Prospects for Future Neutron Facilities

XIV School of Neutron Scattering (SoNS)
International School of Neutron Science and Instrumentation
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John M. Carpenter
Argonne National Laboratory and
Oak Ridge National Laboratory

CONTENTS

About neutron sources

Types of sources

Reactors

Accelerators: short-pulse, long-pulse, steady

Existing facilities

Prospects:

STSs, VCNs, CANS, Laser-driven, Gallium coolant, adapting abandoned e^- machines

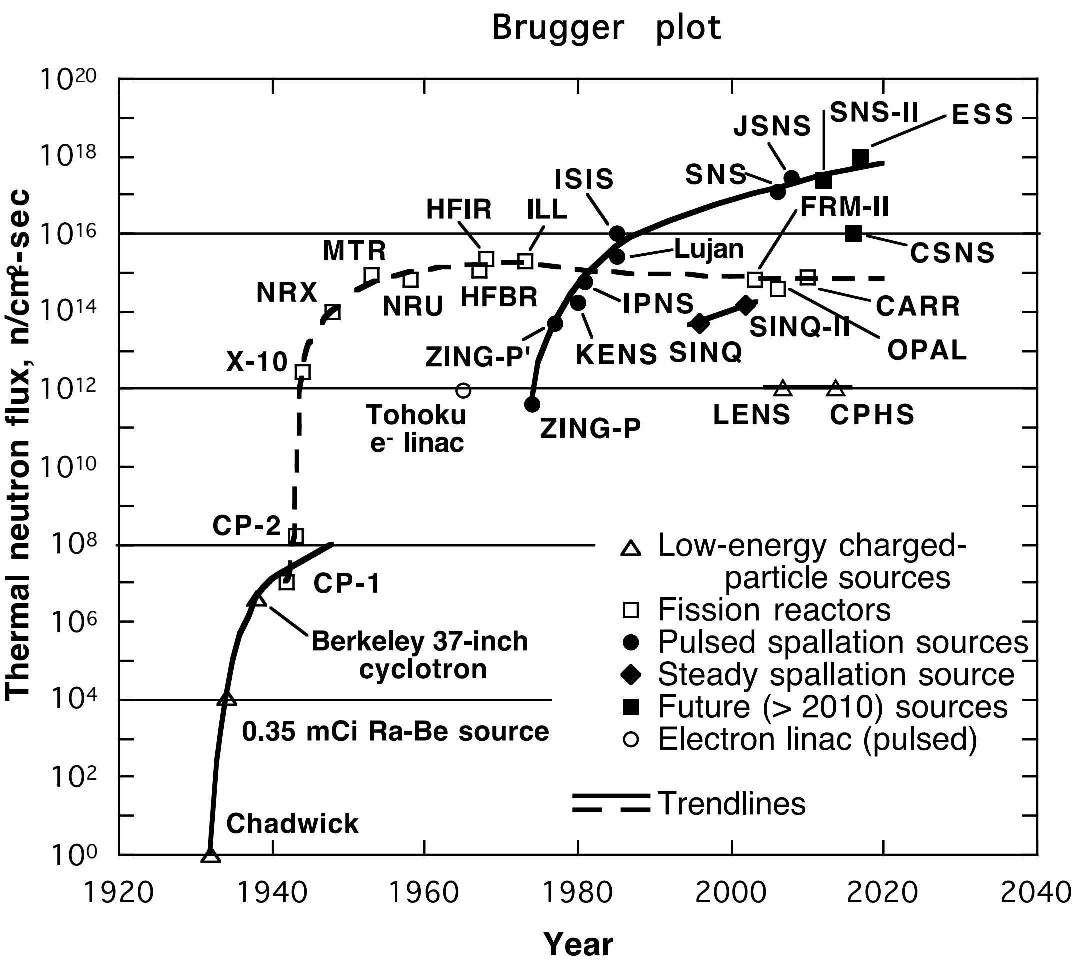
Call for action

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.

See Mason, et al. (2013) The early development of neutron diffraction: science in the wings of the Manhattan Project, *Acta Cryst.* A **69** p. 1-8.

Neutron Science Facilities



Types of Neutron Sources

Reactors:

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

FRM-2 at Munich: fluxes ~ $1. \times 10^{15}$ 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.

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

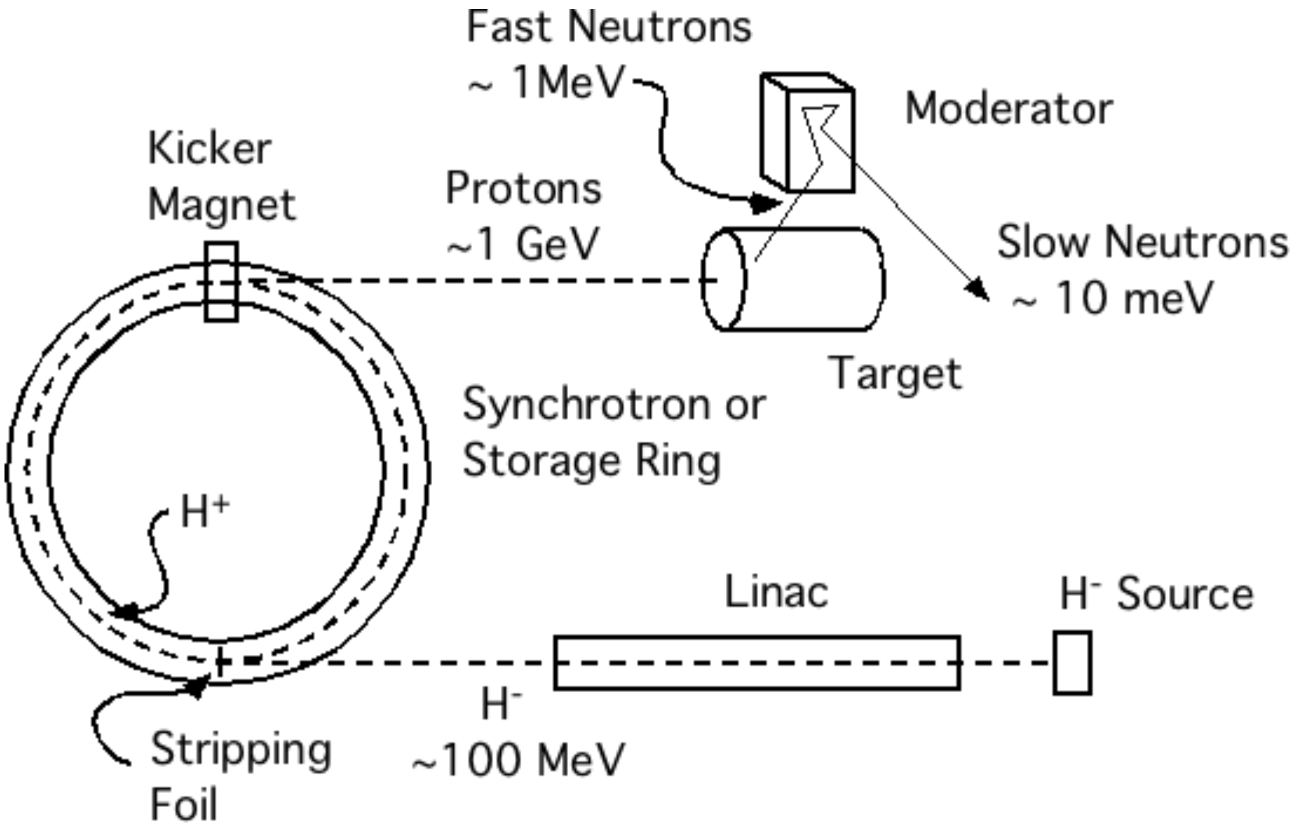
- Low time-averaged flux.
- Not all applications exploit time structure.
- Rapidly evolving technology.
- Thermoelastic shock.

Short-Pulse vs. Long-Pulse Sources

Most of the existing pulsed neutron sources produce fast neutrons in short (~ microsec) 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.

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.

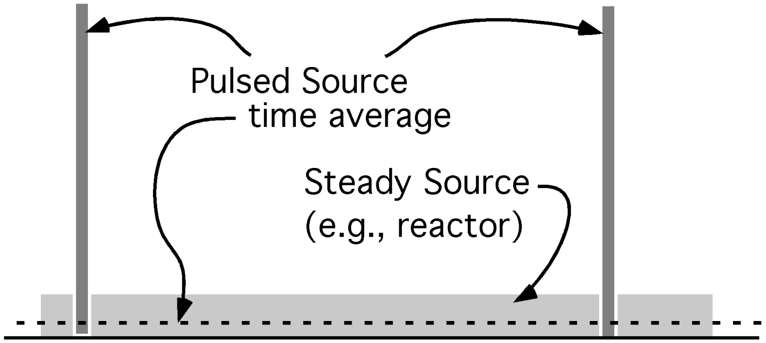
Pulsed vs. Steady Sources

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$f$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 $\Delta t_{\text{mod}} = 20\ \mu s$, the duty-cycle factor is $1 \big/ f\,\Delta t_{\text{mod}} = 10^3$.

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.

Types of Neutron Sources

CW Spallation Source:

SINQ at Paul Scherrer Institut (PSI).

2.2 mA, 590 MeV, 1.3 MW

2×10^{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.

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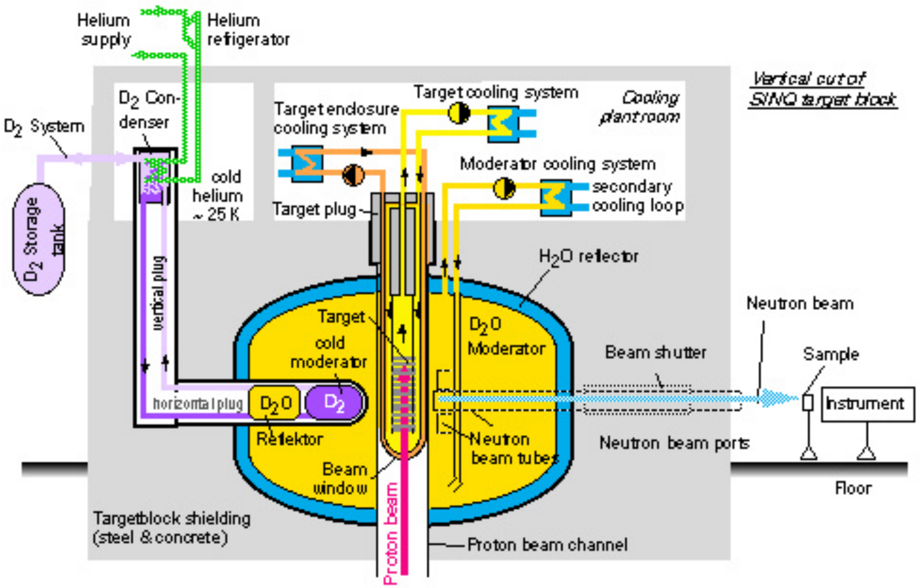
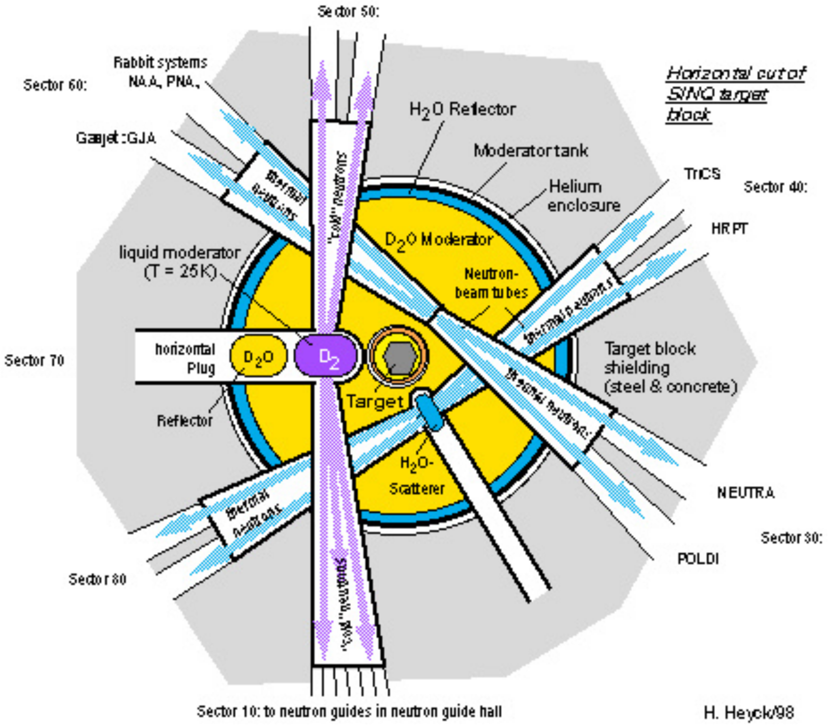
The Spallation Neutron Source SINQ





Types of Neutron Sources

Low-Energy Neutron Sources

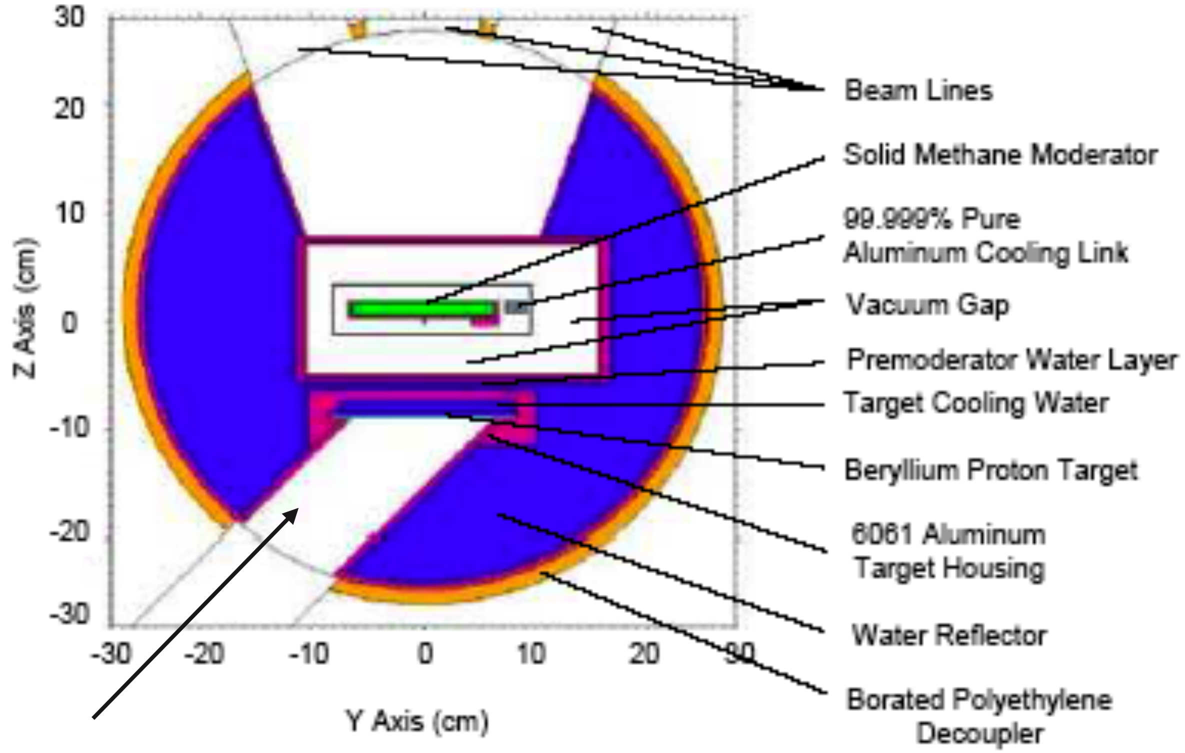
Advantages:

- 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.



protons

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Lists of Sources

Research Reactors

Reactor	Location	First Operation	Power, MW	Flux, n/cm^2-s	Cold a Hot Sourc
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 Neutron Sources

Pulsed Spallation Sources

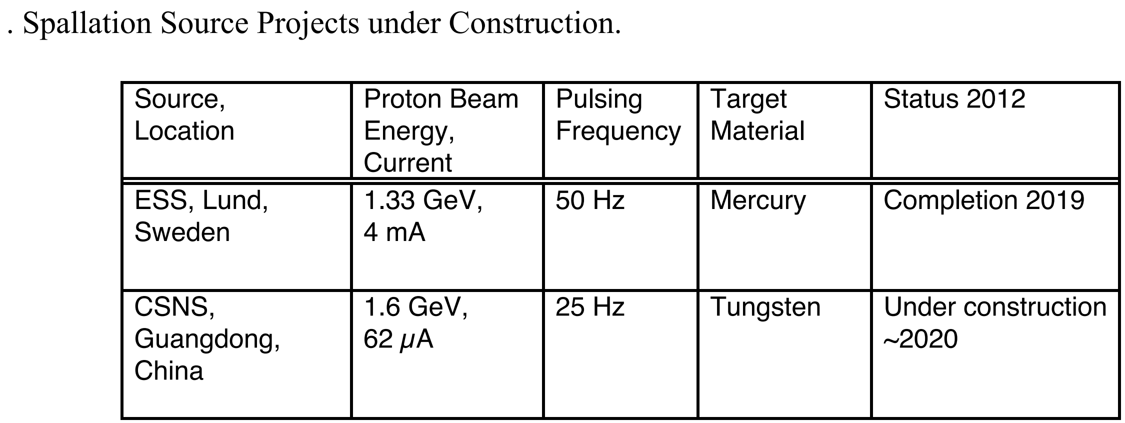
Source, Turn-on date	Proton Beam Energy, Current	Pulsing Frequency	Target Material	Moderators	Statu 2012
ZING-P, Argonne 1974	300 MeV ~100 nA	30 Hz	Pb brick	Polyethylene ($(CH_2)_n$)	Shut 1975
ZING P', Argonne 1977	500 MeV, 3 μA	30 Hz	W, natural U	$(CH_2)_n$, L-H_2	Shut 1980
IPNS, Argonne, US 1981	450 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	Comn 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

Source, Turn-on date	Proton Beam Energy, Current	Pulsing Frequency	Target Material	Moderators	Status
TNTF, TRIUMF, Canada, 1978	500 MeV, 400 μA	Steady	Liquid Pb	D_2O, H_2O	Shut down 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	Operating

Sources Studied or Under Construction

Pulsed Spallation Sources



. Spallation Source Projects under Construction.

Source, Location	Proton Beam Energy, Current	Pulsing Frequency	Target Material	Status 2012
ESS, Lund, Sweden	1.33 GeV, 4 mA	50 Hz	Mercury	Completion 2019
CSNS, Guangdong, China	1.6 GeV, 62 μA	25 Hz	Tungsten	Under construction ~2020

Pulsed Fast Reactor

The IBR-2

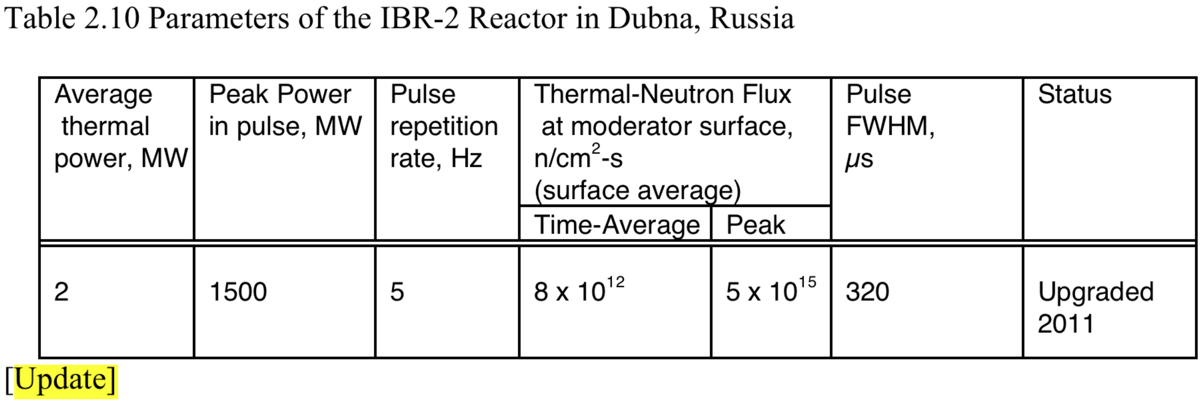
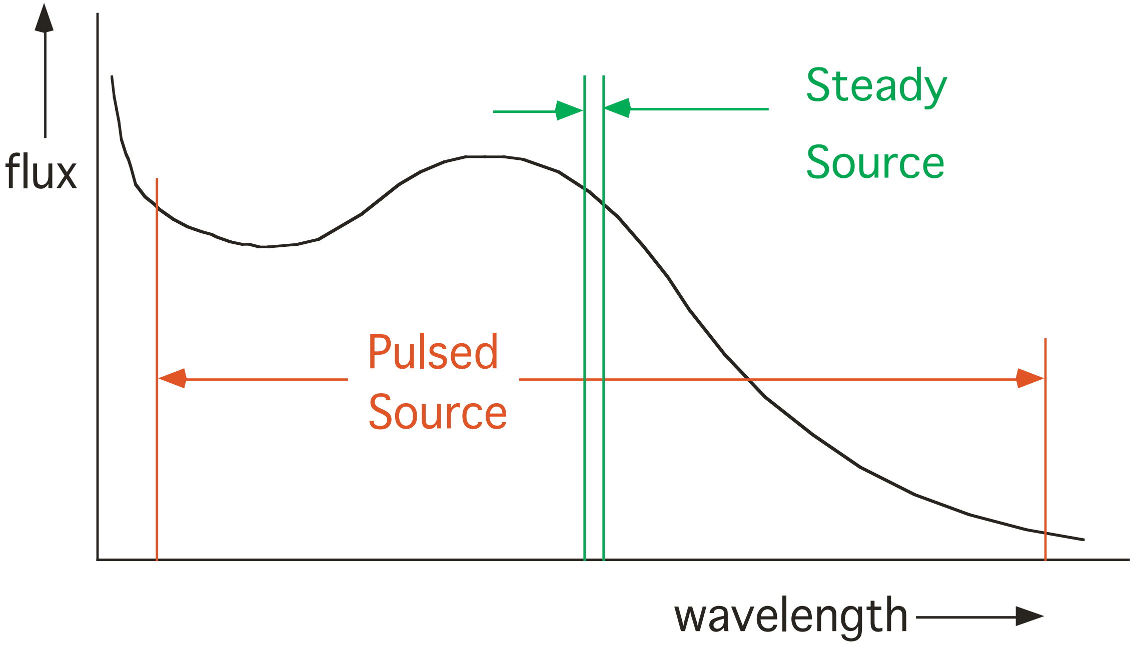


Table 2.10 Parameters of the IBR-2 Reactor in Dubna, Russia

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]

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.

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;.

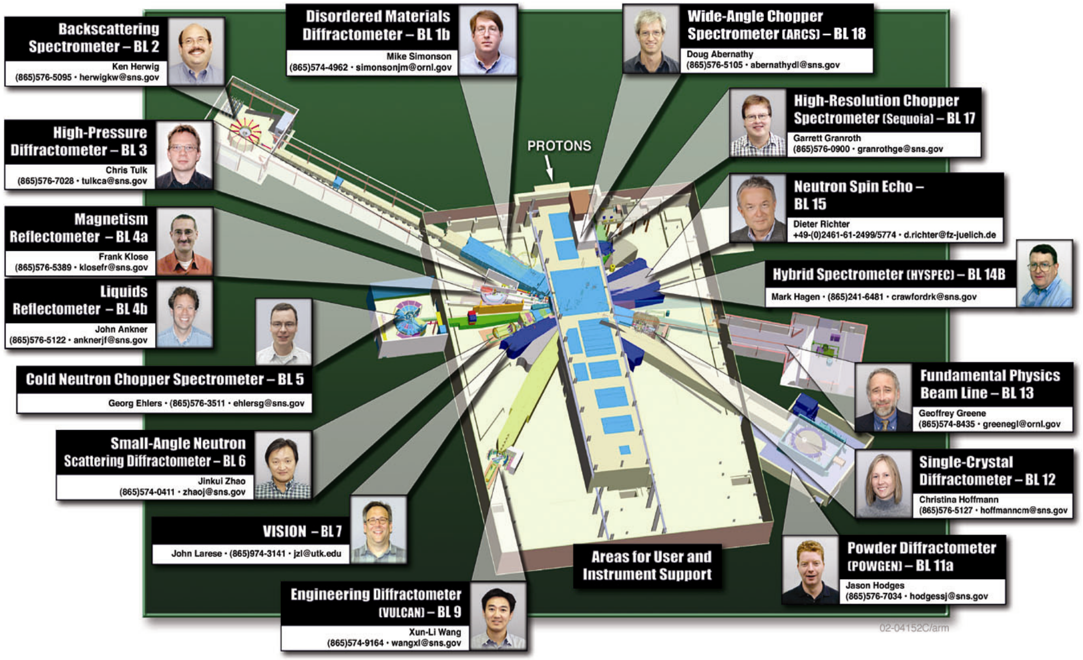
SNS and Instruments

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

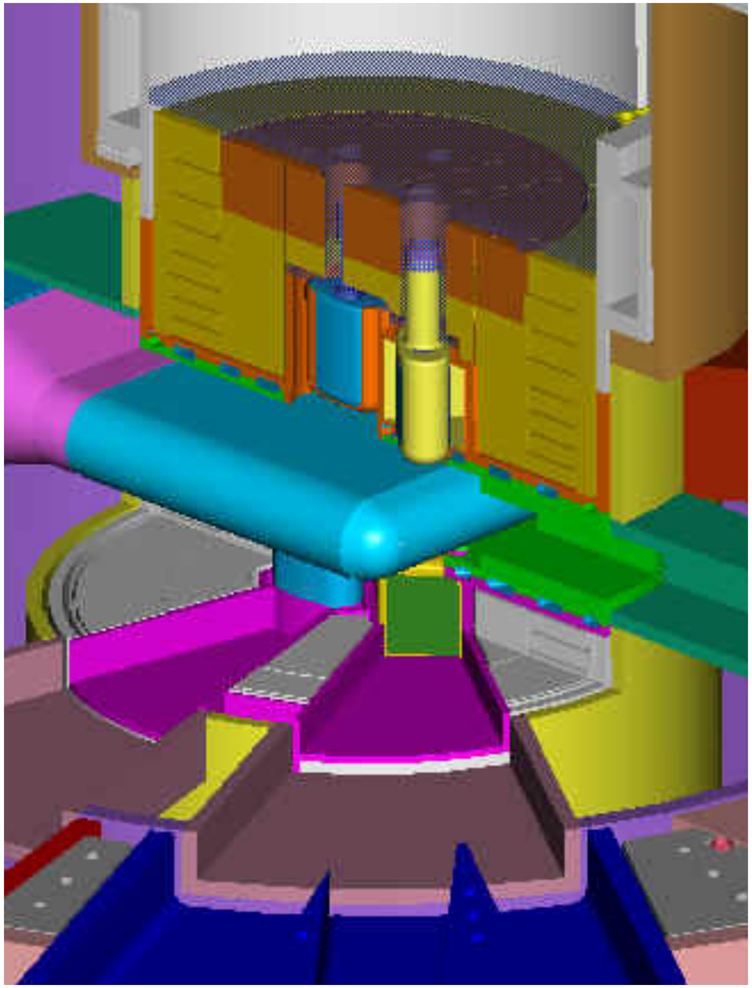
- DOE, including SING1 and SING2 instrumentation projects, foreign, and NSF initiatives.

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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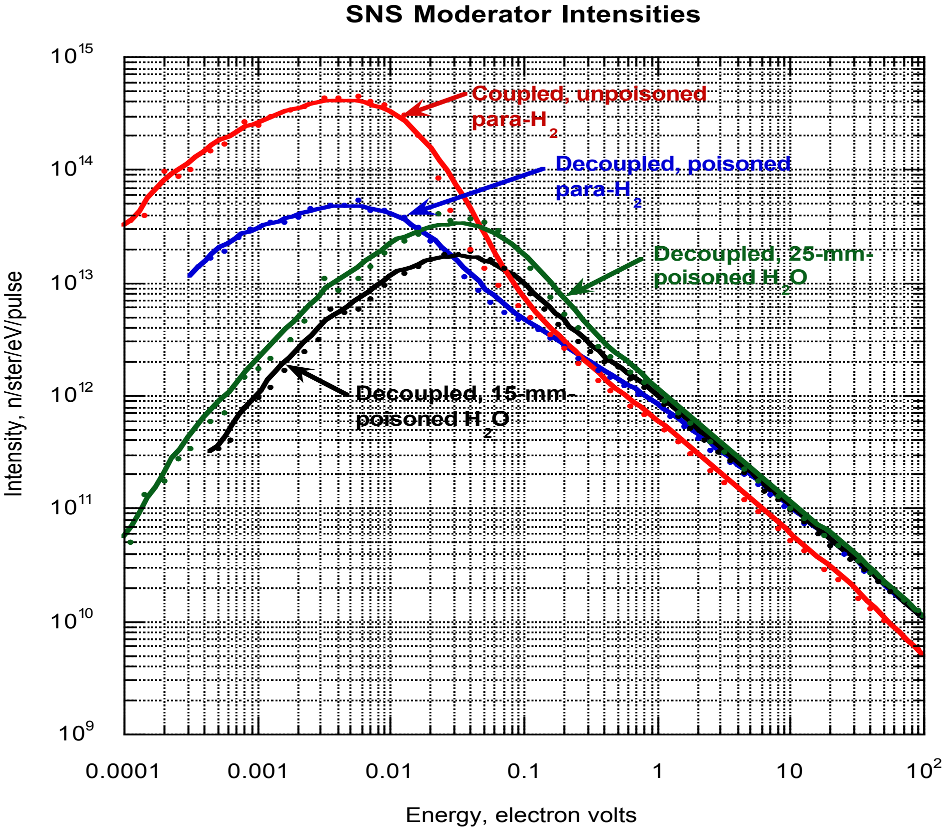
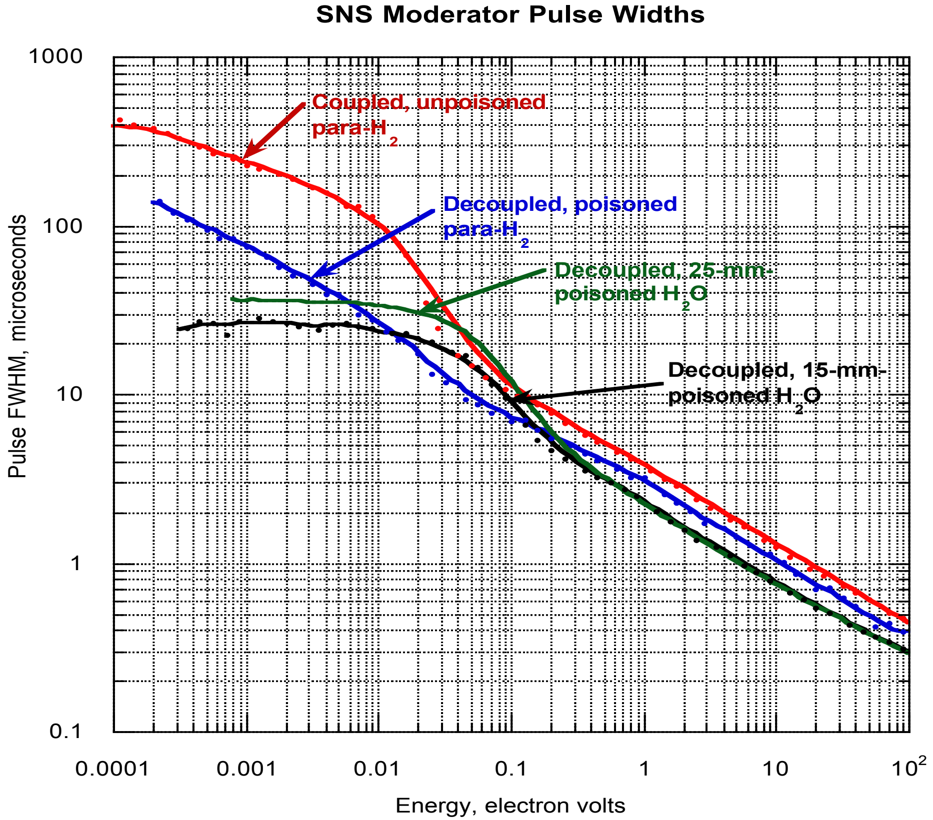
SNS Moderator Intensities and Pulse Widths



SNS Moderator Intensities



SNS Moderator 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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Japan Spallation Neutron Source (JSNS) at J-Parc

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

New Prospects: Second Target Stations

- The large pulsed spallation sources can accommodate more than one target station, consisting of distinct primary shields, target/moderator systems, and instrument arrays. Driven by the same accelerator systems and optimized for different applications than the existing, first target stations and typically operating at considerably lower pulsing frequency.

Second Target Stations

Such second target stations, STSs, are under serious consideration for SNS (ORNL) and JSNS (J-PARC), and one at ISIS (RAL, UK) already exists, called TS2, has been operating since 2010.

These are aimed to serve the needs for long-wavelength neutrons. The SNS may have two separate target/moderator systems in the same shield, one for “conventional” cold neutrons, the other for VCNs.

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. See Carpenter and Micklich (1996), Applications of a very cold neutron source, ANL report ANL-05/42.

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

Compact Accelerator-driven Neutron Sources (CANS)

Small-scale, inexpensive, accelerator-driven neutron sources can, at least partially, fill the roles of small research reactors, many of which are being shut down. Chun Loong's talk yesterday described these sources.

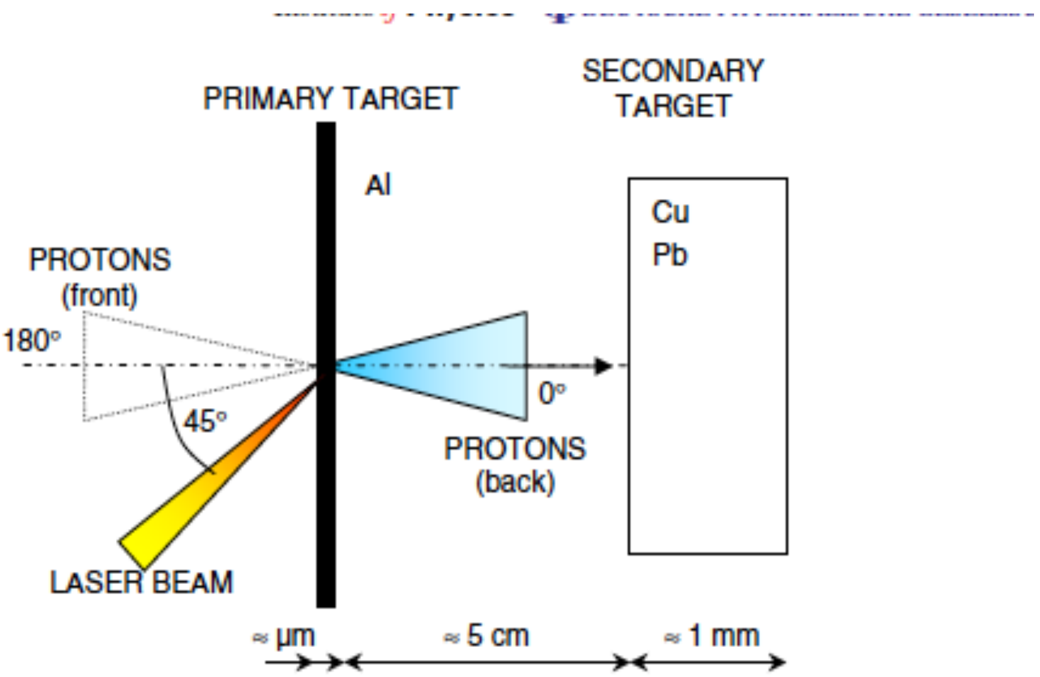
See also, Anderson, et al. (2016). Research opportunities with compact accelerator-driven neutron sources, *Physics Reports*, in preparation.

Adventurous Ideas

Here I mention some concepts that may represent new opportunities for neutron sources in the future. (Some, not so adventurous.)

Laser-generated nanosecond pulsed neutron source

Tomaˇz Zagar, *Jean Galy, Joseph Magill and Mark Kellett (2005),* *New Journal of Physics* ***7 253***



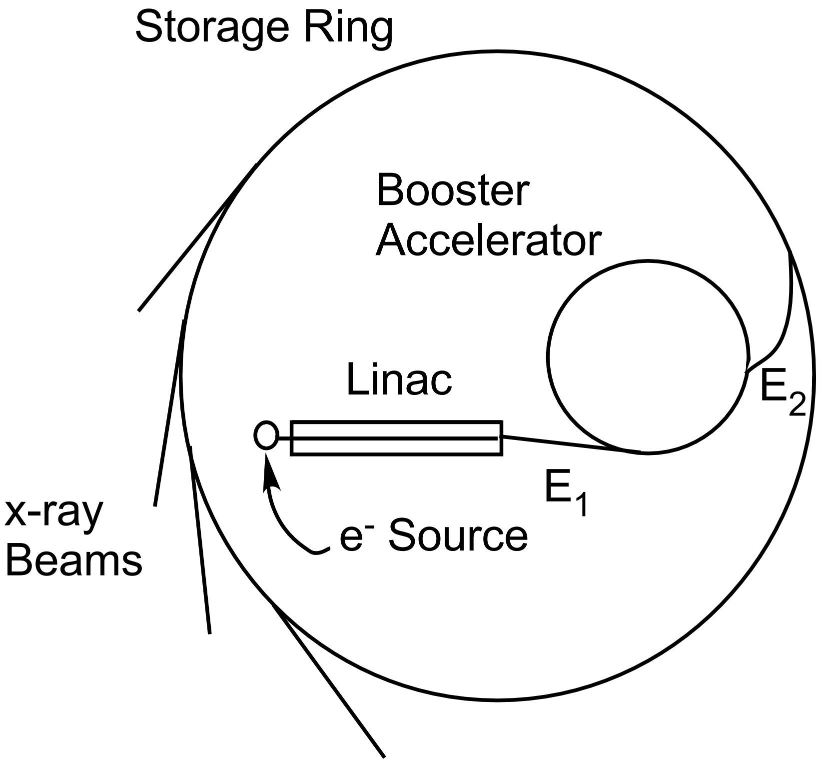
Adapting e$^-$ Synchrotrons as Proton Synchrotrons

Abandoned GeV electron-synchrotron injectors at synchrotron light facilities might be converted in the course of facility upgrades into drivers for neutron facilities, for example, a case with accelerated electron energy 1.5 GeV, as at NSRF Hsinchu, Taiwan. We did this at ANL in 1972, on a 2-GeV machine from Cornell University to provide a prototype for IPNS.

Adapting e^- Synchrotrons

The opportunity would come about when the Storage Ring was replaced with one storing higher-energy electrons.

In the adaptation, the e^- Source would become a proton (H^-) source, the Linac would accelerate H^- ions to the Booster Accelerator at energy E_1, which after stripping injection accelerates protons to energy E_2.



The Source-Linac-Booster is then a high-energy pulsed proton source to drive a neutron source.

Adapting e^- Synchrotrons

The fundamental observation is that the maximum field and bending magnets and the vacuum chamber radius are given, for the existing electron energy. The radius is $R=p/(qB)$, where p is the particle momentum, q is the particle charge, and B is the magnetic field strength. For the case at hand, $R = 4.584$ m. For the (fully relativistic) electrons, $p=1.5$ GeV/c.

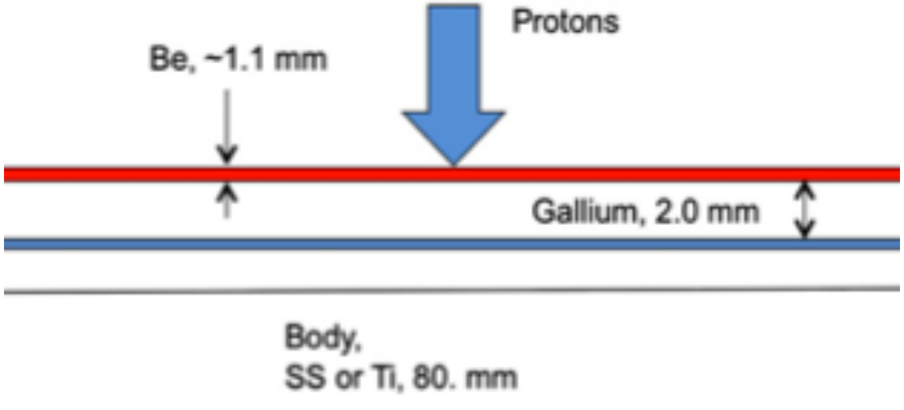
The kinetic energy of a proton (circulating oppositely) with the same momentum is $E_p=[(m_pc^2)^2+c^2p^2]^{1/2}-m_pc^2$, which for the same momentum as 1.5 GeV electrons is $E_p=0.834$ GeV—good for spallation neutron production.

Gallium Coolant

Gallium has many advantages for cooling CANS targets:

- Low melting (~ 30 C), high boiling (~ 2200 C) (No DNB problem).
- Desirable thermophysical properties like H_2O.

Disadvantage: incompatible with some materials, OK with others. E. g., a gallium-cooled beryllium metal target for 13-MeV protons:



Gallium Coolant

Demonstrated at MIT in 1997: tandem accelerator,
4.1 MeV, ~ 2 mA protons on Ga-cooled Be metal target.

See Blackburn, B. W., and J. C. Yanch, Liquid gallium cooling of a high-power beryllium target for boron neutron capture therapy. www.trshare.triumf.ca/ buckley/wttc/pdf/ 1999/p7.pdf.

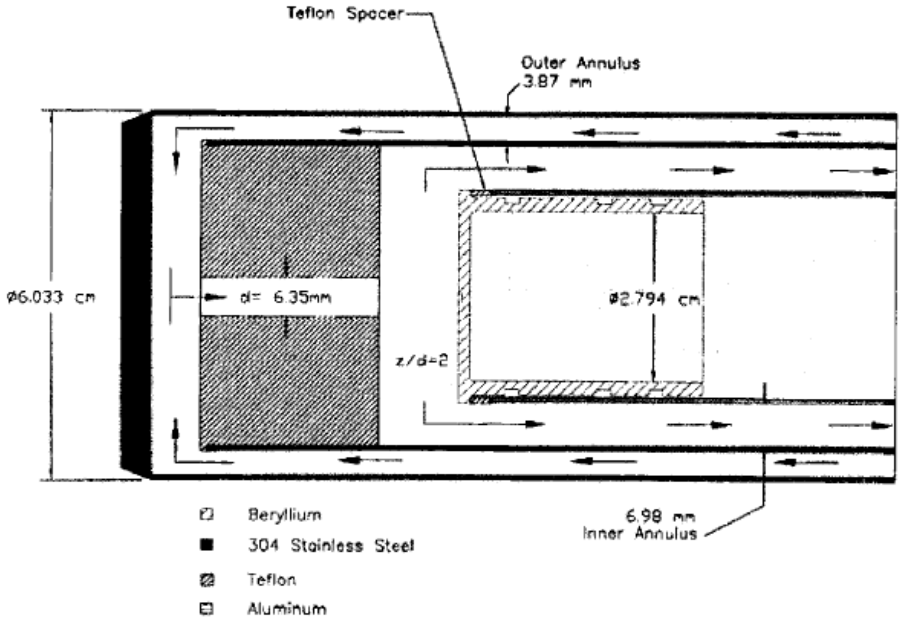
See also J. M. Carpenter, Gallium-cooled target for CANS, NIM A (2011), doi:10.1016/j.nima.2010.12.032 (UCANS-1 proceedings).

A high-power Beryllium target for use in accelerator boron neutron capture therapy: The Blackburn experiment

Liquid gallium metal has been tested as the working fluid in a heat removal system for a neutron-producing beryllium target which will be capable of operating under conditions that would be beyond the critical heat flux of water under similar flow rates. Liquid gallium possesses thermo-physical properties that make it ideal for applications with heat fluxes as high as 20 MW/m^2.

B. W. Blackburn and J. C. Yanch, 2003.

Blackburn’s Ga-cooled target



Coolant passes through the outer annulus, impinges on the beryllium target, and travels back in the inner annulus.

B. W. Blackburn, High power target development for accelerator-based neutron capture therapy, PhD. Thesis, MIT February 2002.

Summary

Large neutron scattering facilities exist that well serve the community.

Some new ones are now in prospect, but several existing ones face being shut down in the near future. (One hopes not!)

Replacements and additional facilities are needed. Start planning now!

See SCIENCE magazine, 18 March 2016 vol. **325** p.1252.

CANSs are coming–support and use them.

RESEARCH FACILITIES

Europe on course for a neutron drought

Billion-euro accelerator won't make up the shortfall, experts say

By **Edwin Cartlidge**, *in Rome*

Neutrons may be ubiquitous in matter, but the intense, energetic neutron beams that scientists use to probe materials are a scarce commodity. In Europe, they will soon get a lot scarcer, according to a panel commissioned to assess the impact of the imminent closure of many of the continent's aging neutron reactors.

The panel, known as the Neutron Landscape Group (NLG), said last week that as the aging reactors shut down over the next 5 to 10 years, the number of neutrons available for research will fall by as much as half. A new, accelerator-based neutron source, the world's most intense, is due to turn on in Sweden by the end of the decade. But it will take years to reach full capacity, and in the meantime scientists who rely on neutrons will face a drought, unless the life span of some of the reactors can be extended. Multiple shutdowns "will have a traumatic effect on the neutron community," says NLG Co-Chair Colin Carlile of Uppsala University in Sweden. "But none of the owners or users want to talk about it in public."

The panel published its findings in the latest installment of a "road map" released last week by the European Strategy Forum on Research Infrastructures (ESFRI), which advises the European Union. The road map provides a rolling list of proposed pan-European facilities that ESFRI deems scientifically excellent and likely to start up within the next 10 years. This one includes five new projects—facilities studying the atmosphere, river-sea systems, and food security, as well as a solar telescope and a cultural heritage center—as well as others that have long been on scientists' wish lists.

It also includes NLG, which takes a special look at neutrons. Chaired by physicists Carlile and Caterina Petrillo of the University of Perugia in Italy, NLG points out that more than 6000 scientists and engineers in Europe use neutrons to study materials ranging from magnets and superconductors to plastics and proteins. However, it says, two-thirds of the continent's operating neutron sources were built in the 1960s and 70s, and most of those are due to close because of their age and antinuclear sentiment.

The €1.8 billion European Spallation Source (ESS) is meant to fill some of that gap. Under construction in Lund, Sweden, the ESS will use a proton accelerator to generate the world's most powerful beams of neutrons and is due to start operating in 2019. But limited initial funding means that the facility will have just 16 instruments up and running by 2028. That, NLG says, will leave researchers considerably worse off than they are today with the 40 instruments at the most powerful existing source, the Institut Laue-Langevin (ILL) research reactor in Grenoble, France.

The ILL is the wild card in the picture. The convention signed by the three countries that operate the ILL—France, Germany, and the United Kingdom—is due to expire in 2023, and neither the United Kingdom nor France has said whether they will extend the reactor's life. (Germany will likely want to finish its current license and so shut down in 2027.) Carlile says that this shortage would not only be devastating for current research, but would also make it much harder for younger researchers to gain experience in making neutron-based measurements. "People who use these facilities have no stepping stone to get there," he says, "unlike users of x-ray sources, which are available at universities."

According to the panel, neutron output over the next 15 years could be kept to within 20% of existing levels if the ILL and the other sources facing closure operate until at least 2030. These extensions, Carlile estimates, would cost about €200 million. But by 2030, he notes, the ILL reactor will be more than 50 years old.

Robert McGreevy, director of the ISIS neutron source in Oxfordshire, U.K., says h facility—one of the few existing accelerator-based sources—will operate at least until 2030 and perhaps beyond. But he believes there is little hope that two of the facilities that NLG wants to remain open, in Paris and Berlin, can be kept operating. The fate of both, he says, has already been announced by the respective national governments.

Meanwhile, uncertainty hangs over the ESS. Its director, James Yeck, says that it is currently being built on schedule and within budget, but he acknowledges the danger that one of the project's 17 member countries could pull out, as happened in 2003. The project's management has delayed a decision about whether to buy additional equipment that would increase the neutron beam power from 3 to 5 megawatts until 2017.

Carlile says that to secure the future of neutron research in the long term, Europe will need several new medium-flux neutron sources, costing about €500 million each. But McGreevy believes Europe's aversion to nuclear power means that any new mid-sized neutron sources will have to be accelerators rather than reactors which, he says, will be "technically very challenging."

And researchers may not be able to rely on the current mainstay, the ILL, even if the countries overseeing it decide to extend its life. McGreevy thinks that the ILL has done all it can to respond to new safety requirements imposed after the Fukushima nuclear disaster in Japan. But another major nuclear accident, he says, "would probably be the death knell for ILL." ■

Architect's vision of the target station and instrument halls of the European Spallation Source in Sweden.

IMAGE: ESS/TEAM HENNING LARSEN ARCHITECTS

Thank You!

Questions?