***Progress in study of ADS scheme with deep subcritical multiplying core for energy production and transmutation of radioactive wastes. Experimental results and perspectives*.**

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INTRODUCTION

- As it was reported at previous 8th International Workshop on Asian Network for Accelerator Driven System (ADS) and Nuclear Transmutation Technology, Suvon, Korea, 2010, the **new ADS project "Energy and Transmutation RAW" (E&T RAW) has started at JINR**.

- The project is aimed at study of possibilities to use deep subcritical natural (depleted) uranium or thorium active core (AC) with **very hard neutron spectrum** inside for effective burning of the core material together with spent nuclear fuel (SNF).

- **To preserve maximally hard neutron spectrum it is necessary to use high temperature helium cooling in primary circuit and large volume (“quasi-infinite”) AC loaded by small size encupsulated fuel elements including these made from SNF without its preliminary radiochemical reprocessing**

- **The essential point of this ADS is direct use of the core load as a target for smeared incident beam with energy up to 10 GeV.**

- **It is very perspective to utilize an original Russian technology BWLAC for creation of compact MWt linac**

- **The new approach to ADS outlined above is called the Relativistic Nuclear Technology (RNT) for energy production and utilization of spent nuclear fuel.**

- **But creation of respective powerful accelerator as well as all related engineering problems are so far out of the current JINR project**

- **The objectives of project “E&T RAW” are to study during 2011-2013 the basic features of model ADS with quasi-infinite deep-subcritical AC irradiating by deuteron (proton) beam from JINR NUCLOTRON in incident energy range 1- 10 GeV**

JINR PROJECT “Energy&Transmutation RAW”

- **For realization of “E&T RAW” project there are two target assemblies at JINR :**

- semi-infinite (~22 tones) depleted uranium AC and smaller (~500kg) nat. U target assembly QUINTA modeling the central part of this AC

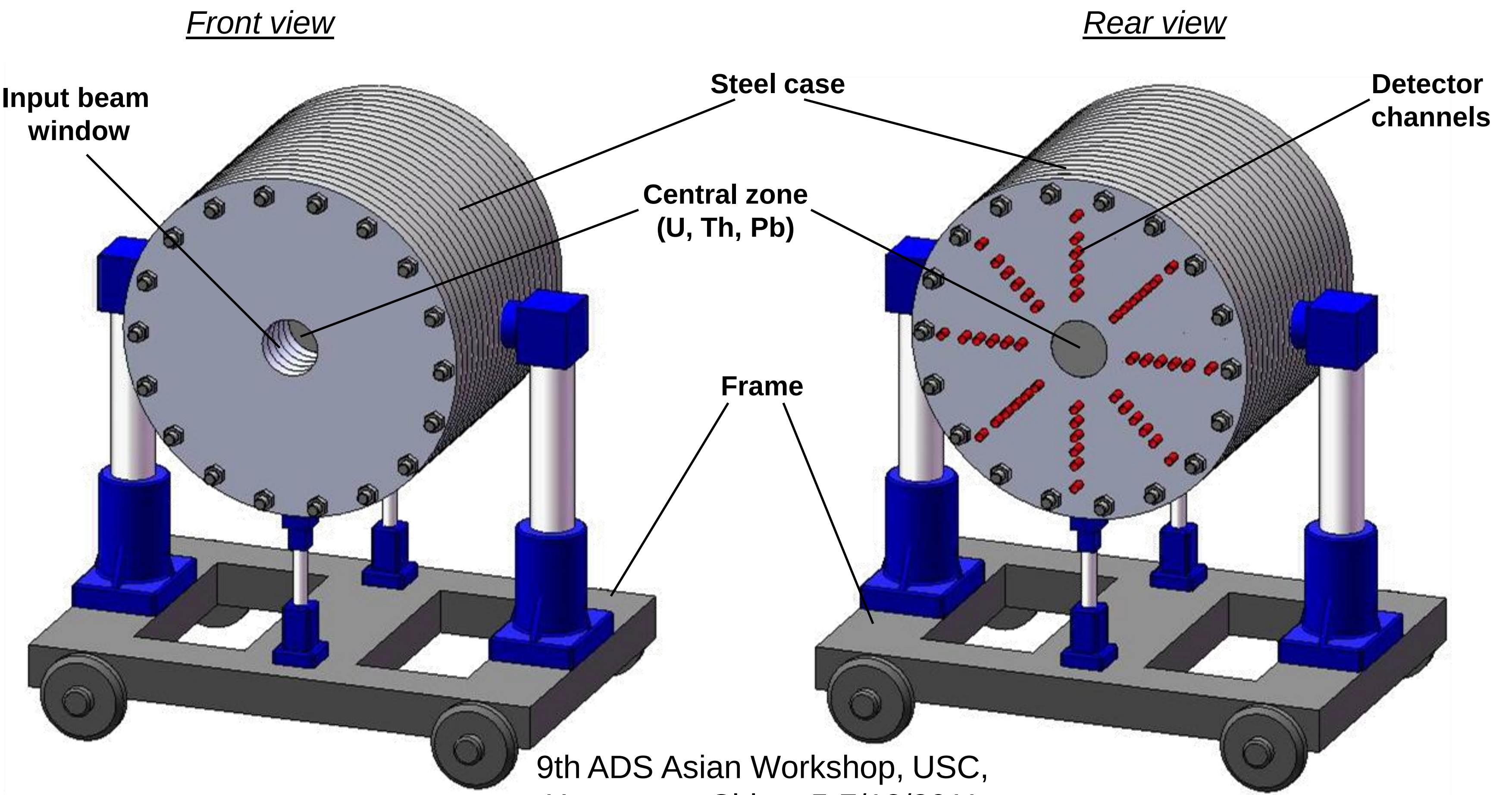
- **In present talk it’ll be discussed mainly the results of experiments carried out with target assembly QUINTA during 2011 aimed at study basic physics of RNT**

- **These experiments are preparatory stage to future measurements with quasi-infinite AC planned for 2013**

Quasi-infinite depleted uranium target (QIUT) with replacement central zone

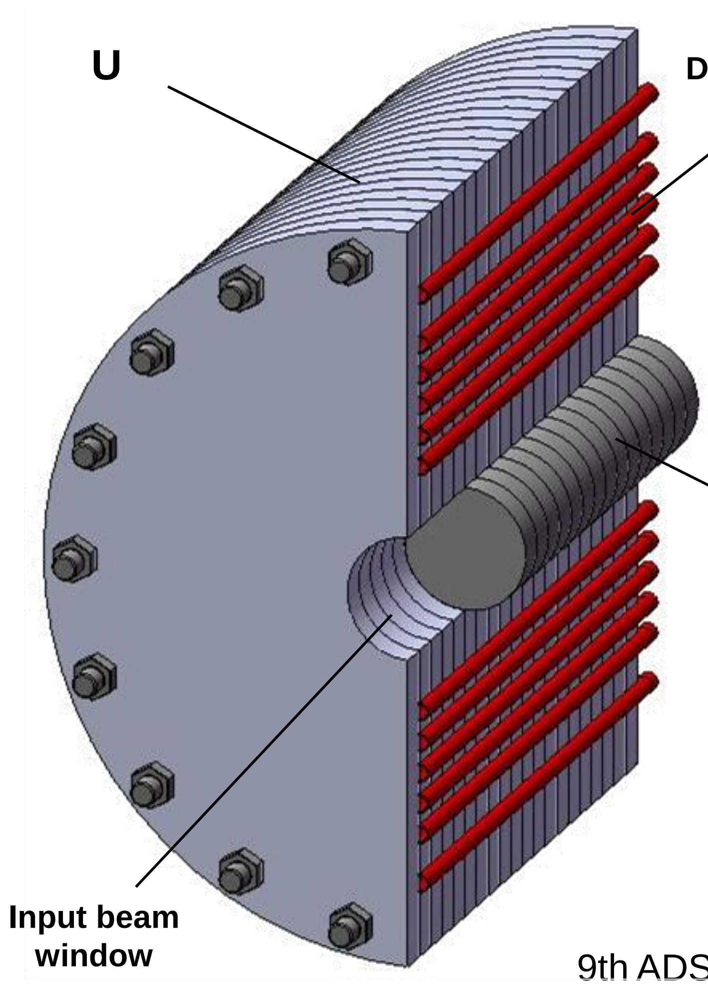
Mass of uranium – 22 т.
Diameter – 1,2 м.
Length – 1 м.

Materials of central zone – U, Th, Pb.
Diameter of central zone – 0,2 м.

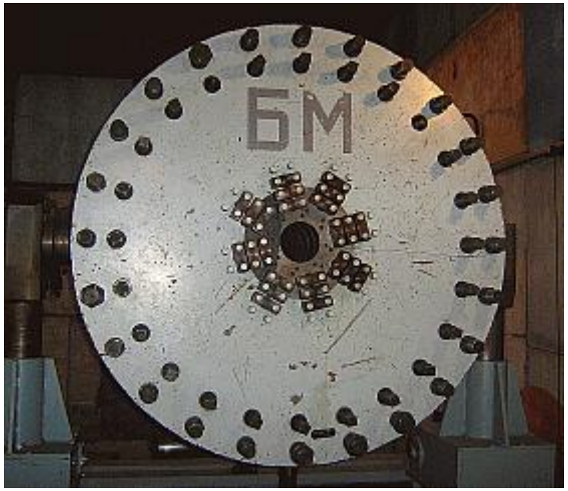


Quasi-infinite depleted uranium target (QIUT) with replacement central zone

Longitudinal section of the QIUT together with central zone and detector sets

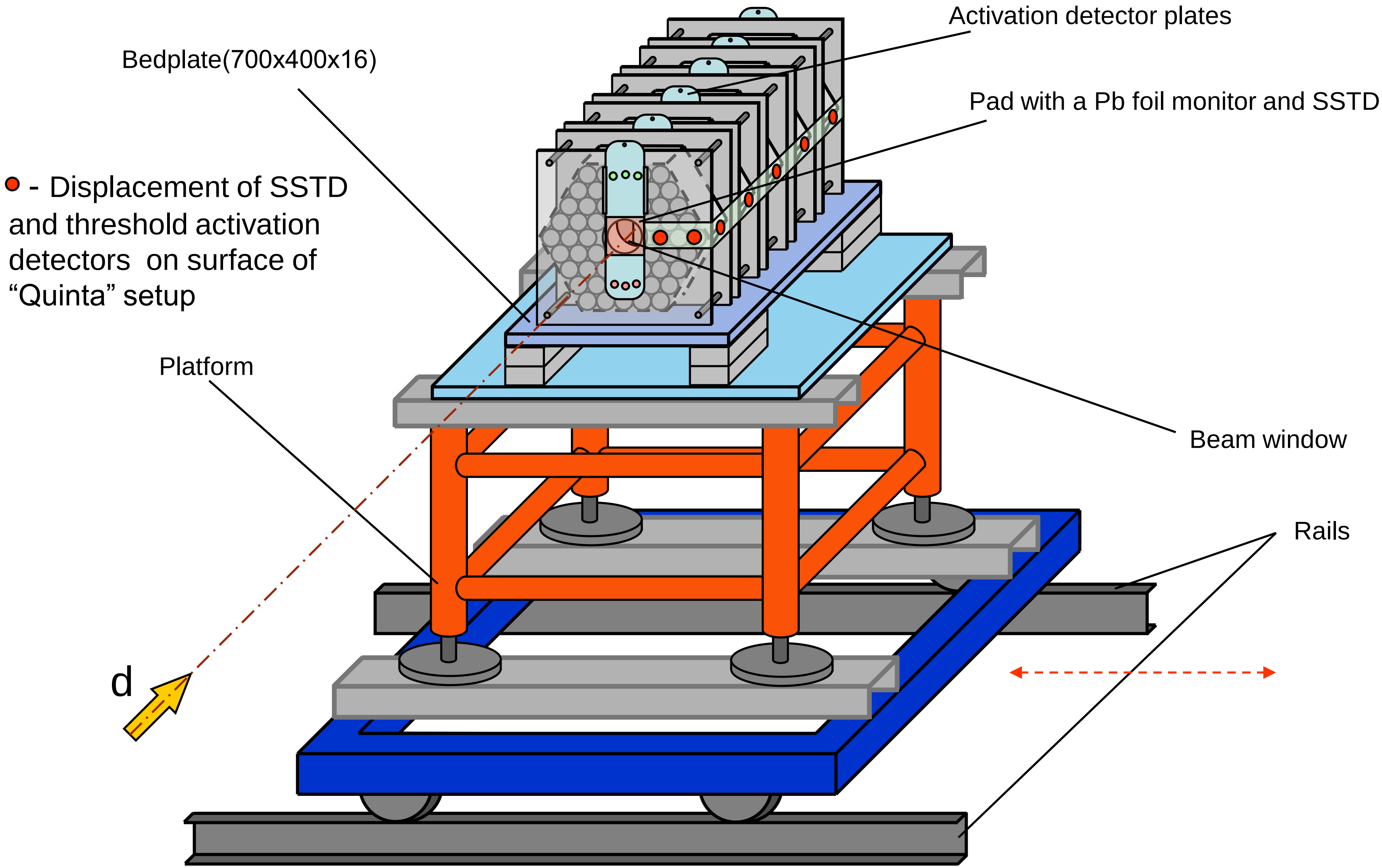


Front view photo



Rear view photo

Target assembly "Quinta" at the irradiation position



- **It is appropriate to note that quasi-infinite subcritical AC from natural or depleted uranium were studied earlier:**

- J.W. Weile et al.~20 tons nat. U+14 Mev neutrons (1961)
- R.Vassil'kov et al. ~7 tons nat. U+660 MeV protons (1978)
- Wang Dalun ~20 tons depl.U+14 MeV neutrons (1991)
- C. Rubbia et al. ~3.6 tons nat.U+0.6-2.7GeVprotons (1995)

- **Only in three first experiments there was realized hard neutron spectrum**
- **In the fourth FEAT experiment U rods were embedded into light water moderator so real neutron spectrum was close to thermal one and neutron multiplicity coefficient k_{eff} of this system was near 0.9.**

- In experiment by Vasil'kov-Goldansky group on Dubna synchrocyclotron it was not used any moderator and was applied a special geometry so their 3.5 tons target was equivalent ~ 7 tones setup with rather small (<10%) neutron leakage.

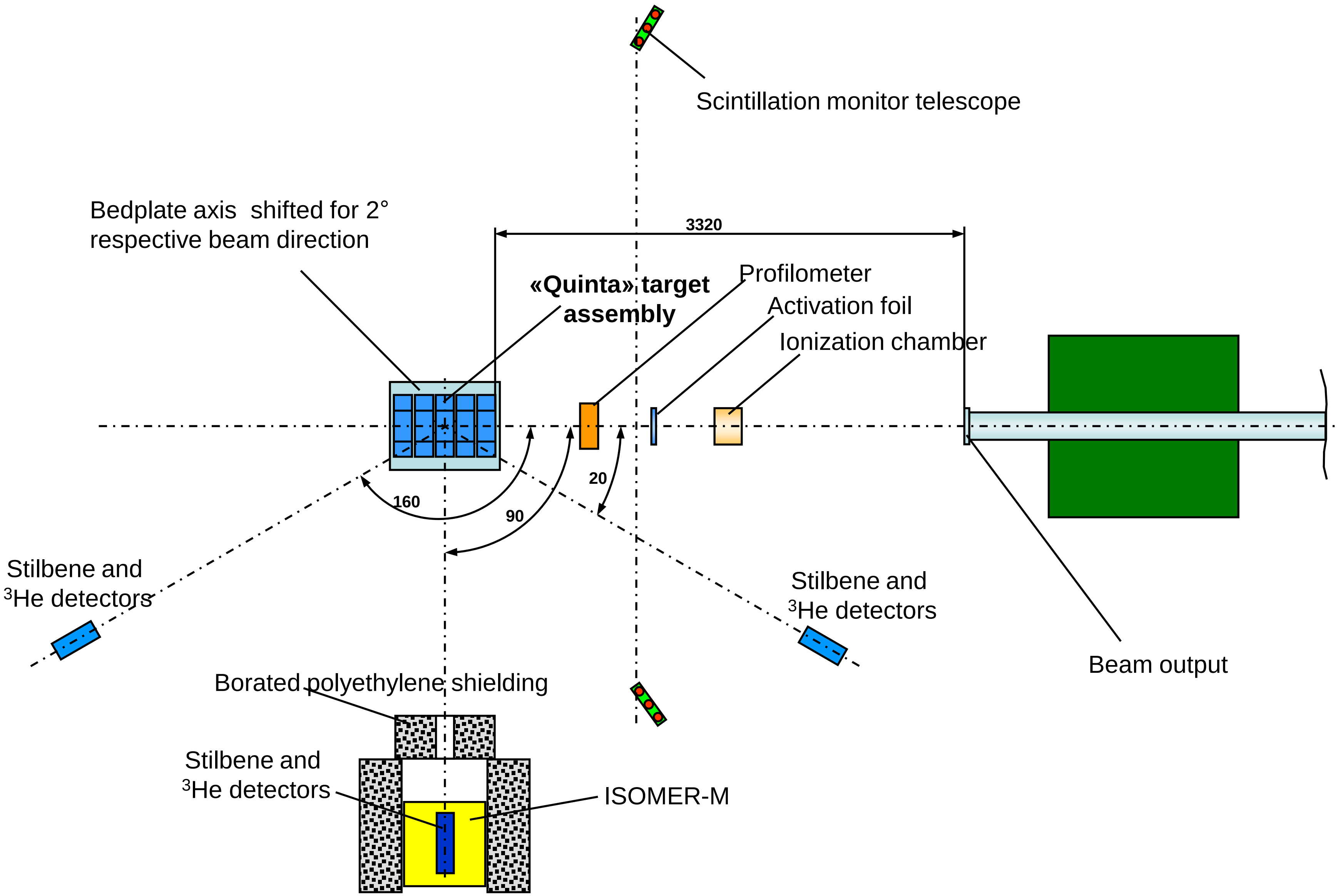
- In this case of "quasi-infinite" AC maximally hard neutron spectrum has been realized with rather low $\boldsymbol{k_{eff}}$ ~ 0.4

- They obtained integral number of fission events N_f ~ 20 and produced ^{239}Pu nuclei $N_{n\gamma}$ ~ 45 per incident proton. It leads to the beam power gain (BPG) ~ 7 for 0.66 GeV protons at rather small $\boldsymbol{k_{eff}}$

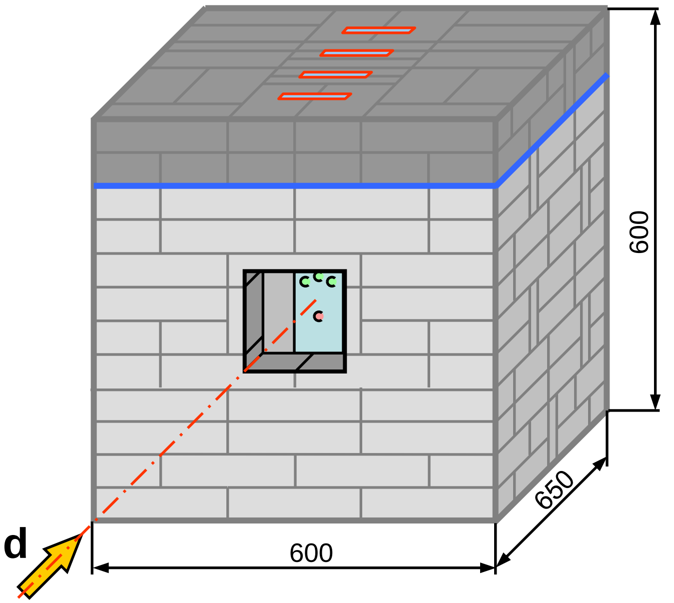
- So it is very important to realize an experiment with quasi-infinite AC such as QIUT for more high energy (up to 10 GeV)

- The measurements with QUINTA target assembly allow us to test experimental technique planned to use for study of the AC QIUT properties and to clear out the basic characteristics of the central “neutron tube-like source” of this AC investigated partly in 2009.

Scheme of experiment with upgraded “Quinta” setup, March 2011 run



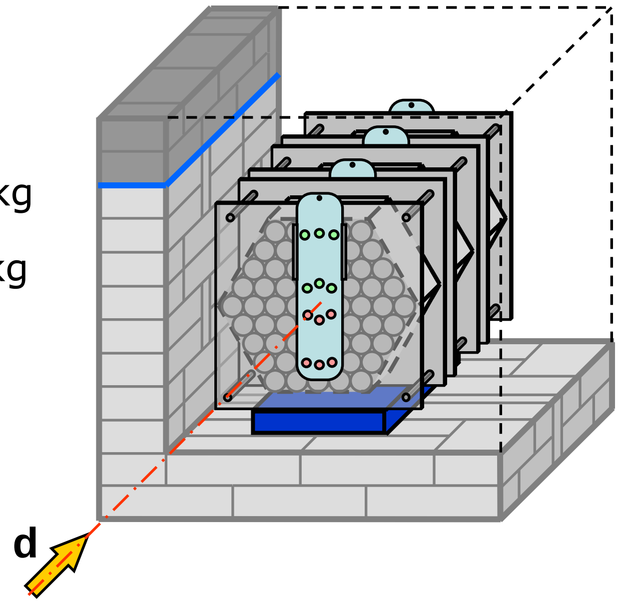
“Quinta UPb” at the irradiation position (June 2009)



m_U= 315 kg

m_{Pb}= 1780 kg

m_Σ = 2125 kg



Analysis of June 2009 measurements with "QUINTA UPb"

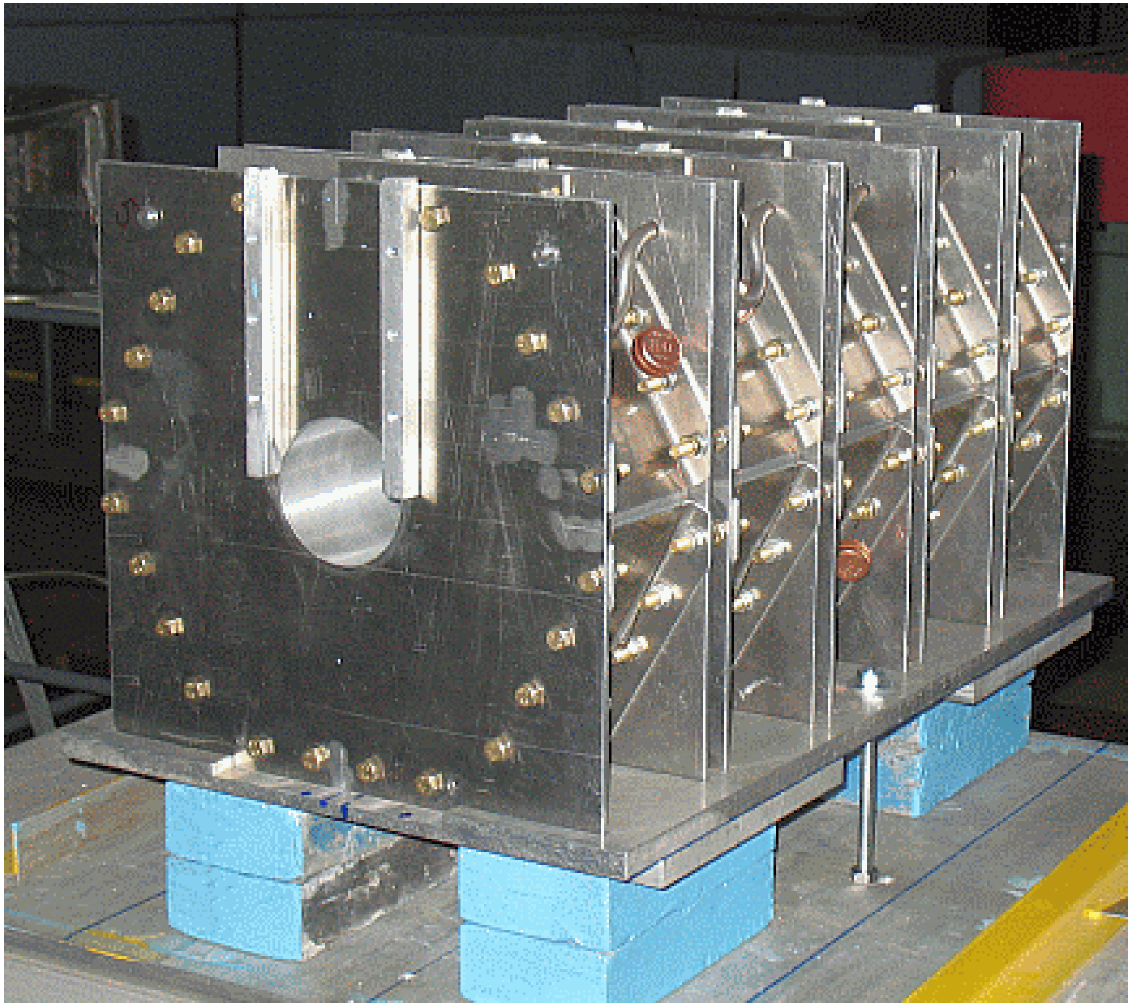
- A comparison of the total DN yields for deuteron energy 1 and 4 GeV has led to very challenging conclusion:

  - *total DN yield per one deuteron for this target assembly increased in about 8 times for that range of incident energy!*

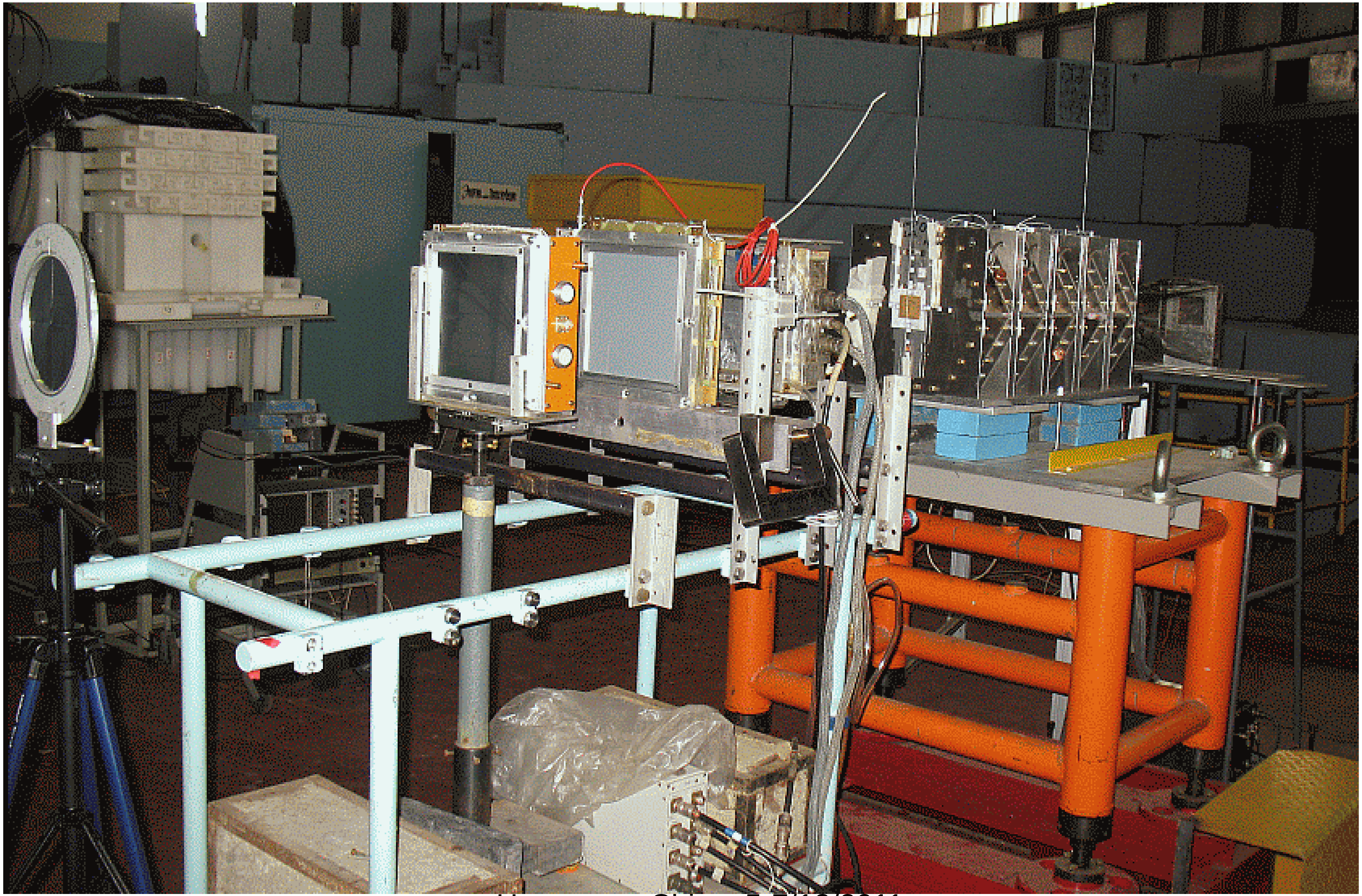
  - *If DN yield is proportional to integral number of fissions in the target assembly so it means that beam power gain increases with growth of its energy?!*

- This result has been tested in new experiment with QUINTA setup carried out by March 2011

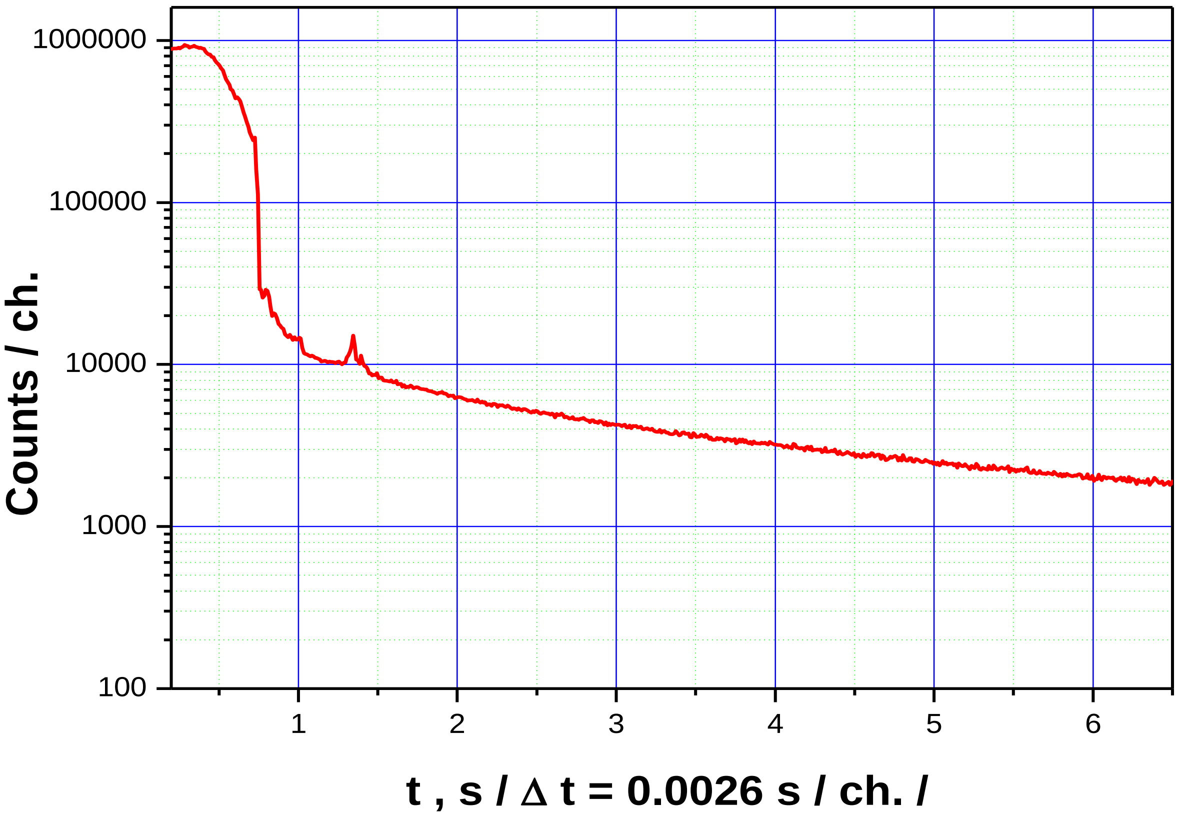
Upgraded target assembly "Quinta" (front view)



General view of the experimental setup



Neutron time spectrum: Ed= 6 GeV.



Results&Analysis of March 2011 run

Ed	2 GeV	4 GeV	6 GeV
DN relative yield/ per one deuteron (arbitrary units)	20 ± 1.4	69 ± 4.9	94 ± 8.4

Gamma-activity method in March 2011 run

Plutonium production

^{238}U(n,γ)^{239}U (23,54 min) β- $\rightarrow$ ^{239}Np (2,36 days) β- $\rightarrow$ ^{239}Pu

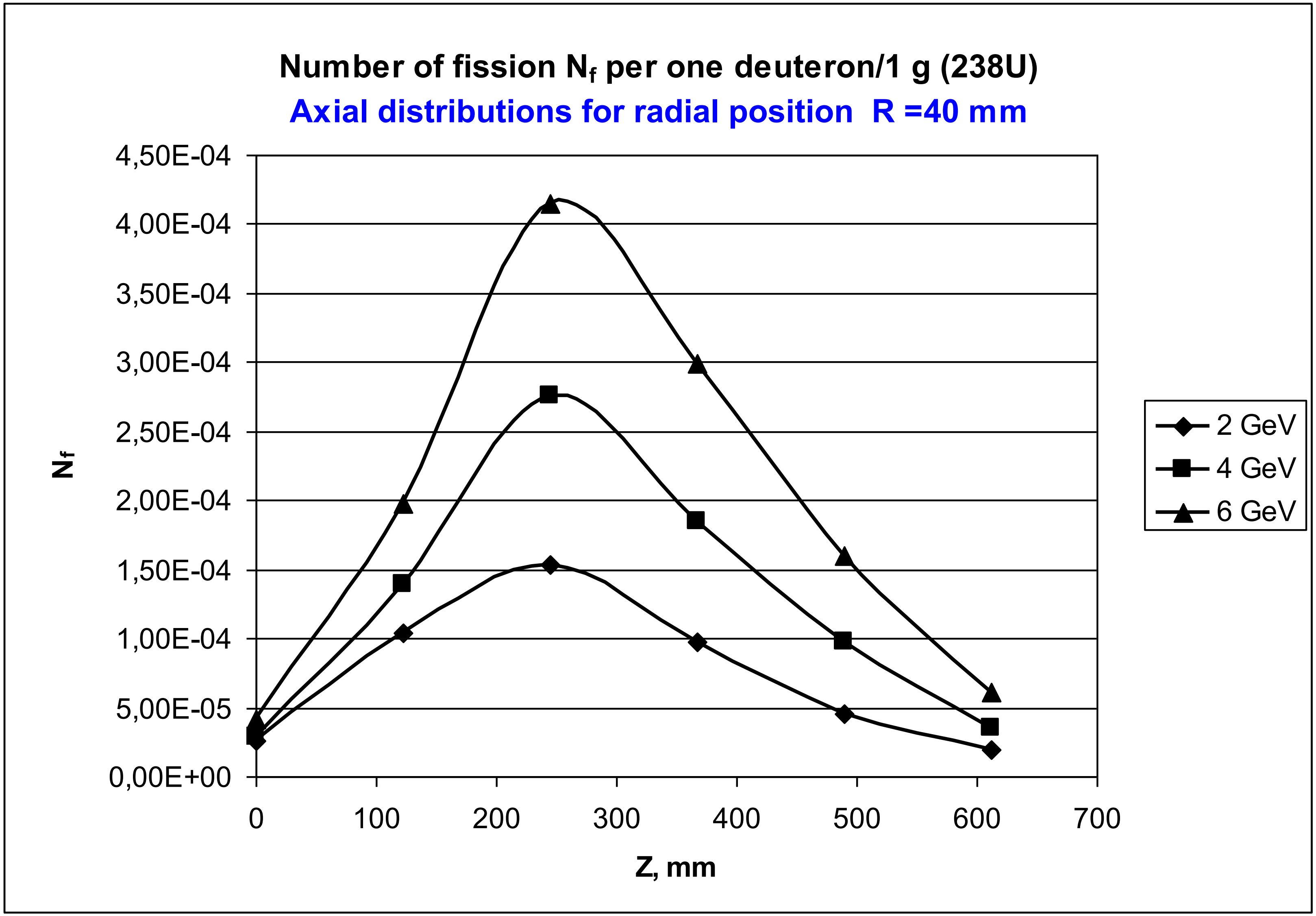
277,6 keV γ-line from ^{239}Np

γ- detector calibrated with ^{60}Co, ^{54}Mn, ^{57}Co, ^{88}Y, ^{109}Cd, ^{113}Sn, ^{133}Ba, ^{137}Cs, ^{139}Ce, ^{152}Eu, ^{228}Th, ^{226}Ra standard sources.

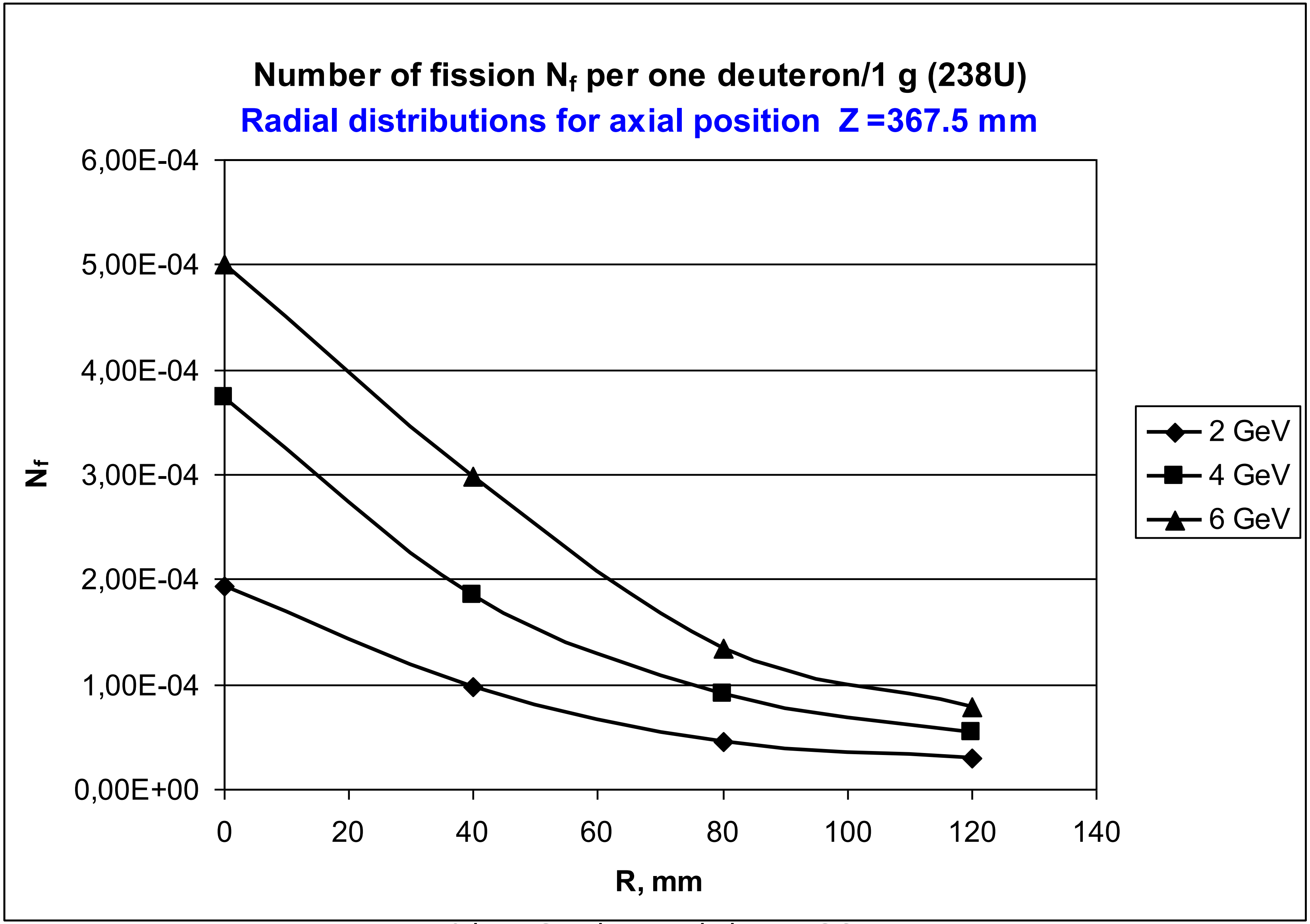
Number of fissions defines by averaging of following fission product yields:

^{97}Zr (5.42%), ^{131}I (3.64%), ^{133}I (6.39%), ^{143}Ce (4.26%)
. ***In brackets there are mean cumulative FP yields***

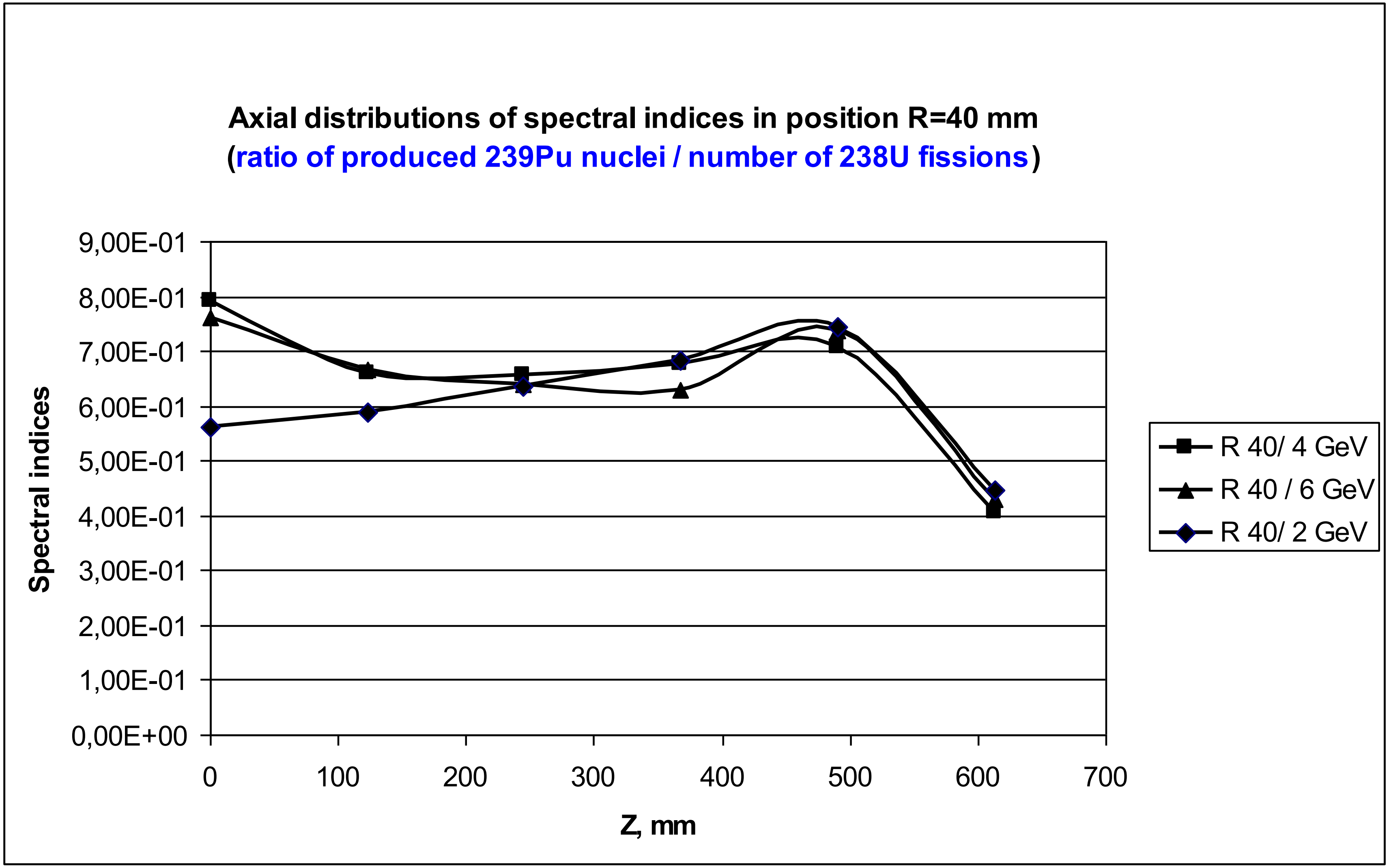
Results&Analysis of March 2011 run



Results&Analysis of March 2011 run

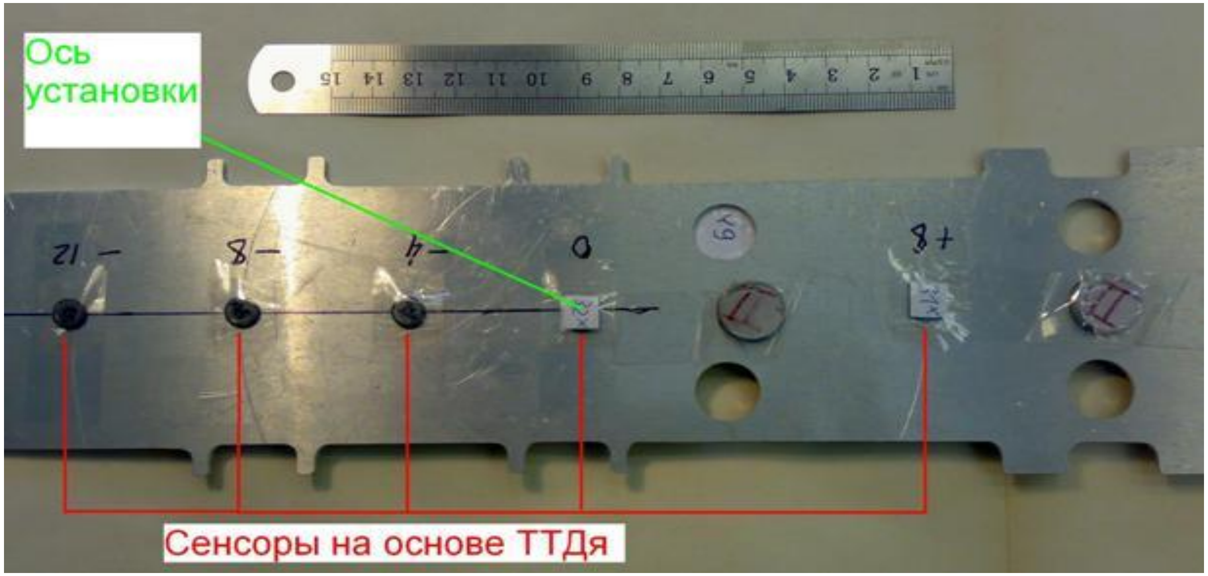


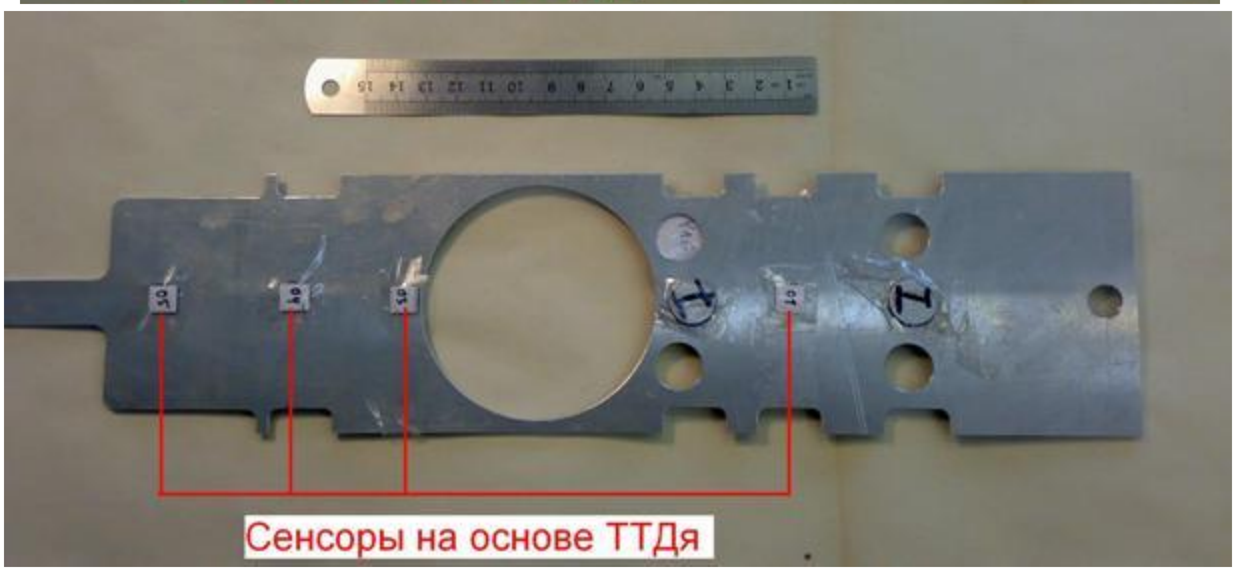
Results&Analysis of March 2011 run



SSTD

- M

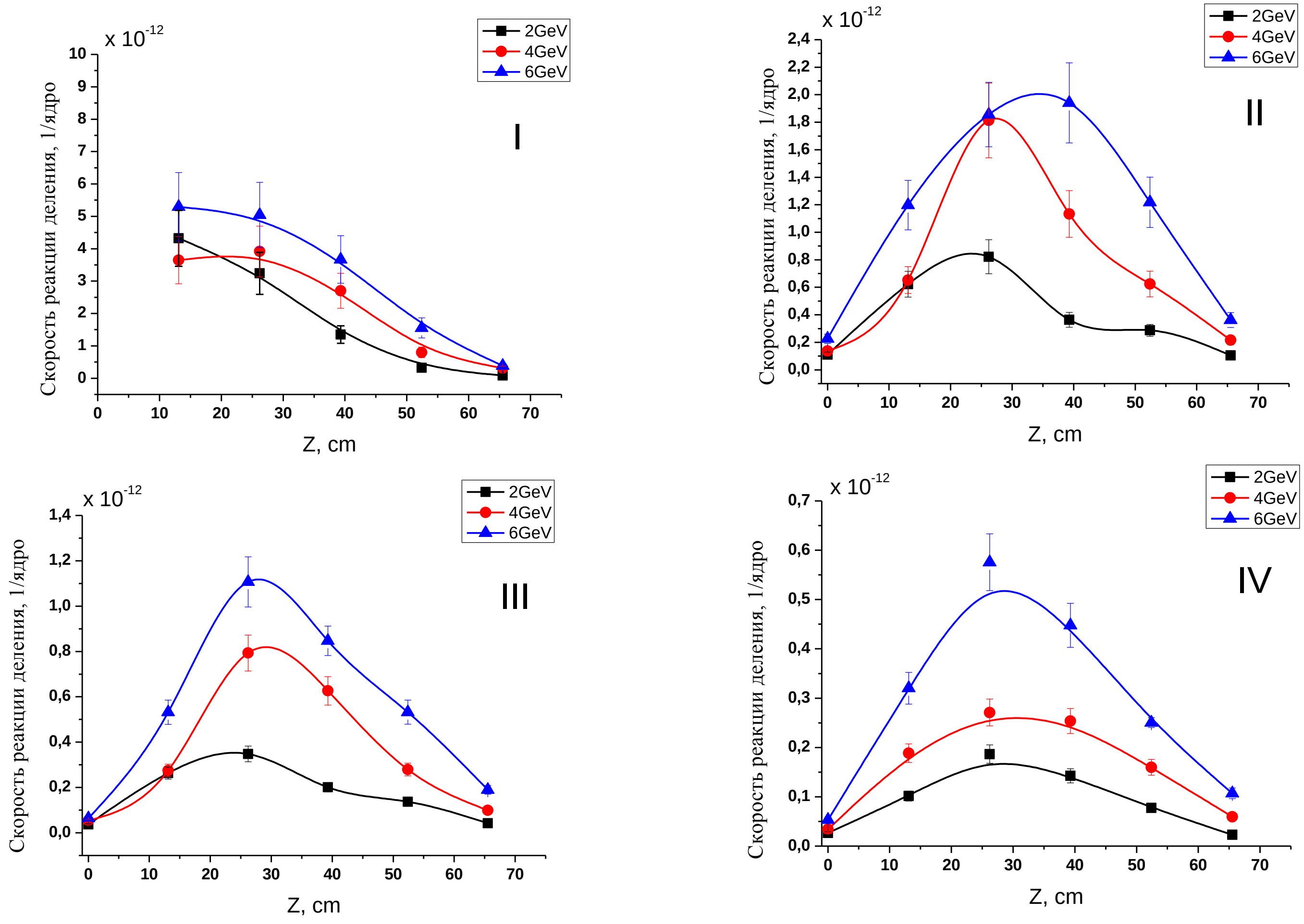




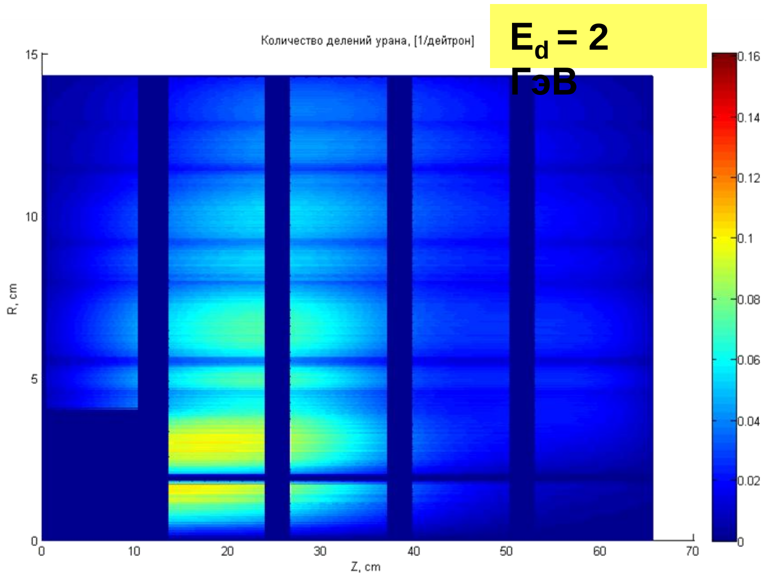
Mica SSTD

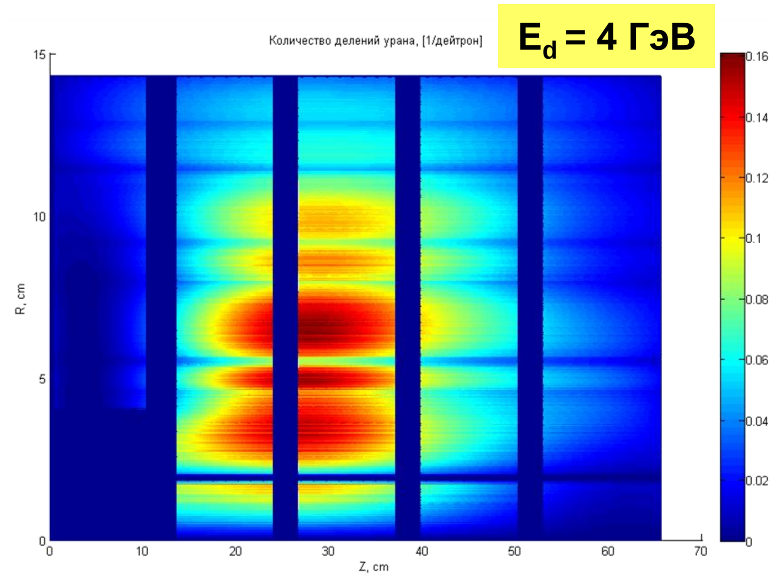
Axial distribution of fission rate per one deuteron measured by SSTD

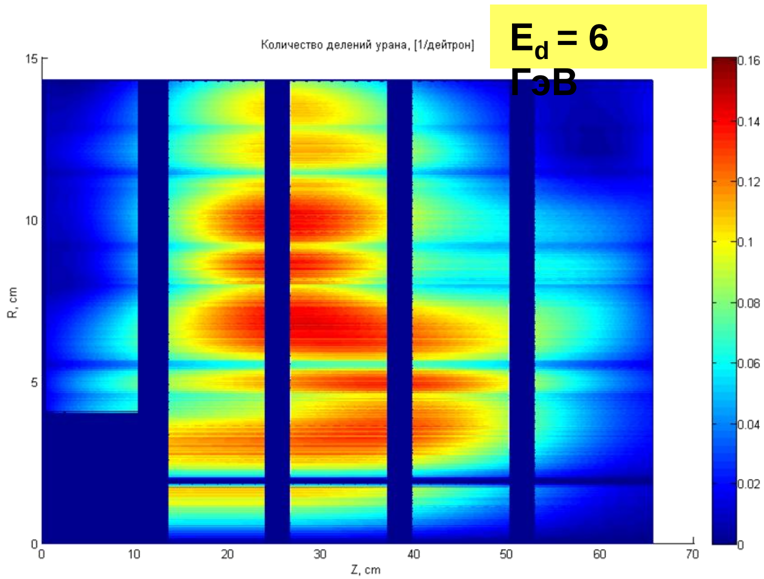
(I – *R = 0,* II – *R = 4cm,* III – *R = 8 cm,* IV – *12cm*)



Preliminary results of March 2011 experiments







Spatial distributions of fission rates (in cm^3/one deuteron) for QUINTA setup irradiated by deuteron beam

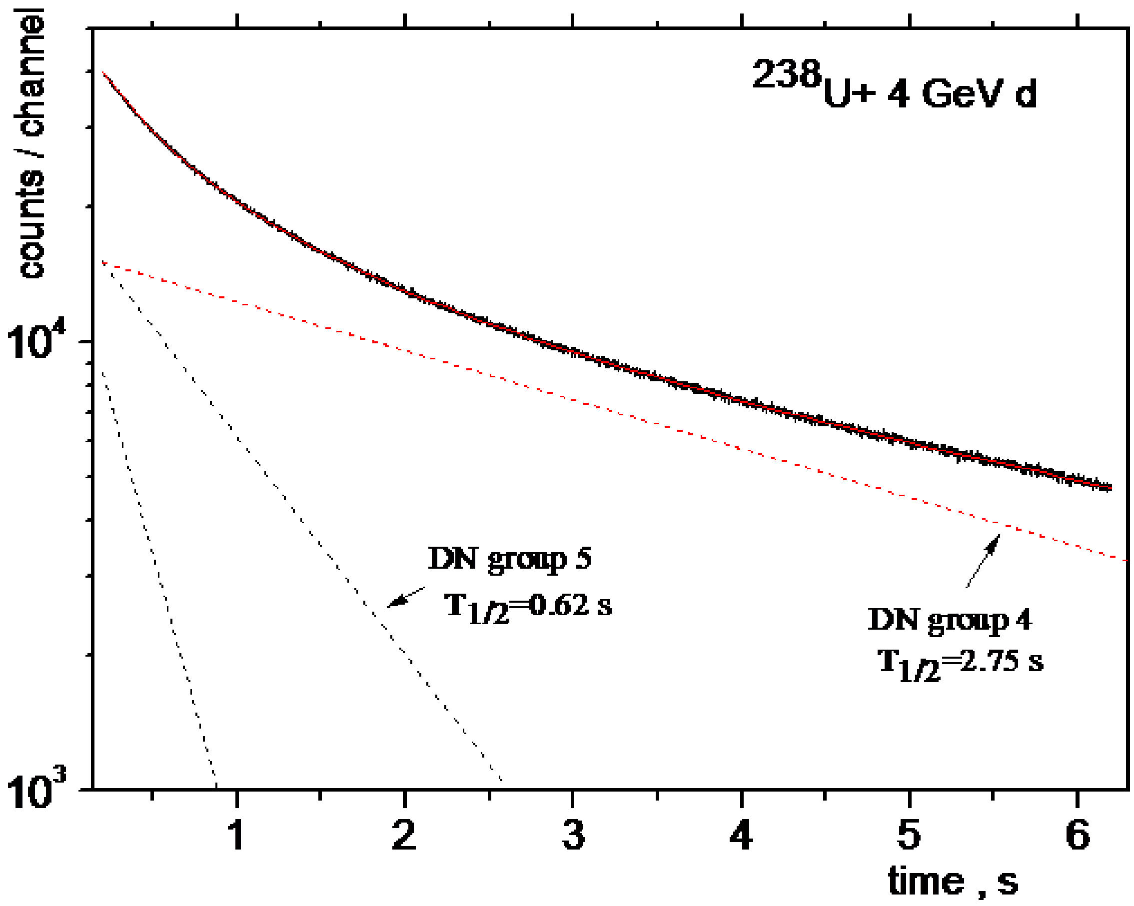
Measurements by solid state track detectors (SSTD)

Discussion of results

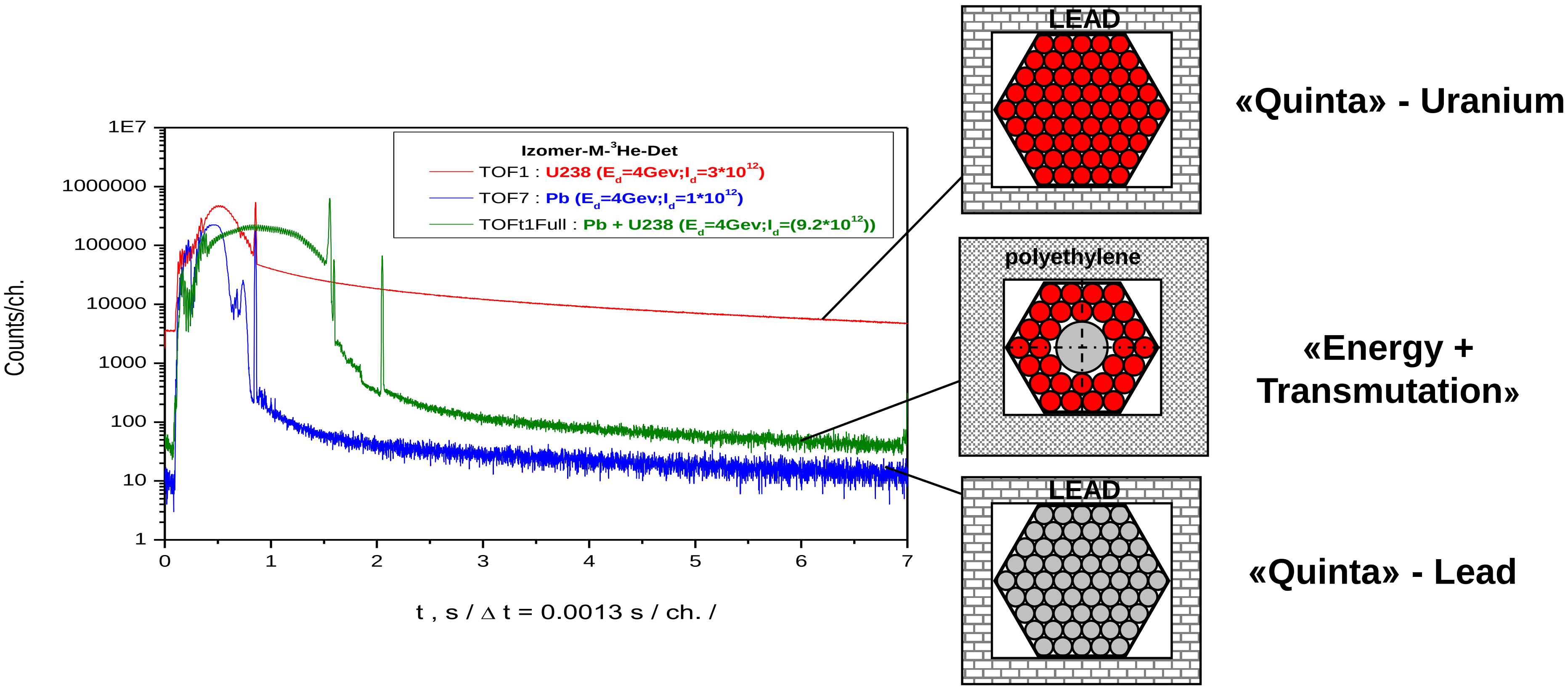
Number per one deuteron

Ed	0,66 GeV *(Vassil'kov et al)*	2 GeV *(Present)*	4 GeV *(Present)*	6 GeV *(Present)*
^{239}Pu production	46 4	17 1,7	30 3,0	45 4,5
^{238}U(n,f)	18,5 1,7	21 3,6	36 3,6	54 5,4
^{238}U(n,f)		20.4 3,8 2	32 6 3.2	44 7 4.4
DN relative yield normalized to fission data at 2 GeV		20 ± 1.4	69 ± 4.9	94 ± 8.4

Analysis of DN decay curve

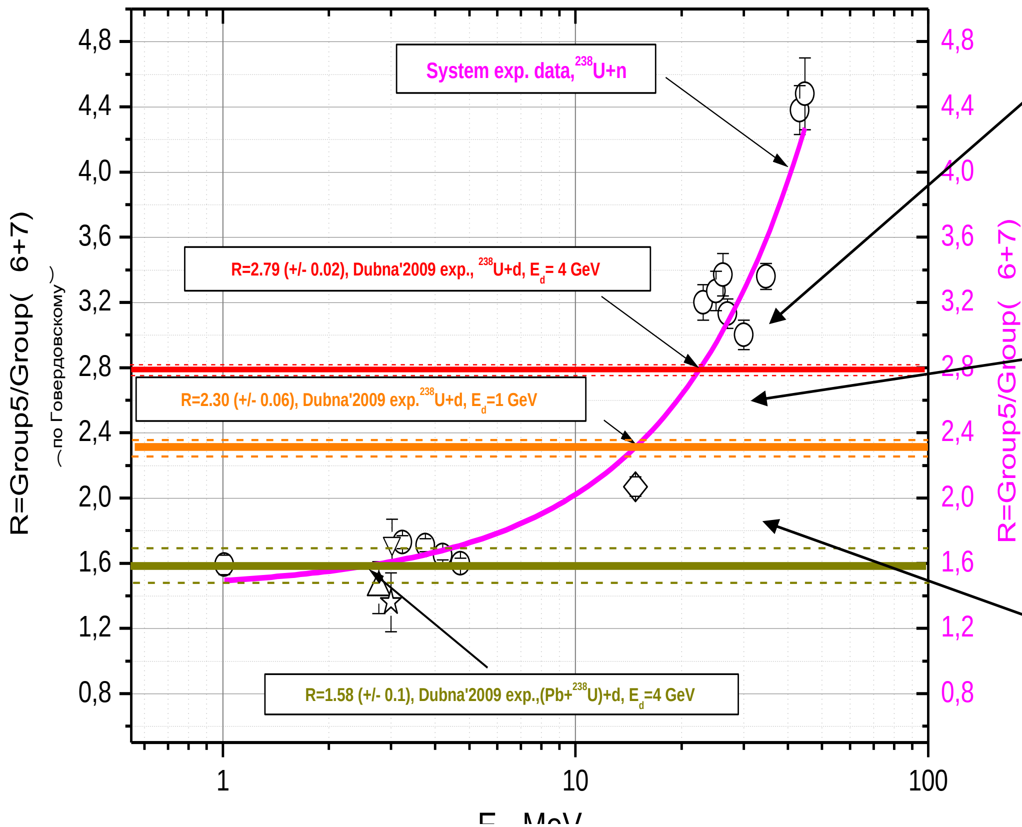


Results measured by June and November 2009



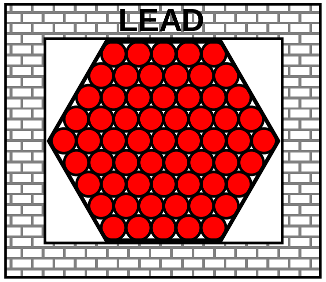
The time dependence of neutron yields from different target assemblies for E_d = 4 GeV.

Results of DN decay spectra analysis of June and November 2009 data



«Quinta» - Uranium

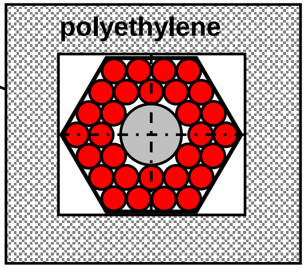
E_d = 4 GeV → $E_{n,f}$ ~ 25 MeV



E_d = 1 GeV → $E_{n,f}$ ~ 15 MeV

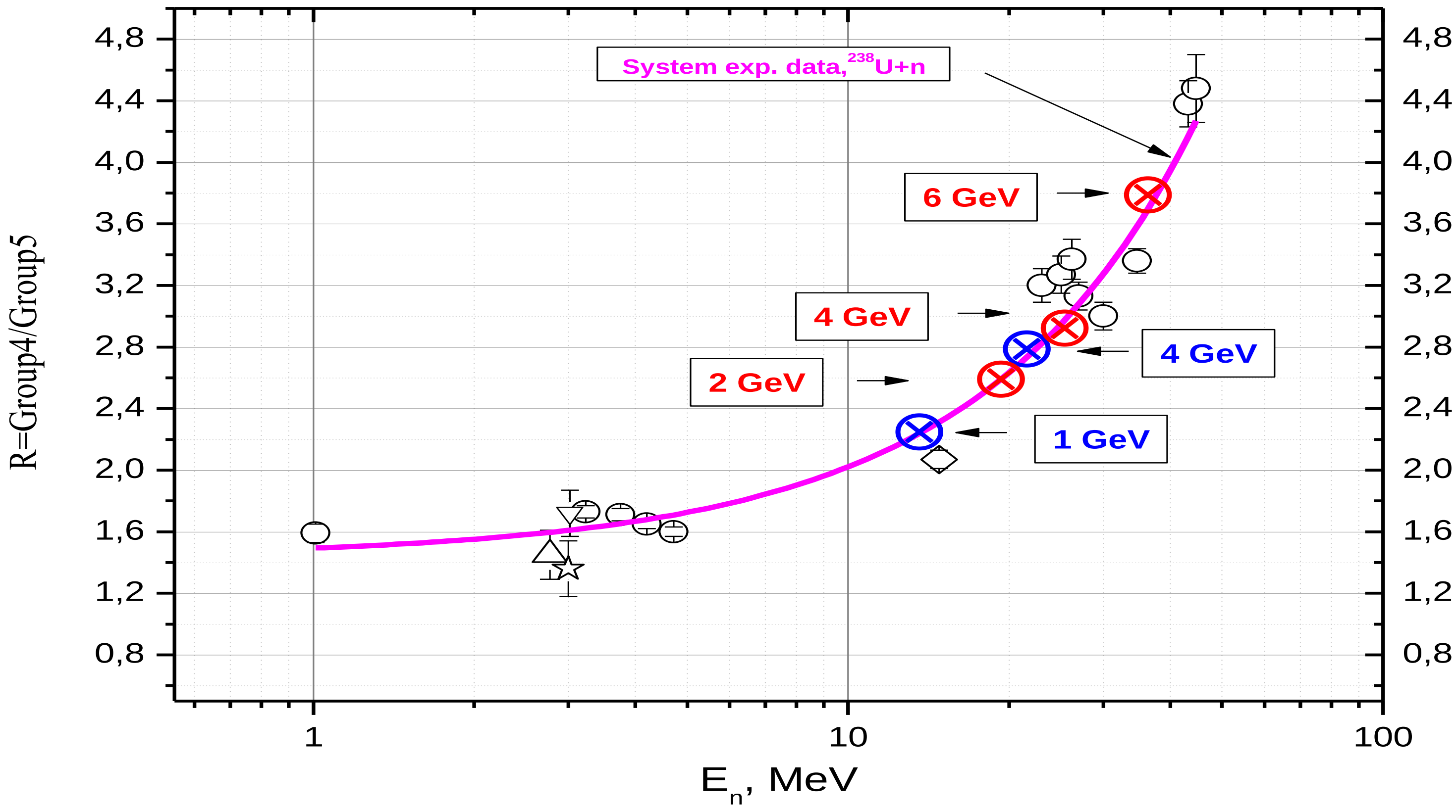
«Energy + Transmutation»

E_d = 4 GeV → $E_{n,f}$ ~ 3 MeV



Comparison of neutron energy dependence of the weight ratios of 5-th to 4-th DN groups from ^{238}U(n,f)-reaction and similar values extracted from DN time spectra measured in present work.

Comparison of neutron energy dependence of the weight ratios of 5-th to 4-th DN groups from ^{238}U(n,f)-reaction and similar values extracted from the DN time spectra measured in June 2009 and March 2011



Conclusion from results of June 2009 and March 2011 runs

"Mean neutron energy" *<En>* inducing fission of target nuclei ^{238}U

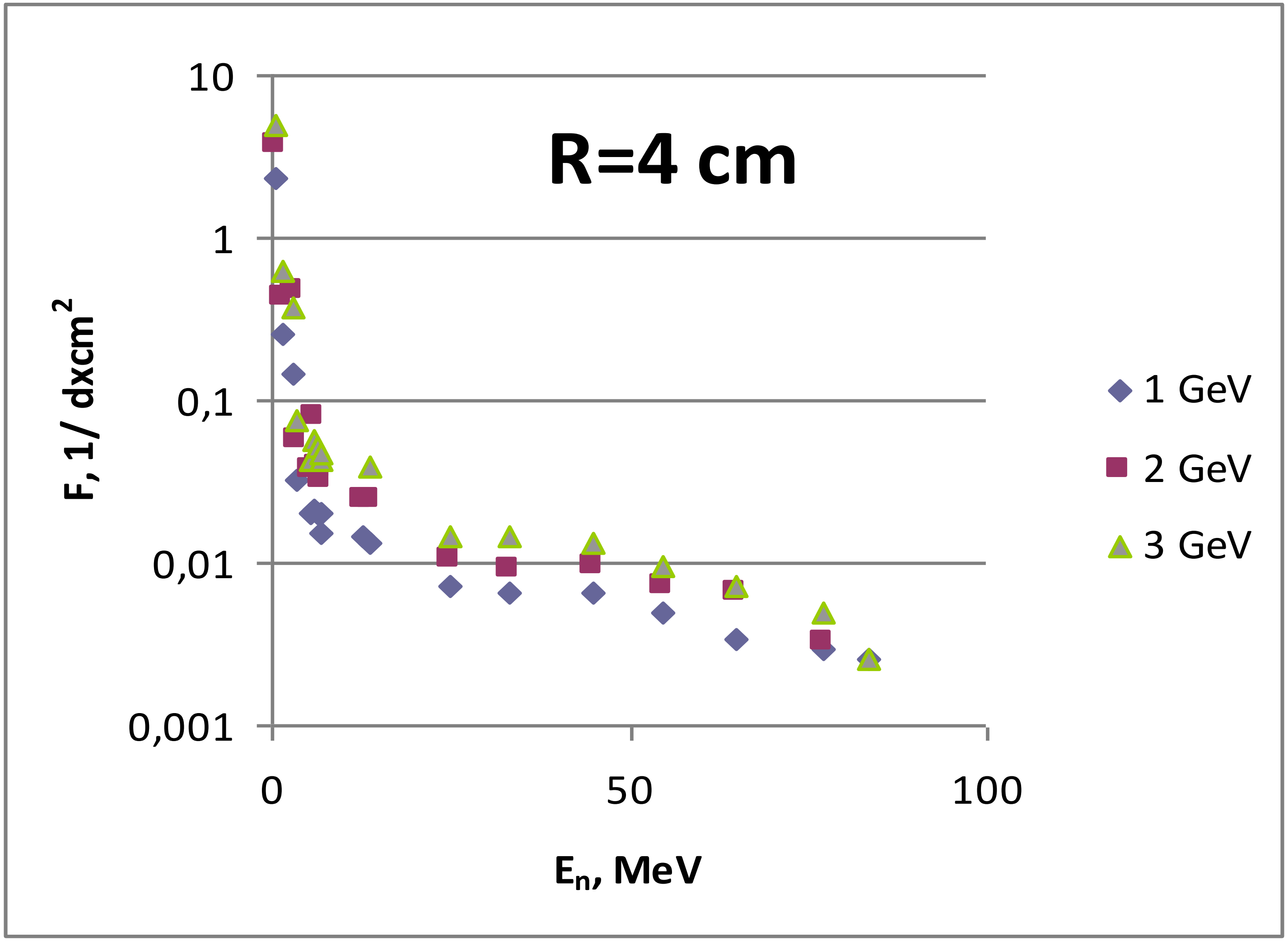
increases

from $<E_n> = (13 \quad 3)$ *MeV* *up to* $<E_n> = (37 \pm 4)$ *MeV*

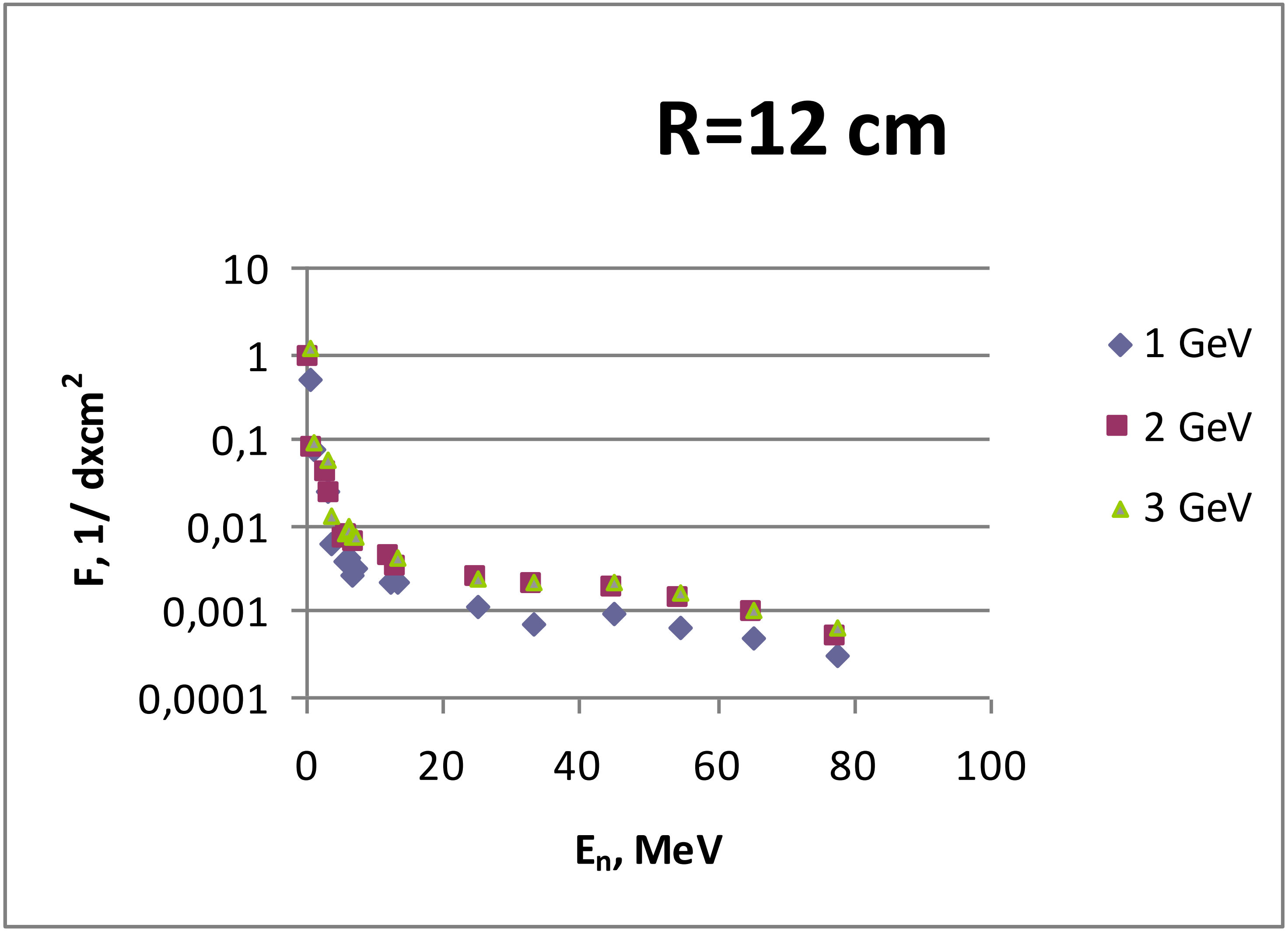
with growth of incident deuteron energy

from $E_d = 1$ *GeV* *to* $E_d = 6$ *GeV*

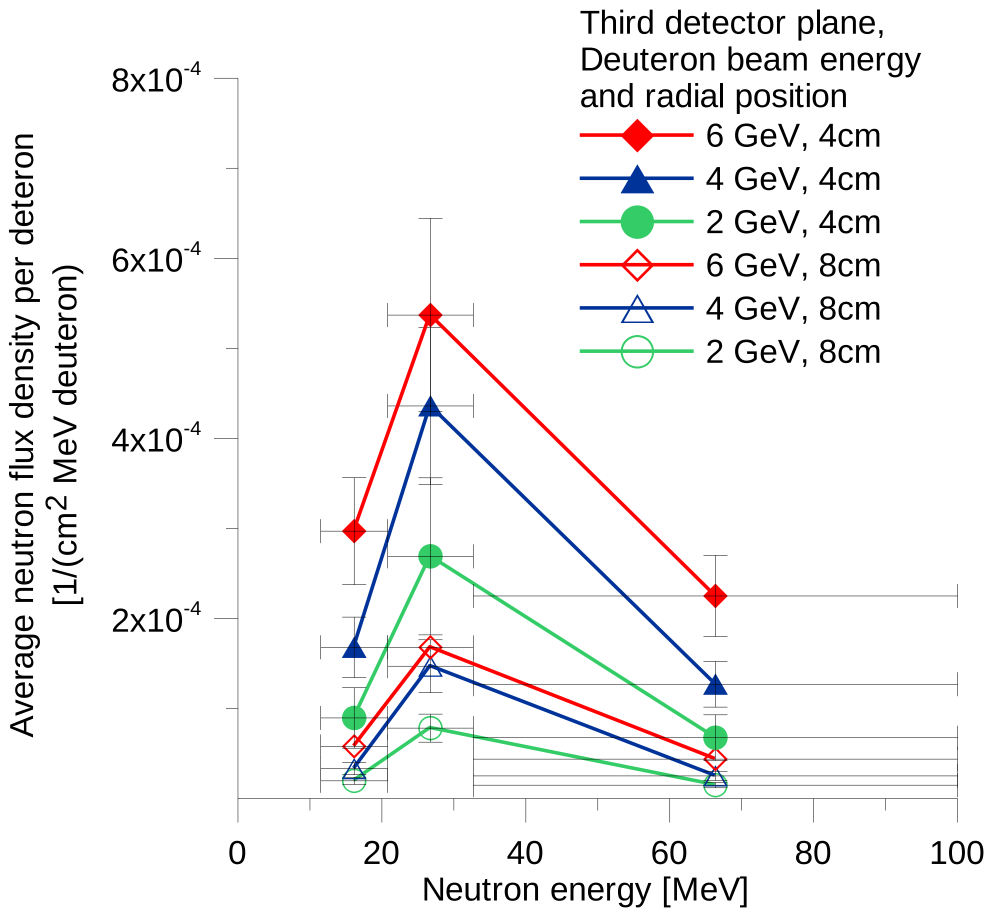
Results from threshold activation detectors (March 2011)



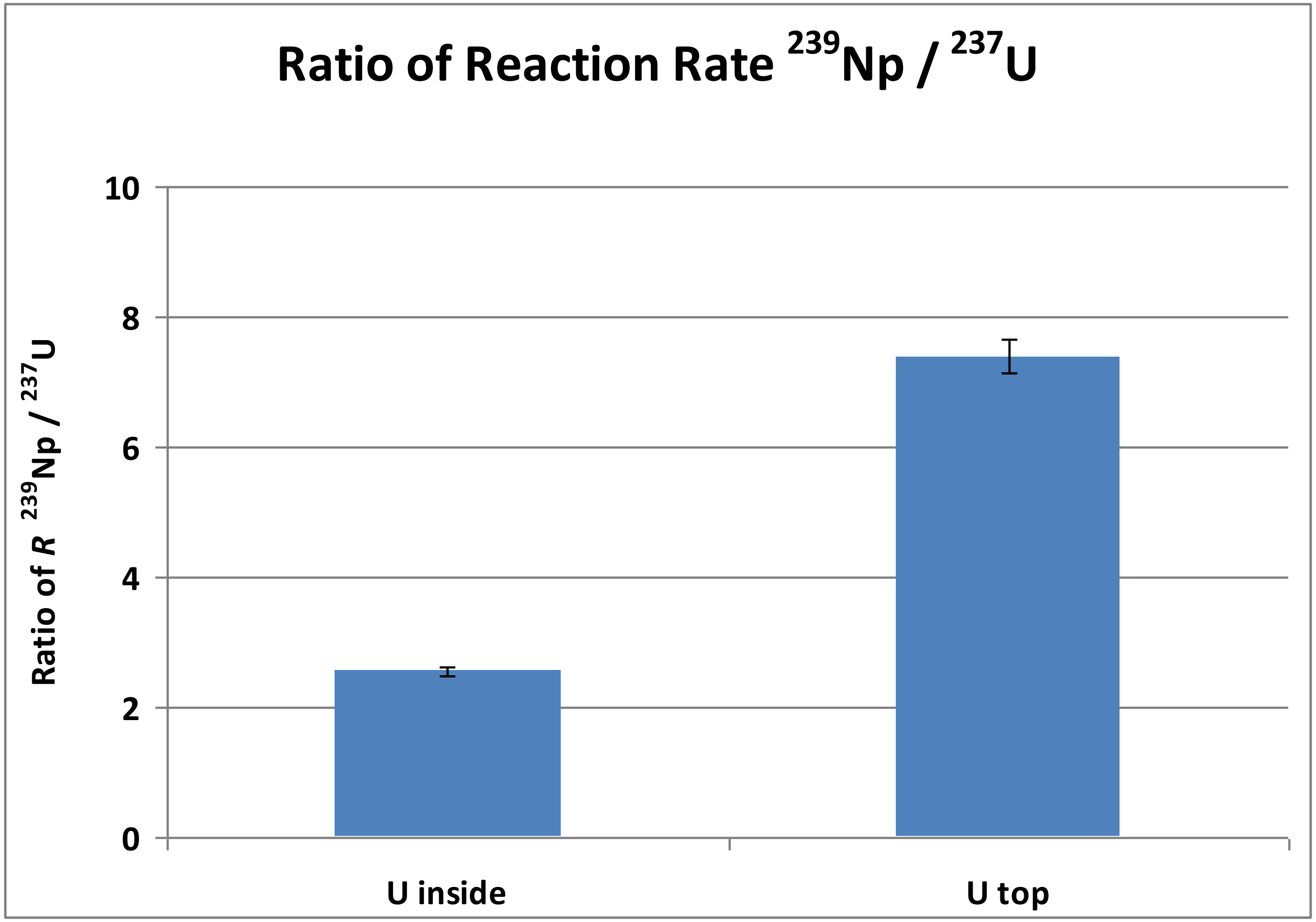
Results from threshold activation detectors (March 2011)



Measurements with ^{89}Y threshold detectors



Measurements with ^{235}U and ^{238}U washers



Intermediate conclusion

The preliminary results obtained for upgraded Quinta seup irradiated by deuterons with energy 2, 4 and 6 GeV.

It was measured time spectra of DN. Extracted "mean neutron energy" inducing fission of ^{238}U increases with growth incident deuteron energy.

Relative DN yield goes up ~5 times with increase of E_d from 2 up to 6 GeV *in qualitative accordance with our previous (June 2009) measurements.*

Total numbers of fission *for the same range of E_d* ***increase only ~ 3 times, proportionally to incident energy growth.***

Difference in incident energy dependence of DN relative yields and total fission rate is the subject for further experimental and theoretical study.

Obtained data for spatial distribution of neutron spectra and fluxes as well as main features of leakage neutrons should be a subject of subsequent analysis

Thanks for your attention

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.

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

Project “E&T – RAW”
Research program

Measurements will be done with protons (deuterons) in range of incident energy 1 to 10 GeV (0.5 up to 5 GeV/nucleon)

Task 1 . Integral data.

It includes wide set of experiments with the targets QINTA and “QIUT”:

- **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.**

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

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.*

Thanks for your attention

Experimental program of March 2011 run

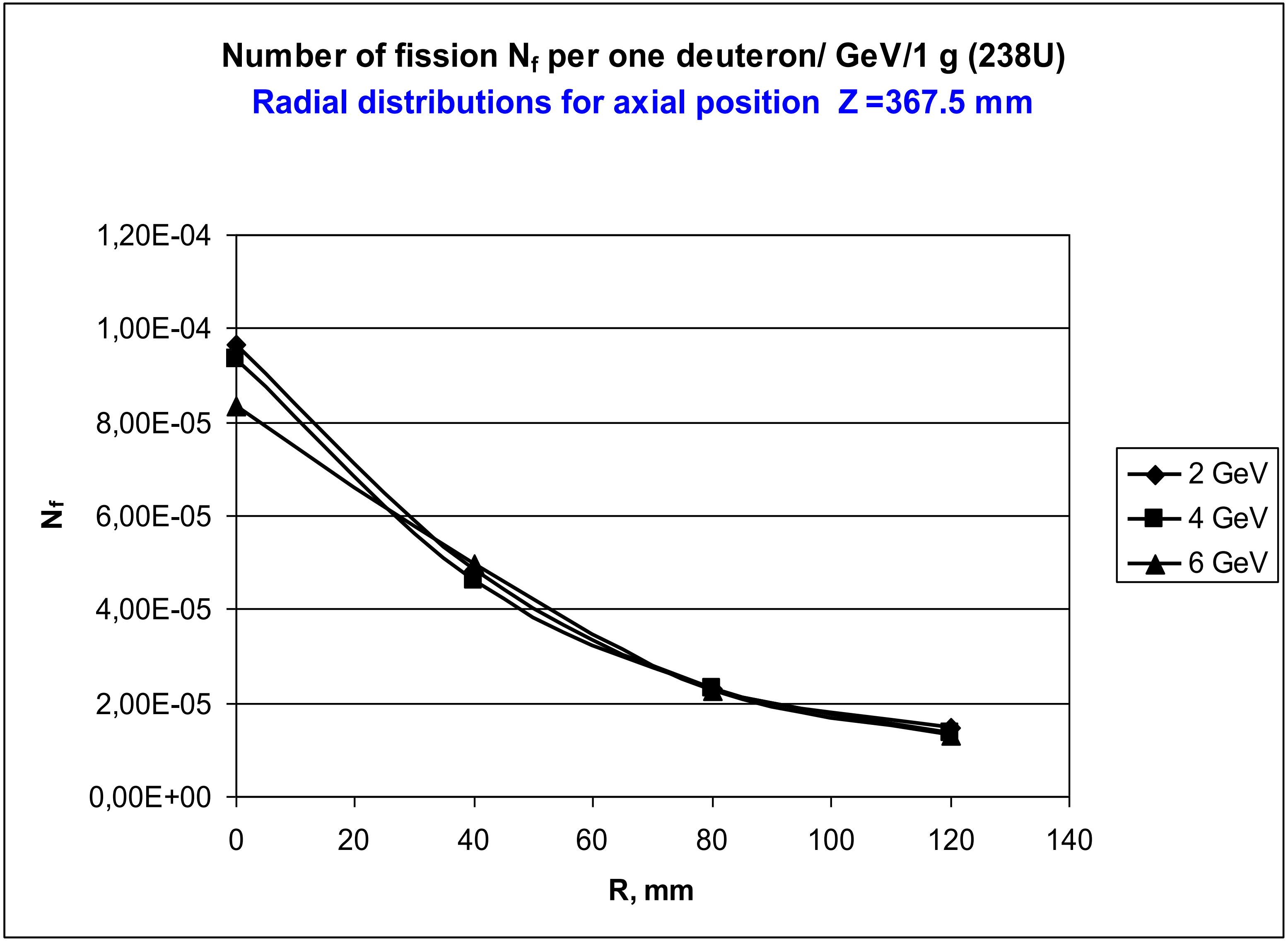
1. Verification of incident energy dependence of total DN yields obtained in June 2009;

2. Study the incident energy dependence of the spatial and energy distributions of neutrons (by threshold activation detectors), spatial distributions of numbers of fission and plutonium production (by SSTD (mica) and γ – activity of specific fission and (n,γ)- products), as well as the spectra and multiplicity of leakage neutrons;

3. Direct determination of total fission numbers within Quinta setup by two independent methods aimed at determination of the dependence of the beam power gain on its energy ;

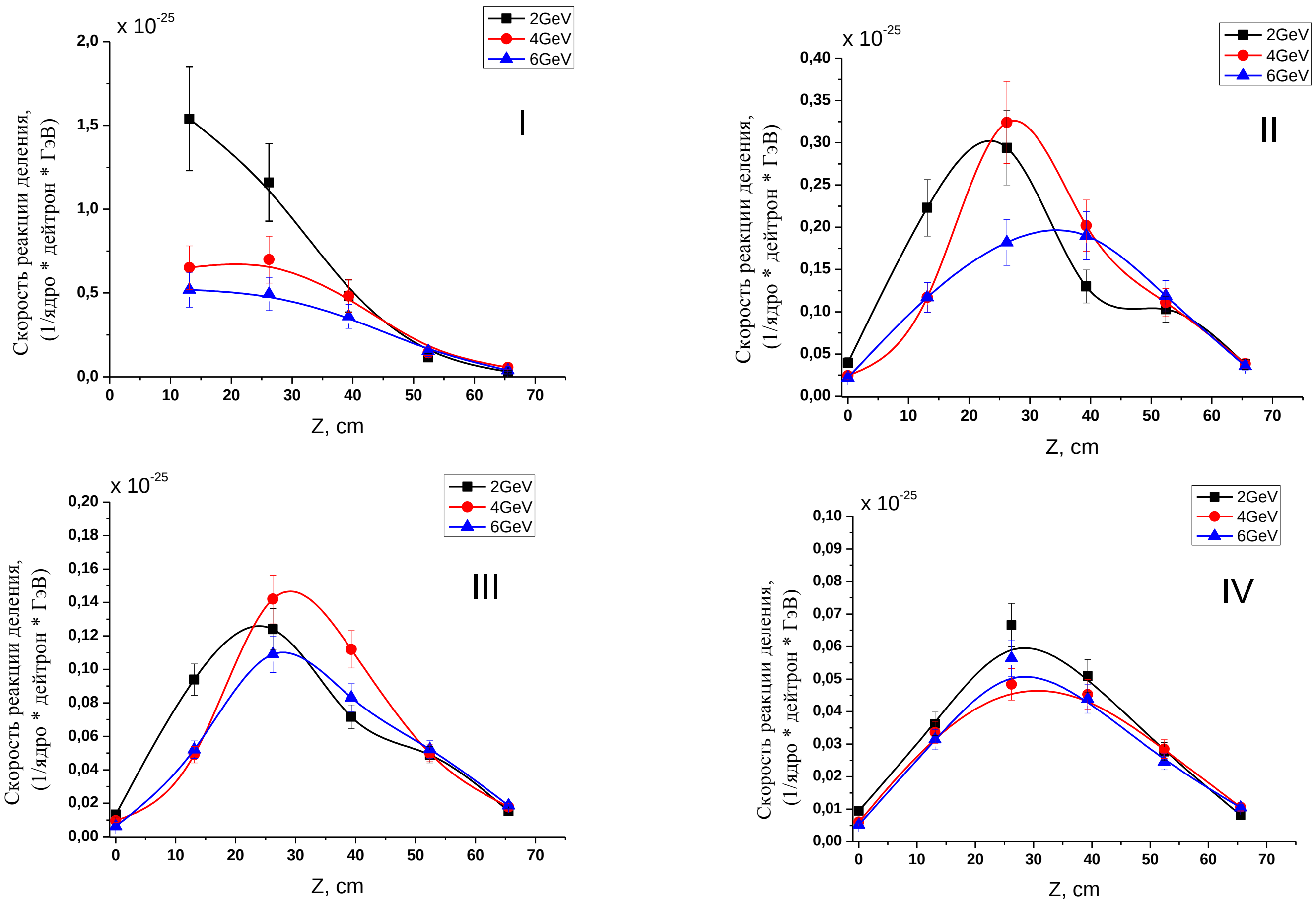
4. Obtaining a wide set of experimental data to proceed with the modification of intra nuclear cascade models and respective MC codes aimed at improvement the reliability of predicting outcomes of future experiments with large (~ 20 t) uranium target under the “E & T –RAW” project.

Results&Analysis



Axial distribution of fission rate per one deuteron per GeV measured by SSTD

(I – *R = 0,* II – *R = 4cm,* III – *R = 8 cm,* IV – *12cm)*

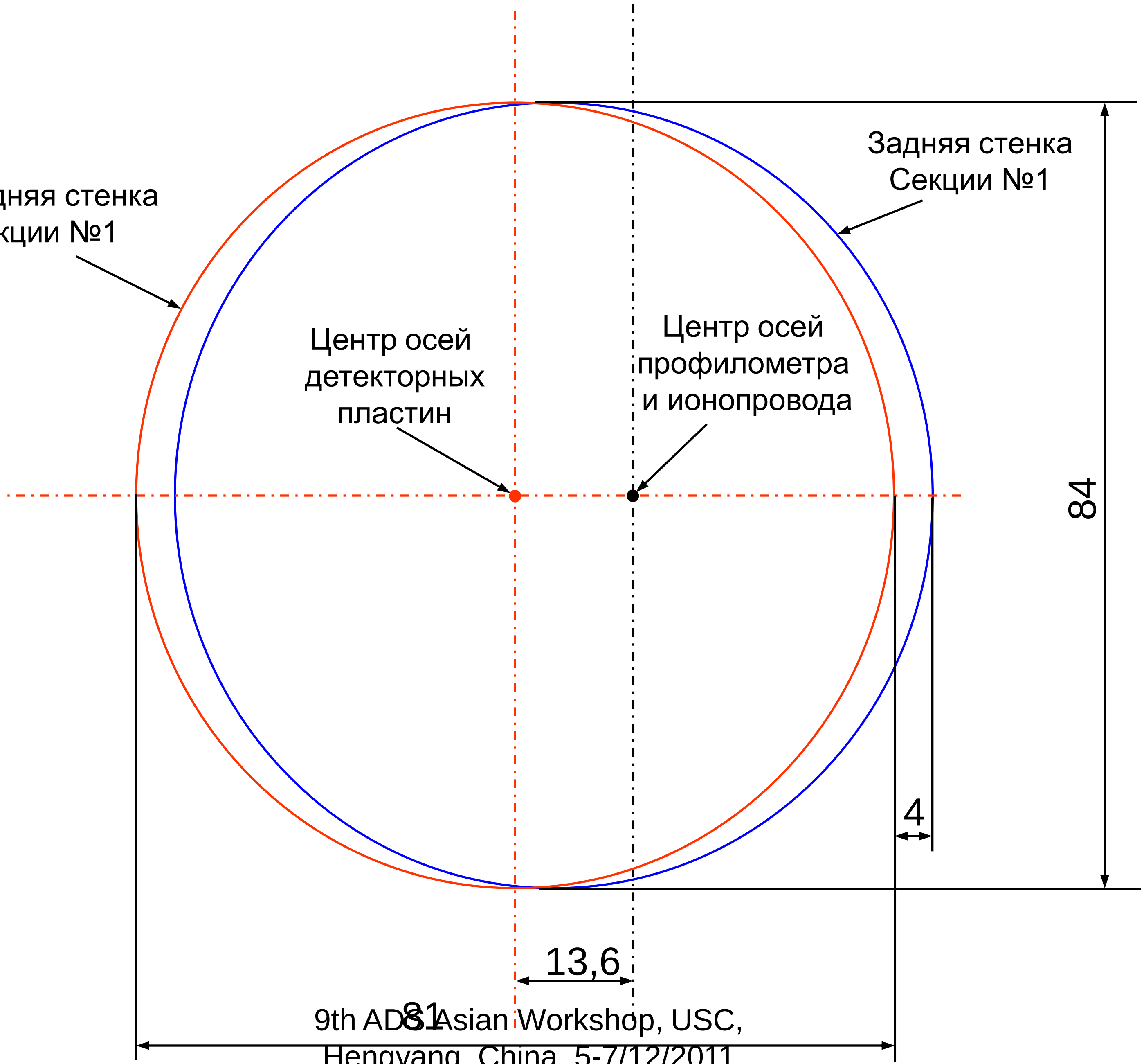


Results&Analysis

SST fission detectors (fission numbers per deuteron)

	Ed	*Ed*	*Ed*
	2 GeV	**4 GeV**	**6 GeV**
$^{238}U(n,f)$	**20.4 3,8 2**	**32 6 3.2**	**44 7 4.4**

Окно входа пучка (вид со стороны пучка)



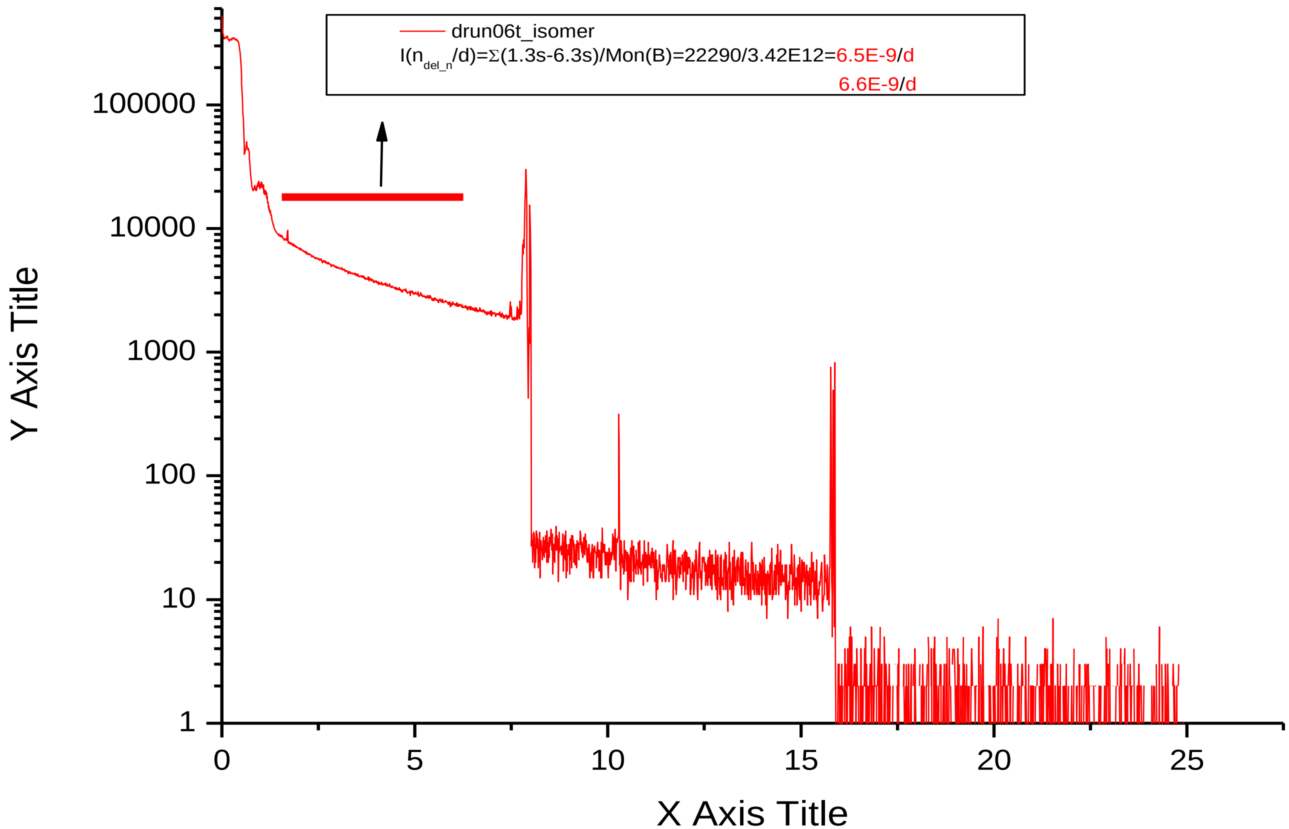
MOTIVATION

- ADS is considered now as tool for the transmutation of the long-lived components of radioactive wastes (RAW) and in principle for the solution of global energy problems.
- This work is aimed at study of basic physics of the ADS with quasi-infinite size active core (AC) from natural uranium irradiates by deuteron beam of (1-6) GeV energy.
- The long-range goal is a study of the possibilities of such ADS with very hard neutron spectrum inside of AC to realize recently proposed so called Relativistic Nuclear Technology (RNT) for transmutation RAW and energy production due to burning of AC material.
- Important aim of the experimental program is to provide comprehensive benchmark data set for verification and adjustment of INC models and transport codes.

Neutron time spectrum

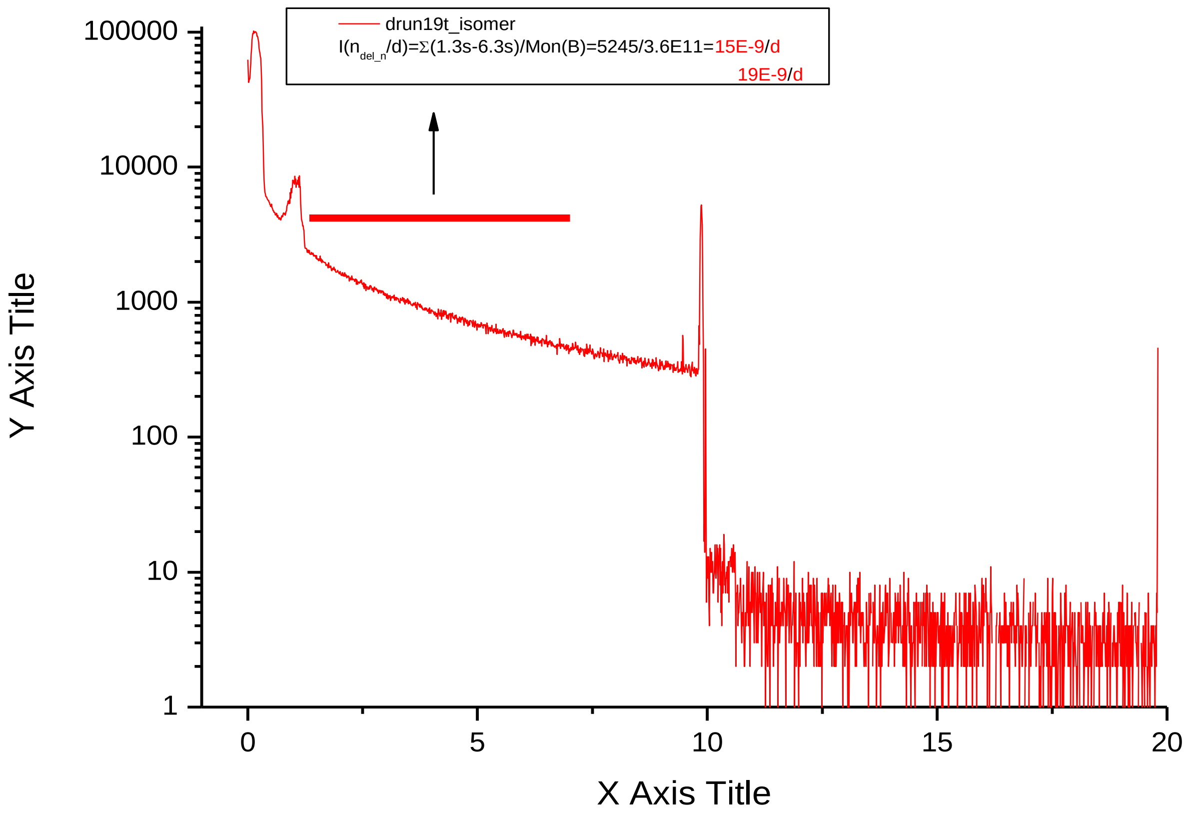
E_d= 2 GeV, (T = 8 s, ΔT = 0.65 s), total DN yield I = (1.3±0.1)·10^{-9}/d

March 2011 run



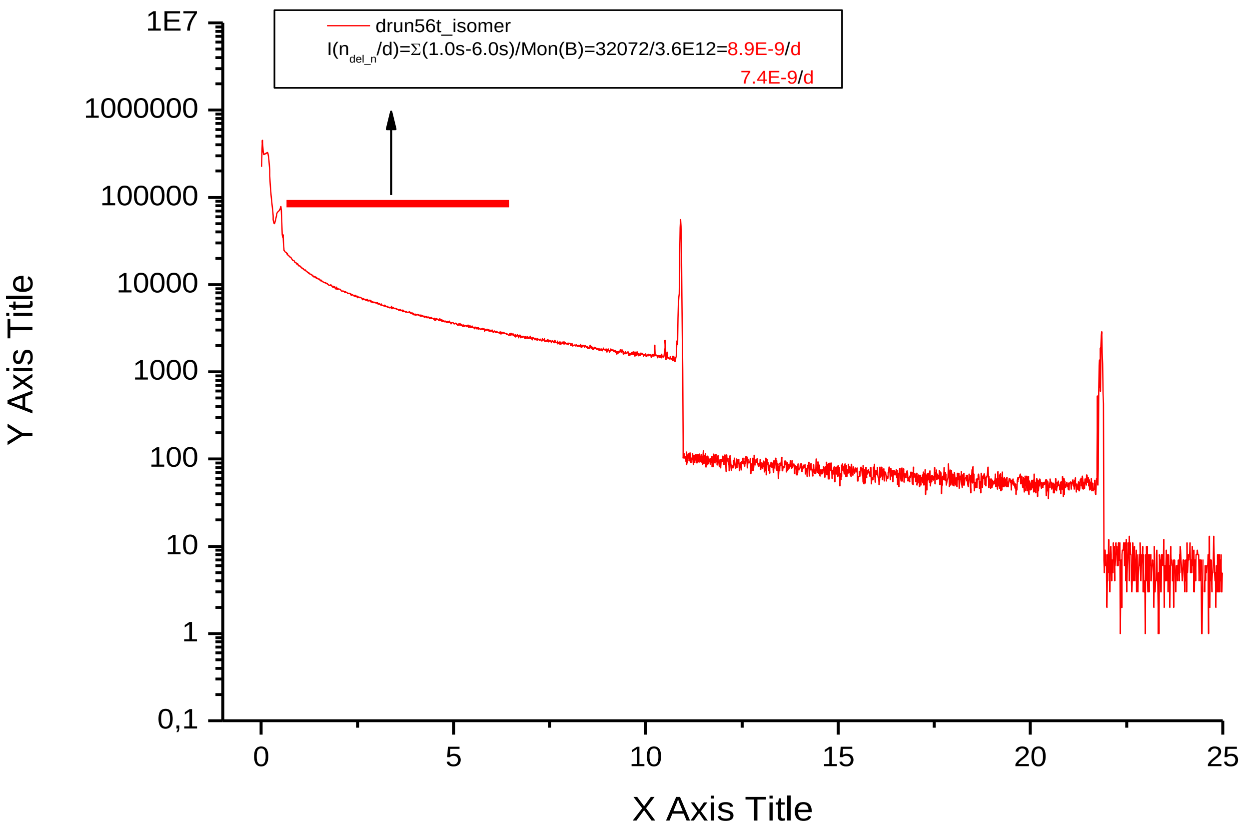
Neutron time spectrum

E_d= 4 GeV, (T = 10 s, ΔT = 0.34 s), total DN yield I = (4.5±0.3)·10^{-9}/d



Neutron time spectrum

E_d= 6 GeV, (*T = 11 s, ΔT= 0.25 s),* total DN yield I = (7.8±0.6)·10^{-9}/d



“Quinta” at the irradiation position (June 2009)

Cover of lead blanket

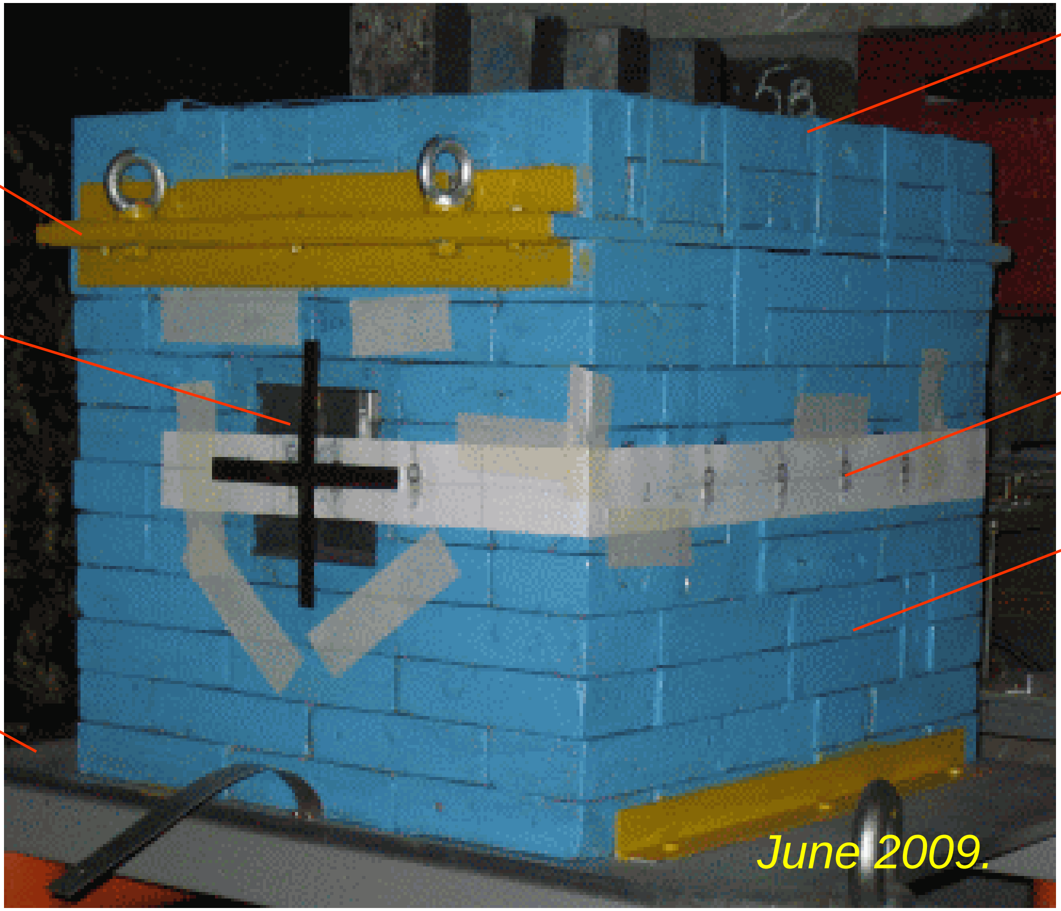
Upper bed

Beam input widow

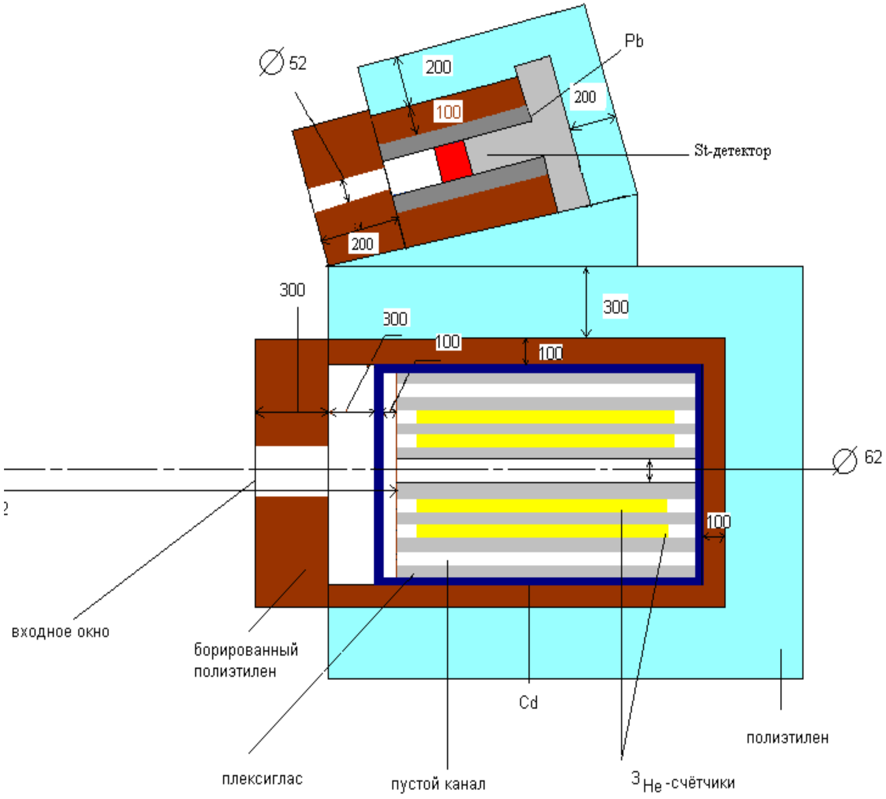
Sets of activation detectors

Lead blanket

Lower bed



Neutron detector assembly IZOMER-M



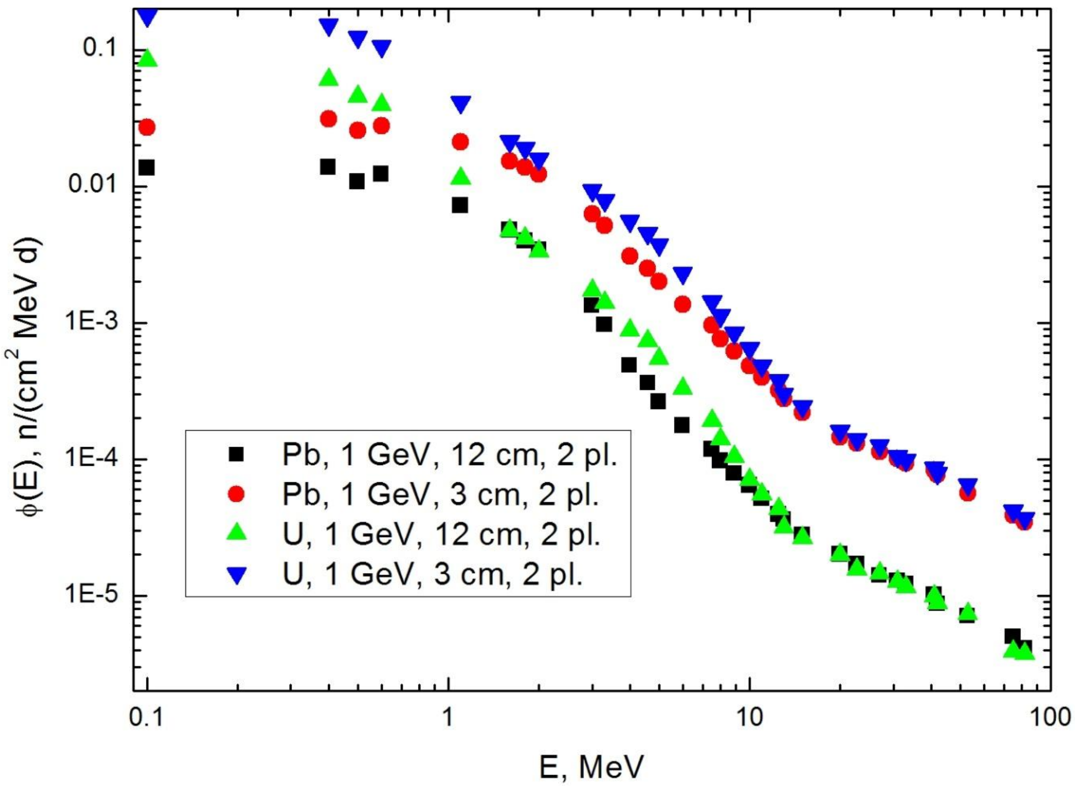
Experiment

For E_d = 1 and 4 GeV it was studied :

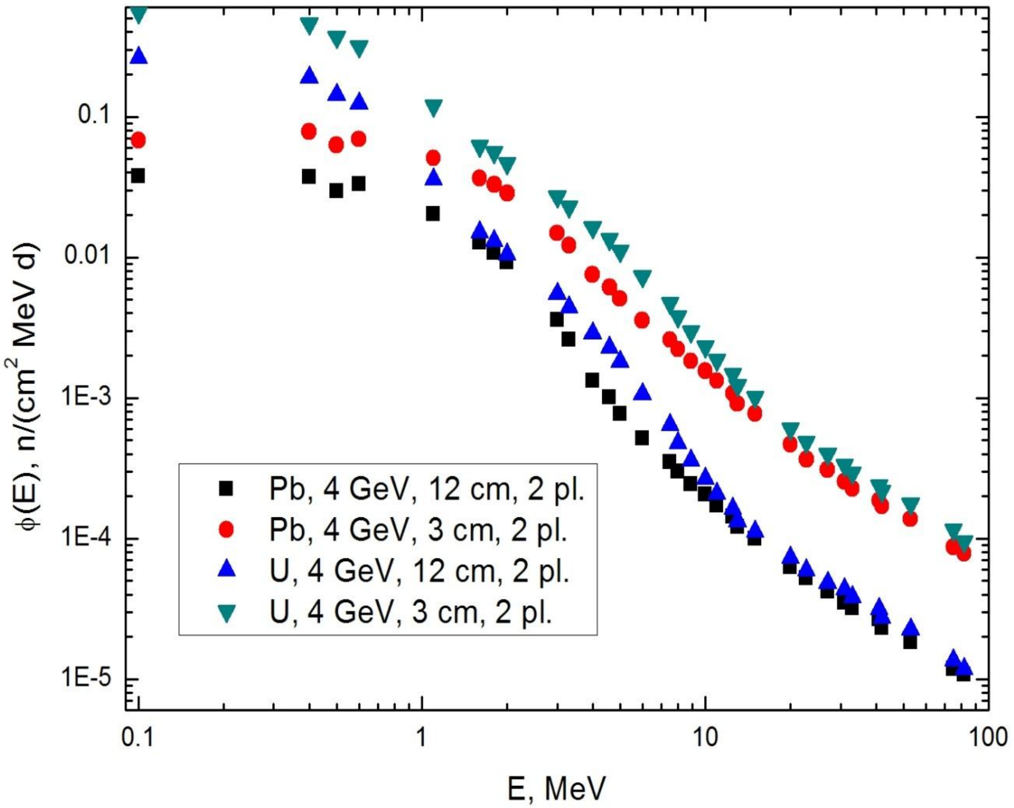
- the neutron spectra inside the extended uranium target (and lead target for comparison)
- the time dependence of the neutron yield, including its delayed component (DN)

Study of DN yield expected to be a very sensitive test for basic mechanisms of the fission process inside of massive target

Analysis of June 2009 results



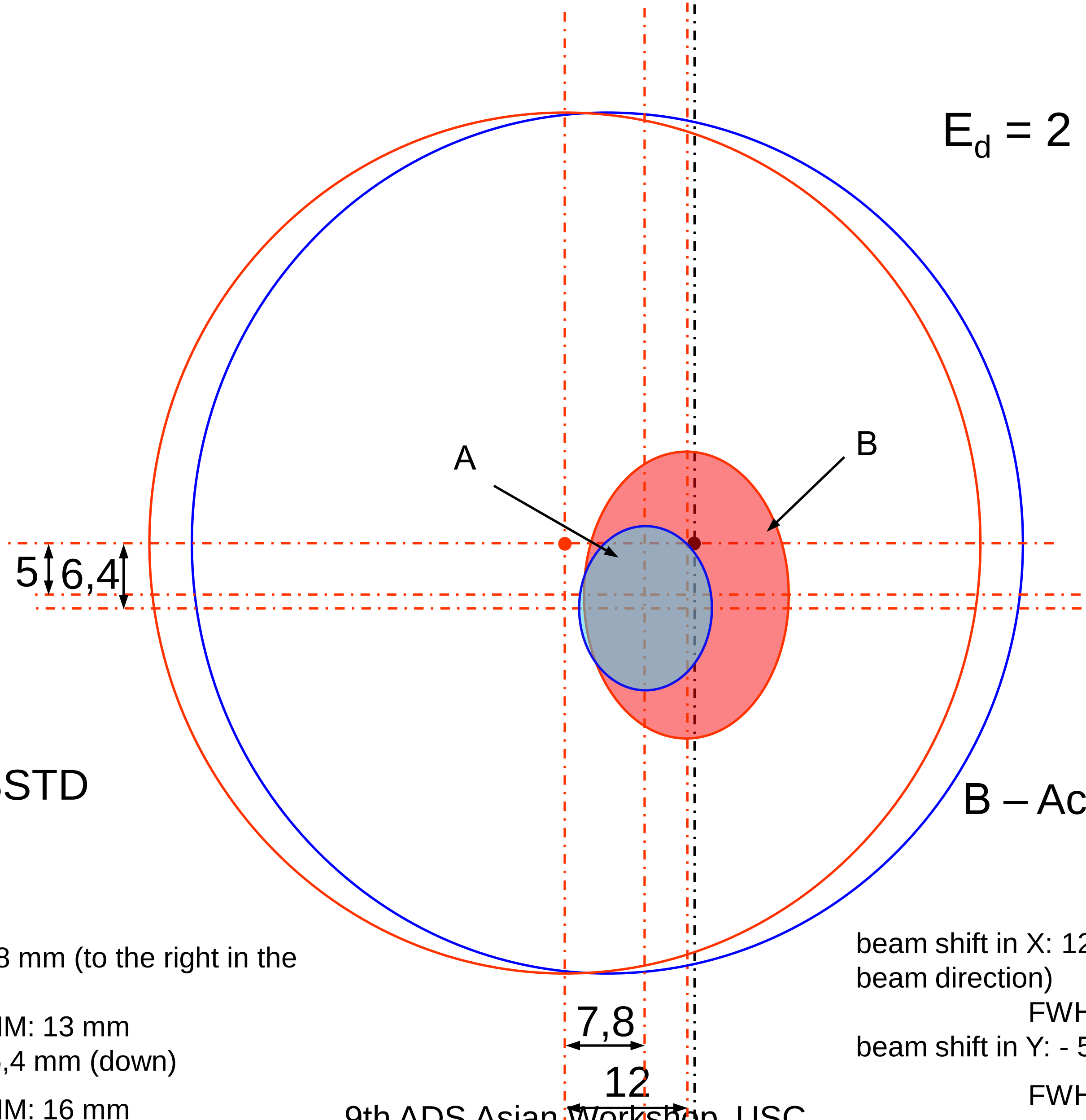
Analysis of June 2009 results



“Quinta” at the irradiation position (front view)

Beam position into input window (front view)

$E_d = 2$ GeV



A – SSTD

B – Activation method

beam shift in X: 7,8 mm (to the right in the beam direction)

FWHM: 13 mm

beam shift in Y: - 6,4 mm (down)

FWHM: 16 mm

beam shift in X: 12 mm (to the right in the beam direction)

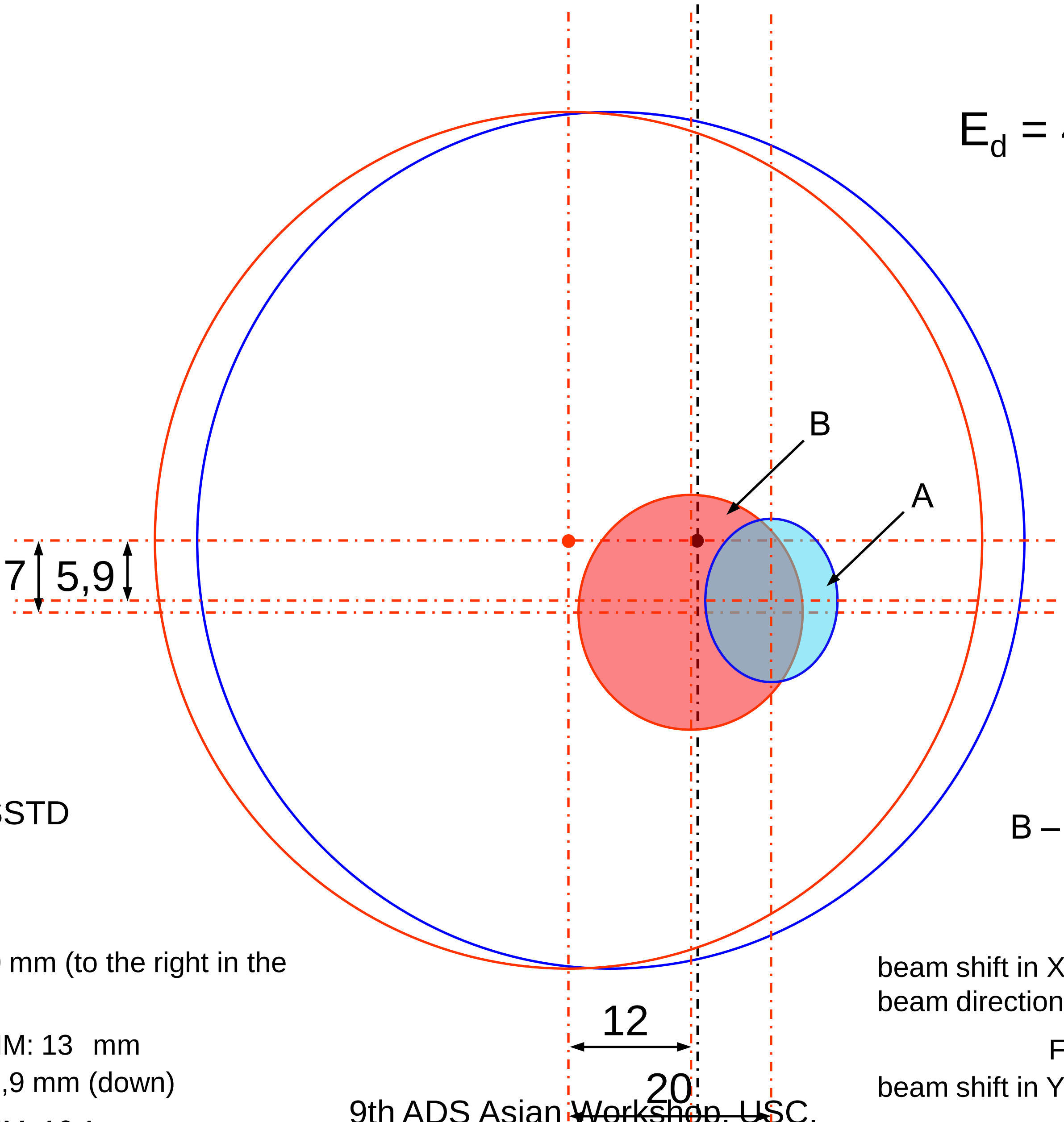
FWHM: 20 mm

beam shift in Y: - 5 mm (down)

FWHM: 28 mm

Beam position into input window (front view)

E_d = 4 GeV



A – SSTD

B – Activation method

beam shift in X: 20 mm (to the right in the beam direction)

FWHM: 13 mm

beam shift in Y: - 5,9 mm (down)

FWHM: 16,1 mm

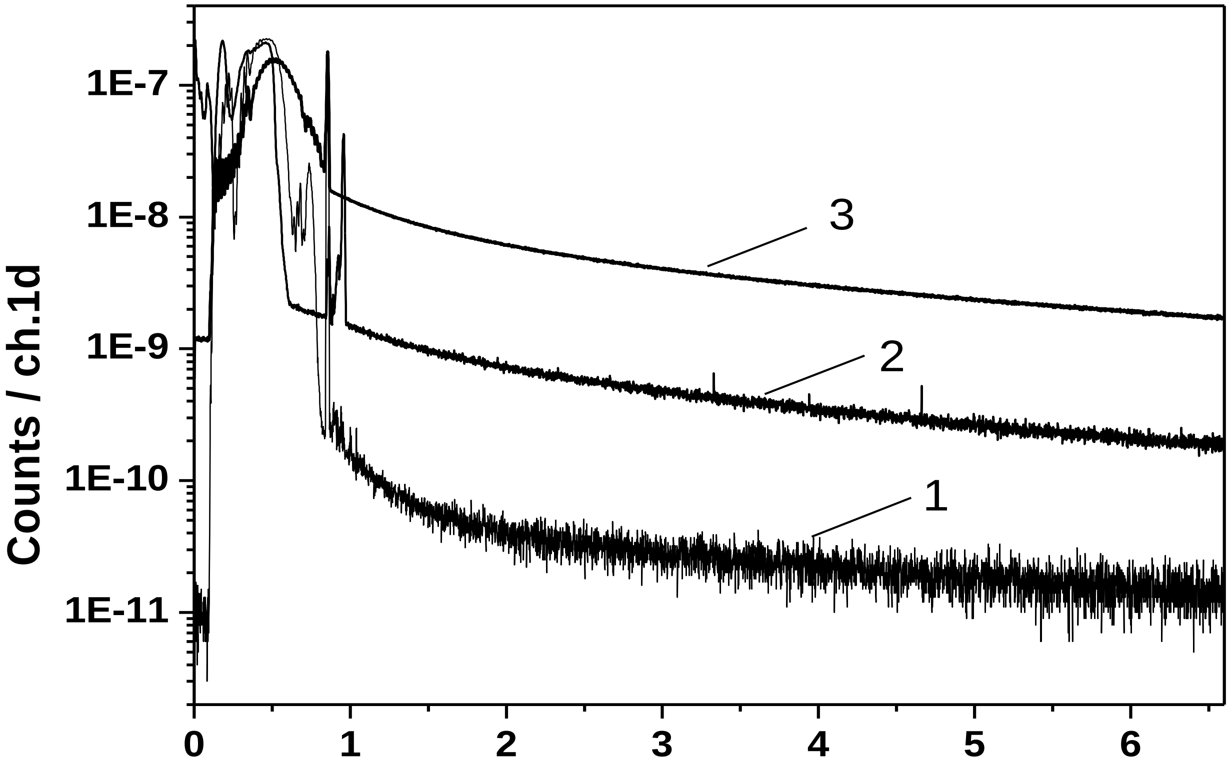
beam shift in X: 12 mm (to the right in the beam direction)

FWHM: 22 mm

beam shift in Y: - 7 mm (down)

FWHM: 23 mm

Results measured in June 2009



The time dependence of the neutron yield from the geometrically identical lead and uranium targets. 1 - (Pb+d) for E_d = 4 GeV; 2 and 3 (U+d) for E_d = 1 and 4 GeV.

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 $\boldsymbol{k_{eff}}$ 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.

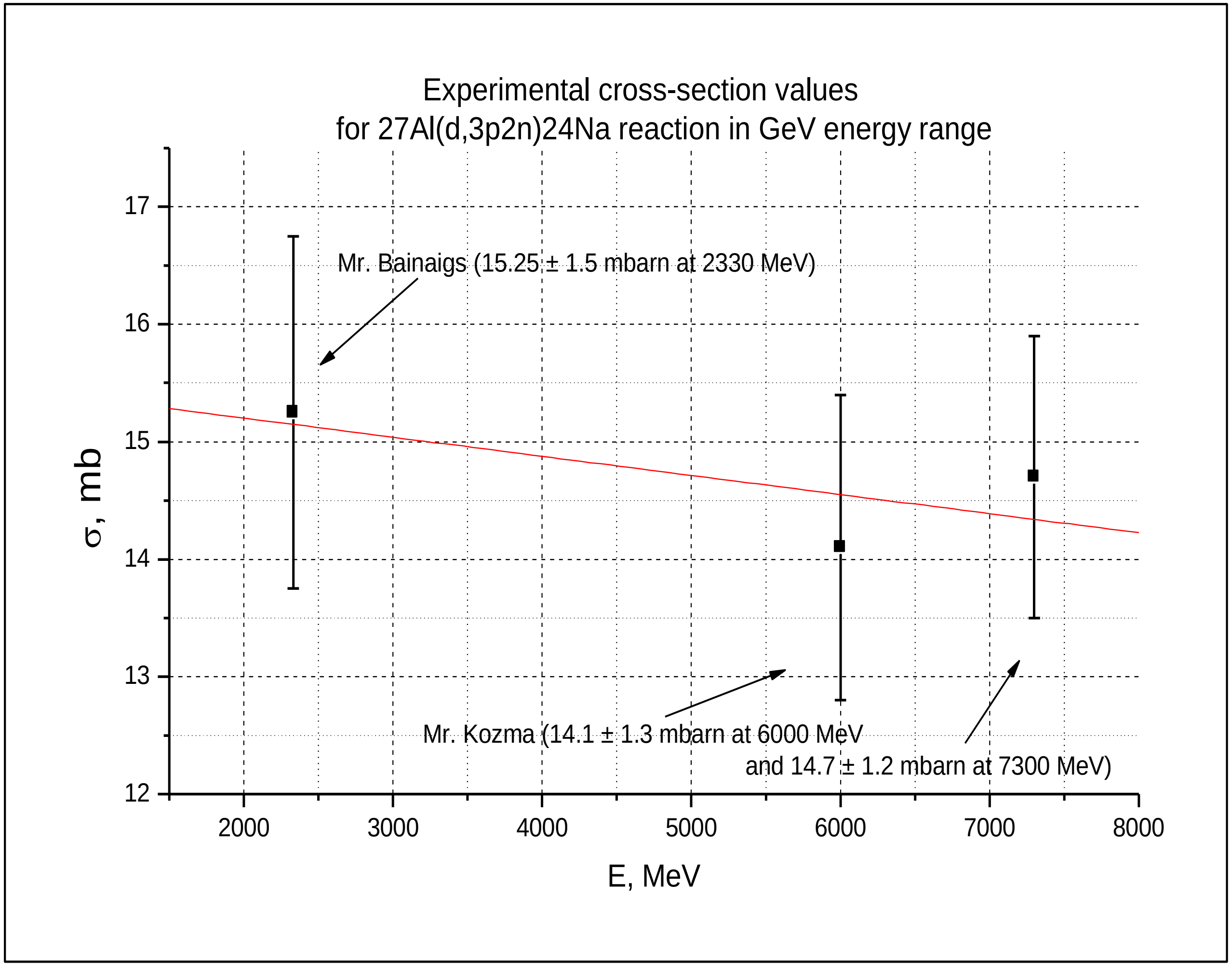
- 3500 kg 238U → 25 kg 235U → GBP !!!

- And actually proposed EA options must move on to the enriched fuel!?

Analysis of June 2009 results

- The comparison of these total neutron spectra demonstrates the pronounced contribution of prompt fission neutrons for the uranium target in the energy range (1 – 10) MeV
- Role of these neutrons is more important for the central zone of the target than for peripheral regions of the target
- This effect becomes more pronounced with increasing incident deuteron energy

Calibration of monitors



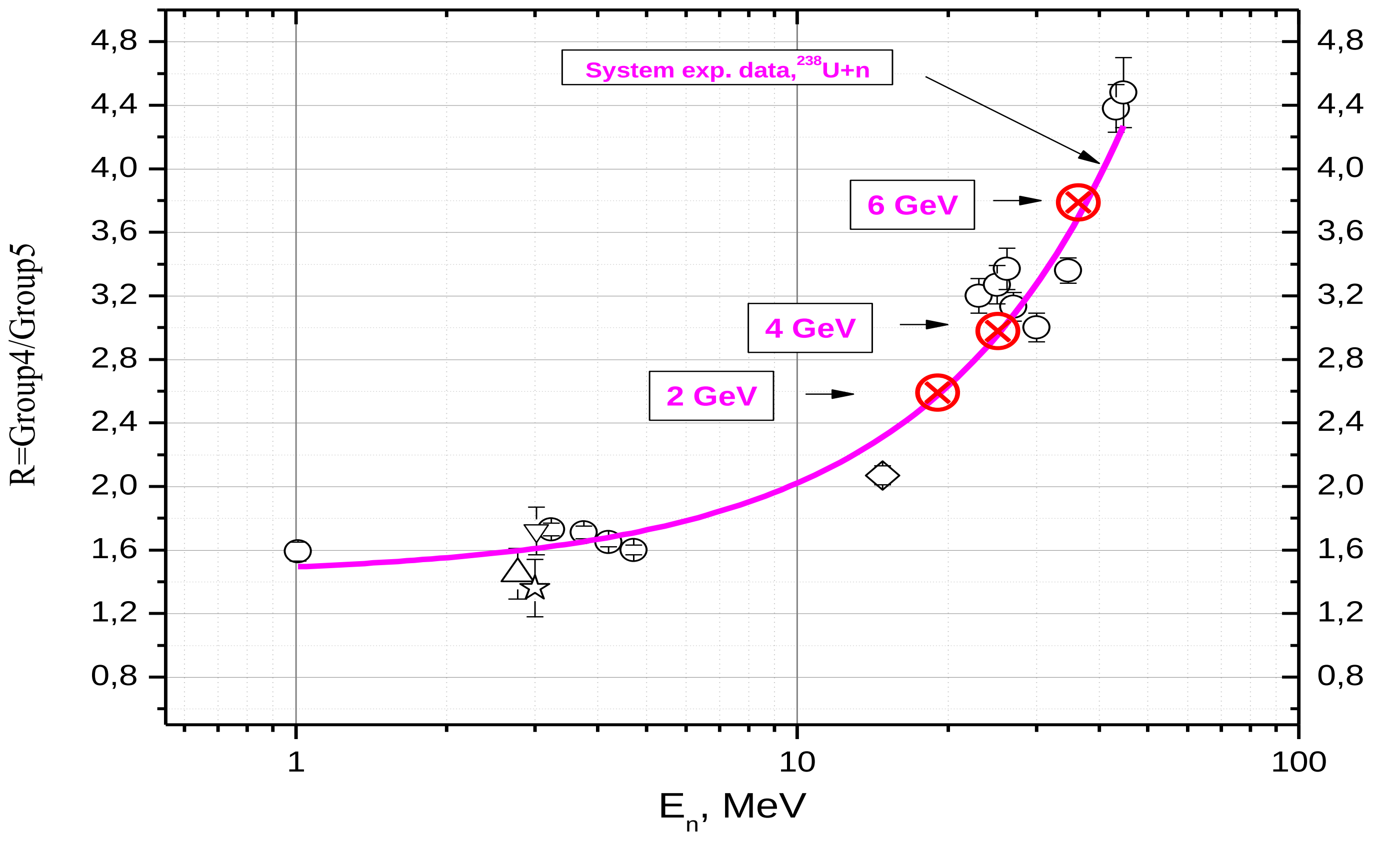
Results&Analysis - *Gamma activity method*

(numbers per one deuteron)

Ed	2 GeV	4 GeV	6 GeV
^{239}Pu production	17 1,7	30 3,0	45 4,5
^{238}U(n,f)	21 3,6	36 3,6	54 5,4

Results&analysis

Comparison of neutron energy dependence of the weight ratios of 5-th to (4+3-th) DN groups from ^{238}**U**(n,f)-reaction and similar values extracted from the DN time spectra measured in March 2011



Rates *I* of $^{47}Ti(n,p)^{47}Sc$ reaction

(at Z = 27 cm, second gap) ***(March 2011 run)***

E_d	R=4 cm		R=12 cm		R=17,5 cm (*Quinta surface*)	
	I, 1/d $\cdot 10^{-27}$	*I*, 1/d / GeV $\cdot 10^{-27}$	*I*, 1/d $\cdot 10^{-27}$	*I*, 1/d / GeV $\cdot 10^{-27}$	*I*, 1/d $\cdot 10^{-27}$	*I*, 1/d / GeV $\cdot 10^{-27}$
2 *GeV* $\cdot R^2$	16,8 268.8	8,40 134.4	2,94 423.4	1,47 211.7	0,79 241.9	0,40 122.5
4 *GeV* $\cdot R^2$	37,4 598.4	9,30 148.8	5,49 790.6	1,37 197.3	1,36 416.5	0,34 104.1
6 *GeV* $\cdot R^2$	44,7 715.2	7,50 120	7,16 1031	1,19 171.4	2,30 704.4	0,38 116.4

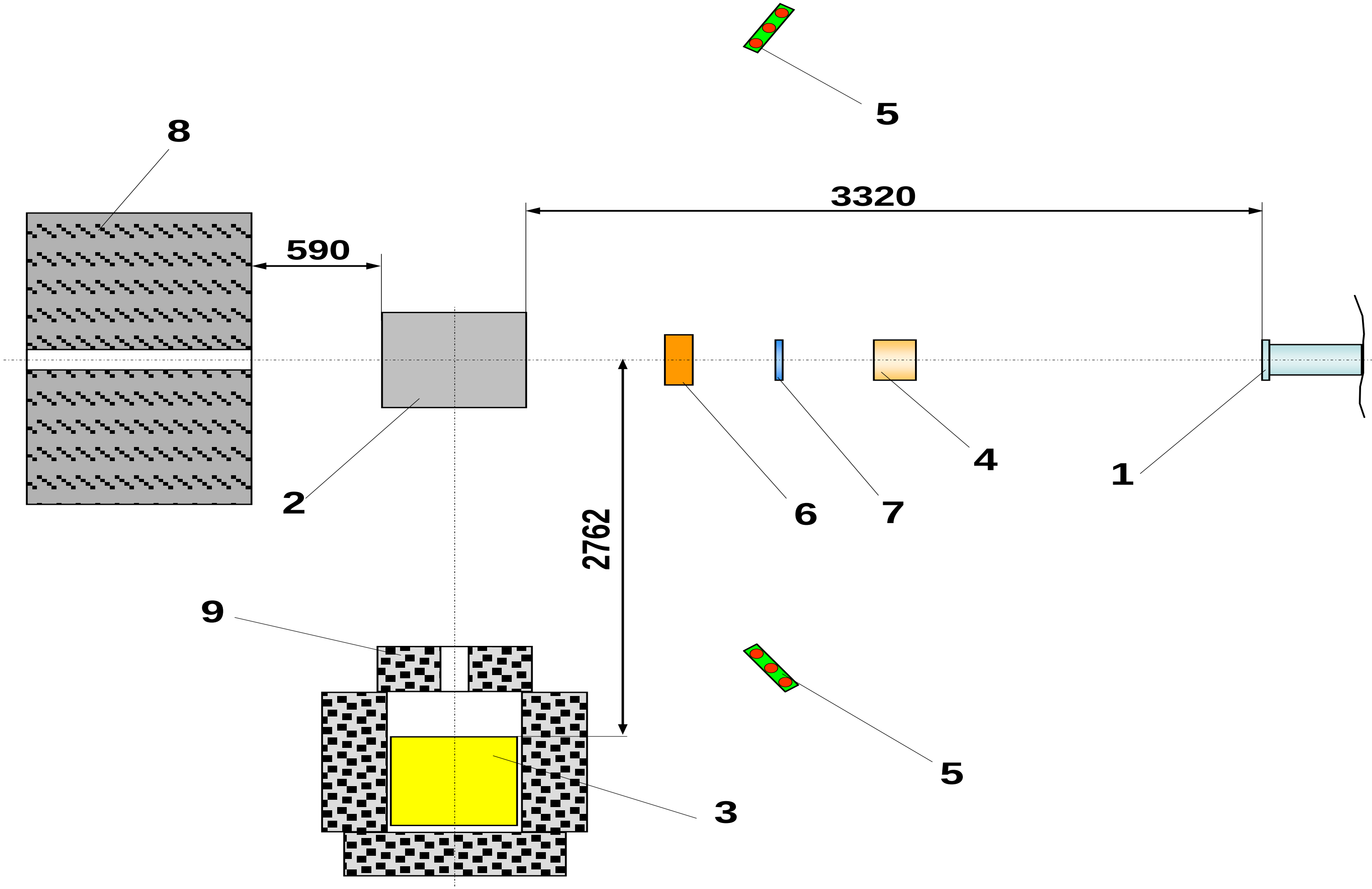
Rates *I* of ^{211}Bi(n,8n)^{204}Bi reaction, E_{th}=54.3 MeV

(at Z = 27 cm, second gap) ***(March 2011 run)***

E_d	R=4 cm		R=12 cm	
	I, 1/d •10^{-28}	*I*, 1/d / GeV • 10^{-28}	*I*, 1/d • 10^{-28}	*I*, 1/d / GeV • 10^{-28}
2 *GeV* • R^2	7.9 0.3 126 5	- 61 2.5	1,1 0.05 155 7	- 77 3.6
4 *GeV* • R^2	15 0.55 243 9	- 61 2.2	5,49 790.6	- 81 3.6
6 *GeV* • R^2	17 0.56 264 9	- 44 1.5	2.3 0.09 330 12	- 55 2

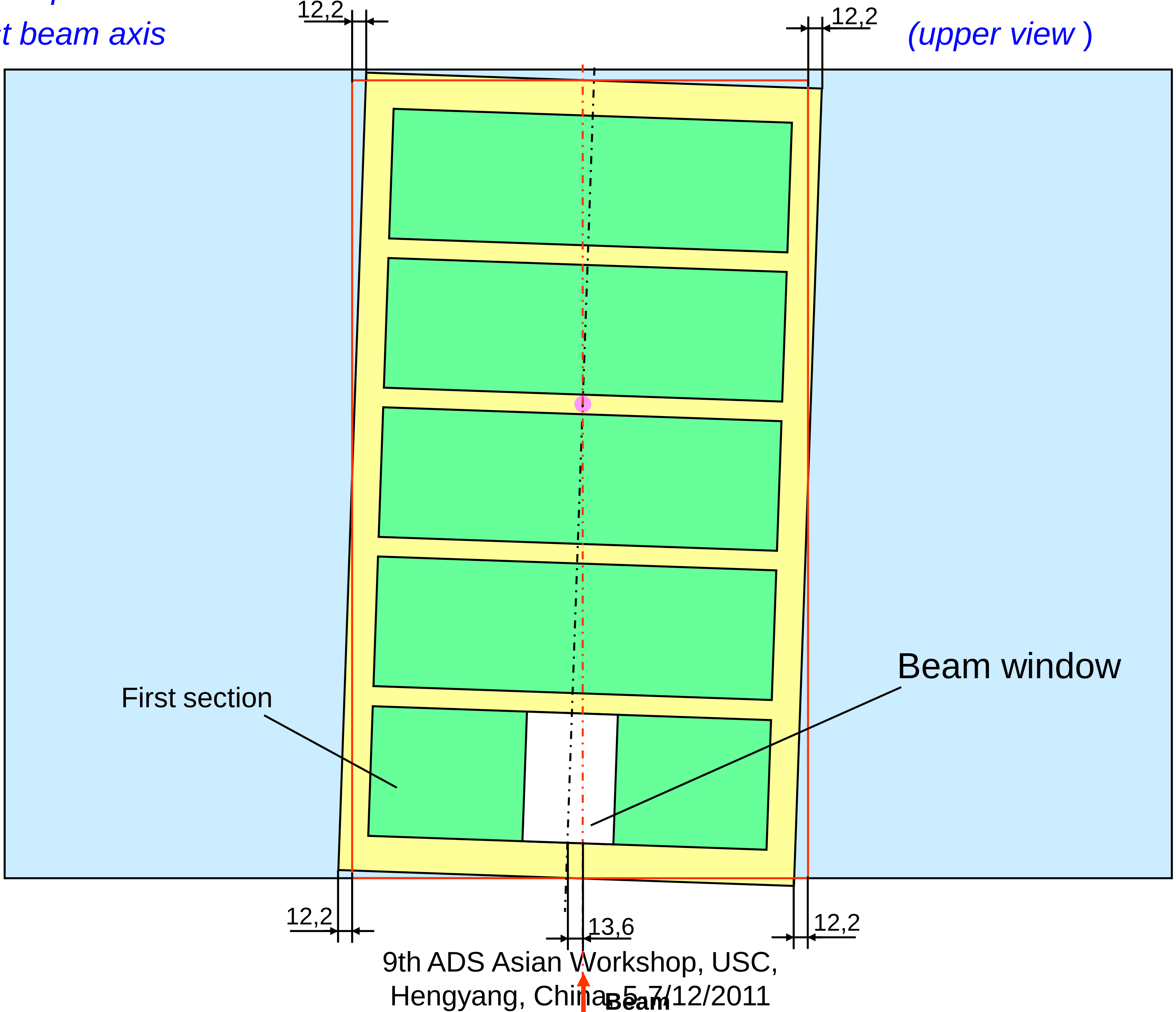
Results&Analysis

Layout of experiment performed in June 2009



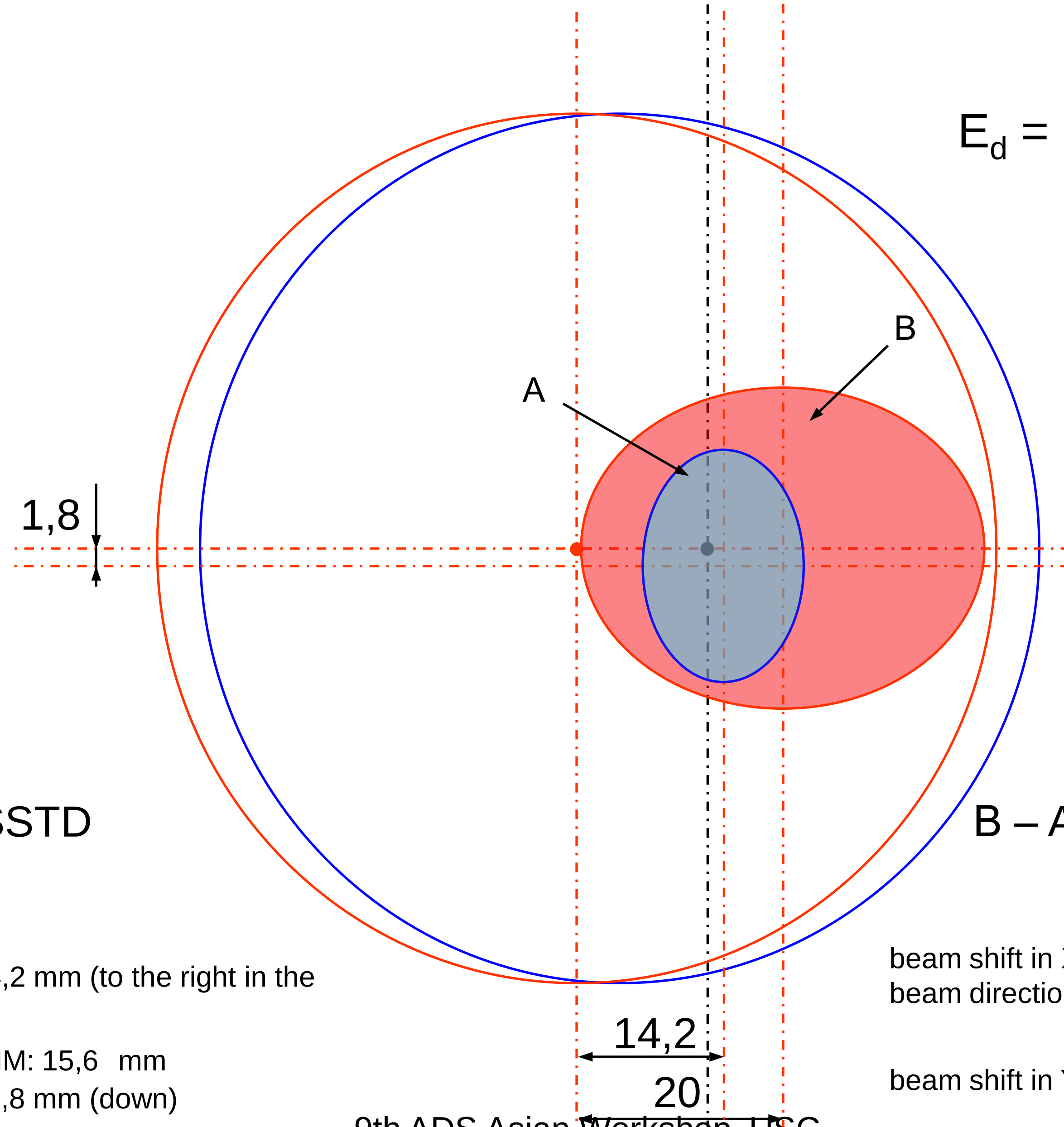
Quinta displacement against beam axis

(upper view)



Beam position into input window (front view)

E_d = 6 GeV



A – SSTD

B – Activation method

beam shift in X: 14,2 mm (to the right in the beam direction)

FWHM: 15,6 mm

beam shift in Y: - 1,8 mm (down)

FWHM: 22,4 mm

beam shift in X: 20 mm (to the right in the beam direction)

FWHM: 39 mm

beam shift in Y: - 1 mm (down)

FWHM: 31 mm