PROJECT OF LOWENERGY ACCELERATOR DRIVEN POWER PLANT

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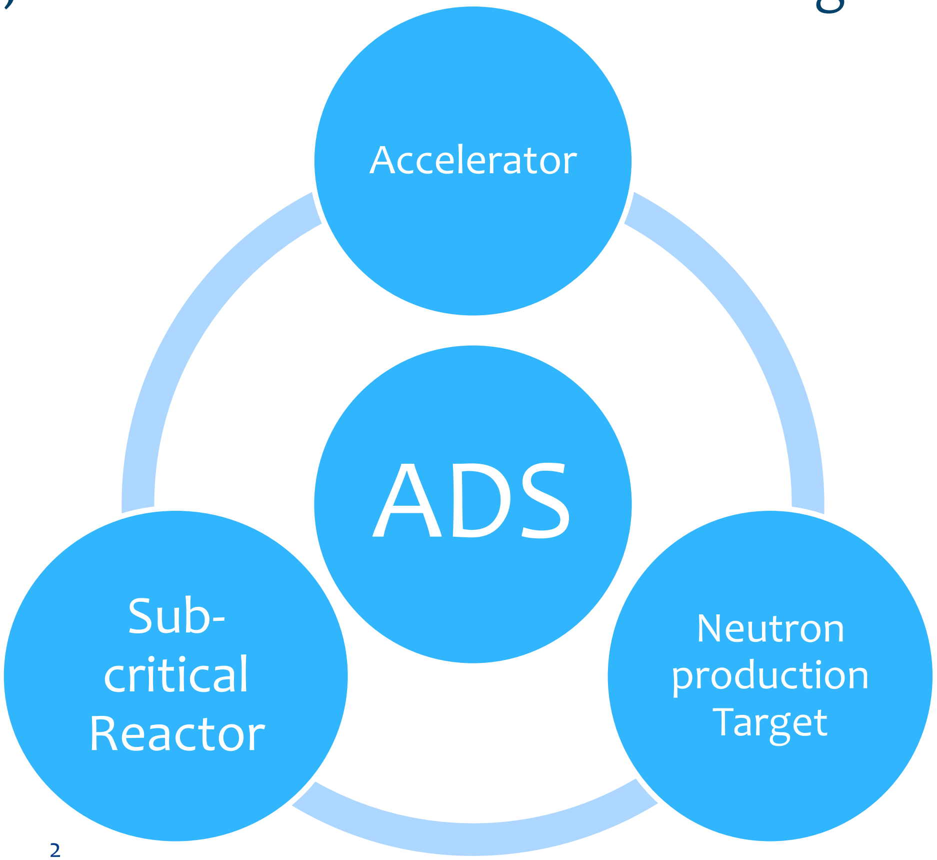
ADS & NUCLEAR TECHNOLOGY

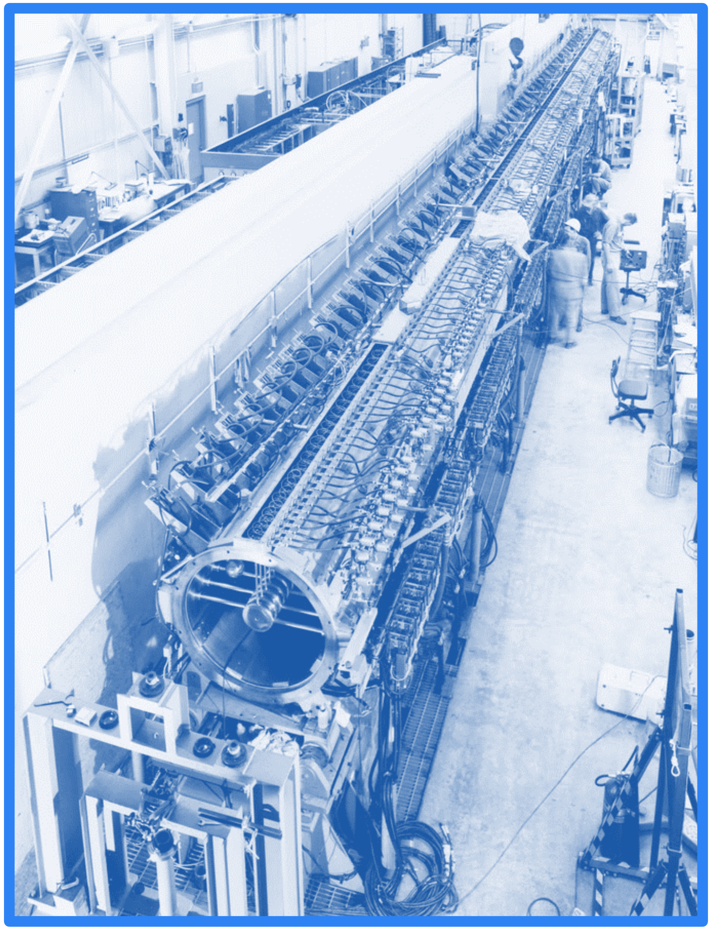
The accelerator driven system – subcritical reactor driven by high power proton accelerators through a spallation target which is neutronically coupled to the core, which remains sub-critical throughout its life.



ADS applications:

- Transmuting actinides and fission products;
- Producing fissile materials;
- Power generation.

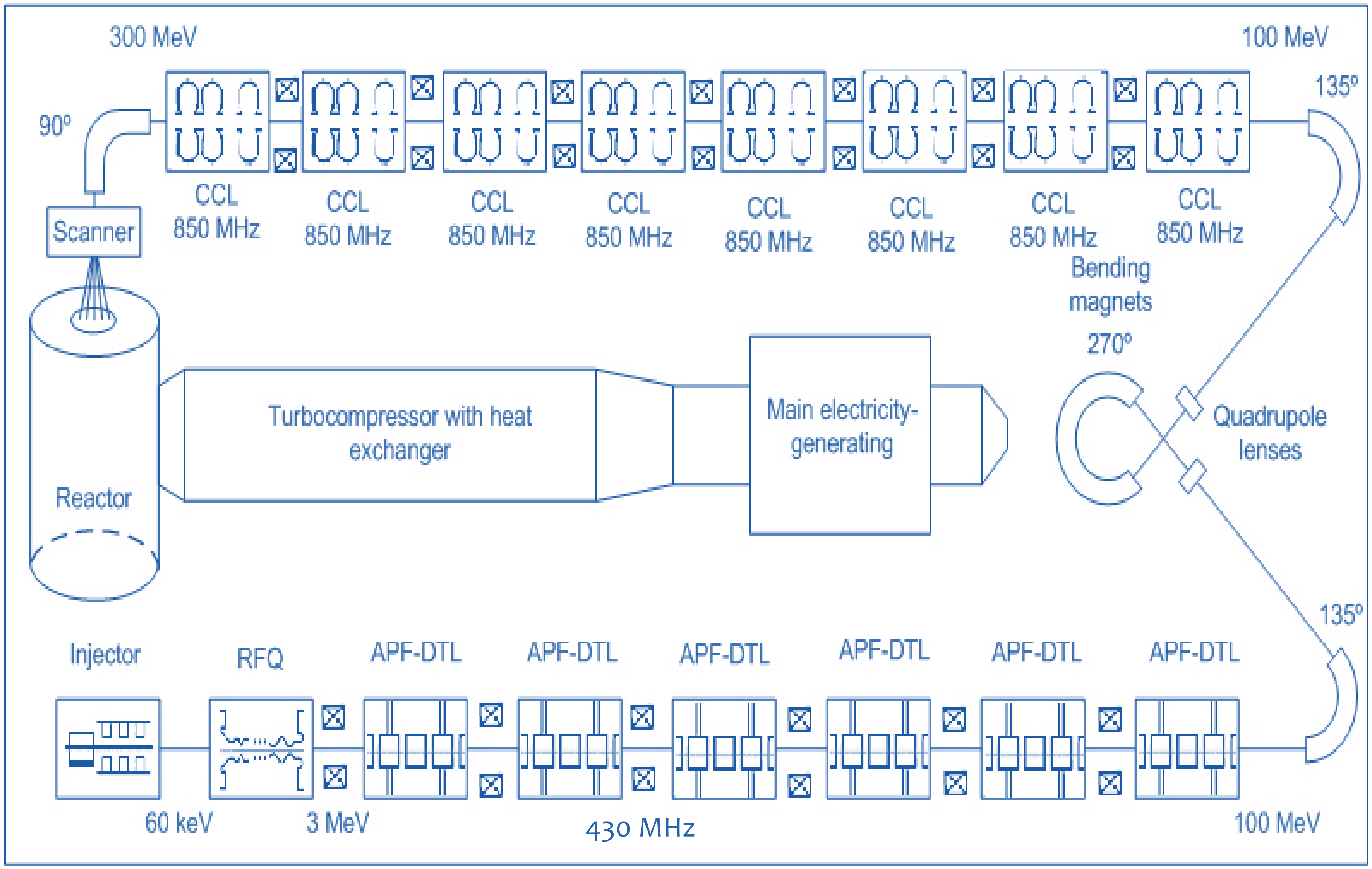
ACCELERATOR



For transmuting and large power ADS there are needed high energy proton beams obtained in unique expensive accelerators. For ADS with reactor power 200-400 MW accelerator requirements are much less and traditional proton linac without superconductivity may be used

ACCELERATOR

Layout of ADS Power Plant with proton linac



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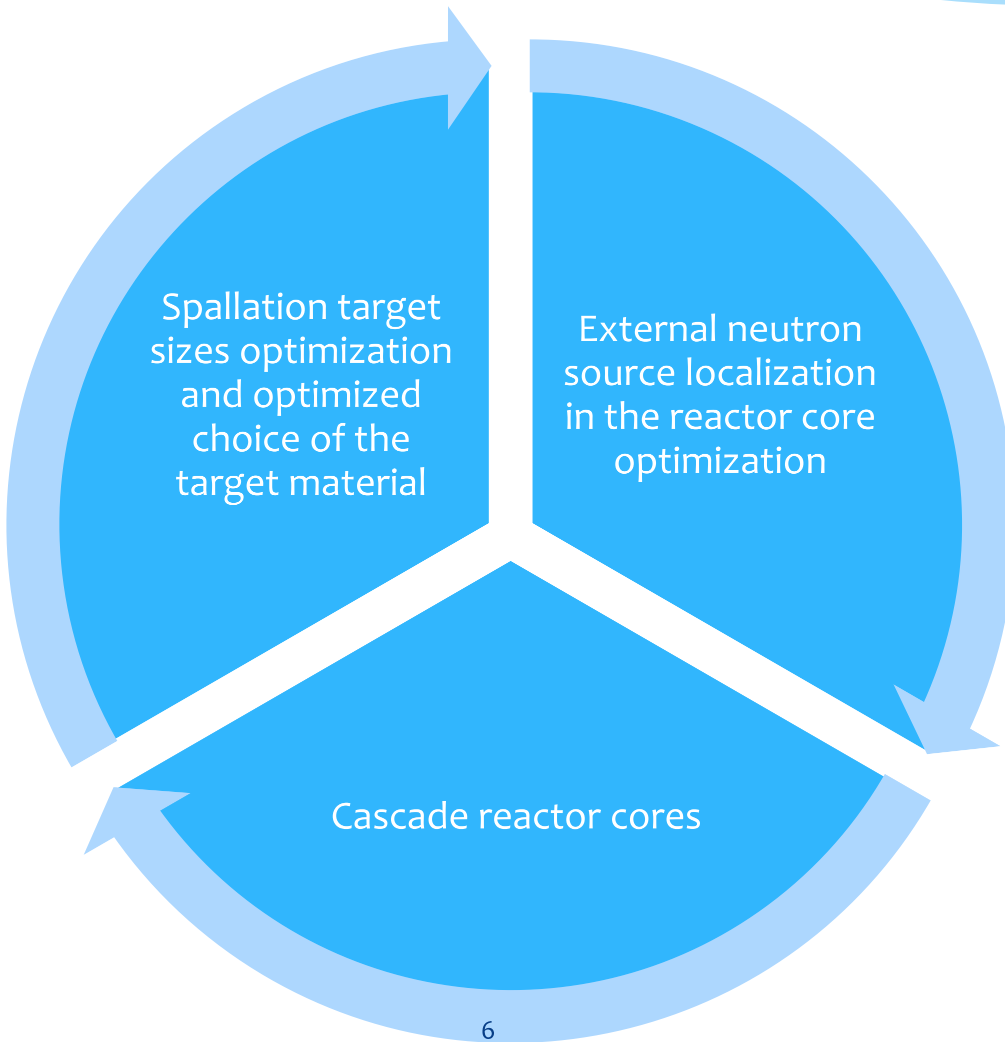
ACCELERATOR

Linac consists of multicusp ion source, 4 vane spatially homogeneous strong focusing structure (RFQ), six resonators with alternating phase focusing structure (APF DTL) and working frequency in diapason 424-433 MHz, coupled cavity linac structure (CCL). Injector, RFQ and six APF DTL resonators are LEBT system, eight resonators of CCL with working frequency in diapason 800-861 MHz are MEBT system. APF DTL structure is IH-cavity which have many cells with thick holders turned on right angle in each following cell and magnetic lenses in the drift tubes.

Main parameters of linac

Output energy	**300 MeV**
Average current	5 mA
Duty factor	10%
Frequency range of RFQ and DTL	424 - 433 MHz
Beam power	1,5 MW
Working frequency of CCL	805-861 MHZ
Number of RFQ	1
Number of APL-DTL resonators	6
Number of CCL modules	8

OPTIMISATION PROBLEM



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TARGET

NEUTRON PRODUCTION TARGET

Fissile material	Non-fissile material
Neutron source intensity is specified by yield of spallation neutrons inside target	Neutron source intensity is specified by leakage from target surface

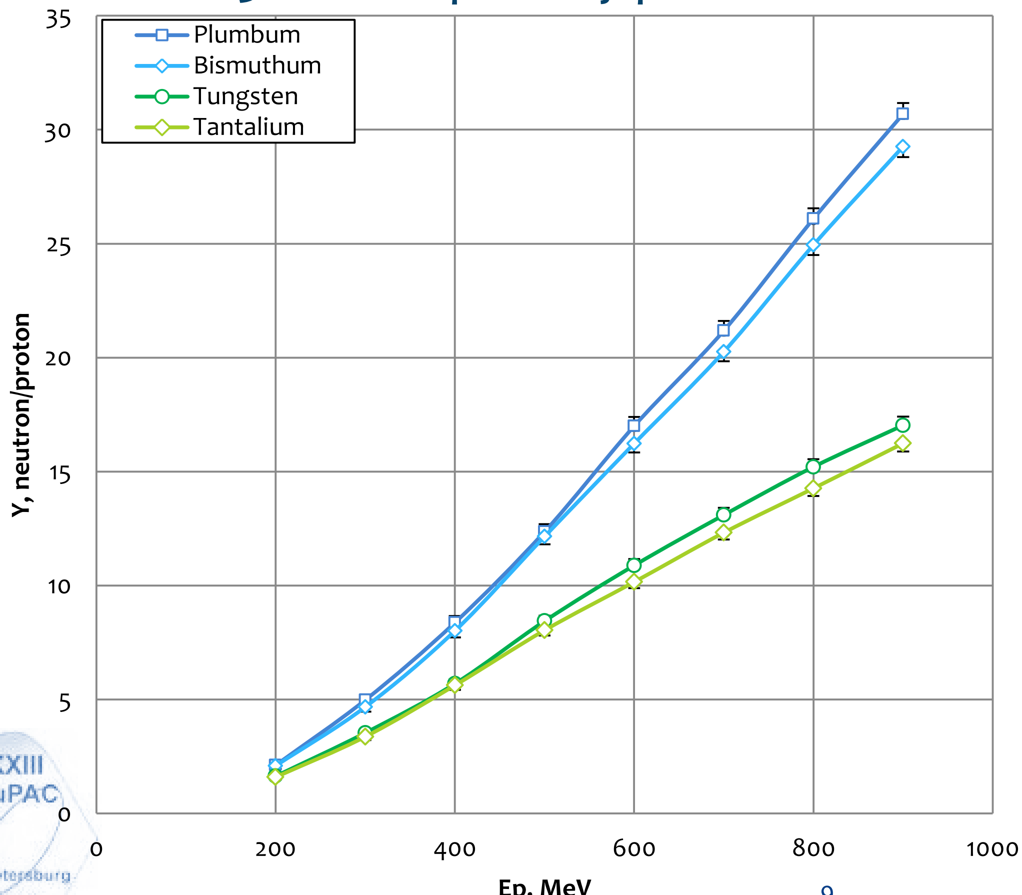
GEANT4.9.5 CALCULATION

Average neutron yield (m_0) from cylindrical Pb targets

Target dimensions	E_P,	m_0, n/p	m_0, n/p
D×L, cm	MeV	GEANT4.9.5	experimental data
10,2×61	470	7.5±0.4	8.0±0.4
	720	13.0±0.3	11.8±0.6
	960	17.6±0.3	16.6±0.8
	1470	25.9±0.4	26.4±1.3
20,4×61	470	8.7±0.1	8.6±0.2
	720	13.9±0.7	15.6±0.3
	960	20.3±1.1	21.9±0.4
	1470	31.5±1.6	33.2±0.5

NON-FISSILE TARGET

Neutron yield from non-fissile target for 300 MeV primary protons.

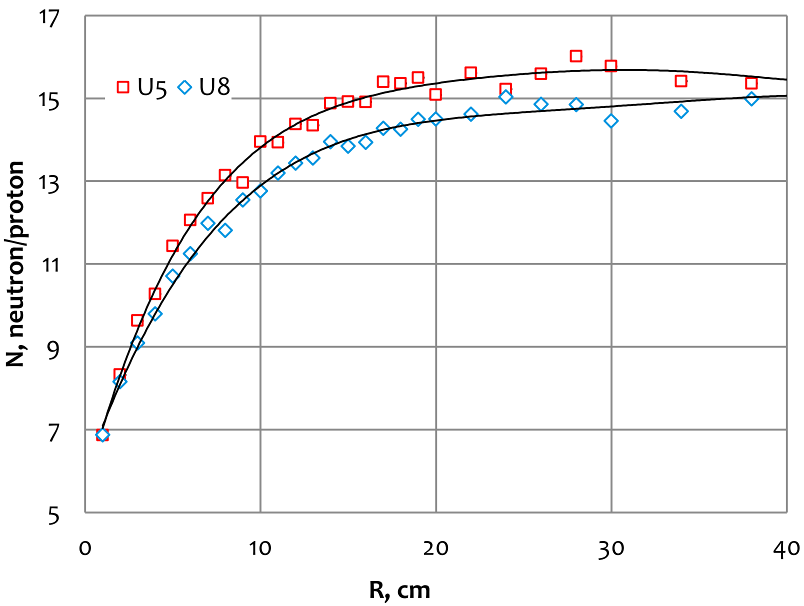


Optimal Sizes of Target

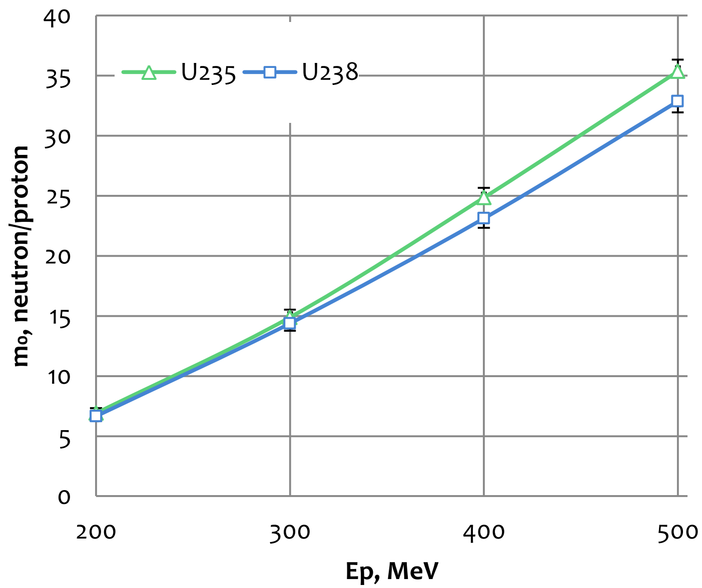
Ep = 300 MeV			
Material	Dopt, cm	Zopt, sm	Lopt, cm
Pb	66	31	76
Bi	95	49	105
W	7	2	10
Ta	7	2	10

FISSILE TARGET

Spallation neutron source vs. Radius



Spallation neutron source inside fissile target



Neutron leakage yield from U target surface (D=32 sm, Ep=300MeV)

Material	Leakage, n/p
U238	10.4±0.5
90%U238+10%U235	27.7±1.3

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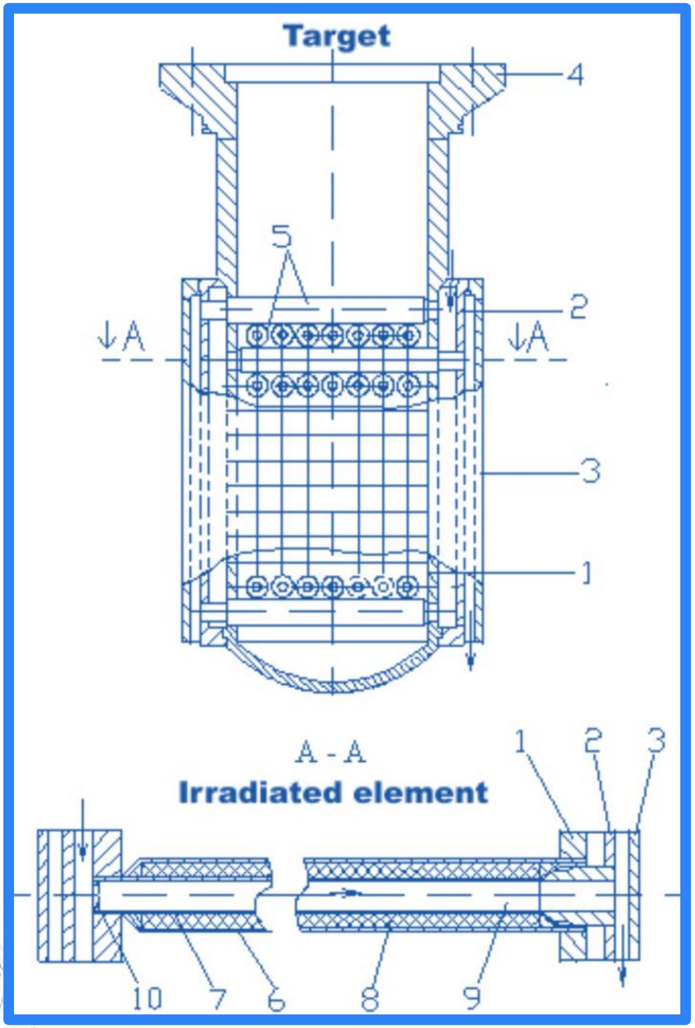
DESIGN OF TARGET



1, 2, 3 – vessel with channels for coolant;
4 – vacuum ion guide;
5 – irradiated elements;
6, 7 – shells of irradiated element;
8 – fissile material;
9 – coolant channel;
10 – throttle.

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SUB-CRITICAL REACTOR POWER

The intensity of electronuclear neutron source is defined as :

- I_p – accelerator current;
- m_0 – spallation neutron yield per primary particle;
- e – charge of primary particle.

$$S = \frac{I_p m_0}{e}$$

For gas cooled target with fissile material UN and structural material W spallation neutron source m_0=12 n/p and intensity S=4,2·10E+17 n/s for I_p=5 mA.

Thermal power of sub-critical reactor with external neutron source spatial distribution similar to fission neutron one (reference neutron source) is evaluated as:

- S_0 - intensity of reference neutron source;
- $k_{eff} < 1$ – multiplication factor;
- ν– mean number of neutrons per fission;
- E_f – energy released per fission.

$$N_T = S_0 \cdot \frac{k_{эф}}{1-k_{эф}} \cdot \frac{1}{\nu} \cdot E_f$$

To maintain constant power rate of ADS over reactor operation period with decreasing *k*eff it's necessary to increase accelerator current. Reactivity reduction as a result of nuclear fuel burning and reactor poisoning is about 8% for thermal-neutron reactor and 1- 3% for fast-neutron reactor. Thus, in ADS with fast neutron reactor accelerator current variety during the operation period is significantly less than one with thermal-neutron reactor. Consequently using fast core in ADS is more preferable.

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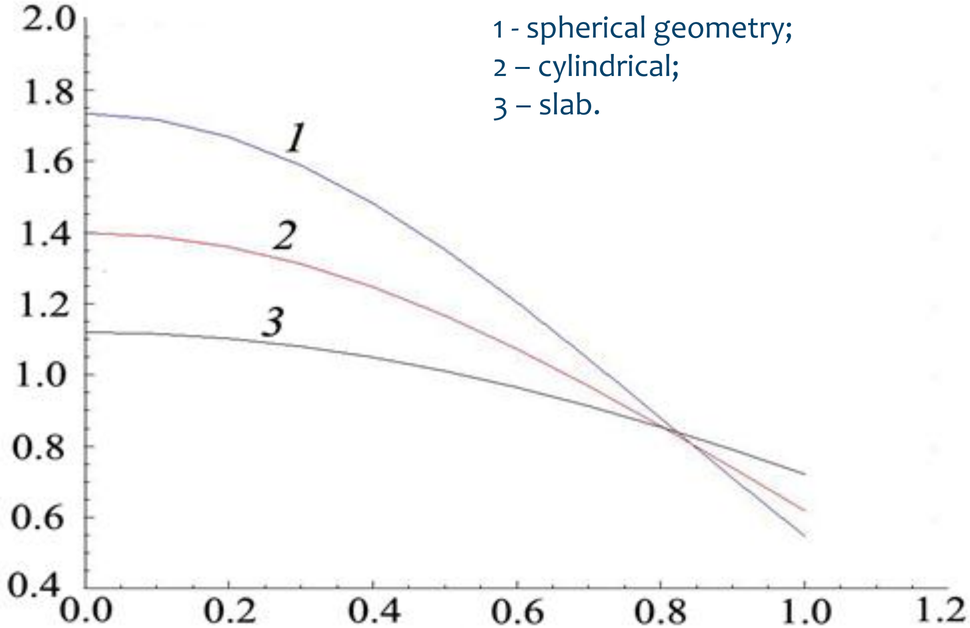
SPATIAL LOCALIZATION OF NEUTRON SOURCE

$$k_{ampl} = \frac{1-k_{eff}}{k_{eff}} \cdot \left(\frac{Q_f}{S_0}\right)$$



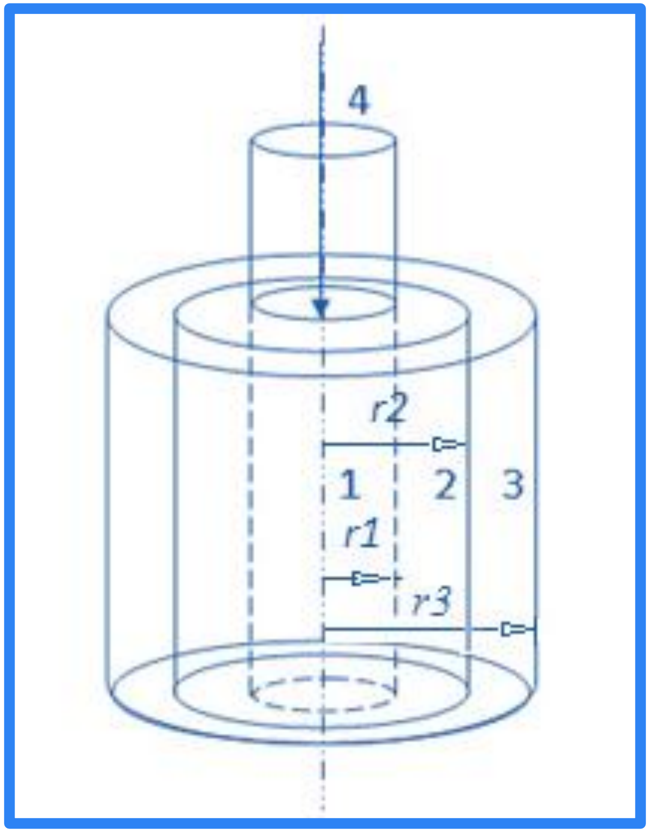
1 - spherical geometry;
2 – cylindrical;
3 – slab.

$$k_{ampl} = \left(\frac{Q_f}{S_0}\right) / \left(\frac{Q_f}{S_0}\right)_{ref}$$

$$\bar{a} = \frac{r_{sourse}}{R_{core}}$$

CASCADE CORE

Cascade reactor core scheme



- 1 – inner section;
- 2 – neutron gate;
- 3 – outer section;
- 4 – charged particles beam.

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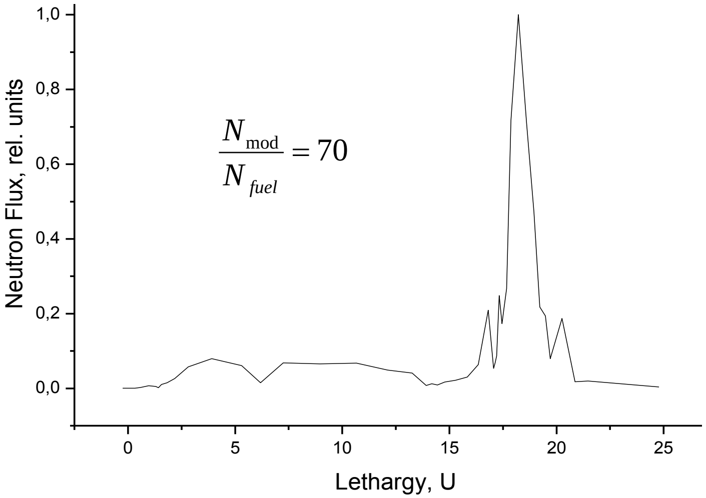
1. Fast-thermal cascade core consists of inner subcritical section in fast neutrons with additional neutron source and outer subcritical section in fast or thermal neutrons. The neutron feedback of inner and outer sections could be broken using neutron gate (thermal neutron absorber).

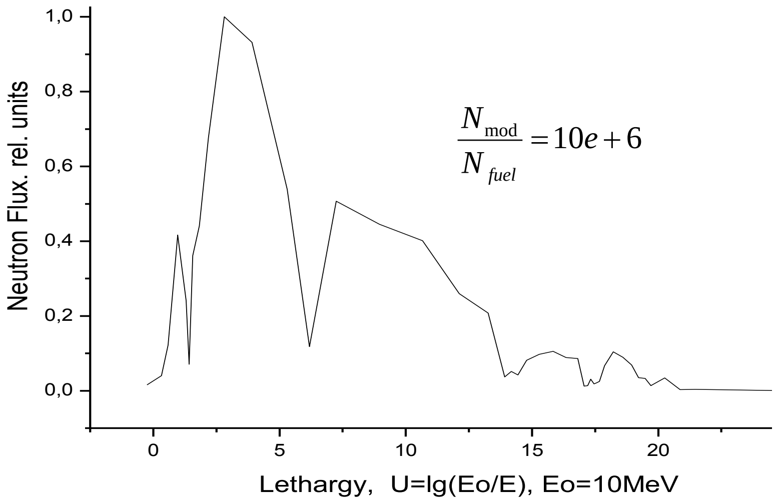
2. In real cascade core it's impossible to break neutron feedback completely, because there is a lot of high energy neutrons in the outer zone, which couldn't be absorbed by the "neutron" gate and come into the inner section. It can be avoided by using the second gate type: "geometrical" gate in cylindrical core (void gap $\Delta r = r2 - r1$). In this case both coupling zones could be fast.

FAST-THERMAL CASCADE CORE

Neutron energy spectrum in reactor

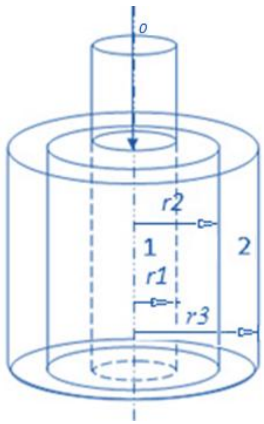


A) Moderator – H_2O, Fuel - ^{235}U;



B) Moderator – Graphite, Fuel - ^{235}U;

CASCADE CORE WITH GEOMETRICAL GAP



$K_{\bowtie 1} = 2.1$ $\quad$ $K_{12} = 0.533$

$K_{\bowtie 2} = 0.98$ $\quad$ $K_{21} = 0$

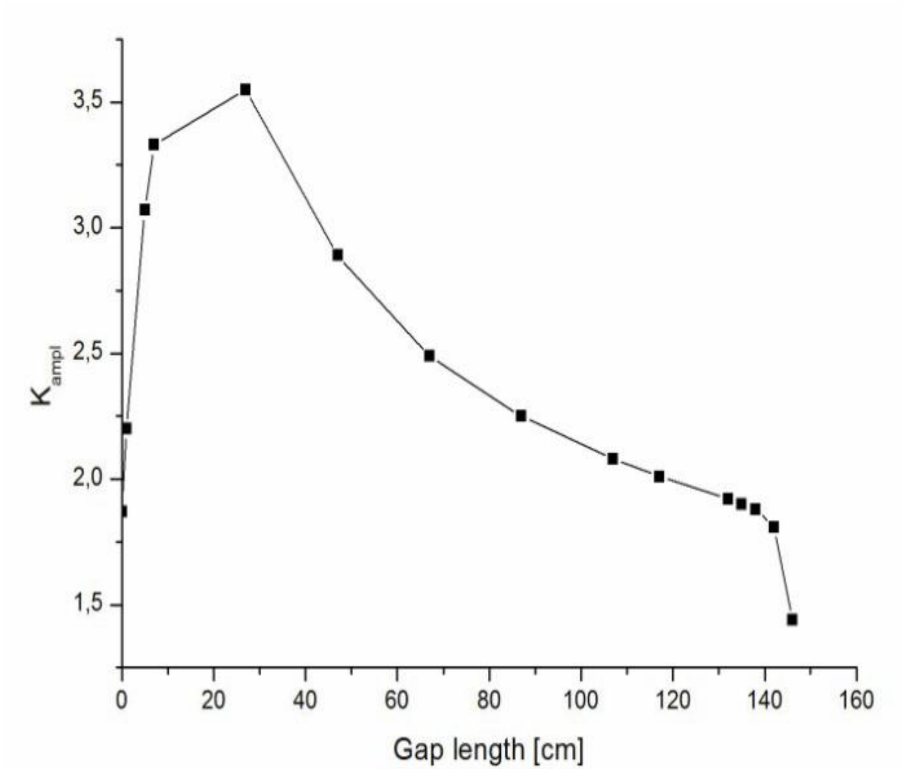
$K_1 = 0.98$ $\quad$ $K_{01} = 2.14$

$K_2 = 0{,}98$ $\quad$ $K_{02} = 0$

$K_{eff} = 0.98$

$K_{ampl} = 58$

$Q_{f2}/Q_{f1} = 20$



Dependence of kampl on gap length
for fast cascade core with r3 = 150 cm
(cylindrical geometry)

REACTOR POWER

Sub-critical reactor power (S_0=4.2·10E+17 n/sec, m_0=12 n/p)

Fissile/ Non-Fissile	Target D, sm	Core D, sm	Fuel enrich. (U238), %	Keff	NT, MW
Fissile	10	160	70.5	0.98	428
Fissile	40	160	70.5	0.98	402
Fissile	60	160	70.5	0.98	383
Non-fissile	40	164	82.0	0.98	268
Fissile	40	160	69.2	0.97	265
Fissile	40	160	68.0	0.96	200
Non-fissile	40	164	79.0	0.96	153
Fissile	40	160	66.6	0.95	152

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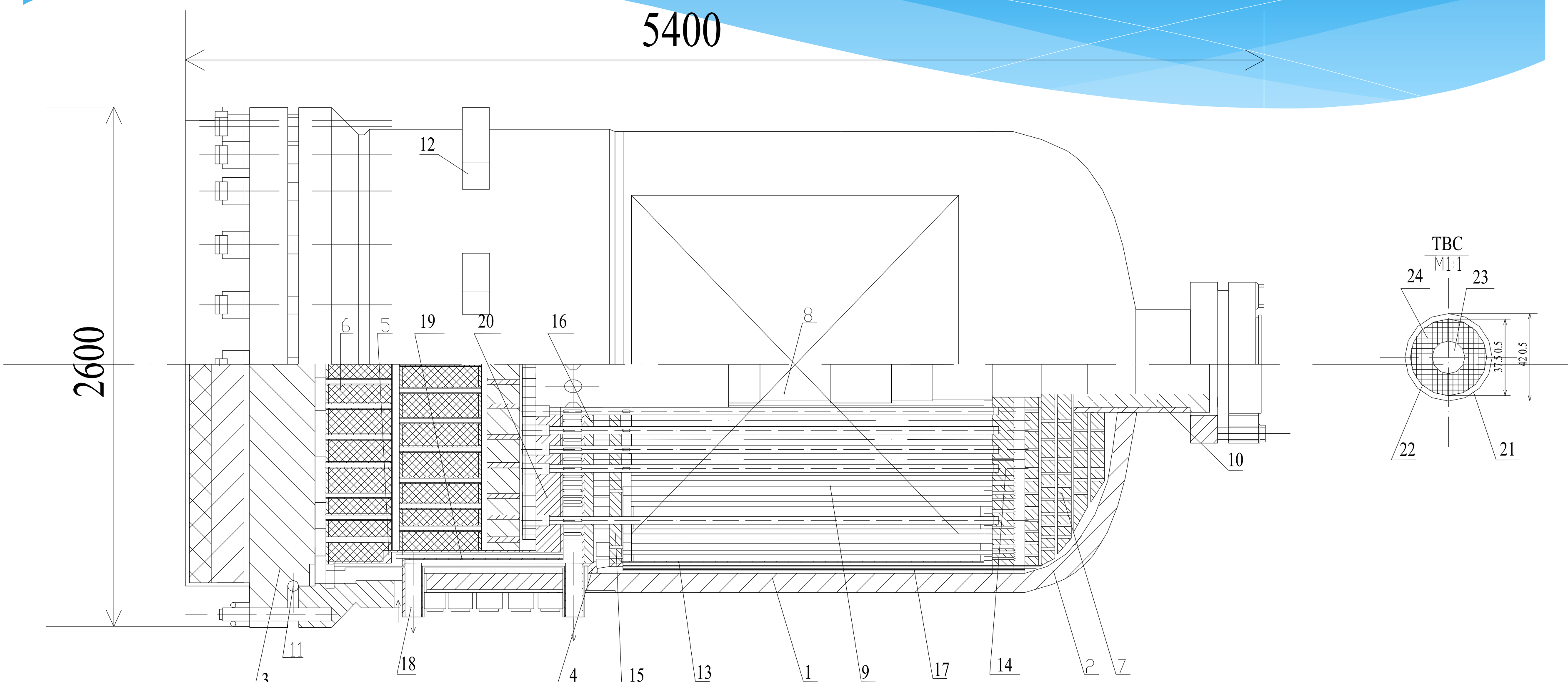
GAS COOLED REACTOR DESIGN



1 – vessel;
2 – bottom;
3 – closure head;
4 – core shroud;
5 – fuel assemblies holder;
6 – upper shield;
7 – edge shields;

8 – target;
9 – core;
10 – nozzle of ion guide;
11 – sealing;
12 – reactor vessel fixing elements;
13 – core shroud shell;

14, 15, 16 – core plats;
17 – shield;
18 – output gas nozzle;
19, 20 – fuel assemblies holder shell, plate;
21, 22, 23 – fuel assemblies' tubes;
24 – cylindrical fuel elements.

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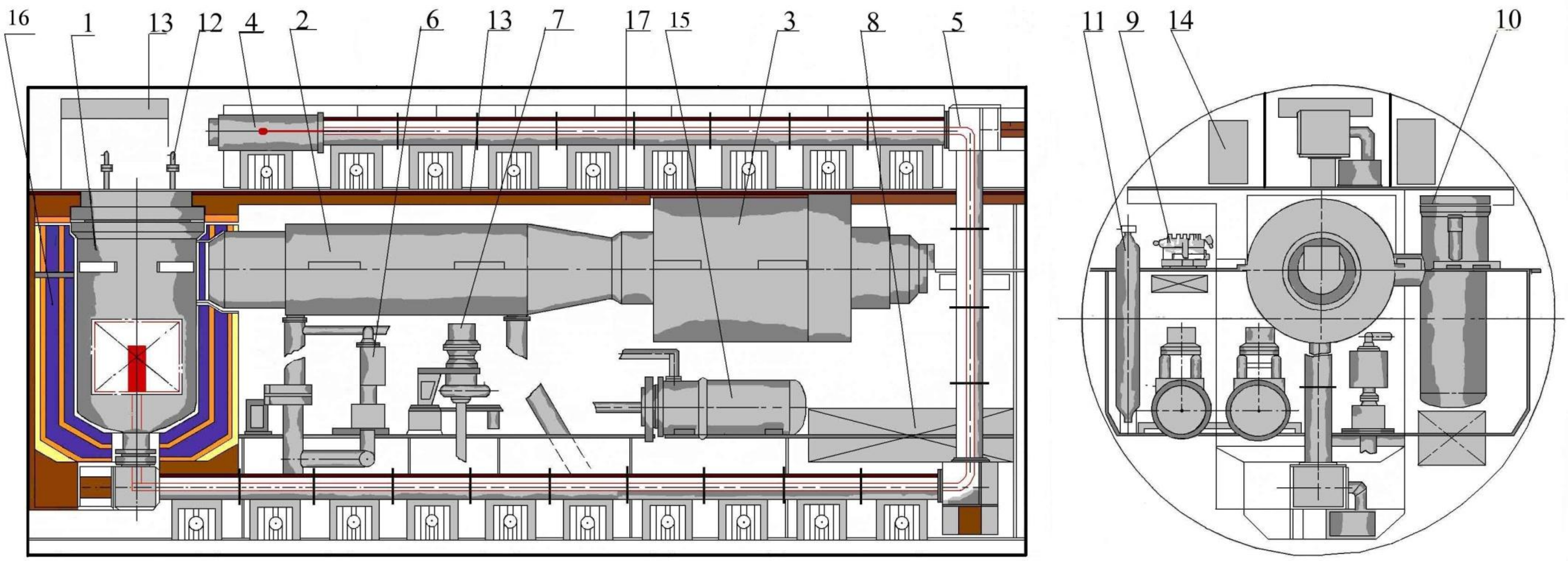
ADS POWER PLANT LAYOUT

ADS Power Plant in containment



1 – reactor;
2 – turbocompressor;
3 – electric – generator;
4 – accelerator;
5 – bending magnets;
6,7 – pumps of cooling systems;
8 – water tank;

9 – vacuum facility;
10 – emergency core-cooling system;
11 – helium balloons;
12 – instrumentation of control system;
13 – electrical equipment;
14 – blocks of RF source;
15 – heat-exchanger;
16 – radiation shielding.

ADS POWER PLANT CHARACTERISTICS

Effective output	25 MW(el.)
Linac: -current - proton energy	 0,5 mA 300 MeV
Target (D)	UN+W (0,4 m)
Reactor: - Thermal power, - Core DxH, - k_{eff} - fuel -coolant (P; T_{in}; T_{out})	Fast HTGR 200 MW 1,6x1,5 m 0,98 - 0,96 UN He(10MPa; 230°C;900°C)
Gas-turbine efficiency	20%
Containment dimension D x L	10x30 m

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CONCLUSION

- Present-day reactor and accelerator technologies allow to create low energy accelerator driven power plant with electrical output 25 *MW*.

- A promising option of a small-size electronuclear power plant could be based on linear high-frequency proton accelerator, fissile target and sub-critical fast reactor.

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