Joint Institute for Power&Nuclear Research – Sosny
National Academy of Sciences of Belarus

3rd SAD/YALINA Steering Committee Meeting
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“Booster (Cascade) Subcritical Assembly”

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“EXPERIMENTAL THEORETICAL RESEARCH OF THE PECULIARITIES OF TRANSMUTATION OF LONG-LIVED FISSION PRODUCTS AND MINOR-ACTINIDES IN SUB-CRITICAL ASSEMBLY DRIVEN BY A NEUTRON GENERATOR” ISTC Project B-070

- **Application of low-energy ion accelerators coupled with sub-critical multiplying systems ($k_{eff} < 1$) allows to carry out the experimental research of different aspects of ADS-technologies and to outline future investigations at high energy particle accelerators.**

The main goals of the ISTC Project #B070

- creation the facility to investigate neutronics of a subcritical system driven by external neutron source;
- measurements of the transmutation reaction rates of fission products and minor actinides;
- investigation of kinetics of the sub-critical systems with external neutron sources;
- validation of the experimental techniques for, e.g., sub-criticality monitoring, neutron spectra measurement, etc;
- investigation of characteristics of sub-critical systems with the external neutron sources with pulse mode of neutron generator operation.

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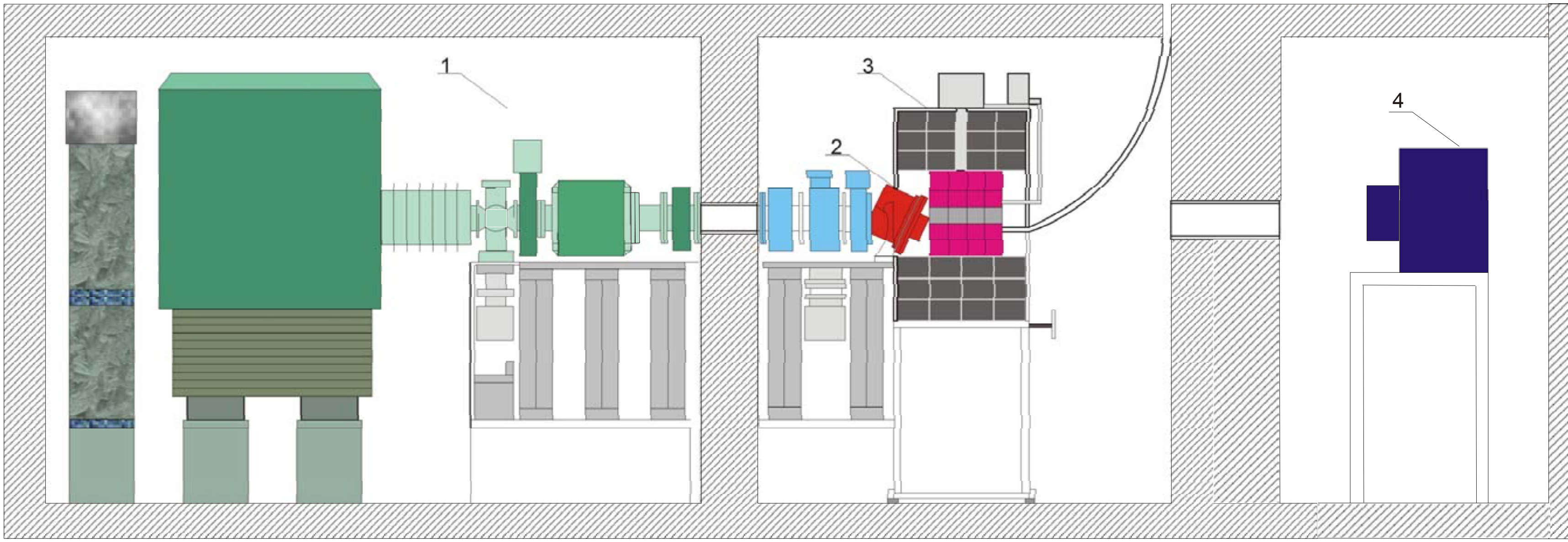

Sub-critical facility YALINA:
1 – neutron generator; 2 - Ti^3H (Ti^2H) target system; 3 - sub-critical assembly, 4 - gamma-spectrometer

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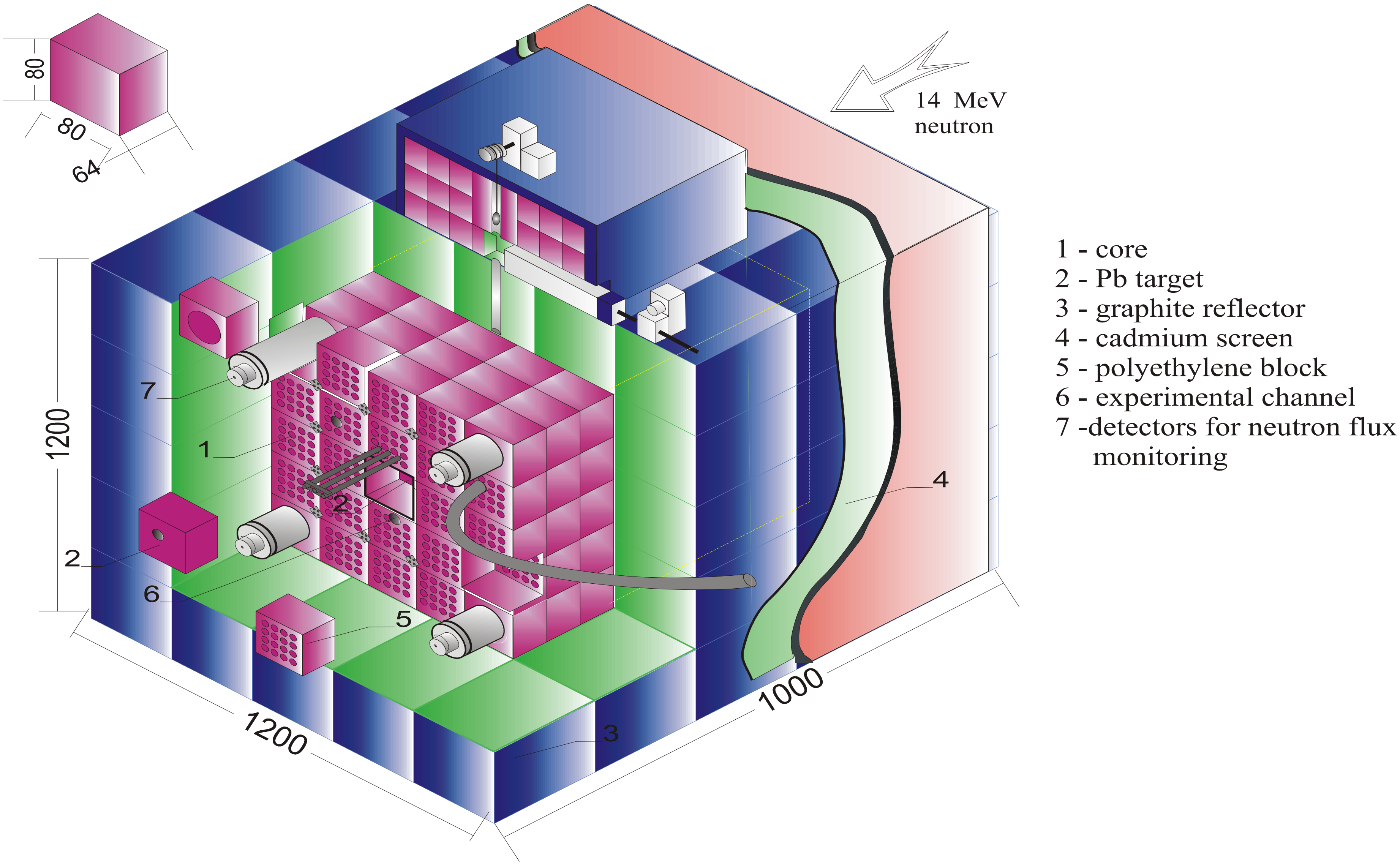

Uranium-polyethylene assembly

The core of the sub-critical assembly is a rectangular parallelepiped with *40.0 cm width, 40.0 cm height and 60.0 cm length*. It is assembled of polyethylene sub-assemblies with 16 fuel pins per sub-assembly, providing large flexibility of core configuration. The sub-critical core is loaded with UO_2 fuel dispersed in Mg matrix (uranium is enriched to 10 % by ^{235}U). Fuel pins are arranged according a square lattice with 2.0 cm spacing. Central part of the subcritical assembly is a neutron producing lead target of 8.0 cm width, 8.0 cm height and 60.0 cm length and the core is surrounded by high purity graphite reflector 40.0 cm thickness and with thin (l = 1.5 mm) Cd layer.

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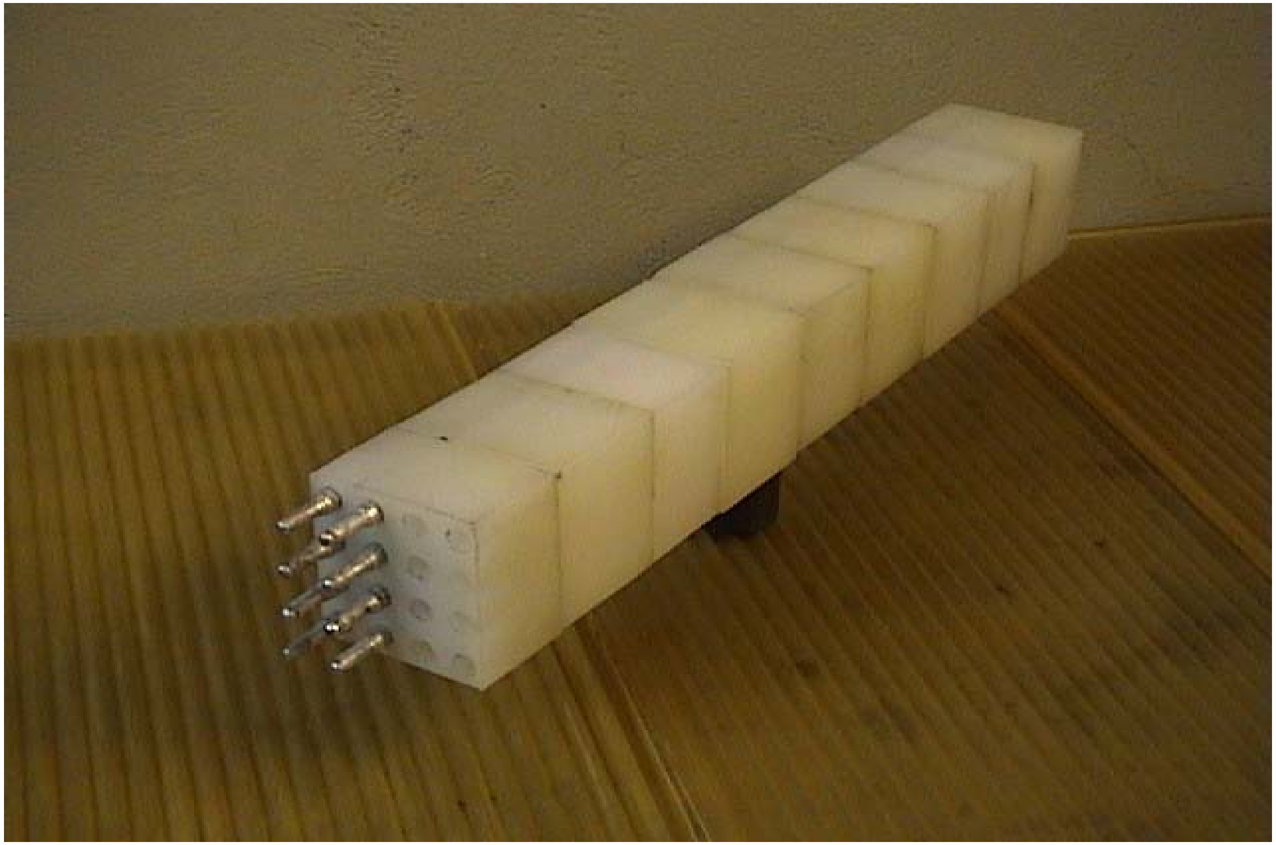
YALINA fuel subassembly.



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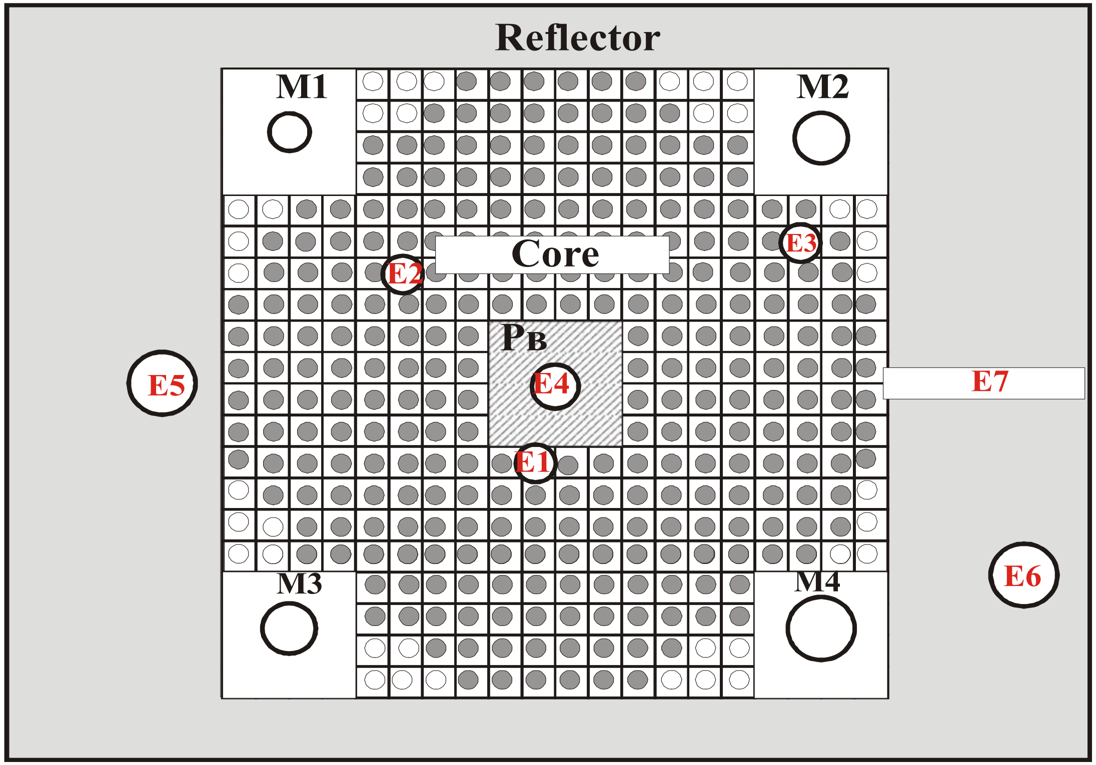


Uranium-polyethylene subcritical assembly

C - cross-section (280 fuel rods)
E1 - E7, M1 - M4 - experimental channels

- Neutron generator is linear accelerator of deuterium ions produced at duoplasmatron and accelerated to energy $E_d = 250$ keV. Accelerator magnet system separates D^+ ions only that by means of electro-magnetic lenses are directed towards the Ti^3H or TiD targets where in reactions $d(T,n)^4He$ and $d(D,n)^3He$ neutrons are generated with energies in the ranges E_n = 13-15 MeV and E_n = 2.5-3.0 MeV, respectively. At present highly effective water-cooled targets with diameters 230 and 45 mm are used in experimental program.

Monitoring of the neutron flux

GENEPI 2

Experimental platform PEREN at LPSC Grenoble

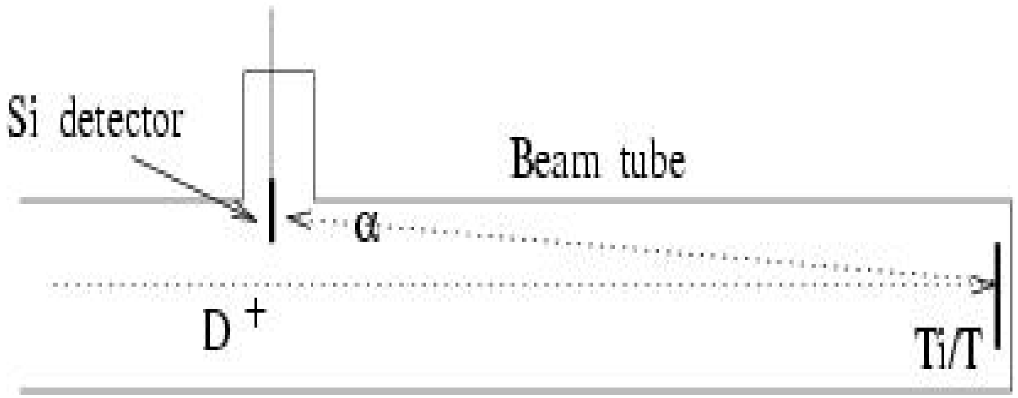
- Detection of the charged particles from $T(d,n)^4He$ or $D(d,p)^3H$ emitted backward

- Relative monitoring only because transmission of the beam line not well known

Absolute monitoring of the neutron flux

•Detection of the charged particles emitted backward by Si detector located at 0.8m of the target

• efficiency e = 10-7 reliable because simply geometrical (no beam optics).



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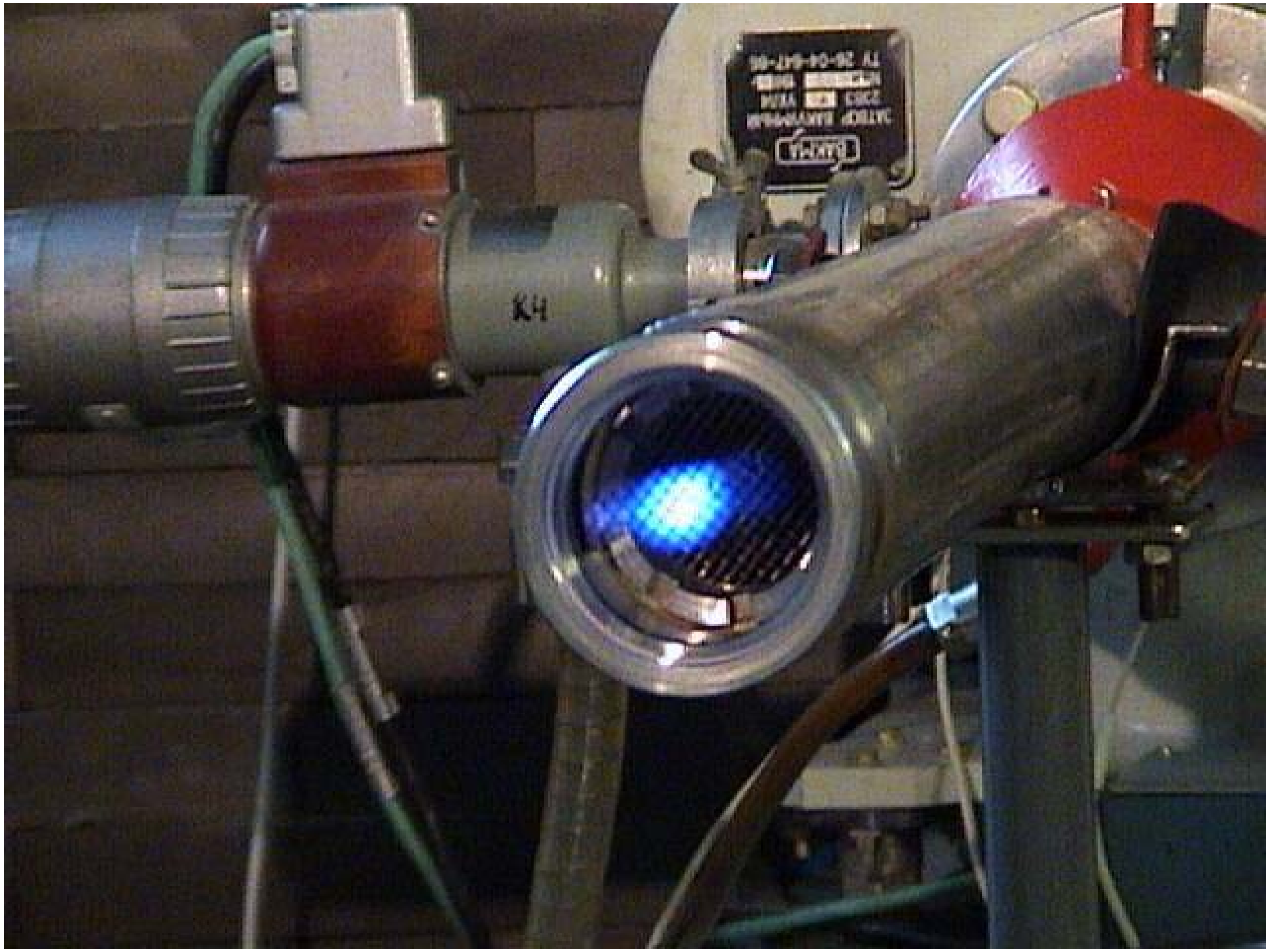

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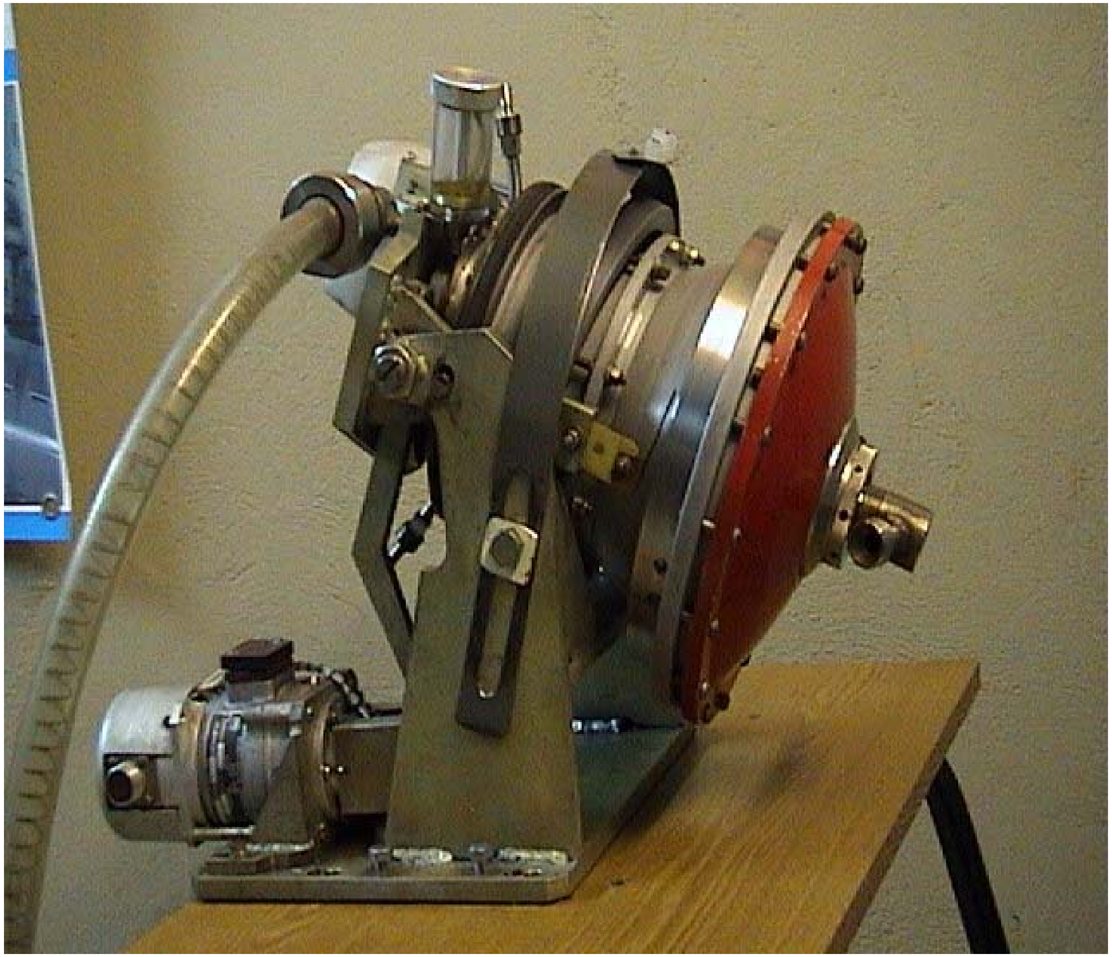
Target diameter
230 mm
Rotation speed
560 rpm
Diameter of reaction
space 100-200 mm
Tritium activity
0.53-0.75 MCi/kg
D/Ti (T/Ti)
atomic ratio
1.5-1.8



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Acelerator	H+ and D+	
Beam energy	100 - 250 keV	
Beam current	1 - 12 mA	1 – 2 mA
Pulse duration	(0.5-100)×10**(-6) s	
Pulse repetition frequency	(1-10 000) Hz	
Spot size	2.0 -3.0 cm	
Ti^3H target (230 mm		45 mm):
Rotation speed, rpm	560	-
Maximal yield of neutrons, n/s	(1.0 – 1.5)x10 ^{12} n/s	2 x10 ^{11} n/s
Neutron energy, MeV	13-15 MeV	
TiD target (230 mm		45 mm):
Maximal yield of neutrons, n/s	(2 – 3) 10 ^{10} n/s	2 x 10 ^{9} n/s
Neutron energy, MeV	2.5 – 3	

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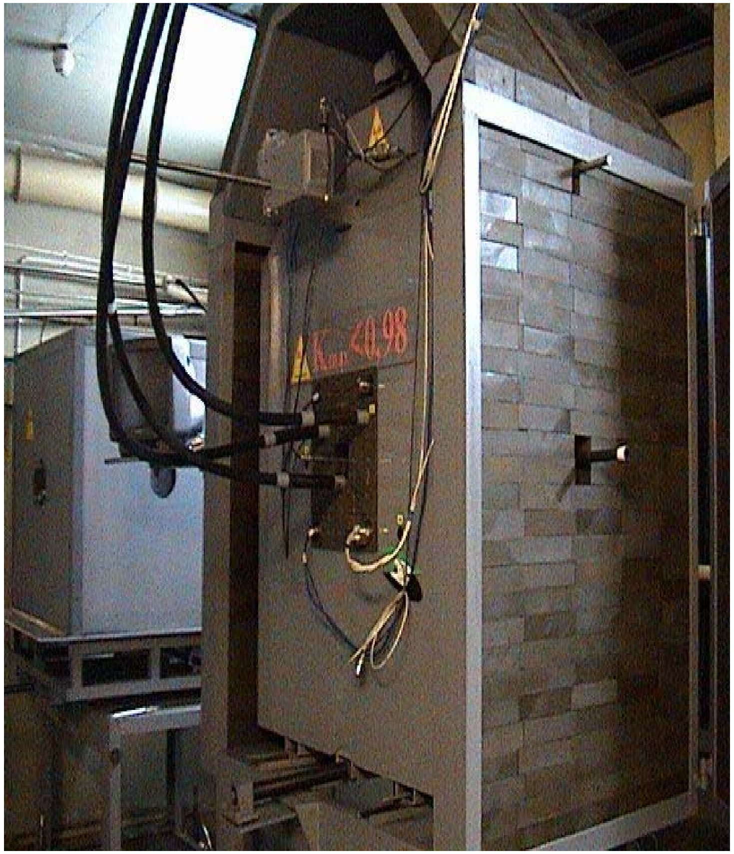
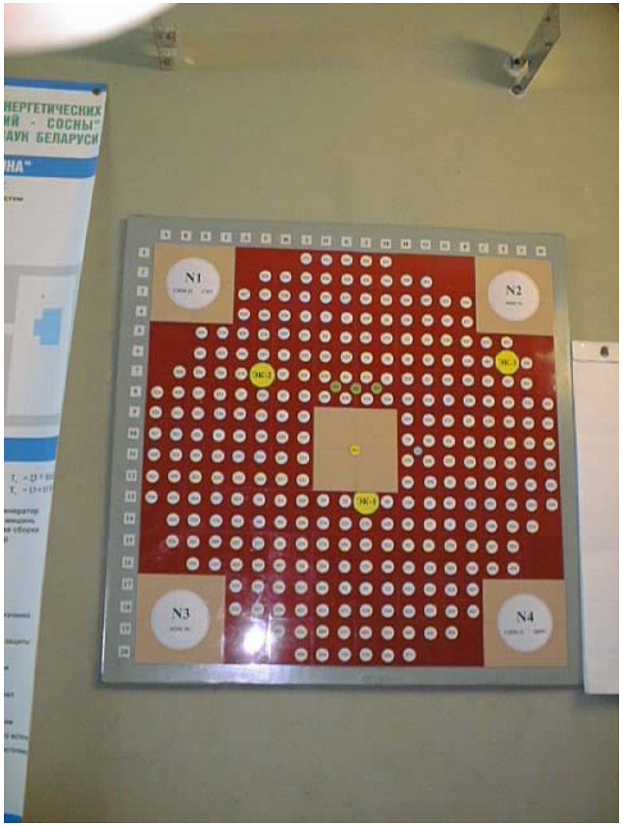
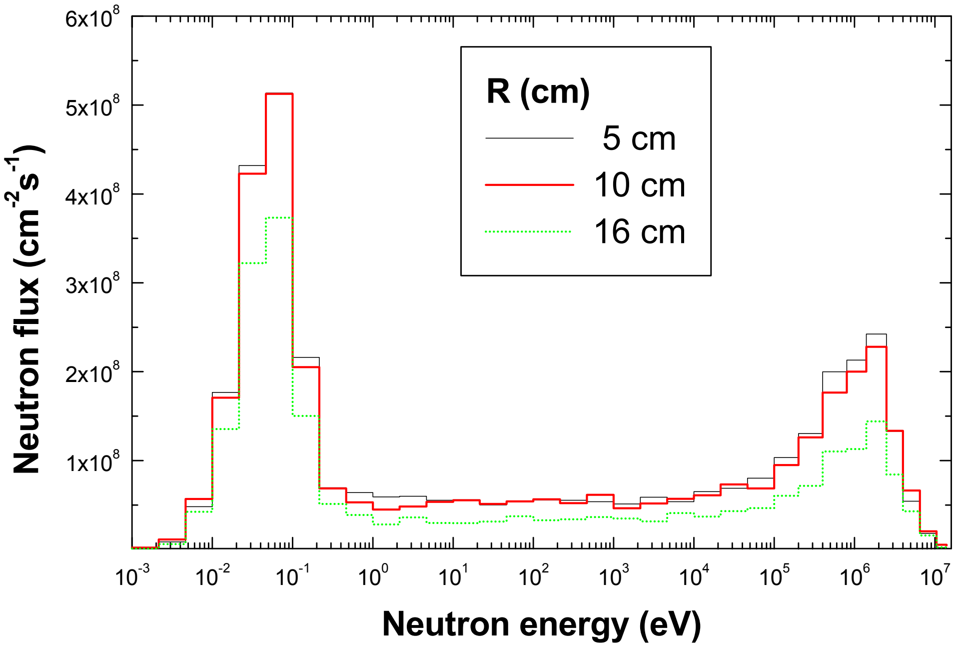
Subcritical Facility Yalina



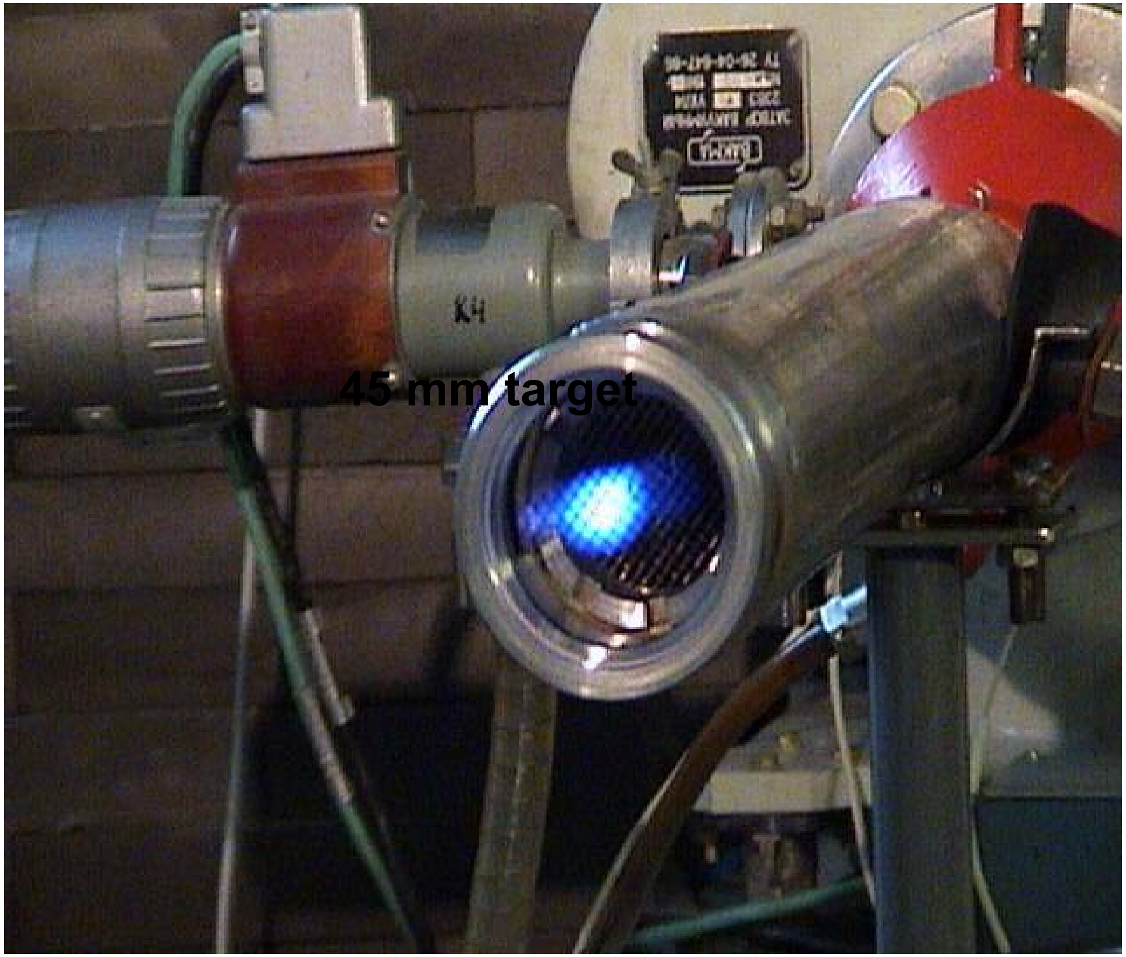


Energy distribution of neutrons flux (calculated) in the *sub-critical* assembly Yalina.



- Neutron generator is linear accelerator of deuterium ions produced at duoplasmatron and accelerated to energy E_d = 250 keV. Accelerator magnet system separates D^+ ions only that by means of electro-magnetic lenses are directed towards the Ti^3H or TiD targets where in reactions $d(T,n)^4He$ and $d(D,n)^3He$ neutrons are generated with energies in the ranges E_n = 13-15 MeV and E_n = 2.5-3.0 MeV, respectively. At present highly effective water-cooled targets with diameters 230 and 45 mm are used in experimental program.

45 mm target unit



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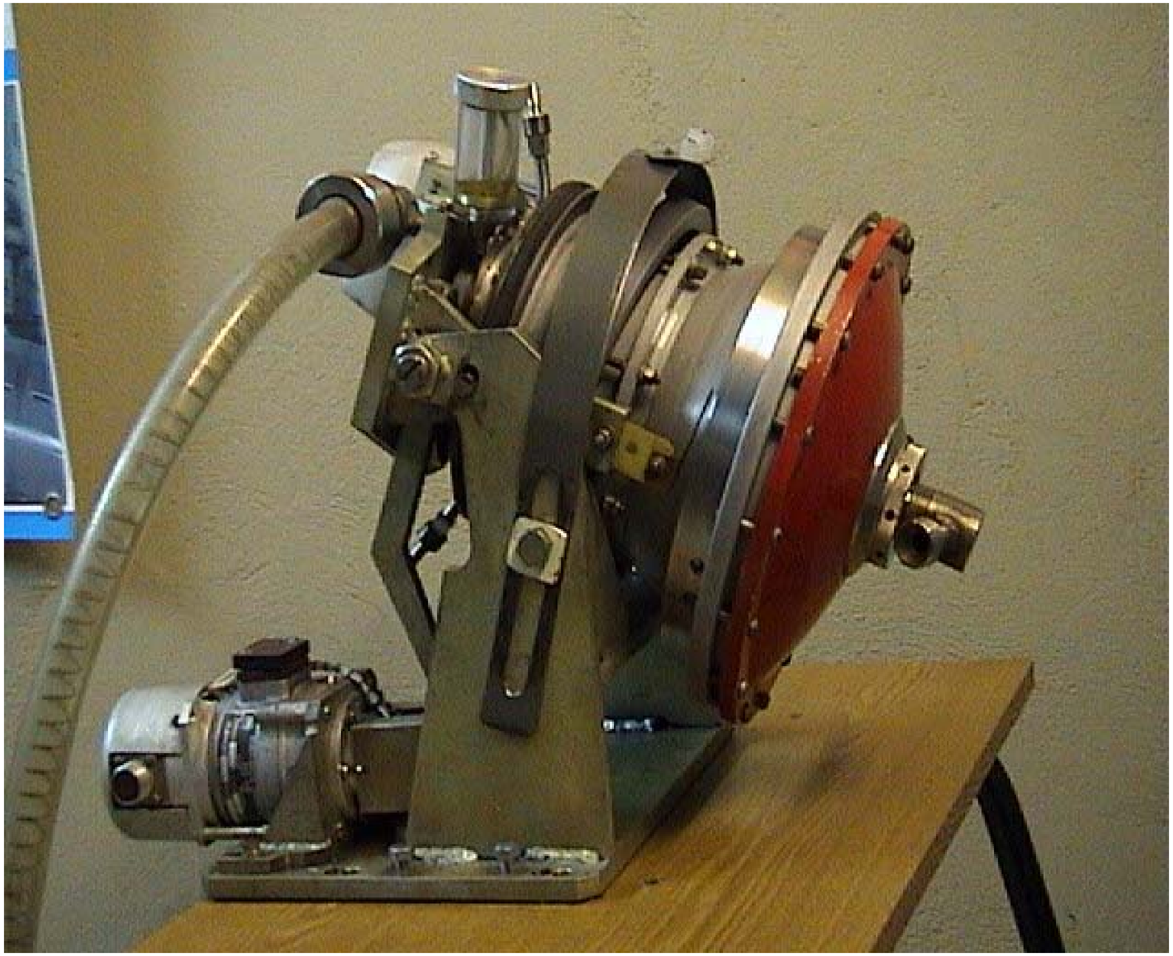
Target diameter
230 mm
Rotation speed
560 rpm
Diameter of
reaction space
100-200 mm
Tritium activity
0.53-0.75 MCi/kg
D/Ti (T/Ti) atomic
ratio 1.5-1.8



Main parameters of the neutron generator NG-12-1

Accelerator	**H+ and D+**
Beam energy	**100 - 250 keV**
Beam current	**1 - 12 mA** **1 – 2 mA**
Pulse duration	**(0.5-100)×10**(-6) s**
Pulse repetition frequency	**(1-10 000) Hz**
Spot size	**2.0 -3.0 cm**
Ti^3H target (230 mm 45 mm):	
Rotation speed, rpm	**560 -**
Maximal yield of neutrons, n/s	**1.0 x10^{12} n/s** **1.0x10^{11} n/s**
Neutron energy, MeV	**13-15 MeV**
TiD target (230 mm 45 mm):	
Maximal yield of neutrons, n/s	**(2 – 3) 10^{10} n/s** **(2-3) 10^{9} n/s**
Neutron energy, MeV	**2.5 – 3**

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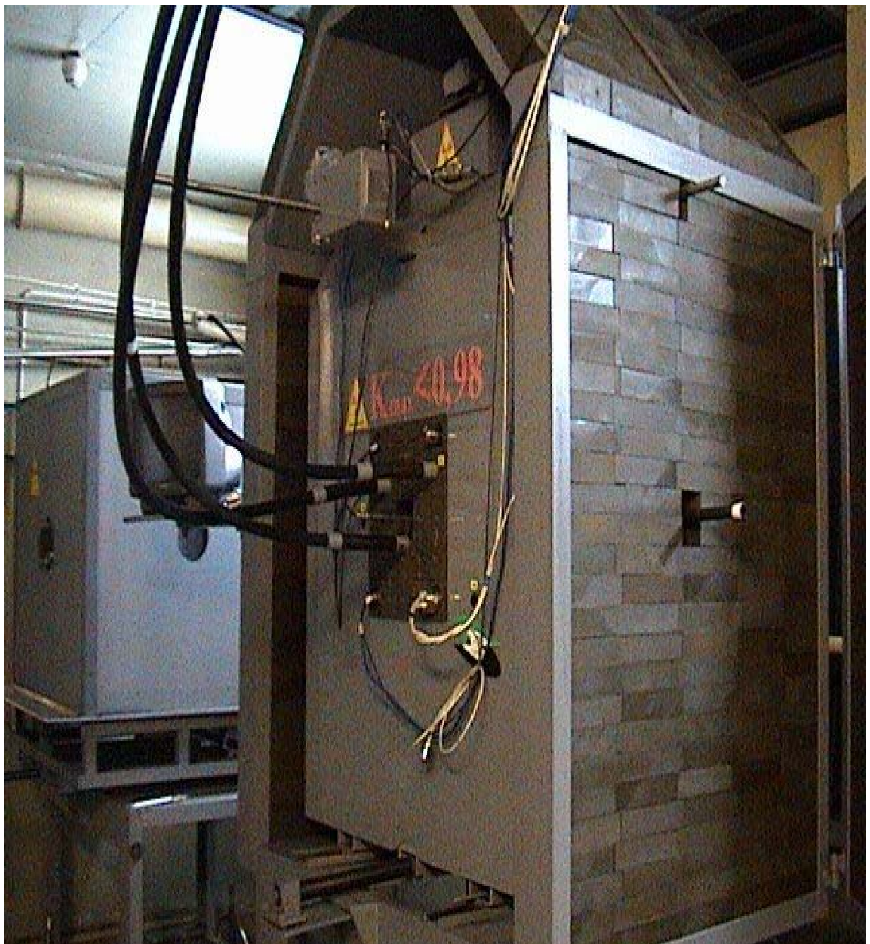
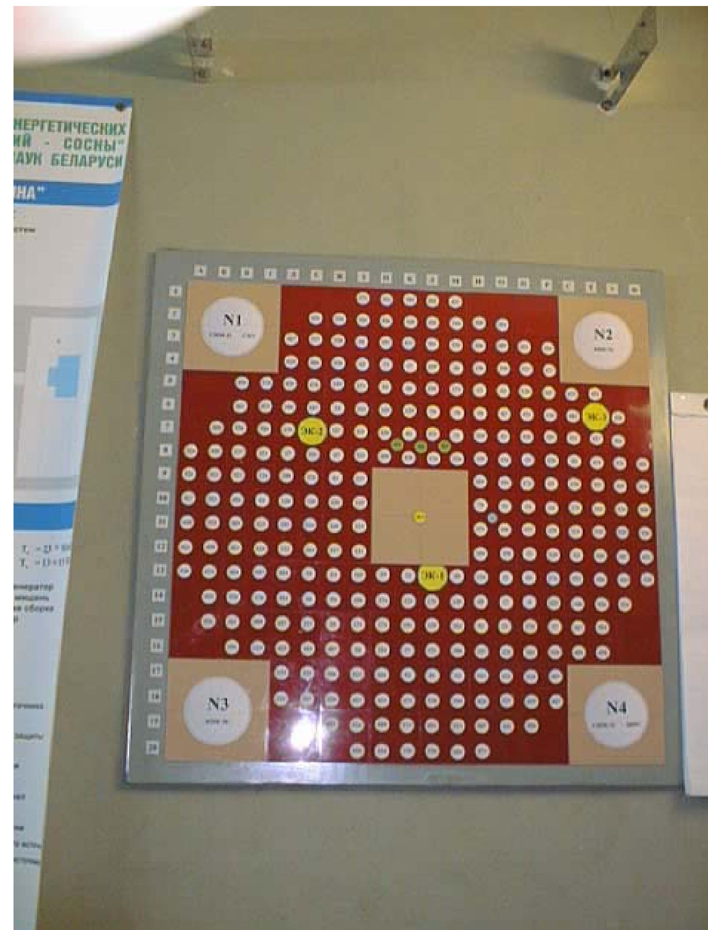
Subcritical assembly with thermal neutron spectrum

$K_{eff} = 0.98$





Experimental and calculated reactivity of sub-critical assembly of various configurations

N_{pins}	*Pulse*	*Neutron method*	*Source*	*Gozani*	*Method*	kef (1/N)	*Sjöstrand*	*Method*	kef MCNP	Life time, μs (MCNP)
	α, s-1	ρα , $	kef_α	ρ Goza-ni , $	$k_{ef\_}$ Gozani		ρS , $	$k_{ef\_}S$		
280	451.6 ± 1,4	4.154	0.969	4.397	0.967	0.964	4.547	0.967	0.9715 ± 0.0007	94.1
280-1 (centr)	473.1 ± 1.7	4.399	0.968	4.844	0.964	0.962	5.205	0.962	0.9686 ± 0.0007	94.4
280-2 (centr)	486.1 ± 1.6	4.548	0.966	4.832	0.964	0.960	5.219	0.962	0.9665 ± 0.0007	94.9
280-4 (centr)	519.6 ± 2.0	4.930	0.964	5.365	0.960	0.955	5.898	0.957	0.9616 ± 0.0006	95.99
280-1 (peref)	458.6 ± 1.05	4.240	0.969	4.307	0.968	0.963	4.536	0.967	0.9703 ± 0.0007	94.04
280-2 (peref)	468.4 ± 1.1	4.346	0.968	4.442	0.967	0.962	4.595	0.966	0.9689 ± 0.0007	94.3
280-4 (peref)	490.5 ± 1.23	4.598	0.966	4.679	0.965	0.960	5.052	0.963	0.9672 ± 0.0007	94.4

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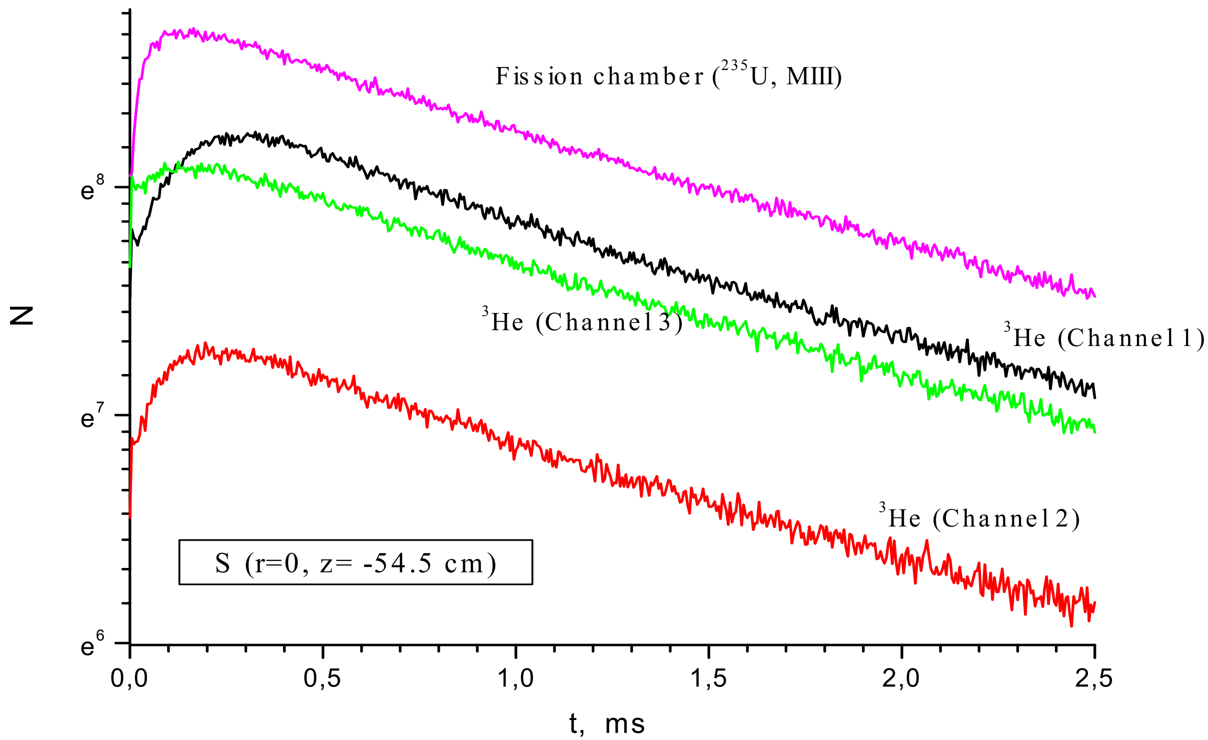

Time behavior of neutron flux density measured with application of ^{235}U fission chamber - CNT-5 and ^{3}He-detector in the experimental channels of the core loaded by N_r = 280.

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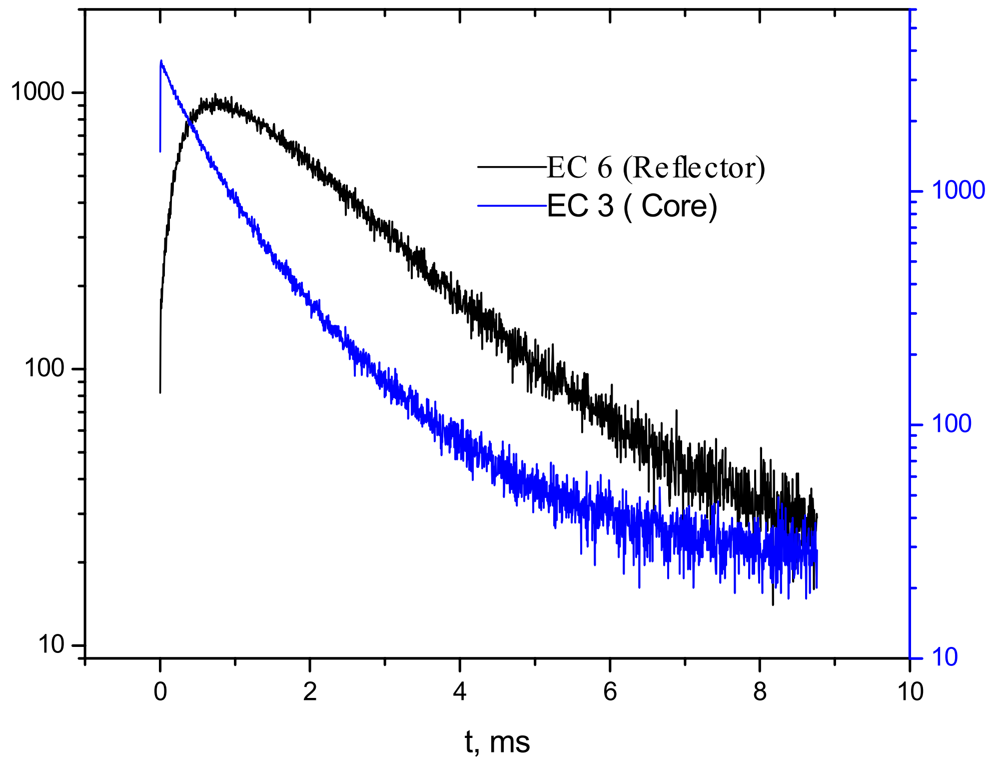

Time dependence of ^{3}He – detector counting rates in the experimental channels EC3 (core) and EC6 (reflector) of the sub-critical assembly YALINA-Pb. (τ=7 μs, 14 MeV)

- Presence of the lead zone at the core center is the reason of remarkable variation of dN/dt distribution in the reflector due to moderation of neutrons formed in lead zone in U(n,f) and Pb(n,2n), U (n,2n) reactions in high energy range.
- Thus the measurements of sub-critical system reactivity based on pulse neutron source method should be performed inside the core because contribution of source neutrons to neutron flux time behavior in reflector can be high enough to result in distribution different from $dN/dt \sim e^{-\alpha t}$ that follows from point kinetics approximation.

Np-237, Am-243 and I-129 samples

Sample	Activity, (10e+8) Bq	Mass, mg	Admixture
• NaI	0.044	1	< 17% I-127
• NpO_2	0.113	366	< 0.2% Pu-239
• AmO_2	1.100	14.8	< 0.2% Pu-239

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- **Energy distribution of neutrons in the sub-critical systems is main parameter that defines most of ADS-technology characteristics and first of all transmutation of minor-actinides and long-lived fission fragments.**
- **Experimental measurement of neutron spectrum in such systems is non-trivial because of a great number of reactions in high energy range (n,xnyp) that to a great extent influence the shape of neutron energy distribution in the core.**
- **One of the main characteristics of thermal neutron spectrum is cadmium ratio R^{Cd} that demonstrates the contribution of thermal neutrons to the total neutron spectrum**

For determination of neutron energy spectrum at YALINA facility the following reactions were used:

^{111}Cd (n,n’)^{111}Cdm (E_{eff} = 0,25 MeV),
^{55}Mn(n,α)^{52}V (E_{eff} = 0,64 MeV),
^{204}Pb(n,n’)^{204}Pbm (E_{eff}=0,90 MeV),
^{115}In(n,n’)^{115}In^{m} (E_{eff}=0,34 MeV),
^{90}Zr(n,p)^{64}Cu (E_{eff}=2,0 MeV),
^{58}Ni(n,p)^{58}Co (E_{eff}=2,7 MeV),
^{59}Co(n,p)^{59}Fe (E_{eff}=2,8 MeV),
^{65}Cu(n,p)^{65}Ni (E_{eff}=3,5 MeV),
^{27}Al(n,p)^{27}Mg (E_{eff} = 4,5 MeV),
^{24}Mg (n,p)^{24}Na (E_{eff}=4,93 MeV),
^{48}Ti (n,p)^{48}Sc (E_{eff}=5.0 MeV),
^{56}Fe(n,p)^{56}Mn (E_{eff} = 6,60 MeV),
^{59}Co(n,α)$_{56}$Mn (E_{eff}=7,10 MeV),
^{27}Al(n, α)^{24}Na (E_{eff} = 7,45 MeV).

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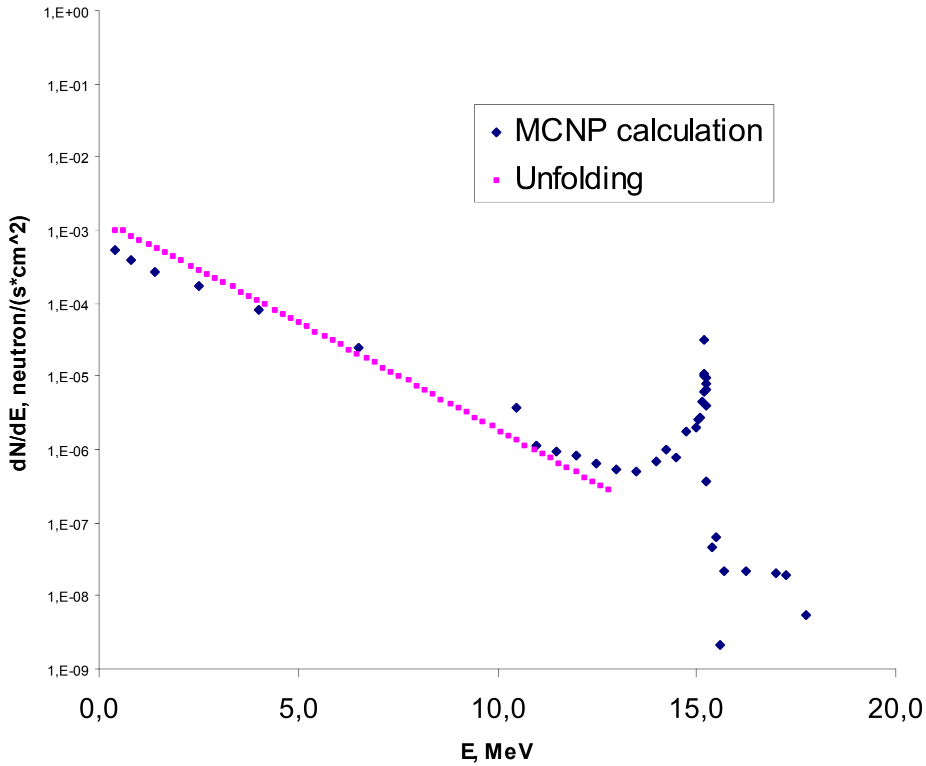
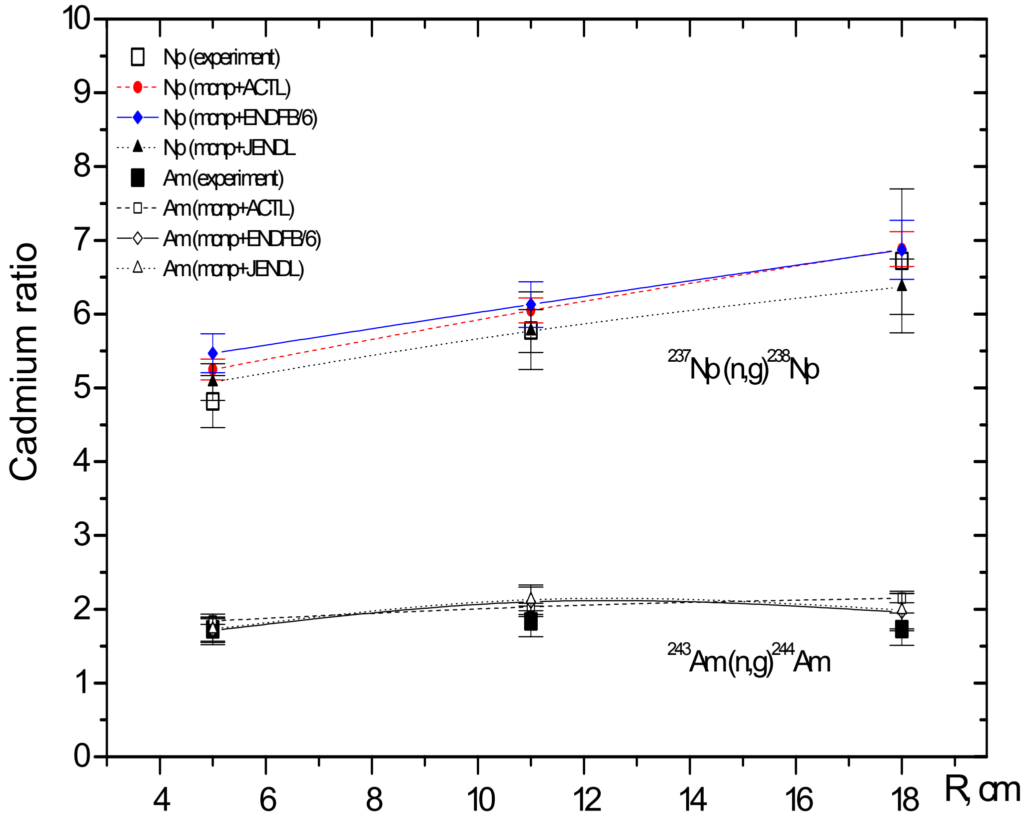


Comparison of neutron spectra in sub-critical assembly YALINA at the point Z = 0 cm and R = 11 cm calculated by MCNP-4B and unfolded by method of effective cross sections of threshold reactions using experimental data in the energy range 0.4 -13 MeV, per one neutron generated by NG-12-1 operating in (d,t) mode.



Experimentally measured and calculated cadmium ratios for ^{243}Am (n, γ) and ^{237}Np (n, γ) reactions by using ACTL, ENDFB/6 and JENDL libraries of evaluated nuclear data.

- In the frame of the B-070 Project an opportunity of investigation of various ADS characteristics at sub-critical assembly Yalina driven by neutron generator has been shown . The similarity of $d2\sigma/d\Omega dE$ distributions in the energy range $E_n \leq 15\text{-}20$ MeV confirms a principal possibility of application of low energy accelerators as well as proton accelerators $E_p \leq 100\ldots150$ MeV for investigations in the field of ADS-technology.

Keff = 0,975 – 0,98

Booster zone (Keff= 0,60):

48x48x50cm

FUEL: X_5=90% U met.

X5=36% UO_2

F(E_n >0,1 MeV)~109 n/(cm^2 s)**

moderator Pb

Load (kg) U_5–62.8;U_8 -54.5

Intermediate zone

thickness, cm 3

material Umet (X_5=0,7%) + B_4C

moderator Pb

load (kg) U_5 – 0.23; U^8 - 31.8

Thermal zone (Keff= 0,95)

thickness, cm 24

fuel : X_5 =10% UO_2

Moderator polyethylene

reflector graphite

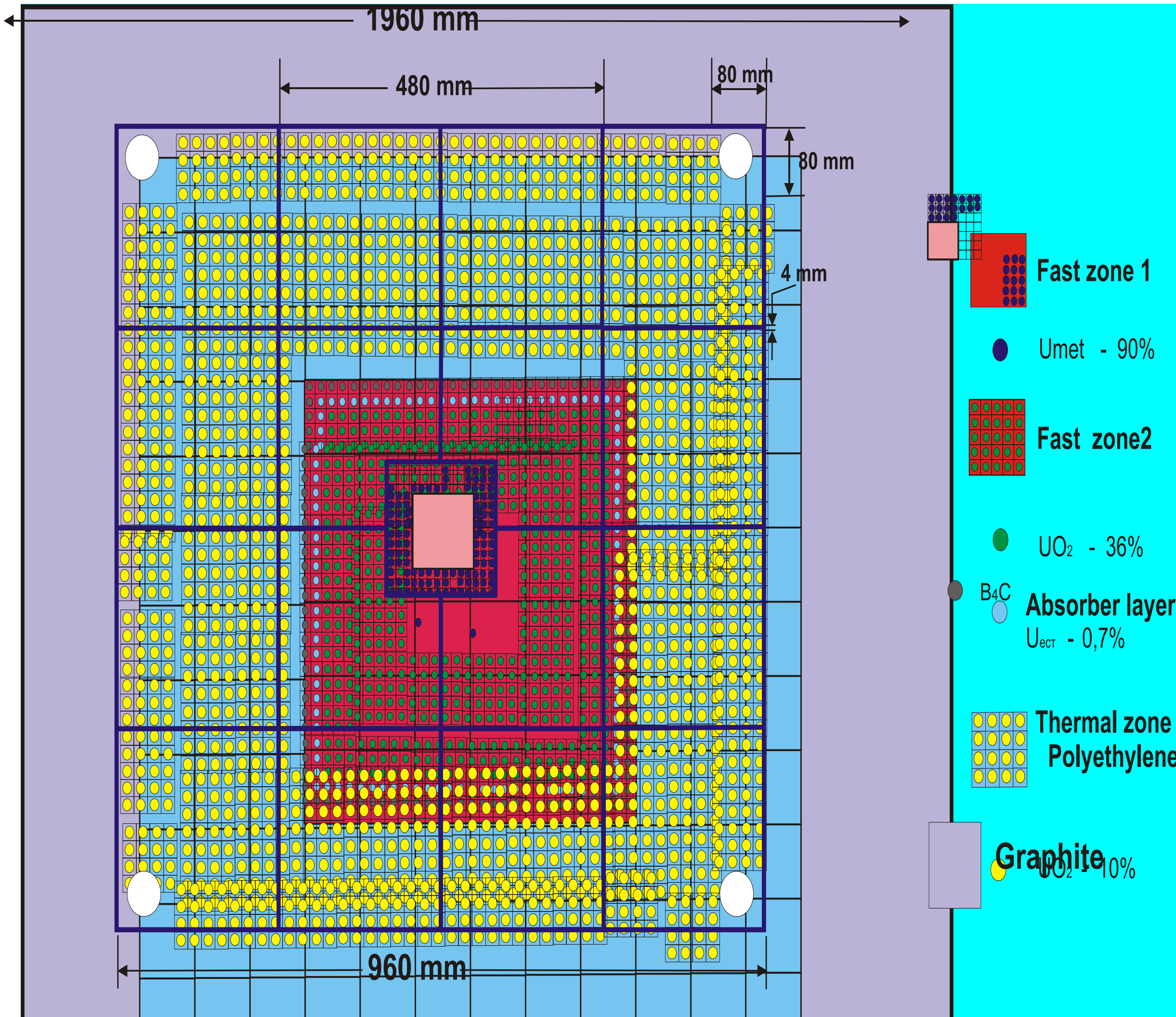
F(th):

Ti3H –target ~ 10^9 n/(cm^2s)

Load (kg) U_5 – 8.5; U_8 -72.6

multiplication factor 50

Total load (kg) U_5 ~ 72; U_8 - 167



Vertical layout of booster subcritical assembly

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Booster (cascade) Subcritical assmbly YALINA-B

Loading of fuel in Yalina-B assembly

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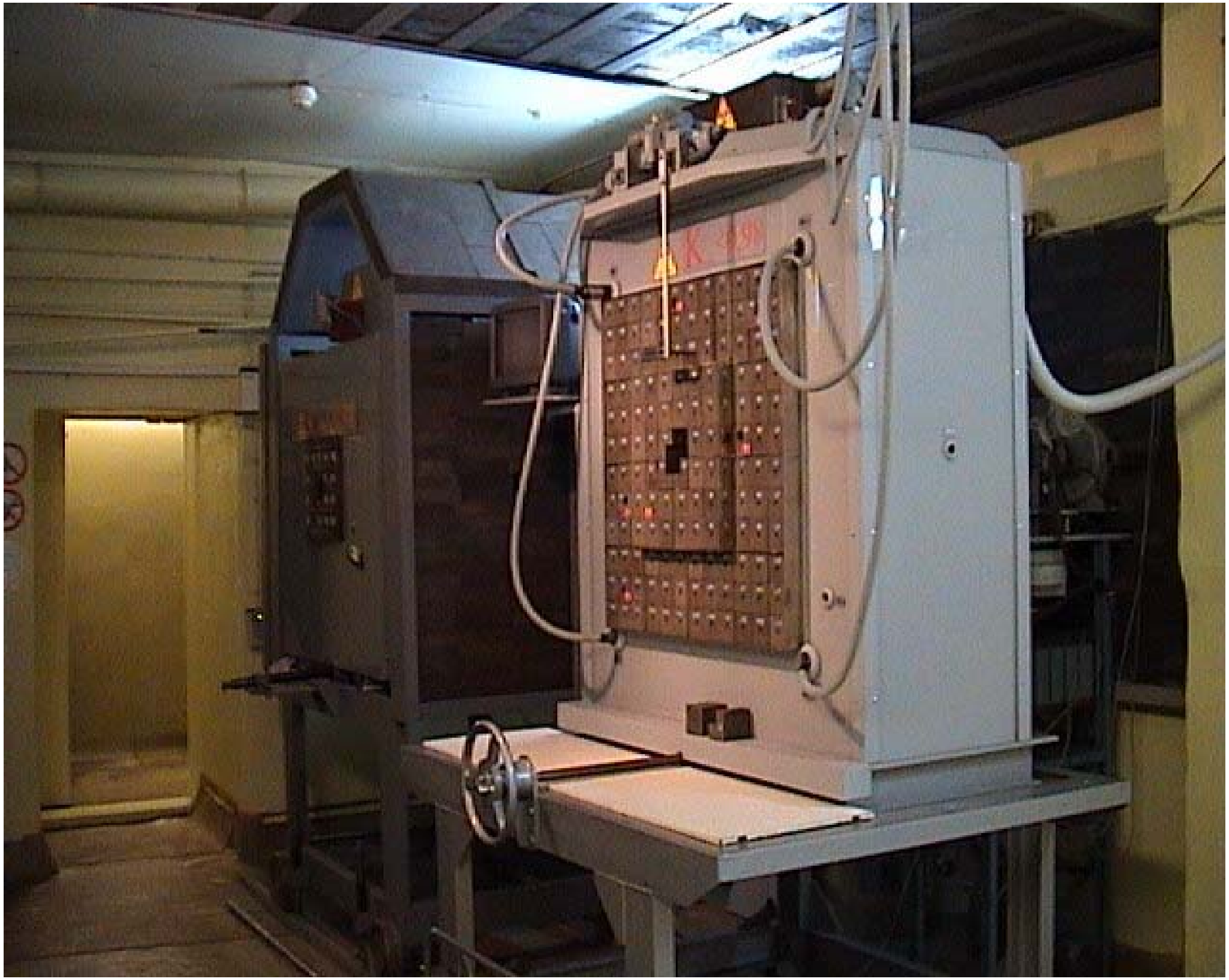
Subcritical facility YALINA



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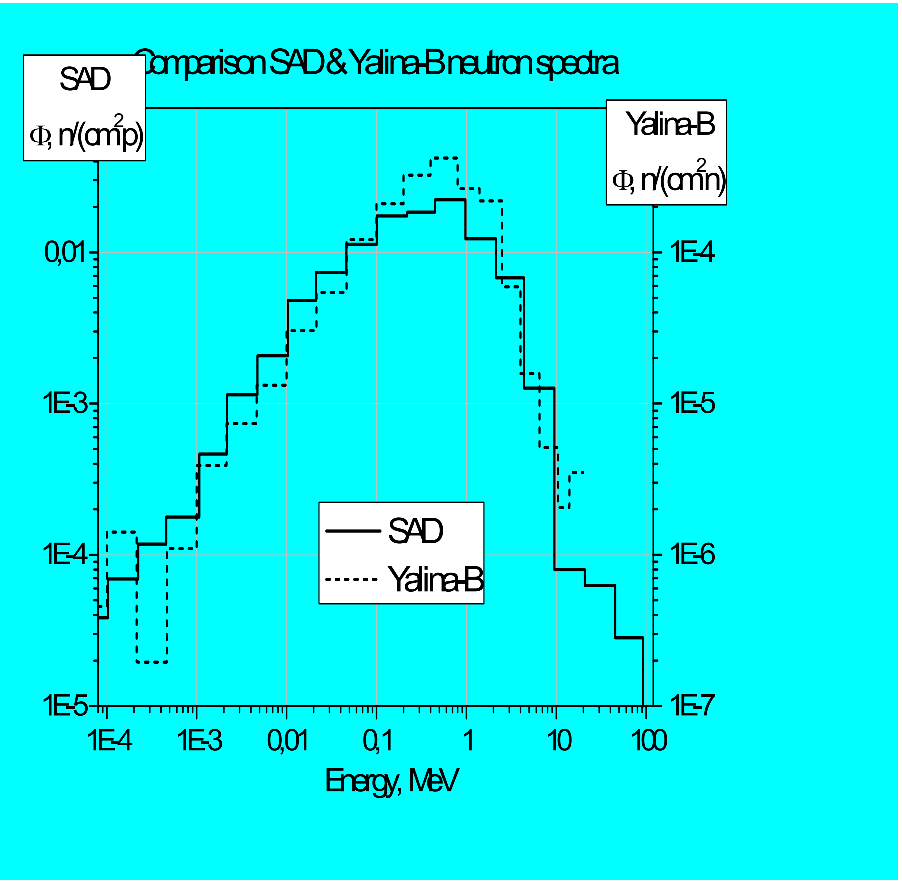
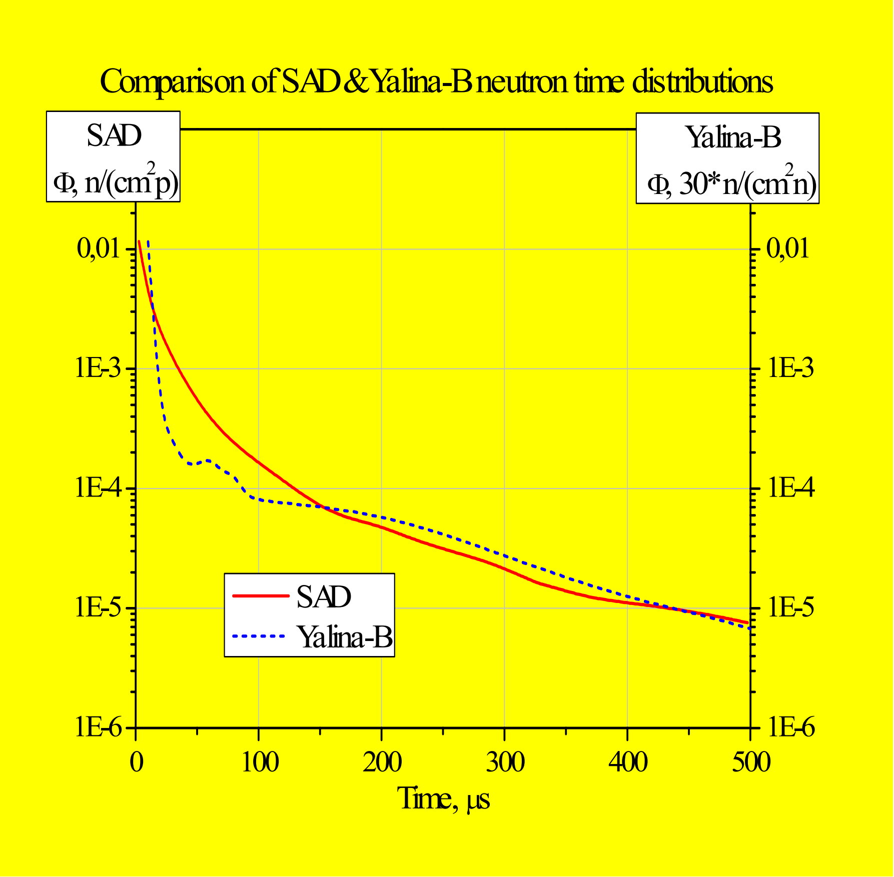
The fast zone of the facility can be considered as a volume neutron source in contrast to YALINA and MASURCA experiments. From this point of view the booster zone is closer to the spallation lead target of the SAD and MYRRHA projects.





Prompt neutron lifetime in the booster subcritical assembly driven by a neutron generator:

SAD: A. Lopatkin L = 24 μs; E. Gonzales L = 0.954 μs ; MUSE -3 L = 0.61 μs; MYRRHA L=6.0 μs.

	Bare booster zone	Booster zone with polyethyle-ne reflector	Thermal zone with 1040 fuel pins	**Booster assembly (832 pins in thermal zone)**	**Booster assembly (448 pins in thermal zone)**	**Booster assembly (1040 pins in thermal zone)**
Promt neutron lifetime	5.6 10^{-8} s (0.056 μs)	4.2 μs with B_4C in the intermediate zone 10.6 μs without B_4C in the inter-mediate zone	6.2 10^{-5} s (62 μs)	5.52 10^{-5} s (55 μs)	4.9 10^{-5} s (49 μs)	5.8 10^{-5} s (58 μs)
Neutron generation lifetime	6.6 10^{-8} s (0.066 μs)	7.3 10^{-5} s with B_4C 8.0 10^{-5} s without B_4C	1.04 10^{-4} s (104 μs)	8.4 10^{-5} s (84 μs)	7.7 10^{-5} s (77 μs)	9.5 10^{-5} s (95 μs)

MYRRHA-Yalina collaboration

Proposals on YALINA, SAD, MYRRHA experimental investigations

- Simulation of SAD and MYRRHA neutron spectra at the facility YALINA-B.
- Spectral indices, transmutation reaction rates measurements.
- Validation and development of the techniques of sub-criticality measurements in the neutron fields with time response characteristic for SAD facility (1/N, Sjöstrand, Source Jerk methods etc.)

Proposals on YALINA, SAD, MYRRHA experimental investigations

- Unfolding of neutron spectrum by the method of threshold reactions effective cross sections (fast neutron spectrum).
- Reactor oscillator and sub-criticality measurements at the facilities driven by external neutron sources.
- Detectors testing, validation of the experimental techniques intended for the measurements of neutron flux functionals.

Proposals on YALINA, SAD, MYRRHA experimental investigations

- Experimental measurements of neutronics in fast spectrum zone with different reflectors

  (polyethylene, graphite, steel, beryllium).
- Monitoring of neutron yield from neutron-producing target.

Conclusion

The experimental facilities YALINA and YALINA-B allow to deliver valuable data in the following fields:

- measurements of transmutation rates of fission products and minor actinides,
- investigation of spatial kinetics of the sub-critical systems with external neutron sources,
- validation of the experimental techniques for, e.g., sub-criticality monitoring,
- neutron spectra measurement,
- safety research on sub-critical systems,
- technological applications such as, neutron activation analysis
- production of isotopes for calibration of gamma spectrometers etc.

Proposal of New Project

Project Proposal

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Section 2. SUMMARY INFORMATION

1. Project title

Full title: Experimental investigations of ADS physics, creation of the neutron sources for the purposes of fundamental and applied research on the basis of sub-critical assemblies with uranium fuel of high/low enrichment driven by neutron generator	
Short title: creation of the neutron sources with uranium fuel of high/low enrichment	
Technology area:	Hybrid systems and fuel cycles FUS-HSF Atomic and nuclear physics PHY-ANU
Category of Technology Development:	Fundamental and applied researches