Spallation-Driven Cold Neutron Sources

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Accelerator-Driven Spallation Sources

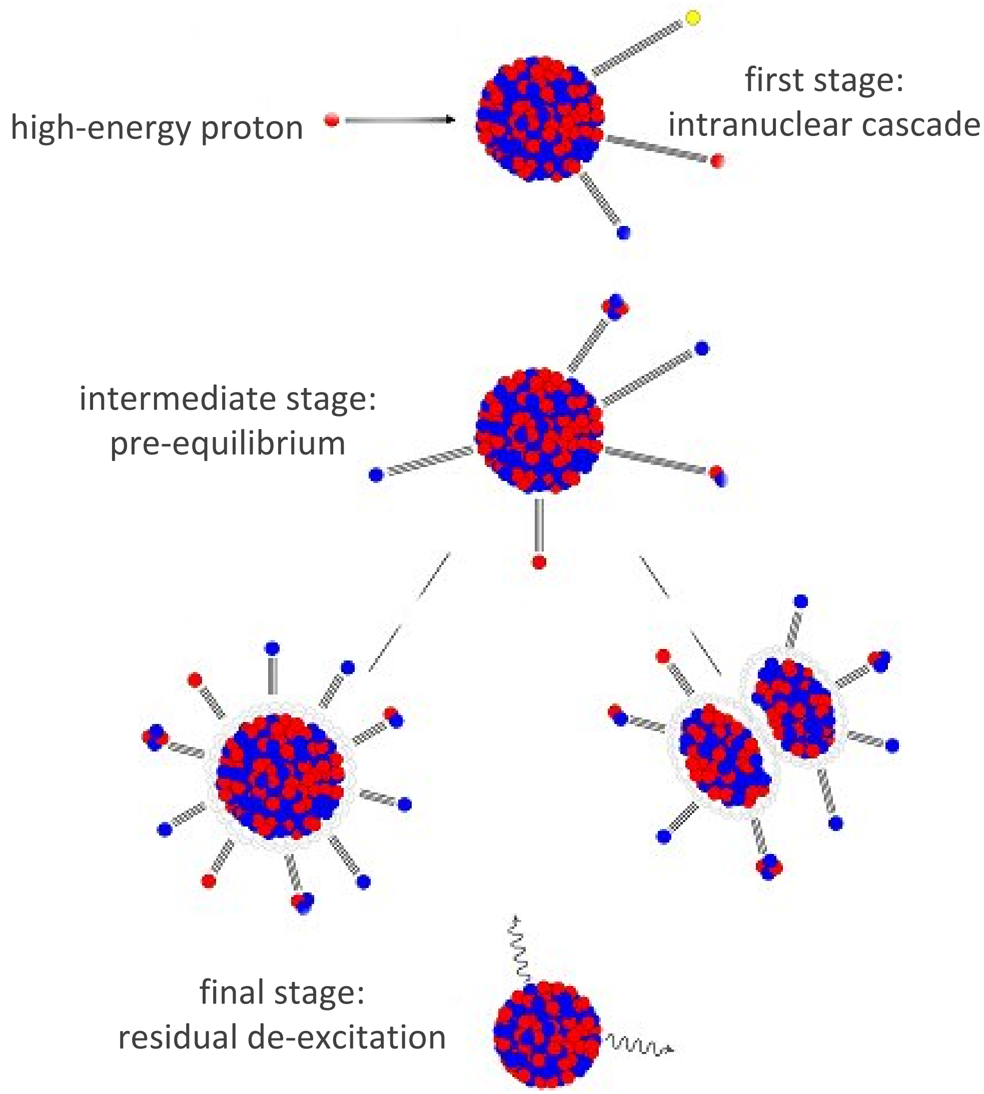
- Produce neutrons for use in condensed matter and basic physics research
- Want neutron wavelengths about the dimensions of interest, or neutron energies that can probe the dynamics of interest
- The pulsed nature of the neutron beams allows for energy determination by time of flight (which you can't do with a reactor source)
  - Exception noted for the SINQ source which uses the PSI cyclotron

What's Important?

- Accelerator parameters
  - power on target – 7 kW (IPNS) to 1 MW (SNS)
  - proton energy – 450 MeV (IPNS) to 3 GeV (JSNS)
  - pulse rate 10 Hz (ISIS TS2) to 25 Hz (JSNS) to 60 Hz (SNS)
  - pulse length – sub-μs (short pulse), 1-2 ms (long pulse), CW (SINQ)
- Neutron economy in target (production, absorption)
- Moderator efficiency, coupling to target
- Neutron energy spectrum and emission time distribution

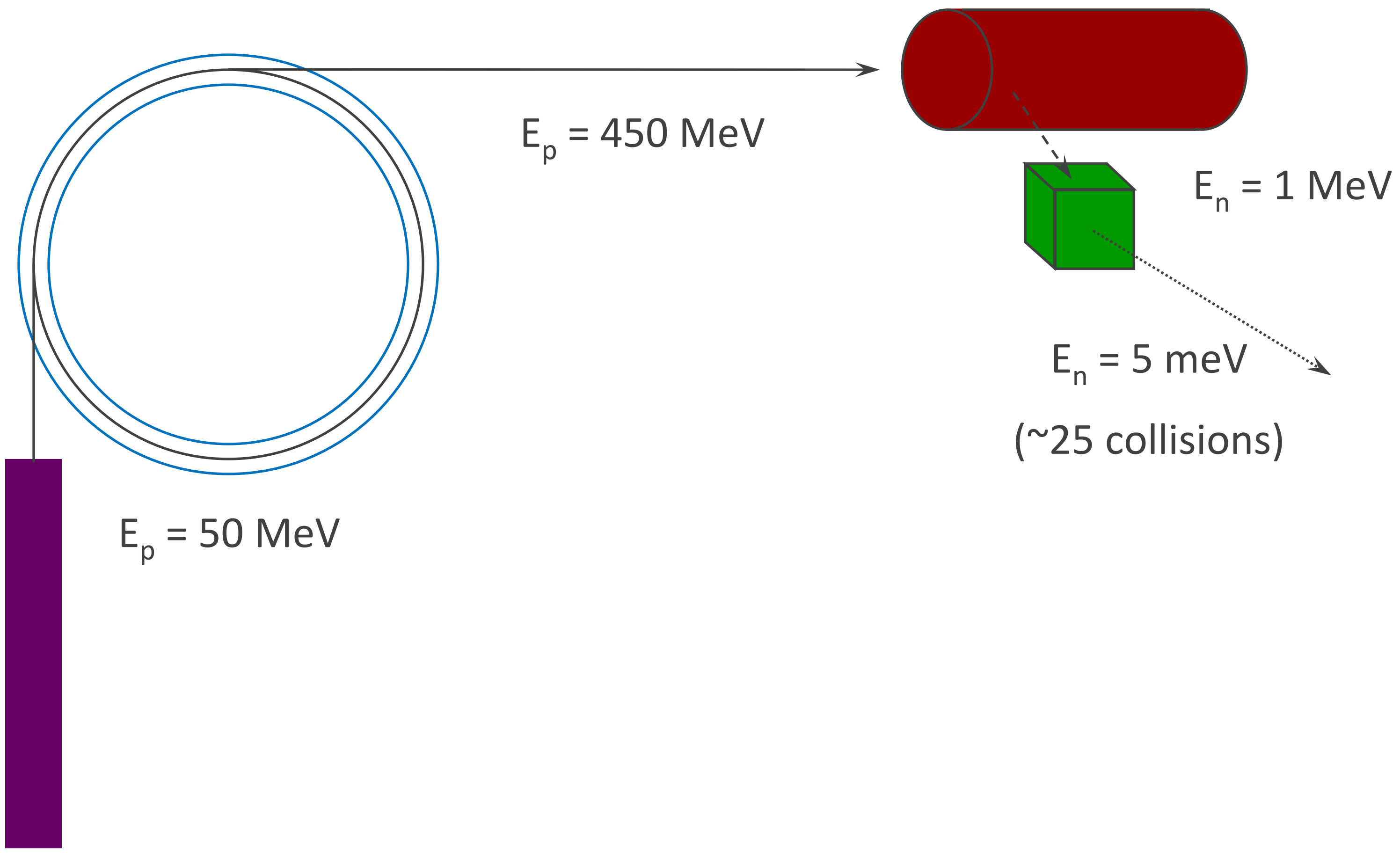
Neutron Production

- A fundamental truth – all neutrons are born fast
- Neutrons are produced by the processes of spallation, fission, and neutron multiplication



How Do We Make Cold Neutrons?

- Cold neutron production at the IPNS

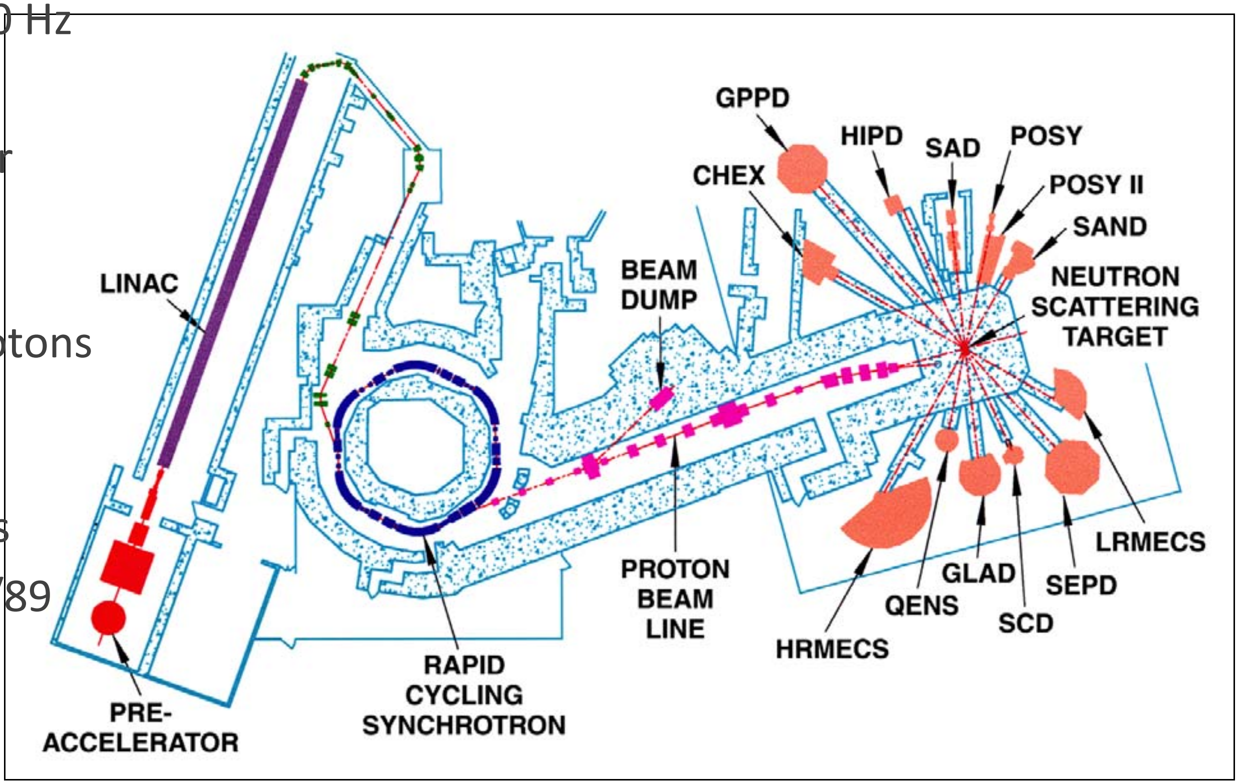


Types of Accelerator-Driven Spallation Sources

- Linac + synchrotron (IPNS, ISIS, JPARC)
- Linac + accumulator (compression) ring (SNS, LANSCE, original ESS)
- Cyclotron (SINQ)

Intense Pulsed Neutron Source (ANL)

- IPNS was the first user-dedicated accelerator-driven neutron source in the world, commissioned in 1981
- Neutrons were produced by spallation/fission by 450-MeV protons striking depleted uranium target
- Proton beam pulsed at 30 Hz
- Average current 15 µA
- Target lifetime about four years operating 20-25 weeks per year
- Accelerated $2.63 \cdot 10^{22}$ protons (1.17252 A-hrs) in 9,368,550,687 pulses
- Liberated 0.53 g neutrons
- 95.4% reliability from 10/89 to end of operation

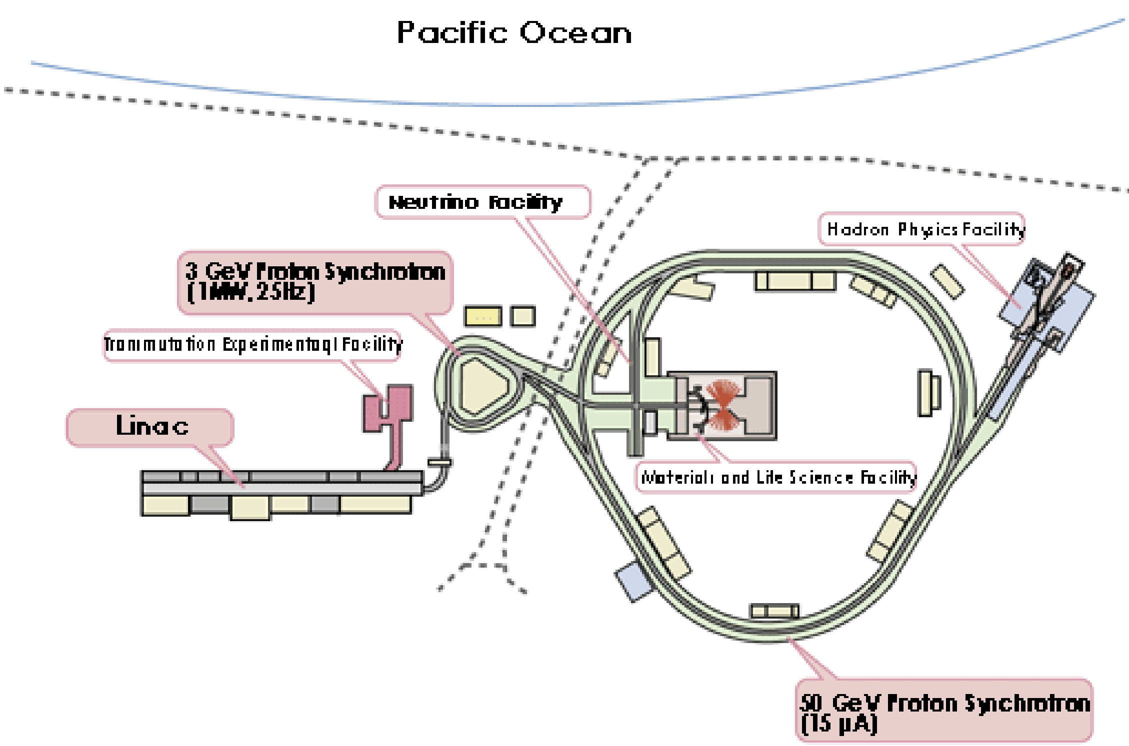


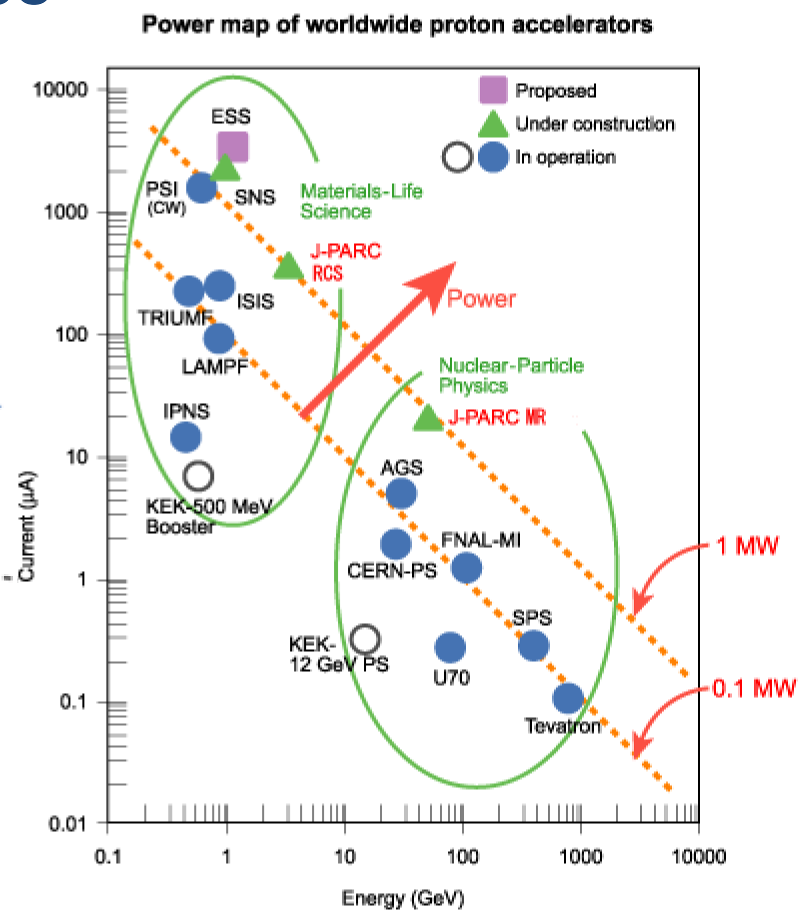
ISIS

- Accelerator parameters
  - Linac 70 MeV, 200 μs, 50 Hz
  - RCS 800 MeV, 50 Hz, 160 kW, (2) 100 ns pulses

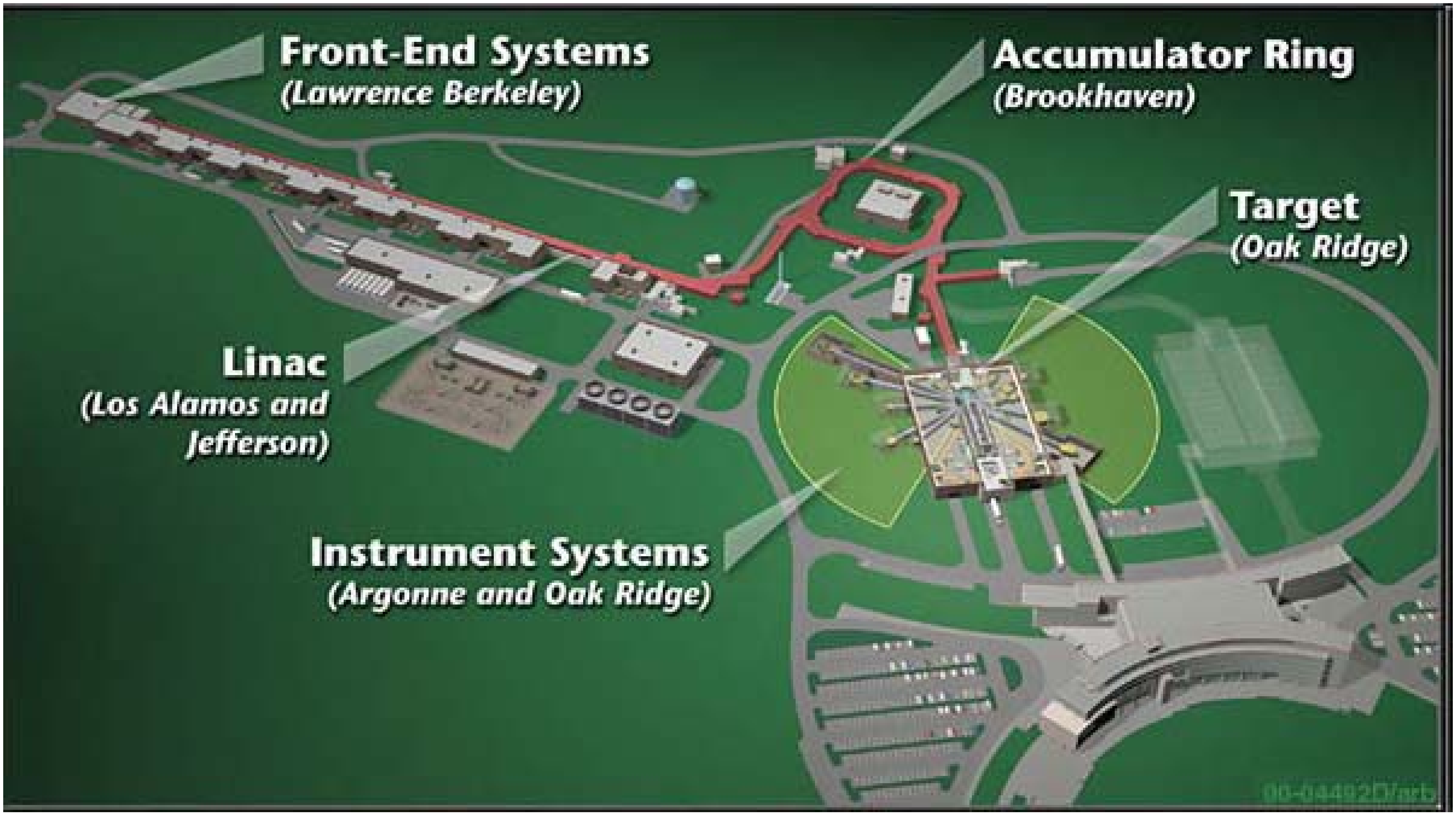
Japan Spallation Neutron Source

- Accelerator parameters
  - Linac 400 MeV, 500 μs, 50 Hz
  - RCS 3 GeV, 25 Hz, 1 MW



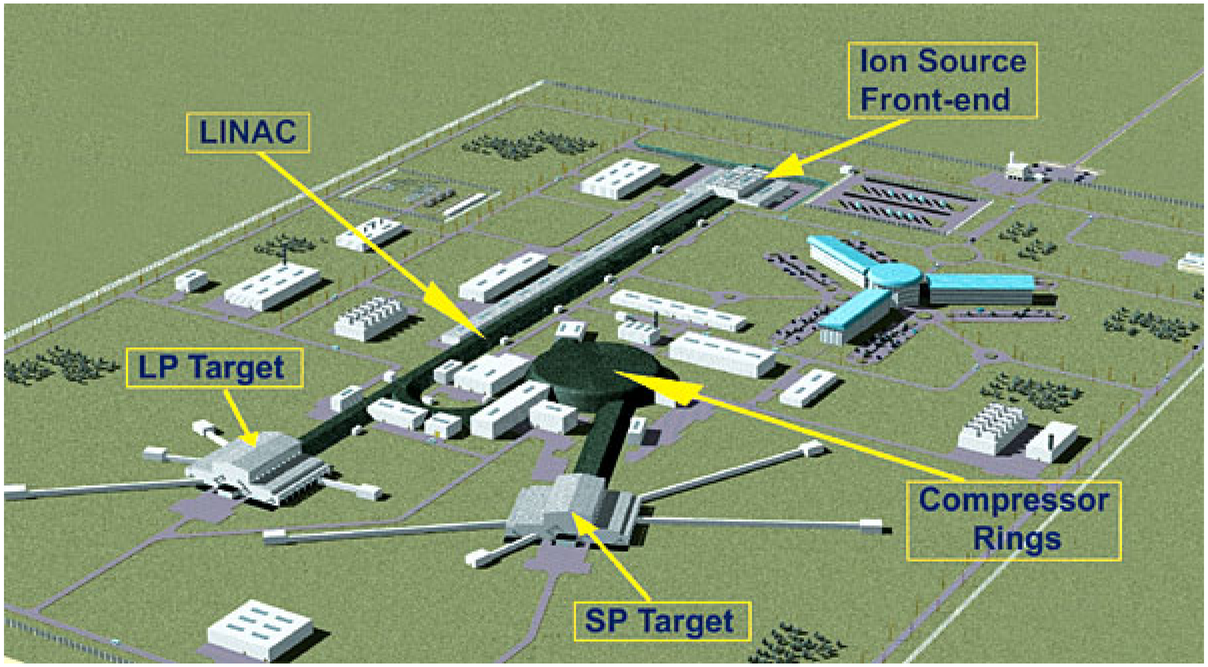


Spallation Neutron Source (ORNL)

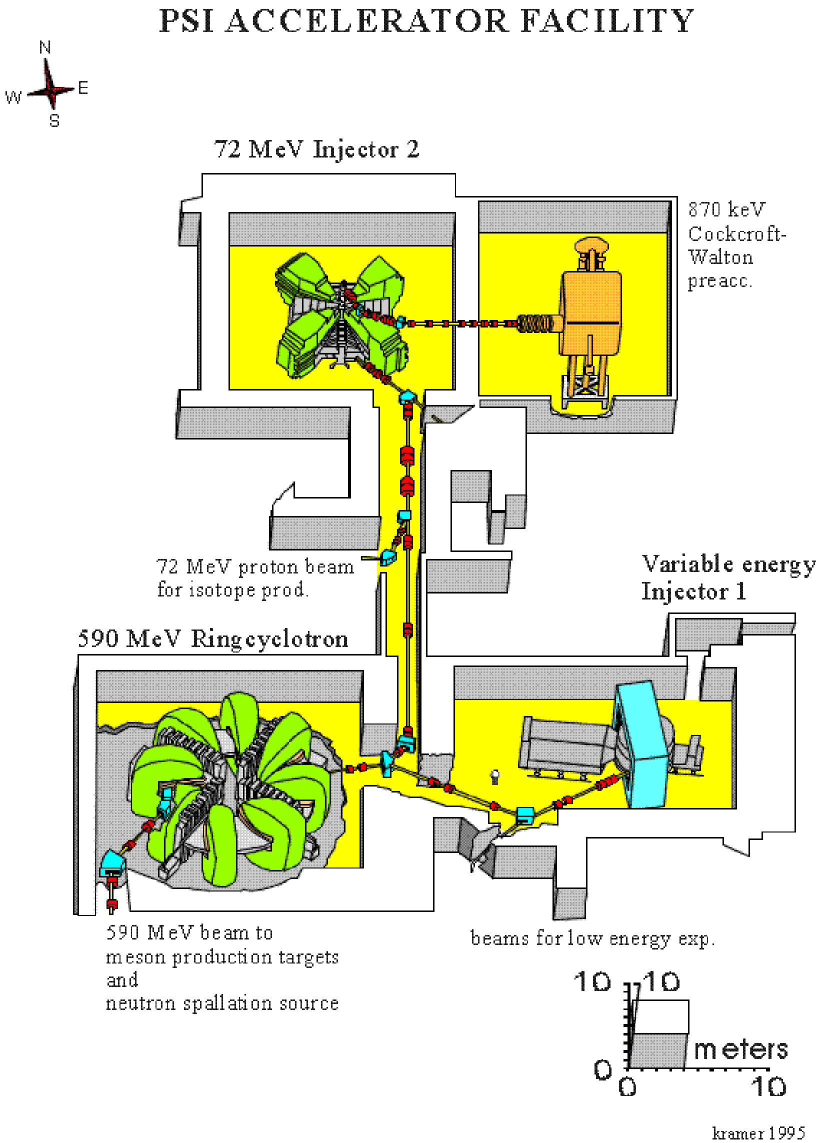


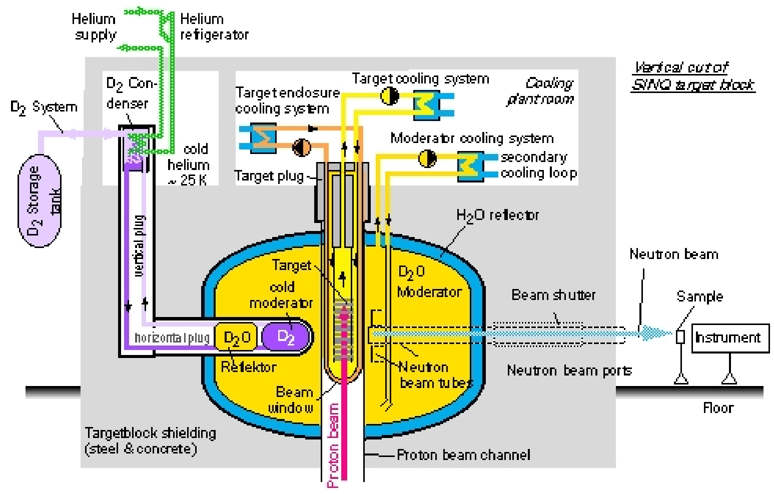
European Spallation Source

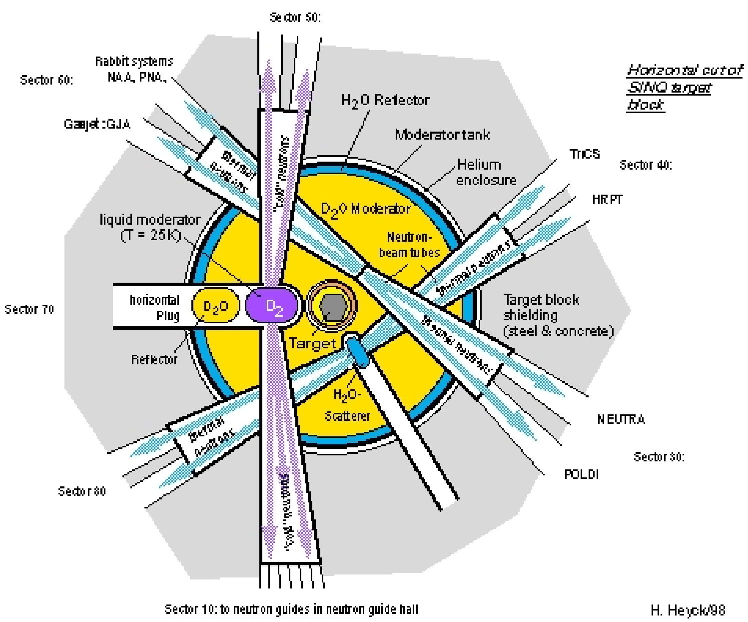
- Linear accelerator + compression ring (short pulse target station)
- Accelerator parameters
  - 10 MW
  - 1.33 GeV
- Short pulse target station
  - 5 MW
  - 1.4 us
  - 50 Hz
- Long pulse target station
  - 5 MW
  - 2 ms
  - 16 2/3 Hz



Paul Scherrer Institute - SINQ

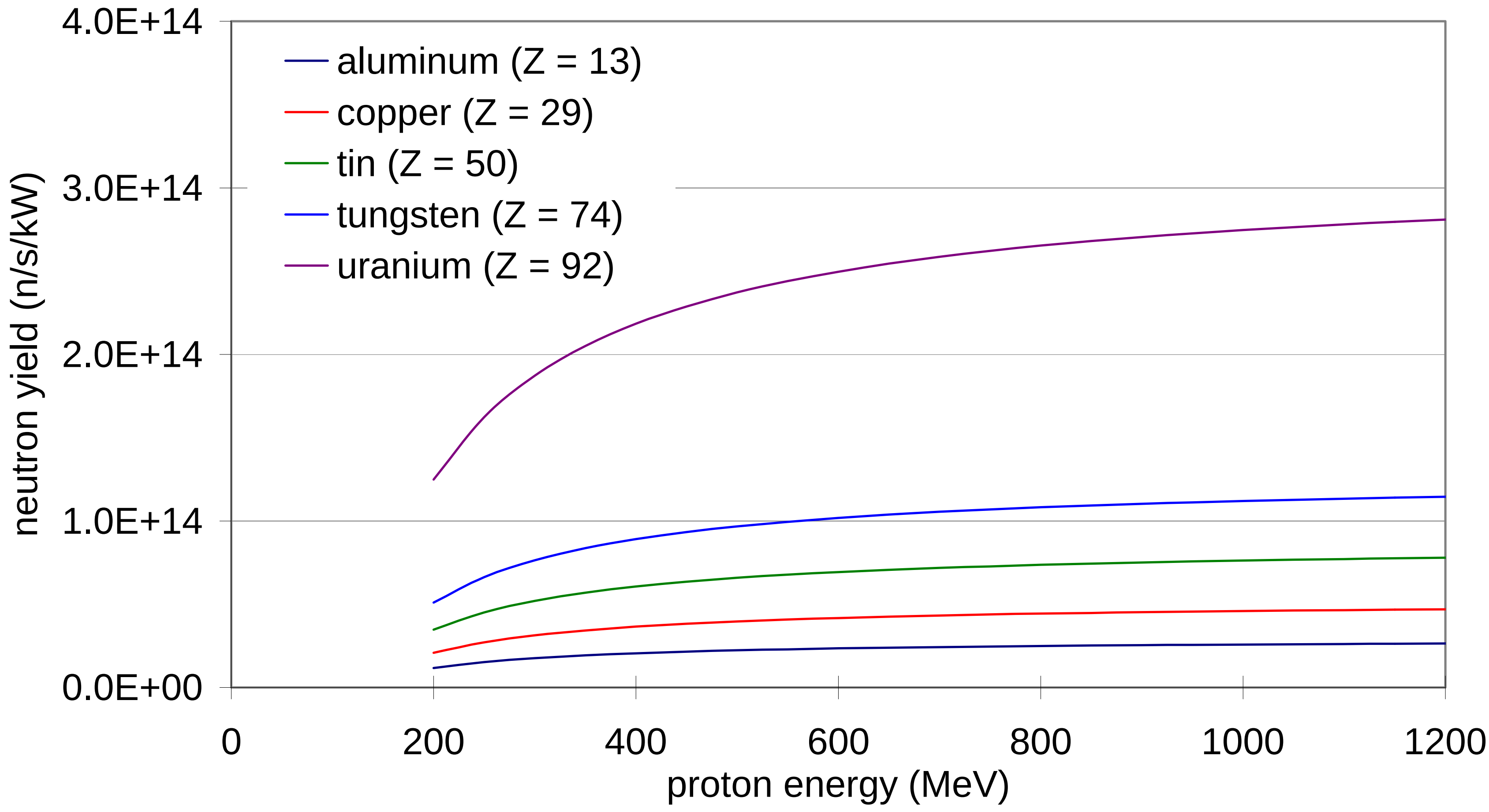






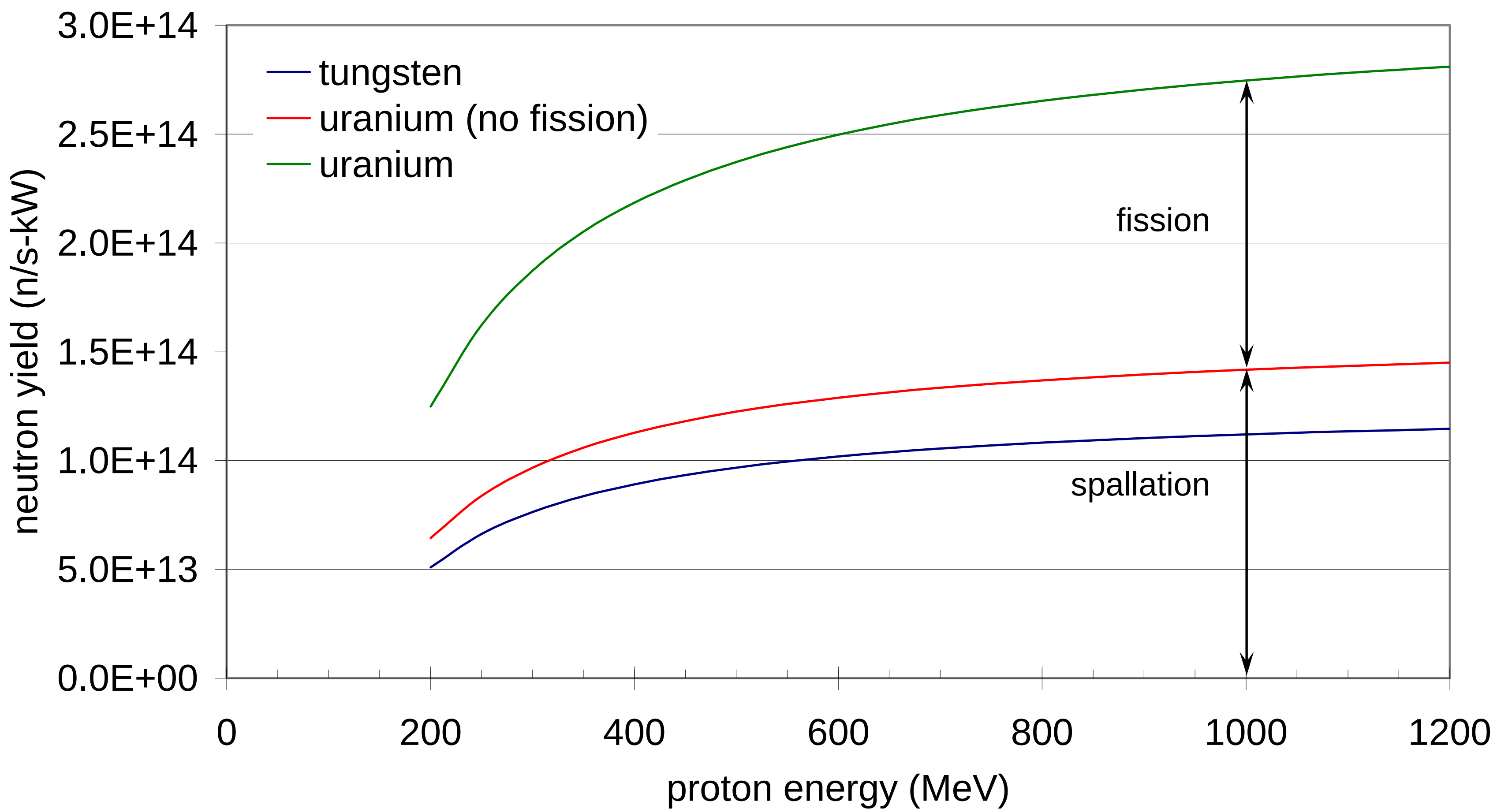
What is the Optimum Target Material for Neutron Production?

- Higher atomic number targets favor greater neutron production

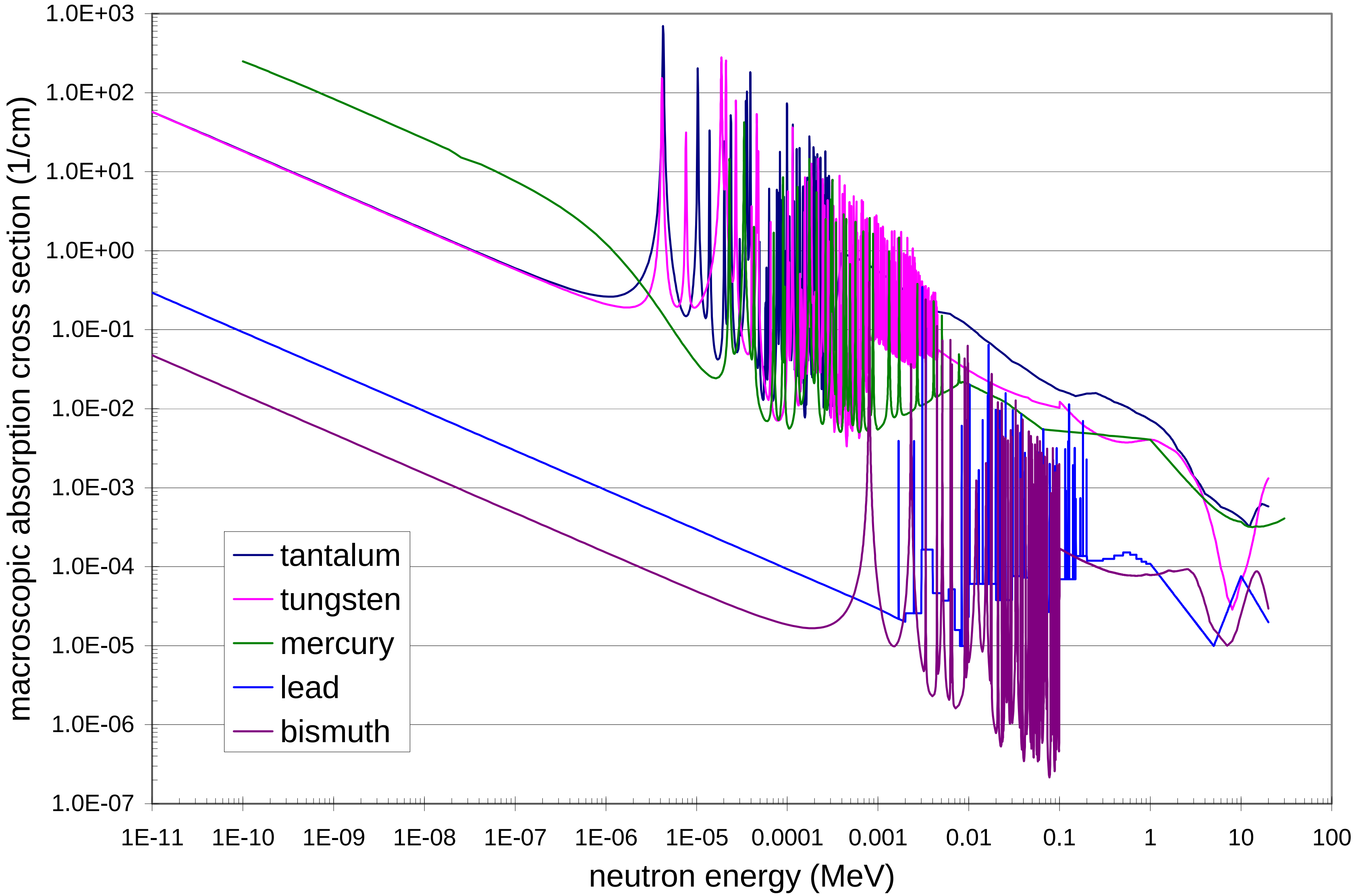


What is the Optimum Target Material for Neutron Production?

- Part of uranium's advantage comes from fission, part from higher Z



Neutron Absorption of Candidate Target Materials

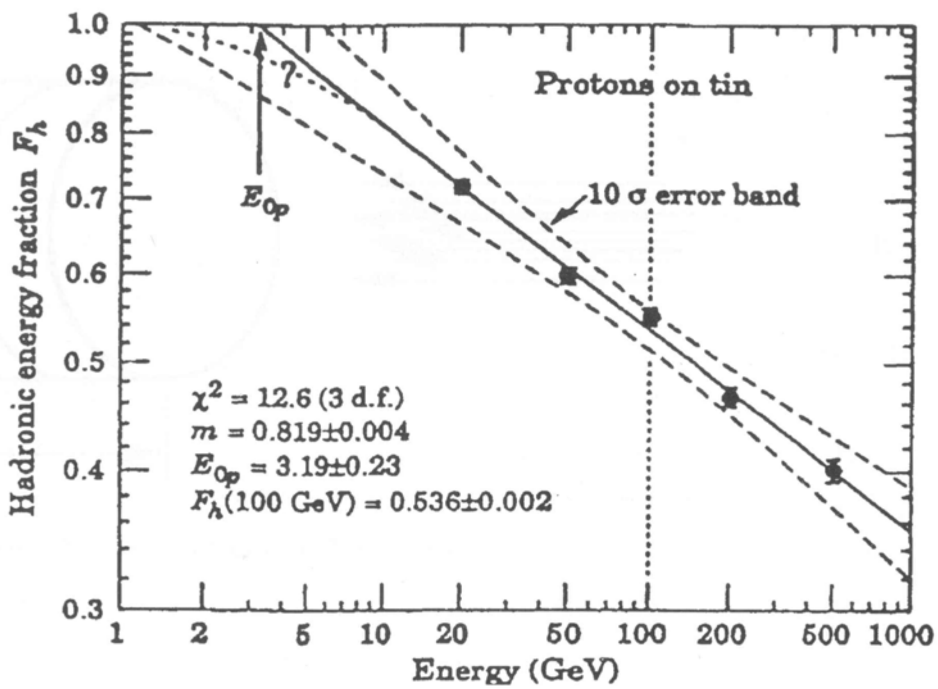


What is the Optimum Energy for Spallation Neutron Production?

- Examined by Carpenter et al. in Physica **B270**, 272-279 (1999).
- Discussed the matter in general terms, not as an engineering solution to the problem
- Background of discussion is how best to reach high beam power, with high current or with high energy
- Concludes that higher proton beam energy
  - has advantages in potentially lower capital costs, potentially lower operating costs, and potentially lower beam losses
  - probably somewhat relieves radiation damage problems in accelerator and target beam windows
  - has a possibly slight positive affect on target station design
- Superconducting ion accelerators had not been demonstrated to high energies at the time – warm accelerator forces choice of high current to maximize wall plug to beam energy efficiency

What is the Optimum Energy for Spallation Neutron Production?

- The fraction of proton energy that goes into producing neutrons decreases as the proton energy increases



E_p (GeV)	F_h	I_1 (mA)	I_n (mA)
1	1.0	1.0	1.0
2	0.97	0.5	0.515
3	0.94	0.333	0.353
5	0.89	0.2	0.224
8	0.84	0.125	0.149
10	0.815	0.1	0.123
20	0.72	0.05	0.0695

I_1: current for 1 MW power
I_n: current for constant neutron production

Target Station - JSNS

- Target building must accommodate target, reflectors, moderators, beam gates, instruments, biological and instrument shielding, services

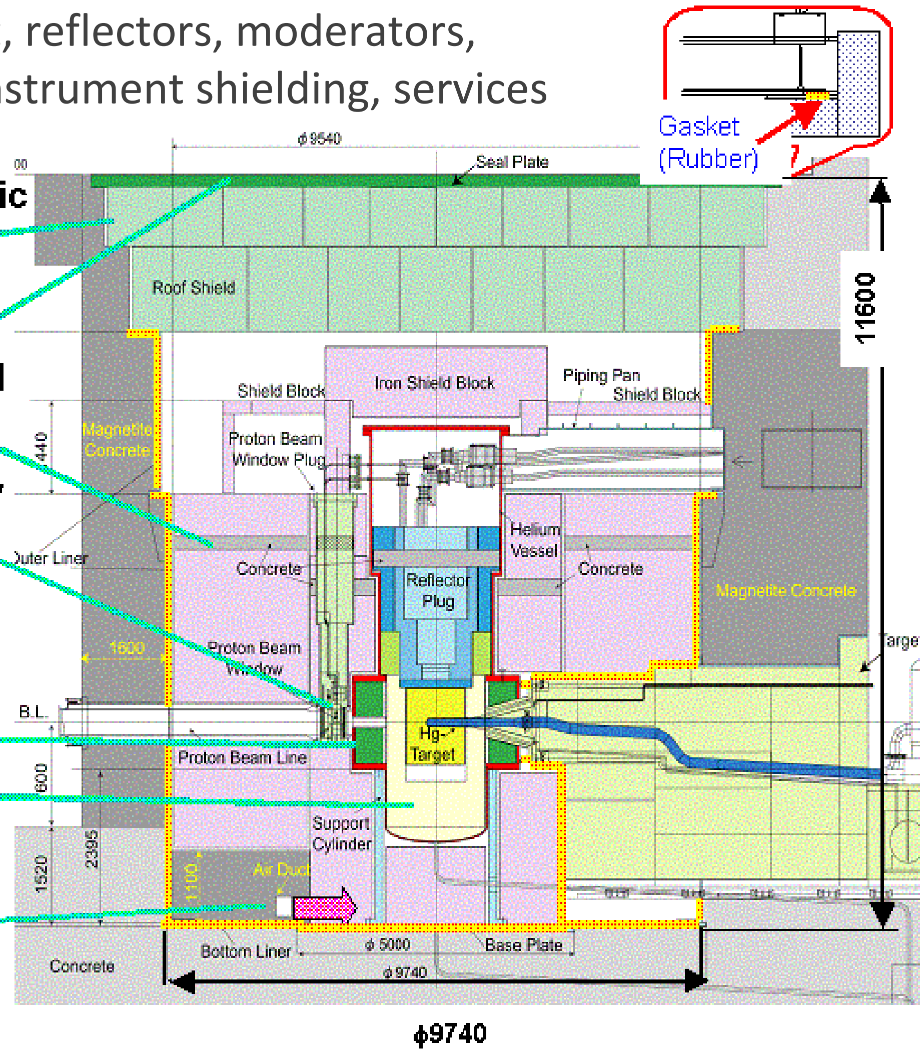
- **Thick roof shield without explicit metallic liners.**
- **Seal plate on the top.**
- **Concrete layer in steel shield.**
- **Proton beam window near vessel.**

Water-Cooled Portion in Helium Vessel.

Middle section

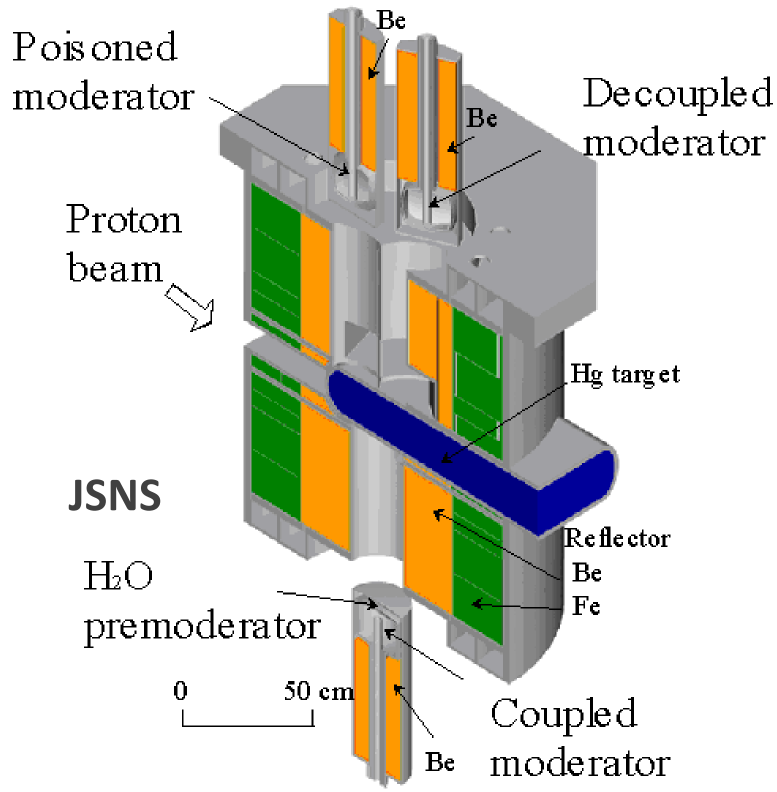
Shielding around reflector

Dry air ventilation



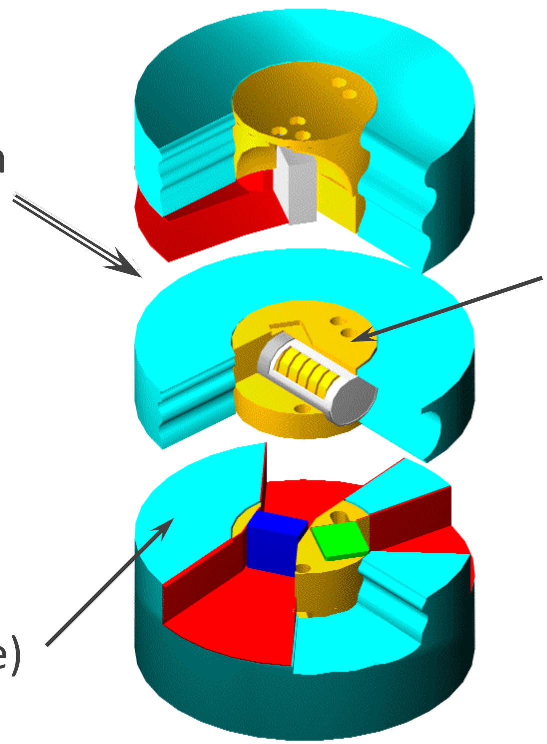
Moderator Coupling to Target

- Moderators can be in wing or slab or flux-trap configurations
- Non-symmetric target shape improves coupling
- Best results for target "radius" about 2.5 cm larger than beam "radius"



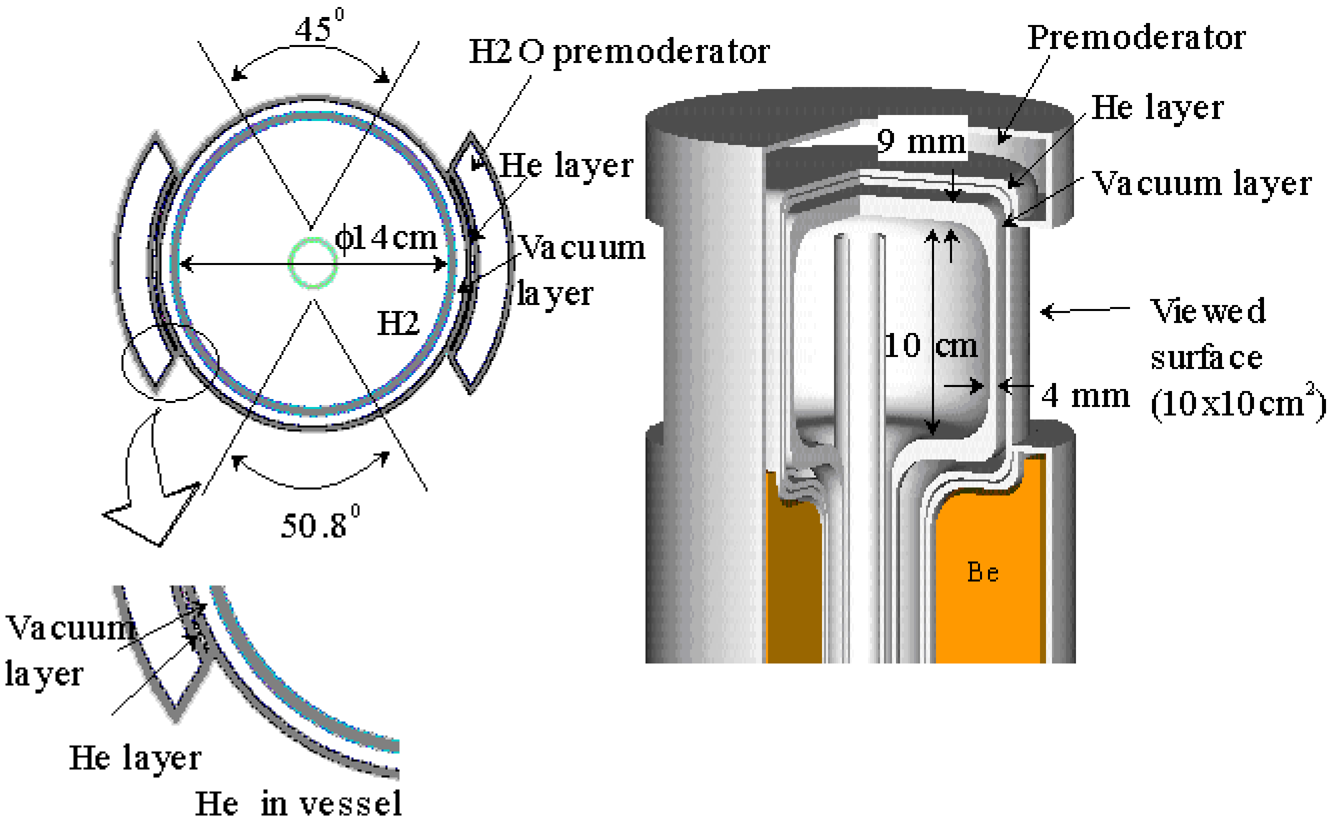
Reflectors

- Reflectors are used to keep neutron population in the moderators high
- Decouplers (e.g., cadmium) used to reduce low-energy neutrons entering moderator (sharpens pulse by reducing long tail of pulse
- IPNS reflectors illustrated



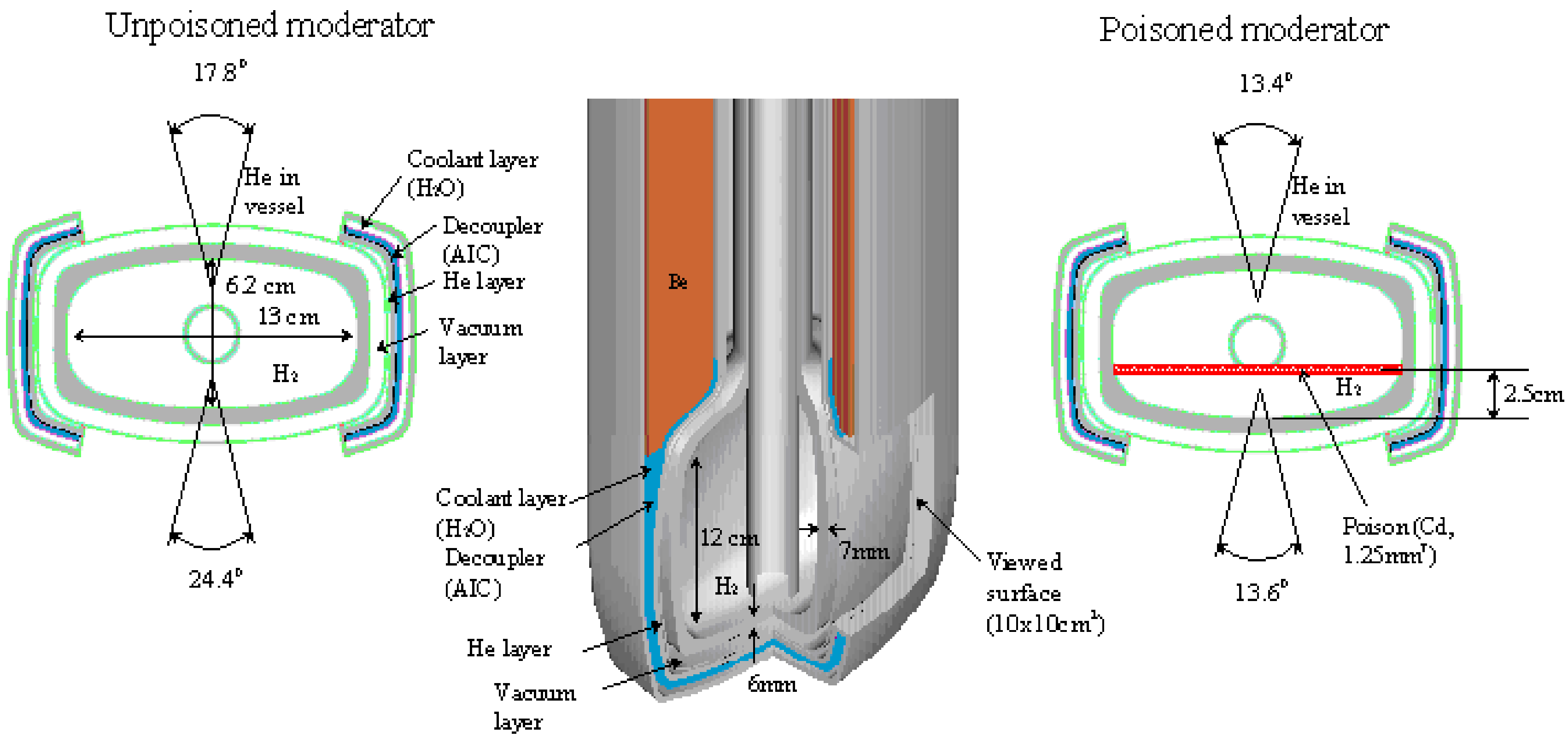
Moderators

- Moderators reduce the neutron energy to ~ meV levels
- High-power moderators are all liquid hydrogen due to heat load, rad damage
- Typical viewed area 10 x 10 cm (IPNS) or 10 x 12 cm (SNS)



Moderators

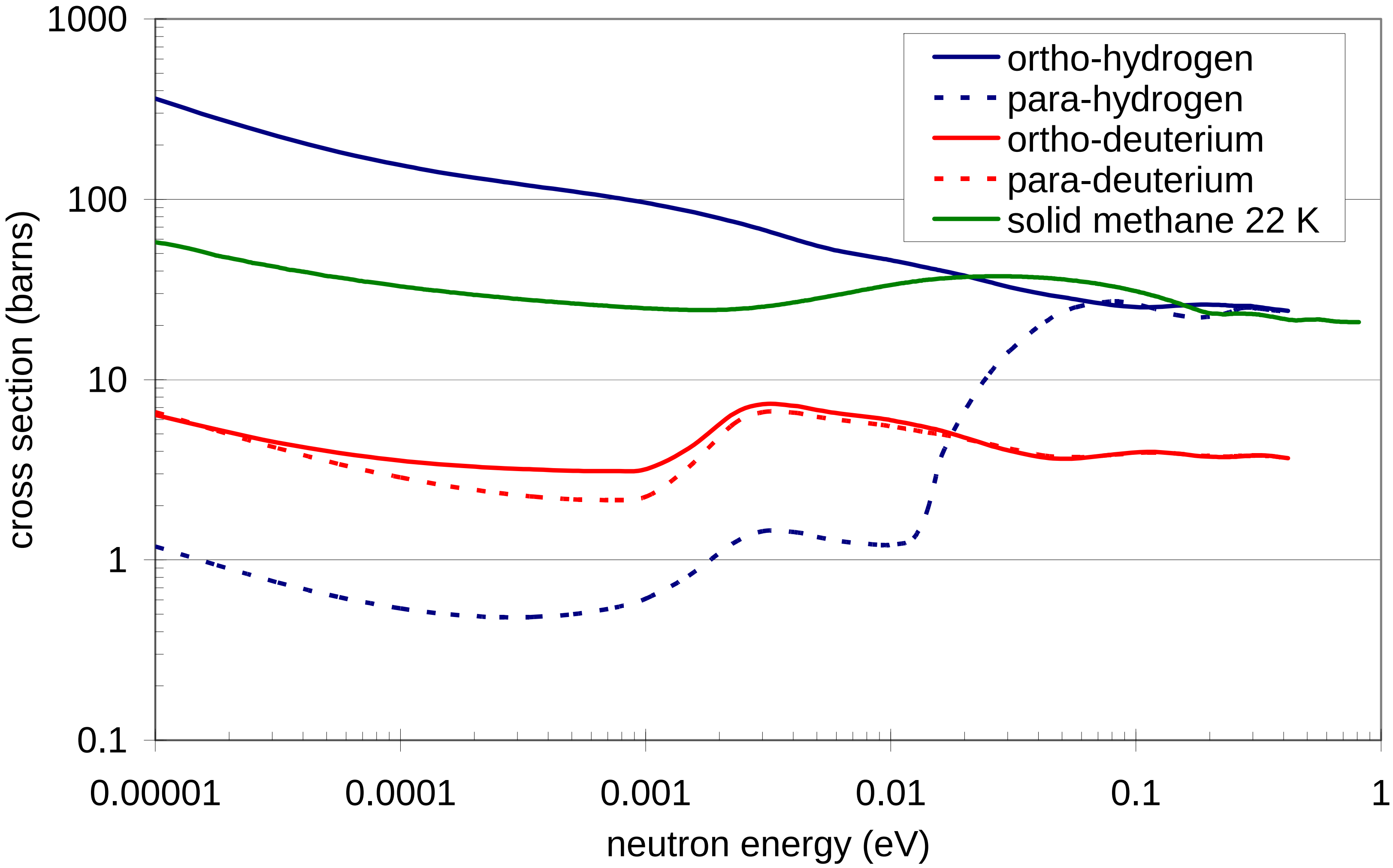
- Internal poison layers used to sharpen pulse (make moderator appear thinner for lower-energy neutrons
- JSNS moderators illustrated



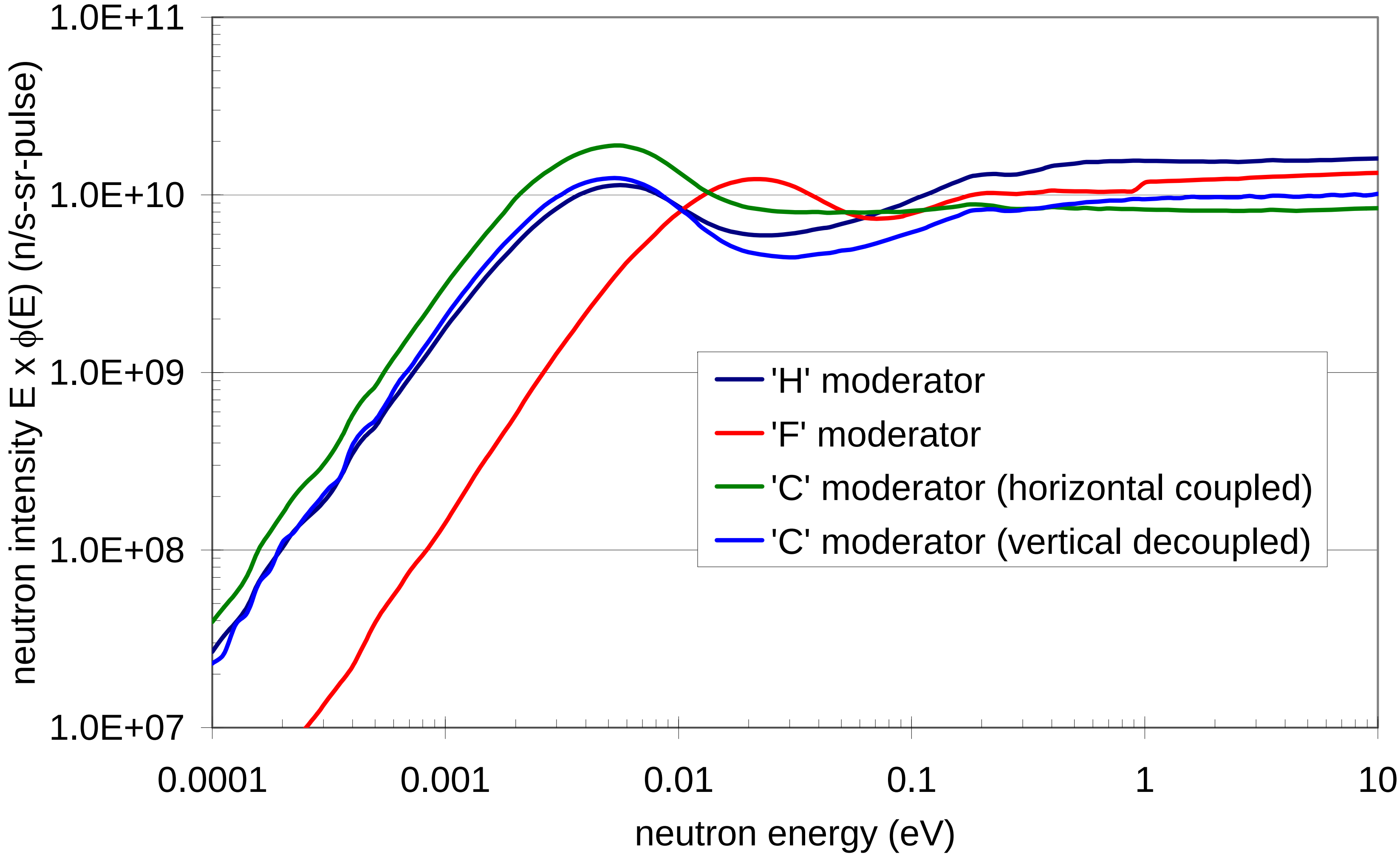
What is the Best Moderator Material?

- High hydrogen density – high moderating power
- Low neutron absorption
- Inelastic scattering modes in the range 0-10 meV
- Typical choices
  - Water
  - Methane (liquid or solid)
  - Hydrogen
  - Advanced materials – mesitylene , benzene, ammonia
- Lack of data on candidate moderator materials is a severely limiting factor in evaluating new concepts

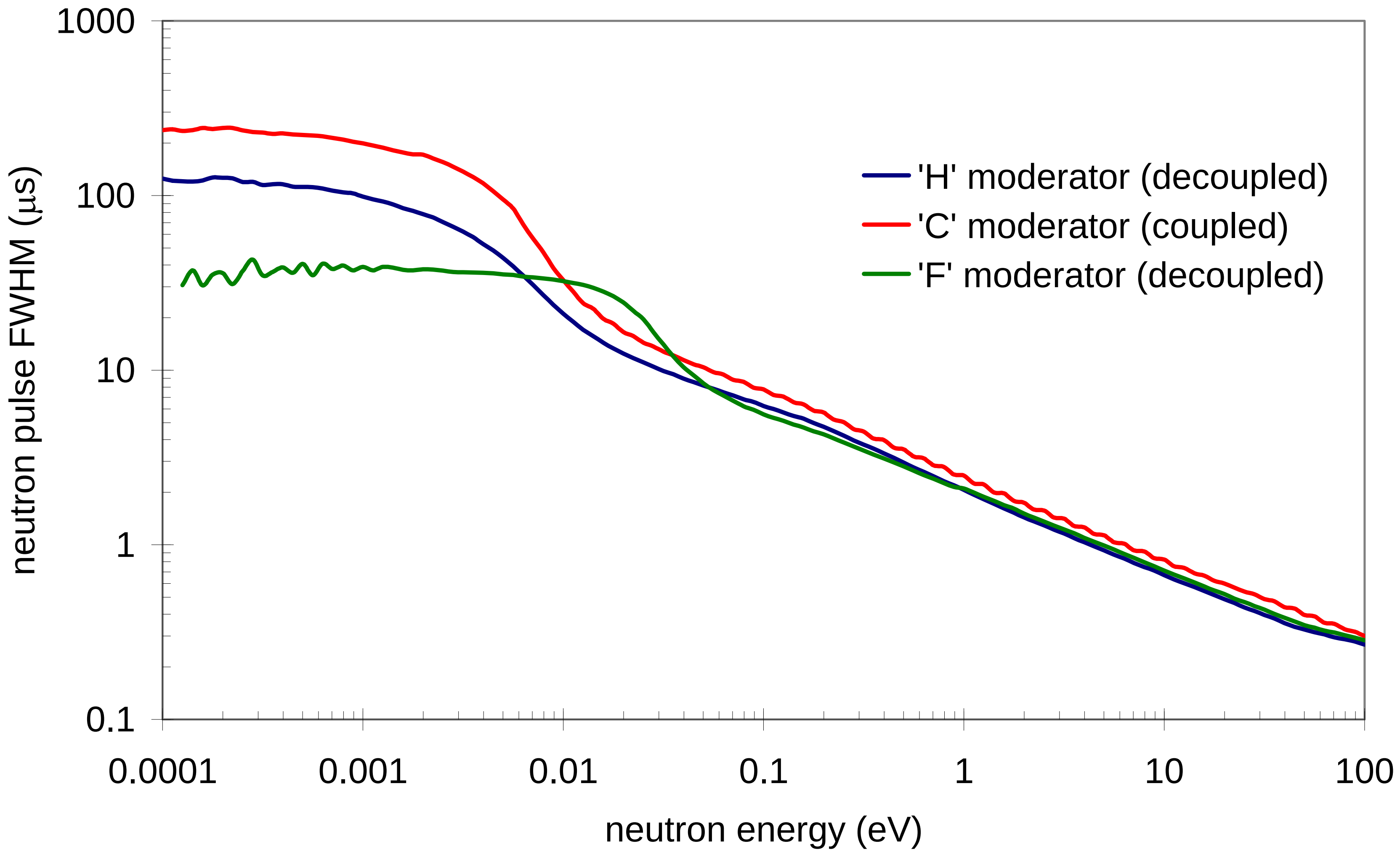
Neutron Cross Sections for Moderator Materials



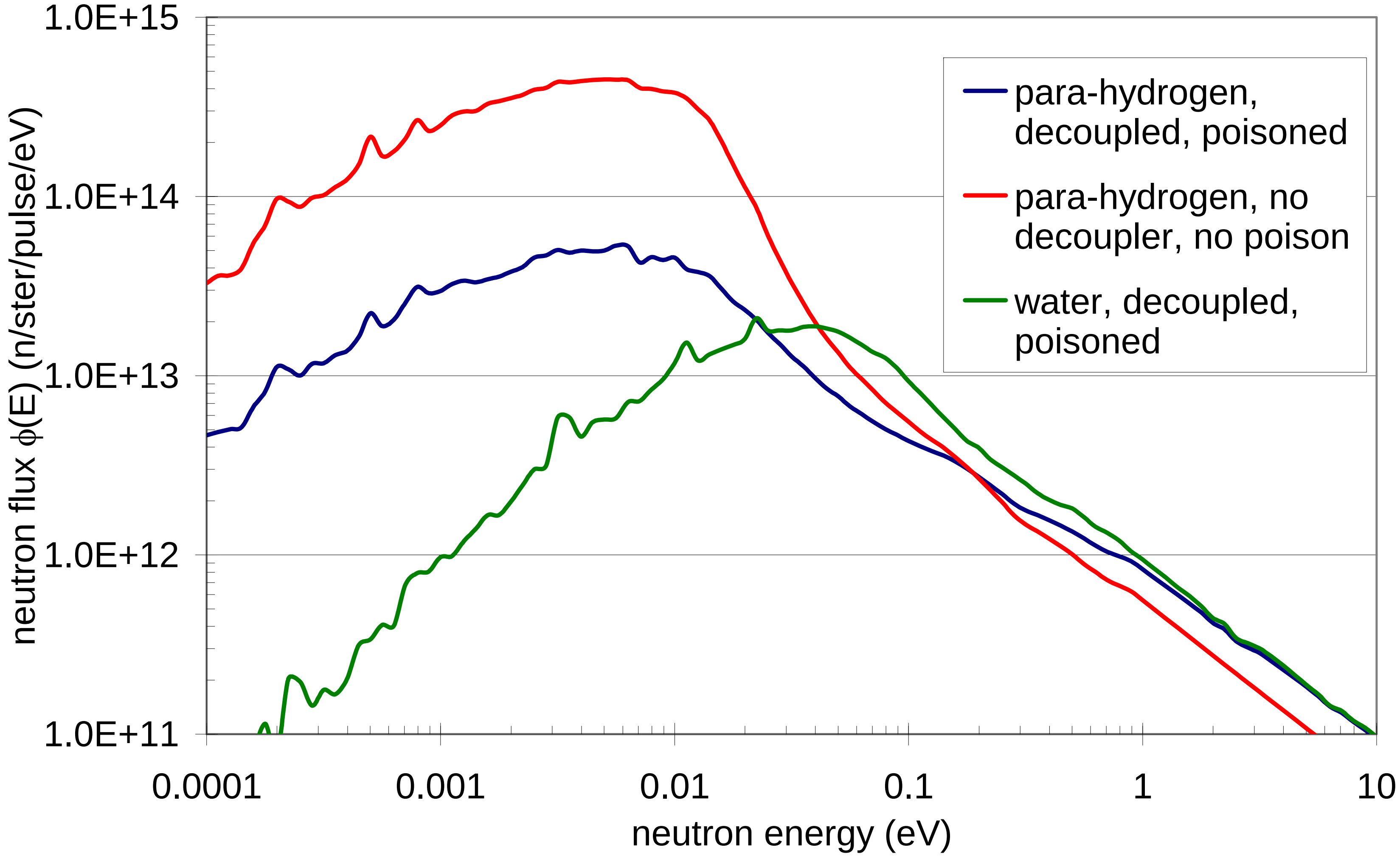
Neutron Spectral Intensities for IPNS Moderators



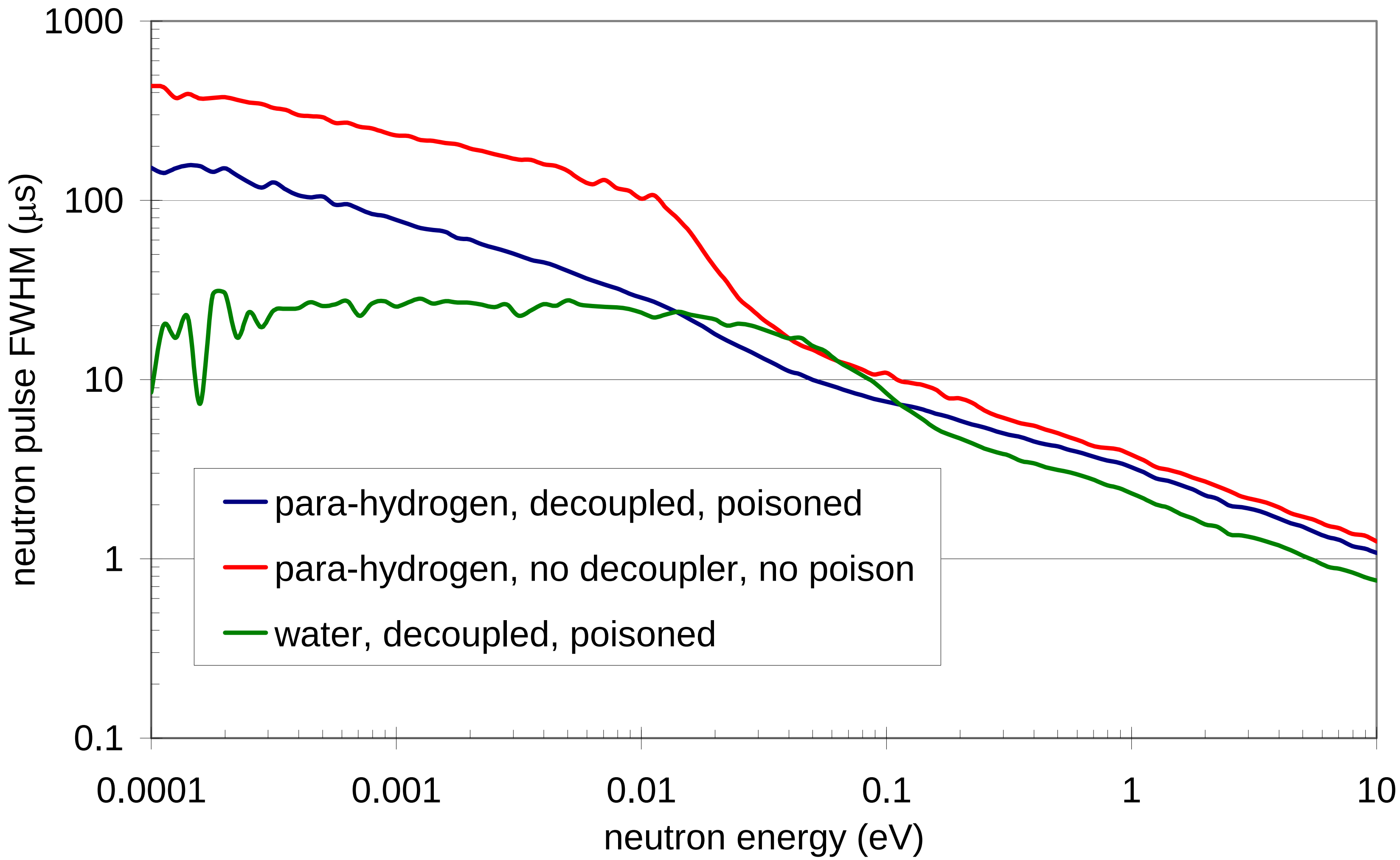
Neutron Pulse Widths for IPNS Moderators



Neutron Spectral Intensities for SNS Moderators



Neutron Pulse Widths for SNS Moderators



A Very Cold Neutron Source

- Many problems at longer length scales and slower time scales can be addressed using an intense source of longer-wavelength neutrons
  - fundamental nuclear physics (neutron half-life, EDM)
  - spin dynamics in magnetic nanostructured materials
  - the motion of proteins and molecular motors within living cells
  - hydrogen transport in storage and photoproduction materials
  - direct-imaging neutron techniques (microscopy, tomography, holography, radiography)
- Present cold neutron sources peak in the range 2-4 Å
- The goal of VCNS is an intense peak flux around 20 Å and usable flux extending out to 100 Å
- Develop a source providing neutrons at the "lowest practical temperature" - implies the use of liquid helium as the moderator coolant
- Notional parameters – long pulse, 5-10 Hz
- A VCN moderator is being considered as a supplement to more conventional cold moderators for the second target station at SNS

Summary

- Spallation neutron sources for condensed matter research are complex interconnected systems
- Parameters for accelerator, target, moderators, etc. are dictated by the science to be conducted at the facility
  - Proton pulse repetition rate and pulse width are somewhat narrowly constrained
- Pulse rates 5 Hz to 60 Hz, with slower pulsing frequencies used for lower-energy neutrons
- Pulse lengths sub-μs for short-pulse sources or 1-2 ms for long-pulse sources
- While no one has yet build a long-pulse source, there continues to be considerable interest, since they offer the best possibility to utilize > 1 MW of proton beam power