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Neutron Generation

National School on Neutron and X-ray Scattering

Oak Ridge

22 June 2014

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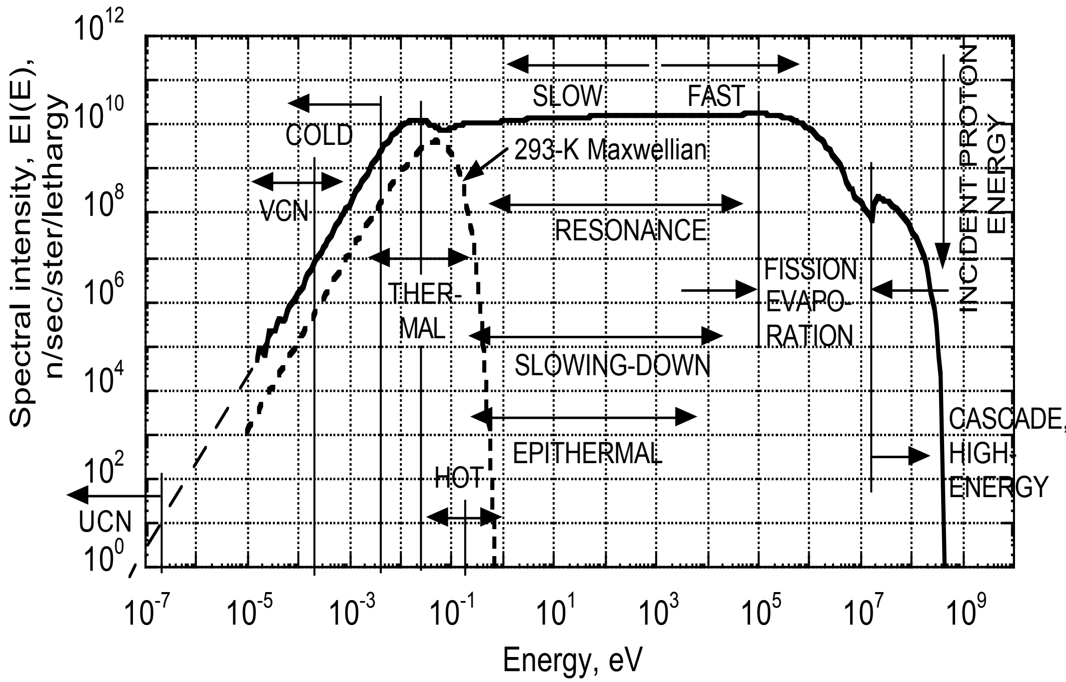
ANL, ORNL/SNS

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 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.
- Free neutrons decay by e^- emission to a proton, accompanied by a neutrino, and have a half life T_e = 881.5 seconds = 14.7 minutes and a half-life $T_{1/2}$ = 611.0 seconds. Although the decay process is interesting from a fundamental physics point of view, we don't need to account for it in materials science applications.

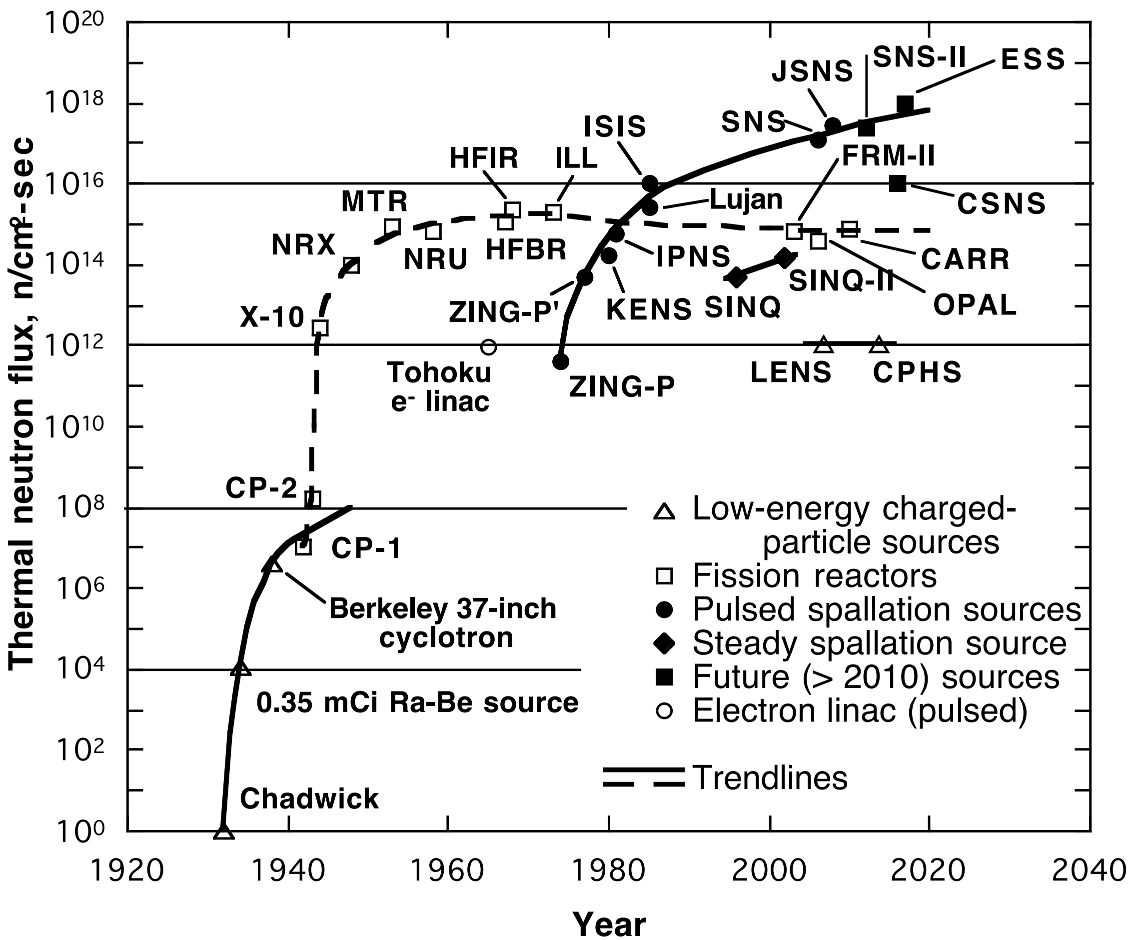
Fast and slow neutrons, etc.



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.

Development of Neutron Science Facilities

Brugger plot



Redrawn 2009

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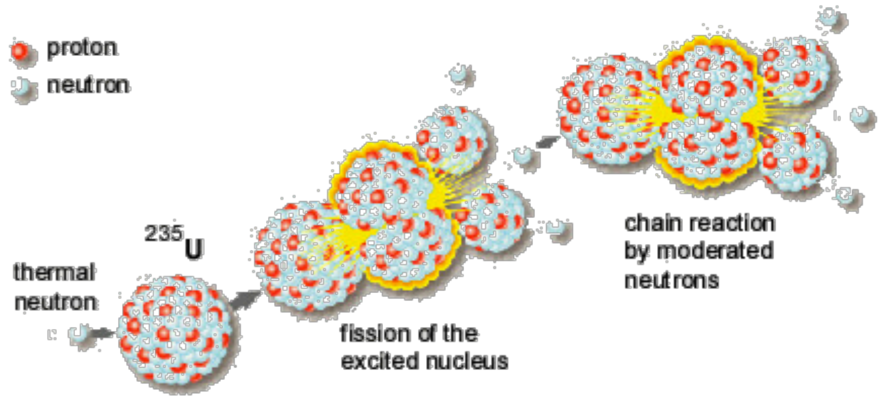
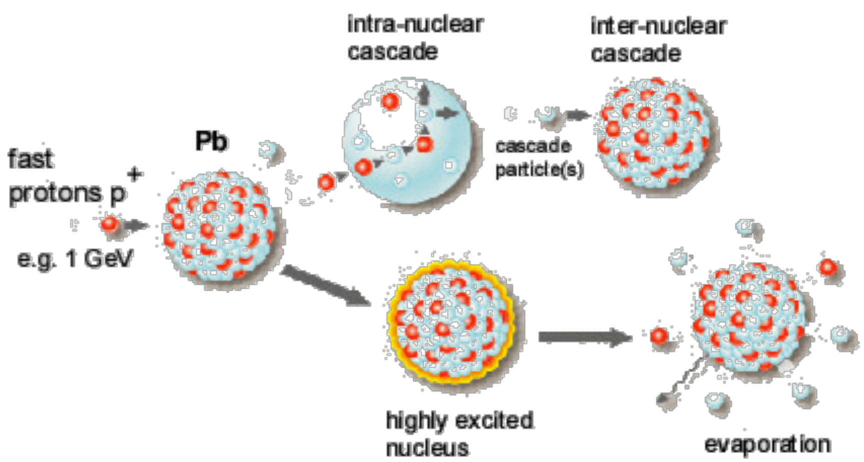
How do we produce neutrons?



Fission

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



Spallation

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

Neutrons: Where do they come from?

Fission:

$$n + {}^{235}U = 1.5n + n + \text{fragments}$$

Sustain chain reaction

Available

~ 180 MeV/n (as heat)

Spallation:

p + heavy nucleus = 20 ~ 30 n + fragments

1GeV e.g. W, Pb, U

~ 30 MeV/n (as heat)

Neutrons: Where do they come from?

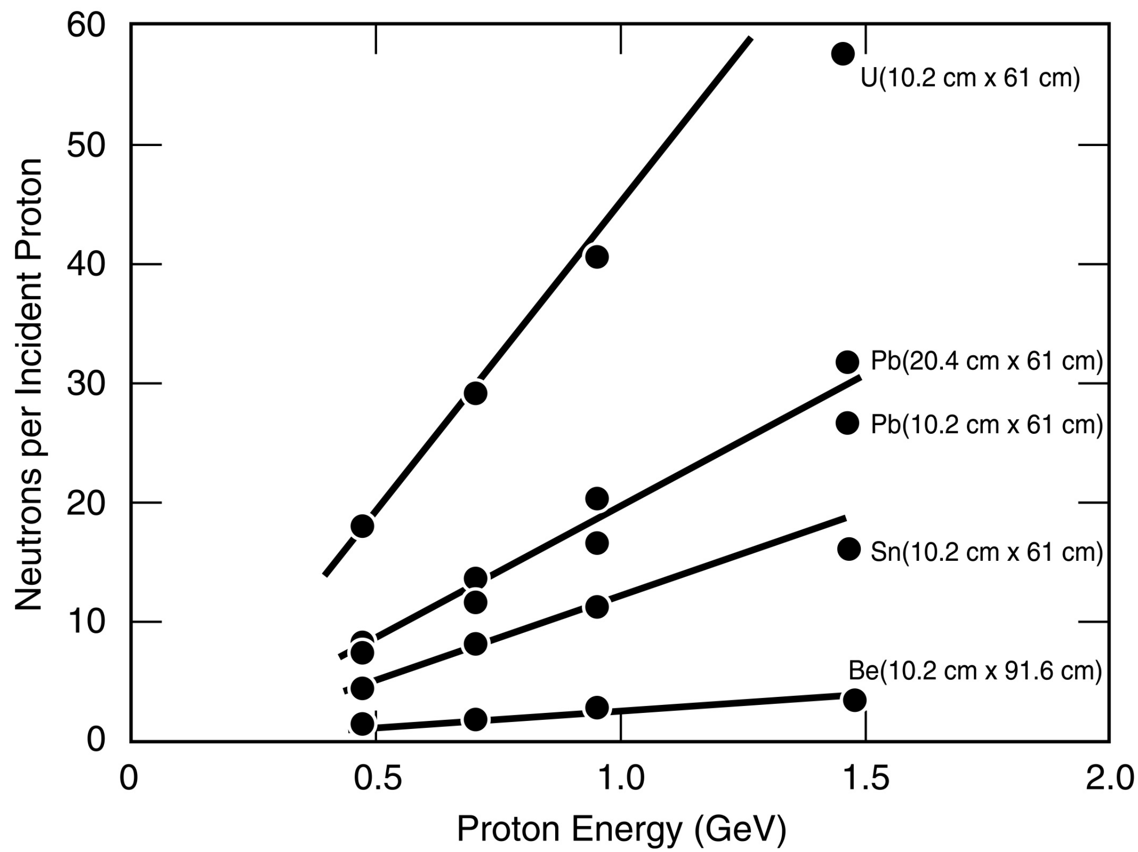
Measured Spallation Neutron Yield vs. Proton Energy for Various Targets, J. Frazer, et al. (1965)

Absolute Global Neutron Yield

Yield (neutrons/proton)

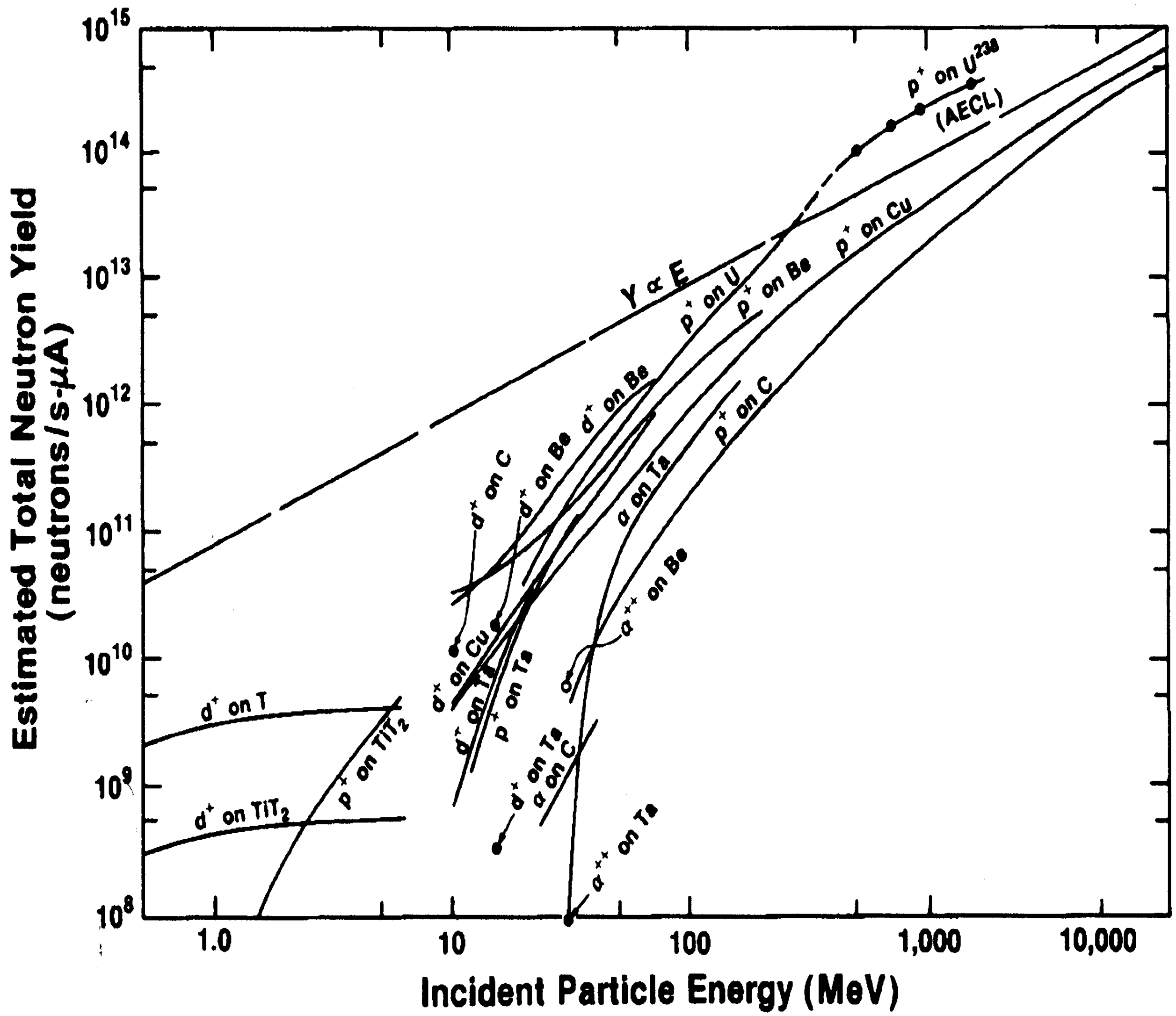
$= 0.1(E_{GeV} - 0.12)(A+20)$,
except fissionable materials;

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

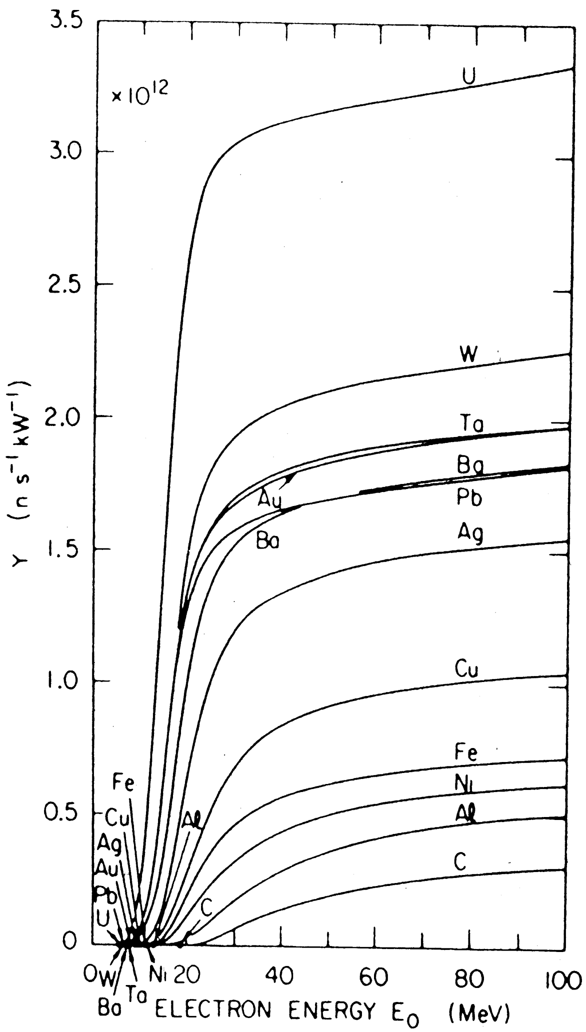


From Fraser *et al.,* measurements at Brookhaven Cosmotron

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

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

Types of Neutron Sources-cont’d

- Reactors, e.g., HFR at ILL, HFIR at ORNL, ~1.5×10^{15} n/cm^2/s,
  FRM-2 at Munich, ~$1. \times 10^{15}$ n/cm^2/s

Advantages

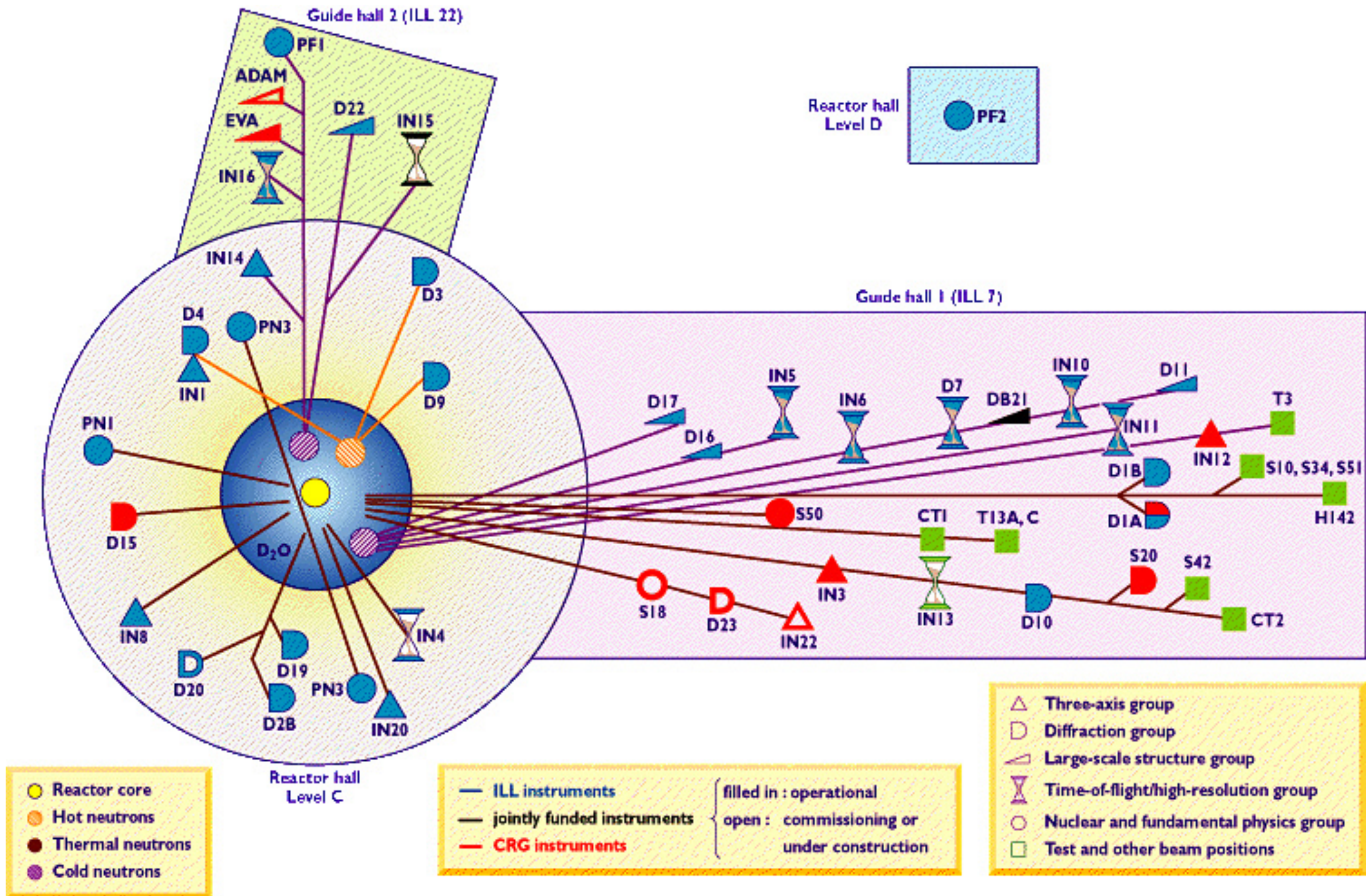
- High time averaged flux.
- Mature technology (source; instruments–development continues).
- Very good for cold neutrons.

Drawbacks

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

Types of Neutron Sources

The Institut Laue-Langevin, Grenoble



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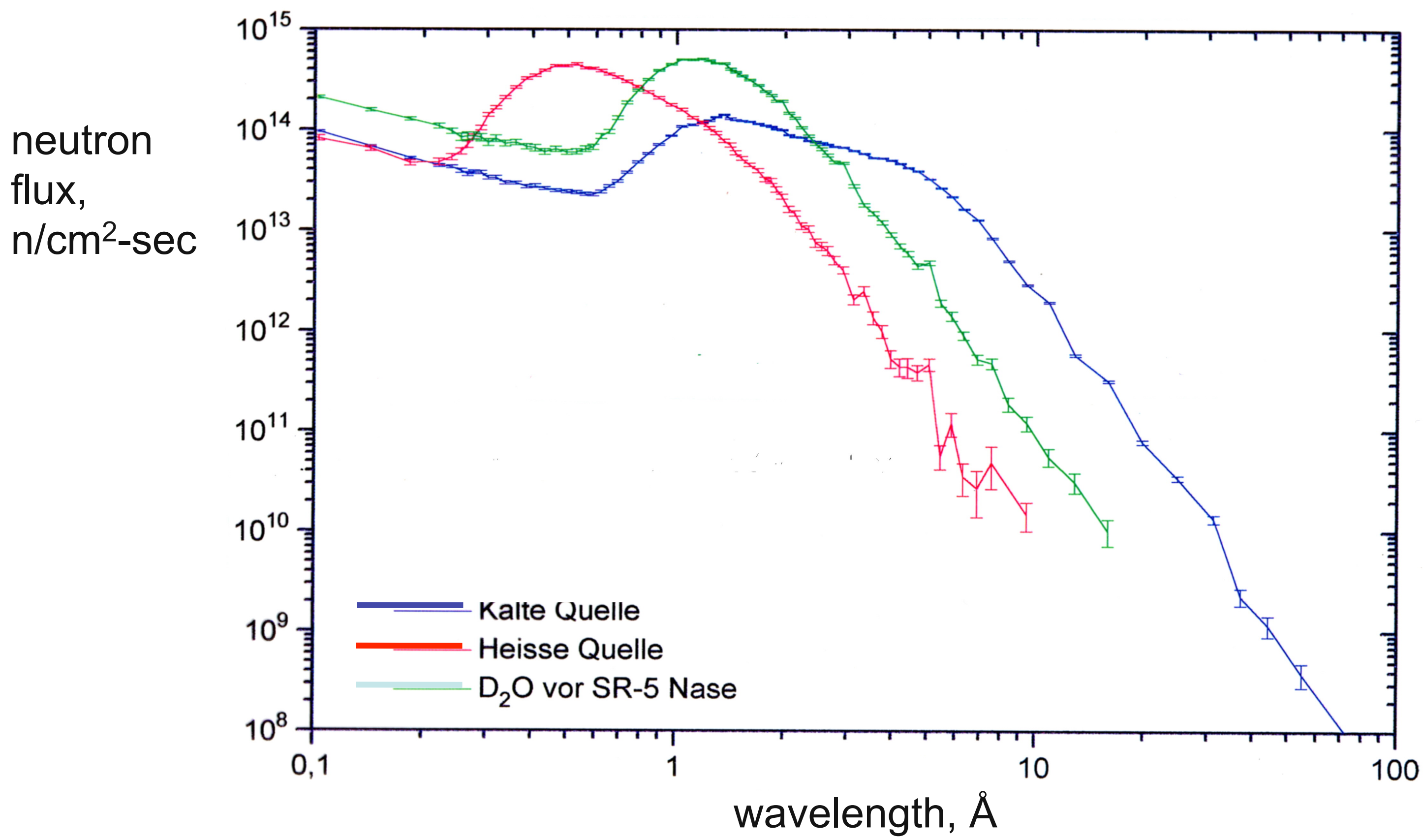
Types of Neutron Sources-cont'd

Source Spectra of the FRM-II Reactor



Types of Neutron Sources-cont'd

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

200 μA, 0.8 GeV, 160 kW

ISIS 2×10^{13} n/cm^2/s average flux SNS 1.4 mA, 1.0 GeV, 1.4 MW

8×10^{15} n/cm^2/s peak flux

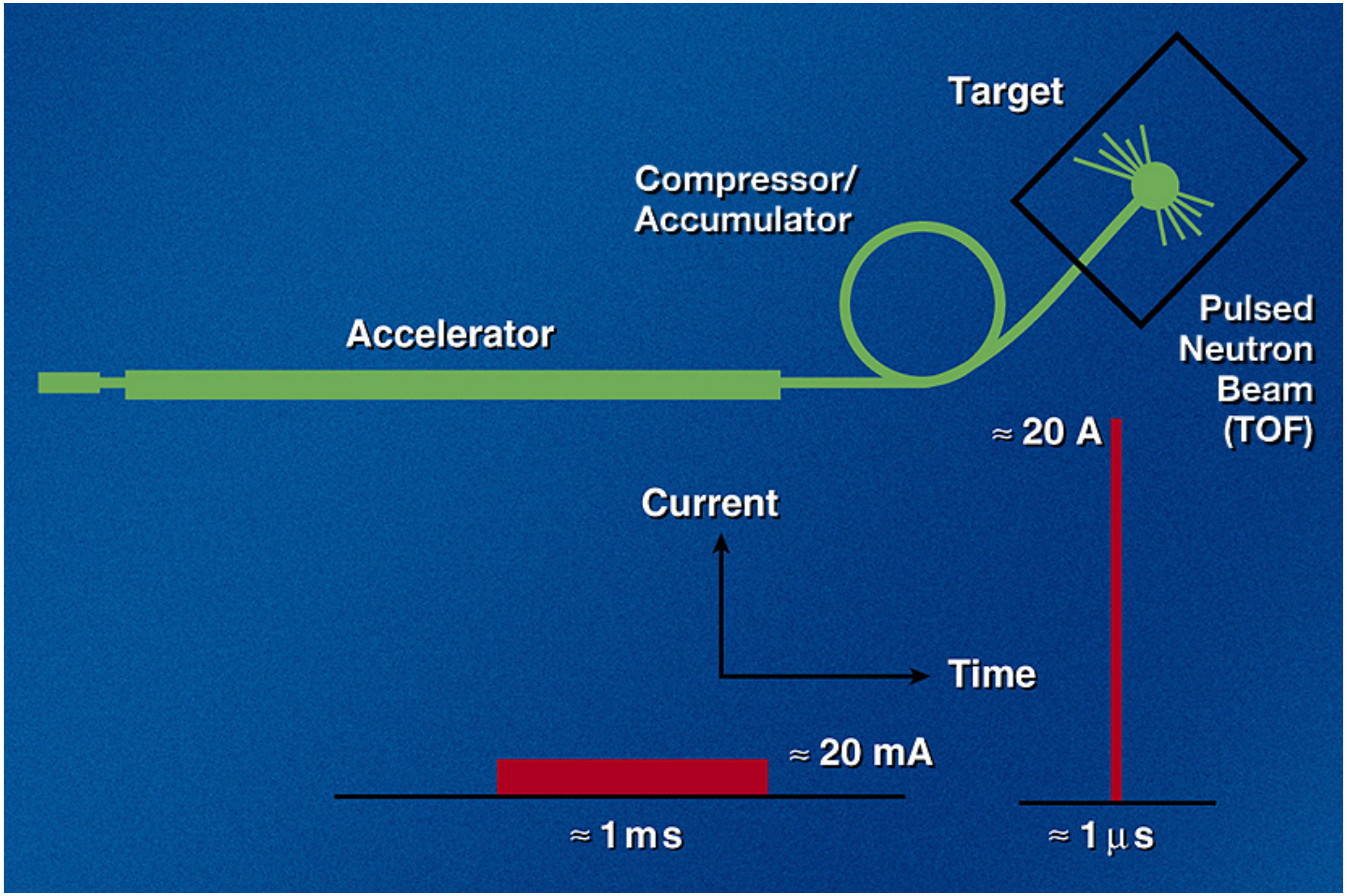
Advantages

- 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.

Anatomy of a Pulsed Spallation Neutron Source



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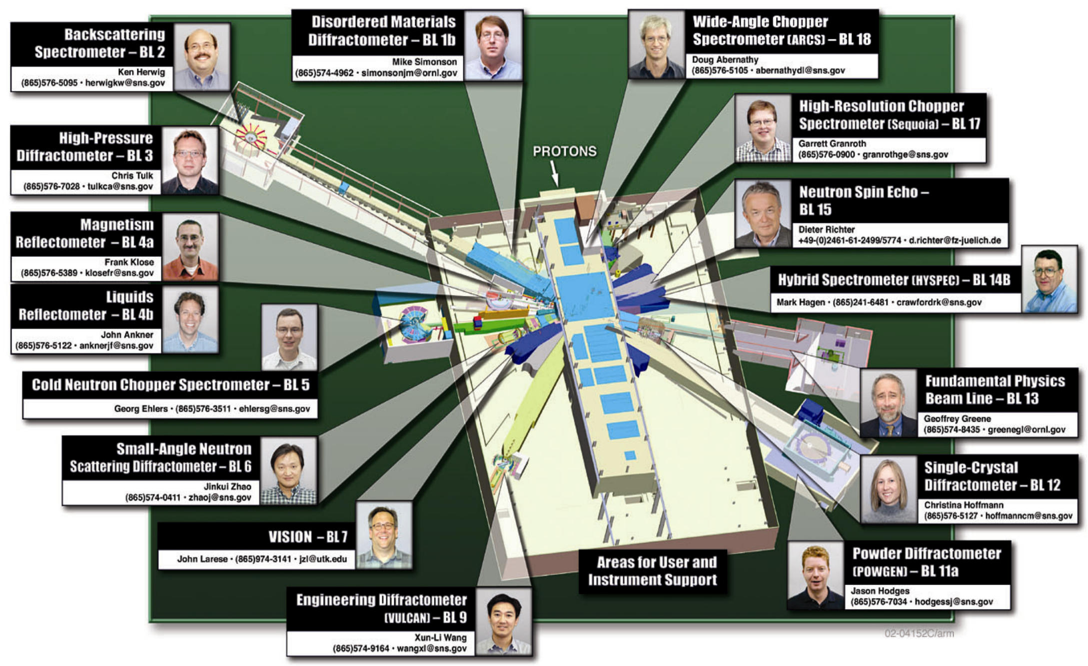
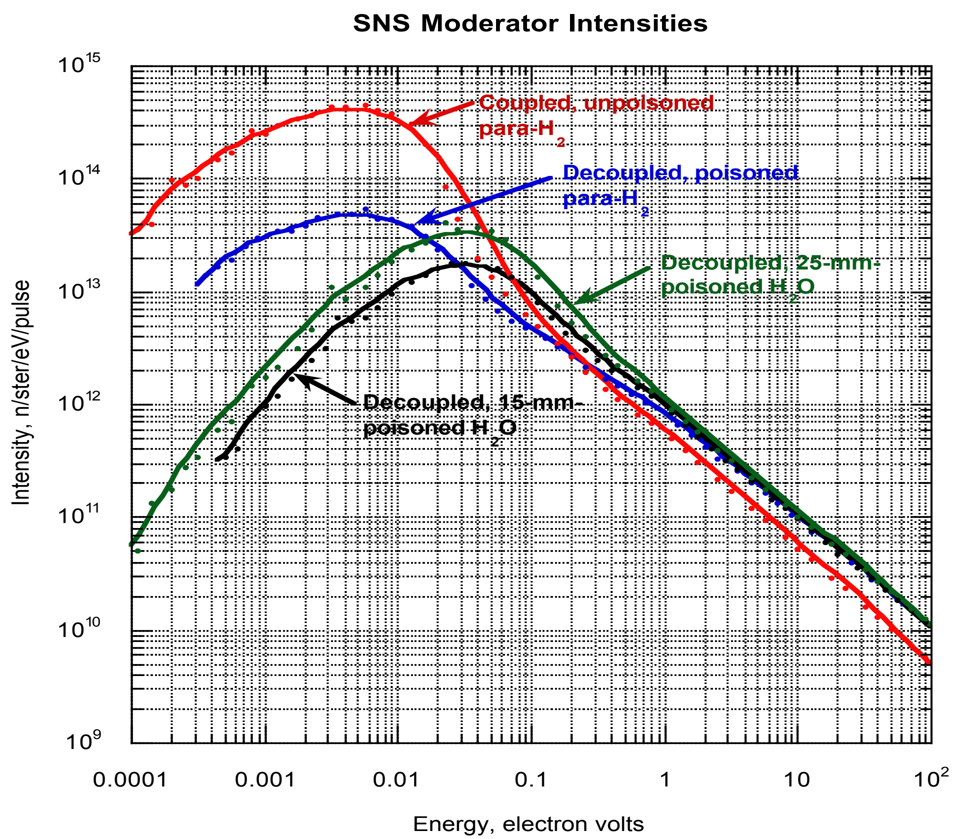
SNS Instruments

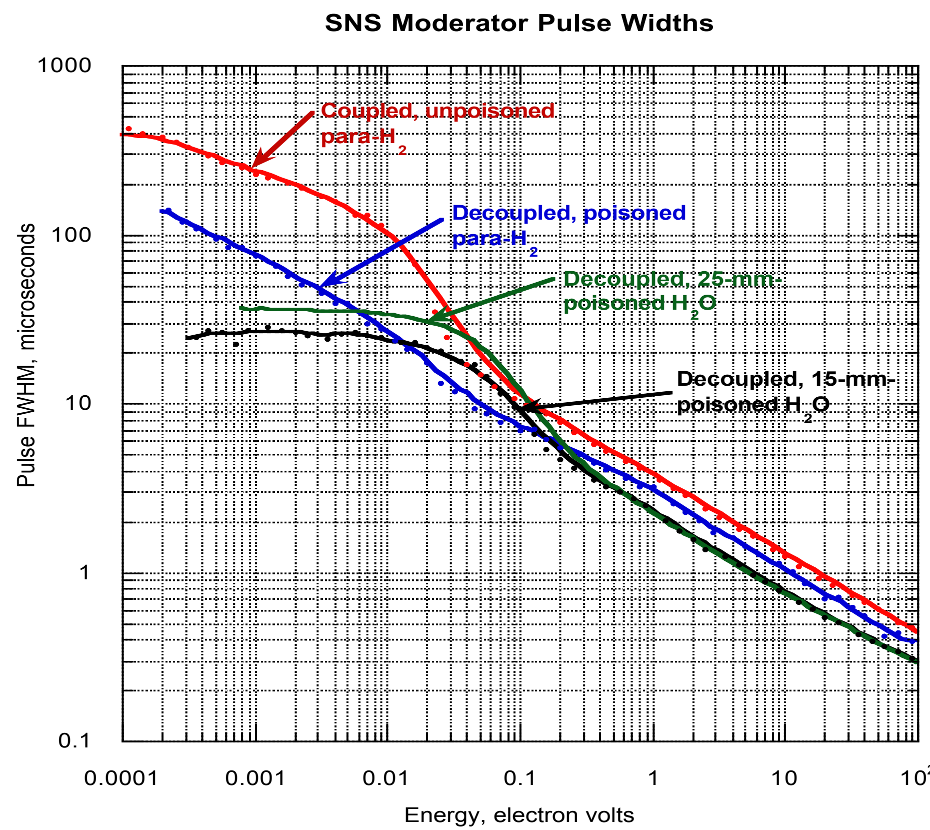
- ~20 instruments approved.
  - Excellent progress with funding.
    - DOE, including SING1 and SING2 Projects, foreign, and NSF initiatives
- Working to enhance instrument technology

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



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-cont'd

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

  0.85 mA, 590 MeV, 0.9 MW

  $1x10^{14}$ n/cm^2/s average flux

Advantages

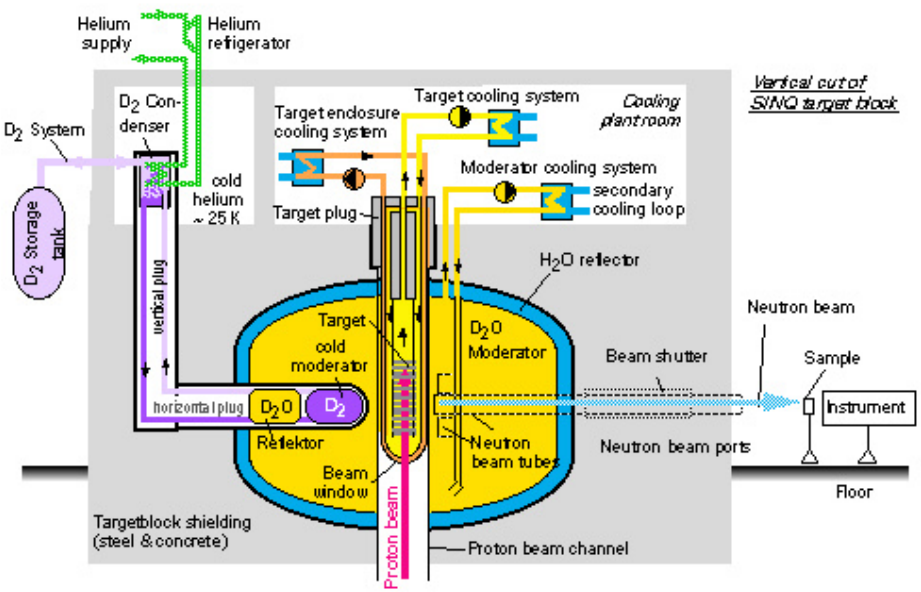
- High time averaged flux.
- Uses reactor type instrumentation (mature technology).
- Politically acceptable.
- piggy-backed on existing accelerator.

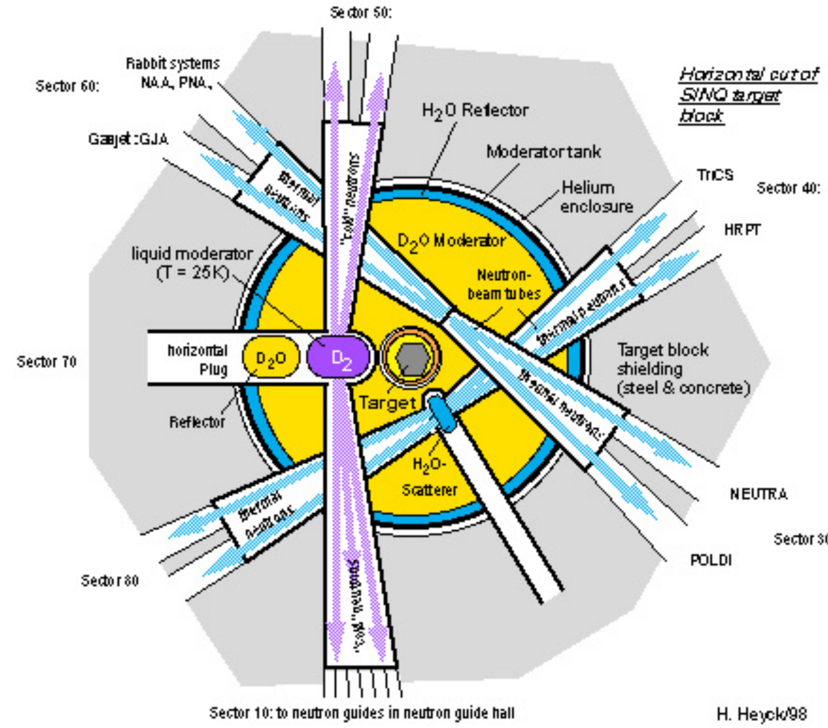
Disadvantages

- No time structure.

Types of Neutron Sources-cont'd

Principles of the Spallation Neutron Source SINQ





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 a few neutron beams.

Neutrons: Where do they 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.)

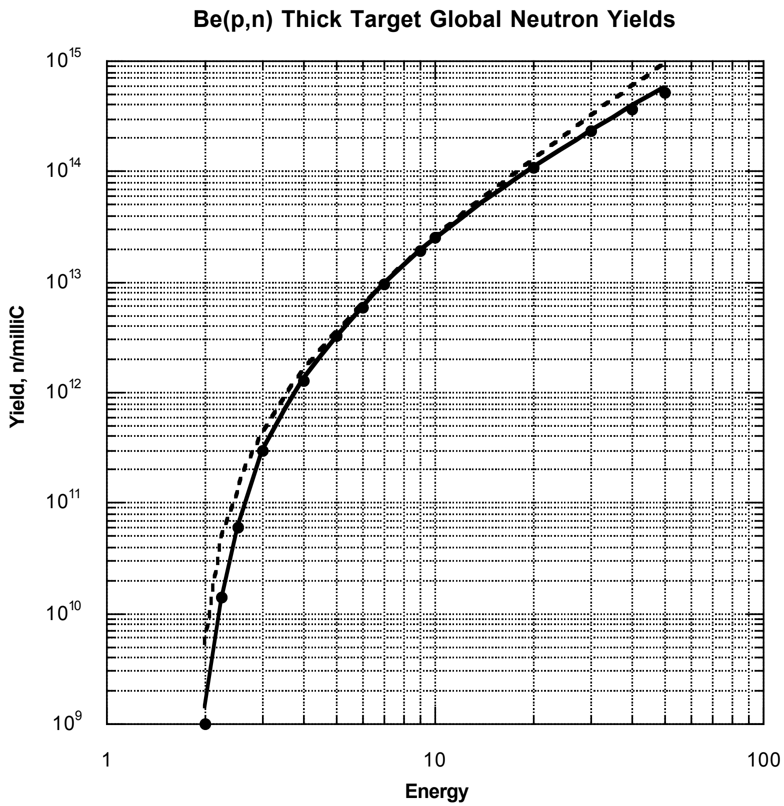
  5-15 MeV

  ~ 1300 MeV/n @ E_p = 13 MeV

  (deposited in ~ 1.1 mm)

  3.5×10^{-3} n/p

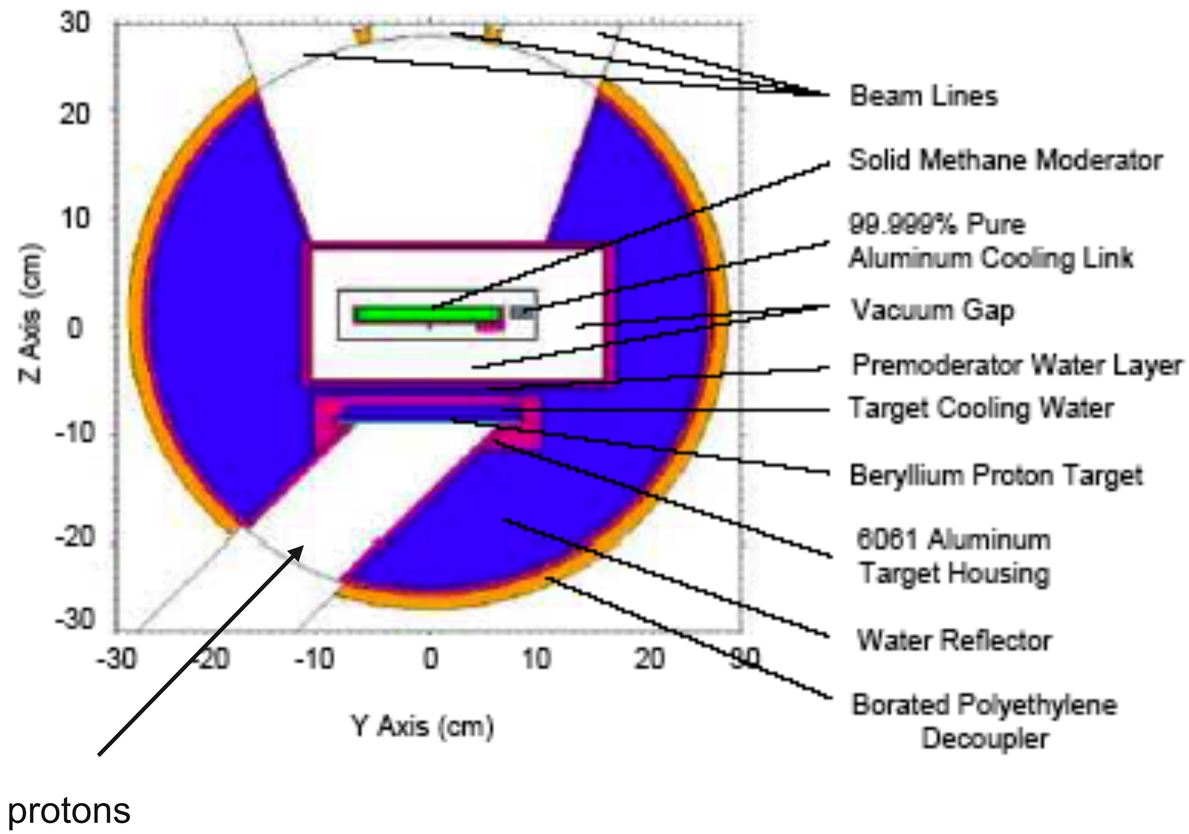
Be (p,n) Neutron Yields



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.

Types of Neutron Sources-cont' d

The LENS Low-Energy Neutron Source, Indiana U.



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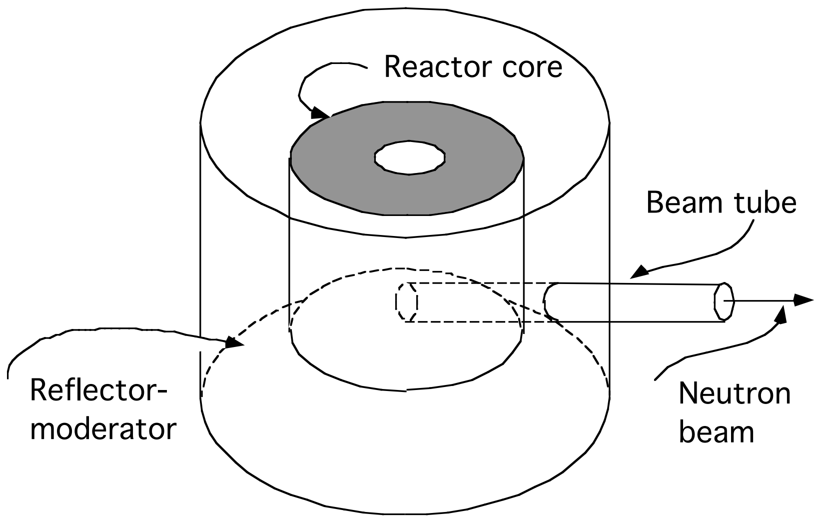
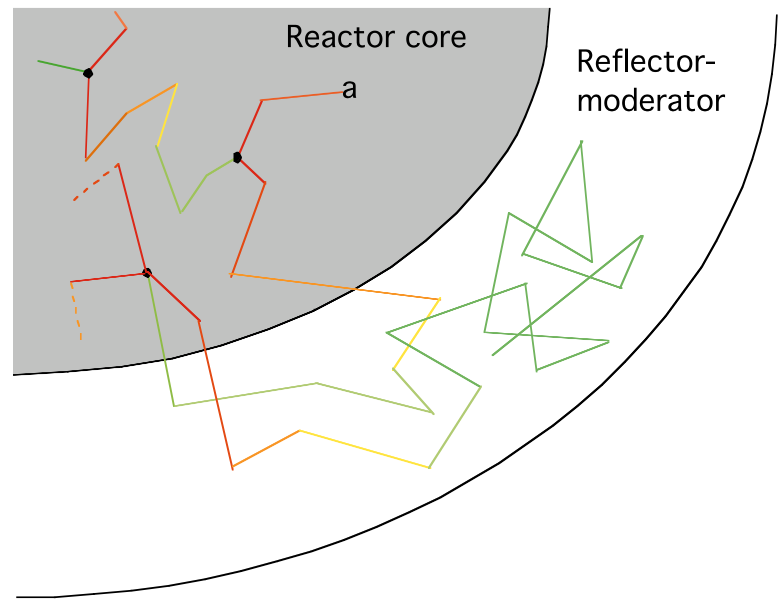
How Do Moderators Work?

Steady sources





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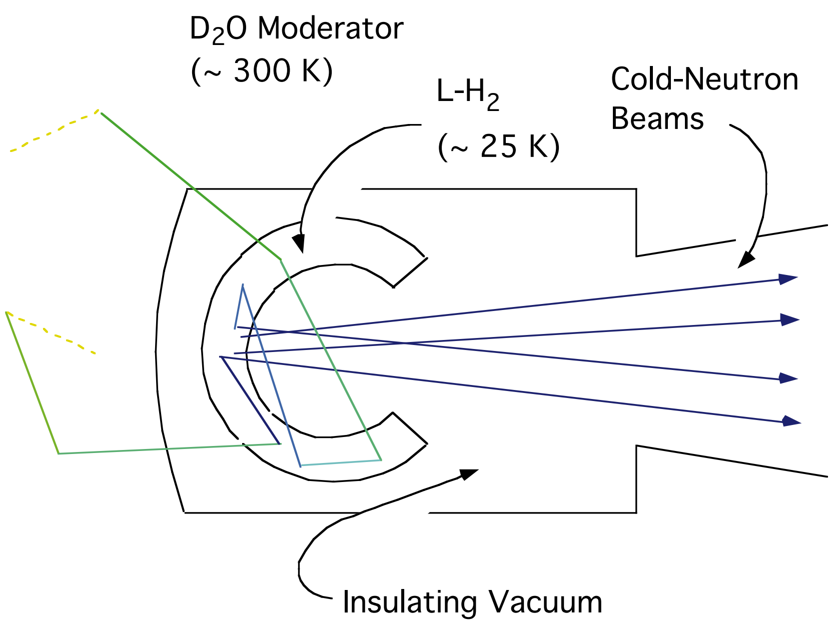
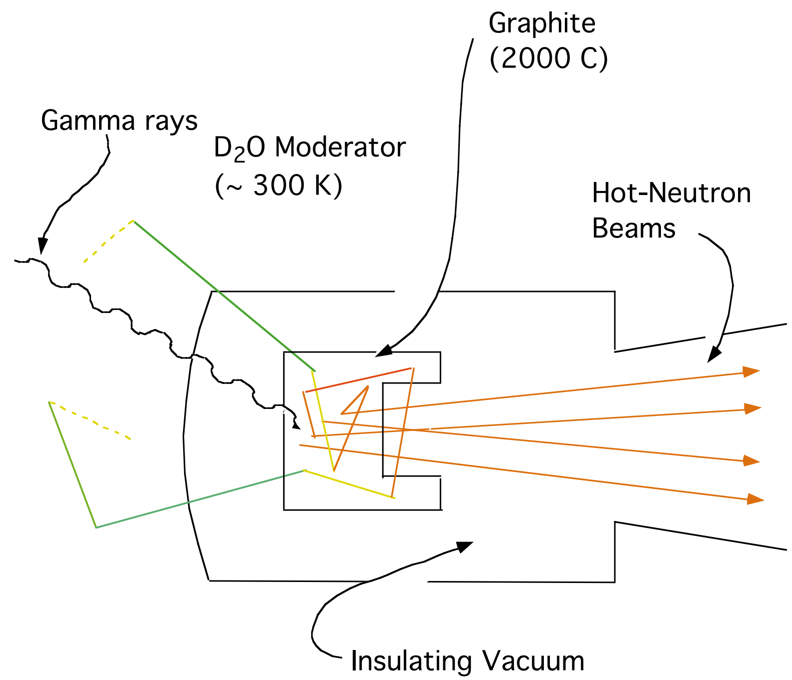
How Do Moderators Work?

Steady sources



Cavity-type cold source



Hot source

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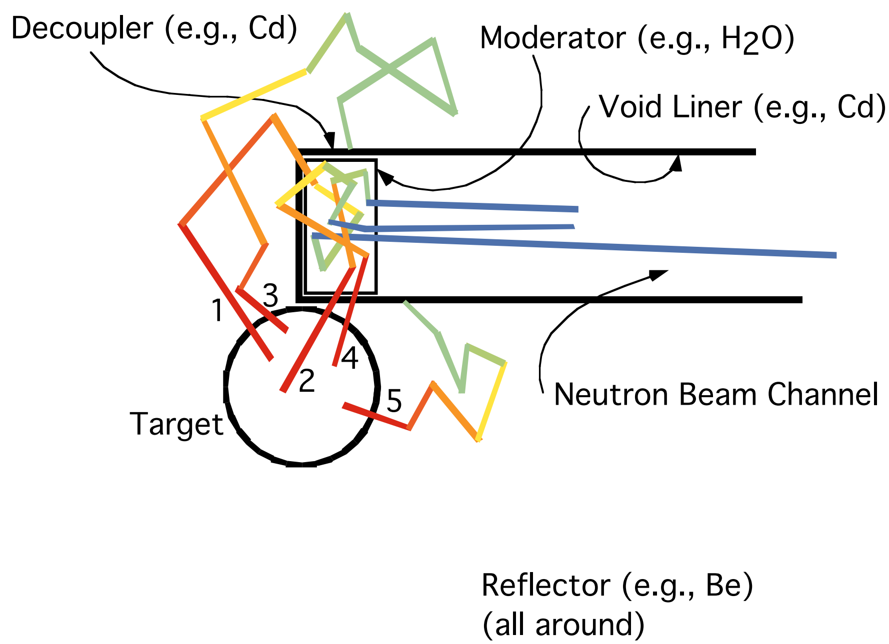
How Do Moderators Work?

Pulsed sources

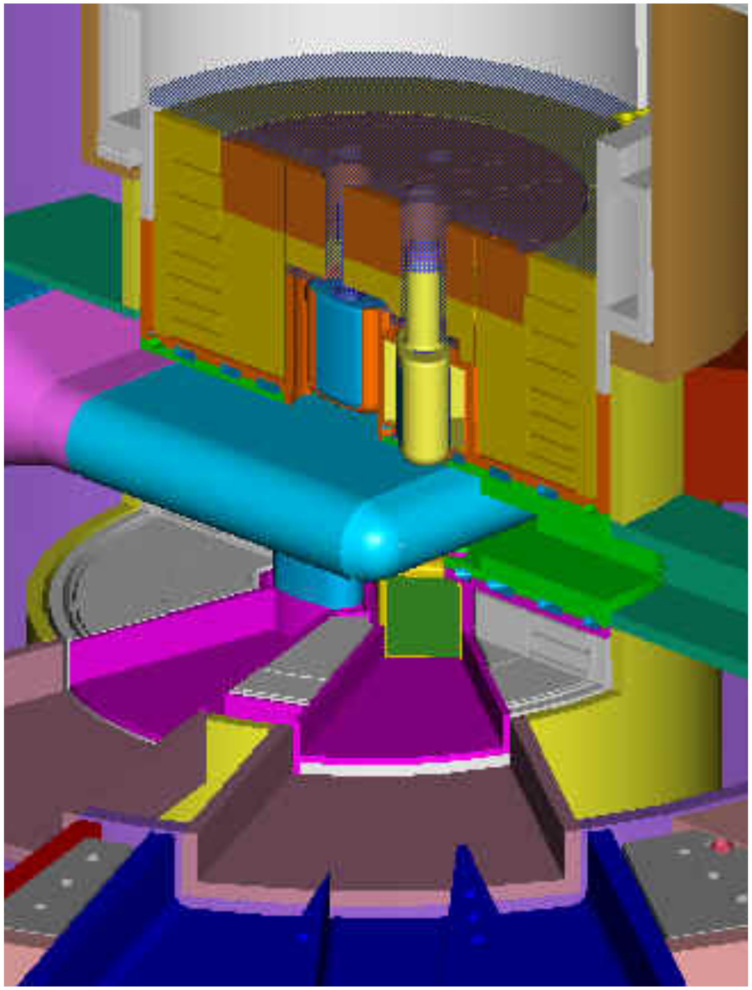


Decoupled, reflected
pulsed-source moderator

The Spallation Neutron Source

- SNS first operation April 2006. Shown in 2009.
- At 1.4 MW it will be ~ 8x ISIS, the world's leading pulsed spallation source.

SNS Target-Moderator-Reflector System



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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	190	800	50	1985/Operating
ISIS TS2	"	40	800	10	2009/Operating
MLNSC (Lujan Center)	Los Alamos	60	800	20	1985/Operating
SNS	Oak Ridge, TN	1400	1000	60	2006/Operating
JSNS	Tokaimura, Japan	1000	3000	25	2008/Operating
ESS	Lund, Sweden	5000	1500	15	2019/Planned

Primary source pulse widths of all except ESS are less than 1.0 µsec. ESS pulse width ~2000 µsec.

Very Cold Neutrons—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*
- *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.

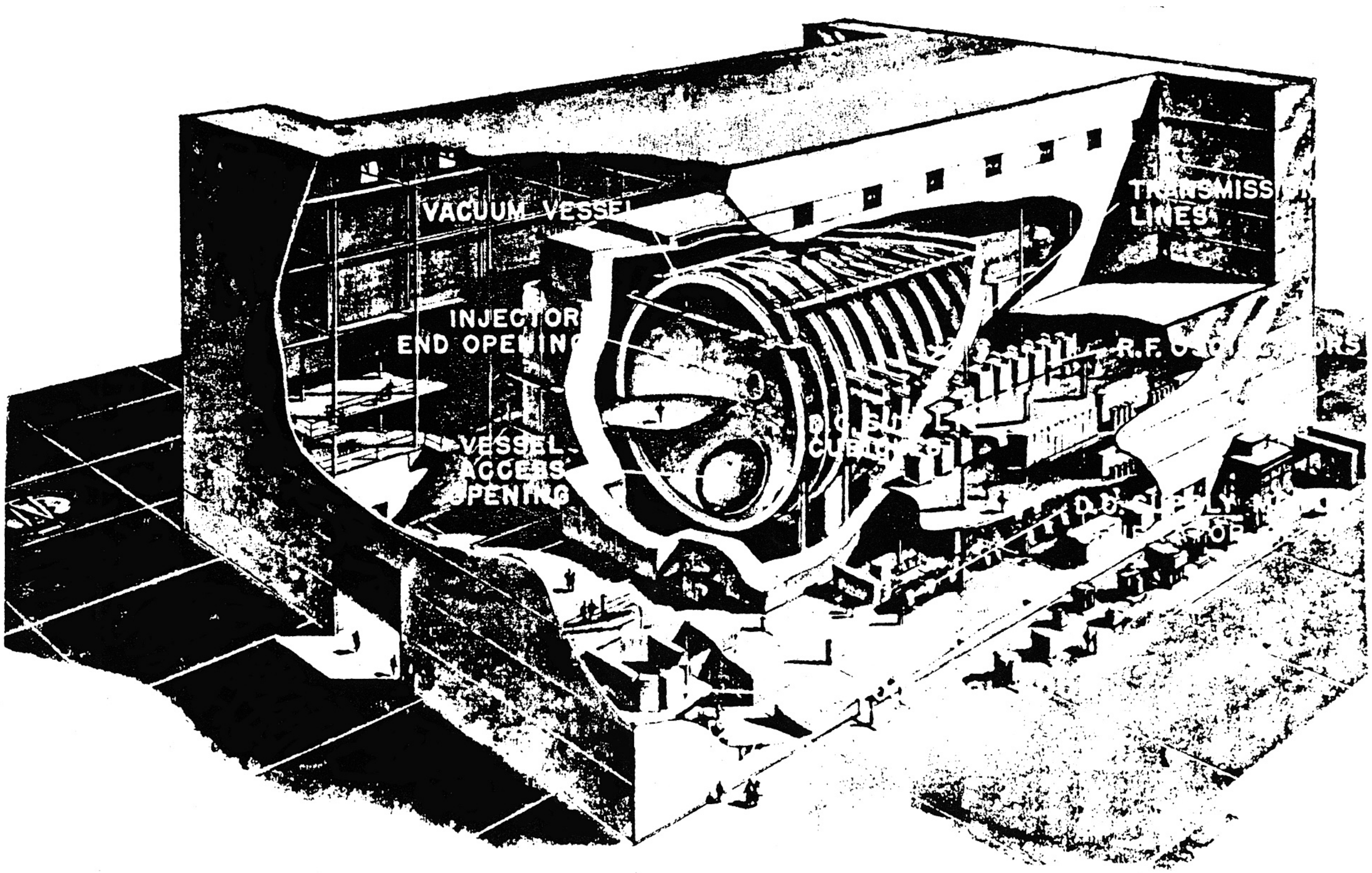
Magnetic lenses have advantages over material lenses because they present no absorption and scattering material to the passing neutron beams.

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

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

Just for historical fun: MTA, ~1950

Cutaway View of Linear Accelerator – Looking from the Injector End



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End of Presentation

Thank you!