CONSTRUCTION OF THE SUBCRITICAL ASSEMBLY WITH COMBINED NEUTRON SPECTRA DRIVEN BY PROTON ACCELERATOR AT PROTON'S ENERGY 660 MEV FOR EXPERIMENTS ON LONG LIVED FISSION PRODUCTS AND MINOR ACTINIDES TRANSMUTATION

Project ***S**ubcritical* ***A**ssembly* ***at*** ***D**ubna* *(**SAD**)*
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PROJECT APPROVAL PAGE

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NOMENCLATURE:

LIST OF SYMBOLS:

k_{eff}	Effective multiplication coefficient

LIST OF DEFINITIONS:

AC	Active core
ACS	Automatic Control System
ADCS	Automatic Dosymetry Control System
ADS	Accelerator Driven System
ALI	Annual Limit on Intake
DCS	Dosymetry Control Subsystem
EDR	γ- Radiation Exposure Dose Rate
FA	Fuel Assembly
FE	Fuel Element
FEICS	Fuel Elements Impenetrability Control System
FP	Fission Products
FR	Fast Reactor
IC	Ionization Chambers
LLFP	Long-Lived Fission Products
LWR	Light Water Reactor
MA	Minor Actinides: all actinides heavier than U except Pu
MCL	Maximum Concentration Limit
MOX	Mixed Oxide fuel
PC	Personal Computer
RW	Radioactive Waste
SAD	Subcritical Assembly at Dubna
SF	Spent fuel
TRU	Transuranic Elements

1 Introduction

After unprecedented development of a nuclear physics and technology in the first half of 20-th century seemed, that the processes of fission in nuclear reactors and synthesis in thermonuclear ones will provide mankind with practically inexhaustible source of cheap and enough safe energy. To the end of the last century it became clear, that the thermonuclear power engineering as is far from creation of production plants, as well as 50 years back, and atomic engineering at all advantages hides in itself enormous dangers and main of them - radioactive waste. So the total amount of radwaste on the nuclear complex plants of Russia makes size of more 600 millions cubic meters with activity more than 10^{20} Bk.

The radioactive waste derivated at all technological stages of nuclear fuel cycle – at production and processing of uranium ore, at manufacture and usage of nuclear fuel, regeneration of the irradiated fuel, decommissioning of nuclear objects. For the sake of justice it is necessary to mark, that the radwaste derivated not only in nuclear fuel cycle, but also in traditional thermal power engineering. So in a petroleum industry of USA in 70th – 80th years of the last century was annually derivated about 450 thousand tons of the radwaste and for 20 years total amount has made more than 8 millions tons the similar situation took place and for the oil refining complex of Russia [1]. However all sources of the radwaste irrelevant with nuclear fuel cycle and military applications, make some percents from total volume of radwaste.

At nowadays none of the countries transferred to usage of technologies permitting completely remove all concerns connected with spent nuclear fuel and the radwaste.

1.1. *Strategies of RW treatment (open or partially closed fuel cycles)*

1.1.1 Basic radiative and thermal characteristics of the SF [2]

The complexity of problems connected with SF treatment caused, first of all, by extremely high radioactivity reaching millions Curie per ton, considerable heat release after extracting from reactor, presence in SF of considerable quantity of fissile materials. Serious danger represents also toxicity of some radionuclides contained in SF. To have the flavor of some basic problems cause by SF one can look at the following tables:

Table 1: some characteristics of the SF from Russian power reactors [3]

Parameter	Reactor		
	VVER-440	VVER-1000	RBMK-1000
Electric power, MW	440	1000	1000
Fuel load UO_2, t	40	70	192
Number of FA	349	163	3386
Burnup, GW·day/t	30	40	20
SF specific activity: – after irradiation, 10^{18} Bq/t – after three years storage, 10^{16} Bq/t	 6,6 3,0	 9,6 4,1	 4,2 2,0
EDR at 1 meter distance from 1 kg of SF: – after irradiation, 10^{-4} A/kg – after three years storage, 10^{-8} A/kg	 14,1 214	 20,38 322,5	 8,77 136
Reactor campaign, year	3	3	3

Residual heat after storage, year:			
– 0,5	1,8	9,1	0,59
– 1,0	1,0	5,2	0,34
– 3,0	0,32	1,7	0,1
– 10,0	0,11	0,58	0,034

Table 2: specific activity of the FP and TRU in SF [4]

Nuclide	Half-life	Specific activity, 10^{15} Bq/t	
		Thermal reactor*	Fast reactor**
FP			
^{144}Ce	284,893 day	33	47,36
^{95}Nb	34,975 day	32,15	98,42
^{95}Zr	64,02 day	19,39	77,7
^{106}Ru	373,59 day	16,98	47,7
^{89}Sr	50,53 day	7,92	23,6
^{137}Cs	30,07 years	3,96	4,04
^{147}Pm	2,6234 years	3,85	13,06
^{90}Sr	28,79 years	2,84	1,61
TRU			
^{241}Pu	14,35 years	4,29	22,2
^{242}Cm	162,8 day	0,71	2,42
^{238}Pu	87,7 years	0,103	0,414
^{244}Cm	18,1 years	0,0925	0,046
^{240}Pu	6,564E3 years	0,0178	0,016
^{239}Pu	2,411E4 years	0,0122	0,13
^{241}Am	4,322E2 years	0,0063	0,058
^{243}Am	7,37E3 years	0,62E-3	1,85E-3
^{242}Pu	3,733E5 years	0,052E-3	0,48E-3

* - LWR, 1000 MW electric power, load 90 tons enriched uranium, burnup 33 GW·day/t, specific power 30 MW/t, storage 90 days

** - FR , 1000 MW electric power, load 50 tons (AC + blanket: uranium + plutonium + depleted uranium), average burnup 33 GW·day/t, average specific power 58 MW/t, storage 30 days

Table 3: specific activity and heat release of the irradiated fuel with burnup 33 GW·day/t (PWR)[5]

Storage time, days	90	150	365	3650
FP specific activity 10^{18} Bq/t	22,9	16,2	8,214	1,17
Specific heat release, 10^{4} W/t	2,71	2,01	1,04	0,106

Dose rate – one of the main characteristics of the irradiated fuel. Approximately on 95% dose rate is caused by γ- radiation of the FP, remaining is due to actinides. Short-lived isotopes of zirconium, niobium, molybdenum, technetium, ruthenium, rhodium, iodine, xenon, cesium, barium, lanthanum, cerium, and praseodymium import the greatest contribution to a dose rate. Dose rate significantly decreases during storage time. In three years the dose rate makes approximately 1/600 parts from the just unloaded fuel. The total radioactivity of the FP varies in time similarly though fallout of its value is slower. Next figure (Figure 1) illustrates the time dependence of the irradiated oxide fuel toxicity after burnup 50 GW·day/t. This value is compared with the toxicity of the same fuel after 4 years storage and 99.9% uranium and plutonium separation. The latter is decomposed on the contributions from separate actinides and FP.

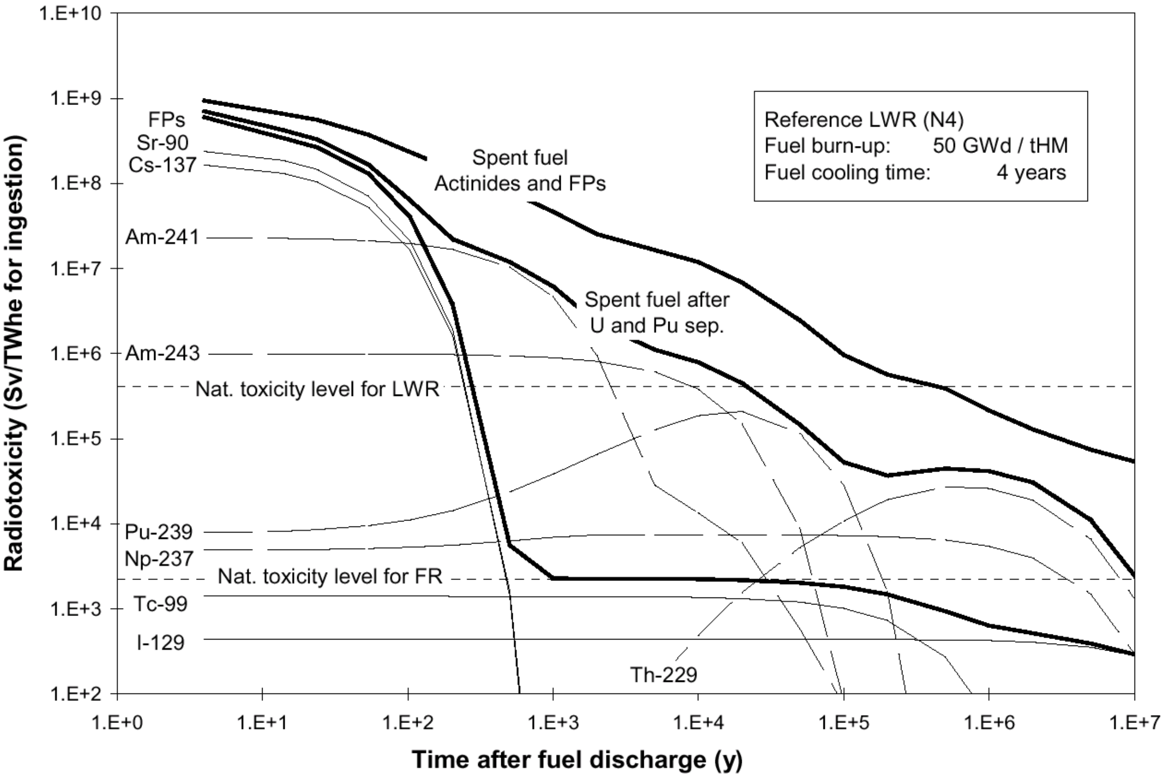

Figure 1: radiotoxicity of the irradiated LWR fuel

One can see, that in the beginning irradiated fuel activity is determined in main by the short-lived FP, and after several hundreds years of storage – actinides. Through some hundreds thousand years the irradiated fuel activity is reduced down to an equilibrium level of natural uranium used at manufacture of fuel. The irradiated fuel reprocessing with extraction of uranium and plutonium essentially reduces this period down to several tens thousand years.

The greatest contribution to radioactivity of irradiated fuel with three-years storage time comes from: ^{137}Cs + ^{137m}Ba (24 %), ^{144}Ce + ^{144}Pr (21 %), ^{90}Sr + ^{90}Y (18 %), ^{106}Ru + ^{106}Rh (16 %), ^{147}Pm (10 %), ^{134}Cs (7 %), the relative contribution from ^{85}Kr, ^{154}Eu, ^{155}Eu is equal approximately 1 % from each isotope.

Before the beginning of an irradiation 1 ton of uranium standard fuel of a reactor VVER-1000 contains 44 kg ^{235}U and 956 kg ^{238}U. At the end of three-years campaign the uranium fractionally burns out, leaving 40 kg of FP and 11 kg of actinides, in which about 10 kg of plutonium, 0.6 kg of neptunium, 0.2 kg of americium, 60 grams of curium. The contribution of actinides to the total gamma dose rate at the moment of fuel discharge is unimportant and does not exceed 5 %. Their relative contribution to the total radioactivity is much higher – about 20 %. Approximately 4/5 of all actinides are α- emitters and about 1/5 β- emitters. Average energy of γ- quanta of actinides mixture is 5-7 times lower than average energy of γ- quanta from FP mixture. A noticeable role plays low energy X-radiation with energy from 20 up to 100 keV. Some actinides are free to spontaneous fission (Figure 2). The neutrons of spontaneous fission do not import the noticeable contribution to the neutron flux density at the operating nuclear reactor, however their presence in SF applies essential restrictions on the SF recycling technology.

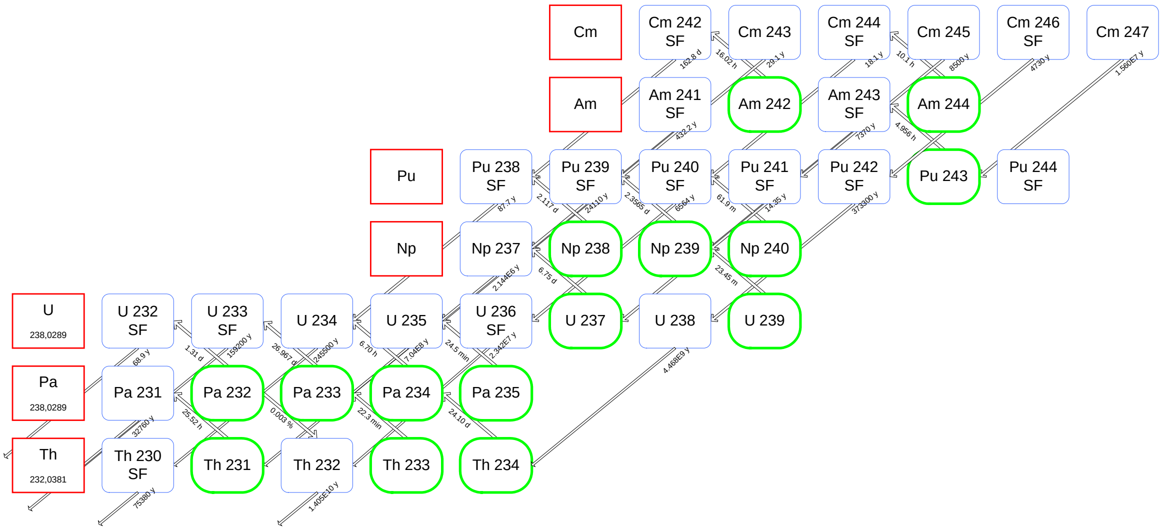

Figure 2: table of actinides involved in nuclear fuel cycles

It is necessary to mark also extreme toxicity of the majority of actinides. MCL for actinides in water and air, as a rule, is some thousand time less, than for FP. At essentially higher half-lives of actinides this circumstance is extremely essential in the long-term strategies of SF treatment.

1.1.2 **Storing of the unprocessed SF (Once Through Fuel Cycle)**

Now the OFC strategy is accepted, in particular, by Department of energy of USA and is implemented as immediate stacking of SF elements in metal canisters in deep geological formations. It causes criticism of the experts in connection with danger of distribution of nuclear materials and absence of safety warranties during long-time (some thousand years) storage of the SF [6,7,8]. Thus the situation with main SF storage facility in USA (Yucca-Mountain) is those, that capacity of this facility will be exceeded already to the middle of XXI century, so it is necessary to United States already now to select the strategy of SF treatment. Alternatives are the possibilities of construction of the new centralized storage facility near to existing, of transition to dry stacking of the SF near to nuclear plants or development of technologies of SF reprocessing and transmutation [9].

1.1.3 **SF Recycling**

Other countries with a developed nuclear power production (Great Britain, Russia, France, Japan) in this or that sort realize SF processing, recycling of uranium, plutonium manufacturing from the processed materials fuel elements their reuse in LWR which form a basis of a global nuclear power production. The radwaste obtained in nuclear fuel cycle, is separated and disposed with traditional technologies. The most effective structure of spent fuel and radwaste treatment is created in France, where the multicomponent nuclear power technology is implemented. It includes LWR power reactors, fast reactors - "burners", complexes of spent fuel and radwaste processing.

1.1.4 **Radwaste transmutation**

The idea of nuclear transmutation of elements is completely not new; it counts almost as much of years, as nuclear physics does. The first result on transformation of macroscopic quantities of one element into another was reported by E. Rutherford in 1919[10]. For transmutation it is possible to use practically any nuclear radiation, including gamma quanta, however neutrons give the greatest efficiency due to absence of a Coulomb barrier and high cross sections. Now some variants of the concept of the radwaste transmutation are designed. As a rule, all these concepts contain in a basis the approaches implemented in the French nuclear complex, where the essential role belongs to fast reactors – "burners" or Japan with the double-strata scheme of spent fuel processing. At the same time in all concepts of the radwaste transmutation the essential role is assigned to subcritical fast systems driven by proton accelerators (ADS), in which long-lived components of the radwaste are incinerated, first of all, minor actinides – isotopes of americium, curium, and also, neptunium – which isotopes have essentially smaller part of delayed neutrons in comparison with fission neutrons. Except minor actinides subcritical systems are able to incinerate the LLFP, such as ^{99}Tc and ^{129}I, representing the greatest danger from the point of view of long-term (some thousand years) safe storage of the radwaste. Without application of the subcritical systems on the basis of high-current proton accelerators, it seems will be not possible completely incinerate minor actinides. The question is that for these isotopes the part of delayed neutrons is very small that doesn't allow providing steady operation of a usual critical reactor. Thus it is impossible to construct a steadily operating critical reactor with fuel consisting more, than on 15 - 20 % from minor actinides.

So, the concepts of the radwaste transmutation, which have folded for today, look like this[11] (Figure 3): the traditional nuclear power production on LWR is saved. After spent fuel processing in all schemes the plutonium is recycled and is routed or back in LWR (Japan, EU – CERN scheme, France), or in subcritical transmuting systems – (USA). Minor actinides and the long-lived fission products in all concepts are processed in subcritical systems. The differences of the concepts are stipulated by the folded structure of nuclear industry of the country (USA, France, Japan) or interest to new directions of nuclear power engineering (introducing into fuel cycle ^{232}Th). The important moment in all schemes is the possibility of incineration in subcritical systems or fast reactors of plutonium from warheads dismounted according to the international treaties.

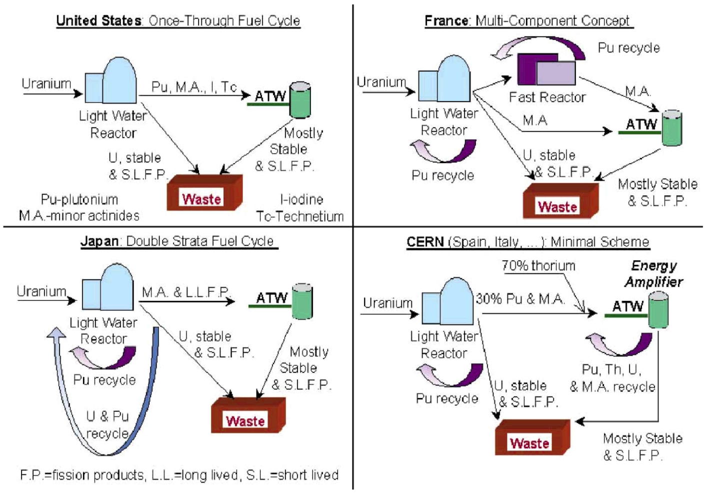

Figure 3: Multi-national ADTT Concepts. Key: U – uranium, Pu – plutonium, M.A. – minor actinides, I – iodine, Tc – technetium, L.L. – long lived, S.L. – short lived, F.P. – fission products

2 **Basic data, composition**

2.1. ***Basic data of the SAD facility project***

SAD basic features are determined with “Phasotron” JINR proton accelerator and usage as a basic fuel elements (FE) serially released in Russia MOX FE of a BN-600 reactor. Rather modest proton current of accelerator (maximum value is 3.2 μA) and correspondingly, power released at heavy target, determine the net thermal power of the installation. That occurs because of fixed effective multiplication coefficient k_{eff}[1], which will be equal to 0.95. Thus, the installation described in the project, is the prototype of the future subcritical installations of an industrial scale, which projects now are actively considered in all countries with a developed nuclear power engineering, for example project of installation MYRRHA with power of a proton beam about a megawatt and net thermal power of 10 – 25 MW [12].

Project basic features are listed in the following table (Table 4).

Table 4: SAD installation basic data

Thermal power	15 ÷ 20 kWt
Protons energy	660 MeV
Beam power	0.75 ÷ 1 kWt
Proton beam / target orientation	Vertical
Fuel elements orientation	Vertical
Criticality coefficient	$k_{eff} <0.95$
Fuel	MOX, $UO_2 + PuO_2$
Cladding tubes maximum temperature	400° C
Spallation target	Replaceable: Pb, Pb-Bi, W
Reflector	Pb
Coolant	Air

Proton accelerator parameters are listed in the Table 5.

Table 5: JINR Phasotron parameters

Intensity of the extracted proton beam:	3.2 μA ($1.997\cdot10^{13}$ protons/s)
Beam emittance:	$\Sigma_x = \pi(5.1 \pm 2.3)$ cm·mrad $\Sigma_y = \pi(3.4 \pm 1.4)$ cm·mrad
Time macrostructure	
Fast extraction	
Frequency	250 Hz
FWHM	20 mks
Number of protons in pulse	$0.8\cdot10^{11}$
Slow extraction	
Frequency	250 Hz
FWHM	3500 mks
Beam microstructure	
Micropulse FWHM	10 ns
Micropulse period	70 ns

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[1] Effective multiplication coefficient could be defined as the ratio of the effective average number of neutrons appearing in the reactor in a unit of time to the effective average number of neutrons disappearing in a unit of time.

SAD facility will be equipped with experimental channels permitting installation and extraction in different parts of subcritical assembly, reflector and shielding different detectors and isotopic samples. At present time SAD potential user are requested to propose their requirements for locations, dimensions and design features of such channels.

2.2. *Key solutions on arranging and allocation of installation*

The main part of the SAD installation is multiplying subcritical blanket. GSPI team together with DLNP and FLNP employees considered different modifications of subcritical blanket allocation:

- Allocation between outer walls of the Phasotron main building and complex YASNAPP outhouse;
- Allocation near outer wall of the main Phasotron building near communication gallery;
- Allocation at the ground floor of the Phasotron main building.

The most extensively were worked out variants with blanket allocation outside accelerator building. Cardinal differences of the blanket allocation inside accelerator building are the next:

- Absence of the external radiation shielding (accelerator building walls will act as radioprotection);
- Necessity to arrange inside accelerator hall another separate secured room with heavy concrete body for blanket accommodation.

For normal operation of the installation SAD the following locations should be arranged:

- Control room – 36 m^2;
- Switchgear room – 36 m^2;
- Blanket cooling system room – 36 m^2;
- Incoming vent chamber – 54 m^2;
- Exhaust vent chamber – 36 m^2;
- Sanitary inspection room for 20 person – 80 м^2;
- Corridors, stairs. Total area – 130 м^2.

For allocation of the indicated rooms the outhouse to the main accelerator building should be created. Total area of that outhouse should be about 400 m^2. It could be designed as two-storied annex with dimensions in plan 15 x 9 m^2, at the same time some rooms of the Phasotron building should partially used.

Technical and economic estimations of different variants of the installation allocation (see part **Ошибка! Источник ссылки не найден.**) lead us to the conclusion about final SAD allocation between Phasotron building and YASNAPP annex (Figure 4).

Accepted variant envisages vertical allocation of the multiplying blanket.

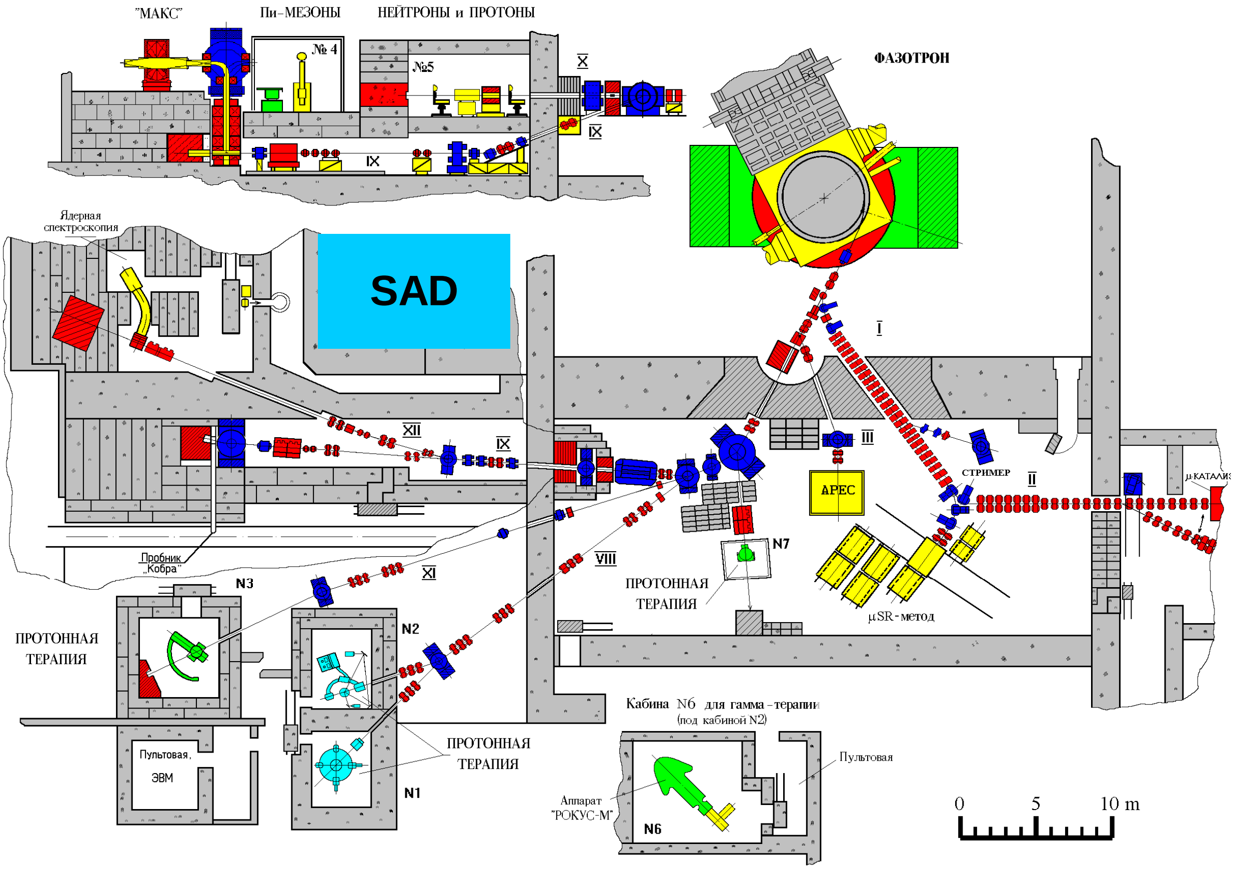

Figure 4: General plan view of the JINR "Phasotron" accelerator complex (in the left upper corner side view of the neutron/meson therapy complex). SAD facility will be constructed between accelerator and YASNAPP buildings. Span between Phasotron and YASNAPP is equal to 18 meters.

3 Basic requirements on SAD separate systems

*3.1. **The basis of the SAD cooling system***

According to the basis characteristics of the subcritical multiplying blanket and heavy metal neutron-producing target it is offered to have two cooling systems.

The first system is projected for cooling blanket AC and represents a closed air-cooling loop consisting of two ventilators (or blowers), heat exchanger air – air, filters for clearing air of radioactive aerosols and iodine, and adsorbents for clearing air of a moisture. The second system is projected for cooling a target and represents the open-air loop consisting of two ventilators (or blowers), filters for clearing air of radioactive aerosols. At further project developments it could be possible to combine both in one closed system. Using air-cooling systems instead of water caused by the nuclear safety requirements, though it gives increase of its surface and accordingly of weight.

Criterion of a necessary level of cooling for a reflector and target should be temperature of these units, which value is installed in the project and which should not exceed (with a warranted reserve) melting point temperature for materials used.

*3.2. **Beam transport line***

Beam transport channel is intended for reliable and safe proton beam transportation from Phasotron extraction point to the SAD spallation target. Beam transport channel should incorporate the following elements:

- Deflecting magnets;
- Focusing quadrupole doublets;
- Beam guide;
- Vacuum system;
- Power supply system;
- Cooling system;
- Supporting structures;
- Beam monitoring and diagnostics tools;
- Other tools and elements.

3.2.1 Requirements on magnetic elements (deflecting and beam-positioning magnets, focusing quadrupoles)

Magnetic elements should provide:

- Beam transportation from Phasotron extraction point to the spallation target;
- Beam focusing on the target with forming spot of required size;
- Beam spot size positioning on the target with accuracy ±1 mm;
- Total beam loss should not exceed 5%;

The magnetic elements should be supplied with thermal and hydraulic relays for protection them from overheating.

3.2.2 Requirements on the vacuum system

Along the whole length of the proton beam channel forevacuum should not exceed $5{\cdot}10^{-2}$ Torr. Beam guide design should provide installation of additional vacuum gauges without breaking vacuum in the channel. For vacuum system existing at Phasotron pumps, traps etc. should be used.

3.2.3 Requirements on power supply system

For the magnetic elements power supply one should use modernized version of the existing at Phasotron constant current sources. System should provide time stability of the current at the level of $3{\cdot}10^{-4}$ for deflecting magnets and 10^{-3} for focusing quadrupole lenses and automated power supply control.

3.2.4 Requirements on cooling system

Magnetic elements of the beam transport channel should be cooled with distilled water from existing at Phasotron water-cooling system. Water-circulating circuits should be manufactured from the radiation-resistant materials.

3.2.5 Requirements on supporting structures

Supporting structures should provide necessary stability and positioning of the beam proton channel elements. In some cases they should provide small displacements of the beam line units without using hoisting devices. Supporting structures should be manufactured from nonmagnetic materials. Supporting structures allocated in embrasure of the Phasotron outer wall should provide extraction of the equipment on them to the Phasotron hall for its maintenance and repairing.

3.2.6 Requirements on beam diagnostic and monitoring tools

Beam diagnostic tools (profile meters) should provide reliable measurements of the beam profile and focal point position especially in front of spallation target. Beam focal point position should be measured with accuracy not worse than 1 millimeter. Beam intensity monitors should provide on-line control of the beam intensity. Monitors should be calibrated routinely with absolute intensity meter – Faraday cup. Signal from beam diagnostic tools could be used in control and protective systems and also should be available for experimentalists.

3.2.7 Requirements on other parts and systems of beam transport channel

Electronics, computers, software used in beam channel diagnostic and control systems should be unified with similar devices used in scientific measurements.

3.3. *Requirements on subcritical multiplying core*

Subcritical multiplying core is intended for multiplication of the spallation neutrons generated at protons interaction with heavy target. Subcriticality of the AC should be higher than 2% (reactivity lower than $-2\%\beta_{eff}$) at any operation conditions including foreseen by the project incidents. Subcriticality level for regular operation conditions is determined by AC designer and tentatively is equal to 5%.

Subcritical multiplying core should be composed of:

- FE assembled in FA, designed with separate requirements specification;
- Vertical experimental channels meant for samples allocation and irradiation;
- Forcedly pumped through FA air coolant;
- Other elements, necessary for reliable and safe exploitation of the AC;

As a fuel the mixed oxide (MOX) fuel composition should be used. It consists of uranium dioxide and plutonium dioxide (BN-600 fuel). Main fuel parameters are listed in Table 6.

Table 6: SAD fuel basic properties

Parameter	Value
Composition	$(UO_2 + PuO_2)$
PuO_2 content, %(mass)	До 30*
^{239}Pu content in Pu, %(mass), not less than	95
Fuel density, g/cm^3	From 10,0 to 10,7
Fuel pellet diameter, mm	5,95*

*- parameters are specified during FE design stage

FE dimensions:

- Cladding diameter – 6.9 mm;
- Fuel height – 500-600 mm.

FE should be assembled in FA. AC design features and requirements of the safety normative documentation determine FA design. It should be established by FA creator (NIKIET), negotiated by FE creator (VNIINM) and by operating organization (JINR). Thermal power of fission in AC should not exceed 20 kW. In accordance with requirements of RF safety regulation documents AC should have not less than two channels for average power (neutron flux density) monitoring. Working range should be from the source level up to regular operation.

Starting source should be stipulated and its location determined. AC should be enveloped by a single course (case), at the central part of AC vertical cavity for 160 millimeters in diameter target should be predetermined. Besides that within AC one should allocate not less than three vertical experimental channels for samples irradiation with inner diameter up to 30 mm.

AC design should guarantee it easy dismantling with remote tools and appliances.

As a coolant in AC cooling system dry air should be used.

3.4. **Requirements on reflector**

Reflector of the subcritical AC is intended for providing necessary neutronic parameters of the AC. Reflector should gather round AC in radial and axial directions. As a material of a reflector use of solid lead is provided. Reflector design and dimensions should be specified at the design stage.

3.5. **Requirements on the spallation target**

Heavy target is intended for producing primary spallation neutrons at proton beam interaction with target nuclei.

Target should be placed in the centre of AC to be uniformly surrounded with fissile material in radial direction. Target diameter could be in a range 80 – 160 mm.

Target should be able to be replaced routinely. Three targets manufactured from solid lead, lead-bismuth and tungsten should be designed.

For all targets heat release ensuring their solid state should be provided at all operation modes of the installation including foreseen by the project incidents.

As a coolant in target cooling system dry air should be used.

3.6. **Requirements on radiation safety control system**

Radio protective shielding of the SAD facility will be designed first of all in accordance with requirements to protect personal from high-energy neutrons resulting after high-energy protons interaction with SAD components.

For variant with vertical beam input the neutron radiation of high energy formed as a result of beam loss during its transportation in the SAD AC hall is determining.

In conceptual SAD design project for shielding calculation the accepted losses make 5% of the total beam intensity. Protection provided in conceptual design against activation of subsoil waters and designs of the AC hall was determined to reduce the neutron flux density down to $10^4 – 10^5$ n/cm^2·s.

Besides radiation protection in conceptual design the following actions directed on ensuring the radiation safety are provided:

- Closed I-st loop of the blanket cooling system;
- Refinement of the coolant in I-st loop from radioactive aerosol's and iodine;
- Organization of the obligatory sanitary inspection room;
- SAD installation radiation control;

Radiation safety control system should include:

- Biological shielding of the installation;
- Air purification system to clear the air thrown out from the installation from radioactive gases and aerosols;
- Radiation monitoring of the internal and external irradiation and control of radioactive impurity of surfaces;
- Complex of organizational - technical actions;
- Radwaste treatment;

The purpose of designing of effective biological protection is decreasing of the high levels of the radiations arising at operation of installation and the equipment connected to it, down to acceptable levels at optimum cost of protection and without deterioration of the parameters of the unit stipulated by the project. Protection should provide non-raising of the established limits of dozes in adjacent with installation served rooms, and also in an environment at regular SAD operation (thermal power of the assembly up to 20 kW) in view of the contribution to radiation conditions from working accelerator. Actions for reduction of the induced activity in protective material should be stipulated and the opportunity of disassembly of parts of shielding, directly adjoining to AC, after a installation decommissioning is stipulated. Activation of the ground and soil water should not exceed the established limits.

Actions on air activity reduction at SAD experimental hall and air at cooling system emission to the atmosphere (from radioactive gases and aerosols) down to allowable levels should be stipulated. Radiation monitoring of an external and internal irradiation should include:

- Subsystem of permanent radiation control (measuring neutrons and gammas in SAD rooms and surrounding territory) integrated into existing at Phasotron automatic dosymetry control system (ADCS);
- Radiometers of gases and aerosols at air venting to atmosphere;
- ADCS should be connected with ACS and switch off beam extraction on the spallation target in case of excess of established radiation levels;
- Signals from radiometers in case of accidental venting of radioactive aerosols should also switch off beam extraction on the target (air venting also should be stopped at that case);
- Control of radioactive impurities at the skin, clothes, the equipment and materials on exits from SAD experimental hall and radwaste storehouse;
- On exit from SAD experimental hall sanitary inspection room with storage of clean and contaminated working clothes should be stipulated;
- Operative radiation control with the help of portable dosimeters in zones of the SAD radiation influence, carried out by existing service of the Phasotron radiation control;
- Individual radiation control of the personnel making experimental and maintenance works on SAD installation, carried out by existing JINR service of radiation control
- The control of a radioactivity in an environment caused by SAD work, carried out by existing JINR service of radiation control;

Organizational - technical actions should include:

- Radiation zones classification inside and outside SAD;
- System of unauthorized access to SAD rooms with high radiation levels locking, integrated into ADCS and ACS;
- Signaling and informative system integrated into ADCS and ACS;
- System of actions on protection of the personnel at realization of target, experimental samples and FA replacement;
- In the project schematic and technological solutions of FA unloading, targets and samples replacement should be developed. Works with highly active SAD elements should be carried out with the help of the remote equipment and with application of protective screens. The design of installation, and also transport devices and tools should be developed for limiting carrying capacity of the crane of AC hall equal to 20 tons;

- System of actions i a case of possible radiation incidents;

In the project the estimation of possible volume and activity of radwaste production at SAD (AC fuel, reserve FA, targets, other possible elements of installation) should be made. Radioactive waste produced at SAD should be maintained in the special storehouse, which is meeting the requirements of works with radioactive substances in an open kind. In storehouse constant monitoring of gamma- radiation with the help of ADCS gauges should be carried out. At the storehouse room with highly active waste products, an entrance should be blocked by ADCS signals up to the moment of reduction of radiation levels below allowable. On exit from storehouse the control of the surface contamination at skin and clothes of the personnel should be carried out.

3.7. ***Requirements on the nuclear safety system***

The next parts of the SAD installation are related to the nuclear safety system: heat removal from AC, reflector and target; guaranteeing FE tightness; ACS.

Heat exchange system(s) for AC, reflector and target should provide necessary cooling of these elements at all provided in the project operation modes and also at all foreseen by the project incidents.

Criterion of a necessary level of cooling is non-raising of the operational temperature limits established by the project for considered elements. In AC heat removal should provide non-raising the level of safety established by the project on temperature of fuel (for FE with highest energy release).

As a coolant in AC, reflector and target cooling systems dry air should be used.

FE cladding tightness control is based on registration in AC air-coolant gaseous FP.

Criterion of a necessary level of cooling for a reflector and target should be temperature of these units, which value is installed in the project and which should not exceed (with a warranted reserve) melting point temperature for materials used.

Automated control system (ACS) is intended for providing reliable stabilization of basic SAD parameters within limits and on the levels, corresponding to the safe operation modes, described in the project.

ACS provides control over neutronic, thermal, radiation and other characteristics of the installation systems and elements.

The list of controllable parameters and their values are established and proved by developers of the appropriate systems and elements in technical projects. ACS should incorporate:

- Necessary measurement tools;
- Necessary equipment for signals transfer from gauges;
- Necessary equipment for logic processing of signals;
- Necessary equipment for command signals generation;
- Necessary equipment for command signals transfer to the final control elements;
- Devices providing unambiguous action of the final control elements in respond to command signals;
- Command signals processing by the final control elements control tools;

ACS project should be elaborated with separate requirements specifications

4 **Basic conceptual features of the SAD AC**

Installation is projected counting on use existing at JINR proton accelerator – Phasotron, that considerably reduces the price of a total cost of the project. Installation is projected with orientation to the MOX fuel – such as BN-600. SAD should be the demonstration installation of the electronuclear type demonstrating and investigating both actinides and LLFP incineration and to operate under specially developed program of experimental researches. Installation is created at the territory of Russia and should satisfy to all normative documents regulating nuclear facilities operation at Russian Federation. The program of experimental researches for this installation is developed now, therefore the service life is not established, but is accepted, that it should not be less than 10 years.

4.1. ***Design description***

SAD blanket (Figure 5, Figure 6) is placed within biological shielding (position 6, 7, 8), which is 1200 mm thick in radial and top directions from AC. Shielding is made of heavy concrete with density of γ=4.5 tons/m^3. In a downward direction the shielding thickness is 2000 mm of the ordinary concrete (γ=2.3 tons/m^3). There are borings within shielding bulk intended for allocation of the vertical and horizontal experimental channels proton guide, cooling systems pipes and neutron power control channels. Upper part of the biological shielding (position 6) is made demountable to provide access to the blanket and target (position 27) during charge/discharge operations. In radial direction the biological shielding represents empty cylinder enveloped with stainless still sheets. To the outer part of the cylinder the beryllium insert with two vertical channels of 30 mm in diameter joins. Channels are made of aluminum alloy and equipped with steel plugs.

Inside the cylinder of biological shielding at the supports embedded into concrete the stand representing stainless steel cylindrical shell with two flanges is installed. Into that stand the lead plates forming lower faceplate reflector (position 4, 5) are installed. Lead plates thickness is equal to 500 mm.

In the reflector two horizontal experimental channels are disposed (Figure 7, Figure 8). Channels are made of stainless steel their diameter is equal to 80 mm. These channels are located 650 mm lower than AC center, at that one of them crosses the central axis of the installation and the other one is located tangentially at 375 distance from the first. Both channels are equipped with stepped protective plugs (position 21).

On the upper flange of the support the AC stainless steel case (position 9) is placed. The case represents two concentric shells welded at the bottom to the joint floor and at the top connected with the cover (position 10).

Case is intended for allocation of the replaceable targets, fuel blanket and also for creating cooling air flows. Replaceable targets are made identical but of different materials (Pb, Pb-Bi eutectic, W). Target represents cylindrical core with spiral groove on generatrix and six outlying segments. Core is installed into the inner shell and its spiral groove creates path for cooling air. Air supply is providing bottom-up with pipes ∅42x2 in dimensions (position 13) into the lower part of outer shell and piping-bend from the outer part.

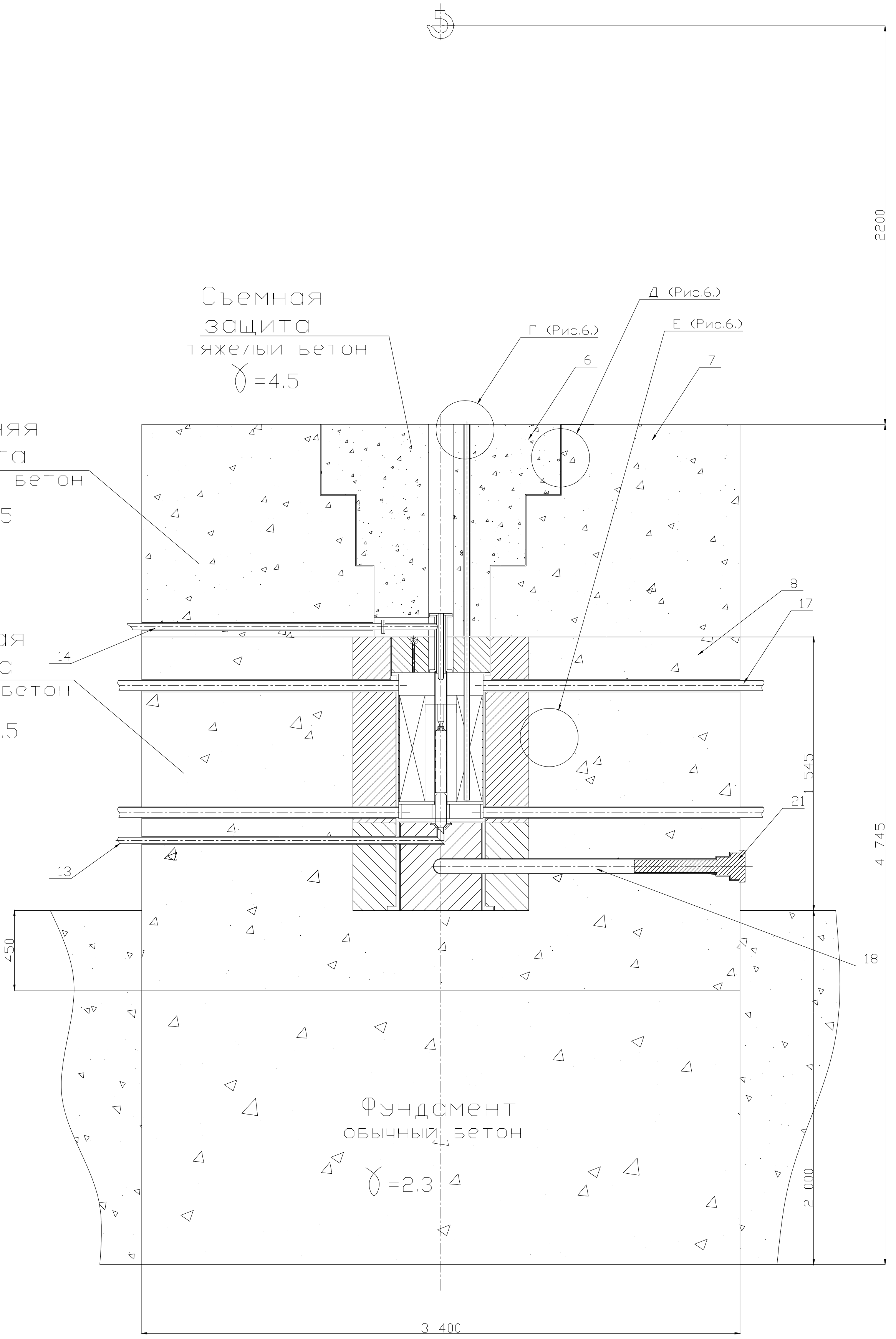

Figure 5: SAD AC general view

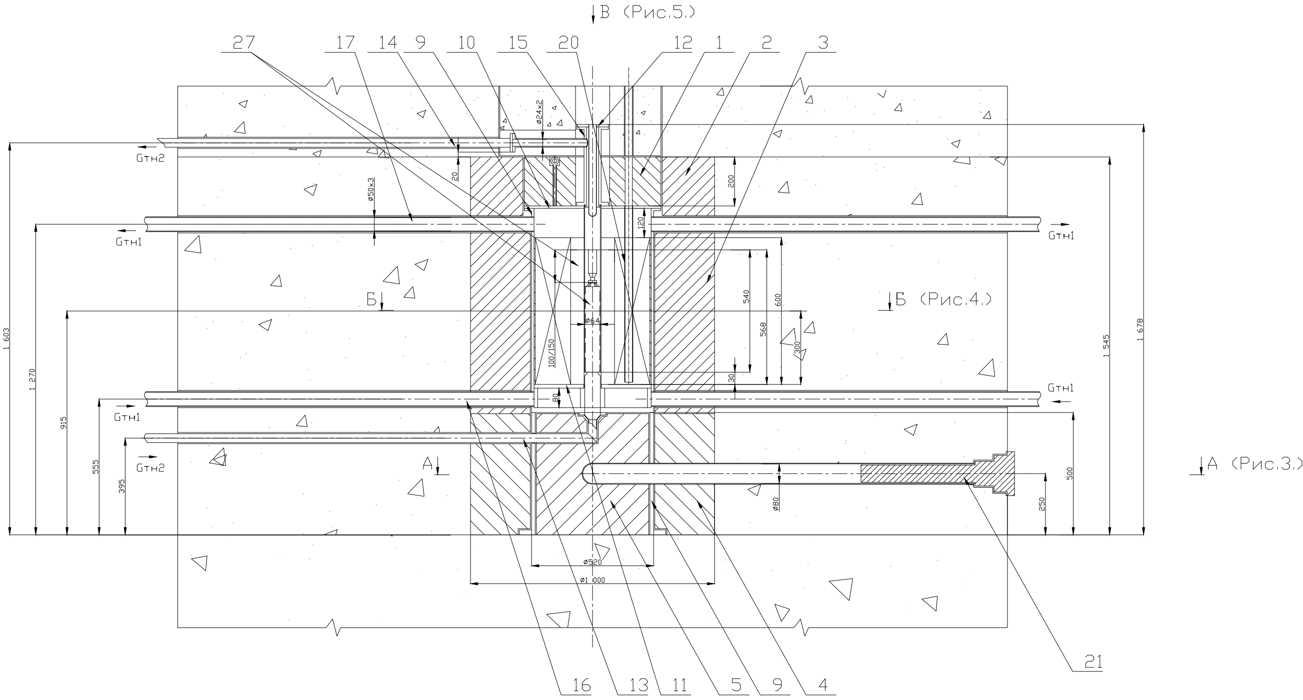

Figure 6: SAD AC general view (enlarged)

Outlying segments create closed structure, which mates with the first FA row by outer surface and with inner shell by inner surface (Figure 8). In the upper part of the shell the proton guide (position 12) is located.

AC consists of 129 FA, which are installed into support grid with spacing 36 mm. Support grid (position 11) is made of stainless steel and perforated with holes for FA installing and cooling air supply. Support grid is fixed inside AC case on the ledges at inner and outer shells and forms with the case floor the cavity for cooling air distribution. FA (Figure 9) represents set of 19 FE with MOX fuel, positioned between each other with the FA end pieces. FE are situated in a triangle lattice with 7.5 mm pitch. FE cladding is made of stainless steel EP-450 tube with dimensions ∅6.9x0.4. Outer diameter of the fuel pellet is equal to 5.95 mm, inner one – to 1.7 mm. Average $(U+Pu)O_2$ fuel density is 10.2 g/cm^3. About possible fuel composition see paragraph **Ошибка! Источник ссылки не найден.**.

Bearing element of the FA is the central tube, welded with end pieces. Lower end piece has shank for FA positioning in support grid, upper end piece has spacers and head for locking on the charge/discharge tools.

Through AC three vertical experimental channels (position 20) on diameters of 190, 314 and 438 mm pass. Experimental channels are made of stainless steel and their diameter is equal to 30 mm. Channels are equipped with stepped protective plugs.

In the upper part of the case between cover and AC faceplate the cavity (collector) formed for coolant pipe-bend with two pipes ∅50x2 (position 17)

Gap between outer case shell and AC is filled with lead insets.

Between case and envelops of the concrete shielding blocks the side lead reflector 200 mm thick is located (position 2,3). Inside reflector at diameters 562, 686 and 810 mm three vertical experimental channels 30 mm in diameter (position 20) pass. At diameter 810 mm three channels with diameter 75 mm of neutron power control are placed (position 28).

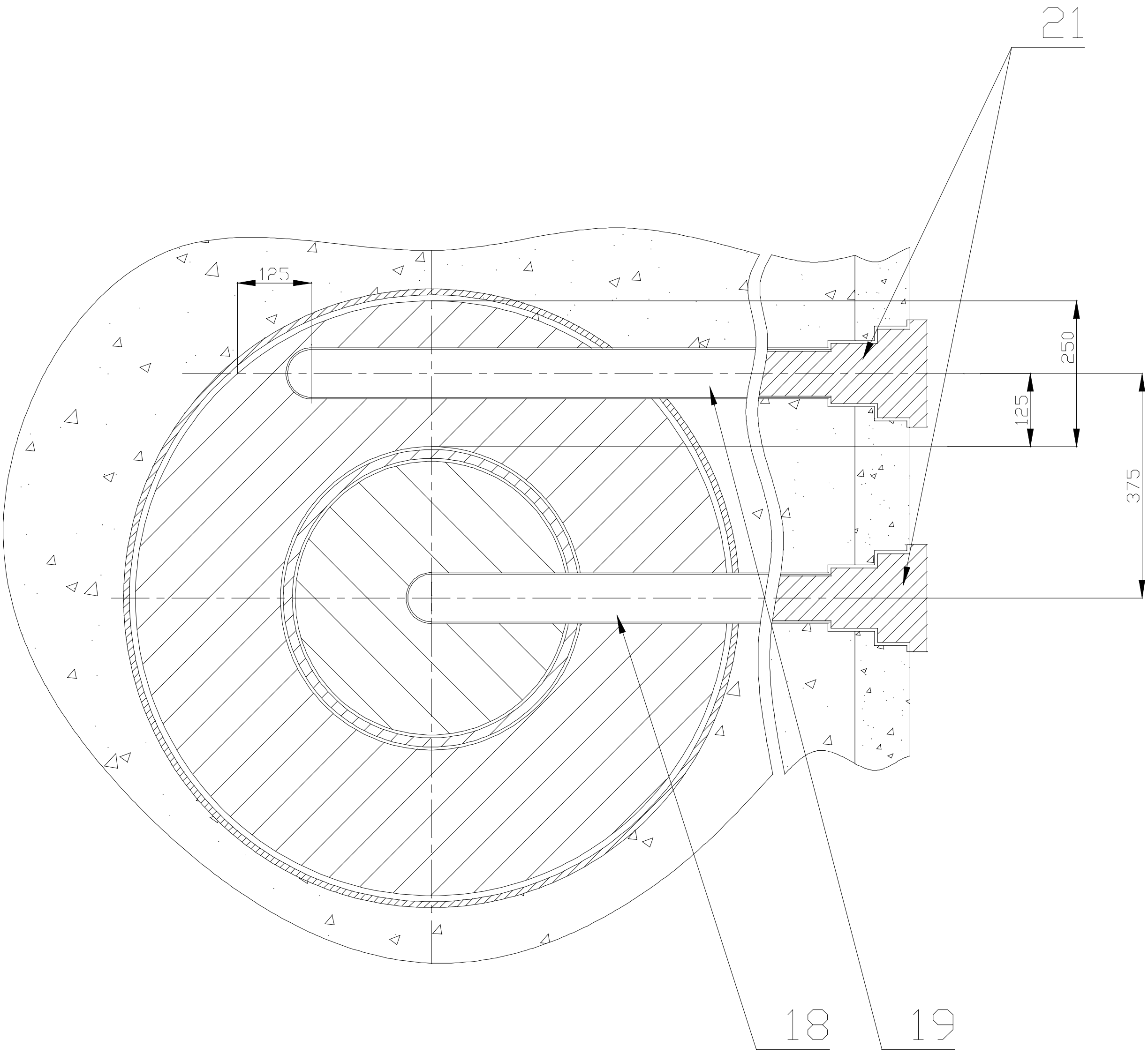

Figure 7: AC cross section over horizontal experimental channels

Inside these channels the neutron ionization chambers are installed. Channels itself are made of aluminum alloy and equipped with stepped protective plugs.

At the AC cover the upper faceplate lead reflector is placed with thickness 200 mm (position 1).

Cooling of the blanket and replaceable targets is carried out with air coolant by two independent systems. The cooling of a target is designed using the broken loop. Cold air for target cooling moves in a lower collector in an internal shell, transits into the spiral channel of the core of a target, cooling it and proton guide. After that coolant is taken away by output pipe, send on filters, after which is thrown out in an environment. The AC and peripheral segments cooling happens within the closed loop. Air through two input pipes moves in a lower collector, transits through holes in the support grid splits between FE and segments of the target, getting in a upper collector, whence on two output pipes comes into the technological part of the cooling system which includes heat exchangers and filtering equipment.

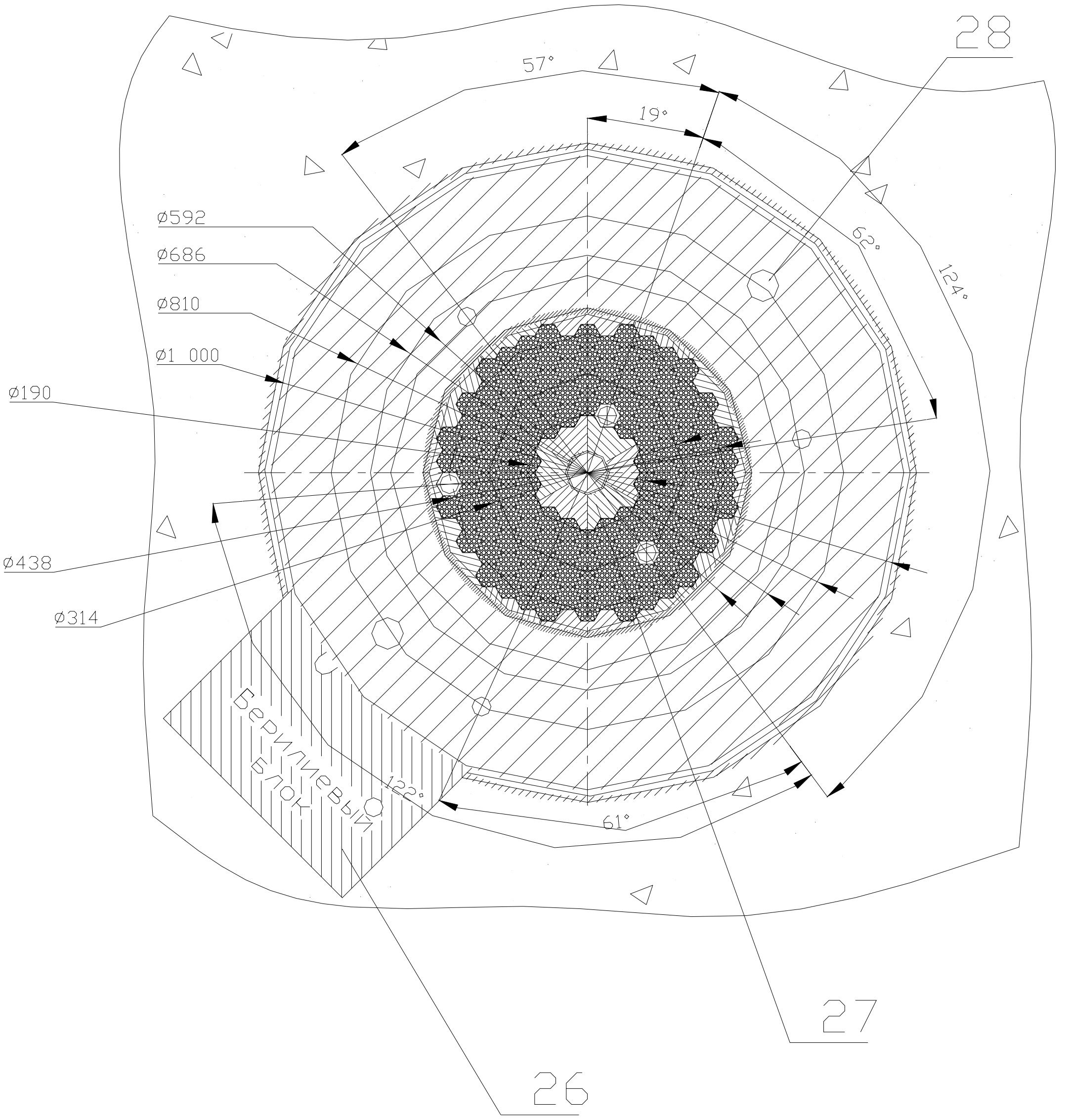

Figure 8: AC cross section

FA charge/discharge works and targets replacement is carried out on the stopped installation, at removed upper part of biological shielding, upper edge reflector and cover of the AC case. Hand-held tools with collet clamp designed on weight-lifting ability 40 and 5 kg with usage of the crane make FA charge/discharge works.

The operations are carried on under the control of the JINR radiation safety service.

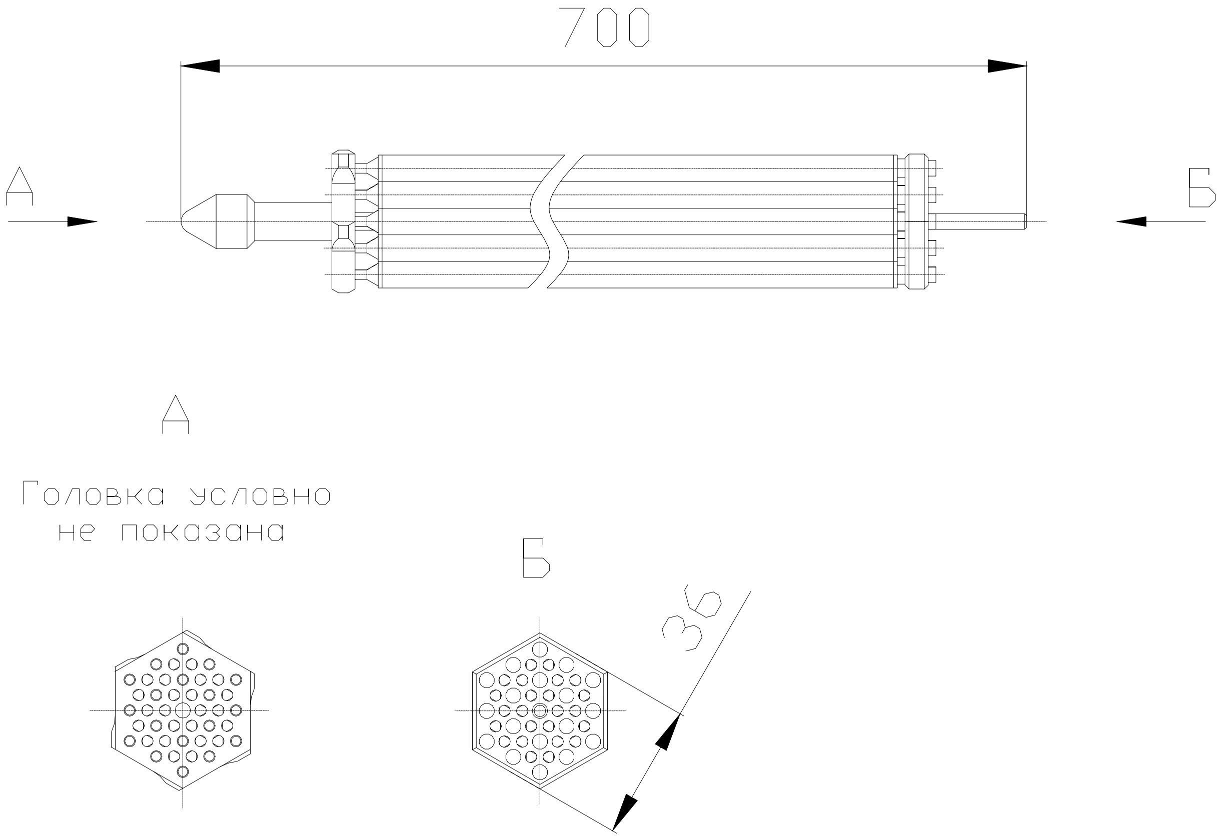

Figure 9: SAD FA general design

4.2. *Results of the estimations of the SAD cooling system parameters*

For all types of the target and AC the heat releases providing their solid-state phase at all modes of operation of installation, including the foreseen by the project incidents, should be provided. As the coolant in target and AC drained air should be used.

The results of thermal design estimations show, that optimum from the point of view of an energy release and hydraulic resistances the speed of the coolant is about 10 m/s, that has allowed previously to chose such mode of cooling. According to it the flow sections of units of circulation loops in AC and target are selected. The input data for calculation of AC and target cooling systems, and also results of calculations are given in the following tables.

Table 7: basic data for calculations of the thermal and hydraulic AC parameters

FA number	129
FE per FA number	19
FA dimension to receive a box wrench	36 mm
FE diameter	6.9 mm
FE pitch	7.95 мм
Fuel pellet diameter	5.95 мм

Hydraulic diameter of the space between FE		3.20 mm
Flow section of the 129 FE		0,0531 m^2
FE fuel part height		509.5 mm
Thermal power (max)		25 kW
Variation factor of an energy release	Along radius Kr	2,0
	Along height K_z	1,5
Coolant input temperature		25° C
Coolant pressure		0,1MPa

Table 8: results of AC cooling system parameters calculations

	Average coolant velocity between FE, m/s	
	6,3	10
Air consumption, kg/s	0,35	0,6
Air output temperature, °C	96	66
FE cladding max temperature (inner FA row), °C	185	154
Drop of pressure at AC, Pa	200	310

Table 9: basic data for calculations of the thermal and hydraulic target parameters

Target core diameter		64 mm
Equivalent diameter of the outer “cylinder”		160 mm
Target height		400 mm
Spiral channel parameters	Propeller pitch	60 mm
	Average diameter	61 mm
	Groove depth	3 mm
	Height (along the axis)	40 mm
Net heat release in the target		400 W
Specific energy release variations range W/cm^3		from 5 to 0,0002
Input coolant temperature		25 °C
Coolant pressure		0,1 MPa

Table 10: results of target cooling system parameters calculations

		Average coolant velocity in target channels, m/s	
		6,3	10
Average air velocity in spiral channel, m,/s		44	42
Air consumption in spiral channel, kg/s		0,005	0,005
Air output temperature, °C		124	105
Target temperature	Target core top, °C / bottom, °C	185 / 60	168 / 57
	Outer “cylinder” top, °C / bottom, °C	126 / 65	95 / 54
Drop of pressure in spiral channel, Pa		3500	3400

4.3. ***Neutronic characteristics***

4.3.1 **Basic parameters of the subcritical assembly**

On the basis of preliminary calculations and design studies the following configuration of AC is selected:

FA number	129
FE number per FA	19
Fuel:	MOX – UO_2+PuO_2;
Fuel density	10.2 g/cm^3
FA pitch in triangle lattice	36 mm
FE pitch in triangle lattice	7.95 mm
FE clad outer diameter	6.9 mm
FE clad wall thickness	0.4 mm
Fuel pellet outer diameter	5.95 mm
Fission thermal power	20 kW

Along the AC vertical axis instead of 19 central FA the lead target is placed. AC is surrounded with lead reflector. Horizontal cross section of the AC is represented below (Figure 10) – this is drawing representation of the basic data for MCNP calculations.

For selected AC map after calculations the following values are defined:

- Plutonium content in fuel necessary to provide k_{eff}=0.95;
- Energy release distribution in AC and reflector;
- Variations of the k_{eff} at plutonium content, fuel density and FE pitch variations.

For the basis AC map the value keff=0,95 is reached at a content of plutonium in fuel 29.5 % (masses) and fuel column height of 50.95 cm. In this case fuel mass in AC is equal to 354.4 kg.

Distribution of the energy release in AC is presented in the next tables (Table 11 and Table 12). At calculation of a heat release in FA the unit of symmetry consisting of 14 FA was selected; their indexing is represented in Figure 10. The net fission power of in AC makes 20 kW. The height distribution of the energy release was calculated for averaged on

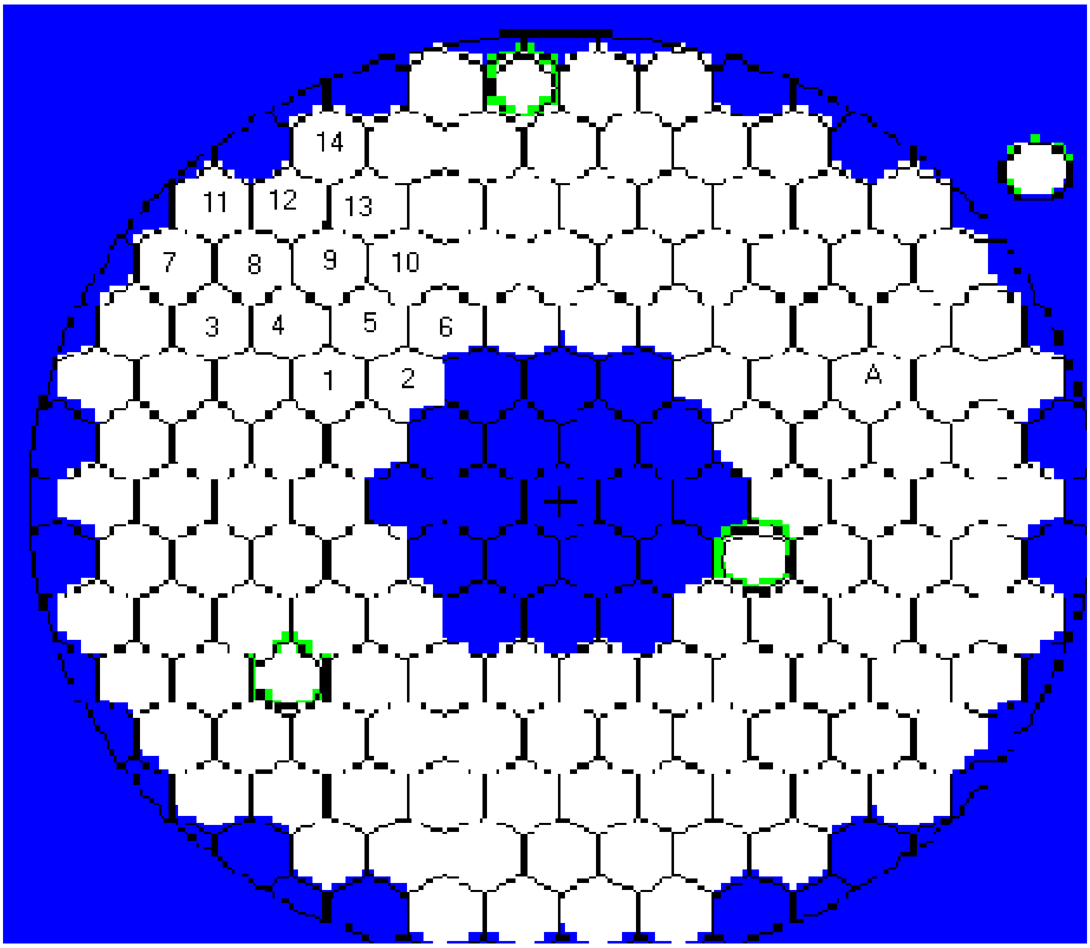

Figure 10: AC map (open hexagonal – FA, blue – lead). FA with numbers – FA for which the energy release was calculated, FA, marked "A" – for which energy release height distribution was calculated.

AC FA, result obtained K_z=1.136. The energy release in the lead reflector parts caused by neutron and photon induced reactions, is given in Table 13. The indexing of reflector zones of a reflector is given in Figure 11. The net energy release in reflector makes ~518 W.

Table 11: energy release in FA (FA numbering see in Figure 10)

# FA	Energy release in FA, MeV/neutron	Energy release in FA, W	Average energy release, W/cm^3
1	1,051E+01	1,472E+02	3,637E-01
2	1,082E+01	1,515E+02	3,745E-01
3	9,309E+00	1,303E+02	3,221E-01
4	9,956E+00	1,394E+02	3,445E-01
5	1,044E+01	1,461E+02	3,611E-01
6	1,070E+01	1,497E+02	3,701E-01
7	9,188E+00	1,286E+02	3,179E-01
8	9,232E+00	1,292E+02	3,194E-01
9	9,789E+00	1,370E+02	3,387E-01
10	1,016E+01	1,423E+02	3,516E-01
11	9,317E+00	1,304E+02	3,224E-01
12	9,213E+00	1,290E+02	3,188E-01

13	9,449E+00	1,323E+02	3,269E-01
14	9,376E+00	1,313E+02	3,244E-01
Total:	1,375E+02	1,924E+03	

Table 12: energy release distribution along FA “A” height from the bottom

Height, cm	Power, relative units	Height, cm	Power, relative units
0-2	0,754	26-28	1,135
2-4	0,787	28-30	1,132
4-6	0,828	30-32	1,116
6-8	0,872	32-34	1,102
8-10	0,919	34-36	1,075
10-12	0,958	36-38	1,041
12-14	0,999	38-40	1,008
14-16	1,034	40-42	0,962
16-18	1,069	42-44	0,919
18-20	1,090	44-46	0,869
20-22	1,112	46-48	0,827
22-24	1,122	48-50,95	1,131
24-26	1,136		

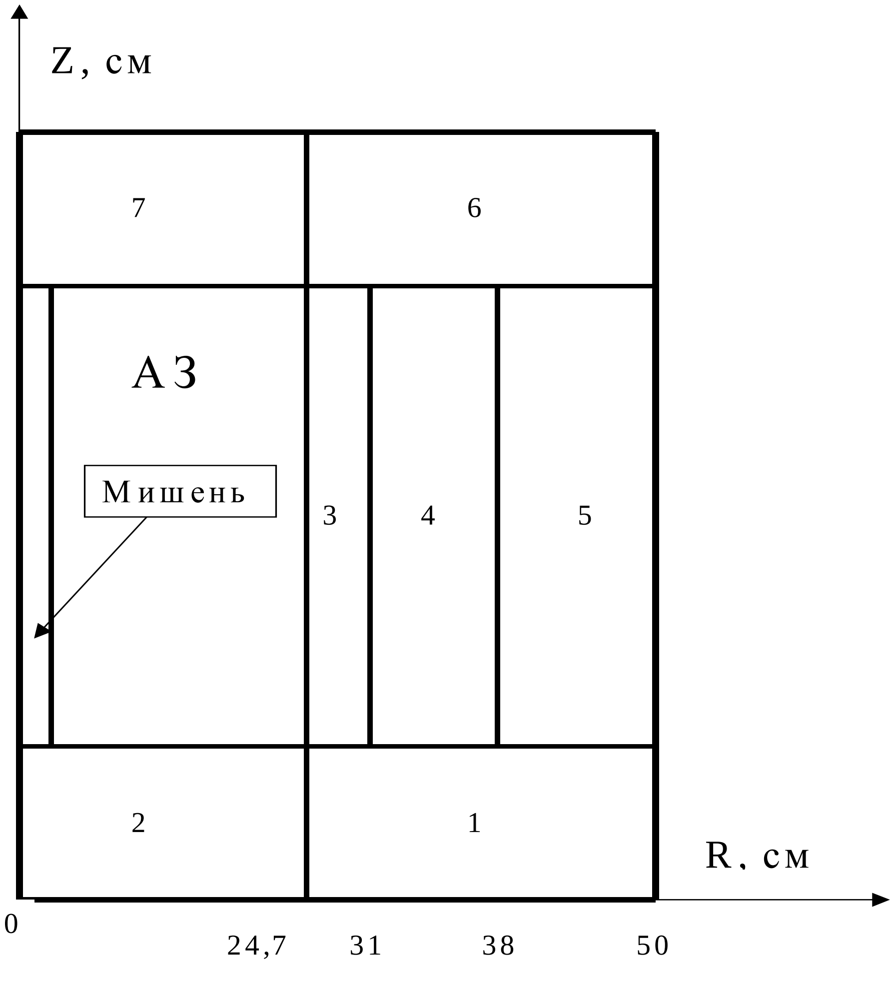

Figure 11: lead reflector zones indexing

The variations of the k_{eff} are calculated at change of plutonium content in fuel, fuel density and FA/FE pitch. The main purpose of these calculations was to find possibility of lowering the plutonium content in fuel down to desirable value (27% mass) and decreasing of total mass of fuel, loaded into AC, down to 300 kg. The calculations show, that one cannot satisfy both requirements simultaneously at selected FA and AC design. Lowering the plutonium content in fuel down to 27 % can be reached either at the cost of increasing fuel column height from 50.95 cm up to 62.35 cm (mass of fuel in AC becomes equal to 433.5 kg), or at the cost of increasing the number of FA in AC at decreasing target diameter (mass of fuel in AC becomes equal to 381.7 kg), or at allocation of additional FA on peripherals of AC (mass of fuel in AC becomes equal to 420.2 kg). To reduce fuel mass down to 300 kg one have to raise the plutonium content in fuel up to 35.35%.

Another approach to desired result was also studied – decreasing FE pitch from 7.95 down to 7.4 mm.

Table 13: energy release in lead reflector

Zone number	**Energy release, MeV/neutron**	**Energy release, W**	**Averaged over reflector volume energy release, W/cm^3**
	Neutrons		
3	5,113E-01	7,1583E+00	1,1475E-04
4	4,047E-01	5,6652E+00	6,5864E-05
5	3,939E-01	5,5143E+00	2,9249E-05
1	2,183E-01	3,0559E+00	1,7156E-05
2	1,886E-01	2,6398E+00	4,5910E-05
6	2,199E-01	3,0781E+00	1,7281E-05
7	1,914E-01	2,6789E+00	4,6590E-05
Total:	2,128E+00	2,9791E+01	3,3680E-04
	Gammas		
3	7,316E+00	1,0243E+02	1,6420E-03
4	3,526E+00	4,9362E+01	5,7389E-04
5	9,391E+00	1,3146E+02	6,9731E-04
1	4,977E+00	6,9679E+01	3,9119E-04
2	2,656E+00	3,7181E+01	6,4662E-04
6	4,642E+00	6,4984E+01	3,6483E-04
7	2,347E+00	3,2851E+01	5,7133E-04
Total:	3,485E+01	4,8795E+02	4,8871E-03

Thus the FA size diminishes and FA pitch also can be diminished from 36 mm down to 33.6 mm. In this case plutonium content in fuel can be reduced down to 27% at saving k_{eff}=0.95 (mass of fuel in AC becomes equal to of 354.4 kg).

To estimate nuclear safety during fuel charge/discharge operations k_{eff} variations at extraction of some FA from AC were calculated. It appears that “weight” of one FA will make (0.36 – 0.56)% that provides a necessary level of a discretization at AC charge.

The three-dimensional program MCNP-4B was applied for neutronic calculations of the subcritical assembly SAD[13], implementing a Monte-Carlo method. For today this program is most known and used in a world for calculation of AC of composite geometry. It allows adequately describe three-dimensional structure and materials of the reactor, using pointwise representation of cross sections; within one calculation it simulates transport of neutrons, gammas and electrons; enables to get all data, necessary for the project, with high accuracy. Possibility of usage of the given program and libraries of neutron and photon cross sections ML-45[14] was justified at designed simulation of the experiments which have been carried out on at operating reactor IBR-2 and other similar on the characteristics critical assemblies[15].

For calculations of the neutronic characteristics of AC the design SAD model was prepared, in which are in details circumscribed FE, FA, target, reflector, concrete biological shielding.

4.3.2 Energy release distribution in lead target

In calculations it was supposed, that the target represents the cylinder of 55 cm height and 15 cm in diameter. Along the central axis from above target has central channel 1 cm in diameter and 15 deep. Proton beam with energy 660 MeV (beam power 500 W) heats the target on the bottom of this channel. The calculations are fulfilled with the LAHET program code.

The energy release is calculated for cylindrical layers of 1 cm height and radial thickness 1 cm. Below (Figure 12) represented energy release averaged within volume of the indicated zones in terms of (MeV/cm^3), normalized at 520 MeV.

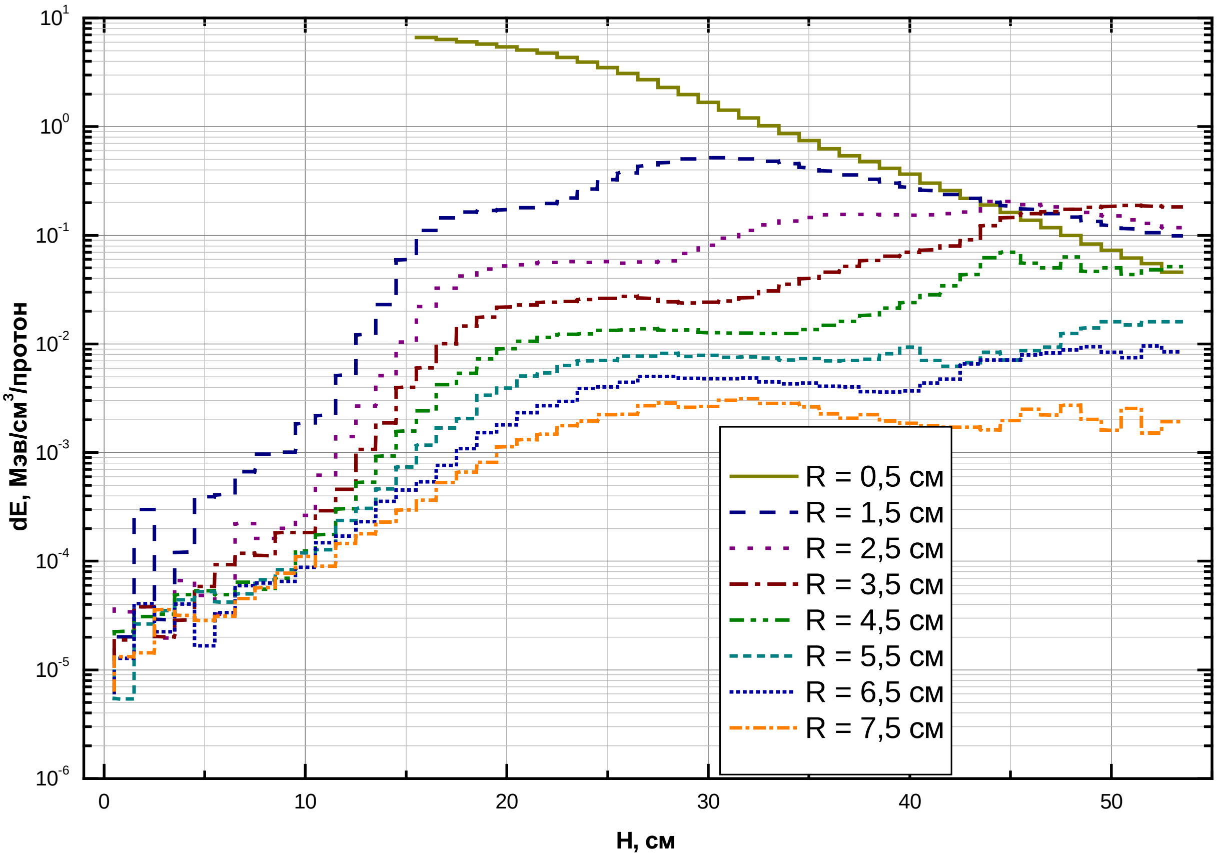

Figure 12: Energy release in target, MeV/cm^3/proton

*4.4. **Radiation safety and protection***

The technical solutions on radiation safety of SAD installation, introduced in the present project, are elaborated according to the requirements of the following operating normative documents:

- The federal law "About a radiation safety of the population" from 09.01.96;
- Norms of a radiation safety NRB-99, SP 2.6.1.785-99;
- Main sanitary rules on providing radiation safety OSPORB-99, SP 2.6.1.799-99;
- General provisions of a safety of research nuclear installations NP-033-01;
- Sanitary rules on design and maintenance of research nuclear reactors SP 1128-73;
- Safety rules at storage and transportation of nuclear fuel on objects of nuclear power engineering PB-YaT-XT-90, PNAE G-14-029-91;
- Safety rules at transportation of radioactive materials PBTRV-73;

Providing of the radiation safety of SAD installation is grounded on the following principles:

- Keeping the values of individual doses and number of the irradiated personal at the so low level, with what can be reasonably reached in view of economic and social factors;
- Non-raising of the approved dose limits (on an internal and external irradiation) for staff of installation and population at normal operation and foreseen by the project incidents;
- Usage of a principle of echeloned protection implemented as the system of protective barriers between ionizing radiations and radioactive substances and environment with application of technical and organizational actions on protection of the barriers and preservation of their efficiency.

For SAD installation such barriers are:

- Fuel matrix, which temperature at normal operation does not exceed projected values, that provides retention of FP;
- FE cladding tubes with automated tightness control system;
- AC case with experimental channels and hermetic cooling loops;
- Hermetic rooms (boxes) of the installation;

For increasing safety at charge/discharge and other operations usage of special equipment and protective canisters is provided.

Equipment and pipes containing radioactive substances are disposed in boxes, behind concrete walls providing in serviced locations and feed-through corridors low radiation levels according to the requirements NRB-99 and OSPORB-99.

According to normative documents the following design limits of radiation doses are accepted:

- For installation staff (according to NRB-99) – effective dose 20 mSv/year (2 rem/year) at an average for five years, on conditions that the effective dose for any year will not exceed 50 mSv (5 rem);
- Design value of equivalent dose rate for locations where personal spend whole time (according to OSPORB-99) – no more than 6 mkSv/hour (0,6 mrem/hour);

- In observation zone at normal operation and decommissioning of the SAD installation the annual limit of radiation dose for population should not exceed a limit of radiation dose for population established by operating normative documents.

Multiplying target and part of the technological equipment are disposed in the forbidden area in the AC hall, which falls into a category of maintenance-free locations. The staying of staff in AC hall at operating installation SAD is strictly forbidden. The experimental hall is qualified as periodically serviced locations. The biological protection is selected reasoning from the following requirements:

- Providing conditions for fixed staying of staff in neighboring serviced locations at installation operation on power level of 20 kW;
- Providing conditions for experimental hall maintenance at installation operation on power level of 20 kW and plugged experimental channels;
- Providing conditions for AC hall maintenance after shutting down and cooling;
- Providing safety during charge/discharge operations with FA and targets;
- Barring of the soil and ground water activation.

Maintenance of the equipment installed in AC hall, will be carried out after stopping of installation and cooling, at closed by plugs target channel, neutron power control and experimental channels. During maintenance operations the radiation condition should nbe monitored continuously. Time limit for staff operation in AC hall of a target is determined by radiation conditions.

As the AC protection in radial direction the following constructions and materials serve:

- Lead inserts with average thickness of 20 mm;
- Target stainless steel case with thickness of 10 mm;
- Lead reflector with thickness of 240 mm;
- AC stainless steel case with thickness of 10 mm;
- Shielding made of heavy concrete (density 4.5 tons/m^3) with thickness of 1200 mm;
- AC hall walls width of 500 mm made of heavy concrete with thickness of 500 mm.

The vertical and horizontal channels of a target are supplied with protective stepped plugs.

In upper direction from AC behind an edge lead reflector (200 mm thick) the heavy concrete shielding 1200 mm thick is disposed.

Closely to the proton guide the protective blocks overlapping splits in upper direction are disposed.

Radiation conditions above AC at stopped installation are determined by radiation penetrating from AC through the proton guide channel and also gamma radiation from activated constructions of AC.

The protection of an experimental hall is provided with walls separating it from AC hall. Walls will have thickness of 500 mm (heavy concrete). The protection in a lower direction (concrete with thickness of 2000 mm) eliminates activation of a soil and ground water. SAD installation should be supplied with a monitoring system of FE cladding tightness.

The operation of a target with not hermetic FE is forbidden. As an operation limit and limit of safe maintenance by quantity and value of damaged FE for SAD multiplying target the absence of not hermetic FE is installed. There should not be not hermetic FE in the limits of sensitivity of a method of operating registration on activity of aerosol and FP in air of the AC cooling loop. In case of reliable exceeding of background values registered by the equipment of the system of FE tightness, the operation of installation immediately will stop. After cooling down the search of FA with not hermetic FE is realized, for what FA are in turn extracted from AC and their control with the help of special equipment is done.

If necessary to make operations on FA charge/discharge, these operations in AC hall could be started not earlier than 3 day after stopping. The FA charge/discharge operations are carried out with the help of the special lead container.

For neutron flux density monitoring (AC power) 3 blocks of detection with fission chambers are provided. Detection blocks are disposed in the inclined channels passing in the bulk of concrete shielding so, that the sensitive areas of chambers are installed opposite to AC.

The radioactive effluents of the SAD installation in an atmosphere during normal operation are negligible.

5 Physicotechnical substantiation of the proton beam channel

5.1. *Components of the proton beam channel*

JINR Phasotron has the branchy system of 10 beam channels of used in various experiments (Figure 4).

On DLNP Phasotron experience of development, creations and maintenance of proton beam channels is already accumulated. Beam lengths are as high as 50 meters – to YASNAPP-2 and “Wide-aperture pi- meson lens” installations [16, 17] (channels XII and IX) with beam transition down to the level of the first floor of the Phasotron building with efficiency up to 94 %.

The existing radiation protection allows completely absorb output proton beam with intensity up to 2.0 μA in accelerator hall or in beam-stops at channels XII and IX.

In the beam transportation system usage of the following main magnetic elements is supposed: a deflecting magnet such as an OM-1, doublet of quadrupole lenses such as ML-3, and also their different modifications. The beam transfer from horizontal in a vertical plane is planed to realize with usage of two bending magnets made on the basis of ARES installation [18] coils. ARES installation was dismantled on summer 2002.

Magnets OM-1 and doublets ML-3 are exploited in proton beam channels for a long time. The modifications to their design have been made several times and for designed installation their last variant is selected.

The general view of the OM-1 deflecting magnets located in series is shown in Figure 13.

Figure 13: photo of two OM-1 magnets in series

Three projections of one such magnet are figured in a Figure 14.

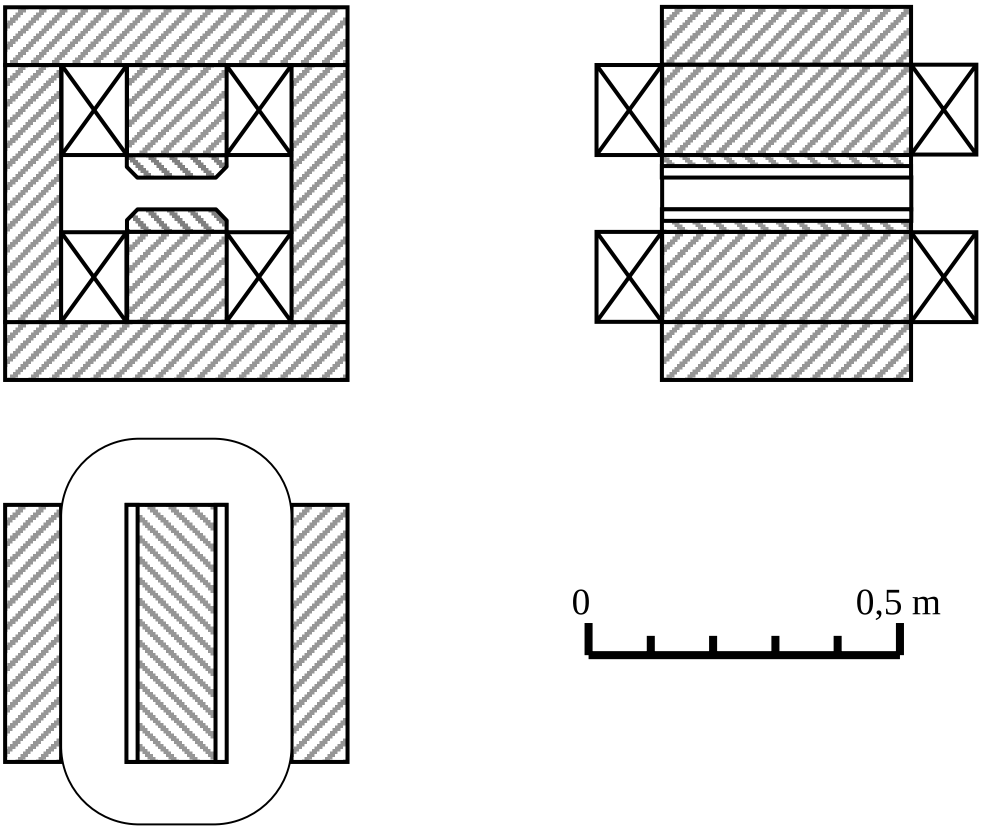

Figure 14: OM-1 magnet basic modification (three projections)

The magnetic field 1,2 T, providing beam deflection on 7,6 degrees angle, forms at excitation current equal to 330 A. The homogeneity of the magnetic field in a transverse direction is reached for working area of ±50 mm from an axial trajectory. The basic parameters of the OM-1 magnet are given in Table 14.

Table 14: OM-1 magnet parameters

Vertical gap	5 cm
Pole length	42 cm
Pole width	14 cm
Эффективная длина полюса	43 см
Maximal excitation current	500 A
Maximal magnetic field	1,37 T
Maximal deflection angle	8°
Drive winding	Copper tube 8,5x8,5 ∅5,3 mm
Drive winding number of turns	220
Winding resistance at 20° C	0,12 Ohm
Cooling water consumption at 40° C heating	33 l/min

Winding weight	150 kg
Yoke weight	750 kg

The general view of quadrupole lenses doublet of ML-3 type is shown in Figure 15.

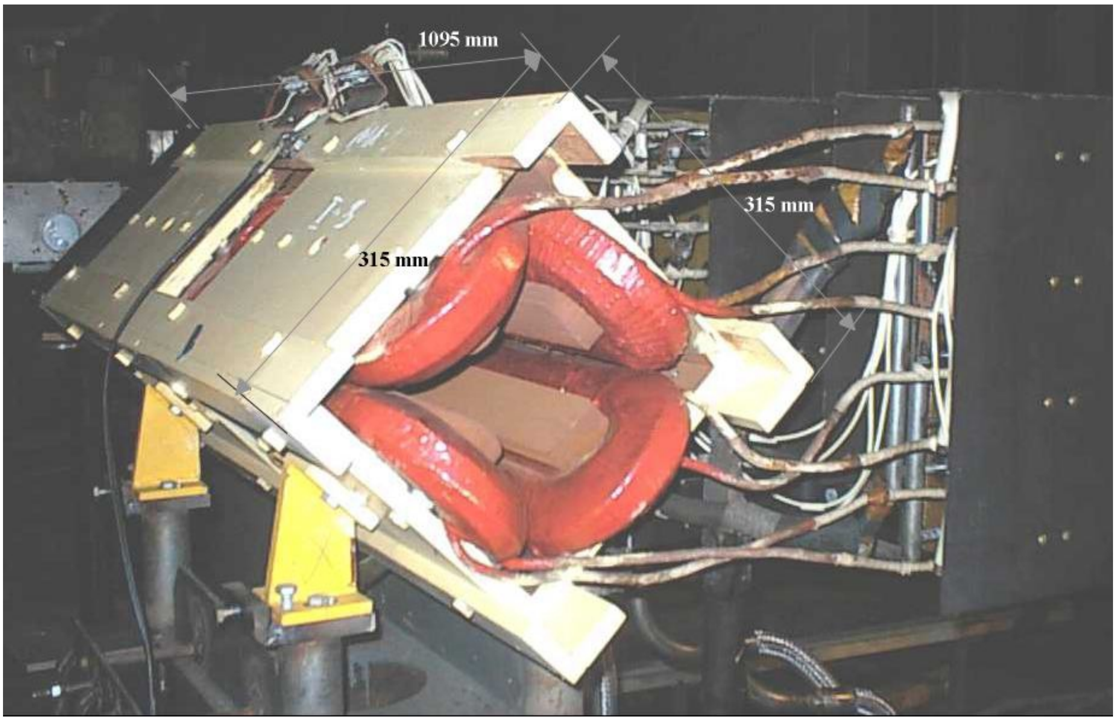

Figure 15: photo of the ML-3 magnetic lenses doublet

ML-3 basic parameters are shown in

Table 15: ML-3 basic parameters

Lens’s aperture	10 cm
Pole length	42 cm
Pole effective length	43 cm
Maximal excitation current	380 A
Maximal field gradient	1000 Oe/cm
Drive winding	Copper tube ∅7mm x ∅4 mm
Drive winding number of turns (at one pole)	39
Winding resistance at 20° C	0,28 Ohm
Water consumption at 30° C heating	23 l/min
Winding weight	86 kg
Lens’s yoke weight	300 kg
Dissipated power at nominal current 300 A	25 kW

In some places of the channel the lens's with 120 mm aperture will be used. These lenses will differ only by the shape of pole shoes of a lens. To provide reliable beam transportation on existing "T" – route and new route to the SAD installation without mechanical motion of the magnetic elements one suppose using of modified C- shape magnet, which design now is in progress. Such magnet which has been schematically shown in Figure 16, will have identical with OM-1 magnet drive winding, but modified yoke for saving the value of a magnetic field in its gap.

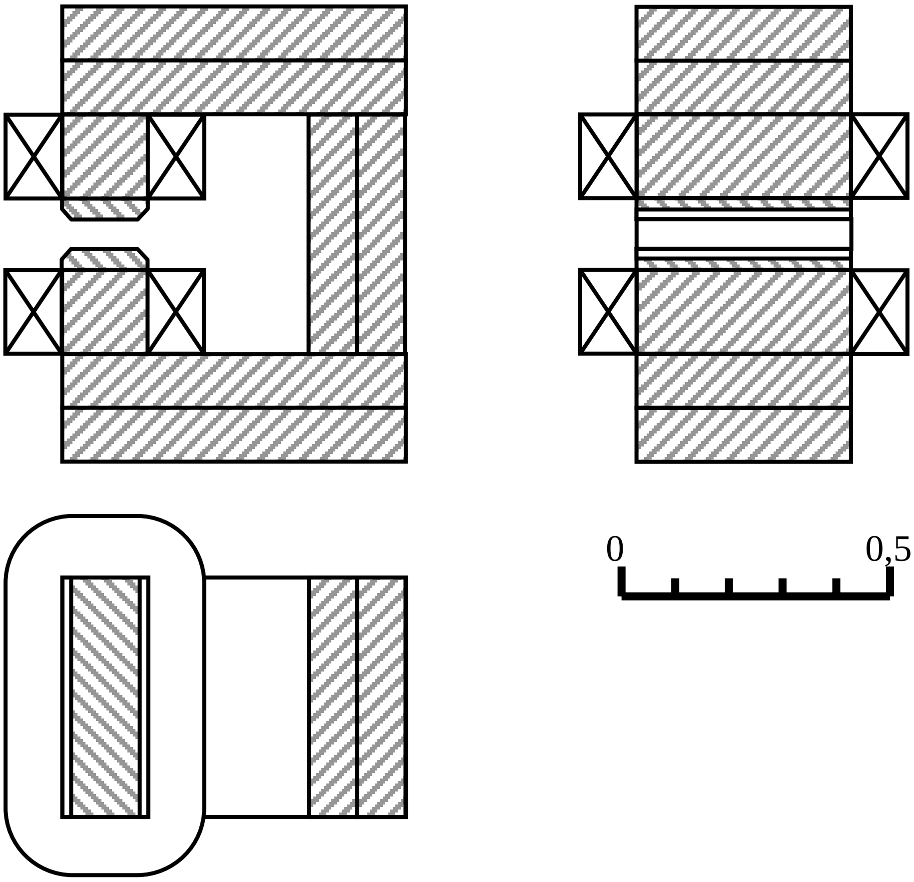

Figure 16: C- shape modification of the OM-1 magnet

Besides other modification of the OM-1 magnet are studied which can increase deflection angle owing to reallocation of a magnetic field in a gap by decreasing width of a magnetic track its simultaneous elongation, and also decreasing influence of edge fields.

Both in the basic OM-1 magnet, and in its modified variants, the form of the pole shoe will be profiled on side edges of a pole gap for the extension of area of a homogeneous magnetic field in a transverse direction or decreasing pole width for increasing magnetic field in a gap.

In some schemes of transport channels it will be possible to use profiled pole extensions, providing a strong focusing in systems with high number of the sequentially located deflecting magnets with interleaving signs of magnetic field gradient. All these variants of pole shoes for OM-1 magnets are represented in Figure 17.

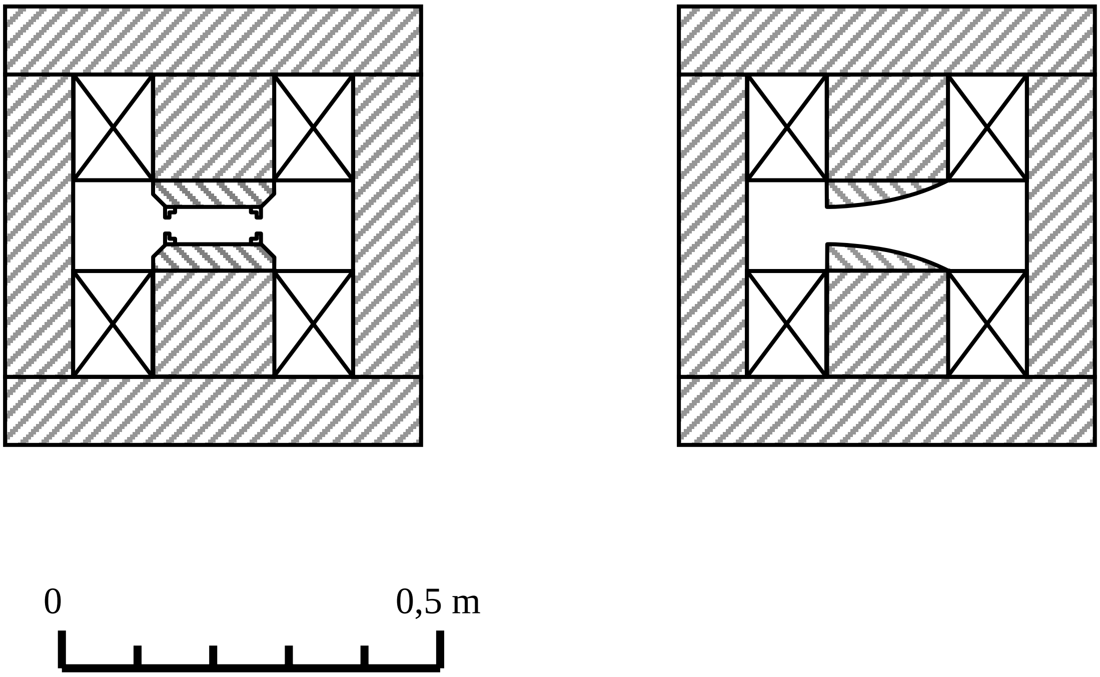

Figure 17: OM-1 magnets with modified pole shoes shape

Proton beam is transported inside vacuum pipe. Inside lenses it is completed from pipes with an outer diameter of 100 or 120 mm, and in magnets the box-type chambers with steel covers and sidewalls from stainless steel are applied. The assembling of vacuum system is fulfilled with application of centering sealing and quick disconnect clamps. The compensation of inaccuracies of assembly is yielded by sylphons. The modular structure of beam transport system allows creation of different channels depending on choice of SAD place location, its layout and direction beam input.

Strong deflecting magnets on the basis of ARES installation windings now are not designed. The calculations of several variants with usage 2D and 3D computer models are carried out only. These calculations allowed to select final variant of beam transfer into vertical plane turning it on 120 degrees with two magnets, each providing 60 degrees deflecting angle and has radius of curvature of a magnetic track of 3 meters (required field in a gap – 1.45 T). The schematic representation of three-dimensional design model of a magnet is given in Figure 18.The calculations have shown, that at usage of the trapezoidal form of a pole the efficiency of a magnet is boosted approximately on 15 % in comparison with rectangular. The calculations were carried out on the basis of two two-dimensional models (program SUPERFISH) and three-dimensional model (program RADIA). The magnetization curves of a magnet for two values of a pole gap – 6 and 8 cm were calculated.

To obtain most homogeneous magnetic field distribution in a gap the geometry of a pole was adjusted (end edges 10 x 45° and pole extensions 1.5 x 20 mm were added).

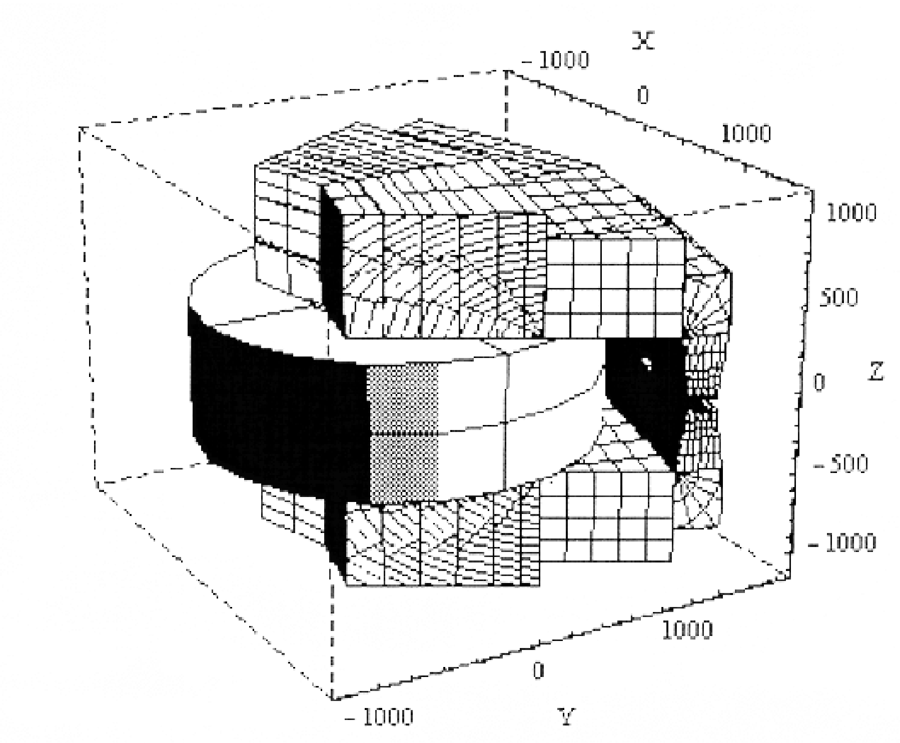

Figure 18: 3D model of the 60° deflecting magnet (RADIA code)

As a result of calculations the following outputs are obtained:

- The most optimal configuration is represented by the structure consisting of two 60° magnets with radius of curvature of a magnetic track 3 meters;
- Working field in each magnet (1,45 T) can be provided at a pole gap 6 – 8 cm with a reserve on an exciting current, as a minimum, 100 % - 22 %, accordingly;
- Usage of two strong deflecting magnets, at growth of an overall dimensions and weight of entire installation, makes it more cost-effective.

*5.2. **Proton beam transport channel project***

5.2.1 **Channel trace choice, allocation**

The designed channel and system of diagnostics should provide:

- Distributing of the output proton beam on an existing “T” trace and on the designed channel without mechanical motion of head elements of these channels by changing only values and polarities of excitation currents;
- Transportation of the proton beam from phasotron to the SAD target with losses not exceeding 5 %;
- Focusing beam on the SAD target with transversal sizes not exceeding 4 cm;
- Simplicity and easy visualization of the procedures of output and control;

The deflection of the output proton beam in the designed channel of transportation without change position of the head elements will be done in scheme of beam distribution figured in Figure 19.

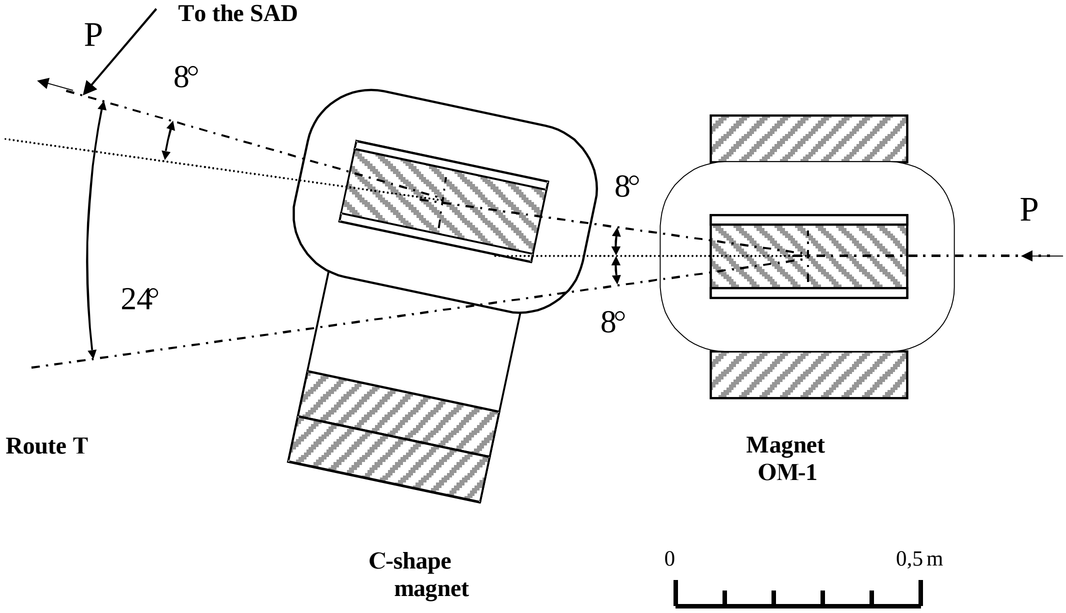

Figure 19: beam distribution scheme for SAD channel and “T” route

In the first OM-1 magnet the polarity of an excitation current varies on return, thus the proton beam deviates on an angle 16° in relation to the route “T” direction.

Further C- shape modified magnet in addition deflects beam for an angle 8°, rising up the total deflection angle to 24°. It allows disposing of the head magneto-optical elements of the designed channel in conditions of restricted space outside of structural elements of “T” route and components of the Phasotron chamber how it is shown in Figure 20.

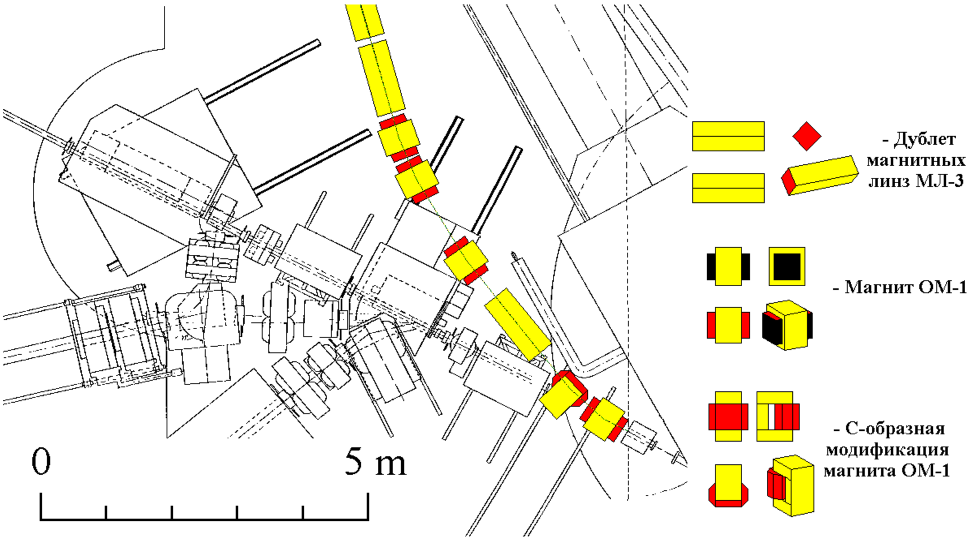

Figure 20: head elements of the SAD & “T” beam transport channel

The further transportation of a proton beam from this initial position can be carried out on different directions. All calculations of modes of transportation of a proton beam and their optimization was carried out with the help of the “TRANSPORT” code [19].

At sketch study the conceptual project was created, in which the set of variants of channels of transportation of a proton beam were considered: with SAD allocation in an interval between a northwest wall of a Phasotron and protective wall of the YASNAPP-2 complex; near to a northeast wall of a phasotron; inside a hall of a phasotron. The conclusions of this conceptual project consist in the following:

1. The allocation of SAD installation within of main Phasotron building, despite of its attractiveness in view of the least amount of concrete, hardly is possible for the following reasons:
    - Difficulties in organization of physical protection of the subcritical blanket;
    - Difficulties in organization of sanitary control;
    - Difficulties in substantiation of the safety of SAD operation at possible falling down the 50- tons crane;
    - Necessity to stop all experiments on Phasotron during constructing-and-mounting works at SAD installation;
    - Difficulties in organization building works at high levels of induced activity from Phasotron components;
2. The variant of arranging of subcritical blanket with vertical input of a proton beam has advantage: more convenient service of a blanket at charge/discharge operations.
3. The variant of allocation of multiplying subcritical blanket between Phasotron building and YASNAPP-2 complex annex, in comparison with its allocation at the external side of building near to communication gallery, has advantage consisting in much smaller quantity of magnetic elements necessary for proton beam transport. To disadvantages of this variant it is necessary to attribute:
    - Difficulties in providing building works at constrained space;
    - Necessity to place auxiliary locations approximately on 20m apart from AC because of intolerable levels of radiation outside Phasotron protective wall;

On the basis of above-stated the following variants in details surveyed:

- SAD is located between Phasotron main building and YASNAPP-2 annex, beam is inserted horizontally;
- SAD is located in the same place, but beam is inserted vertically by means of OM-1 magnets;
- SAD is located in the same place, but beam is inserted vertically by means of 60° magnets;

In view of technical and economic estimations of amount and cost of civil works and requirements of nuclear safety at SAD blanket allocation the variant of vertical (from below) input of a proton beam in subcritical blanket (Figure 21) was chosen. This variant requires ten magnets such as an OM-1, one C- shape magnet four doublets of ML-3 lenses with the aperture of 100 mm two doublets of ML-3 lenses with the aperture of 120 mm and two 60° magnets.

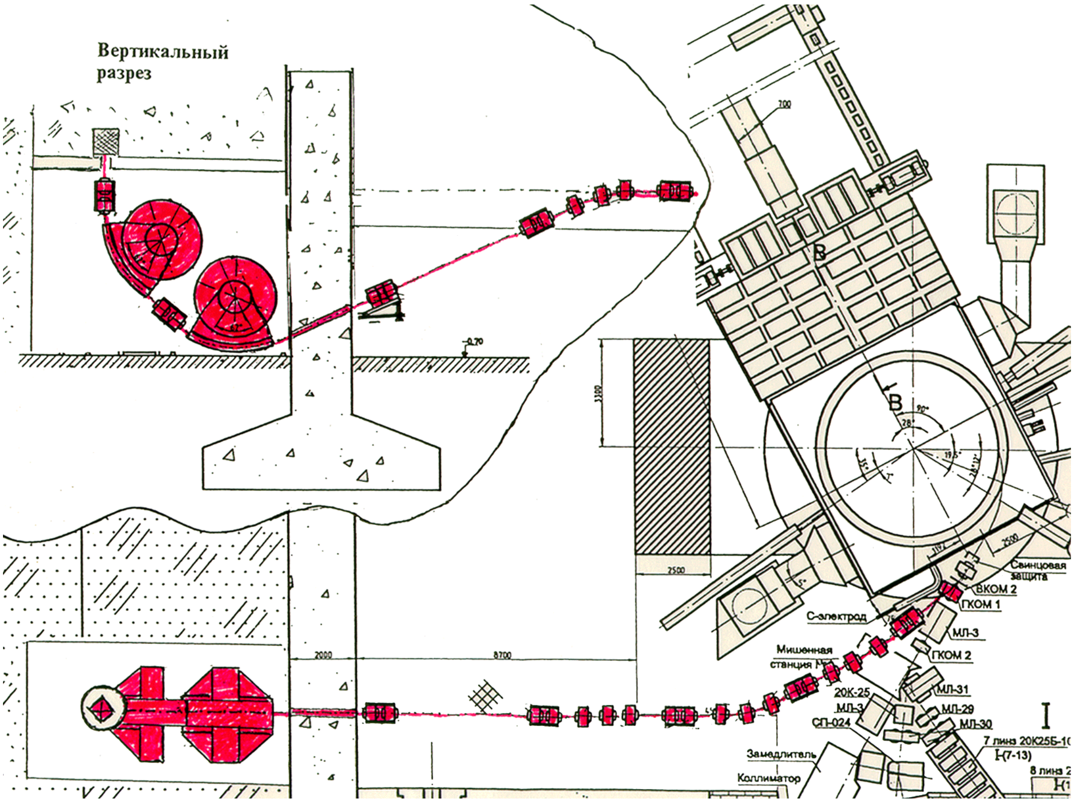

Figure 21: proton beam channel of the SAD installation

5.2.2 Proton beam adjustment and providing operational reliability and radiation safety

To solve correctly the task of beam transportation and it's focusing on a target of subcritical assembly it is necessary to know with an adequate accuracy the initial conditions[20, 21]:

- Phase characteristics (matrix) of a beam at input in the channel;
- Average energy and energy dispersion of protons in a beam;

For measurements and control of beam parameters the system of diagnostics will be designed and created on the basis of existing at DLNP modules.

Average energy and energy dispersion of a beam are well enough known, but in the information on components of a beam matrix on a new direction there is a certain uncertainty, to save from which it will be possible only with the help of new measurements of a beam matrix after installation the head elements of the channel. For these measurements it will be necessary to make the copy of the instrument "Scanning diode array" [22, designed, created and successfully used for beam diagnostics on channels IX, X and XII. The instrument allows to measure intensity distribution in the beam cross-section with space accuracy not worse than 0.5 mm on both coordinates and has exposure time in one section – 2-5 min. Operating range 10^6 – 10^{10} particles / mm^2 for protons with energy 660 MeV.

As restricted accuracy of knowledge of parameters of magnetic elements, inaccuracy of preliminary adjustment the unaccounted aberrations and so forth can bring essential distinctions between designed and actual conditions of beam transportation, it is obviously necessary to carry out with the help of this instrument similar measurements and in other sections of beam route, that will allow to minimize influence of these distinctions.

The control of beam position in the channel during its adjustment or operation will be carried out with the help of designed at DLNP vacuum profilometers disposed after each group of deflecting magnets.

Such profilometer can be inserted and removed in/from the beam easily, without disturbing vacuum, and to measure transversal distribution of the beam in two orthogonal directions. For the designed channel of transportation some profilometers (one profilometer on 3 – 4 magnets) will be manufactured.

The multichannel system of inductive sensors will be applied also to control and customization of the channel of transportation [23]. The system allows in some seconds with accuracy 2-3 % without breakings vacuum to meter and inspect pulse proton beam output (in the mode of fast output) on different locations of the transportation channel. The operating range of a measured average proton current fits into interval 0.3-3 μA. The system is exploited already for a long time on beams IX and XII. The designed channel will require manufacture of such system with number of inductive sensors defined from the rate of one sensor on 4 - 5 elements of the channel. For proton current monitoring on input and output from the channel the air ionization chamber will be used [24].

Such chamber provides practically linear condition of registration of a current of a proton beam up to 5 μA (without the extension), and is applied now for proton beam monitoring at exit from Phasotron chamber. For the SAD channel it will be necessary to create 3 – 4 chambers.

On the beam channel it will be designed and created the automated system of setting and measurement of currents of all magnetic elements of the channel [25]. The system is controlled by the computer and inspects more than 50 power supplies with currents up to 1100 A. The system allows fulfilling the automated customization of the channel of transportation, and also its self-tuning at long-lived maintenance. The automated system has shown sufficient reliability at long-lived maintenance on beam channels at Phasotron.

The reliability of maintenance of elements of the channel of transportation of a proton beam will be provided also with set of instrumentations: temperature sensing devices on all sections of drive windings of lenses and magnets; by manometers for measurement of pressure in the water cooling system; by vacuum gauges for measurements of pressure in proton guide.

The radiation safety at maintenance of the channel of transportation of a proton beam will be provided with the multichannel automated system of a health-monitoring control of a phasotron [26, 27], permitting to measure with the help of informational - measuring sensors located in all parts of building and annexes of the Phasotron, pick-up, analysis and accumulation of data, including preventive and alarm signals in case the levels of radiations in the locations of sensors exceed set values, and also disconnecting of an internal phasotron beam at a radiation incident (spontaneous change excitation current at any element of the channel of transportation).

The second level of a radiation protection will be carried out also by disconnecting an internal Phasotron beam in case of change of the current mode of elements of the channel with the help of automated beam management system.

The additional level of a radiation safety in case of holding operating operations on subcritical assembly will be provided with the help of vacuum shutter – massive brake block inlet into the beam in one of intervals of the channel in a building of a phasotron.

The service of the channel of transportation at the inoperable accelerator is carried out according to the requirements of norms of a radiation safety NRB-99, main sanitary rules of support of a radiation safety OSPORB - 99 and internal instructions for operation of staff in a zone of special access. At the operating accelerator the hall of a phasotron is a zone of the prohibition, and the access of staff in this hall is eliminated by the system of doors with the locks.

6 SAD perspective scientific program

Research program for SAD installation now is forming in collaboration between scientific teams and design organizations. Experimentalist's requirements are reviewed by designers and receive evaluation from point of view of reliability. Dimensions and positions of the experimental channels, which are necessary for scientific experiments, are determining, requirements on locations are establishing, necessary equipment is listing.

6.1. ***SAD neutronic properties***

Calculations of neutron spectral flux distributions inside fuel blanket, lead reflector and surrounding concrete shielding are carried out. Simplified SAD model, represented in Figure 22, was used in calculations.

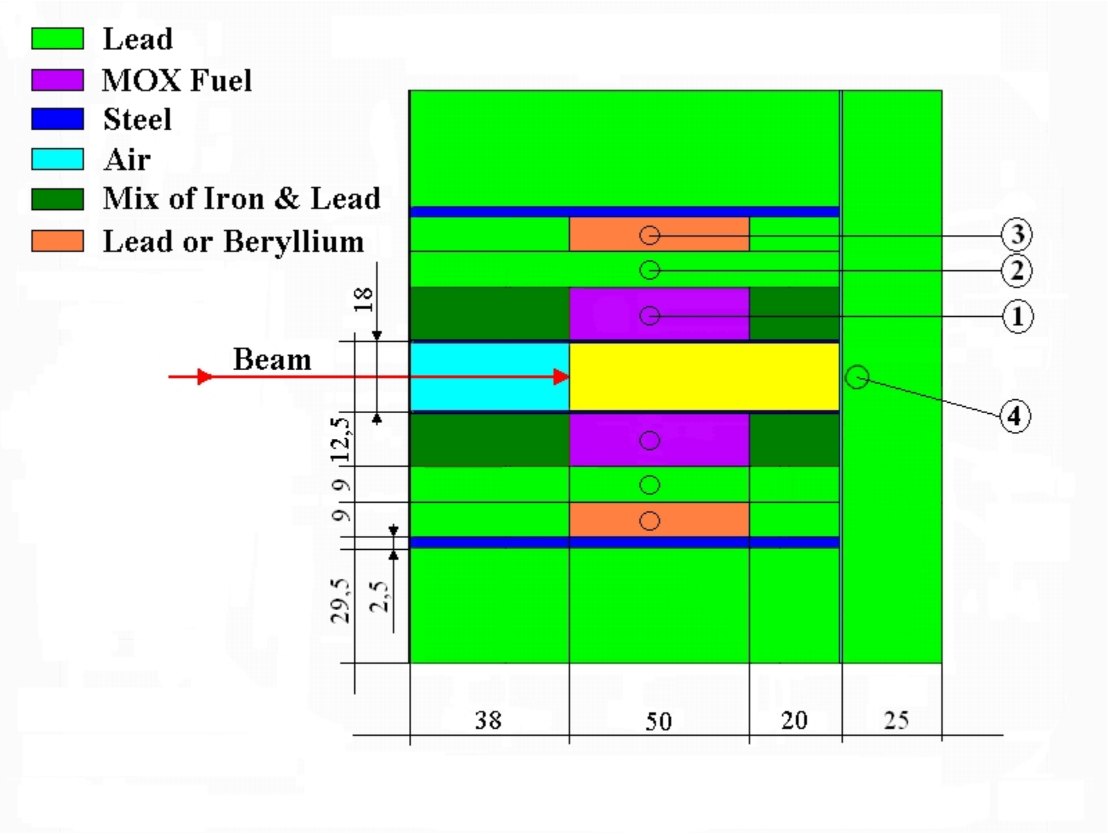

Figure 22: SAD blanket simplified model

Results of the neutron spectra calculations are figured below (Figure 23, Figure 24). Neutron flux density value, integrated over all spectra doesn't exceed 10^{12} n/cm^2·s that restricts SAD experimental possibilities in measurement reaction rates with reactions having relatively high cross sections.

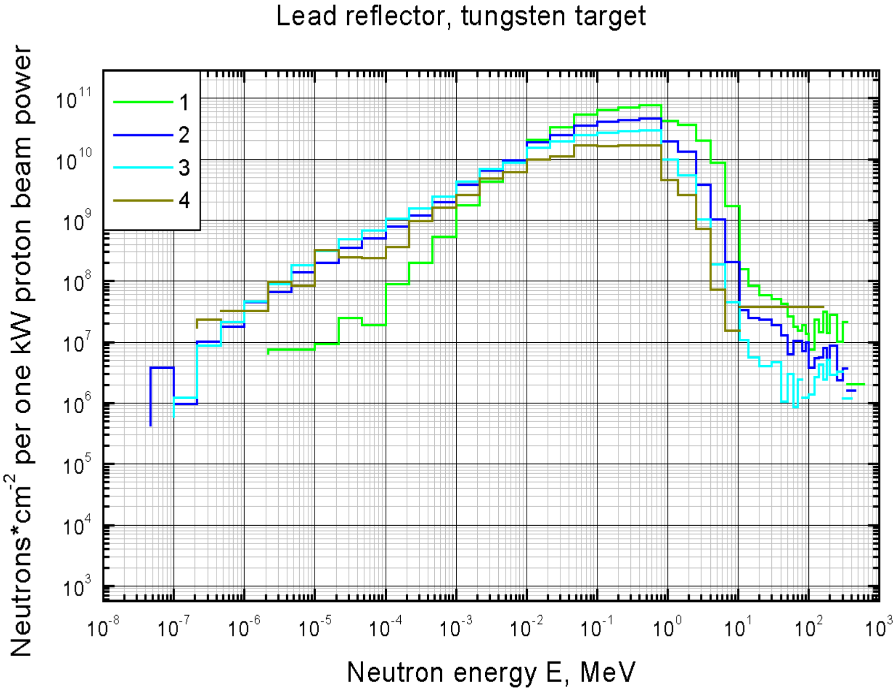

Figure 23: SAD neutron spectra (tungsten target)

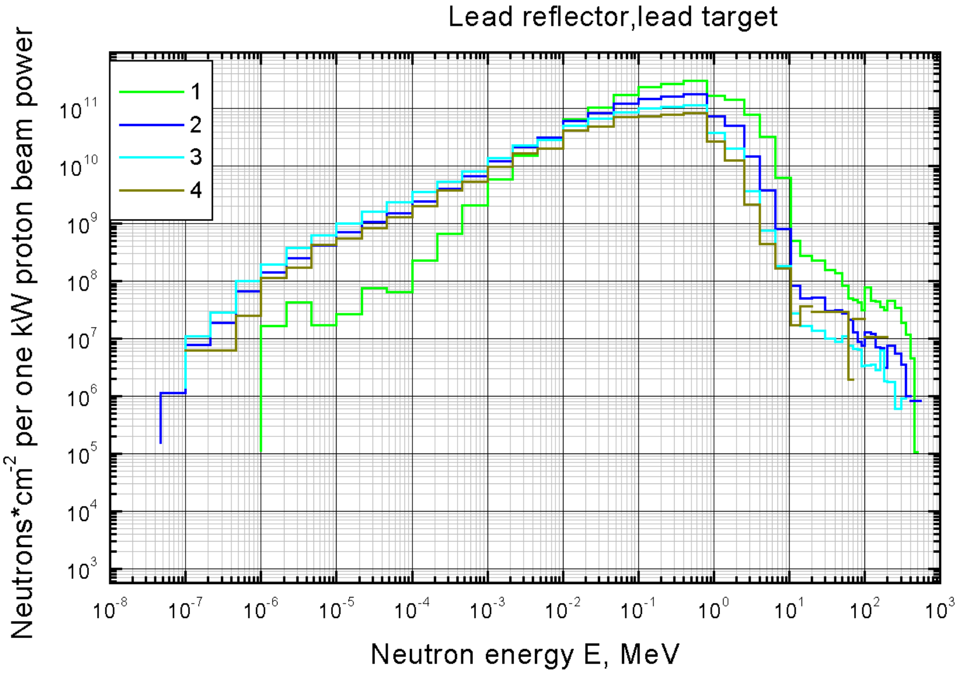

Figure 24: SAD neutron spectra (lead target)

6.2. ***SAD operational modes and kinetic investigations***

One of the most important tasks for subcritical assemblies physics is the problem of reactivity measurements and monitoring at high subcriticality. Investigations in that direction are carrying out at zero power subcritical assemblies with fast (MASURCA) and thermal (YALINA) neutron spectra. This task resolution is extremely important step on the way to creation of the industrial scale ADS facilities, dedicated for radwaste transmutation, because reactivity fluctuations, proton beam parameters influence on reactivity characteristics of the subcritical blanket determine drastically the safety substantiation for such systems.

In SAD scientific program it is proposed to pay attention for experiments on measurements and monitoring of the k_{eff}. It is planned to measure k_{eff} average value by means of inverse multiplication, asymptotic period and other techniques. Time structure of the proton beam (see Table 5) gives wide possibilities in application of the so-called pulse technique of reactivity measurements, in which one measures neutron flux decreasing time constant. That time structure also gives possibility to measure the influence of blanket surrounding (concrete shielding) on its neutronic properties.

The program on measurements neutron spectral flux densities and power release at different parts of the installation, prompt neutrons lifetime, and effective fraction of the delayed neutrons is planned.

To measure spatial and energy characteristics of the neutron field inside subcritical assembly one suppose to place in the target and fuel part of the core specially selected experimental samples, which permit to measure threshold reactions rates. To investigate neutron field in fast energy region absolute reaction rates will be determined for ^{209}Bi, ^{115}In (or ^{197}Au), ^{59}Co, and ^{27}Al.

Besides that samples made of multi component alloy ^{55}Mn+^{63}Cu+^{197}Au+^{176}Lu will be used for measurements (n,γ) reaction rates in thermal and resonance energy region (up to 1 MeV).

It is planned to measure also following spectral indices using ^{235}U, ^{239}Pu, and ^{238}U:

- ^{235}U(n,f)/^{238}U(n,γ);
- ^{239}Pu(n,f)/^{235}U(n,f);
- ^{238}U(n,f)/^{235}U(n,f).

Isotopes, which can be used for measurements of the spectral characteristics of the assembly, are listed in the Table 16.

Table 16: Threshold reactions parameters

Reaction	E_{th}(MeV)	Product	$T_{1/2}$		Reaction	E_{th}(MeV)	Product	$T_{1/2}$
^{115}In(n,n')	0.6	^{115m}In	4.486h		^{209}Bi(n,5n)	30	^{205}Bi	15.31d
^{27}Al(n,p)*	1.9	^{27}Mg	9.46m		^{115}In(n,5n)	35	^{111}In	2.8047d
^{59}Co(n,p)	2.6	^{59}Fe	44.50d		^{209}Bi(n,6n)	38	^{204}Bi	11.22h
^{27}Al(n,α)	3.3	^{24}Na	15.02h		^{209}Bi(n,7n)	45	^{203}Bi	11.76h
^{59}Co(n,α)	6.5	^{56}Mn	2.58h		^{59}Co(n,6n2p)	50	^{52}Mn	5.59d
^{197}Au(n,2n)	8.5	^{196}Au	6.18d		^{115}In(n,7n)	60	^{109}In	4.2h
^{59}Co(n,2n)	11	^{58}Co	70.92d		^{209}Bi(n,8n2p)	65	^{200}Tl	26.1h
^{115}In(n,2n)	13	^{114}In	49.51d		^{59}Co(n,8n4p)	75	^{48}V	15.97d
^{59}Co(n,3n)	20	^{57}Co	271.7d		^{59}Co(n,10n6p)	95	^{44}Sc	3.97h
^{209}Bi(n,4n)	22	^{206}Bi	6.24d		^{115}In(n,12n4p)	120	^{100}Rh	20.8h
^{197}Au(n,4n)*	23	^{194}Au	39.5m		^{209}Bi(n,12n5p)	130	^{191}Pt	2.80d
^{59}Co(n,4n)	25	^{56}Co	77.23d		^{115}In(n,18n8p)	300	^{90}Nb	14.6h

All mentioned measurements would be conducted by means of the γ- spectrometry technique.

6.3. **Cross sections and reaction rates measurements**

One of the experimental fields of investigation at SAD facility AC will be actinides (^{235}U, ^{237}Np, ^{238}Pu, ^{239}Pu, ^{240}Pu, ^{241}Pu, ^{242}Pu, ^{244}Pu, ^{241}Am, ^{242m}Am, ^{243}Am, ^{243}Cm, ^{244}Cm, ^{245}Cm, ^{246}Cm, ^{247}Cm, ^{248}Cm) fission rates measurement. This cycle of research will be conducted in collaboration with ITEPH. One suppose using layers of ^{235}U, ^{237}Np, ^{238}Pu, ^{239}Pu, ^{240}Pu, ^{241}Pu, ^{242}Pu, ^{244}Pu, ^{241}Am, ^{242m}Am, ^{243}Am, ^{243}Cm, ^{244}Cm, ^{245}Cm, ^{246}Cm, ^{247}Cm, ^{248}Cm, manufactured and certified during ISTC projects #17, #1145 and #2405 implementation.

For FP registration the dielectric (glass) track detectors (SSNTD), insensitive for another radiation will be used. In each measurement one array containing studied isotope and track detector will be placed in corresponding location inside the blanket together with similar array consisting of track detector and monitor isotope (^{235}U or ^{239}Pu).

Corresponding reaction cross-section ratios to fission cross-section of the monitor isotope one can consider as spectral index.

Each glass will be developed manually, that permits to decrease significantly errors caused by false tracks.

6.4. **Studying spallation products yields in the target**

It is planned to place inside the target samples made of the same material and also samples of other enriched isotopes in which spallation products yields due to irradiation with target/blanket proton/neutron field will be investigated. Using data on isotope yield cross sections obtained in ISTC projects #1372, #2002, proton spectra at sample locations will be unfolded.

To measure secondary product yield cross section for the target material the helium gaseous loop passing through the target at different distances from the beam entrance point will be designed and created.

Secondary products represented by the recoil nuclei entered in the channel inside a target are picked up by a stream of gas and transported to the gamma-detector analyzing isotope composition and absolute values of activities of spallation products. Extremely small time of transportation (1 – 5 seconds) permits one to measure precisely short-lived products and to restore initial isotope composition with much higher accuracy in comparison with other methods.

6.5. **SAD benchmark program**

May be the most important scientific task for the SAD installation will be computer codes and nuclear data used for ADS modeling tests and adjustment. At present time some reaction rates calculated by different codes, differ in some times, completely excepting an opportunity of accurate calculation of physical characteristics and technology requirements for installations of industrial scale. At SAD design and manufacturing stages the basic task will be to describe with maximum precision isotope and element composition of SAD components its geometry. It will enable to expect in future that all experiments described above could be compared with results of calculations. Thus, all experimental works spent on installation, become benchmark tests of computer codes and nuclear data bases used today.

7 Financial and economical assessment

7.1. *Components of the proton beam transport channel*

Amount of the necessary materials, work time and cost estimation for separate components of the beam transport channel are given in the following tables (the exchange rate is taken for the beginning of 2001 – 28.55 rubles per dollar, cost in dollars – approximate).

Table 17: List of materials and working time, necessary for manufacturing ML-3 lens and cost estimations

Materials and working time	**Amount**	**Cost**
Copper tube (∅ 7 x 1,5) mm^2	90 kg	150 rub x 90=13500 rub
Iron plate (h=25 mm)	300 kg	15 rub x 300=4500 rub
Stainless steel tube (∅ 18 x 1,5) mm^2	5 kg	150rub x 5 = 750 rub
Glass fiber laminate plate (h=10mm) 0,8 m^2	14 kg	200rub x 14 =2800 rub
Stainless steel rod (∅ 40 mm)	80 kg	150rub x 80 = 12000 rub
Ceramic plug (∅ 25mm x 5) mm^2 l=75 mm	32 pcs	500rub x 32 = 16000 rub
Brass, plate (35 mm)	50 kg	150rub x 50 = 7500 rub
Aluminum plate (h=2 mm) 3 m^2	20 kg	150rub x 20 = 3000 rub
Flow relay	1 pcs	3000 rub
Thermal gauges	16 pcs	100rub x 16=1600 rub
Rubber sealing 250 pcs	0,2 kg	250 rub
Working time, hours	2000	60 rub x 2000 = 120.000 rub
Total: materials cost		65.000 rub
Total: ML-3 cost		185000 rub or 6500 $

Table 18: List of materials and working time, necessary for manufacturing OM-1 magnet and cost estimations

Materials and working time	**Amount**	**Cost**
Copper tube (square section) (8,5 x 8,5 x ∅ 5,2)	152 kg	150rub x 152=22800 rub
Iron plate (h=100 mm)	750 kg	15rub x 750=11250 rub
Glass fiber laminate plate (h=10m) 0,2 m^2	3,6 kg	720 rub
Stainless steel tube (∅24 x 2) mm2 l=2 m	4 kg	600 rub
Ceramic tube 13 mm	13 pcs	6500 rub
Brass	20 kg	3000rub

Stainless steel rod (∅ 40 mm)	30 kg	5000 rub
Aluminum plate (h=2 mm) 2 m^2	14 kg	2000 rub
Thermal gauges	12 pcs	1200 rub
Flow relay	1 pcs	3000 rub
Working time, hours	2000	60 rub x 2000 = 120000 rub
Total: materials cost		57000rub
Total: OM-1 cost		177000 rub or 6200$

Table 19: List of materials and working time, necessary for manufacturing support constructions and vacuum guide for beam channel of 50 meters long containing 50 magnetic elements

Materials and working time	**Amount**	**Cost**
Stainless steel tube (∅100 x 2,5) mm2 l=1 m	6,150 kg	920 rub
Steel tubes l= 50 m	350 kg	46000 rub
Channel № 20 (200 x 76) mm^2 l=1 m	18,5 kg	280 rub
Total channels 200 m	3700 kg	56000 rub
L-beam № 30 (300 x 135) mm^2 l= 1 m	36,5 kg	540 rub
Total l-beams l= 100 m	3600 kg	54000 rub
Steel plate (h=5 mm), 1 m^2	41 kg	615 rub
Total: 50 m^2	2000 kg	30000rub
Channel № 10 (100 x 46) mm^2 l=1 m	8,5 kg	128 rub
l= 100 m	850 kg	12800 rub
Tube (∅20 x 2) mm^2 l=1 m	0,9 kg	16 rub
l=100 m	100 kg	1500 rub
Working time, hours	10000	600000 rub
Total: materials cost		200300 rub
Total: support constructions and vacuum guide cost for 50 magnetic elements		800300 rub or 28000$
Cost for one element		560 $

Table 20: List of materials and working time, necessary for manufacturing water-cooling system for beam channel of 50 meters long containing 50 magnetic elements

Materials and working time	**Amount**	**Cost**
Rubber tube ∅25 mm	160 m	50rub x 160=8000 rub
Stainless steel tubes (∅80 x 2) mm^2	100 kg	975 rub x 100=97500 rub
Water connectors	200 pcs	725 rub x 200=145000 rub

Total: material costs		250500 rub
Working time, hours	6000	360000 rub
Total: water cooling system cost for 50 elements		610500 rub or 12300 $
Cost for one element		240 $

Table 21: List of materials and working time, necessary for manufacturing power supply system and control sensors for beam channel containing 53 magnetic elements

Materials and working time	Unit	Amount	Price, rub	Cost, rub
Wire PV3-95	m	12000	114	1368000
Cable KVVG 5 x 0.75	m	3000	9.5	28500
Cable end piece 95 mm^2	pcs	500	60	30000
Thermal relay	pcs	700	90	63000
Connector	pcs	53	60	3180
Cable support 400 mm wide	pcs	220	233	51260
Cable stand 600 mm	pcs	140	56	7840
Console 460 mm	pcs	440	44	19360
Electric switch box	pcs	35	10000	350000
Total: materials and equipment				1921140

Cost of installation works is accepted equal to the cost of materials, i.e. about 2000000 rubles. Total expenses for power feeding of 53 elements of the channel makes about 4000000 rubles or 140000$. Cost of power supply for one element of the channel is equal to 2640$. The electric power consumed by one element of the channel in view of losses in cables and power supplies will make for the maximal current of excitation about 60 kW.

Table 22: List of materials and working time, necessary for manufacturing one vacuum profilometer and cost estimations

Materials and working time	**Amount**	**Cost**
Steel tube (∅57 x 8)mm2 l=350mm	4 kg	200 rub
Steel plate 3 h=4 mm 0,03 m2	3 kg	600 rub
Rod ∅50 mm l=500mm	30 kg	1500 rub
Vacuum case stainless steel plate 3 mm 0,2 m^2	5 kg	150 x 8 = 1200 rub
Aluminum plate h=4 mm 0,03 m^2	3 kg	700 rub
Transfer device UR–6 or its equivalent	1 pcs	5000 rub
Working time, hours	400	24000 rub
Total: cost		33200 rub or 1163 $

Vacuum profilometers will be installed after each group of deflecting magnets, i.e. one profilometer per 5 magnetic elements. So profilometers cost, referred to one element of the channel, will make about 240$. Cost of one inductive gauge which will be installed, approximately, in the same manner as profilometers, referred to one element will make 100$. Thus total expenses for manufacturing, installation and power supply of one element of the channel of transportation will make on the average:

$$\sum = \frac{6500+6200}{2} + 560 + 240 + 2640 + \frac{240+100}{5} = 9858\$ \approx 10000\ \$.$$

Cost of manufacturing of two 60° magnets with use of windings from magnets of ARES installation and iron for yokes from same installation will make on tentative estimations of 50 thousand dollars. Cost of their installation is estimated in 15 thousand dollars. Thus, cost of manufacturing and installation of the channel of transportation will make $235,000.00. Cost of design works on the channel of transportation of protons is estimated by number $30,000.00. These estimations are made in the assumption, that for power supplies and water-cooling of the channel, and also vacuum guide pumping system the equipment available at DLNP will be used.

7.2. ***Subcritical blanket***

Amount of the necessary materials, work time and cost estimation for subcritical blanket manufacturing are given in the Table 23.

Table 23: List of materials and working time, necessary for manufacturing subcritical assembly AC and cost estimations (positions shown from drawings at paragraph 4)

Material		Pos.	Name	Dimensions, mm	Amount, pcs	Mass, kg	Total mass, kg
1	Lead	1	Upper plate	∅ 590, h200	1	774,7	24180 (29000)
		2	Upper ring	∅1000, δ195, h280	1	14000	
		3	Side ring	∅1000, δ235, h714	1	5000	
		4	Lower ring	∅1000, δ235, h520	1	3300	
		5	Lower insert	∅490, h500	1	1100	
2	Concrete (γ=4,5)	6	Removable block	∅1400, h1100	1	38700	107900 (130000)
		7	Upper shielding block	∅3400, δ1000, h1200	1	59200	
		8	Side shielding block	∅3400, δ1200, h1595	1	10000	
3	Stainless steel	9,28	Case + support shell	∅520, δ10(20), h1340	1	250	
		10	Cover	∅ 600, h20	1	45	
		11	Support grid	∅ 496, h30	1	30	
		12	Membrane + connection flange	∅ 30, δ1, h300	1	1,5	

		13	Feeding pipe	∅ 24, δ2, h3000	1	4,5	450,5 (540)
		14	Exhaust pipe	∅ 24, δ2, h3000	1	4,5	
		15	Exhaust flange	~~~~~~~	1	13	
		16	Feeding pipe	∅ 50, δ2, h3000	2	15x4=60	
		17	Exhaust pipe	∅ 50, δ2, h3000	2		
		18	Horizontal channel	∅ 84, δ2, h2200	1	18	
		19	Horizontal channel	∅ 84, δ2, h2500	1		
		20	Vertical channel	∅ 34, δ2, h725	8	3x8=24	
4	Steel	21	Horizontal channel plug	∅100, h600	2	35x2=70	2680 (3220)
		22	Vertical channel plug	∅54, h600	10	10x10=100	
		23	Envelope of the removable block	~~~~~~~~~~~ δ10	1	950	
		24	Envelope of the upper block	~~~~~~~~~~~ δ10	1	1120	
		25	Envelope of the side block	~~~~~~~~~~~ δ10	1	440	
5	Beryllium	26	Block	350x540x220	1	5	5 (6)
6	Lead	27	Target	∅180, h540	1		116,5
7	Tungsten		Target		1		198,5
8	Lead-Bismuth		Target		1		109
9	Aluminum	28	IC channel	∅80x2,5	3	3x5=15	15(18)
9	*******		Bolts and nuts	M12	6		
				M10	36		
			Tools	Collet clamp (lift capacity 5.40 kg)	2		

Cost of the materials necessary for manufacturing of the subcritical assembly is estimated by value of $70,000.00. Design works, including the working design documentation, will cost $200,000.00. Manufacturing of the subcritical assembly and installation works – $80,000.00.

*7.3. **General project cost estimations***

Cost of the SAD installation FE manufacturing and transportation as well as cost estimations for other components of the project, was coordinated at a stage of preparation of ISTC proposal and development of the conceptual project. These estimations are given in final tables (Table 24, Table 25) according to forms 26, 29 of the “Rules of preparation of JINR projects”[28] correspondingly.

Form # 26

Table 24: preliminary time schedule and resource table for the project "CONSTRUCTION OF THE SUBCRITICAL ASSEMBLY WITH COMBINED NEUTRON SPECTRA DRIVEN BY PROTON ACCELERATOR AT PROTON'S ENERGY 660 MEV FOR EXPERIMENTS ON LONG LIVED FISSION PRODUCTS AND MINOR ACTINIDES TRANSMUTATION"

Parts and subsystems of the installation, resources, sources of financing				**Cost k$. Resources. Sources of financing.**	**Laboratory proposal on resources time distribution**			
					1y.	2y.	3y.	4y.
Main subsystems and equipment	Beam transport line			**330**	90	195	45	0
	Subcritical assembly			**350**	128	140	82	0
	FA with FE			**390**	100	250	40	0
	Automated control system			**50**	15	25	10	0
	Cooling and ventilation systems			**80**	20	40	20	0
	Automated system of dosymetry control			**30**	5	25	0	0
	Building works			**500**	20	150	300	30
Necessary Resources	Working hours	JINR Workshop		**20.000 h.**	1000	8000	8000	3000
		Mechanical works						
		Electronics		**10.000 h.**	500	2000	4500	3000
		Design bureau		**10.000 h.**	4000	4000	2000	0
		DLNP workshop		**15.000 h.**	2000	2000	8000	3000
		Phasotron		**200 h.**	0	0	50	150
		Operating costs						
Sources of financing	Budget	Budget costs		**245**	21,5	64	93,5	66
	Extra budget sources	Contributions from collaborators, grants, other sources	ISTC collaborators	**40**	40	0	0	0
			ISTC grant	**1200**	300	300	550	50
			Romanian PP grant	**120**	20	70	30	0
			Czech PP grant	**120**	20	30	30	40
			Poland PP grant	**120**	20	30	30	40
			Bulgarian PP grant	**70**	10	20	20	20
			Belarus PP grant	**60**	10	20	20	10

Project leader
Director of the Laboratory
Leading economist of the Laboratory

Form #29

Table 25: cost estimations for the project "CONSTRUCTION OF THE SUBCRITICAL ASSEMBLY WITH COMBINED NEUTRON SPECTRA DRIVEN BY PROTON ACCELERATOR AT PROTON'S ENERGY 660 MEV FOR EXPERIMENTS ON LONG LIVED FISSION PRODUCTS AND MINOR ACTINIDES TRANSMUTATION"

№	Name	Total cost	1 year	2 year	3 year	4 year
	Project direct costs					
1.	JINR workshop	35000 hours	3500	12000	13500	6000
2.	DLNP workshop	15000 hours	2000	2000	8000	3000
3.	DLNP Phasotron	200 hours	0	0	50	150
4.	Contracts	518 k$	100	318	100	0
5.	Materials	280 k$	50	150	80	0
6.	Equipment	367 k$	5	100	250	12
7.	Building works	500 k$	0	50	350	100
	Total direct costs:	JINR and DLNP workshops 40000 hours	5500	14000	21500	9000
		Phasotron, 200 hours	0	0	50	150
		1730 k$	155	618	780	112

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