Proposal of the ADS research stand of the Institute for Nuclear Research RAS

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Outline

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- Linac and experimental complex
- Pulse neutron sources and its infrastructure
- Development and modernization of the neutron sources
- - The ADS proposal
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  - General features
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Introduction

The global problems of modern nuclear power engineering:

- The issues of accumulation of long-lived radioactive products of nuclear reactions in the form of fission fragments and minor actinides (MA), processing and recycling thereof. Closure of the nuclear fuel cycle.
- The potential risk of accidents, including those related to the loss of control over the nuclear chain reaction.
- Development of nuclear power engineering based on the uranium–thorium cycle ($^{232}Th+n \rightarrow ^{233}U$) cycle in which the accumulation of minor actinides (MA) is minimal (negligible).

One of the possible ways to overcome these problems is the development of accelerator-driven systems (ADS) that allows:

- to reduce the risk of a nuclear accident,
- to create the blankets with a large proportion of MA, even if there is the positive void effect of reactivity,
- to use isotopes with a low effective fraction of delayed neutrons (^{239}Pu, ^{233}U, MA),
- to burn out MA effectively since their concentration in the blanket can be significantly higher the equilibrium level,
- to ensure the initial production of ^{233}U without reactors operating in the U-Pu cycle, using for maintaining multiplication only MA or spent fuel unsuitable for use in nuclear reactors,

and etc.

Introduction

- It should be noted that, unlike thermonuclear neutron sources, ADS have no unresolved fundamental physical problems, such as the controlled thermonuclear reaction.

- The fast neutron reactors are also considered for the transmutation of MA but this direction will support the amount of MA in the nuclear power engineering on an equilibrium level and does not ensure their complete destruction.

  For example, the calculated equilibrium isotope composition in the central fuel assemblies after 30 years of recycling for fast reactor BREST-300 with mixed U-Pu nitride fuel and Pb - coolant is the next:

  ^{239}Pu(66.1%), ^{240}Pu(27.1%), ^{241}Pu(3.9%), ^{242}Pu(2.45%), isotopes Am (2.1% from all isotopes of Pu) and ^{237}Np (0.4% of all Pu isotopes). The total weight percentage of plutonium isotopes in the fuel is (13.2 - 13.4)% .

  In some ADS patterns, for example, MA transmutation in the direct proton beam, their number can be reduced to virtually zero.

- All existing questions of ADS are related to technology and the economy.

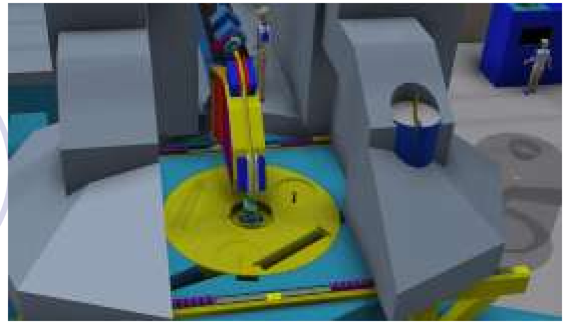
  Main engineering problems:

  Creating a long-lived target modules with high yield of neutrons

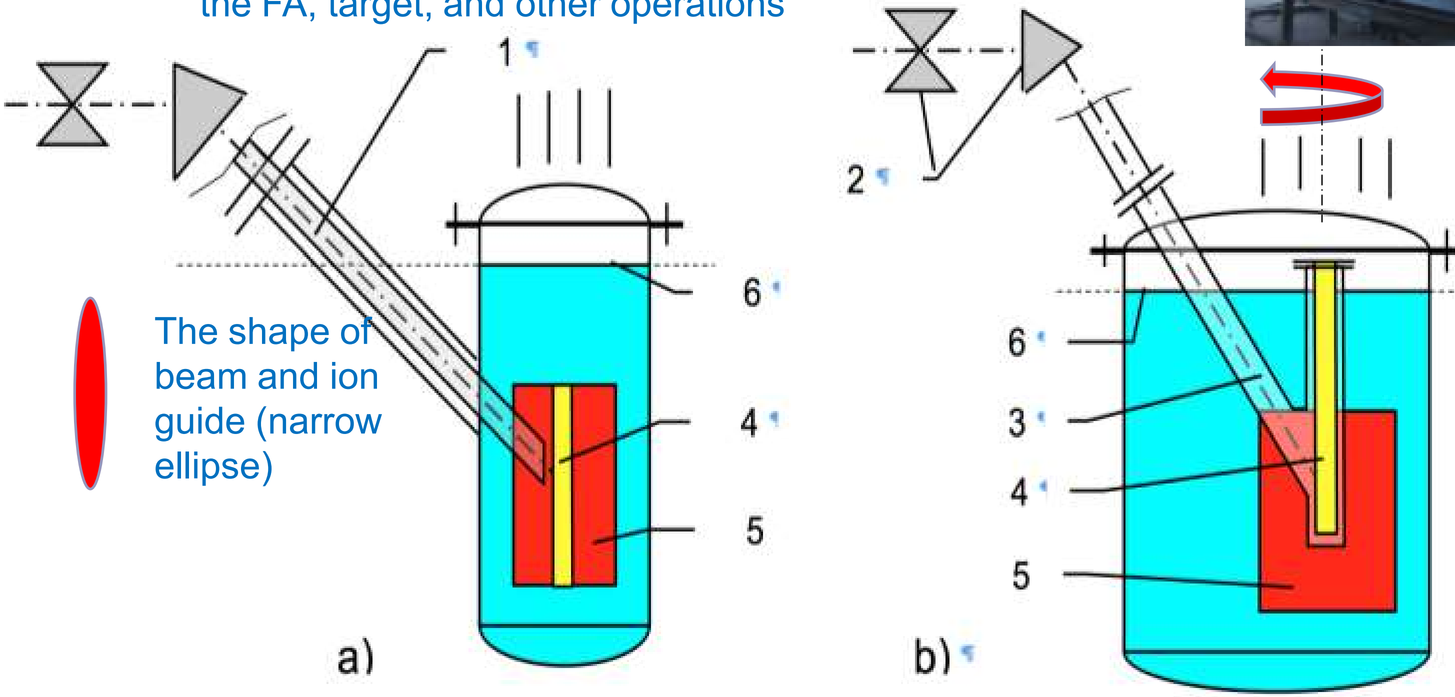
  Entering powerful proton beam in ADS

  Creating ADS configurations with natural internal safety

Possible solutions - Increasing the cross sectional area of the beam and the rotation of target around its axis



Free area above the reactor to replace the FA, target, and other operations



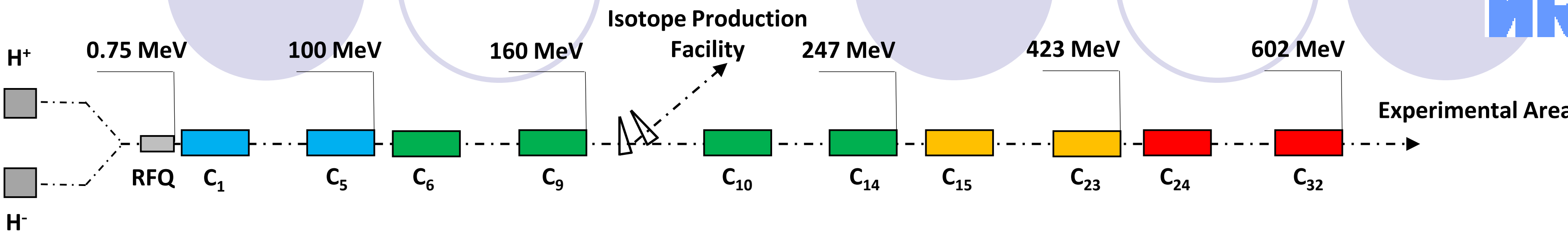
Schematic of the input of a proton beam diagonally (sideways from above): (a) with separate cooling window on the removable portion of the ion guide; (b) with placement of target module inside vacuum chamber that is connected with the proton guide.

(1) Removable part of proton guide; (2) vacuum shut-off gate and beam-bending magnet; (3) vacuum chamber; (4) target module; (5) blanket; (6) water level in body after breakdown of window or target module

Linac

Experimental Complex

Linear Accelerator



Low energy part of accelerator

5 Drift Tube Tanks

Frequency – 198.2 MHz

Output energy- 100 MeV

High energy part of accelerator

27 four-section Disk and Washer cavities

Frequency 991 MHz

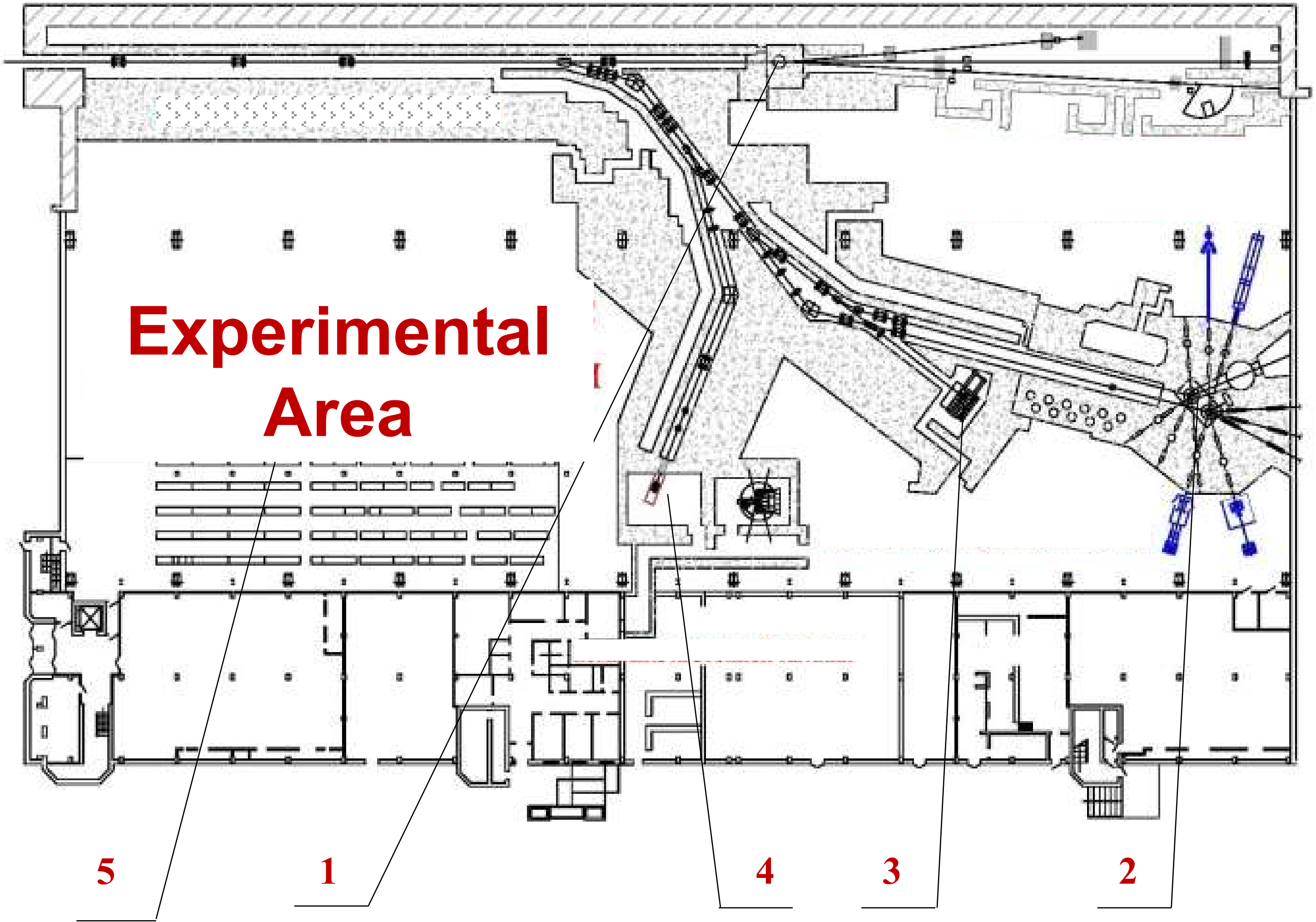
Output energy- 600 MeV

The main accelerator parameters

Parameter	Design	Maximum reached value	February, 2017
Particles	p, H^-	p, H^-	p, H^-
Energy, MeV	600	502	247
Pulse current, mA	50	22	16
Repetition rate, Hz	100	50 - 100	50
Pulse duration, μs	1 - 100	0.5 - 200	0.3÷200
Average current, μA	500	180	150

The nearest purposes are directed to maintenance and development of the accelerator

- Increase of the pulse repetition rate up to 100 Hz. It will allow to double the beam intensity ~ 300 μA.
- Increase of proton energy up to 500 MeV with obtaining of klystrons.
- Starting of H^- ions source operation for experiments and beam therapy.



1 - *Pulsed source of epithermal and resonance neutrons* with TOF spectrometers

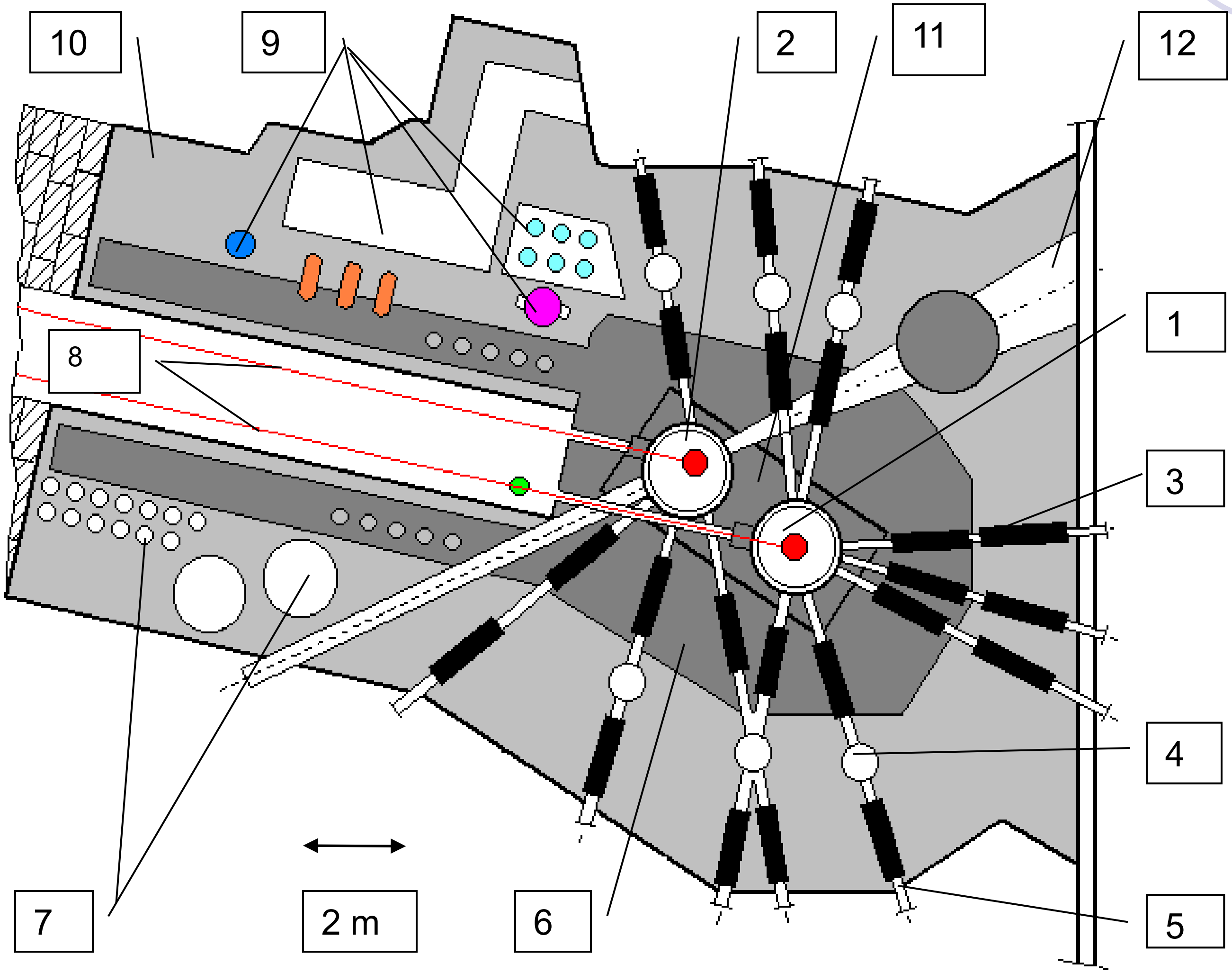
2 - *Pulsed source of thermal neutrons* with TOF spectrometers

3 – *100 t lead slowing-down neutron spectrometer (power up to 3 kW)*

4 - *Beam Therapy Complex*

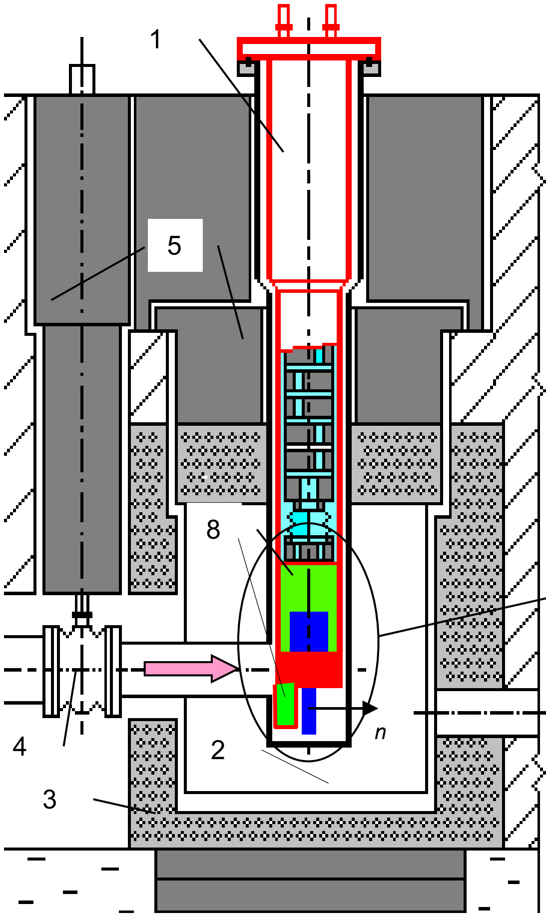
5 - *Power supplies and support systems* (special ventilation, water supply, storage of radioactive isotopes, temporal storages of nuclear waste and irradiated structural elements of experimental complex etc.)

Infrastructure of the neutron sources assembly

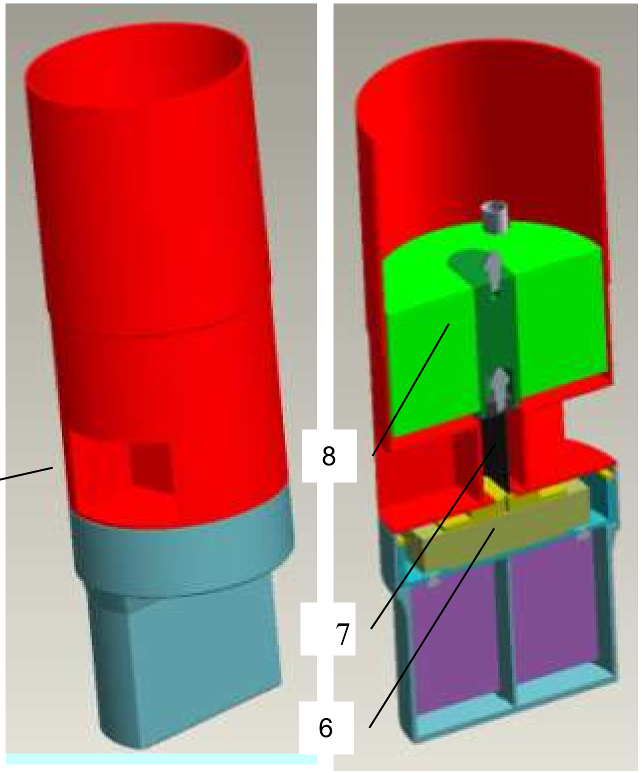


1 – cell of the neutron source,
2 - cell of ADS stand,
3 – neutron gates,
4 – vertical channels,
5 – neutron guides,
6 – iron shield,
7 – storages of modules,
8 – proton guides,
9 – equipment of the first water loop,
10 – heavy concrete shield,
11 – heat shield,
12 – the wide aperture channel.

Scheme of the pulsed neutron source with the new module



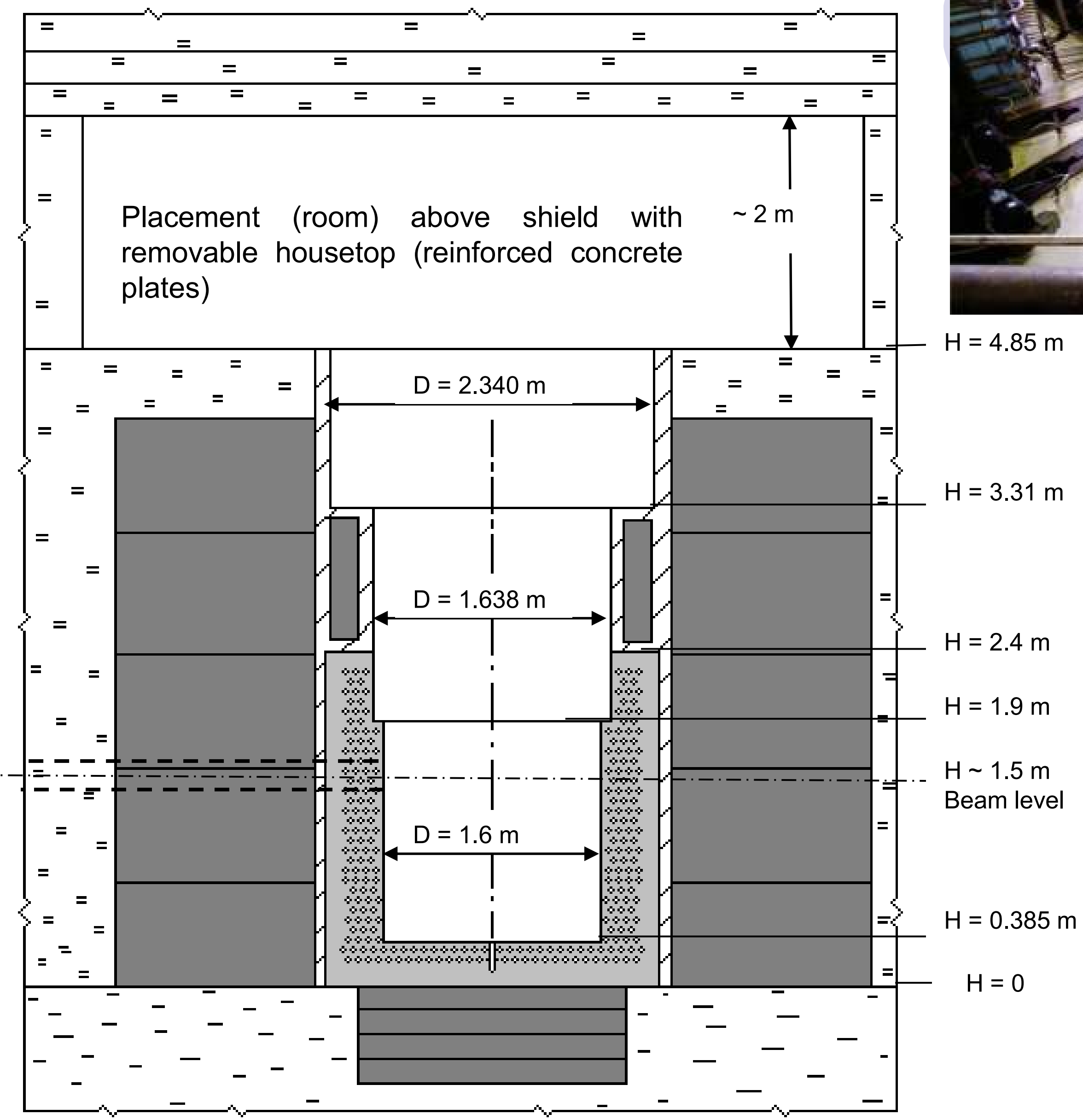
Position of a target module in the neutron source and the arrangement of basic elements



The enlarged lower part of the module containing a target, moderators and reflectors, cut of the lower part of the module.

Pulsed source of thermal neutrons is located in the first box of radiation shield and is intended for research in condensed matter physics.

The design of the neutron source is flexible and allows to use modules with different targets and moderators to carry out full replacement of all equipment of the central part for modernization of the source.



The scheme of the second cell in the shield and its basic sizes.

Placing of the second neutron source or ADS in the free boxing of the shield is planned.

Demo ADS - motivations and goals

According to experts, there is no other prepared experimental site in Europe with an operable high-current accelerator that would meet the requirements of research reactors.

ADS demonstration facility can be realized in a relatively short period of time and at relatively low financial cost (at least one order of magnitude cheaper than any alternative projects).

The spectral characteristics of the external neutron source of the INR RAS accelerator, with a proton energy of 300 - 600 MeV and with a beam energy of about 1.3 GeV, at relative maximum of neutron yield, is identical. It is allows to simulated the main neutron physical characteristics of full-scaled ADS on research ADS stand.

The study of different configurations of blankets and testing of structural elements of ADS.

The use of this stand as the second neutron source for condensed matter physics.

Expected maximal power of Research ADS depend upon proton current – I_P, multiplication coefficient – M, proton energy – E_P and type of target.

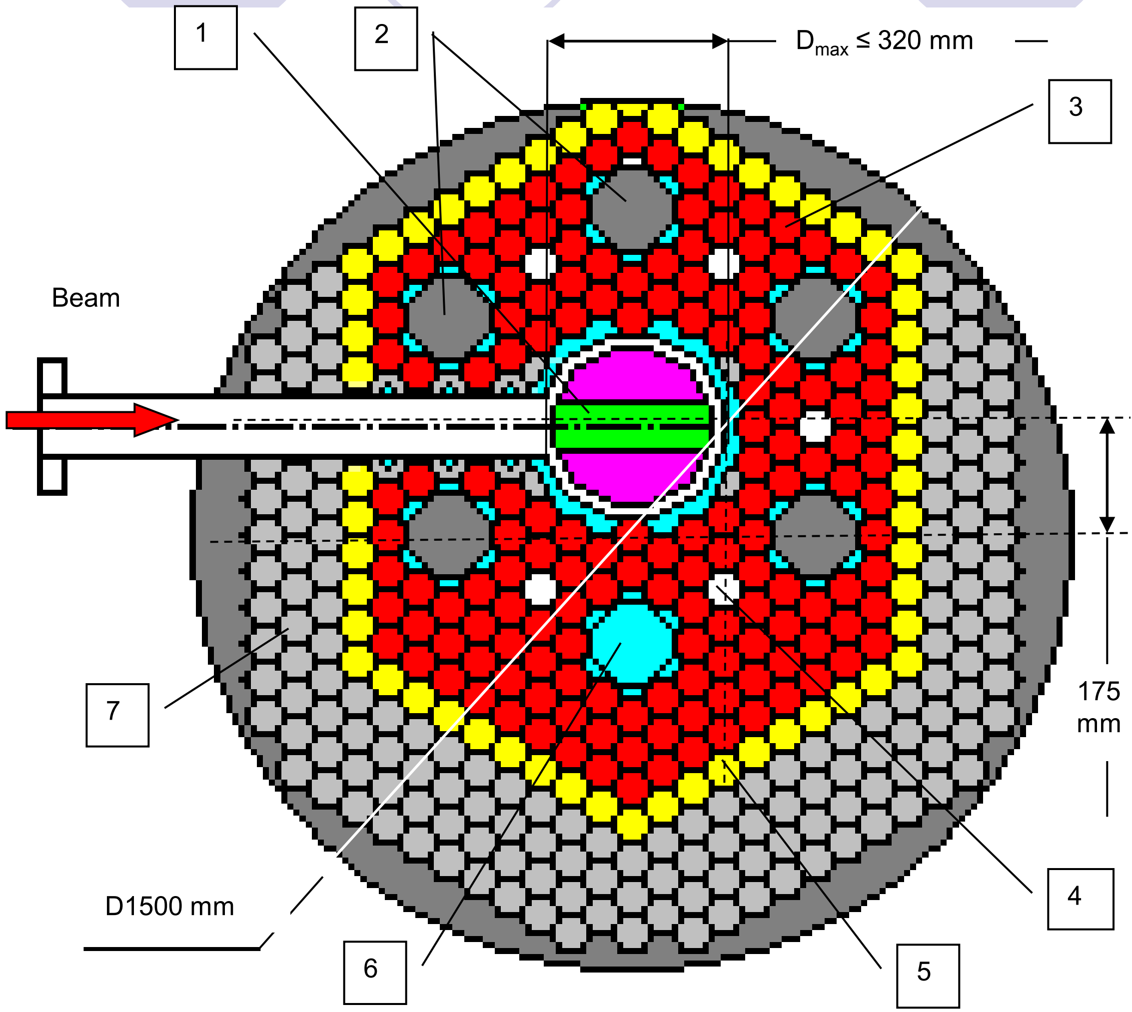
Average proton current I_P (μA)	Multiplication M (k_{eff})	Average power of blanket, P (MW), for proton 300–600 MeV							
		W (plates)				Natural uranium target with rod elements			
		300	400	500	600	300	400	500	600
100	20 (0.95)	0.73	1.16	1.66	2.08	1.02	1.62	2.29	2.91
	50 (0.98)	1.80	2.90	4.15	5.20	2.55	4.05	5.70	7.30
150	20 (0.95)	1.10	1.75	2.50	3.12	1.54	2.44	3.44	4.36
	50 (0.98)	2.75	4.40	6.25	7.80	3.85	6.10	8.60	10.9
200	20 (0.95)	1.47	2.32	3.32	4.16	2.05	3.25	4.58	5.82
	50 (0.98)	3.65	5.80	8.30	10.4	5.15	8.10	11.5	14.6
250	20 (0.95)	1.83	2.91	4.16	5.20	2.57	4.06	5.72	7.28
	50 (0.98)	4.60	7.30	10.4	13.0	6.40	10.2	14.3	18.2
300	20 (0.95)	2.19	3.5	5.00	6.24	3.08	4.86	6.86	8.74
	50 (0.98)	5.45	8.75	12.5	15.6	7.70	12.2	17.2	21.9
Neutron yield, Y (n/p)		~ 3.5	~ 5.6	~ 8	~ 10	~ 4.9	~ 7.8	~ 11	~ 14
Proton range – R, cm		~ 5.2	~ 9.2	~ 13	~ 17				
Target diameter - D ~ 1.3R,		~ 8	~ 13	~ 17	~ 21				
Importance of the primary neutrons, $\omega \approx 1.3$									

The main physical and technical requirements to demo ADS

The research ADS should provide:

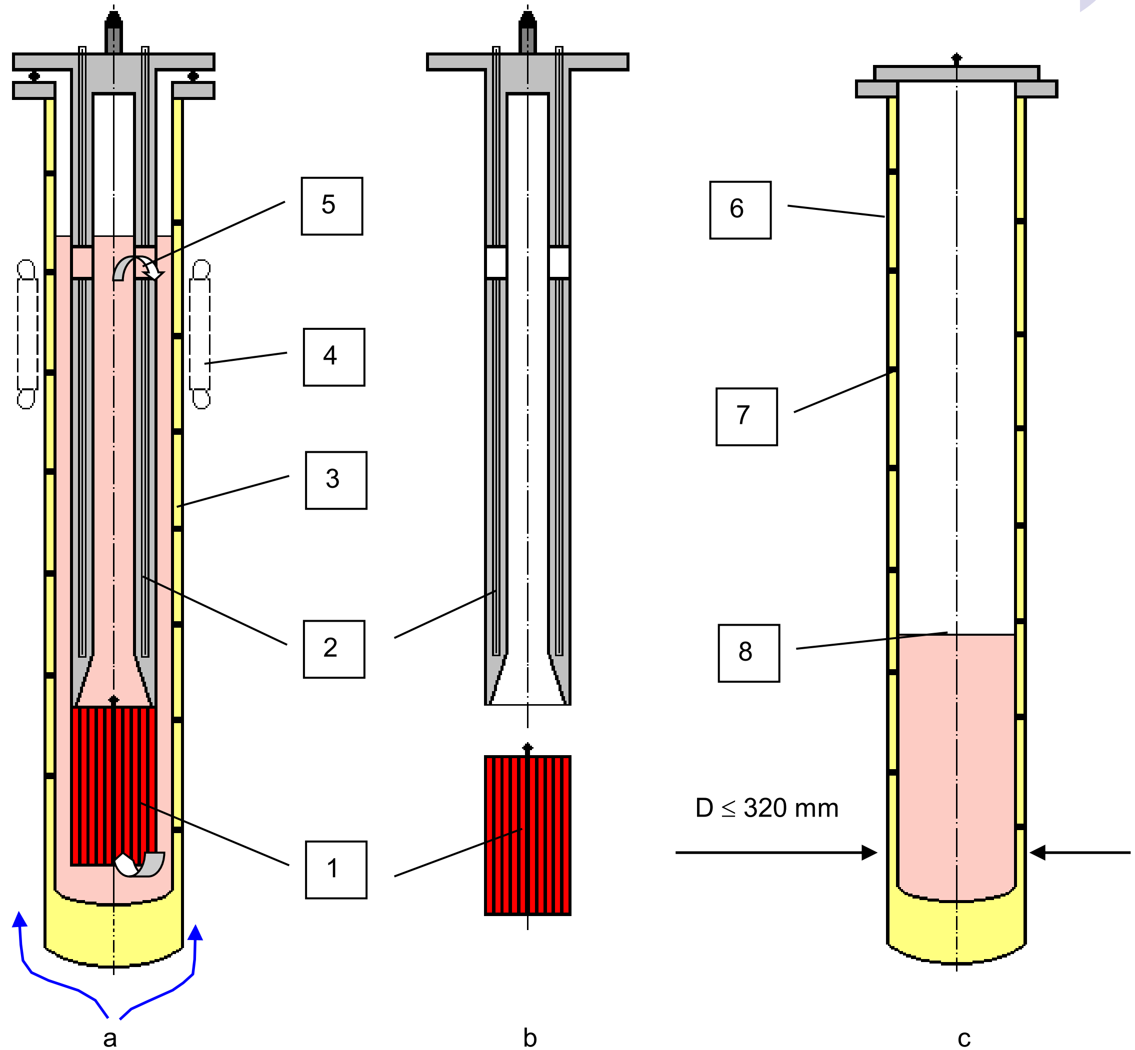
- Fast enough and convenient blanket reprocessing, target change and assembling of the other ADS configurations.
- The study of different fuel compositions with different contents of MA, Th...
- Fast access to the experimental channels of the blanket, the safe extraction of the irradiated heat-generating-assemblies.
- Fast core spectrum for the minor actinides burning.
- Thermal neutron spectrum for transmutation of long live fission products and for work of neutron guides.
- Stability of ADS elements to spontaneous interruptions of accelerator proton current (thermal shock).

Conceptual scheme of research ADS



1 –target module;
2 – hermetical PbBi modules with high enriched fuel and minor actinides or modules with MS (eg FLINAK (46,5 mol.% LiF, 11,5 mol.% NaF, 42 mol.% KF), which provides the highest solubility of U, Pu and MA);
3 – the cassettes of the water-cooled part of blanket with MOX fuel (~ 25% enr.);
4 – the module of controlled systems;
5 – decoupler (if it is required);
6 – traps of thermal neutrons (moderator) can construct in any place ;
7 – reflector.

Conceptual scheme of PbBi capsule



a – collected capsule,
b – cassette with fuel elements and displacer (removable elements),
c – body of capsule with Pb-Bi after removal of fuel cassette and displacer.
1 – cassette wit fuel;
2 – spreader of up-going and down-going flows with build-in heaters, the displacer of liquid metal and holder of fuel cassette;
3 - binary body; 4 – EM pump;
5 – direction of liquid metal flow;
6 – gas gap (~1 mm) of the heat barrier;
7 – spacer;
8 – level of liquid metal after removal of displacer and fuel cassette.

Functions of the basic elements

Module cooling is performed by water of the first loop through the lateral surface.

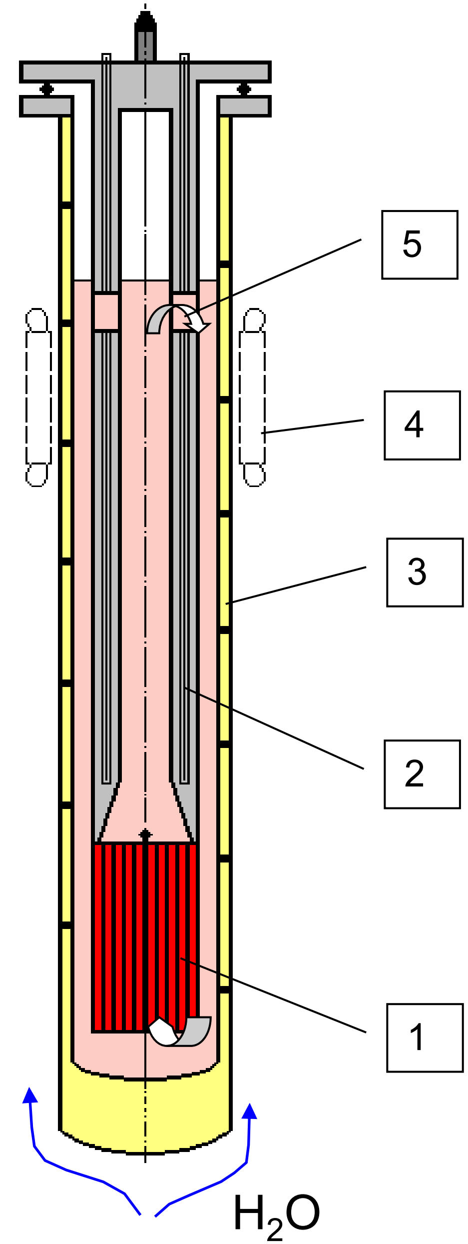
The inset should have double wall to maintain temperature regime and to be safety.

There is also a gas gap ~ 1 mm which acts as a heat barrier.

Each inset is equipped by its own heater (2) for:

- prescribed temperature level support and variation;
- preliminary melting of PbBi and heating of all ampoule after its delivery and its fixing in working position;
- partly compensation of the PbBi temperature decrease and for prevention its freezing caused by automatic increase of current loading in the case of accidental accelerator failure or beam loss.

Apart from these, an inset can have its own electromagnetic pump (4). It permits to vary temperature and velocity of PbBi coolant.



Some technical aspects of safety

Presuppose that:

- The PbBi modules will be manufactured and tested in IPPE (Obninsk ~ 70 km from Troitsk),
- PbBi modules can operate without support systems of coolant within ~ 2 years (findings of IPPE)
- The safety transportation of PbBi modules with fuel elements is carried out in the solid state (Obninsk → Troitsk → Obninsk, for post irradiation study).

Localization of flaw in SS casings (solidification of PbBi leakage by cold water) under operation of PbBi module is possible.

Probable use of the fuel elements of the IBR-2M (JINR, Dubna) as a prototype. This elements has specific character for preventing levitation of the fuel pills under the heat shock.

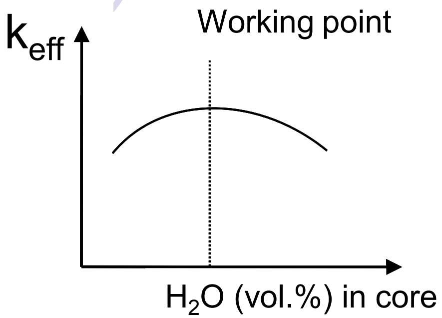
Some physical features of the ADS stand and the fast water cooled blanket

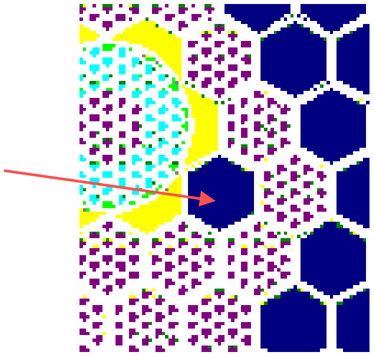
- High sensitive to density of water. Decrease density of water including boiling and full loss makes assembly deep subcritical.
- Water cavity (it appears after replaced a fuel cassette or PbBi capsule - refuelling) is the source of thermal neutrons. It is big positive effect of reactivity can makes assembly above-critical.
- Using of hafnium alloy for covering the fuel assemblies (cassettes) allows to exclude the positive effect of reactivity at replacement fuel assemblies and PbBi - insertions under water layer.

Nuclear safety and the other features

This two effects (the high sensitivity of the blanket to the concentration of water and the using of hafnium for the covering of fuel assemblies***) allow:***

- to make the blanket with intrinsic safety
- to change configuration of fast blanket and replace the irradiated heat-generating-assemblies and modules (target and PbBi) under a water layer as in the swimming pool-type thermal reactors;
- to create traps of thermal neutrons and moderators in any place of fast blanket;
- To create the effective control and safety systems on base neutron traps in any place of fast blanket. This can be the hollow displacers of water moving and floating by Archimed force. It is possible to displace water by gas. It is allow to avoid the mechanical movement of the regulators.

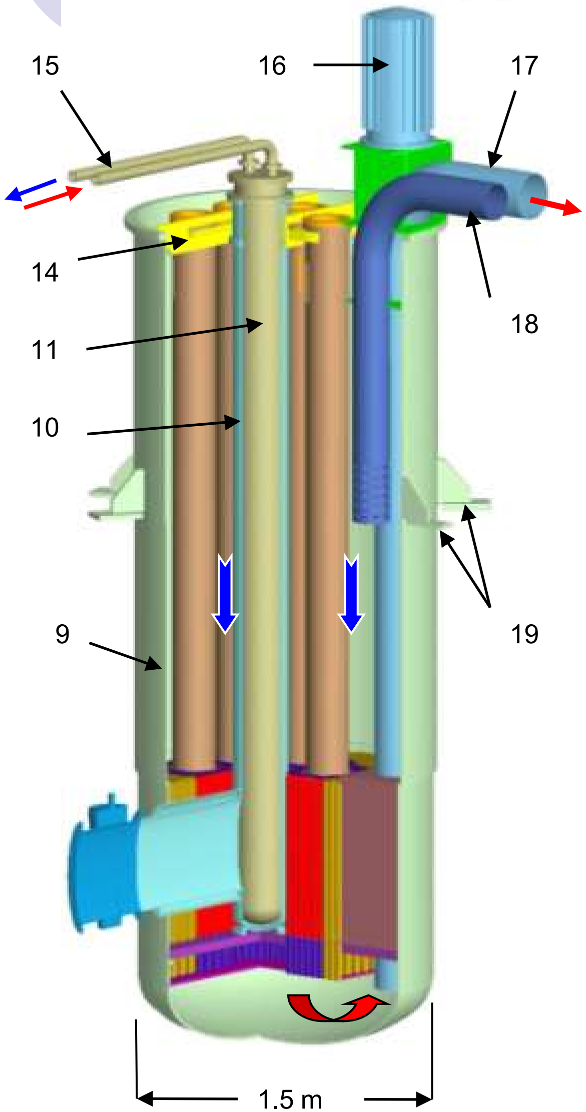


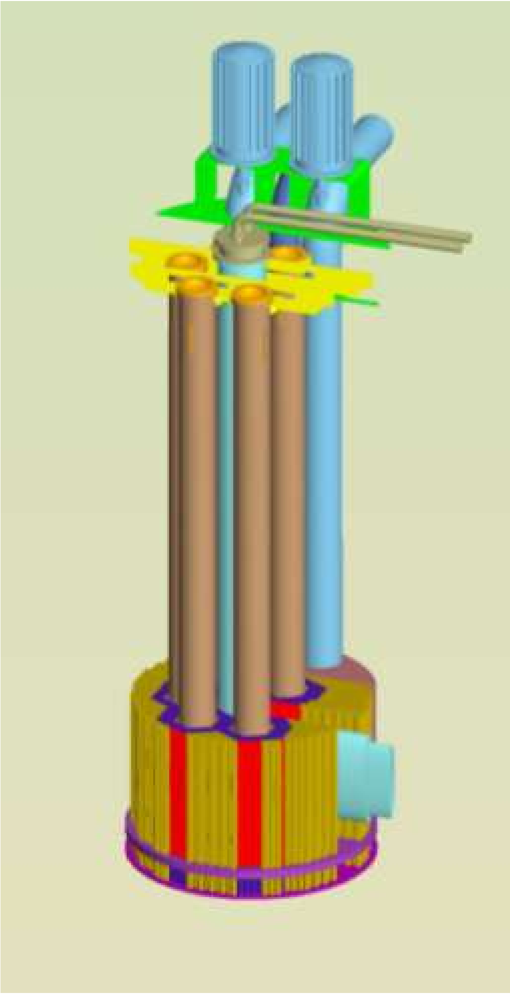


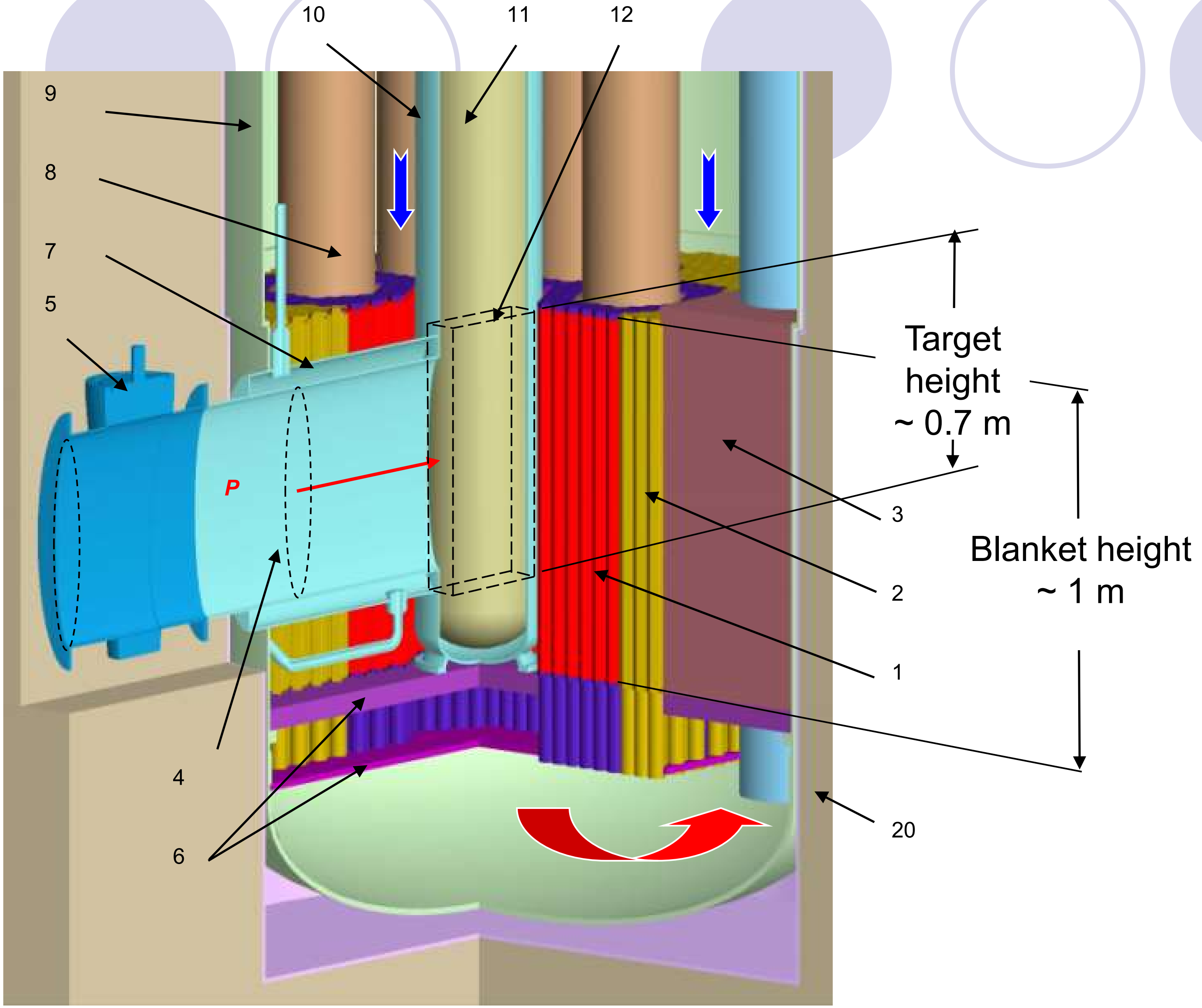
Research ADS and Pulsed Neutron Source

*The research ADS can work as the **pulsed** neutron source with coefficient of multiplication up to 20 if to **use** ^{239}**Pu** (main fission isotope with low fraction of delay neutrons) or ^{237}**Np**.*

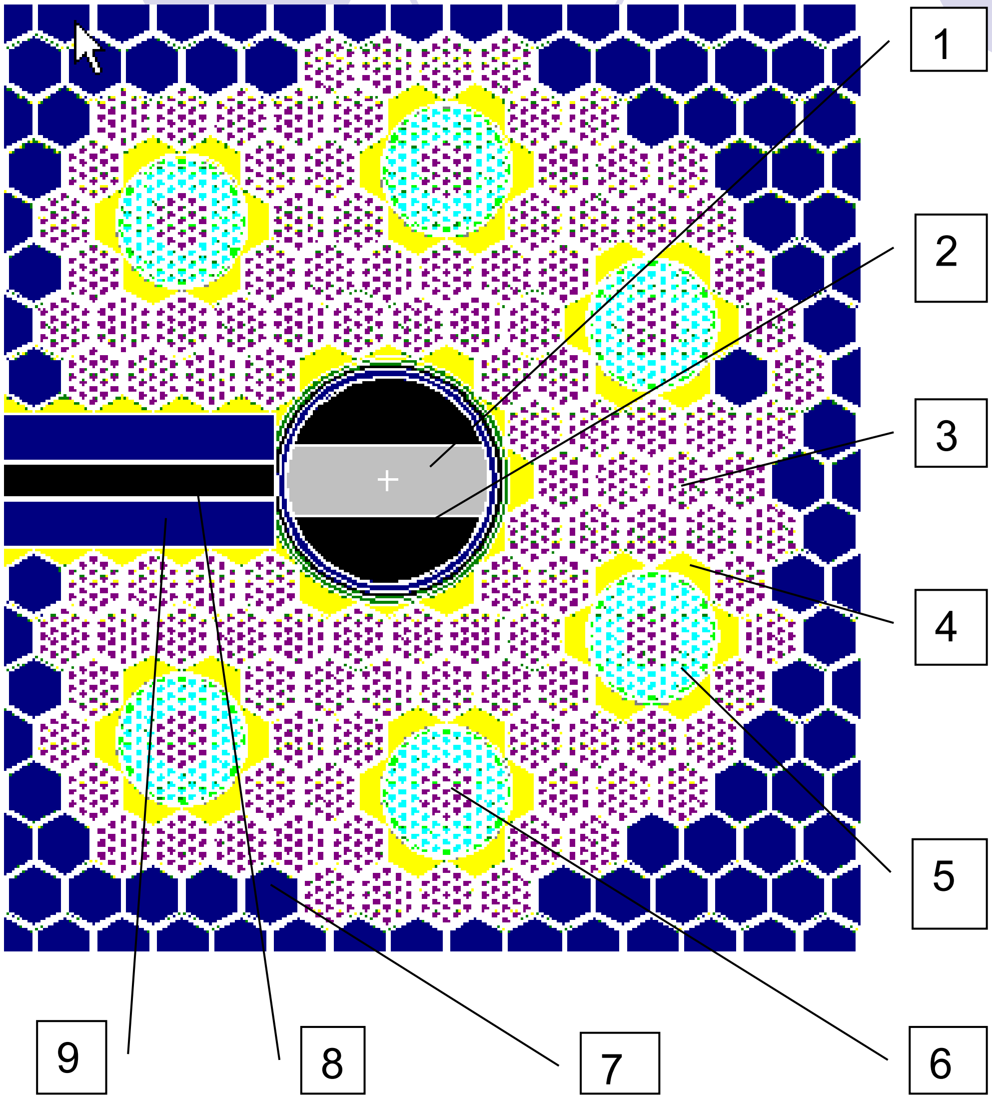
One of the possible ADS schemes






10
11
12
9
8
7
5
P
Target
height
~ 0.7 m
3
Blanket height
~ 1 m
2
1
4
6
20

Basic geometry for studying



1 – Target,
2 – hollow or Al displacer between target and cylindrical body of target module,
3 – Assembly of fuel elements (19),
4 – Water cavity between cylindrical body of PbBi module and the fuel elements assembles,
5 – PbBi module,
6 – 19 central fuel elements with NpO_2 in PbBi module (MA imitation),
7 – Elements of Al reflector.
8 – proton gaide,
9 – displacers and constructional elements between proton guide and blanket.

Varied parameters in calculations:

- The number of fuel assemblies in water-cooled parts of the blanket, which were replaced by Al inserts.
- The number of PbBi modules from six to three.
- The distance between the PbBi modules and the target.
- Percentage of PuO_2 in fuel elements in both parts of the blanket.
- The thickness of the Hf shell in the fuel assembly.
- The environment of the proton guide.
- The core height
- and others

Data from one of the ADS options. Parameter of blanket.

Fuel element dimensions (reactor - IBR-2M)

Outer diameter of fuel pills - 0.71 cm

Outer diameter of fuel element - 0.864 cm,

Inner diameter of fuel covering - 0.77 cm,

The gap between a fuel elements - 0.03 cm

Outside size of the fuel element assembly - 4.2 cm

The covering of cassettes – Hf -alloy, thickness - 1 mm

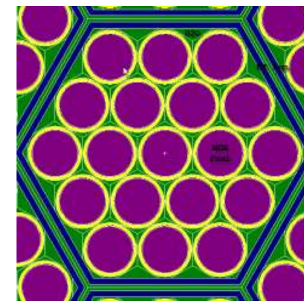
The number of fuel elements in the cassette - 19

Step of fuel elements - 1.03-1.04

Fuel is the mix of natural UO_2 (80%) with PuO_2 (20%).

The enriching of ^{239}Pu - 95%.

The number of assembles with MOX- fuel - 112



The number of PbBi modules 6

The module each replace the seven fuel assembles in water cooled part of blanket.

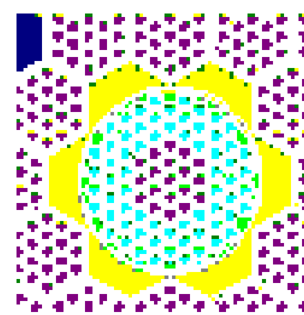
The total number of fuel elements in PbBi module - 95

Among them 19 central fuel elements with NpO_2 (for simulating minor actinides)

Others contain PuO_2.

The geometrical dimensions of the fuel elements are the same.

The height of blanket - 90 cm.



Reactivity effects

The wall thickness of cassette – 1.0 mm (Hf)

Replacement of one PbBi module by water *- 0.029 k_{eff} (- 2.9%)*

Replacement of one fuel assembly by water *- 0.001 k_{eff} (- 0.1%)*

Replacement of four fuel assembles by water *- 0.010 k_{eff} (-1.0%)*

The wall thickness of cassette – 0.5 mm (Hf)

Replacement of four fuel assembles by water *- 0.004 k_{eff}.*

The wall thickness of cassette – 1.0 mm (SS)

Replacement of four fuel assembles by water **+0.0057 k_{eff},**

The k_{eff} of ADS increase from 0.95 (Hf-wall) to 1.172 (SS-wall)

Assembling and rebuilding of the fast water cooled blanket is impossible under water layer.

Usage of the fuel assembles with 37 fuel elements for decrease of the volume fraction of hafnium in blanket and the additional neutron capture is expedient

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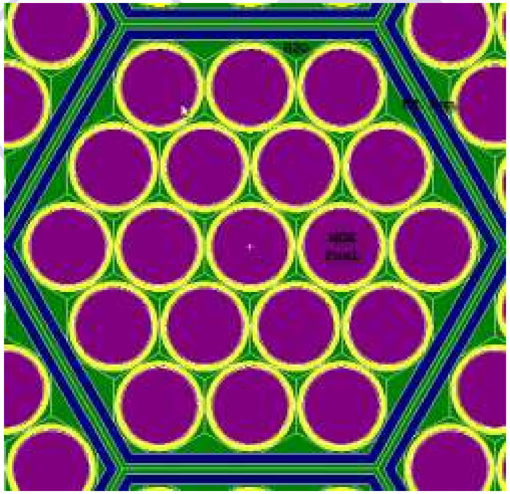
Maximal value of importance is equal ω = 1.35.

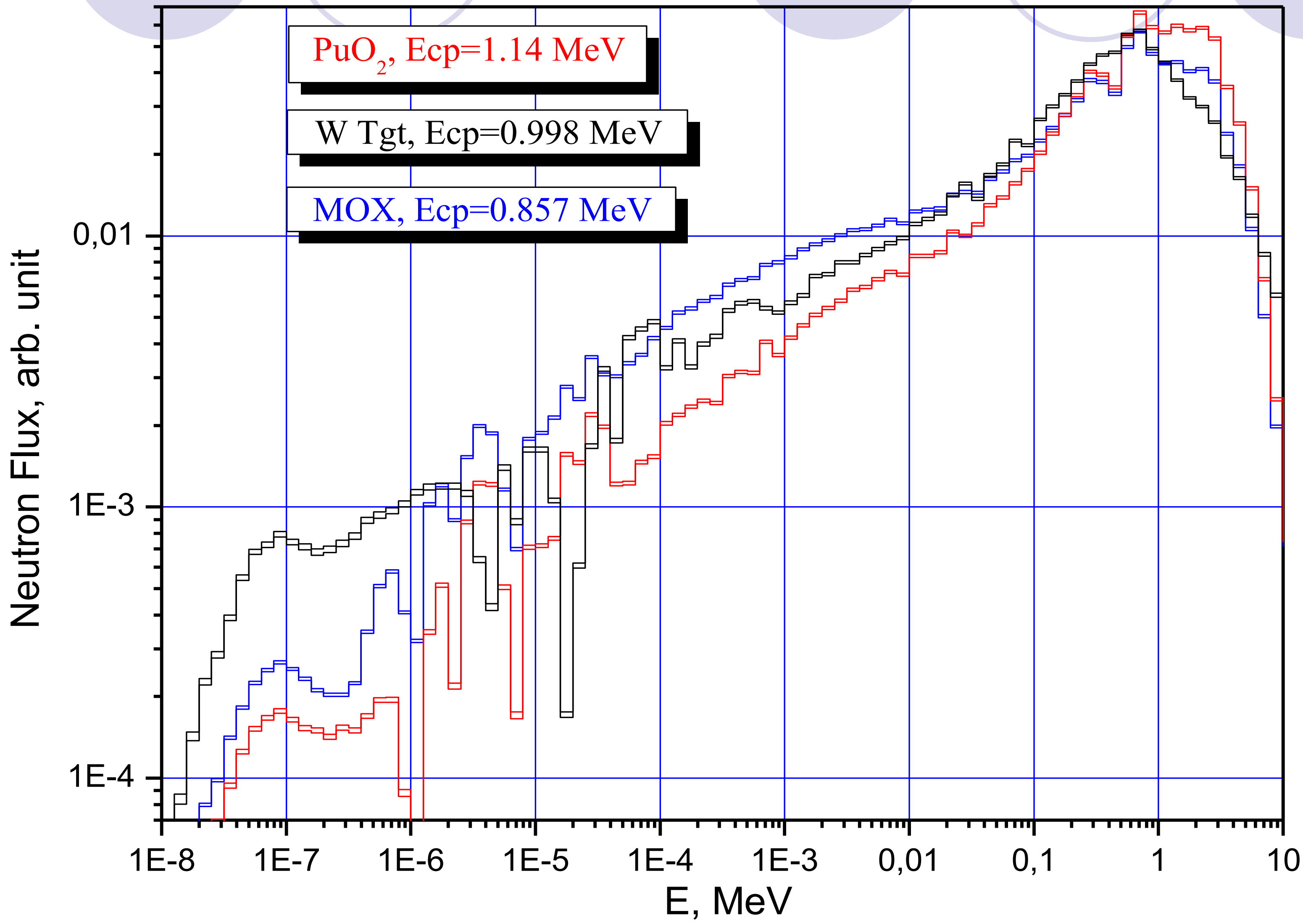


The fuel cassette scheme of the water cooled part of blanket

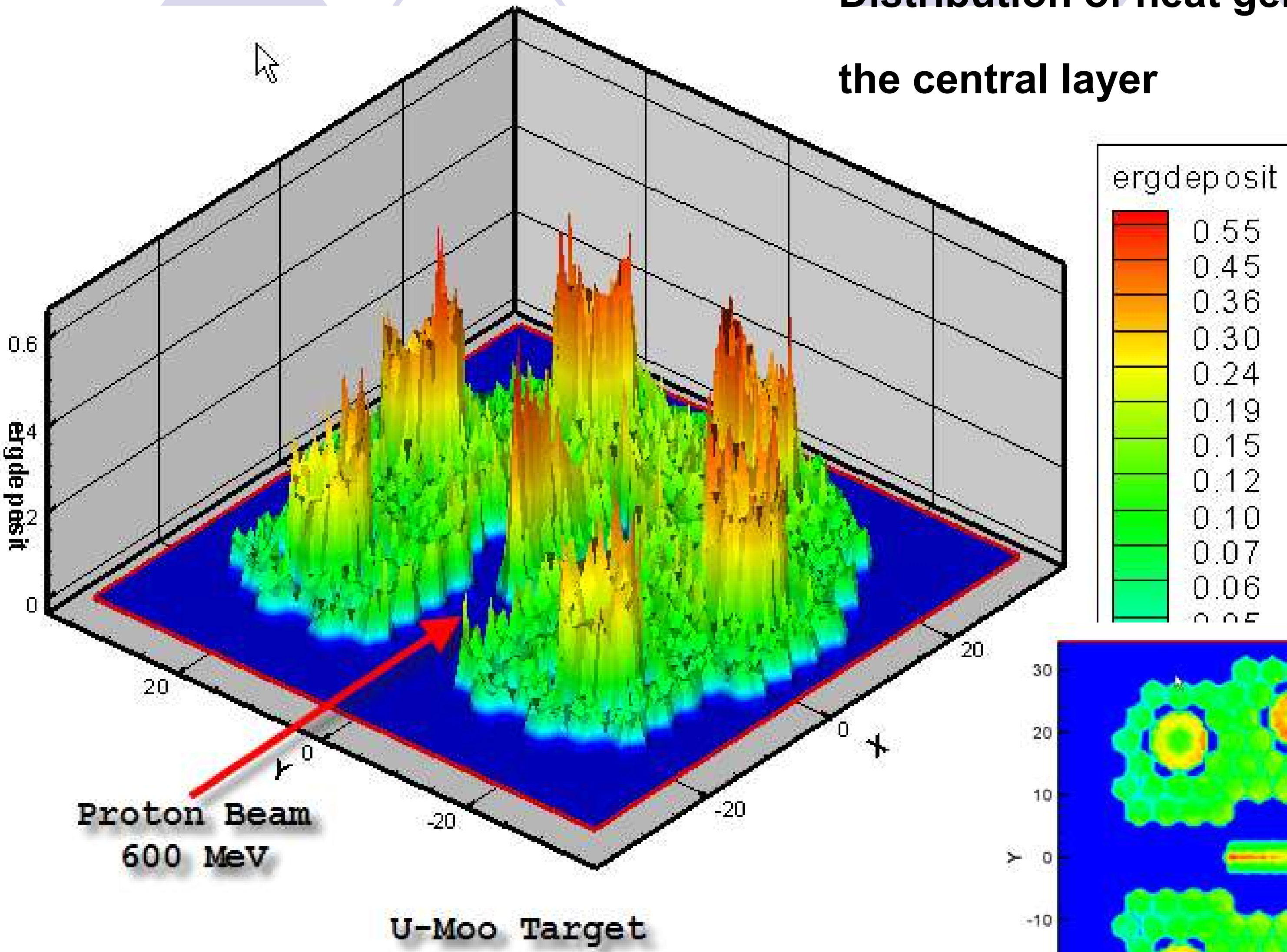
There are three parameters for minimization of the additional neutron capture in hafnium at keeping of the negative effect of reactivity:

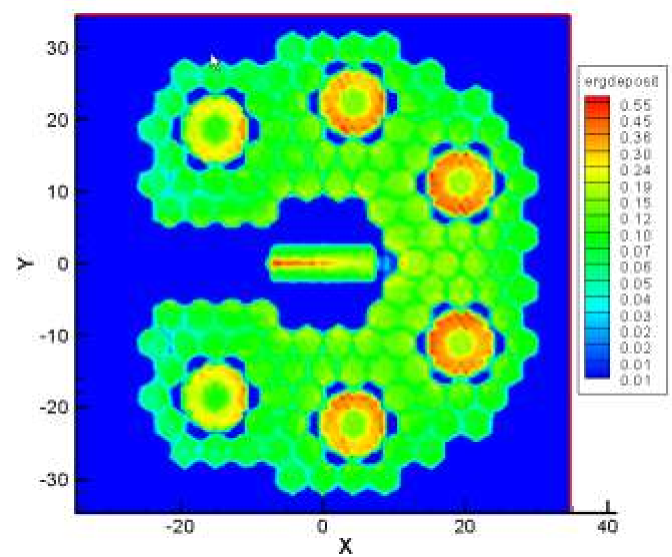
- Percentage hafnium in alloy. For ex. Hf(78%)Nb(2%)Zr(20%),
- The wall thickness of cassette,
- **The number of fuel elements in cassette**

Spectrum of the water cooled part and PbBi



Distribution of heat generation in the central layer



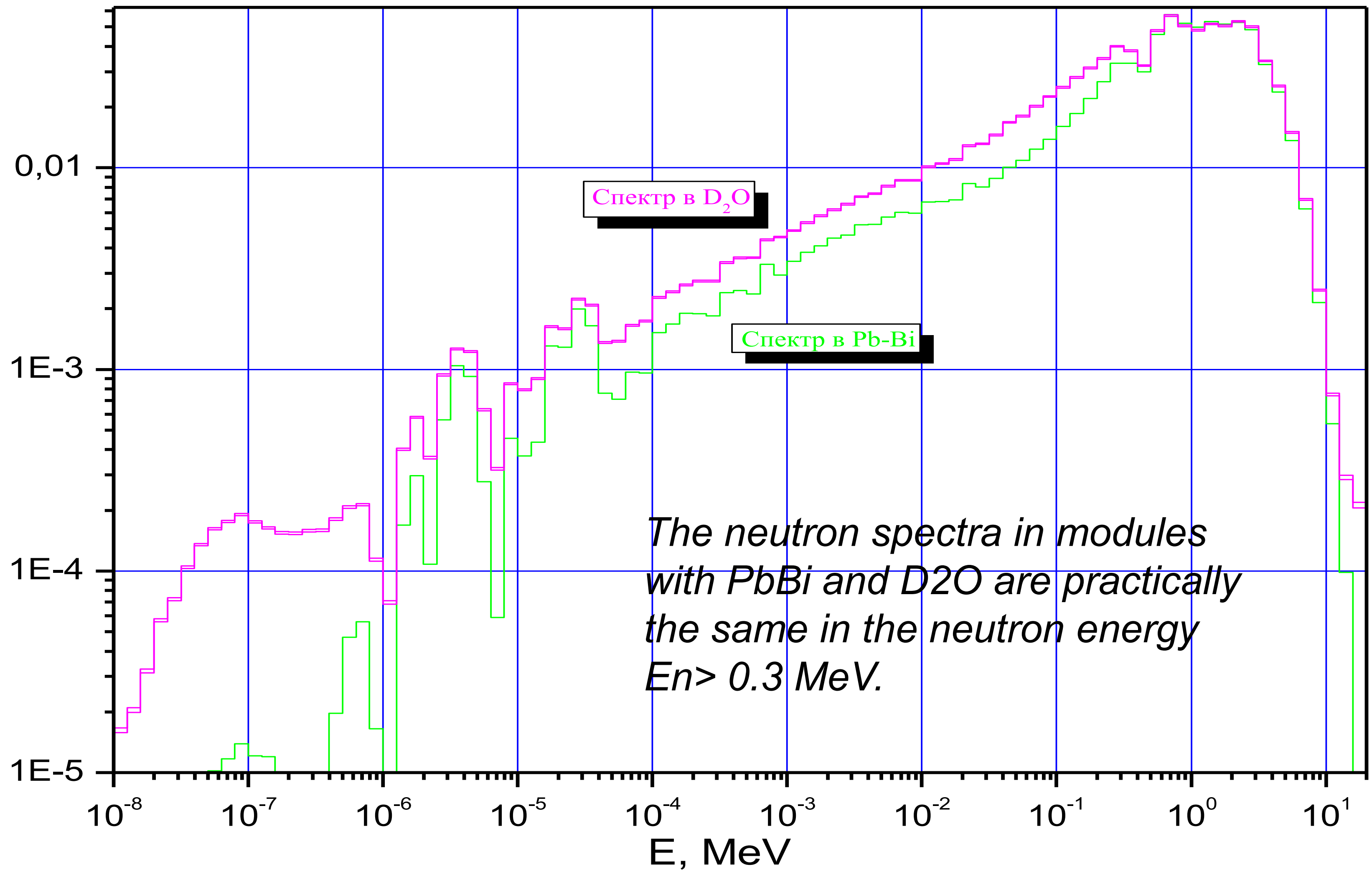


Comparison of ADS with PbBi и D_2O modules

Parameter	**PbBi**	**D_2O**
k_{ef}	*0.9542*	*0.9502*
Average energy (MeV):	0.835	0.801
Number of fissions in modules by neutrons:		
E = 0 – 0.645 eV	10.50 %	10.58 %
E = 0.645 eV – 100 keV	42.36 %	44.67%
E > 100 KeV	47.15 %	44.75%
Heat generation in:		
MOX (water cooled part)	**58.2%,**	**57.69%,**
PuO_2 (modules)	**41.8%**	**42.3%**

Number of fissions in the modules and parts of the water-cooled blanket is substantially the same. ***Manufacture and operation of the D_2O module are simpler.***

Comparison of ADS with PbBi и D_2O modules (spectrum)



Activity: directions of studies

We carry out the similar study for the molten-salt modules.
Melt of 46.5LiF–11.5NaF–42KF has the high solubility of Th and MA in the interval 550–700°C.

The investigation of the ADS with ring blanket and lead diffusor

Analyzing of possibility to use ^{237}Np
Reasons:
- To exclude usage of ^{239}Pu and high enriched uranium.
- ^{237}Np in target or blanket has low effective fraction of delayed neutrons – $\beta_{eff} << \beta$ that obeys to use the ADS facility as the neutron source. It provides with a low background between pulses.

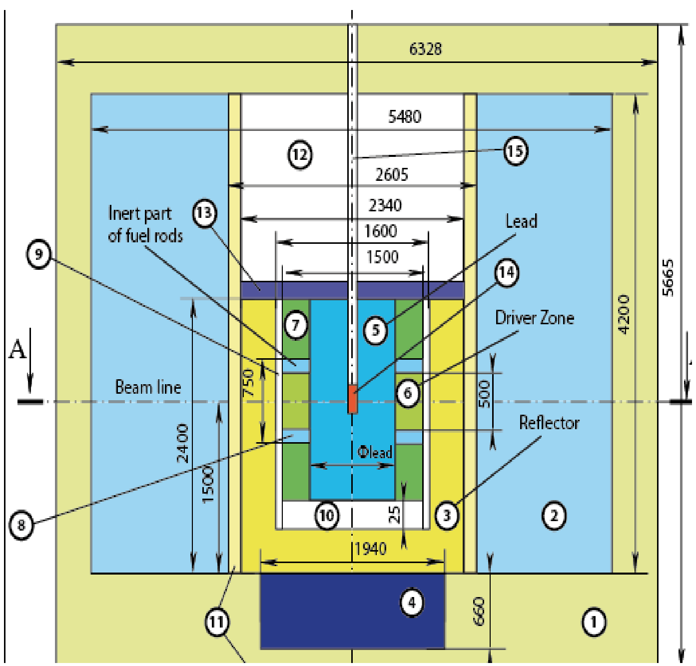
Transmutation of minor actinides (MA) just under the proton beam.

Estimation of the basic parameters of the ADS with ring blanket and lead diffusor

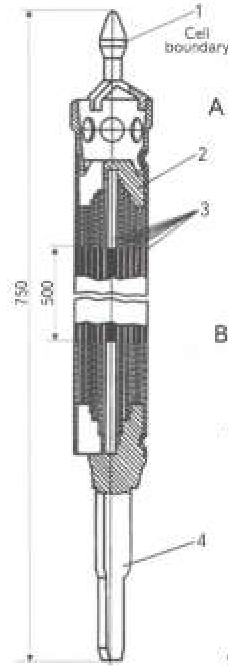
$k_{eff} = 0.98$
$E_{proton} = 300$ MeV
$I_P \sim 100$ μA (30 KW)

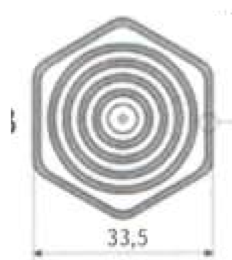
Total power – 1.17 MW

Core - 1080 KW
W target - 25 KW
Reflector - 41 KW (38 KW – γ-rays)
Lead - 24 KW (22.7 KW – γ-rays)

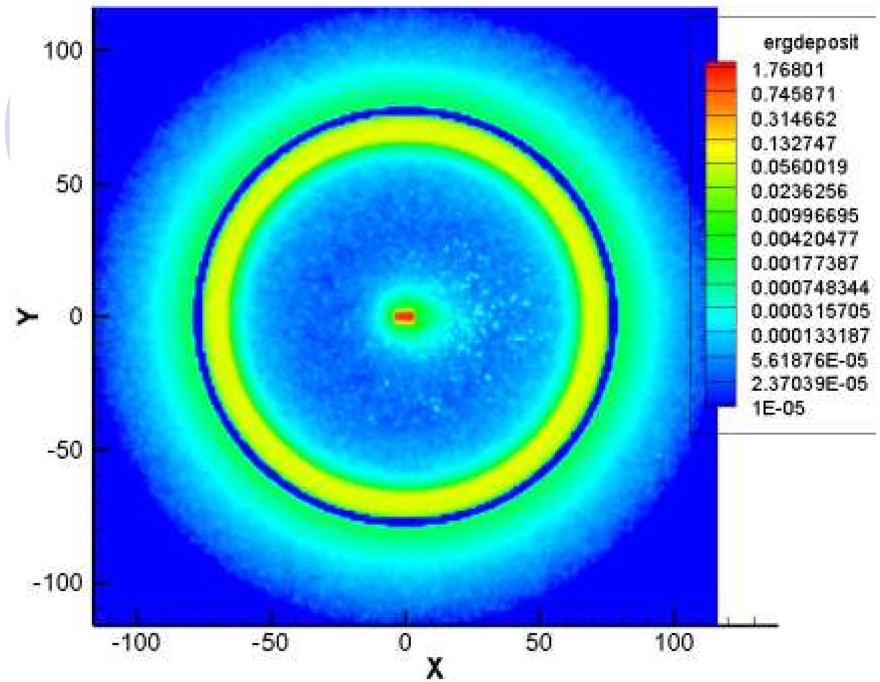


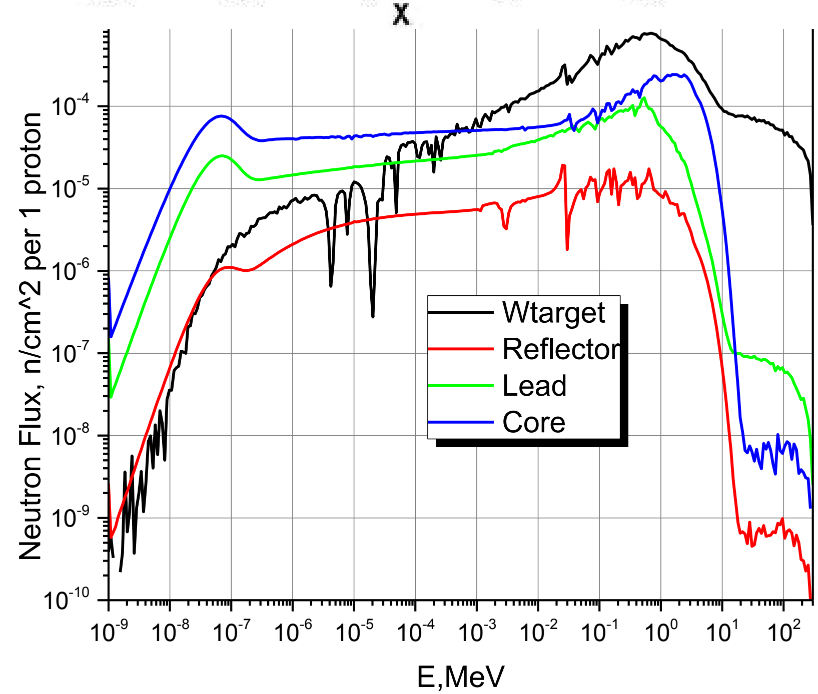
VVR-M5 (90% ^{235}U)





VVR-M5 FA based on U-Al fuel





The percentages of fissions caused by neutrons in the **thermal**, **intermediate**, and **fast** in ranges are:

(<0.625 ev): 85.65%

(0.625 ev - 100 kev): 13.31%

(>100 kev): 1.04%

The thickness of the annular fuel layer ~ 8.7cм

The standard fuel assemblies VVR-M2 (19.8% ^{235}U) or VVR-C (36% ^{235}U) follows use instead VVR-M5 (90% ^{235}U).

Conclusion

Existing infrastructure of the Neutron Complex gives a possibility to creation and operation of a ADS research facility

Modeling shows that practically all starting ideas may be realized. Among them the possibility for a system with intrinsic (natural) safety exists.

Further development of the project depends on the following events and restrictions:

- a result of the RAS status change,
- a situation with future development of new areas (and Troitsk) that are included in the territory of Moscow