PROJECT:

Study of deep subcritical electro-nuclear systems and feasibility of their application for energy production and radioactive waste transmutation.

SYMBOL OF THE PROJECT OR COLLABORATION
E&T – RAW (Energy and Transmutation RAW)
THE THEME CODE NUMBER
1089/2011–2013

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21 June 2010 Dubna

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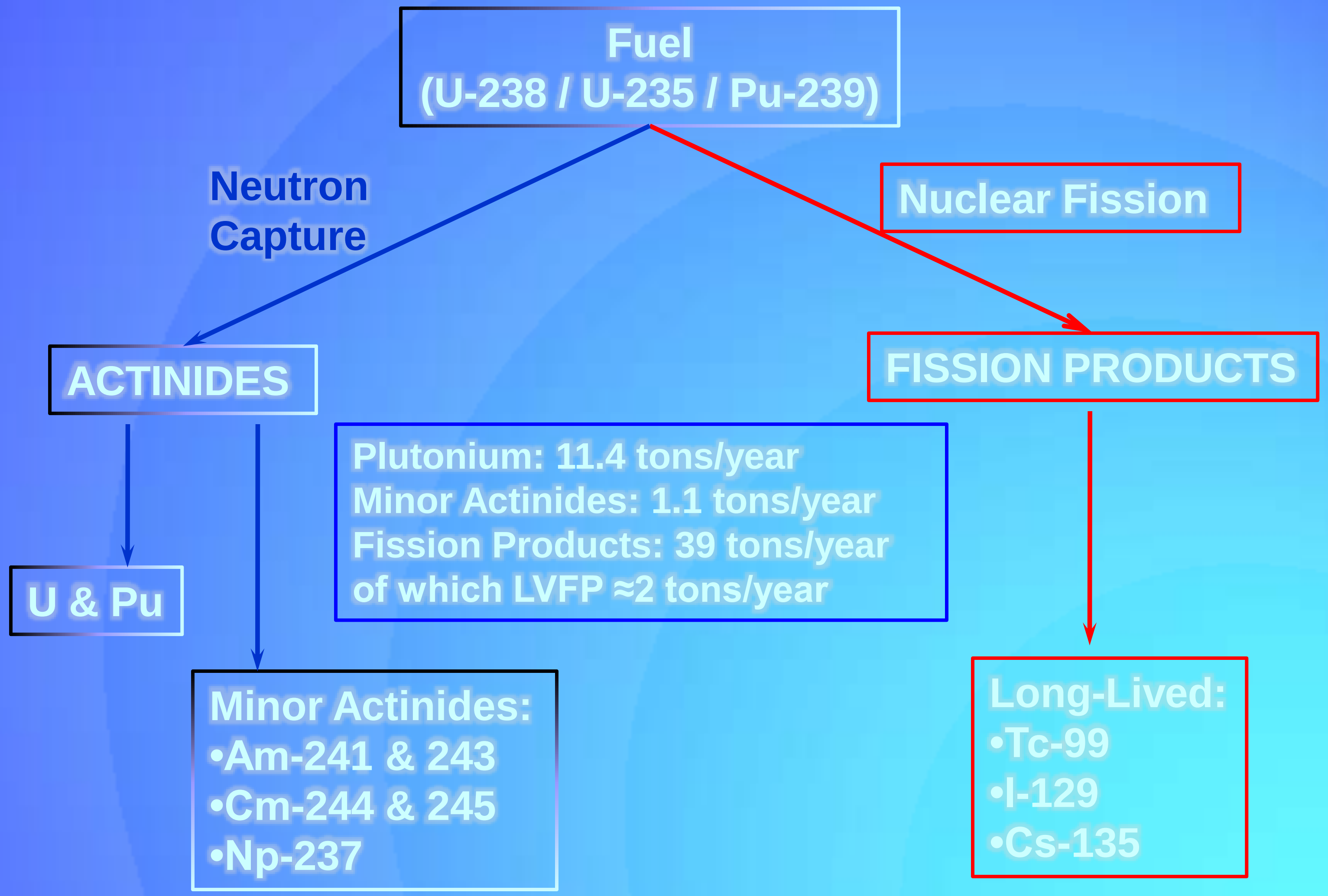
Burning of actinides by nuclear reactors:



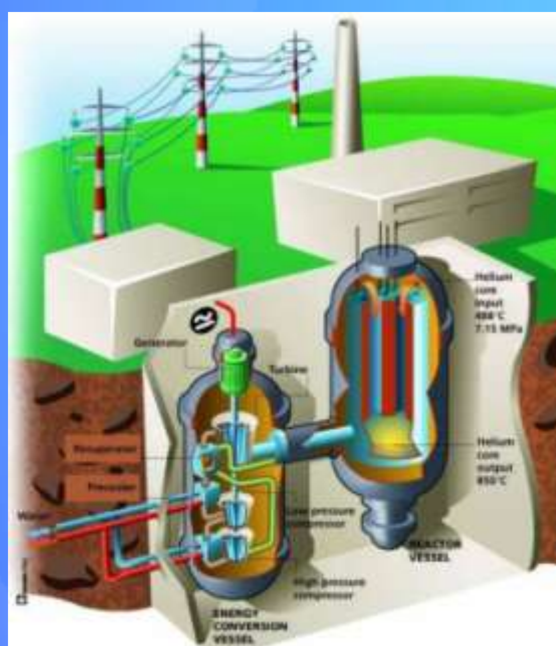
In 1999: US 666 TWh, France 395 TWh, WORLD 2393 TWh

Radiotoxic Inventory

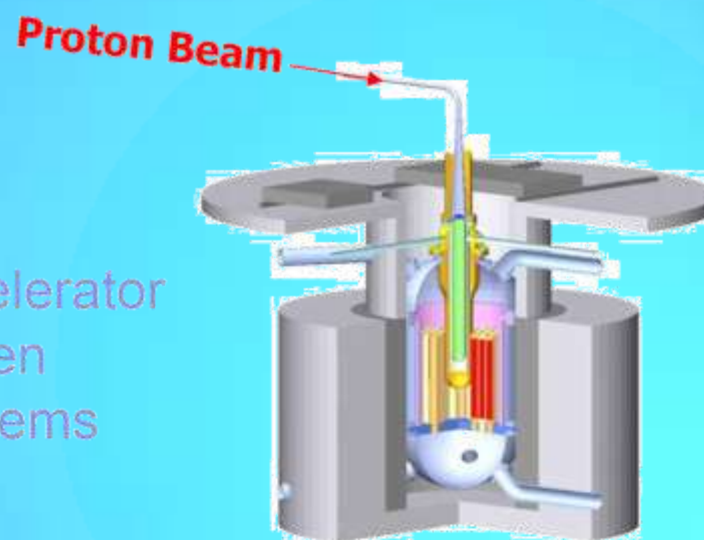
Transmutation with present technology

Innovative Concepts

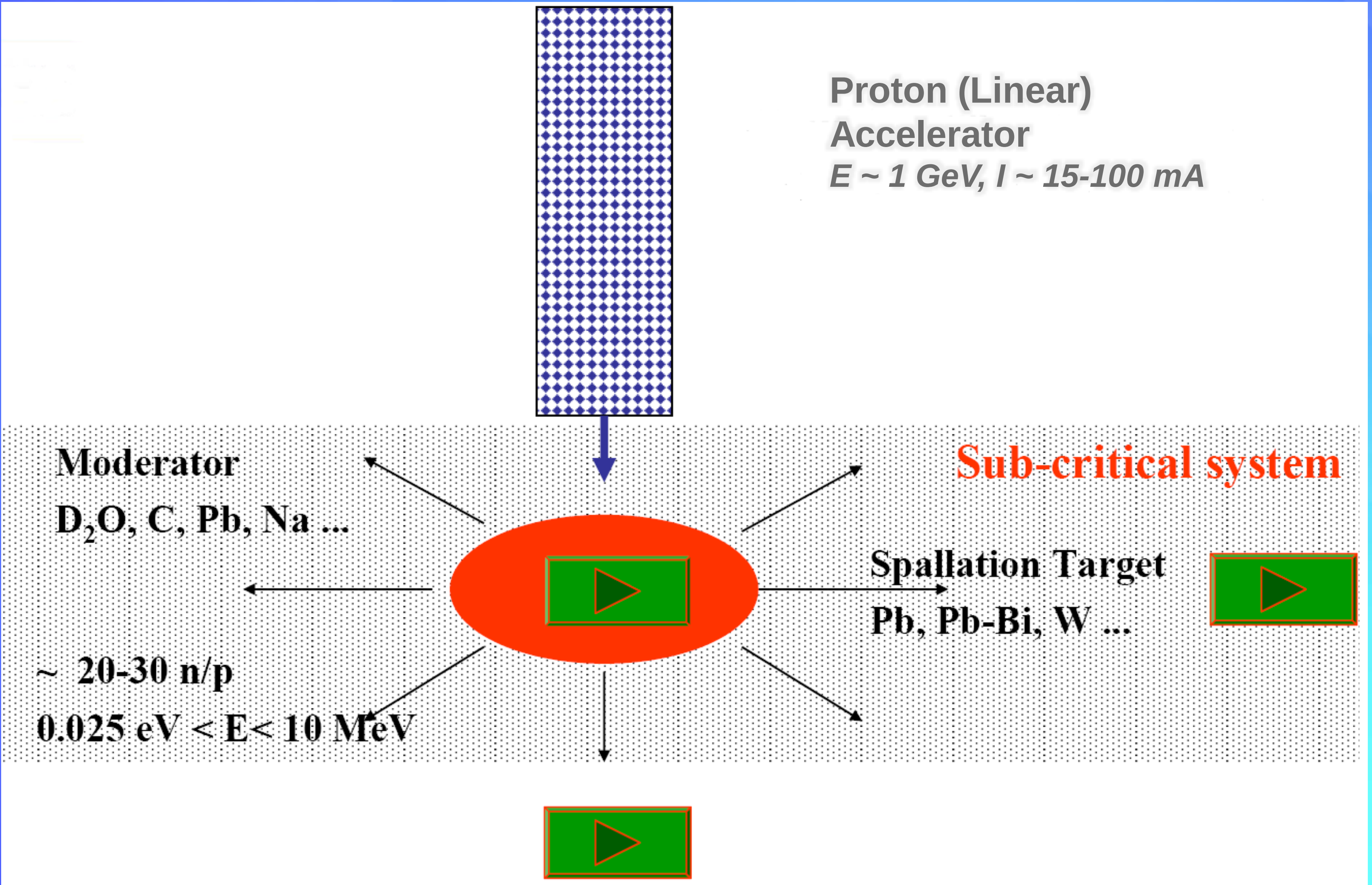
Innovative Gene IV Reactors



Accelerator Driven Systems



Accelerator Driven Systems



Results of the ^{241}Am Incineration Experiment at ILL-Grenoble

19 days irradiation in a thermal neutron flux of 5.6 ·1014n/s/cm2:

TRANSMUTATION RATE: (46.4 ± 4.5)%

of the initial ^{241}Am, of which

(19 ± 7)% was incinerated by nuclear fission

^{241}Am (n, γ) branching ratio : 0.914 ±0.007

^{241}Am (n, γ) = (696 ±48) barns

^{242gs}Am (n, γ) = (330 ±50) barns

G. Fioni et al., Nucl. Phys. A 693 (2001) 546-564

Introduction.

The physical aspects of electro-nuclear energy production method are actively studied today in many scientific centers all over the world: USA, Germany, France, Sweden, Switzerland, Japan, Russia, Belarus, China, India etc. Most activities are concentrated on the classical electro-nuclear systems – Accelerator Driven Systems (ADS) – based on spallation neutron generation, with a spectrum harder than that of fission neutrons, by protons with an energy of about 1 GeV in a high-Z target. These neutrons can also be used for generating nuclear energy in the active zone having criticality of 0,94-0,98 and surrounding the target.

The large national projects devoted to the creation of industrial ADS demonstration prototypes are implemented in Japan (JPARC) [1], USA (RACE) [2], the joint European project EUROTRNS is carried out [3].

The main advantage of electro-nuclear technology, as compared to conventional reactor technologies, is that subcritical active core and external neutron source (accelerator and neutron-producing target) are used. This advantage doesn't provides only intrinsic safety of the system but also makes it possible to obtain high fluxes of high energy neutrons independent of fission neutrons of the subcritical assembly material. The high-energy neutrons are an ideal tool to induce fission in most trans-uranium isotopes and thus transmute most of the dangerous radioactive waste from nuclear power production and other sources.

“ E & T RAW ” (“ Energy and Transmutation of Radioactive Wastes ”)

Motivation of the project

Physical substantiation for investigation of new schemes of electronuclear power production and transmutation of long-lived radioactive wastes based on nuclear relativistic technologies is presented. “E & T - RAW” (“Energy and Transmutation of Radioactive Wastes”) is aimed at complex study of interaction of relativistic beams of Nuclotron-M with energies up to 10 GeV in quasi-infinite targets.

Feasibility of application of natural/depleted uranium or thorium without the use of uranium-235, as well as utilization of spent fuel elements of atomic power plants is demonstrated based on analysis of results of known experiments, numerical, and theoretical works.

“E & T - RAW” project will provide fundamentally new data and numerical methods necessary for design of demonstration experimental-industrial setups based on the proposed scheme.

The results on Plutonium yield and number of fission events per proton in quasi infinite targets with a mass of about 3,5 t made from depleted and natural uranium under 660 MeV proton irradiation at synchrotron DLNP JINR, obtained by R.G.Vasilkov and V.I.Goldansky et al. [4], are presented in Table 1.

These targets are equivalent to those with a mass of 6,0 t due to non-central beam injection.

The general view of a part of uranium target in a lead shielding is shown in Fig.1. The system of channels for detector and beam input are shown.

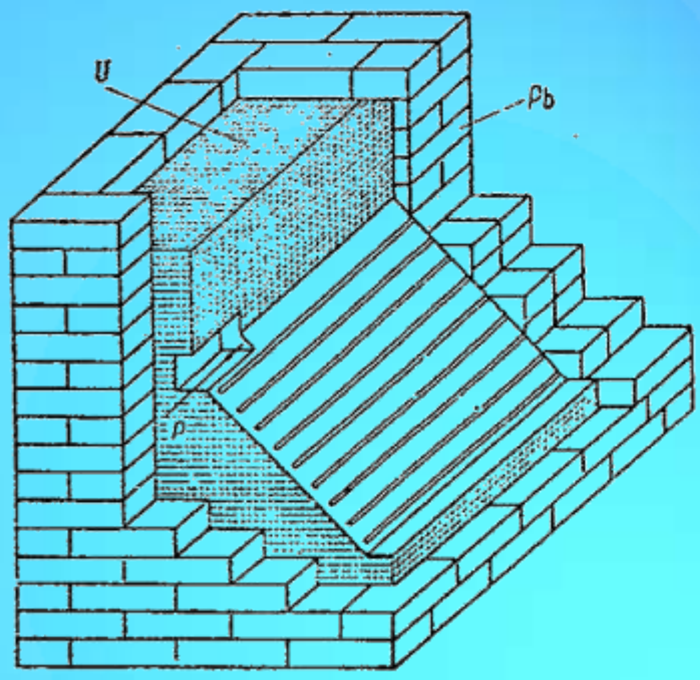
Plutonium yield and number of fission events in targets per one 660 MeV proton [4]

Table 1

	Plutonium yield (number of nuclei)	Number of fissions
Depleted uranium	38±4	13,7±1,2
Natural uranium	46±4	18,5±1,7

Schematic cut-open view in the target containing 3.5 t of uranium inside a lead shield. The opening “p” on the left side is the beam entrance and long holes traversing the uranium block are experimental openings for detectors

The energy release was on average ~3950 MeV per proton in depleted Uraniun and ~4900MeV per proton in natural uranium. Therefore the power amplification of the 660 MeV proton beam is ~6,0 in depleted Uraniun and ~7,4 in natural uranium for a system subcriticality of about K_{eff} ~ 0,3.



It should be noted that in the experiments of C.Rubbia and his group [4] at CERN with a large 3,6 t target from natural Uranuim the neutron spectrum in the active core was fully thermalized at a primary proton energy of 0,6 ÷ 2,75 GeV. So these experiments are the opposite extreme case to experiments [4] in which the hardest neutron spectrum was obtained. In [5] the obtained amplification coefficient was about 20 for an energy of 0,6 GeV and deeply subcritical active core, k_{eff} ~ 0,9.

Energy characteristics of neutron radiation leaving a limited Ø20×60 cm lead target depending on protons energy [10] (obtained in the complex experimental group V.I .Yurevich, executed in LHE)

Here, < E > is the average neutron energy, E_{kin} is the total kinetic energy of neutron radiation, E_p is the proton energy, and W is the energy of the proton beam spent for neutron production.

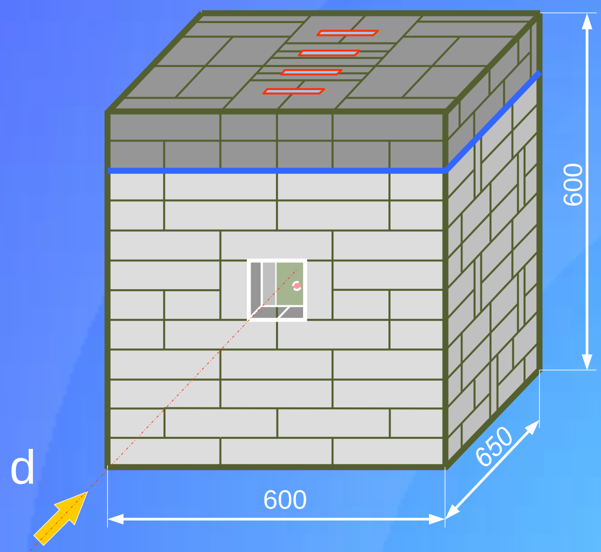
It can be seen from Table 2 that the average neutron energy, the kinetic neutron energy E_{kin}, and the proton beam energy W spent for neutron production increase with increasing beam energy. The fraction of primary proton energy spent for neutron production for a proton energy of ~ 660 MeV is ~ 20 % according to our estimates of data [4]. It follows from [10] that for $E_p \approx 1$ GeV it increases to 38,2%, reaching almost 46 % for 3,65 GeV. The extrapolation of this dependence to $E_p = 10$ GeV results in the following estimate of this fraction: ~ 60% (see [11] for details). Note that the growth of the ratio W/E_p is to a large extent connected with the growth of meson production with increasing incident proton energy.

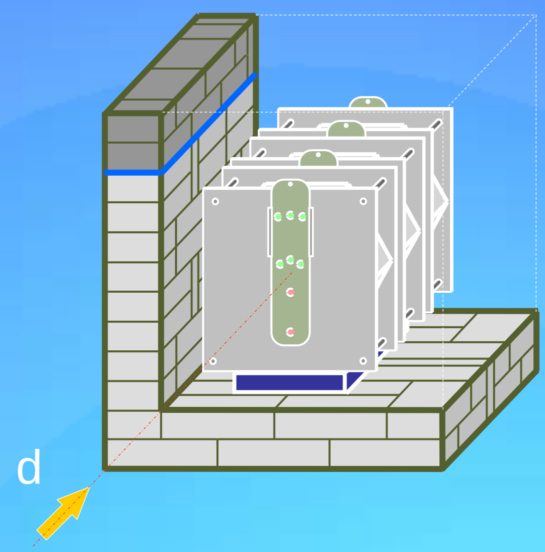
E_p, GeV	< E >, MeV	E_{kin}, MeV	E_{kin} / E_p, %	W, MeV	W / E_p, %
0,994	8,82	213	21,3	382	38,2
2,0	11,6	513	25,6	822	41,1
3,65	13,7	1106	30,3	1670	45,6

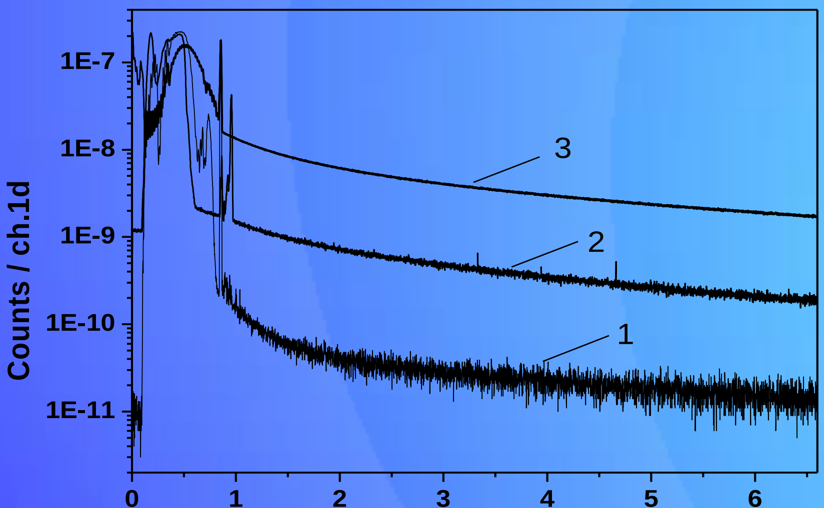
Estimates power amplification coefficient for proton beam incident on quasi-infinite target from metallic natural uranium.

E_p, GeV	Initial K_{PA}	Equilibrium K_{PA}
0,66	7,4	40
1,0	12,0	70
10,0	22,0	130

Methodological experiments conducted in 2009 on the initiative of the JINR & Center of Physical and Technical Projects “Atomenergomash” on the "E + T" (Quinta)





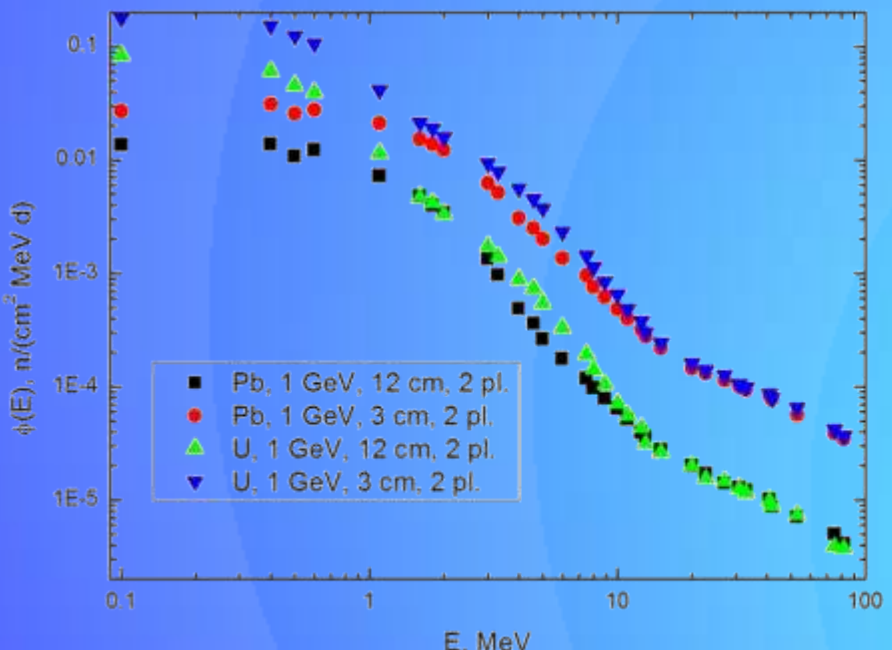


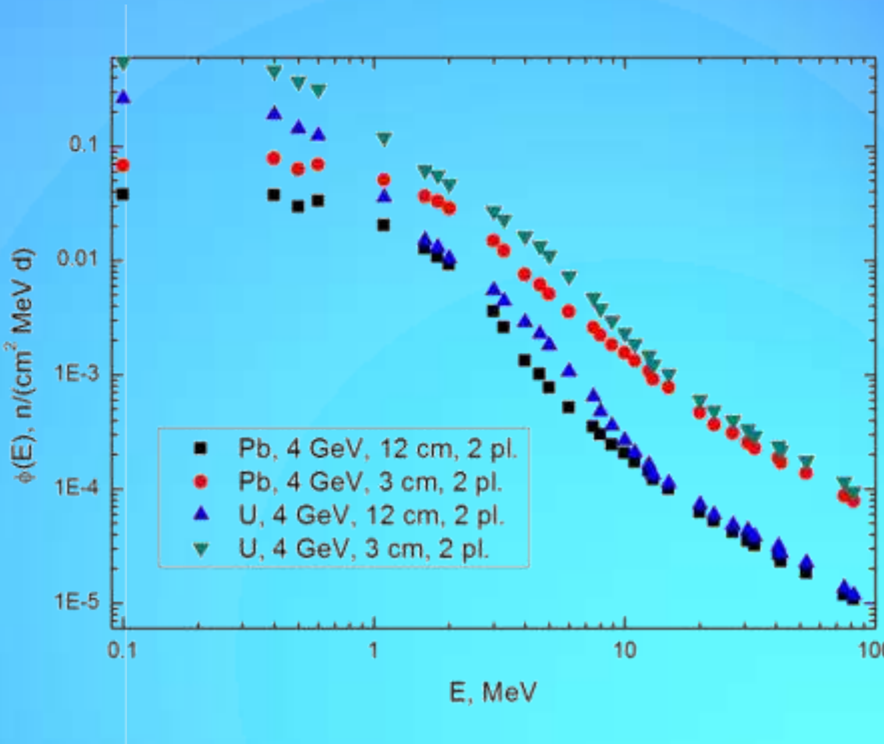
Time dependence of neutron yield from a geometrically identical target assemblies of lead and natural uranium (uranium mass of ~ 315 kg) irradiated with a deuteron energy of Ed = 1 and 4 GeV
1 - (Pb + d) for Ed = 4 GeV;
2 and 3 (U + d) for Ed = 1 and 4 GeV, accordingly.

With increasing energy of the deuteron from 1 to 4 GeV, the number of divisions and the energy release increases to ~ 8-9 times. In this case the gain of the beam power in natural uranium is increased ~ 2 times.

The energy spectra of neutrons measured in a geometrically identical uranium and lead targets at a distance of 11 cm from the entrance of the beam at a radius of 3 cm and 12 cm at a deuteron energy of 1 GeV and 4 GeV [25].

Pb -● - 3cm, ■ - 12 cm; U - ▼ - 3 cm, ▲ - 12 cm.





Average total Y and partial Y_{20} (for neutron energies higher than 20 MeV) neutron yields for long lead target (Ø 20 × 60 cm) irradiated by proton beams in comparison with calculated yields

E_p, ГэВ	Experiment (n/p)		MCNPX: INCL4+ABLA		MCNPX: BERTINI		Fluka 2008.3	
	Y	Y_{20}	Y	Y_{20}	Y	Y_{20}	Y	Y_{20}
0.994 **C/E**	24.1±2.9	2.1±0.4	23.7(2%) **0,983**	1.62(2%) **0,771**	24.1 **1,000**	1.45 **0,690**	24.4 **1,012**	1.40 **0,667**
2.0 **C/E**	44.4±5.3	4.7±0.8	46.1(2%) **1,038**	3.29(3%) **0,700**	49.7 **1,119**	3.02 **0,643**	48.7 **1,097**	3.21 **0,683**
2.55 **C/E**	63.5±7.6	5.8±1.9	50.5(1%) **0,795**	3.99(1%) **0,688**	62.5 **0,984**	3.88 **0,669**	60.1 **0,946**	4.10 **0,707**
3.17 **C/E**	71.6±8.6	6.8±1.2	57.9(1%) **0,809**	4.66(1%) **0,685**	76.3 **1,066**	4.89 **0,719**	72.14 **1,008**	5.03 **0,740**
3.65 **C/E**	80.6±9.7	8.5±1.5	62.6(1%) **0,777**	5.14(1%) **0,605**	86.8 **1,077**	5.5 **0,647**	80.2 **0,995**	5.67 **0,667**

The results of the estimates and the experiments show that in the scheme NRT we have the opportunity to carry out with a hard neutron spectrum, having a large enough component of the far abroad fission spectrum throughout its life cycle.

Hard neutron spectrum in the volume of active zone RAW-system ensures efficient treatment all threshold of actinides.

Moreover, for all treatment actinides there is shift of the elemental composition of the fission fragments of nuclei in the isobaric chains in the direction of short-lived or stable neutron-deficient nuclei. For example, instead of generation a long-lived ^{129}I, formed stable isotope ^{129}Xe.

In addition, this spectrum provides an intensive course of reactions of type (n, xn), which leads to a shift of the integral of the fission products in the direction of short-lived neutron-deficient nuclei. For example, as a result of reactions (n, 2n), (n, 3n) one of the most dangerous isotopes from the spent fuel - a long-lived ^{90}Sr - processed (transmuted) in the short-lived ^{89}Sr or stable ^{88}Sr.

Finally, the tightening of the neutron spectrum leads to an additional suppression of the neutron capture reaction and significantly reduced operating time more long-lived radioactive materials.

OBJECTIVES

The project objectives are:

1. To study the possibilities and specific features of using hard neutron spectrum of deeply subcritical quasi-infinite uranium target irradiated by 1-10 GeV protons and deuterons for implementation of a new scheme of electro-nuclear method for energy production and transmutation of long-lived radioactive wastes – nuclear relativistic technology (RNT).
2. To improve existing theoretical models and verify computer codes for guaranteeing precise simulation of electro-nuclear systems for RNT experimental-industrial prototype design.

PROGRAM

A set of integral macro- and micro-experiments in combination with necessary theoretical calculations will be carried out during the project realization.

The reliability and completeness of experimental data are provided by application of independent mutually verifying systems for measurement of physical processes in a quasi-infinite uranium target under the action of relativistic protons and deuterons.

The project schedule includes experiments in the framework of the physical program at the facilities are: “Energy + Transmutation” and “Gamma-3”. It is planned to develop and test measurement systems for experiments with the new uranium target in parallel with these experiments.

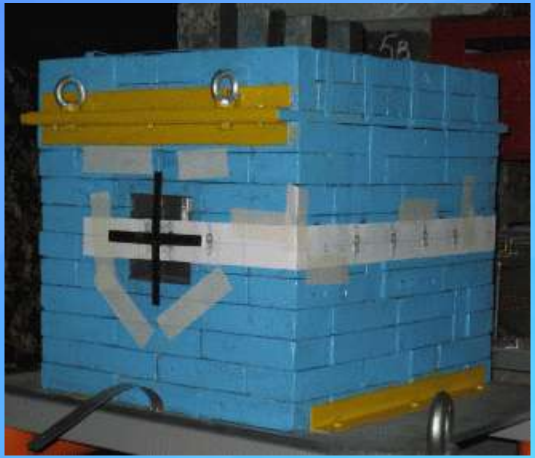
The main experiments of the project are planned to be performed on the basis of the new flexible target diagnostic complex “EZHIK” which represents a quasi-infinite target from metallic uranium equipped by measurement channels whose position and design should provide optimal execution of the research program.

" E & T RAW " (" Energy and Transmutation of Radioactive Wastes ")

Experimental Setup

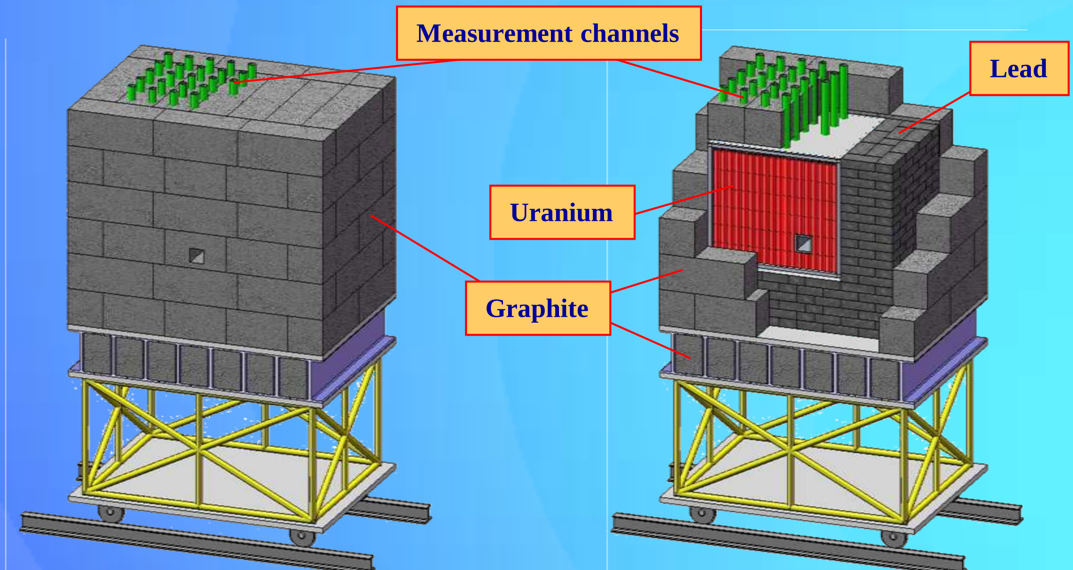
"Energy + Transmutation"

"Energy + Transmutation" (Quinta)



"Gamma-3"

"EZHIK-U"

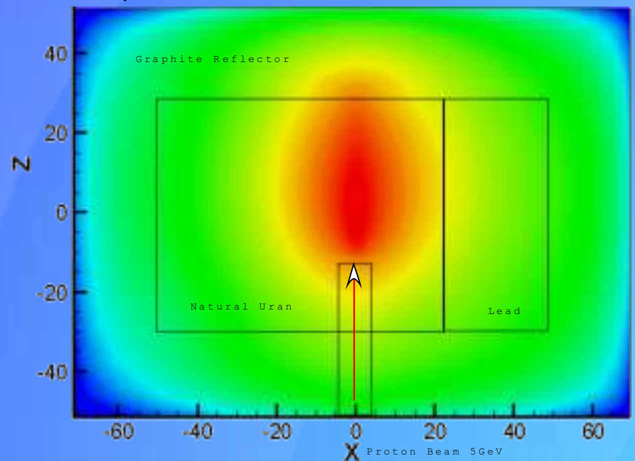


MCNPX 2.5 code simulated Spatial Neutron Distribution in U and U-Pb target with the asymmetric beam input

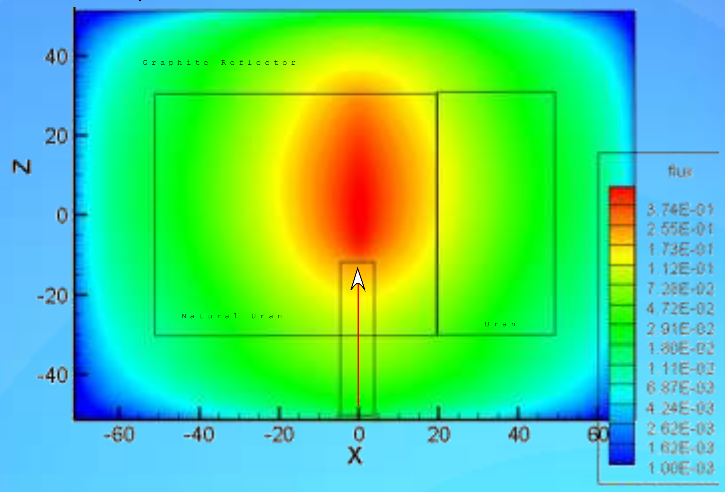
Target: uranium and lead, graphite moderator

Target: uranium, graphite moderator (lead exchanged to uranium)

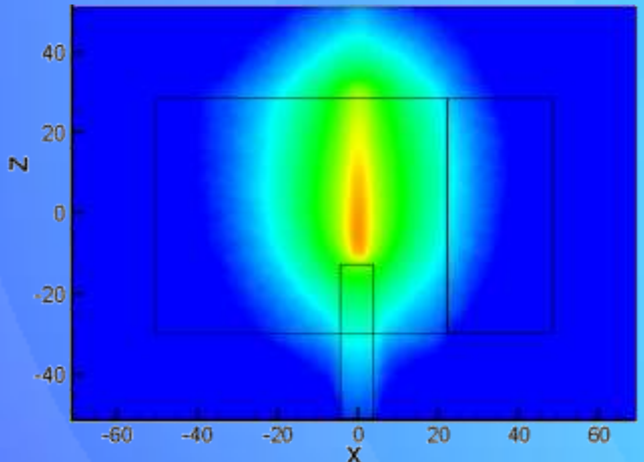
Spatial Neutron Distribution 0 – 2 МэВ



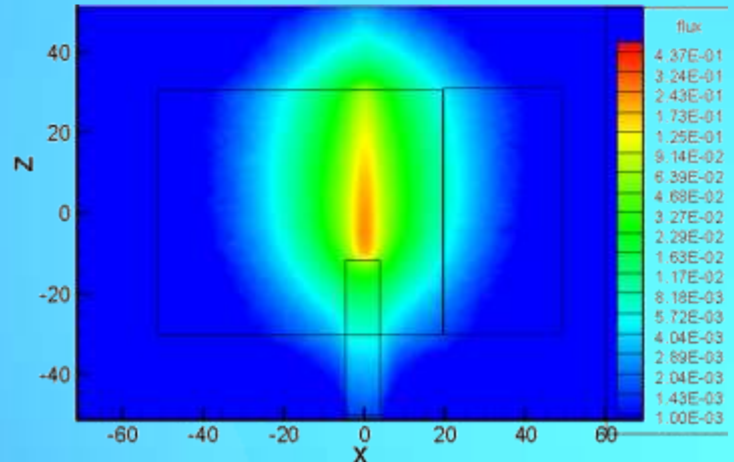
Spatial Neutron Distribution 0 – 2 МэВ



Spatial Neutron Distribution 2 – 1000 МэВ

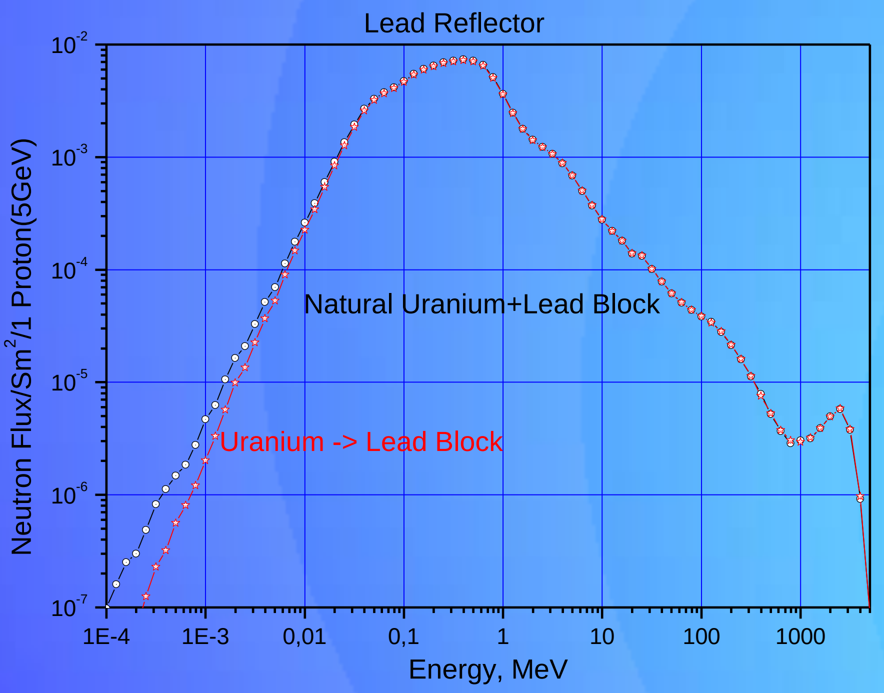


Spatial Neutron Distribution 2 – 1000 МэВ

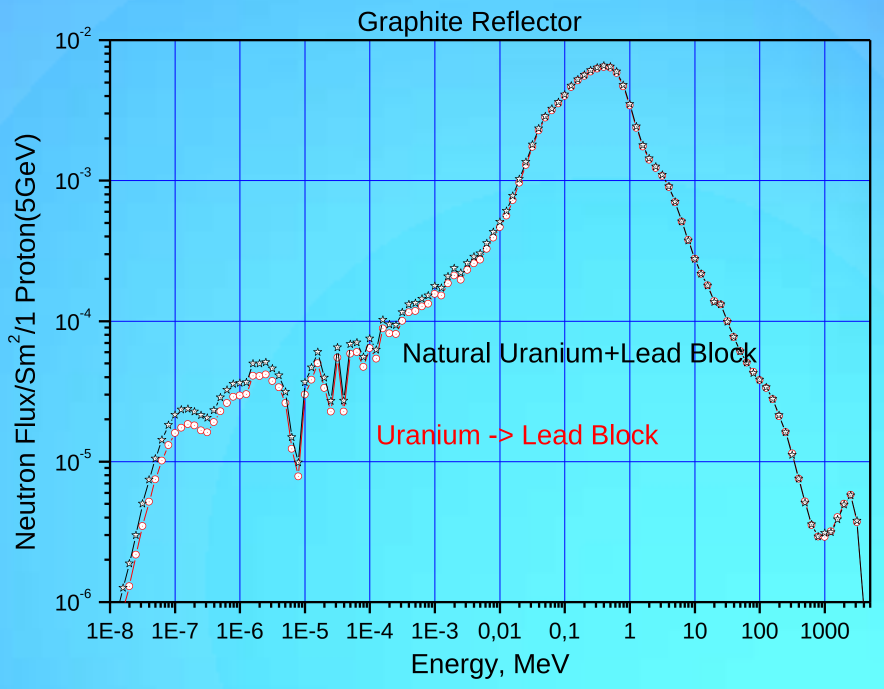


This graphics show the results of calculation of the influence of replacement of uranium by lead in most of the volume of the target «EZHIK-U» obtained using MCNPX 2.5 in the variant of Bertini cascade model for 5 GeV incident protons. The results of calculations of neutron flux densities and energies for two variants of reflectors surrounding the target, those from graphite and lead, are presented.

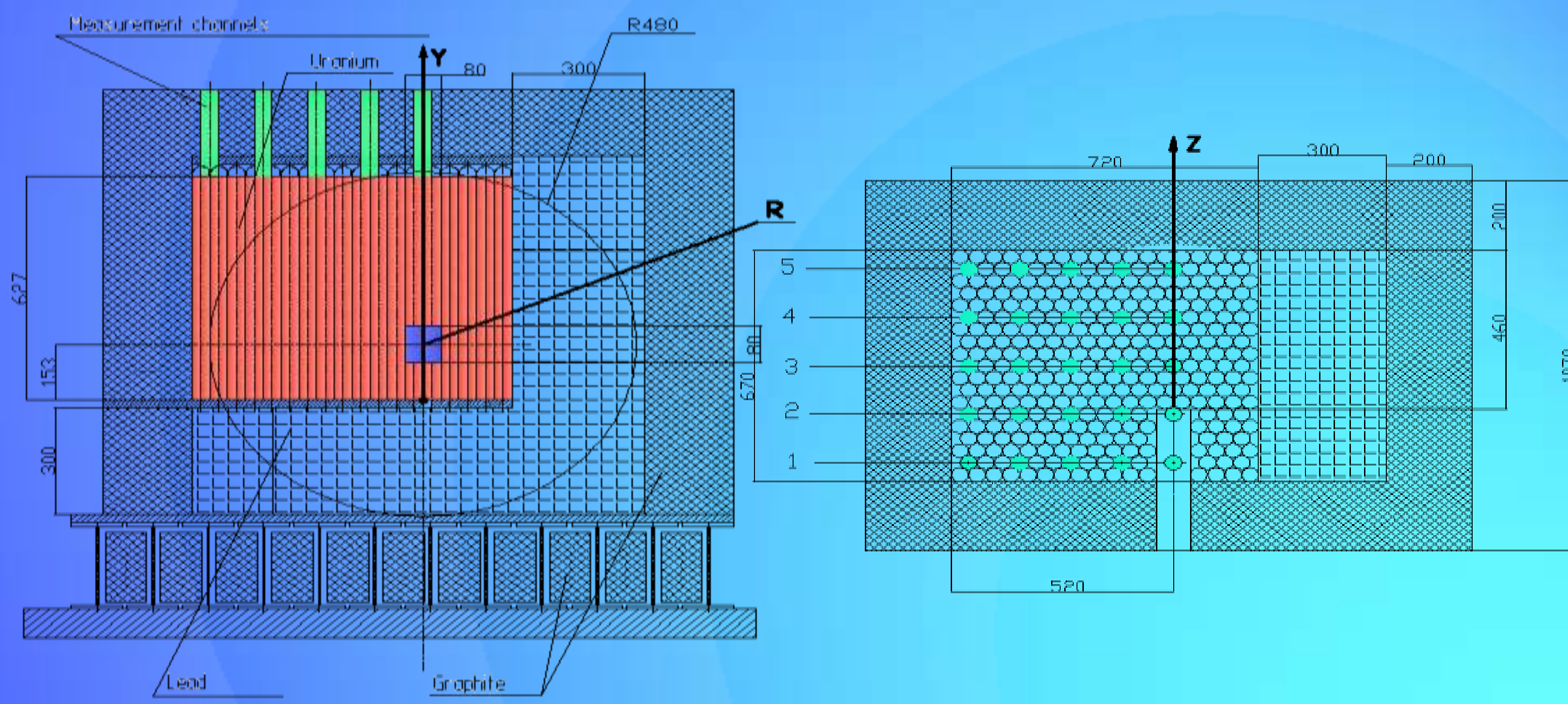
Option: uranium, lead reflector



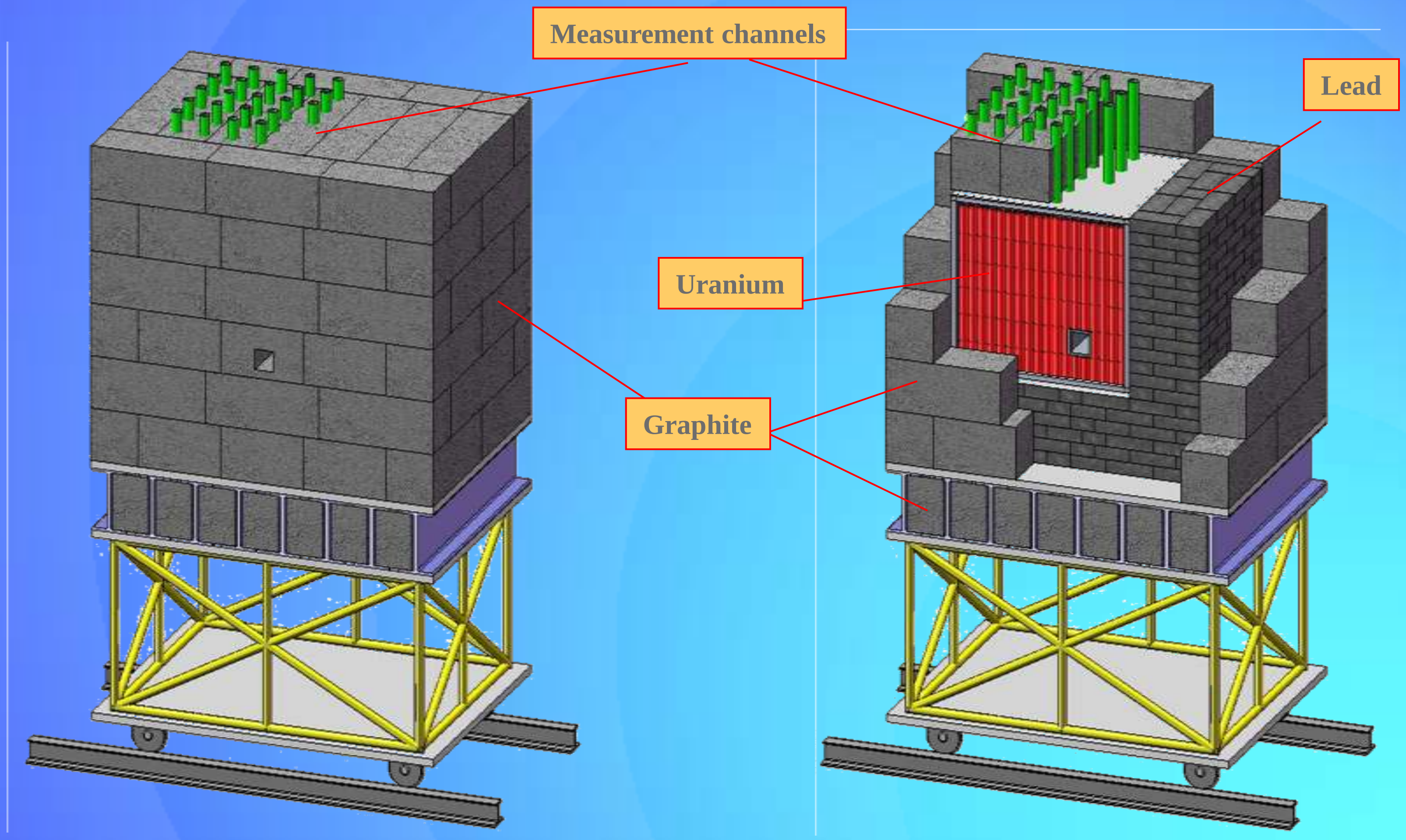
Option: uranium, graphite reflector



The main experiments of the project are planned to be performed on the basis of the new flexible target diagnostic complex “EZHIK” which represents a quasi-infinite target from metallic uranium equipped by measurement channels whose position and design should provide optimal execution of the research program.



New flexible target diagnostic complex "EZHIK"



Direction 1 ("Integrals")

The first direction includes the set of integral experiments with the targets «EZHIK-U», proton energies from 1 to 10 GeV and deuteron energies from 1 to 5 GeV/nucleon.

These experiments include:

1. study of neutron spectra at various points in the target volume in the presence and absence of graphite reflector (below, different target configurations);
2. study of spatial distributions of fission rates and transmutation cross sections of actinide fission fragments at different target configurations for determination of optimal transmutation regimes;
3. study of spatial distributions of radiative capture (n, γ) and (n,xn) reactions in samples from long-lived isotopes of spent fuel placed in measurement channels for different neutron spectra;
4. measurement of heat release distribution in the target volume depending on the target configuration and different enrichment by easily fissionable isotopes;
5. study of spatial distributions of parity between ^{239}Pu isotope accumulation and fission for determination of the value and time of achieving equilibrium concentration of this isotope for different target configurations;
6. obtaining power amplification coefficients depending on the characteristics of the neutron spectrum inside the target determined by its configuration and beam particle type and energy;
7. study of prompt and delayed neutron spectra and multiplicity depending on the target configuration, particle type and energy;
8. improvement and optimization of on-line and off-line methods for monitoring intensity, geometric characteristics, and Nuclotron beam position on the target;
9. study of desactivation rates for targets irradiated with different doses.

These studies will be accompanied by numerical and theoretical simulation in combination with activities in Direction 3 described below.

Direction 2 ("Constants")

Carrying out a complex of constant measurements with thin samples, proton energies from 0,6 to 10 GeV and deuteron energies from 1 to 5 GeV/nucleon.

It is planned to perform the series of experiments for obtaining data on energy dependence of fission cross sections of the required set of target nuclei by relativistic protons and deuterons; delayed neutron yields, and fission products.

For reliable simulation of electronuclear systems it is necessary to know the characteristics of corresponding reactions in both thin and thick (≥2000g/sm^2) targets .

Particularly, dielectric track detectors will be used to measure the cross-sections of fission reactions induced by primary and secondary particles.

This method is practically the only one that provides measurement of fission cross-sections for intensive primary and secondary particles fluxes. Track detectors with different registration thresholds provide distinguishing fission fragments from protons and neutrons, the mass spectrum of fission fragments can be also studied.

All data obtained within the second direction "Constants" should be converted into the complete nuclear data files according to the existing standards adapted for basic computer codes.

Direction 3 ("Simulation")

Improvement of physical models, constant base, and computer programs by taking into account neutron multiplicity in extended fissionable media, especially in the energy range above 10 MeV.

The task of obtaining neutron-physical characteristics of the electro-nuclear method under study applies to two physics areas: interaction of high energy beams with condensed matter and reactor physics.

An appropriate account of high energy fission channels is of great importance for calculating neutron fields and heat release in such systems, because the results obtained using existing numerical models differ greatly (several times) from very limited experimental data obtained with small targets, and for quasi-infinite fissionable matter the expected deviation is more pronounced.

The complex of theoretical and numerical activities in the field of phenomenology of multiple particle production in a quasi-infinite fissionable target irradiated by a high energy beam will be performed in the framework of the third direction ("Simulation").

The theoretical activity and simulations performed to support preliminary planning of experiments in the framework of the project and subsequent processing of results of measurements will make a reliable basis for creation and development of models, methods, and algorithms. The activity in this direction should provide reliability of simulation support for designing future prototypes of experimental-industrial RNT-setups after the proof of principle of the proposed electronuclear scheme.

Direction 4 ("Materials")

Investigation of relativistic beam impact on structural and fuel materials.

Within this direction we plan to carry out measurements of integral gas ($^{3,4}He$) production rates in interaction of relativistic beams and fast neutrons with the structural elements and the fuel. Radiation damage depending on the energy and type of primary particles will also be studied.

The activities within this direction are performed in parallel with the activities within the first and second directions. For this activity is necessary to provide minimal possible Nuclotron beam size in front of the target.

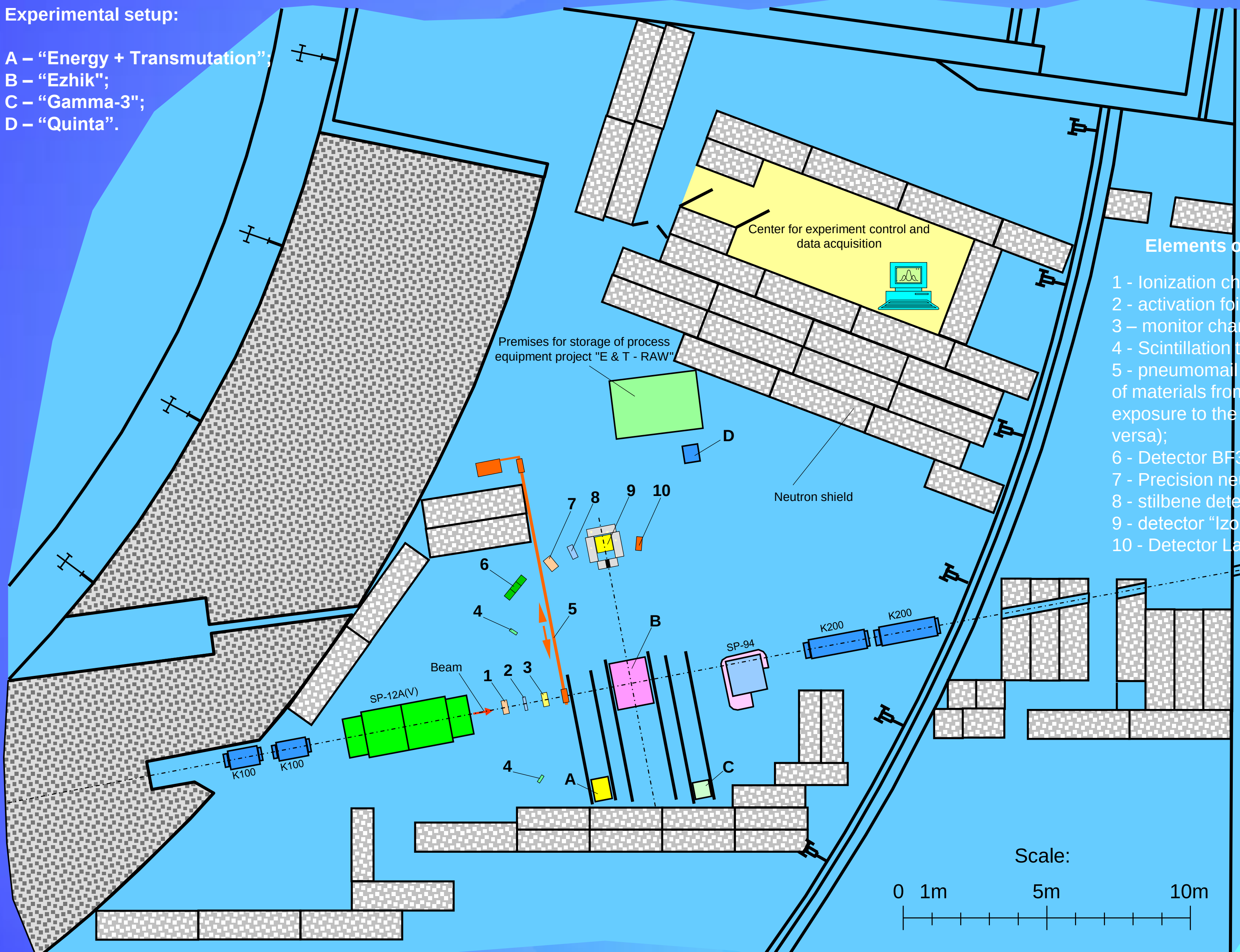
The basic types of measurement systems and detectors that will be used for execution of the scientific program of the project are given Table .

No	Basic types of measurement	Basic measurement systems (detectors types, techniques)	Brief description of measurement systems (detectors types, techniques)
1.	Spatial-energetic distribution of neutrons	Activation samples; SSNTD; γ spectrometers; Small ionization chambers.	53 reactions at each measurement point; 7 reactions at each measurement point; HPGe; ^{3}He detectors.
2.	Spatial distribution of fission reaction rates and fragment mass spectra	SSNTD	7 reactions at each measurement point
3.	Spatial distribution of (n, γ) and (n, xn) reactions rates	Samples from spent fuel; γ-spectrometers; Radiochemistry	Sets of samples at each measurement point; HP Ge.
4.	Spatial distribution of energy release in the target	Sets of heat-insulated uranium samples with thermal sensors	Heat-insulated uranium samples with different enrichment levels (natural; 2-3% and 5-6%) – three samples at each measurement point
5.	Parity (Pu accumulation and burn up) distributions in the target volume	Sets of samples from natural uranium containing Pu-239; γ-spectrometers; Radiochemistry	Seven samples containing Pu-239 (from 0 to 6%) at each measurement point; HP Ge;
6.	Beam power amplification	Systems for thermophysical measurements (item 4); System for fission rate measurement (item 2)	Solution of direct of heat exchange problem by volume integration; Volume integration of the number of fission events.
7.	Prompt and delayed neutron spectra, neutron multiplicity	System of neutron multiplicity measurement based on BF_3 counters; System of neutron multiplicity measurement «Isomer-M» based on ^{3}He counters; Precision spectrometer based on ^{3}He ion chamber with a Frisch grid; Stilben detector; $LaBr_3$(Ce) detector	15 Boron counters in a polyethylene moderator. 12 ^{3}He counters in a polyethylene moderator; Neutron spectra in the energy range up to 5 MeV Ø 3×3 inch
8.	Beam monitoring	Aluminum foils ; SSNTD; System for on-line beam monitoring based on ion chamber and scintillation telescope.	
9.	Decontamination rates for targets after irradiation	Standard set of dosimetric devices	

Experimental zone F-3

Experimental setup:

A – “Energy + Transmutation”;
B – “Ezhik";
C – “Gamma-3";
D – “Quinta”.



Elements of diagnostic systems :

1 - Ionization chamber;
2 - activation foil
3 – monitor chamber
4 - Scintillation telescope;
5 - pneumomail (for delivery of samples of materials from the standpoint of exposure to the detector and vice versa);
6 - Detector BF3;
7 - Precision neutron spectrometer;
8 - stilbene detector;
9 - detector “Izomer» (3He);
10 - Detector LaBr3 (Ce).

Scale:

0 1m 5m 10m

21 June 2010 Dubna

The approximate plan of works under the project

"Study of deep subcritical electro-nuclear systems and feasibility of their application for energy production and radioactive waste transmutation"

Stages of the project	2011				2012				2013			
	I	II	III	IV	I	II	III	IV	I	II	III	IV
1. Design.												
Design of large uranium target EZHIK-U and identical target EZHIK-Pb												
Choice, preparation, testing of systems of experimental and measurement equipment												
Development of experimental schemes for setups «Energy-Transmutation», «Gamma-3», «EZHIK-U», «EZHIK-Pb», «Study of Materials Resistance and Gas Production»												
2. Manufacture, mounting, and adjustment of experimental equipment and measurement systems.												
Manufacture of large uranium target EZHIK-U and identical target EZHIK-Pb												
Development and adjustment of methods and systems of experimental and measurement equipment.												
3. Physical experiments at «Nuclotron-M» (according to the schedule the installation)												
"Energy plus Transmutation"												
"Gamma-3"												
«EZHIK-Pb»												
«EZHIK-U»												
«Study of materials resistance and gas production»												
4. Complex of numerical and theoretical activities of predictive and improving character												
5. Processing of experimental results. More precise determination and development of new algorithms, models, and programs for realization of the project objectives.												

ORGANIZATIONAL AND TECHNICAL ASPECTS

The project “E&T – RAW” will be performed in the framework of a large scientific and technical cooperation including: JINR (LHEP, DLNP, FLNP et al.), Center of Physical and Technical Projects “Atomenergomash” (Moscow), State Research Center Institute of Physics and Power Engineering (Obninsk), JINPR-Sosny NASB, IF NASB, and participants of “Energy plus Transmutation” and “GAMMA-3” collaboration.

Positive experience of joint activities, including long-term fruitful experiments at JINR, as well as successful experience of performing a complex of experimental studies initiated by Center of Physical and Technical Projects «Atomenergomash» at JINR and Petersburg Nuclear Physics Institute RAS in 2008-2009 and the GAMMA-3 / E+T Collaboration ensure successful realization of the proposed research program.

It is very important that JINR possesses unique capabilities for performing planned experiments, namely, operating relativistic particle accelerator Nuclotron, required amount of fissionable materials, developed measurement methods, as well as the basic international team of highly qualified scientists and technicians.

Workshop Collaboration "E + T"
(" Energy plus Transmutation")
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