Joint Institute for Nuclear Research
Frank Laboratory of Neutron Physics

Proton-driven high-flux pulsed neutron source for beam research

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Requirements for the source

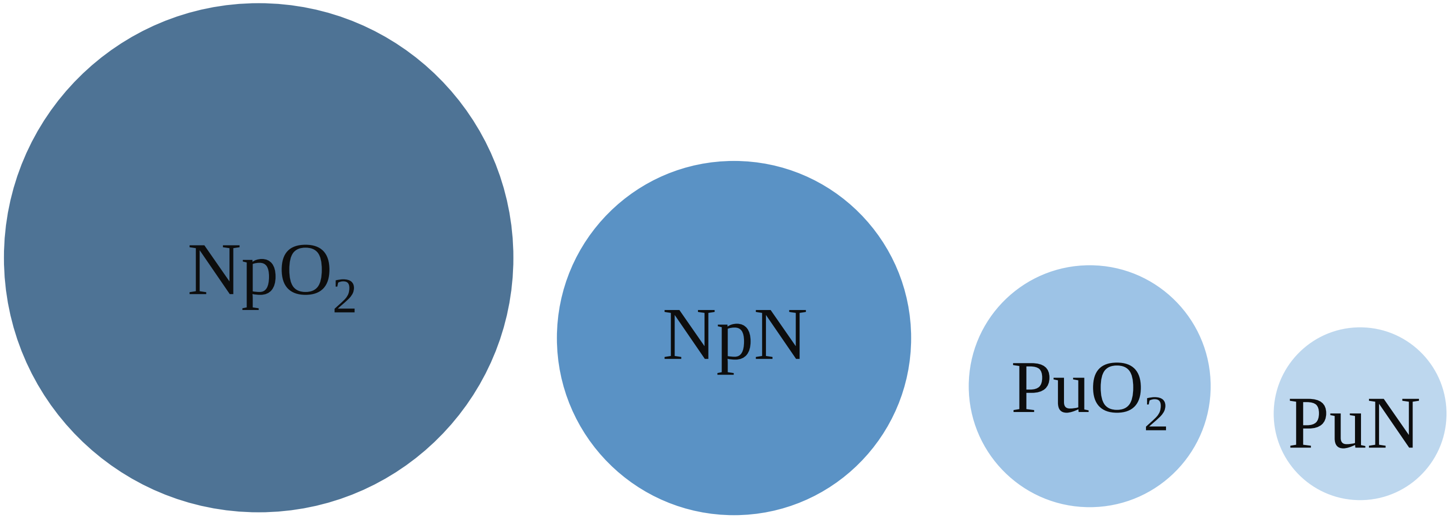
- Thermal neutron flux density on water moderator surface
  $\Phi > 10^{14}$ n/(cm^2 s);

- According to nuclear safety rules at $K_{eff} < 0.98$ there is no need for a protection system. In the future, nuclear safety rules for high-power (MW) subcritical systems may be changed to meet more stringent requirements. In this case, nuclear safety can be ensured by a deep subcriticality of the core. Multiplication factor $K_{eff} \leq 0.98$ (0.95);

- Proton beam power on target Ep+ = (0.1- 0.15) MW;

- Use of reliable materials and proven technologies.

Illustrative representation of critical size of the sphere



NpO_2

NpN

PuO_2

PuN

Critical size of the sphere

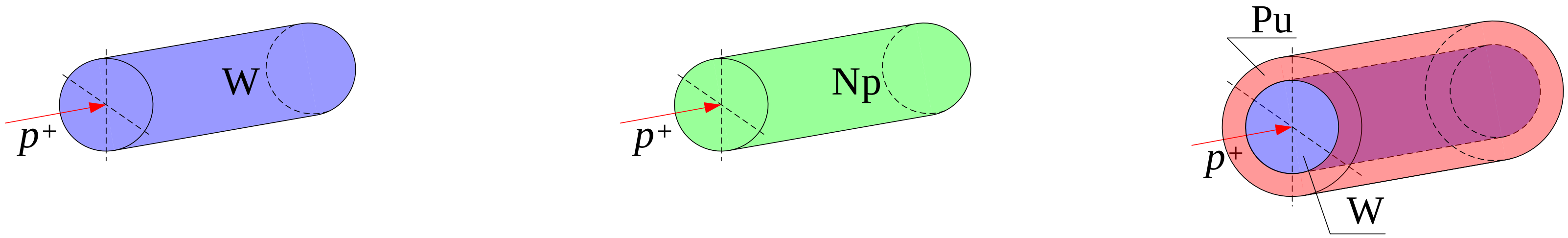
Compare Fast Pulsed Reactors with Pu-239 and Np-237 Fuel

Pu Fuel (IBR-2)	**Np Fuel**
+Critical Mass: ~50-100 kG	**-Critical Mass: ~400-500 kG(**money)
+Fuel License: YES	**-Fuel License: NO(**money)
+Na Void Effect : -5%	**-Na Void Effect: +0.5% _+1%(NS)**
+Fission Lifetime: ~50 nsec	**-Fission Lifetime: ~10 nsec(NS)**
+Delayed Neutrons β_{eff}: ~2.16e-3	**-Delayed Neutrons β_{eff}: ~1.3e-3(NS)**

Sensitivity to Perturbation of Reactivity

-High	**--Ultrahigh(Nuclear Safety-NS)**
-Power Limit(Dynamic Instability): >2MWt	**-Power Limit(Dynamic Instability):>1-2MWt**
-Pulse Half-width: ~200 µsec	**+Pulse Half-width: ~50 µsec**
Thermal Flux(2 MWt): ~5e12 n/cm^2sec	**Thermal Flux(2 MWt): ~3e12 n/cm^2sec**

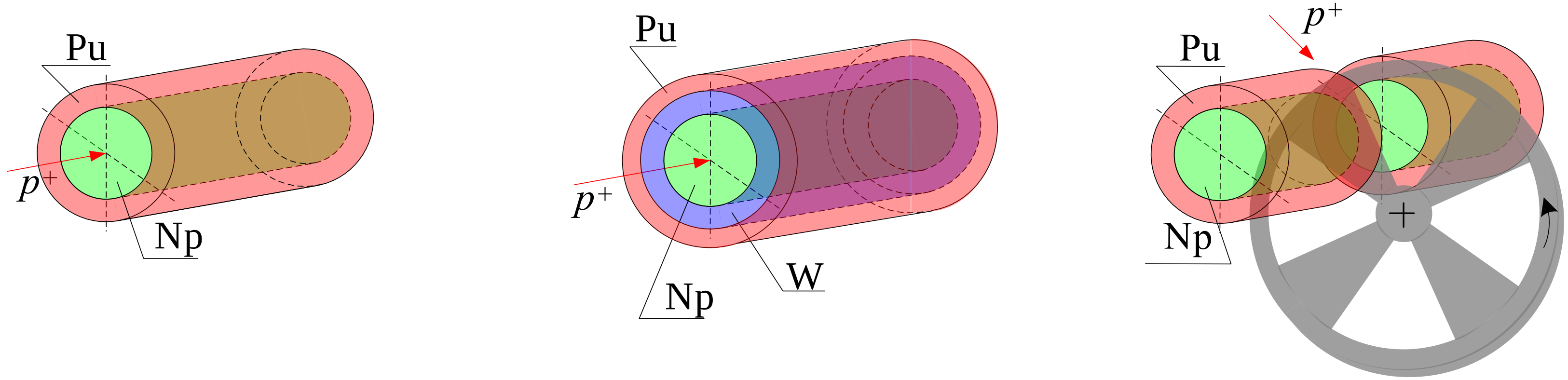
Illustrative representation of categories of neutron sources driven by a proton accelerator



1. Non-multiplying target

2. Multiplying target

3. One-core booster



4. Two-core booster

5. Two-cascade booster

6. Pulsed booster

Fig. 1. Illustrative representation of categories of neutron sources driven by a proton accelerator.

Table 1. Comparison of design characteristics of optimal variants of proton-driven neutron sources.

№	Parameter	1. Non-multiplying target		2. Multiplying target	3. One-core booster		4. Two-core booster	5. Two-cascade booster
1	**Multiplication factor, K_{eff}**	-		0.98	0.98	0.98	0.98	0.98
2	**Target**	W	U-238	Np-237	W	U-238	Np-237	Np-237
	Coolant	Water	Water	Pb-Bi	Water	Water	Water	Sodium
	Target volume, l	19.6	19.6	39.7	37	37	37	
	Target mass, kg	340	337	536	640	634	500	60
3	**Parameters of core**							
	Fuel				**PuO_2**	**PuO_2**	**PuO_2**	**Metallic Pu**
	Volume, l				20	20	20	
	Fuel mass, kg				170	170	170	210
	Coolant				Water	Water	Water	Sodium
4	**Full power of booster, MW**	**0.1**	**0.13**	**7.6**	**10.0**	**13.0**	**10.3**	**15.0**
5	**Thermal neutron flux density on the surface of flat (grooved) water moderator φ_{th}, 10^{13} n/(s·cm^2)**	0.6 (1.0)	1.2 (1.9)	9.0 (15.3)	25.0 (42.5)	28.0 (47.6)	34.0 (57.8)	8.8 (15.0)
6	**Lifetime of prompt neutrons, s**			$1.40 \cdot 10^{-6}$	$2.0 \cdot 10^{-6}$	$2.0 \cdot 10^{-6}$	$1.98 \cdot 10^{-6}$	$2.80 \cdot 10^{-6}$

Optimal variant of the source (1)

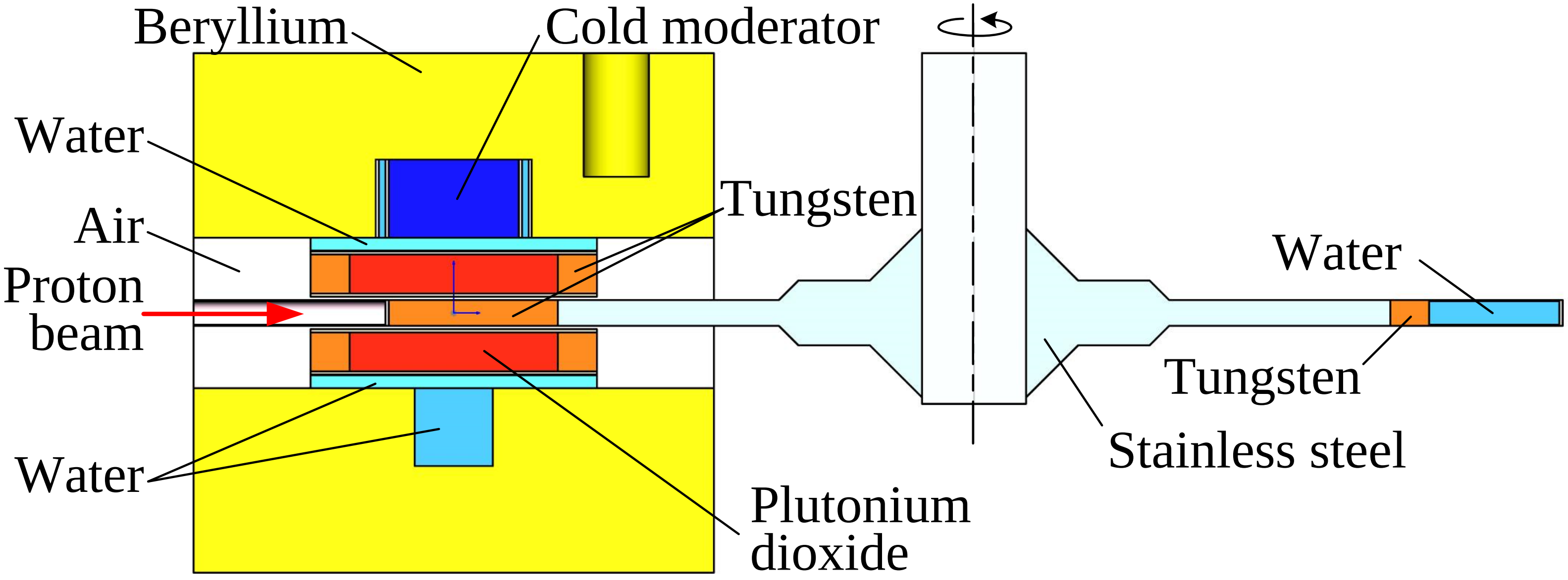


Fig. 2. Evaluation model of a booster with a rotating tungsten target and plutonium dioxide core

Optimal variant of the source (2)

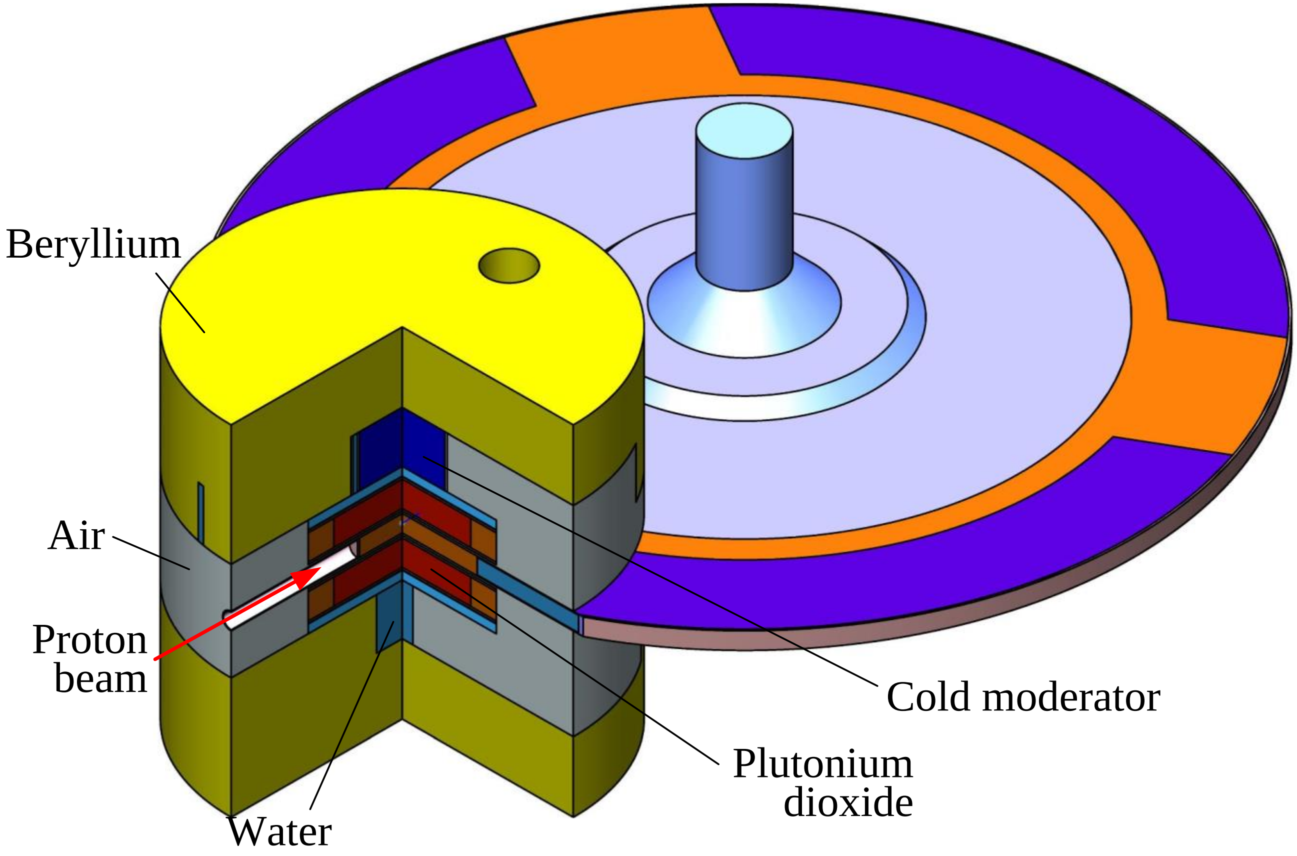


Fig. 3. Evaluation model of a booster with a rotating tungsten target and plutonium dioxide core.

Rotating target

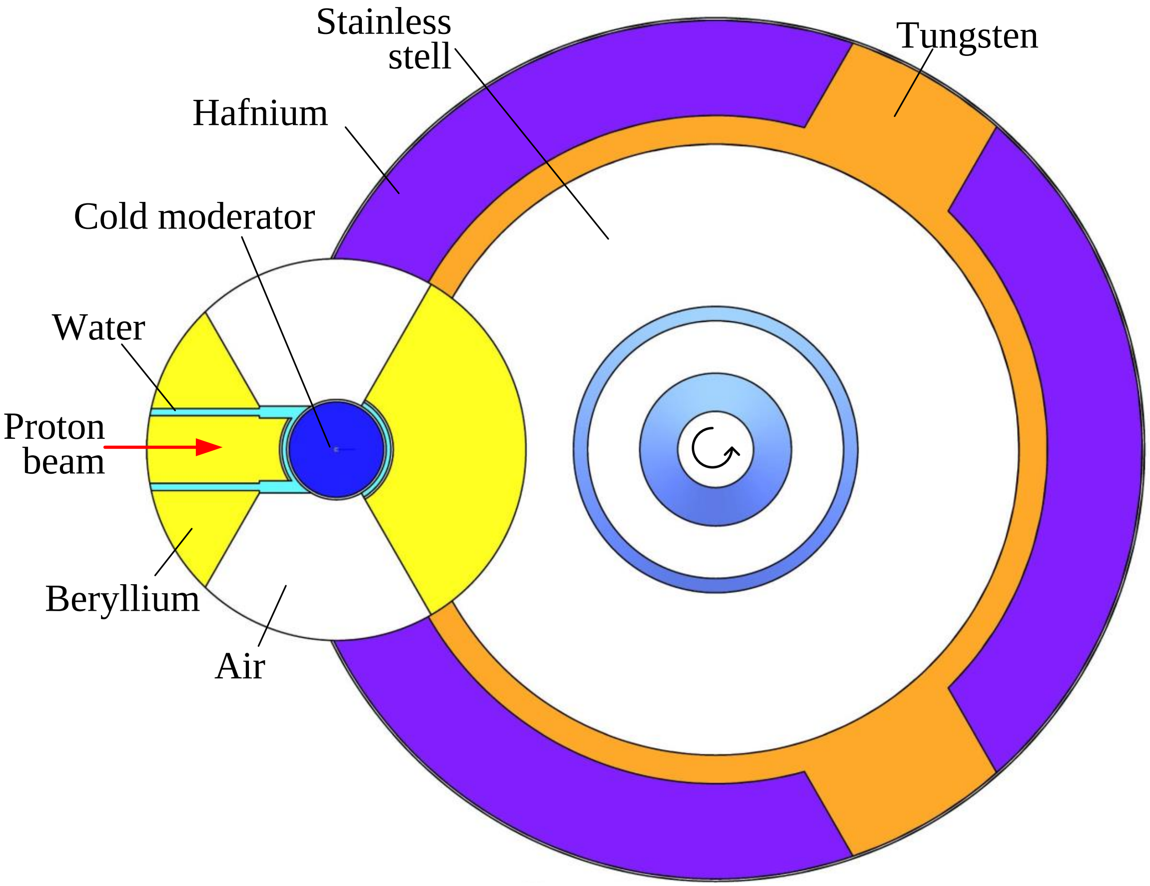


Fig. 4. Schematic representation of the target disk

- Rate of rotation: 10 rpm
- Linear velocity of rim: 100 m/s

Target as a reactivity modulator

Reactivity on prompt neutrons

$$\varepsilon = \rho - \beta = \varepsilon_m + \varepsilon_{MR}$$

ε_m – maximum reactivity

$$\varepsilon_m < 0$$

Multiplication $Y = \dfrac{1}{-\varepsilon_m}$

Parabola coefficient near the maximum reactivity:

$$\alpha = 1{,}14 \cdot 10^5 \ 1/\mathrm{s}^2$$

Modulation depth:

$$\Delta k_{\mathrm{mr}} = 0.02 – 0.04$$

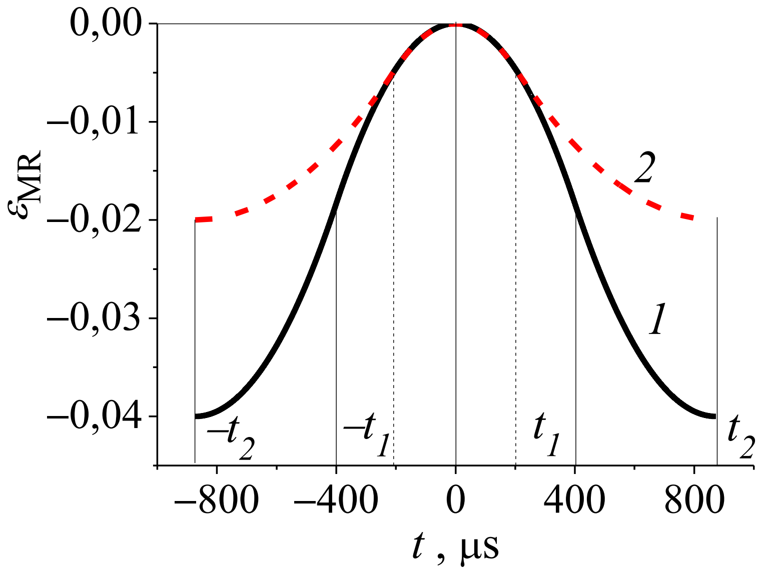


Fig. 5. Reactivity pulse determined by the modulator

Background between pulses

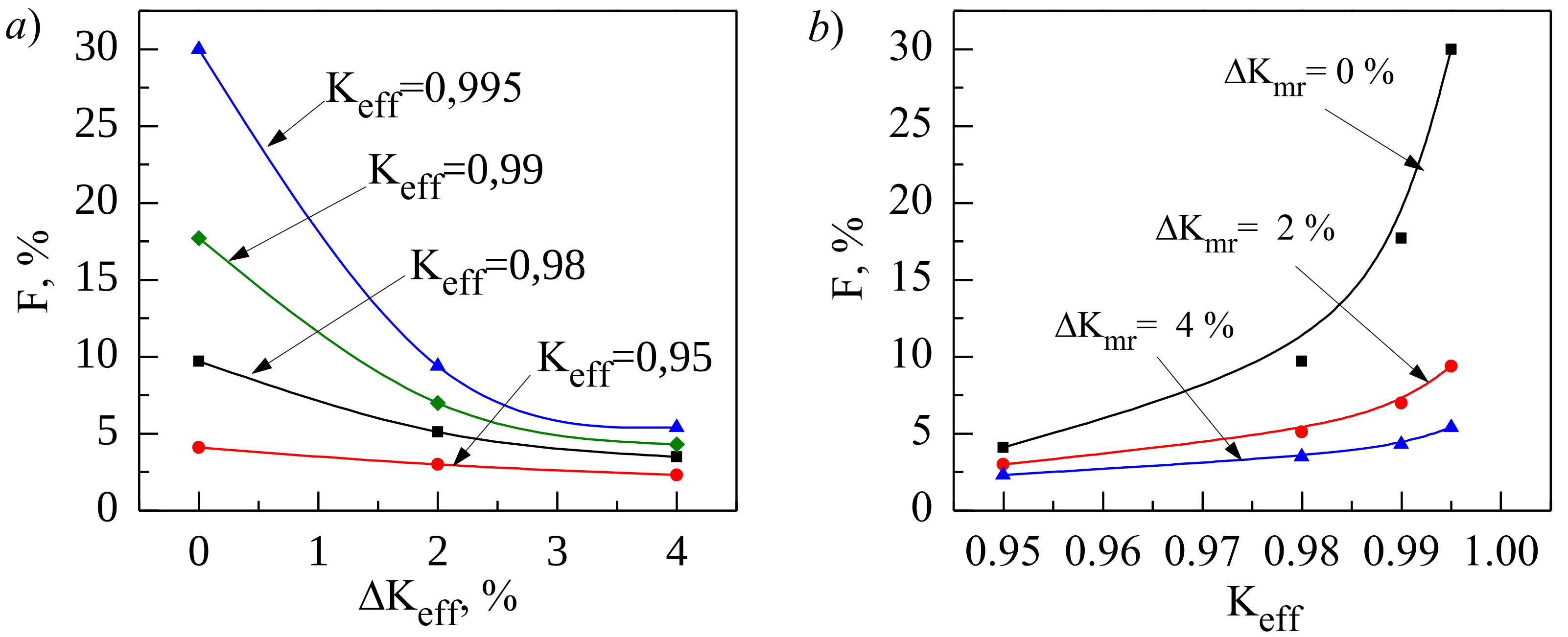


Fig. 7. Neutron background between pulses, F, in percentage of total power, as a function of reactivity modulation depth ΔK_{mr} at a multiplication of 20 (K_{eff} = 0.95), 50 (K_{eff} = 0.98), 100 (K_{eff} = 0.99) and 200 (K_{eff} = 0.995) (a) and on K_{eff} at ΔK_{mr} = 0, 2 and 4% (b). Prompt neutron lifetime is $\tau = 0.5$ µs.

Power pulse

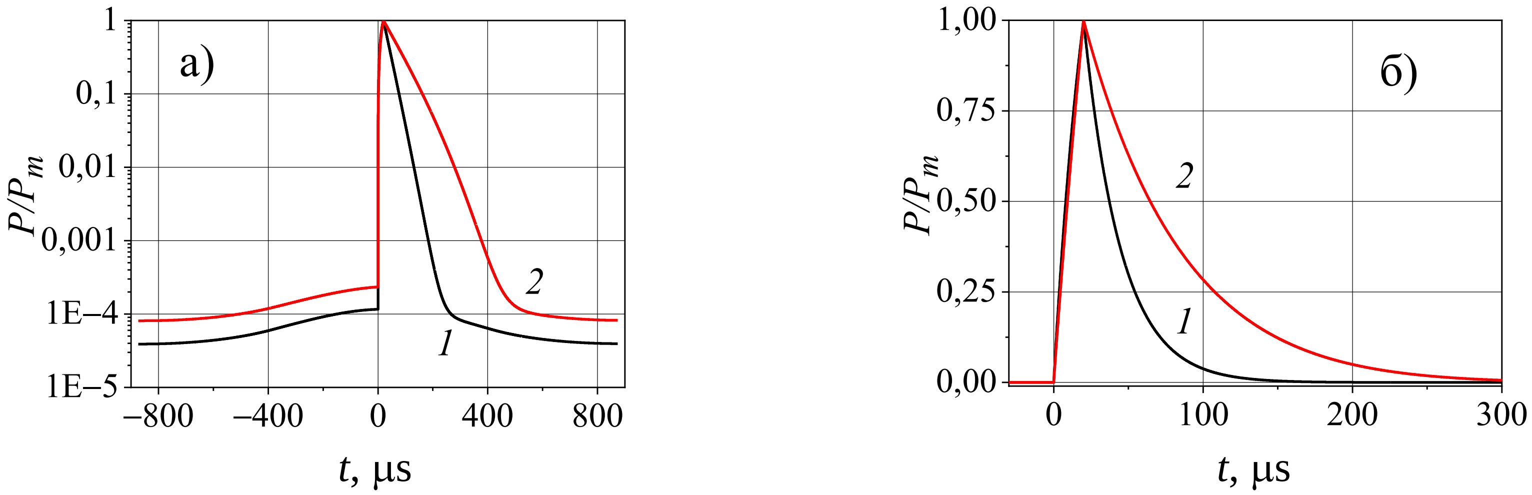


Fig. 6. Calculated power pulse shape at $K_{\mathrm{eff}} = 0.98$ for two neutron lifetime values of 0.5 (1) and 1.3 µs (2) at a pulse frequency of 30 Hz and proton pulse duration of 20 µs: (a) - logarithmic and (b) - linear scale

Power pulse parameters

Table 2. Power pulse parameters in calculations using a point model.

Parameter	**Value**
Multiplication factor, K_{eff}	0.98
Average thermal power of source, MW	8.0
Target	W
Pulse repetition rate, 1/s	30
Average proton current, mA	0.083
Proton beam power on target, MW	0.1
Proton energy, GeV	1.20

Parameter	**Value**	
Proton pulse duration, μs	20	
Reactivity modulator efficiency, abs	0.04	
Pulse energy, MJ	0.45	
Neutron lifetime, μs	0.5	1.3
Pulse duration, μs	27	45
Background during pulse period,% of total energy	3.5	3.6
Amplitude of power pulse, MW	9500	5700

Moderators (1)

- Moderators are positioned in two planes.
- A grooved moderator is at the bottom.
- Moderators are visible from both sides.
- For all beamlines the direct passage of fast neutrons is excluded.

- The upper moderator consists of two parts: a water flat one poisoned with boric acid to shorten the pulse duration and a cold moderator.

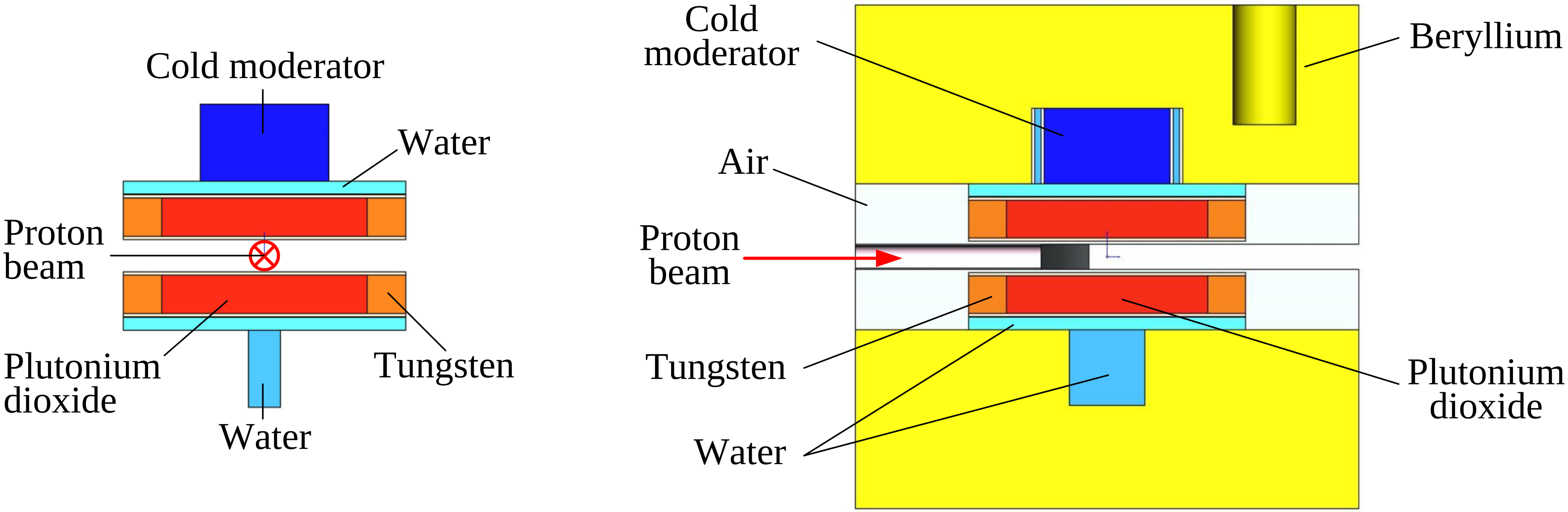


Fig. 8. Scheme of evaluation model of the core surrounded by moderators

Moderators (2)

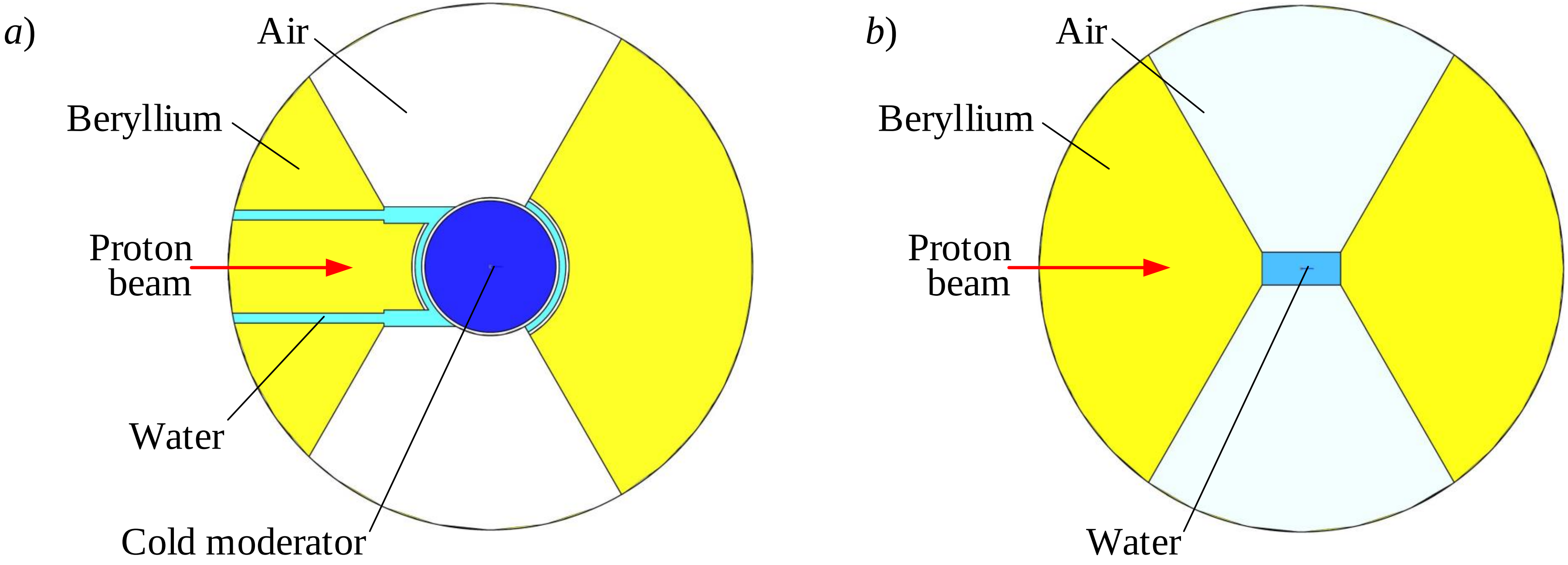


Fig. 9. Layout of neutron moderators: a) top view, b) bottom view

Moderators (3)

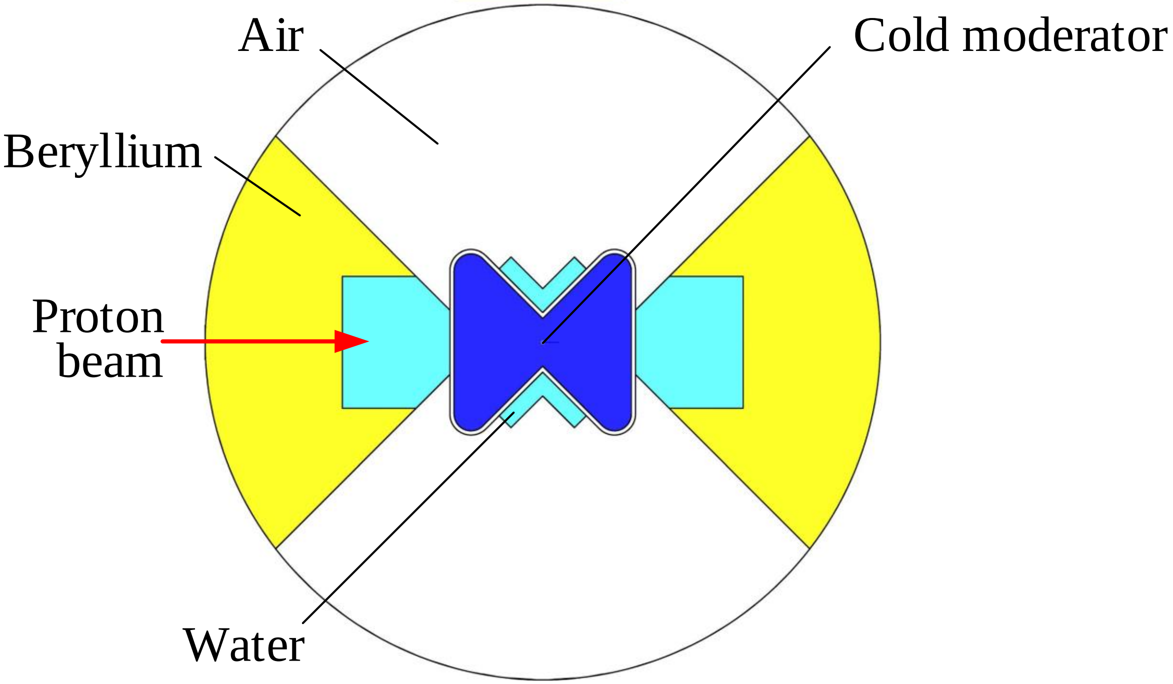


Fig. 10. Layout of a “butterfly”-type neutron moderator

Thermal neutron pulse

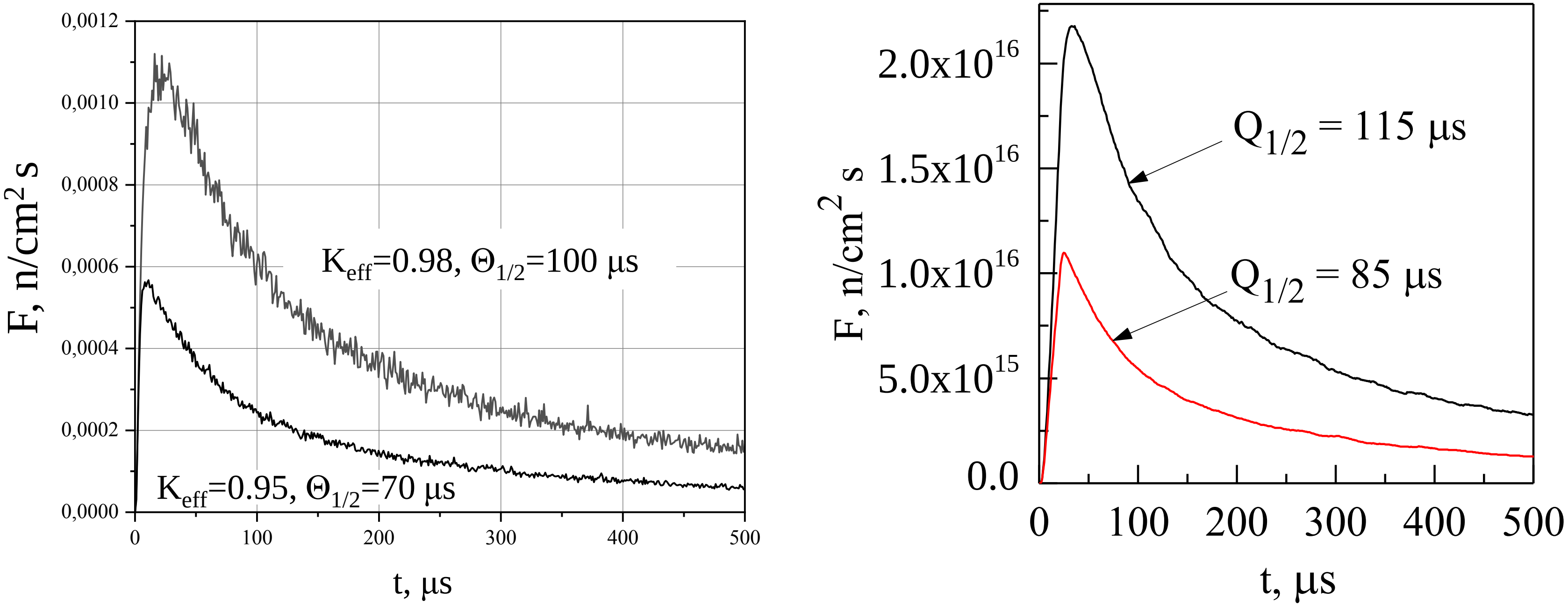


Fig. 11. Thermal neutron pulse shape on the surface of a flat water moderator for two multiplication factor values K_{eff} = 0.98 and 0.95 without reactivity modulation:
a) δ-function proton pulse irradiation; b) proton pulse with a duration of 20 μs.

Thermal neutron pulse parameters

Table 3. Parameters of thermal neutron pulse on the surface of flat water moderator under irradiation of tungsten target with δ-function proton pulse without reactivity modulation.

Parameter	Value
Pulse repetition rate, 1/s	30
Average proton current, mA	0.083
Proton beam power on target, MW	0.1
Proton energy, GeV	1.2
Proton pulse duration	δ-function pulse
Neutron lifetime, s	$1.0\ 10^{-6}$

Parameter	Value	
Multiplication factor, K_{eff}	0.98	0.95
Full width at half maximum, μs	100	70
Average thermal neutron flux density on flat moderator surface, $10^{14}\ cm^{-2} \cdot s^{-1}$	2.0	1.0
Peak thermal neutron flux density, $10^{16}\ cm^{-2} \cdot s^{-1}$	6.4	4.5

Neutron spectrum on flat water moderator surface

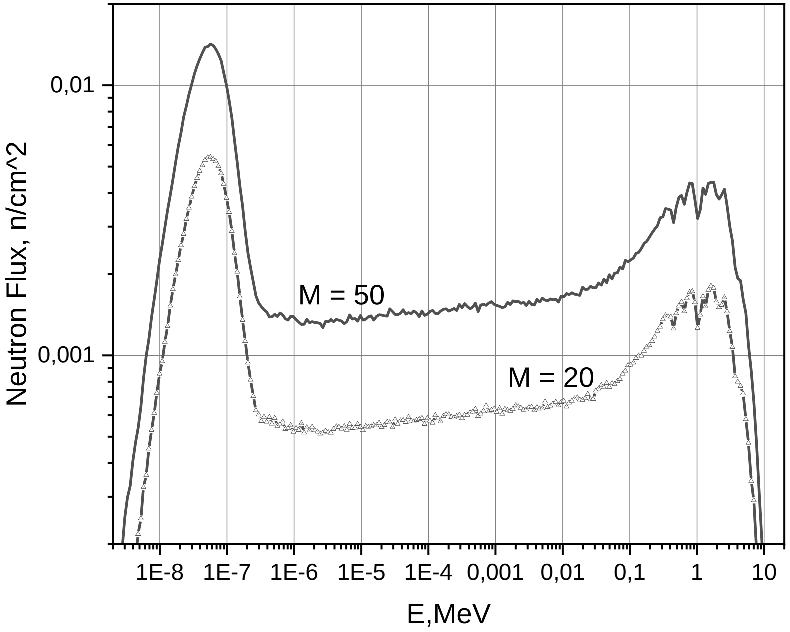


Fig. 12. Energy distribution of thermal neutron flux on the surface of a flat water moderator for two values of multiplication — 50 and 20

Neutron spectrum on the surface of flat water and cold moderators

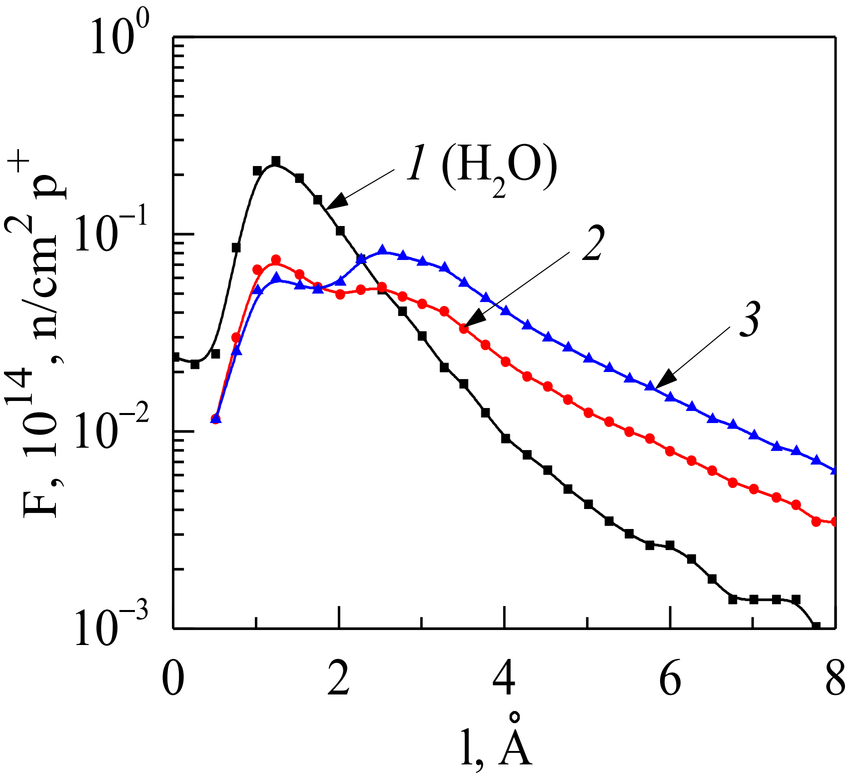


Fig. 13. Dependence of neutron flux density on energy (a) and wavelength (b) on the surface of moderators: *1* – lower water moderator; *2* – upper bispectral moderator; *3* – only cold moderator

Neutron beams

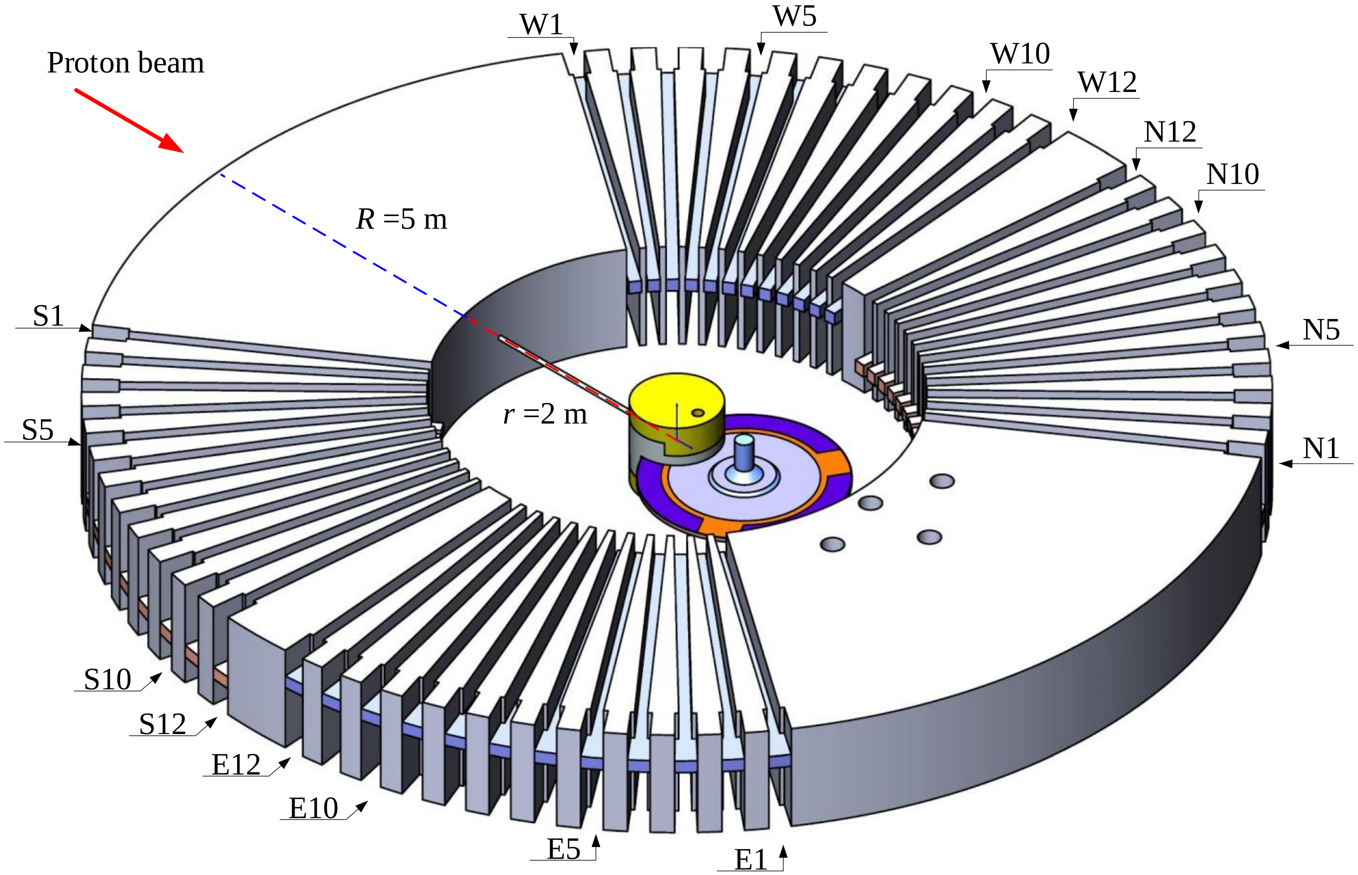


Fig. 14. Layout of the maximum number of horizontal neutron beamlines for two planes of moderators. In the direction of the proton beam one can see vertical irradiation beamlines

Neutron spectrum near vertical beamline

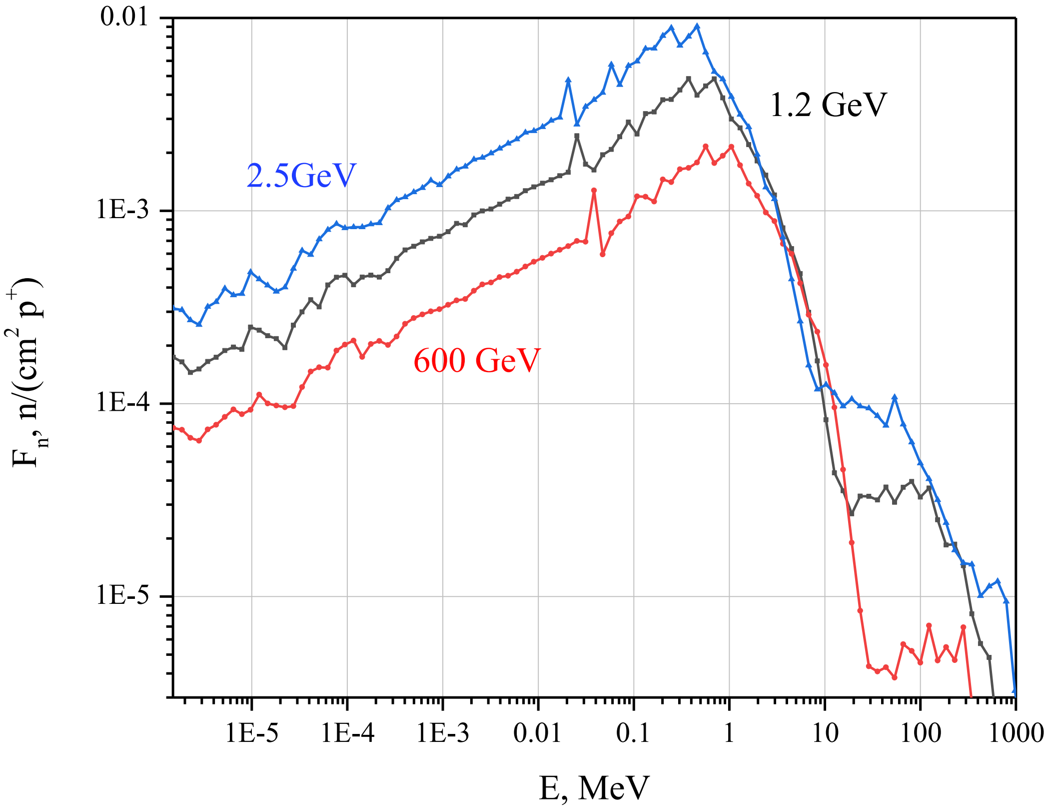


Fig. 15. Neutron flux density per one proton as a function of energy of neutrons coming from the end surface of the tungsten target at proton energies of 0.6, 1.2 and 2.5 GeV.

Heat removal

Table 4. Basic parameters of core cooling system.

Parameter	**Value**
Nominal power, MW	7 – 10
Specific power density of the core, kW/*l*	350÷550
Volume, *l*	20 – 26
Height, cm	46
Cross-section area of the core, cm^2	
Coolant flow area, cm^2	90 (570 cm^2 x 0.153 = 87.2)
PuO_2 load, kg	172 (26 *l* x 0.691 x 9.6 g/ cm^3)
Volume fraction of materials of the core:	
fuel PuO_2	0.691
steel	0.157
water	0.153
Water flow rate, m^3/h	94 ÷ 157
Water velocity, m/s	3 – 4
Water temperature at the core inlet, °C	45 ÷ 50
Water heating in the core with 120 m^3/h, K	35 ÷ 40 (~ 4 atm)

Nuclear safety

- The source has inherent safety features.

- The main design-basis accident involving a loss of coolant causes a negative reactivity effect $\Delta k_{mr} = -0.06$, which puts the core into a deeply subcritical state.

- Various water effects associated with core refueling have zero or negative values.

Basic characteristics of the neutron source

Parameter	Value
Source power, MW	8.0
Fuel	PuO_2
Fuel mass, kg	172
Fuel volume, l	23
Target material	W
Coolant	H_2O
Pulse repetition rate, 1/s	30 (10)
Average proton current, mA	0.083 (0.03)
Maximum pulse current, mA	50
Proton beam power on target, MW	0.1 (0.036)
Proton energy, GeV	1.2
Proton pulse duration, μs	55 (20)

Parameter	Value
Prompt neutron lifetime, s	$0.5\ 10^{-6}$
Multiplication factor, K_{eff}	0.98 (0.95)
Effective fraction of delayed neutrons, β_{eff}	$2.165\ 10^{-3}$
Maximum fuel burnup, % Evaluation of burnup in the long term, %	10 20
Average thermal neutron flux density on flat water moderator surface, 10^{14} $cm^{-2} \cdot s^{-1}$	2.0 (0.8)
Average cold neutron flux density on CM surface, 10^{13} $cm^{-2} \cdot s^{-1}$ (at λ>2,5 Å)	4.2
Peak thermal neutron flux density, 10^{16} $cm^{-2} \cdot s^{-1}$	5.3 (6.2)
Full width at half maximum for thermal neutron pulse, μs	<125 (85)

Conclusions

- The source is feasible and falls into the category of high-flux sources both at present and in the long run.

- The source is a deeply subcritical system to which nuclear safety requirements for critical nuclear facilities do not apply.

- Thermal neutron flux density is at the level of ESS.

- The power of the proton accelerator is an order of magnitude lower than the power of accelerators of the highest-flux neutron sources.

Thank you for your attention!