NUCLOTRON DEUTERONS BEAM PARAMETERS MEASUREMENTS USING SSNTD

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Abstract

Accelerator Driven System (ADS) are considered as prospective nuclear installations for energy production and nuclear waste transmutation or recycling. The international project "Energy and Transmutation of Radioactive Wastes" ("E&T RAW") running in the Veksler and Baldin Laboratory of High Energy Physics (VBHEP) of the Joint Institute for Nuclear Research (JINR) (Dubna, Russia) at the accelerator complex "Nuclotron" is aimed at a feasibility study of using a deeply subcritical natural or depleted uranium or thorium active core with very hard neutron spectrum inside for effective burning of the core material together with spent nuclear fuel. For any ADS experiment a necessary and a key element is beam diagnostics. In this paper a technique for precise measurement of deuteron beam parameters using solid state nuclear track detectors (SSNTD), developed within the bounds of "E&T RAW" project, is presented. The deuteron beam parameters, specifically beam shape, size and position on a target, are obtained from track density distribution on the irradiated track detectors. The presented technique has a resolution of 1 mm. The experimental results of beam parameter measurements for deuterons with energies of 2, 4 and 8 GeV at the irradiation of the uranium subcritical assembly "QUINTA", obtained with the SSNTD technique, are presented.

INTRODUCTION

The experience of nuclear power reactors operation with uranium and plutonium isotope fuel fissioned by neutrons has shown that future extensive nuclear power usage is impossible without solutions of some scientific, technological and ecological problems. One possible solution to these problems is to create ADS. It is a combination of a subcritical reactor coupled with an external accelerator. The basic principle consists in production of a large number of neutrons in the spallation process induced by relativistic ions impacting on a heavy metal target, and their multiplication in a subcritical blanket, resulting in a dense neutron field which can be used for transmutation of long-lived nuclear waste to short-lived radioisotopes.

Introduction to the "E&T RAW" project

There is a long tradition of spallation and high energy neutron studies in the JINR. During the 1980s and 1990s, wide range of spallation targets was irradiated and the neutron production was studied with the respect to the target shape, dimensions, material and to the surrounding volumes. This aim culminated at the end of 1990s in the Energy plus Transmutation (E+T) project. The leader of this project was for almost last two decades M. I. Krivopustov, who established a big international team with interest in transmutation studies. Target systems Gamma-2, Energy plus Transmutation and Gamma-MD were developed and irradiated with protons and deuterons from the Nuclotron accelerator.

Since 2009, M. Kadykov has been a new leader of the collaboration. The collaboration was renamed to Energy and Transmutation of Radioactive Waste (E&T RAW) and got a better position in the JINR structure, so a further development is foreseen. Collaboration is still growing and has nowadays approximately 85 members from 15 countries (Armenia, Australia, Bulgaria, Czech Republic, Poland, Germany, Russian federation, Belarus, Ukraine, Mongolia, Serbia, Kazakhstan, Greece, India, and Moldova). Two new target systems are developed, the first setup called Kvinta was already tested in experiment, the Large Uranium Target setup is in the phase of technical design.

The JINR project "E&T RAW" is based on so called Relativistic Nuclear Technology (RNT) proposed recently by one of the institutions (CPTP «Atomenergomash», Moscow) participating in "E&T RAW" collaboration.

About all RNT engineering problems including creation of appropriate accelerator can be discussed only after detailed study and verification of physics ideas of the proposed approach. This is the aims of JINR project "E&T RAW" adopted for realization during 2011 – 2013 on the basis of deuteron and proton beams of Nuclotron in incident energy range from 1 to 10 GeV and natural (or depleted) massive uranium targets available at JINR.

EXPERIMENTAL INSTALLATIONS

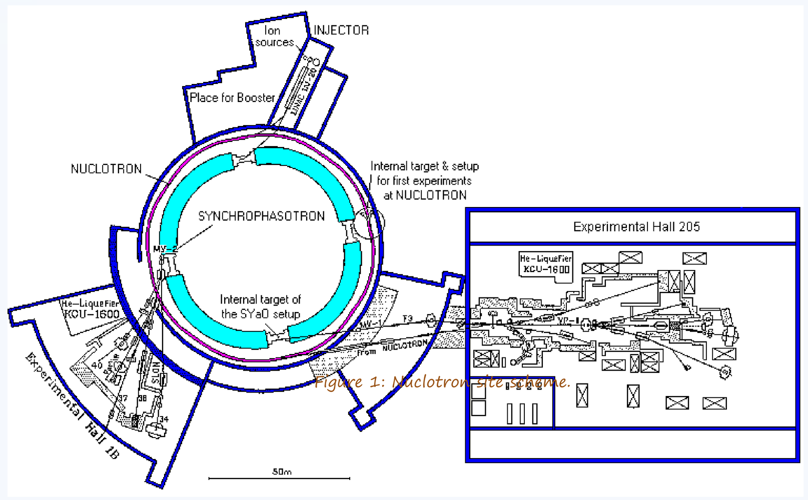

Figure 1: Nuclotron site scheme.

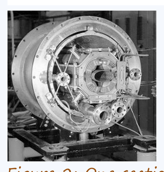
Figure 2: One section of the Nuclotron accelerator (inside beam tube surrounded with superconducting magnet, He and LN2-cooling pipes, isolation and steel shell).

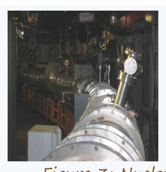
Figure 3: Nuclotron accelerator ring in the Synchrophasotron cable tunnel. Underlying is the beam outlet.

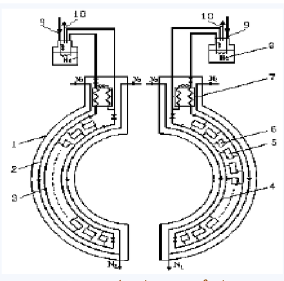
Figure 4: General scheme of the Nuclotron cryogenics. 1 – vacuum shell; 2 – heat shield; 3 – supply header; 4 – return header; 5 – dipole magnet; 6 – quadrupole magnet; 7 – subcooler; 8 – separator; 9 – helium flow from the refrigerator; 10 – return helium flow to the refrigerator.

Nuclotron accelerator

The Nuclotron lattice is typical for strong-focusing synchrotrons with separated functions. It contains 8 super periods and 8 straight sections, one of which is "warm". General view of the Nuclotron dipole and quadrupole magnet is presented on Fig. 2. The magnets are fastened to a vacuum shell of the cryostat Ø540 mm by 8 suspension parts of stainless steel. A nitrogen shield Ø490 mm covered with 20 layers of super insulation is placed in the vacuum space between the magnet and the vacuum shell. The dipole magnet has a window-frame type iron yoke with the sizes of window of 110 x 55 mm². The quadrupole lens has the iron yoke with hyperbolic poles. The SC-cable was manufactured of a 5 mm in diameter copper-nickel tube with a wall thickness of 0.5 mm and 31 in parallel connected multifilament strands of 0.5 mm in diameter covering an outer surface of the tube. The strand consist of 1045 NbTi filaments 10 μm in diameter stabilized by copper.

The design parameters of the dipoles are: B=2.2 T and dB/dt=2 4 T/s. Nominal current amplitudes are: up to 6.3 kA and 6 kA for the dipoles and quadrupoles respectively. There are 96 dipoles, 64 quadrupoles, and 32 correcting SC-magnets in the Nuclotron ring with circumference of 251.5 m. Averaged specific weight of the magnetic system is only 0.32 t/m.

General scheme of the Nuclotron cryogenics is presented in Fig. 4. All the magnets are connected in parallel with supply and return helium headers. The internal diameters of the headers are 36 mm and 52 mm respectively. The cooling of the magnets is performed by two-phase helium flow. The liquid-vapor content varies from 0 at the inlet of the magnet to 0.9 at its outlet. The temperature sensors are placed at the helium inlet and outlet of the winding and also at the helium outlet of the iron yoke of each magnet. Totally, the temperature measuring system includes about 600 points. The Nuclotron operational temperature is 4.5-4.7 K. The cryogenic supply system is based on three industrial helium refrigerator/liquefiers with a total capacity of 4.8 kW at 4.5 K.

Target assembly description

The scheme of experiments is presented in Fig. 5.

The extracted pulsed deuteron beam of the JINR NUCLOTRON hits the target from the exit window located on it in 3.32 m. The spatial and time profile, as well as an intensity of each deuteron pulse were monitored using calibrated and position sensitive ionization chambers in coincidence with two scintillation telescopes. The beam position on the target and the integral deuteron flux were controlled by the profilometer and activation monitors from aluminum foil and SSNTD placed before the target. Prompt neutrons were measured by the detector DEMON with the liquid scintillator NE213 inside. This detector has a large (~ 30%) efficiency for neutrons of high (up to 100 MeV) of energy. Delayed neutrons (DN) were recorded by the detector system ISOMER-M. It consists of 11 proportional 3He-counters placed into the 50 x 50 x 60 cm Plexiglas moderator block. Each counter was equipped with the preamplifier and discriminator. The ISOMER-M efficiency for registration of neutrons from the Pu-Be-source with the average spectrum energy of 4.4 MeV was 11.4±0.1%.. The detector was surrounded by appropriate shielding from borated polyethylene. The DAQ system provided measurement of the neutron yield as a function of time for each deuteron pulse.

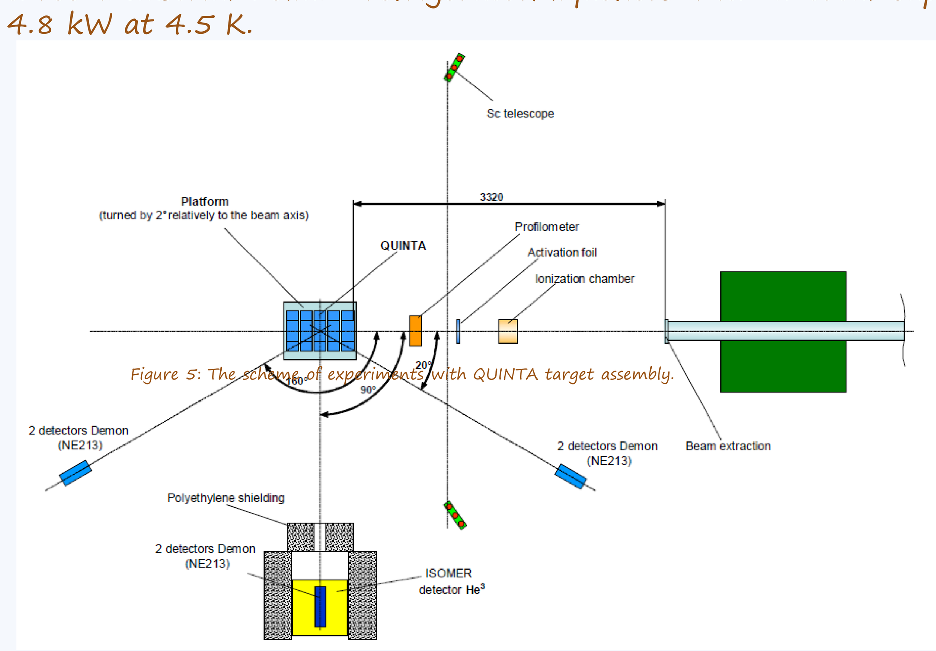

Figure 5: The scheme of experiments with QUINTA target assembly.

The target assembly "QUINTA" (Fig. 6) consists of five identical sections of hexagonal aluminum containers with an inner diameter of 284 mm, each of which is filled with 61 cylindrical metallic natural uranium blocks of 36 mm diameter and a length of 104 mm aluminum cover. One block weight is 1.72 kg and the total mass of uranium in one section is 104.92 kg. The front section has the cylindrical input beam channel of 8 cm in diameter. The total mass of uranium in the target assembly is about 500 kg.

In front of the target and between the sections as well as behind it, there are 6 experimental plates for detectors and samples. To prevent the free passage of some part of an incident beam through the horizontal empty space between the tightly packed uranium cylinders, an axis of the target assembly is shifted by 2 degrees with respect to the beam axis.

The lead blanket with thickness of 10 cm with the input beam window (150 x 150 mm) surrounds "QUINTA". In the top cover of the blanket there are special slots for quick removal of the detector's plates.

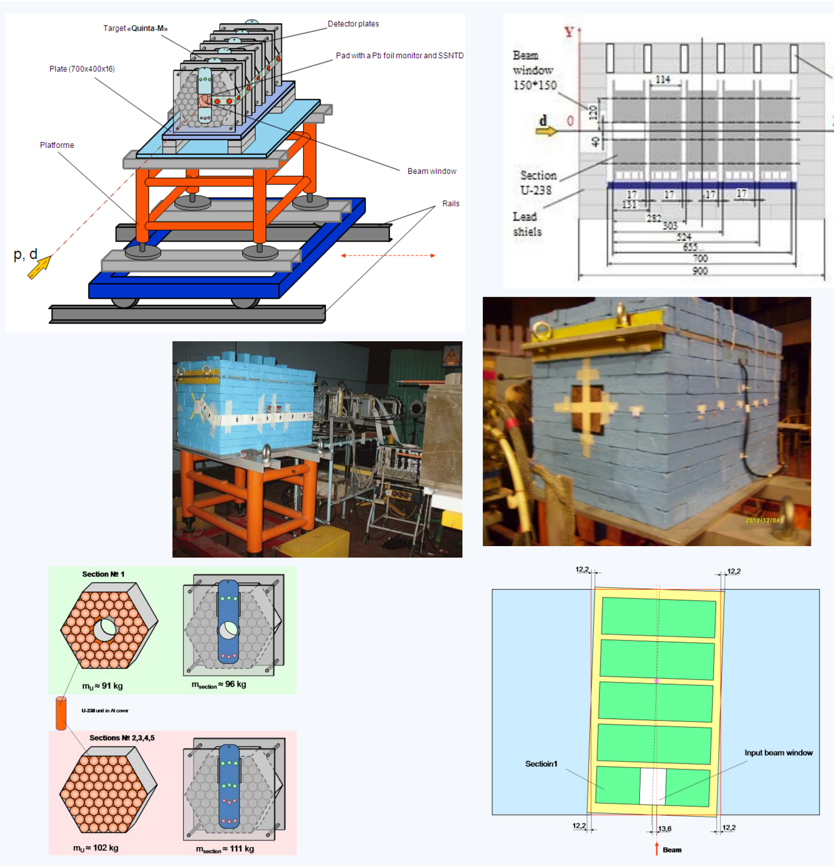
Figure 6: The target assembly "QUINTA" equipped by lead blanket.

The main objectives of the experiments with the target assembly "QUINTA" were:

Testing methods to measure the basic characteristics of nuclear processes occurring in the active core under the influence of relativistic particles. It is necessary for the further experiments at quasi-infinite uranium target (mass ~ 21 t) available at JINR.

Basic and applied studies of the interactions of relativistic particles with massive multiplying target.

It is important to note that basic aim of all measurements with this target is to prepare and to test the experimental technique for realization of main research program with Large Uranium Target (LUT) (19.5 t, diameter 120 cm, length 100 cm) setup. Of course, the results obtained in experiments with QUINTA and presented below have independent meaning for understanding and modeling the processes occurring in the central zone of LUT setup.

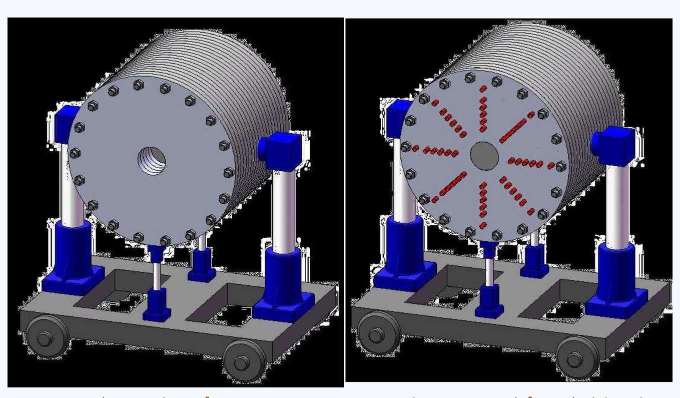
Figure 7: Front and rear view of target setup Large Uranium Target (left and right pictures respectively).

The design of LUT setup is shown in Fig. 7. It has a steel case, the replaceable central zone diameter of 20 cm and many axial detector channels are shown in red. The frame provides a precise positioning of the target In general Large Uranium target setup is well suited for realization of extended research program adopted in the "E&T RAW" project for 2013-2014.

Experiment details

Irradiation of the "QUINTA" setup was carried out with 2 GeV, 4 GeV and 8 GeV deuterons beams.

The axis of the setup was aligned with beam axis with the help of the adjustable stand under the whole setup. The alignment of the beam center with the center of the setup was achieved by examining polaroid films placed in front of the target and exposed to a couple of deuterons pulses prior to the installation of the sample plates and the start of the main irradiation.

Deuteron beams shape and position on the target were obtained from track density distributions on the irradiated track detectors. Sensors made of ^{nat}Pb foils and artificial mica as SSNTD were used for registration of $^{nat}Pb(d,f)$ reaction. Sensors were placed directly onto the beam input window in the lead blanket surrounding the uranium target and at the first experimental plate (Plata 0). The sensors had the size 3 x 4 cm.


Figure 8: The location of the sensors to measurement the beam parameters.

EXPERIMENTAL TECHNIQUE

In our experiments we used a SSNTD method to determine the beam parameters such as beam shape and size, beam center position on the target, total beam intensity.

SSNTD technique is based on correlation between the track density on a track detector and a flux density of the investigated beam.

Sensors made of track detectors placed in contact with a fission foil are irradiated by the beam. Fission fragments produced in spallation reactions in fission foils form tracks on the track detectors surface.

After the exposure the detectors are etched in appropriate chemical reagents (depending on the detector type) to make tracks "visible" in an optical microscope (Fig. 10). To obtain an accurate measure of the track densities the tedious method of manual track counting is chosen. We count tracks in many photomicrographs produced for each detector using an optical microscope. The distributions of the track density along the X- and Y-axis are used to obtain the beam intensity distribution on the target.

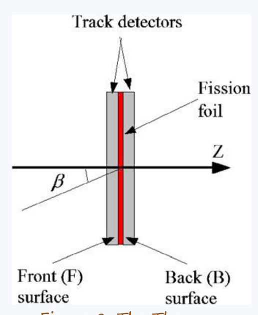

Figure 9: The The schematic drawing of the foil-detector assembly that was used in the calculations and in the experiments.

Figure 10: SSNTD after etching, RUN DECEMBER2012.

The most common formula for the relationship between the tracks density and the flux density is determined as:

$$N^{i} = A^{i}\mu^{i}\varepsilon\, d\, \rho\, t_{\exp}\int_{0}^{\infty}\sigma_{f}^{i}(E)\varphi^{t}(E)dE$$

where A^{i} – number of charged particles produced in the fission reaction of i-nuclides; μ^{i} – the fraction of charged particles reaching the detector in the fission reaction of i-nuclides; ε – detection efficiency of the charged particle track detectors; d – i-layer thickness of nuclides in the radiator, cm; ρ – nuclear density of i-nuclides in the radiator, nuclei/cm³; $t_{\exp}$ – duration of sensors the exposure, sec; σ_{f}^{i} – differential microscopic fission cross section of i-nuclides with deuterons, cm².

The technique was developed by I. Zhuk and A. Malikhin. It was applied for fission reactions rates measurements in reactor systems. The presented technique has a resolution of 1 mm.

In this work thick radiators were used. In the context of SSNTD technique "thick" radiator means that the radiator thickness is exceeded significantly the mean free path of fission fragments in the radiator material. This circumstance allows to reject an uncertainty caused by radiator thickness determination (as for thin foils) and to increase the total number of fission fragments. At the same time, due to the radiator thickness, we can register the only one fission fragment from the binary fission process and cannot distinguish it by using two correlated tracks. So, the fission process cannot be discriminated from the other high energy processes (such as spallation, multifragmentation and strong asymmetric fission) in which heavy and medium mass particles can be generated. FLUKA, intranuclear cascade model and the model of the nucleon-nucleon interactions RQMD-2.4 were applied to study this effect. The overall contribution of this effect into the relative variation of the sensitivity of the sensor is ~ 0.5 % and was taken into account when analyzing the results.

In addition, the influence of the kinematics of ^{nat}Pb fission process on the track density on the track detectors has to be taking into account for the whole deuterons energy range. Pulse transfer effect for ^{nat}Pb can be compensated by the "sandwich-like" composition of sensors, which allows to register tracks in 4π geometry.

EXPERIMENTAL RESULTS

The experimental tracks density distributions of fission fragments of ^{nat}Pb, which characterize the spatial distribution of the incident deuteron beams at the front end of a uranium target, are shown in Fig. 11. These distributions are well approximated by a three-dimensional Gaussian function. Calculated from the experimental data the beam position parameters of the Gaussian distributions are shown in Tables 1 and 2. Total deuteron beam intensity in 46th Nuclotron Run (December 2012) measured with SSNTD is presented in the Table 3. Full width at half-maximum (FWHM) of a Gaussian distribution is expressed in terms of its standard deviation σ as

$$FWHM = 2\sigma\sqrt{2\ln 2}$$

Table 1: Primary Beam Parameters (at the Beam Input Window in the Lead Blanket

Deuterons energy, GeV	Beam centre coordinates, cm		FWHM of distribution, cm	
	X	Y	$FWYM_X$	$FWHM_Y$
2	2.0±0.2	0.0±0.1	2.2±0.3	1.5±0.3
4	2.1±0.1	-0.3±0.2	1.4±0.2	0.9±0.1
8	1.0±0.2	-0.1±0.1	0.9±0.1	1.0±0.1

Table 2: Primary Beam Parameters (at the Plata 0)

Deuterons energy, GeV	Beam center coordinates, Cm		FWHM of distribution, cm	
	X	Y	$FWHM_X$	$FWHM_Y$
2	1.5±0.2	0.1±0.1	2.0±0.1	1.7±0.2
4	1.8±0.1	-0.3±0.1	1.5±0.2	1.1±0.1
8	0.9±0.1	0.1±0.1	1.0±0.1	1.3±0.1

Table 3: Total Deuteron Beam Intensity in 46thNuclotron Run (December 2012) Measured with SSNTD

Deuterons energy, GeV	Total deuteron intensity, number of deuterons
2	$(3.0±0.3)10^{13}$
4	$(3.1±0.3)10^{13}$
8	$(8.6±0.9)10^{12}$

The figure 12 shows the position of the deuteron beams at the central uranium rods of the target. At the figure the 2D projections of the tree-dimensional distributions of the deuteron beam intensity on the input surface and the first plate of the "QUINTA" assembly are presented. Dotted lines show the uranium rods cross-sections. The ellipse semi-major and semi-minor axes (thick lines on the figure) correspond to the 1σ and 2σ parameters of the Gauss distribution. Integration over the surface of the minor and major ellipses gives respectively 68 % and 95 % of the total number of primary deuterons hitting the target.

From the Fig. 12 it is obvious that in all experiments the beam center was shifted from the assembly central point. This has to be taking into the account for analyzing the experimental data on nuclear reactions inside the setup.

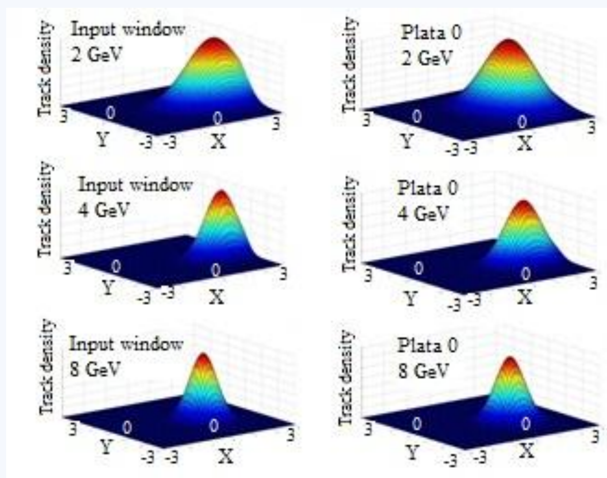

Figure 11: The spatial distributions of the beam at the target.

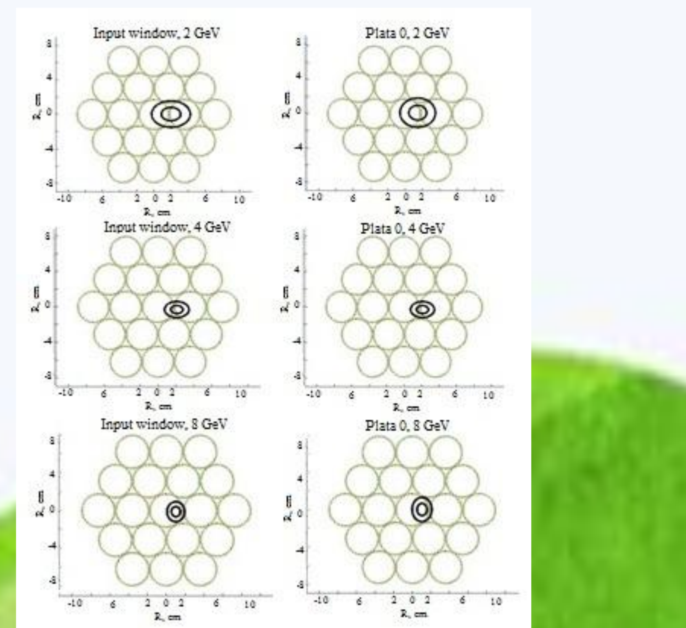

Figure 12: 2D projections of the tree-dimensional distributions of the deuteron beam intensity on the target.

CONCLUSION

Beam position measurements, as well as beam size and beam shape, on a massive target irradiated by relativistic particles, allow to determine the analysis correctness of spatial distributions of nuclear reactions measured inside the target. In our case, it is number of fission of ^{238}U and the rate of production of ^{239}Pu, recorded by different detectors located inside and on the surface of the assembly. In addition, the experimental results of the beam parameters determination using the presented SSNTD technique can be used for the correct modeling of the experiments using by different program codes (such as MCNPX, GEANT4, FLUKA) and testing them by comparison with measurements.

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