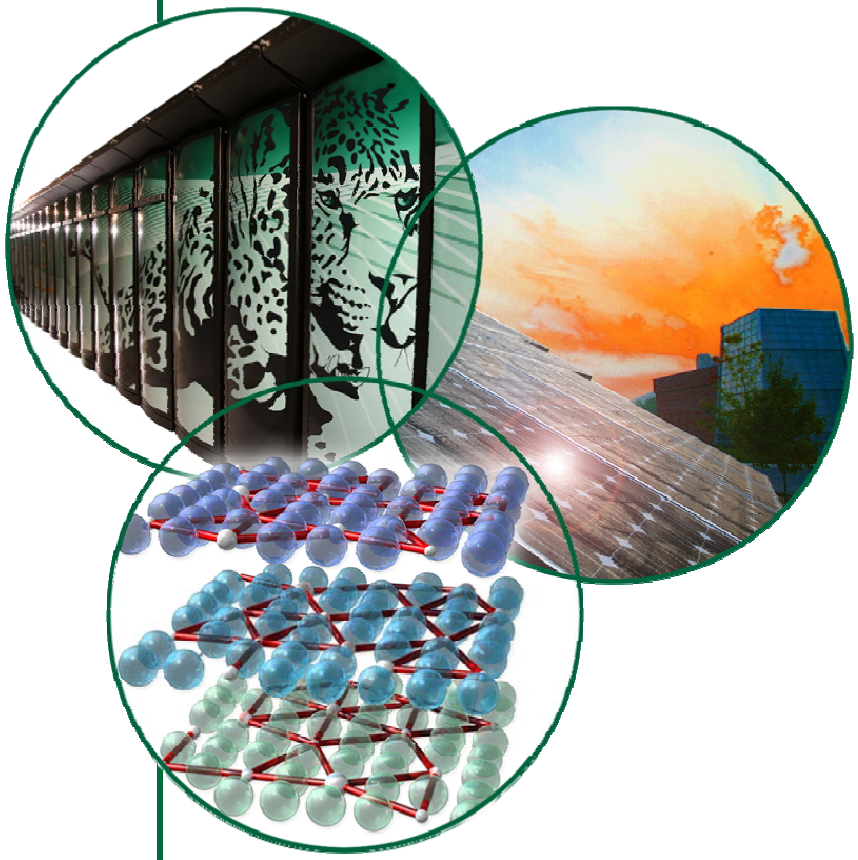
Neutron Sources – Apples and Oranges

Ken Herwig

Instrument and Source Development Division

Oak Ridge National Laboratory

July 16, 2012



U.S. DEPARTMENT OF ENERGY

OAK RIDGE NATIONAL LABORATORY

MANAGED BY UT-BATTELLE FOR THE DEPARTMENT OF ENERGY

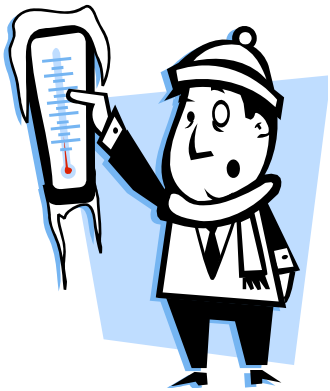
Outline

- **Trends in neutron production – reactors and spallation sources**
  - **Why build spallation neutron sources?**
- **What about power?**
  - **Apples and Oranges**
- **What do instrument designers need to know?**
  - **Accelerator basics and how they impact instrument design**
  - **Moderators**
- **Where do all the neutrons go?**

A Short Neutron History

- **1920 - E. Rutherford proposed a combination of electron/proton that**
  - **Would move freely through matter**
  - **Be difficult to detect**
  - **Perhaps impossible to contain in a vessel**
- **1920 – W. D. Harkins used the term "neutron" in the literature**
- **1932 – J. Chadwick demonstrated the existence of the neutron (α-particles from Polonium on Beryllium) – 1935 Nobel Prize**
- **1943 – The Clinton Pile at Oak Ridge National Laboratory was the world's first continuously operated nuclear reactor**
- **1974 – ZING-P – (ZGS-Intense-Neutron-Generator Prototype) become operational as the first demonstration of a spallation neutron source for neutron scattering**

Neutron Energies

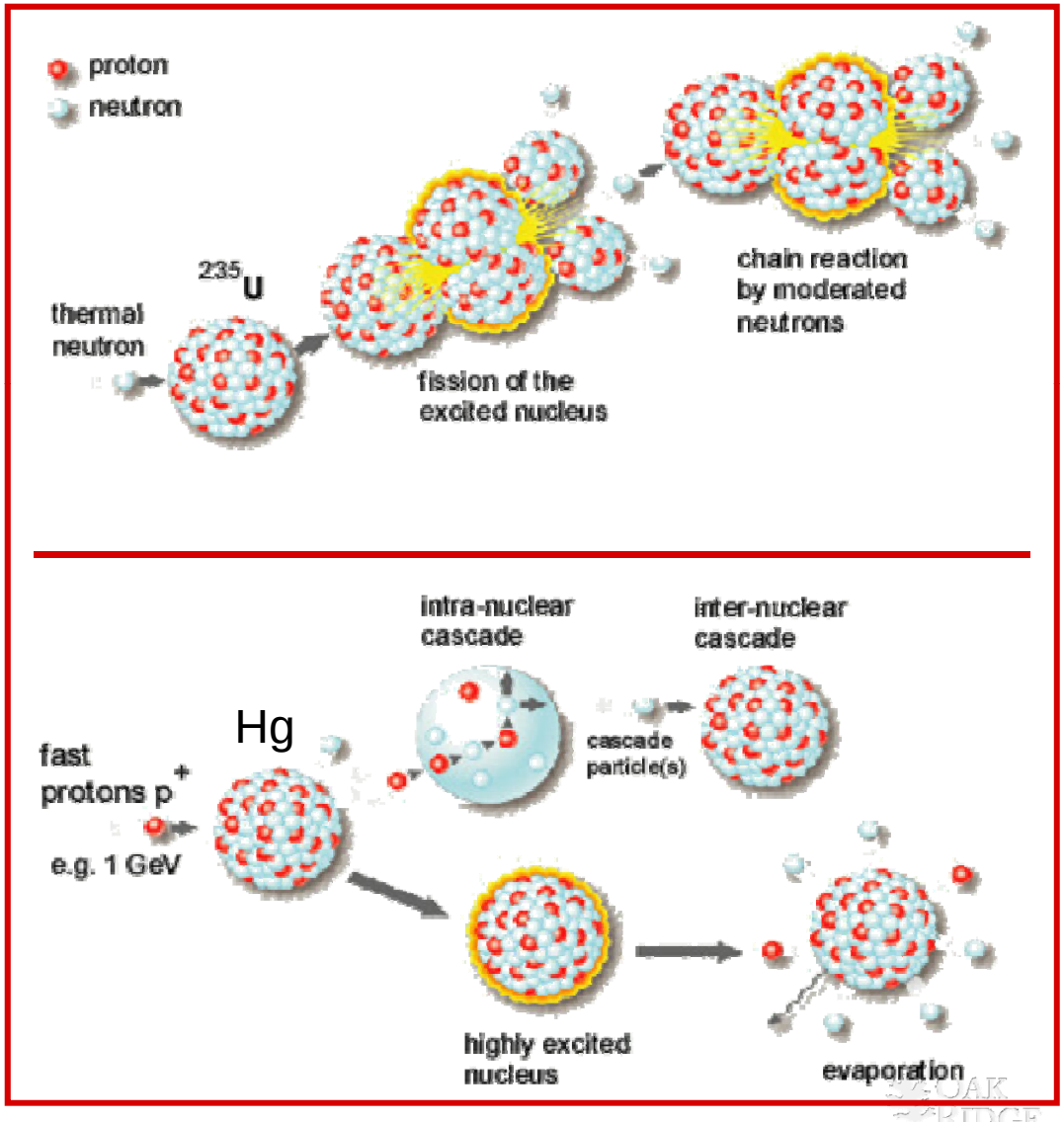


Neutron Classification	Energy (meV)	Velocity (m/s)	λ (nm)
Ultra-Cold	0.00025	6.9	57
Cold	1	437	0.9
Thermal	25	2187	0.18
Epithermal	1000	13,832	0.029

From D. L. Price and K. Sköld in N*eutron Scattering*, edited by K. Sköld and D. L. Price (Academic Press, Orlando, Fl., 1986), Vol. A.

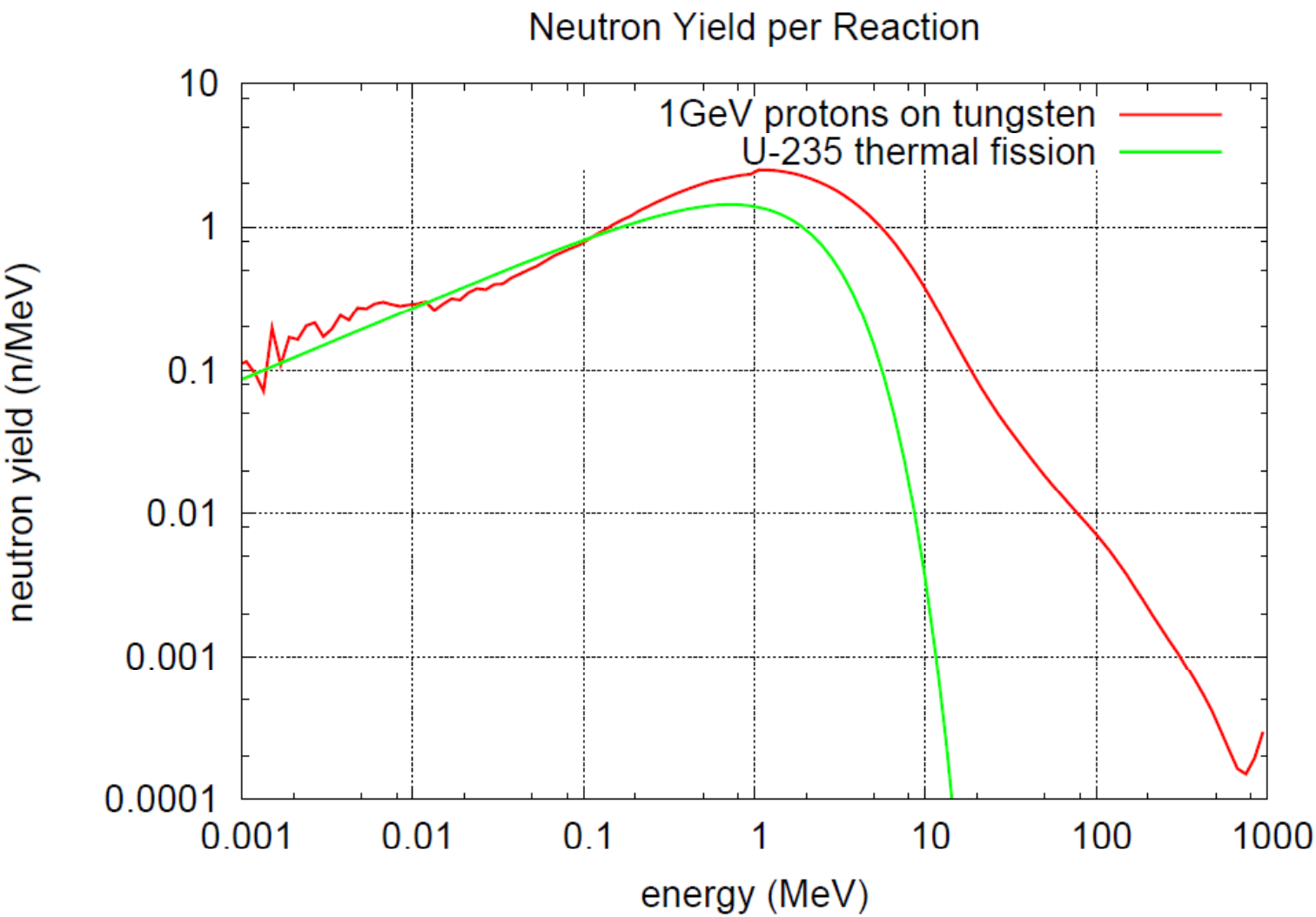
Fission and Spallation (+others)– How are neutrons generated?

- **Neutrons Produced**
  - **fission: 2.5 n/fission (1 required to sustain reaction)**
  - **spallation: 10+ n/reaction (highly energy dependent)**
- **Energy deposited**
  - **fission: ~190 MeV/useful n**
  - **spallation: ~25 MeV/useful n**
- **Nuclear debris**
  - **fission: typically light and heavy fission products, includes actinides**
  - **spallation: most products similar in mass to target, no actinides**
- **Energy distribution of neutrons**
  - **spallation neutrons can have energies up to the incident proton energy – massive iron shielding**



Courtesy Phil Ferguson

Fission and Spallation Neutron Spectra



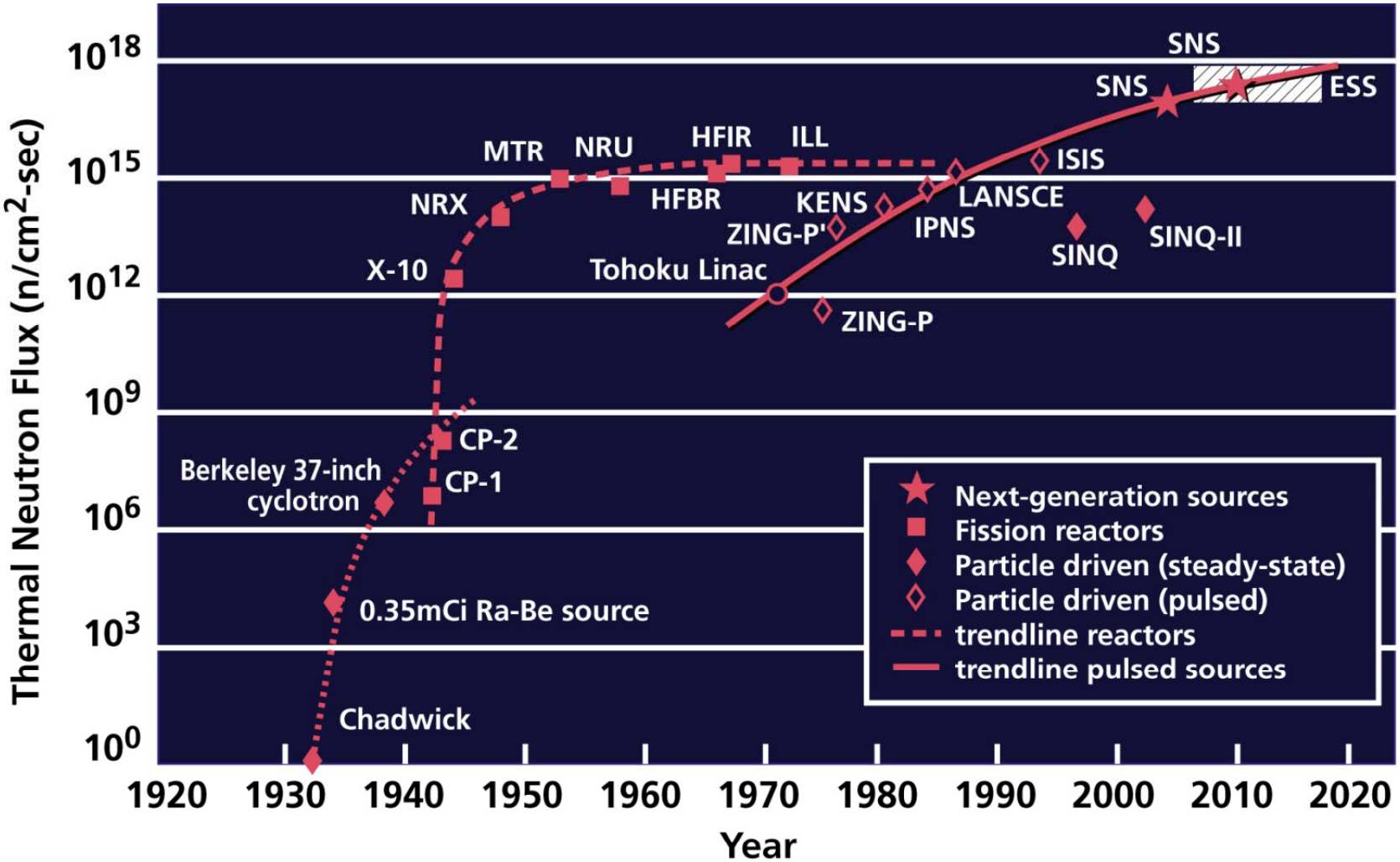
Courtesy – Franz Gallmeier

Reactors and Spallation Sources

Reactors	Spallation Sources
Continuous (in general)	Pulsed (in general)
Mature	Developing
Regulatory and Environmental issues related to fuel	Accelerator driven
High time-averaged flux	High peak-flux
Monochromators (crystal, chopper, velocity selector)	Time-of-flight

- **Why use time-of-flight techniques?**
  - **No practical energy-sensitive detectors available in the cold to thermal neutron energy range.**

Neutron Source Trends – Why build Spallation Sources?



(Updated from *Neutron Scattering*, K. Skold and D. L. Price: eds., Academic Press, 1986)

Pulsed spallation sources are peak thermal flux.

Apples and Oranges – What about power?

- Reactor power (MW) is the thermal power released by the fission reactions
  - Example, ORNL's HFIR is 85 MW reactor

$$\frac{\text{n}}{\text{sec}} = 85 \bullet 10^{6}\ \text{W}\ x\ \frac{\text{J}/\text{sec}}{\text{W}}\ x\ \frac{1\,\text{n}}{190 \bullet 10^{6}\,\text{eV}}\ x\ \frac{6.24 \bullet 10^{18}\,\text{eV}}{\text{J}}$$

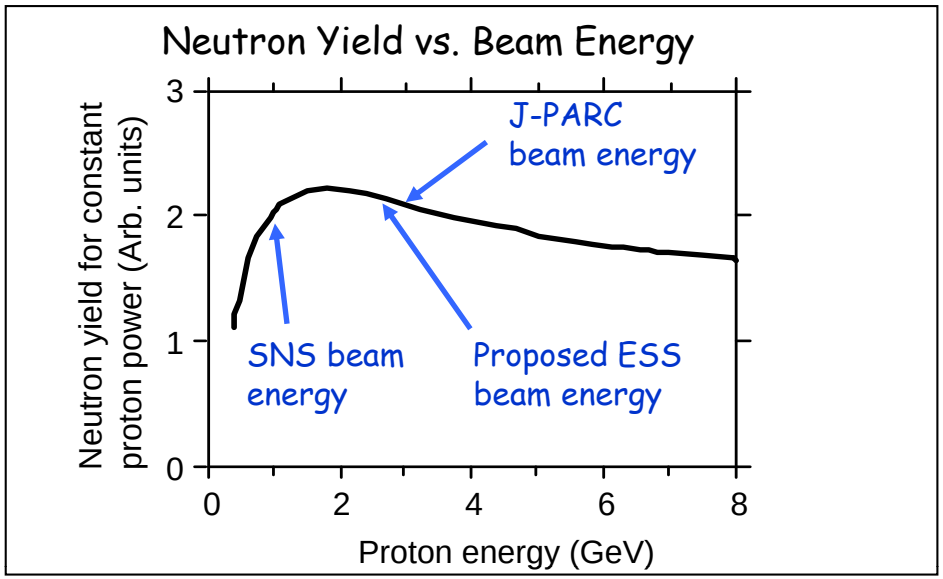
$$= 2.79 \bullet 10^{18}\ \frac{\text{n}}{\text{sec}}$$

- Spallation Source power is the power of the proton beam
  - Example, ORNL's Spallation Neutron Source at 1 MW proton beam (1 GeV protons @ 1 mA, approx. $1.04 \bullet 10^{14}$ protons/pulse, 60 Hz)

$$\frac{\text{n}}{\text{sec}} = 26\ \frac{\text{n}}{\text{p}}\ x\ 6.24 \bullet 10^{15}\ \frac{\text{p}}{\text{sec}} = 1.62 \bullet 10^{17}\ \frac{\text{n}}{\text{sec}}$$

- On a time averaged basis HFIR makes ≈ 17 times more neutrons than the SNS

Accelerator Basics



- **Requirements**
  - **High neutron flux requires high proton beam intensity (SNS goal 1.4 10^{14} p/pulse; ESS target is 8.9 10^{14} p/pulse)**
  - **For short-pulse source, proton burst <1 μs (SNS – 700 ns, ESS proposed – 2.86 ms)**
  - **Proton energy in 1-3 GeV range to maximize neutron production**
  - **High availability and reliability > 90%**
  - **Repetition rate < 60 Hz (SNS – 60 Hz, ESS proposed 14 Hz)**
- **Spallation source accelerators belong to a class of accelerators called "proton drivers" which push toward high beam intensity rather than high beam energies**

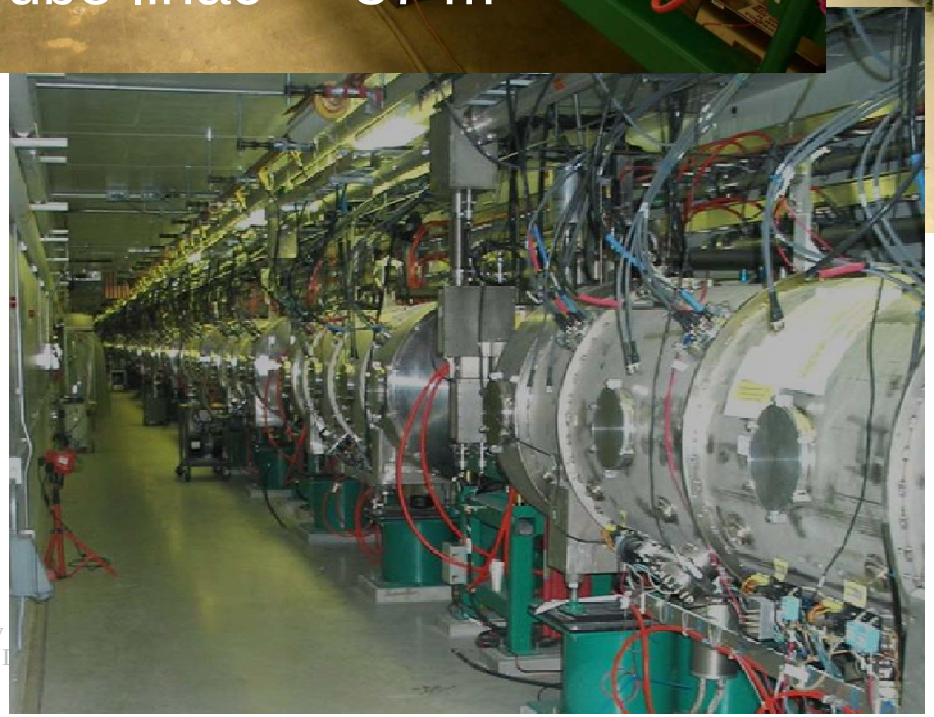
Accelerator Components

- **Ion Source – produces the charged particles accelerated in the linac**
- **Linac – linear accelerator – accelerates ions to desired energy (could be full beam energy (SNS, ESS) or not (J-PARC, ISIS)**
- **Ring – short-pulse sources require a ring**
  - **Accumulator**
    - **Linac provides all the acceleration – full-energy linac**
    - **Amplifier (for the SNS the accumulator ring is ~x1000 amplifier)**
    - **Ring is simpler**
  - **Synchrotron**
    - **Provides a large part of the acceleration**
    - **Shorter linac**
    - **Ring is more complex**

The SNS linac

Drift Tube linac ~ 37 m

Coupled Cavity linac ~ 55 m



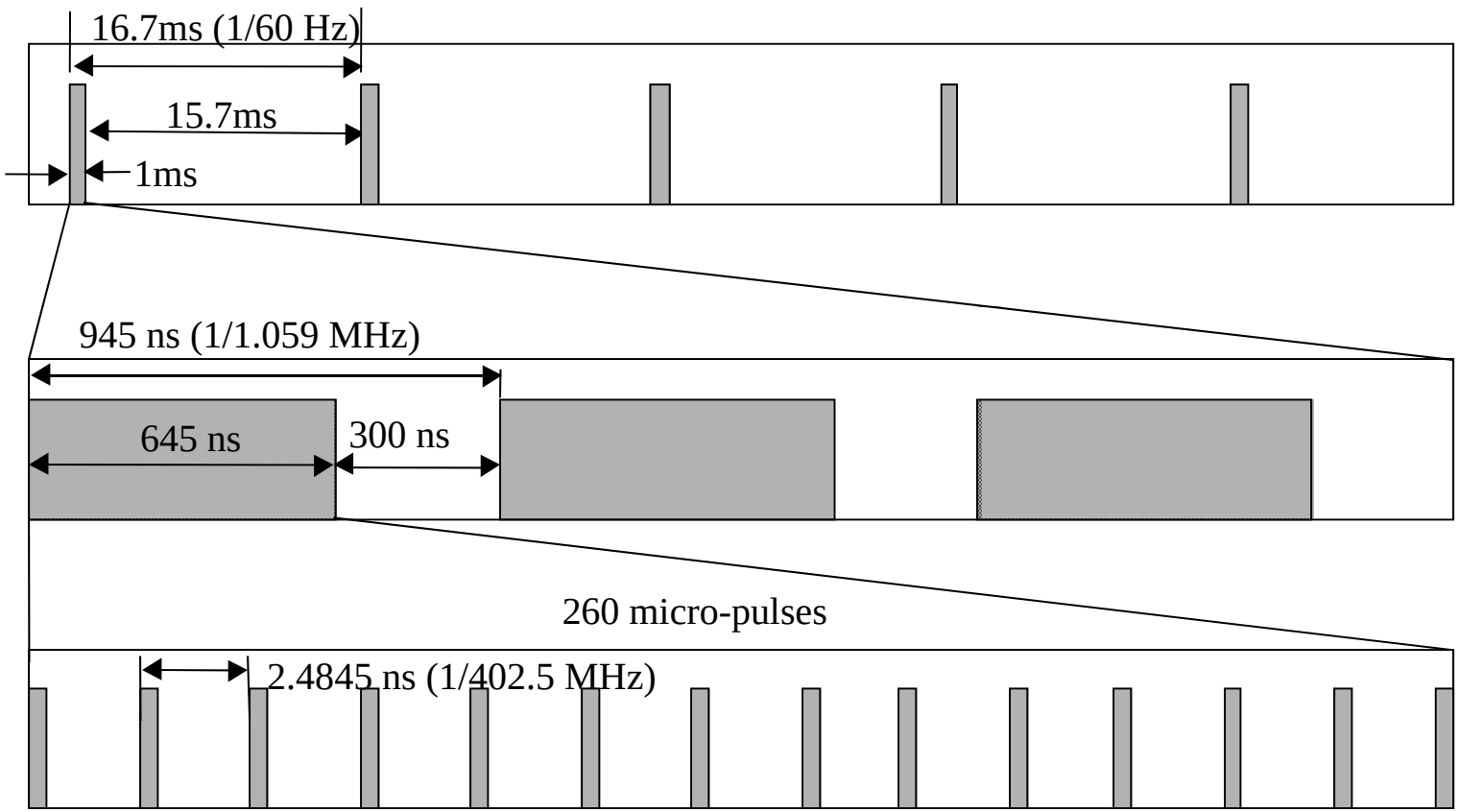
Superconducting linac ~ 150 m

SNS Linac Pulse Time Structure

Macro-pulse Structure (made by the High power RF)

Mini-pulse Structure (made by the choppers)

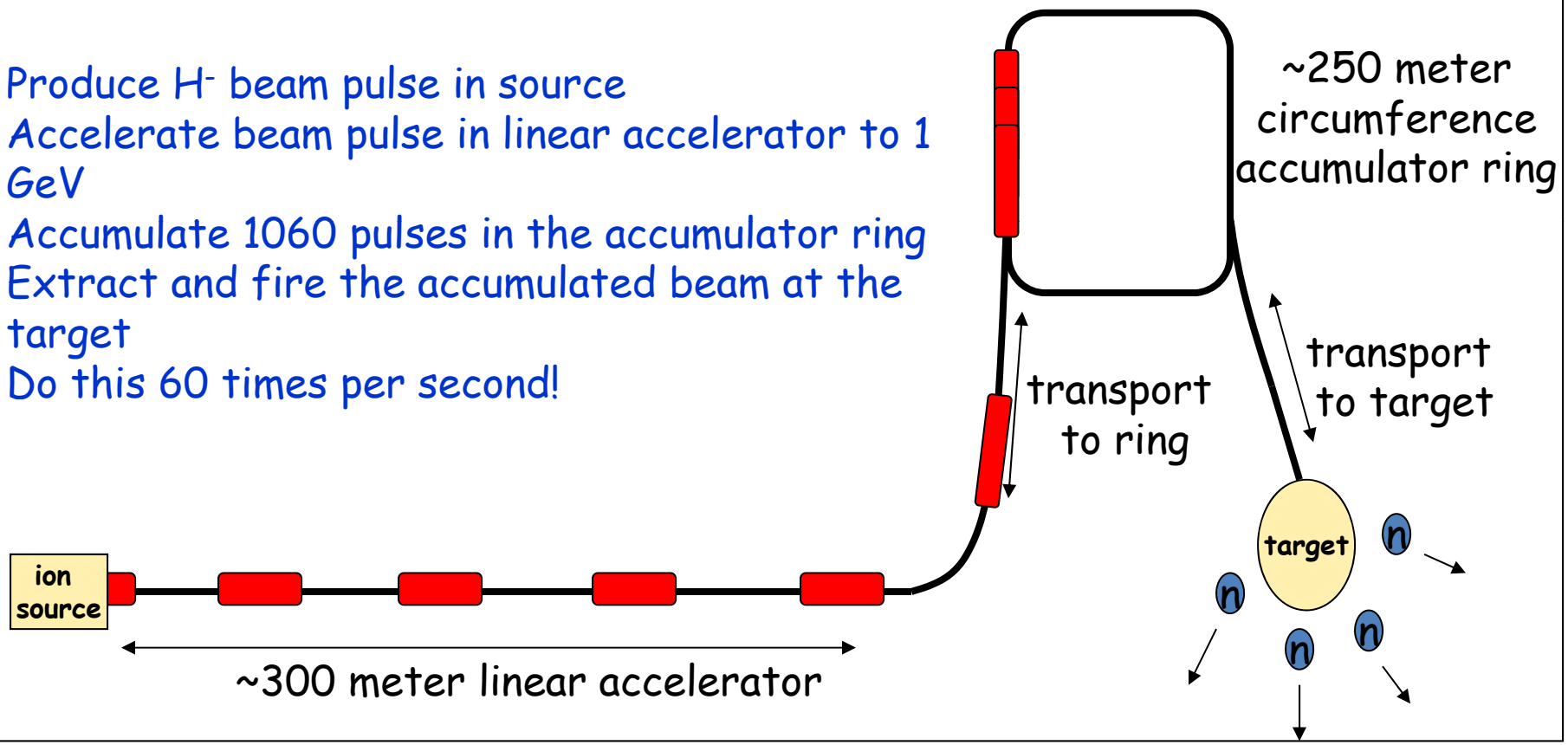
Micro-pulse structure (made by the RFQ)



The SNS Accelerator

Final Design

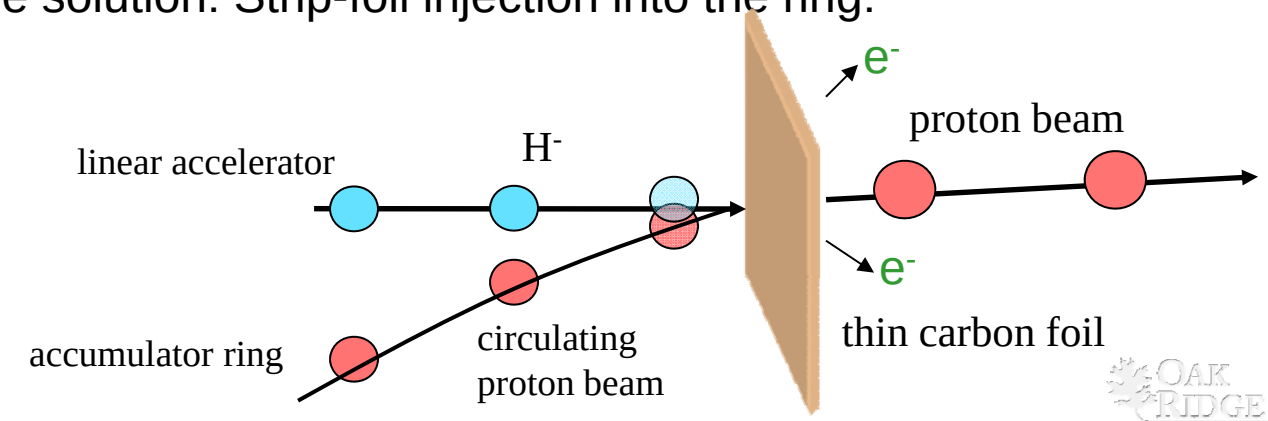
1) Produce H^- beam pulse in source
2) Accelerate beam pulse in linear accelerator to 1 GeV
3) Accumulate 1060 pulses in the accumulator ring
4) Extract and fire the accumulated beam at the target
5) Do this 60 times per second!



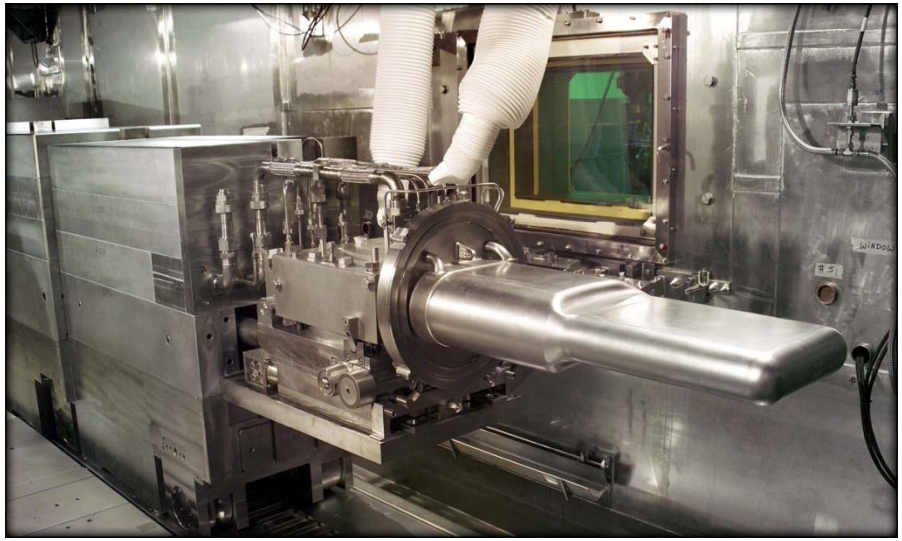
Why accelerate H^- ions, if we need protons hitting the target?

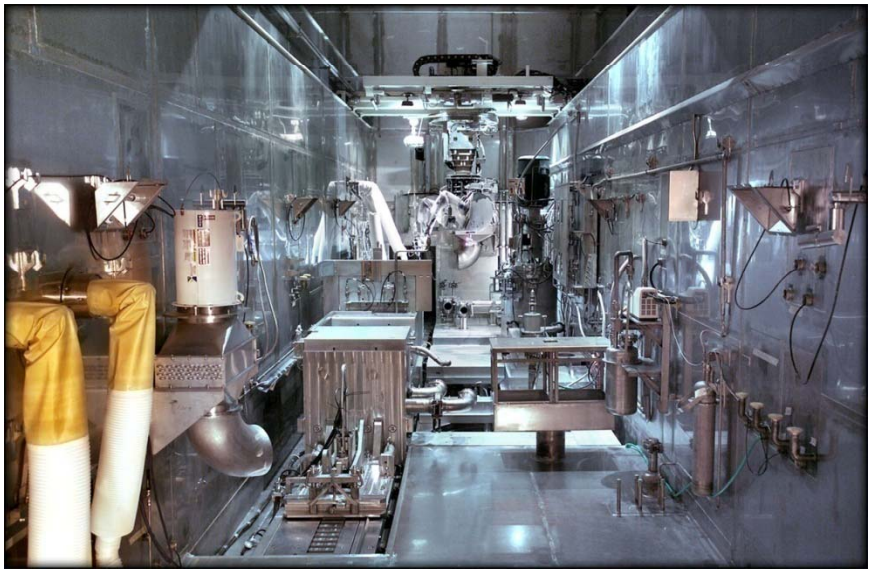
- **Because we need to merge two charged beams coming from different directions.**
- **It is not possible to merge an injected proton beam with a previously stored proton beam**
- **Solution: merge an H^- beam with a proton beam by stripping the two electrons of using a foil**

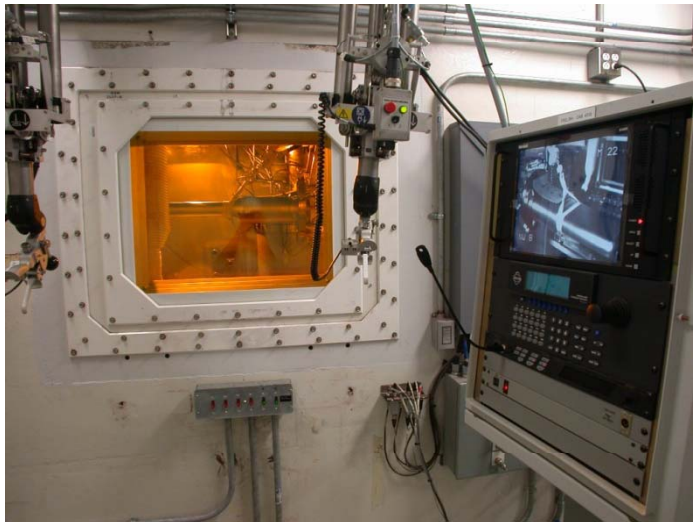
The solution: Strip-foil injection into the ring:



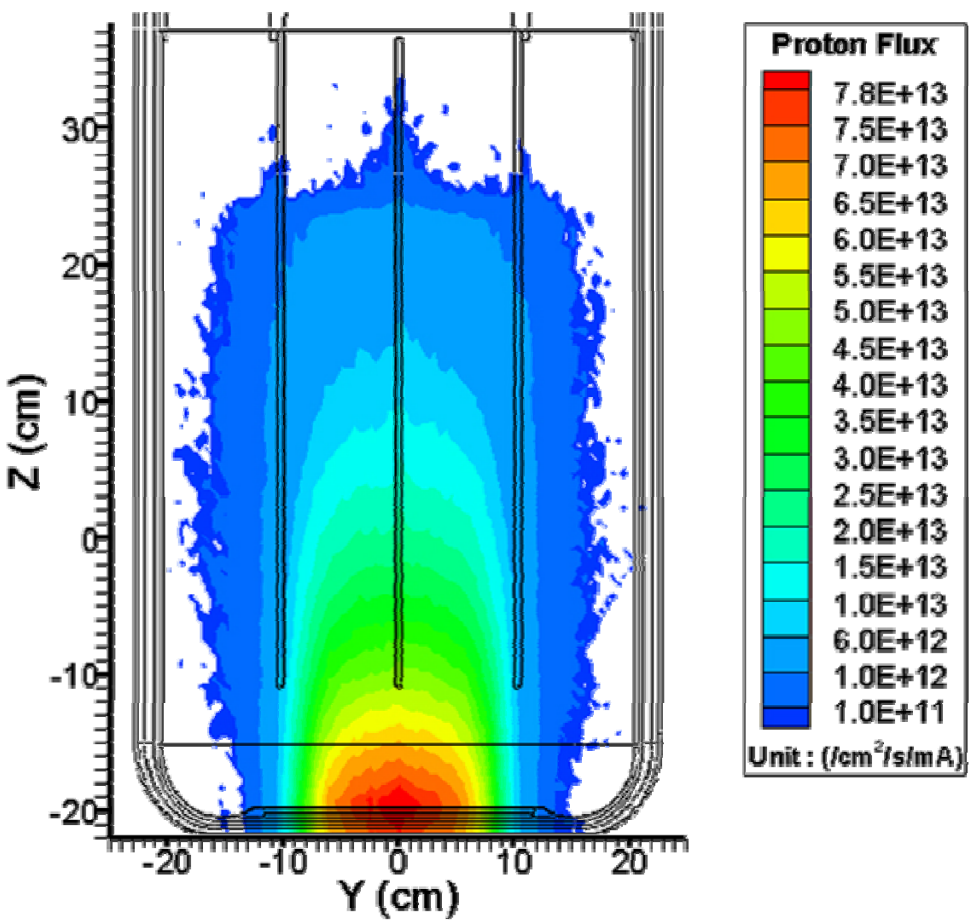
The SNS Target Facility

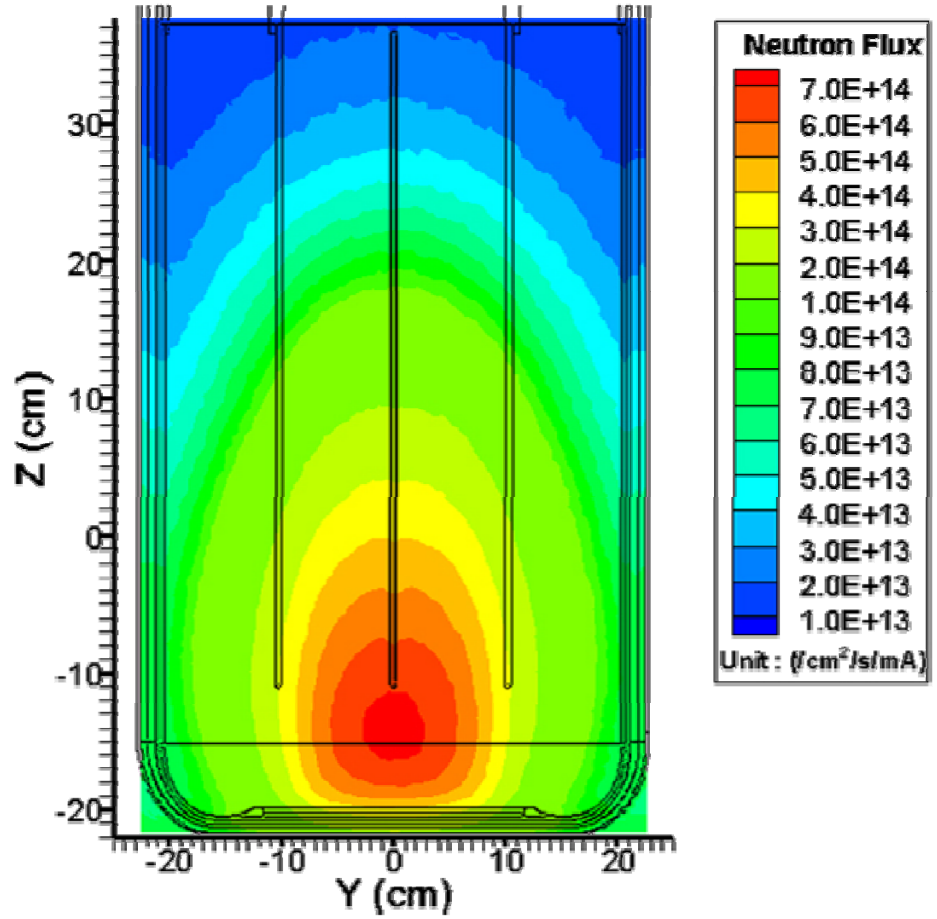




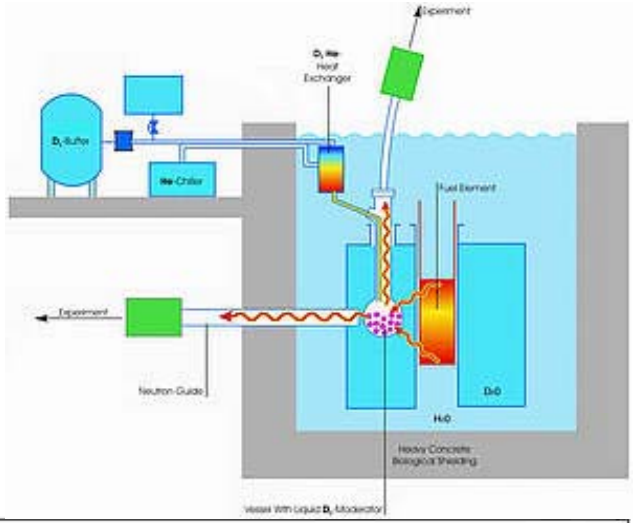


Proton and neutron distributions in the SNS target

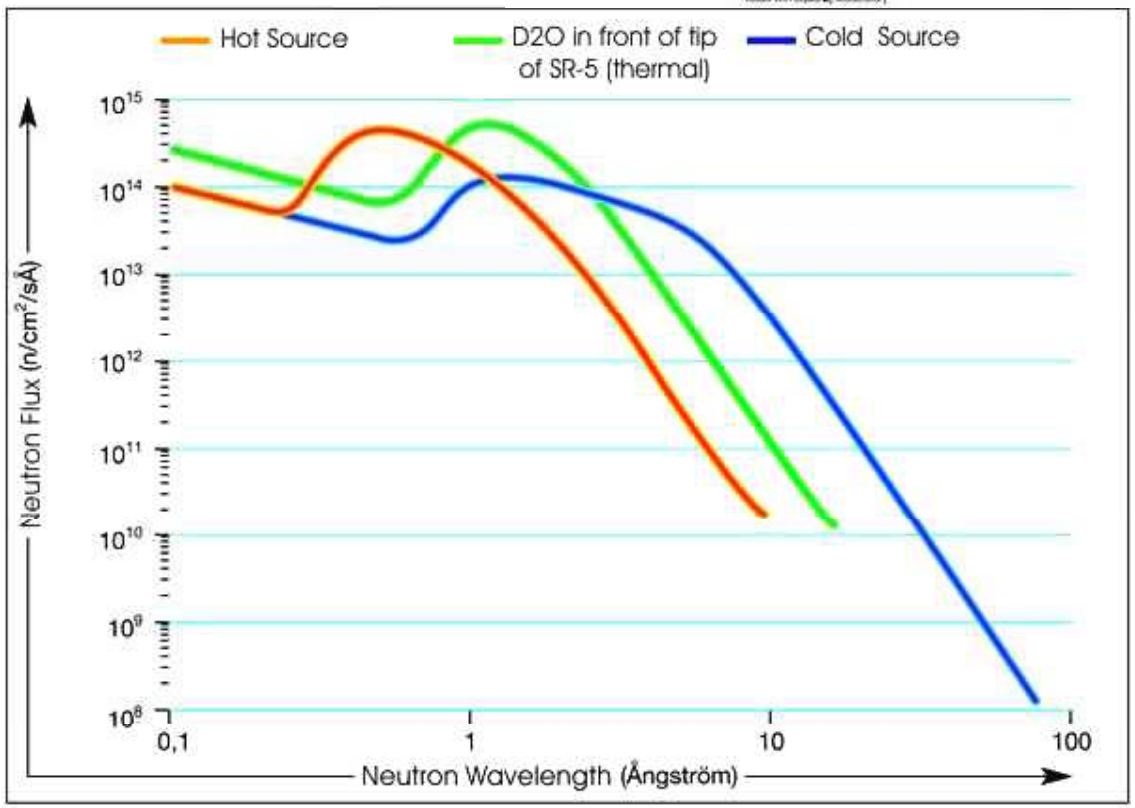




Moderators – modifying the fission or spallation spectra

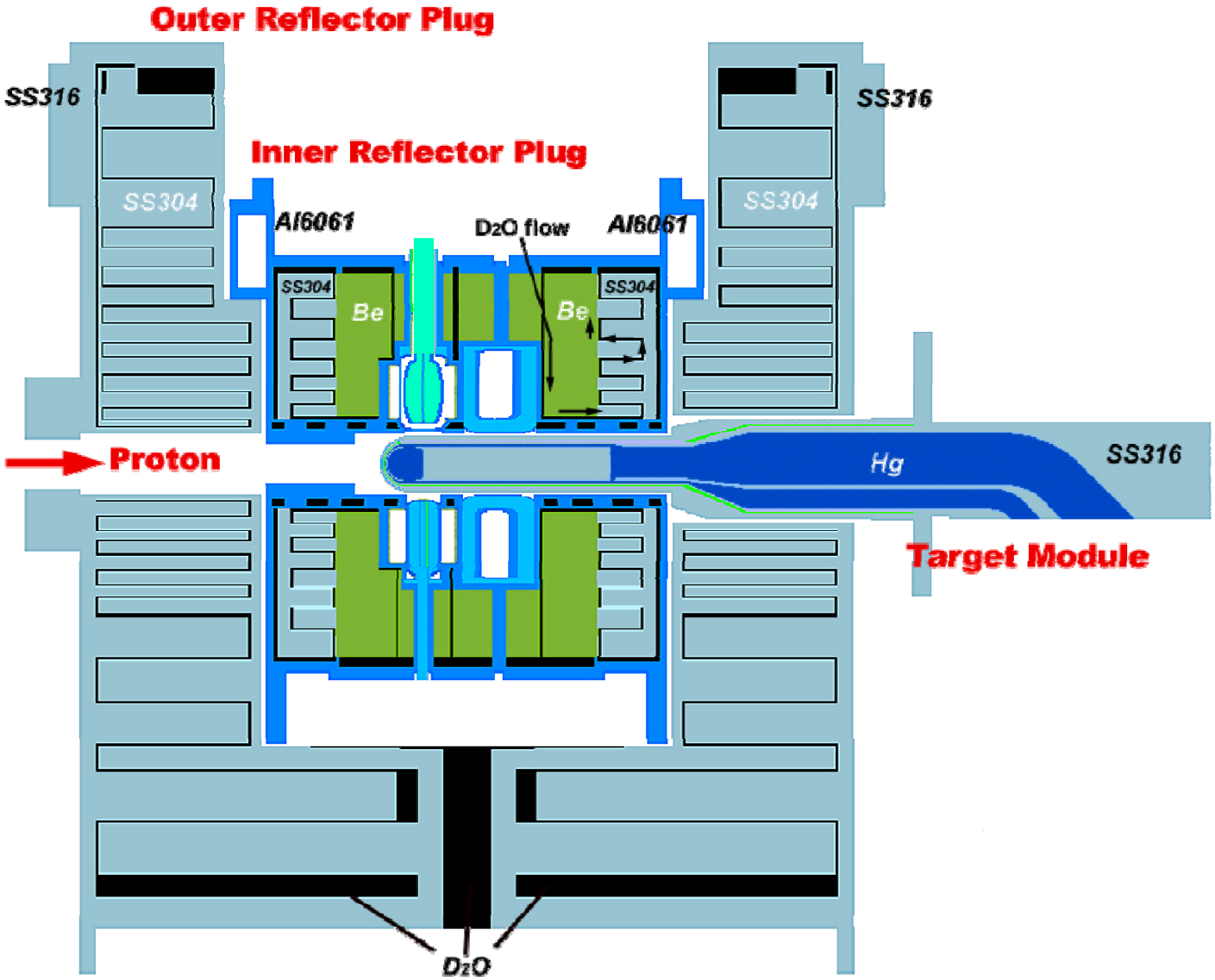


- **Reactors ("Sources")**
  - **Thermal (D_2O reflector)**
  - **Cold (25 K, 2.5 kg D_2)**
  - **Hot (2400 C, graphite)**



FRM II Web-site - http://www.frm2.tum.de/en/technik/secondary-sources/index.html

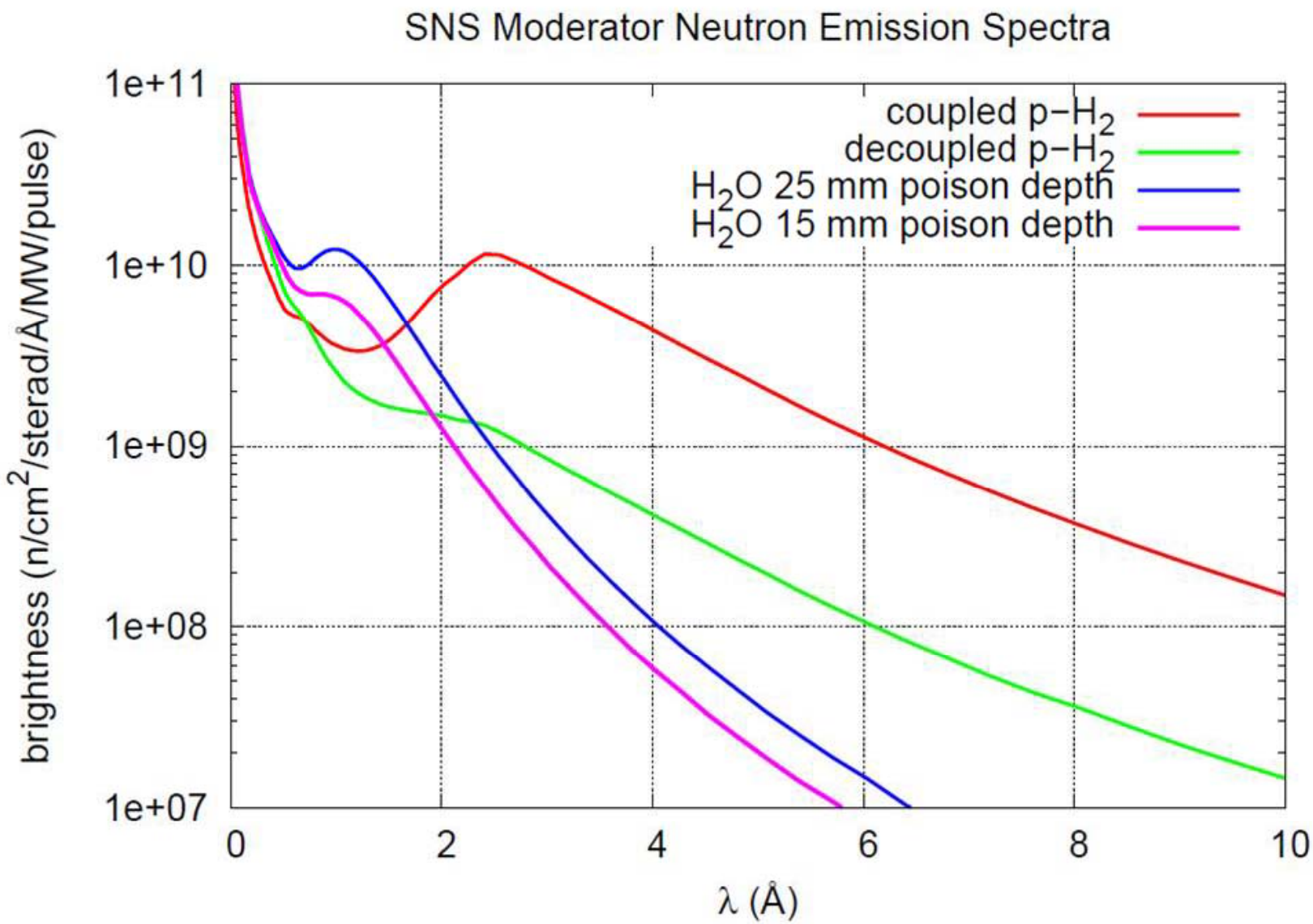
SNS Target System Geometry



Spallation Source Moderator Considerations

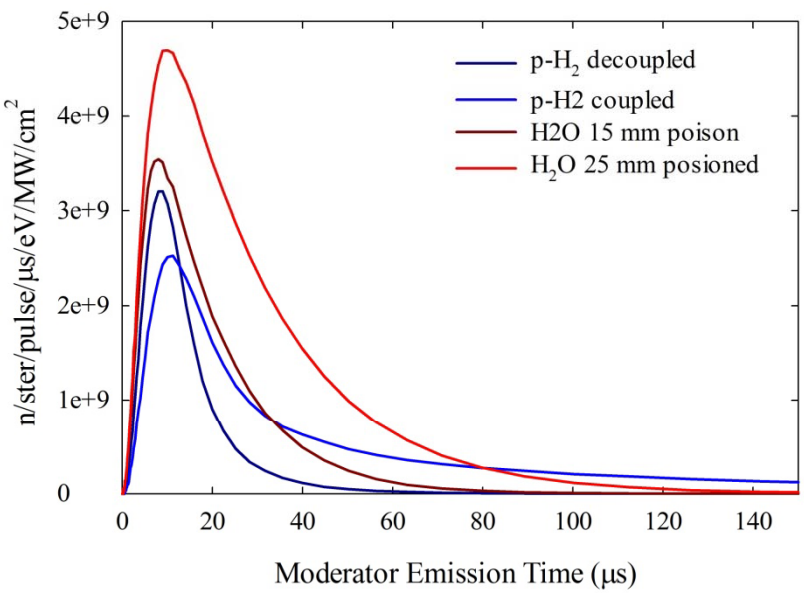
- **Spectral Characteristics (neutron wavelength dependence)**
  - **Largely determined by moderator temperature**
  - **Location relative to peak neutron density**
- **Time Structure (pulse width vs neutron wavelength)**
  - **Hydrogen density**
  - **Moderator Size**
  - **Moderator Thickness/Poison**
  - **Coupled/decoupled (absorber isolating the moderator from reflector or other surfaces) preserve the pulse width**

Moderator Spectra - SNS

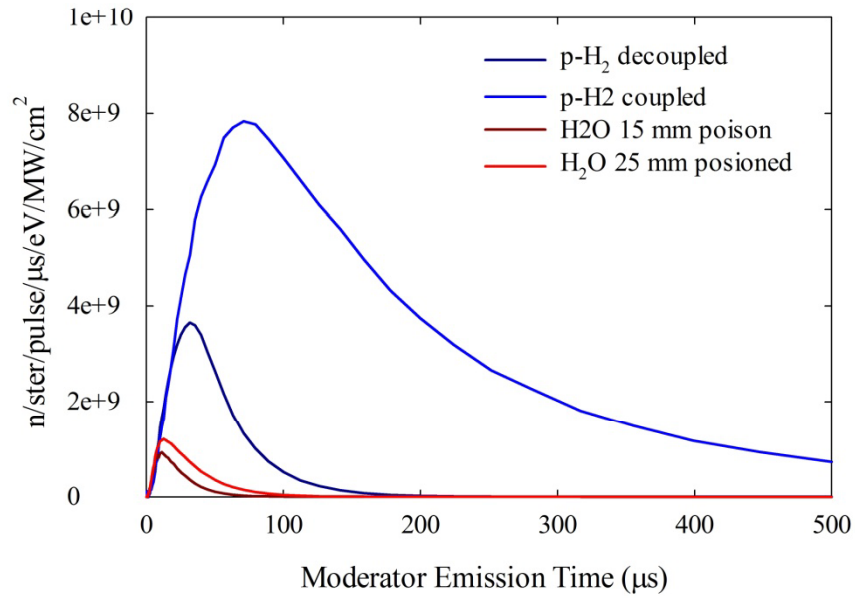


Moderator Pulse Widths - SNS

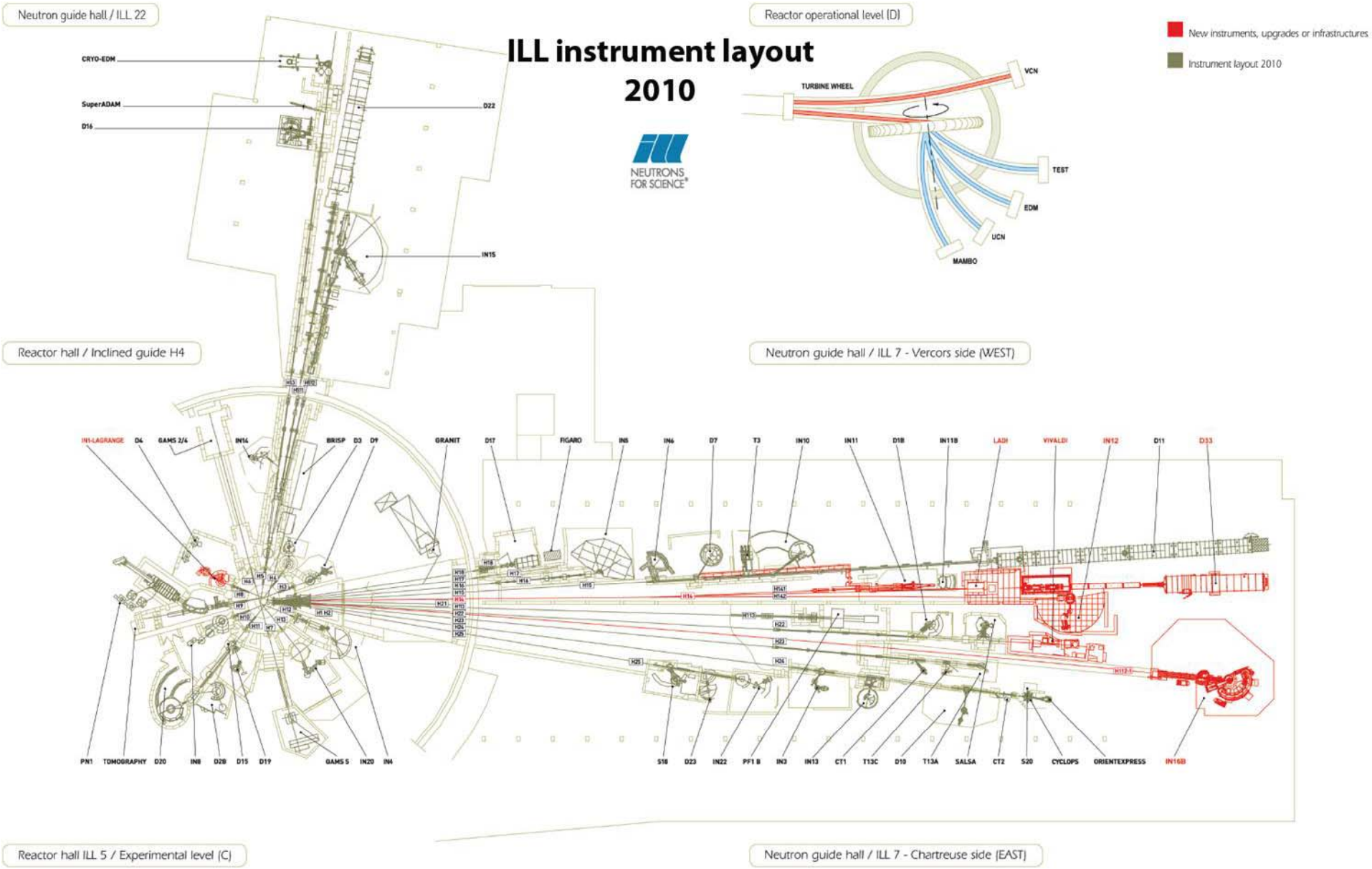
1.5 Å



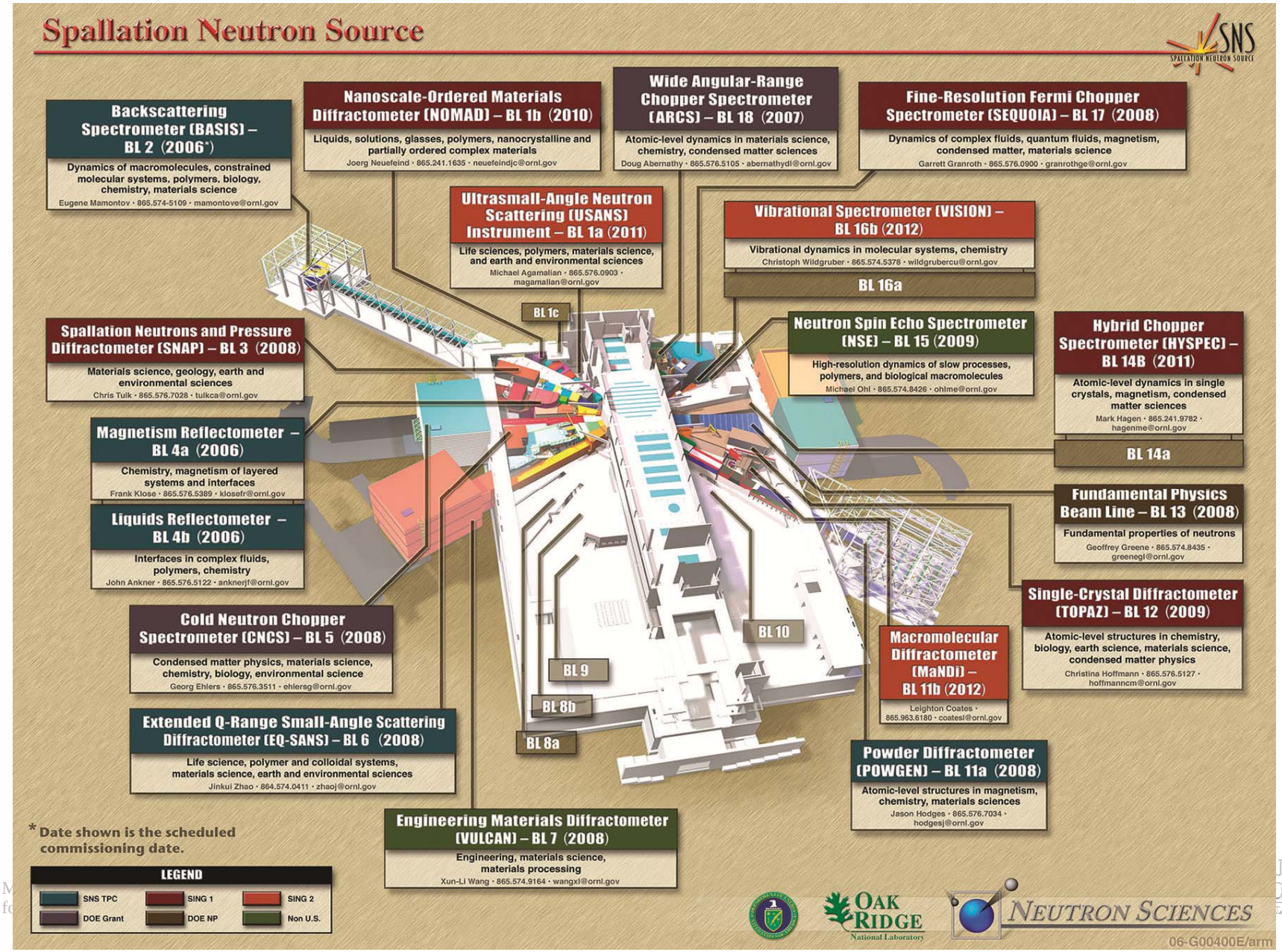
5.1 Å



Neutron Instrument Layouts – ILL Reactor

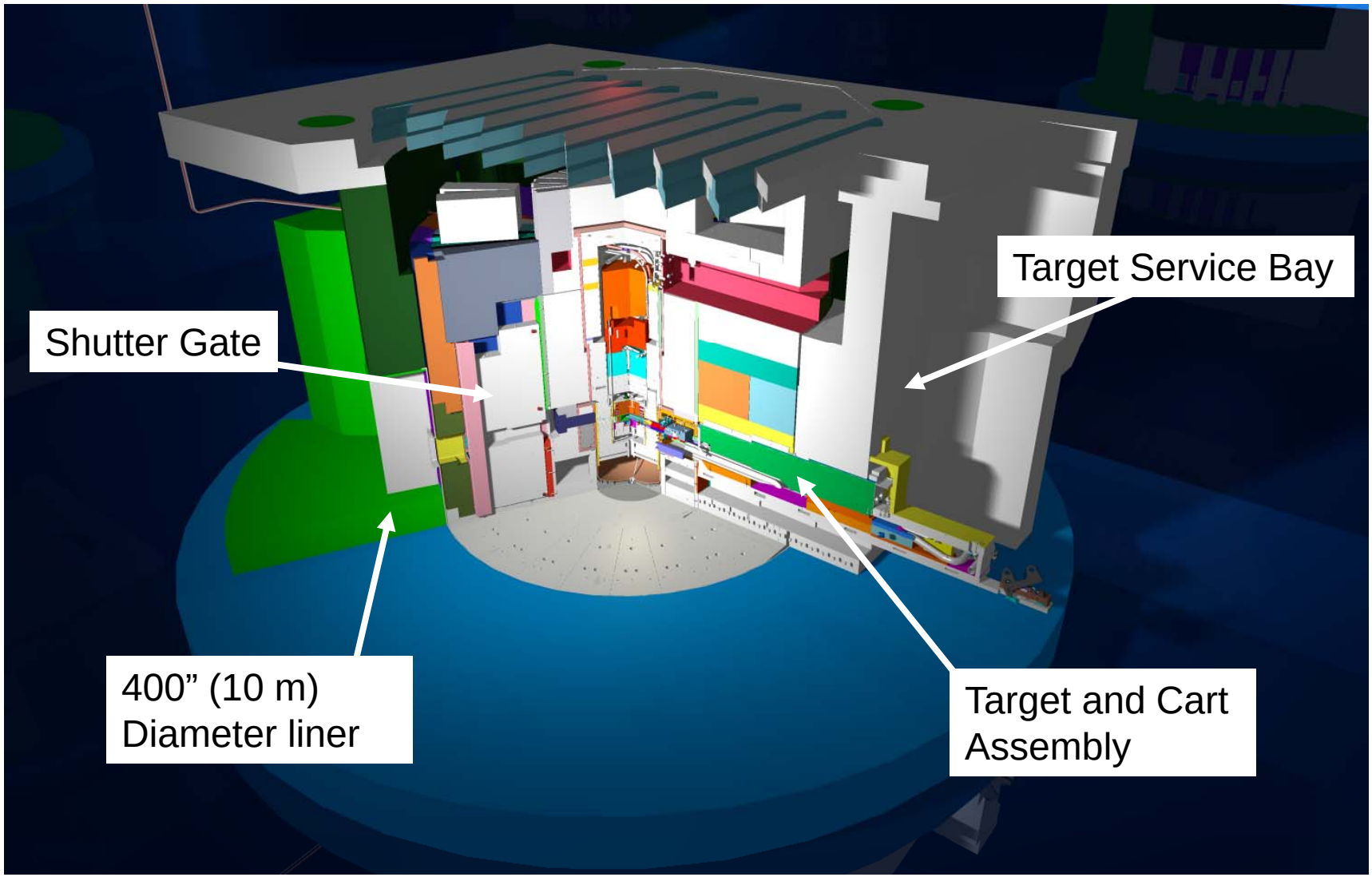


Neutron Instrument Layouts- Spallation Source



Where do all the neutrons go?

SNS Target Monolith



Where do all the neutrons go?

Systems	Production (n/p)	Capture (n/p)
Target Module	21.7 (85%)	5.1 (20%)
Moderator System	0.1	2
Inner Reflector Plug	2.4 (9%)	8.8 (34%)
Outer Reflector Plug	1	5.9 (23%)
Proton Beam Window	0.4	0.4
Total	***25.6***	22.2

2.1 n/p are deposited into the shielding
1.3 n/p (5%) exit the outer reflector (1m radius) towards the instruments

How many neutrons does SNS make in a year?

- **26 neutrons/ 1 GeV proton**
- **SNS at 1 MWatt**
  - **1 GeV protons @ 1 mA (time averaged) (approx. $1.04 \cdot 10^{14}$ protons/pulse, 60 Hz)**
- **Neutrons/sec = 26 x $6.24 \cdot 10^{15}$ = $1.6 \cdot 10^{17}$ n/sec**
- **Neutrons/year (5000 hours) = $2.9 \cdot 10^{24}$ = 4.8 moles/year**

How many neutrons do we count on BaSiS – the near backscattering spectrometer?

- **Guide transmits about $2 \cdot 10^7$ n/sec to sample**
- **10% scattering sample into $4\pi = 2 \cdot 10^6$ n/sec**
- **Analyzer is 1.2 sr, 10% scattered neutrons reach analyzer = $2 \cdot 10^5$ n/sec**
- **Analyzer accepts about 0.004, reflecting back to detectors = 800 n/sec**
- **There is some loss in radial collimator 80% transmission so count about 600 n/sec**
- **SNS produces about $1.6 \cdot 10^{17}$ n/sec**
- **BaSiS counts $4 \cdot 10^{-15}$ of those produced**

What does an instrument designer need to know about the source?

- **Source characteristics**
  - **Operating Frequency**
    - **Available neutron band width/time frame**
  - **Moderator Spectra (get the moderator source files)**
    - **Pulse shapes**
    - **Wavelength dependence**
    - **Moderator brightness (n/cm^2•ster•eV•μs•pulse)**
  - **Geometry**
    - **Beam transport**
    - **Background sources**
    - **Beam line spacing**
      - **Who are my neighbors?**
      - **End positions**

Additional Information

- **Low-power sources – Union for Compact Accelerator-driven Neutron Sources - http://www.indiana.edu/~lens/UCANS/**
  - **Look at presentation slides**
- **Previous school lecture notes**
  - **(see, for example, talk on Neutron Sources by Jack Carpenter in 2011 at ORNL/ANL National School on Neutron and X-ray Scattering: http://neutrons.ornl.gov/conf/nxs2010/pdf/lectures/Sources_Carpenter%20ORNL.pdf)**
- **International Collaboration on Advanced Neutron Sources**
  - **(see, for example, this years meeting proceedings: http://www.icansxx.com.ar/)**
- **For a historical snapshot – see Nuclear Instruments and Methods volume 145 (1977), pages 1-218.**