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Monte Carlo modelling of distributions of the d–d and d–t reaction products in a dedicated measuring chamber at the fast neutron generator

U. Wiącek *, J. Dankowski

The Henryk Niewodniczański Institute of Nuclear Physics Polish Academy of Sciences, Cracow, Poland

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ABSTRACT

A fast neutron generator with a tritium target can be used to generate d–d and d–t reaction products corresponding to thermonuclear reactions in tokamaks or stellarators. In this way, convenient laboratory conditions for tests of spectrometric detectors – prior to their installation at the big fusion devices – can be achieved. Distributions of the alpha particles, protons, deuterons, and tritons generated by the fast neutron generator operating at the Institute of Nuclear Physics PAN in Cracow, Poland, were calculated by means of the Monte Carlo (MC) codes. Results of this MC modelling are presented.

1. Introduction

Diagnostics of hot plasma in large thermonuclear devices, like International Thermonuclear Experimental Reactor ITER, requires new technologies and alternative materials. In particular, extremely hard conditions close to, the so-called, first wall create the needs for new tools and detectors for *in-situ* measurements. Thus, new concepts, methods, materials and technical solutions are needed and wanted. Department of Radiation Transport Physics of the Institute of Nuclear Physics Polish Academy of Science (IFJ PAN Cracow, Poland) is employed in this research. In our laboratories studies on the usability of CVD (Chemical Vapour Deposition) diamond detectors for spectrometric measurements at the fusion devices are conducted. The CVD diamond detectors are checked and tested for various factors which can occur inside the thermonuclear facilities [1,2]. Part of these investigations can be performed in clear laboratory conditions by the use of a fast neutron generator, where a tritium target is irradiated by the deuterium beam. The external conditions and the beam–target geometry are totally different than those in tokamaks, the fusion d–d and d–t reactions and their products are, however, the same. Thus, one can expect, that also the whole radiation field created near the generator target should to be similar to those fields existing in the fusion devices, at least qualitatively. Our IFJ laboratory is equipped with such a 14 MeV neutron pulse generator (named IGN-14). Also, a special measuring vacuum chamber with the T/Ti target was designed and constructed to perform series of diamond detectors experiments according to the above assumptions.

All these possible, already performed or still waiting for execution experiments call for the support of more or less reliable calculation. To fulfil these requirements the Monte Carlo simulations were performed under a few additional assumptions.

The calculations were done in two succeeding steps. First, the energy-angle distributions of the particles emitted from the T/Ti target, irradiated by the 80 keV deuteron beam, were calculated by means of SIMNRA code [3]. These results of the SIMNRA code were directly applied in the course of further calculations. Afterwards, in the second step, spatial distributions inside the measuring chamber, were found by the use of MCNPX code [4,5]. Separately for each type of considered particles (alpha, p, d, t). Previously calculated energy-angular distributions were used in these simulations for the source definition. All details are explained further in the text.

For the whole data processing, preparing data for simulations, making final recalculations and drawings, the MATLAB program [6] was applied. Results are presented in the next chapters.

2. Mixed radiation field in the IGN-14

IGN-14, the fast pulsed neutron generator used at the Institute of Nuclear Physics of the Polish Academy of Sciences (IFJ PAN) in Cracow, is a linear accelerator [7]. Its principle of operation is

* Corresponding author.
E-mail address: Urszula.Wiacek@ifj.edu.pl (U. Wiącek).

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simple: the beam of accelerated deuterons (to circa 100 keV) hits the tritium target, and alpha particles and 14 MeV neutrons are emitted from the target according to the well-known nuclear reaction (1):

$$^{2}\mathrm{d} + {}^{3}\mathrm{t} \rightarrow {}^{1}\mathrm{n}\,(14.1\ \mathrm{MeV}) + {}^{4}\mathrm{He}\,(3.5\ \mathrm{MeV}) \quad Q = 17.6\ \mathrm{MeV} \tag{1}$$

Moreover, owing to implantation of deuterons into the target two other fusion reactions are possible:

$$^{2}\mathrm{d} + {}^{2}\mathrm{d} \rightarrow {}^{3}\mathrm{He}\,(0.82\ \mathrm{MeV}) + {}^{1}\mathrm{n}\,(2.45\ \mathrm{MeV}) \quad Q = 3.27\ \mathrm{MeV} \tag{2}$$

$$^{2}\mathrm{d} + {}^{2}\mathrm{d} \rightarrow {}^{3}\mathrm{t}\,(1.01\ \mathrm{MeV}) + {}^{1}\mathrm{p}\,(3.02\ \mathrm{MeV}) \quad Q = 4.03\ \mathrm{MeV} \tag{3}$$

Cross sections of the presented reactions are relatively high, even when the bombarding deuteron energy is relatively low (Fig. 1) [8]. Reaction (1) has a wide resonance maximum at E_d = 107 keV. At the same deuteron energy the total cross section for reactions (2) and (3) is about two orders of magnitude less than that of reaction (1). Energy of reaction products depends on the deuteron beam energy and on the particle emission angle.

The target used in the IGN-14 is made of a thin metallic film (titanium in this case) spread on a copper substrate and containing tritium. This target is bombarded by the 80–120 keV deuteron beam. Some of deuterons penetrate to their maximum range i.e., 0.58–1.17 μm at 100–200 keV [9], and are retained in the target material (T/Ti) at that depth. Tritium decays to He-3 ($T_{1/2}$ ≈ 12.3 years) and, therefore, some amount of He-3 appears in the older targets. This decay is not the only way for the He-3 production. During target irradiation also part of the He-3 nuclei from reaction (2) get stack in the target volume. Deuterons react with He-3 and alpha particles are emitted according to reaction (4):

$$^{2}\mathrm{d} + {}^{3}\mathrm{He} \rightarrow {}^{1}\mathrm{p}\,(14.7\ \mathrm{MeV}) + {}^{4}\mathrm{He}\,(3.6\ \mathrm{MeV}) \quad Q = 18.3\ \mathrm{MeV} \tag{4}$$

Particles generated in the IGN-14 target in reactions (1) ÷ (4) are listed in Table 1.

In the IFJ PAN Cracow the study on fast spectrometric detectors dedicated to plasma diagnostics has been conducted. Part of this works is focused on measuring d–d and d–t reaction products at the IGN-14 generator. For this purpose a new measuring vacuum chamber was designed and manufactured. The chamber gives the possibility to perform experiments with the mixed radiation field. Reaction products, which appear inside the measuring vacuum chamber, are analogous to those in tokamaks. A photo of the measuring vacuum chamber is presented in Fig. 2.

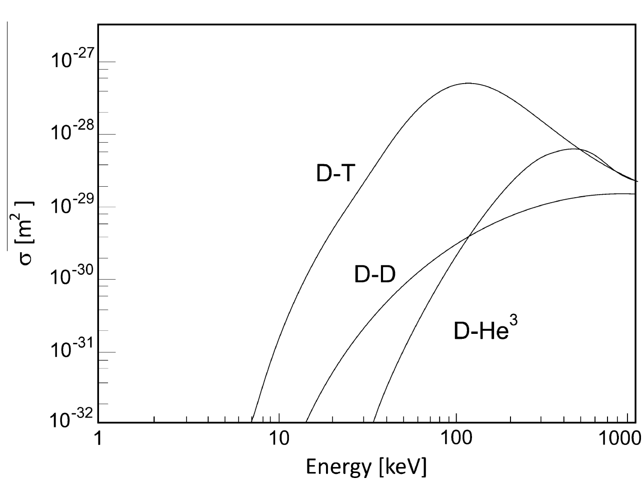

Fig. 1. Cross section as a function of deuteron energy for d–d, d–t and d–^{3}He reactions.

Table 1
Energies of particles generated in the IGN-14 target in reactions (1) ÷ (4).

Particle	Energy (MeV)
Neutron	2.45, 14.1
Alpha	3.50, 3.60
He-3	0.82
Triton	1.01
Proton	3.02, 14.7
Scattered deuteron	<0.12

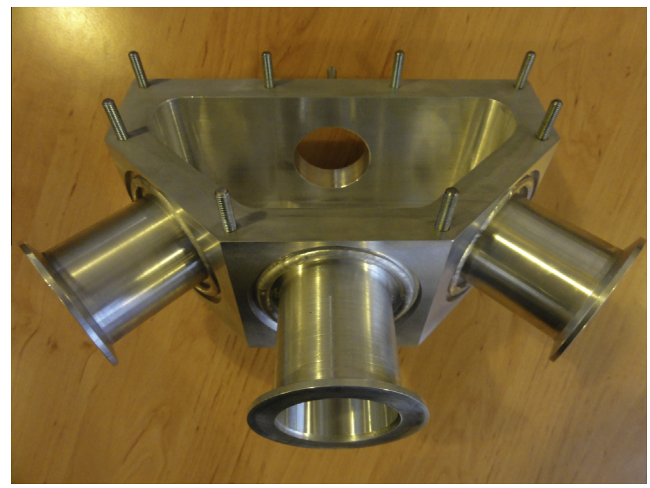

Fig. 2. The measuring vacuum chamber.

2.1. MCNPX model of the measuring vacuum chamber

The radiation field inside the measuring vacuum chamber has been evaluated using the MCNPX™ code, version 2.7.0 [4]. This version is one of the last in the long series of the MCNP/MCNPX Monte Carlo transport codes developed at the Los Alamos National Laboratory. Monte Carlo simulations are convenient and usual way to establish the best experimental conditions. For obtaining the above described distributions the model of the chamber was created as first.

The measuring vacuum chamber consists of a main body and of four external slots. The outer overall size of the chamber main body is as follows: the length is 24 cm, the thickness is 13 cm and its height is equal to 10.6 cm. One of the slots is destined to place the T/Ti target, the second one is for leading the deuteron beam, and the two remaining slots are used as the measuring channels. The length of the channels is equal to 6 cm and their diameter is equal to 5 cm.

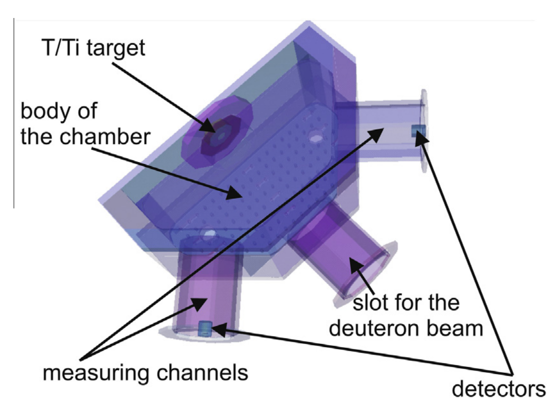

Fig. 3. The MCNP model of the measuring vacuum chamber.