THE HIGH-CURRENT DEUTERON ACCELERATOR FOR THE NEUTRON THERAPY

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Abstract

Physical project of neutron sources for the neutron therapy and neutron activation analysis is proposed. The neutron sources are based on beam provided by the high-current deuteron accelerator. The fast neutrons with intensity up to $5 \cdot 10^{12}$ n·s^{-1} are produced using T(D,n)^{4}He reaction at the energy of deuteron beam about 430 keV and average current up to 20 mA. Neutron source can be used for the fast neutron and neutron capture therapy. Liquid-crystalline DNA-Gd nanoparticles, as a potential biomaterial for the neutron capture therapy were investigated on a thermal neutron beam.

INTRODUCTION

Progress in the physics and technology of linear accelerators ion promotes the wider use in various sectors of the linear accelerators of protons and deuterons at low energies. In particular, such accelerators are used for the production of medical radioisotopes, neutron activation analysis, fast neutron therapy and neutron capture therapy of cancer [1]. Creation of fast and thermal neutrons through nuclear reactions (d, n), (p, n) without the use of fissile materials is a safe alternative to nuclear reactors. At low deuteron energy for high intensity neutron fluxes is most preferable DT and DD fusion reactions.

Currently in Russia powerful neutron generators (NG) using DT reaction produces NIIEFA. One of them, NY-12-2, provides a flow of 14 MeV neutrons of about $2 \cdot 10^{12}$ n·s^{-1} at an accelerating voltage of 250 kV and a current of 10 mA of deuterium ions. From foreign producers should be noted the firm "IRELEC" (France), which produces NG with fast neutron flux of about $5 \cdot 10^{12}$ n·s^{-1} at an accelerating voltage of 430 kV and a deuteron current of 20 mA. In the INR, was assembled and tested a NG based on high-current accelerator of deuterons (HCAD). The impact of a 20 mA deuteron beam accelerated at 430 kV on tritium target produces a neutron flux of $2 \cdot 10^{11}$ n·s^{-1}·cm^{-2} for a neutron output of $5 \cdot 10^{12}$ n·s^{-1}.

DEUTERON ACCELERATOR

The machine consists of: an electrostatic particle accelerator, supplying a 20 mA/430 kV beam of monoatomic deuterium ions, a target assembly, an ISU type high voltage DC power supply, providing the 400 kV acceleration voltage, a control and monitoring system.

The electrostatic particle accelerator consists of a high voltage electrode with the injector and associated power supplies, accelerating tube, quadrupole focalization double, an extension tube, leading to the targets assembly (see Fig. 1). The high voltage (HV) electrode is mechanical assemble designed to house the high voltage components (400 kV) and supported by three insulated legs.

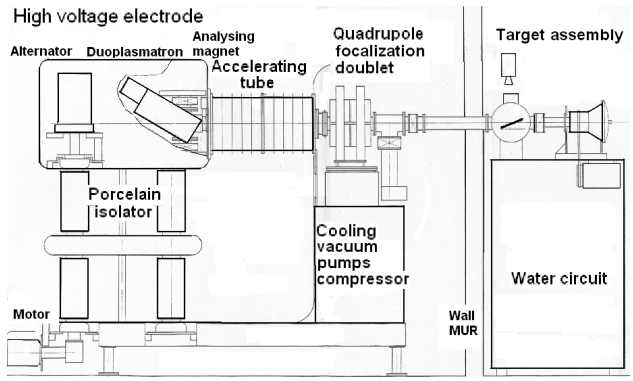

Figure 1: Deuteron accelerator.

The HV electrode includes the vacuum chamber of the injector with deflecting magnet and associated power supplies, the magnet enclosure auxiliaries, the ion source equipment, the alternator supplying power to the HV electrode. The injector has the ion source (the duoplasmatron type), beam extraction optics, atomic ion analysing magnet. A low pressure discharge is created between a hot cathode and an anode. The plasma expands through the anode into a expansion cup. Oven-heated oxide cathode has lifetime greater than 300 hours for discharge current of 15 A and discharge voltage of 150 V. The beam extraction optics (the pierce type) has maximum deuterium beam current of 55 mA.

Accelerating tube fixed to the high voltage head and consists of two half-length tubes, each made up of 5 porcelain rings and electrodes bonded together, providing a 12.5 kV/cm outside the accelerating space. A rated voltage, diameter and length of the tube are 400 kV, 0.5 m and 1.03 m respectively. The beam hits the target at a distance of 3.3 m. To compensate for divergence and to adjust the impact dimension, a quadrupole doublet is located. A throat diameter and a nominal gradient of the doublet are 102 mm and 1.9 T/m respectively.

The target assembly consists of the retractable target designed for beam adjustment, the rotating target containing the tritiated layer, representing the neutron source, a cryopump, the target water cooling system.

The retractable target used to focus the beam by examining the impact dimension on a tantalum network through a window using a video camera. The power of the beam is determined by a calorimetric measurement of the cooling water. Considering the angle of 18° between the target and the horizontal plane, it can receive a maximum power of 8.6 kW for a 20 mm beam diameter.

The rotating target consists of a 345 mm diameter spherical sector, a double rotating seal to ensure an air-tight vacuum, an insulated tube, DC motor rotating the target at 1500 rpm. The axis of rotation is shifted by 30° with respect to the beam axis. The target and the rotating seals are water cooled.

The ISU DC power supply consists of a transformer set enclosed in cylindrical tank. In the ISU 400 kV – 30 mA single – phase configuration, multi-turn induction system is powered directly from a motorized variable auto-transformer connected to mains power. The control and monitoring system includes the Control Bay, centralizing the controls, adjustments for the various beam parameters, operating modes, fault indications and safety; the information transmission system, the power box, centralizing the power components.

Overall dimensions of the deuteron accelerator are 6.8×1.7×3 m. A power consumption is about 60 kW. Dangers related to the use of the accelerator is 400 kV high voltage of the HV electrode, X-rays of secondary electrons at the entrance to the accelerating tube, neutron radiation, radiation from neutron activation, the high radioactivity of the target (1000 curies).

NEUTRON THERAPY FACILITY

The physical project of compact neutron sources for the fast neutron therapy (FNT), the neutron capture therapy (NCT) and the neutron activation analysis (NAA) is proposed. The layout neutron sources based on HCAD for FNT, NCT and NAA is illustrated in Fig. 2. This sources can be used to investigate neutron scattering (NSF).

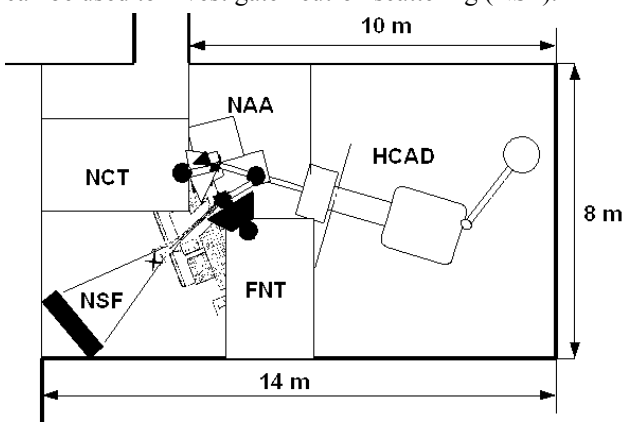

Figure 2: The layout neutron sources and facilities for the FNT, NCT, NAA and NSF.

Thermal neutron flux at moderation DT neutrons is of $1 \cdot 10^{10}$ n·s^{-1}·cm^{-2}. This neutron flux can be used for the NAA and will allow several times the sensitivity of NAA in the determination of quantitative properties of the element in the sample (1 ng) [2]. Fast neutron flux is equal to $1 \cdot 10^{8}$ n·s^{-1}·cm^{-2} can be obtained for FNT. The neutron source could be employed for NCT experimental investigations by using an irradiation facility consisted of the tungsten neutron converter, a bismuth reflector, a graphite and polyethylene moderator. The thickness of W converter and Bi reflector is about 10 cm. Thickness of graphite moderator is about 20 cm.

A Monte-Carlo transport program, NCNP4B, was used to calculate the neutron fluxes from such a system. Thermal neutron flux is equal to $1 \cdot 10^{9}$ n·s^{-1}·cm^{-2} can be obtained at the facility for NCT (see Fig.3).

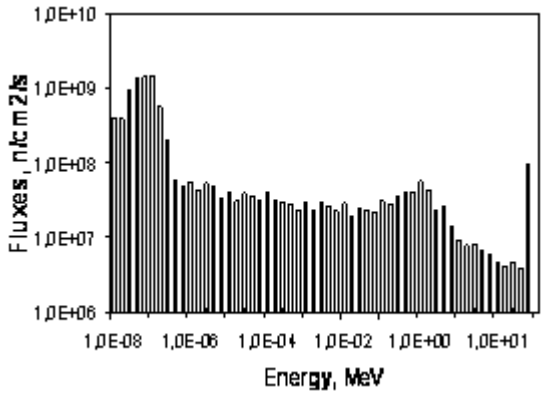

Figure 3: Spectrum of the neutrons from moderator system of the neutron sources for NCT.

THE DNA-GD RBE RESEARCH

In [3] have proposed particles of liquid-crystalline dispersions formed by the cholesteric double-stranded DNA and Gd ions as a potential platform for NCT. We have investigated the radiobiological effectiveness (RBE) of the secondary photon and electron radiation, generated after the thermal neutron capture by the DNA-Gd particles. Each particle contains 10^{8} gadolinium atoms and the corresponding natural gadolinium concentration in the biomaterial is about 250 mg/g. The conversion electrons, X-rays and gamma rays have a range in tissue about of 50 μm and can induce a tissue dose and DNA double strand breaks in cell nucleus when the DNA-Gd particles located on the surface of cells.

The biological samples containing cell suspension and DNA-Gd particles has been irradiated into the polyethylene phantom by neutrons from generator NG-400. The thermal and fast neutron fluxes for each biological sample were measured by means of the neutron activation analysis. The killing of a major part of tumor cells in biological samples with nanoparticles was produced the thermal neutron fluence about 10^{11}cm^{-2} for a nanoparticle density of the order of 10^{3} particles per cell. In our experiment samples were irradiated inside the polyethylene phantom of the size 20×20×20 cm^{3}. We have identically irradiated two sets of samples: one is the cell culture added with the solid particles of (DNA-gadolinium) complex, and another one is the cell culture without these particles. In the latter case, the killing effects can be caused only by fast neutrons. Therefore the difference in the cell killing efficacy for the two sets of samples might be due to the thermal neutron capture by

the solid particles only. The irradiation time was about 1 h and the thermal neutron fluence of about $5 \cdot 10^{11}$ n·cm^{-2}. The thermal and fast neutron fluence was measured by means of the activation method. The fast neutron (~ 1 MeV) fluence of about $1 \cdot 10^{11}$ n·cm^{-2}. The absorbed dose of the thermal neutron was ~ 20 Gy. The absorbed dose of the fast neutron was ~ 2 Gy and the effect of this types of radiation was smaller and did not produce the cell killing. The examination of irradiated samples has proved it: the tumor cells in the samples with gadolinium were killed while the cells in control samples survived under the same conditions.

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