Massive 238U target as new type of ADS core – first results and perspectives

On behalf
of collaboration «Energy&Transmutation – RAW»

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Introduction

- The problems of rapidly growing energy consumption in the world can not be solved without the use of nuclear energy.

- The key issue here is the availability of an adequate supply of nuclear fuel. In the long term aspect, the use of such materials as enriched ^{235}U or artificial ^{239}Pu can not solve the problem of global energy.

- Indeed, they receive is very energy intensive, and the total value is rather limited and certainly does not exceed the forecast amount of hydrocarbon fuel.

- So only involvement in the production of energy is practically unlimited reserves of natural (depleted) uranium and thorium can provide long-term prospects for nuclear energy.

Problems of natural uranium and thorium use

- In the last decade of last century on the initiative of Carlo Rubia was carried out extensive work on exploring the possibilities of so-called energy amplifiers (EA) based on accelerator driven subcritical (ADS) systems.

- Were investigated up to sketchy engineering work options such systems, as fuels to be used natural (depleted) uranium or thorium.

- The main positive finding of a key experiment FEAT performed at CERN by C. Rubbia group, that it is possible to reach the gain power of the incident proton beam (GBP)* around 30 at an energy of 1 GeV. With increasing proton energy up to 2.7 GeV this value goes to constant.

**The ratio of energy released in the subcritical target to the energy of the incident proton beam is the Gain of the Beam Power (GBP)*

Main result of the FEAT experiment
(S. Andriamonje et al.,CERN/AT/94-45(ET))

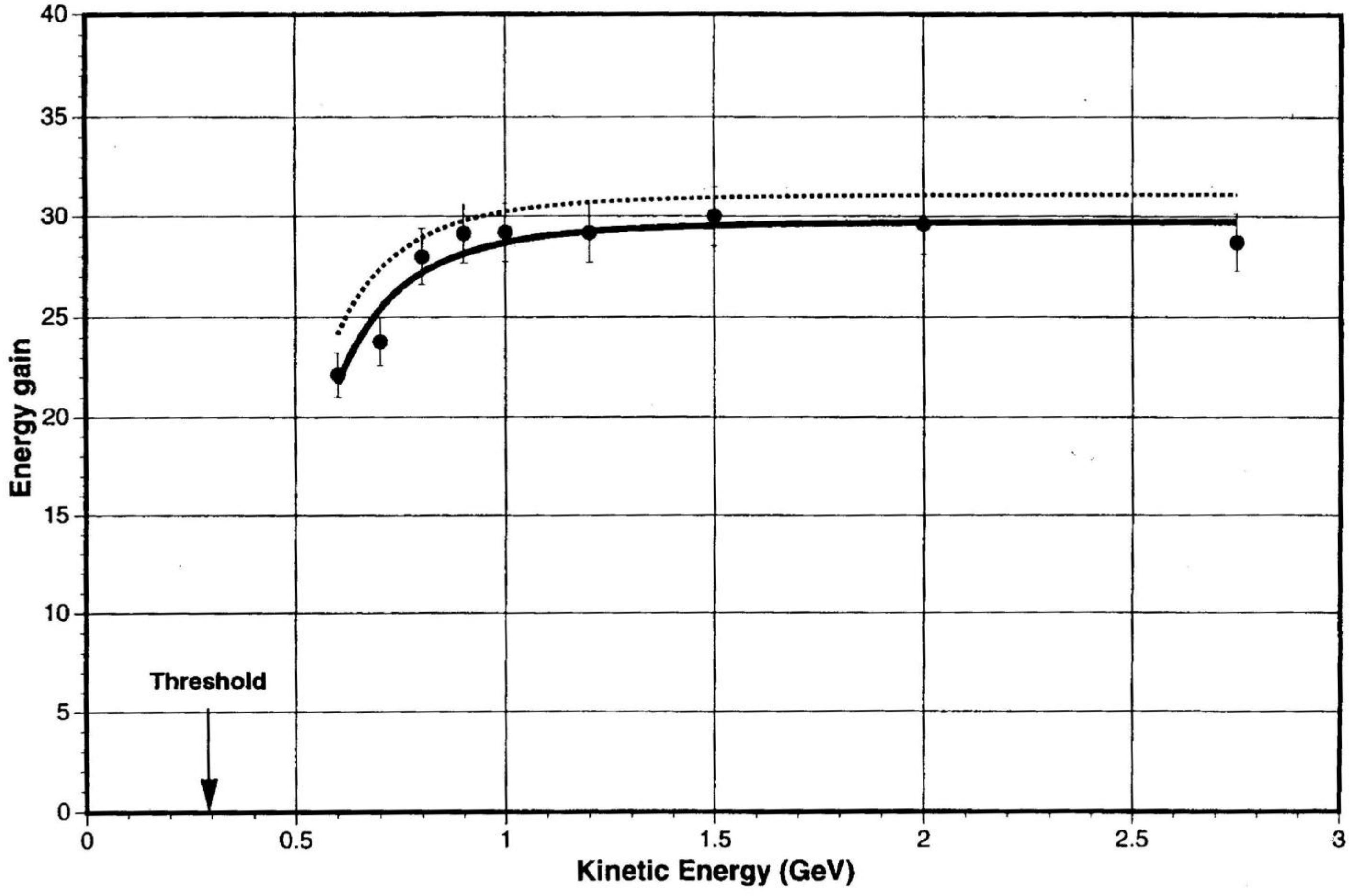


Figure 7

Problems of natural uranium and thorium use

- But in this experiment the massive uranium target (~3.5 tones) was embedded into light water moderator. As consequence the neutron spectrum inside of active core was practically fully thermalized and neutron multiplicity coefficient k_{eff} this system was near 0.9.
- In these circumstances in spite of rather promising GBP~30 it is difficult to implement "burning" of the base core material (natural uranium or thorium) because of their high fission threshold.
- And actually proposed EA options must move on to the enriched fuel!?

New is a forgotten old …

- About 50 years ago at Dubna by Vasil'kov-Goldansky group it was obtained GBP ~ 7 with only 0.66 GeV protons and 3.5 tones of natural uranium target.
- They did not use any moderator and appied a special geometry so their target was equivalent ~ 7 tones setup with rather small neutron leakage.
- In this case of "quasi-infinite" active core maximally hard neutron spectrum has been realized with rather low $\boldsymbol{k_{eff}}$ ~ 0.4
- So it is very attractive to investigate GBP of such type of ADS active core for higher incident energy

The JINR project “Energy&Transmutation RAW”

- Recently as direct continuation of Vasil’kov-Goldansky experiment the new project to study the basic properties of ADS system with large natural uranium core driven by proton and deuteron Nuclotron beams with energy up 10 Gev was proposed and adopted for implementation at JINR during next three years.

- The project has name “Energy&Transmutation RAW” and is aimed at study of basic features of such AD systems (so called Relativistic Nuclear Technology (RNT)) for energy production and utilization of spent nuclear fuel.

Main features of RNT scheme

1. Large volume (“quasi-infinite”) of subcritical core from natural (depleted) uranium or thorium.

- Such cores are deeply subcritical. Indeed the coefficient of fission neutron multiplication within infinite medium of natural uranium consists of $\boldsymbol{k_{eff}} \sim 0,36$.
- It is important that only in deeply subcritical system we can obtain the neutron spectrum much more hard than fission one.
- As many experiments show large volume of subcritical core allows to involve in neutron production secondary and subsequent intra-nuclear cascades.

Main features of RNT scheme

2. More high (up to 10 GeV) incident energy in comparison with traditional ADS value (~ 1 GeV)

- This allows to diminish the beam flux for the same beam power and essentially increases a share of beam energy contributing to generation of high energy part of neutron spectrum inside of an active core.

- In particular due to increasing incident energy an additional mechanism of hardening of neutron spectrum is switching on- namely generation of different mesons.

Advantages of RNT scheme:

1. Extremely hard neutron spectrum allows effectively “burn” a basic material of subcritical core (^{238}U or ^{232}Th) without use of additional “classical” fissile materials ($^{233-235}U$ and ^{239}Pu).

2. Increase of incident beam energy with simultaneous decrease of its flux makes much more simple the problems of entrance beam window and cooling of subcritical target. It is understood that will be used scanning option input beam into a uranium target to alleviate the problems of heat removal

3. There are some plausible grounds to adopt that RNT could provide new promising possibilities for direct (without complicated radio-chemical procedures) utilization of spent fuel elements from nuclear power plants and profitable production of nuclear energy.

Main features of RNT scheme

- Of course a practical realization of the relativistic nuclear technology needs in creation of new generation of powerful and reliable in operation (and cheap enough !) high energy hadron accelerators

- However, only after receiving evidence of the viability of the basic design ideas of RNT can be taken scientifically and economically sound decisions on the development of a full-scale prototype installation that implements the relativistic nuclear technology.

The JINR project "Energy&Transmutation RAW"

- The motivation of the project research program is partly based on extrapolation of previous pioneering results obtained at JINR by groups of R. Vasil'kov et al, V. Yurevich et al and V. Barashenkov et al as well as on first essential results of measurements carried out during 2009 at JINR on Nuclotron beam and discussed below.

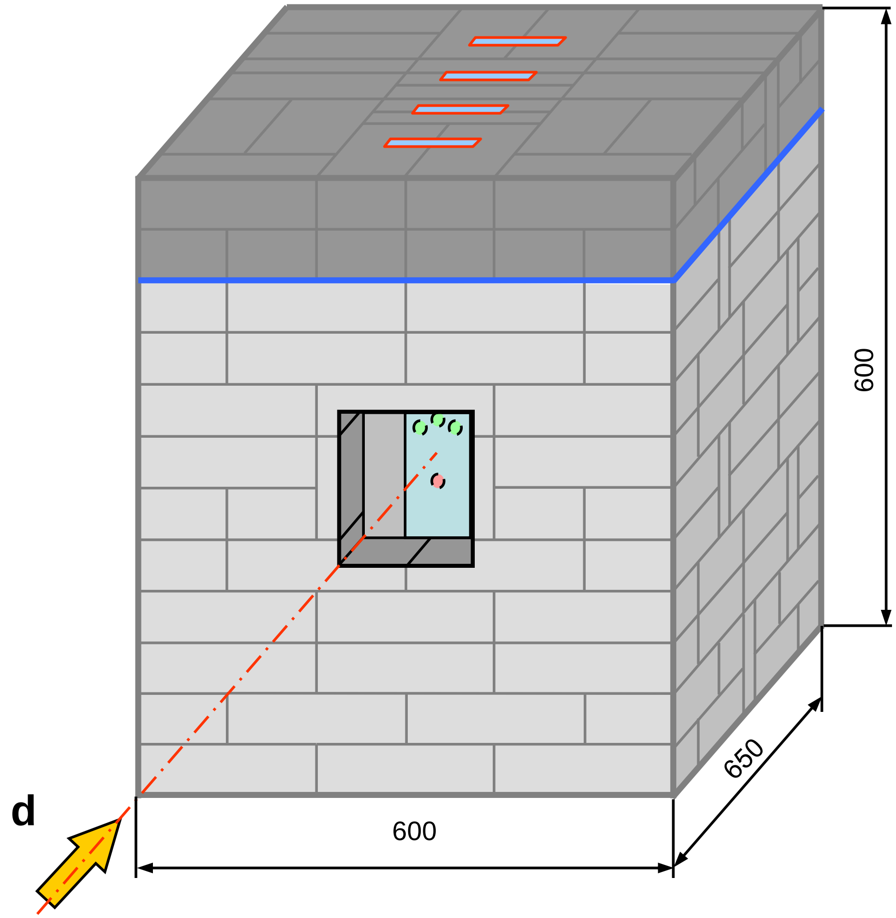
The JINR project "Energy&Transmutation RAW"

- In preparation of the project proposal we carried out during 2009 preliminary experiments available at the presence of a massive target of natural uranium metal

- These experiments on lead-uranium assembly «Quinta» performed by joint team of JINR & Center of Physical and Technical Projects (CPTP) «Atomenergomash»

- The results of these experiments allowed us to estimate the project's prospects and to plan its research program.

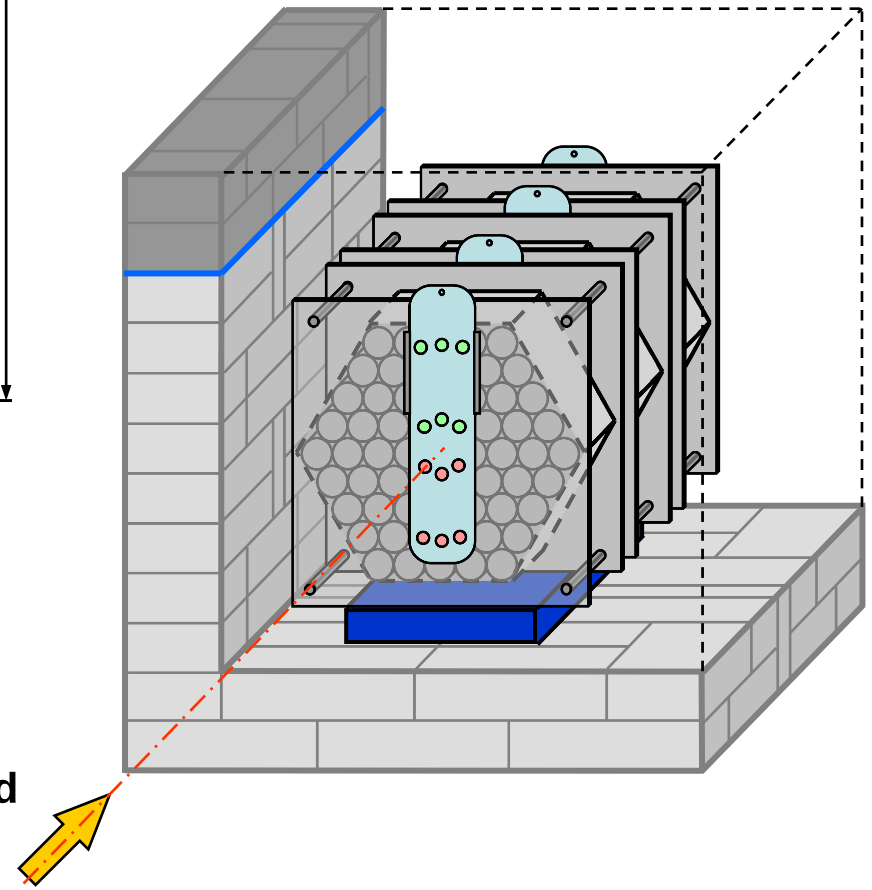
Preliminary experiments with uranium-lead assembly «Quinta» in June 2009



m_U = 315 kg

m_{Pb} = 1780 kg

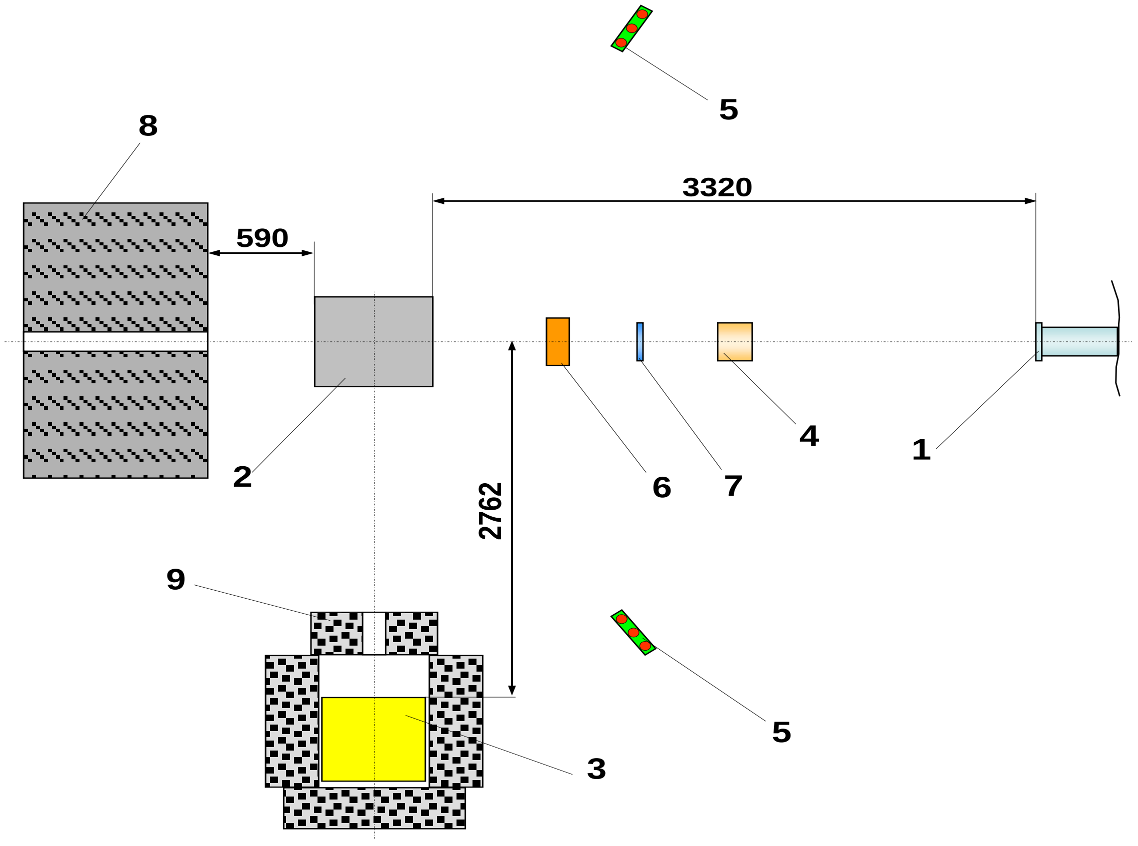
m_{Σ} = 2125 kg



Why lead blanket?

Accelerate access to the target
for replacement activation detectors

Preliminary experiments with uranium-lead assembly «Quinta» in June 2009

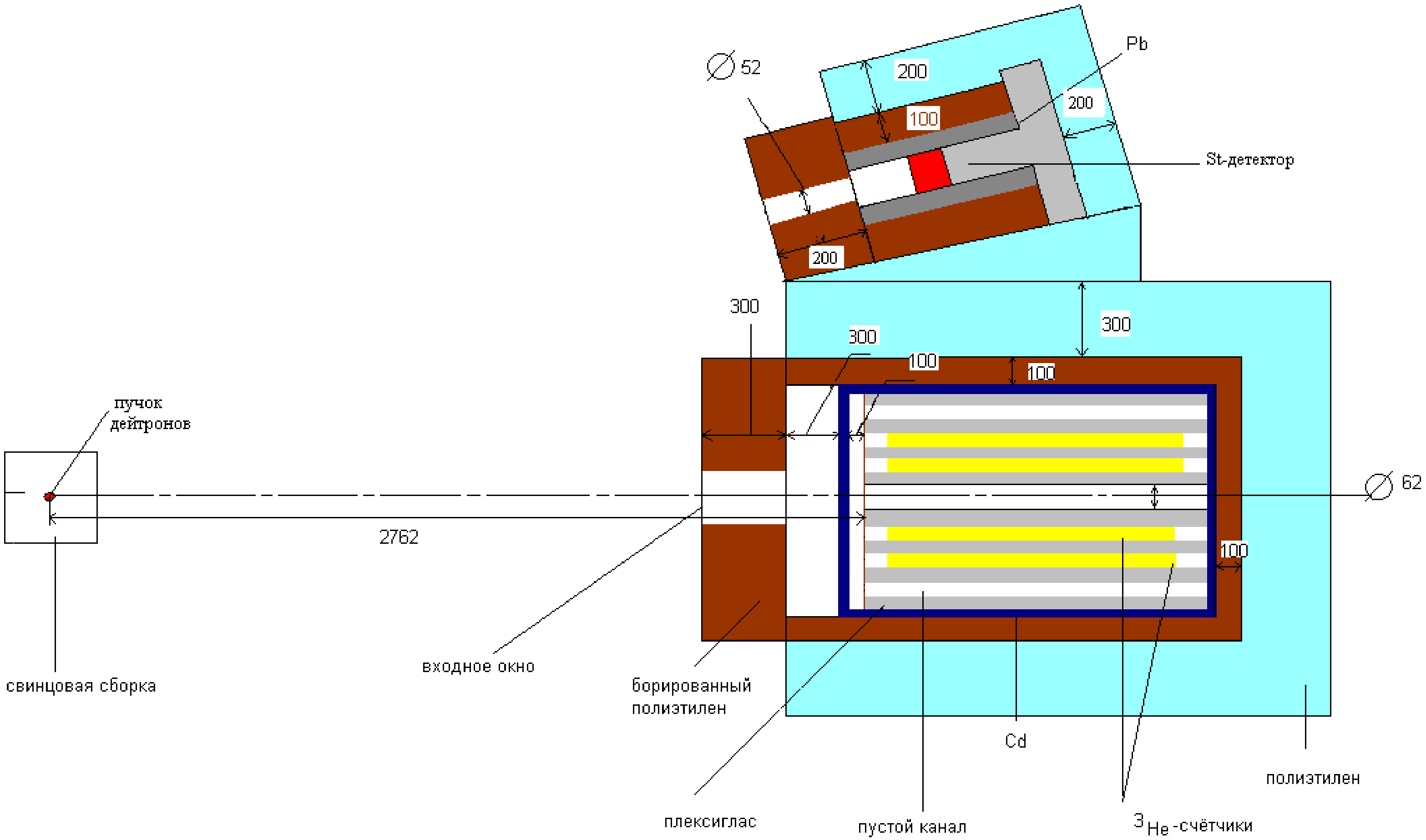


1 – d beam
2 – target
3 – n-detector
4-5 – on-line beam monitoring system

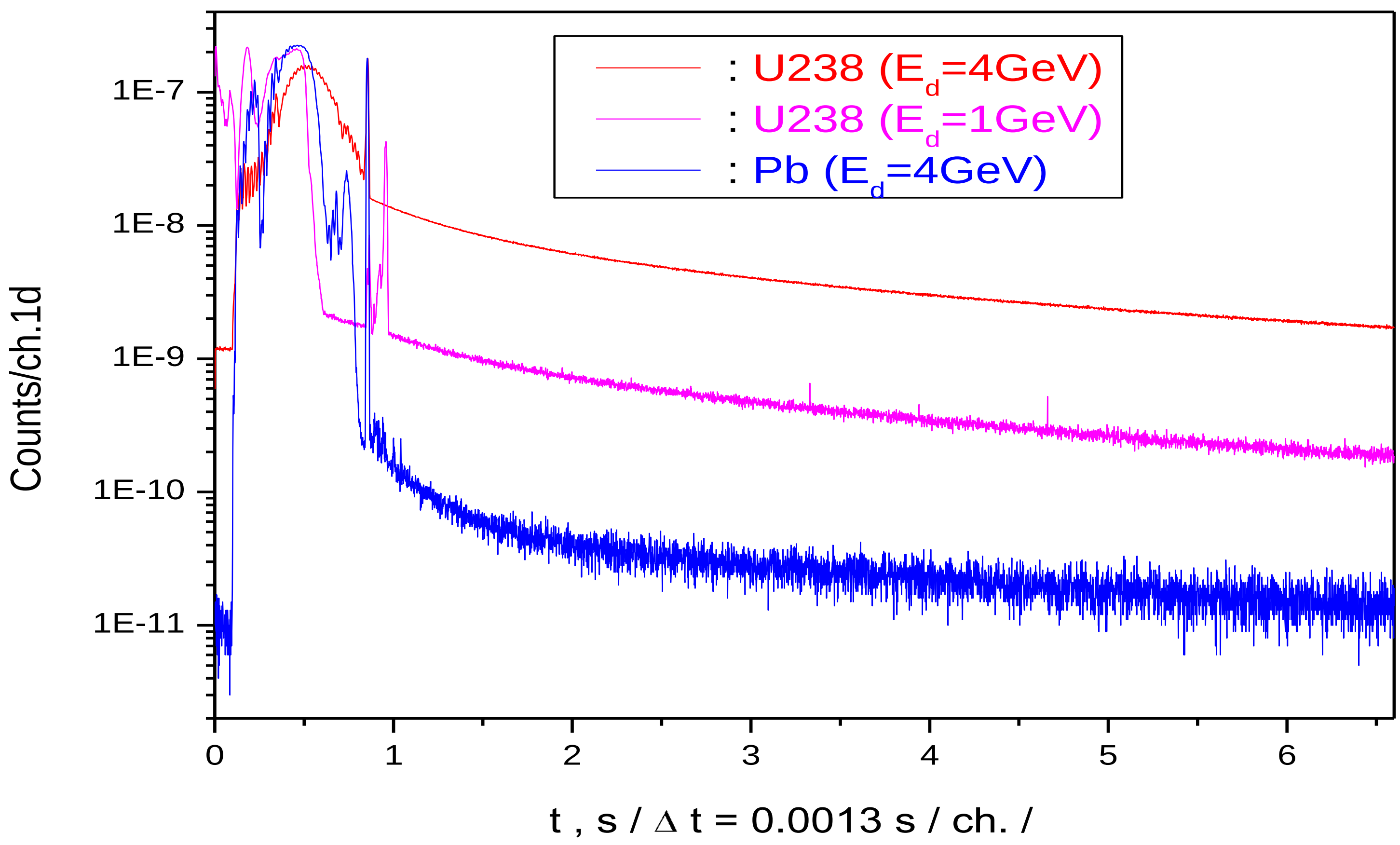
Lay-out of setup

Preliminary experiments with uranium-lead assembly «Quinta» in June 2009

Neutron detectors: IZOMER assembly and St-one



Preliminary experiments with uranium-lead assembly «Quinta» in June 2009



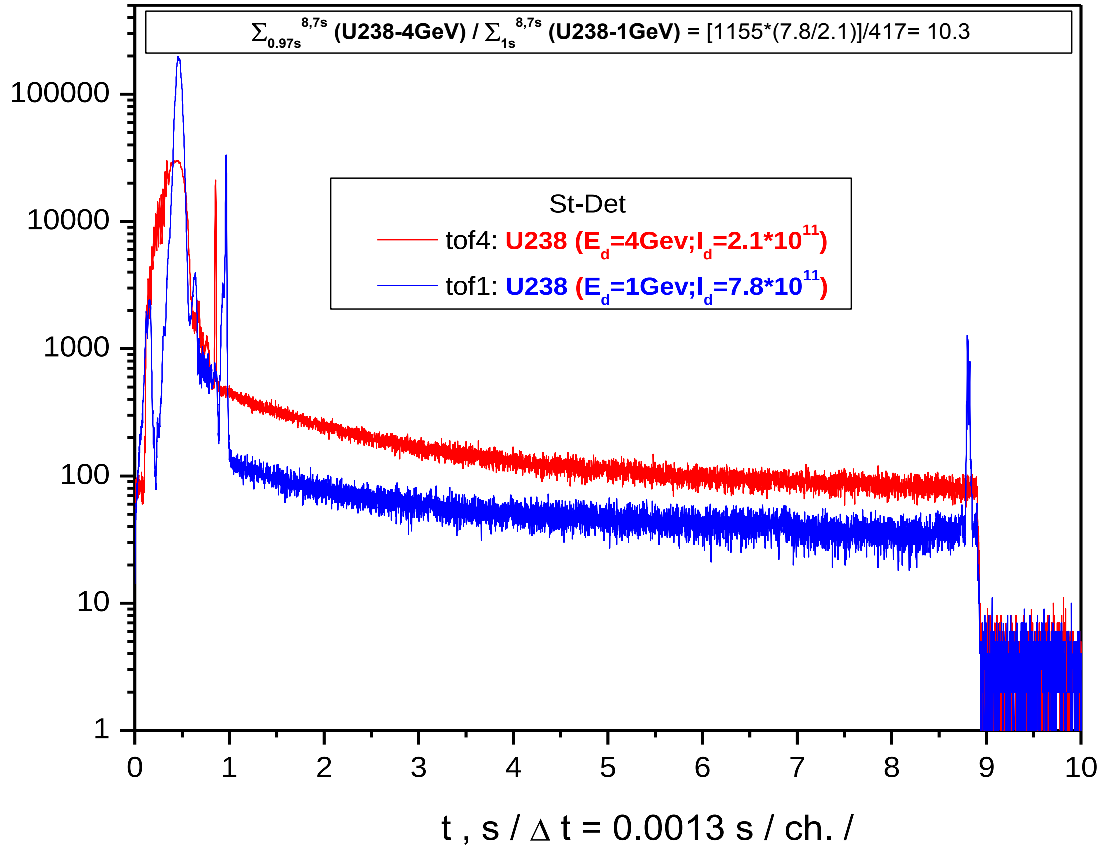
Time dependence of neutron yields from a geometrically identical target assemblies of lead and lead-uranium irradiated by deuterons with energy of Ed = 1 and 4 GeV

Preliminary experiments with uranium-lead assembly «Quinta» in June 2009

Time dependent neutron spectra from assembly of ^{3}He-counters IZOMER for natural uranium target irradiated by deuterons with energy 1 and 4 GeV.

A respective increase of the fission event numbers with growing of incident beam energy consists of ~ 8,7 1,2

Preliminary experiments on uranium-lead assembly «Quinta» in June 2009



Time dependent neutron spectra from St-detector for natural uranium target irradiated by deuterons with energy 1 and 4 GeV.

A respective increase of the fission event number with growing of incident beam energy consists of ~ 10,3 ± 1,5

Preliminary experiments on uranium-lead assembly «Quinta» in June 2009

- So main result of our preliminary experiments:

for massive but limited (only 315 kg) uranium target ***GBP increases about two times*** with growing of incident deuteron energy from 1 to 4 GeV !

Discussion of results

In Table 4 from JINR Communication *E1-2010-61, J. Adam et al* *the predictions for GBPs based only on extrapolation of theoretical and experimental Dubna results obtained with proton beams of different energies are shown.*

Table 4. Estimated gain of beam power for proton iradiation of the quasi-infinite metallic uranium target

Ep GeV	Initial GBP	Equilibrium GBP (***after prolonged exposure when the equilibrium concentration of 239Pu is achieved***)
0.66	7.4 1.4 (Vassil'kov&Goldansky)	~ 40
1	~ 12	~ 70
10	~ 22	~ 130

Discussion of results

- Taking into account in first approximation that the difference between intranuclear cascades caused by protons and deuterons at the same incident energy per nucleon is not essential, one can see that predictions presented in above Table have rather conservative character.

- Indeed applying Quinta's result for relative grows of GBP it is possible to estimate an absolute GBP near **15** for 4 GeV deuterons.

- This number is in reasonable agreement with the values presented in Table 4 above.

Discussion of results

- The absolute values of GBP and their dependence on the energy Ep given in Table 4 is not agreed with the results of the FEAT experiment discussed above.

- This discrepancy is probably related to a significant thermalization of neutron spectrum in CERN experiment and to corresponding suppression of the influence of high energy neutrons.

- It should be noted that values of equilibrium GBP shown in the last column of Table 4 are the important parameters requiring special study of the time to achieve the equilibrium concentration of 239Pu in the target after the start of irradiation.

Further analysis

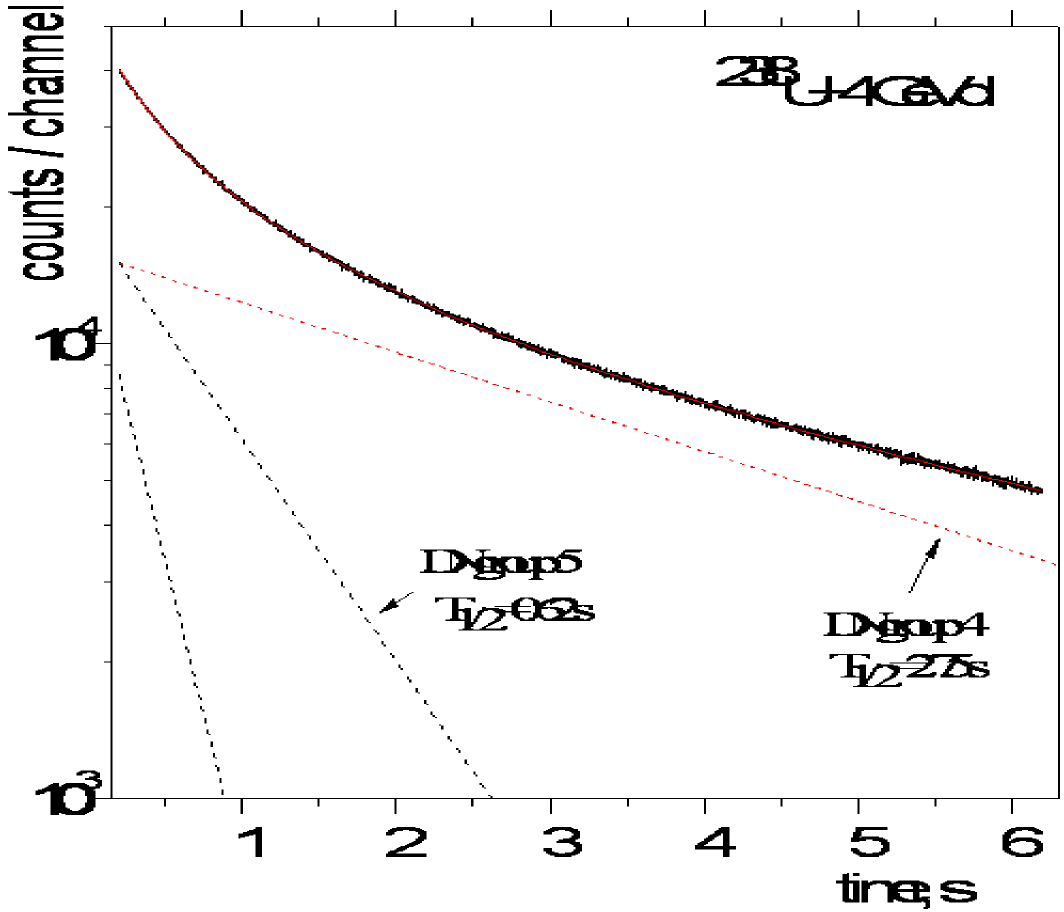
- As the total DN yield for uranium target is much higher than that for lead one uranium data were analyzed only with nuclear fission as the DN source.

- In our experimental conditions information on long-lived (1-3) DN groups is lost due to narrow time window.

  So the data were analyzed only for short-lived DN groups (4-6) with characteristic periods of order of 2.5 s, 0.6s and 0.2 s

- Contribution of long-lived DN groups (4-6) was fitted as constant background

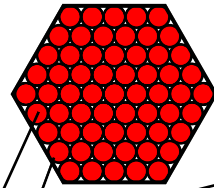
Further analysis



Decomposition of DN spectrum for U + d, Ed=4 GeV

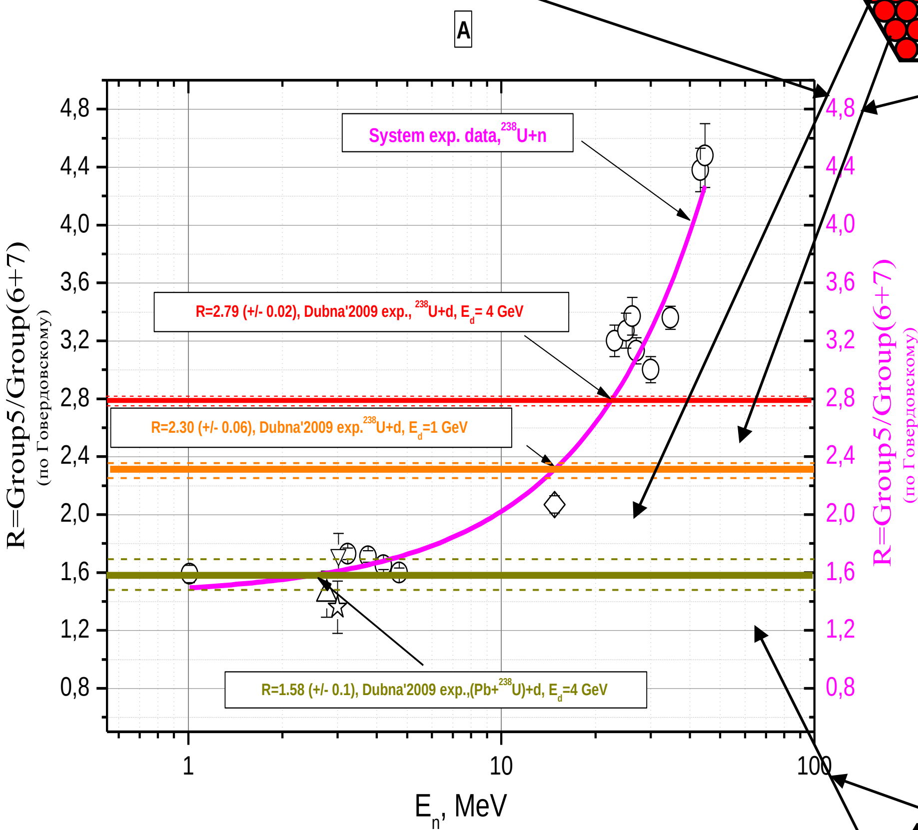
Further analysis

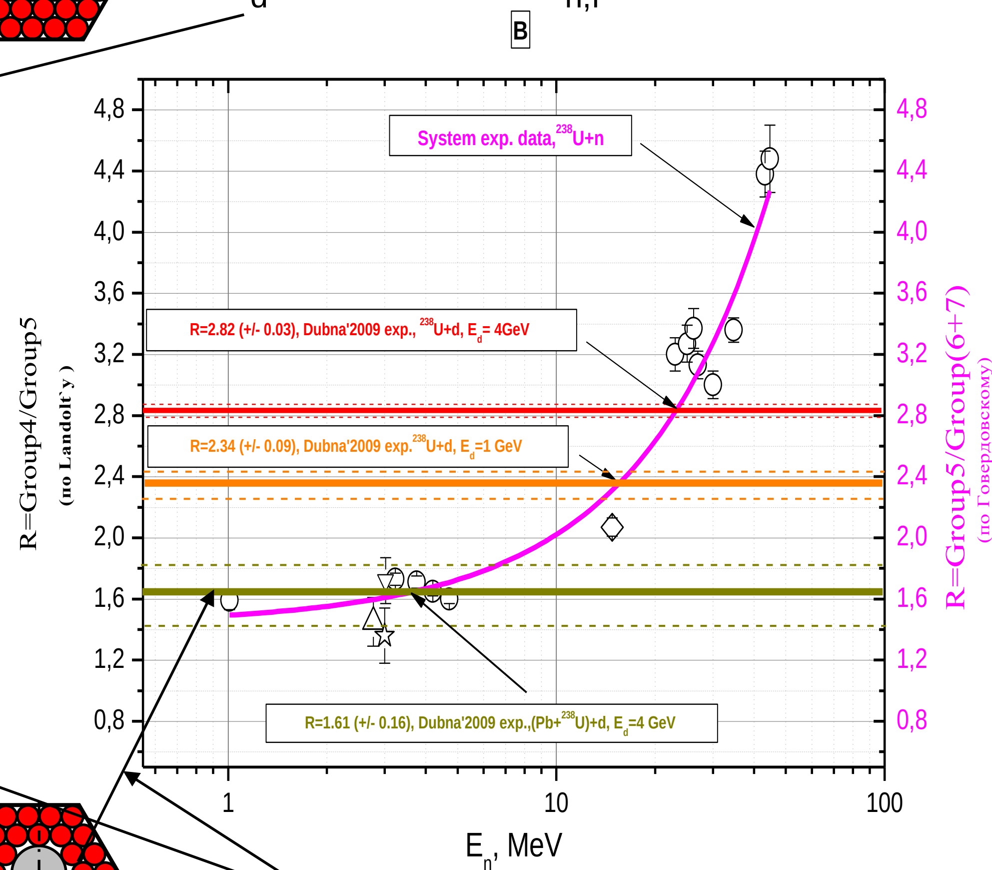
E_d = 1 GeV → $E_{n,f}$ ~ 15 MeV

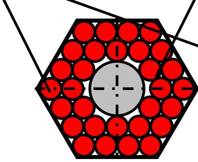


«Quinta» - Uranium

E_d = 4 GeV → $E_{n,f}$ ~ 25 MeV





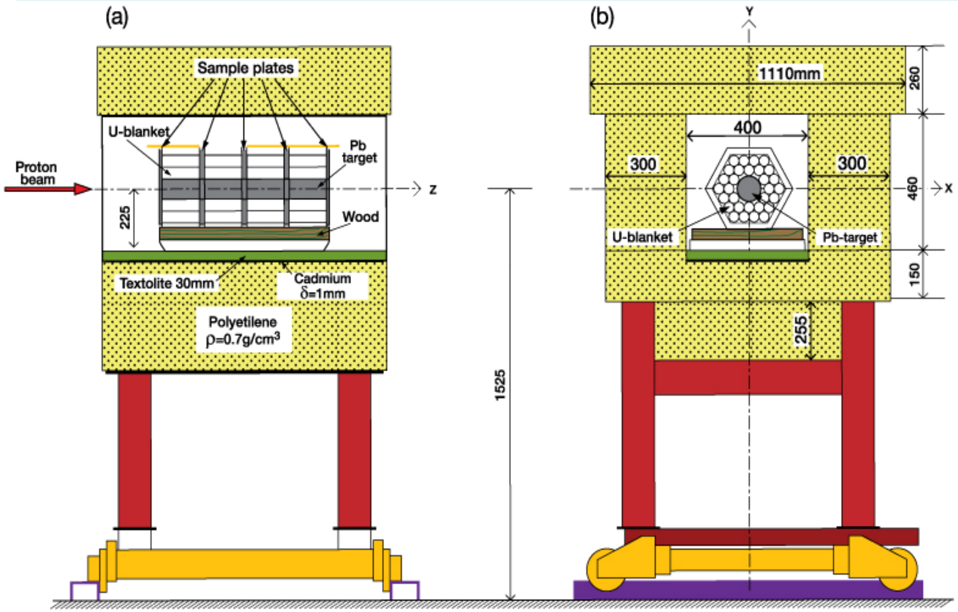


E_d = 4 GeV → $E_{n,f}$ ~ 3 MeV

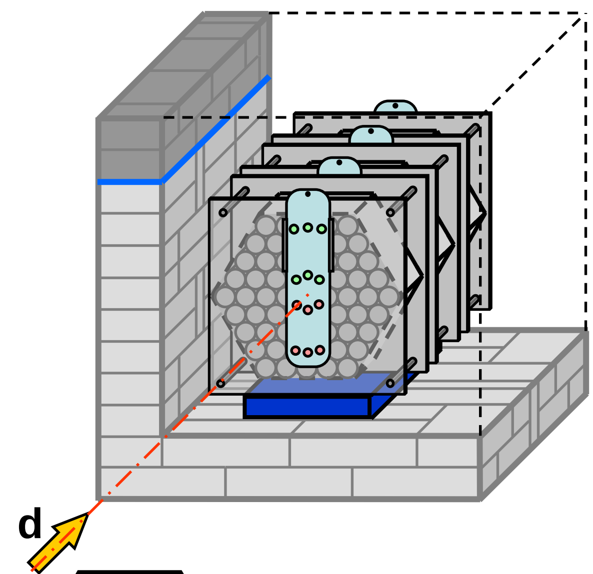
«Energy + Transmutation»

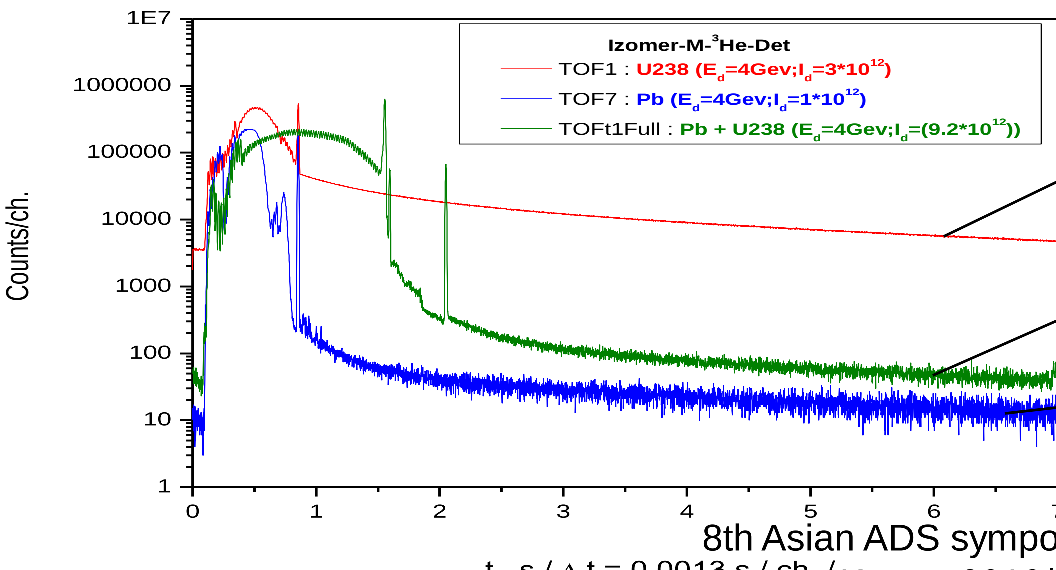
Dependence of ratios of DN groups (5/(6+7)) **(A)** and (4/5) **(B)** from $^{\mathbf{238}}$U(n,f)-reaction on neutron energy in comparison with the same ratios extracted from our data taken in measurements with targets "Quinta" and "Energy + Transmutation"

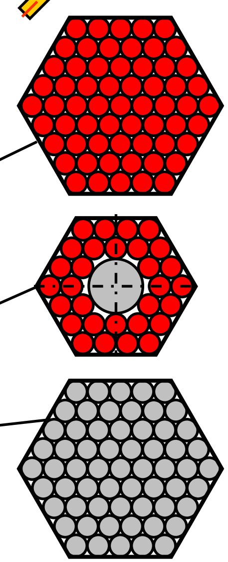
Measurements with target assembly «Energy + Transmutation» (E_d= 4 GeV, November 2009)



«Quinta»







«Quinta» - Uranium

«Energy + Transmutation»

«Quinta» - Lead

Discussion of results

- The values <E_n> obtained above give some indications that with our intermediate size of uranium target most of secondary neutrons leave the target volume without producing fission of target nuclei

- It can be stated that the study of the decay spectra of DN predecessors provides an important and sensitive tool for investigation of basic characteristics of fission process in a massive fissile target used as the active core of an AD system.

The results obtained by virtue of their non-triviality, of course, require more experimental confirmation.

In December of this year planned for a large set of measurements during irradiation setup "*Quinta*" by deuterons with energies of 2 GeV, 4 GeV, and ~ 6 GeV.

Tasks of experiments

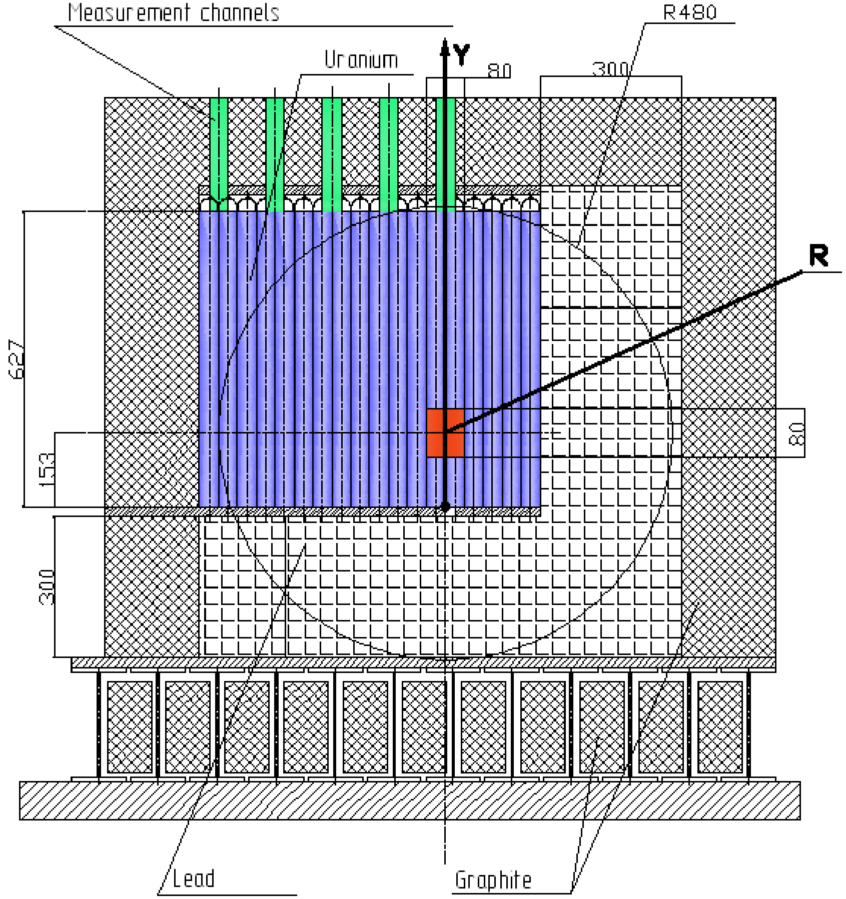
1. Determine the dependence of the gain of beam power on the deuteron energy in the lead-uranium assembly *Quinta* with aid of different methods and to obtain the base for extrapolation of its behaviour on case of quasi-infinite target.

2. Determine the spatial distribution of the plutonium production in the uranium target aimed at prediction of its growth in the transition to quasi-infinite target.

3. Get a set of experimental data to test and if necessary, modify the existing cascade models and transport codes, which will improve the reliability of predicting outcomes of future experiments under the **«E&T – RAW»** project.

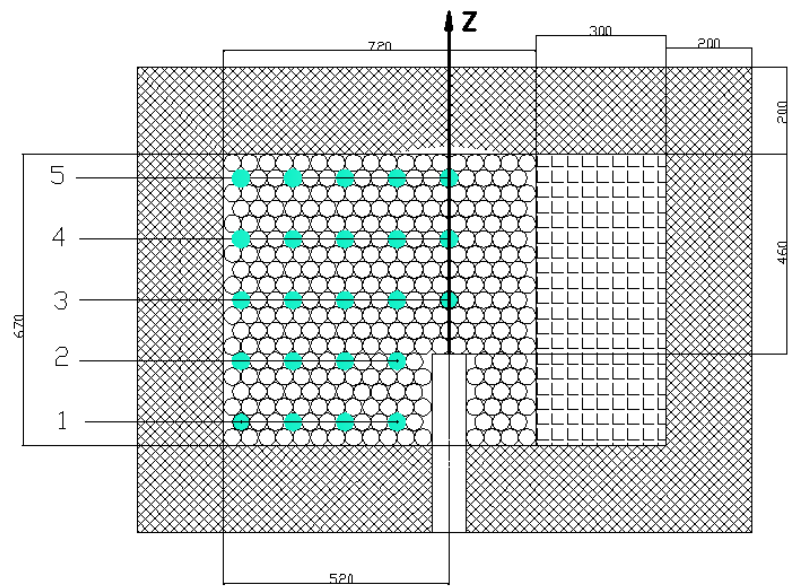
Additionally, in the course of the experiments setup "Quinta" will be used as a source of high-energy neutrons with a controlled spectrum for research on transmutation .

Project "E&T – RAW"
New large metallic uranium target "EZHIK - U"



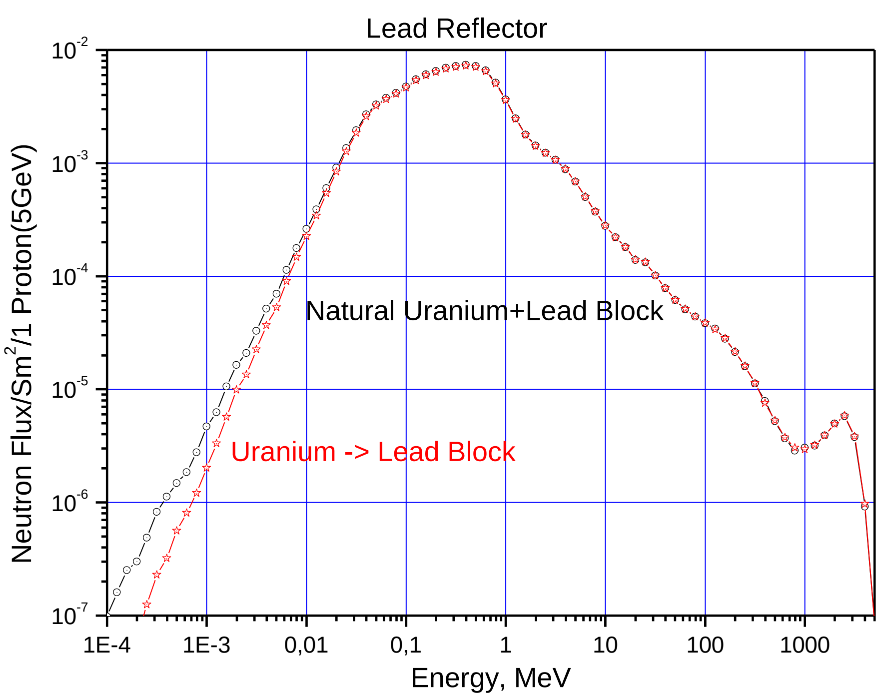
Due to an asymmetric beam insert the equivalent mass of the target could be estimated as ~7 tones

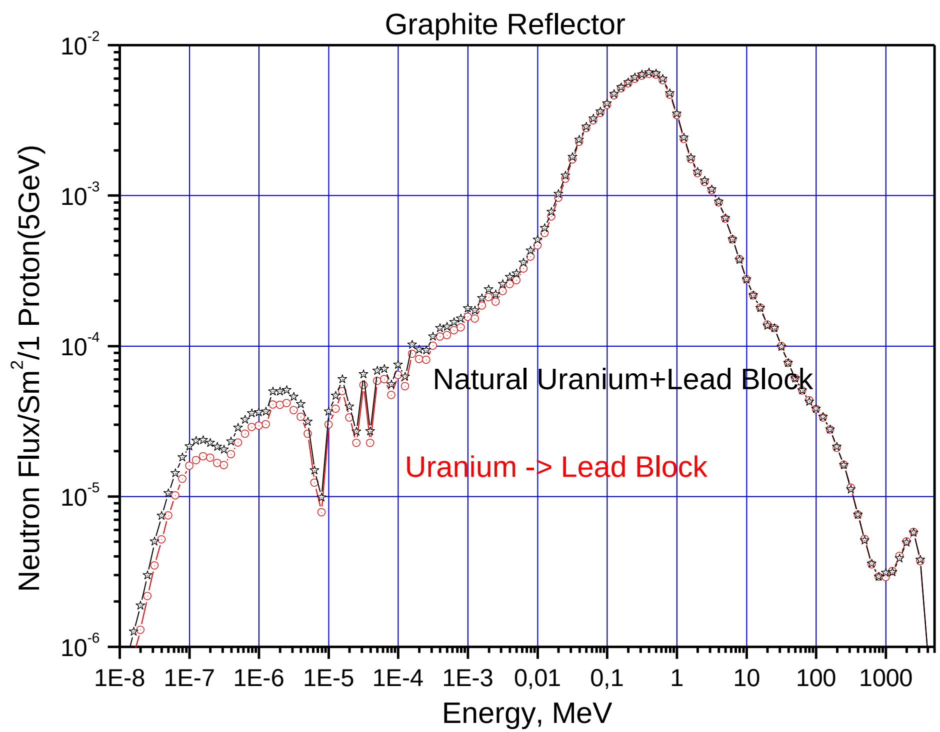
Upper view



Project "E&T – RAW"
New large metallic uranium target "EZHIK - U"

- Calculated neutron spectra inside of "EZHIK-U" target





Project “E&T – RAW”
Research program

Program consists of four tasks.

Measurements will be done with protons (deuterons) in range of incident energy 2 to 10 GeV (1 to 5 GeV/nucleon)

Task 1 . Integral data.

It includes wide set of experiments with the target “**EZHIK-U**” for

Namely:

- study of spatial distributions with and without a graphite reflector (below - for different target configurations):
  - of neutron spectra within the target volume and spectra of leakage neutrons;
  - of fission rates and transmutation cross sections of actinide fission products
  - of radiative capture (n, γ) and (n,xn)- reactions in the samples of long-lived isotopes from spent fuel placed in measurement channels;
  - of accumulation and burn-up of ^{239}Pu aimed at evaluation of main parameters of its “equilibrium” concentration – the value and a necessary irradiation time to reach it;
  - of heat release;
- study of prompt neutron spectra and multiplicity, the delayed neutron time yields for different target configuration as well as beam particle type and energy;
- measurements of GBP in dependence on incident particle type and its energy for different target configurations;
- improvement and optimization of on-line and off-line methods for monitoring intensity, geometric characteristics and position on the target of the Nuclotron beam;
- study of integral decay rates of target irradiated with different doses.

Project "E&T – RAW"
Research program

Task 2 . Nuclear data.

- It includes the series of measurements of fission cross sections for relevant set of target nuclei and delayed neutron yields.
- For reliable simulation of AD systems it is necessary to know the characteristics of corresponding reactions in both thin and thick (≥2000 g/cm2) targets.

Task 3. Simulation.

- It is aimed at an improvements of underlining physical models and the constant databases of the computer codes designed to describe multiple particle production in a quasi-infinite ADS active cores for incident energy up to 10 GeV per nucleon.
- An appropriate account of high energy fission channels is of great importance for calculation of neutron fields and heat release in such systems, because the present options of these codes could not reproduce even qualitatively the respective experimental data obtained up to now.
- An implementation of this task provides a theoretical support of the experimental part of the research project program and helps to improve a planning of subsequent experiments

Project “E&T – RAW”
Research program

Task 4 . Materials

Investigation of relativistic beam impact on structural and fuel materials.

- It is planned to measure of the gas ($^{3,4}He$) production rates in interaction of relativistic beams and fast neutrons with the construction elements and the fuel.
- Radiation damage depending on the energy and type of primary particles will also be studied.
- For this task it is necessary to form a minimal size of Nuclotron beam on the target.

Project "E&T – RAW"

- More detailed information on program of future measurement in the framework of the project is presented in

  J.Adam et al. ***"Study of deep subcritical electronuclear systems and feasibility of their application for energy production and radioactive waste transmutation" («E&T – RAW» Collaboration), JINR Communication E1-2010-61.***

- ***Our project is open for all collaborators interested in its main goals***

- *We hope that this project has serious innovation potential.*

The authors express their gratitude to all those who contributed to the experimental results underlying the study of the project «E & T - RAW», and also participated in the analysis of the results and discussions of the main provisions of the present work, in particular:

A.V. Butenko, A.F. Elishev, B. Gus'kov, V.D. Kekelidze, E. Kostyukhov, A.D. Kovalenko, V.A. Krasnov, M.I. Krivopustov, I.I. Mar'in, G.V. Trubnikov, V.I. Yurevich (BVLPHE, JINR, Dubna);

O.B. Badunov, A.N. Kuznetsov, S.S. Pavlov, N. V. Rebrova, V.N. Shvetsov (FLNP, JINR, Dubna);

V.I. Smirnov (FLNR, JINR, Dubna)

S.N. Berezhnoi, A.A. Goverdovsky, A.S. Egorov,B.V. Kebadze, D.N. Kovalev, V.P. Kornilov,V.F. Mitrofanov, G.A. Myakishev,V.M. Piksaikin, V.A. Roschenko,, B.F. Samylin (SNC RF IPPE, Obninsk, Russia);

E.M. Ivanov, F.V. Moroz, G.A. Ryabov, O.A. Scherbakov L.A. Vaisheine, A.S. Vorobiev (PNPI RAS, Gatchina, Russia);

T.N. Korbut (SIP NAS Belarus)

A.S. Potapenko, A.A. Safronova, I.V. Zhuk (JIE&NR-Sosny NAS Belarus)

E.P. Maksyakov (CPTP «Atomenergomash», Moscow);

L.N. Fal'kovsky, B.I. Fonarev («Atomenergomash», Moscow).

Thanks for your attention