MARIA Nuclear Reactor
The Low-Energy Nuclear Physics Research Infrastructure

NARODOWE CENTRUM BADAŃ JĄDROWYCH ŚWIERK

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Świerk, Poland

The MARIA Research Reactor

- high neutron flux density research reactor
- water and beryllium moderated
- pool-type reactor with pressurized fuel channels
- concentric tube assemblies of fuel elements
- fuel channels in conical matrix of beryllium blocks surrounded by graphite reflector
- 30 MW of nominal thermal power
- thermal neutron flux density up to $2 \cdot 10^{14}$ cm^{-2} s^{-1}
- fast neutron flux density up to $1 \cdot 10^{14}$ cm^{-2} s^{-1}
- 35 years of operation (1975-1984, 1993-2004, 2005-.
- current operation licence 2015-2025, exp. >2040
- over 4500 hours operation per year
- radioisotope production 600 TBq/year
- Mo-99 production 6000 TBq/year

The MARIA Research Reactor

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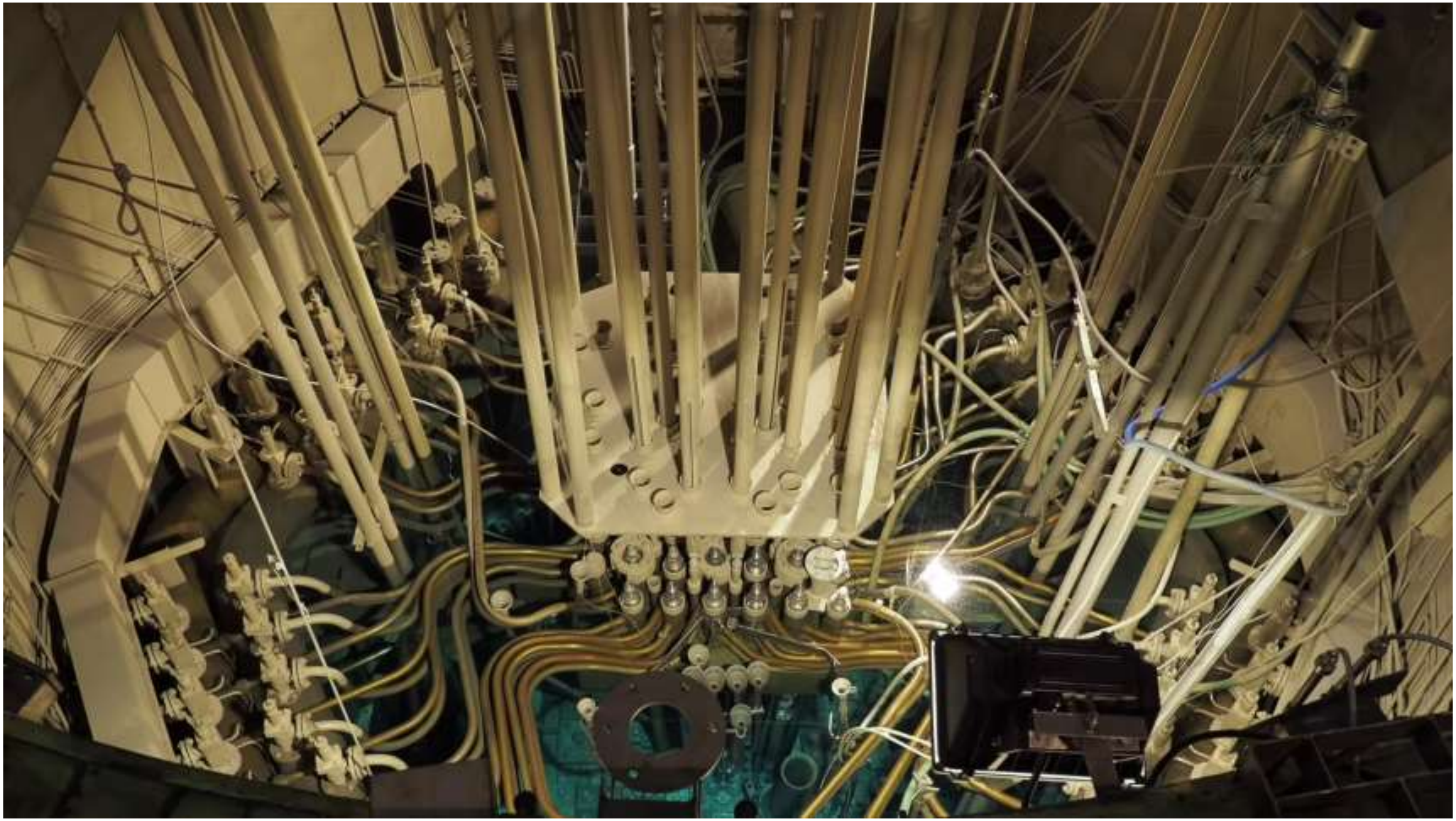

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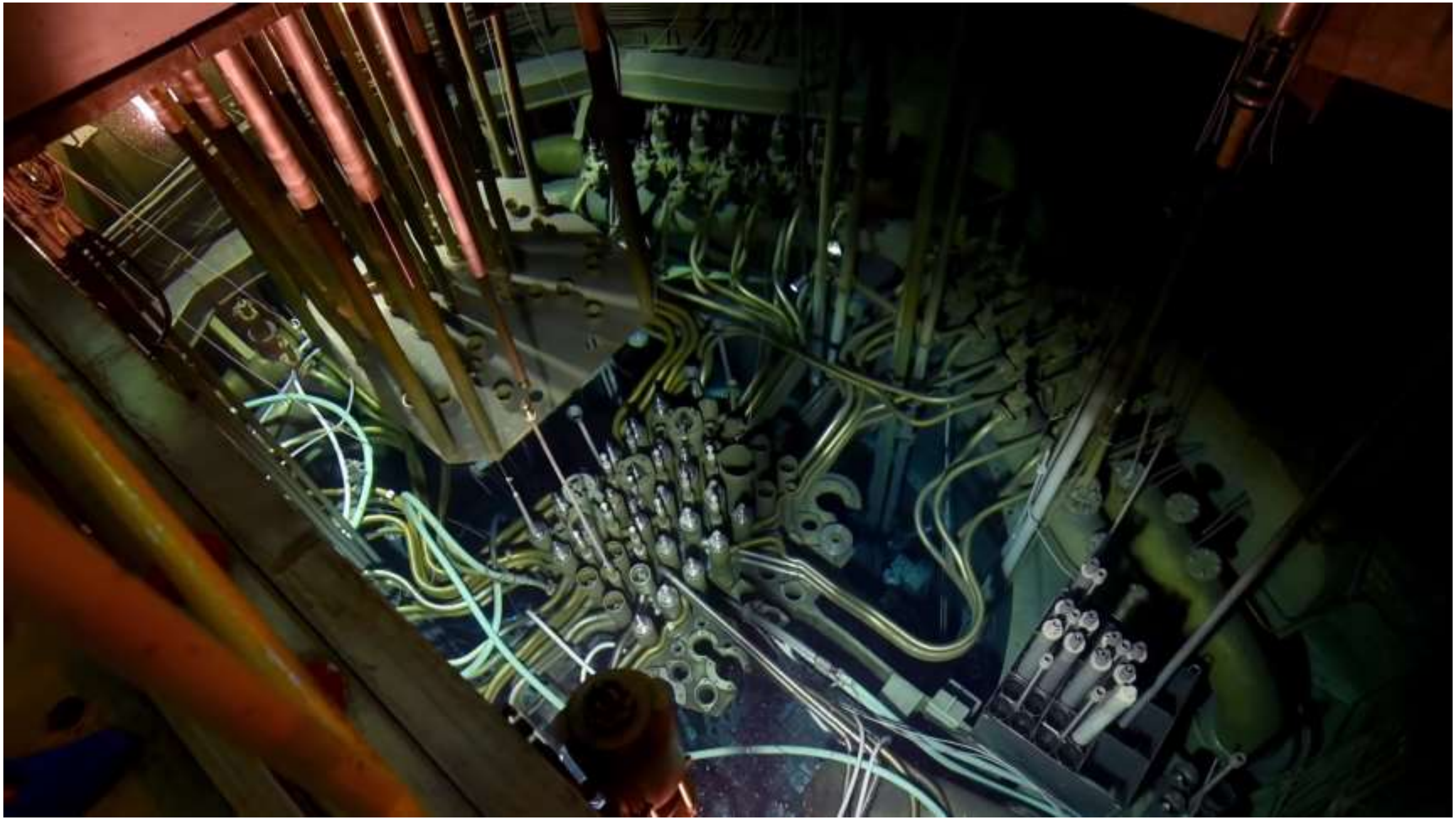

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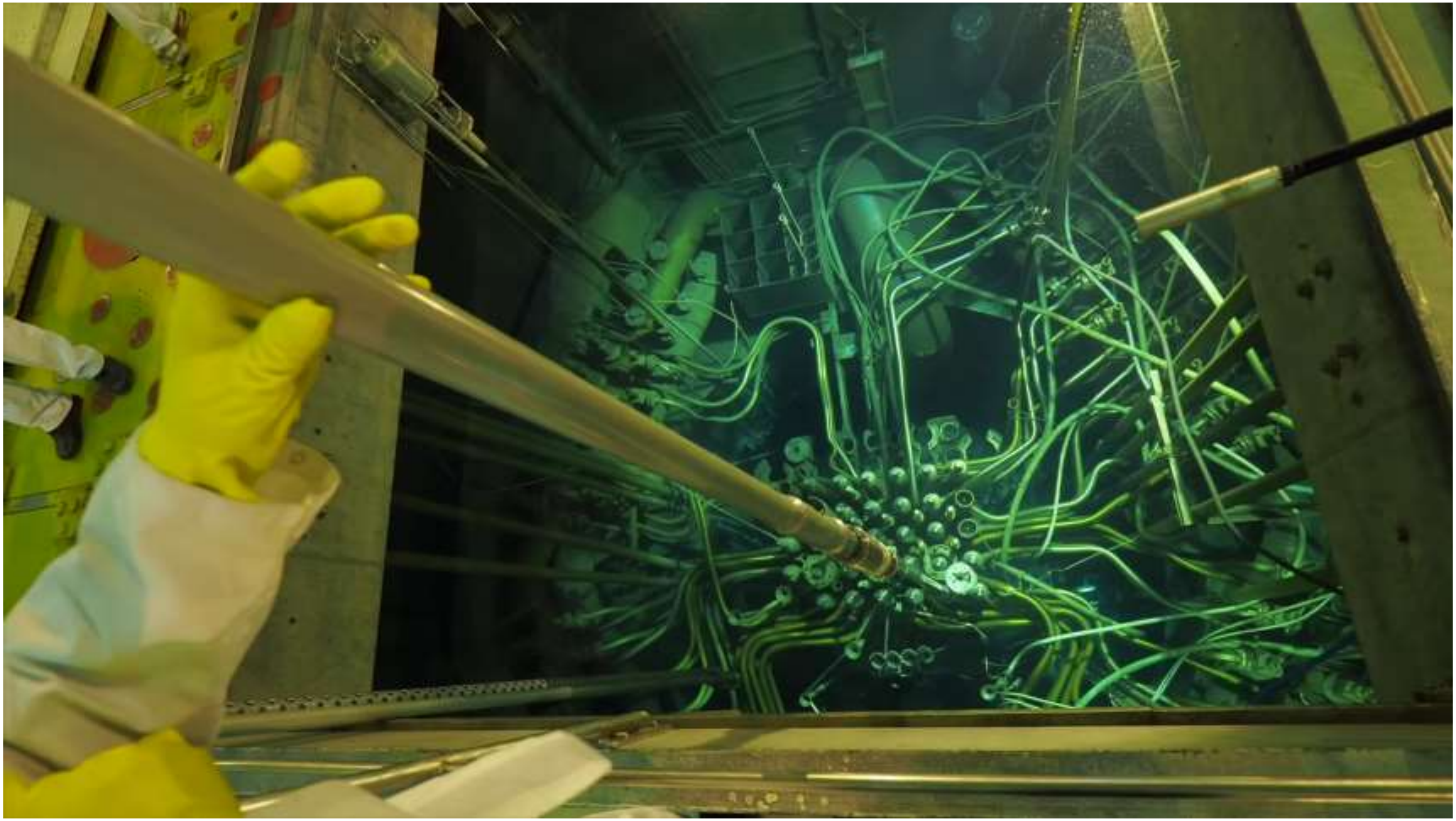

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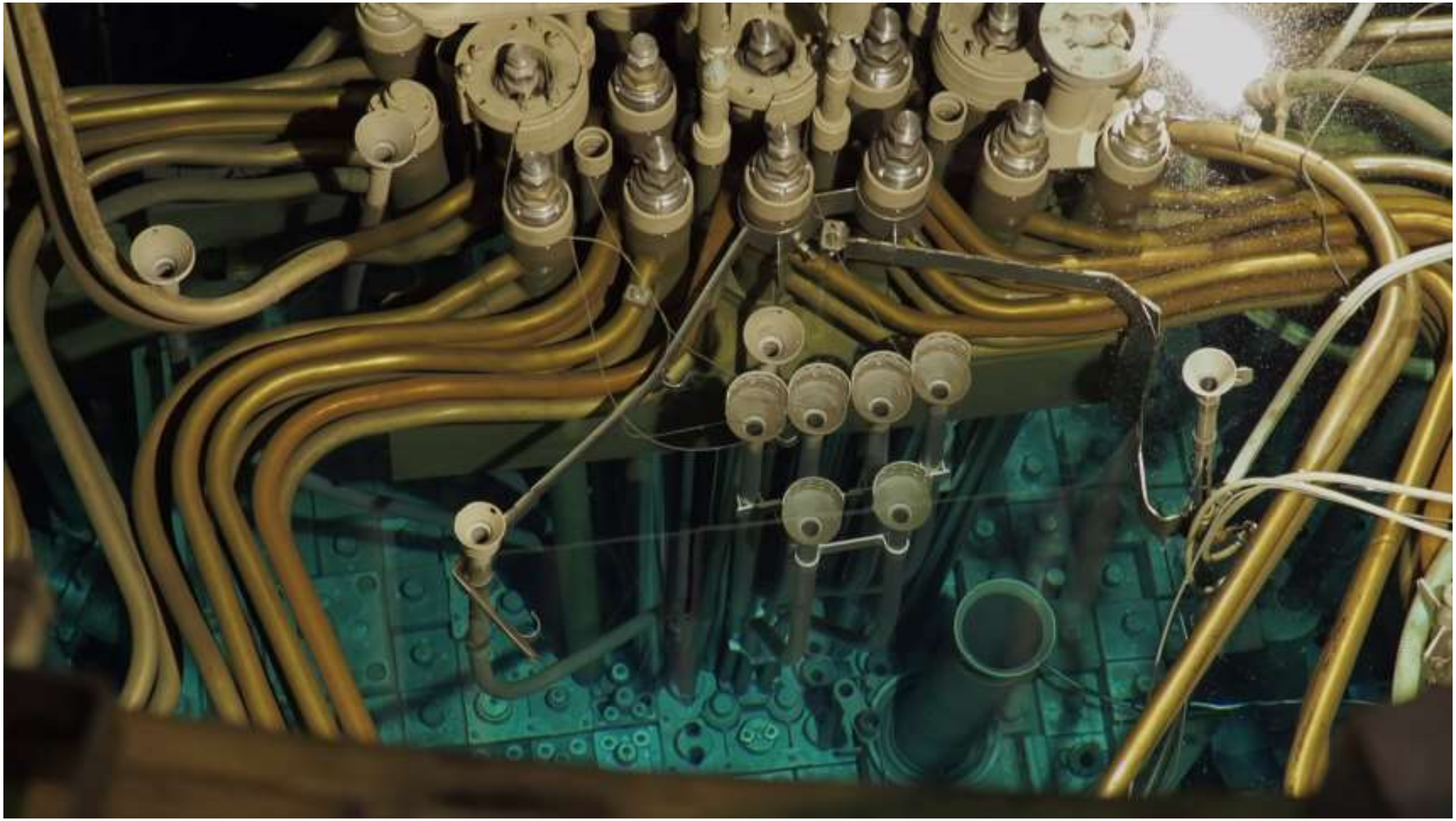

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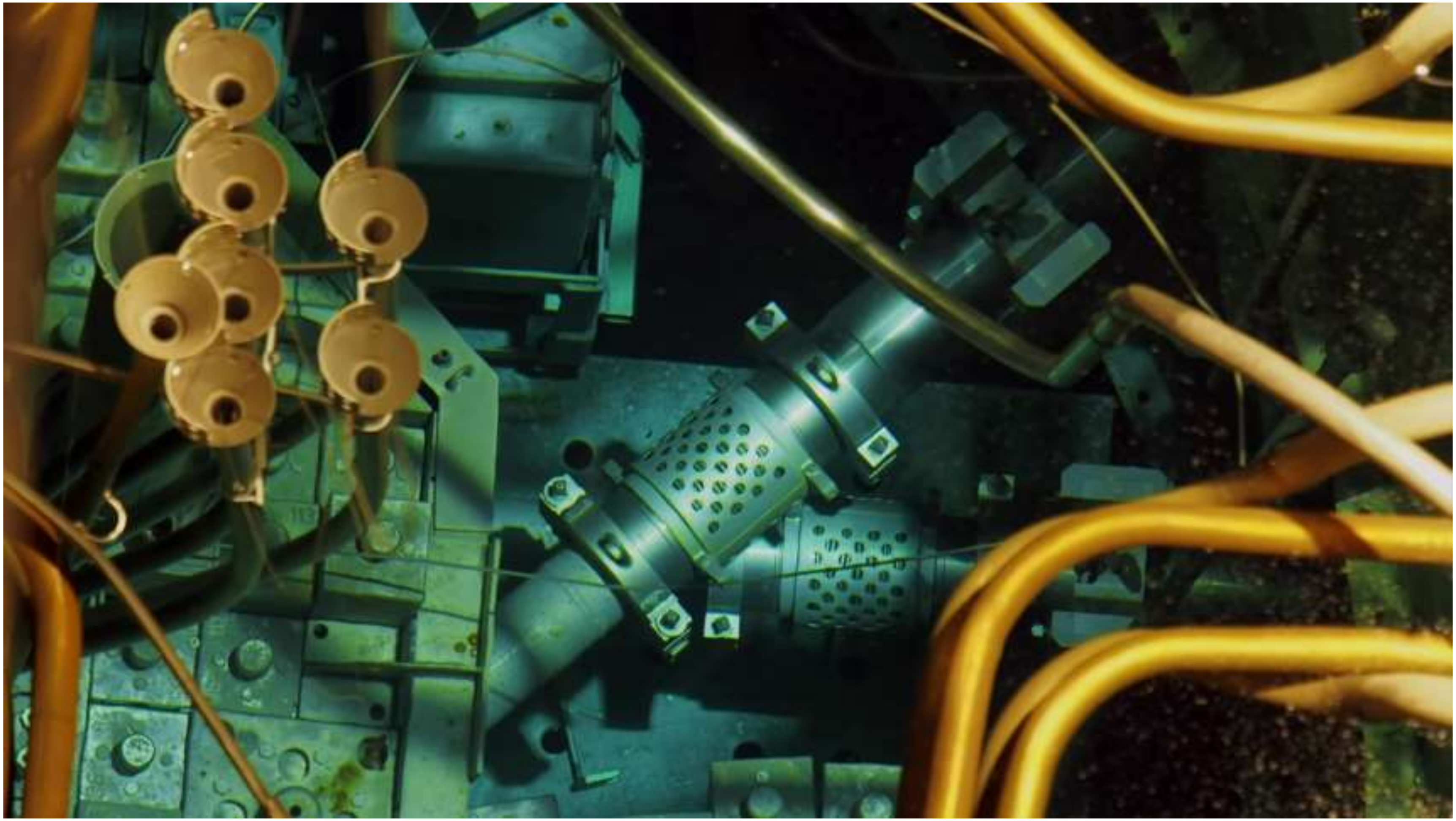

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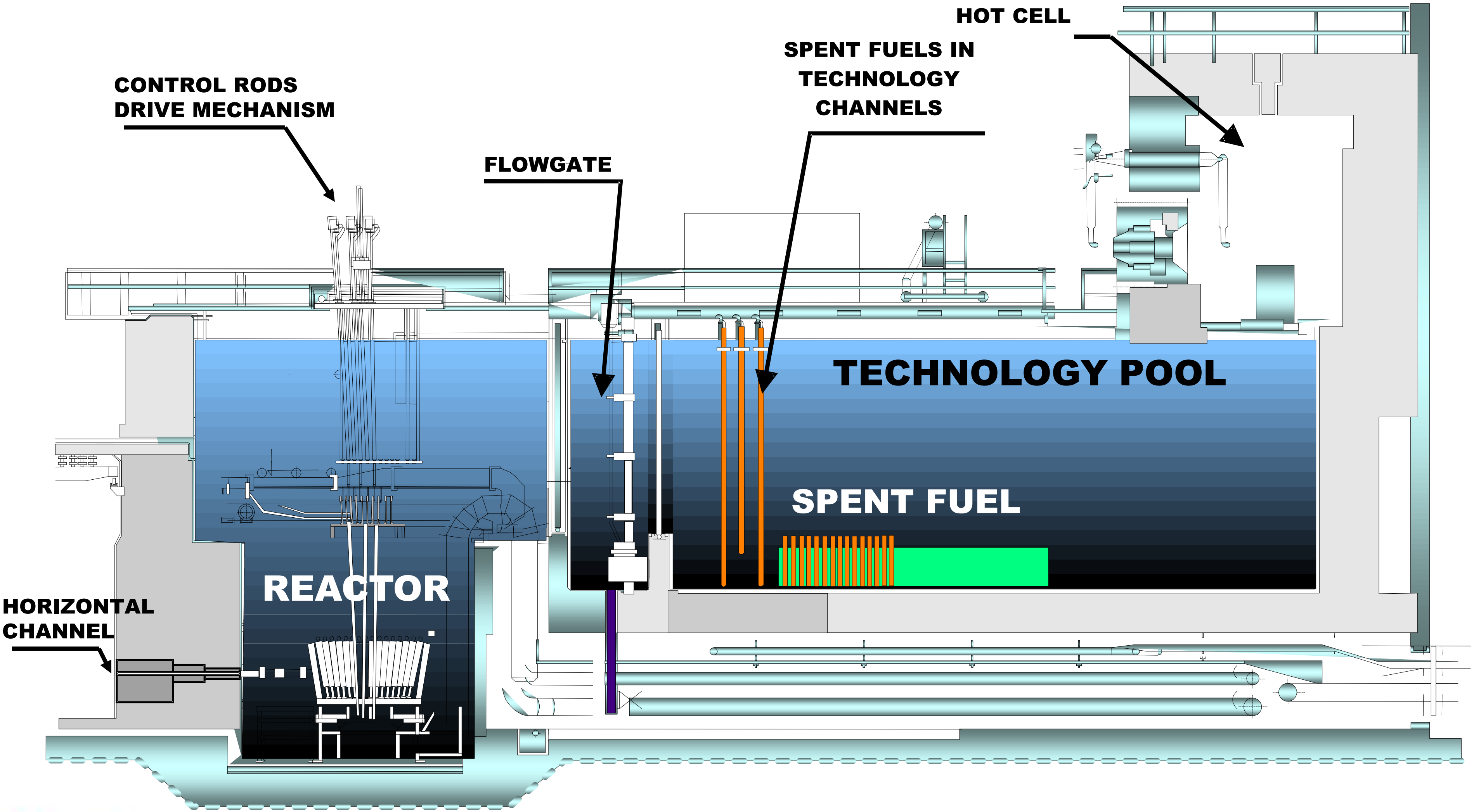

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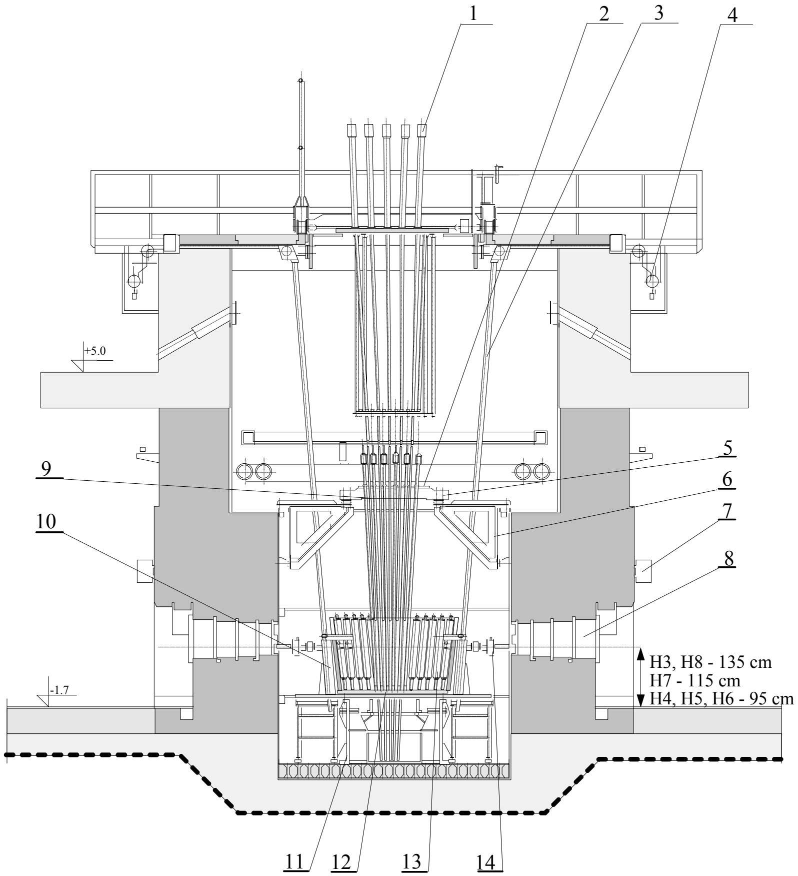
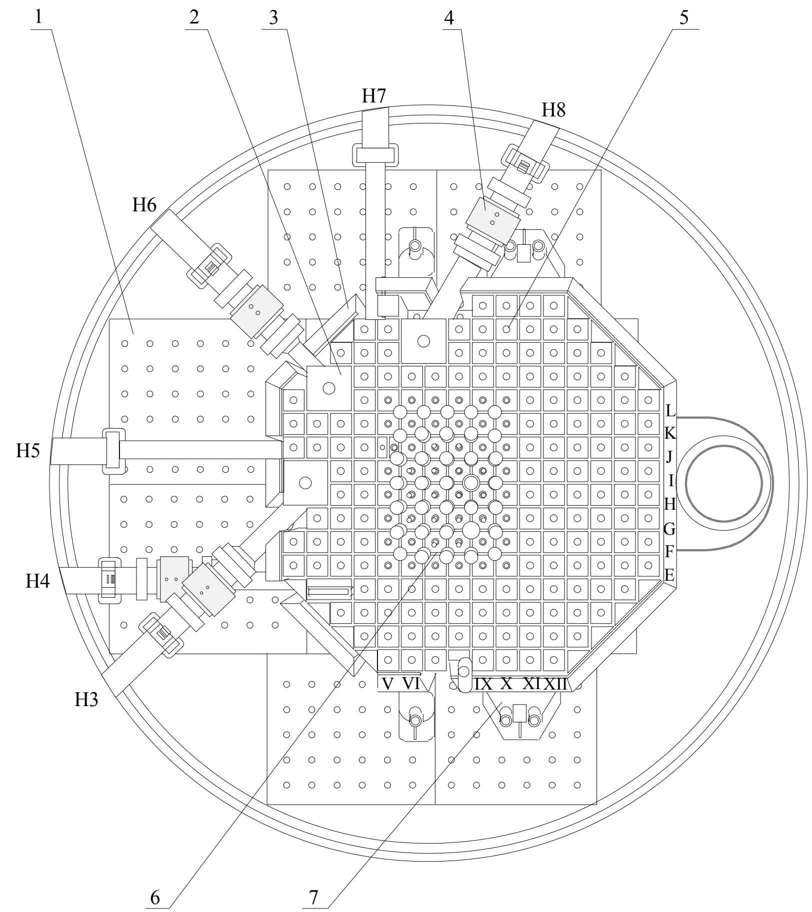


1. control rod drive
2. mounting slab
3. ionisation chamber channel
4. ionisation chamber drive
5. slab supporting structure
6. slab bracket
7. horizontal beam slide damped drive
8. horizontal beam slide damper
9. fuel channel
10. ionization chamber shielding
11. basket basis
12. reflector housing
13. reflector blocks
14. horizontal neutron beam compensator



1. table
2. multiple graphite block
3. housing
4. compensator
5. graphite block
6. beryllium block
7. shielding of ionisation chambers

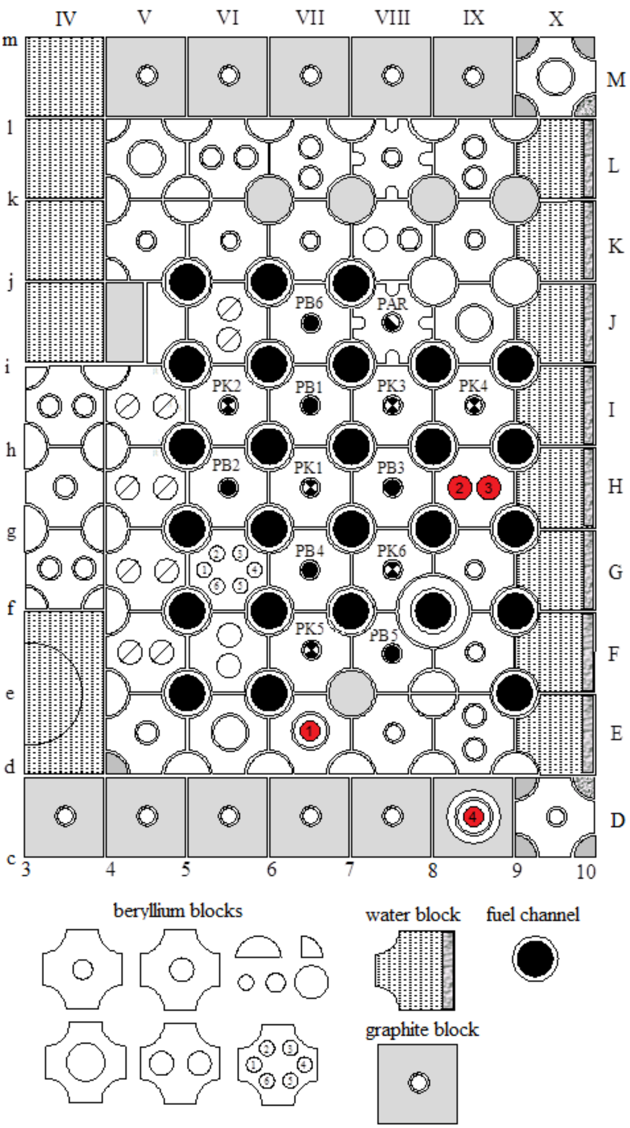
Neutron irradiation

- in-core thermal neutron irradiation channels
  - thermal neutron flux density up to $2 \cdot 10^{14}$ cm^{-2} s^{-1}
  - fast neutron (Watt spc.) flux density up to $3 \cdot 10^{13}$ cm^{-2} s^{-1}
  - containers Ø24 mm
- in-core fast neutron irradiation channels
  - thermal neutron flux reduced down to $3 \cdot 10^{10}$ cm^{-2} s^{-1}
  - fast (Watt) neutron flux density up to $3 \cdot 10^{12}$ cm^{-2} s^{-1}
  - 16 irradiation channels (Ø90 mm); irrd. samples, apparatus

Neutron irradiation

- neutron transmutation doping facility
  - 6” Si crystal ingots
- in-core thermal to 14 MeV neutron converter
  - 14 MeV neutron flux density $1 \cdot 10^{9}$ cm^{-2} s^{-1}
  - thermal neutron flux density up to $1 \cdot 10^{9}$ cm^{-2} s^{-1}
  - fast neutron (Watt spc.) flux density $1 \cdot 10^{12}$ cm^{-2} s^{-1}
  - channel Ø20 mm, container Ø15 mm
- in-fuel irradiation channel, container Ø34 mm

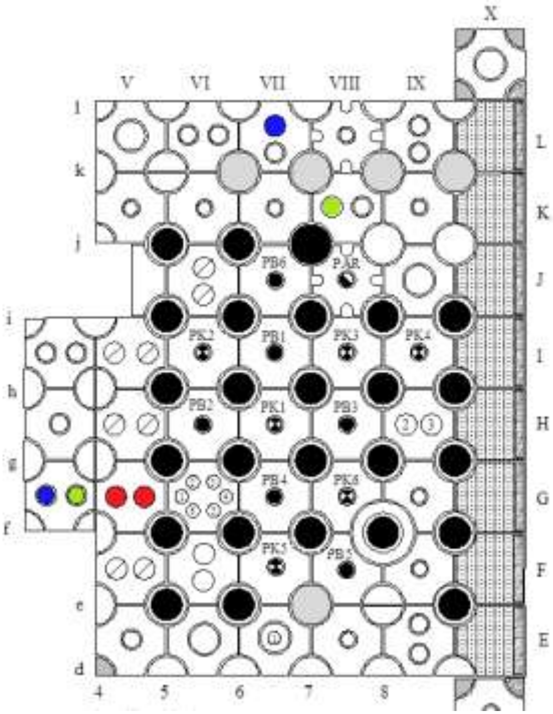
Hydraulic 'rabbit' system

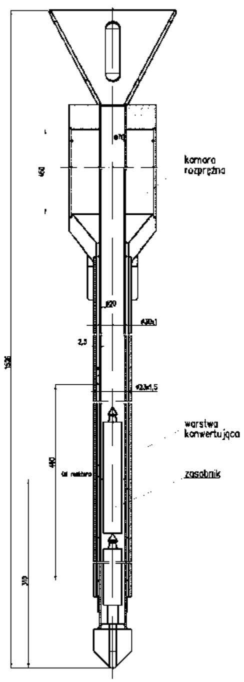


- 4 'rabbit' systems
- precise neutron irradiation
  - **thermal neutron flux density up to 1.8·10^{14} cm^{-2} s^{-1}**
  - fast neutron (Watt spc.) flux density up to 3·10^{13} cm^{-2} s^{-1}
  - containers Ø24 mm
- irradiation time accuracy 1 sec.

Thermal to 14 MeV neutron converter

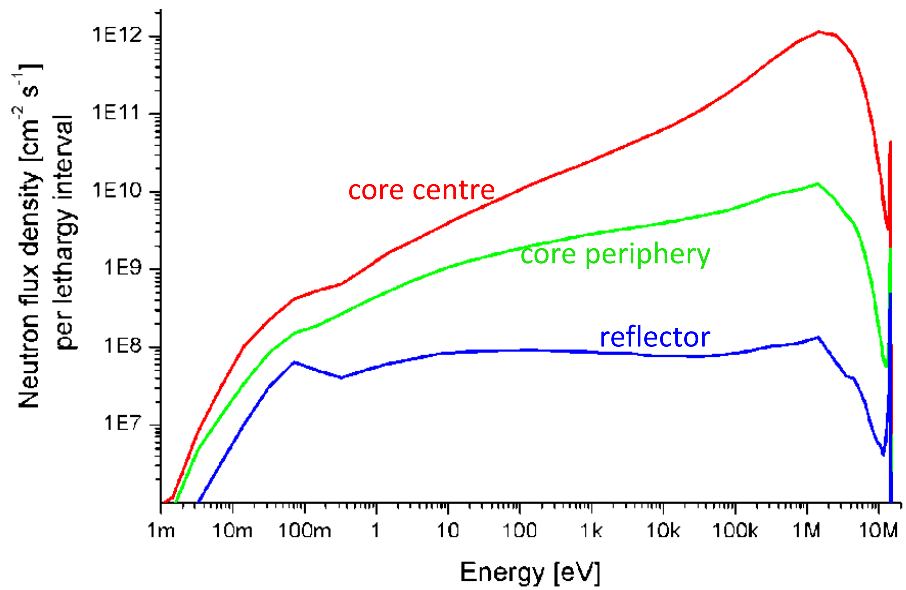
- convert. ^{6}LiD (10g), ^{6}LiOD·D$_2$O (55g)
- outside thermal neutr. $9\cdot10^{13}$ cm^{-2} s^{-1}
- conversion efficiency < 10^{-4}



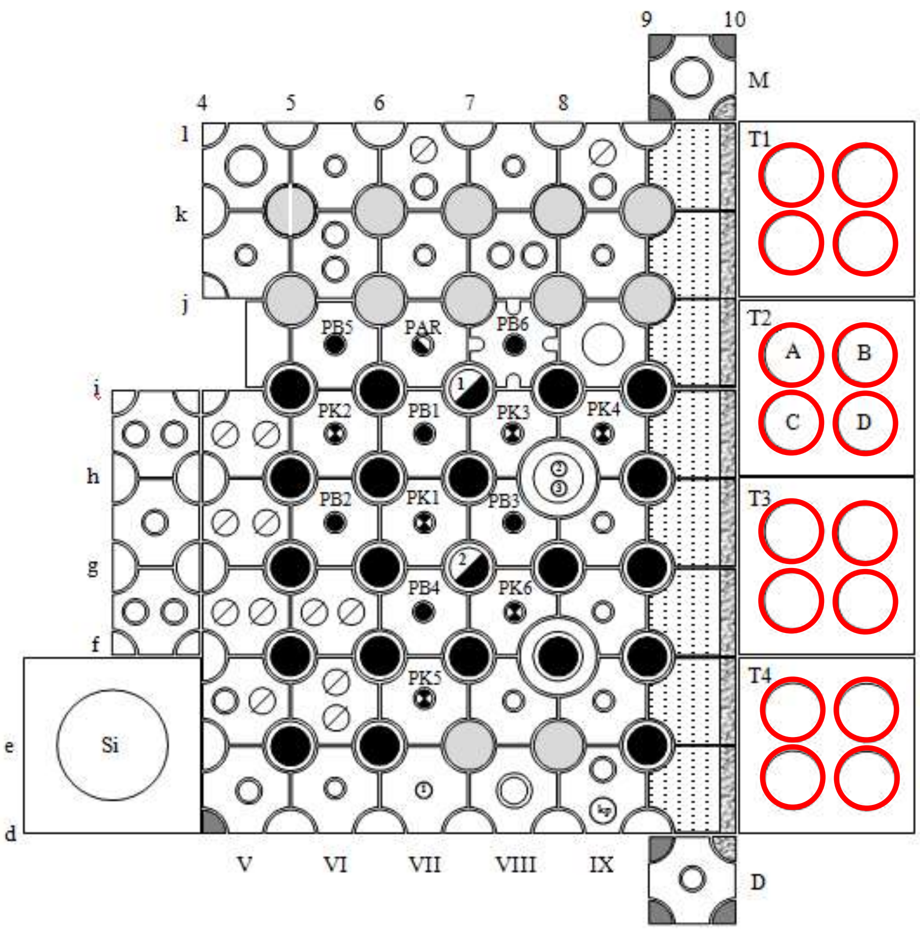


inside converter

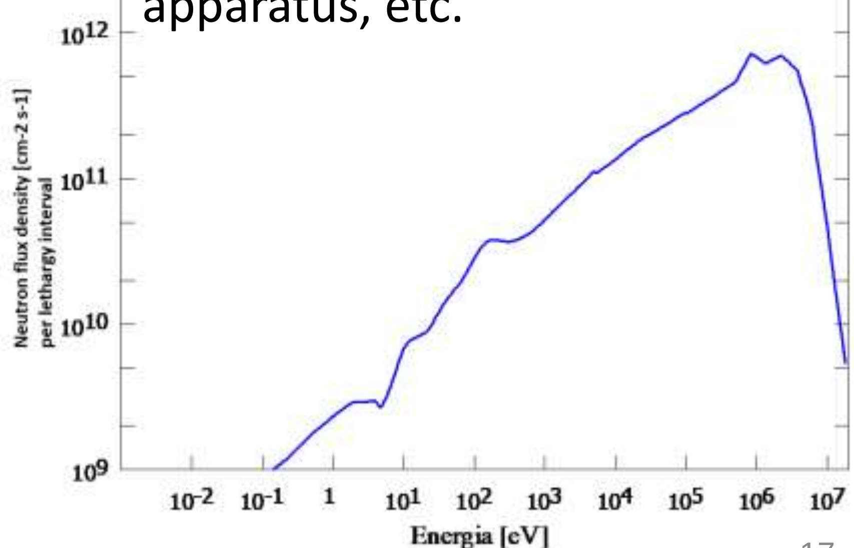
- thermal neutron flux density > $1\cdot10^9$ cm^{-2} s^{-1}
- fast fission neutron flux density > $1\cdot10^{12}$ cm^{-2} s^{-1}
- **14 MeV neutron flux density > $1\cdot10^9$ cm^{-2} s^{-1}**
- channel Ø20 mm



Fast neutron irradiation channels

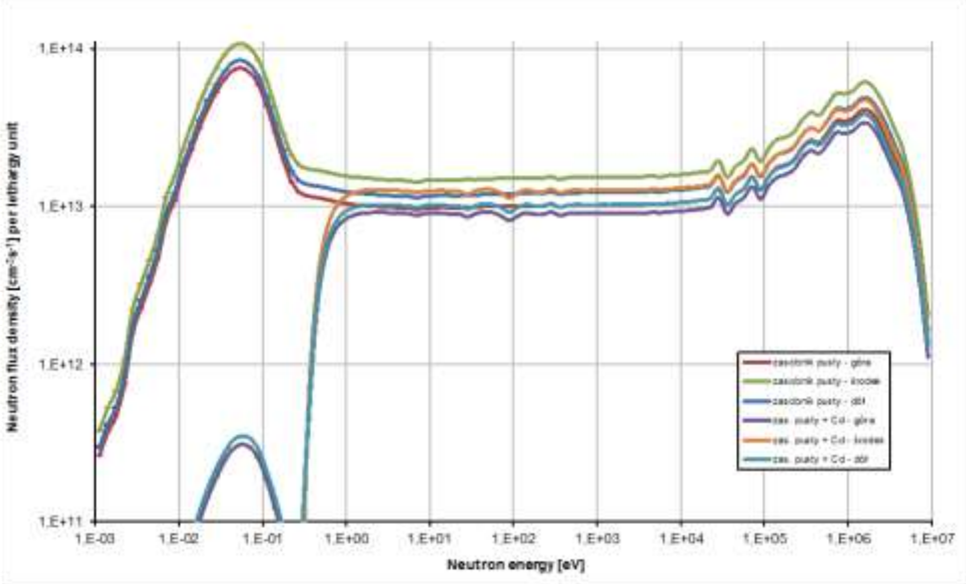


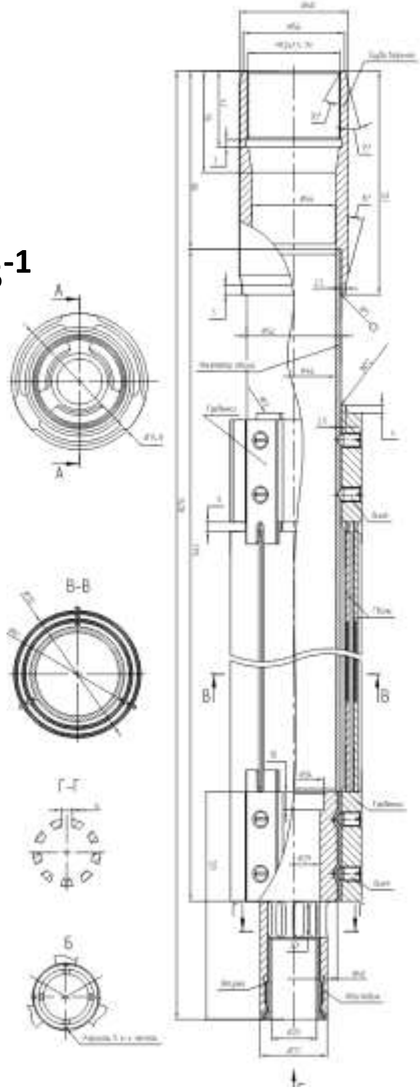
- fast neutron (Watt spc.) flux density **$1 \cdot 10^{11} \div 3 \cdot 10^{12}$ cm^{-2} s^{-1}**
- thermal neutron flux reduced down to $3 \cdot 10^{10}$ cm^{-2} s^{-1}
- irradiation channels 8 x Ø90 mm, 8 x Ø80 mm, h=900 mm
- possible irradiation of large samples, apparatus, etc.



In-fuel irradiation

- fast neutron irradiation inside purpose-build fuel element (*2019*)
  - **fast neutron (Watt spc.) flux density ca. $1\cdot10^{14}$ cm^{-2} s^{-1}**
  - thermal neutron flux density $3\cdot10^{12} \div 2\cdot10^{14}$ cm^{-2} s^{-1}
  - container Ø34 mm





Neutron activation analysis

Investigation of chemical composition

- irradiation of samples in known neutron field
- induced activity measurement
- identify neutron reaction
- reconstruct chemical composition

Available

- various neutron irradiation facilities
- gamma-ray spectrometry
- radiochemical laboratory

Solid-state neutron transmutation

Silicon neutron transmutation doping

- thermal neutron irradiation

$$^{30}_{14}\mathrm{Si} + ^{1}_{0}\mathrm{n} \rightarrow ^{31}_{14}\mathrm{Si} \xrightarrow{\beta^-} ^{31}_{15}\mathrm{P}$$

High-temperature semiconductor modification

- $YBa_2Cu_3O_{7-x}$ fast neutron irradiation

Material science investigation

- fast & thermal neutron irradiation

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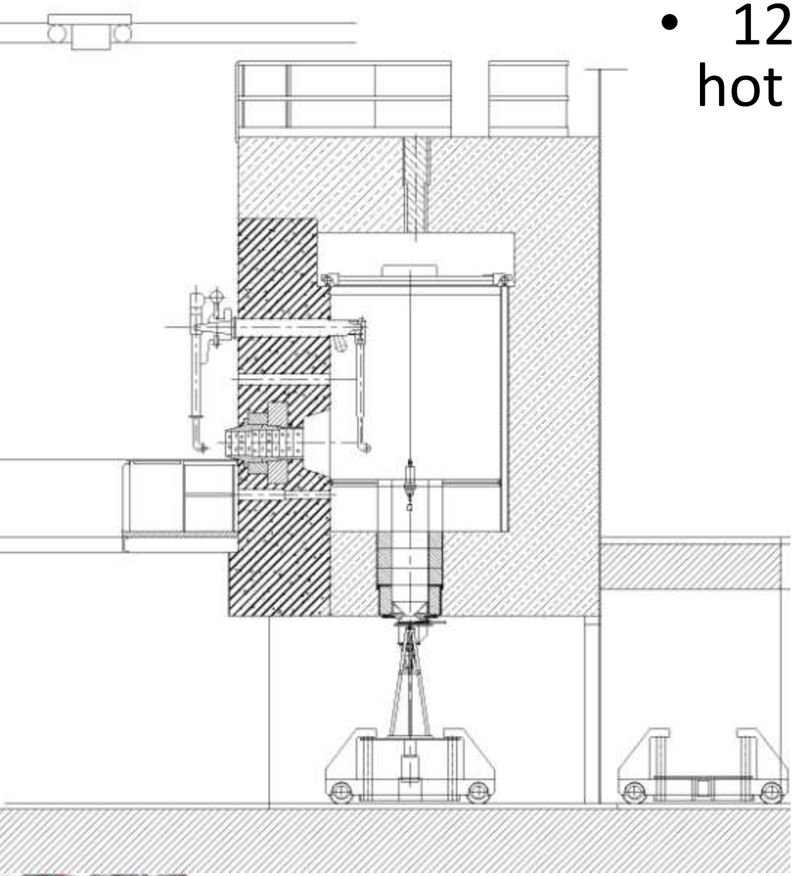
Post-irradiation examination

- 3 reactor hot cells (10^{12}÷10^{15} Bq) with instrumentation
- 12 NCBJ Material Research Laboratory hot cells (10^{12} Bq) with instrumentation
- transport system of radioactive materials form reactor



Gamma-ray irradiation

- Spent nuclear fuel storage pool
- High gamma dose rate ~**1 kGy/h**
- Long period irradiation possible

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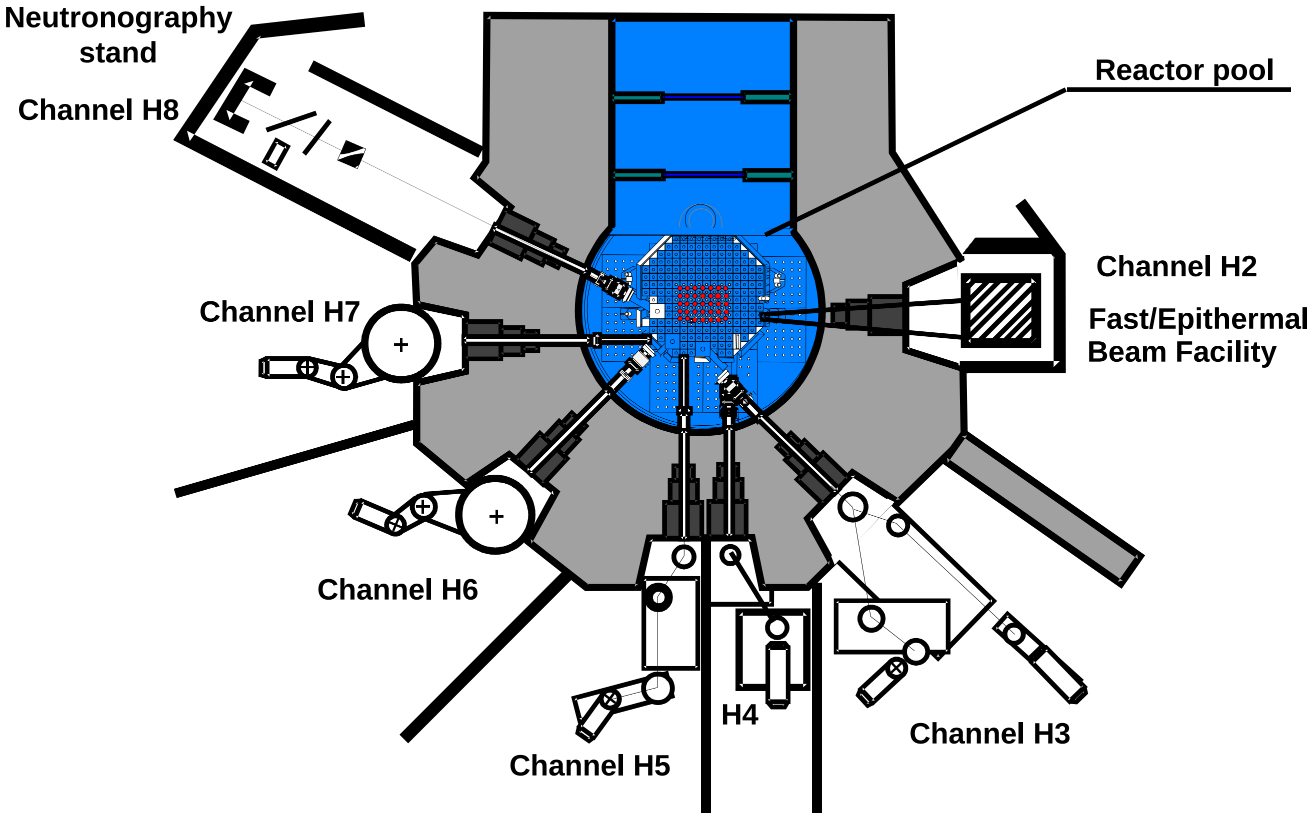
Reactor horizontal channels



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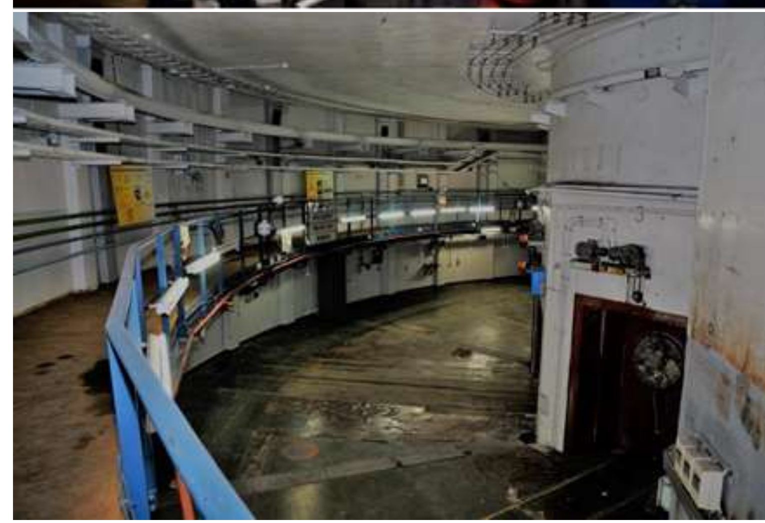
Reactor horizontal channels

Collaboration between NCBJ
and Helmholtz-Zentrum Berlin

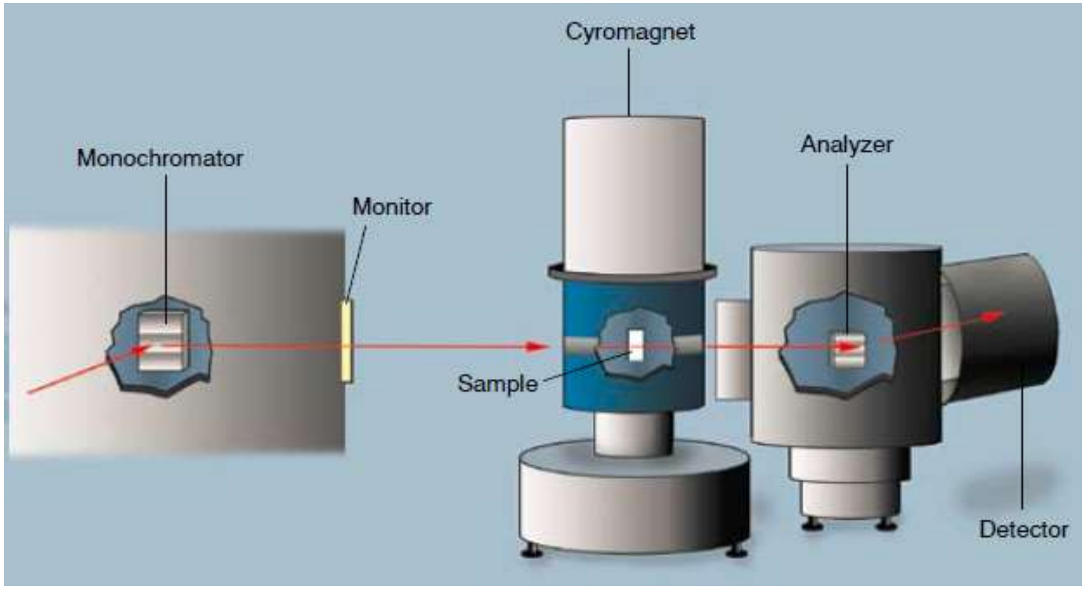
- E1 Triple-Axis Spectrometer with Polarization Analysis
- E4 Two-Axis Diffractometer
- E5 Four-Circle Diffractometer
- E6 Focusing Diffractometer



E1 | Triple-Axis Spectrometer with Polarization Analysis

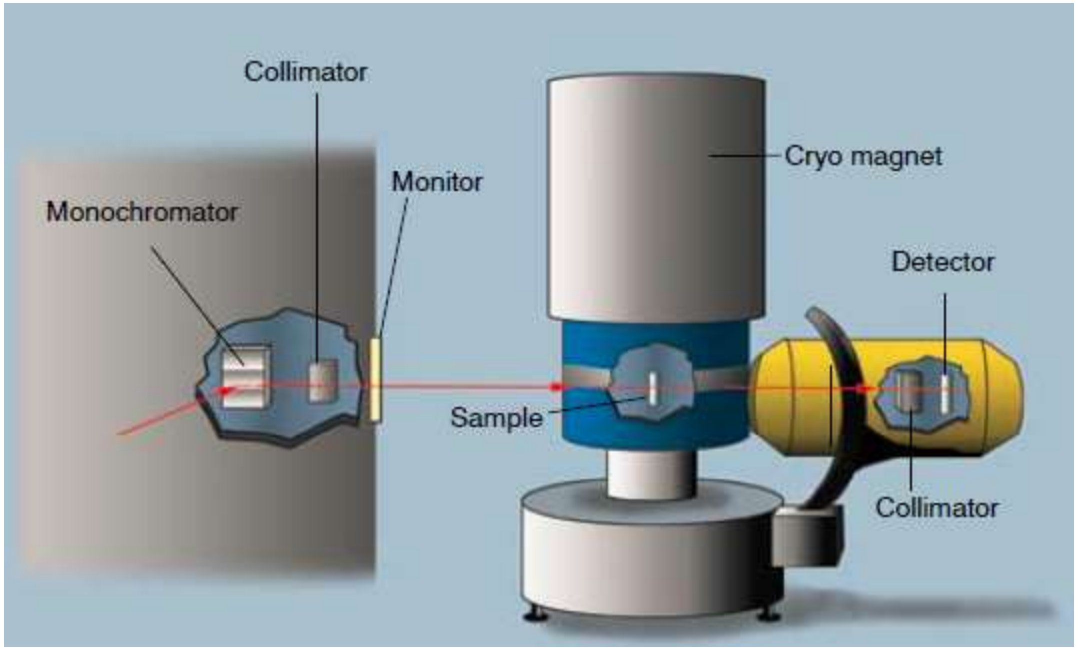
The spectrometer with polarization analysis was designed to separate the magnetic scattering unambiguously from non-magnetic scattering processes, which is particularly useful for:

- distinguishing between spin waves and phonons, when both excitations have similar energies;
- analysing the paramagnetic scattering in q,w-space;
- determining spin densities.



E4 | Two-Axis Diffractometer

- magnetic structure determination
- study of magnetic and structural phase transitions
- determination of magnetic phase diagrams
- study of critical points as a function of magnetic field and temperature
- measurement of correlation functions above demand temperature



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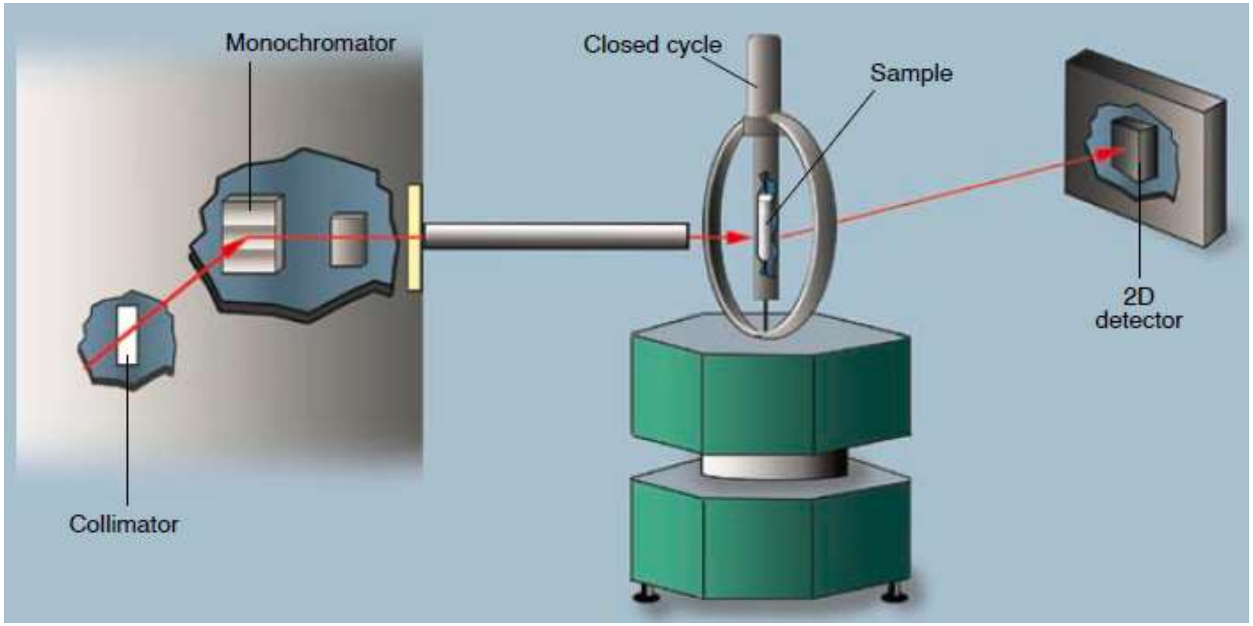
E5 | Four-Circle Diffractometer

The instrument is commonly used for standard crystallographic work, especially for the determination of the positional and thermal parameters of hydrogen atoms in crystal structures of molecular, ionic or intermetallic systems.
The dynamic orientational disorder and the long-range order of NH4 -ions in ammonium halides has been investigated (Paasch, M. et al., Z. Physik B 99, 1996, 339), as well as the mechanism of proton conductors (Melzer, R. et al., Sol. State Ionics 92, 1996, 119), the hydrogen bond system and the hydrogen atom disordering in mixed-anion salts (Troyanov, S.I.et al., Z. Kristallogr. 218,2003, 470).



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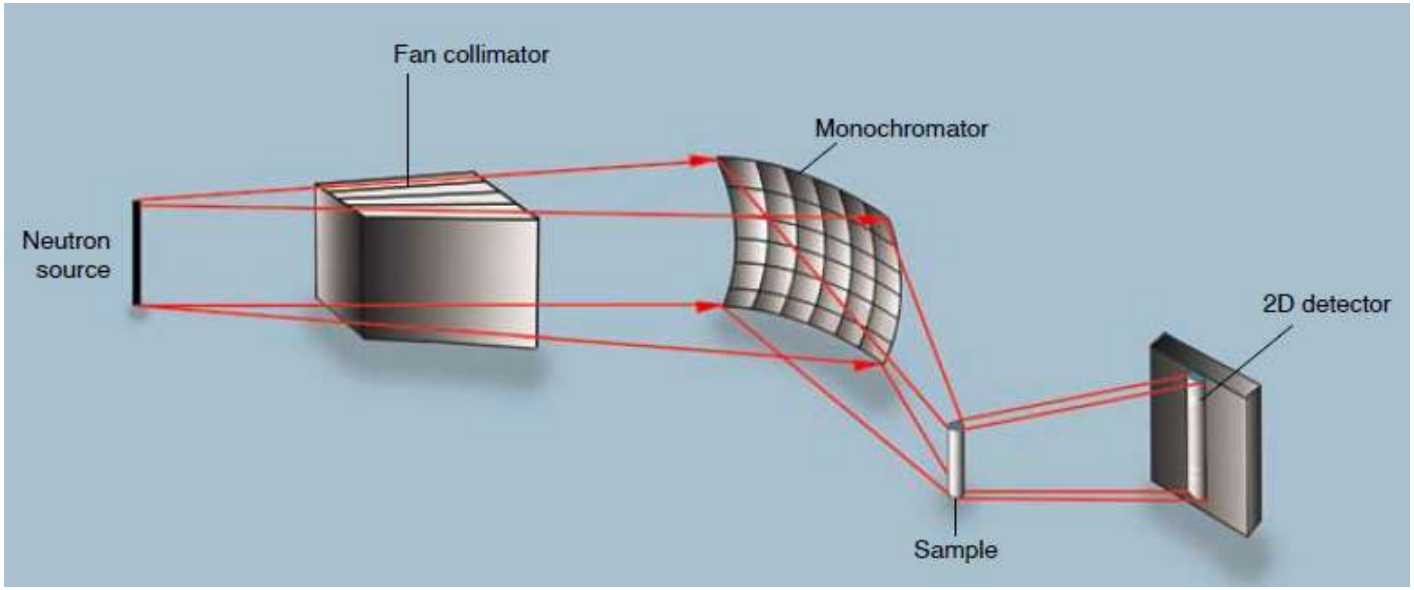
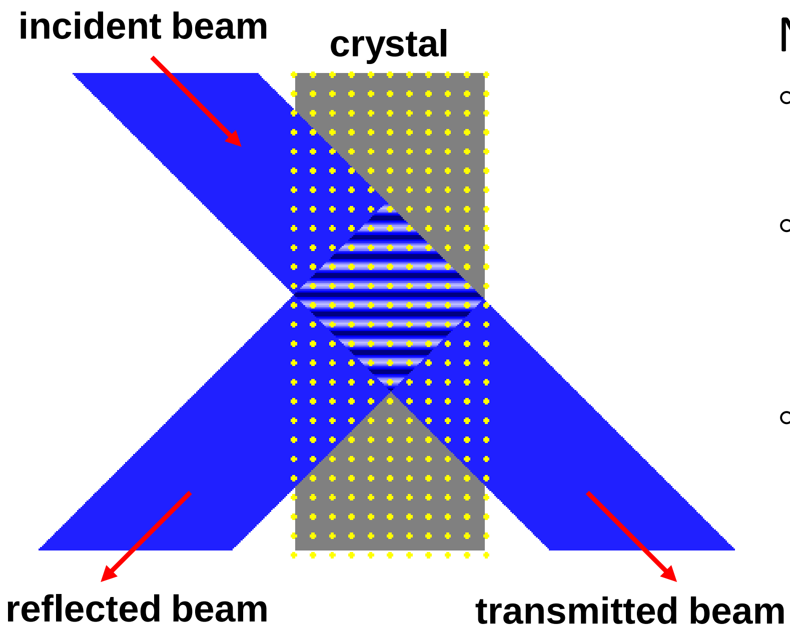
E6 | Focusing Diffractometer

- measurements of critical scattering close to a phase transition
- separation of diffuse scattering from Bragg reflections
- measurement of Bragg reflections of powder samples and single crystals



Horizontal neutron beams

- Investigation of nuclear structure and reaction models
  - verification of neutron cross-sections
- Investigation of neutron ‚quantum nature'

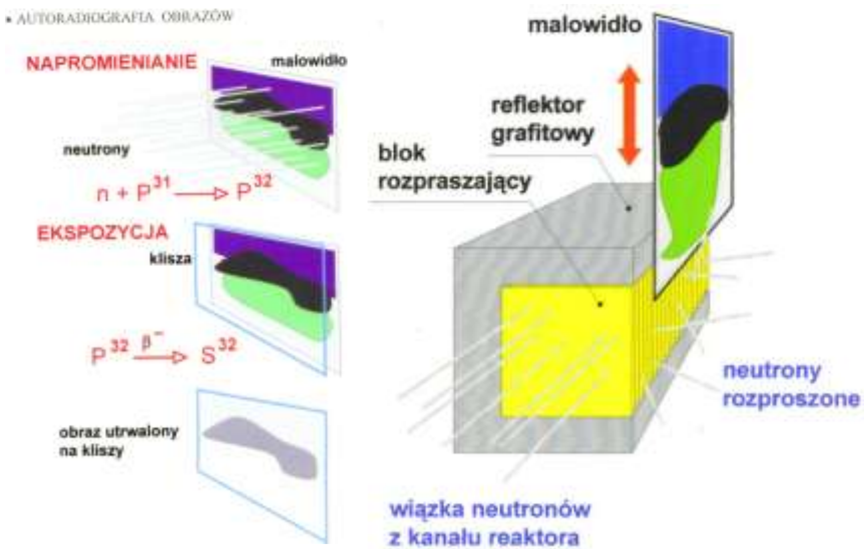


Neutron Bragg scattering on perfect crystal

- inside a crystal arise non-trivial neutron interference distribution $|\psi(\mathbf{r},t)|^2 \neq \text{const.}$
- nuclear force range (~10^{-15} m) few orders of magnitude lower than thermal neutron de Broglie wavelength (~10^{-10} m)
- neutron radiative capture by crystal nuclei and measuring of subsequent gamma-rays as a method of detection of fluctuation of probability density function $|\psi(\mathbf{r},t)|^2$

Horizontal neutron beams

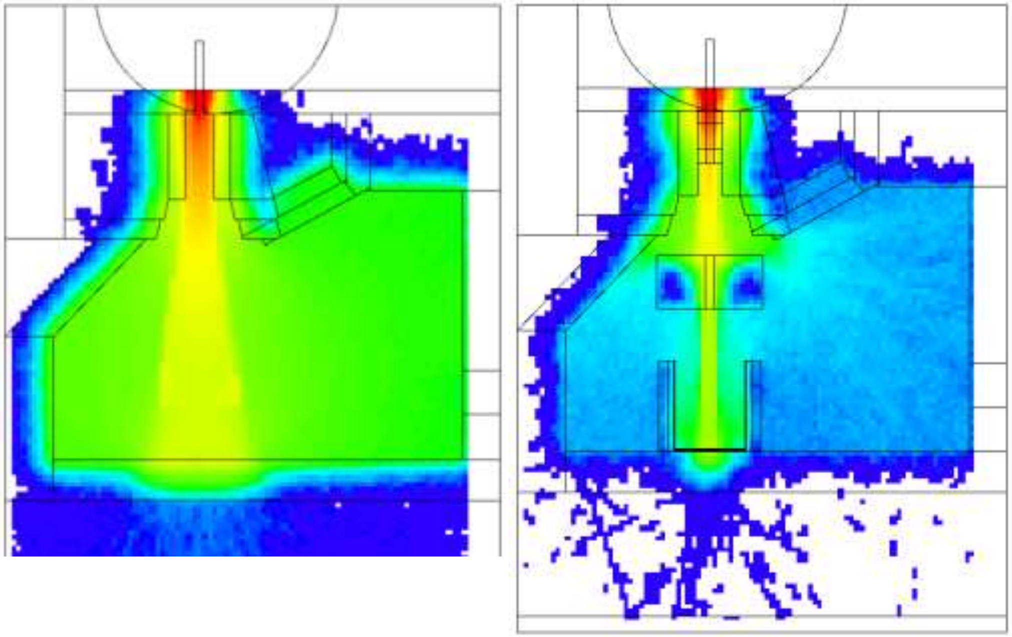
- Neutronography
- Autoradiography
  - painting investigation



Horizontal neutron beams

Shielding materials testing

- concrete composition
- concrete production for long-term utilization
- neutron and gamma attenuation



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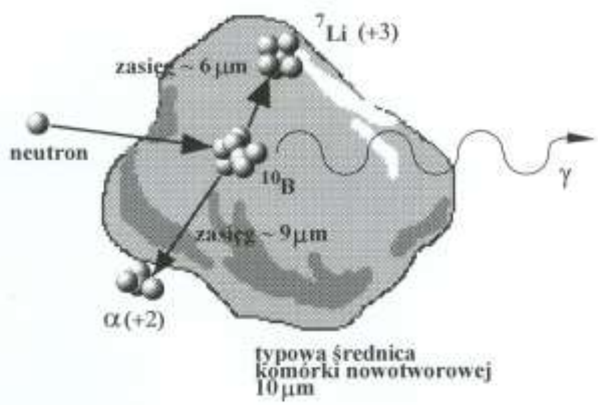
Horizontal neutron beams

- High-intensity **fast** or **epithermal neutron beam** ~10^9 $cm^{-2}s^{-1}$
- Boron neutron capture **bio-medical research**

$$^{10}_{5}\mathrm{B} + ^{1}_{0}\mathrm{n} \rightarrow ^{7}_{3}\mathrm{Li} + ^{4}_{2}\alpha + \gamma(0.48\ \mathrm{MeV}) + 2.31\ \mathrm{MeV}$$



Nuclear astrophysics

r-process

- $10^9 \div 10^{10}$ K (k*T*≈0.1÷1.0 MeV), neutron density >10^{20} cm^{-3}

s-process

- ca. $3.5 \cdot 10^8$ K (k*T*≈30 keV), neutron density $10^7 \div 10^{10}$ cm^{-3}

MARIA reactor

- 320 K (k*T*≈25 meV), neutron density 10^9 cm^{-3}
- 1 eV÷100 keV, neutron density 10^5 cm^{-3}
- 0.1÷3 MeV, neutron density 10^4 cm^{-3}

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Nuclear astrophysics

MARIA reactor

- 320 K (kT≈25 meV), neutron density 10^9 cm^{-3}
- 1 eV÷100 keV, neutron density 10^5 cm^{-3}
- 0.1÷3 MeV, neutron density 10^4 cm^{-3}

Verification of neutron reaction cross-sections
in astrophysical processes

- existing vertical irradiation channels
- possibility of in-core loop installation for minute half-lives

DOI: 10.1051/epjconf/201714601003

Current research on ^{186}Re(n,γ)^{186}Re/^{186m}Re cross section and its impact on ^{187}Re-^{187}Os cosmochronometer

Reactor antineutrinos

Reactor as a very strong antineutrino source

- beta decay of fission products

$$n \rightarrow p + e + \bar{\nu}_e$$

- yield ~$5 \cdot 10^{18}$ s^{-1}
- exceed solar neutrinos in ca. 25 m dist. from reactor core
- minimal distance outside reactor shielding ~5 m
- Neutrino oscillation investigation possible

arXiv:1702.00941v2 arXiv:1811.05694v1 Nucl Instr Meth A845 2017 467

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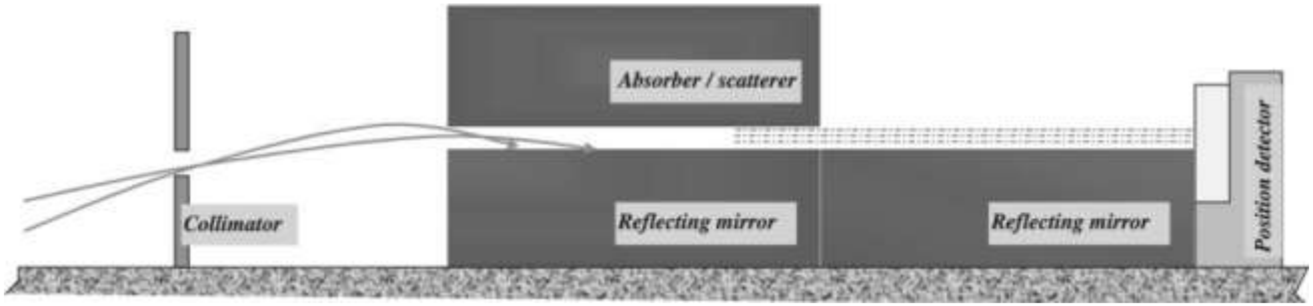
Other possible research infrastructure

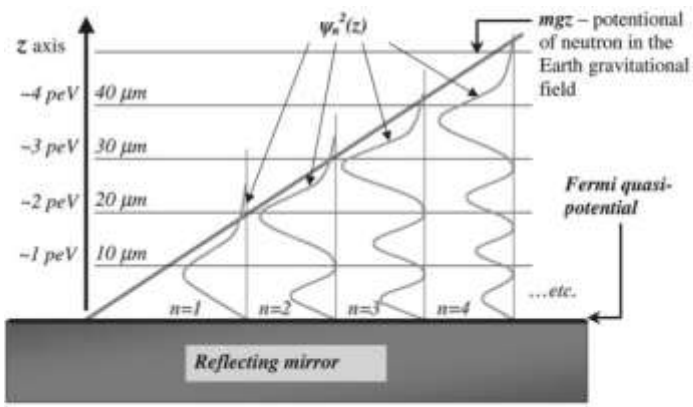
Reactor as a very strong neutron source

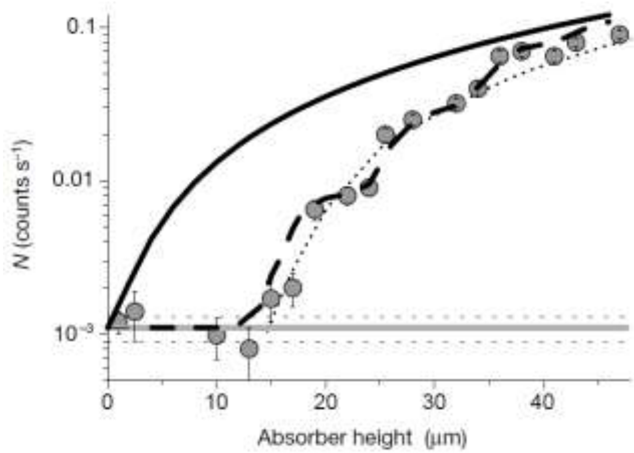
- Neutron induced positron source (guided outside facility)
- Cold neutron source (long distance guide, no gamma-ray)
  - fast neutrons E > 0.5 MeV
  - intermediate-energy neutrons 1 keV < E < 500 keV
  - resonance-energy neutrons 1 eV < E < 1000 eV
  - thermal-energy neutrons 20 meV < E < 100 meV
  - cold neutrons 0.05 meV < E < 20 meV
  - very cold neutrons 0.3 µeV < E < 50 µeV
  - **ultra cold neutrons E < 300 neV**

Cold and ultra-cold neutrons

Measurements of neutron quantum states
in Earth's gravitational potential





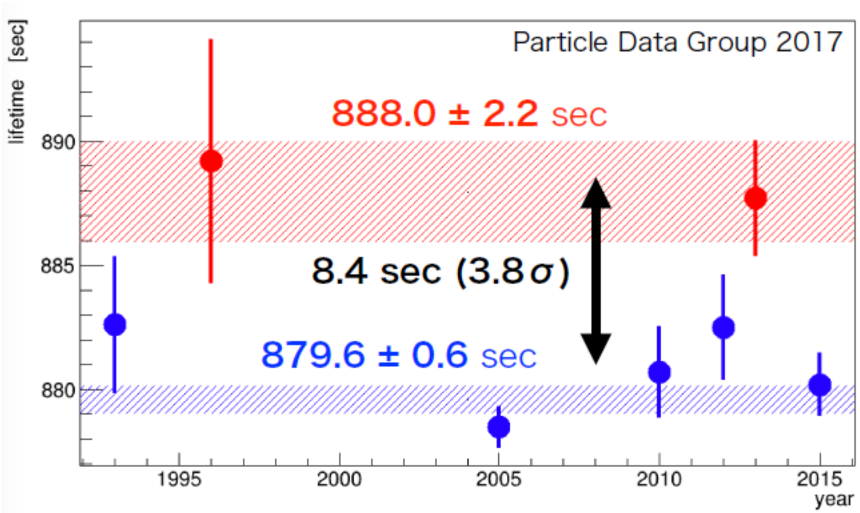


Nucl Instr Meth A 440 (2000) 754 Phys Rev D67 (2003) 102002 Nature 415.297.2002

Cold and ultra-cold neutrons

Neutron lifetime measurements $n \rightarrow p + e + \bar{\nu}_e$

- (thermal) neutron beam approach
- cold neutron bottle approach (magneto-gravitational trap)



in-flight method

inject neutrons into detector and detect protons from β decay

UCN storage method

store ultra-cold neutrons and count the remaining neutrons

Cold and ultra-cold neutrons

- significant discrepancies in neutron lifetime measurements by means of two methods
  - impact on primordial nucleosynthesis Phys Rev D71(2005)021302
  - Dark Matter decay interpretation
    B.Fornal Phys Rev Let 120 (2018) 191801, M.Pfützner Phys Rev C97 (2018) 042501
- low-range gravitational force investigation
  - Dark Energy – scalar field; potential depends on local mass density
    Phys Rev Lett 112 (2014) 151105, Phys Lett B743 (2015) 310
- neutron electric dipole moment investigation
  - CP symmetry violation   Phys Rev D92 (2015) 092003
- neutron-antineutron oscillations investigation Phys Rep 612 (2016) 1
  - Baryogenesis, B-violation, beyond Standard Model

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