Development of Deuterium-loaded Targets for D-D Neutron Generator Based on High-current Gasdynamic ECR Ion Source

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Abstract. Development of a new generation of D-D neutron generators based on high-current gasdynamic ECR sources of deuterium ions requires engineering and creation of a neutron-generating target containing deuterium. Existing D-D neutron generators consist of deuterium ion (deuteron) source with extracted beam energy of 100–200 keV and deuterium saturated neutron production target. The deuteron beam is directed towards the target, provoking the nuclear reaction and neutron emission. However state-of-the-art D-D generators based on conventional ion sources deliver only 1–10 mA/cm^2 deuteron current density to the target and do not provide necessary neutron flux density for modern applications. Increasing the current density of deuterium ion beams bombarding the target is one of the obvious ways to amplify the neutron yield in D-D generators. A so-called high current quasi-gasdynamic ECR ion source with plasma heating by millimeter wave gyrotron radiation was suggested to be used in a scheme of D-D neutron generator. Ion source of that type was developed in the Institute of Applied Physics of Russian Academy of Sciences. It can produce deuteron ion beams with current density up to 700–800 mA/cm^2. The use of this source allows a significant increase in neutron yield, though increasing the target stress. In order to fulfill requirements of modern applications for neutron flux the target must be able to withstand a constant load of up to 1 eA of deuterium ion current with energy of 100 keV, providing efficiency of neutron generation on the level of 10^{11} neutrons per second. A lot of investigations on the proper target and wafer materials selection to be done along with target saturation technique working off for successful creation of the target. An experimental setup built for target saturation with deuterium is described in the present work. The setup consists of water-cooled vacuum chamber, set of vacuum pumps, oxygen, deuterium and air gases feeding system, programmable target and wafer heater, and load-unload system. In the frame of conducted experimental studies optimal parameters of target material annealing for its proper degassing and pumping the impurities were found. Optimal saturation process stages parameters such as time, temperature, temperature gradient and deuterium pressure have been determined for creating effective deuterium-saturated titanium targets. Experimental investigations of target quality were performed with secondary ion mass-spectrometry method (SIMS). SIMS results showed that despite oxidation of the target surface the quality of obtained samples and deuterium content are high enough for its successful use in the D-D neutron generator.

INTRODUCTION

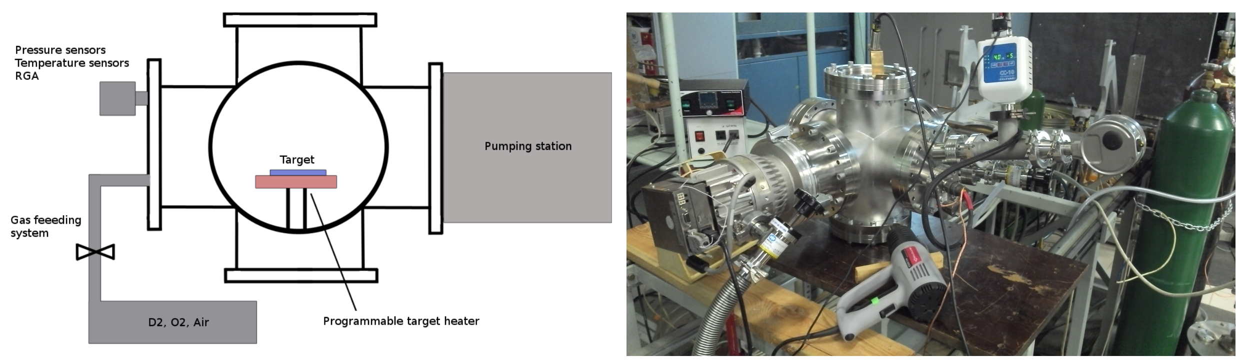
Neutron radiation is now widely used in various applications, such as materials science (analysis of the composition and structure of objects), medicine (neutron capture cancer therapy), security systems (neutron scanners, cargo inspection), etc. One of the most interesting and important applications of neutron flux may be BNCT (boron neutron capture therapy) - a method of radiation treatment of malignant neoplasms, characterized by an extremely high biological efficiency. Advantages of BNCT have been clearly demonstrated in the treatment of tumors resistant to any other type of therapy. Unique results were obtained during boron-neutron capture therapy of the most malignant and aggressive brain tumors - Glioblastoma multiforme and melanoma metastasis. However, for BNCT it is necessary to provide epithermal neutron flows with a density of more than 10^9 cm^{-2}s^{-1}. Such a density of neutron flux is provided by only nuclear reactors and accelerators. The lack of affordable compact neutron source today is a major problem in the development of BNCT method [1].

D-D fusion based neutron generators are an alternative to nuclear reactors and high energy accelerators (D-D generator is an accelerator in a way, but it utilizes significantly lower energies of 100-300 keV range). These devices consist of two main elements - the source of deuterium ions and neutron-generating target containing deuterium. Such generators are used world-wide, their main components are well developed, there are commercially available neutron sources based on that scheme (for example, Adelphi Technology Inc., USA). However, the density of the generated neutron flux more than an order of magnitude lower than that required for the BNCT. This is due to the fact that they use ion sources forming a deuteron beam with a current of 100 mA and a current density not exceeding 10 mA/cm^2 [2, 3]. Such beam flux densities do not require any special target cooling system, as the heat load do not exceed several hundreds of W/cm^2 (i.e. modern gyrotron complexes are dealing with heat loads up to 1.2 kW/cm^2, and the technique of such colling systems is well-developed [4]), and titanium targets having poor thermal conductivity still can be used, as the target do not heat up to critical temperature of deuterium desorption [5]. Using more powerful ion sources in the classical scheme of D-D neutron generator would allow a significant increase in the neutron yield up to the desired level. Ion source of different type, offering much higher ion beam yield, has been developed (this source is working in pulsed mode by now, development of CW source is undergoing) by the authors at IAP RAS. They are called high-current gas-dynamic ECR sources. These devices are using powerful gyrotrons to heat the plasma and form deuterium ion beams with a density of 700 -1000 mA/cm^2 (absolute record for ion sources of any type) [6]. Ion beams with current up to 1 A and current density more than 1 A/cm2 were not available before for D-D generator, therefore there are no studies of neutron-generating target able to sustain up to 100 kW heat load which authors are aware of.

Development of such target able to withstand prolonged bombardment by ion beams with currents up to 1 A and the energy up to 100 keV is needed. As the first step, the facility for thin films saturation with deuterium was built and tested.

EXPERIMENTAL SETUP

The experimental facility for target saturation with deuterium is shown in Fig. 1. The facility consists of a vacuum chamber with CF160 flanges, loading port, a water-cooled view-port, oxygen, air and deuterium gas feeding system, turbomolecular pump, spiral fore-pump, pressure gauges, temperature sensor, residual gas analyzer, specialized programmable heater able to heat the target in a vacuum or in a gas atmosphere to temperature of 1000 ^{O}C.



(a) (b)

FIGURE 1. Principal scheme (a) and overview of the facility (b).

The main goal of these preliminary experiments was to create a deuterium-loaded target with good efficiency of neutron production and to find out the optimum parameters of saturating process, such as annealing time, temperature and gas pressure, temperature vs time dependence and deuterium pressure. Within these studies the problem of target cooling was not considered.

The round target was made out of titanium foil of ~20 microns thickness and 3 cm in diameter. After a series of processes, the following found out to be the most effective. At first, etched titanium foil was placed in the vacuum chamber, vented and heated up to 500 deg. while pumping with turbopump (see Fig. 2) until the RGA showed negligible amount of impurities.

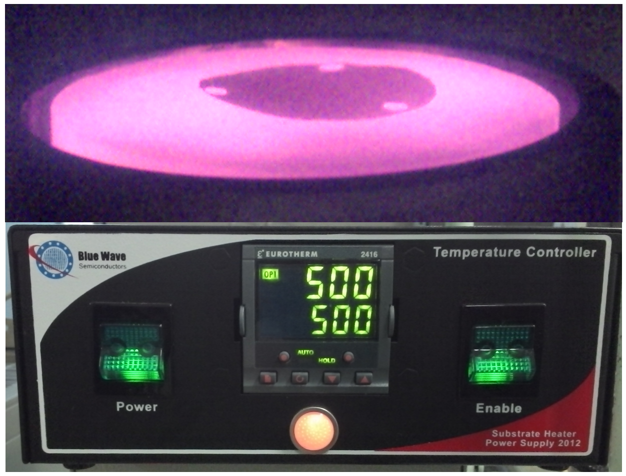


FIGURE 2. Target annealing in vacuum.

Next, the target was cooled down to room temperature, and the temperature sequence was programmed to the heater controller. The chamber was evacuated down to 10^{-6} Torr, and the heater was turned on with simultaneous slow injection of of deuterium through a leaking valve. The overall process is illustrated in Fig. 3.

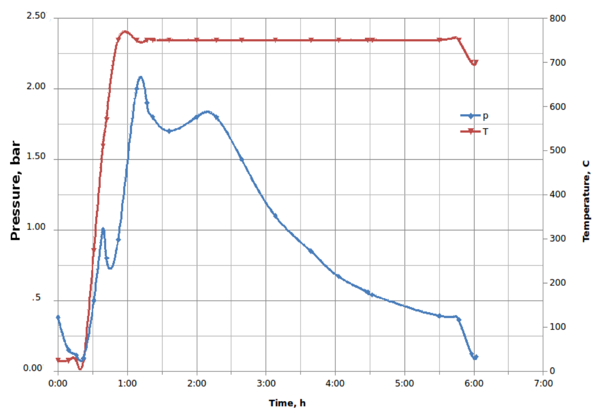


FIGURE 3. Pressure-temperature chart of saturation process.

As one can note from the Fig. 3, deuterium was absorbed by the target, as its pressure went down with time. The process slowed down after 5 hours since pressurizing, at that moment the heater was turned off. The target was naturally cooled down to a room temperature and removed from the chamber.

The described process seems to be one of the optimum ones, as it gave the best surface deuterium layer out of all processed foils. An important part of the work was the experimental verification of target quality by means of secondary ion mass spectrometry (SIMS), by characteristic emission in the electron microscope and while bombardment of target with pulsed deuterium ion beam. SIMS analysis of the saturated foil showed that the foil is well-saturated with Deuterium, though oxidation level of a surface layer is quite high to a depth of ~1micron. Oxide layer may significantly reduce the efficiency of the target since the penetration depth of 100 keV deuterium ions is less than 1 micron.

As a final step, the real test of the target was performed by bombarding the saturated foil with deuterium ion beam in SMIS 37 facility and measuring the neutron yield [7]. The results are summarized in Table 1.

TABLE 1. Comparison of different neutron producing targets efficiency at 45 keV ion beam energy

Target	Neutrons per 1 mA	Total neutron flux, 1/s
Titanium foil (experimental)	$0.7*10^6$	$0.2*10^9$
Titanium-on-tungsten (factory)	$1*10^6$	$0.3*10^9$
Heavy ice	$4*10^6$	$1*10^9$
TiD_2 (theoretical maximum)	$2*10^7$	$5*10^9$

Despite the efficiency of produced target is lower than that of commercial target, it gives a good yield. The processes learned while studying foil saturation will help a lot for developing of CW water-cooled target.

CONCLUSION

Despite titanium is very convenient in terms of machining and availability, it seems to be not the best material for heavily loaded targets, as desorption process starts since 400-600 ^{O}C. One of the most interesting materials is zirconium deuteride, which decays only above 1000 ^{O}C [8,9]. Palladium is one of the best and well-known deuterium absorbers [10], which significantly enhances potential target emission capability, however low destruction temperature (about 100 ^{O}C.) and poor thermal conductivity complicate the target cooling system – as well as for titanium target. Therefore, titanium targets are the most suitable for preliminary experiments, though CW water-cooled targets would be most probably developed based on zirconium foils.

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