two layers are separated by the stainless steel structure. Both of the stainless steel parts are well grounded.

As shown in Fig. 2, the neutron tube fixed by nylon sleeve is placed reversely. High voltage multiplier module is composed of high voltage thin-film capacitors and high voltage silicon diodes. The target side of neutron tube is placed against high voltage multiplier module. As a result, the high voltage area is concentrated in the central axes of the stainless steel cylinder. The ion source and reservoir side of neutron tube is placed close to the end of the stainless steel cylinder. By such arrangement, it is convenient to connect the power to the tube, because the lower voltage cable is placed close up to the inner wall of stainless steel cylinder while the high voltage is directly connected to the end of the tube. This setting provides adequate insulation distance between high voltage area and low voltage area. The cross section area of high voltage multiplier is decreased and the multiplier can generate voltage from 0 to −120 kV. The high voltage multiplier and the neutron tube are rolled up tightly by NOMEX insulation paper, and they are inserted into the stainless steel cylinder. After that, the stainless steel cylinder is filled with silicone oil. The silicone oil not only has the function of insulation protection, but also can conduct the heat from the neutron tube and high voltage multiplier to the stainless steel shell. Some air is left in the lower layer and an air release valve is installed in this layer. When the inner temperature is increased and the silicon oil is expanded, the internal and external air pressure is balanced (see Fig. 2).

DC/pulse ion source drive circuit is installed in the upper layer of the square-shaped case. The pulsed voltage electric field is shielded into the encapsulated module, so that the electromagnetic radiation to the outer space is decreased. Meanwhile, the length and capacitance of pulsed voltage cable are decreased. The upper and lower layers of the square case are isolated entirely and the outer connector is sealed. The whole encapsulated module can be placed horizontally or vertically.

3.2. Controller and power supply design

The controller consists of several independent modules: (1) reservoir drive circuit supplying 0–1 A current, (2) DC/pulse ion source drive circuit supplying 0–2.5 kV voltage, (3) HV drive circuit, (4) HV transformer and voltage multiplier, (5) digital controller, (6) LCD module, (7) buttons and rotary knobs. The second and

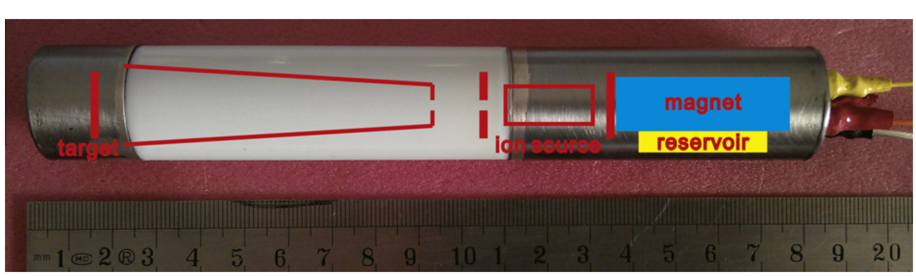

Fig. 1. The ceramic drive-in target neutron tube is 25 mm in diameter.