Neutron Sources:
Neutron Production and Facilities

XIII School of Neutron Scattering (SoNS)

International School of Neutron Science and Instrumentation

Erice, Sicily, 28 July-4 August 2015

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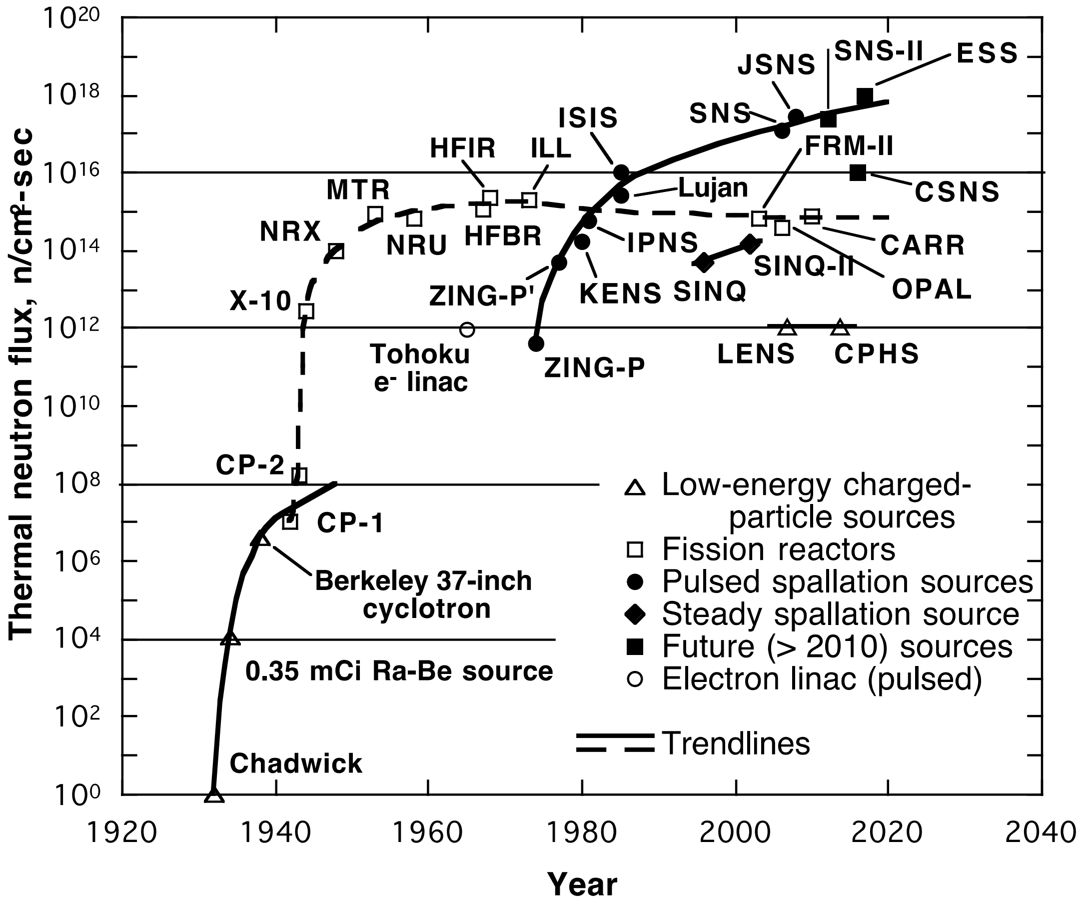
Oak Ridge National Laboratory

Neutrons and Neutron Sources

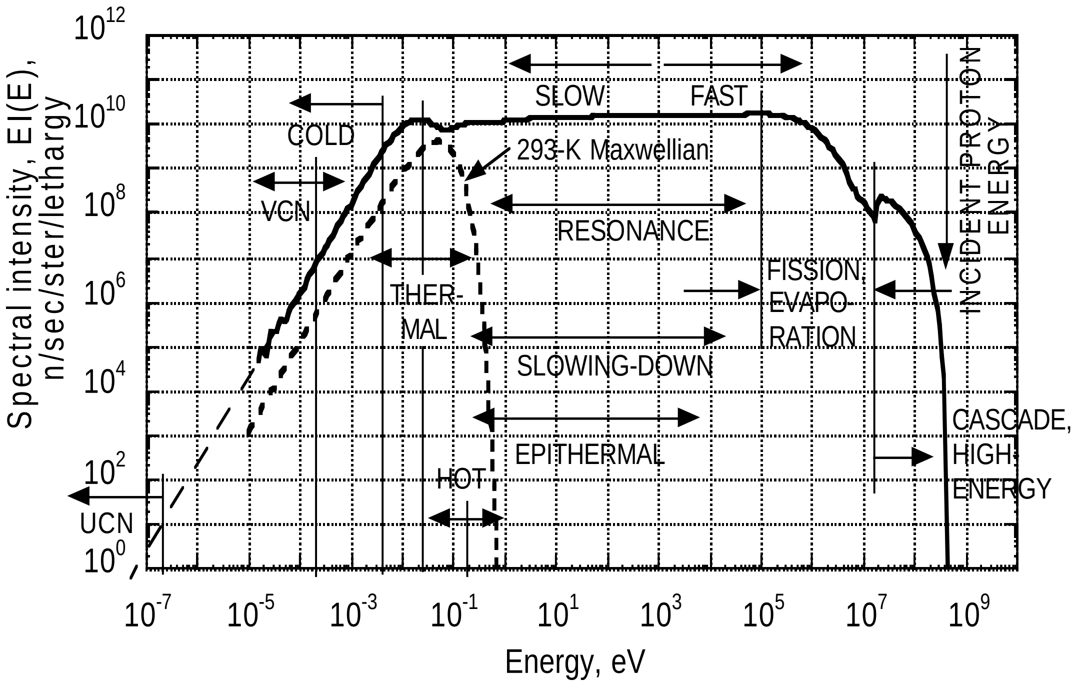
The possibility of using the scattering of neutrons as a probe of materials developed after 1945 with the availability of copious quantities of slow neutrons from reactors. Fermi and Zinn's group at Argonne's CP-3 reactor used Bragg scattering to measure nuclear cross-sections and develop diffraction methods. Wollan, Shull, and others worked in parallel at the Oak Ridge Graphite reactor.

Neutron Science Facilities

Brugger plot

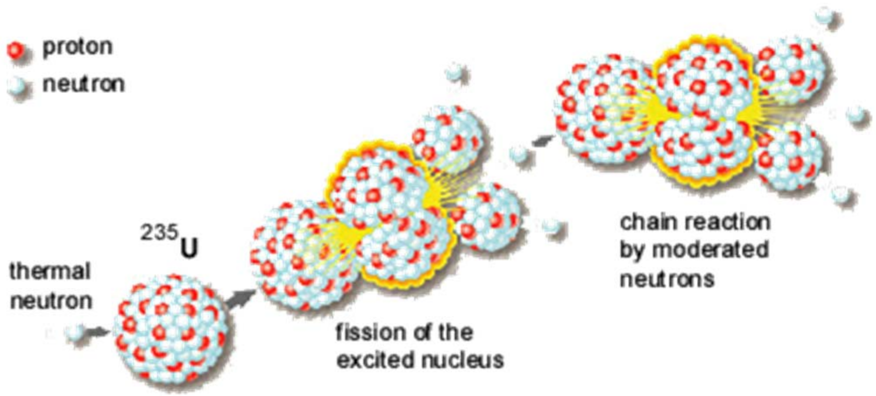


Fast and Slow Neutrons, Nomenclature



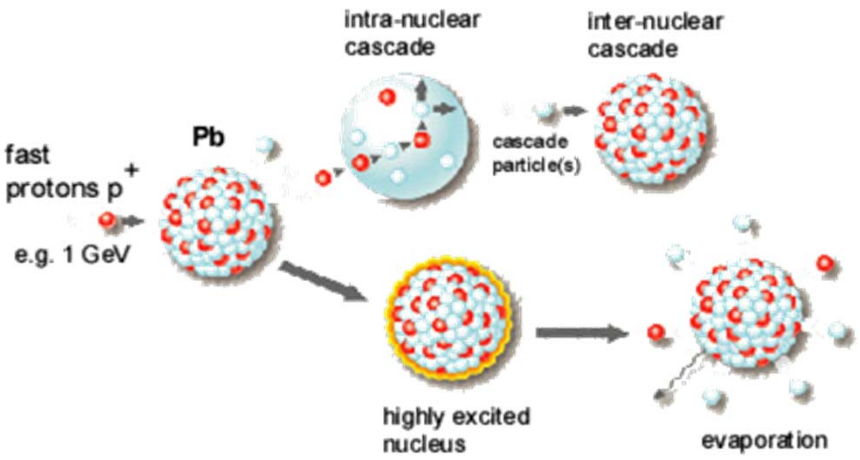
Nominally "Thermal" neutrons: Energy=25 meV, corresponds to the average energy in a Maxwellian distribution at 293 K temperature; Wavelength = 1.8 Å; speed = 2200 m/s.

How Do We Produce Neutrons?



Fission

- Chain reaction
- Continuous flow
- Net ~ 1 neutron/fission

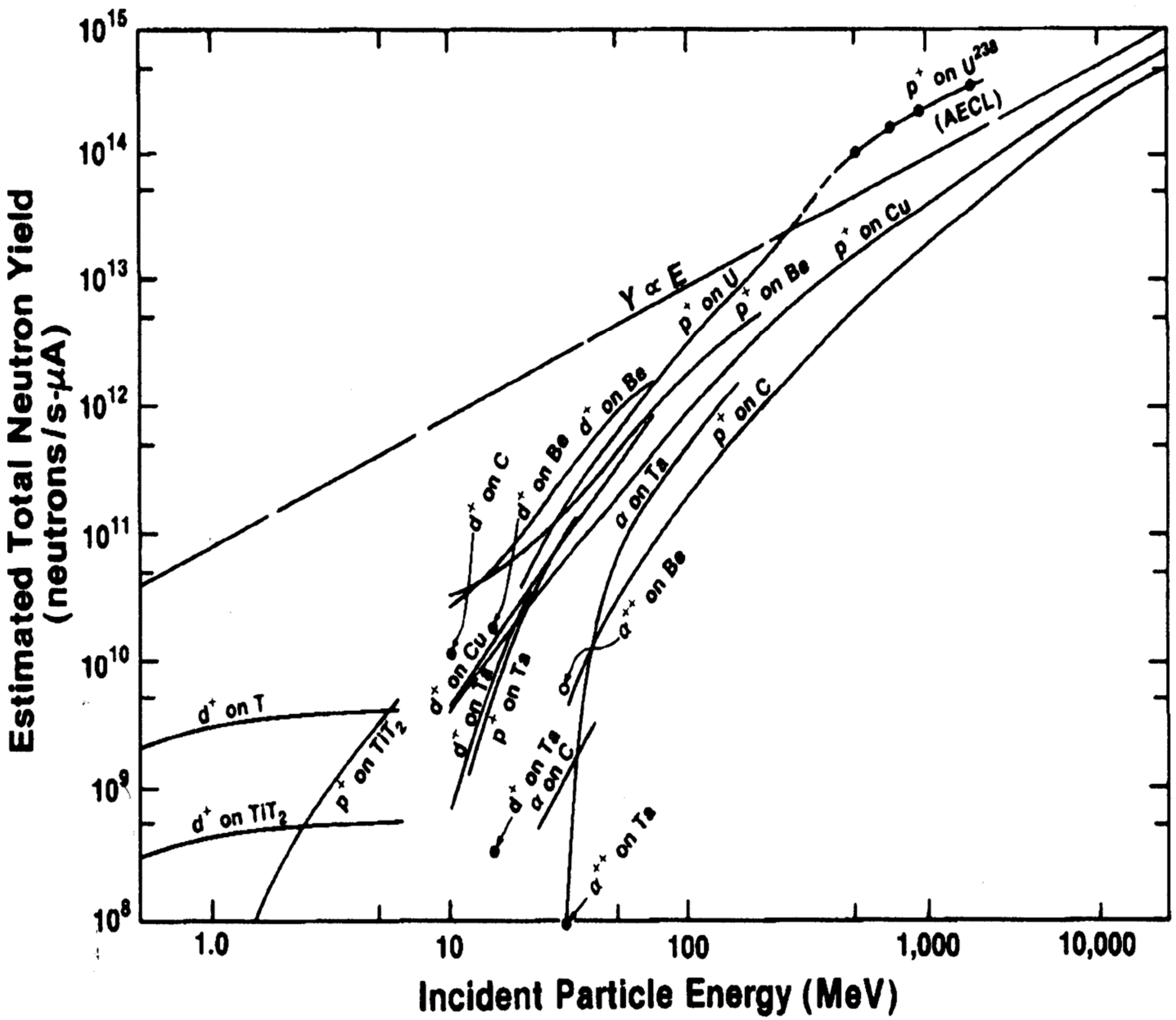


Spallation

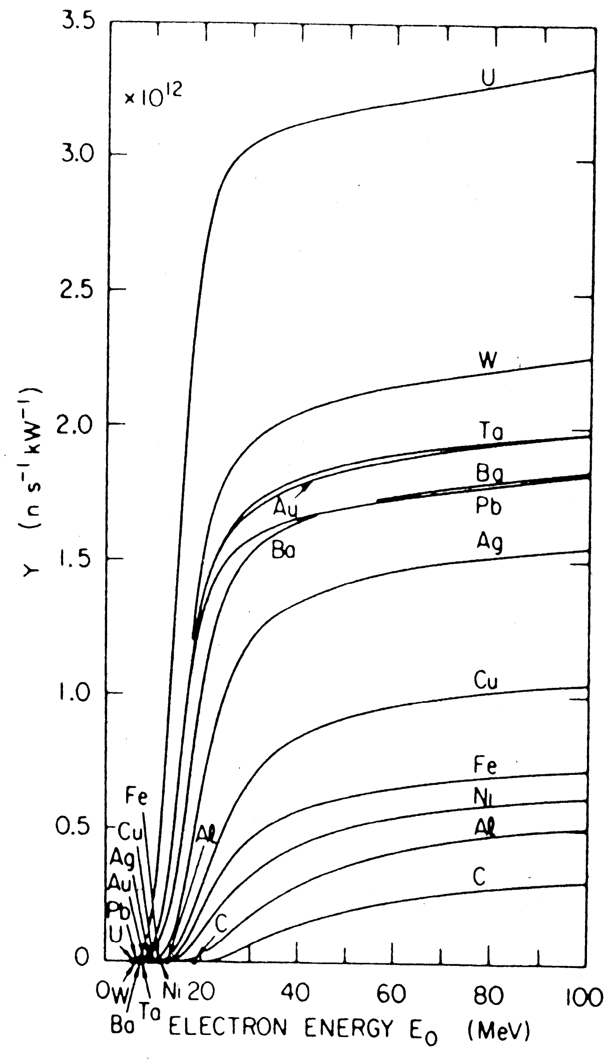
- No chain reaction
- Accelerator driven
- Pulsed operation
- ~ 30 neutrons/proton

Low-Energy Charged-Particle Reactions

Neutron yields vs. particle energy



e⁻ Bremsstrahlung Photoneutron Yields



Electron linacs.

Heavy element targets are preferred.

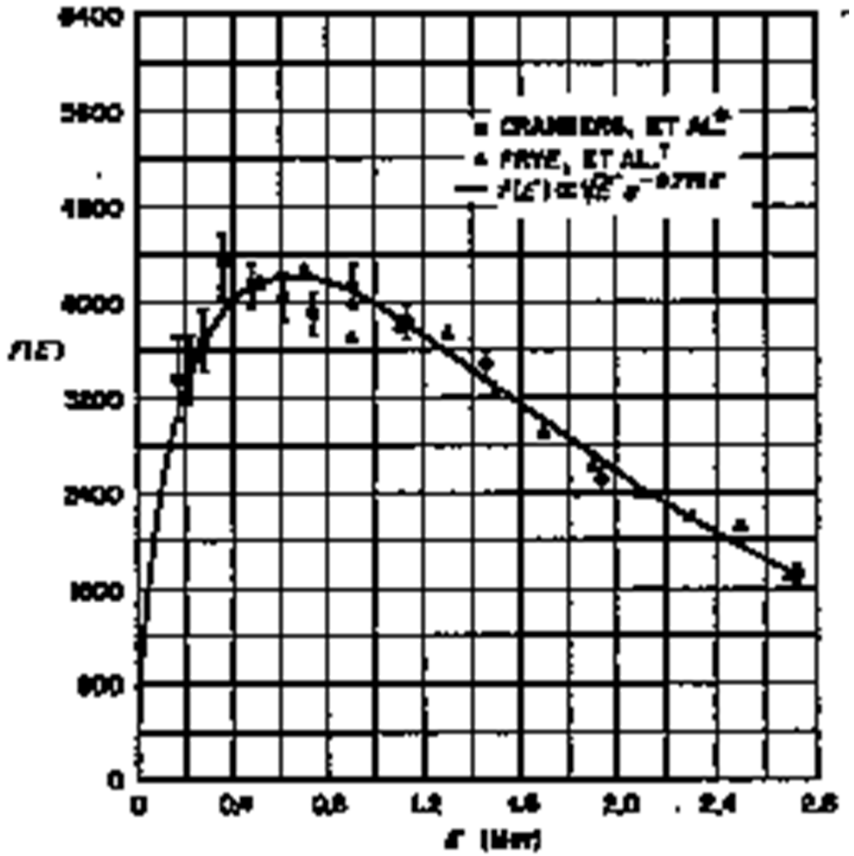
For W on the plateau, the energy deposited in the target per neutron produced is

$$E / Y(E) \approx 2800\ MeV / neutron.$$

Neutrons produced have an evaporation energy distribution.

Evaporation Neutron Spectrum

The function shown in the figure has a mean energy of 1.98 MeV. A more accurate form is $f(E) = \exp(-1.036E)\sinh\sqrt{(2.29E)}$, where E is expressed in MeV. This is, strictly speaking, the spectrum of neutrons produced by fission in ^{235}U, but it applies approximately and in form to most other evaporation neutron spectra.



A. M. Weinberg and E. P. Wigner, *The Physical Theory of Neutron Chain Reactors*, The University of Chicago Press (1958). p 111-115.

Where Do Neutrons Come From?

Fission:

n + ^{235}U = 1.5n + n + fragments

~ 180 MeV/n (as heat)

Sustain chain reaction

Available

Spallation:

p + heavy nucleus = 20 ~ 30 n + fragments

1 GeV *e.g., W, Pb, U*

~ 30 MeV/n (as heat)

Bremsstrahlung photoproduction:

e^- on heavy target —> photons

photons on heavy nucleus —> giant resonance

excited nucleus decay —> neutron

~ 3000 MeV/n (as heat)

98-6239 uc/vlb

Where Do Neutrons Come From?

Spallation yields measured in support of the ING project.

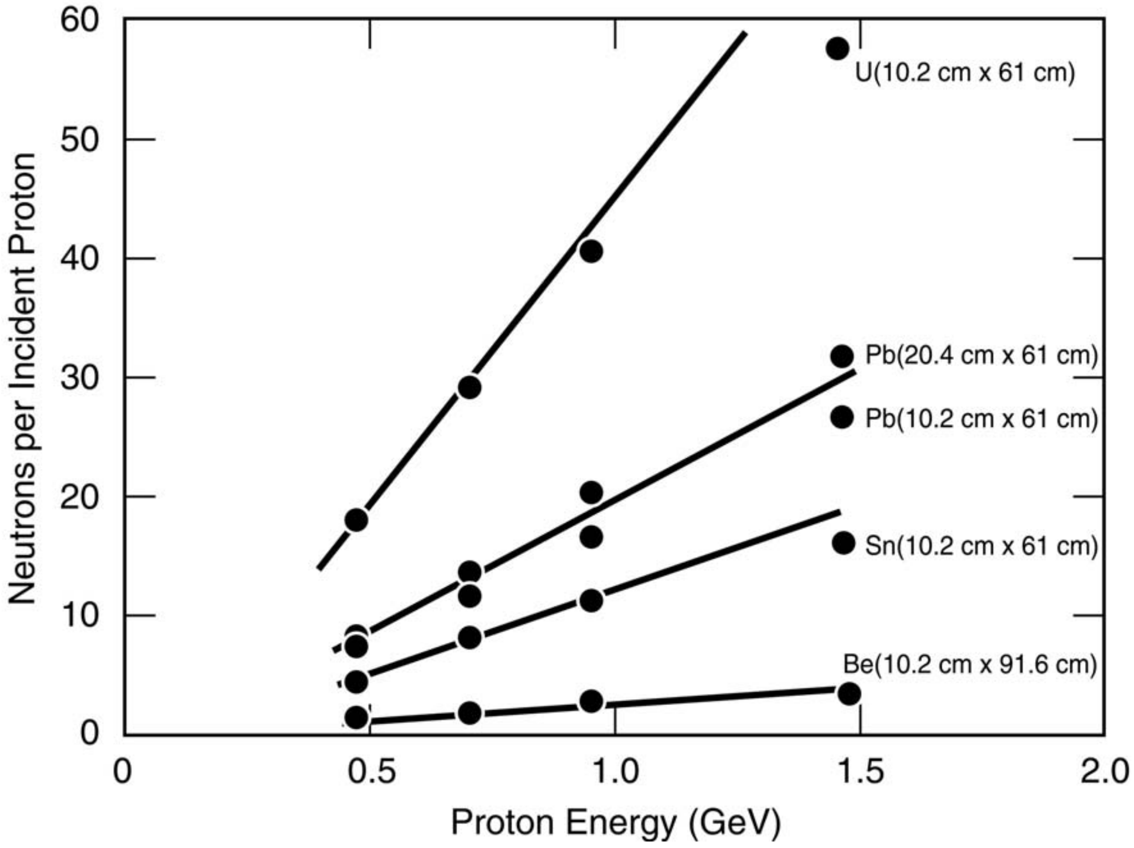
Absolute global neutron yield (neutrons/proton)

$= 0.1(E_{GeV} - 0.12)(A+20)$,

except fissionable materials;

$= 50.(E_{GeV} - 0.12)$,

for ^{238}U.



Measured Spallation Neutron Yield vs. Proton Energy for Various Targets, J. Frazer, et al. (1965).

From Fraser *et al.*, measurements at Brookhaven Cosmotron

The 10,000,000,000-Volt Question

A summary observation is that the total neutron yield, proportional to the proton energy in the neighborhood of 1 GeV falls off at higher energies due to the loss of energy from the hadron cascade through the very rapid π^0 decay (two 70-MeV photons escape). For energies above about 3.0 GeV, the yield of neutrons per proton varies as $E^{0.80}$.

In spite of this, it may be that to achieve given power or neutron production rate, higher energies are preferable to lower ones, because higher energy may be cheaper and easier to accomplish than higher current.

Where Do Neutrons Come From?

Low-energy (p,n) reactions, e.g.,

p + ^{9}Be —> n + 2alpha + p and

—> n + ^{9}B.

Most of the proton energy appears as heat, deposited in ~ 1. mm .

Yield ~ 1300 MeV/n @ E_p = 13 MeV

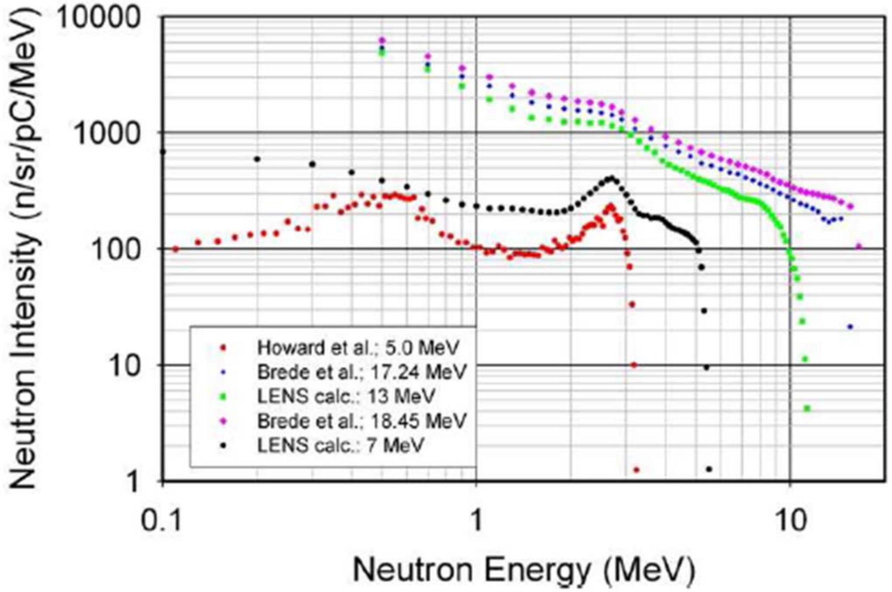
⟶ *3.5 x 10^{-3} n/p.*

Neutron Energy Distribution From Be(d,n)

Beryllium is likely most attractive as a target for low-energy neutron facilities because the yield is high and the material is easy to manage.

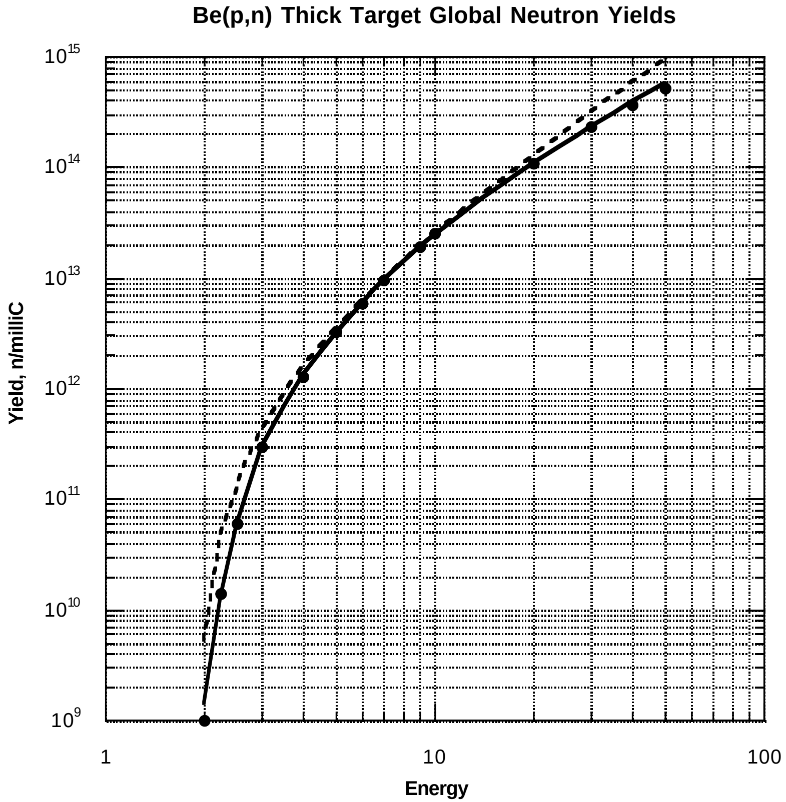
Targets are very thin for low-energy charged-particle sources because particle ranges are small for the energies involved (~ 1 mm for 15 MeV protons in Be).

LENS neutron spectra



LENS is the Low-Energy Neutron Source operating at Indiana University. A comparable source, the China Pulsed Hadron Source (CPHS), is nearing completion at Tsinghua University, Beijing.

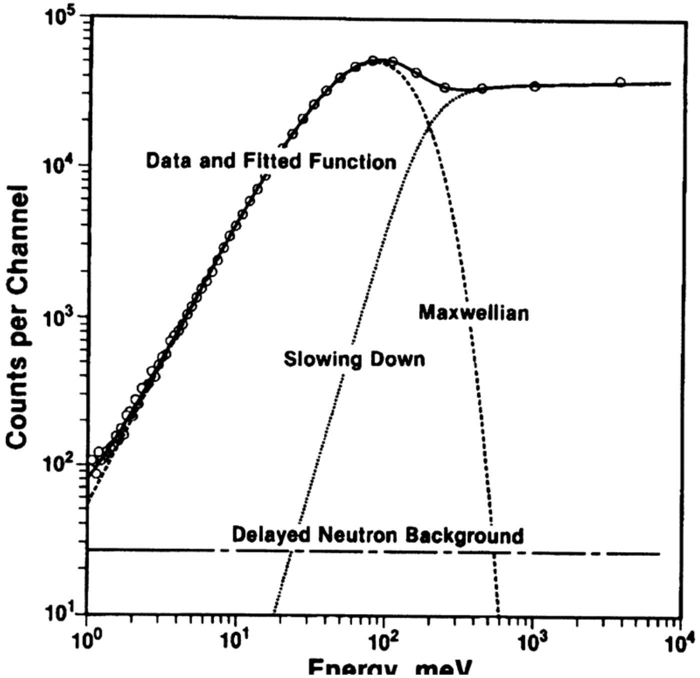
Be (p,n) Neutron Yields



A simple function fits the Be(p,n) data reasonably well, dashed line, $Y(E_p) = 3.42\text{x } 10^8 (E_p - 1.87)^{2.05}$ neutrons per millicoulomb.

Energy Distribution of Neutrons from a Pulsed-Source Moderator

The modified Westcott function describes most moderated source spectra quite well and is the sum of a Maxwellian form and a slowing-down function with a low-energy cutoff.

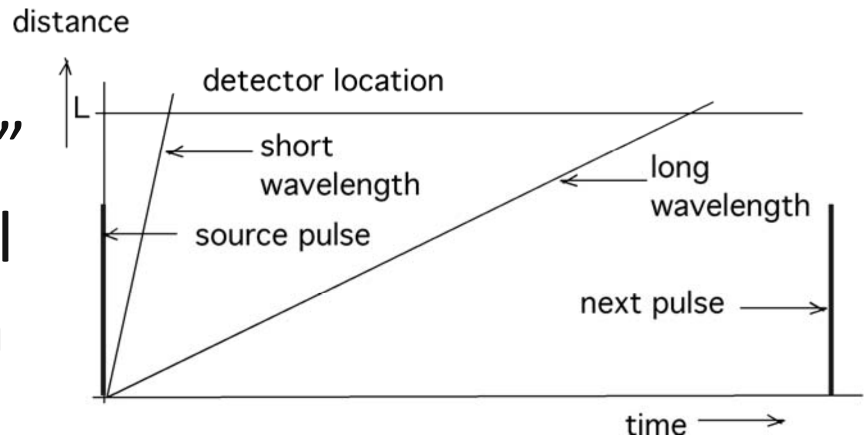


$$EI(E) = I_{Th}\frac{E^2}{E_T{}^2}\exp\,(\,-E/E_T) + I_{epi}\left(\frac{E}{E_{Ref}}\right)^{\alpha}\Delta(E)\ ,$$

$$\Delta(E) = 1\,/\,[1-(E\,/\,E_{co})^{s}]\ .$$

Time-of-Flight Wavelength Analysis

Pulsed sources usually rely on the narrow source pulse to define the time origin of neutrons at the source.



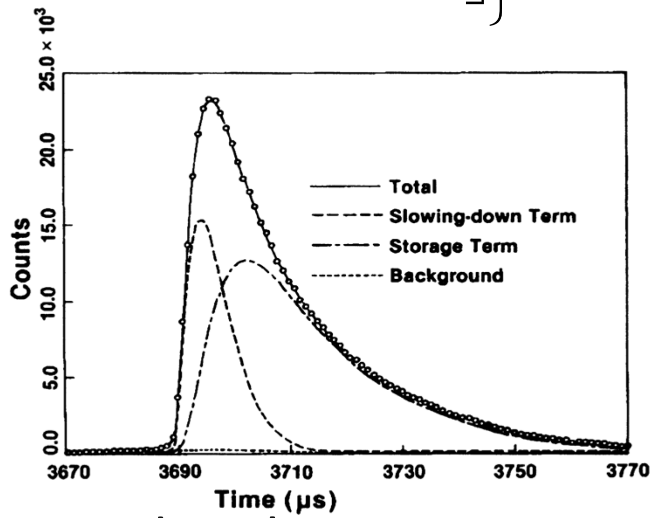
A "neutron time schedule" Illustrates. Neutrons of all wavelengths emerge from the source (moderator) at time zero. They travel a distance L at speed $v = (h/m\lambda)$ and arrive at the detector at time $t = L/v$. Thus, the wavelength is $\lambda = (h/m)t/L$.

Moderated-Neutron-Emission Pulse Shape

Neutrons emerge from the moderator as a function of time, which varies according to the energy (i.e., wavelength), the I-C function:

$$f(E,t) = \frac{a}{2}\left\{(1-R)\frac{a}{2}(at)^2 exp(-at) + +2R\frac{a^2\beta}{(a-\beta)^2}\left[exp(-\beta t) - exp(-at)\left(1+(a-\beta)t+\frac{1}{2}(a-\beta)^2 t^2\right)\right]\right\}.$$

The first term represents neutrons emerging in the process of slowing down from high energies. The second term is the "storage" term, which represents neutrons that have "thermalized" in the moderator, broadened by the slowing-down source time distribution. Parameters are smooth functions of the neutron energy.



Target Materials

Target materials must withstand tough operating conditions:

Radiation damage, High heat-flux cooling, Corrosion, Chemical compatibility, Safety. Of course, they must also have appropriate nuclear properties for neutron production.

Preferred coolants: H_2O or D_2O. Gallium has attractive qualities as a coolant.

Used in spallation targets: U, W, Ta, Hg, Pb, and Pb-Bi.

- U is metallugically unstable, and, like W, corrodes in H_2O, so needs cladding and may suffer disadvantage in LOCA conditions.
- Ta resists corrosion but produces excessive radioactive after-heat.
- Hg, Pb, and Pb-Bi are convenient for heat removal in liquid form, but are chemically hazardous.

Types of Neutron Sources

Reactors:

HFR at ILL, HFIR at ORNL, ~1.5×10^{15} n/cm^2/s

FRM-2 at Munich: fluxes ~ $1.\times10^{15}$ n/cm^2/s

Advantages

- High time-averaged flux.
- Mature technology (source; instruments–development continues).
- Very good for cold neutrons.

Drawbacks

- Licensing (cost/politics of HEU).
- No time structure.

98-6237 uc/rra

Types of Neutron Sources

Pulsed spallation sources:

IPNS, ISIS, LANSCE, SNS, JSNS, ESS.

ISIS—200 µA, 0.8 GeV, 160 kW , $2x10^{13}$ n/cm^2/s average flux

SNS— 1.4 mA, 1.0 GeV, 1.4 MW, $8x10^{15}$ n/cm^2/s peak flux

Advantages

- High peak flux.
- Advantageous time structure for many applications.
- Accelerator based – politics simpler than reactors.
- Technology rapidly evolving.

Disadvantages

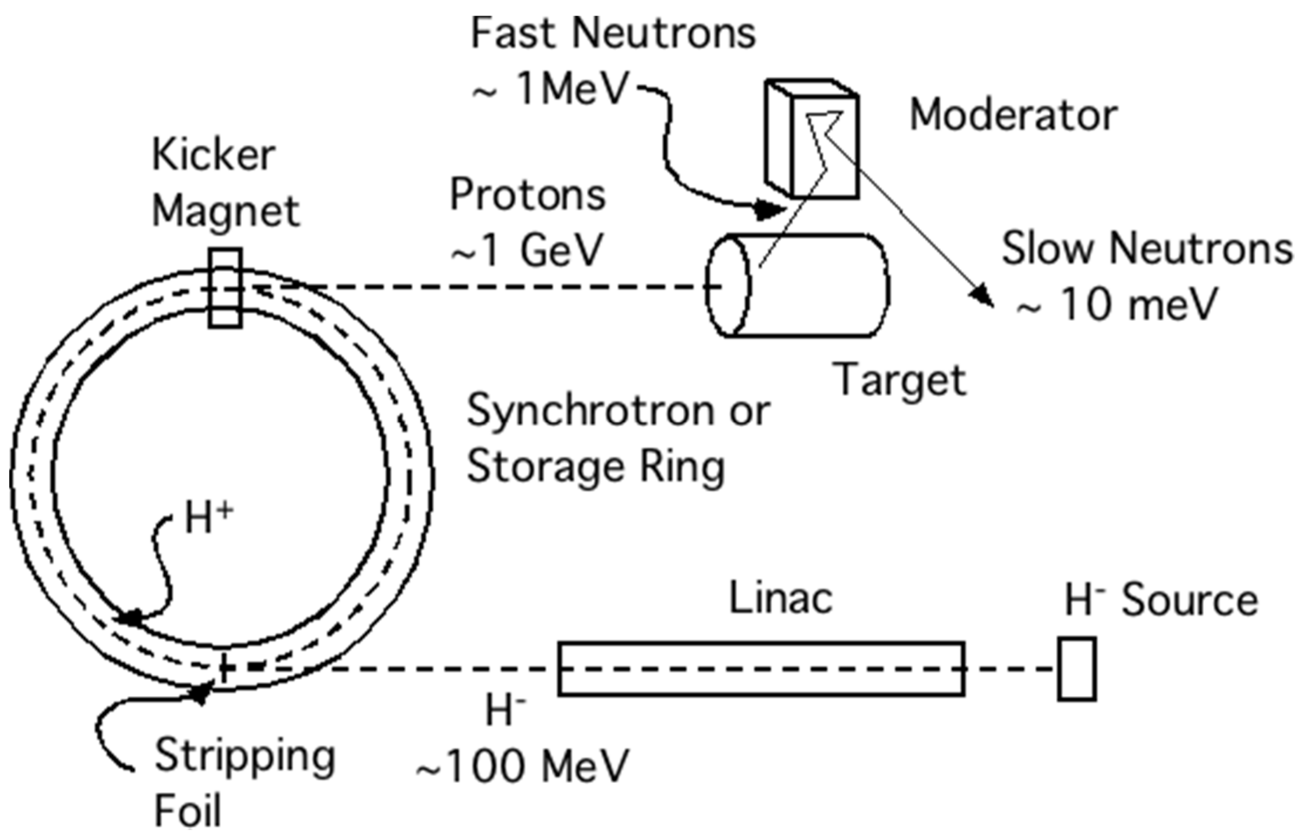
- Low time-averaged flux.
- Not all applications exploit time structure.
- Rapidly evolving technology.
- Thermoelastic shock.

Short-Pulse vs. Long-Pulse Sources

Most of the existing pulsed neutron sources produce fast neutrons in short (~ μιχροsec) pulses of protons extracted from the ring: *short-pulse sources*. Recent considerations take long (~ millisec) pulses from the linac and omit the ring: *long-pulse sources*.

Short-pulse sources exploit the short pulse, broadened by the wavelength-dependent moderation time, to define the starting time for time-of-flight instruments. Most instruments at long-pulse sources require trimming pulses to meet time- resolution requirements.

Accelerator-Based Pulsed Neutron Source



Moderator(s) close to the target slow down fast neutrons to energies useful for applications.

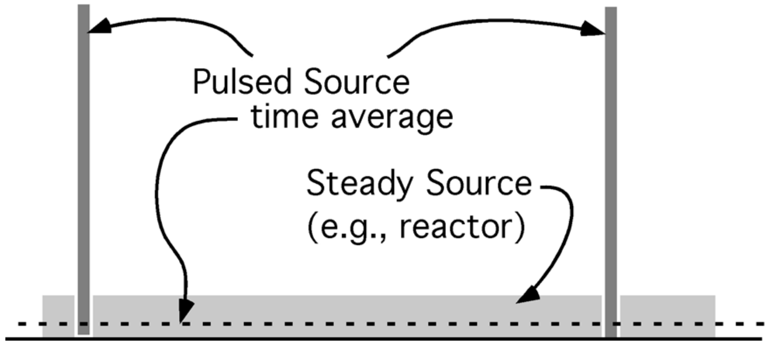
Pulsed vs. Steady Sources

Pulsed sources relate naturally to accelerators that operate in pulsed mode. In this mode, pulsed sources have a *duty-cycle advantage*, in that the source is "on" and at full power only part of the time and "off" most of the time, during which heat in the target and moderators is (slowly) removed. If the source is on for time Δt_{source} and pulses at frequency f, the peak power is related to the average power as $P_{peak} = P_{average} \big/ f\,\Delta t_{source}$.

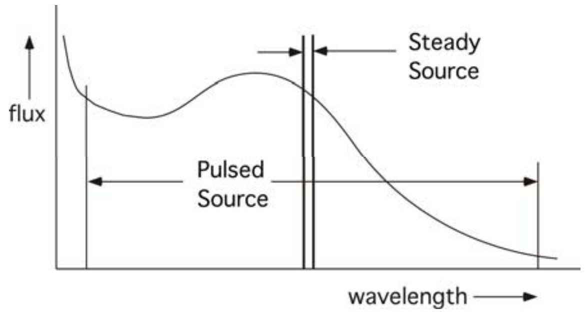
The same is true for the neutron flux, for which the source is "on" for the duration of the moderated pulse, which depends on the wavelength. For example, for f = 50 Hz and $\Delta t_{\mathrm{mod}} = 20\ \mu\mathrm{s}$, the duty-cycle factor is $1\big/ f\,\Delta t_{\mathrm{mod}} = 10^3$.

Use of Pulsed vs. Steady Sources

The figure illustrates the duty-cycle advantage.

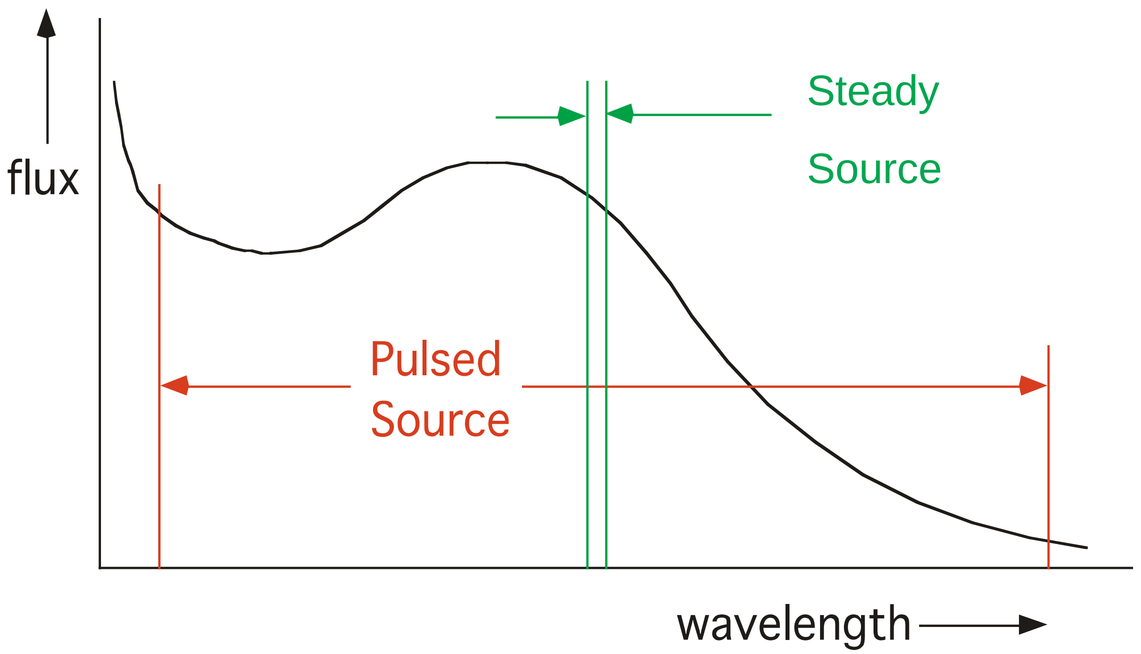


Because in pulsed sources most of the neutrons of all wavelengths can register at the detector, they use most of the neutrons in a wide band of wavelengths.



This is different from a steady source, where wavelength analysis requires selecting a narrow band from the broad spectrum and rejecting the rest.

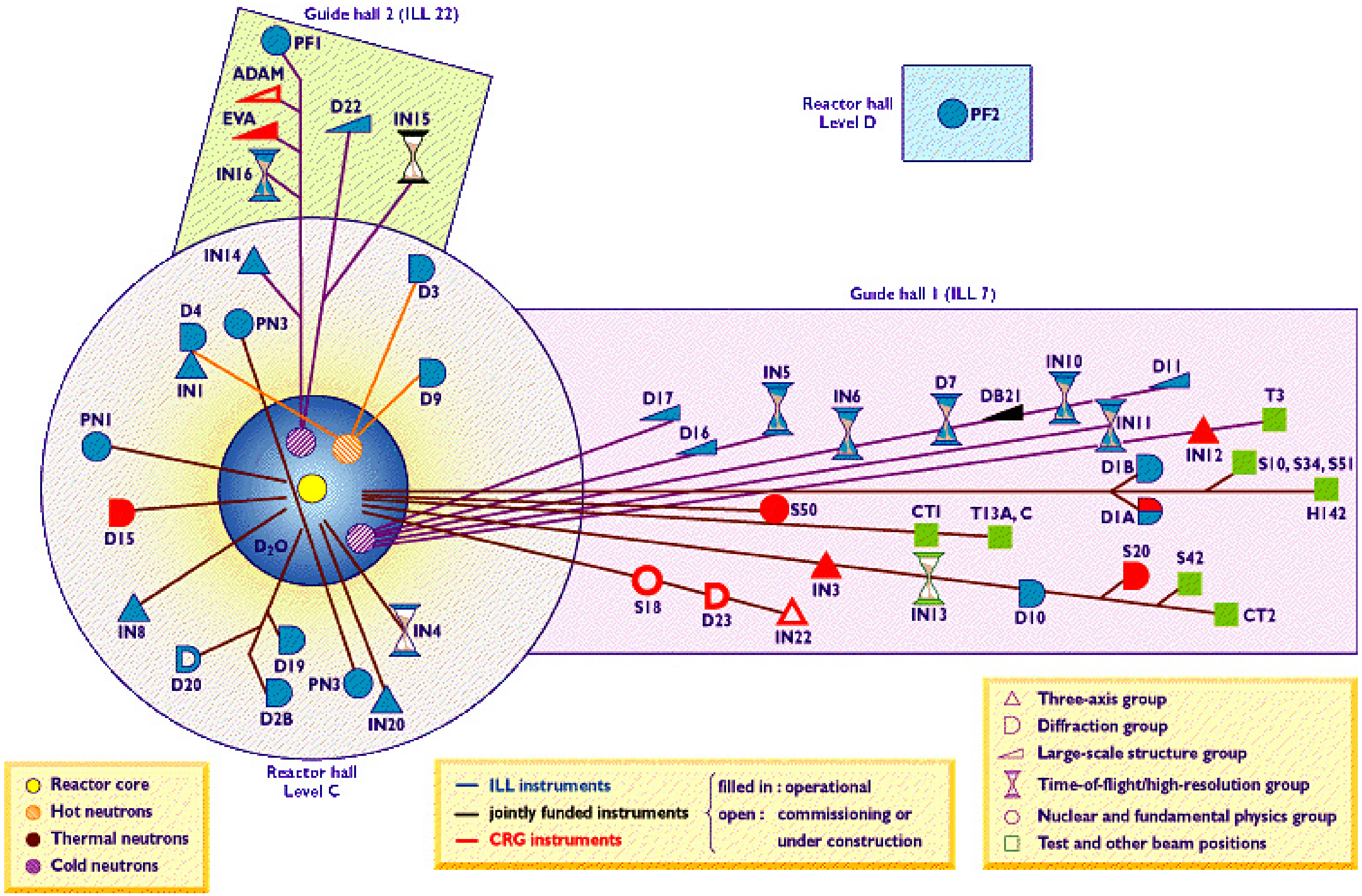
Use of Pulsed and Steady Sources



Steady sources use some of the neutrons
all of the time.
Pulsed sources use all of the neutrons
some of the time.

Types of Neutron Sources

The High-Flux Reactor at Institut Laue-Langevin, Grenoble



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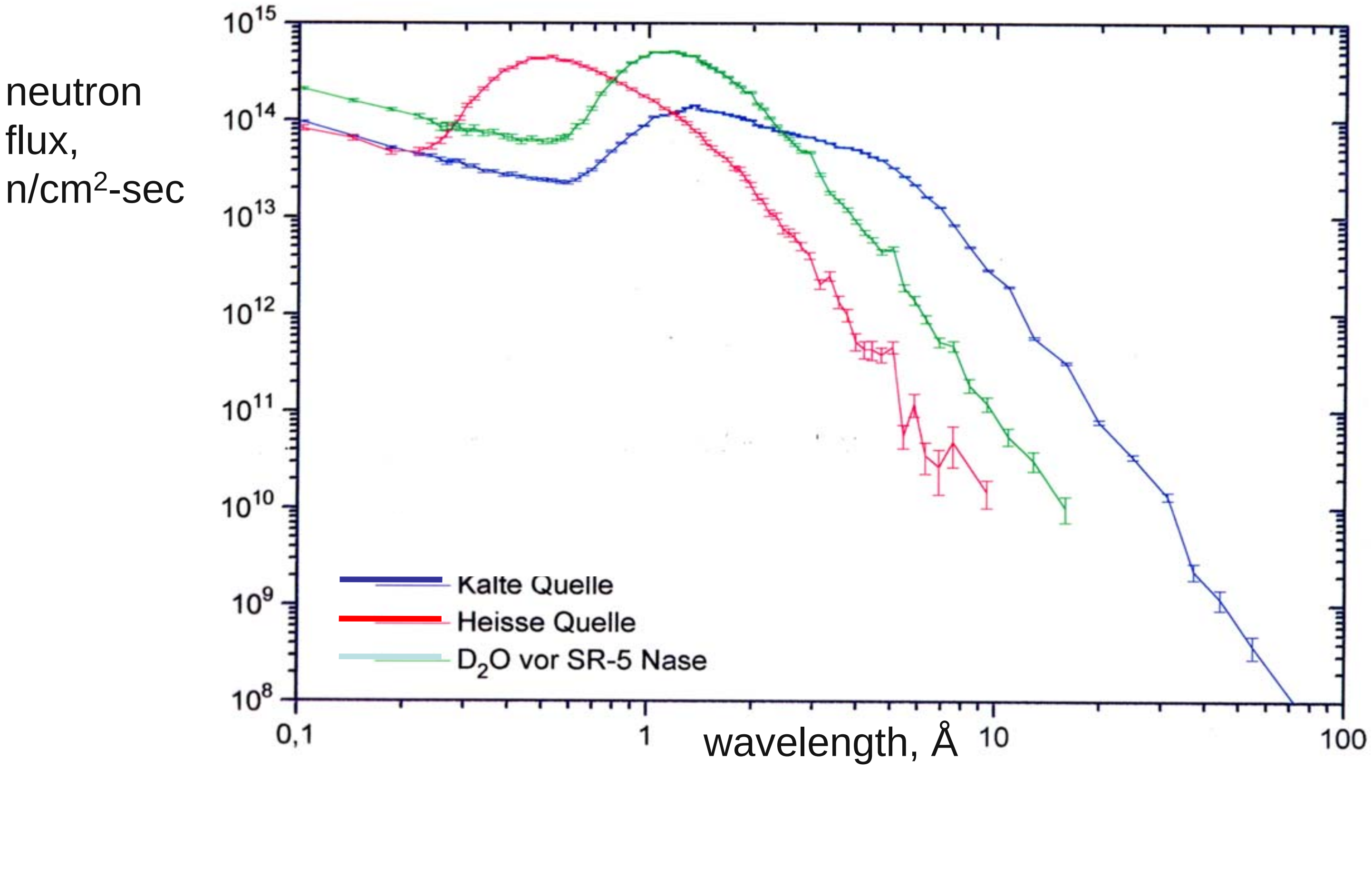
Source Spectra of the FRM-II Reactor



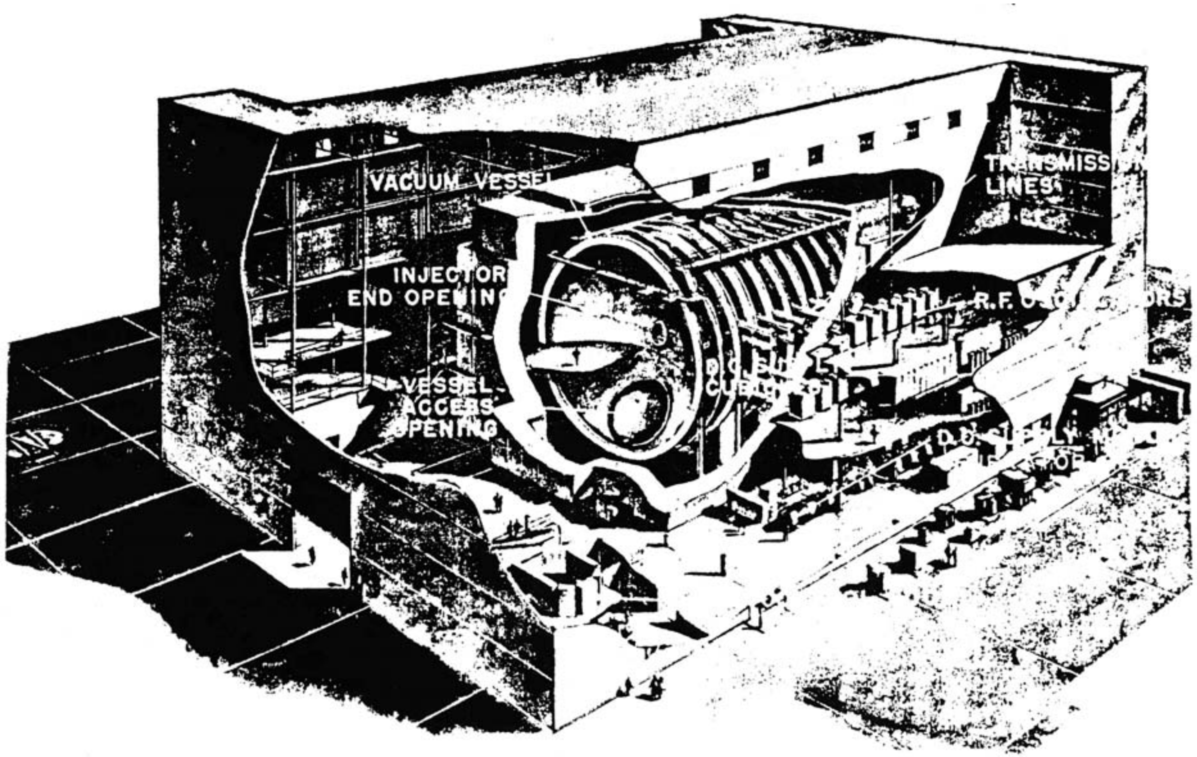
Moderators

Because all mechanisms of neutron production release fast neutrons, all slow-neutron sources have moderators to slow down fast neutrons from the source to lower energies of interest for applications, from MeV —> meV. In reactors, the coolant serves as internal moderator; L-H_2, L-D_2, graphite, beryllium, or water are external moderators.

In pulsed sources the most effective moderators are dense hydrogenous materials, L-H_2, L-D_2, H_2O, D_2O, L-CH_4, S-CH_4,$(CH_2)_n$ … , which can be tailored (size, material, temperature, "poisoning", "decoupling") for different purposes (cold, not-so-cold …) favoring either short moderation times or high intensity.

Just For Historical Fun, MTA: The Materials Testing Accelerator, ~1950

Cutaway View of the Linear Accelerator



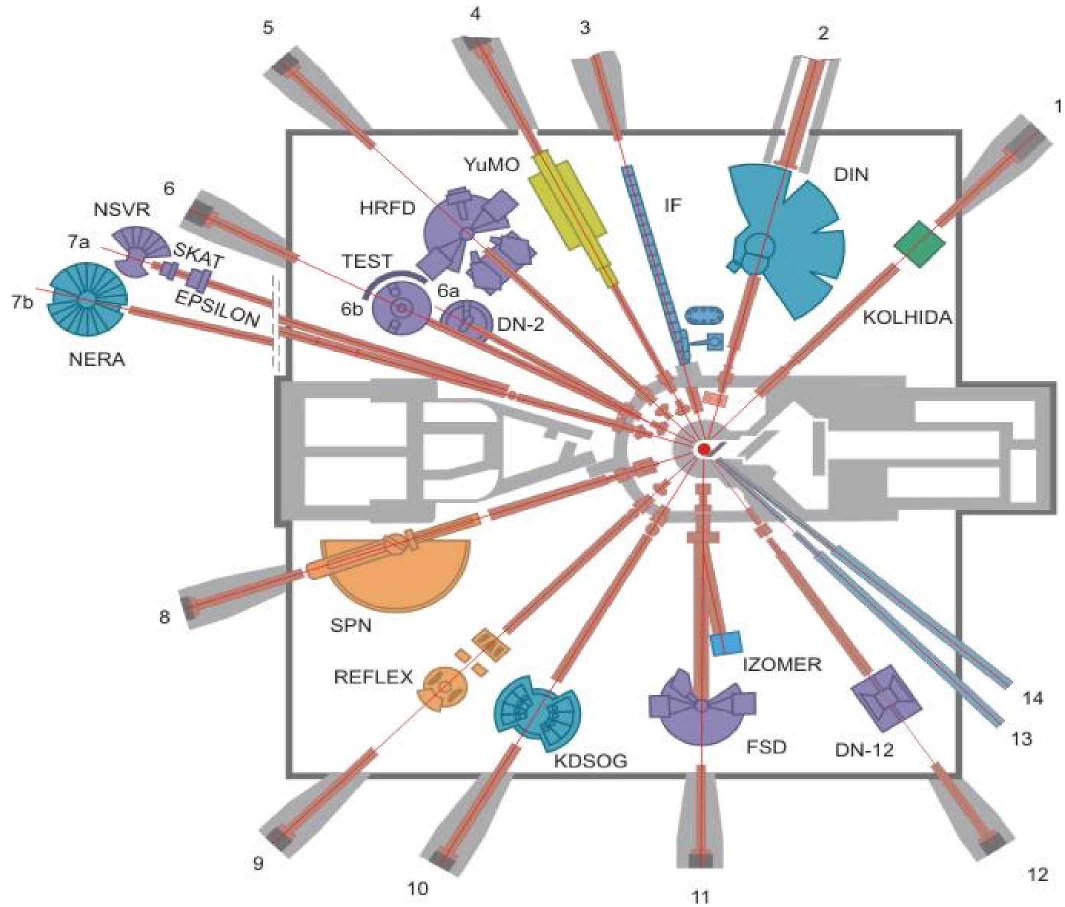
A. P. Armagnac, "The Most Fantastic Atom Smasher", *Popular Science* Vol. 173: No. 5 Nov. 1958, p. 114.

2000-05268 uc/arb

The IBR-2 Reactor
JINR, Dubna, Russia

One-of-a-kind
pulsed fast
reactor

Average power
2 MW
Frequency
5 Hz
Pulse width
250 microsec



The Intense Neutron Generator

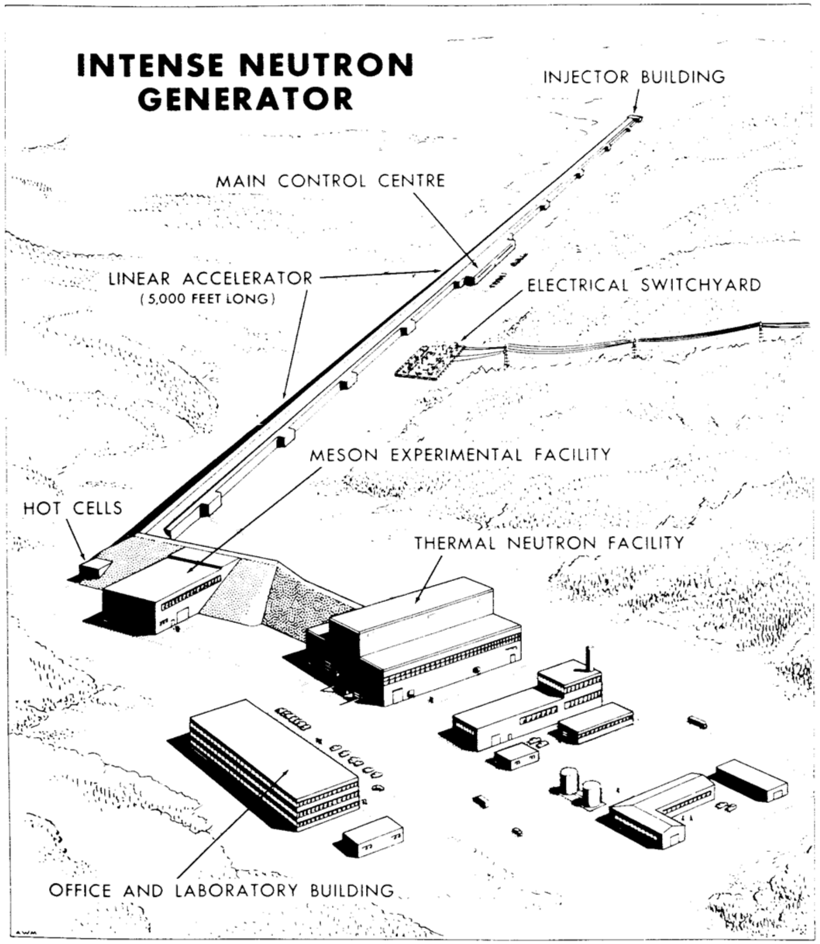
In 1963, the Chalk River Laboratory of Atomic Energy of Canada launched the Intense Neutron Generator (ING) project. The goal was a "versatile machine" providing a high neutron flux for isotope production and neutron beam experiments. The effort continued until 1968 when the project was cancelled.

- Proposed installation: 1.5-km-long proton linac delivering 1.0-GeV, 65. mA (65 MW) steady beam.
- Target: flowing lead-bismuth eutectic (LBE), 20. cm diameter, 60. cm long.
- Proton beam vertically downward, annular beryllium "multiplier" 20 cm thick.
- Technical developments from the ING project were seminal, although ING was never built.

The ING Facility

Canadian scientists conceived the ING project in the early 1960s. ING was never built because the proposed accelerator was not feasible at that time.

The figure shows the ING facility layout.



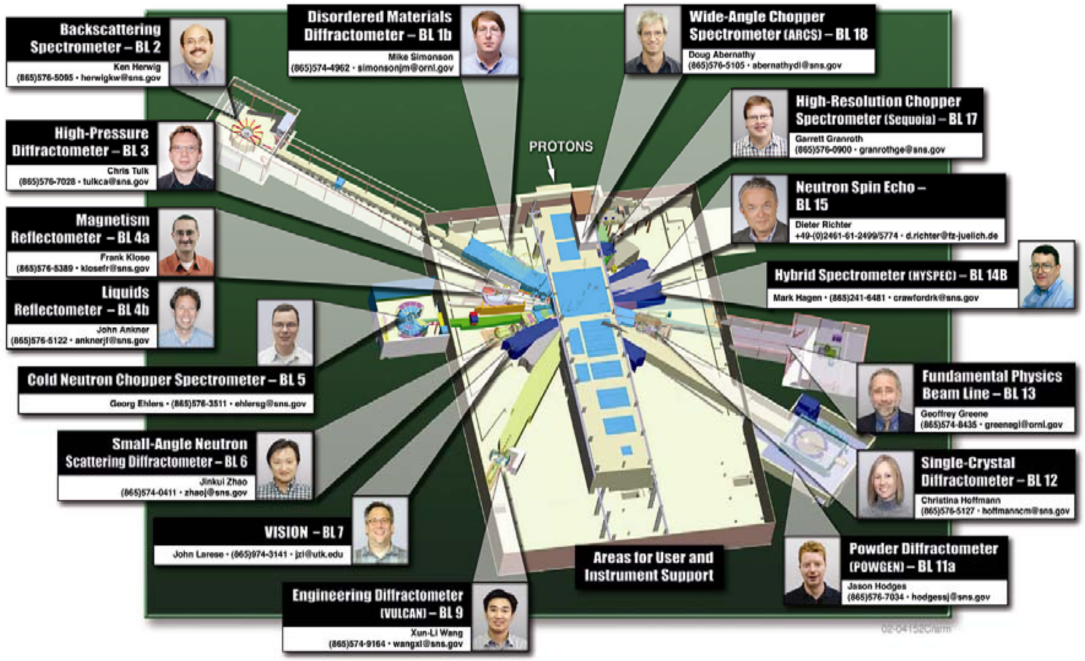
SNS and Instruments

~20 instruments approved, most in operation, excellent progress with funding. Operating in 2014 with 1.4 MW proton beam power.

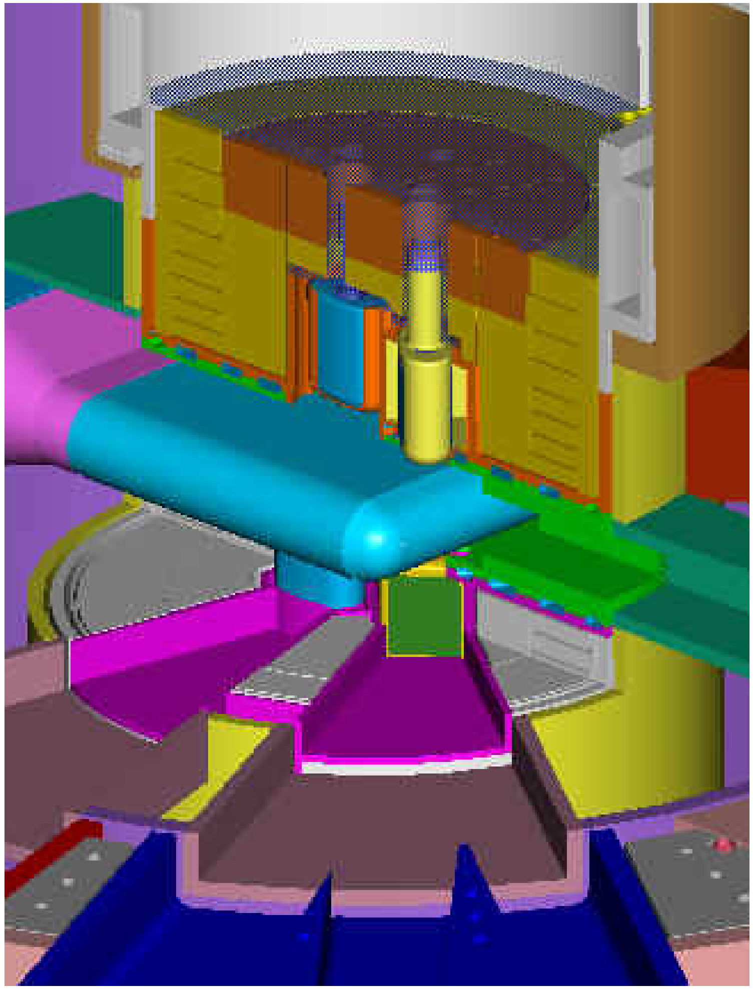
- DOE, including SING1 and SING2 instrumentation rojects, foreign, and NSF initiatives.

Work continues to enhance instrument technology.

- International engagement and interest in the instrument suite.
- Continuing engagement with scientific community.



SNS Target-Moderator-Reflector System



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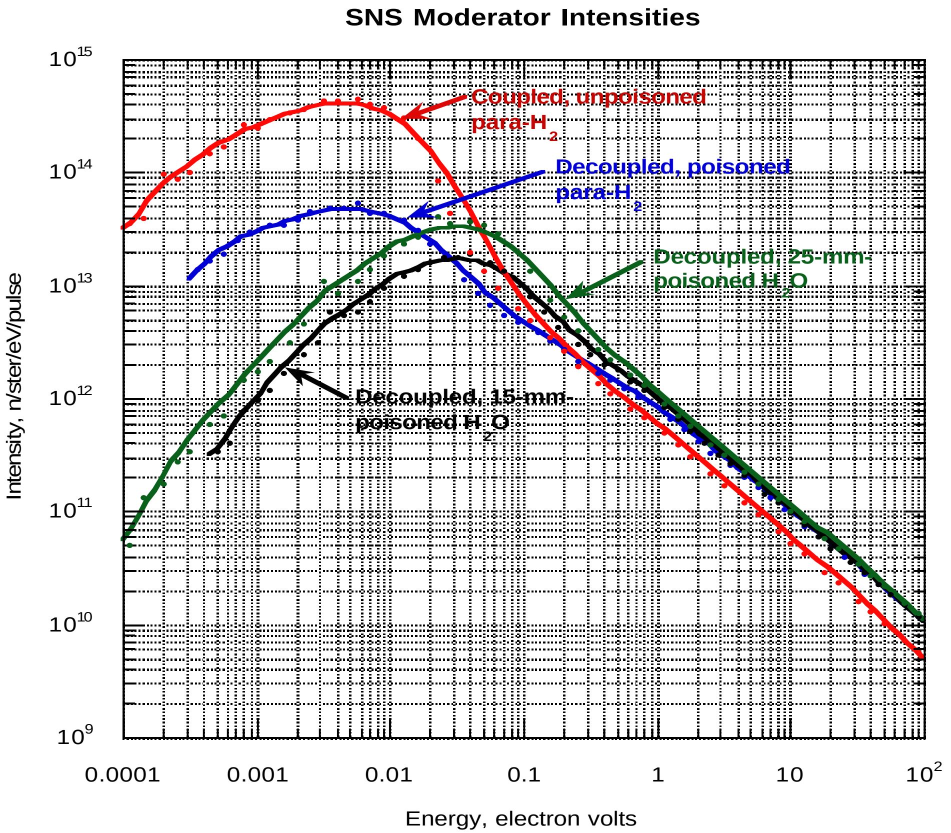
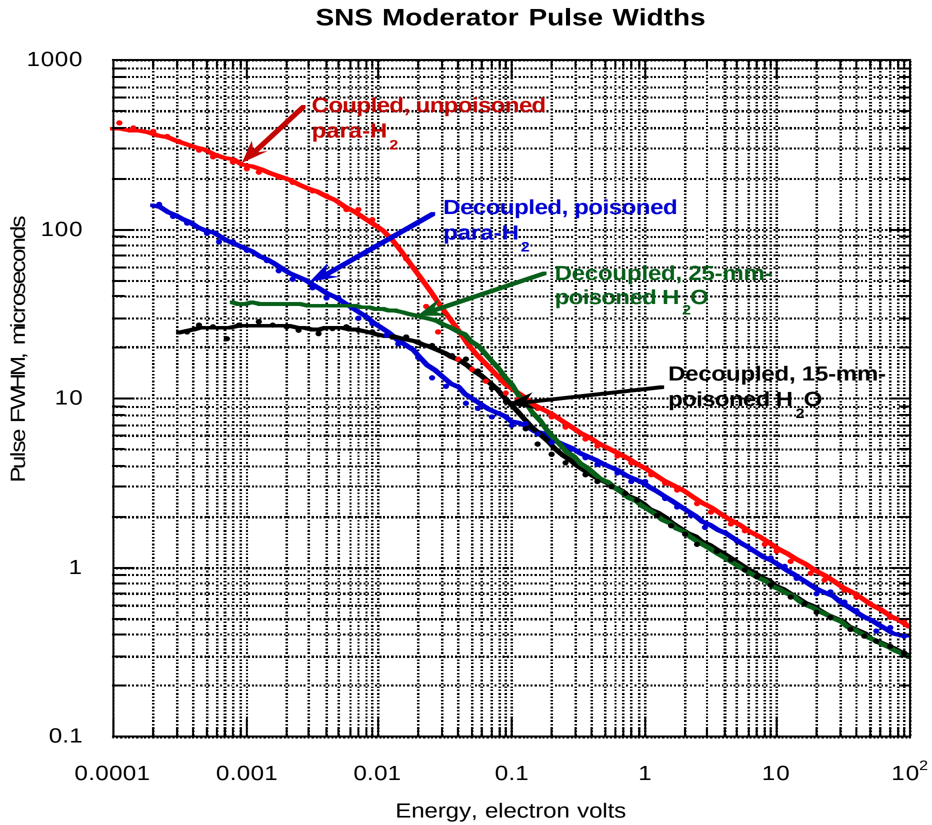
SNS Moderator Intensities and Pulse Widths





Results for 2 MW beam power, 60 Hz pulsing frequency—2.08 x 10^{14} protons/pulse at 1. GeV.

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Types of Neutron Sources

CW Spallation Source:

SINQ at Paul Scherrer Institut (PSI).

2.2 mA, 590 MeV, 1.3 MW

$2x10^{14}$ n/cm^{2}/s average flux

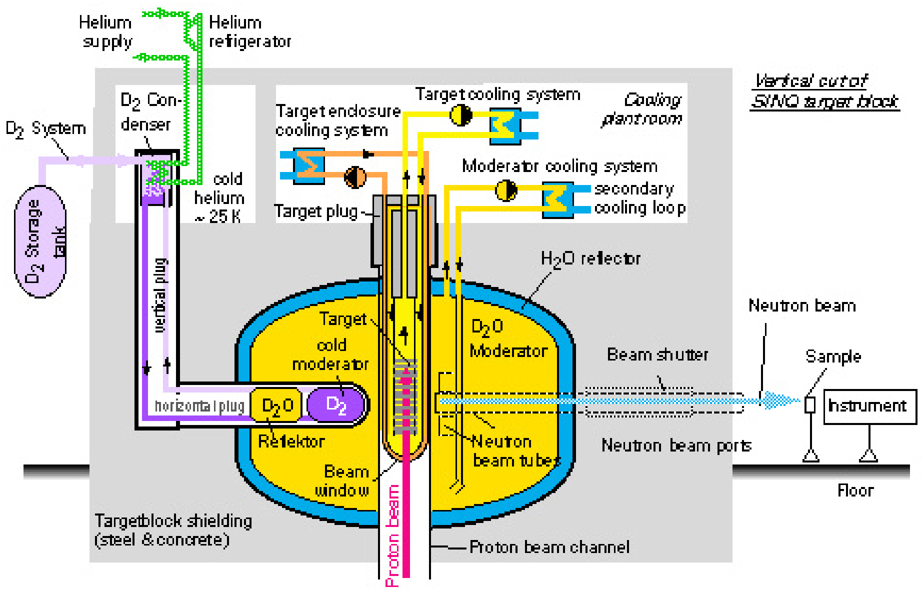
Advantages

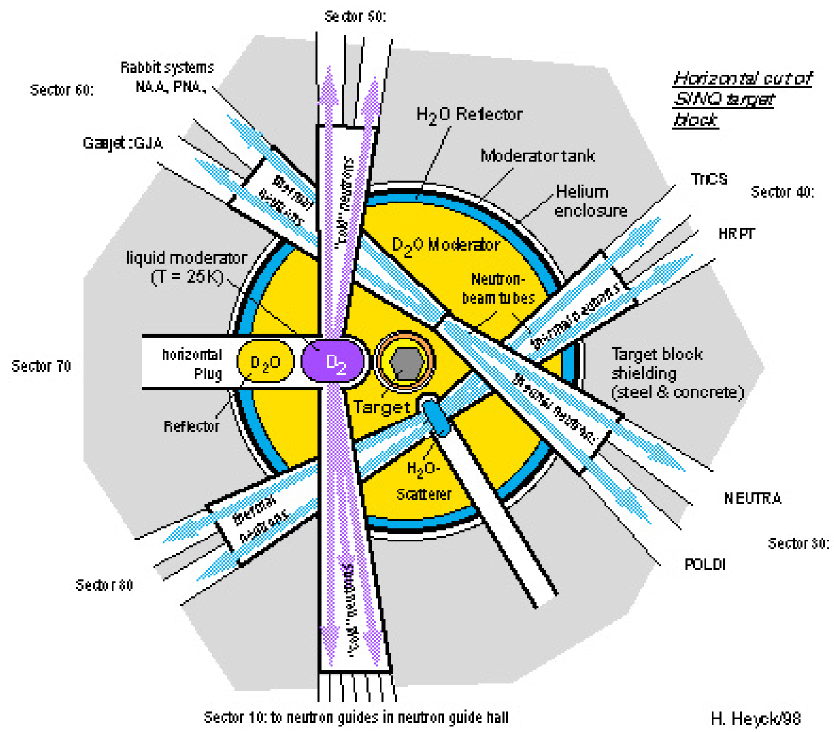
- High time-averaged flux.
- Uses reactor-type instrumentation (mature technology).
- Politically acceptable.
- Piggy-backed on existing accelerator.

Disadvantages

- No time structure.

The Spallation Neutron Source SINQ





Types of Neutron Sources

Low-Energy Neutron Sources

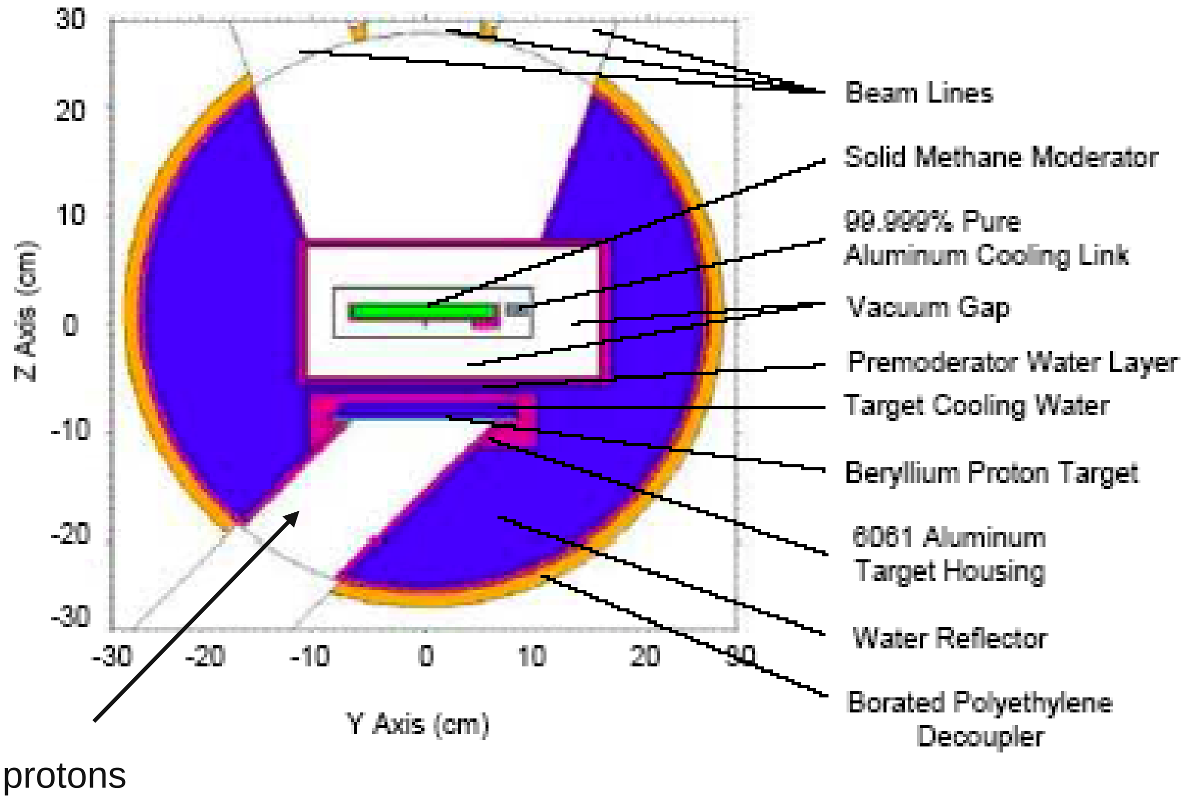
Advantages:

- Low cost of accelerator.
- Low cost of operation.
- Minimal shielding because of low proton energy.
- Cold moderators easy.
- Easily adaptable for testing, development and training.
- Modest flux implies low activation of components.

Disadvantages:

- Modest flux implies long experiment times.
- Optimal design provides only a few neutron beams.

The LENS Low-Energy Neutron Source, Indiana U.



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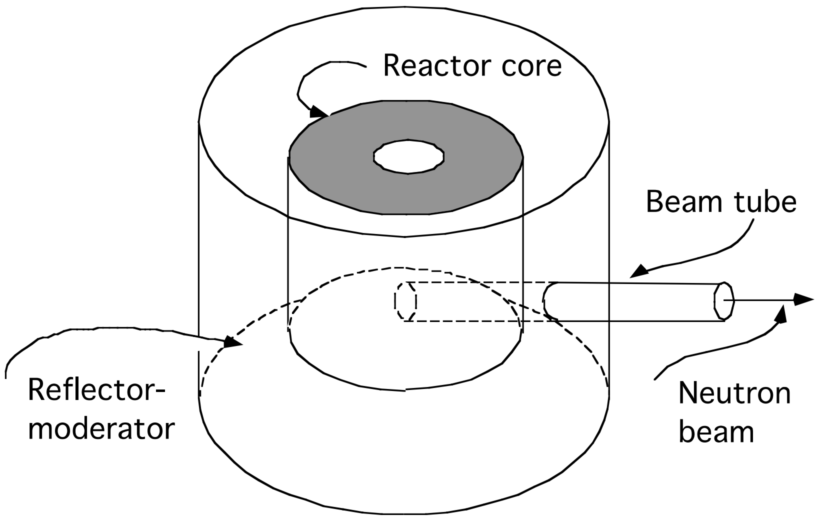
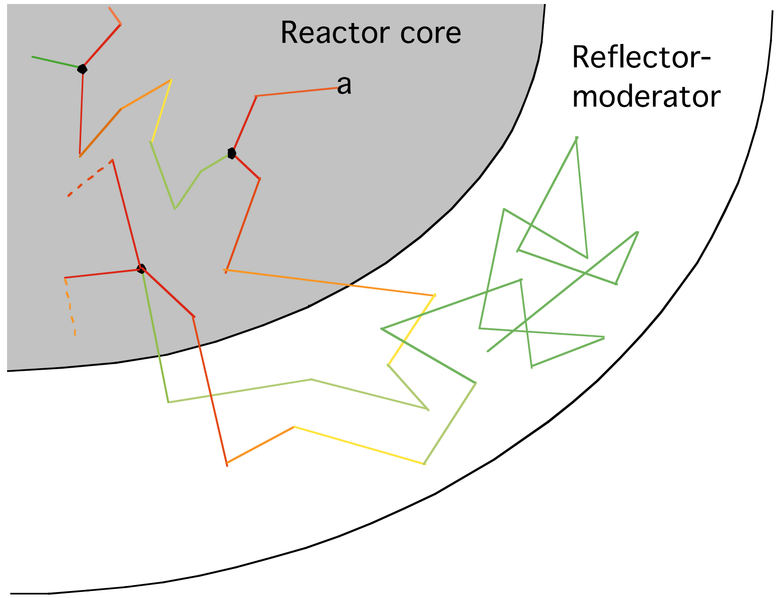
How Moderators Work

Steady Sources, e.g., reactors





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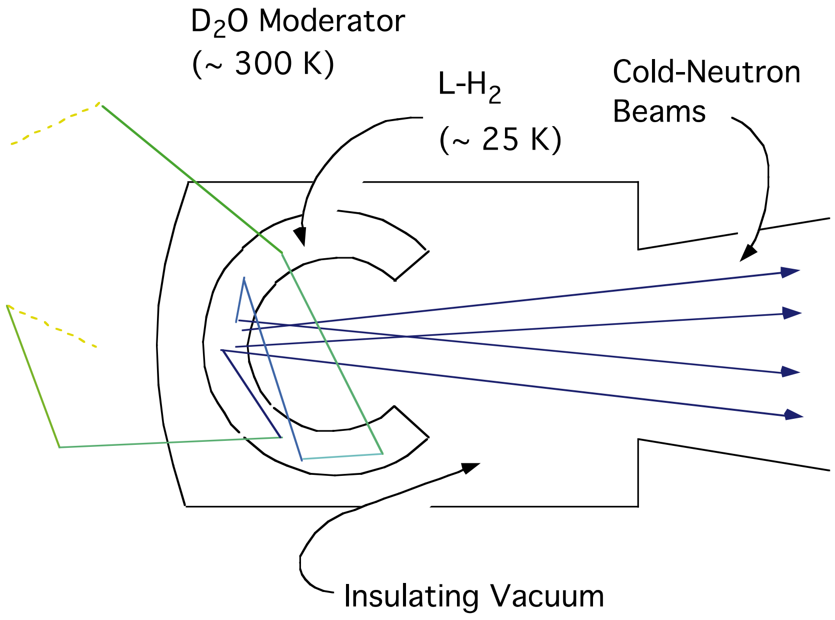
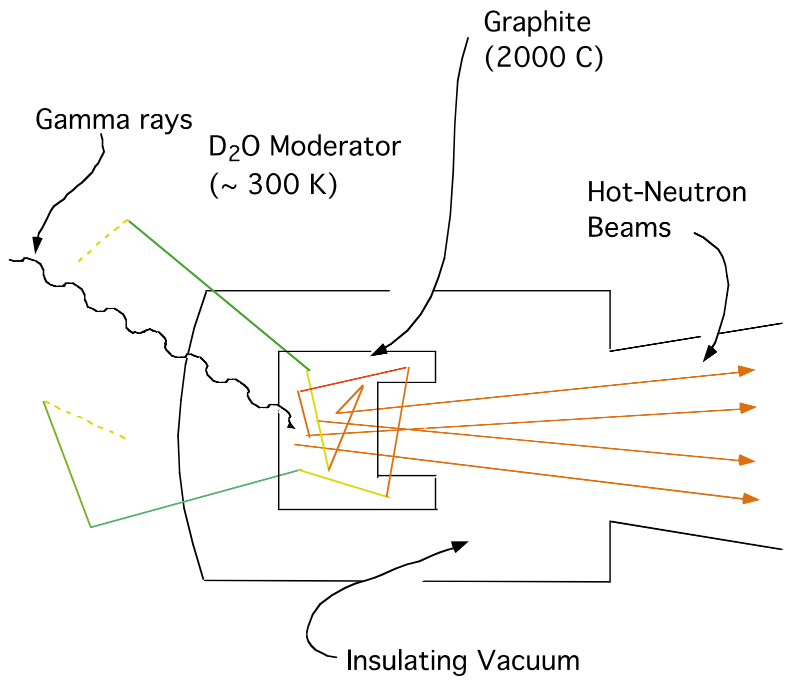
Cold and Hot Moderators

Steady sources



Cavity-type cold source



Hot source

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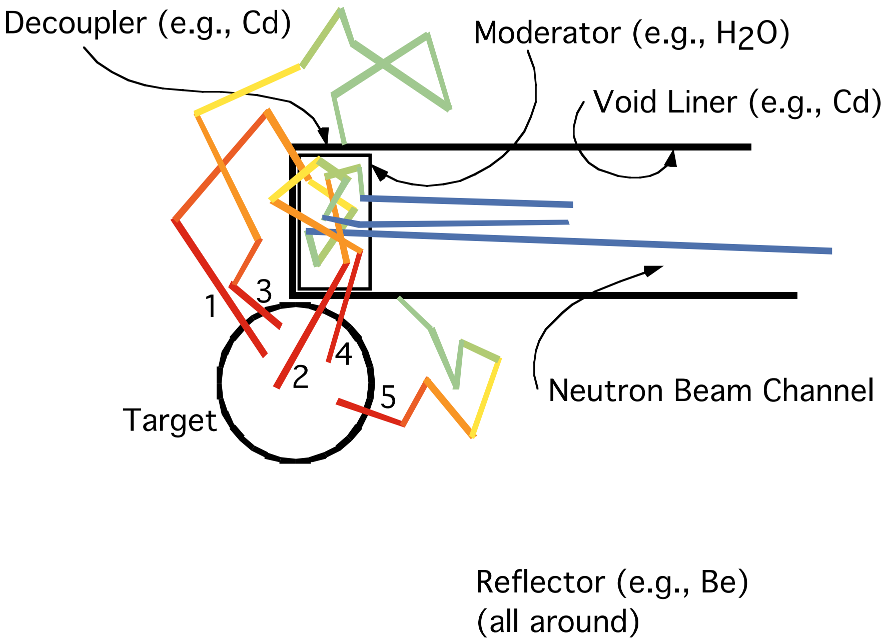
Pulsed-Source Moderators

Decoupled, reflected pulsed-source moderator
(Usually cold)



Lists of Sources

Research Reactors

Reactor	Location	First Operation	Power, MW	Flux, n/cm^2-s	Cold a Hot Source
HIFAR [a]	Lucas Heights, Australia	1958	10	1.4×10^{14}	—
OPAL [a]	Lucas Heights, Australia	2006	20	4.0×10^{14}	1 Cold
NRU [a]	Chalk River, Canada	1957	120	3.0×10^{14}	—
HWRR [b]	Beijing, China	1958	15	2.8×10^{14}	1 Cold
CNS [d]	Saskatoon, Saskatchewan	?	20.	4.0×10^{14}	1 Cold
CARR [b]	Beijing, china	2008	60	8.0×10^{14}	1 Cold 1 hot (
ETRR-2 [b]	Egypt	1997	22	2.8×10^{14}	—
ILL-HFR [a]	Grenoble, France	1972	58	1.2×10^{15}	2 Cold 1 Hot
Orphée [a]	Saclay, France	1980	14	3.0×10^{14}	2 Cold 1 Hot
BER-2 [a]	Berlin, Germany	1973	10	2.0×10^{14}	1 Cold
FRJ-2 [a]	Jülich, Germany	1962	23	2.0×10^{14}	1 Cold
FRG [a]	Geesthacht, Germany	1958	5	0.8×10^{14}	1 Cold
FRM-2 [a]	Munich, Germany	2003	20	7.0×10^{14}	1 Cold 1 Hot
BNC [a]	Budapest, Hungary	1959	10	1.6×10^{14}	1 Cold
Dhruva [b]	Trombay, India	1985	100	1.8×10^{14}	
RSG-GAS [b, c]	Serpong, Indonesia	1987	30	2.5×10^{14}	—
JRR-3M [a]	Tokai, Japan	1962	20	2.0×10^{14}	1 Cold
Hanaro [a]	Taejon, Korea	1996	30	2.8×10^{14}	—
MINT [b, c]	Bangi, Malaysia	1982			
HOR [a]	Delft, Netherlands	1963	2	0.2×10^{14}	—
JEEP2 [a]	Kjeller, Norway	1966	2	0.2×10^{14}	1 Cold
IR8 [a]	Moscow, Russia	1957	8	1.5×10^{14}	1 Cold
IWW-2M [a]	Ekaterinberg, Russia	1966	15	1.0×10^{14}	
WWR-M [a]	Gatchina, Russia	1960	18	1.4×10^{14}	1 Cold
PIK [a]	St. Petersburg, Russia	?	100	1.2×10^{15}	1 Cold 1 Hot
R-2 [a]	Studsvik, Sweden	1960	50	1.0×10^{14}	
TRR-1 [b, c]	Bangkok, Thailand	1997	10	2.0×10^{14}	
HFIR [a]	Oak Ridge, United	1966	85	1.2×10^{15}	1 Cold

Pulsed Spallation Sources

Table 2.7 Pulsed Spallation Neutron Sources

Source, Turn-on date	Proton Beam Energy, Current	Pulsing Frequency	Target Material	Moderators	Status 2012
ZING-P, Argonne 1974	300 MeV ~100 nA	30 Hz	Pb brick	Polyethylene $((CH_2)_n)$	Shut 1975
ZING P', Argonne 1977	500 MeV, 3 μA	30 Hz	W, natural U	$(CH_2)_n$, L-H_2	Shut 1980
IPNS, Argonne, US 1981	450 MeV 15 μA	30 Hz	natural U, (enriched U)	L-CH_4 @ 100 K(1), S-CH_4 @ 25 K (2)	Shut 2008
ISIS, RAL, UK 1985	800 MeV 300 μA	50 Hz	Ta, W, (natural U)	L-CH_4 @ 100 K(1), L-H_2O @ 300 K(2), L-H_2 @ 35 K(1)	Opera
KENS, KEK, Japan 1980	500 MeV 7 μA	20 Hz	W, (natural U)	S-CH_4 @ 20 K (1), L-H_2O @ 300 K(1)	Shut 2006
MLNSC, LANL, US 1986	800 MeV 100 μA	20 Hz	W	L-H_2O @ 300 K(3) L-H_2 @ 20 K(1)	Opera
IN-6, INR Troitsk, Russia, 1998	600 MeV up to 500 μA	50 Hz	W	Polyethylene, H_2O @ 300 K	Comm sionin
SNS, ORNL, US, 2006	1.0 GeV, 1.4 mA	60 Hz	Mercury	L-H_2O @ 300 K(2) L-H_2 @ 25 K(2)	Opera
MLS, J-PARC, Tokai-mura, Japan, 2008	3 GeV, 0.333 mA	25 Hz	Mercury	L-H_2O @ 300 K L-H_2 @ 25	Opera
ISIS TS-2 RAL, UK, 2008	800 MeV, 60 μA	10 Hz	W	L-H_2O @ 300 K L-H_2 @ 25 K S-CH_4 @ 30 K	Opera

Steady Spallation Sources

Table 2.8 Steady Spallation Sources

Source, Turn-on date	Proton Beam Energy, Current	Pulsing Frequency	Target Material	Moderators	Status
ING, Chalk River, Canada, 1965	1 GeV, 65 mA	Steady	Pb-Bi	D_2O	Design S
TNTF, TRIUMF, Canada, 1978	500 MeV, 400 μA	Steady	Liquid Pb	D_2O, H_2O	Shut dow 1985
SINQ, PSI Switzerland, 1996	600 MeV, 1.5 mA	Steady (RF only)	Zr, Steel-clad Pb, Pb-Bi (2006)	D_2O, L-H_2	Operatin

Sources Studied or Under Construction

Pulsed Spallation Sources

. Spallation Source Projects under Construction or under Study.

Source, Location	Proton Beam Energy, Current	Pulsing Frequency	Target Material	Status 2012
ESS, Lund, Sweden	1.33 GeV, 4 mA	50 Hz	Mercury	Site decided, Completion 2019
CSNS, Guangdong, China	1.6 GeV, 62 μA	25 Hz	Tungsten	Design Study underway
AUSTRON Austria	1.6 GeV, 150 μA	25 Hz	Tungsten	Abandoned 1998

Pulsed Fast Reactor

The IBR-2

Table 2.10 Parameters of the IBR-2 Reactor in Dubna, Russia

Average thermal power, MW	Peak Power in pulse, MW	Pulse repetition rate, Hz	Thermal-Neutron Flux at moderator surface, n/cm^2-s (surface average)		Pulse FWHM, μs	Status
			Time-Average	Peak		
2	1500	5	8 x 10^{12}	5 x 10^{15}	320	Upgraded 2011

[Update]

The Spallation Neutron Source (SNS) *at ORNL*

SNS first operation April 2006. Shown in 2009.

At 1.4 MW is the world's leading pulsed spallation source, ~ 8x ISIS;.

Japan Spallation Neutron Source (JSNS) at J-Parc

The European Spallation Source (ESS) at Lund, Sweden (2019)

A Future Prospect?

Very Cold Neutrons (VCNs) are those with "Rule of 2" parameters that could be produced from moderators with the spectral temperature of superfluid He (< 2.2 K) and in a broad range thereabout:

- *Energies ~ 200 micro-eV*
- *Spectral Temperature ~ 2 K.*
- *Wavelengths ~ 20 Å*
- *Speeds ~ 200 m/s.*

Very Cold Neutrons

Neutron optical devices work better at long wavelengths than at conventional wavelengths, because refractive indices are proportional to (wavelength)^2, as is gravity droop. Critical angles are proportional to wavelength.

Magnetic lenses have advantages over material lenses because they present no absorption and scattering material to the passing neutron beams.

New opportunities and new science certainly lie in instruments and techniques based on VCNs.

Only one VCN beam relevant for instrument testing exists, PF2 at ILL.

Thank You!

Questions?