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EXPERIMENTAL STUDY OF NEUTRON-PHYSICAL CHARACTERISTICS OF THE U/PB ASSEMBLY OF ELECTRONUCLEAR SETUP "ENERGY+TRANSMUTATION" UNDER 1.6, 2.5 AND 4 GeV DEUTERON BEAMS IRRADIATION

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Outline

- **Introduction**
- **Experiment : Neutron generation in the «Energy plus Transmutation» setup**

    Experimental setup and equipments

    Experimental techniques and results

    Monte Carlo simulations

- **Conclusions**

I N T R O D U C T I O N

Idea of transmutation

Transmutation – transformation of long-living nuclides into shot-living or stable.

The first result on nuclei transmutation has been reported by E.Rutherford in 1919.

For a transmutation it is possible to use practically any nuclear radiation, however neutrons more effective (in the absence of Coulomb barrier).

Fission products transmutation - by neutron capture reaction X(n,γ)

Minor actinides transmutation - by fission reaction X(n,f)

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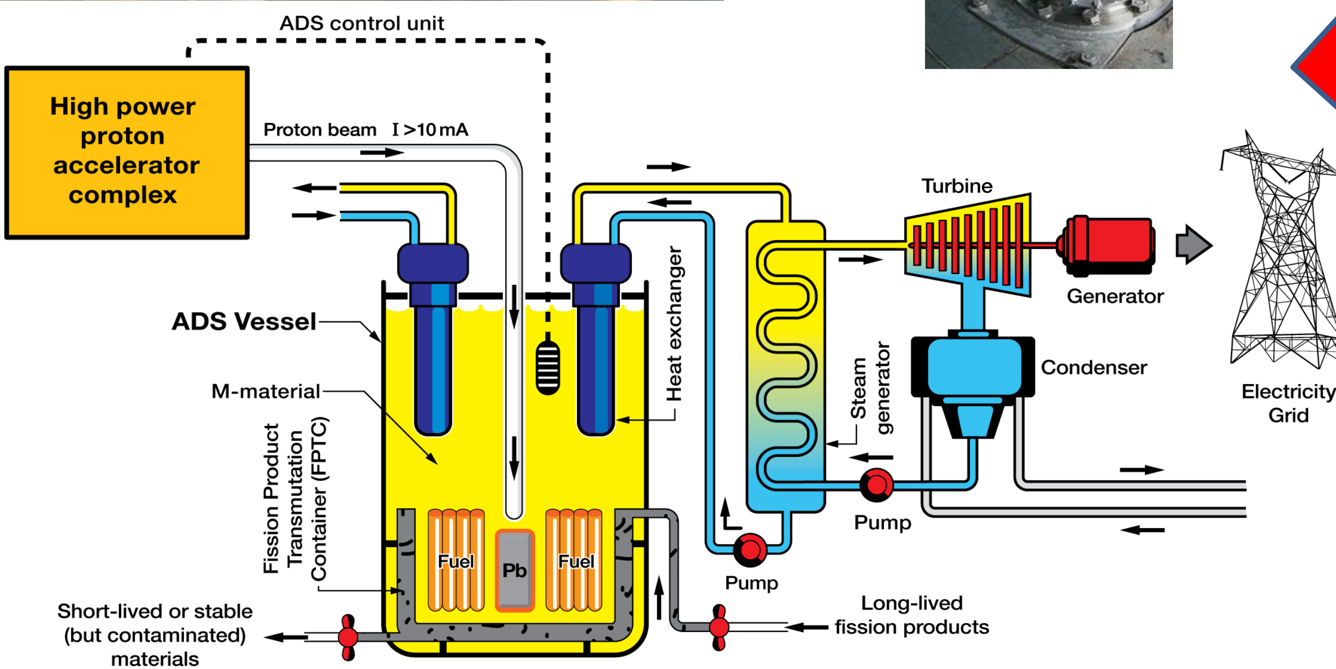
«Accelerator + subcritical core»

+



I N T R O D U C T I O N

Accelerator driven system (ADS)

Accelerator + Neutron generating target + Subcritical core

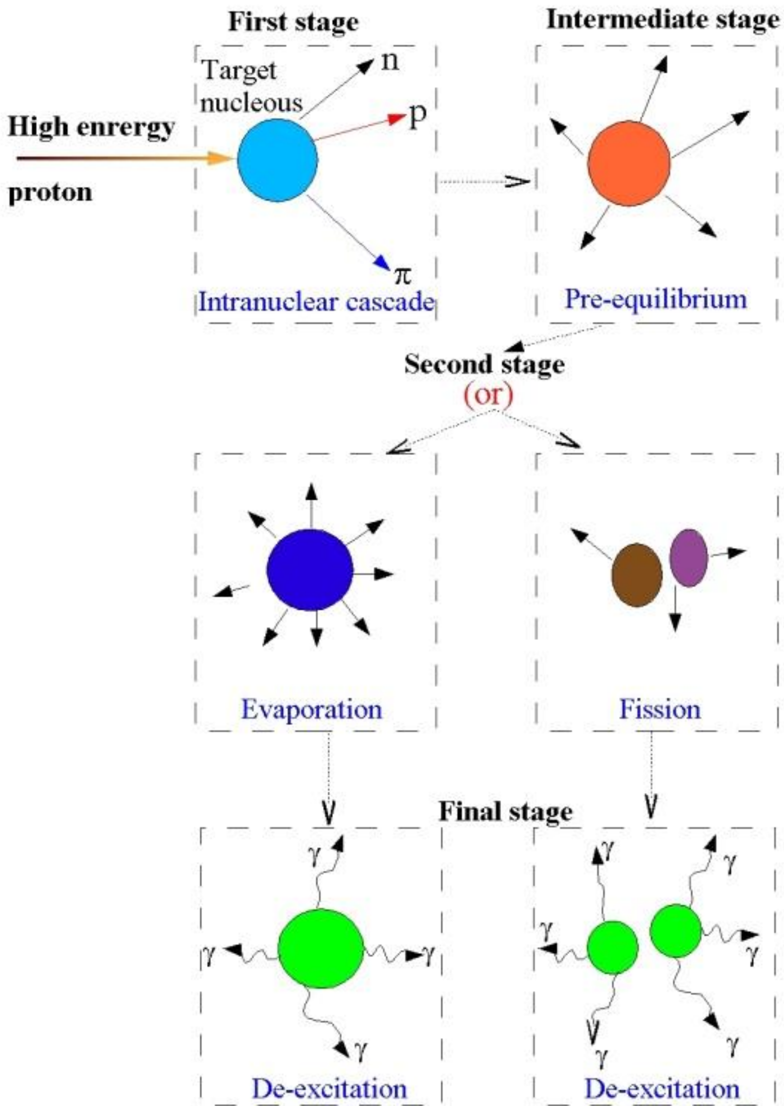
Advantages:

- New Fuel cycles (^{238}U, ^{232}Th)
- Nuclear waste transmutation (FP and MA)
- Nuclear Safety (subcritical condition)

First experimental (by E.O.Lawrens in USA, V.N. Semenov in USSR): spallation neutron source on the basis of a lead target bombarded by high energy protons

I N T R O D U C T I O N

Spallation



Pictorial representation of high energy proton interaction with target nucleolus.

In the fist stage the incident particle interacts of with individual nucleons [Intranuclear cascade phase]. This is followed by intermediate stage (pre-equilibrium). In both of these stages high energy light particles (dominated by neutrons) are emitted which then interact with other nuclei in the extended target (internuclear cascade). In the second stage the residual nucleus either undergoes evaporation releasing neutrons and light ions (with energies around 1 MeV) or fission. In the final stage the residual nucleus (or nuclei) de-excite via gamma emission.

I N T R O D U C T I O N

Problems for experimental studies

1. Neutron reactions cross-sections
2. Neutron spatial and energy distributions
3. Neutron and gamma multiplicity

(in the energy range from 20 MeV to ~150 MeV)

4. Simulation codes verification

INTRODUCTION

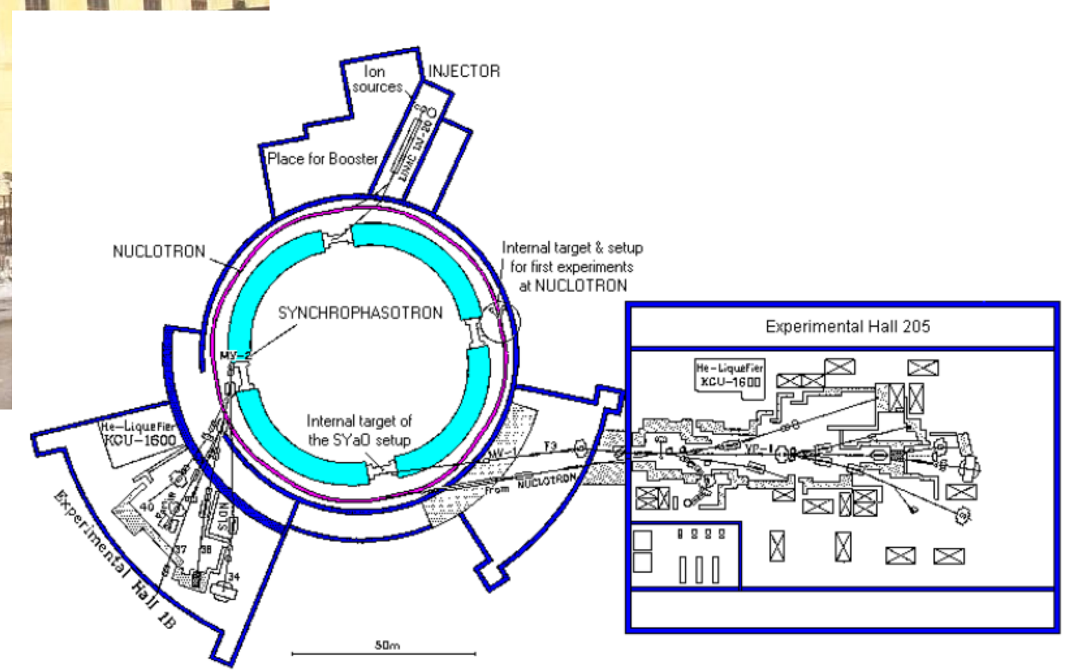
Experimental

Collaboration “Energy plus Transmutation”

Joint Institute for Nuclear Research (Dubna, Russian Federation) since 1997

Accelerator building (Laboratory of High Energy Physics, JINR)

Layout of accelerator complex and experimental hall



INTRODUCTION

“Energy plus Transmutation” project

During 1999-2009 various experiments were made with “Energy plus Transmutation” assembly.

The experiments were focused on general aspects of energy generation by future ADS, such as:

- **Neutron generation and multiplication**
- **Neutron spectra determination**
- **Generation of secondary isotopes inside the Pb-target and U-blanket**
- **Energy generation**
- **Neutron induced transmutation** of:
  1. long-lived minor actinides (^{237}Np and ^{241}Am),
  2. fission products (^{129}I)
  3. Plutonium isotopes (^{238}Pu and ^{239}Pu).

$$^{129}I(n,\gamma)^{130}I^* \xrightarrow{\beta^-;T_{1/2}=12,36h} {}^{130}Xe$$ (stable)

$^{129}I(n,nx)$ and $^{129}I(n,xnyp) \rightarrow$ stable and radioactive isotopes

$$^{237}\mathrm{Np}(n,\gamma)^{238}\mathrm{Np} \xrightarrow{\beta^-;T_{1/2}=2,2d} {}^{238}\mathrm{Pu}^*$$ ($T_{1/2}$=87.74 y)

$^{238,239}Pu(n,f) \rightarrow$ fission products

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EXPERIMENTAL

Experimental technique

Experimental setup

Deuteron beams parameters

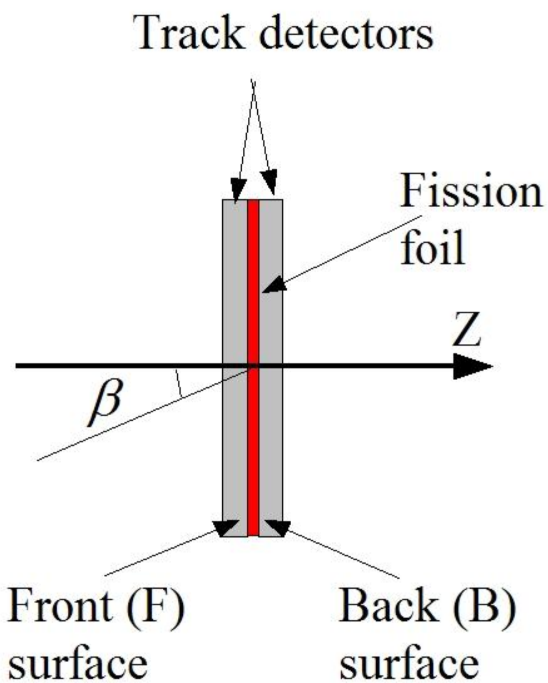
Fission and capture rates distributions

Experiment vs. simulation

Conclusions

EXPERIMENTAL

SSNTD for fission rate measurements:



The basis of fission reaction rates measurement using **solid nuclear track detectors** (SSNTD) is the parity between a density of tracks formed on the surface of the detector, (irradiated at close contact to a radiator which is a source of fission fragments), and investigated neutron flux.

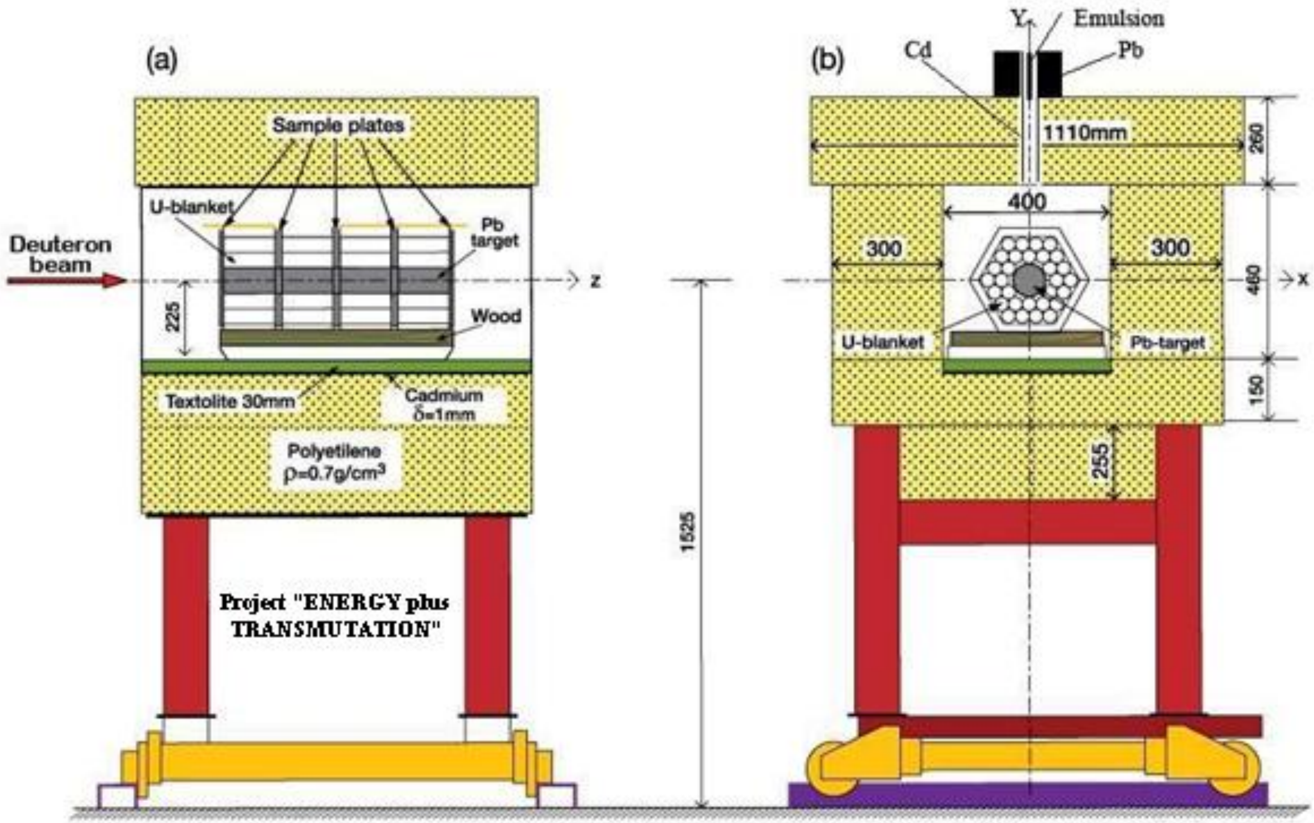
Reaction rate is proportional to the track density on the detector.

Activation analysis for radiation capture rate measurements:

$^{238}U(n,\gamma)^{239}U$ (23,54 min) $\beta^- \rightarrow$ **^{239}Np** (2,36 day, 277,6 keV) $\beta^- \rightarrow {}^{239}Pu$

EXPERIMENTAL

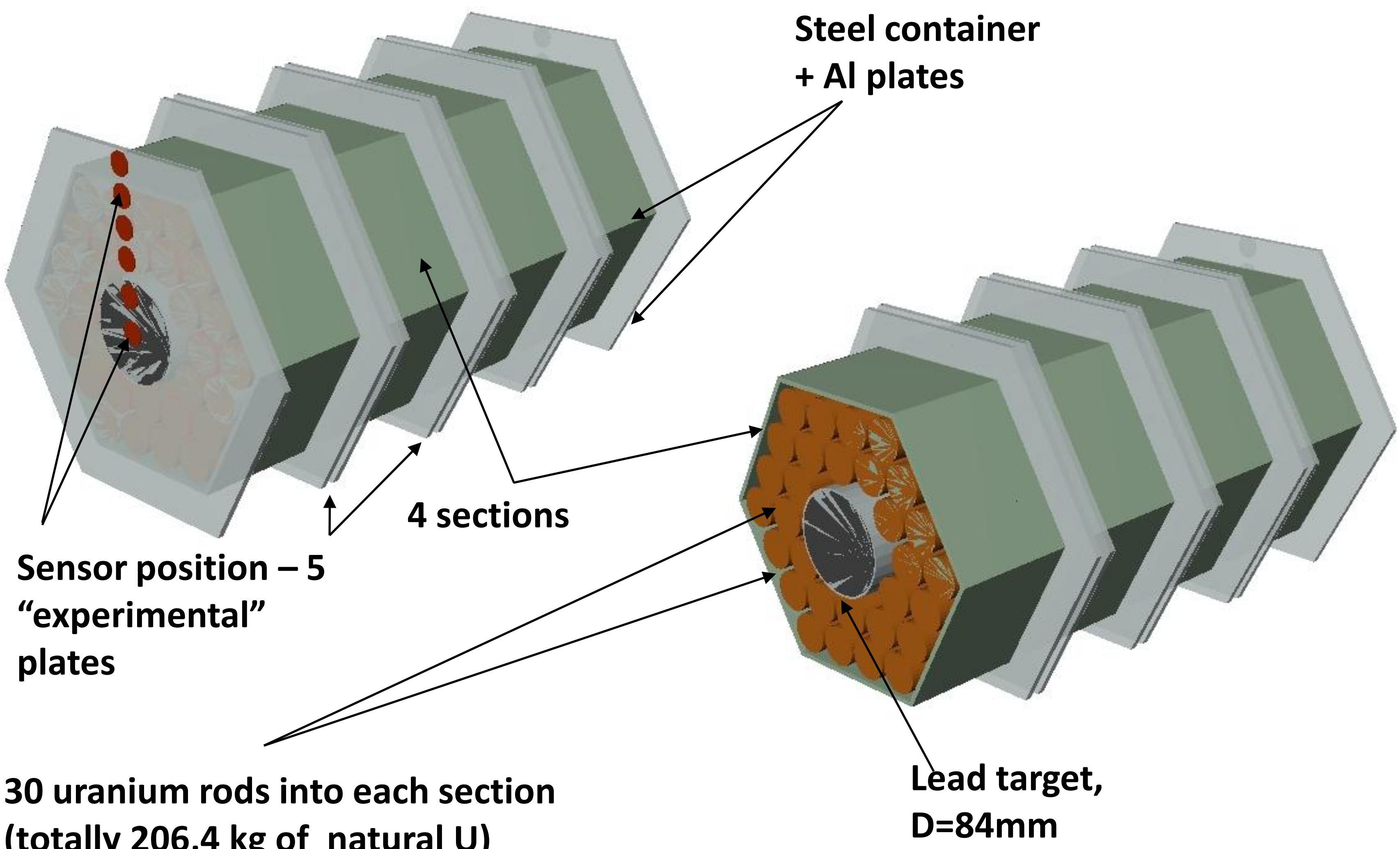
Experimental setup «Energy + Transmutation»

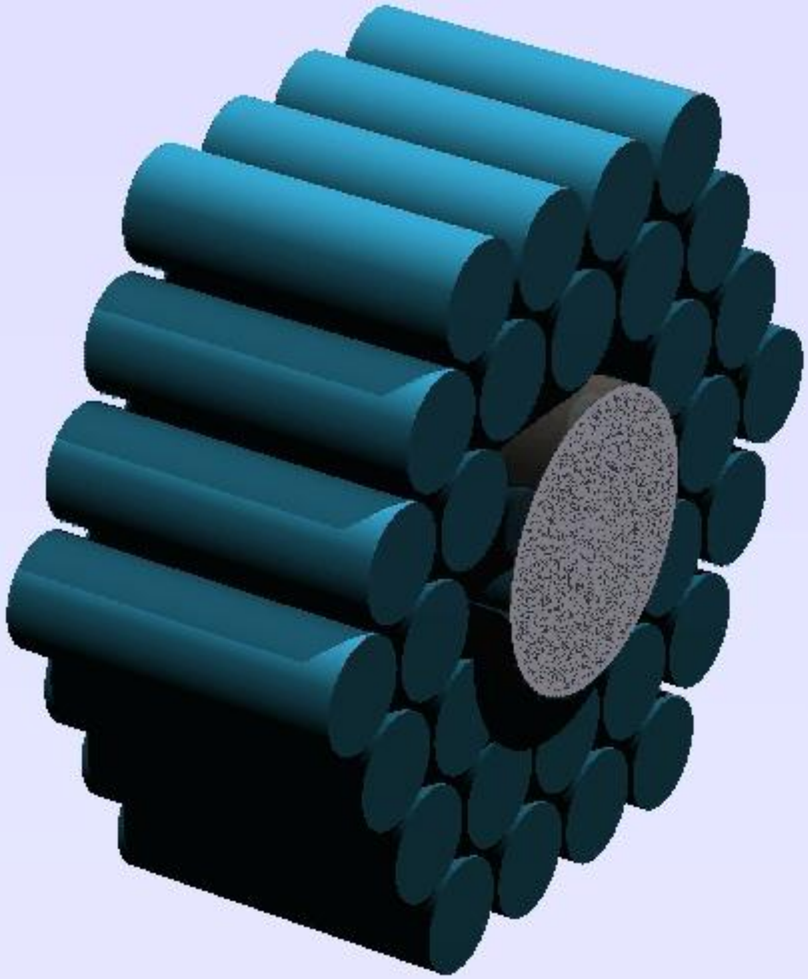


1) Cylindrical lead target with diameter 8.4 cm and length 45.6 cm.
2) A natural Uranium blanket surrounds the target.
3) The whole target-blanket system is placed within a wooden container filled with granulated polyethylene. The inner walls of the container are covered with a Cd foil of 1mm thickness.

EXPERIMENTAL

U/Pb subcritical assembly of the "E+T" setup





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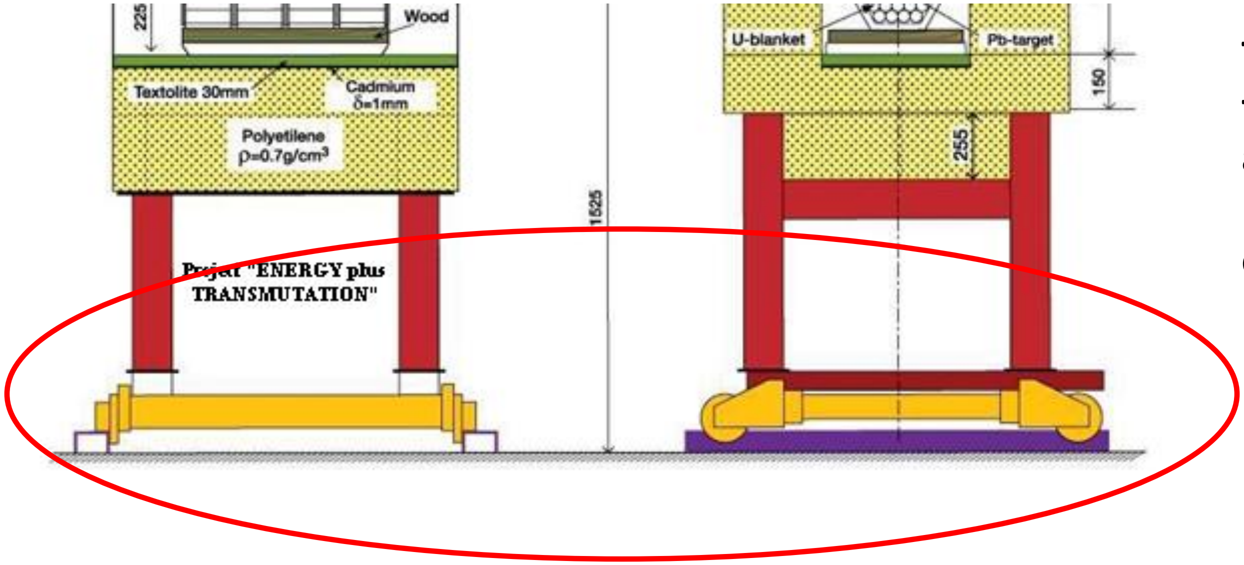
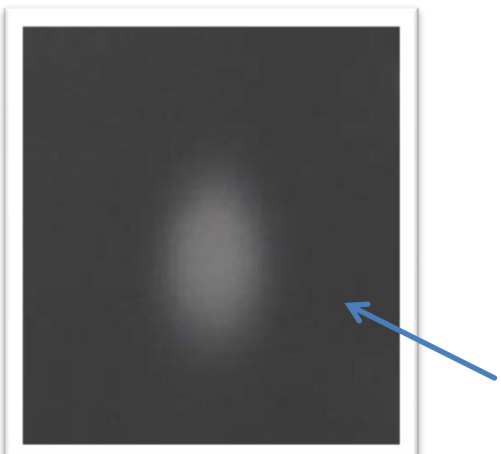
Beam focusing on the target



The setup can be moved to the irradiation place at focus F3N of the Nuclotron experimental complex using a special rail system.

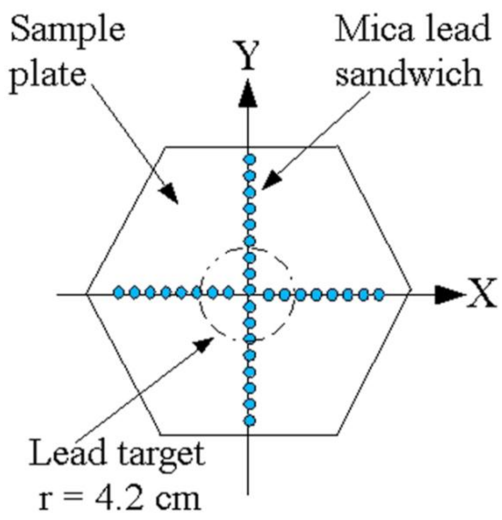


Before the irradiation the target was carefully adjusted concerning a direction of the Nuclotron beam using polaroid films, i.e. the longitudinal axis of a target was combined with a direction of Nuclotron beam.

The traces of one bunch of beam particles on polaroid film placed in front of the target

EXPERIMENTAL

Deuteron beam parameters determination

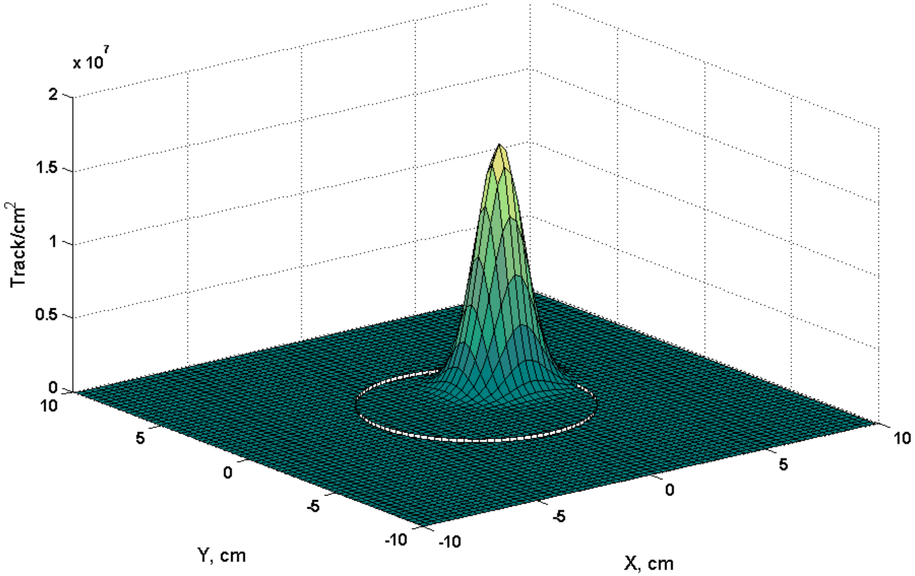


The first experimental plate with a lines of sensors.

Each sensor contains lead foil and two track detectors at both sides of the fission foil.

Gaussian approximation of experimental data from SSNTDs.
Pb(d,f) reaction

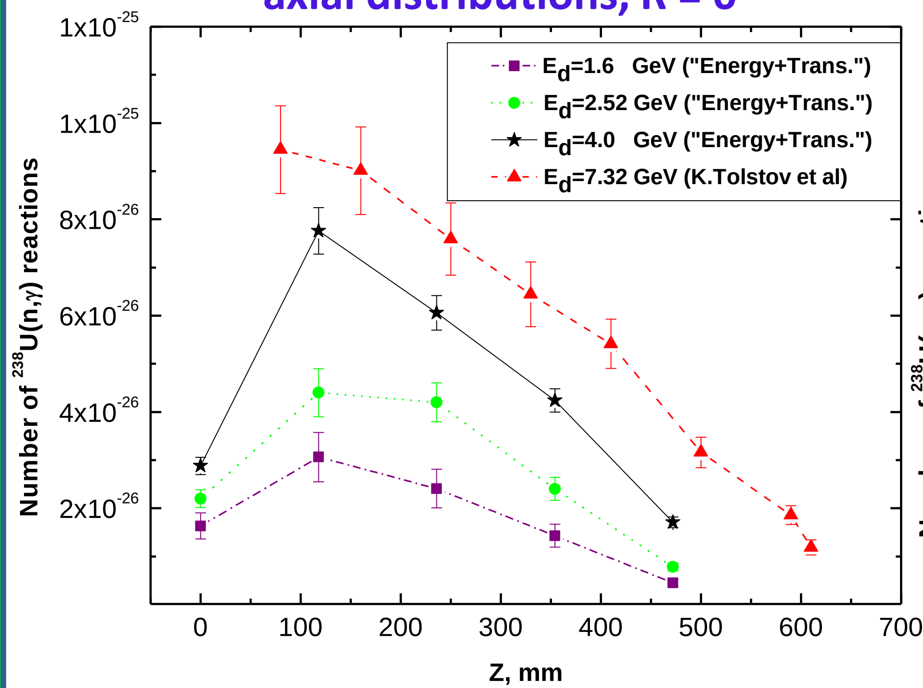
Track densities on the top of the assembly is proportional to spatial distribution of primaries particles.



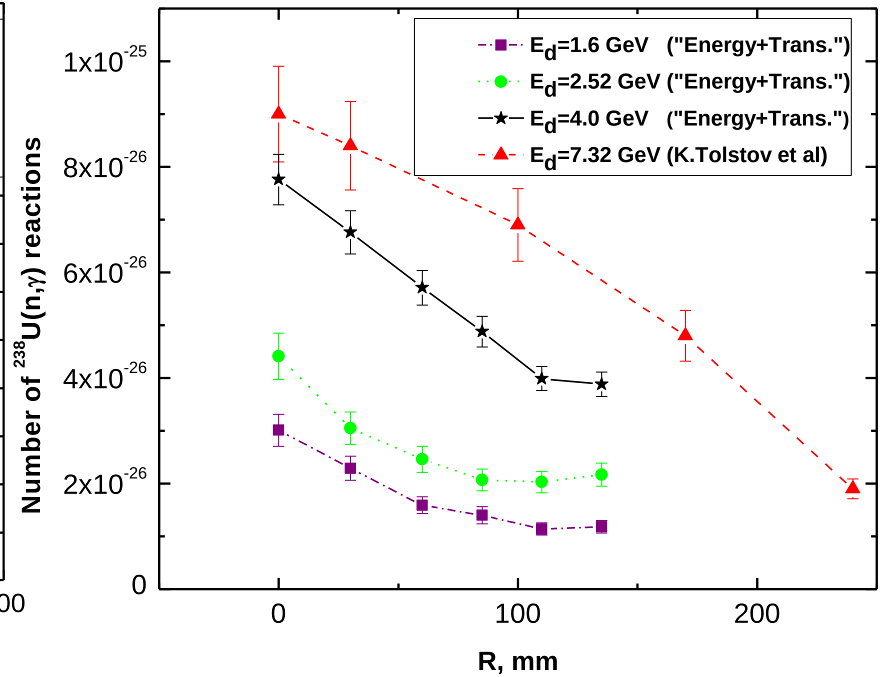
EXPERIMENTAL

The spatial distributions of the number of neutron capture reactions $^{238}U(n,\gamma)$

axial distributions, R = 0



radial distributions, Z = 118



Purple, **green**, **black lines** – data for U/Pb assembly at deuteron energies **1,6 GeV**; **2,52 GeV** and **4 GeV** correspondingly.

Red line – data for lead target (50×50×80 cm) irradiated by **7.3 GeV** deuterons with.

The data is given per one ^{238}U nucleus and one fell on the target deuteron

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The spatial distributions of the number of neutron fission reactions $^{238}U(n,f)$

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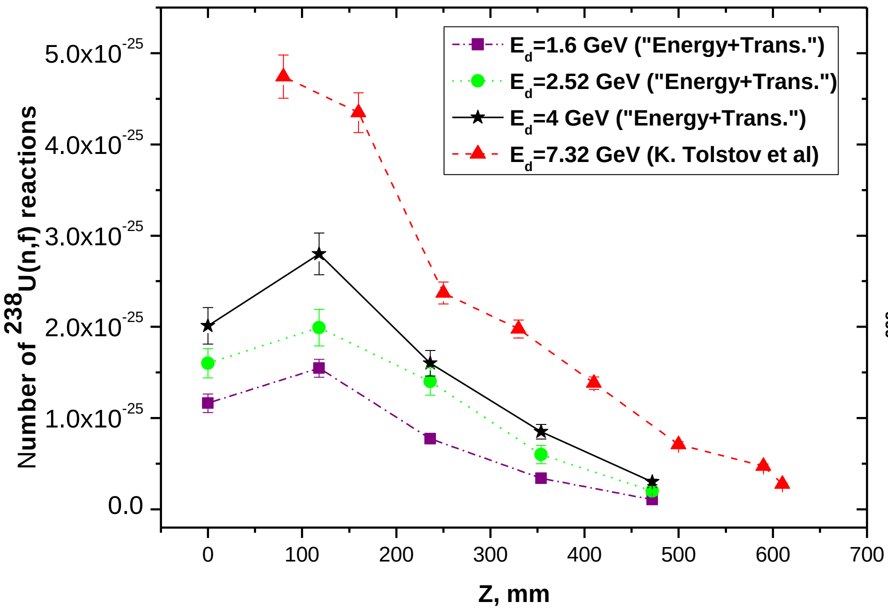
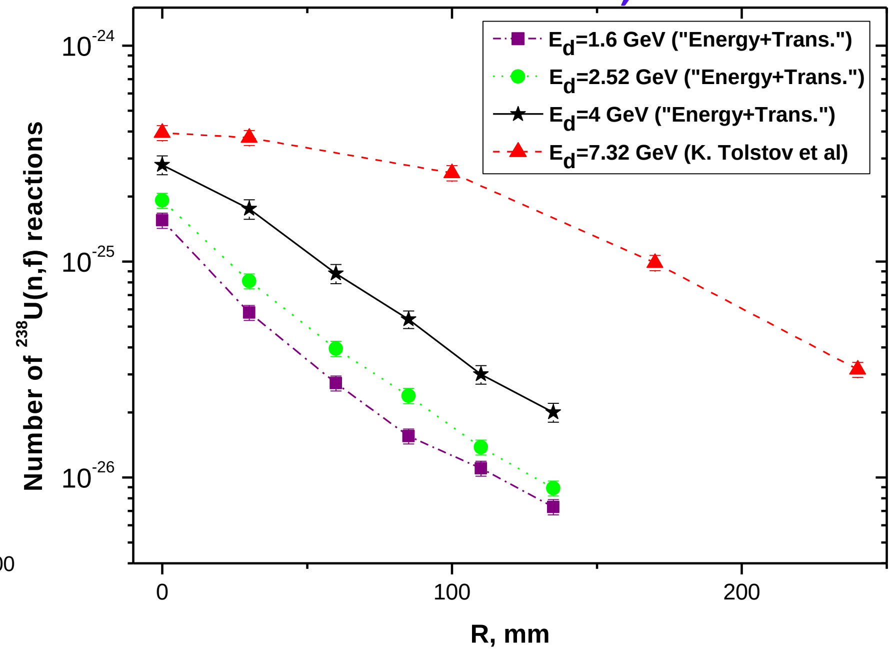


radial distributions, Z = 118



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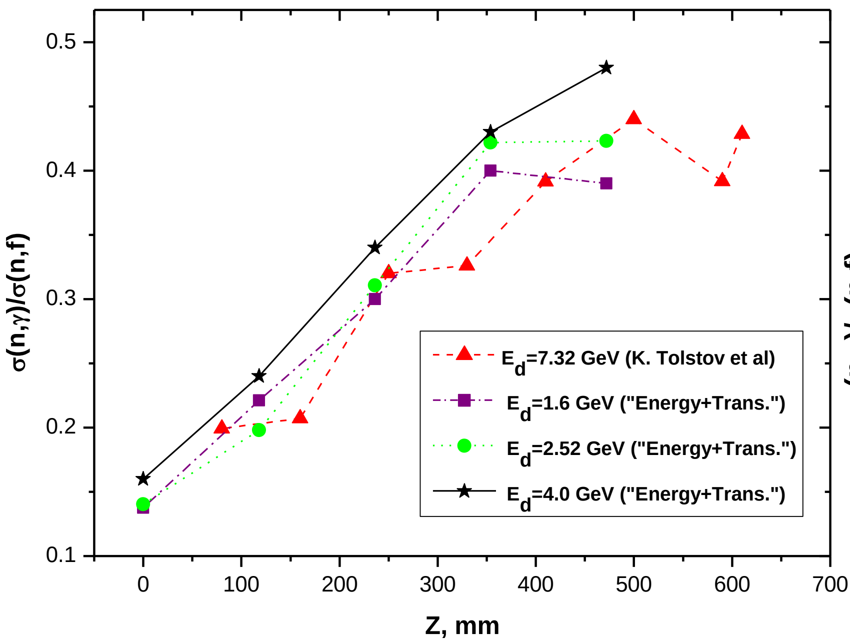
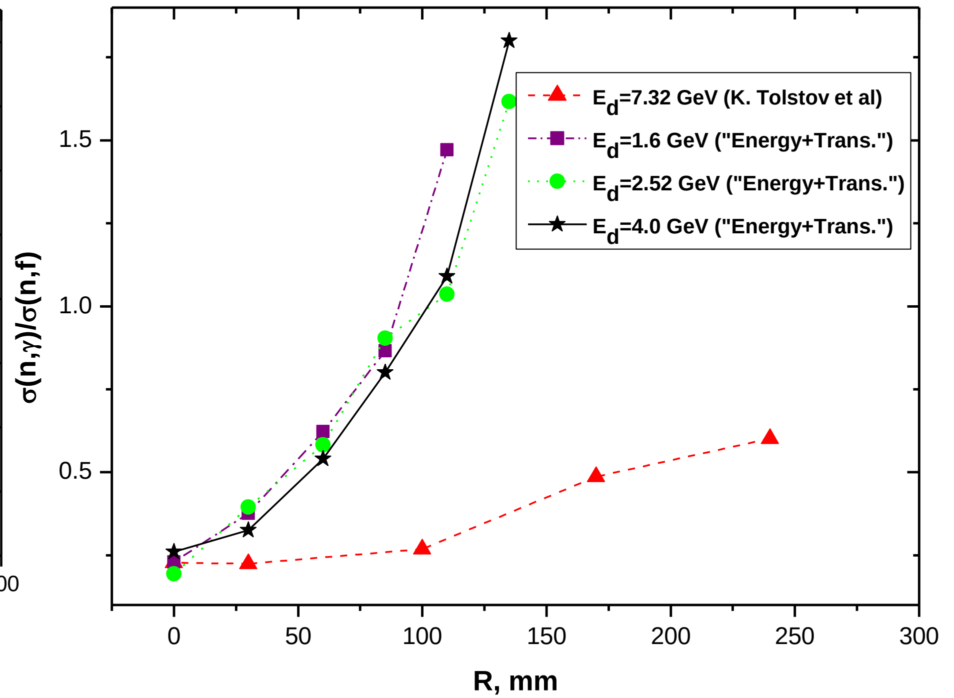
EXPERIMENTAL

The spatial distributions of spectral indices $\sigma_{capture} / \sigma_{fission}$ for ^{238}U

axial distributions, R = 0



radial distributions, Z = 118



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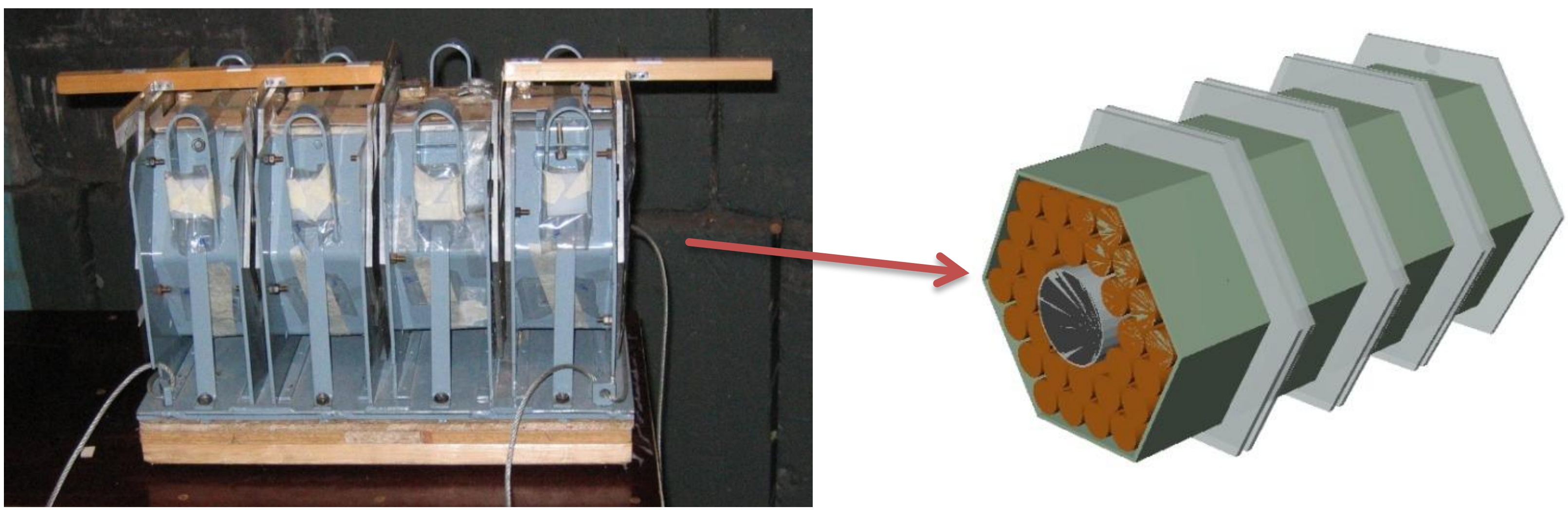
Simulation codes

FLUKA - version 2006.3b

calculation was made by A.S. Potapenko, JIPNR, Belarus

From the real view …to the geometrical module for Monte Carlo codes… and simulation



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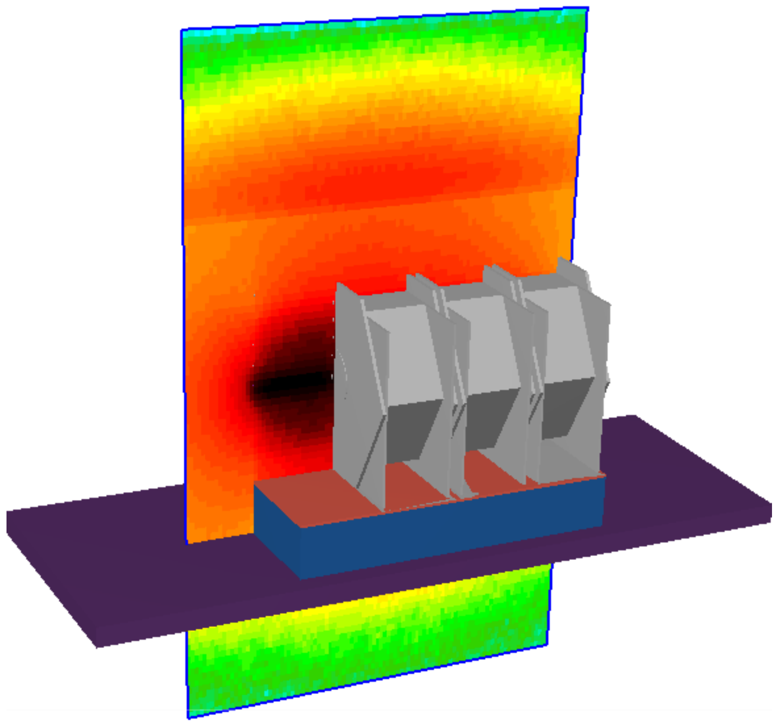
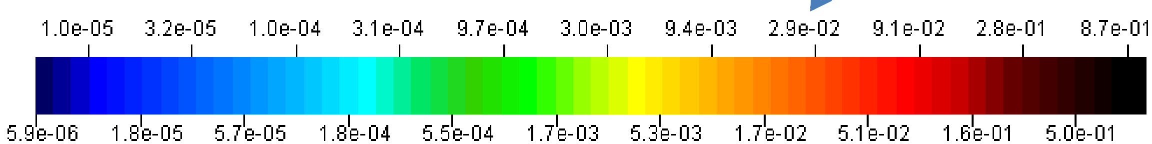
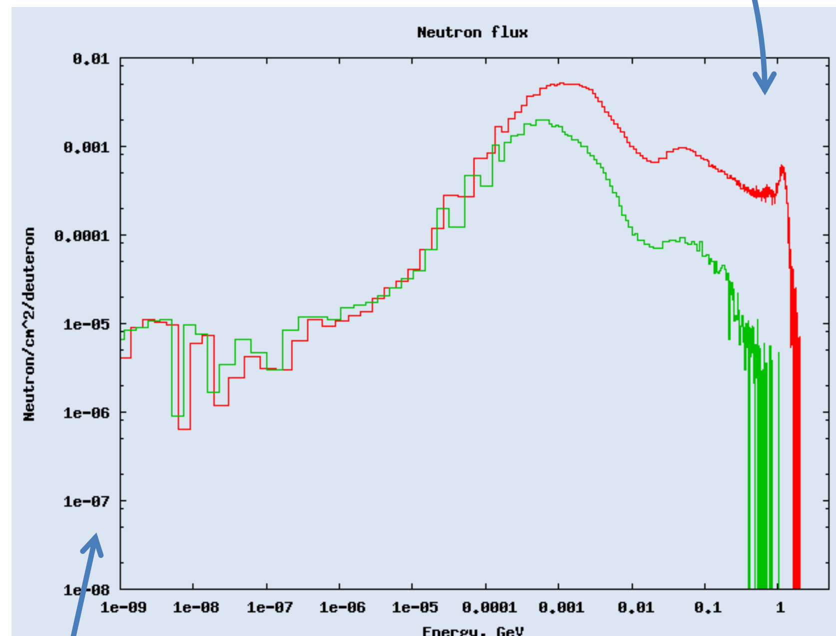
FLUKA simulations

Neutron spatial distribution: slice yz (the first section and shielding were removed for better view)





Neutron spectrum for points:
Z=118 mm, R=0 mm (red line)
Z=118 mm, R=85 mm (green line)



Normalized on the primary particles

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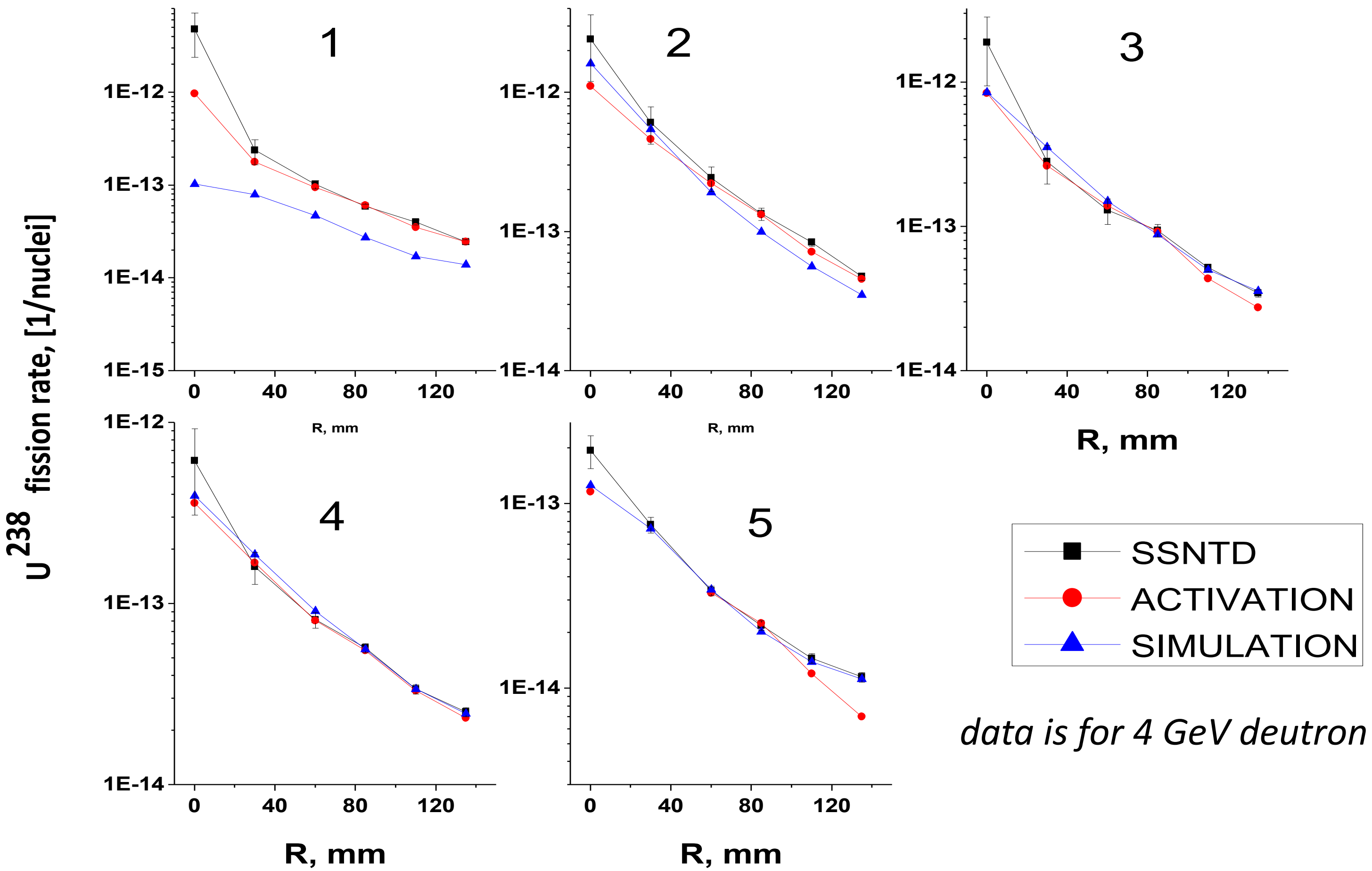
Radial distributions of ^{238}U fission rate



data is for 4 GeV deutron beam

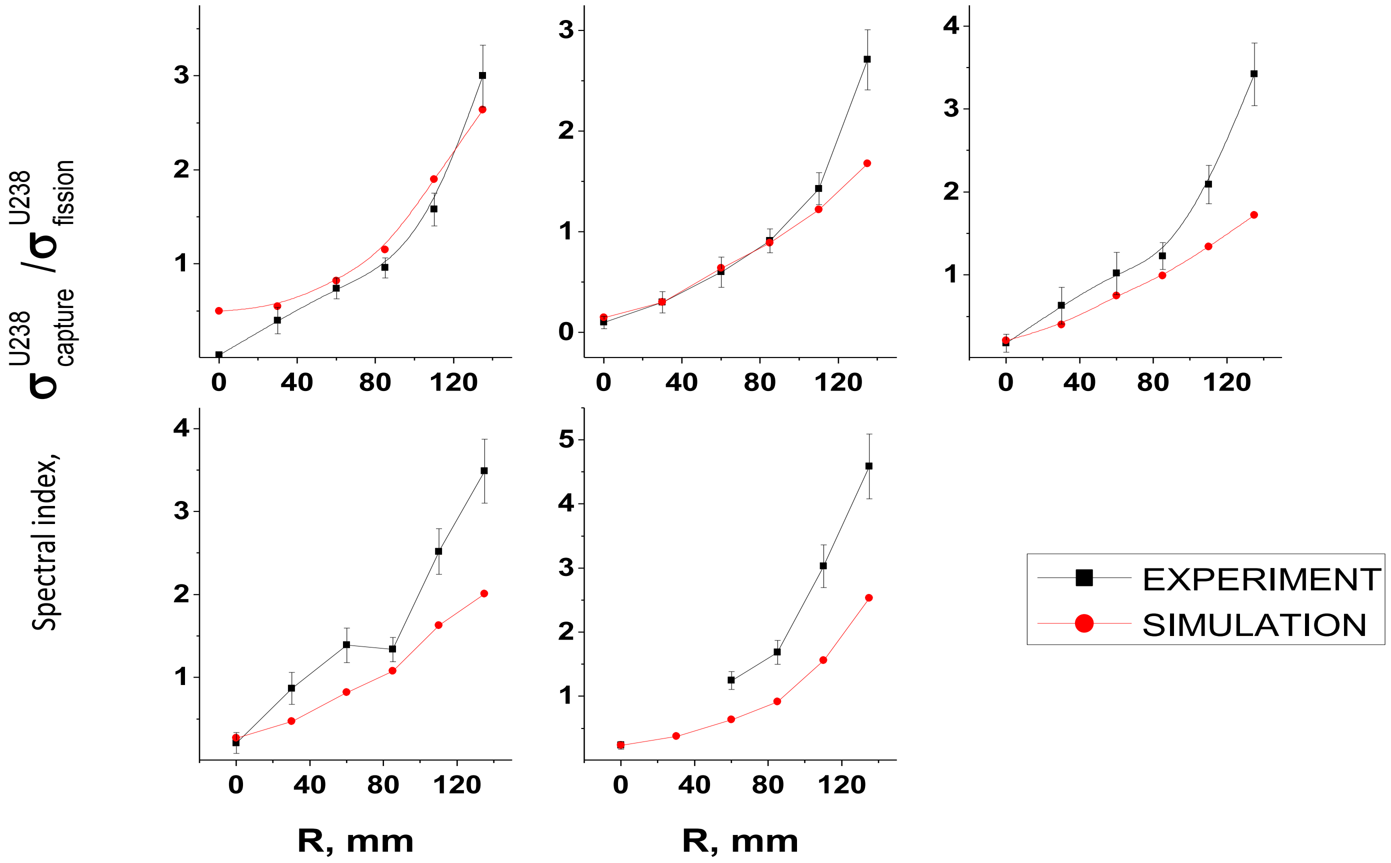
1-5 – number of detector plate

R - radial distance from the axis of the lead target

Lines are drawn to guide the eyes

> 96% of fissions are neutron induced reactions - (n,f)

Radial distributions of spectral indices $\sigma_{capture} / \sigma_{fission}$ for ^{238}U



spectral indices are the best data for comparison with Monte Carlo simulation

uncertainty in the number of primary particles is rejected

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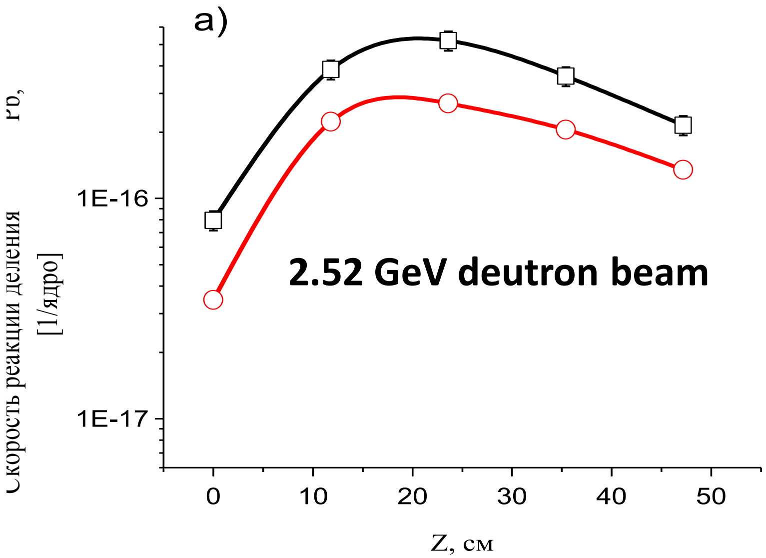
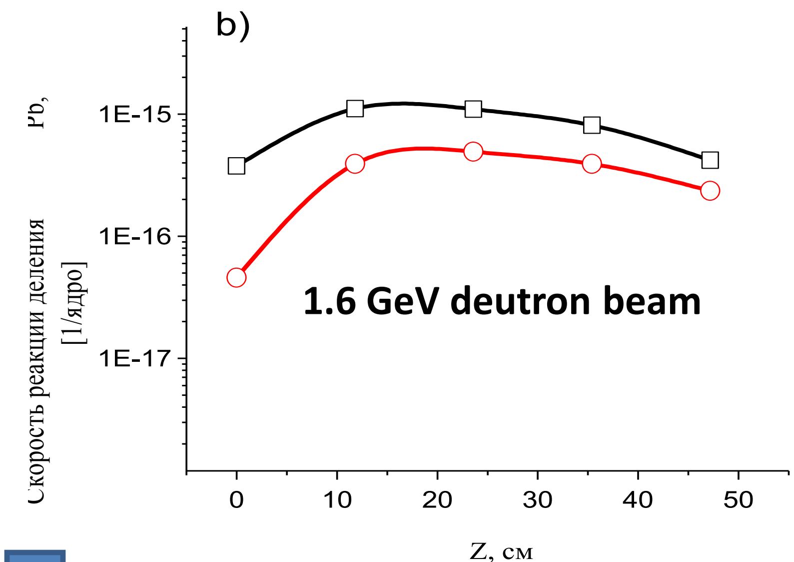
Axial distributions of natural Pb fission rate



Black lines – experimental
Red lines – FLUKA simulation



Error in RQMD algorithm for 30 and > MeV neutrons production in spallation reactions

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SIMULATION

Contribution of different fission processes to total number of fission events in the natural uranium blanket

Fission reaction	D / 4.0 GeV	D / 2.52 GeV	D / 1.60 GeV
^{238}U (n,f)	96,2%	96,2%	96,3%
^{238}U (p,f)	3,1%	3,1%	3,0%
^{238}U (π,f)	0,6%	0,6%	0,5%
^{238}U (γ,f)	0,1%	0,1%	0,2%
^{238}U (*,f)	100,0%	100,0%	100,0%

Projectile / Energy	MC Code / version	Number of secondaries per one primary		
		n	p	π^{+-}
P / 1.50 ГэВ	MCNPX 2.6C	49,97	8,04	0,54
P / 1.50 ГэВ	FLUKA/2006b	47,14	8,64	0,50
D / 1.60 ГэВ	FLUKA/2006b	69,33	11,05	0,36
D / 2.52 ГэВ	FLUKA/2006b	90,77	17,43	0,91
D / 4.0 GeV	FLUKA/2008c	137.22	24.10	1.65

Radial distributions of spectral indices σ_f (^{238}U) / σ_f(^{235}U)

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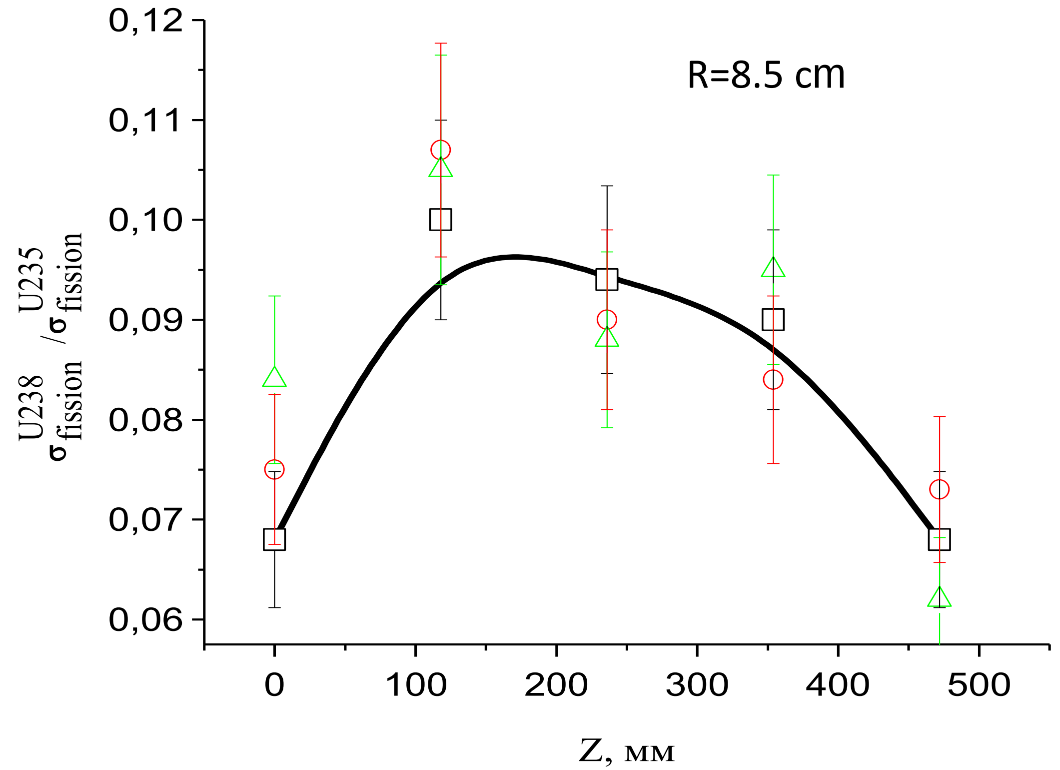
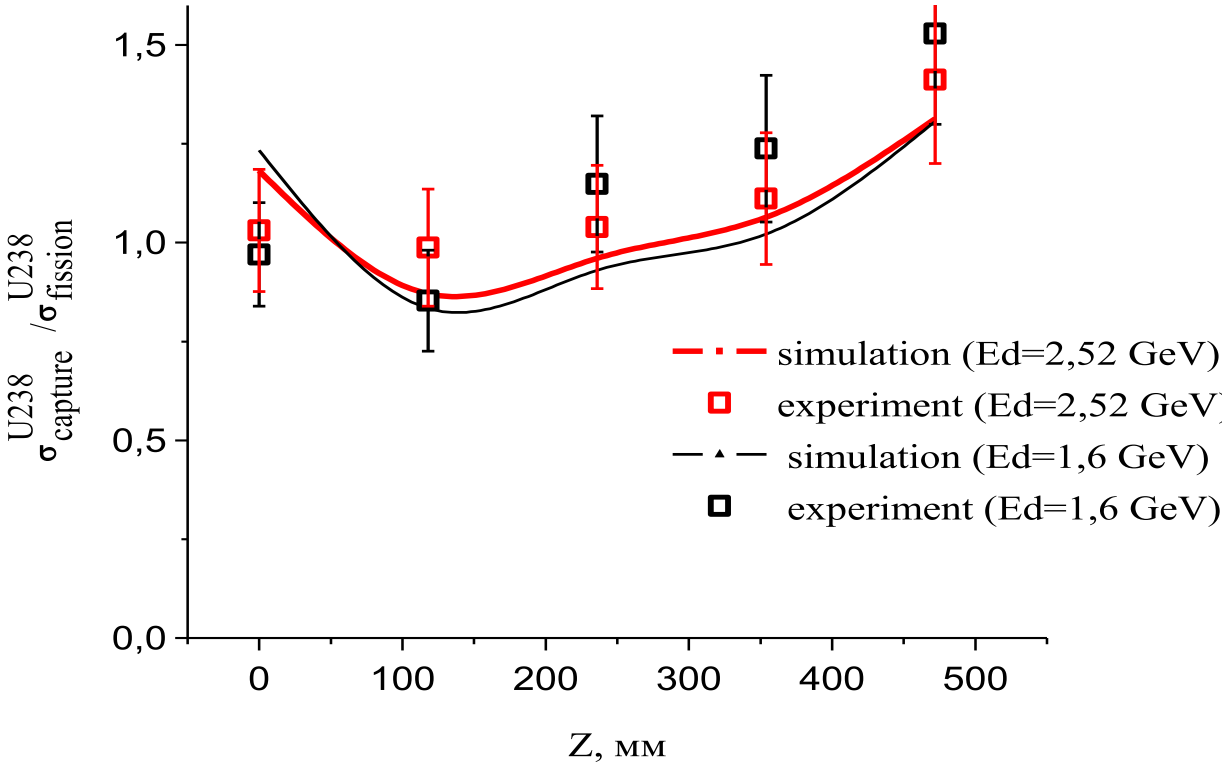


Black line – experimental data for 1.5 GeV primary protons
Red circles – calculated data 1.6 GeV primary deutrons
Green triangles – calculated data for 2.52 geV primary deutrons

No (or weak) dependence of neutron spectrum on primary particles type and energy

Radial distributions of spectral indices $\sigma_c\ (^{238}U)\ /\ \sigma_f\ (^{238}U)$

SIMULATION



<u>**No (or weak) dependence of neutron spectrum on deutron energy**</u>

Conclusions

- The spatial distributions of ^{238}U fission and radiation capture rates in the "Energy plus Transmutation" subcritical experimental setup were measured using SSNTD and activation analysis for incident deuterons energies of 1.6, 2.52 and 4.0 GeV.
- FLUKA-2008 code was used for simulation of the interactions of the primary and secondary particles in the system.
- Deuteron beams shape and position on the target were determined using SSNTD technique.
- It is shown that deuteron, proton, pion and photon induced fissions contribute significantly to the total fission-rate in the samples within the target volume and its immediate vicinity.
- On the basis of the experimental and calculated results it is shown that spectral indices in U-blanket don't depend (within the experimental uncertainties) on primaries energy.
- It is shown that calculations (RQMD) underestimate neutrons with energy > 30 MeV.
- It is shown that neutron spectra in U-blanket don't depend on the type of primary particle.

ACKNOWLEDGEMENT OF THANKS

We would like to thank

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- **JINR** for the hospitality during our staying in Dubna

- **"E+T" collaboration** for well co-ordinated work

- **National Academy of Sciences of Belarus** for supporting of this work

THANK YOU

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