Neutron facility at JINR after 2036 -

Pulsed Reactor on Np-237

6 December 2018, Dubna

V.L.Aksenov, E.P. Shabalin, G.G. Komyshev, M.V. Rzyanin

1. Е.П. Шабалин, А.Д Рогов.   The Comparative Capabilities of the Modified Versions of the IBR-2 Neutron Source. In: "Pulsed Nuclear Reactors: New Capabilities for Scientific Research", Proc. of the Internat. Workshop on Pulsed Advanced Neutron Sources (collected papers), held in Dubna, June 23-27 1991. JINR, Dubna, D3-92-76,1992
2. Aksenov V.L., Balagurov A.M., Pepelyshev Yu.N., Rogov A.D. (2016) JINR P13-2016-49
3. Aksenov V.L. (2017) JINR E3-2017-12
4. V. L. Aksenov, V. D. Ananiev, G. G. Komyshev, A. D. Rogov, E. P. Shabalin . On the limit of neutron fluxes in the fission-based pulsed neutron sources. Physics of Particles and Nuclei Letters, 2017, Vol. 14, No. 5, pp. 788–797.
5. H. H. Saleh, T. A. Parish, W. H. Miller et al. *Nucl.Instr. and Methods in Phys. Res. B,* 103,393-400 (1995).
6. L. Aksenov, A 15-year forward look at neutron facilities in JINR. JINR Communication E3-2017-12, JINR, Dubna, 2017.
7. Буклет ОИЯИ «IBR -IV: New Highly Intense Neutron Source in Dubna», Dubna 2018. Аксенов В.Л., Шабалин Е.П., Комышев Г.Г., Покотиловский Ю.Н.,Рзянин М. В., Лопаткин А.В., Третьяков И.Т. Куликов С.А., Рогов А.Д ., Доля С.Н., Швецов В.Н., Кулевой Т.В
8. Аксенов В.Л., Комышев Г.Г., Рогов А.Д, Шабалин Е.П, Высокопоточный импульсный исследовательский реактор на основе нептуния, Сообщение ОИЯИ Р13-2017-57, Дубна, 2017. Журнал Атомная энергия. Т.124, вып.6, стр. 309-313, 2018
9. В.Л.Аксенов, В.Д.Ананьев, Г.Г.Комышев, А.Д.Рогов, Е.П.Шабалин, О пределе нейтронных потоков в импульсных источниках на основе реакции деления. ОИЯИ Р3-2016-90. 18 с. ОИЯИ, Дубна, 2016; Physics of Particles and Nuclei Letters, 2017, Vol. 14, No. 5, pp. 788–797.
10. Рзянин М.В., Шабалин Е.П., Динамика импульсов мощности в исследовательском реакторе с нептуниевым ядерным топливом. Сообщение ОИЯИ Р13-2017-69. Журнал Атомная энергия. Т.124, вып.4, стр. 193-196. 2018 г.
11. etc ……

1/ The tentative research studies in FLNP in 2015-2017 it has been shown that pulsed sources of slow neutrons **based on the fission reaction (pulsed reactors and pulsed boosters)** may be competitive with spallation neutron sources and even significantly (by an order of magnitude) exceed them in peak slow-neutron fluxes using already mastered nuclear technologies. The time-average vector density of the thermal neutron flux can reach $\sim 2 \ 10^{14}$ n/cm^2/s (in terms of an angle of 2π – the so-called "2π-equivalent flux") at a reactor power of 15-20 MW.

2/ Pulsed booster (superbooster) suits the purposes of neutron spectroscopy best, and it was concluded in Booklet of FLNP 2018. **The most advantage (and sooner – just single one)** of superbooster with Np-237 loaded multiplying target of proton from linear accelerator up to 1GeV is generation of **Short thermal neutron pulses – 20-30 mks**

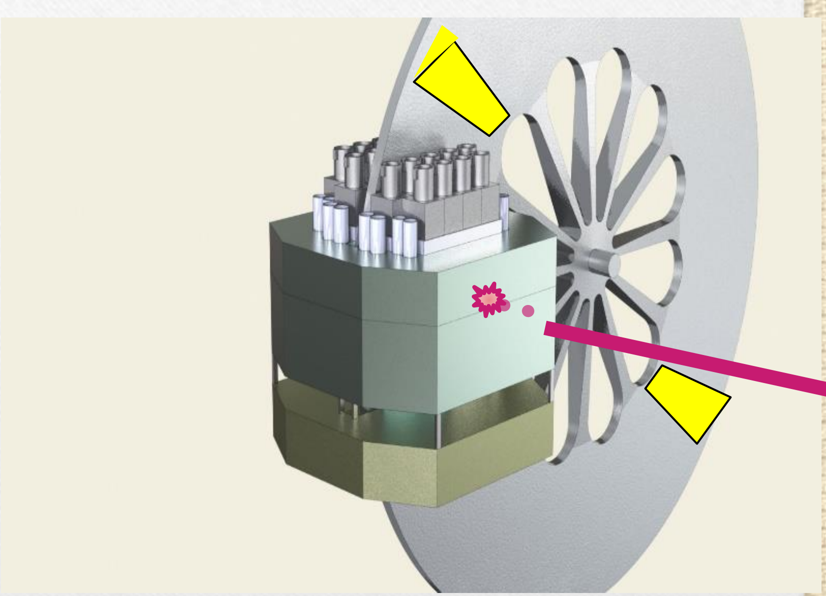
Why NEPTUN, not Superbooster?

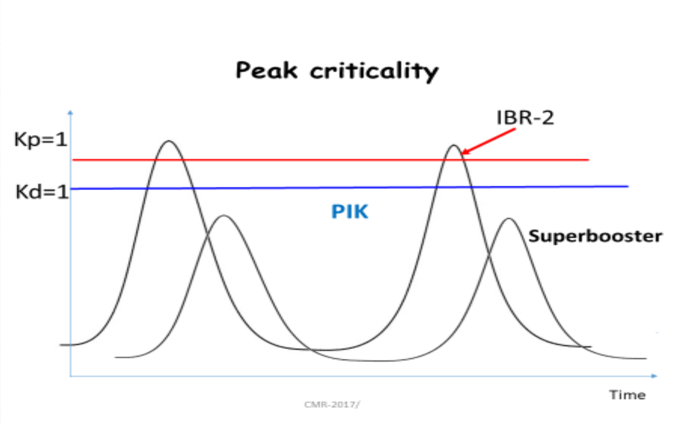
Short thermal neutron pulses – 20-30 mks - is single advantage of SP – because periodically pulsed reactor based on Np provides

the same convenience for neutron spectroscopy, except inelastic scattering..

But safety aspects?

Cost





Superbooster mode was regarded unsafe and more reliable because peak factor neutron multiplication factor *K* is lower unity. However, safety is determined not by factor itself but its stability. Really, **proton beam of high energy is not in fact stable.**
Short-term loss of proton pulse leads to a decrease in temperature of reactor target, and, accordingly, to an increase in reactivity.

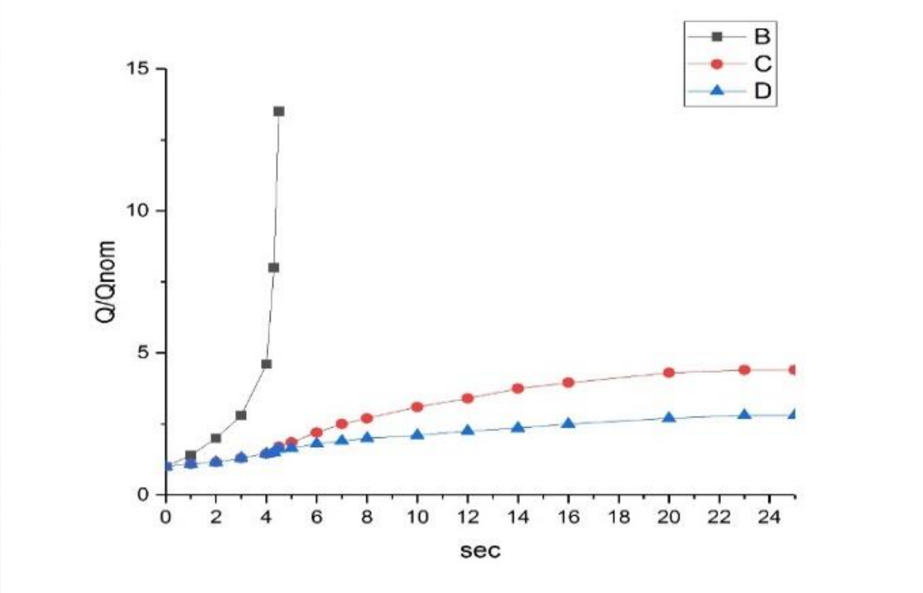


Figure displays magnitudes of abnormal energy release in the first neutron pulse generated by the restored proton beam after loss of beam for several seconds.

Each emergency pulse causes long interruption in reactor operation for restoration of nominal regime. So, *we can't consider superbooster mode of operation as reliable one*

The most distinctive properties of pulsed reactor conception:

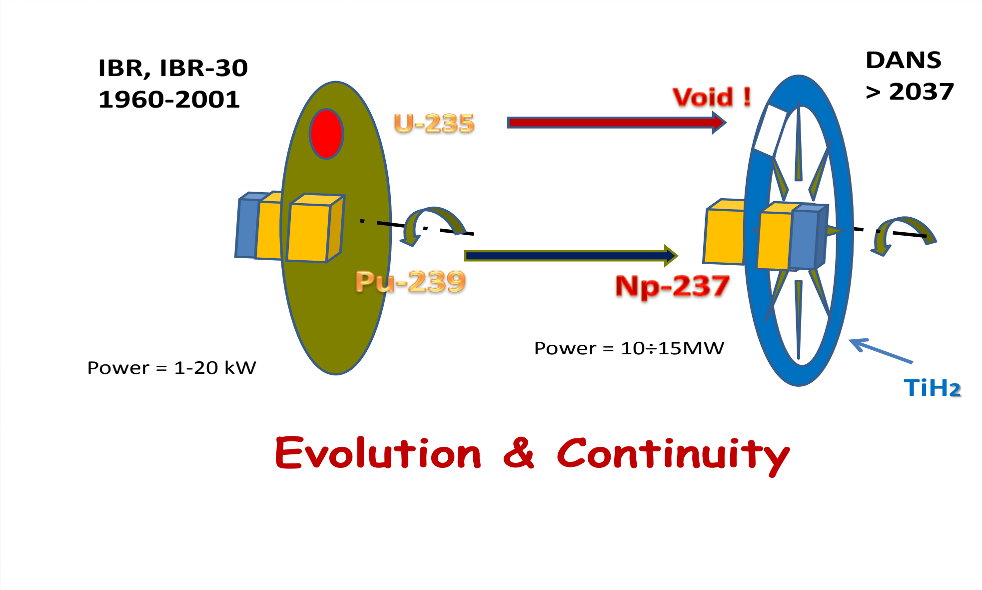
Satisfies in a great degree the world's best demands for thermal and cold neutron experimental investigations,

Feasible configuration & construction,

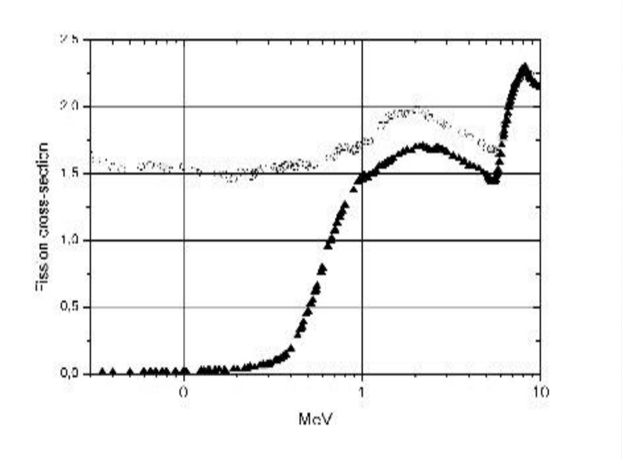
Safety operation, reliability

Not so expensive.

Follows the evolution and continuity of pulsed neutron facilities of FLNP.,



Why Neptunium?



Np-237 in contrast to conventional nuclear fuels based on U-235 and Pu-239, has a threshold character of the fission cross section. The effective fission threshold about 0.4 MeV is below the fission threshold of U-238, and this makes it possible to create a critical mass of Np-237 (near 40 kg).

There are four important positive consequences of using neptunium in the core of a pulsed reactor:

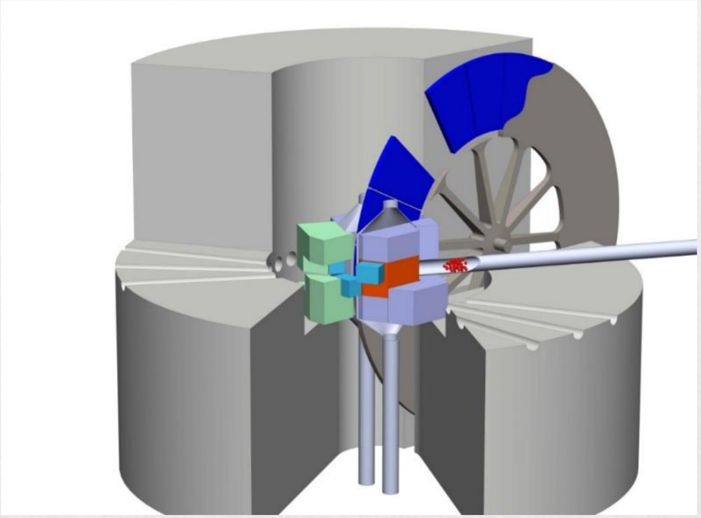
1. Lifetime of generation of fast neutrons τ in the neptunium core is much lower than in the plutonium core (9 ns instead of 65 ns at IBR). Duration of pulse in NEPTUN expected to be shorter than in IBR-2M -150 mks vs 240 mks. For fast pulsed reactor of high power (10-15 MW) loaded with Pu-239 modulated with moving reflector , duration pulse is estimated to be as long as 500 -700 mks.

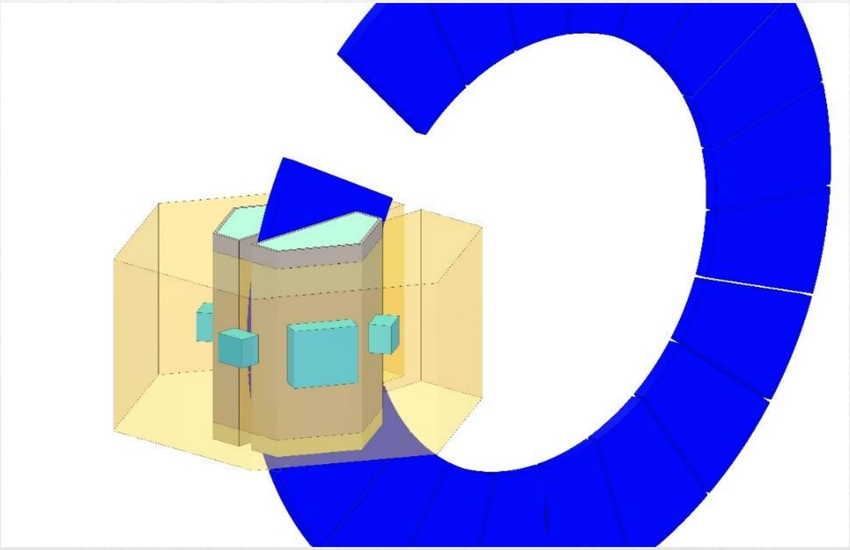
2. The background power of a pulsed source is proportional to the effective fraction of delayed fission neutrons β_{eff}, which in the neptunium zone is expected to be 1.2- 10^{-3} - 1.8 times lower than the same value for plutonium-239. Background in NEPTUN would be as low as 2%

3. The third consequence of the threshold character of neptunium fission is the possibility of using neutron-moderating materials for the reactivity modulator. In the neptunium core, hydrogen serves as effective absorber of fast neutrons, therefore substitution titanium hydrid for void provides high positive reactivity effect.

4. Neptunium nuclear fuel has one more remarkable property: in such reactor there will be no reduction in the multiplication factor with neptunium burnup, which is usual for uranium and plutonium reactors.

NEPTUN composition



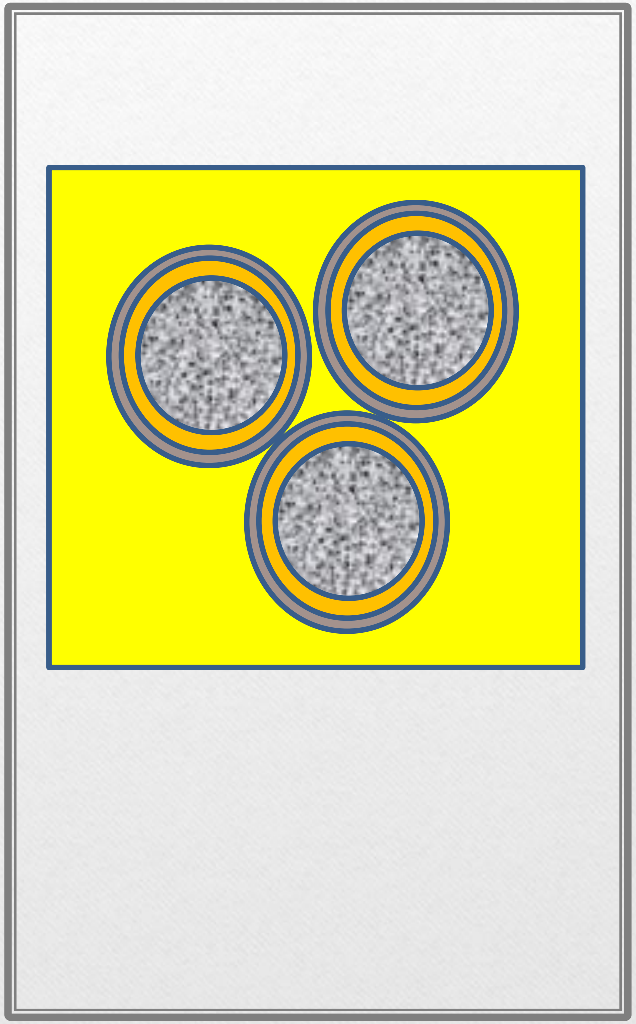


NEPTUN Fuel Elements

~ 1000 pcs,

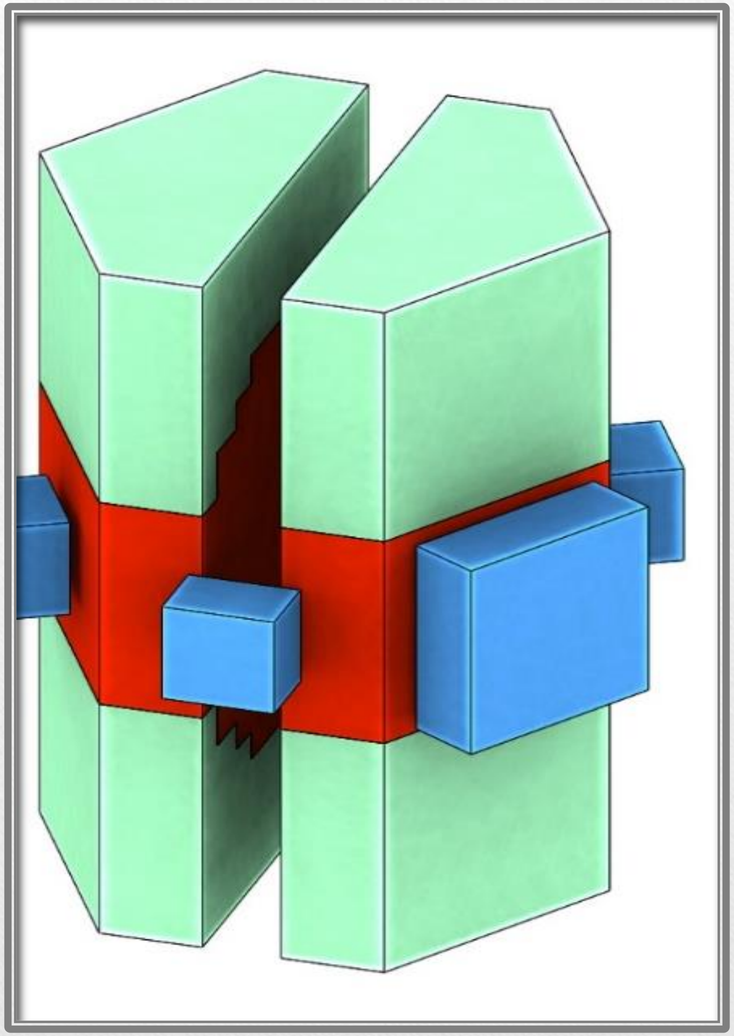
~0.4 kg NpN per one FE

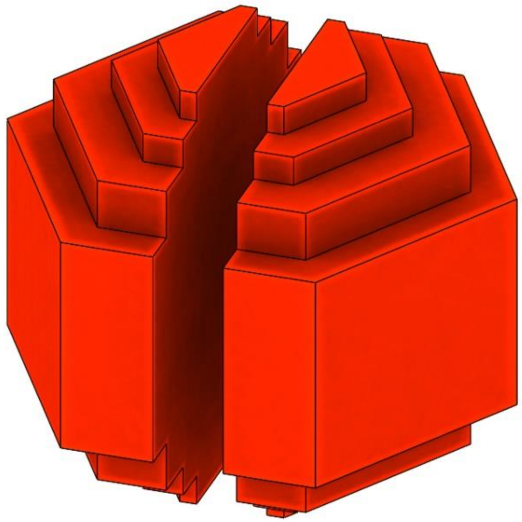
Liquid sodium cooling



Ensemble of fuel elements (FE), only core (all casings removed) + moderators

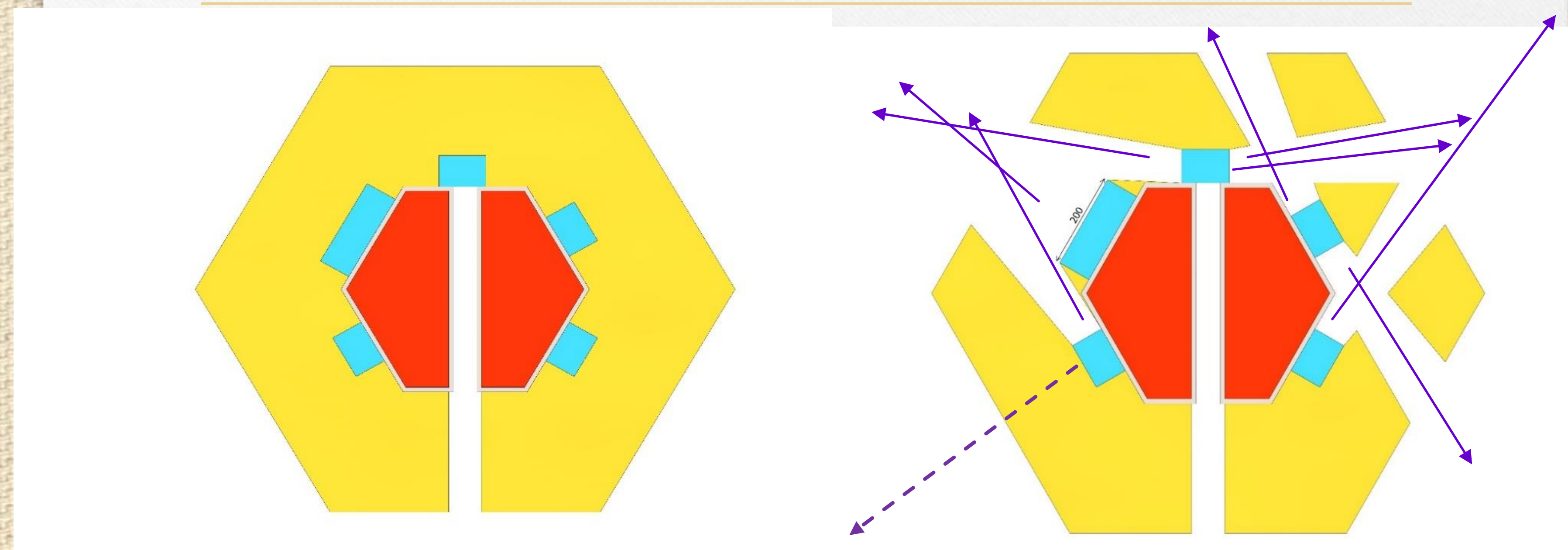
Red is fuel part of FE, green is nickel reflector part of FE.





Fuel part of the reactor core
– NpN only shown

Moderators inside of reflector and one scheme of beam extraction of many other possible



Neutron flux from wing-type water moderator of NEPTUN

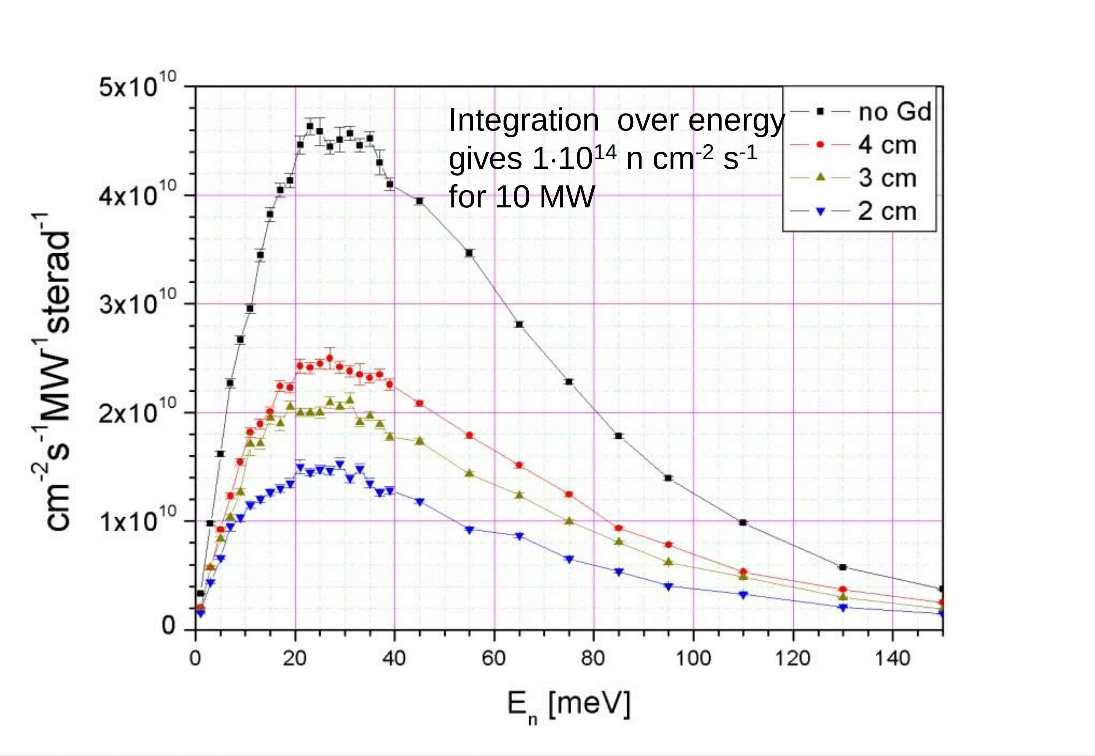


Table. Basic parameters of NEPTUN

Thermal neutron flux density, time-average: (depends on moderator and power)	(0.5÷1.5)·10^{14} n cm^{-2} s^{-1}
Peak density of tposition and type hermal neutron flux:	(3÷6)·10^{16}
Half-width of fast/thermal neutron pulse:	150/ 200-300 μs
Pulse repetition rate:	10 Hz
Number of neutron beamlines	18- 21
Number of moderators	4-5
Thermal power	10-15 MW
Maximum fuel temperature	1500 K
Coolant temperature	250 - 450 °C
Coolant flow rate	up to 200 m^3/h
Reactor service life (in respect to fuel burnup) 20,000-25,000 MW/days	
Neptunium nitride loading	~350-400 kg
Total efficiency of reactivity modulator	~6 % k_{eff}
Prompt neutron generation lifetime	9 ns
Effective fraction of delayed neutrons	1.2 10^{-3} k_{eff}
Background power (percentage of the average)	2-2.5%

Conclusion

In result of closer consideration it became evident that **operational stability** of the facility will depend of **stable operation of accelerator**. Basing on practice of proton linear accelerators in operation, it is sure that **operation of SNS is not reliable** in the sense of stable supply target with proton beam.

If for nonmultiplying target this is not dramatic, it hardly acceptable for superbooster mode of IBR-3. Besides that, cost of superbooster realization near factor 3 more than NEPTUN.

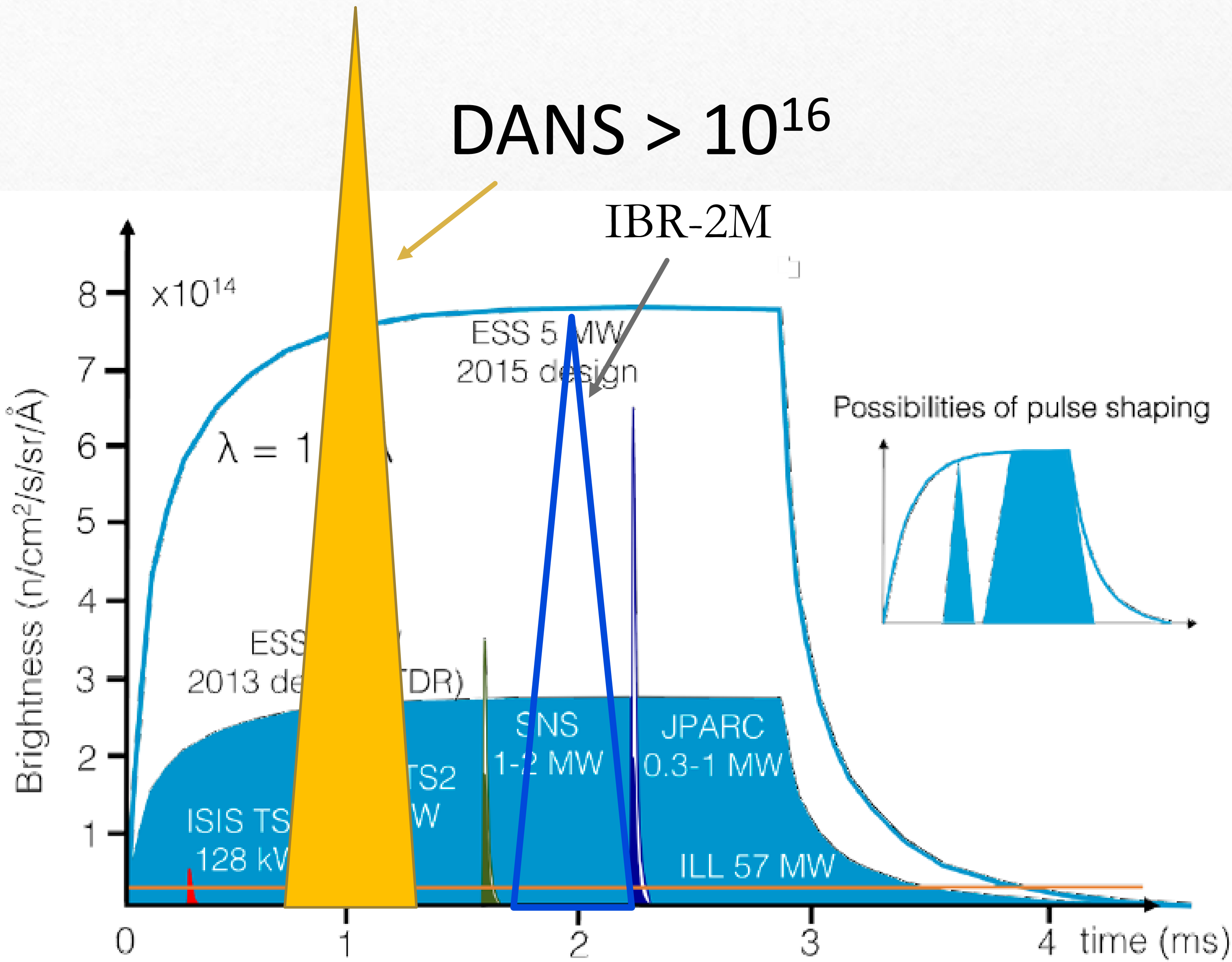
From all the above, it seems reasonable that the **new neutron source for JINR** should be **pulsed reactor with Np-237** as nuclear fuel. Its parameters satisfies in great degree the world's best demands on thermal and cold neutron experimental technics.

NEPTUN realization schedule:

Start of the project -- 2018
Start of construction – 2027
Power start-up - 2036

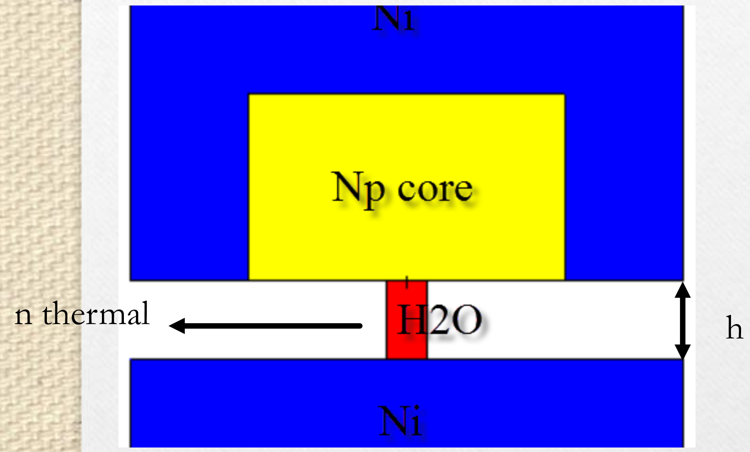
Cost of creation:

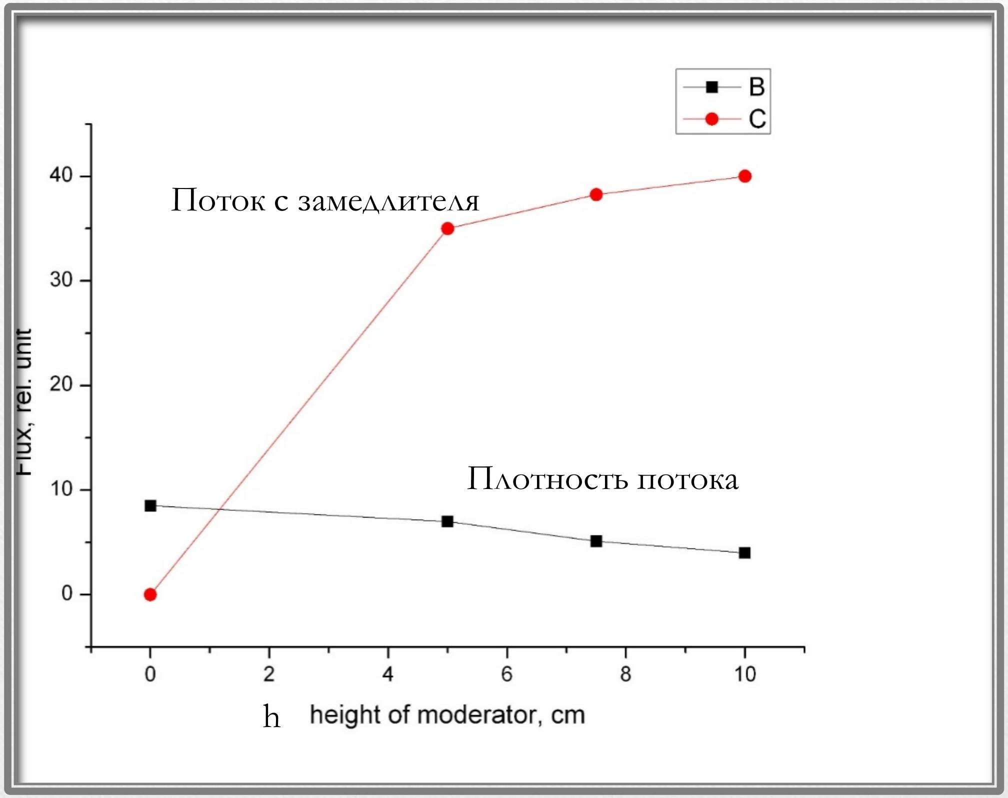
Reactor – 200 M€
Complex of cold moderators – 50 M€
Engineering infrastructure – 100/200 M€
Total: 350/450 M€

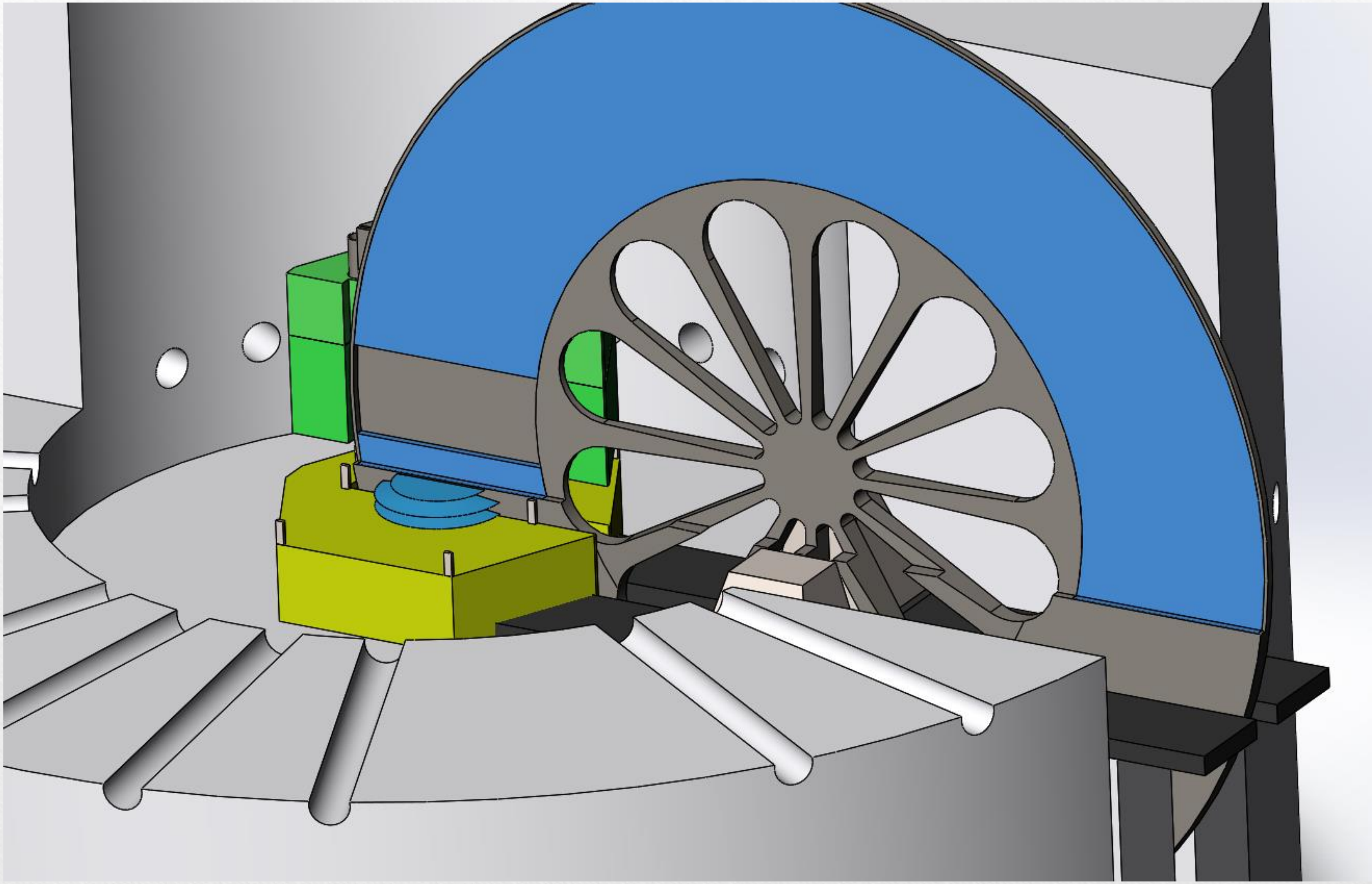


Single-pulse source brightness as a function of time at a wavelength of 1.5 A at ESS, ILL, SNS, J-PARC and ISIS Target Stations 1 and 2. In each case, the thermal moderator with the highest peak brightness is shown.

Влияние зазора на поток в конфигурации «wing moderator»







Pulsed neutron sources: in operation and advanced

	Moderator type	Peak differential neutron flux 10^{14} n/см^2/s/sr/ Ǻ	Peak neutron flux, 2π eqv. 10^{14} n/см^2/s	Fluence per pulse 10^{12} n/см^2/s	Time averaged flux 2π equivalent. 10^{14} н/см^2/с
IBR-2	Grooved, wide	**9**	58	0.28	**0.09**
	Grooved, height 4.5 см	12	77	0.37	0.12
J-Park	Coupled	10	65	0.2	0.3
ESS	Butterfly height 6 см	8	50	2.2	2.0
	Height 3 см	**12**	**75**	**3.4**	**3.0**
PIK, Russia	Stationary, D_2O moderator	1.6	12	-	**12**
DANS *)	**Grooved**	**130**	**800**	**4**	**3.0**

Теплогидравлические параметры реактора

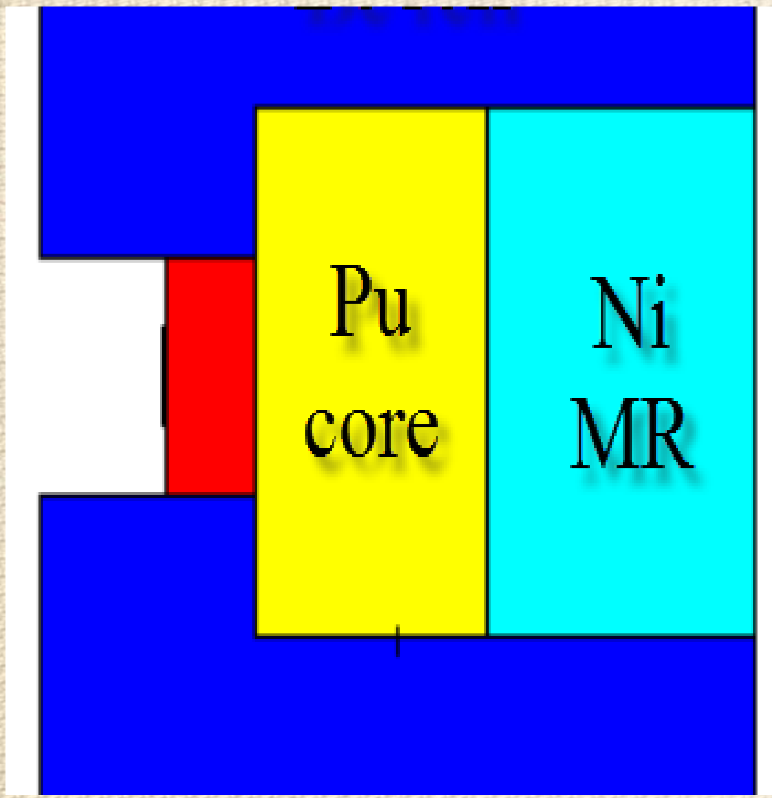
Начальная температура теплоносителя, °C	250
Подогрев теплоносителя	130
При расходе, $м^3$/ч	250
Мощность на прокачку, кВт	14
Максимальная температура топлива, °C	1100
Максимальная температура оболочки, °C	400

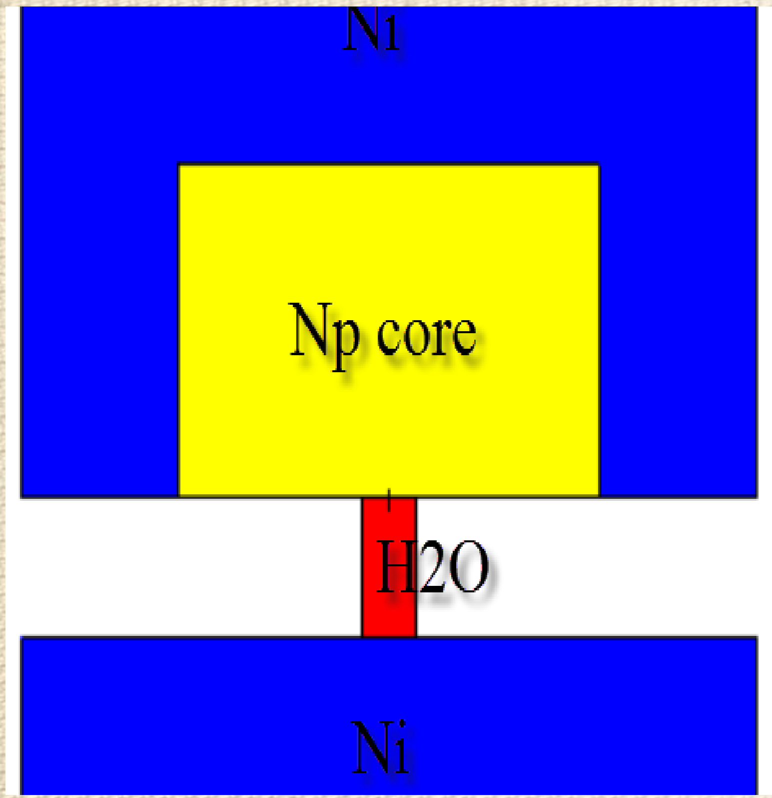
Pulsed LNPh reactors and ESS

Parameter	Neptune reactor	Pu high flux reactor	IBR--2	ESS
Time averaged n/см^2/s Peak neutron flux	$1.5 \cdot 10^{14}$ $6\ 10^{16}$	$3.5 \cdot 10^{13}$ $7\ 10^{15}$	10^{13} $6 \cdot 10^{15}$	$(2 \div 3) \cdot 10^{14}$ $(0.5 \div 1) \cdot 10^{16}$
Thermal power	15 MW	2 MW	2 MW	5 MW
Pulse freguency	10 Hz	10	5	14
Pulse duration	201 мкs	≥ 400 мкs	240 мкs	3 мs
Background power	3.2 %	7 - 8 %	7.5 %	
Number of neutron beams	20-22	14	14	~20

Нейтронно-физические параметры импульсных реакторов

Параметр	Нептун , 10 МВт	ИБР-2 , 2 МВт
Время жизни поколения нейтронов	9 нс	70 нс
Критическая масса и объем а.з.	300÷350 кг / 30÷36 л	~ 80 кг / 20 л
Частота импульсов мощности	**10 Гц**	**5-10 Гц**
Полуширина импульса	206 мкс (325 мкс)	240 мкс
Крутизна модуляции реактивности	10^{-4} см$^{-2}$	10^{-3}
Эффективность модулятора	4.4 %	2.9 %
Надкритичность в импульсе	1,24 10^{-4} $к_{эфф}$	10^{-3} $к_{эфф}$
Импульсная доля з.н.	3 10^{-5} (1.6 10^{-3})	1.5 10^{-4}
Температурный коэффициент реактивности ТВЭ	0.7÷ 0.9 10^{-5} /К	~10^{-5}
Предел импульсной устойчивости	10 ÷15 МВт	7-8 МВт


Pu
core
Ni
MR


Ni
Np core
H2O
Ni

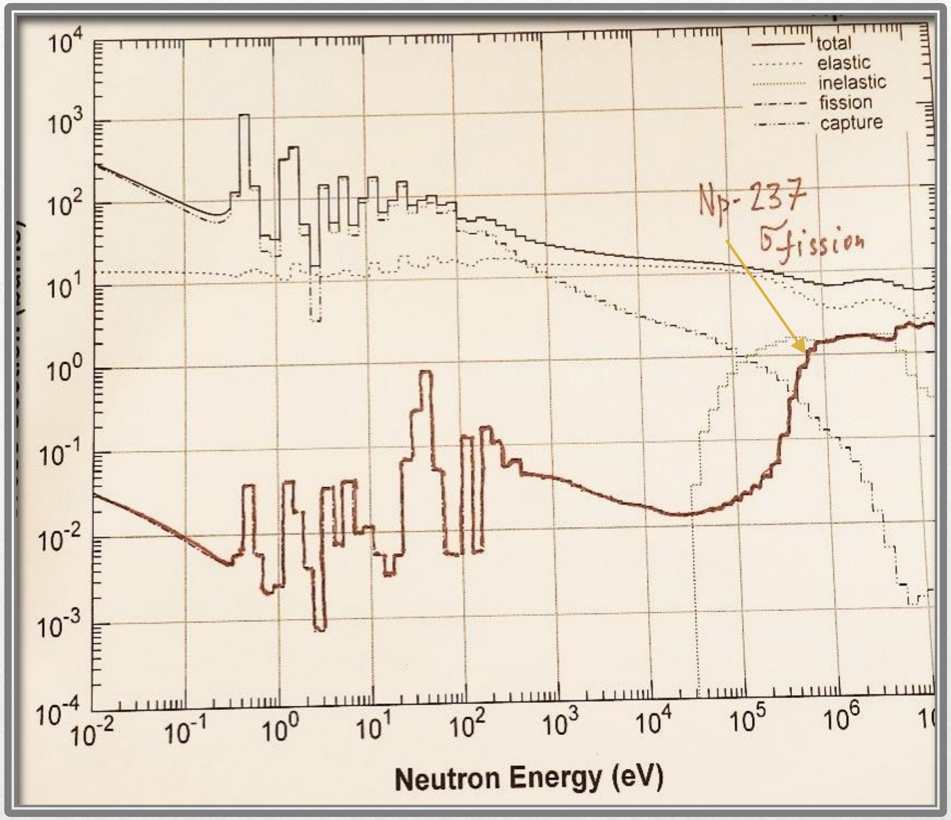
Микросечения деления нептуния- 237

Делится только на быстрых нейтронах.

Поэтому время генерации нейтронов мало - менее 10 нс

Эффективная доля запаздывающих нейтронов - 2/3 от плутония

Минимальная критмасса 40 кг; в реакторе большой мощности – 300-350 кг.



Что даёт пороговый характер деления?

1. Малое время жизни нейтронов деления

10 нс вместо ≥ **100** нс

2. Расширяет возможности модуляции реактивности (с 2-3 % Кэфф до 4-6%)

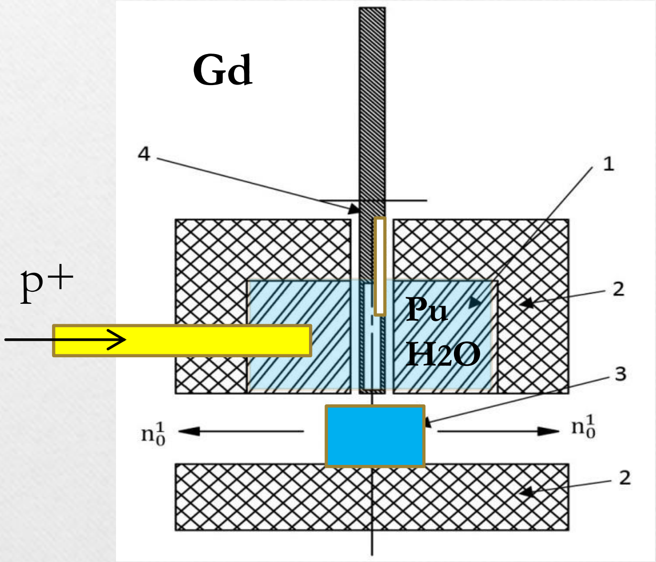
3. Уменьшается доля запаздывающих нейтронов в 1.4 раза

Эти факторы ведут к снижению длительности импульса (в 2-3 раза) и фоновой мощности (в 2.5 раза).

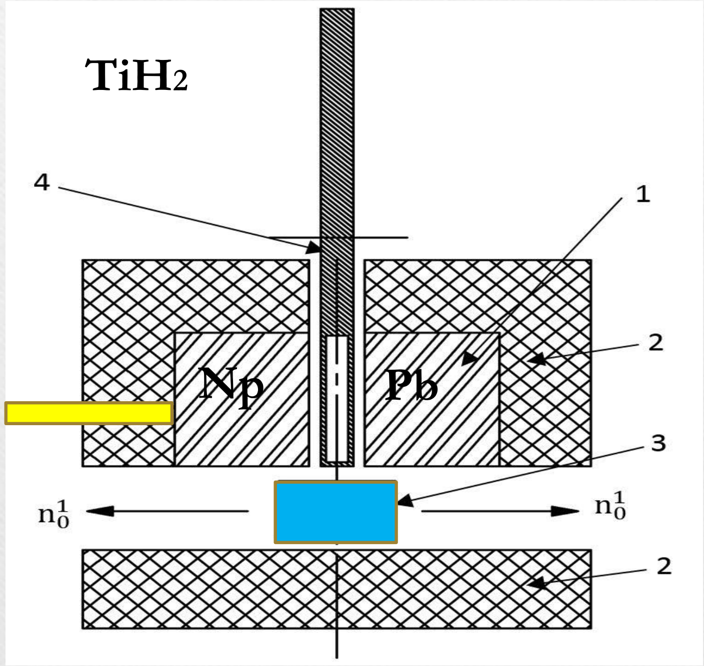
Создать импульсный реактор на быстрых нейтронах на плутонии с такими параметрами – невозможно. Только супербустер, но у него недостатки – частая перегрузка и большое время жизни нейтрона. .

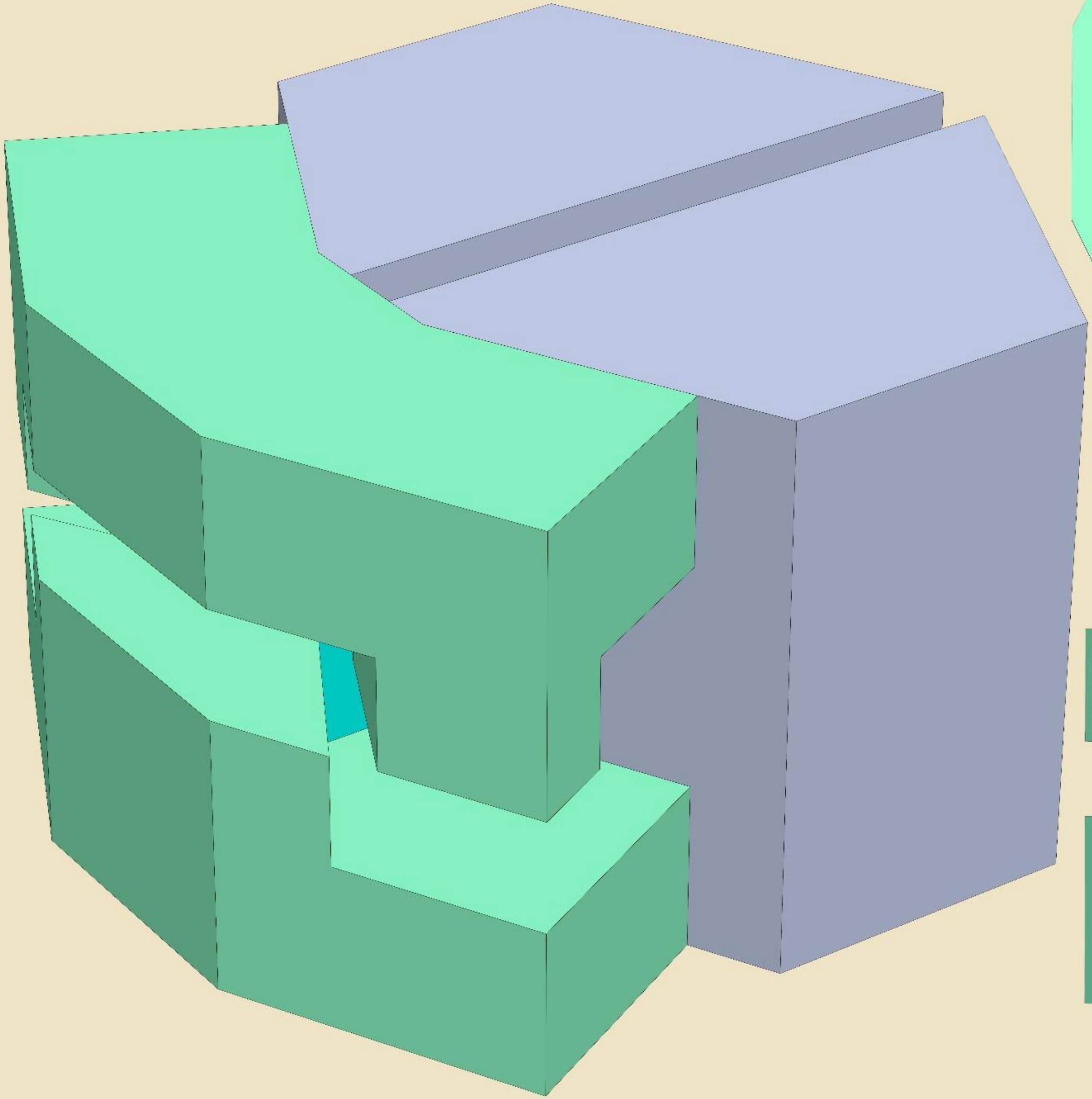
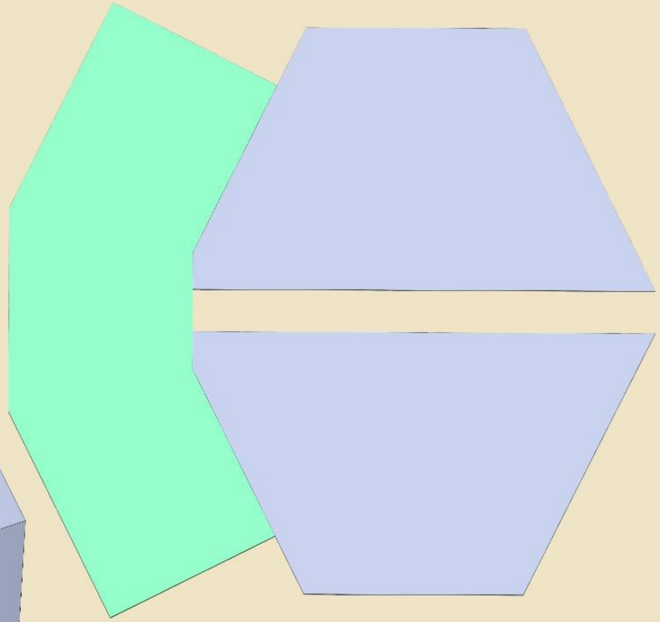
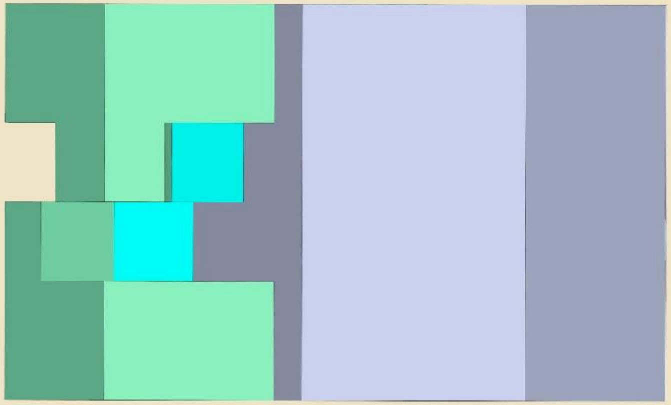
Импульсные источники с предельными потоками

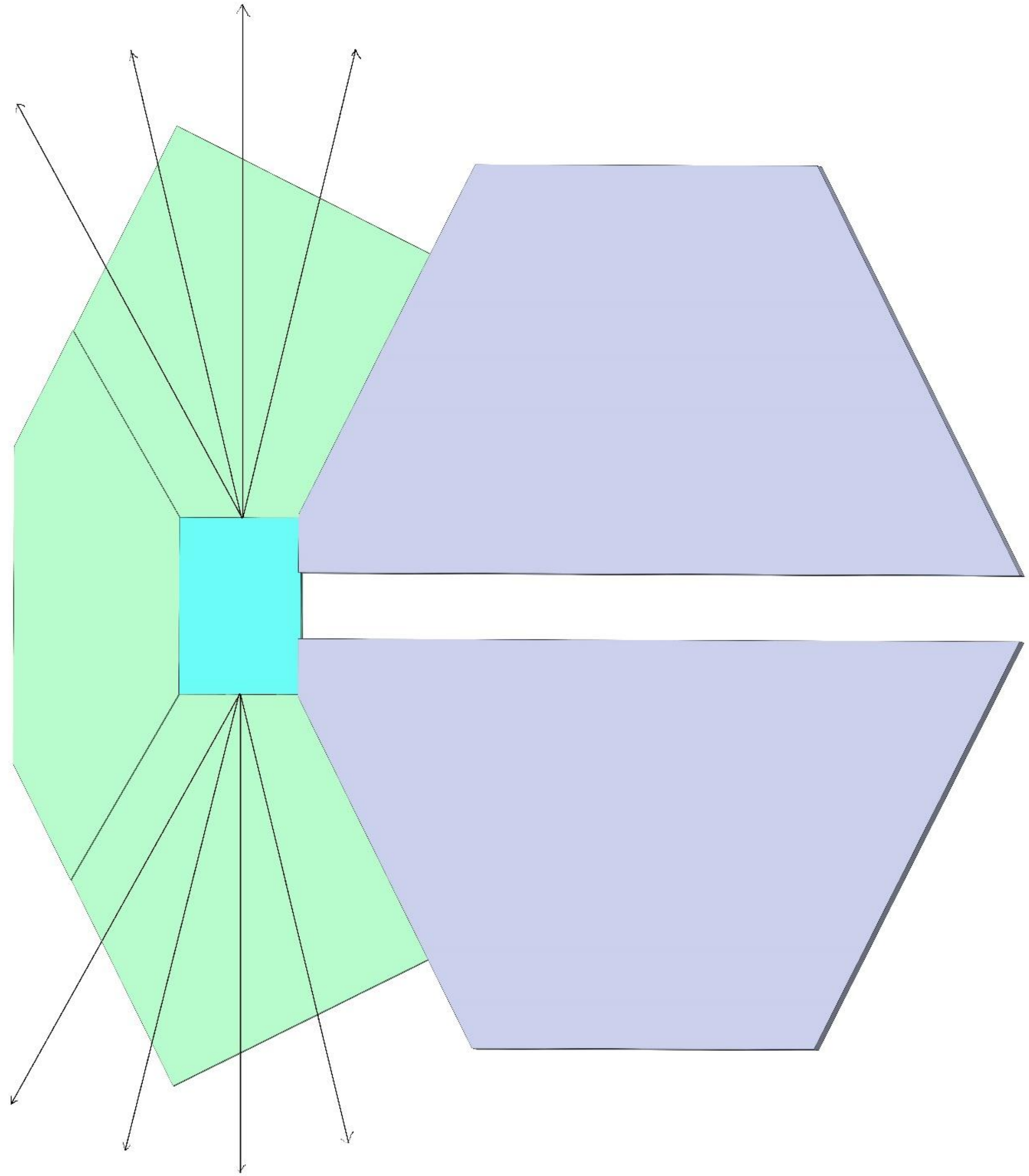
Супербустер, Pu **(DANS)**
(1.5÷3) 10^14
Энергия протонов 1 ГэВ, мощность пучка 100 кВт; длительность импульса протонов 100 мкс, нейтронов - ≥ 200 мкс;
мощность активной зоны 20-30 МВт).

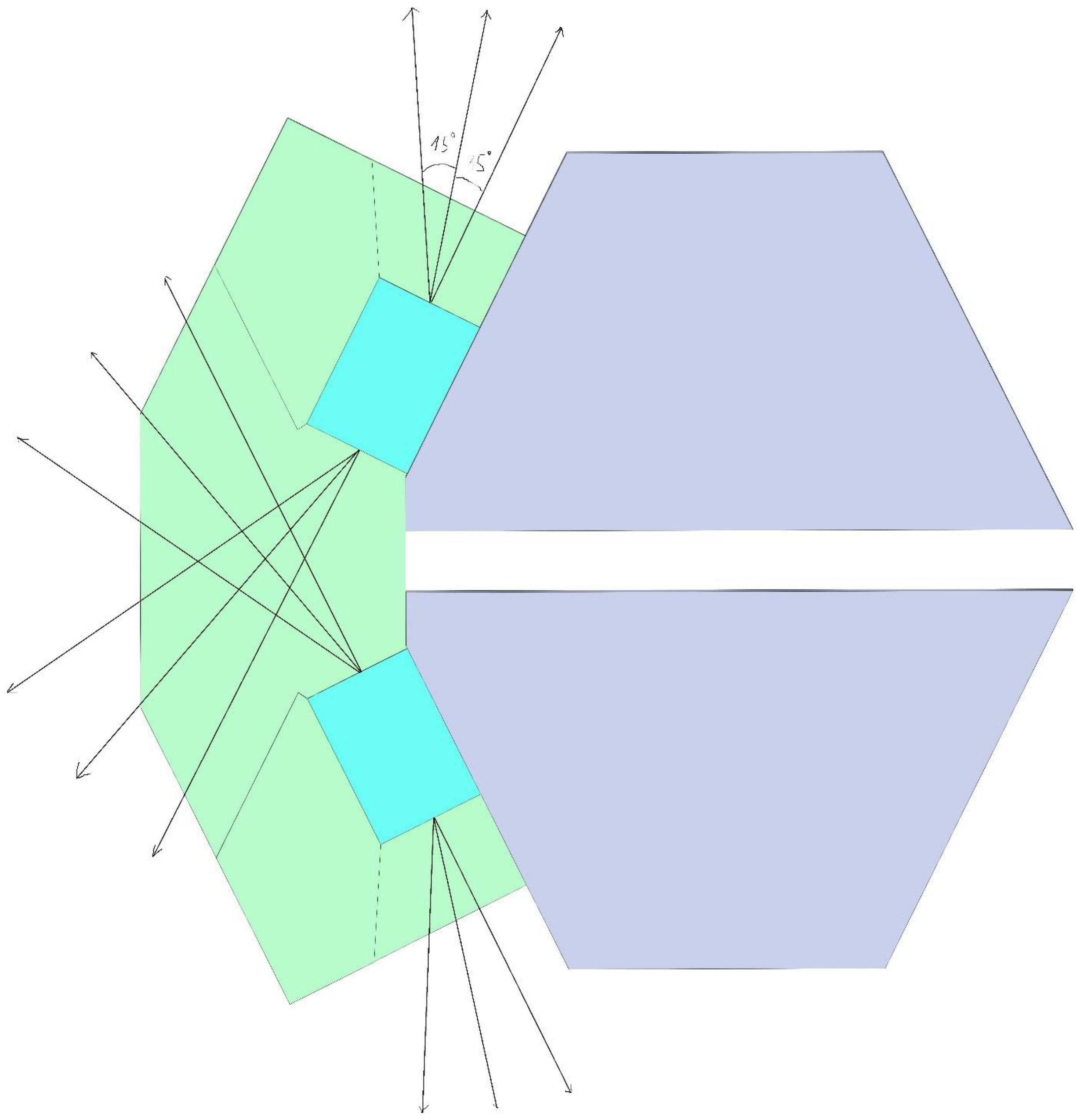


Нептун, импульсный реактор и супербустер (1÷1.5) 10^14
длительность импульса 20- 200 мкс,
мощность активной зоны до 15 МВт
Мощность пучка – ≤ 50 кВт

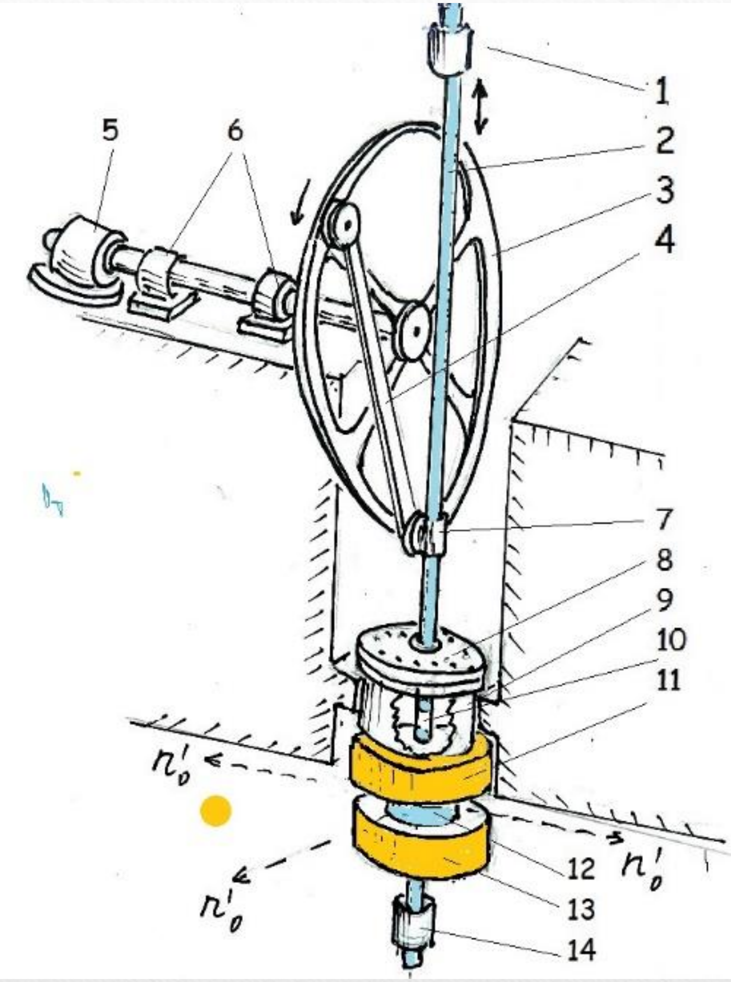






15°
15°



Neptune, the periodically pulsed reactor

conception design

Principles of method to attack the problem :

- We should follow the highway of LNPh, that is fission based pulsed sources.
- Facility should be as economical as possible,
  - But : not to be inferior to the world leading neutron sources

Complexity of the current task –
too many parameters for optimization:

- Flux time averaged
- Peak flux
- Pulse duration
- Pulse frequency
- Background
- Economy
- Safety