Neutron Sources for Materials Research

National School on Neutron and X-ray Scattering

Oak Ridge

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IPNS, SNS

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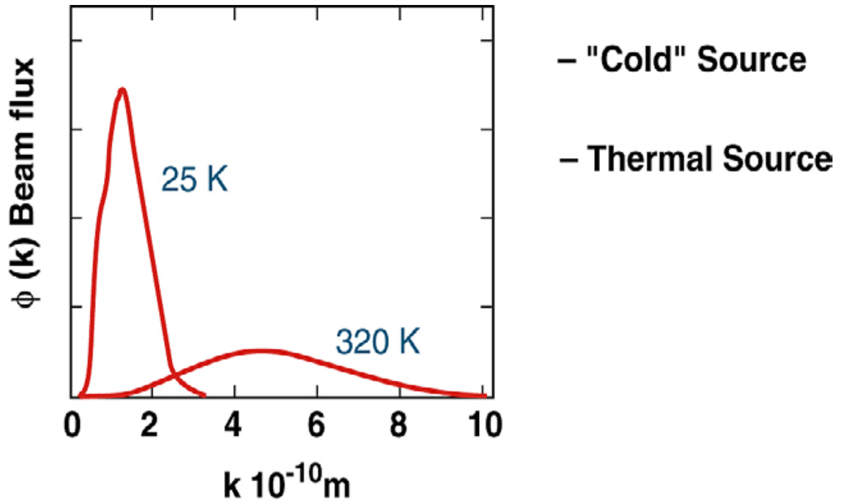
Neutrons and Neutron Sources

- James Chadwick discovered the neutron in 1932.
- In 1936 Mitchel & Powers and Halban & Preiswerk first demonstrated coherent neutron diffraction in (Bragg scattering by crystal lattice planes) as an exercise in wave mechanics.
- 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's group used Bragg scattering to measure nuclear cross-sections at early Argonne reactors.

Neutrons and Neutron Sources-cont'd

- A reactor moderates the neutrons produced in the fission chain reaction resulting in a Maxwellian energy distribution peaked at T (300K).



- "Thermal" neutrons:

$$T = 293\ K$$

$$E = 25.2\ meV \text{ or } 6.12\ THz$$

$$\lambda = 1.798 \quad \text{or } k = 3.49 \times 10^{10}\ m^{-1}$$

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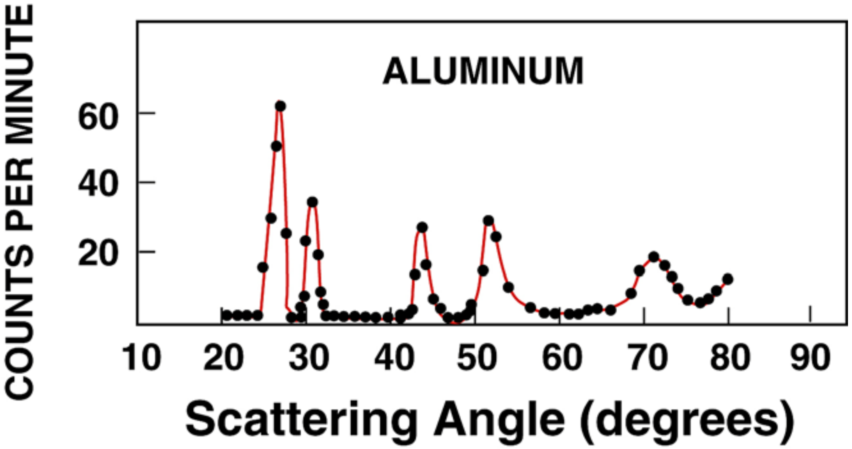
Neutrons and Neutron Sources-*cont'd*

- The application of slow neutron scattering to the study of condensed matter had its birth in the work of Wollan and Shull (1948) on neutron powder diffraction.

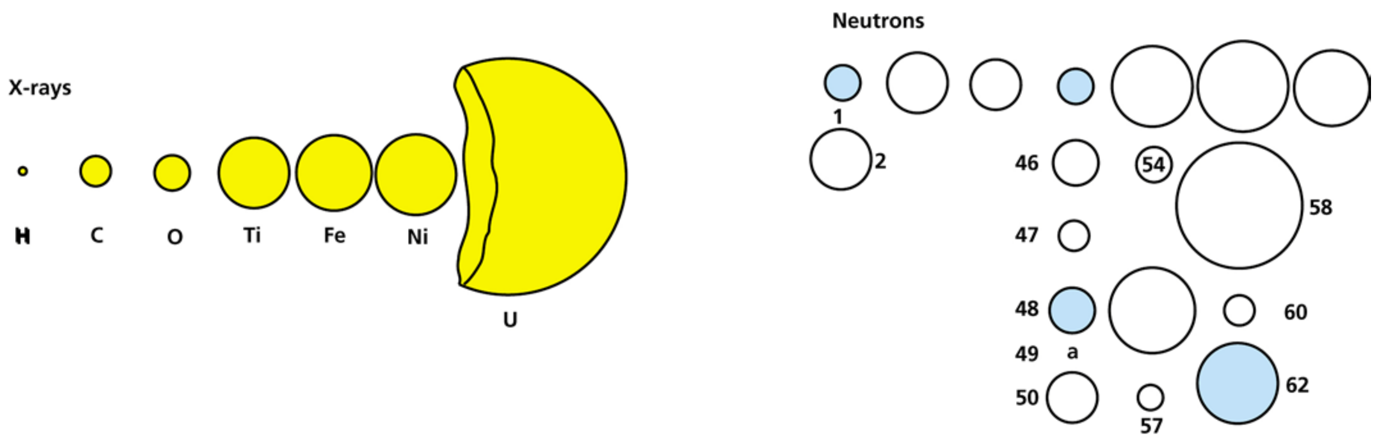


Clinton Pile • Oak Ridge

- The neutron is a weakly interacting, non-perturbing probe with simple, well-understood coupling to atoms and spins.
- The scattering experiment tells you about the sample not the probe.

Neutrons and Neutron Sources-*cont'd*

- You can easily work in extreme sample environments H,T,P,... (e.g.^{4}He cryostat) and penetrate into dense samples.
- The magnetic and nuclear cross-sections are comparable; nuclear cross-sections are similar, but vary randomly across the periodic table.



- Sensitivity to a wide a range of properties, both magnetic and atomic structural arrangements.

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Neutrons and Neutron Sources-cont'd

- Energies and wavelengths of thermal and cold neutrons are well matched to relevant energy scales in condensed matter (300K ~ 30 meV, 50K ~ 5 meV).
  - Inelastic experiments with good energy-transfer (1 meV) and momentum-transfer (0.01 Å-1) resolution are possible.
- Cross-section is proportional to static and dynamic correlation functions.
  - Results are of direct relevance to modern mathematical descriptions of interacting systems.
    - *Superconductivity.*
    - *Magnetism.*
    - *Phase transitions.*
    - *Electronic properties.*
    - *Non-equilibrium phenomena.*
    - *Structure and dynamics.*

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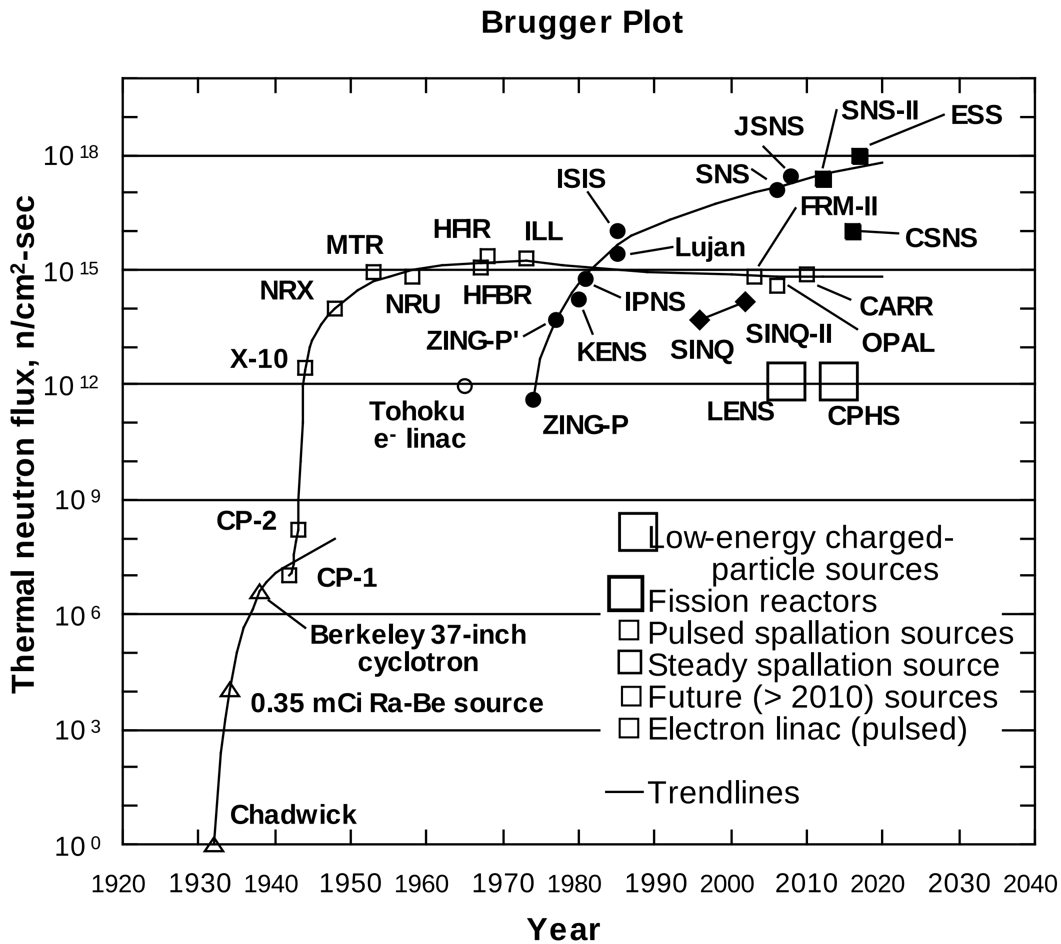
Neutrons and Neutron Sources-cont'd

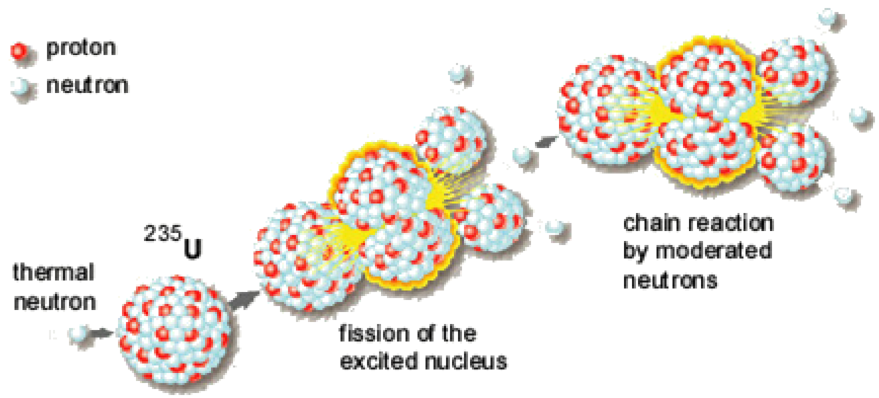
- Scientists carried out work leading to the development of inelastic neutron scattering throughout the 1950s.
- The real breakthrough was the development of the "constant-Q" mode of operating the triple-axis spectrometer pioneered by Brockhouse and co-workers at Chalk River.
  - This permitted the systematic investigation of the dynamic response of the material – concentrating on the regions of interest.

Development of Neutron Science Facilities



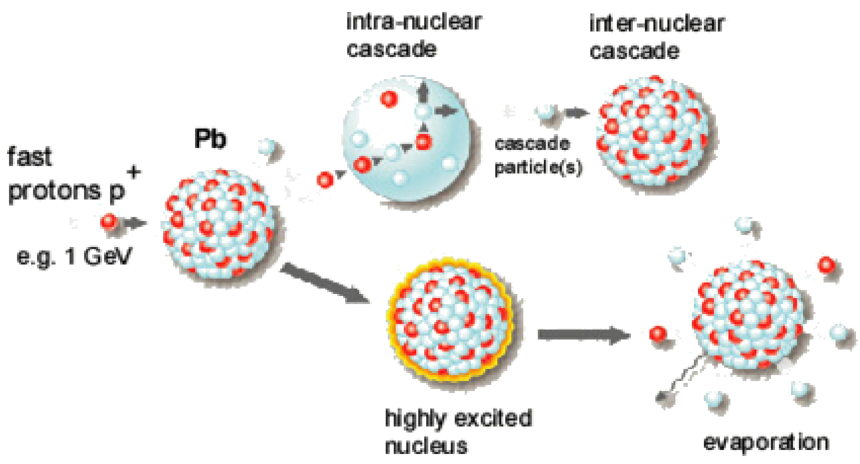
Redrawn 2009

How do we produce neutrons?



Fission

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



Spallation

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

Neutrons: Where do they come from?

- **Fission**:

$n + {}^{235}U = n + n + \text{fragments}$ *~ 180 MeV/n (as heat)*

Sustain chain reaction

Available

Moderated by

D_2O (H_2O)

to $E \sim k_BT$ (Maxwellian)

Neutrons: Where do they come from?

- **Spallation**:

p + heavy nucleus = 20 ~ 30 n + fragments

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

↓

~ 30 MeV/n (as heat)

Compare Fluxes

Reactors

DR3	Risø	2×10^{14} n/cm^2/s
ILL	Grenoble	1.5×10^{15} n/cm^2/s

Spallation sources

ISIS @ 160 kW	average	1.2×10^{13} n/cm^2/s
	peak	6×10^{15} n/cm^2/s
SNS @ 2 MW	average	4×10^{13} n/cm^2/s
	peak	3×10^{16} n/cm^2/s

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Neutrons: Where do they come from?

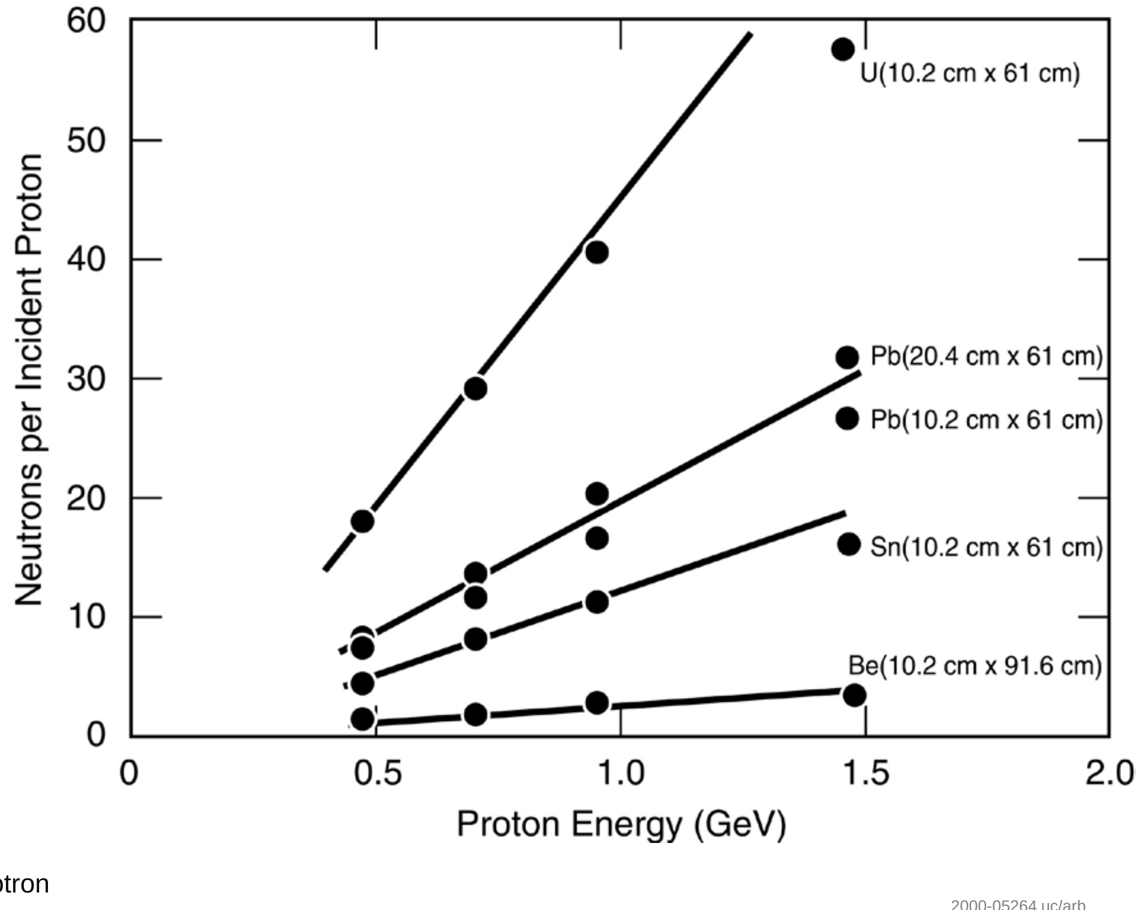
Measured Spallation Neutron Yield vs. Proton Energy for Various Targets, J. Frazer, et al. (1965)

Absolute Global
Neutron Yield

Yield (neutrons/proton)

$= 0.1(E_{GeV} - 0.12)(A+20)$,
except fissionable materials;

$= 50.(E_{GeV} - 0.12)$, ^{238}U.



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

Neutrons: Where do they come from?

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

p + ^{9}Be —> n + 2αλπηα + π ανδ

□> ν + ^{9}B

(Most of the proton energy appears as heat.)

5-15 MeV *~ 1300 MeV/n @ E_p = 13 MeV*

(deposited in ~ 1.1 mm)

3.5x10^{-3} n/p

Fluxes at moderator surface

LENS @ 30 kW	time average	4 X 10^{11} n/cm^2-sec
@ 20Hz	peak	1 X 10^{14} n/cm^2-sec

Global neutron yield for Be (p,n)

$$Y = 3.42x10^8(E_{MeV} - 1.87)^{2.05} \text{ n/}\mu\iota\chi\rho o\text{C}$$

Types of Neutron Sources-cont'd

- Reactor e.g., HFR at ILL, Grenoble, France.

  ~$1.5x10^{15}$ n/cm^2/s (recently underwent major refurbishment)

Advantages

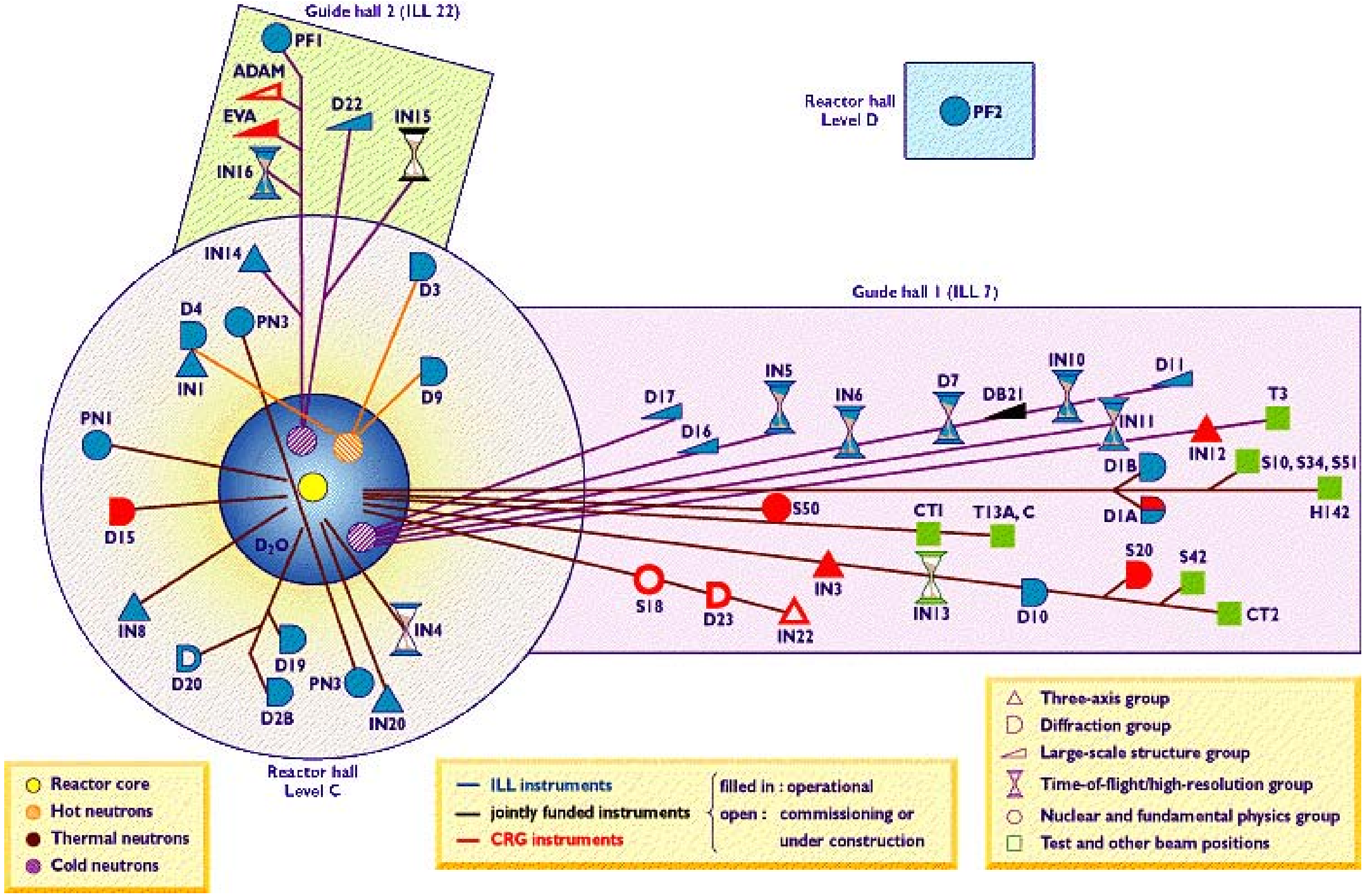
- High time averaged flux.
- Mature technology (source + instruments).
- Very good for cold neutrons.

Drawbacks

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

Types of Neutron Sources

The Institut Laue-Langevin, Grenoble



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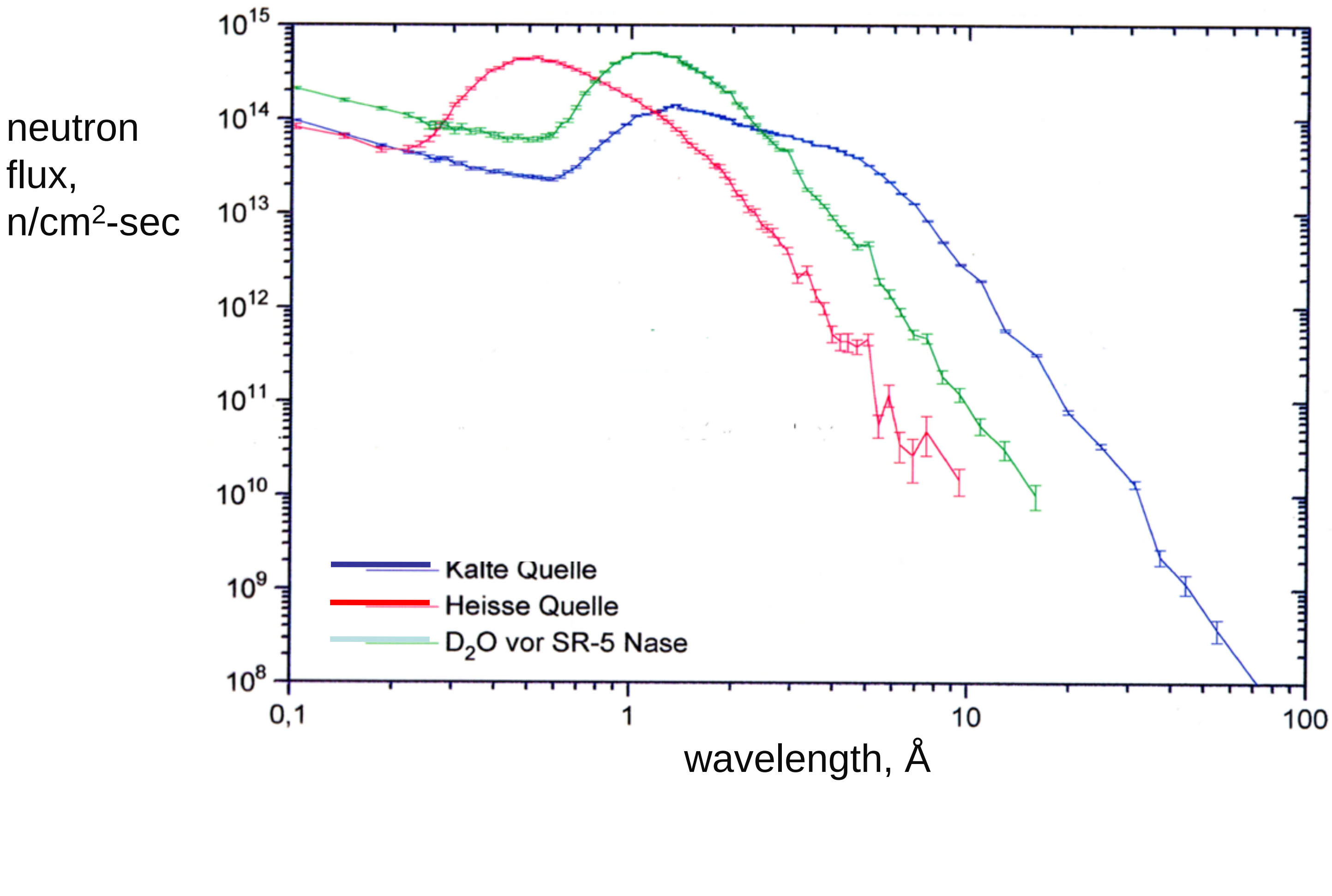
Types of Neutron Sources-cont'd

Source Spectra of the FRM-II Reactor



Types of Neutron Sources-cont'd

- Pulsed reactor
  - Tried only in Russia.
    - *IBR II Dubna.*
  - 2-5 Hz 1500 MW when on.

Advantages

- High peak flux.

Drawbacks

- Time structure not optimal (frequency too low, pulses too long).
- Not licensable in the West.

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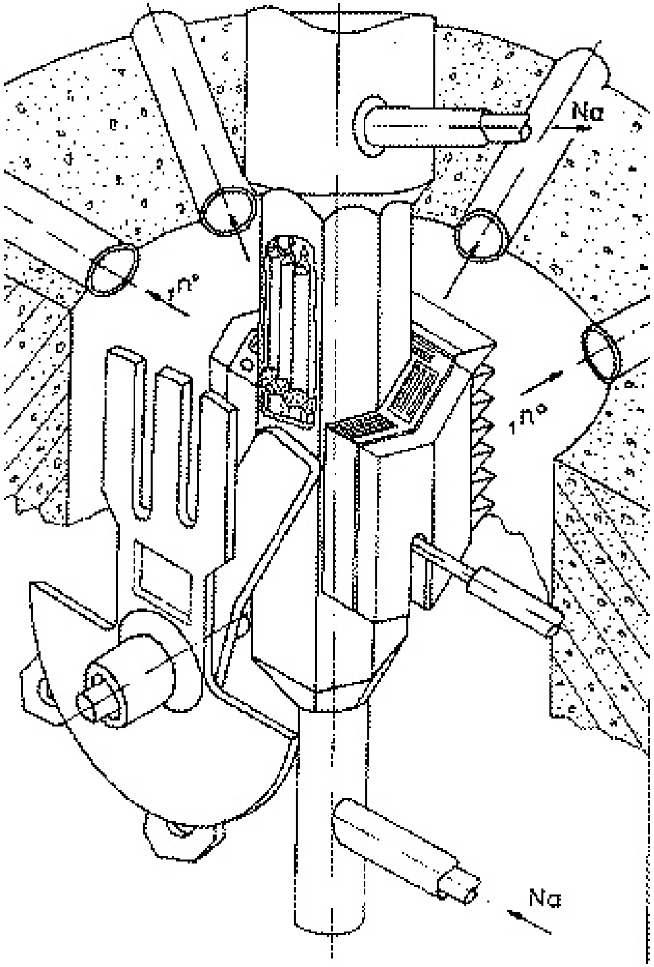
Types of Neutron Sources-cont'd

Schematic View of the IBR-2, Dubna

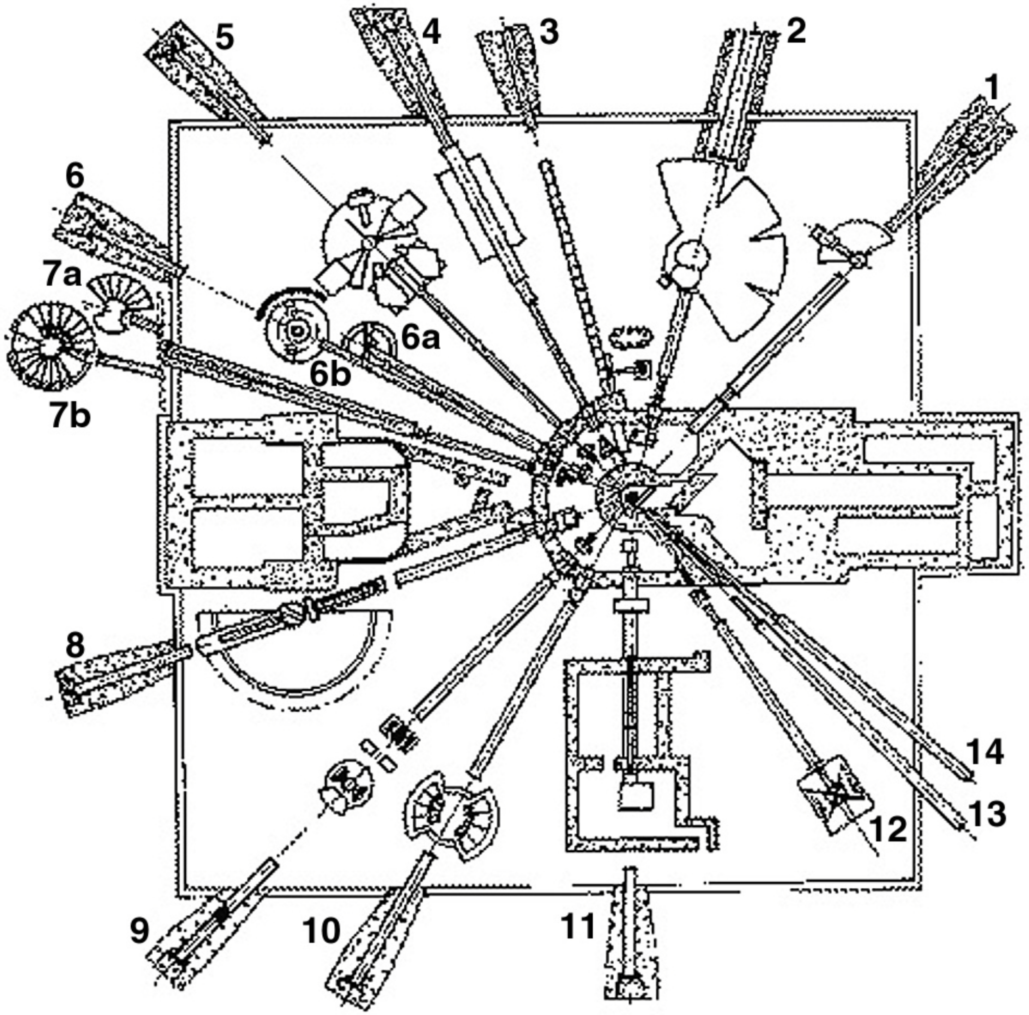


Types of Neutron Sources-cont'd

The Principal Characteristics of the IBR-2 Reactor

Average thermal power	2 MW
Peak power in pulse	1500 MW
Power released between pulses	0.12 MW
Pulse repetition rate	5 Hz
Half-width of thermal neutron pulse	320 µs
Thermal neutron flux density from surface of the grooved-type moderators, space averaged: Ğ time-averaged Ğ at maximum of the pulse	 ϕ - 8x10^{12} n/(cm^{2}sec) ϕ - 5x10^{15} n/(cm^{2}sec) (effective for a beam)
Thermal neutron flux density in moderator at maximum of the pulse	2.4x10^{16} n/(cm^{2}sec)
Flux density of fast neutrons in central channel of reactor Ğ time-averaged – at maximum of the pulse	 3x10^{14} n/(cm^{2}sec) 2.6x10^{17} n/(cm^{2}sec)

Layout of the IBR-2 Experimental Hall



1-DIFRAN
2-DIN-2PI
3-RR
4-YuMO
5-HRFD
6a-DN-2
6b-SNIM-2
7a-NSVR
7b-NERA-PR
8-SPN
9-REFLEX
10-KDSOG-M
11-ISOMER
12-DN-12
13, 14-test channels

Types of Neutron Sources-cont'd

Low-Energy Neutron Sources

- Advantages of a Low-Energy Neutron Source.
  - 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 of a low-energy neutron source.
  - Modest flux implies long experiment times.
  - Optimal design provides only three neutron beams.

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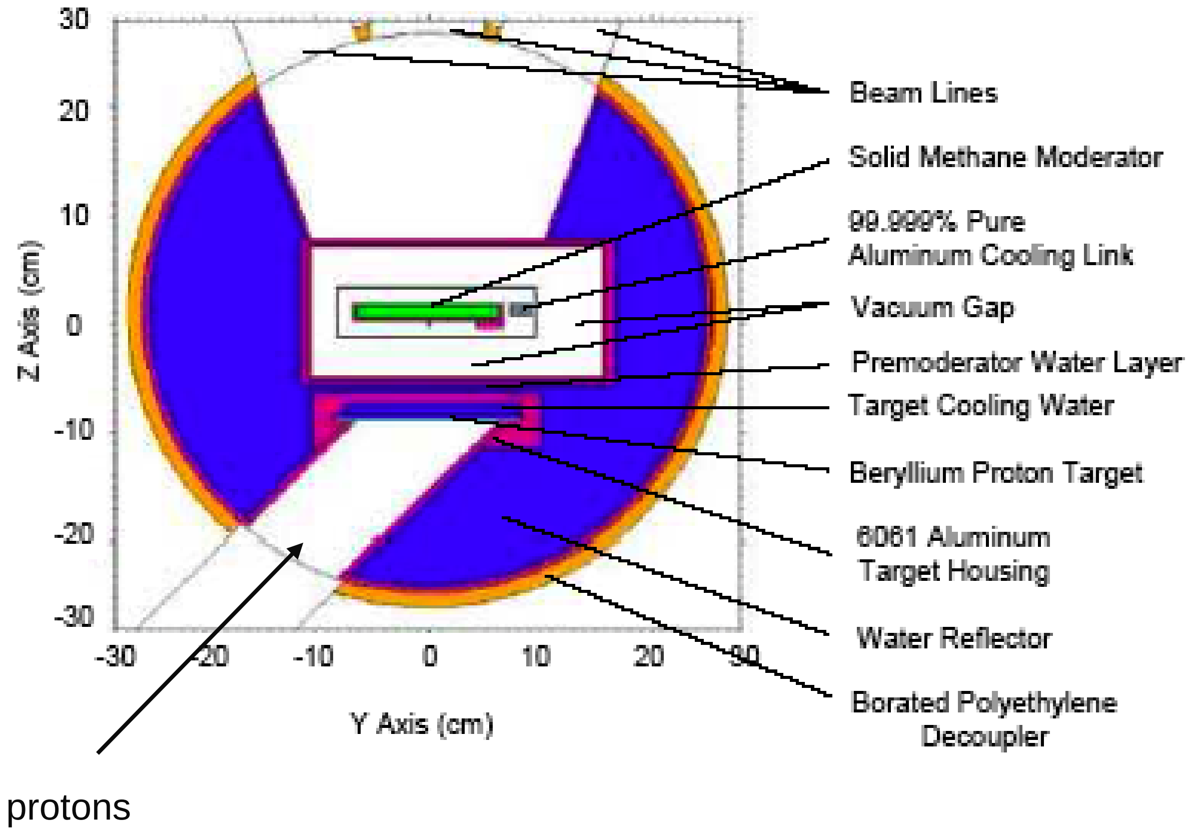
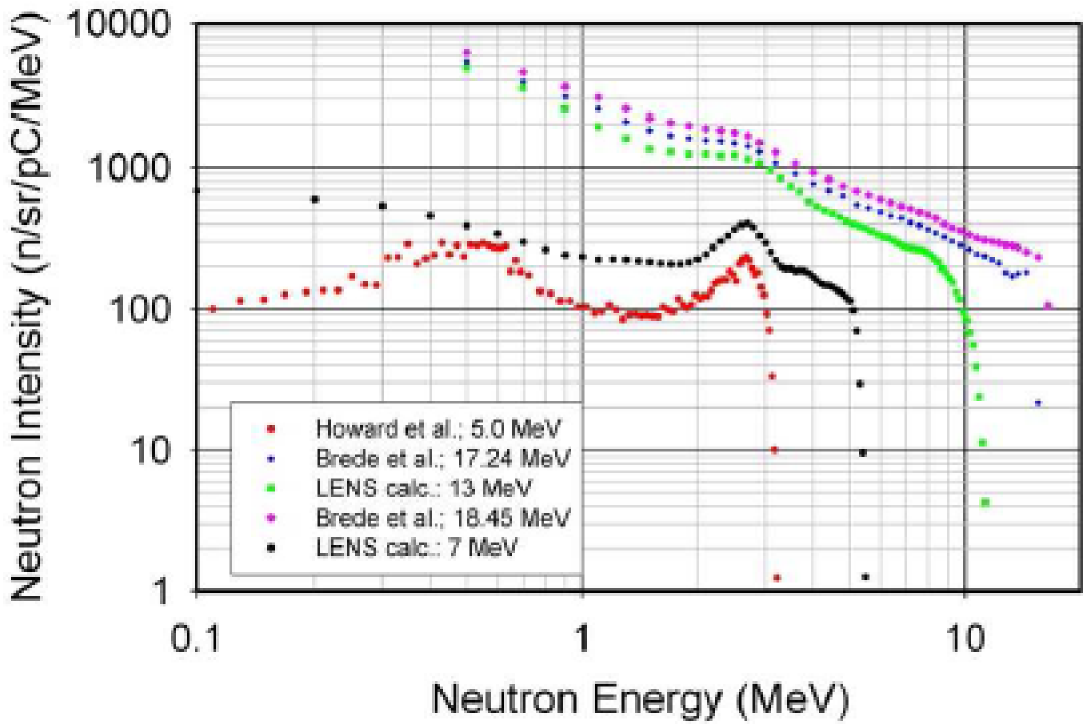
Types of Neutron Sources-cont'd

The LENS Low-Energy Neutron Source, Indiana U.



Low-Energy Neutron Sources

Be(p,n) neutron spectra for different proton energies



Global neutron yield for Be(p,n) neutrons

$$Y(E_p) = 3.42 \times 10^8 (E_p - 1.87)^{2.05}$$ n/μιλλιC

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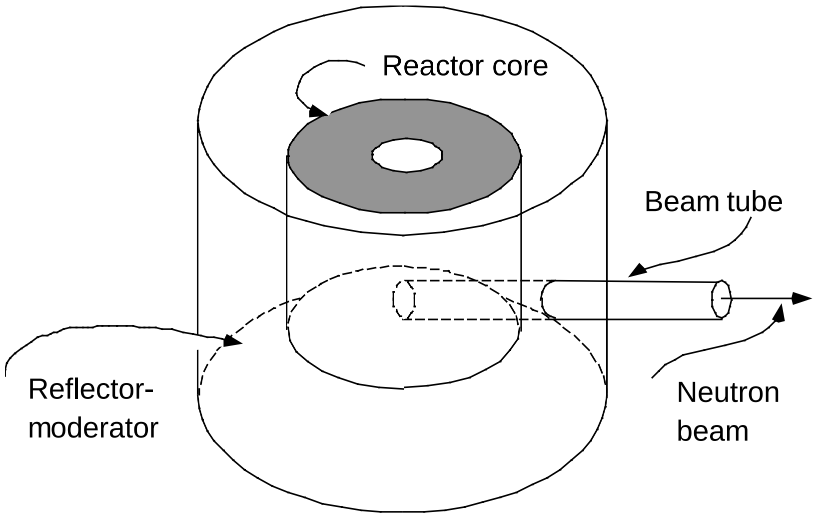
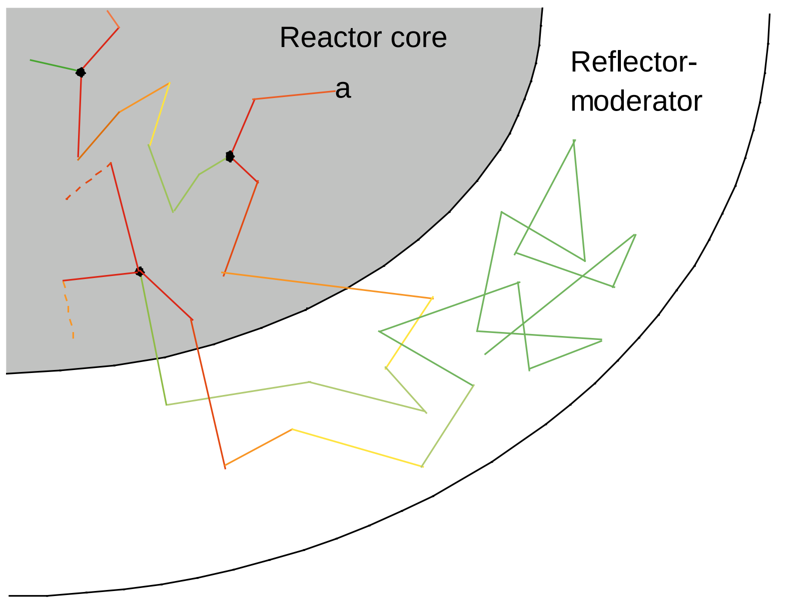
How Do Moderators Work?

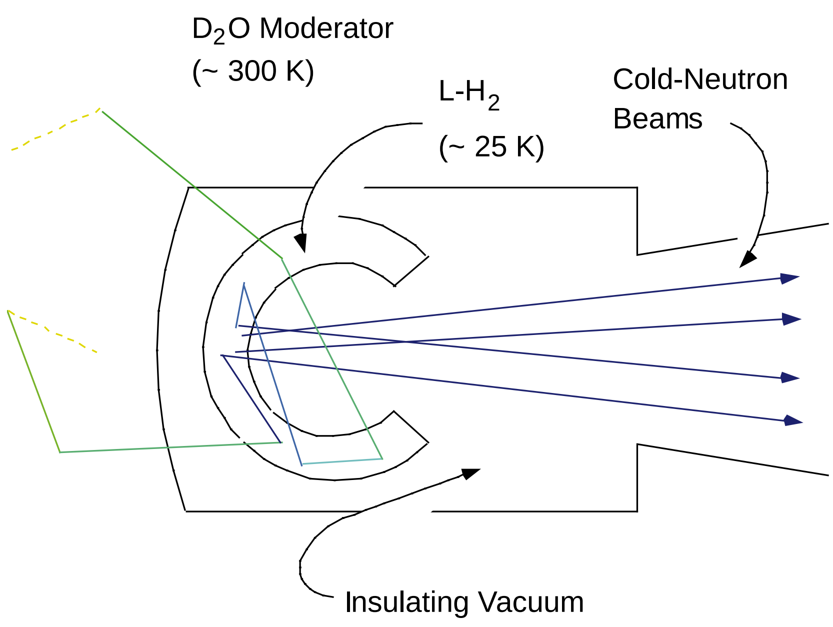
Steady sources



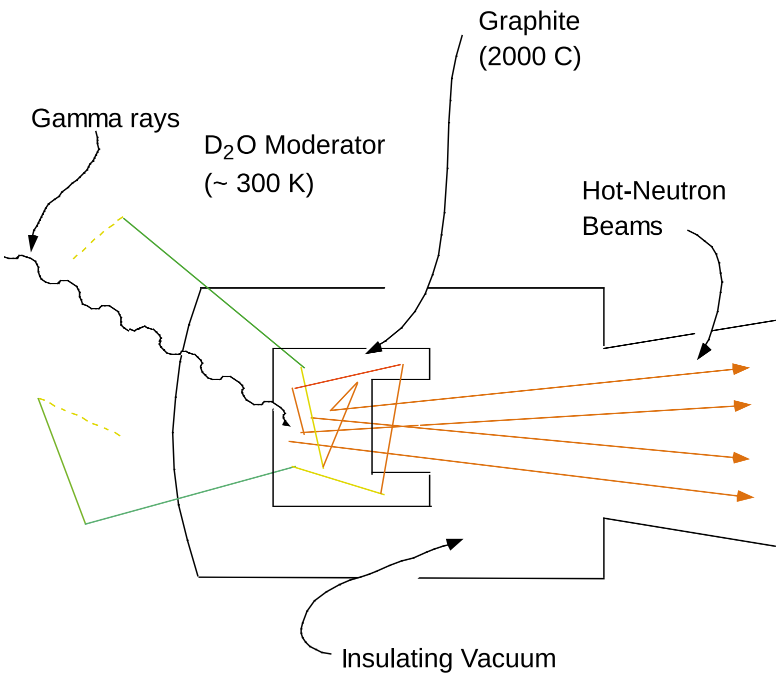


How Do Moderators Work?

Steady sources



Cavity-type cold source



Hot source

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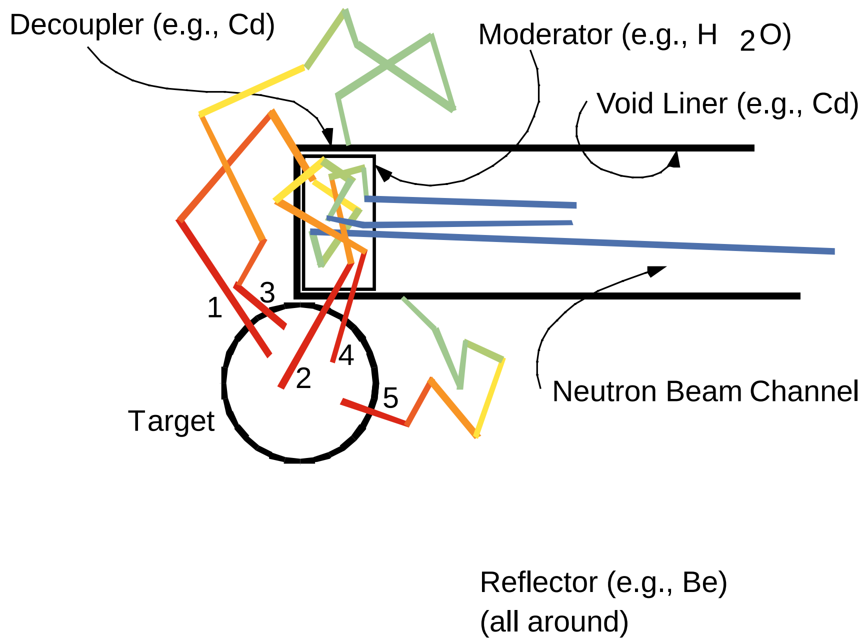
How Do Moderators Work?

Pulsed sources



Decoupled, reflected
pulsed-source moderator

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Types of Neutron Sources-cont'd

- **Pulsed spallation sources** e.g., IPNS, ISIS, LANSCE, SNS.

	200 µA, 0.8 GeV, 160 kW		1.4 mA, 1.0 GeV, 1.4 MW
ISIS	$2x10^{13}$ n/cm^2/s average flux	SNS	
	$8x10^{15}$ n/cm^2/s peak flux		

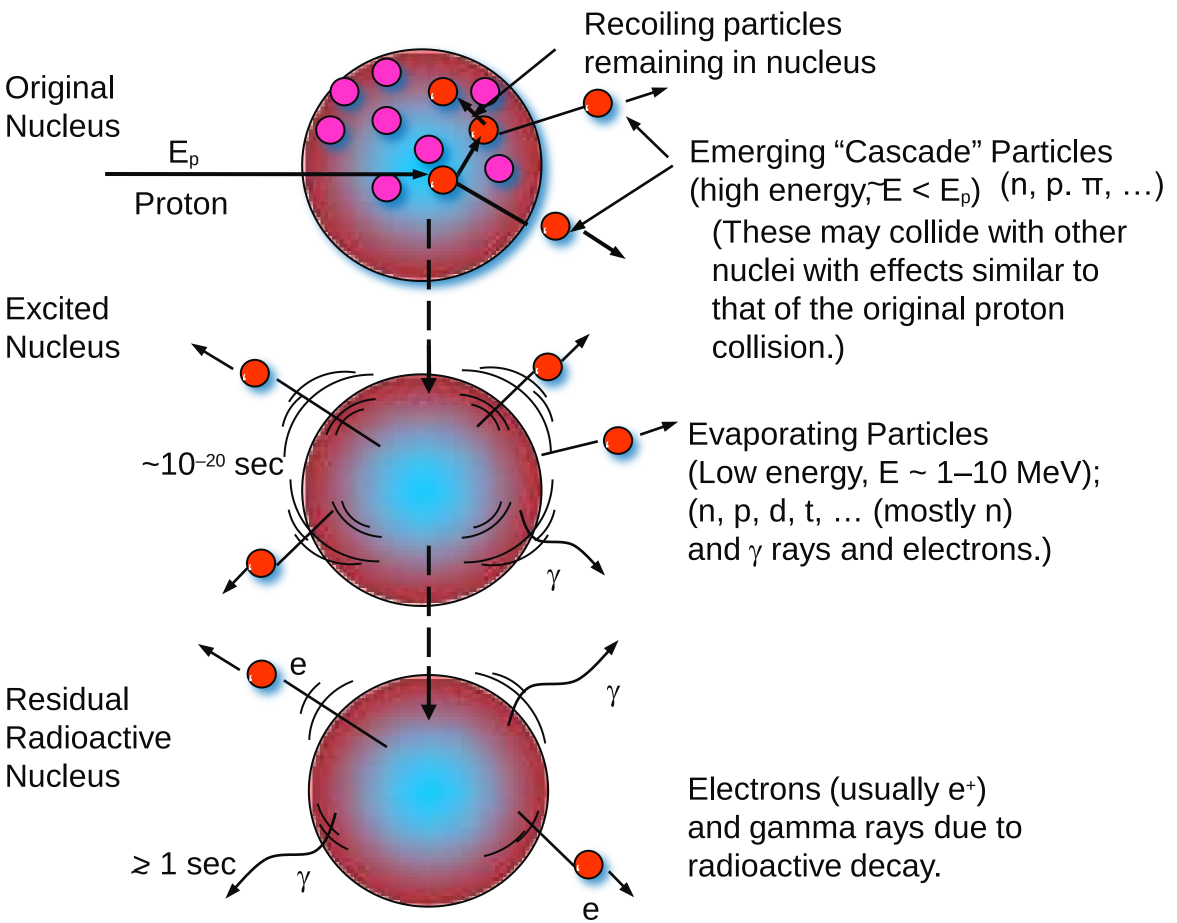
Advantages

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

Disadvantages

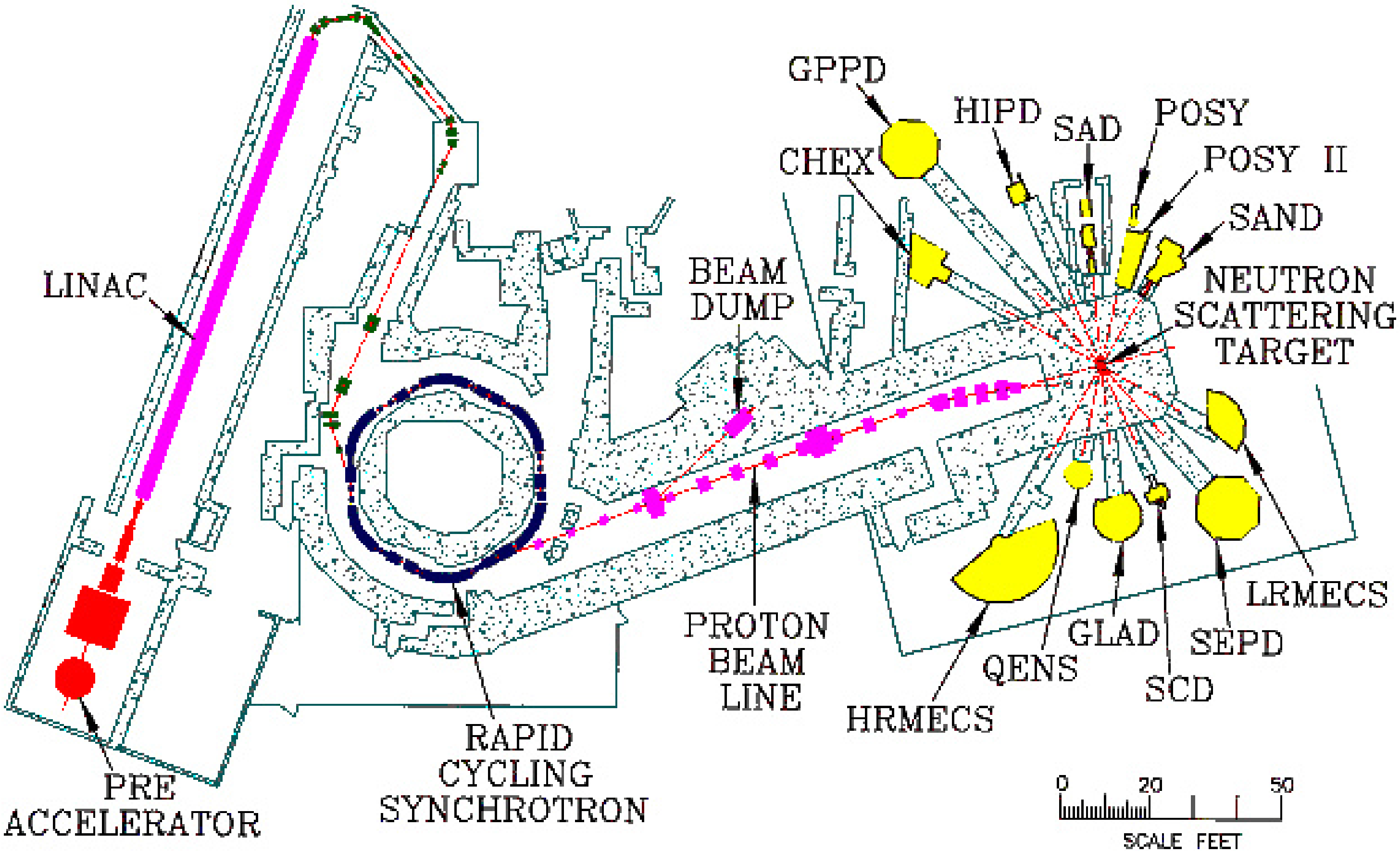
- Low time averaged flux.
- Not all applications exploit time structure.
- Rapidly evolving technology.

Spallation-Evaporation Production of Neutrons



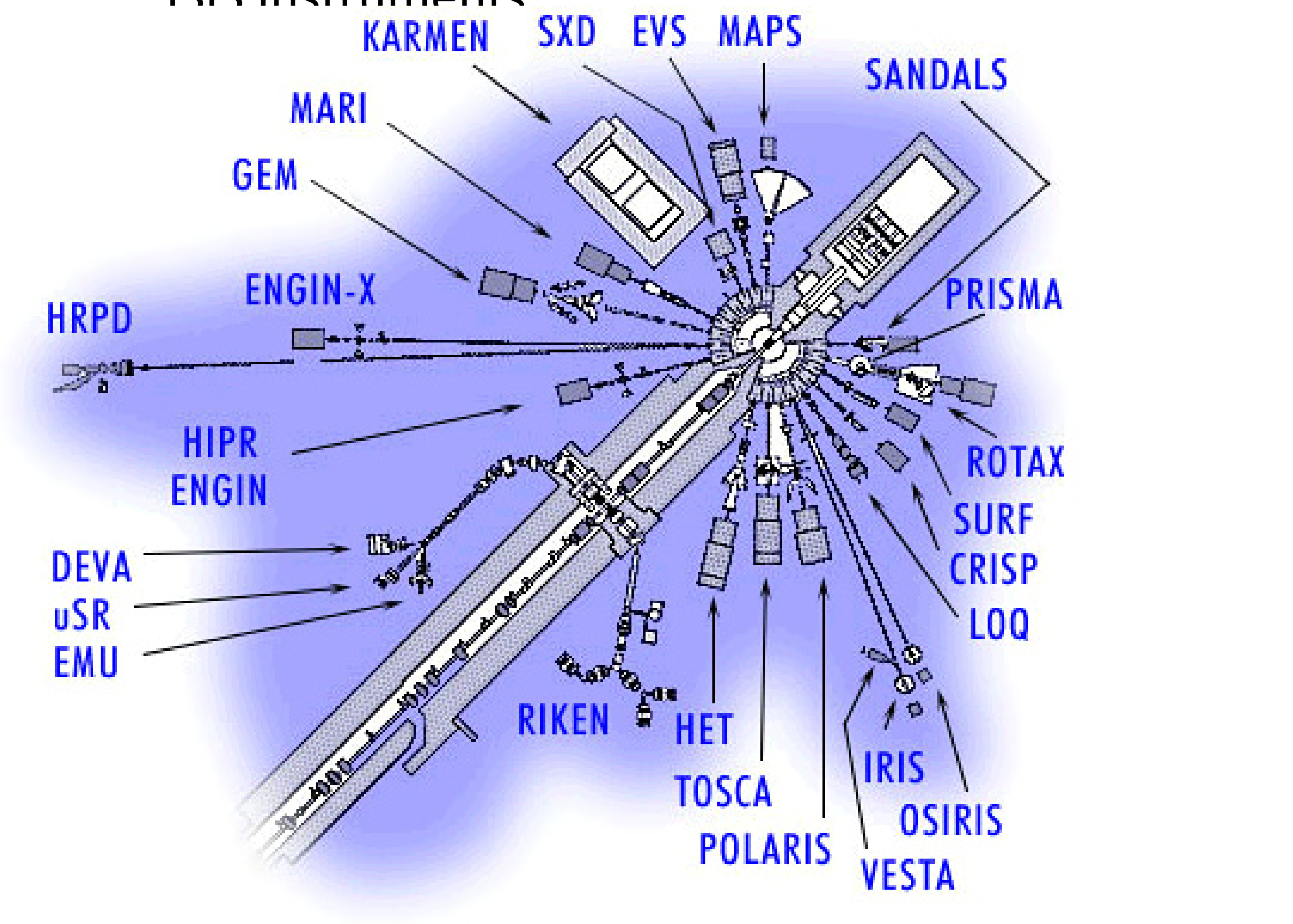
Types of Neutron Sources-cont'd

IPNS Facilities Map



Types of Neutron Sources-cont'd

ISIS Instruments



Types of Neutron Sources-cont'd

- **CW spallation source** e.g., SINQ at Paul Scherrer Institut (PSI).

  0.85 mA, 590 MeV, 0.9 MW

  1×10^{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.
- high background feared but not realized.

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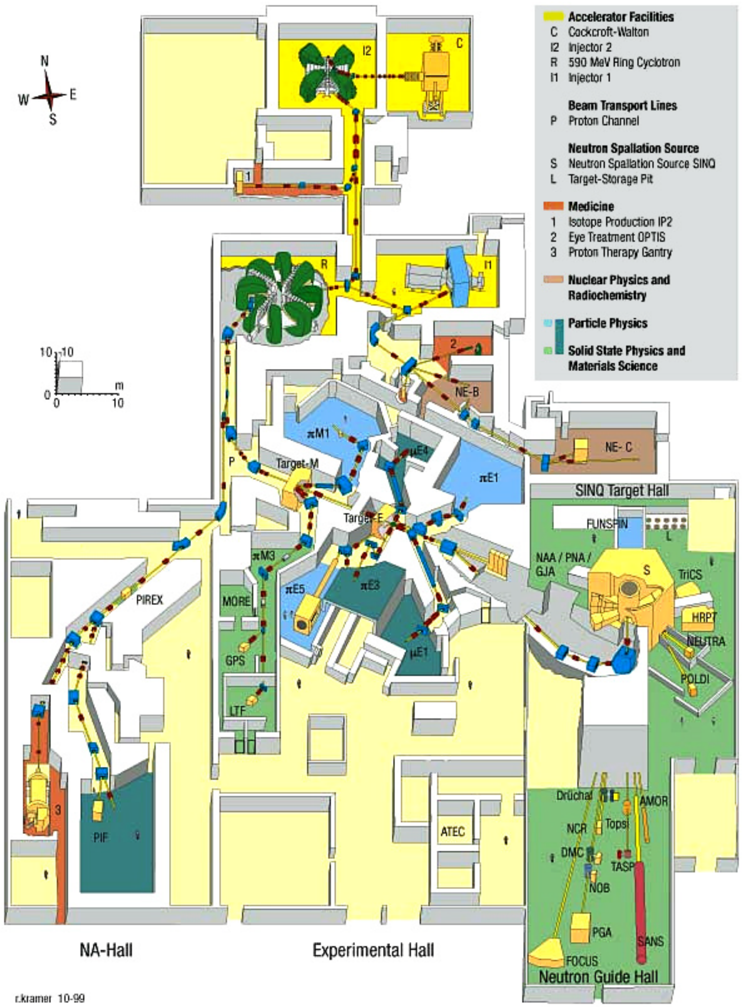
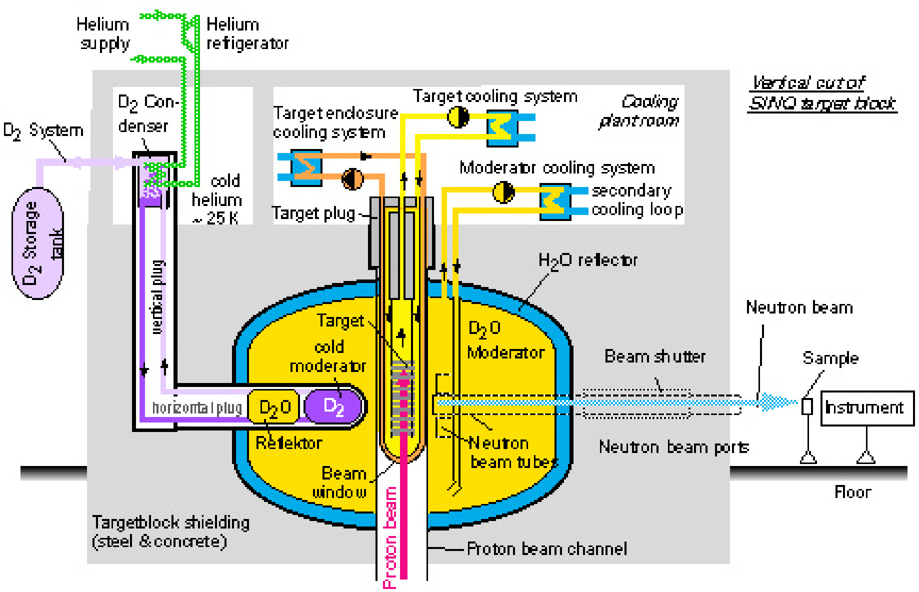
Types of Neutron Sources-cont'd

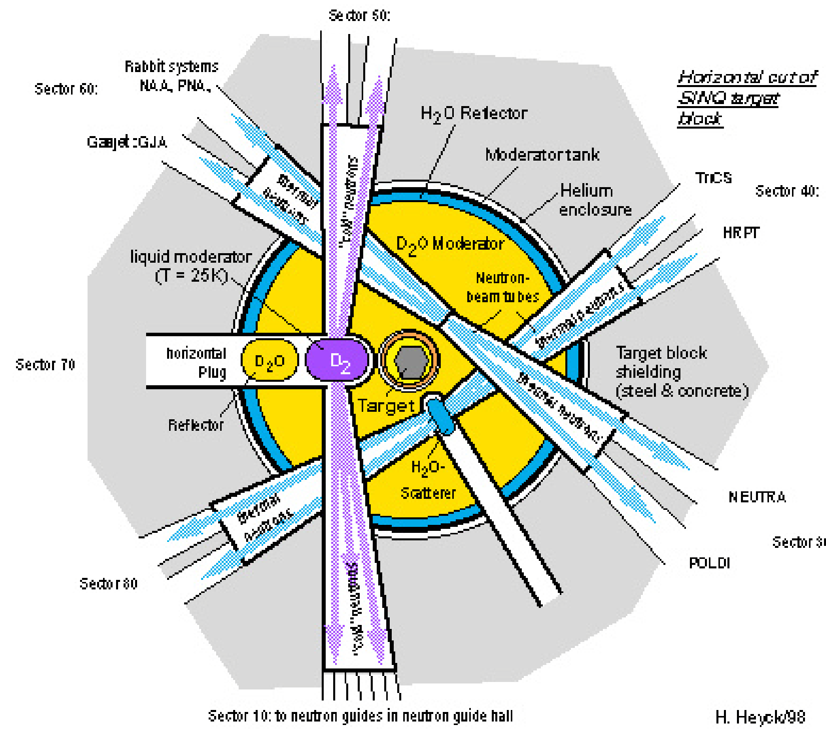
PSI Proton Accelerators and Experimental Facilities



Types of Neutron Sources-cont'd

Principles of the Spallation Neutron Source SINQ





Some History:
The Materials Testing Accelerator

- E. O. Lawrence conceived this project in the late 1940s as a means to produce Pu-239 and tritium and, later, U-233. Despite its name, MTA was never intended for materials research.
- Work went on at the site of the present Lawrence Livermore Laboratory, where scientists accomplished substantial high-power accelerator developments. Efforts continued until 1955 when intense exploration efforts revealed large uranium ore reserves in the U.S. and the project terminated. By that time the pre-accelerator had delivered CW proton currents of 100 mA and 30 mA of deuterons. The work was declassified in 1957.

History

The Materials Testing Accelerator: Machine Parameters

- There was already by that time some information on the production of spallation neutrons by 190-MeV deuteron-induced spallation on Uranium, about 30% more than by protons of the same energy. This guided the choice of accelerated particle type and beam energy. With the anticipated required production rate, the parameters of the accelerator were set:
  - Deuterons.
  - Particle energy – 500 MeV.
  - CW operation – 320 mA (beam power 160 MW).

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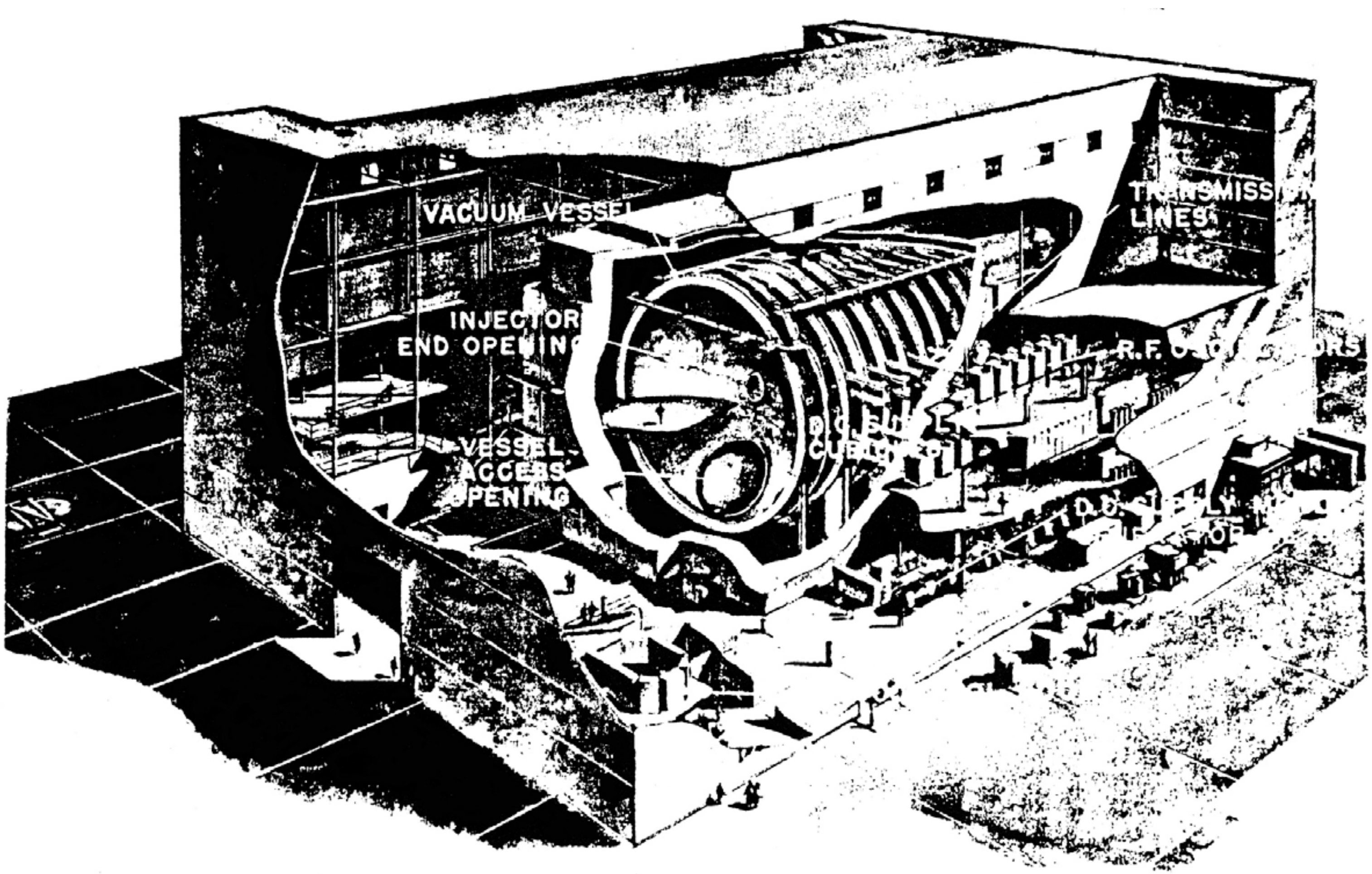
The Materials Testing Accelerator: Target

- Original ideas concerned a Uranium target.
- Subsequent development led to target systems alternatives including moderated subcritical lattices ($k < 0.9$).
- Finally the chosen target system consisted of a NaK-cooled Beryllium primary target, and depleted Uranium secondary target for neutron multiplication, within a water-cooled depleted Uranium lattice for breeding Plutonium.

MTA-cont'd

Cutaway View of Linear Accelerator – Looking from the Injector End



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More History:

The Intense Neutron Generator (ING)

- 1952—W. B. Lewis promotes spallation and accelerators for neutron production.
- 1960s at CRNL—65 mA CW protons to 1 GeV.
  - Accelerator development.
  - Pb-Bi loops.
  - Experimental facilities and design.
  - Cockcroft-Walton limitation – 35 mA CW at 750 keV.
- Led to Accelerator Breeder program in 1970s.
  - ZEBRA in 1980s.

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The ING Project

- The Chalk River Laboratory of Atomic Energy of Canada Ltd launched the Intense Neutron Generator (ING) Project in 1964. The goal was a "versatile machine" providing a high neutron flux for isotope production and neutron beam experiments. Work continued until late 1968 when the project was cancelled due to the perceived high costs and insufficient political support in the Canadian scientific community. ING was estimated to cost about $150 M to build and about $20 M/yr to operate.
- Technical developments that resulted from the ING project were significant, even seminal.

The ING Project:

Machine Specifications

- Proton linac.
- Length
  - Alvarez section – 110 m.
  - Waveguide section – 1430 m.
- Total RF power – 90 MW.
- Energy – 1 GeV.
- Current – 65 mA (CW).
- Proton beam power – 65 MW.

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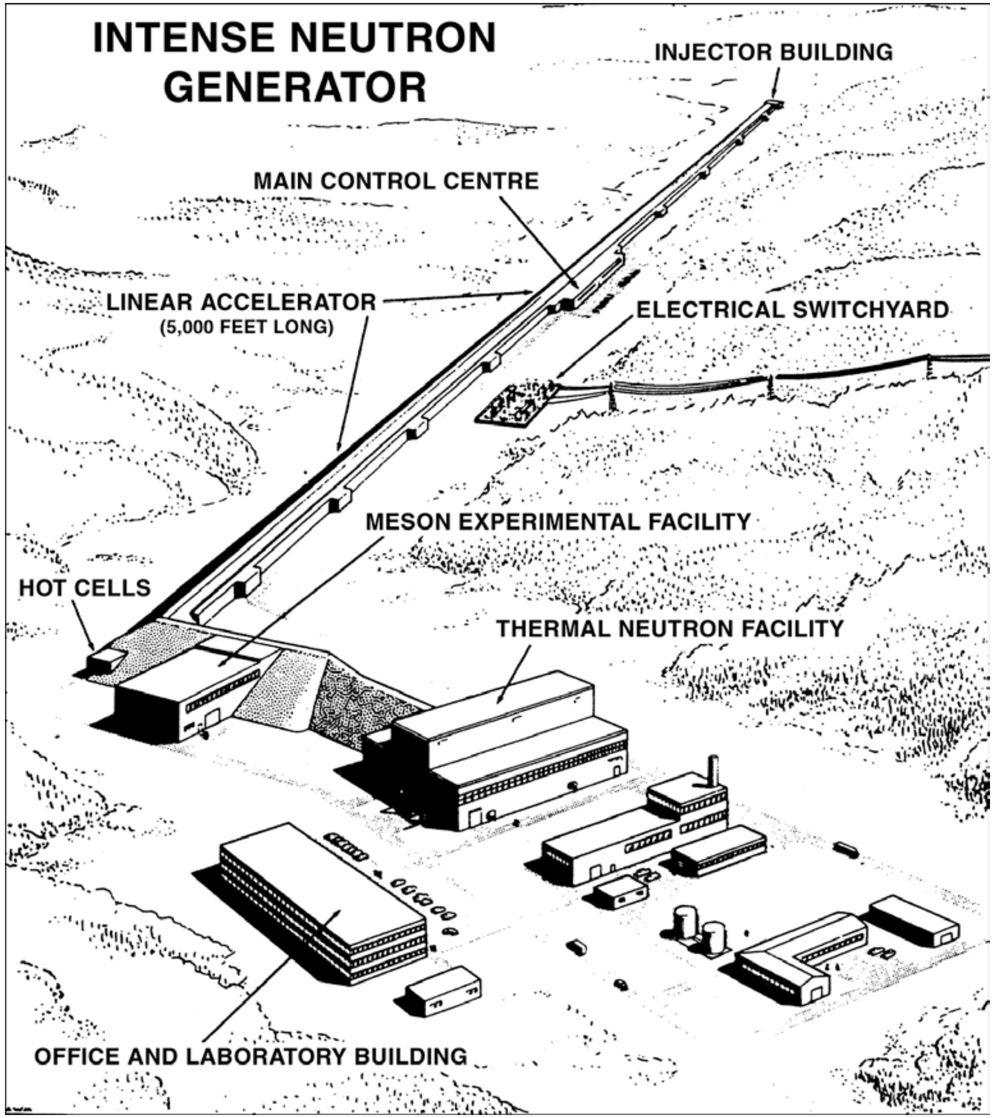
ING: Perspective View



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The ING Project:

Target System

- Flowing Pb-Bi eutectic, 20 cm ø, 60 cm long.
- Vertical (downward) incident proton beam.
- Beryllium "Multiplier" thickness 20 cm.
- D_2O moderator – 100 cm radius.
- Global neutron production rate 10^{19} n/sec.
- Max thermal neutron flux 10^{16} n_{Th}/cm^2-sec.
- Beam tubes, 5 tangential (10 cm ø), one radial (10 cm ø), one through-tube (20 cm ø).

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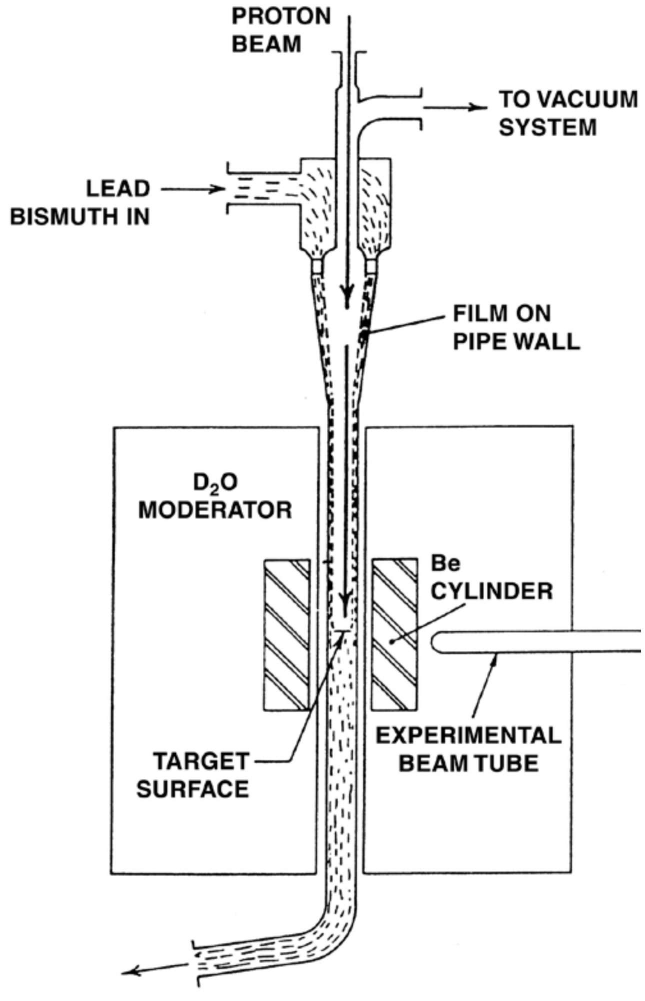
ING: Lead-bismuth Eutectic Flow in the Target



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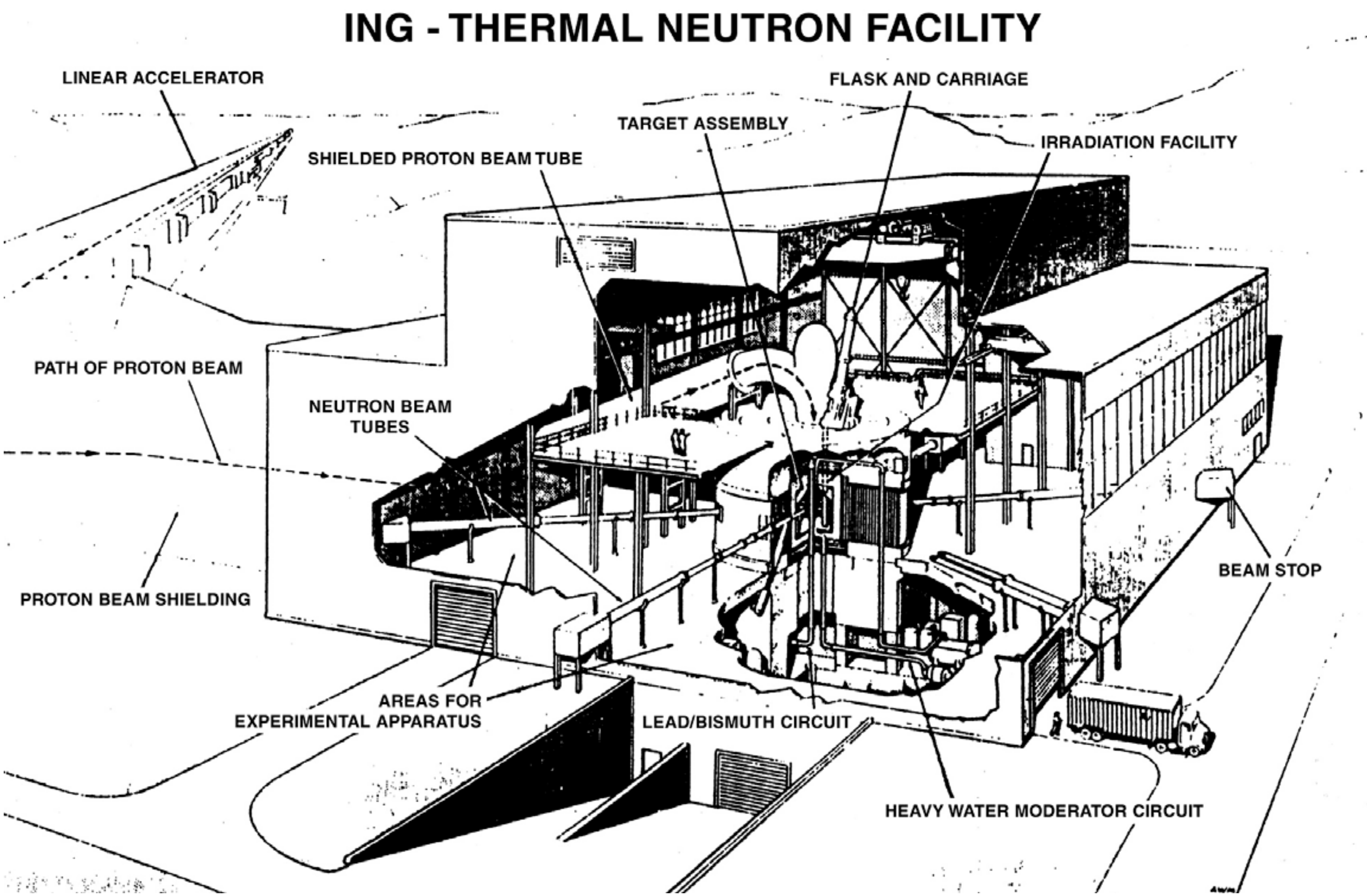
ING Target Building: Cutaway View



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Earliest Pulsed Spallation Neutron Sources

Facility	Location	Time-Average Beam Power (kW)	Proton Energy (MeV)	Pulsing Frequency (Hz)	Startup Date/Status
ZING-P	Argonne	0.1	300	30	1974-75/Shutdown
ZING-P'	Argonne	3	500	30	1977-80/Shutdown
KENS	KEK, Japan	3.5	500	20	1980-2006/Shutdown
IPNS	Argonne	7.0	450	30	1981/Operating
ISIS	Rutherford-Appleton Lab, UK	160	800	50	1985/Operating
MLNSC (Lujan Center)	Los Alamos	60 (upgrade underway to 160 kW)	800	20 (upgrade 30 Hz?)	1985/Operating

Primary source pulse widths of all are less than 0.5 μsec

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Pulsed Spallation Neutron Source Construction, Proposals, and Studies

Name	Location	Proton Beam Power (MW)	Proton Energy (GeV)	Pulsing Frequency (Hz)	Status
IPNS Upgrade	Argonne	1.0	2.0	30	Study complete – terminated
SNS	Oak Ridge	2.0	1.0	60	Complete June 2006
AUSTRON	Austria	0.2 (includes upgrades for beam power up to 1 MW)	1.6	25 (upgrade 50 Hz)	Study complete – Approval pending
ESS	Europe	5.0	1.33	50	Ongoing study
JSNS	JAEA, Tokai-mura, Japan	0.6 (potential for upgrades to 5 MW)	3.0	25 (upgrade to 50 Hz)	Under Construction First operation 2008
LPSS	Los Alamos	1.0 MW	0.8	60	Ongoing study
CSNS	Dongguan, China	100 kW (potential for upgrade to ~1 MW)	1.6	25	Near commitment

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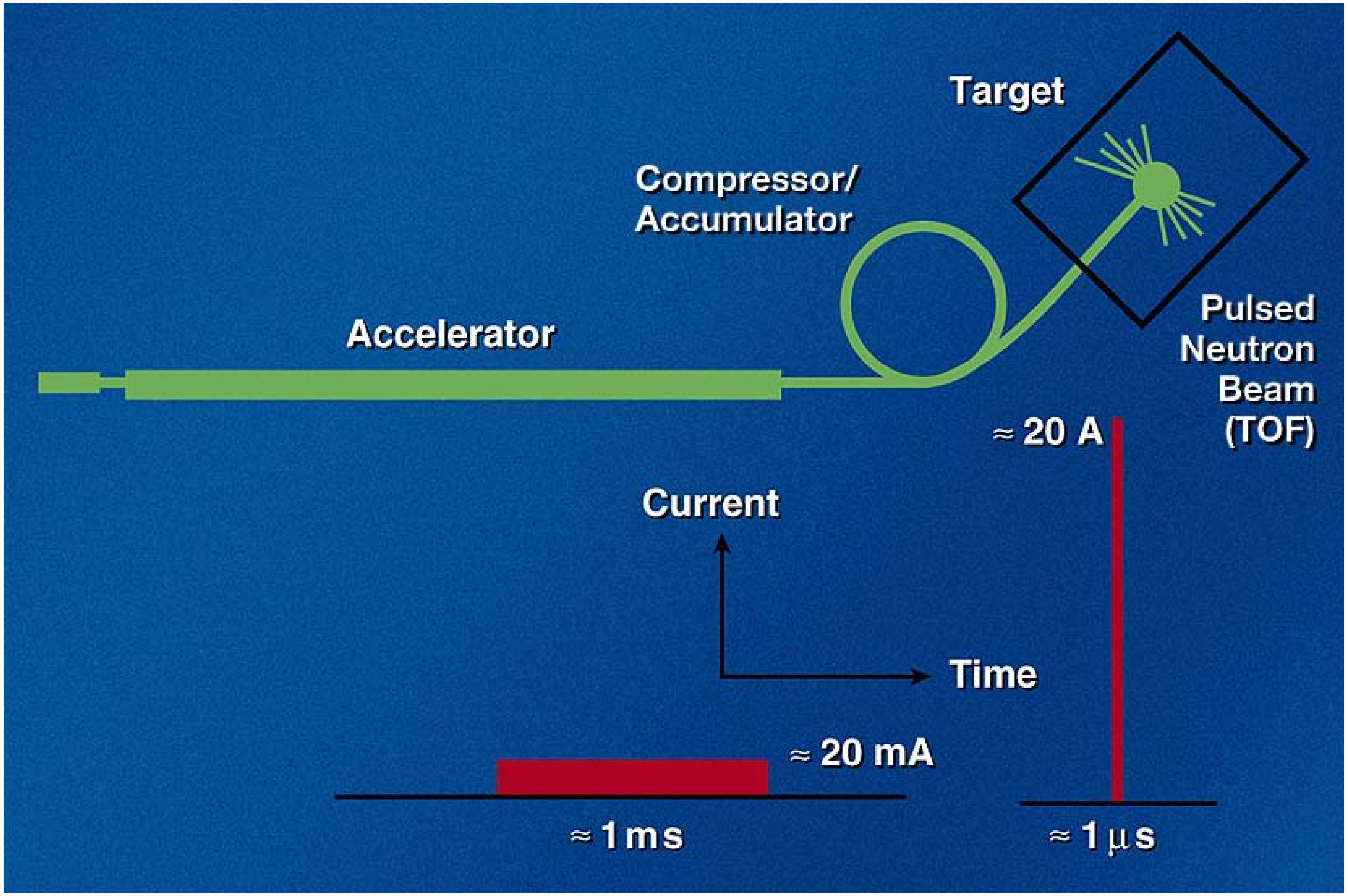
Anatomy of a Pulsed Spallation Neutron Source



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The Spallation Neutron Source

- The SNS construction project concluded in 2006, shown in spring 2007.
- First operation April 2006, 500 kW in July 2008.
- At 1.4 MW it will be ~ 8x ISIS, the world's leading pulsed spallation source.
- The peak neutron flux will be ~ 20 to 100 x ILL.
- SNS will be the world's leading facility for neutron scattering.
- It is a short distance from HFIR, a reactor with a flux comparable to ILL.

SNS - Guiding Principles

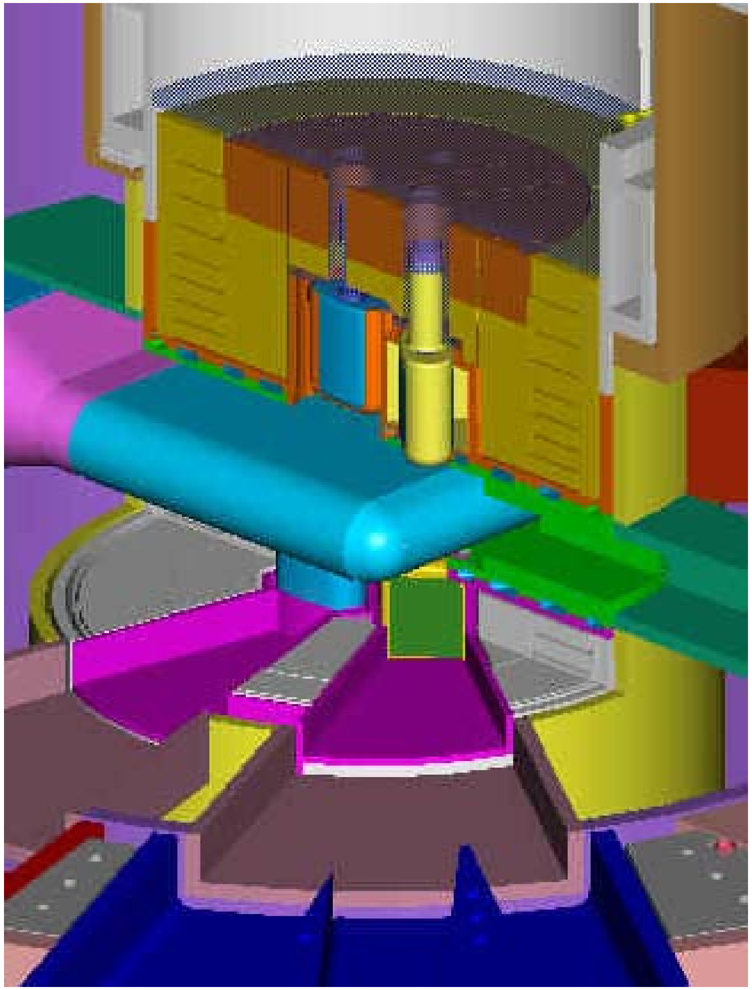
- SNS will provide high-availability, high-reliability operation of the world's most powerful pulsed neutron source.
- It will operate as a User Facility to support peer reviewed research on a best-in-class suite of instruments.
  - Research conducted at SNS will be at the forefront of biology, chemistry, physics, materials science and engineering.
- SNS will have the capability to advance the state of the art in spallation neutron source

SNS Parameter Summary

Proton beam energy on target	**1.0**	**GeV**
Proton beam current on target	**1.4**	**mA**
Power on target	**1.4**	**MW**
Pulse repetition rate	60	Hz
Beam macropulse duty factor	6.0	%
Ave. current in macro-pulse	26	mA
H^- peak current front end >	**38**	**mA**
Chopper beam-on duty factor	68	%
RFQ output energy	2.5	MeV
FE + Linac length	335	m
DTL output energy	87	MeV
CCL output energy	185	MeV

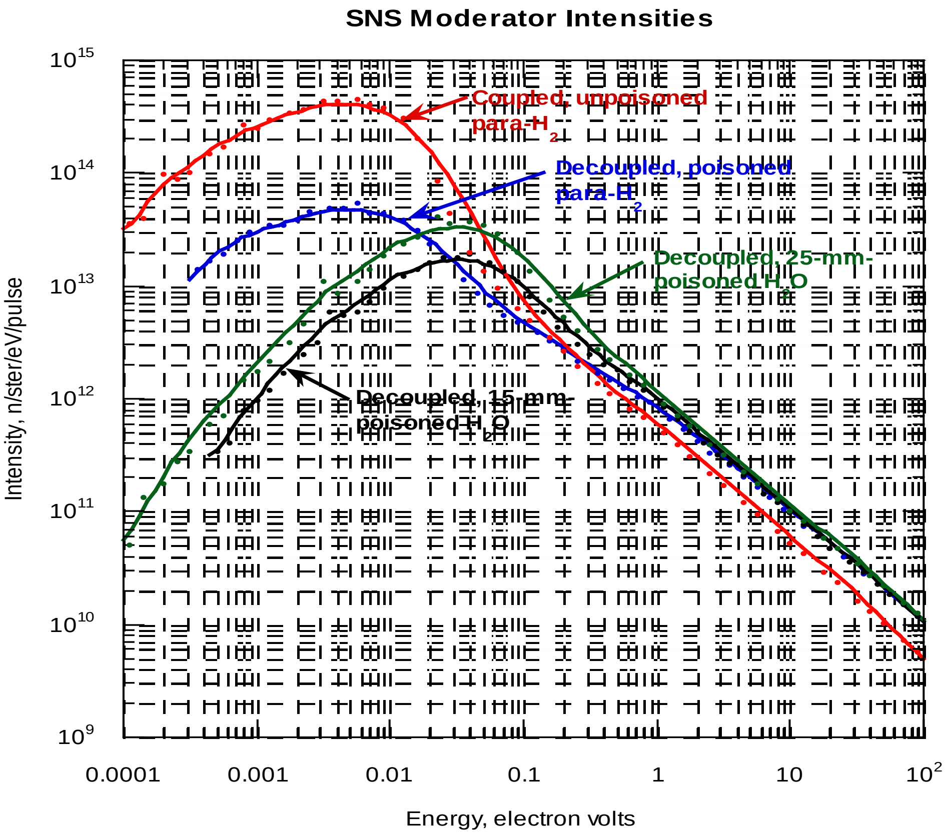
SC linac output energy	1.0	GeV
HEBT length	170	m
Accumulator ring circ.	248	m
Ring fill time	1.0	m
Ring beam extraction gap	250	ns
RTBT length	150	m
Protons per pulse on target	**1.5×10^{14}**	
Proton pulse width on target	695	ns
Target material	Hg	

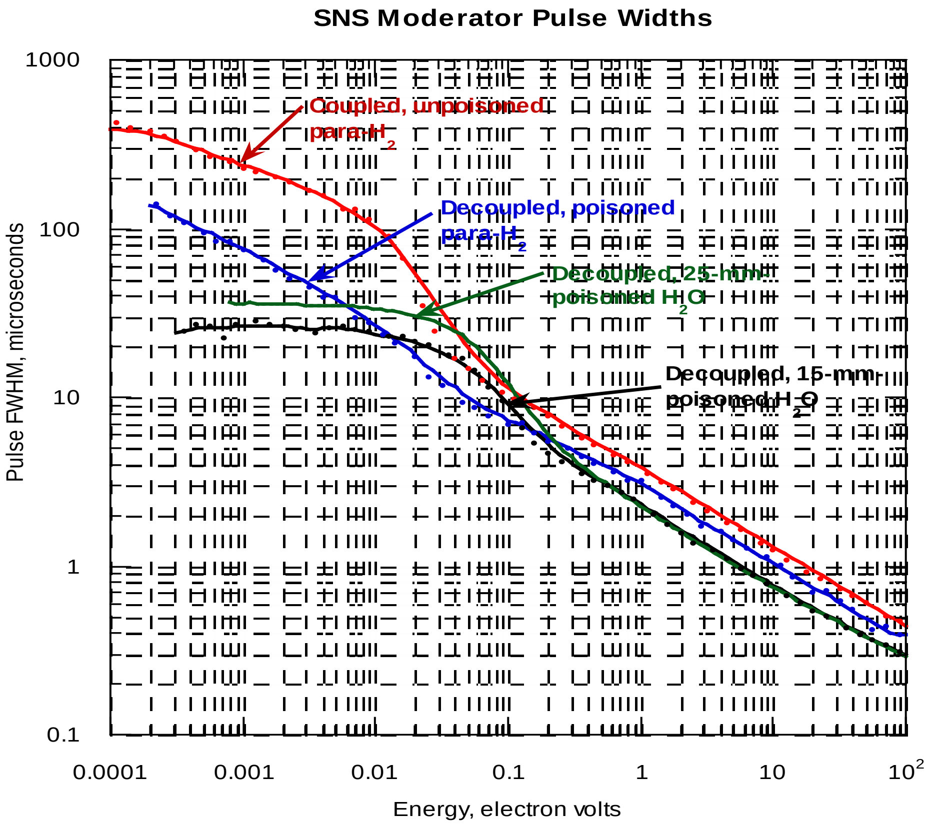
SNS Target-Moderator-Reflector System



98-6245 uc/vlb

SNS Moderator Intensities and Pulse Widths

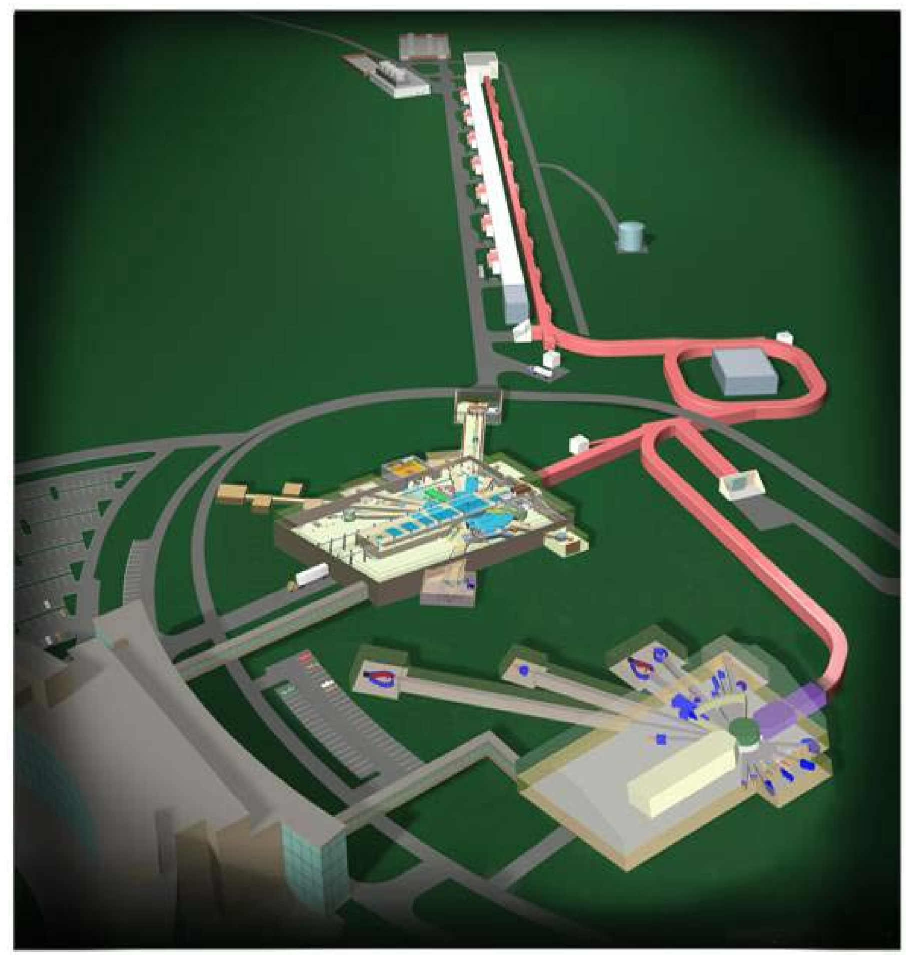




Results for 2 MW beam power, 60 Hz pulsing frequency—2.08 x 10^{14} protons/pulse at 1. GeV.

SNS 20-Year Plan

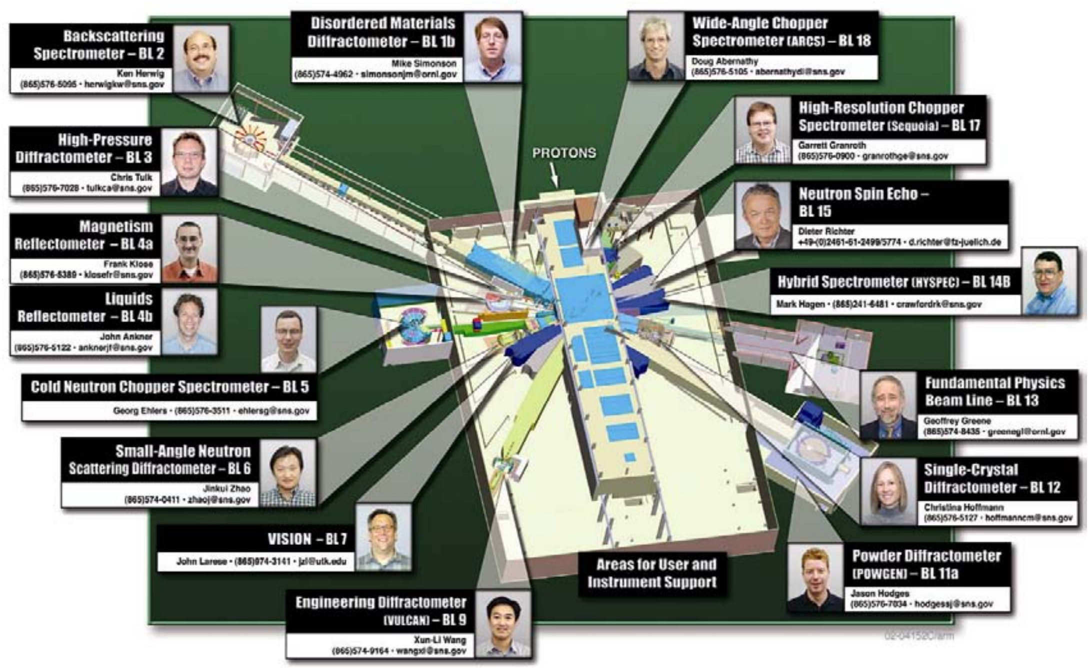
- SNS will evolve along the path envisaged in the Russell Panel specifications.
- In 20 years, it should be operating ~45 best-in-class instruments with two differently optimized target stations and a beam power of 3–4 MW
  - Ultimate target



SNS Instruments

- 18 instruments approved.
  - Excellent progress with funding.
    - DOE, including SING1 and SING2 Projects, foreign, and NSF initiatives
- Working to enhance instrument technology

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



SNS Project Status

- SNS has received full funding every year since FY 2001.
- The total project cost of SNS was $1.4B.
  - Construction completed within budget and schedule constraints.
- ES&H performance has been exemplary.
  - Achieved >5 million hours without a lost workday injury (including combined hours worked for construction site and SNS/ORNL).
  - The first LWC occurred after 3 million construction site work hours.
- SNS started up on 28 April 2006.
  - As of 17 September 2008, SNS had delivered 550 μιχροA proton current (550 kW), currently the world's most powerful.
  - On track for 1-MW operation by 2009.
- The Power Upgrade Program (~ 4 MW) is underway.
- A second target station, optimized for production and use of long-wavelength neutrons (LWTS), is under active consideration.

End of Presentation

Thank you!