Frank Laboratory of Neutron Physics
Joint Institute for Nuclear Research

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# Dubna Research Reactors:
# a Look into the Future

based on the JINR Communications P3-2020-31
by Aksenov V.L., Rzjanin M.V.and Shabalin E.P.

ISINN-28, May 24 – 28, 2021

# Pulsed Reactors

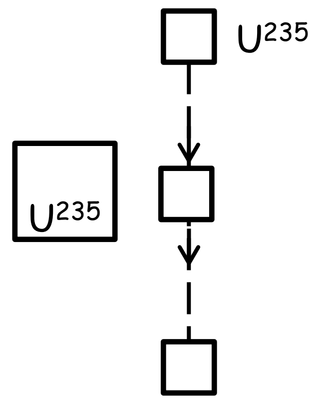
## Pulsed Aperiodic Reactors (Fast Burst Reactors)

**No beam research**

1945 Los Alamos,

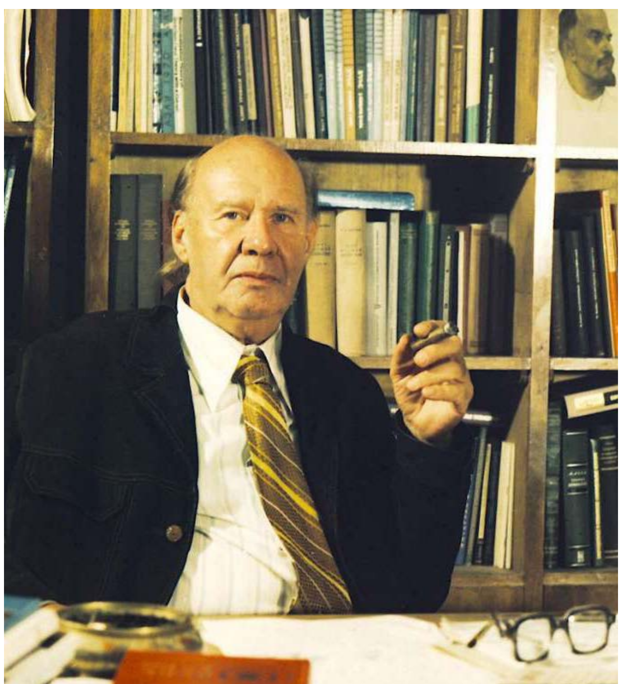
The Dragon Project

O.R. Frish// Nucl. News (1969)




YAGUAR (Snezhinsk)

BIGR (Sarov)



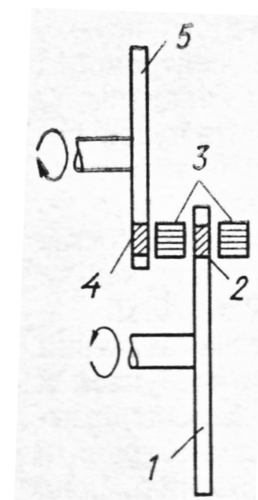
## Pulsed Periodic Reactors (Pulsing Reactors)

**beam research**

1955 Obninsk
D.I.Blokhintsev

1960 Dubna
G.E.Blokhin,
D.I.Blokhintsev et al.
At. Energy (1961)

$W = 3$ kW, $\Delta t = 40$ μs




1 – reactivity modulator disk;
2 – U (main movable core);

3 – Pu core ,

4-U insert (additional movable core);

5 – additional reactivity modulation disc.

# Dubna Neutron Super Boosters

**Superbooster: a pulsing reactor injected by an accelerator**

**1-st Generation IBR (1960); IBR + microtron (1964)**

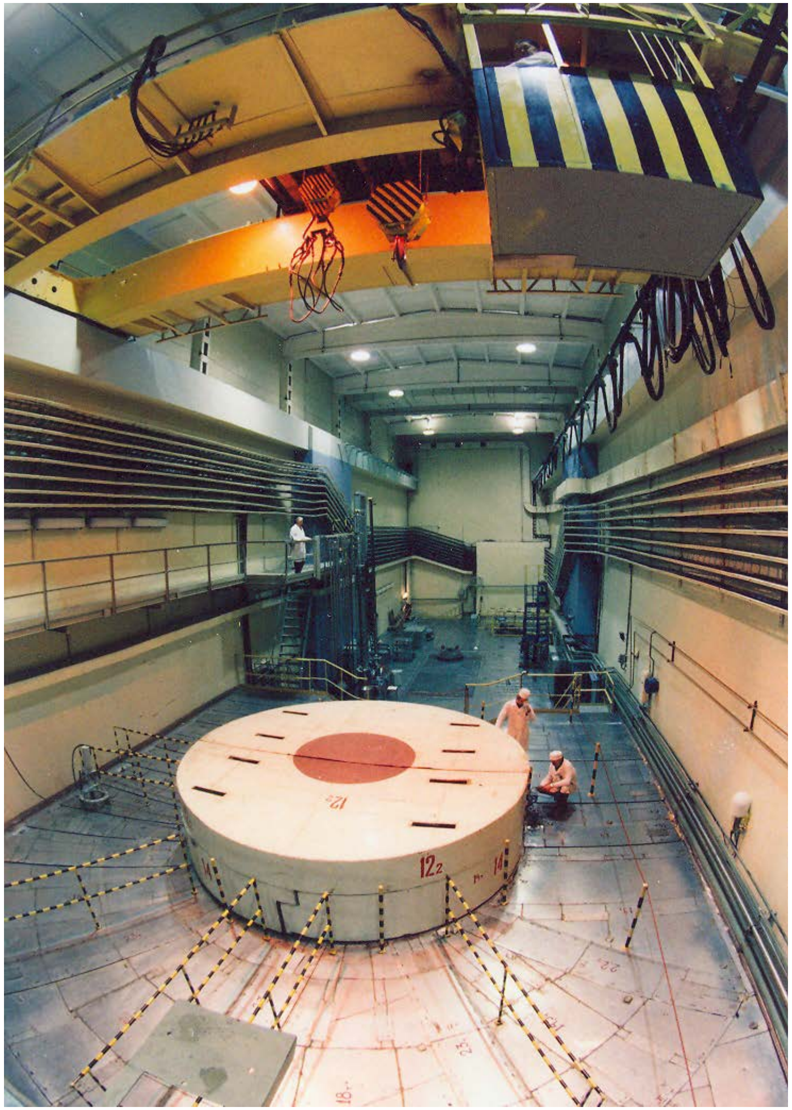
**2-nd Generation IBR30 + LUE40 (1969) Shutdown 2001**

The accelerator was used to reduce neutron pulse duration

**3-nd Generation IBR-2**

**Ananiev V.D., Blokhintsev D.I., Shabalin E.P. et al. JINR 13-4392, Dubna 1969, IBR-2 pulsed reactor with injector (LIU-30: *e*, 30 MeV, 200 A). The construction of the accelerator was stopped in 1990 due to technical problems**

# Pulsing Reactor IBR-2 (JINR, Dubna)

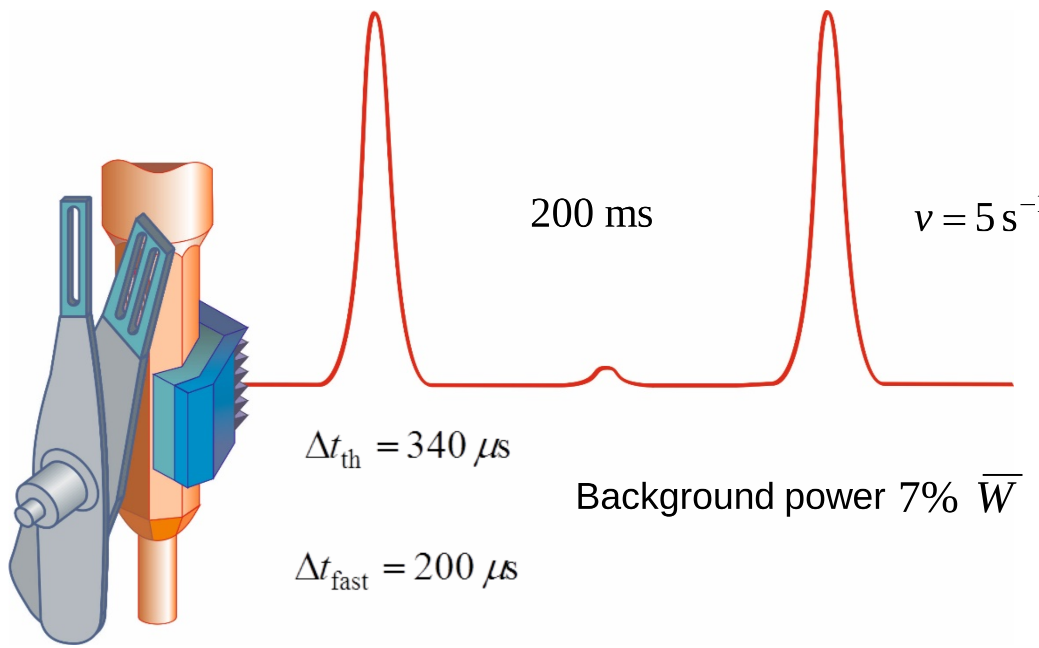


**Commencement of operation - 1984**

**Renovation – 2012; Resource – 2037**

$\overline{W} = 2\,\mathrm{MW}$ (mean); $1860\,\mathrm{MW}$ in pulse

Thermal neutrons : $\overline{\Phi}_n \le 10^{13}\,\mathrm{n/cm^2/s}$ , $\hat{\Phi}_n = 6 \cdot 10^{15}\,\mathrm{n/cm^2/s}$

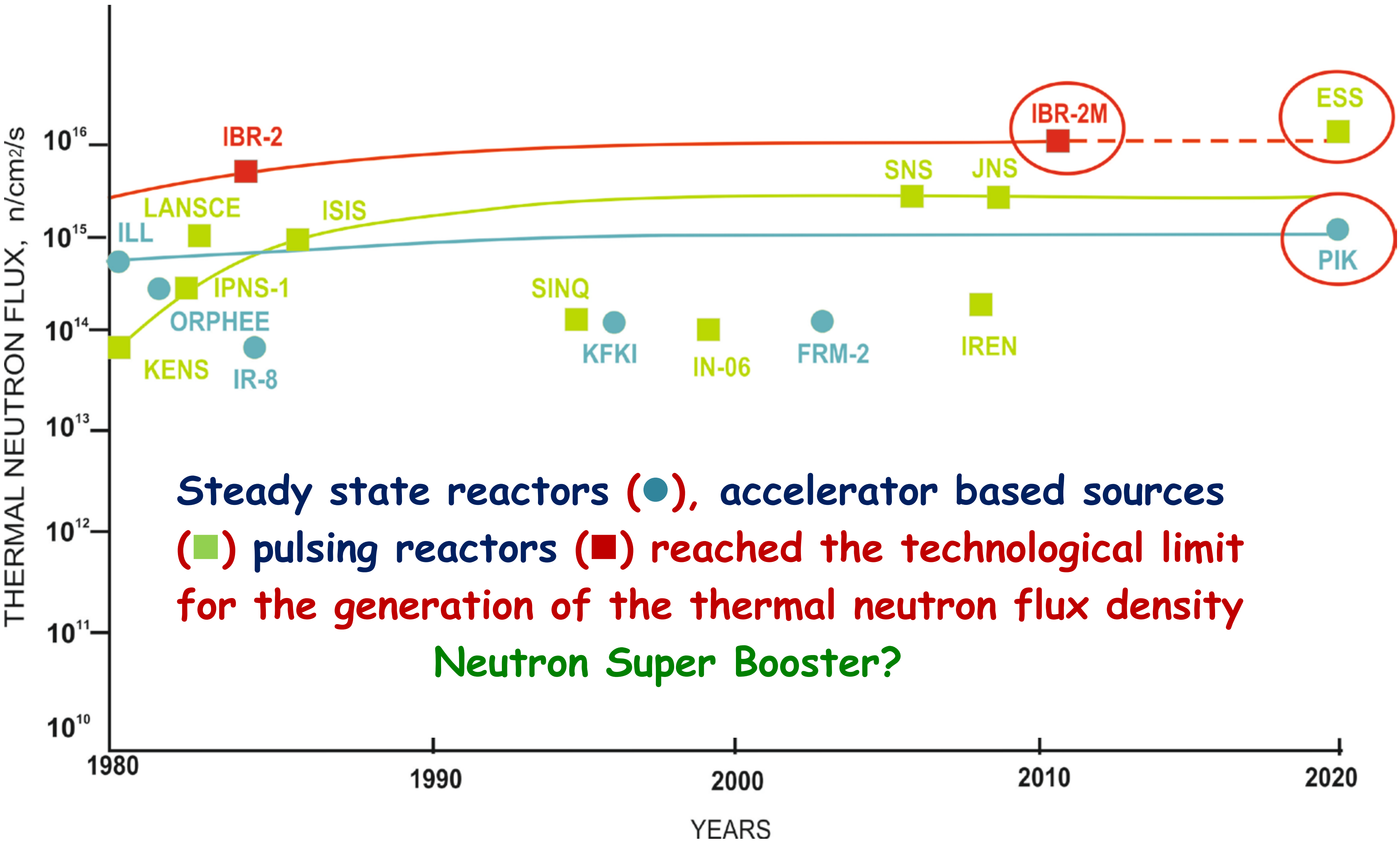


# IBR-2 restrictions
## (the directions of our searches)

1. IBR-2 is effective for Condensed Matter but it is unable to provide for Nuclear Physics (long pulse duration, low mean neutron flux).

2. Instability of pulse power oscillations that developed over time, resulting in performance limitations and reduced neutron flux.

# Advanced Neutron Sources




Steady state reactors (●), accelerator based sources (■) pulsing reactors (■) reached the technological limit for the generation of the thermal neutron flux density

Neutron Super Booster?

# Neutron Super Booster of the 4-th Generation

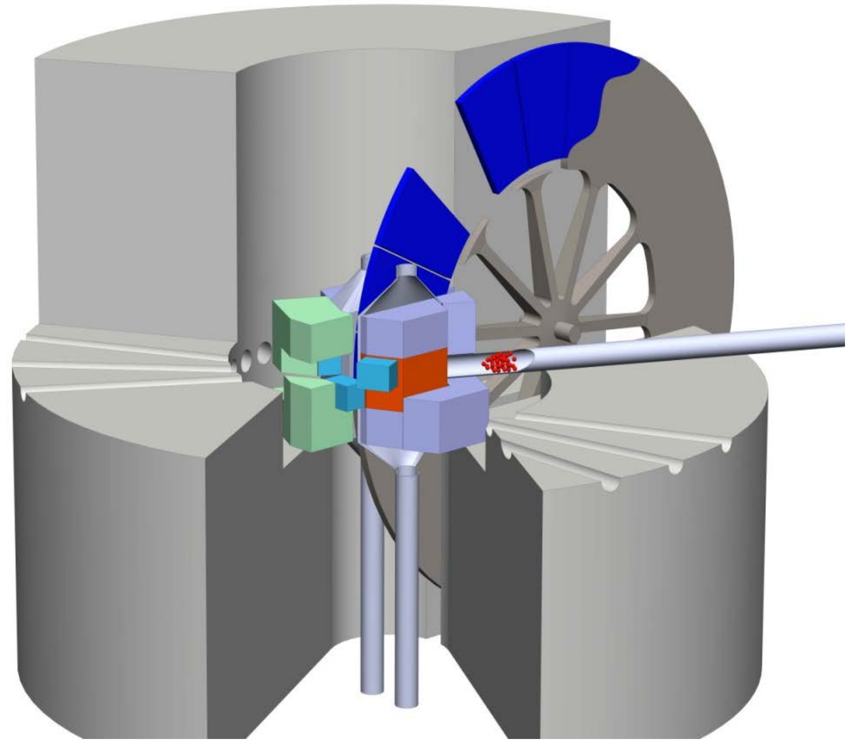
Pulsing reactor injected by a proton accelerator

**<u>Pulsing reactor plays the role of multiplying target station</u>**

reactor with periodic reactivity modulation

deeply subcritical (0.05 - 0.002 $k_{eff}$)

multiplication: 200 ÷500




## <u>Proton Accelerator</u>

$E_p = 1.2 \div 0.8$ GeV

$W \le 100$ kW

$\bar{I}_p = 0.1\ mA,\ \ \hat{I}_p \le 50$ mA

$\Delta t_p = 20, 200$ µs

$\nu = 30, 10$ Hz

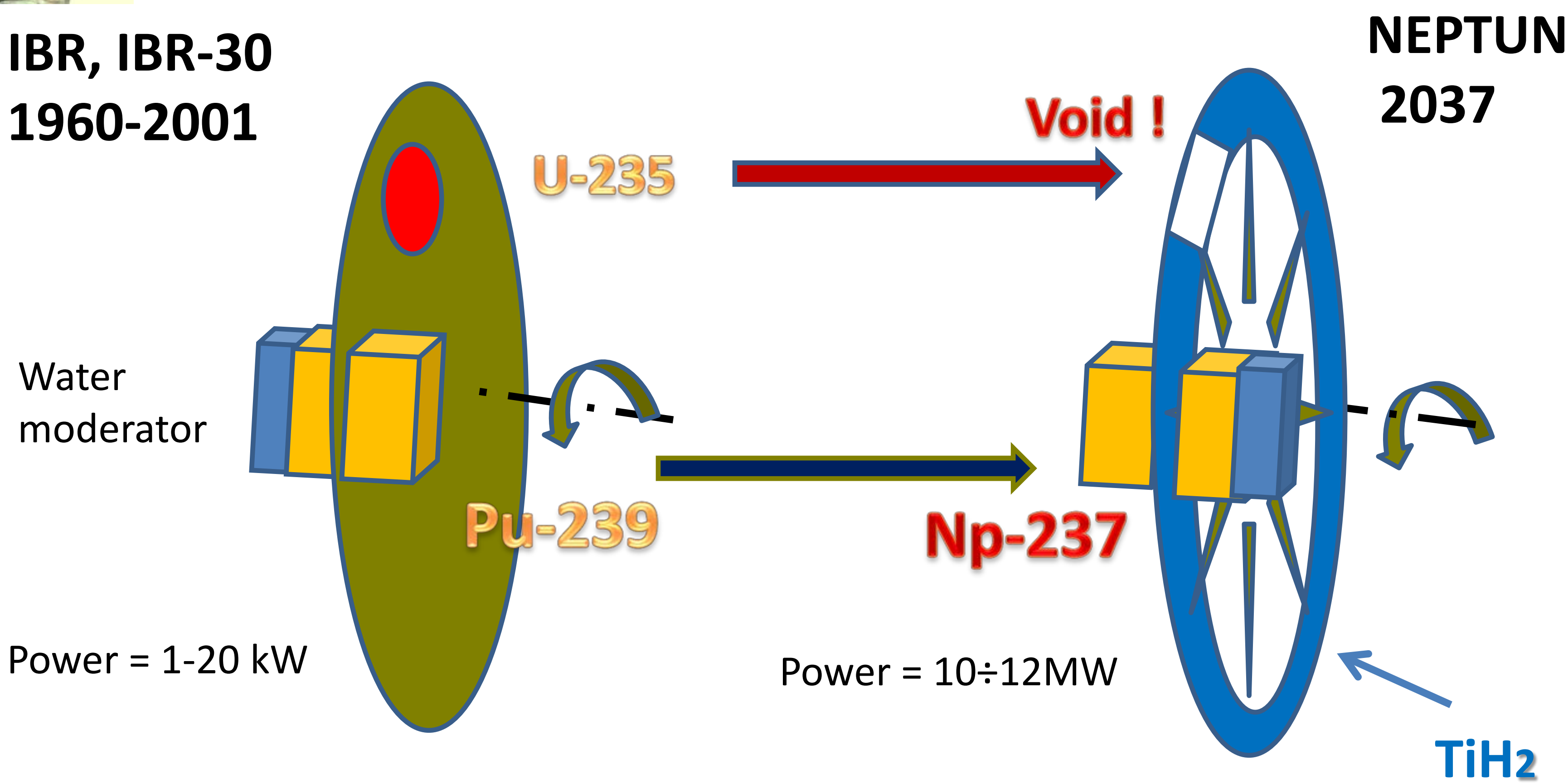
W = 10 – 12 MW

$\overline{\Phi}_{\text{therm}} = 2 \cdot 10^{14},\ \ \hat{\Phi}_{\text{therm}} = 10^{17} \text{n/cm}^2\text{/s}$

Long pulse ≤ 200-300 µs

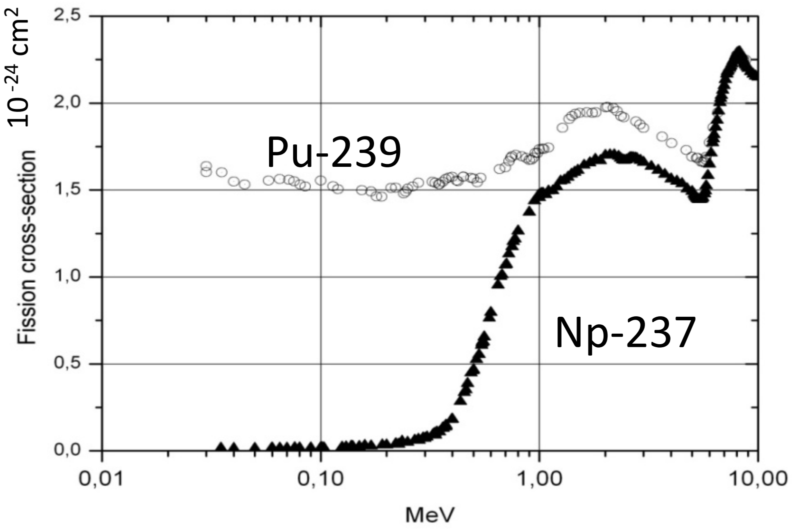
Short pulse 20 – 30 µs

# Target Station NEPTUN




Principle of generation of power pulses in reactors IBR, IBR-30 (serial number IBR-1) and NEPTUN (serial number IBR-3): succession and differences.

# Why Neptunium-237?




The main feature is threshold fission at 0.4 MeV

* $Np^{237}$ is a product of atomic power plants; $T_{1/2} = 2.14 \cdot 10^6$ years

Advantages over Pu-239, each quite important :

1. Short life time of prompt neutrons:

$\tau_{Np}$ =3 - 10 ns; $\tau_{Pu}$ (IBR-2) > 65 ns.

Optimal multiplication factor, shorter neutron pulse

2. Lower background between pulses: 2-3% (due to lower effective delayed neutron fraction)

3. Potencial for reactivity modulation by VOID

(hydrogen is effective absorber of fast neutrons)

4. Almost zero reactivity effect on fuel burnout due to the chain: Np-237 to Np-238 to Pu-238. Operation time to fuel reloading is as long as 10-20 fold of that for Pu-239 core.

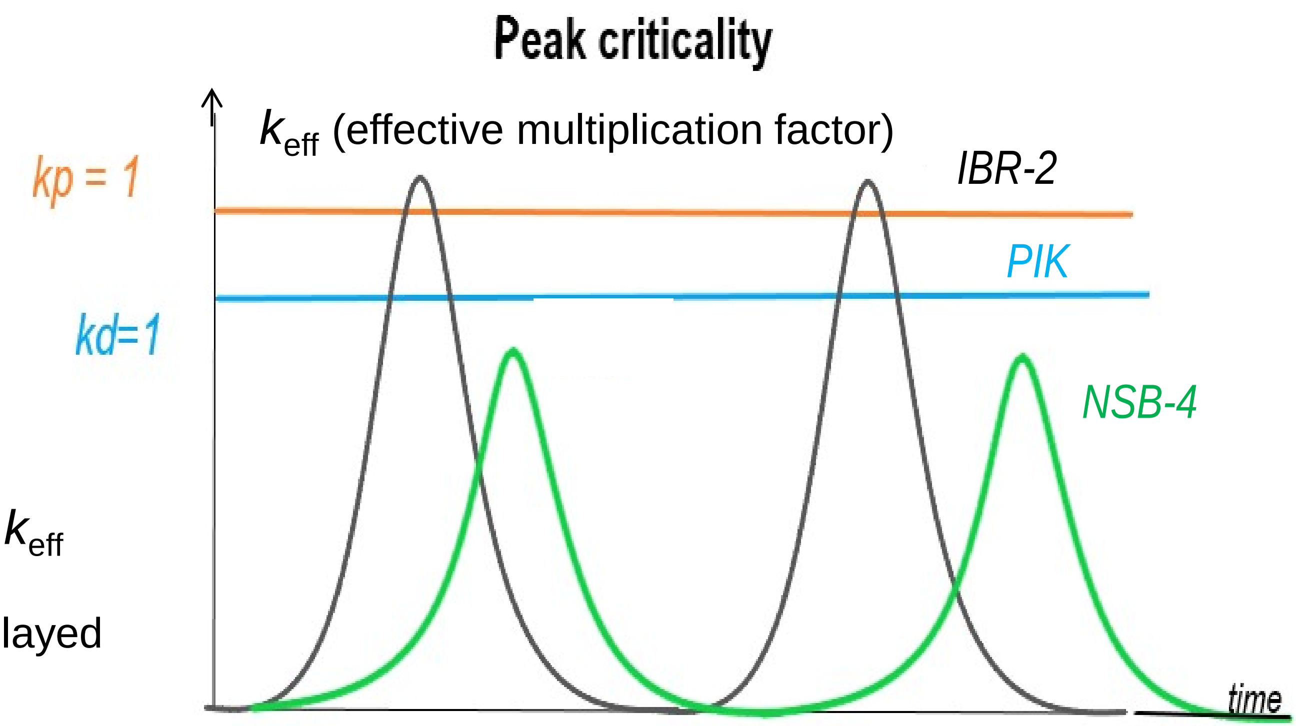
# Nuclear Safety of NSB-4

Target station NEPTUN is in subcritical state in every moment of operation, that is not always the case of power reactors

- For Neutron Super Booster operation with subcritical system NEPTUN pulse power fluctuations are negligibly small
- The reactivity modulator is symmetrically placed in the center of the core that excludes positive reactivity excursion in accidents

Prompt criticality

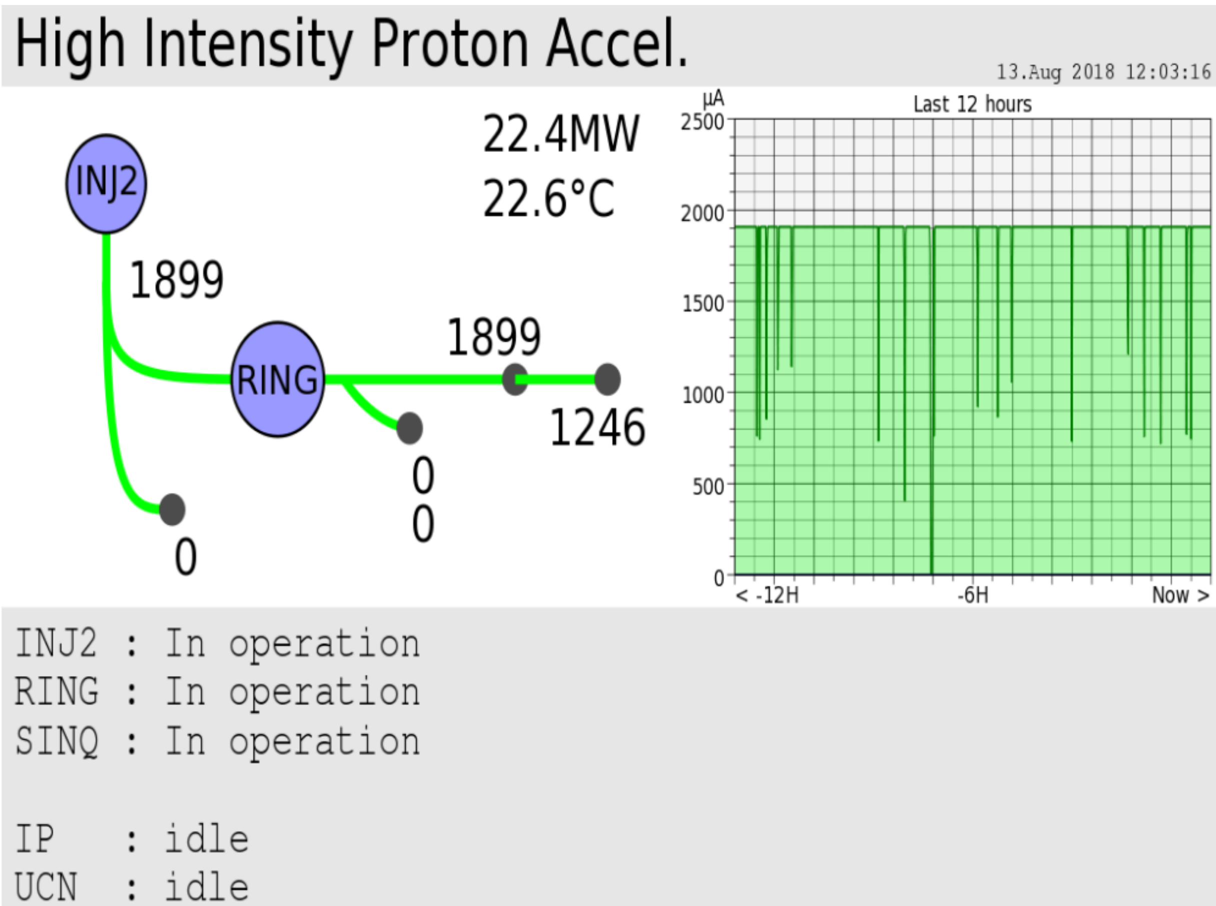
Delayed neutron criticality




$$K_p - K_d = \beta_{eff} \approx 10^{-3}\, k_{eff}$$

effective fraction of delayed neutrons

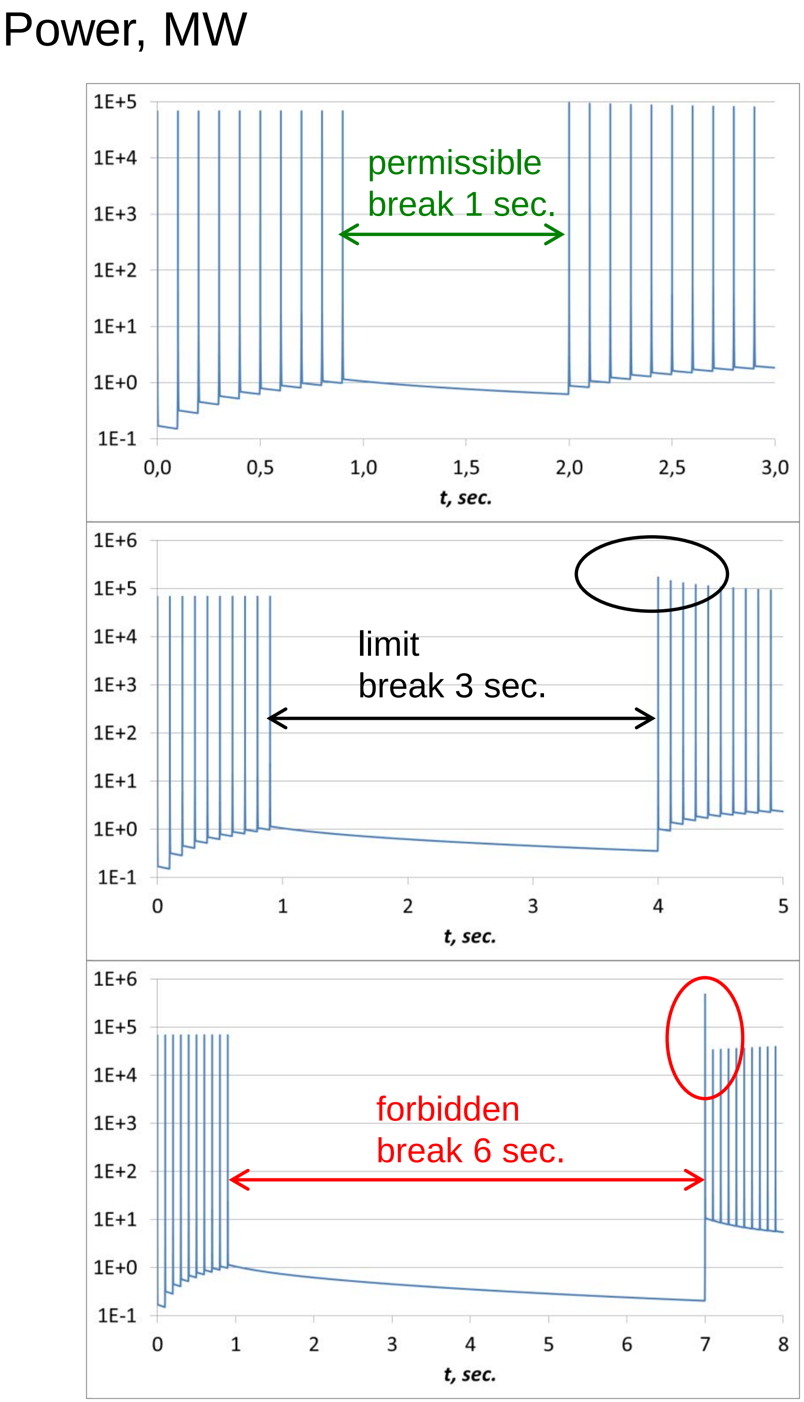
# Example of accelerator operation: Swiss Spallation Neutron Source




| Injektor-1 | |
|---|---|
| Type: | Cyclotron |
| Magnet: | H-Form |
| Magnet mass: | 500 t |
| Poll-plates radius: | 125 cm |
| Poll=plates Distance: | 20 cm |
| Vacuum chamber volume: | 20 $m^3$ |
| Energy: | Variable |

| Injektor-2 | |
|---|---|
| Type: | Isochronous-Cyclotron |
| Magnets: | 4 |
| Total Magnet mass: | 760 t |
| Accelerating elements: | 4 Resonators(50 MHz) |
| Energy: | 72 MeV |

| PSI Ring Cyclotron | |
|---|---|
| Type: | Isochronous-Cyclotron |
| Magnets: | 8 |
| Total Magnet mass: | 2000 t |
| Accelerating elements: | 4<br>(5) Cavities(50 MHz) |
| Kinetic Energy:[4] | 590 MeV |



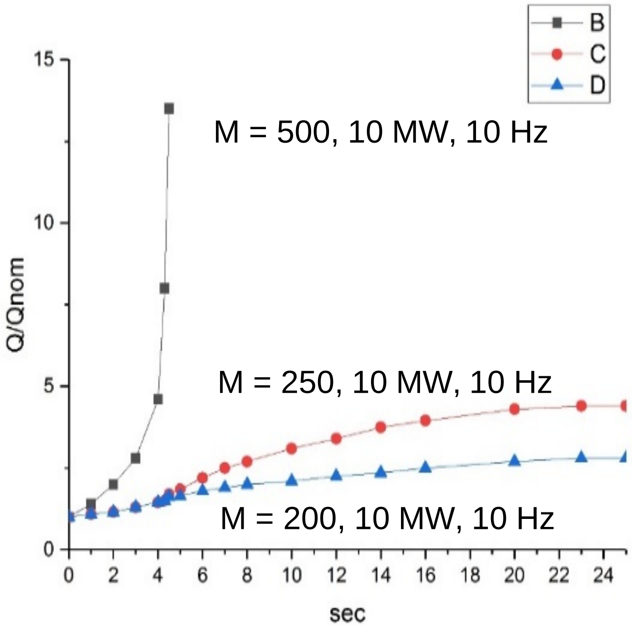

# A proton beam breakdown

- When the proton beam is introduced into the core regularly and synchronously with introduced reactivity, the resulting pulse is stable.
- With a sudden disappearance of the proton beam and its subsequent restoration after a short time, it is possible the generation of a power pulse, that significantly exceeds the nominal value.

Conclusion: The operation of the accelerator must be stable in the sense of temporal lack of proton pulses.

Aksenov V., Rzyanin M., Shabalin E., Europian Cyclotron Progress Meeting, Sept. 2018, Dubna

# Safety of powerful Superbooster




- It is permissible to triple the prompt power exceeding to the nominal value.
- A tenfold excess lead to damage of fuel elements.
- When power is down, coolant decreases temperature of fuel that arises reactivity of the reactor core.

Fig. Excess of the energy of the nominal pulse depending on the silence time of the accelerator and the level of the fixed multiplication factor M.

The stable operation of the facility at planed $\Phi_n$ is possible if

a) M < 250 and proton energy $E_p >$ 2.5 GeV,

b) to introduce negative reactivity in the core for a reactivity temperature feedback, that will allow operation through 1 GeV accelerator outages .

**Rzyanin M., Shabalin E., Physics of Atomic Nuclei, v.83(8), p.1260 (2020)**

# NSB research results

1. An accelerator provide for:
   a) deeply subcritical state during operation: reliable nuclear safety;
   b) short neutron pulse duration.

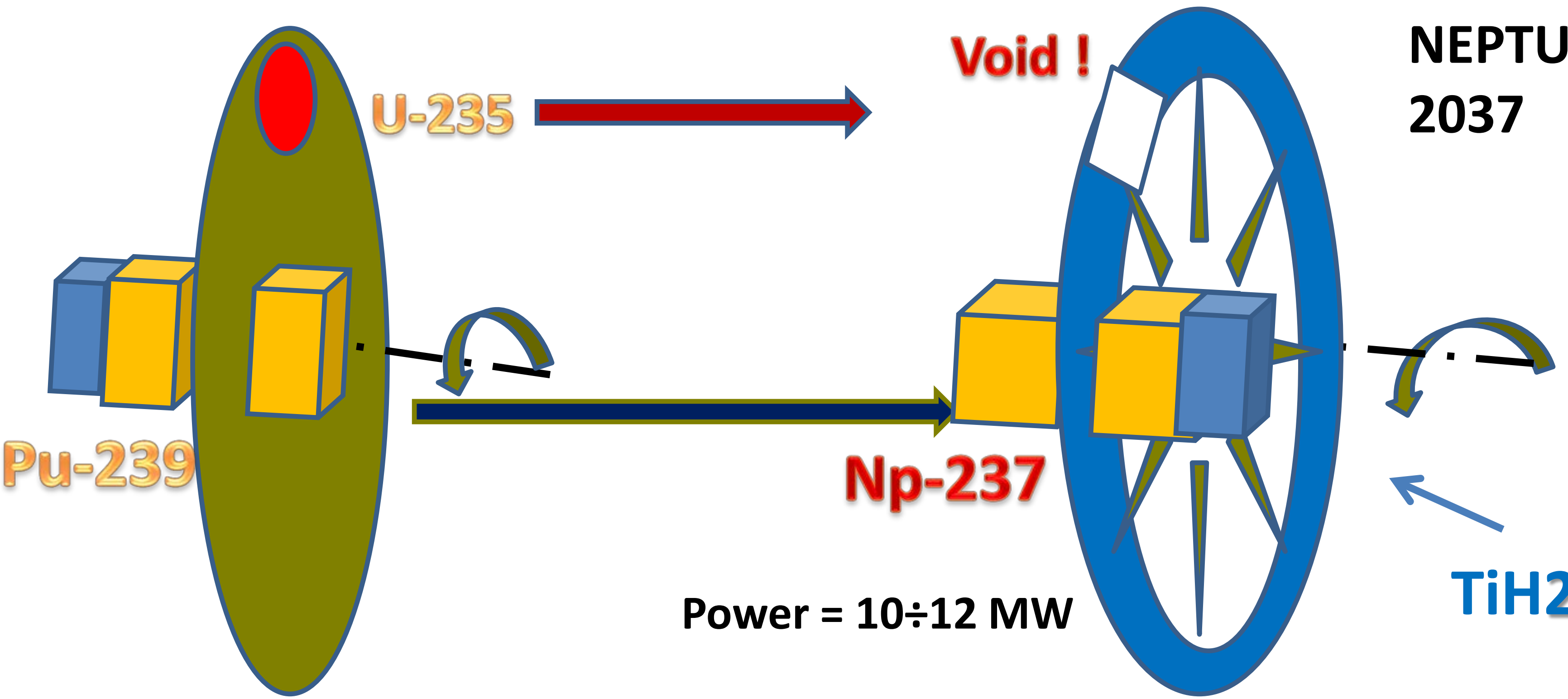
2. There are hard stability requirements to accelerator. We don't see solution today.

3. With existing accelerator technology, new reactor technologies are required.

# Pulsing Reactor NEPTUN

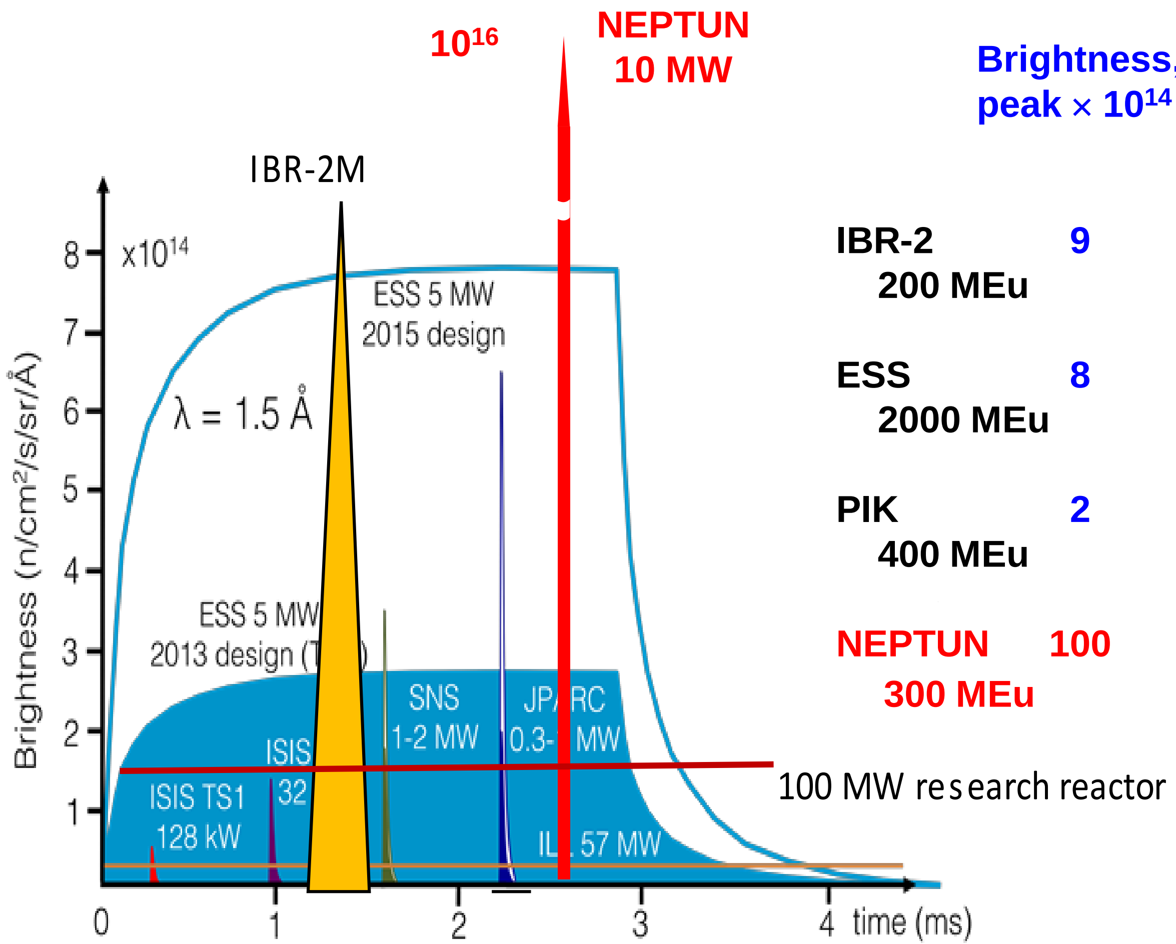
**IBR,IBR-30**
**1960-2001**Power = 1-20 kW

**NEPTUN**
**2037**




NpN loading: 500kg; Fuel elements: tubular, 16 mm, Na sublayer; Colant: liquid Na,290-490 C
Max positive reactivity feedback: 0.3 % $k_{eff}$ ; Pulse overcriticality: 3.3 $10^{-4}$ $k_{eff}$;
Background power: 2-3%; Pulse repetition rate: 10 Hz; Neutron pulse duration: fast 200, thermal 400mks; Neutron beamlines: 32. Reactor service life: 20GW/days.

# Reactor NEPTUN and other (basic figure from the ESS report)



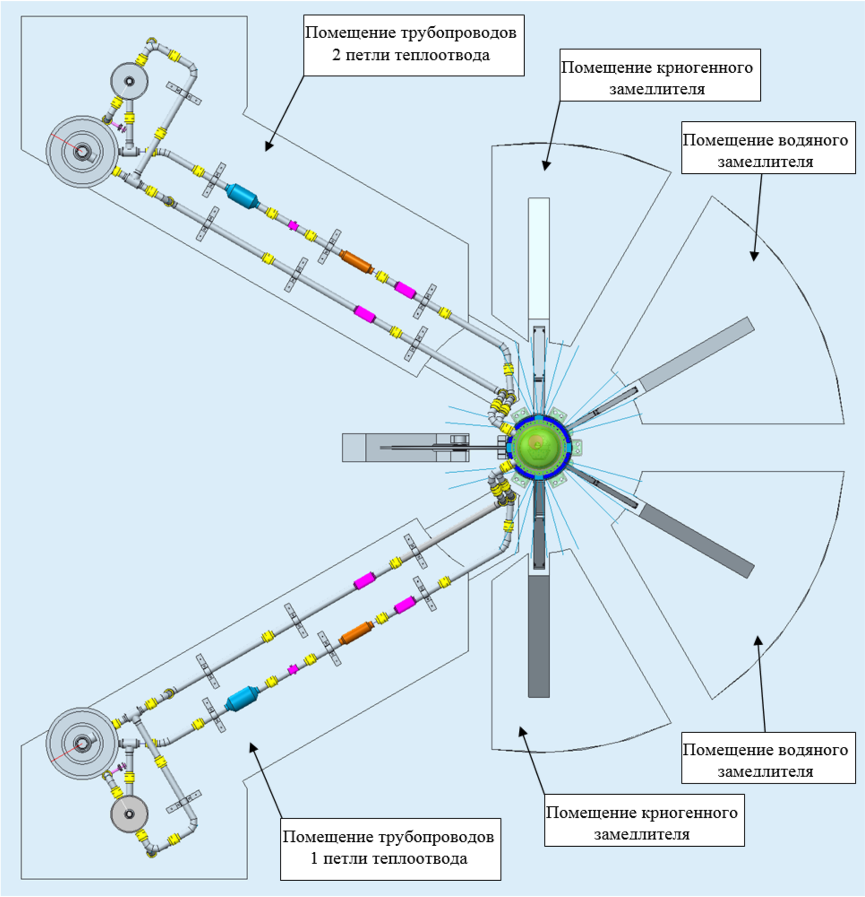

| | Brightness, peak × $10^{14}$ | Flux density, time aver. | Flux density, peak |
|---|---|---|---|
| IBR-2 200 MEu | 9 | 0.1 | 58 |
| ESS 2000 MEu | 8 | 2 | 75 |
| PIK 400 MEu | 2 | 14 | 10 |
| NEPTUN 300 MEu | 100 | 2 | 800 |

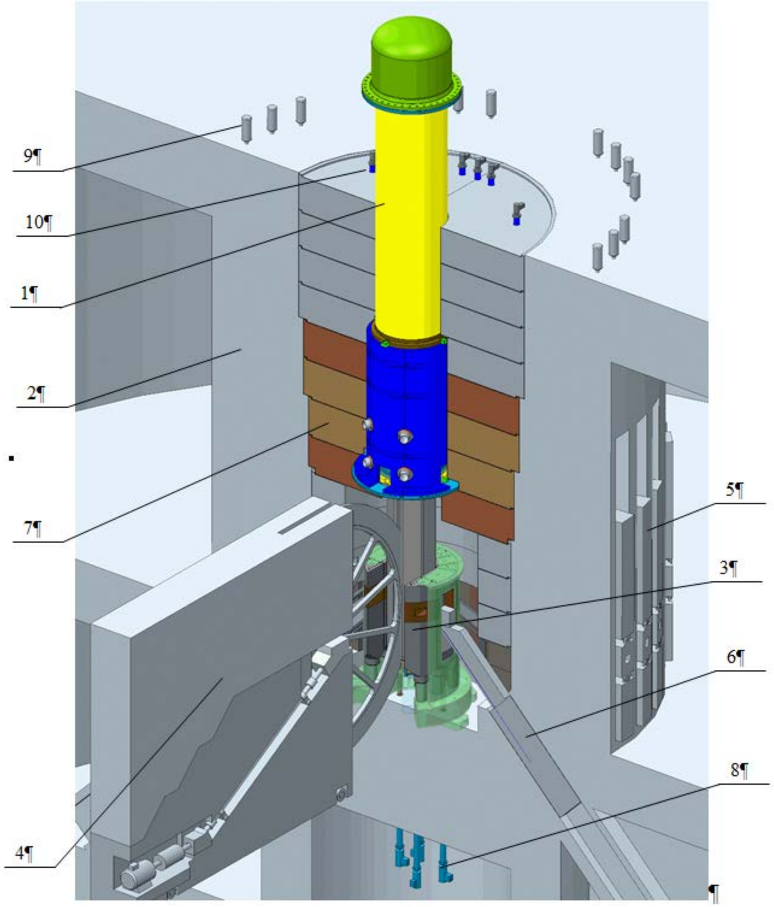
Data $\times 10^{14}$ $[n \cdot cm^{-2} \cdot s^{-1}]$

**The construction of NEPTUN will bring new opportunities and challenges for industries of JINR Member States, especially related to nuclear power industry sectors. We believe that the return for science and technology, which NEPTUN can deliver during 40 years of its expected service life, will be more than sufficient to justify the commitment of funds.**

# Layout of the NEPTUN reactor

## Concept development by Dollezhal Design Institute (Moscow)



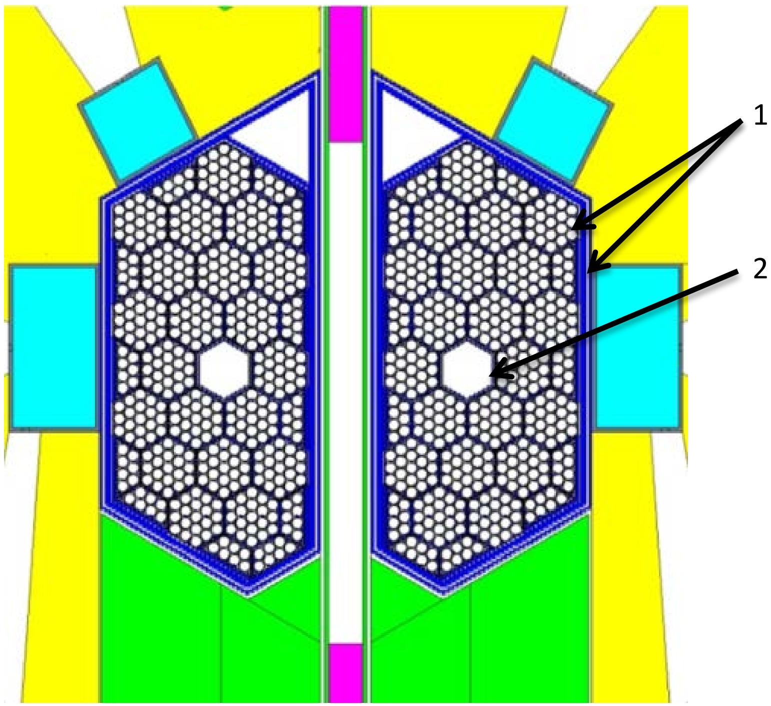



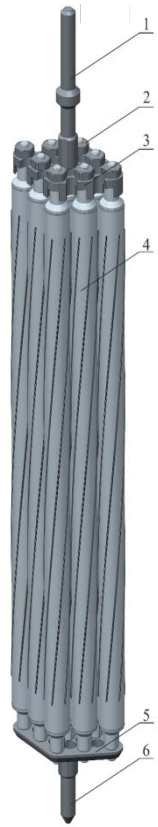

Lopatkin A. V., Tretiyakov I.T., Romanova N.V. et al., At. Energy, v. 129 (4), p.226 (2020)

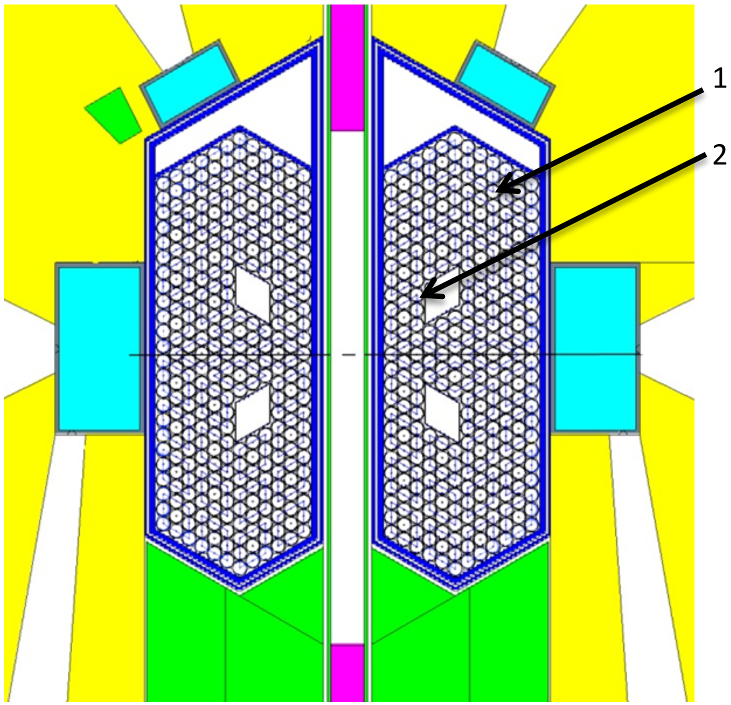
**1 – реактор; 2 – бетонный массив; 3 – отражатель стационарный; 4 – модулятор реактивности; 5 – шибер ЭК; 6 – комплекс замедлителя; 7 – защита тепловая; 8 – ИМ СУЗ; 9 – привод шибера; 10 – привод ИК.**

# Reactor NEPTUN: Layout of the core

## Concept development by Dollezhal Design Institute (Moscow)




1 – Fuel Assembly without cover

2 – Channel for Safety Regulation

1 – Single Fuel Element

2 – Channel for Safety Regulation

Lopatkin A.V., Tretiyakov I.T., Romanova N.V. et al. At. Energy, v. 129(4), p.226 (2020)

# HOW TO GET AWAY FROM INSTABILITIES

## Ideal – a core of single Fuel Elements (FE)

**REACTIVITY FLUCTUATIONS $\Delta\rho$**
**(due to pulse heating of FEs)**

***Power pulse energy deviation***

$$Q \approx Q_{nom} \exp\left(\Delta\rho / \beta_{pulse}\right)$$

$\Delta\rho$ is reactivity fluctuations

$\beta_{pulse}$ is delayed neutron pulse fraction

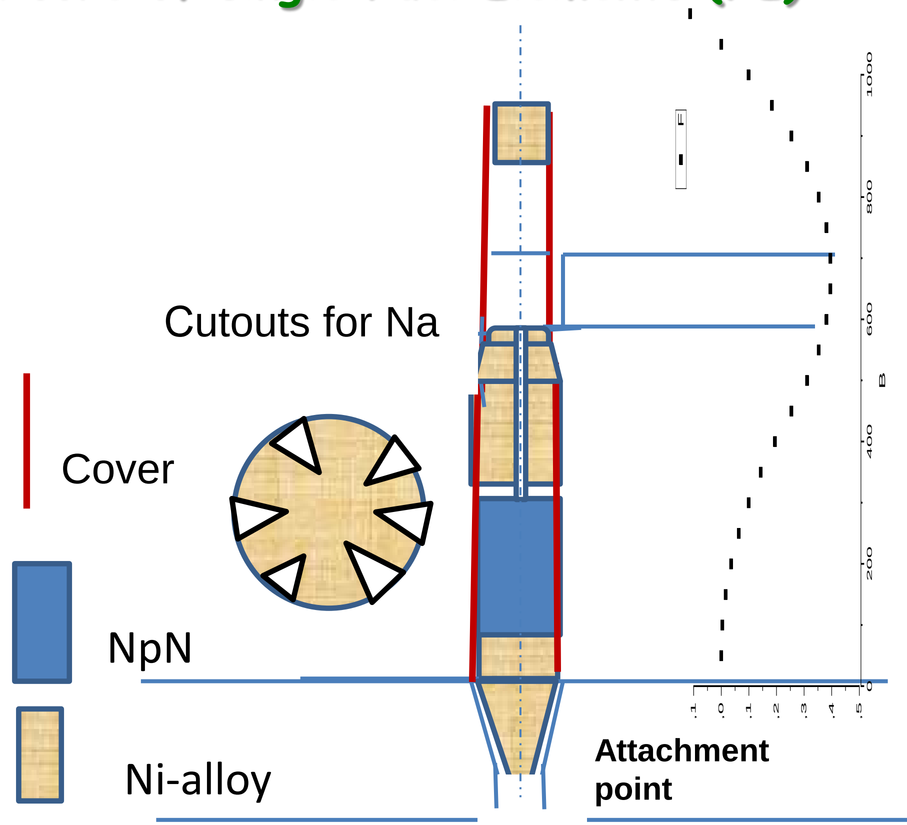
$$\beta_{pulse} \approx 0.5\,(\alpha v^2 \tau^2)^{1/3}$$

$\alpha$ is reactivity parabola coefficient of reactivity modulator (RM)

$v$ is linear velocity of the RM

$\tau$ is average neutron generation lifetime

*E.P.Shabalin et al. (2021)*




Displacement (–0.2 mm) of the FE axis away from the core, providing a negative effect of reactivity: – (4 ÷ 5 )$\beta_{pulse}$.

We need to avoid the positive reactivity which lead to oscillatory instabilities of the IBR-2 reactor.

# Reactor research results

1. The solution of the dynamical instabilities problem is proposed: single FEs instead of assemblies in NpN core.

2. R&D of moderators and of NpN fuel elements should be considered as top-priority tasks for 2021.

3. Core of single FE should be considered.

# New Opportunities for FLNP Research Program

**Flux density: in puls $10^{17}$ n/cm$^2$/s; mean $10^{14}$ n/cm$^2$/s**

**Neutron pulse duration: fast 200 mks; thermal 400mks**

**New opportunities for Condensed Matter**

**What about Nuclear Physics?**

V.L.Aksenov. JINR E3-2012-12, 2017, Dubna

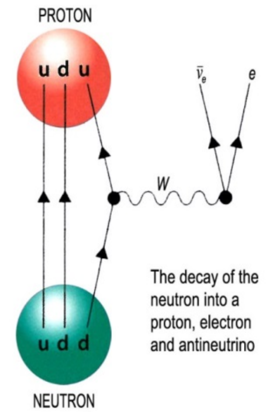
# New Physics (is not available at IBR-2)

## Ultracold neutrons (UCN)

Early Universe : $\tau_n$

Barion asymmetry : EDM

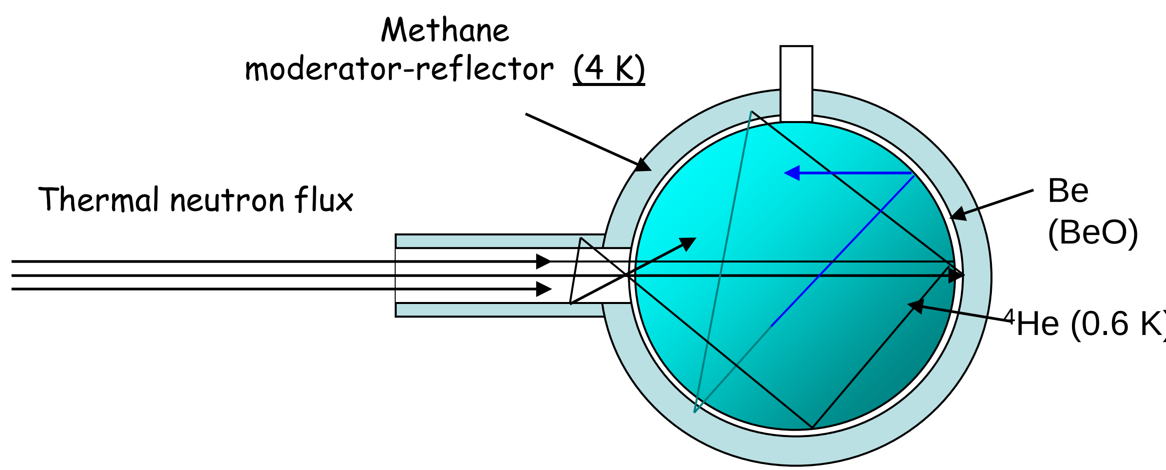
1968: Dubna, F.Shapiro et al.




**Neutron–Antineutron oscillations:**
**Barrion asymmetry, neutrino mass**

**Neutron–Neutron scattering:**
**charge symmetry breaking**

**Quantum measurements (a bridge between physics and consciousness problem)**




**Schematic view of the idea of the helium ultra cold neutron source at thermal neutron source (2015)**

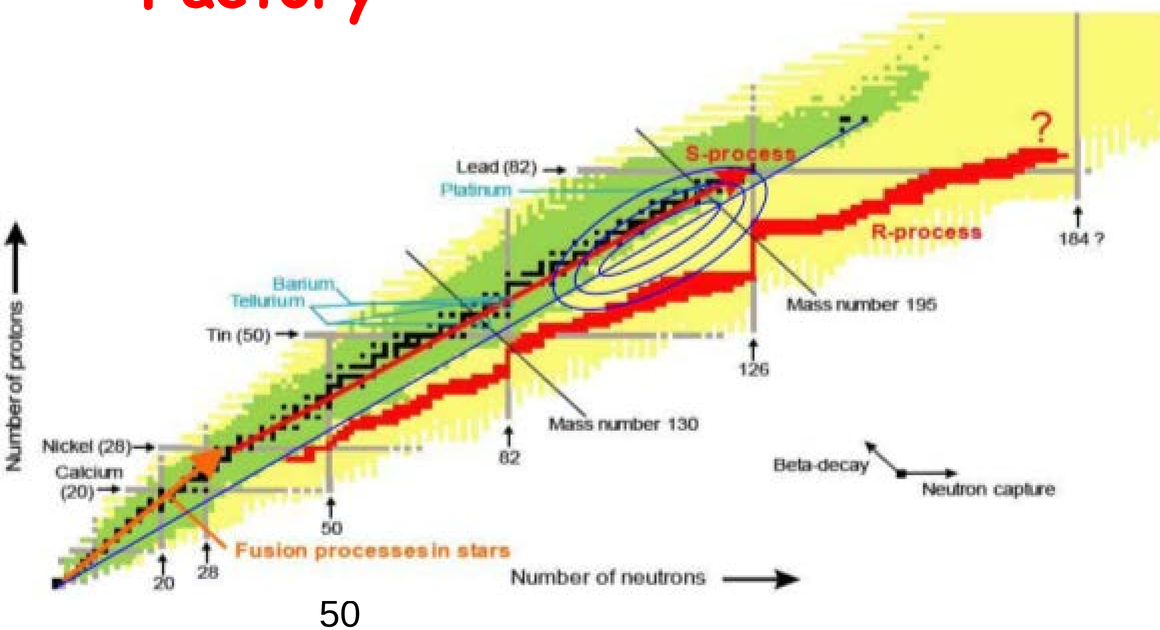
E.V. Lychagin, A.Yu. Muzychka, G.V. Nekhaev, E.I. Sharapov, A.V. Strelkov (JINR, Dubna), V.V. Nesvizhevsky (ILL, Grenoble)

# Neutron Nuclear Physics (is not available at the IBR-2)

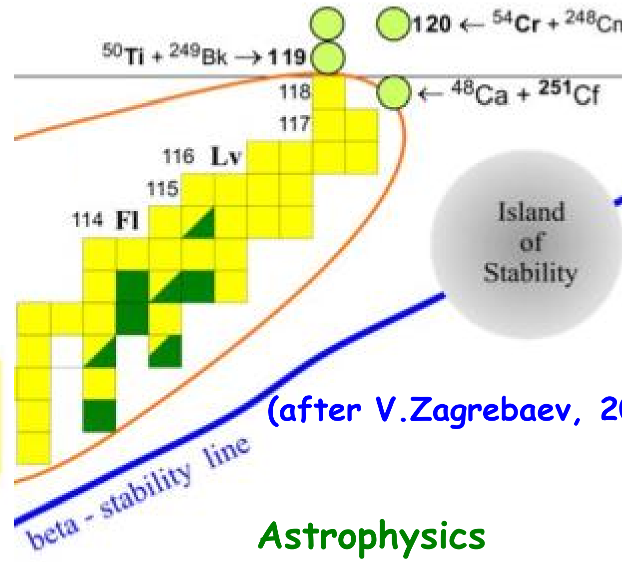
We need to have $\bar{\Phi}_n \approx 10^{14} \frac{n}{sm^2 s}$

n-rich nuclides

Factory




Nuclear landscape (after D.Habs et al., 2010)




(after V.Zagrebaev, 2012)

Astrophysics
(where do the heavy
elements from?)

Nuclear reactions
after $\beta$-stability line

Fission Physics

Nuclear Data

# Conclusions

1. Both NSB and reactor have a mean thermal neutron flux of $10^{14}$ and are able to provide for new opportunities for FLNP research program.

2. High flux superbooster (pulsing reactor NEPTUN driven by 1 GeV proton accelerator) is proposed (new high technologies in accelerator and reactor physics are necessary ).

3. High flux pulsing reactor NEPTUN is designed by Dollezhal Institute for implementation in 2037 – 2042.

**THANKS FOR YOUR ATTENTION !**