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Upgrade of the IGN-14 neutron generator for research on detection of fusion-plasma products

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ABSTRACT

The fast neutron generator (IGN-14) at the Institute of Nuclear Physics of the Polish Academy of Sciences (IFJ PAN) in Kraków (Poland) is a laboratory multi-purpose experimental device. Neutrons are produced in a beam-target D–D or D–T reactions. A new vacuum chamber installed directly to the end of the ion guide of IGN-14 makes it possible to measure not only neutrons but also alpha particles in the presence of a mixed radiation field of other accompanying reaction products. The new experimental setup allows test detectors dedicated to spectrometric measurements of thermonuclear fusion reaction products.

1. Introduction

The deuterium and tritium nuclear reaction, $t(d,n)\alpha$, commonly abbreviated as D–T, is the most promising reaction for energy production from a thermonuclear fusion. This opinion is reflected in the decisions taken by the European Commission on construction of the fusion reactor ITER (International Thermonuclear Experimental Reactor) [1].

This information indicates that the demand for research in the field of diagnostics for D–T nuclear reaction, which is the main component of the thermonuclear synthesis, should be intensively developed. 14 MeV neutron sources of medium neutron yield play an important role in this field of research. There are many issues related to the study of fusion neutrons for which the existing neutron sources are sufficient. For example, laboratory research and preliminary tests of related systems as well as methods for monitoring and spectrometric measurements of neutrons and resultant reaction products (mainly alpha particles) need to be performed prior to their final applications in large tokamaks.

Most of neutron sources based on nuclear reactions require accelerated particles and produce fast neutrons with energies of several MeV [2] in addition to classic fission nuclear reactors that are efficient source of neutrons with energies up to about 2 MeV. A number of nuclear reactions are used as the basis for the construction of radioisotopic and apparatus neutron sources, e.g.: ^{9}Be(γ,n)2α (Q= − 1.67 MeV), ^{9}Be(α,n) ^{12}C (Q= 5.91 MeV), d(d,n) ^{3}He (Q= 3.29 MeV), t(d, n)α (Q= 17.6 MeV).

The first two reactions are used in radioisotopic neutron sources, where gamma and alpha radiation are obtained from other radioactive nuclides. There are other radioisotopic sources like Po–Be, Pu–Be and Am–Be with the broad neutron peak around few MeV. The spontaneous fission of ^{252}Cf also provides a widely used radioisotopic fast neutron source with the maximum yield at 1 MeV [3]. All of these sources do not meet the significant condition of research onthe D–T nuclear fusion – neutron spectra of these sources do not reach energy of 14 MeV.

The D–D and D–T reactions are used in neutron generators (apparatus neutron sources). Both of them are exothermic, thus requiring relatively low energy particle beams (100–500 keV). The D–T reaction has a resonance at about 100 keV with the cross-section of 5 barn, while the D–D reaction has its weaker resonance at about 2 MeV (about 0.1 barn) [4]. The cross-section of the D–T reaction is much higher than that of reaction D–D, which results in a neutron yield of about two orders of magnitude higher.

Neutron generators are a small-sized high-energy beam-target neutron sources still attractive for researchers for its compactness and controllability compared to other neutron sources such as nuclear reactors, accelerators, and radioisotopes. Apart from industrial applications of neutron generators (e.g. sealed neutron tubes) from time to time new reports appear in the literature about new technical solutions for neutron generators, focusing primarily on increasing the neutron yield (e.g. [5–7]).

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Among a variety of applications of the neutron generators, a special interest is focused on experimental research for the thermonuclear D–T plasma. Only the D–T neutron generator is a convenient flexible laboratory device that produces an energy neutron spectrum with a peak around 14 MeV, analogous to the neutron spectrum produced in the D–T fusion plasma [8]. Although such a neutron spectrum can be produced in a plasma-focus devices [9], when working with a deuterium–tritium mixture as a working gas, that solution is not practical because of the difficulty in maintaining the safety of tritium treatment. Another solution may be a deuterium–lithium converter from thermal-to-high energy neutrons in the form of a container placed in neutron flux of a fission reactor [10]. The container walls are filled e.g. with ^{6}LiD. As a result of the thermal neutron reaction with ^{6}Li a fast neutron flux is produced inside the converter. It is a two step reaction: the first is $^{6}\mathrm{Li}(n_{\mathrm{th}},t)\alpha$ (Q=4.79 MeV), and next tritium reacts with deuterium and ^{6}Li: $d(t,n)\alpha$ (Q=17.58 MeV), $^{6}\mathrm{Li}(t,n)\ ^{8}\mathrm{Be}$ (Q=16.02 MeV), producing high energy neutrons. Such solutions are very rare, due to a strong disturbance of neutron field in the reactor.

A small sealed neutron tube can be applied as a 14 MeV calibration source in large tokamaks like JET or ITER working with the D–T plasma. It is a much more reliable calibration, than that with the use of an isotopic since it reproduces the shape of the neutron energy spectrum from D–T plasmas. Neutronic experiments, related to ITER and fusion power plant research, with mock-up of the European helium-cooled lithium-lead (HCLL) test blanket module (TBM) are realized at a D–T neutron generator [11] as well as other irradiation experiments in 14 MeV neutron fields (e.g. [12–15]).

In this paper the D–T pulsed neutron generator at the Institute of Nuclear Physics of the Polish Academy of Sciences (IFJ PAN), in Kraków (Poland) is described. We focus on the possibility to use this device for testing new systems of neutron and other charged particle detection in view of application for thermonuclear reactors.

2. IGN-14 – fast neutron generator at the IFJ PAN

The neutron generator in use at the Institute of Nuclear Physics is a linear accelerator where the deuterium ion incident beam induces the nuclear reaction $t(d,n)\alpha$ in the tritium target. This is a flexible laboratory device which is fully adjustable and its parameters can be controlled according to the needs of the experiments. The device can operate in either continuous or pulsed beam regime with control on both the neutron yield and the pulse parameters. For the basic use (production of 14 MeV neutrons) the tritium water-cooled solid target is used. A deuterium target can be used as well (for execution of the D–D reaction). Deuterium target may be spontaneously created by bombarding a substrate by the accelerated deuterons.

Deuterium is produced on-line from heavy water, D_2O, in an electrolyzer and is supplied to an ion source through a controllable palladium valve. Deuterium ions are produced in the RF ion source working with 50 MHz frequency and then are directed by an extraction voltage up to 4 kV to the acceleration tube. The pulsed mode of the acceleration is realized by a pulsing system of the extraction voltage. Deuterium ions can be accelerated by high voltage adjustable up to 175 kV maximum. This allows choosing the optimal parameters to initiate the $t(d,n)\alpha$ reaction. Solid tritium target contains tritium in titanium, deposited on a copper substrate. Tritium in the target is consumed during operation. The depth of penetration of deuterons into the target can be controlled by the accelerator high voltage. This gives a possibility to keep the neutron yield on a stable level during long-lasting experiments (up to a few hours). Also the deuterium ion current is adjustable by the operating parameters of the ion source.

The obtained neutron yield is in the range of 10^{8}–10^{9} n/s, depending on the working regime and is mainly limited by the activity of the tritium target which depends on the class of laboratory, according to domestic rules. The main technical data of the IGN-14 neutron generator are summarized in the Table 1.

3. Nuclear reactions and mixed radiation field at the IGN-14 neutron generator

The main nuclear reaction in the D–T operational regime is reaction (1). In the D–T fusion plasma research, both reaction products, neutrons and alpha particles are deeply investigated for diagnostic reasons in terms of rate and energy distribution:

$$d+t\rightarrow n(14.1\ \mathrm{MeV})+\alpha(3.5\ \mathrm{MeV}). \tag{1}$$

In the D–T fusion plasma the nuclear reaction between two deuterium nuclei is also possible. In the beam-target regime of the neutron generator, after some time of the operation the deuterium concentration increases due to implantation in the solid target of the bombarding ion beam. In both cases, i.e. in the thermonuclear and beam-target reactions, the following nuclear reactions occur:

$$d+d\rightarrow h(0.82\ \mathrm{MeV})+n(2.45\ \mathrm{MeV}). \tag{2}$$

$$d+d\rightarrow t(1.01\ \mathrm{MeV})+p(3.02\ \mathrm{MeV}). \tag{3}$$

where h is the helion – ion of ^{3}He isotope.

Additionally to reaction (3) some amount of ^{3}He may appear in older targets from the tritium decay to ^{3}He ($T_{1/2}\approx 12.5$ years). ^{3}He reacts with deuterons and alpha particles and protons are emitted [additionally to alphas from reaction (1)]:

$$d+h\rightarrow\alpha+pQ=18.3\ \mathrm{MeV}. \tag{4}$$

Energy partition between alpha and proton depends on the Q-value of the reaction and on the emission angles.

A large number of by-products accompanying the main D–T reaction (1) pose an unwanted background for measurement

Table 1
Technical data of the fast neutron generator 14 MeV – IGN-14 (IFJ PAN).

Continuous regime	Neutron yield:	5×10^{8} n/s	
	Ion current:	~50 μA (up to 100 μA)	
Pulsed regime	Neutron burst:	Duration:	25–1000 μs (step 1 μs)
		Repetition:	0.3–100 ms (step 0.1 ms)
		Neutron yield during the pulse:	Max. 10^{9} n/s
Target	T/Ti,	Max. activity 185 GBq	
H.F. ion source		50 MHz	
Pulsed extraction voltage		Variable up to 4 kV	
Accelerating voltage		Max. 125 kV+50 kV	
Monitors		BF_3 detector in paraffin, scintillation fast neutron probe	
Measuring vacuum chamber		Volume: 1.5 dm^{3}, pressure: 10^{-6} Torr	
External thermostatic chamber for samples (air conditions)		Volume:100 dm^{3} temperature: (0–70) °C	