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Neutron Sources for Materials Research

National School on Neutron and X-ray Scattering

Oak Ridge

30 May-13 June 2009

John M. Carpenter

IPNS, SNS

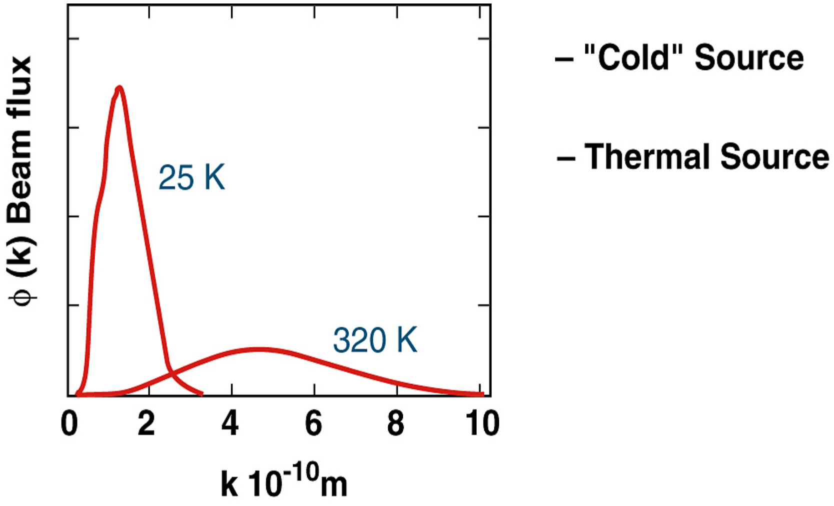
4 June 2009

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.
- 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

- 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 or 6.12 THz

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

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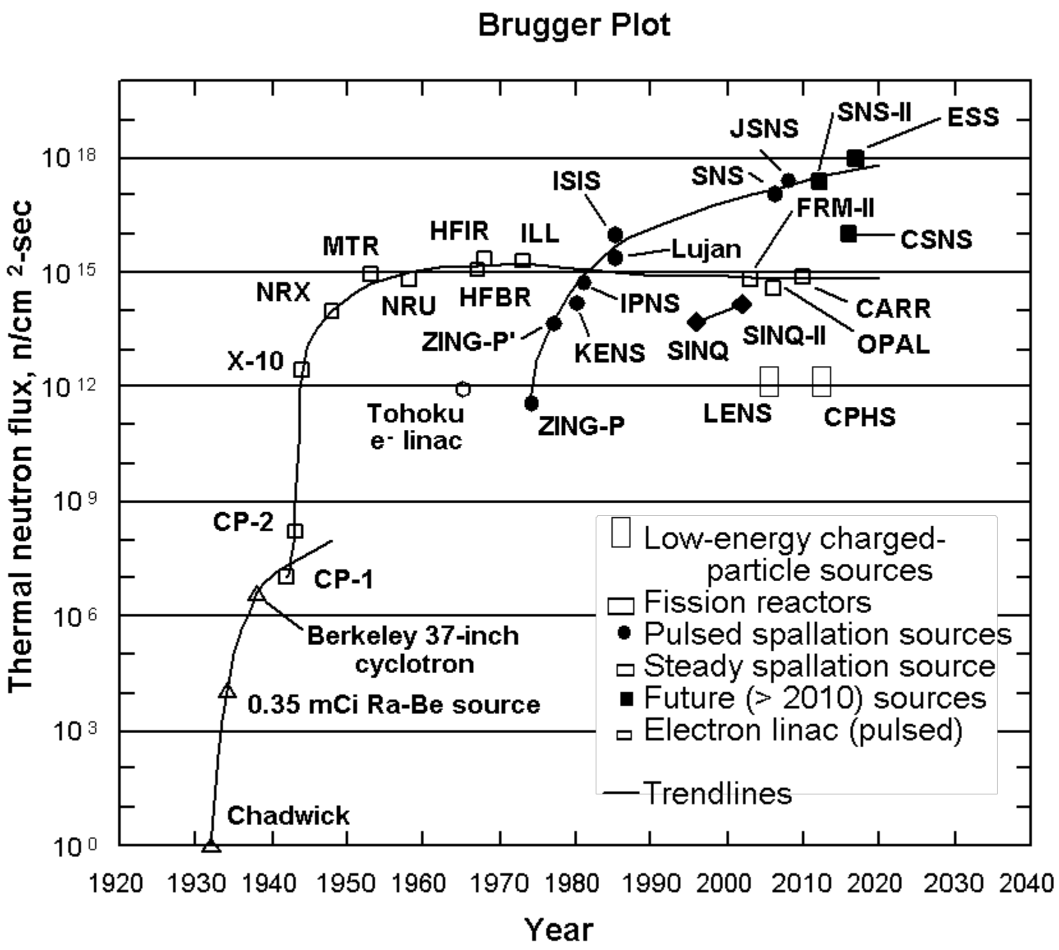
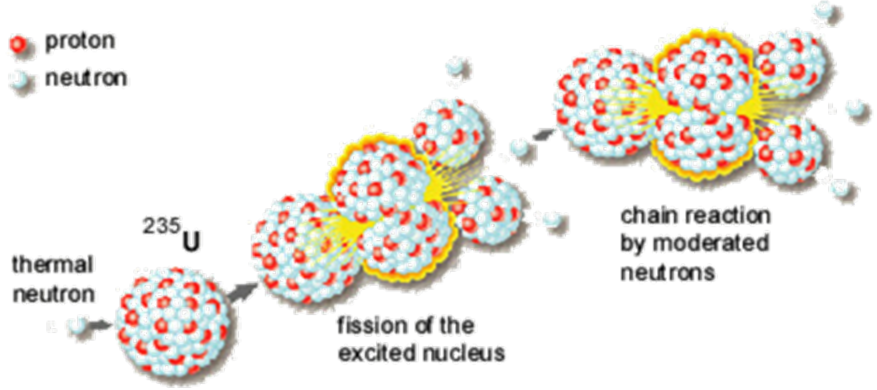
Development of Neutron Science Facilities


Brugger Plot

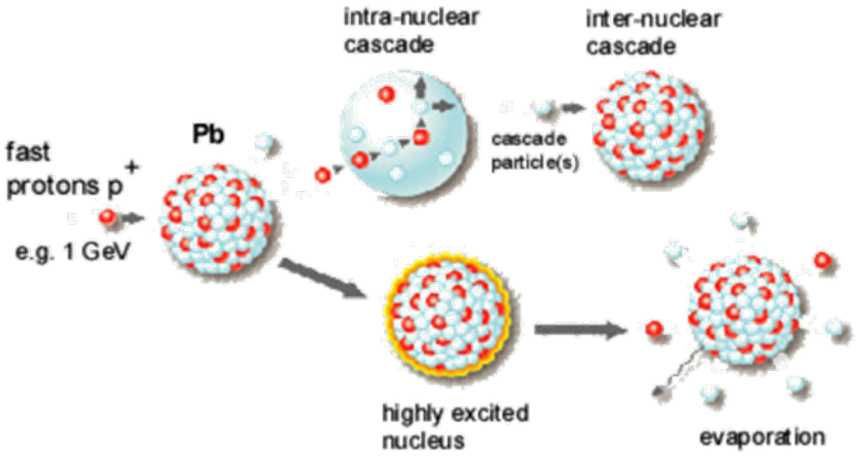
Redrawn 2009

How do we produce neutrons?



Fission

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



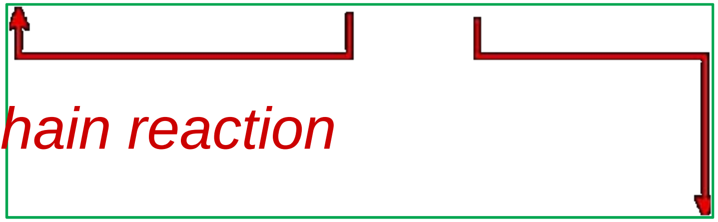
Spallation

- 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 $E \sim k_B T$ (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 x 10^{14} n/cm^{2}/s
ILL	Grenoble	1.5 x 10^{15} n/cm^{2}/s
Spallation sources		
ISIS @ 160 kW	average	1.2 x 10^{13} n/cm^{2}/s
	peak	6 x 10^{15} n/cm^{2}/s
SNS @ 2 MW	average	4 x 10^{13} n/cm^{2}/s
	peak	3 x 10^{16} n/cm^{2}/s

Neutrons: Where do they come from?

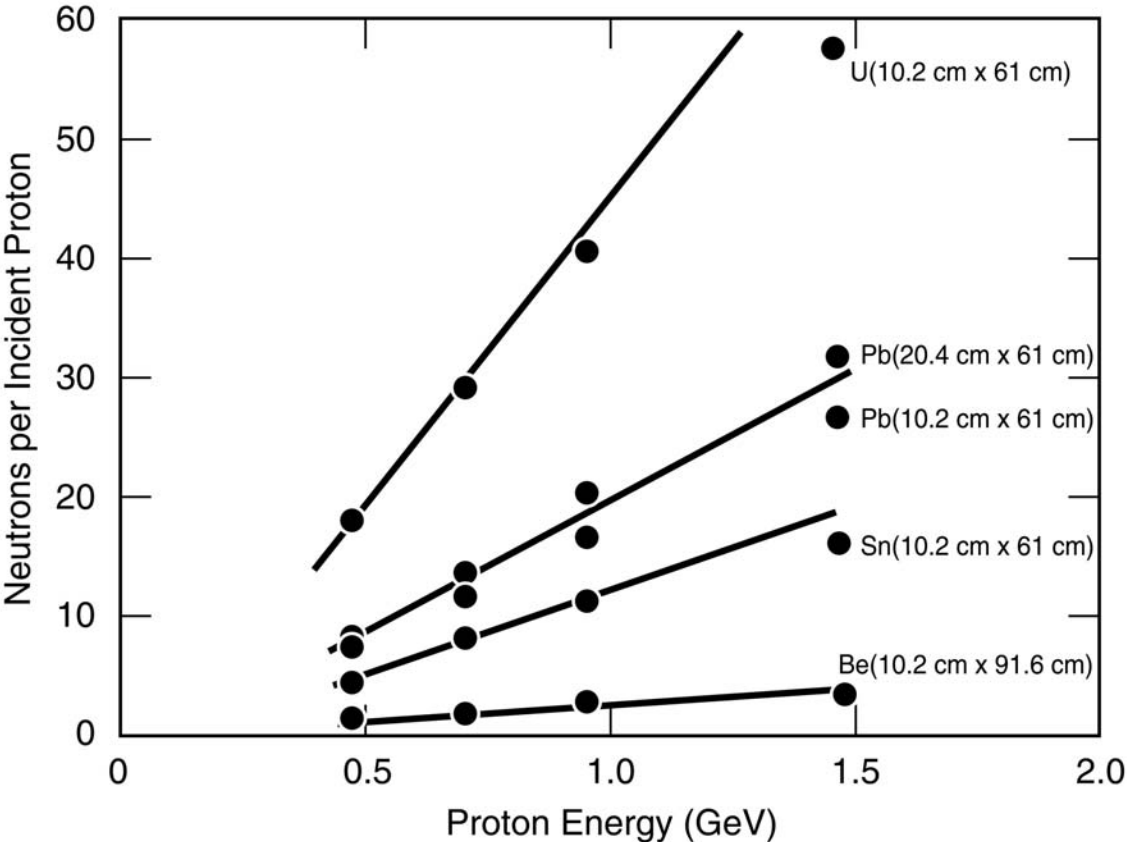
Measured Spallation Neutron Yield vs. Proton Energy for Various Targets, J. Frazer, et al. (1965)

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

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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)

$$Y = 3.42\text{x}10^{8}(E_{\mathrm{MeV}} - 1.87)^{2.05}\ \text{n}/\mu\iota\chi\rho o\text{C}$$

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

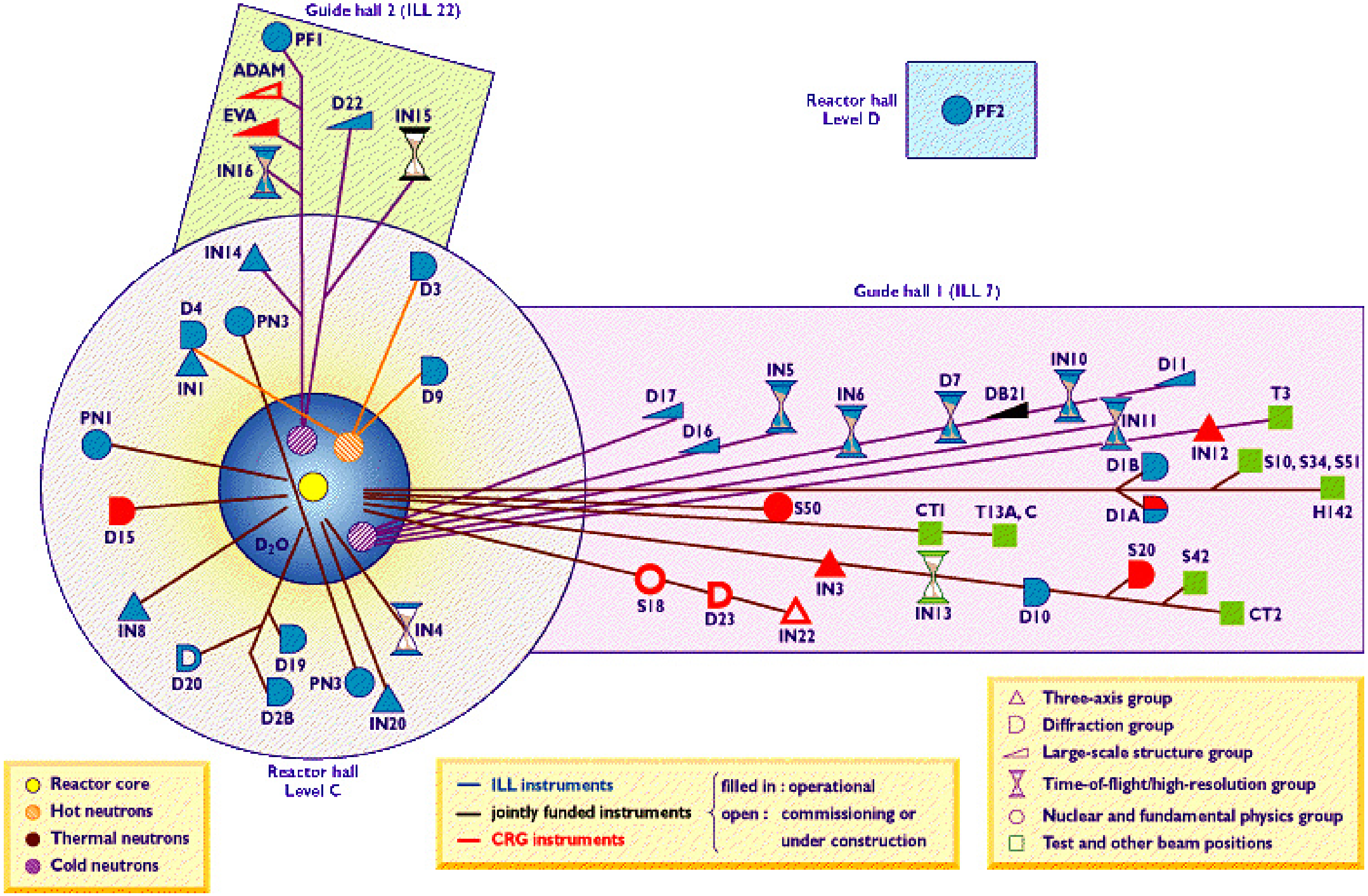
- High time averaged flux.
- Mature technology (source + instruments).
- Very good for cold neutrons.

Drawbacks

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

Types of Neutron Sources

The Institut Laue-Langevin, Grenoble



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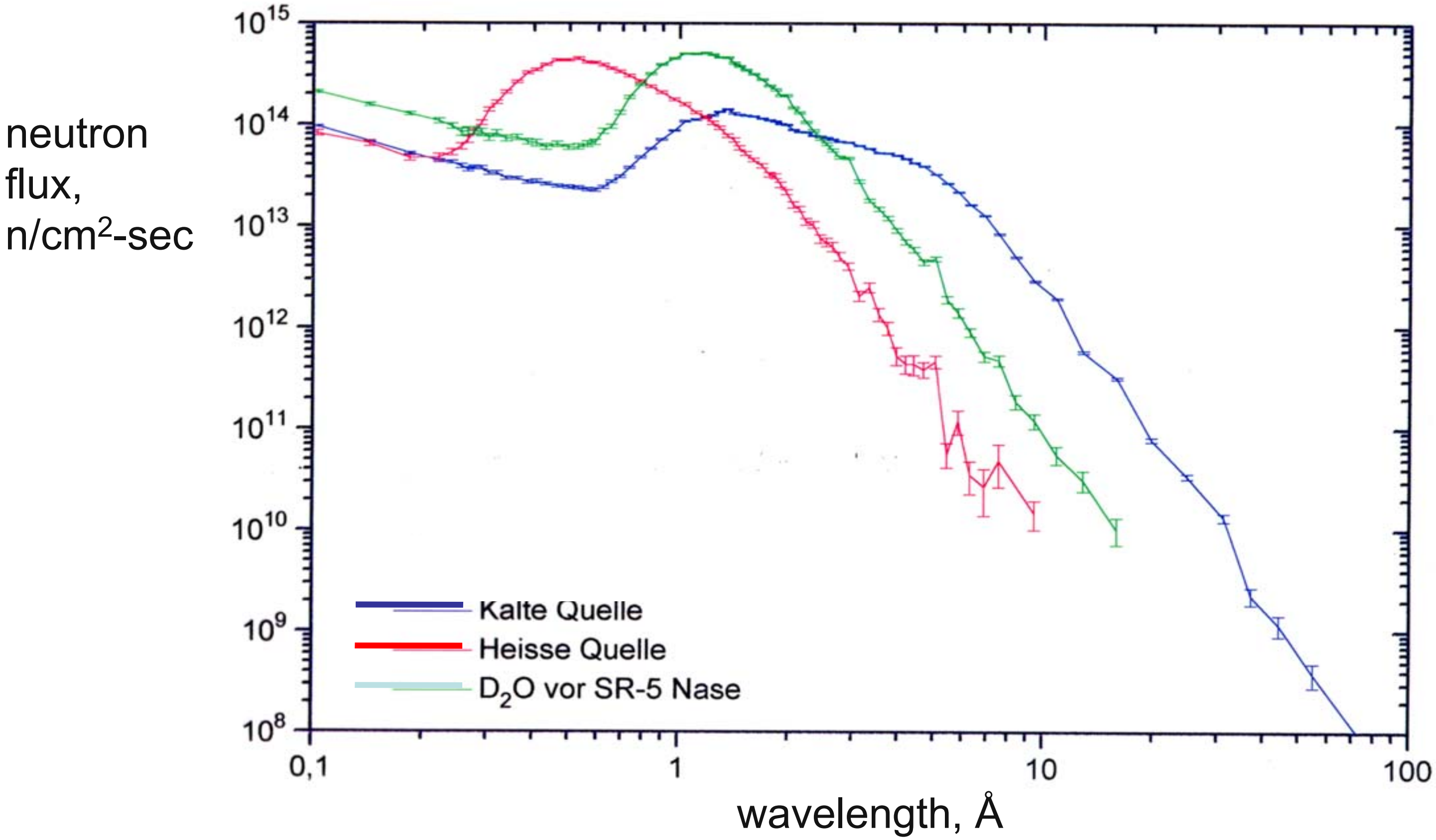
Types of Neutron Sources-cont'd

Source Spectra of the FRM-II Reactor



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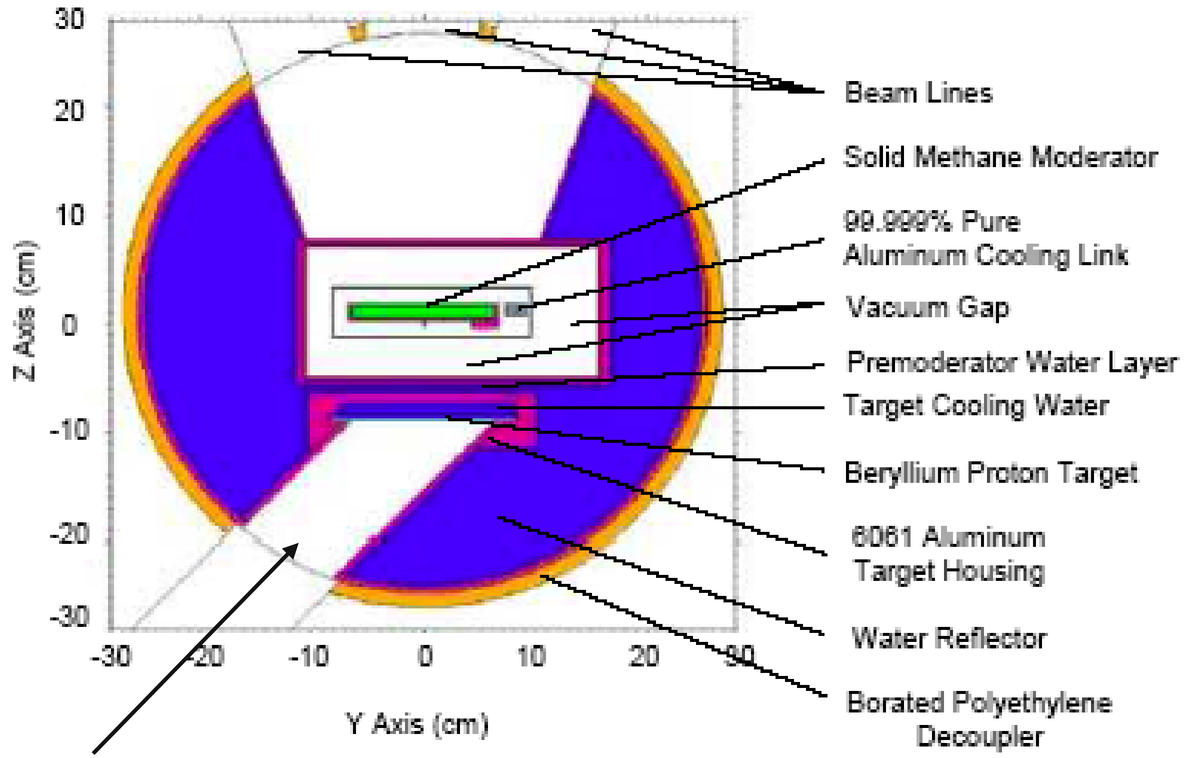
Types of Neutron Sources-cont’d

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.

Types of Neutron Sources-cont'd

The LENS Low-Energy Neutron Source, Indiana U.



protons

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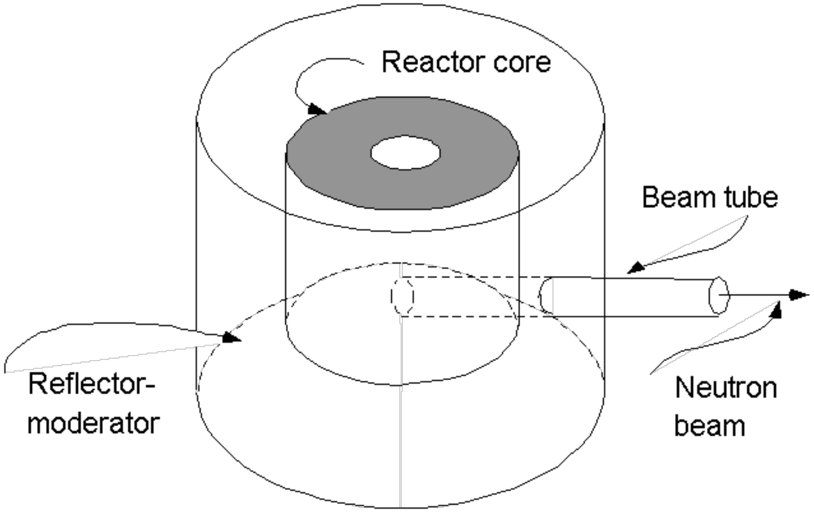
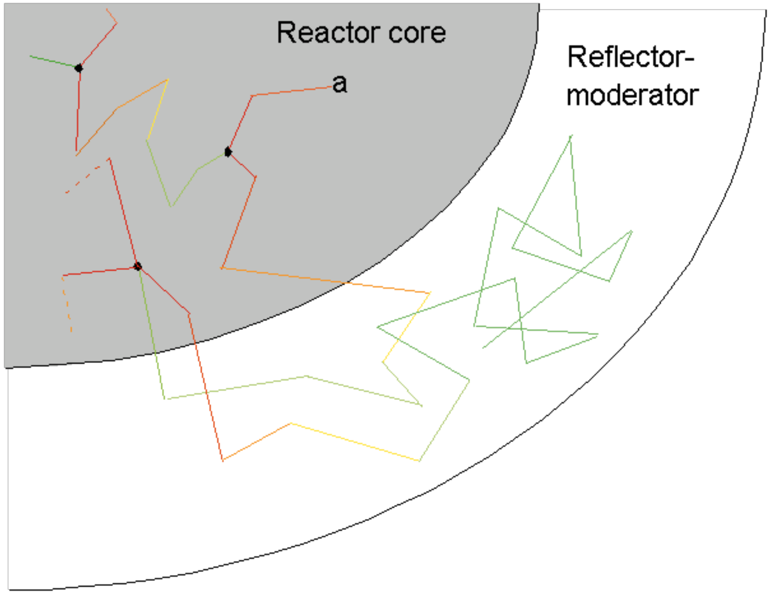
How Do Moderators Work?

Steady sources





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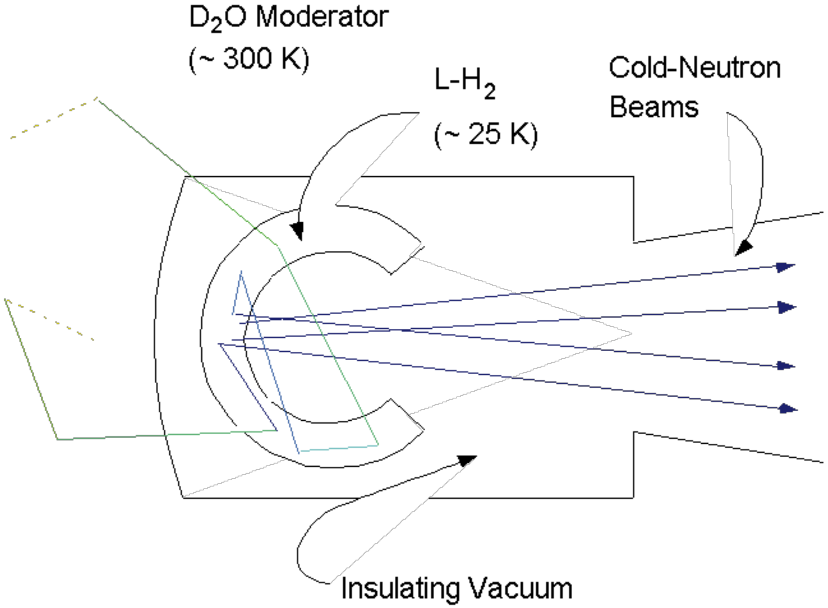
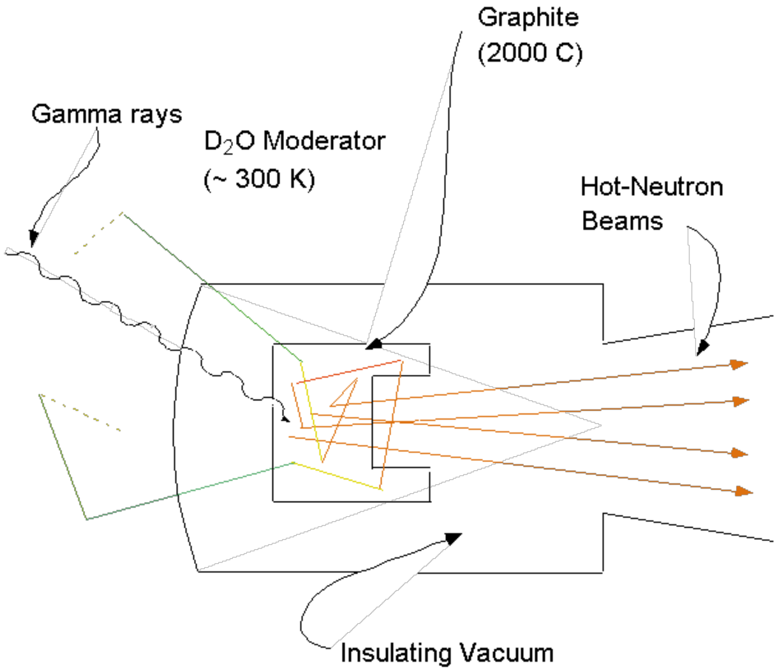
How Do Moderators Work?

Steady sources



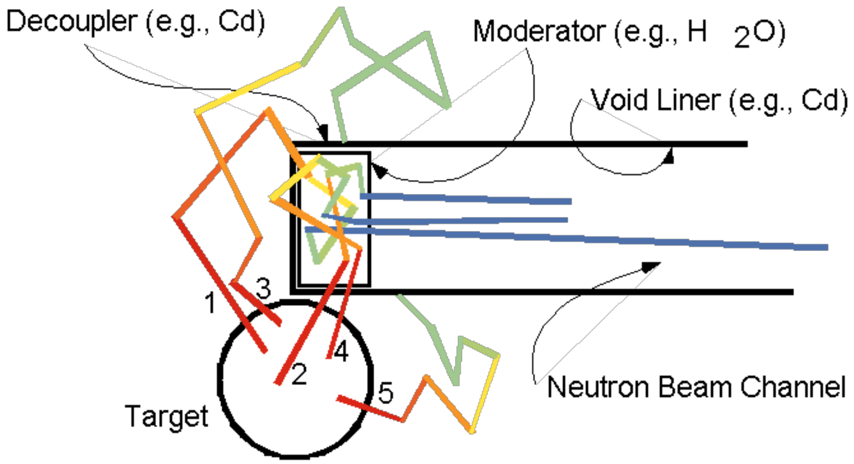
Cavity-type cold source



Hot source

How Do Moderators Work?

Pulsed sources



Reflector (e.g., Be)
(all around)

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.

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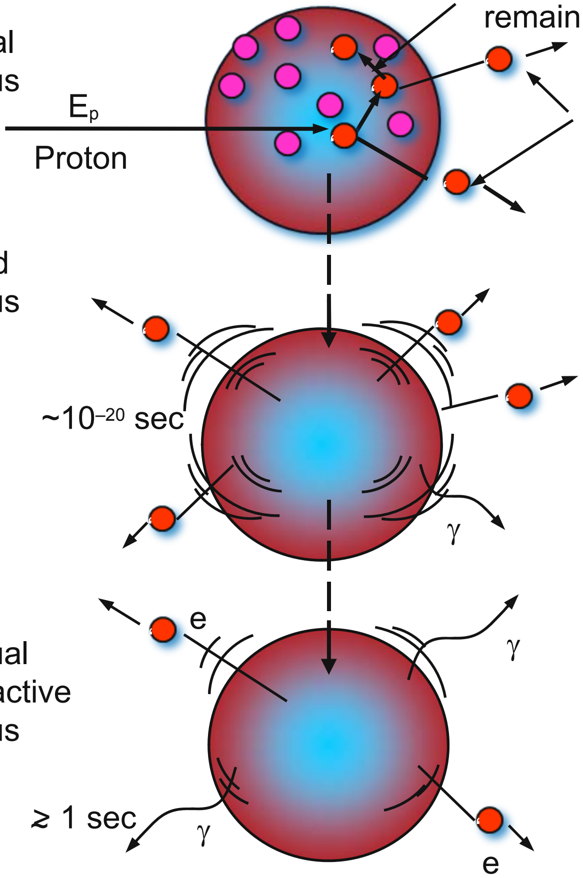
Spallation-Evaporation Production of Neutrons



Original Nucleus

Recoiling particles remaining in nucleus

Emerging “Cascade” Particles (high energy, ~E < E_p) (n, p. π, …)

(These may collide with other nuclei with effects similar to that of the original proton collision.)

Excited Nucleus

Evaporating Particles (Low energy, E ~ 1–10 MeV); (n, p, d, t, … (mostly n) and γ rays and electrons.)

Residual Radioactive Nucleus

Electrons (usually e^+) and gamma rays due to radioactive decay.

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

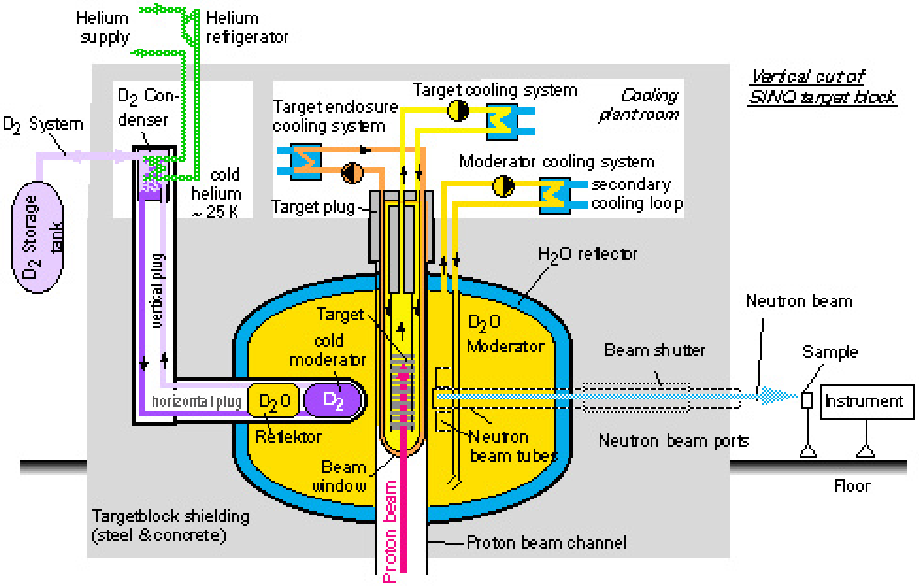
- High time averaged flux.
- Uses reactor type instrumentation (mature technology).
- Politically acceptable.
- piggy-backed on existing accelerator.

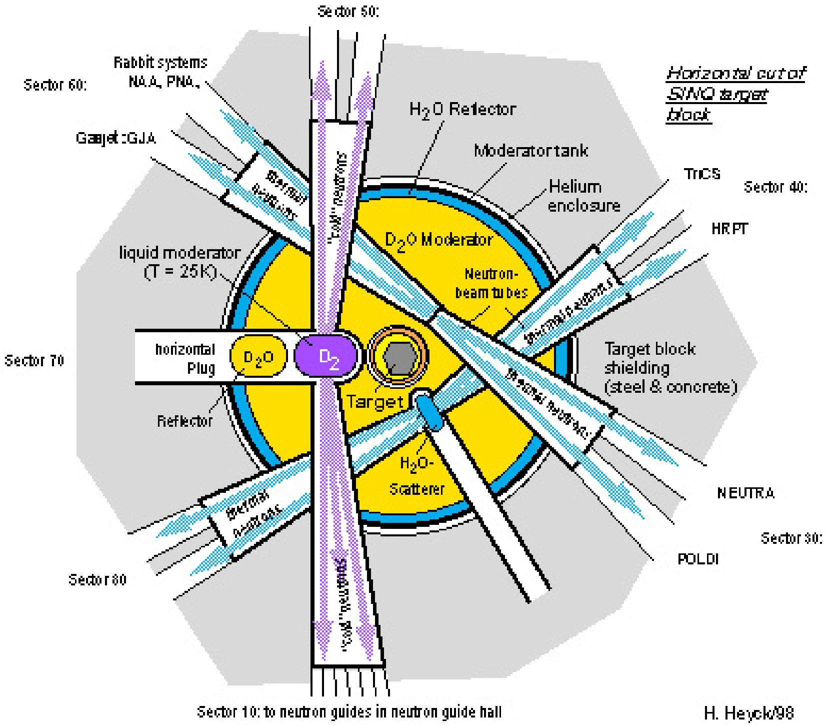
Disadvantages

- No time structure.
- high background feared but not realized.

Types of Neutron Sources-cont’d

Principles of the Spallation Neutron Source SINQ





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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

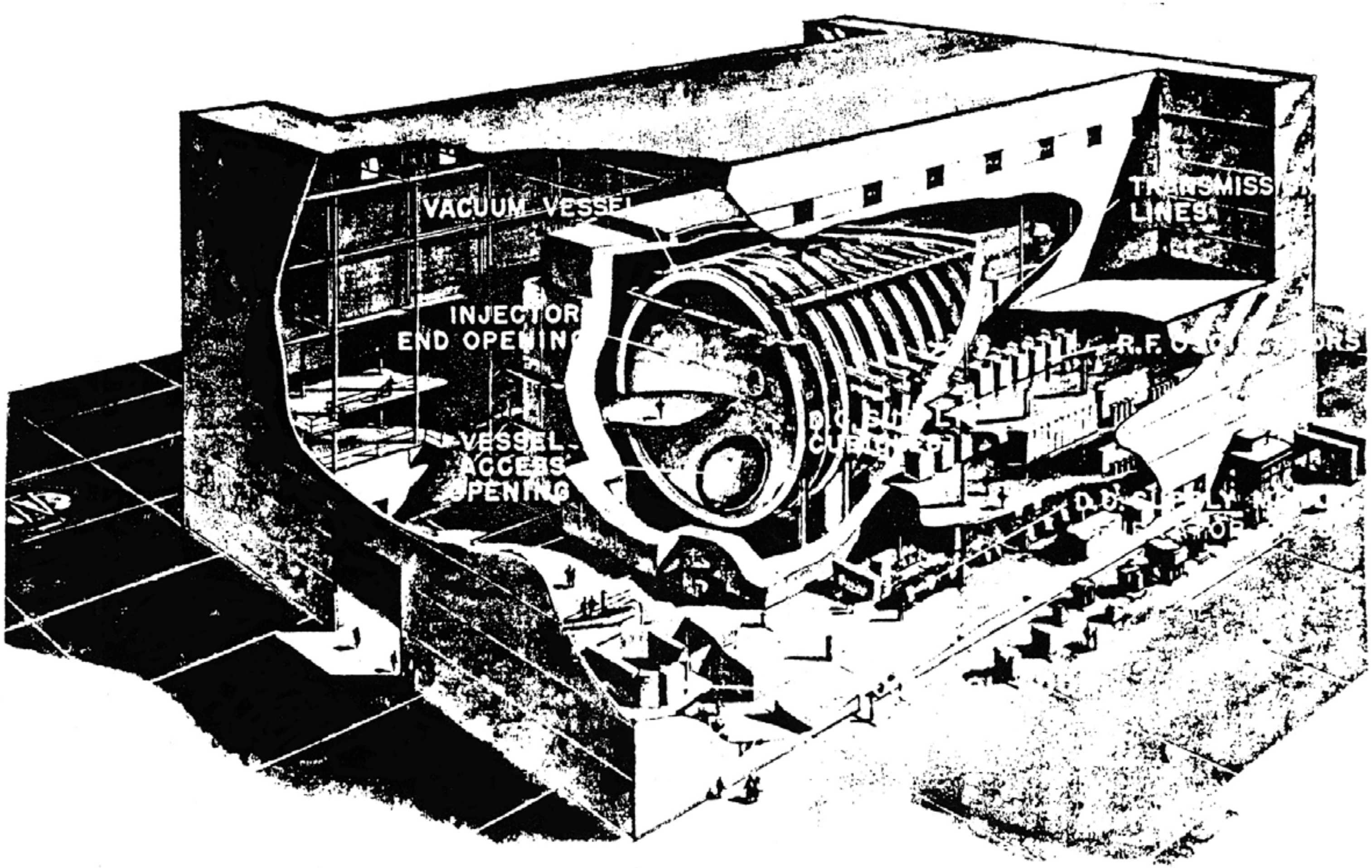
- There was already by that time some information on the production of spallation neutrons by 190-MeV deuteron-induced spallation on Uranium, about 30% more than by protons of the same energy. This guided the choice of accelerated particle type and beam energy. With the anticipated required production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

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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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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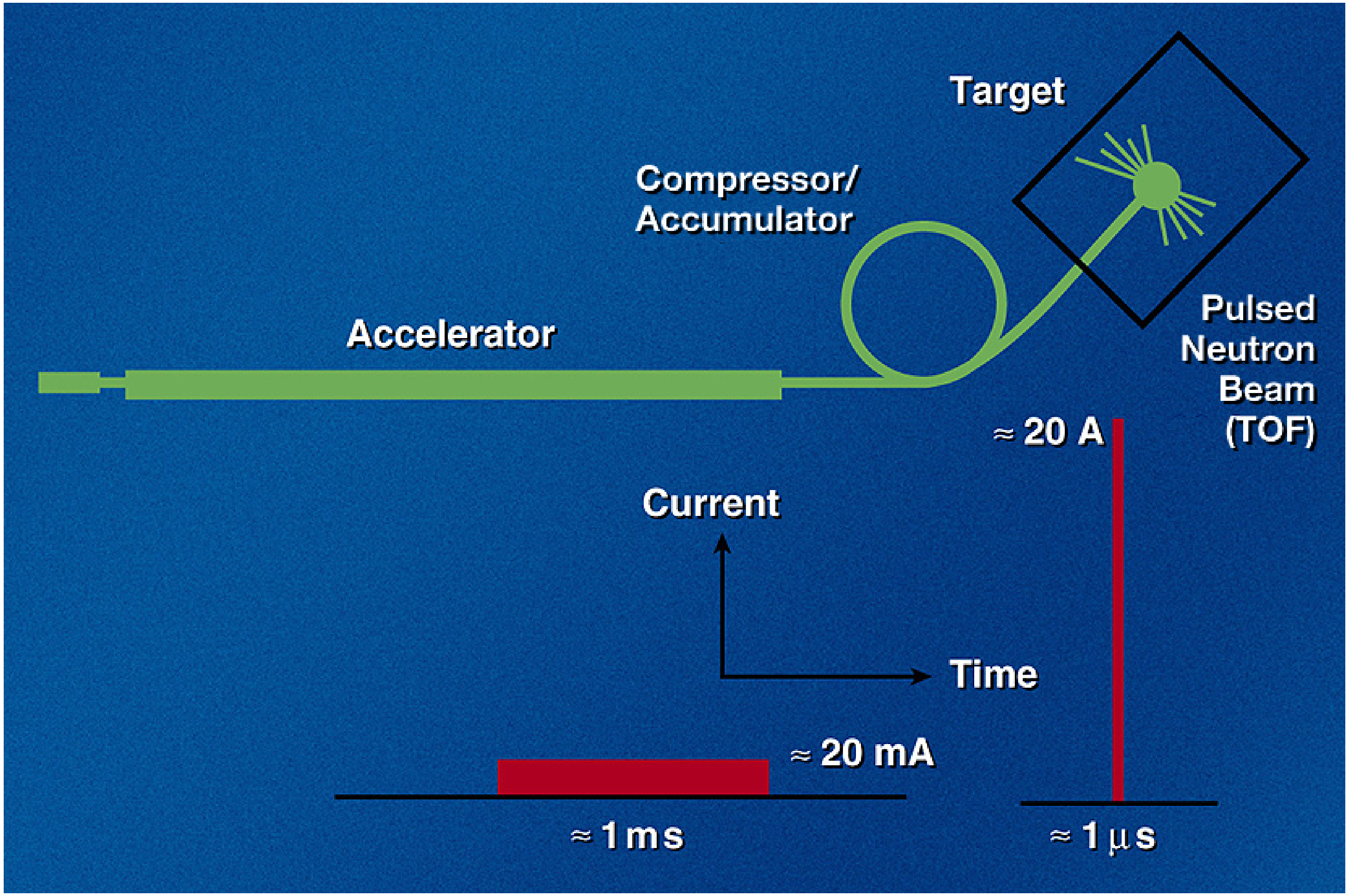
Pulsed Spallation Neutron Source Construction, Proposals, and Studies

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

Anatomy of a Pulsed Spallation Neutron Source



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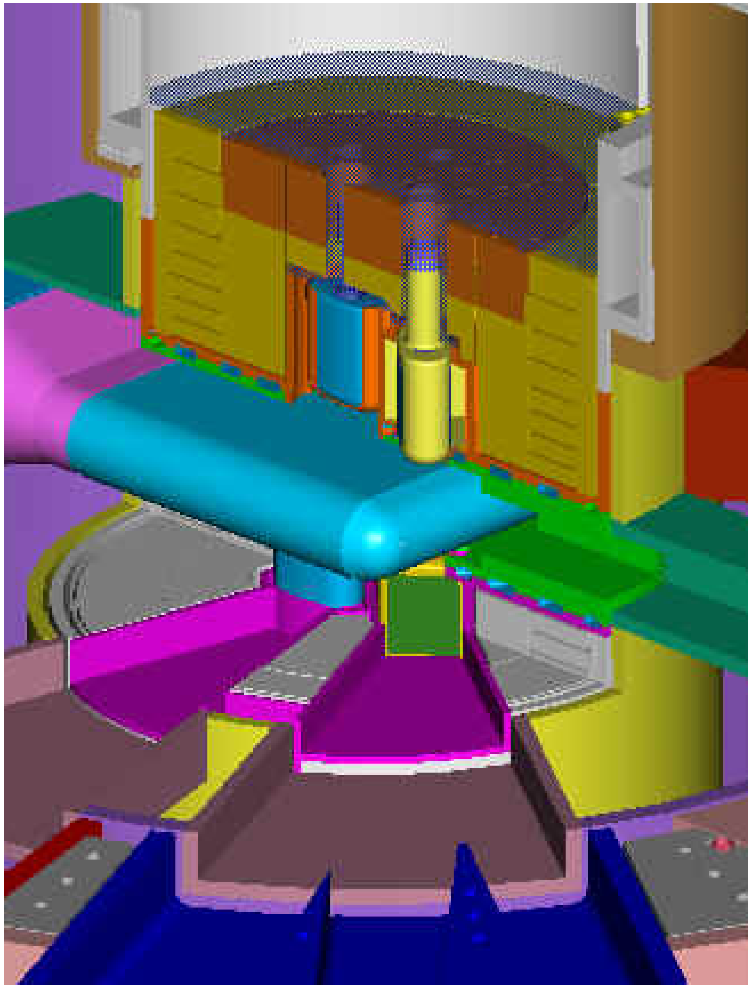
The Spallation Neutron Source

- The SNS construction project concluded in 2006, shown in spring 2007.
- First operation April 2006, 800 kW in June 2009.
- 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 Target-Moderator-Reflector System



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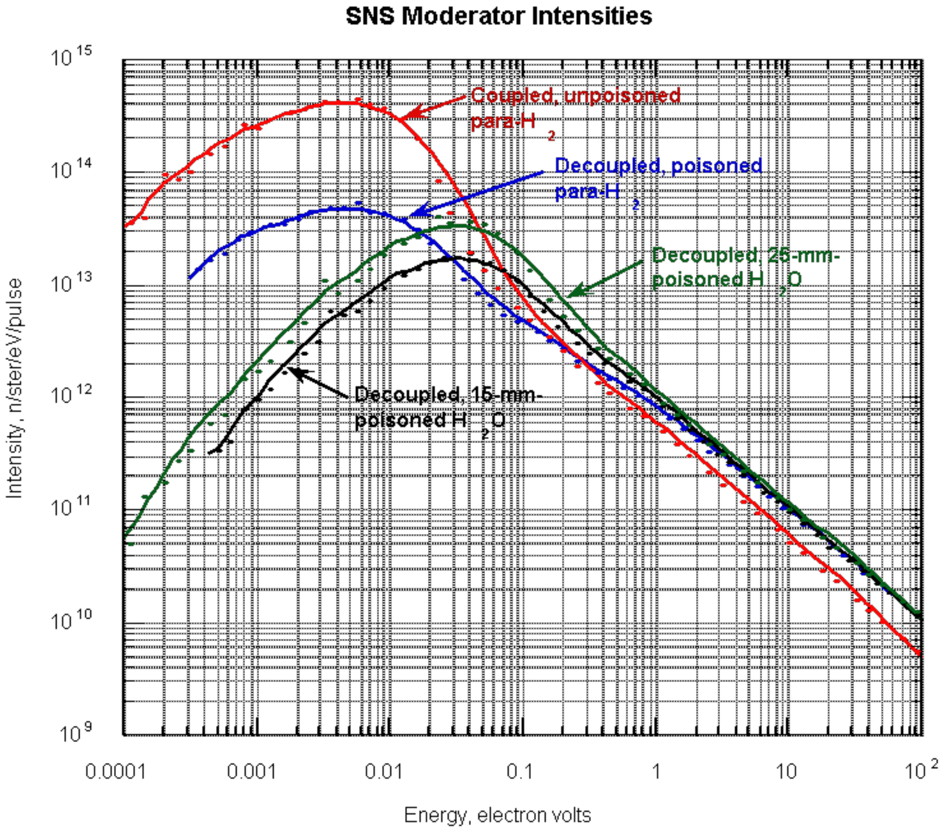
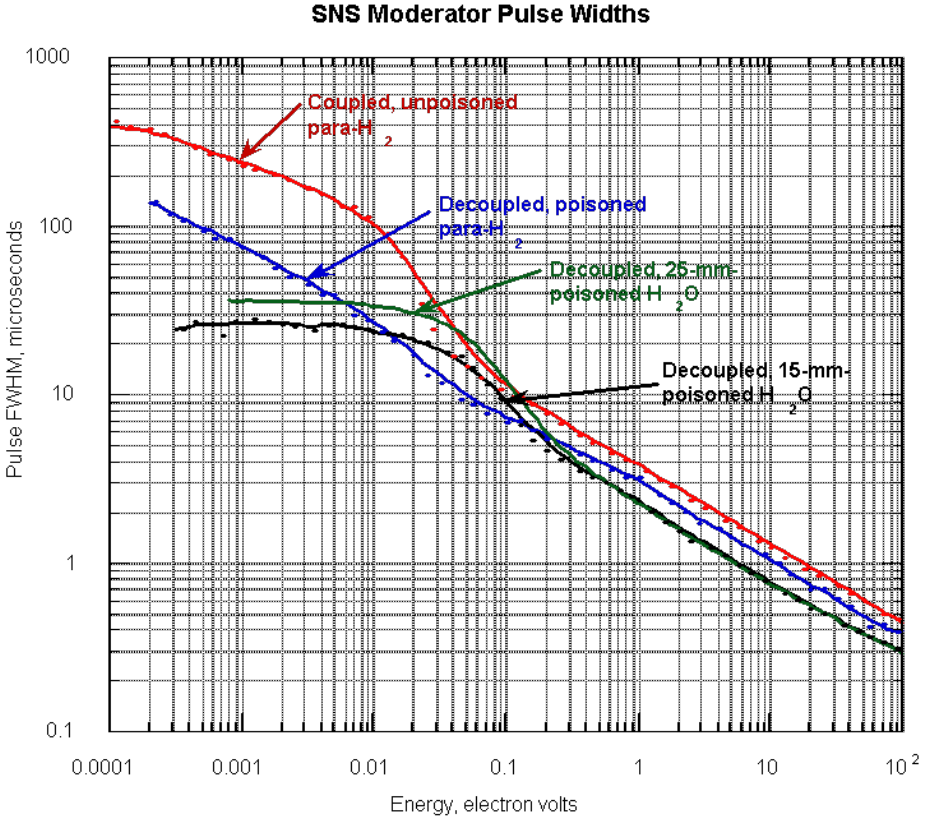
SNS Moderator Intensities and Pulse Widths





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

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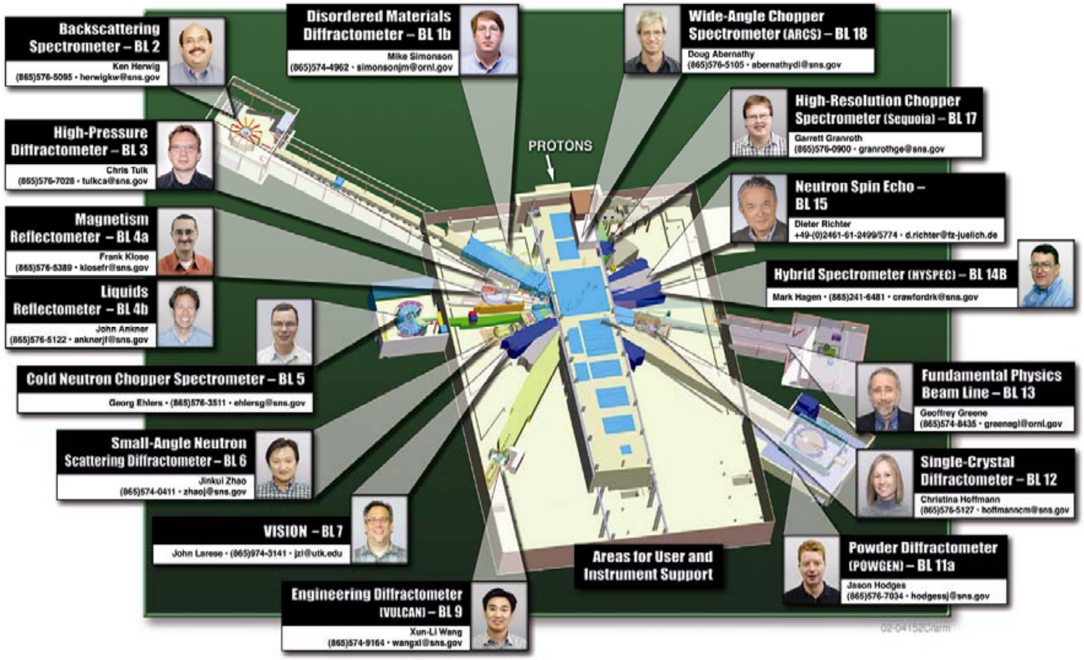
SNS Instruments

- ~20 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.



End of Presentation

Thank you!