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.
Pulsed Reactors

Pulsed Aperiodic Reactors (Fast Burst Reactors)

1945 Los Alamos,
The Dragon Project

No beam research

Pulsed Periodic Reactors (Pulsing Reactors)

1955 Obninsk
D.I. Blokhintsev

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

$W = 3 \text{ kW}, \Delta t = 40 \mu\text{s}$

1 - reactivity modulator disk;
2 - U (main movable core);
3 - Pu core,
4 - U insert (additional movable core);
5 - additional reactivity modulation disc.

YAGUAR (Snezhinsk)
BIGR (Sarov)
Dubna Neutron Super Boosters

Superbooster: a pulsing reactor injected by an accelerator

1-\textit{st Generation IBR} (1960); IBR + microtron (1964)

2-\textit{nd Generation IBR30 + LUE40} (1969) Shutdown 2001

The accelerator was used to reduce neutron pulse duration

3-\textit{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

\[ \overline{W} = 2 \text{ MW (mean); } 1860 \text{ MW in pulse} \]

Thermal neutrons: \( \overline{\Phi}_n \leq 10^{13} \text{n/cm}^2/\text{s} \), \( \hat{\Phi}_n = 6 \cdot 10^{15} \text{n/cm}^2/\text{s} \)

\[ \Delta t_{\text{th}} = 340 \mu s \]

\[ \Delta t_{\text{fast}} = 200 \mu s \]

Background power 7% \( \overline{W} \)

\[ \nu = 5 \text{ s}^{-1} \]
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

Pulsing reactor plays the role of multiplying target station
reactor with periodic reactivity modulation
deepl y subcritical (0.05 - 0.002 \( k_{eff} \))
multiplication: 200 ÷ 500

Proton Accelerator
\( E_p = 1.2 \div 0.8 \text{ GeV} \)
\( W \leq 100 \text{ kW} \)
\( \bar{I}_p = 0.1 \text{ mA}, \quad \hat{I}_p \leq 50 \text{ mA} \)
\( \Delta t_p = 20,200 \mu s \)
\( \nu = 30,10 \text{ Hz} \)

\( W = 10 - 12 \text{ MW} \)
\( \Phi_{\text{therm}} = 2 \cdot 10^{14}, \quad \hat{\Phi}_{\text{therm}} = 10^{17} \text{n/cm}^2 / \text{s} \)
Long pulse \( \leq 200-300 \mu s \)
Short pulse \( 20 - 30 \mu s \)
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?

Advantages over Pu-239, each quite important:

1. Short life time of prompt neutrons:
   \[ \tau_{\text{Np}} = 3 - 10 \text{ ns}; \tau_{\text{Pu (IBR-2)}} > 65 \text{ ns}. \]
   Optimal multiplication factor, shorter neutron pulse

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

3. Potential 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.

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
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

\[ K_p - K_d = \beta_{\text{eff}} \approx 10^{-3} k_{\text{eff}} \]

effective fraction of delayed neutrons

\[ k_{\text{eff}} (\text{effective multiplication factor}) \]

Prompt criticality

- \( k_p = 1 \)

Delayed neutron criticality

- \( k_d = 1 \)
Example of accelerator operation: Swiss Spallation Neutron Source

High Intensity Proton Accel.

INJ2 : In operation
RING : In operation
SINQ : In operation

IP : idle
UCN : idle

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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.

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
Power = 10÷12 MW

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 \times 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.
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)


1 – reactor; 2 – betonnyy massiv; 3 – otrazatel stacionarnyy; 4 – modulyator reaktivnosti; 5 – shiber EK;
6 – kompleks zameldilta; 7 – zashita teplovaya; 8 – IM SUZ; 9 – prived shibera; 10 – prived IK.
Reactor NEPTUN: Layout of the core

Concept development by Dollezhal Design Institute (Moscow)

**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*

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

$\Delta \rho$ is reactivity fluctuations

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

$$\beta_{\text{pulse}} \approx 0.5 \left( \alpha \nu^2 \tau^2 \right)^{1/3}$$

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

$\nu$ is linear velocity of the RM

$\tau$ is average neutron generation lifetime

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

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

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

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)

Ultracold neutrons (UCN)

Methane moderator-reflector (4 K)

Thermal neutron flux

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 \[ \Phi_n \approx 10^{14} \frac{n}{sm^2s} \]

n-rich nuclides

Factory

Astrophysics
(where do the heavy elements from?)

Nuclear reactions
after \( \beta \)-stability line

Fission Physics

Nuclear Data

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