Fundamental Neutron Physics II

Neutron Sources, Neutron Beams, and Ultracold Neutrons

Geoffrey Greene
University of Tennessee / Oak Ridge National Laboratory

Introduction to Neutron Sources

Early neutron sources were based on simple nuclear processes:

$$\alpha + {}^{9}Be \rightarrow {}^{12}C + n$$

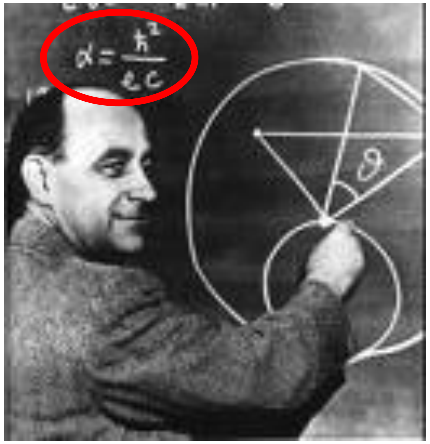
Such sources are still used ("Pu-Be") but are limited in intensity.

Modern neutron research is based at sources of two types:

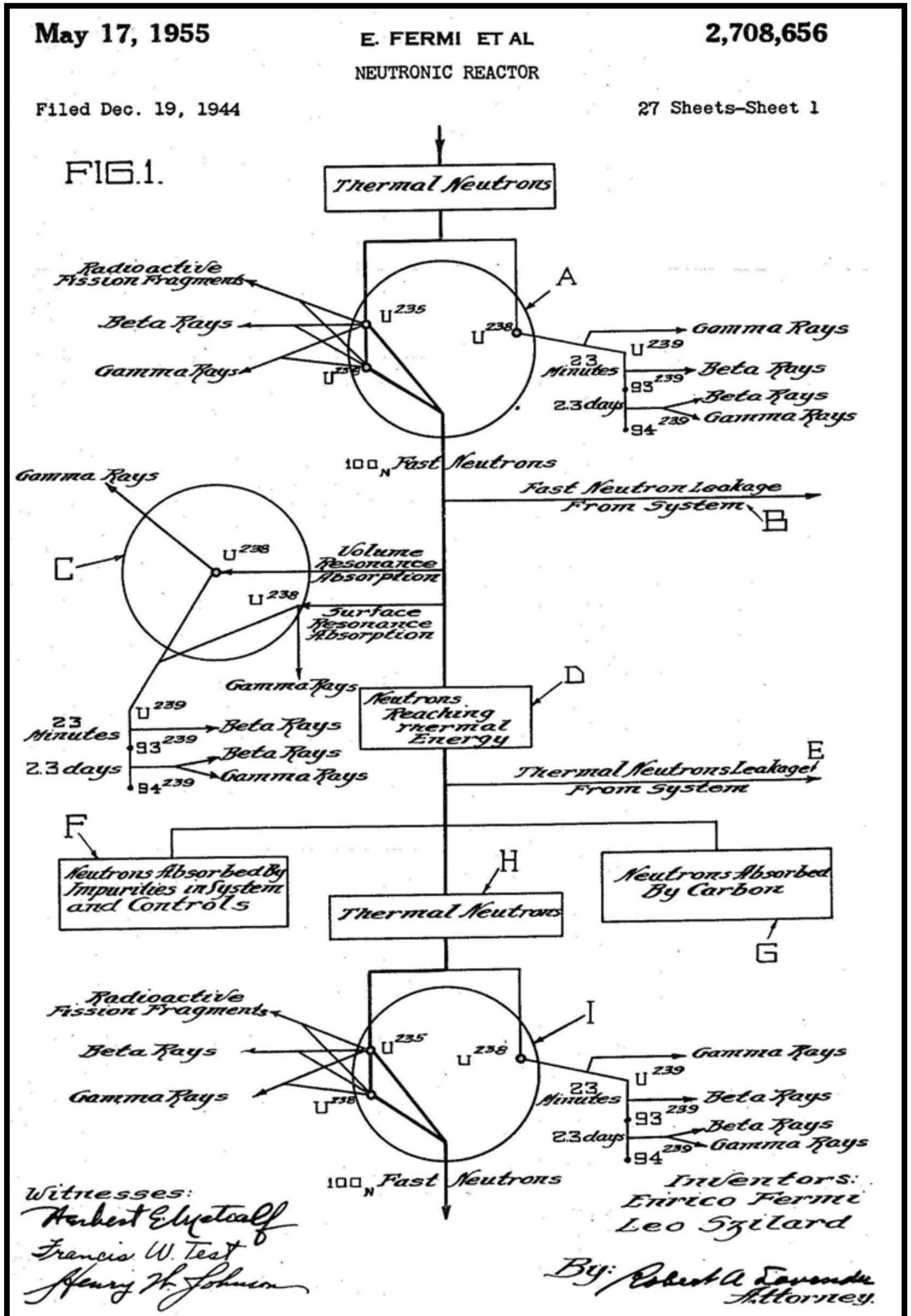
1. **High Flux Fission Reactor**

2. **Accelerator "Spallation" Sources**

The Fission Reactor

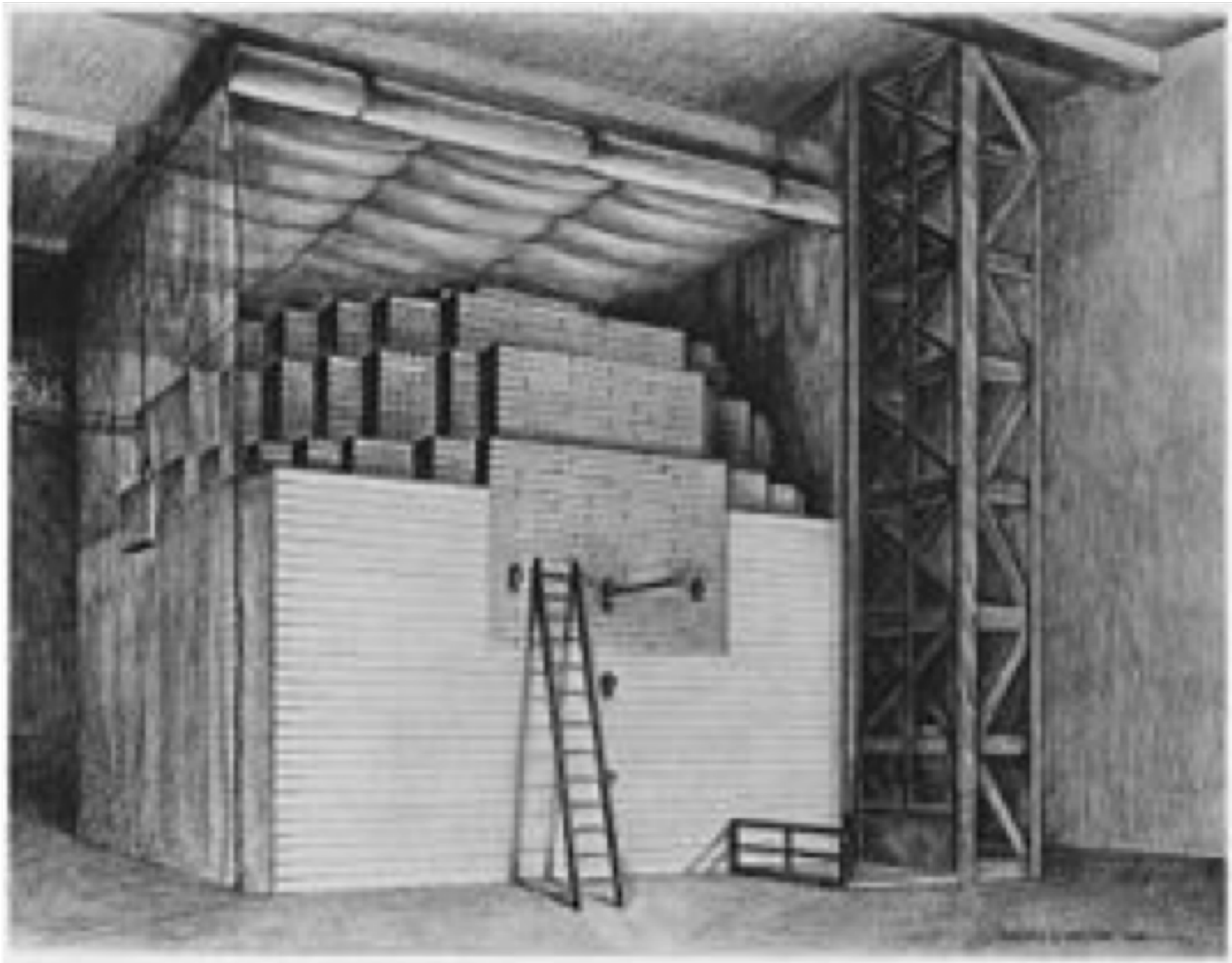


Enrico Fermi



Leo Szilard

Chicago Pile 1 -CP1



Inside a squash court at Stagg Field Stadium
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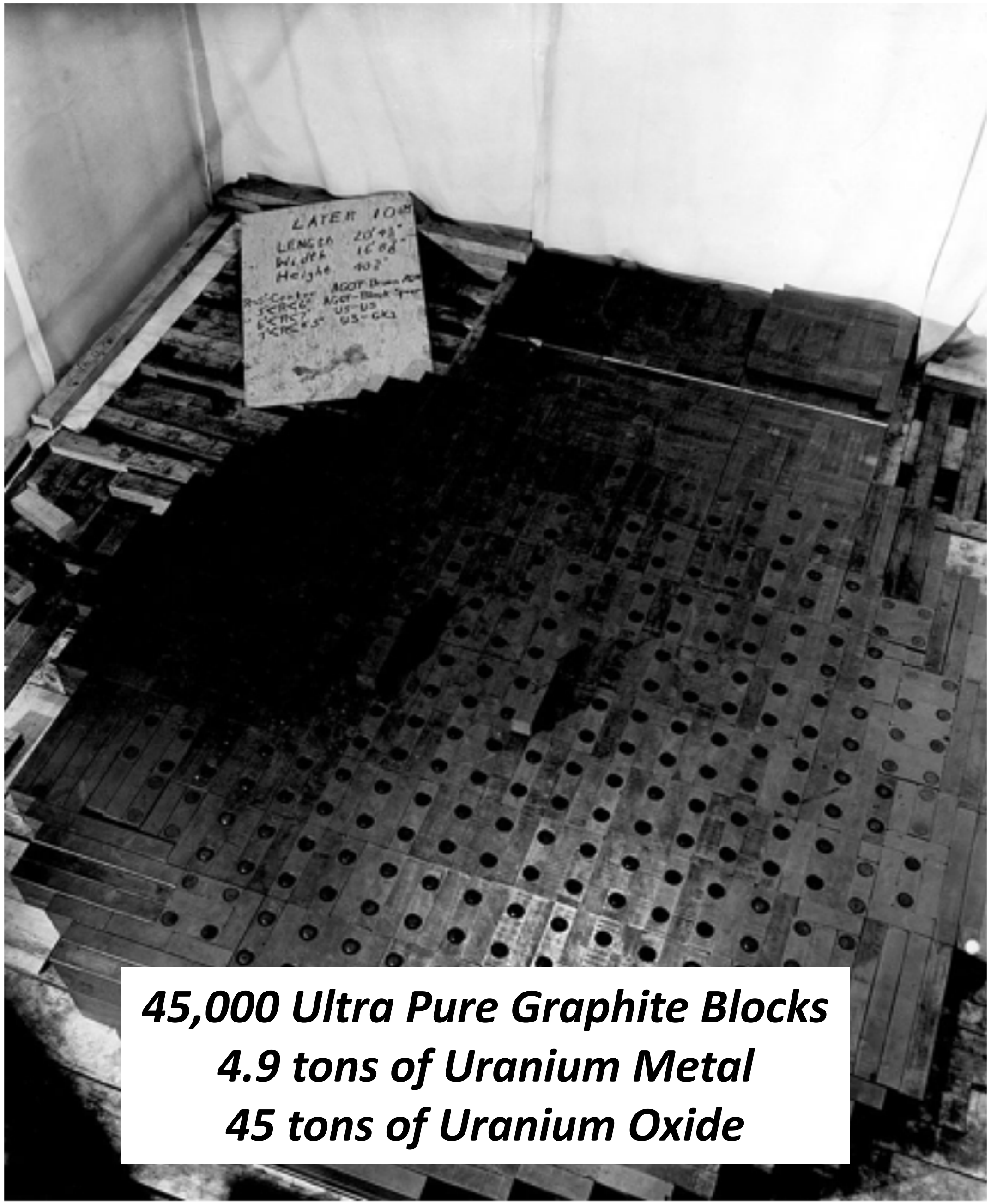
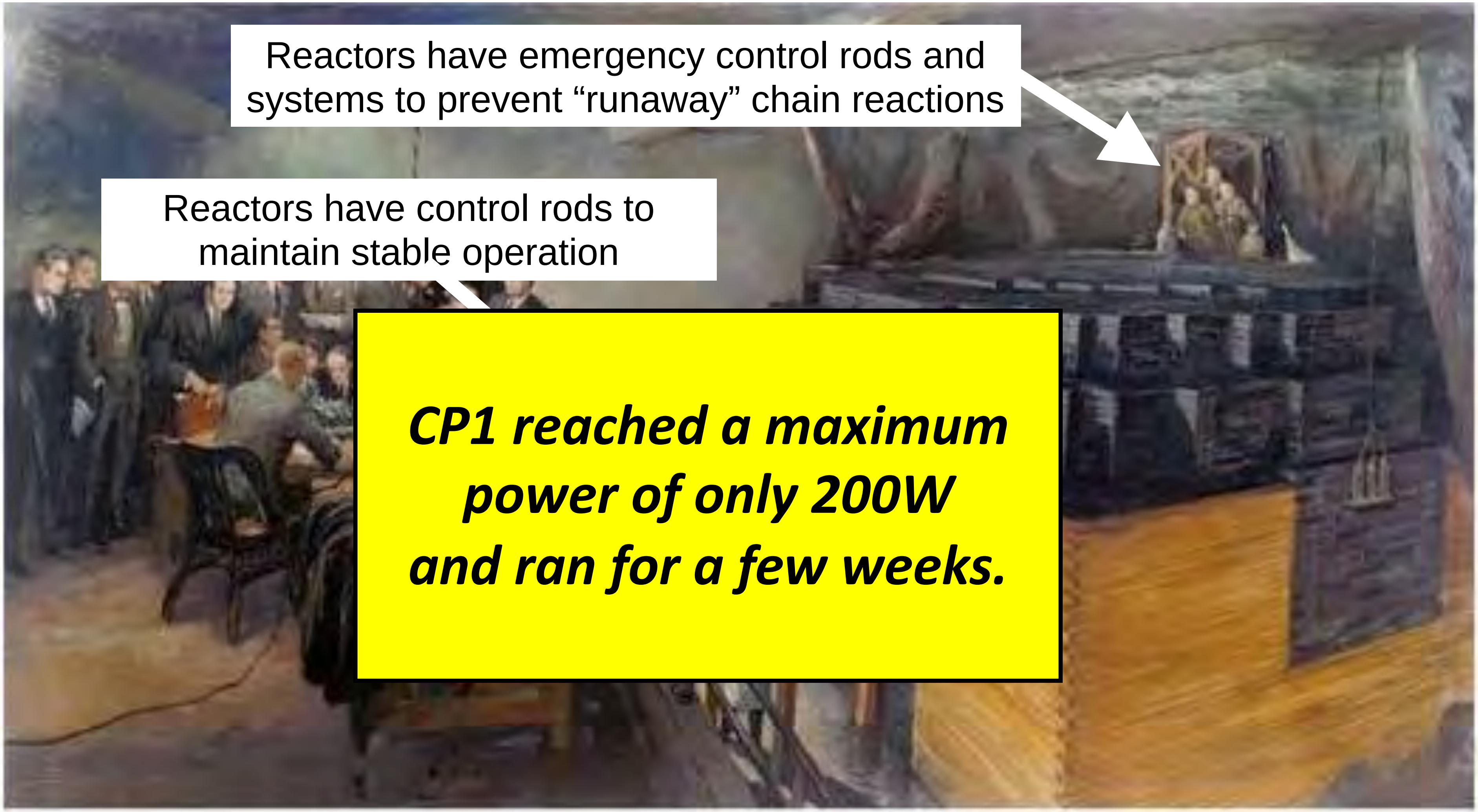

LATER 10
LENGTH
Width
Height
45,000 Ultra Pure Graphite Blocks
4.9 tons of Uranium Metal
45 tons of Uranium Oxide

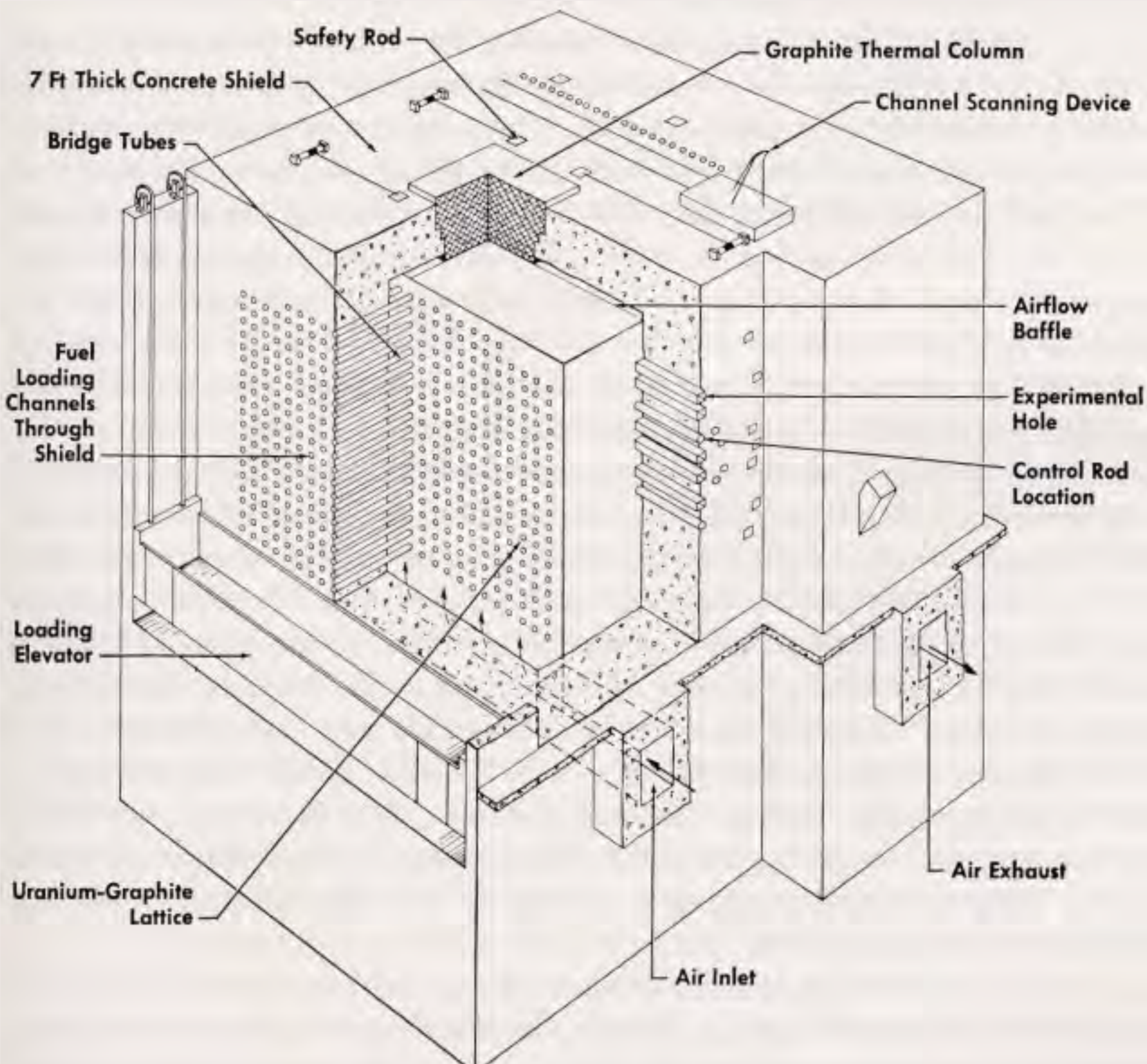
CP1 - Level 10

2 December 1942



2 December 1942

THE GRAPHITE REACTOR AT OAK RIDGE



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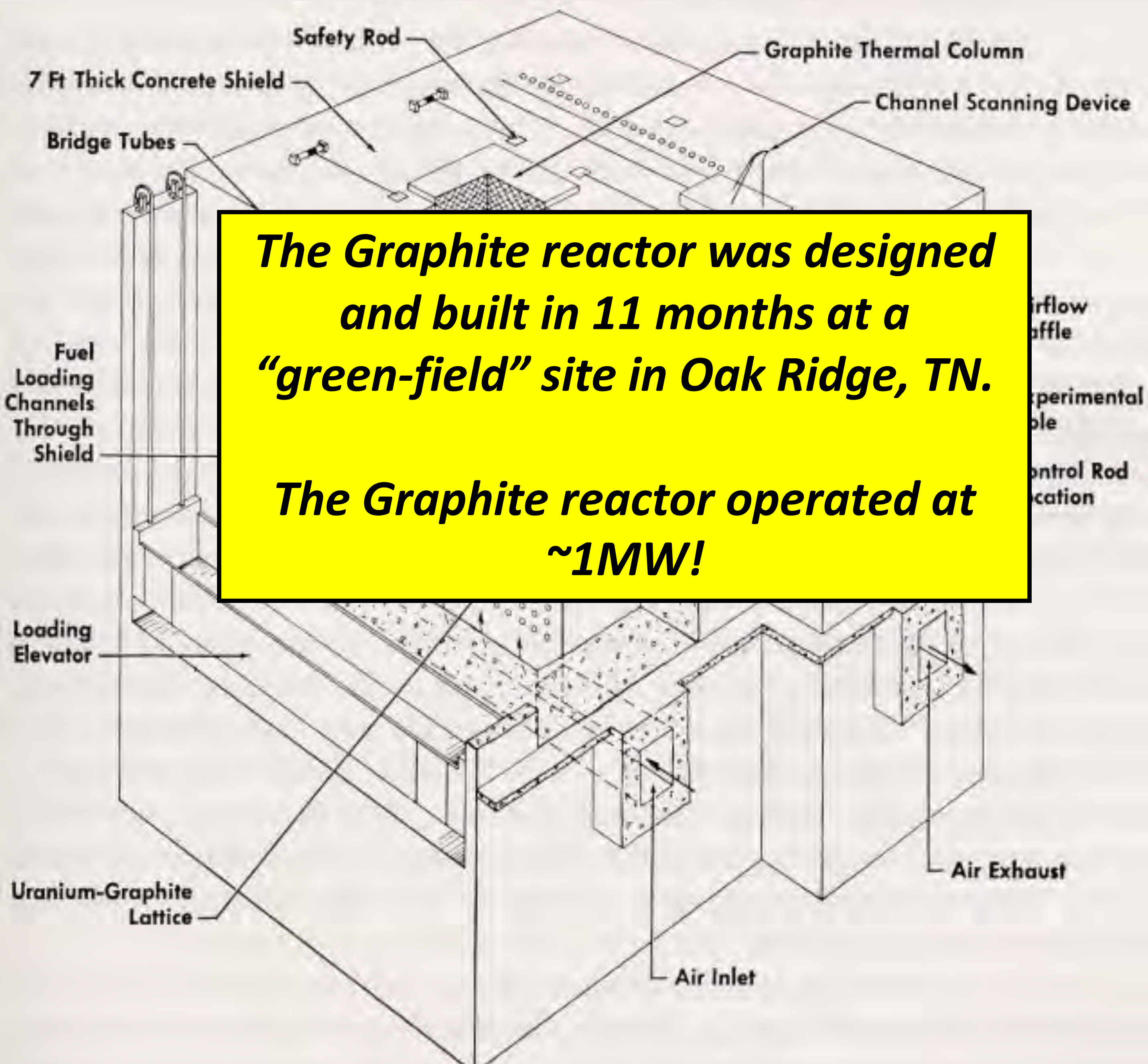

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The Graphite reactor operated at ~1MW!

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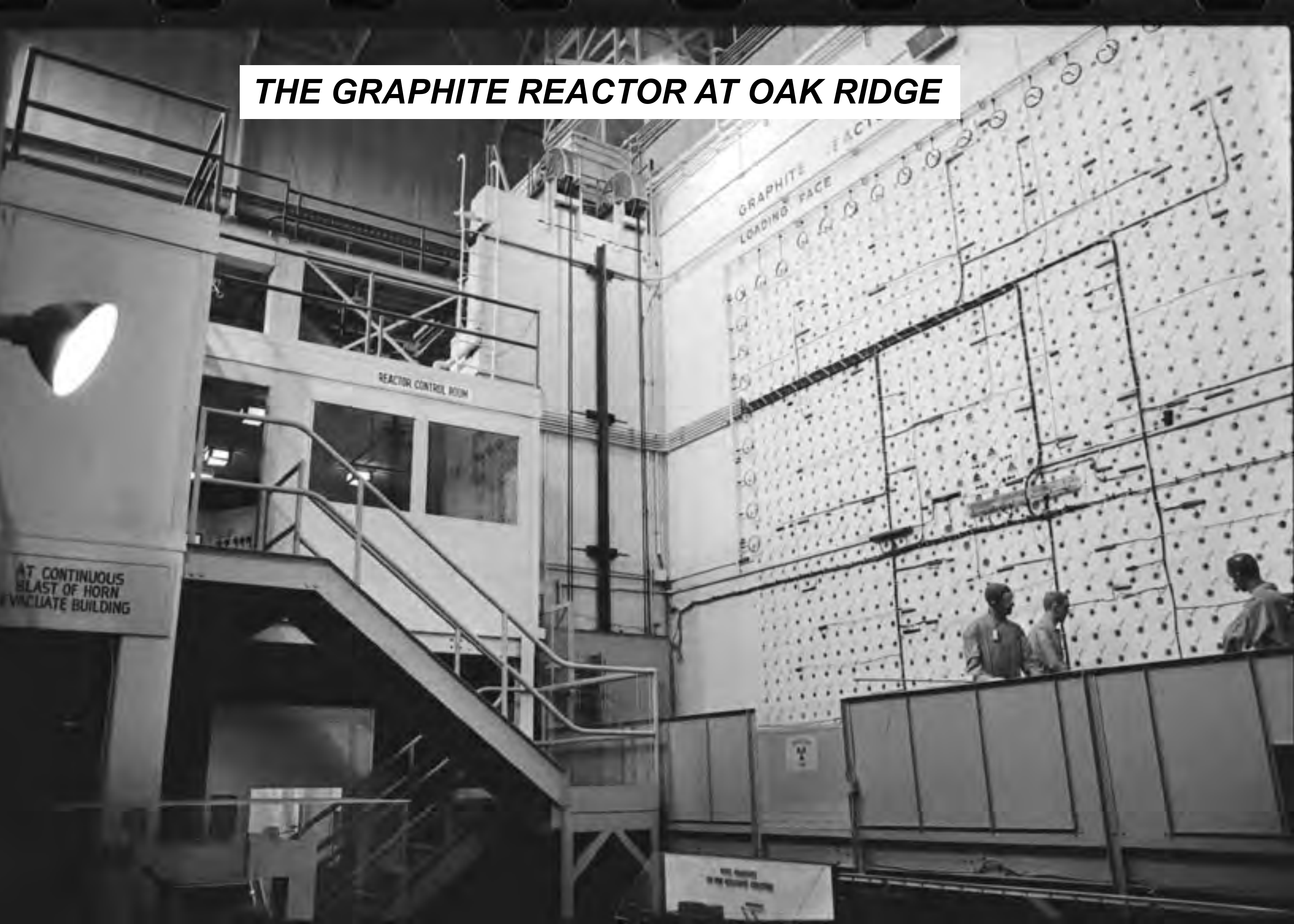

Why Was the Manhattan Project Located in Tennessee?

1. Cheap Electricity from the TVA Hydroelectric Dams,
2. Distance from the East Coast,
3. Distance from major population centers.

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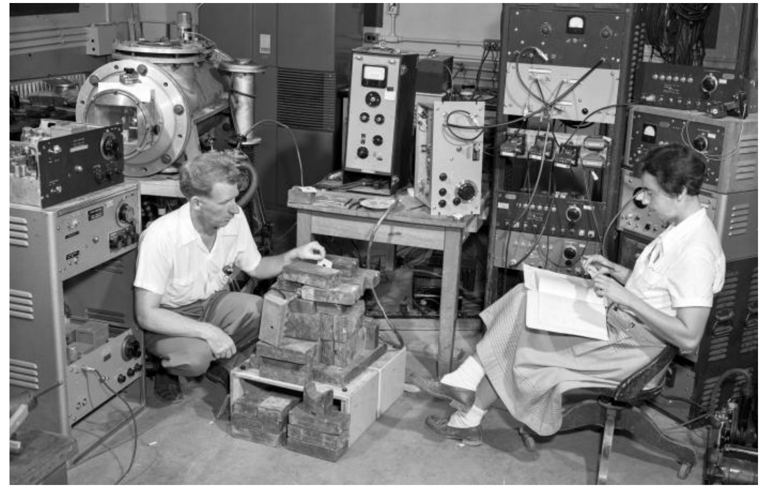
Sen. McKellar replied,

"Mr. President, I have just one question:
Where in Tennessee do you want me to hide it?"

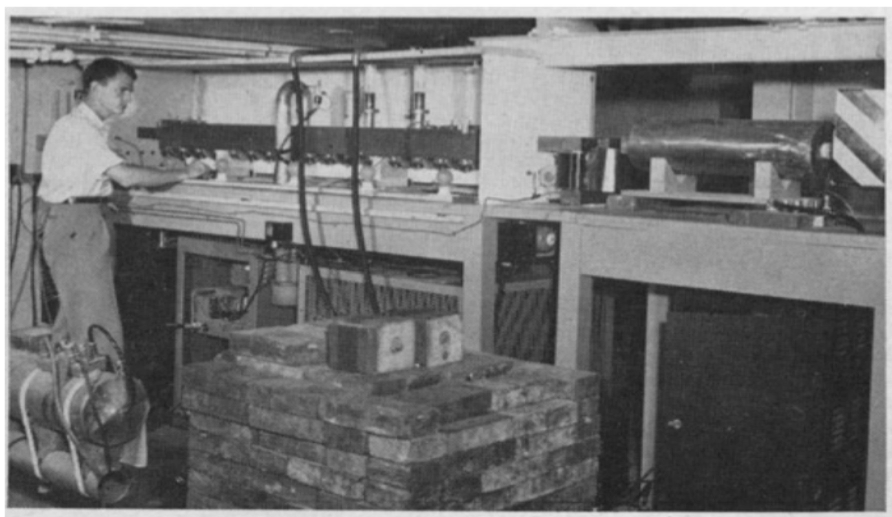
First Intense Neutron Beams at the Graphite Reactor

While the purpose of the graphite reactor was to produce small quantities of Plutonium, a few holes were placed in the shielding to allow beams of low energy neutrons to be extracted

1st Neutron Scattering Experiment
Shull & Wollen (Nobel prize 1994)

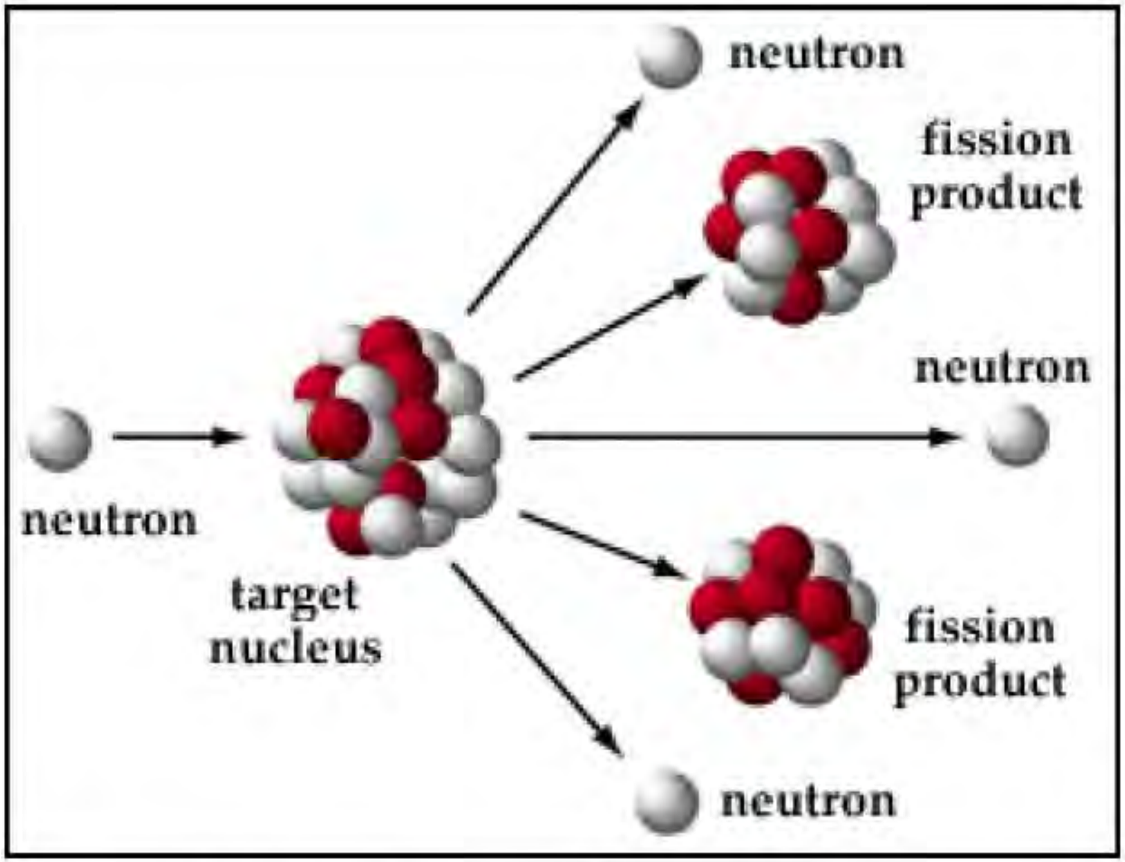


1st Observation of Neutron Decay
Snell & Pleasonton



1st Neutron Electric Dipole Search
Ramsey, Purcell, & Smith (Nobel Prizes 1952 & 1989)

Each Fission Event Produces ~200Mev and ~1.5 "Useful" Neutrons



Nuclear Fission

Some Essential Features of a High Flux Reactor

Figure of Merit is the Peak Neutron Flux at the Core n/cm^2/s

Key Design Features:

1. **High Power Density**
2. **Compact Core**
3. **Highly Enriched Fuel**
4. **D_2O Moderation and Cooling**
5. **Cryogenic Cold Source(s)**

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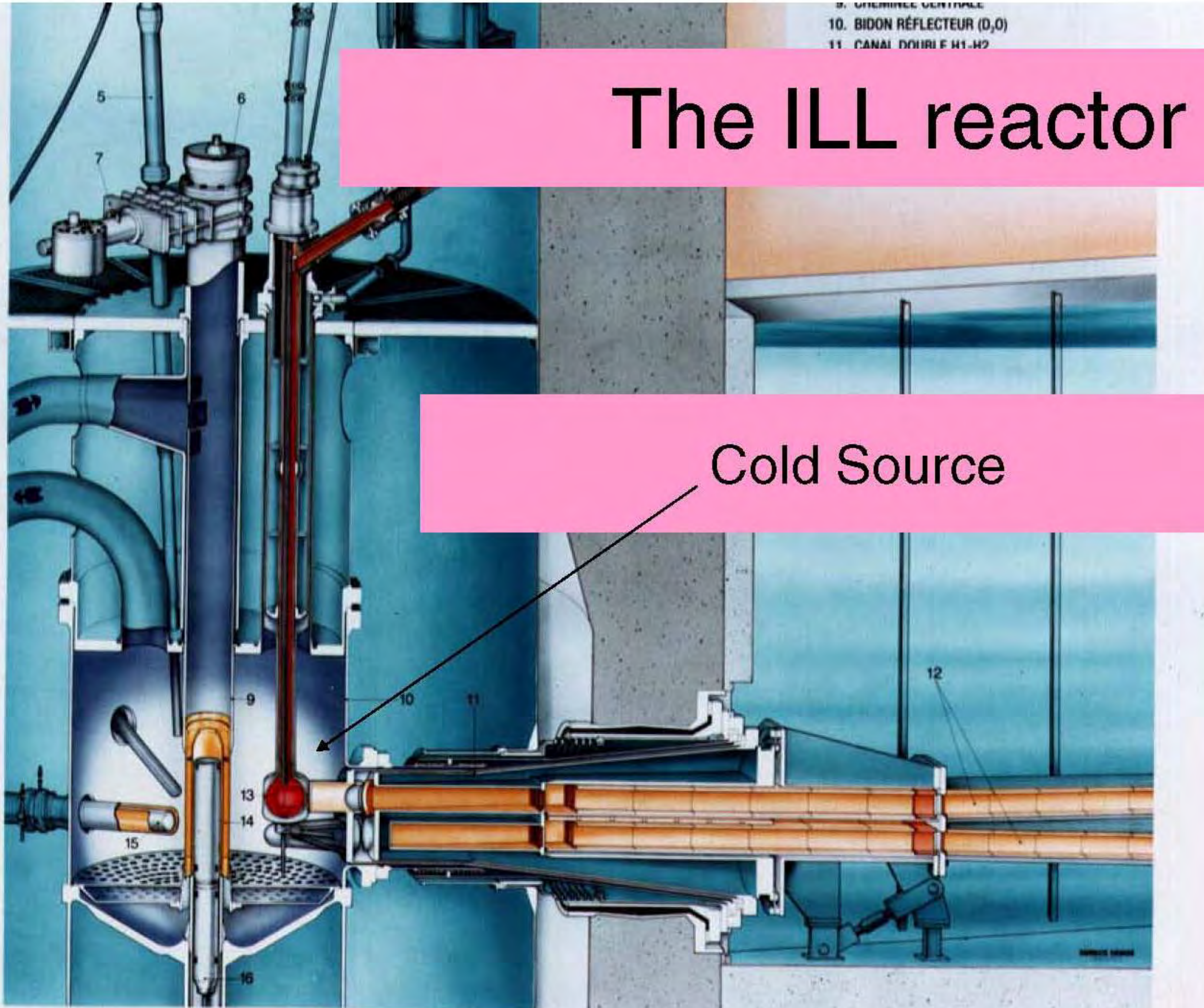
Ultimate engineering limitation is ability to remove heat from the compact core at ~100MW

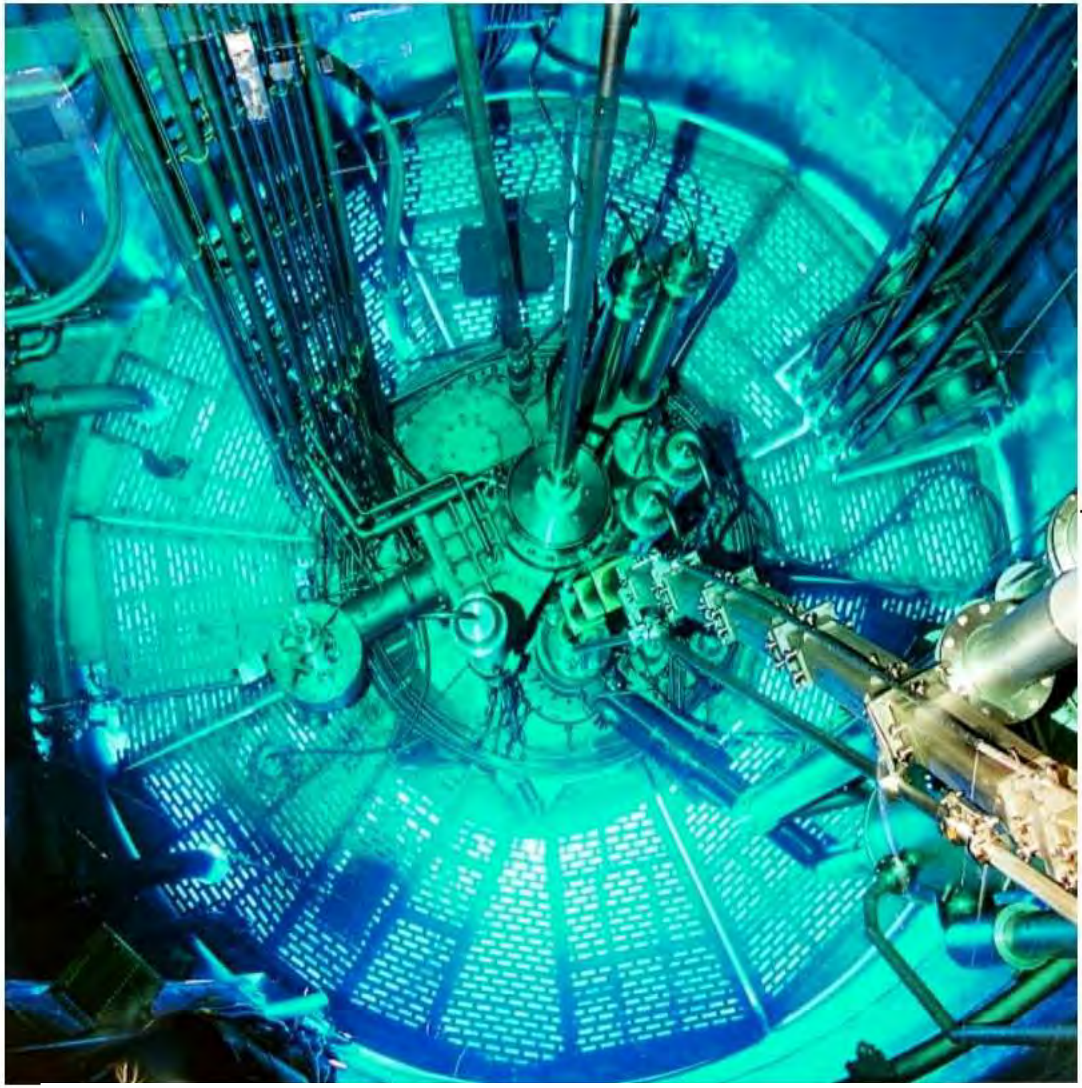
The Institute Laue Langevin, Grenoble

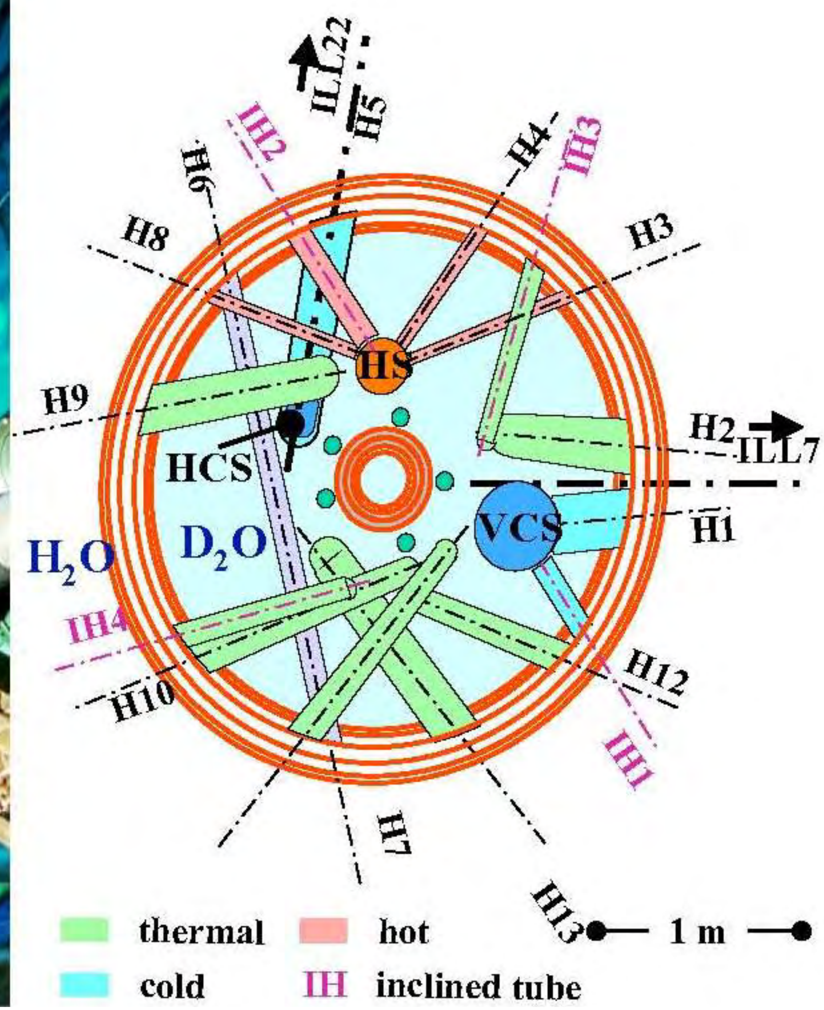
57 MW High Flux Reactor

The ILL reactor



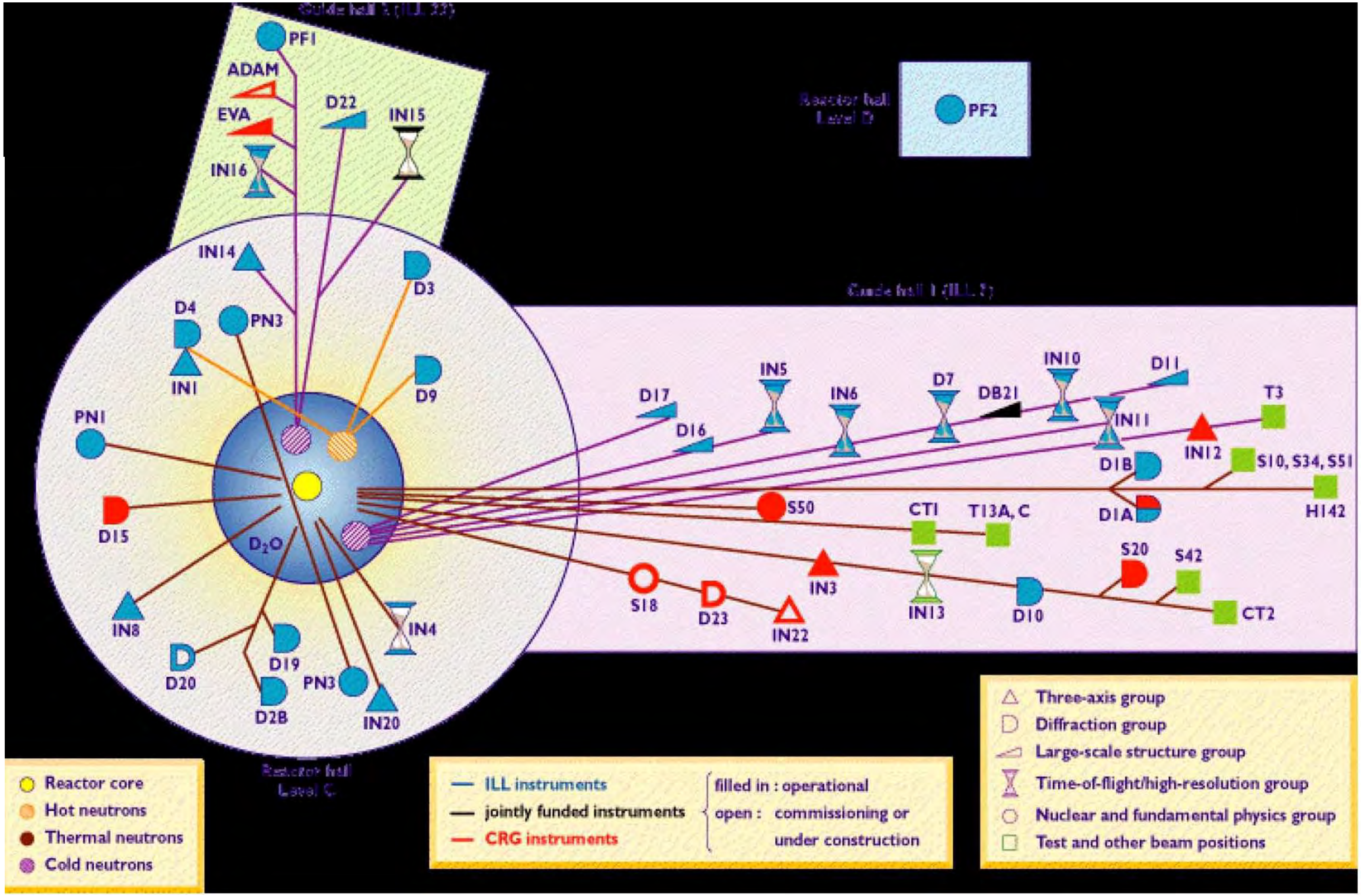
Most Neutron Sources Have Multiple Moderators





The High Flux neutron Source at the ILL

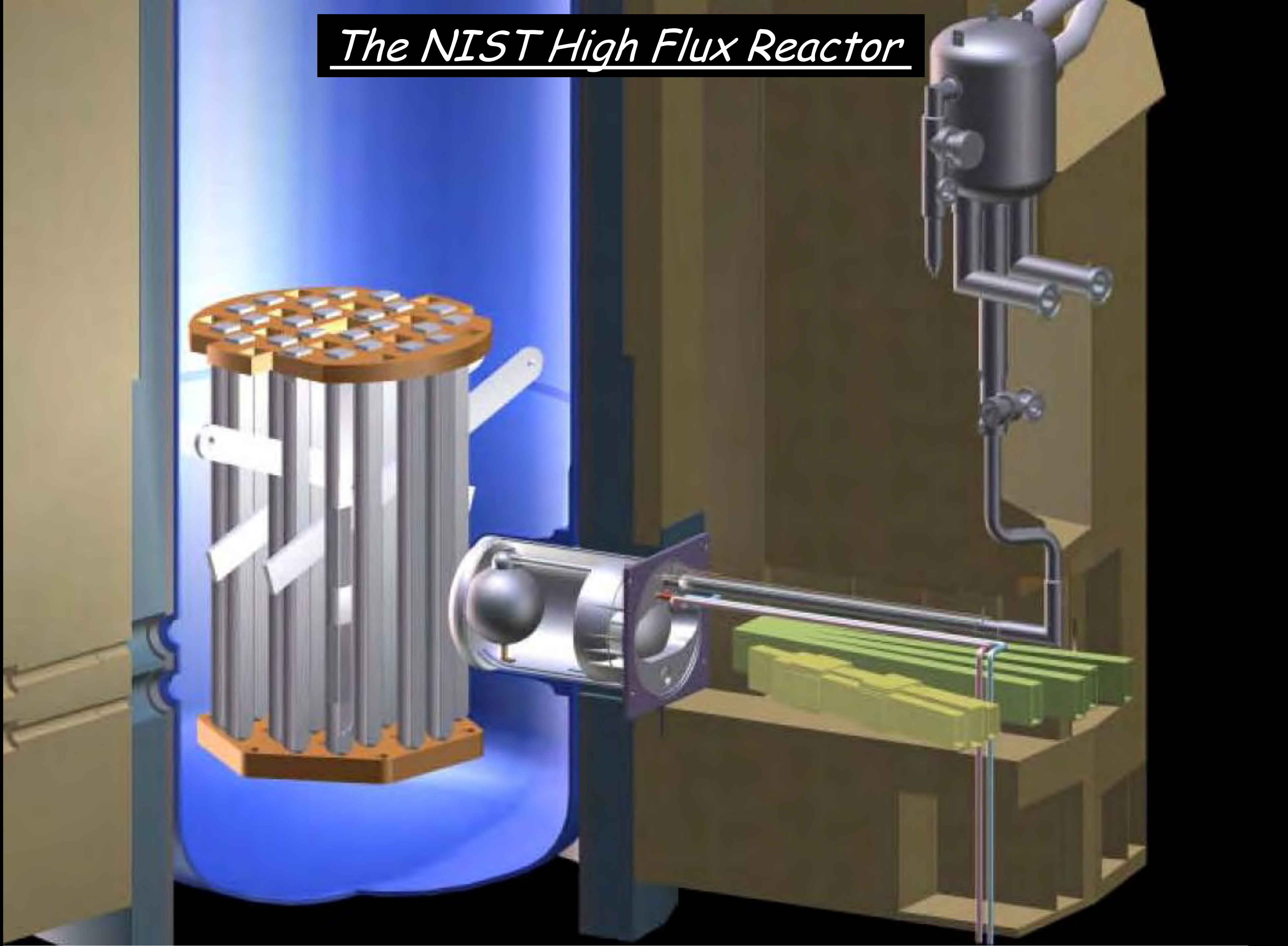
A Neutron Source Can Serve Many Neutron Instruments



Instrument Layout at the Institut Laue Langevin

The Guide Hall at the ILL Houses ~30 Neutron Spectrometers

The NIST High Flux Reactor



The NIST Cold Neutron research Center

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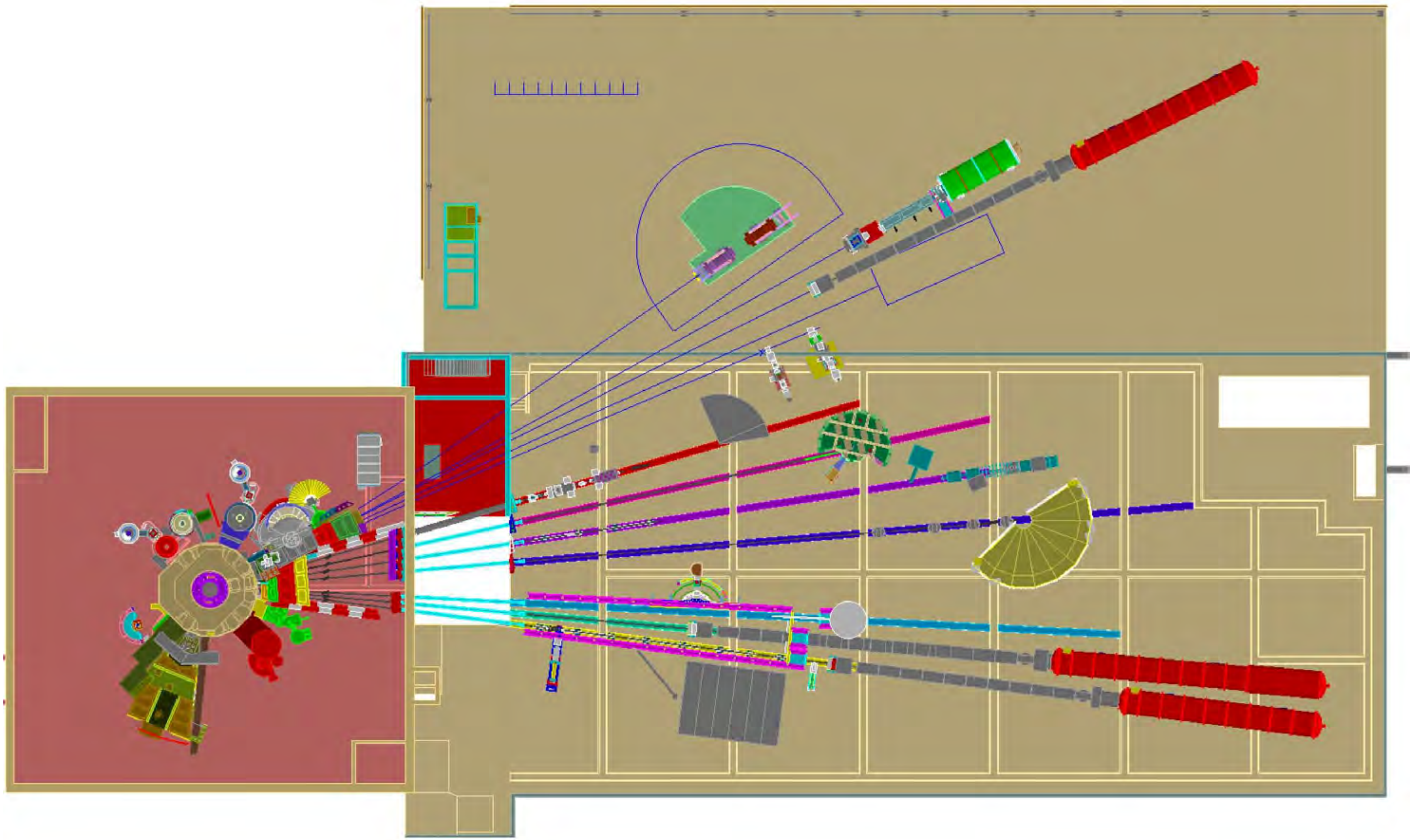
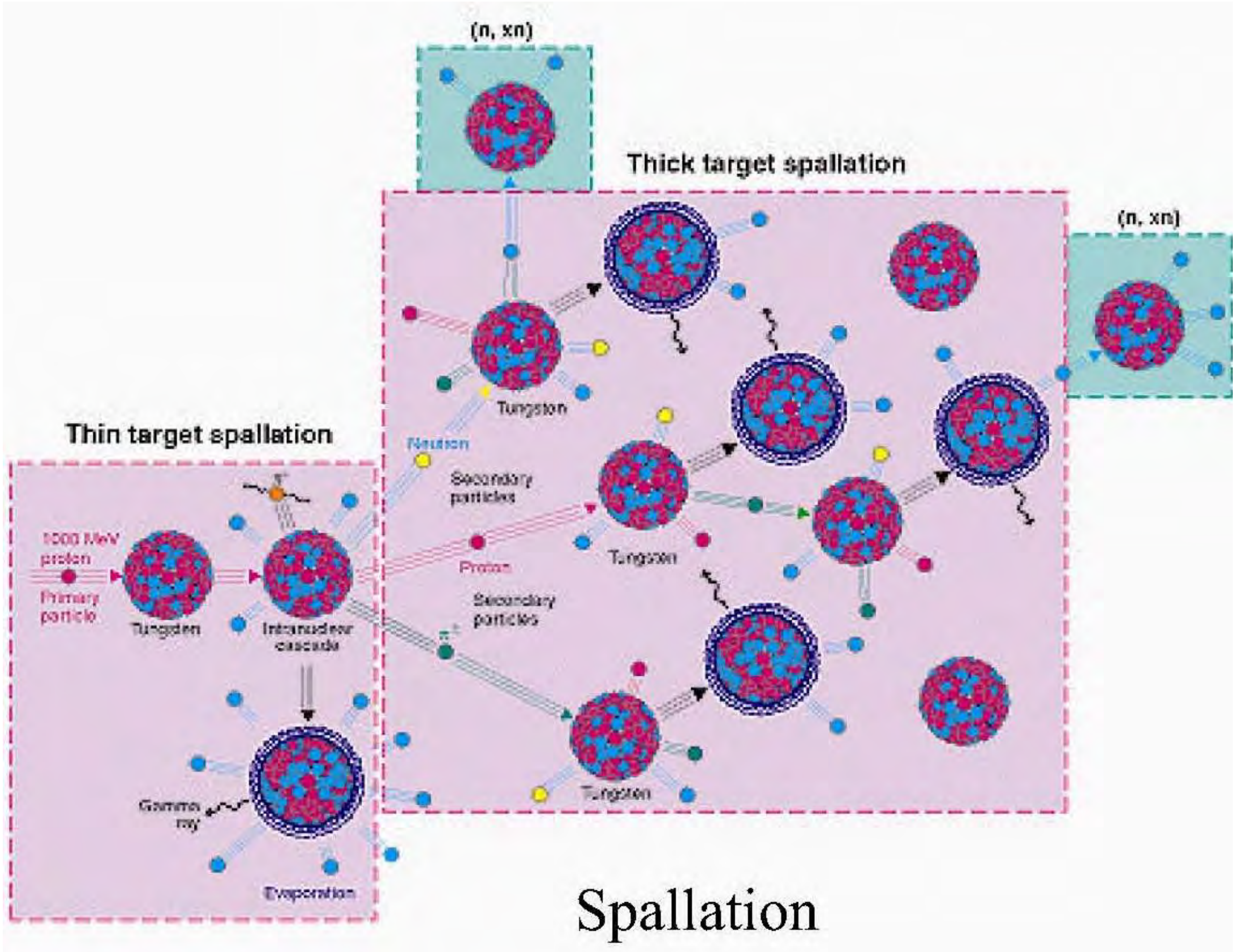
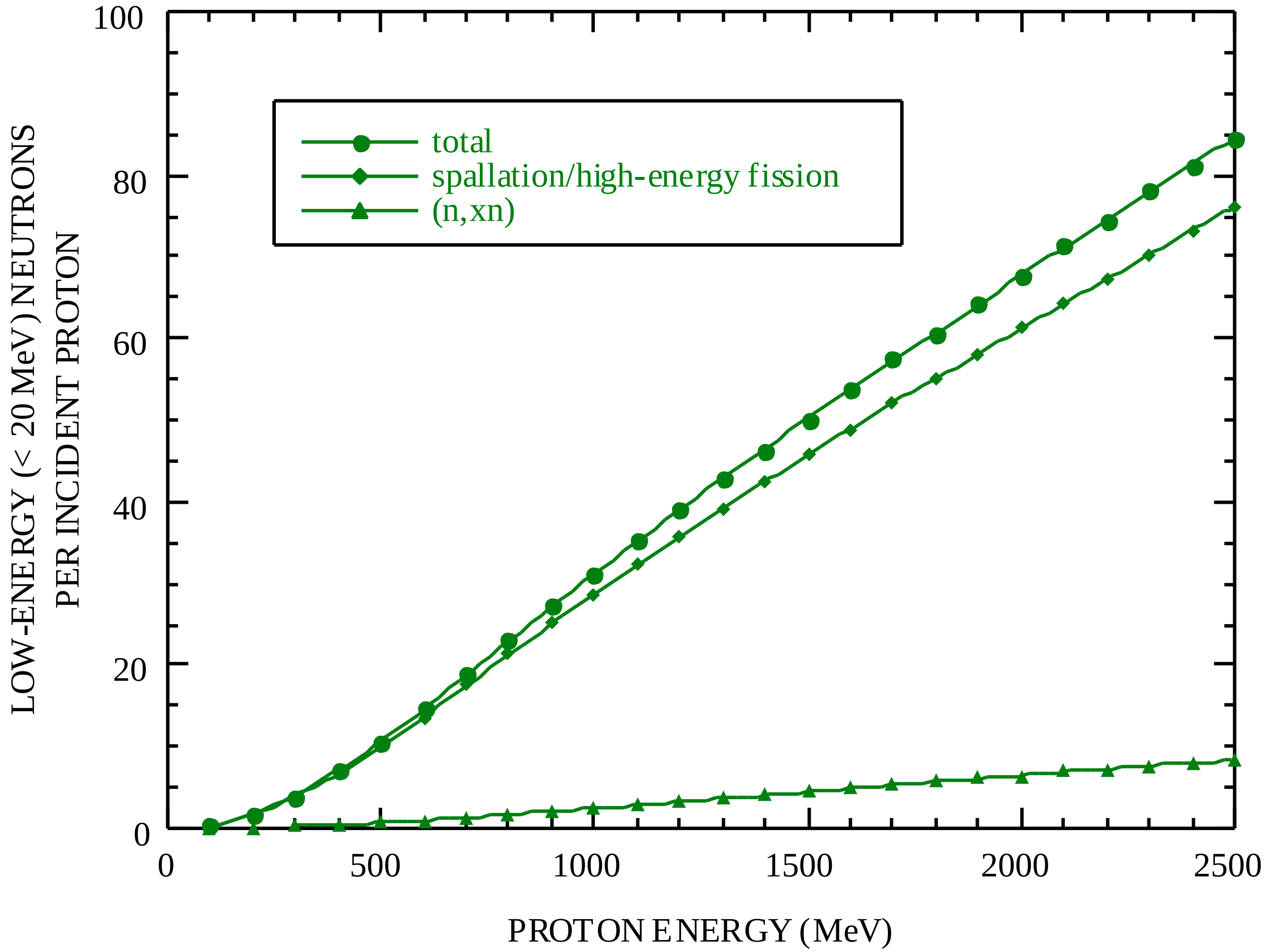


Spallation Sources

At ~1.4 GeV, Each Incident Proton Produce ~40 "Useful" Neutrons



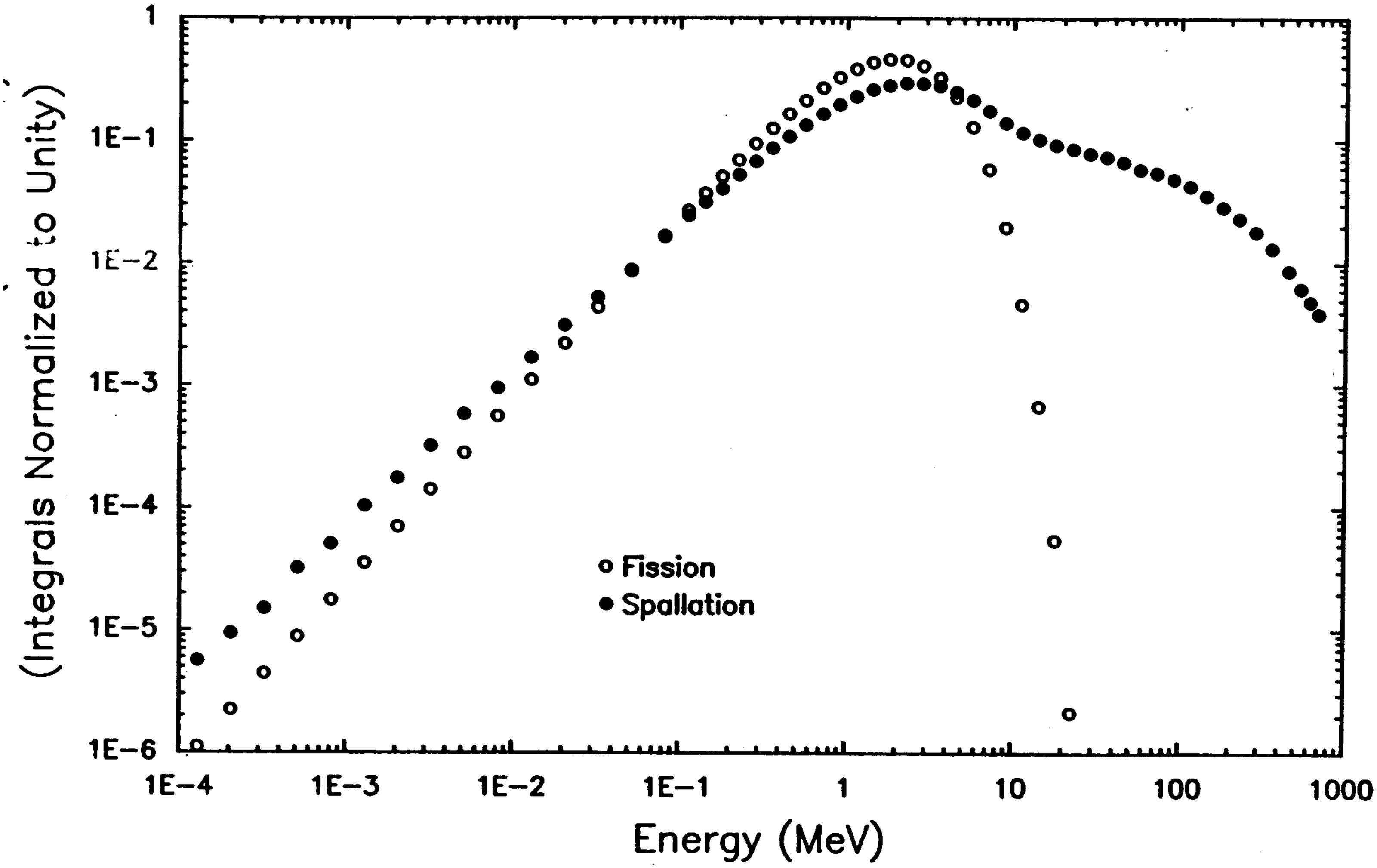
Neutron Production is Roughly Proportional to Power



NOTE: Spallation gives ~x10 more neutrons per MW

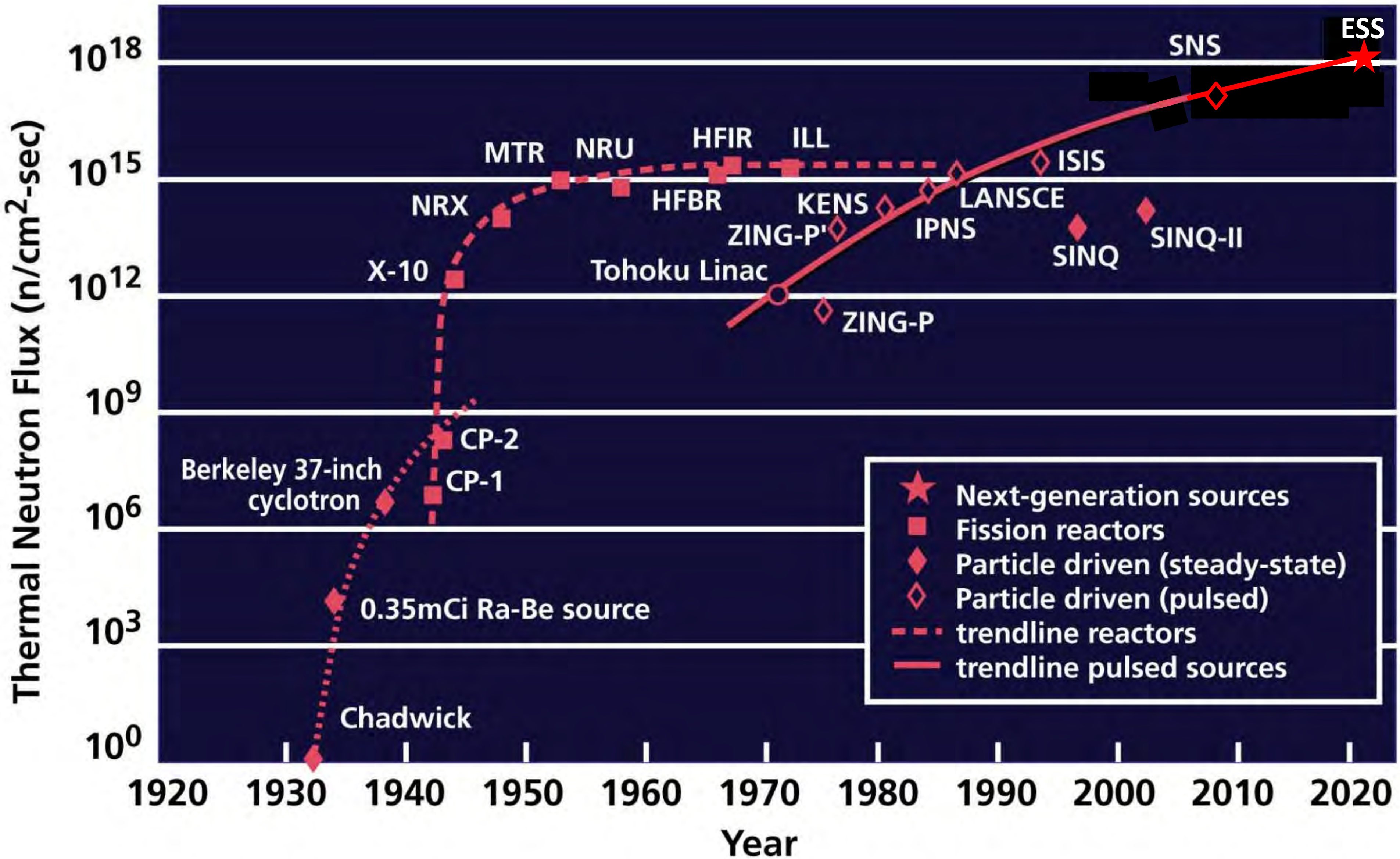
(Courtesy,Gary Russell)

The Spallation Neutron Spectrum is Broad



(Courtesy,Gary Russell)

Neutron Source Intensities Have Increased by Nearly 18 Orders of Magnitude Since Chadwick*



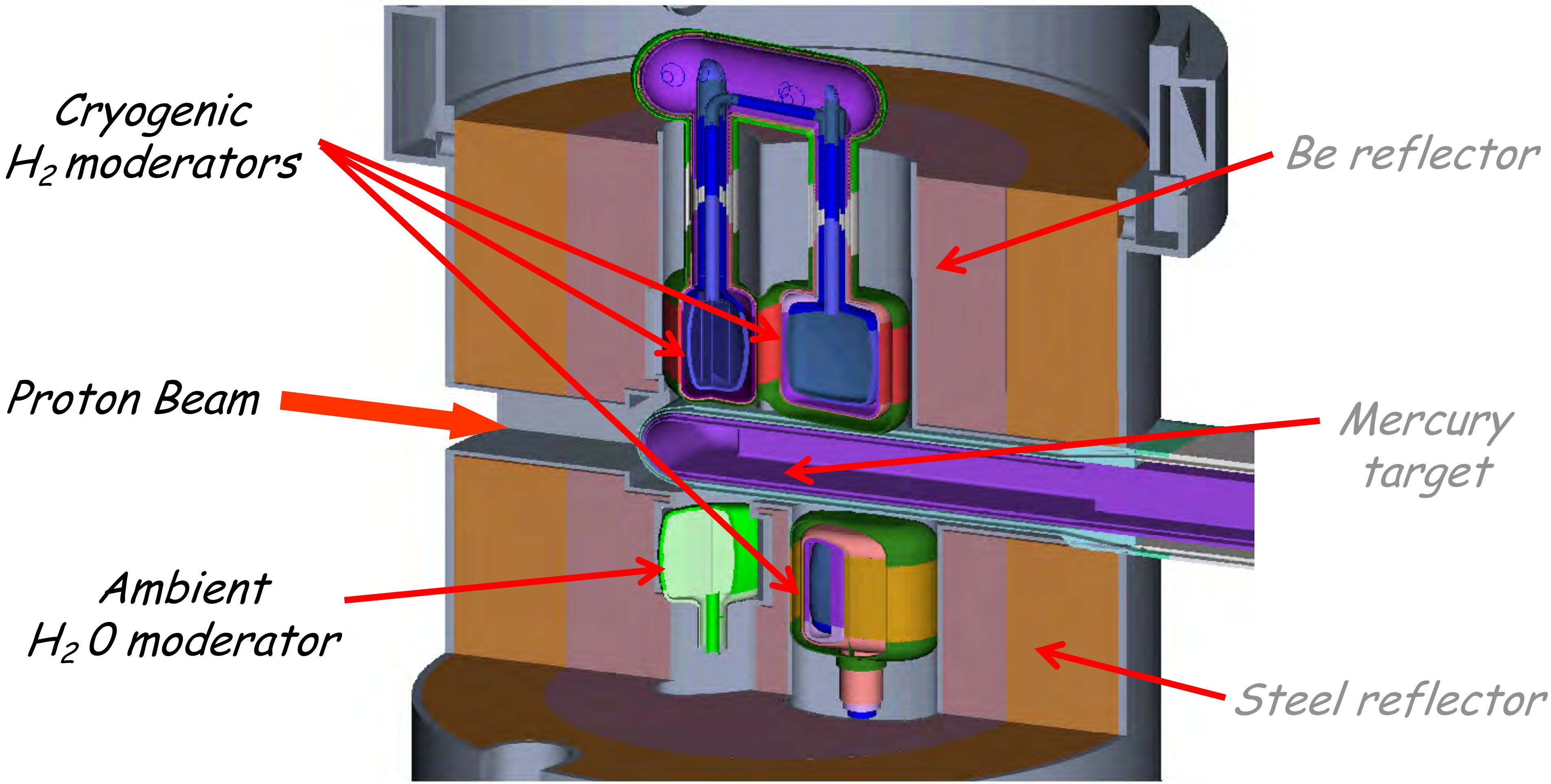
(Updated from *Neutron Scattering*, K. Skold and D. L. Price: eds., Academic Press, 1986)

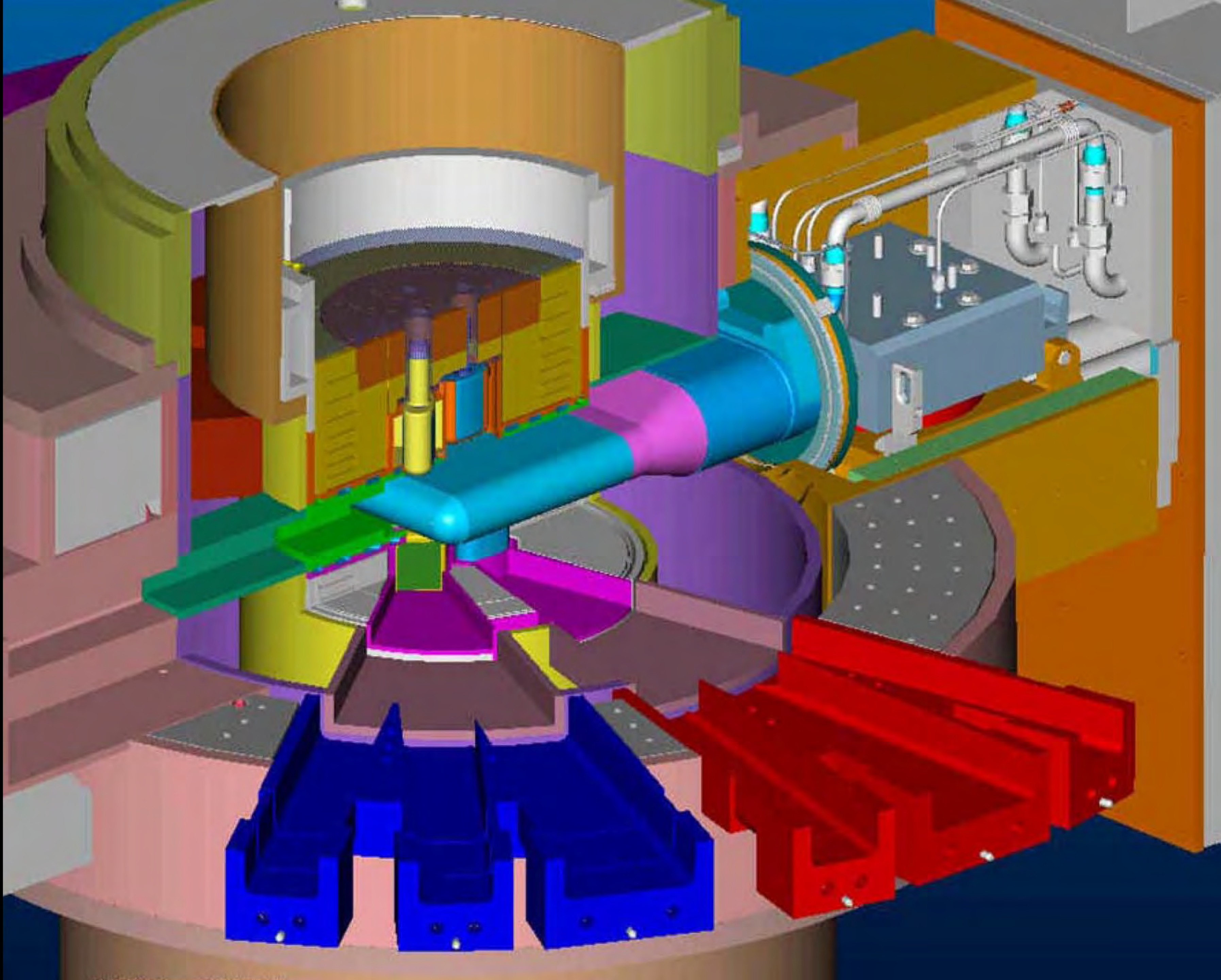
The Spallation Neutron Source

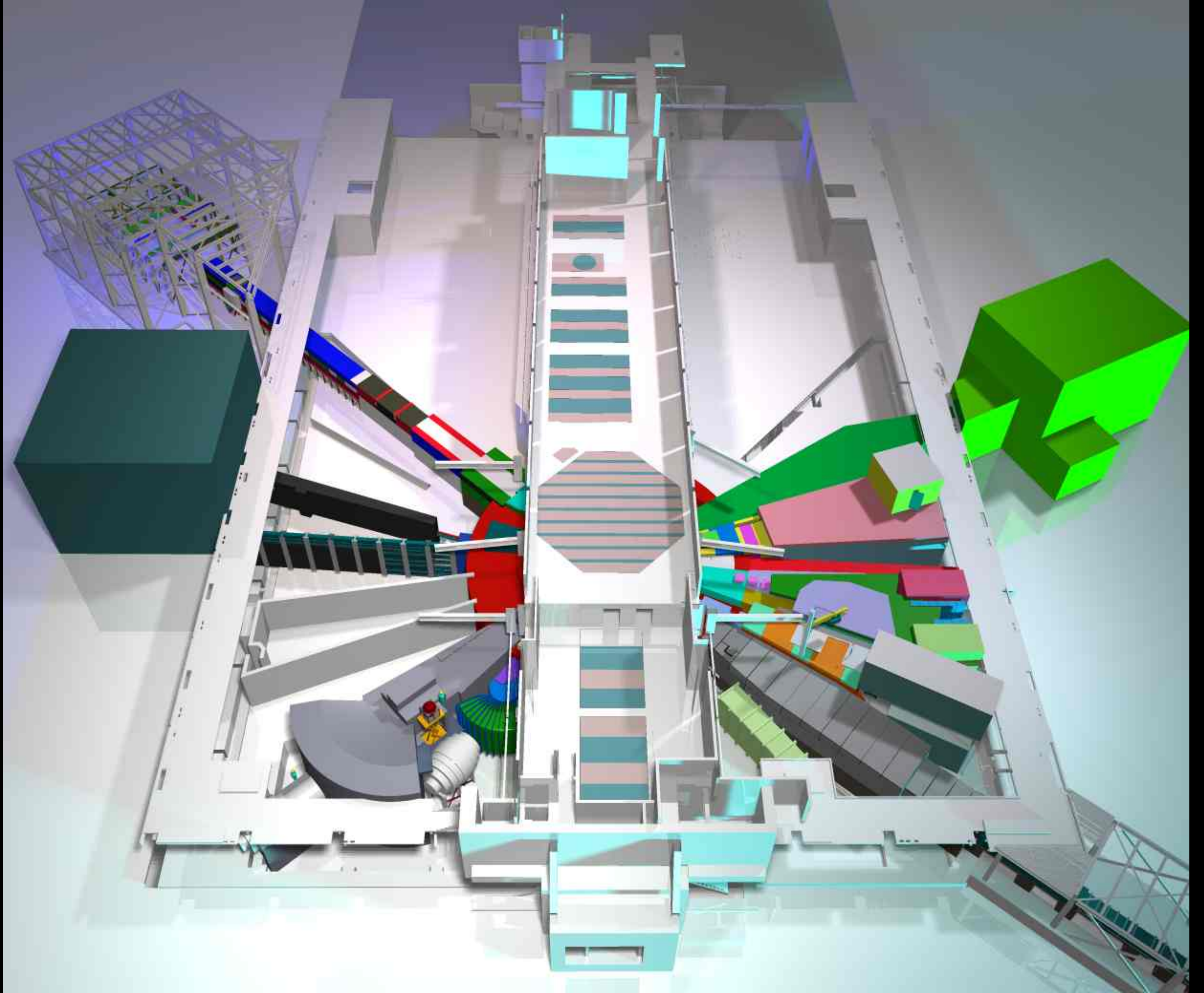

SNS-03671-2005


Front-End Systems
(Lawrence Berkeley)
Accumulator Ring
(Brookhaven)
Target
(Oak Ridge)
Linac
(Los Alamos and
Jefferson)
Instrument Systems
(Argonne and Oak Ridge)

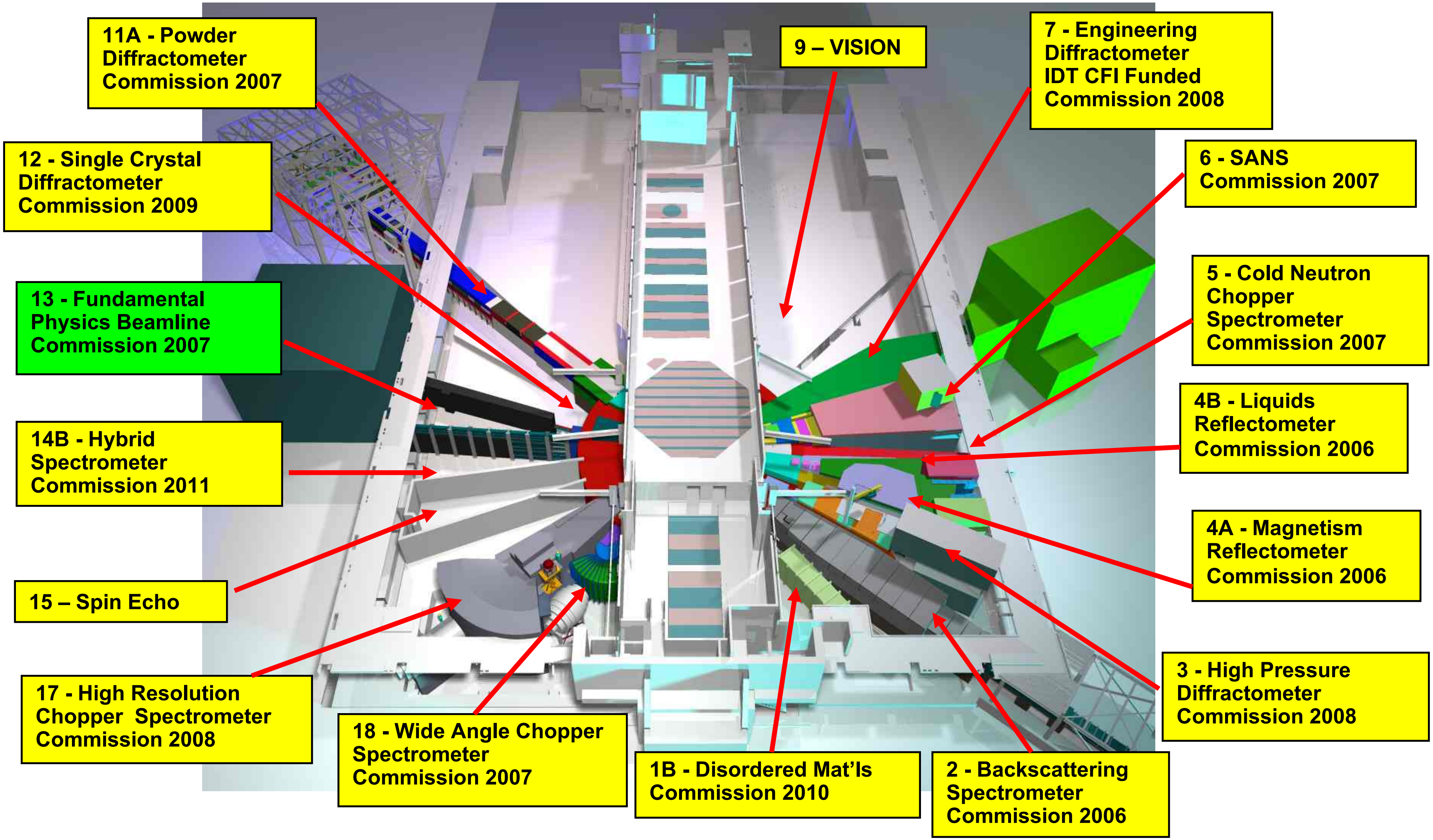
Target, Reflectors, and Moderators







Beamline 13 Has Been Allocated for Nuclear Physics



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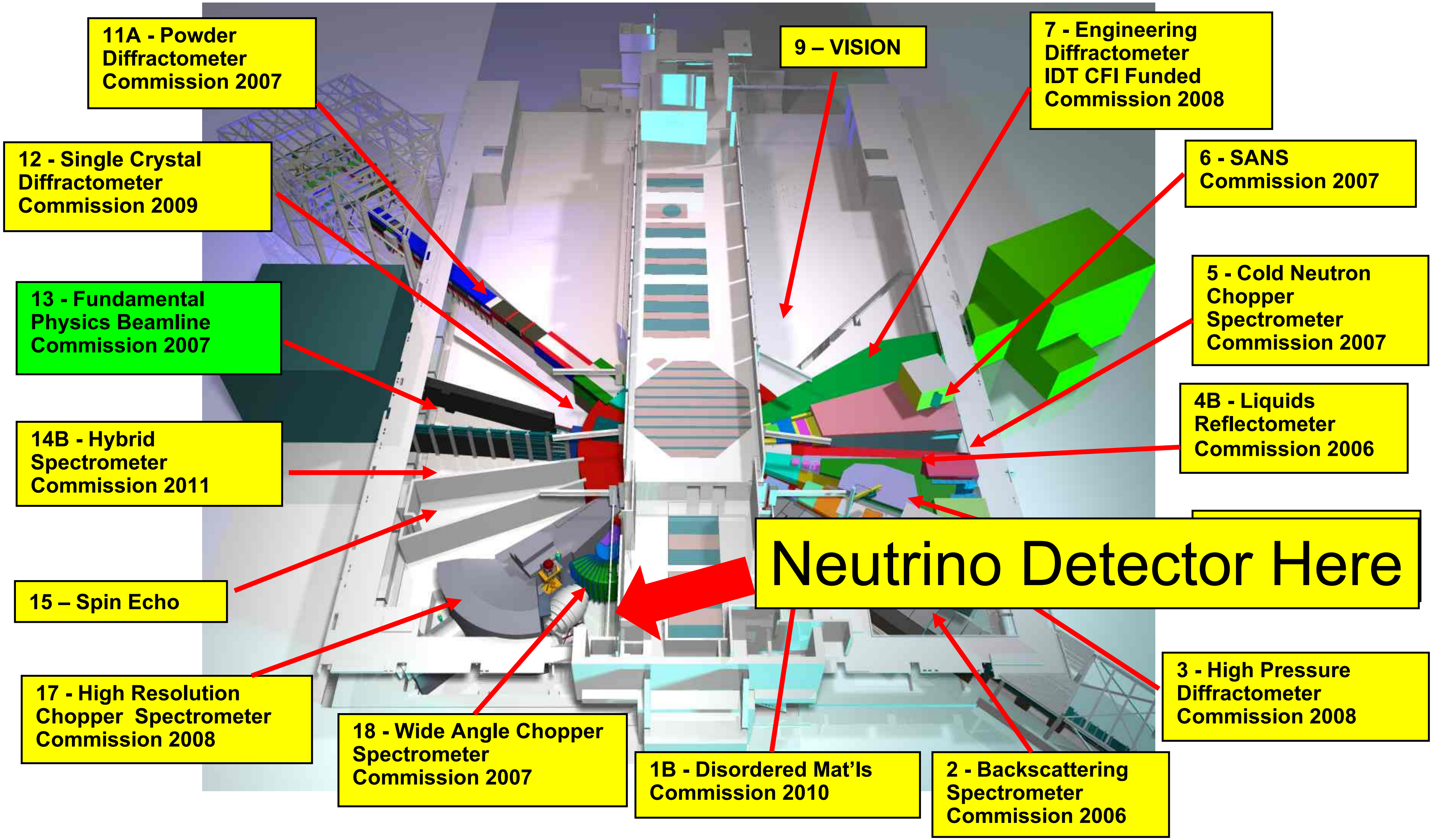
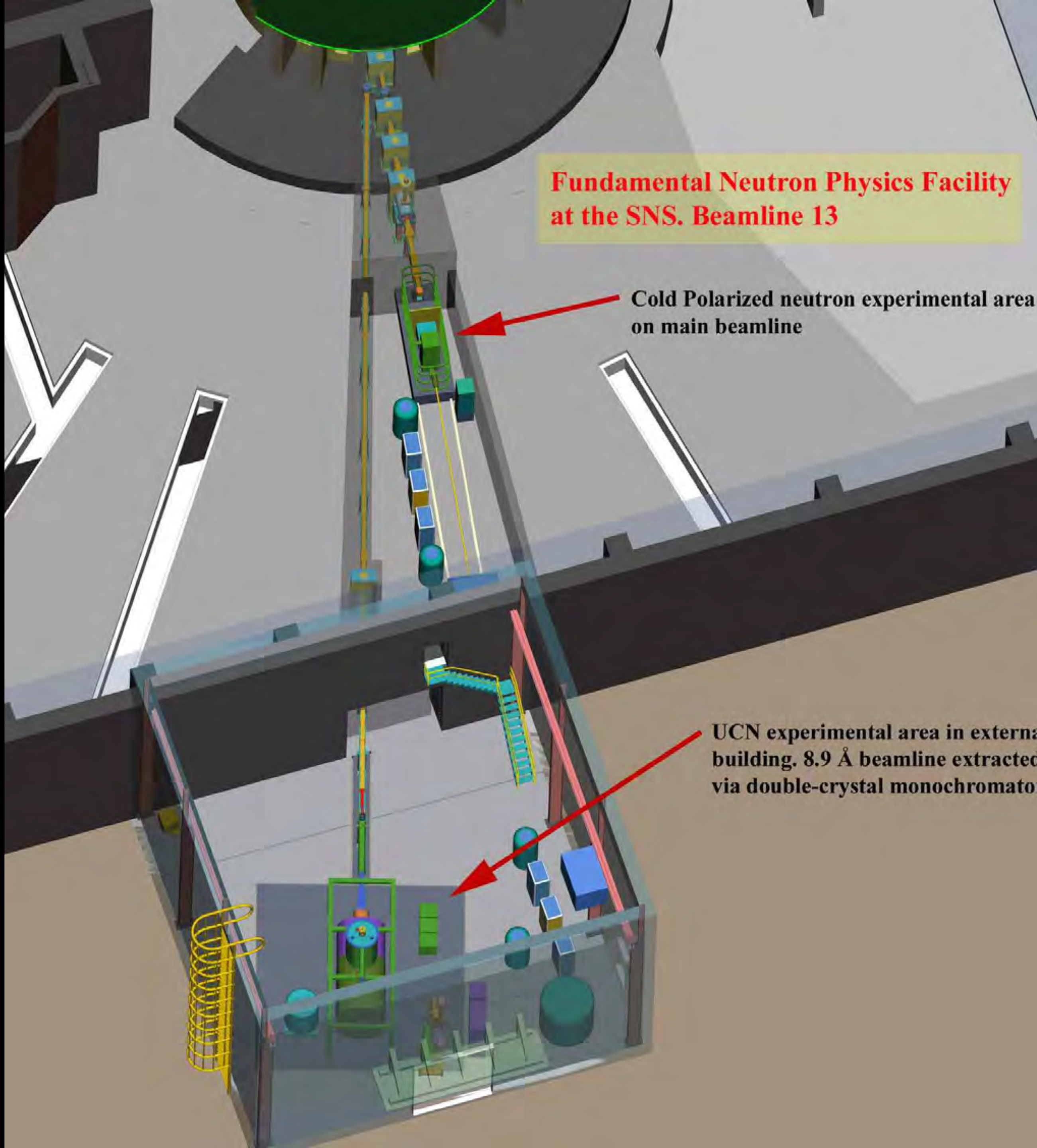
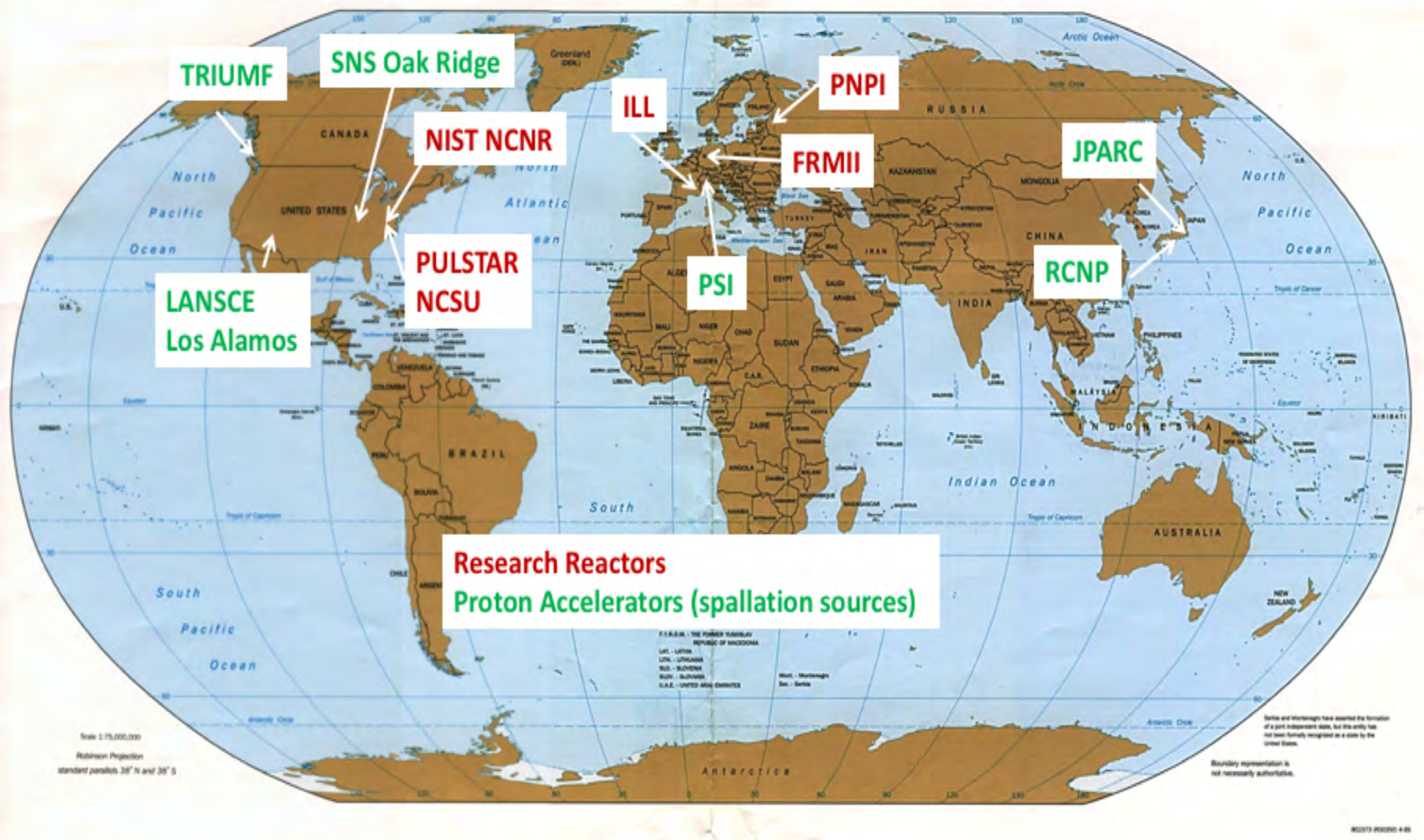


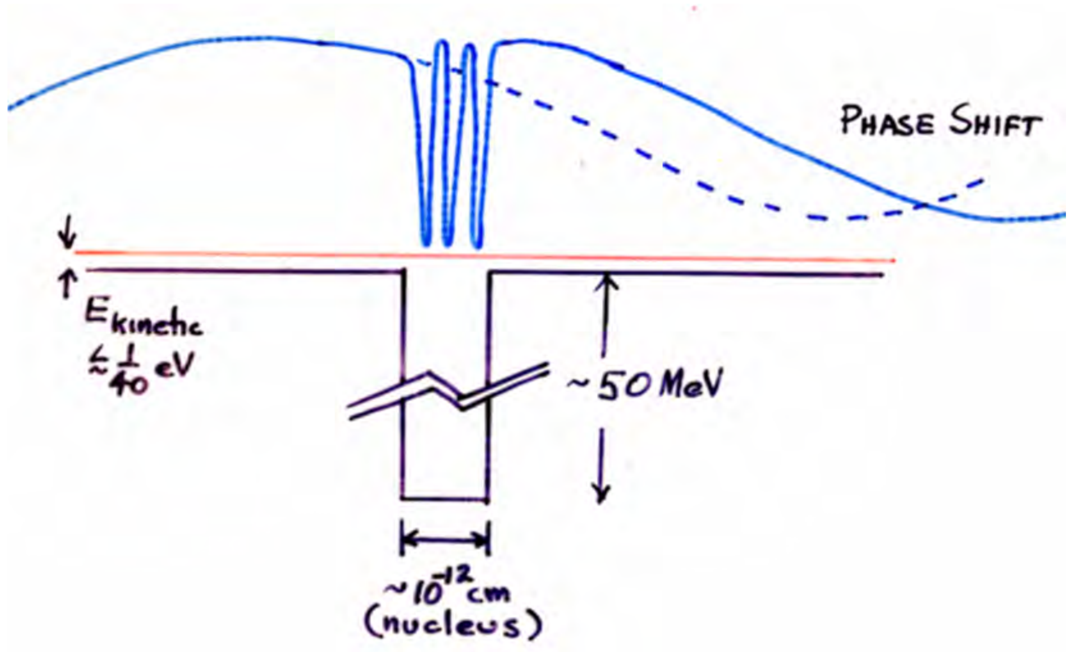

Fundamental Neutron Physics Facility at the SNS. Beamline 13
Cold Polarized neutron experimental area on main beamline
UCN experimental area in externa
building. 8.9 Å beamline extracted
via double-crystal monochromato

Sources for Fundamental Neutron Physics Research



Neutron Guides
&
Ultracold Neutrons

Coherent ("Optical") Interaction Between Neutrons and Matter



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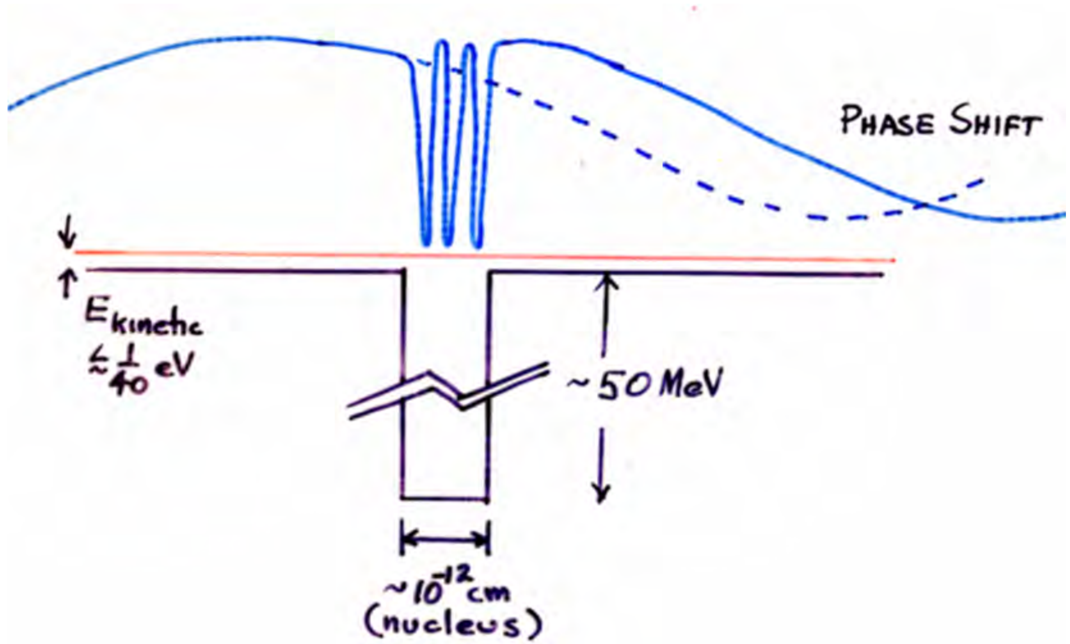
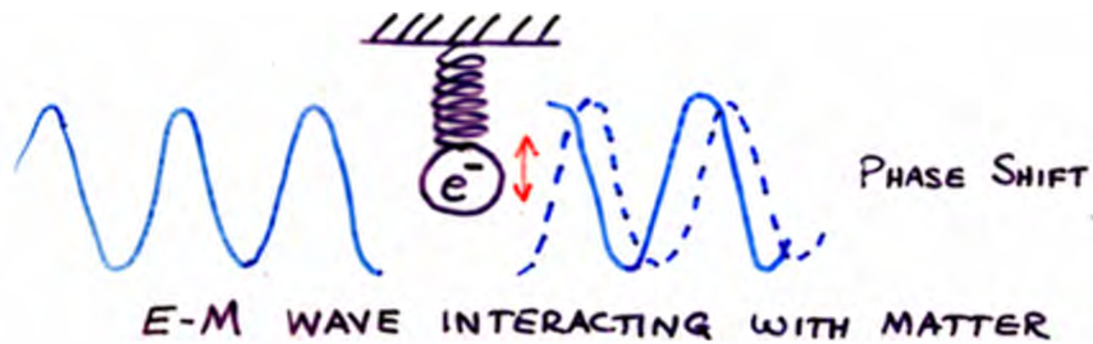
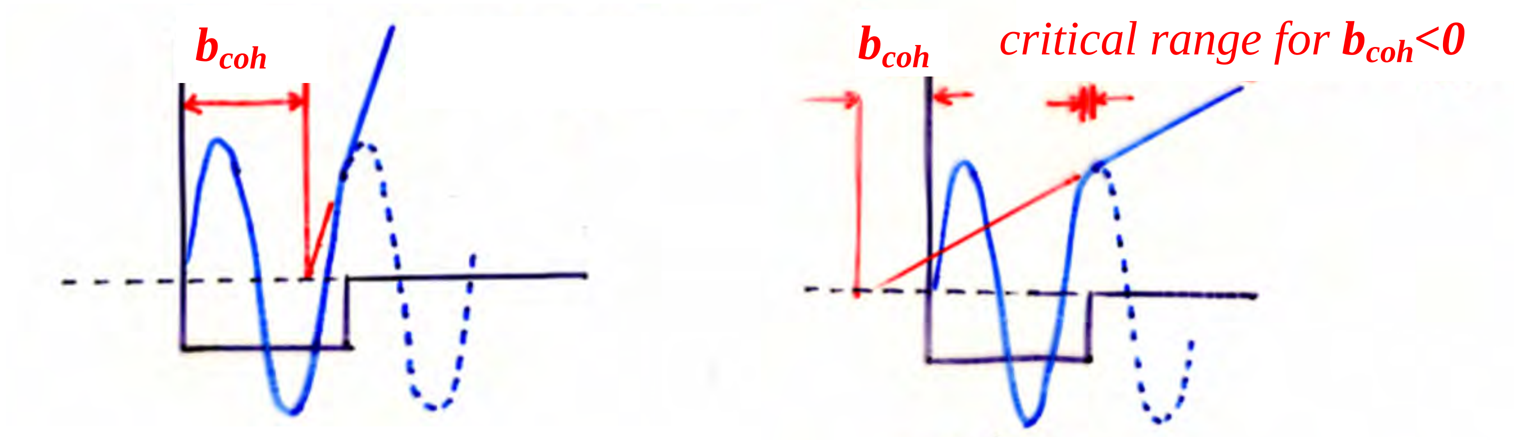




Phase shift leads to Index of Refraction

At low energies S-wave scattering dominates, phase shift is given by $\cot(\delta) = \frac{-1}{kb_{coh}}$



For most nuclear well depths and well sizes,
it is unlikely to obtain a positive coherent scattering length:

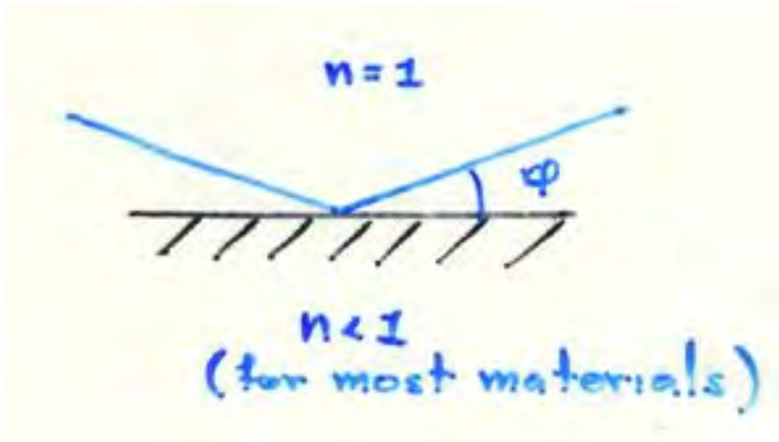
$$n = \sqrt{1 - \frac{N\lambda^2 b_{coh}}{\pi}}$$

Index of refraction is therefore <1 for most nuclei *

*In the vicinity of A~50 (V,Ti,Mn) nuclear sizes are such that b_{coh}<1 and thus n>1

Neutron Reflection from Matter

$$n^2 = 1 - \frac{\lambda^2 N b_{coh}}{2\pi} \longrightarrow \cos\theta_{crit} = n$$



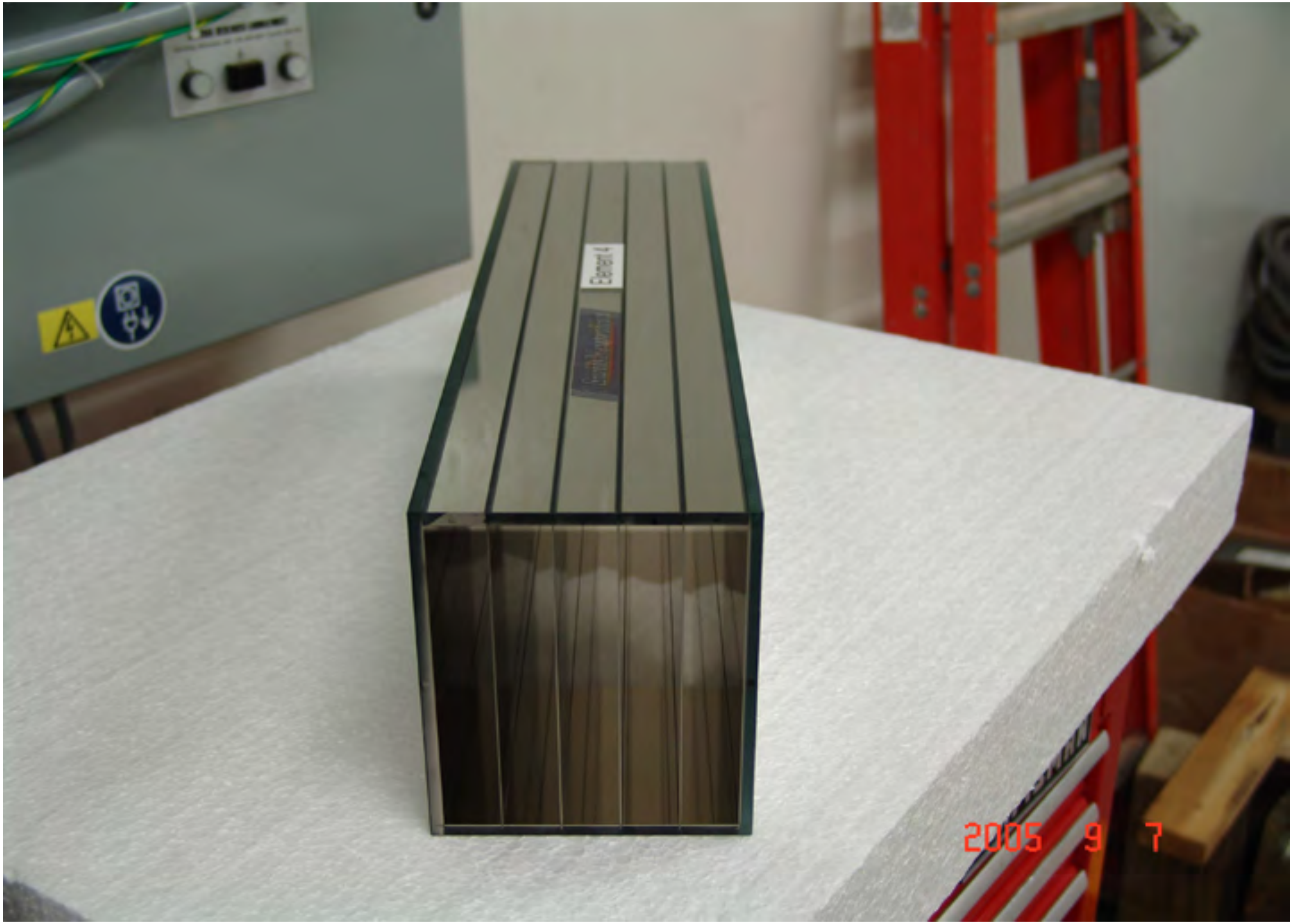
Neutrons will undergo complete "external" reflection from a polished surface for most materials

Ni or ^{58}Ni are particularly useful as a neutron mirror material

$$\theta_{crit}(Ni) \approx 1.7x10^{-3} / \lambda(Angstrom)$$

For most neutron beams this means $\theta_{crit} \leq 10^{-2}$

Guide Section from SNS



Neutron Guides can be used to Focus Neutron Beams

Photo: Swiss Neutronics

Large Cross Section Guides are Commercially Available

Prototype Guide for SNS Ultracold Beam

A Single Moderator can Feed Multiple Neutron Guides

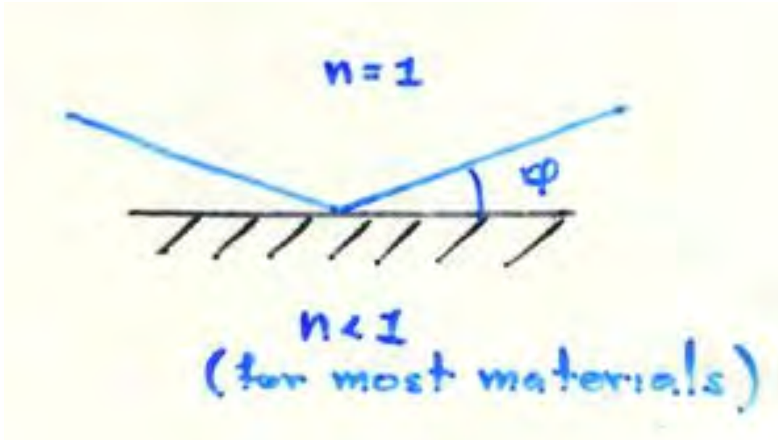
Photo: Institut Laue Langevin

Ultra Cold Neutrons

**see Golub, Richardson, Lamoreaux, Ultracold Neutrons*

Neutron Index of Refraction

$$n^2 = 1 - \frac{\lambda^2 N b_{coh}}{2\pi} \longrightarrow \cos\varphi_{crit} = n$$



For sufficiently large neutron wavelength, λ, n=0 and cosφ$_{crit}$ =90°

This implies that neutrons will be reflected at all angles
and can be confined in a "bottle"

These are known as "Ultracold Neutrons."

Limits to Thermal UCN Production

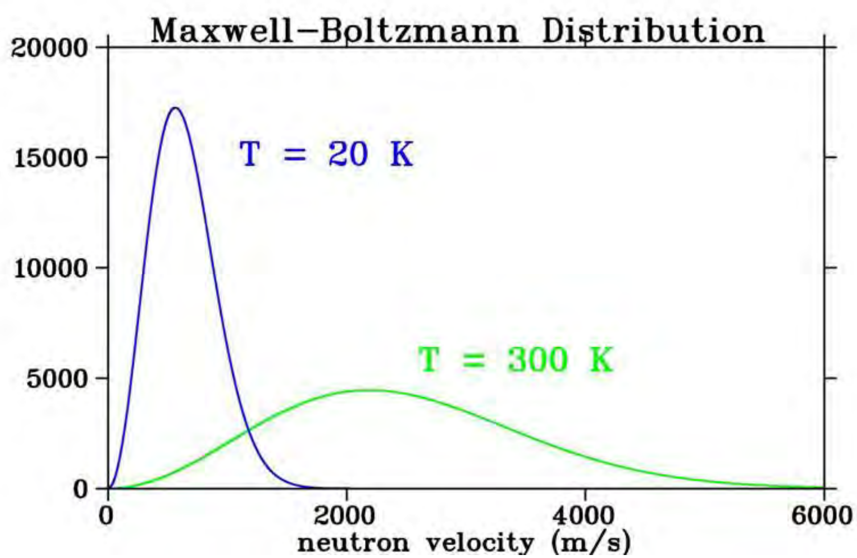
In thermal equilibrium: $\rho_{UCN} = \frac{2}{3}\frac{\Phi_0}{\alpha}\left(\frac{V}{k_B T_n}\right)^{3/2}$

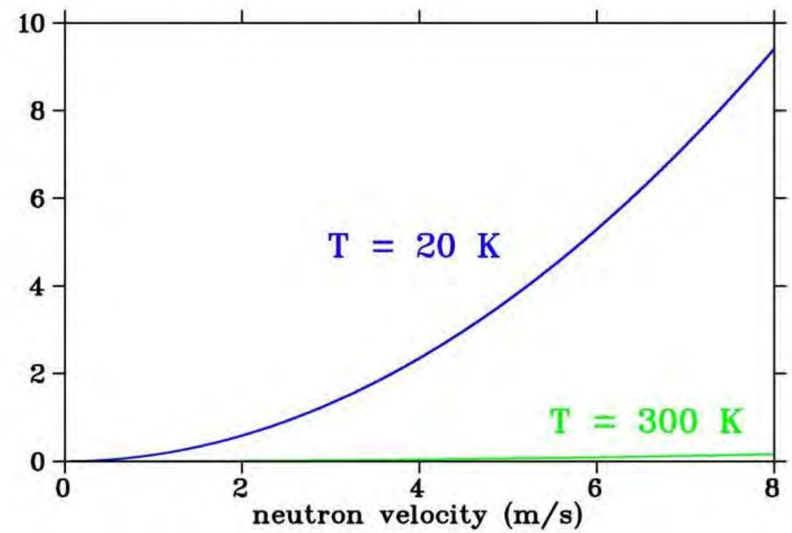
Increase the Flux Φ_0*:*

Reactors are at the practical limit of heat transfer.

Only practical hope would be a 10-20 MW Spallation Source.

Lower the temperature T_n *(also reduces* α*):*





Practical limit for true moderator is about 20k which gives a density increase of ~x20

Practical Thermal Source Limit for UCN production: $\rho_{UCN} \approx 2 \cdot 10^3 cm^{-3}$

Ultracold Neutron Energies are Very Low

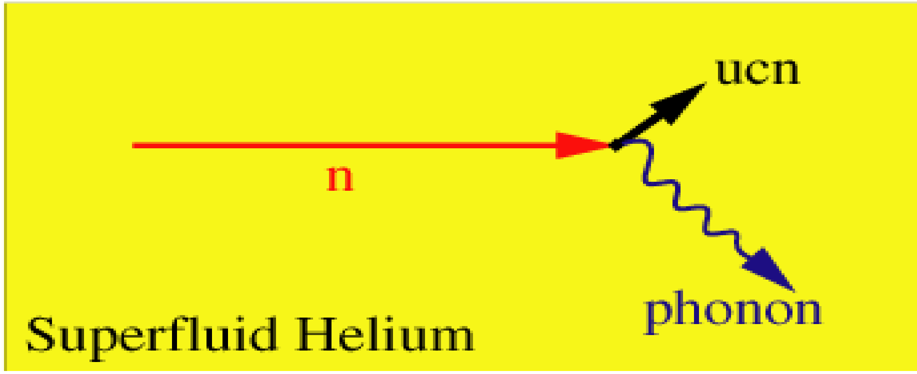
The Fermi "Pseudo-Potential" the most advantageous materials is ~ 100 neV

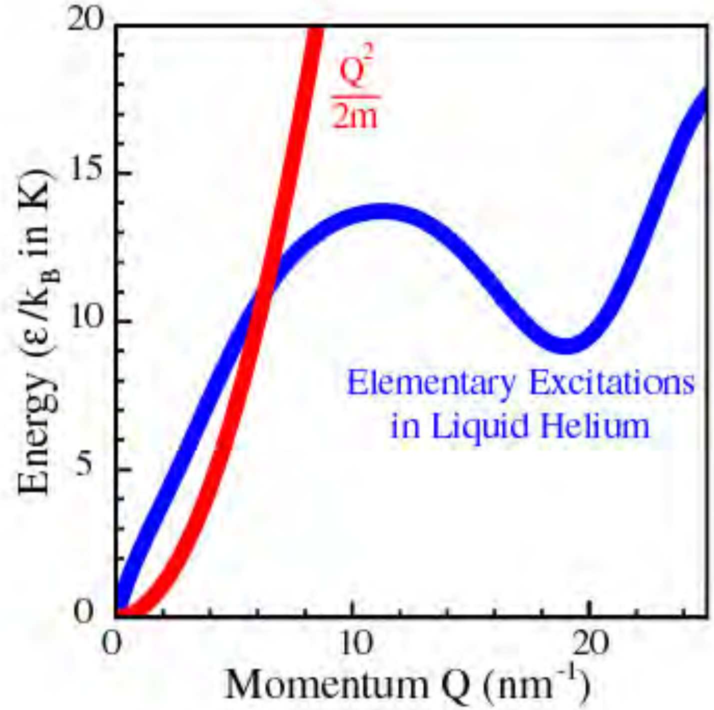
This corresponds to a:

Neutron Velocity	≈ 500 m/s
Neutron Wavelength	≈ 500 Å
Magnetic Moment Interaction	$\mu_n \cdot B$ ≈ 100 neV for B~1Tesla
Gravitational Interaction	$m_n gh$ ≈ 100 neV for h~1 m

Ultracold Neutron can be trapped in material, magnetic, or gravitational bottles

Super Thermal Source of UCN





- *Neutrons of energy E ≈ 0.95 meV (11 k or 0.89 nm) can scatter in liquid helium to near rest by emission of a single phonon.*

- *Upscattering by absorption of an 11 k phonon is a UCN loss mechanism. But population of 11 K phonons is suppressed by a large Boltzman Factor: ~ $e^{-11/T}$ where T~200 mk*

Golub and Pendlebury (1977)

Solid D_2 Superthermal UCN Source

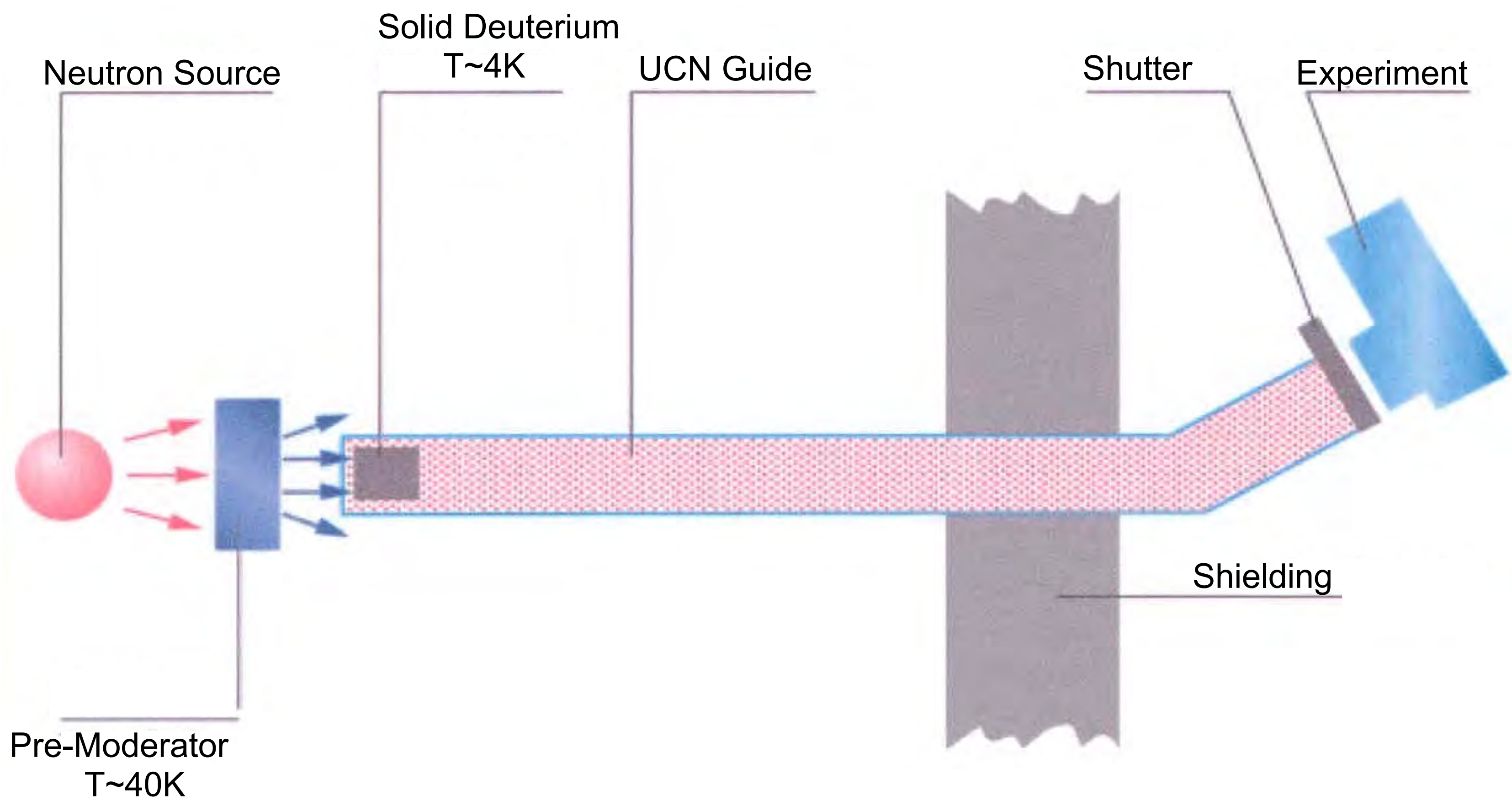
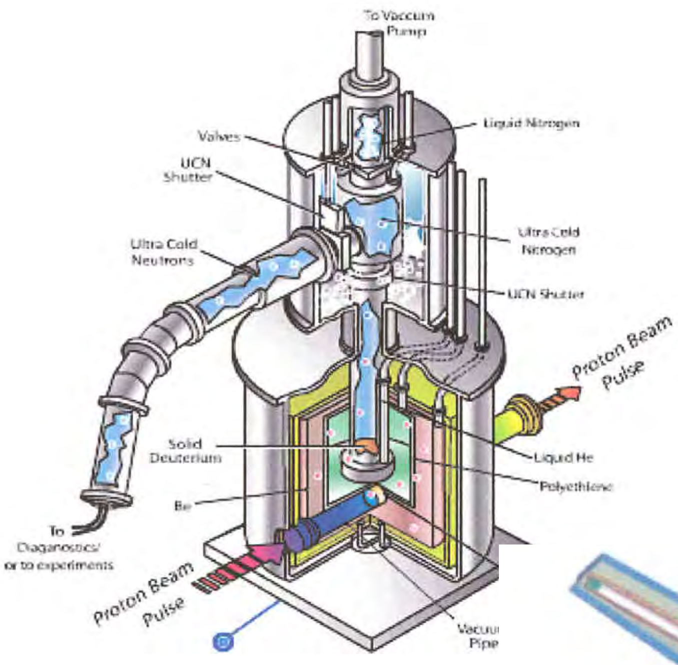


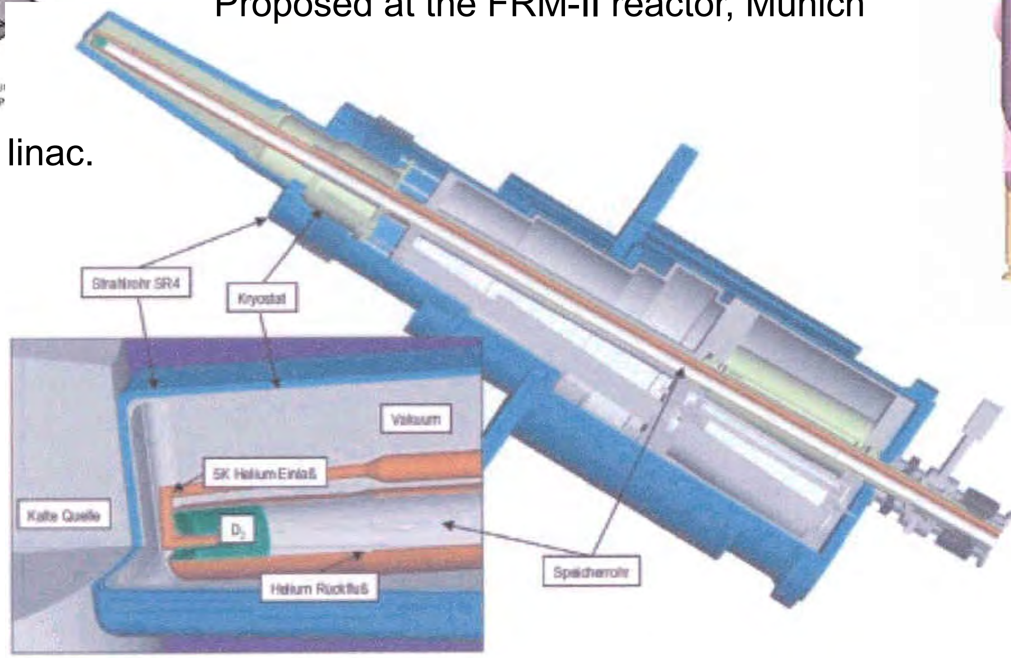
Figure courtesy FRM-11 webpage

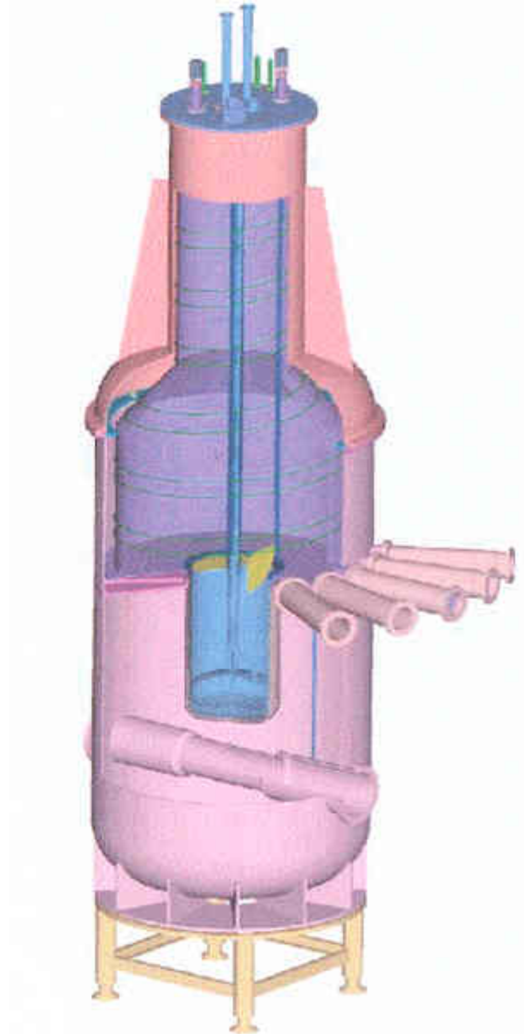
Solid D2 UCN Sources



Operational at the LANSCE linac.

Proposed at the FRM-II reactor, Munich





Operational at the PSI, Switzerland.

End of Lecture 2

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Such sources are still used ("Pu-Be") but are limited in intensity.

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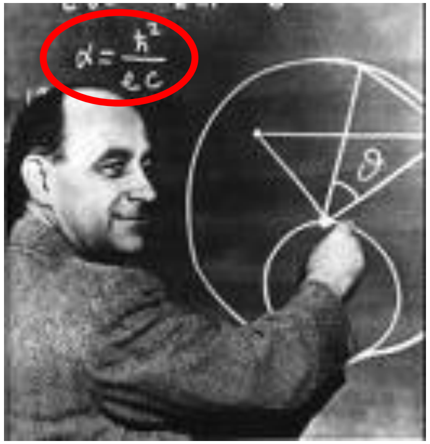
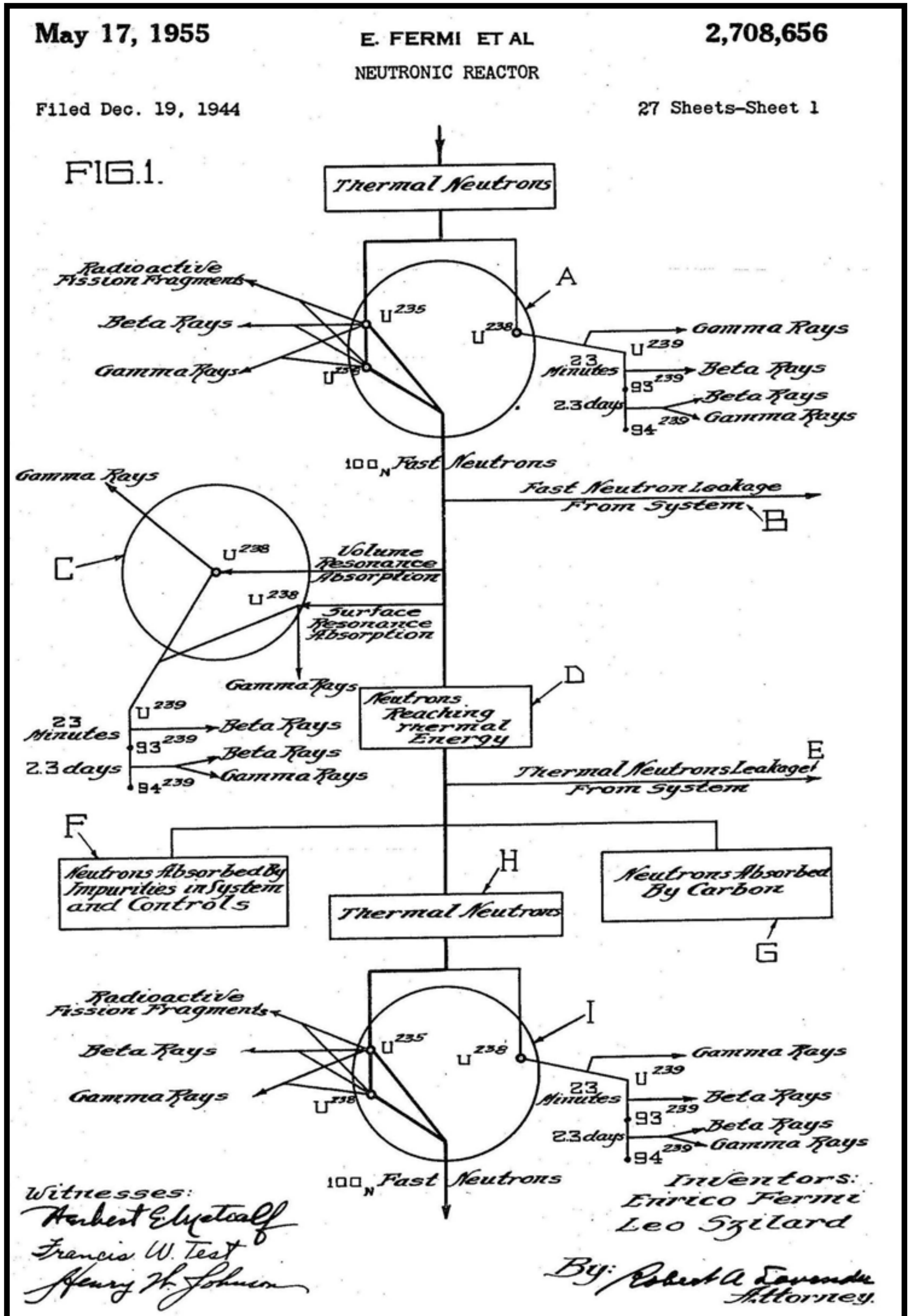
2. ***Accelerator "Spallation" Sources***

The Fission Reactor

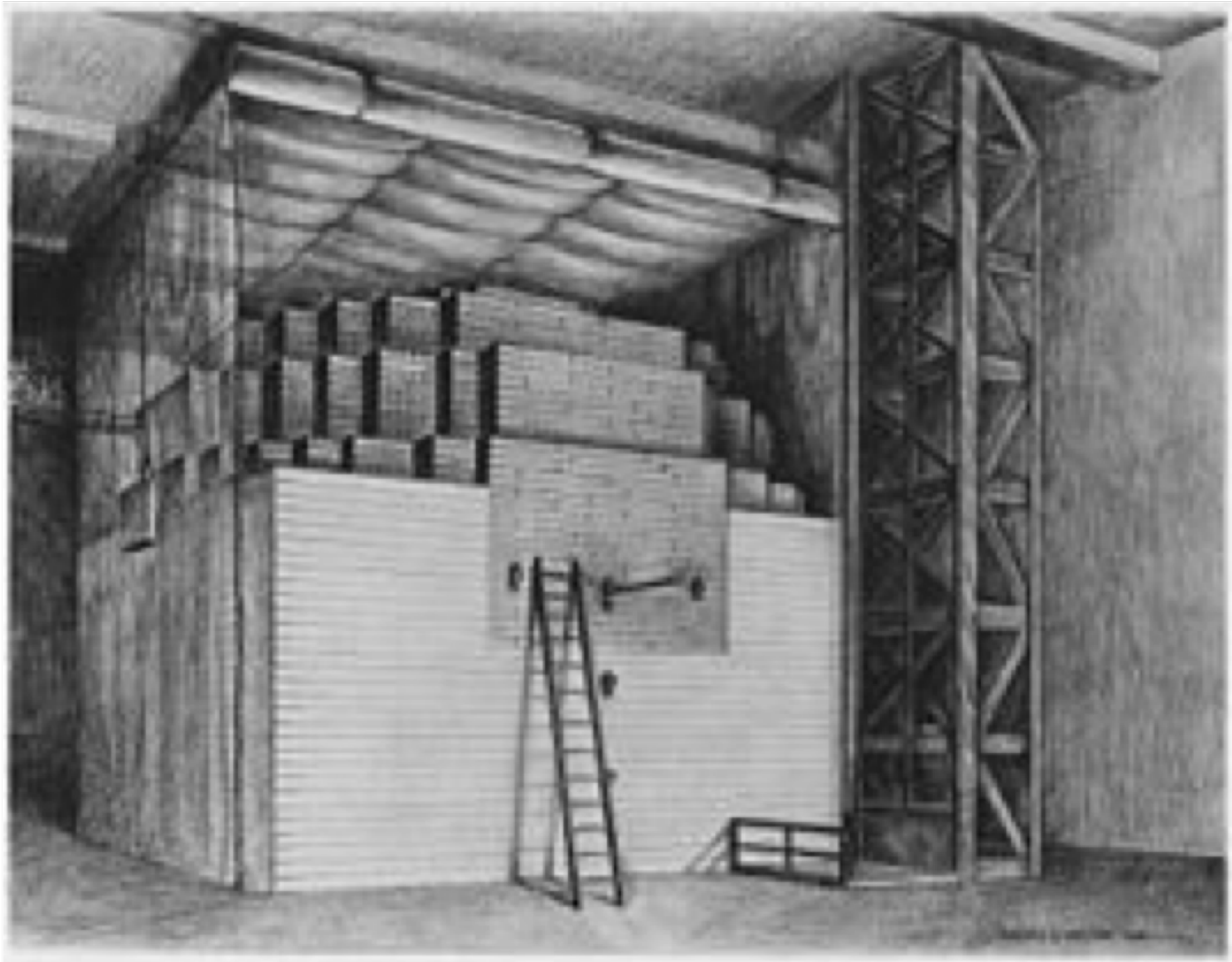


Enrico Fermi



Leo Szilard

Chicago Pile 1 -CP1



Inside a squash court at Stagg Field Stadium
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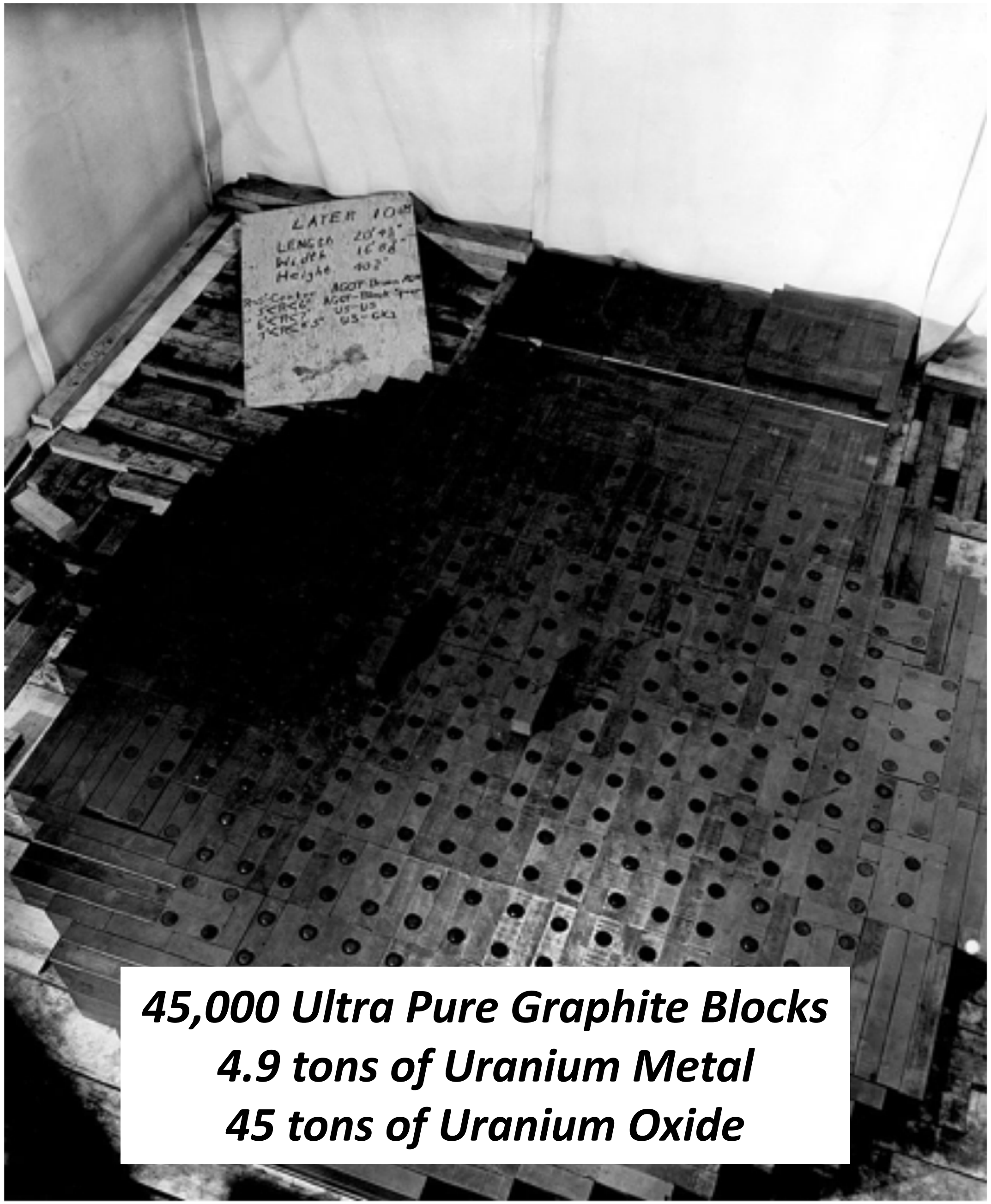
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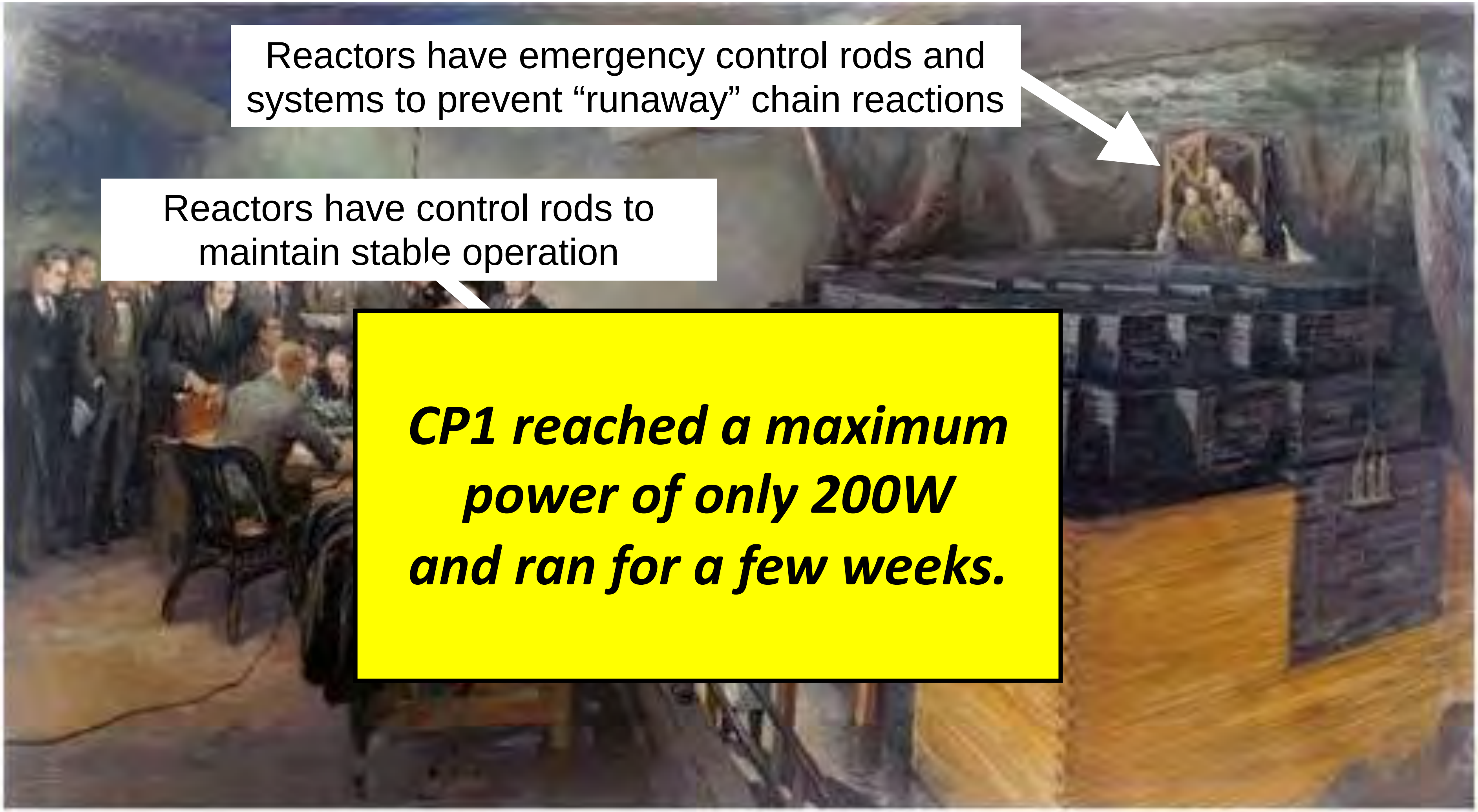
CP1 - Level 10

2 December 1942



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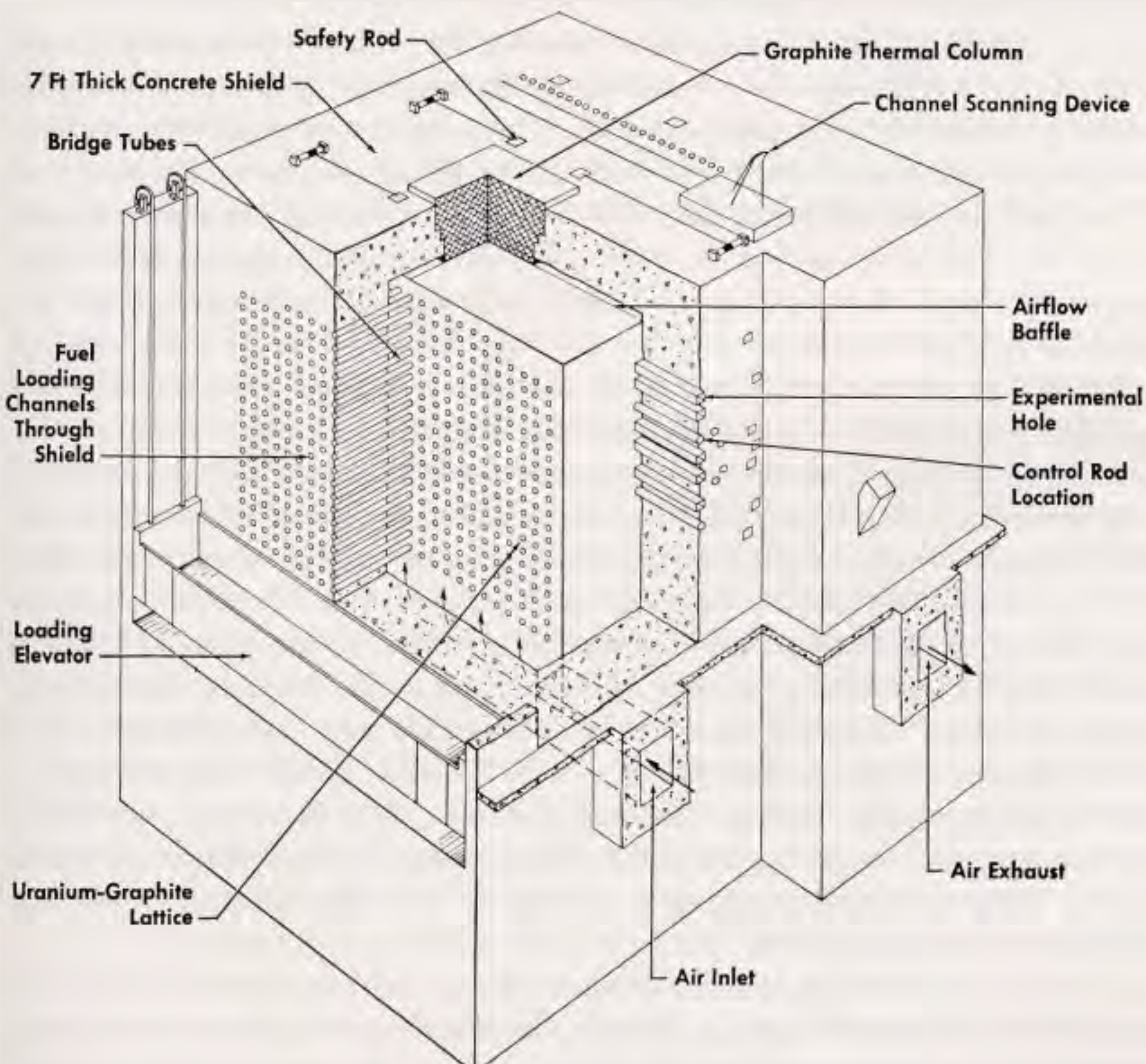

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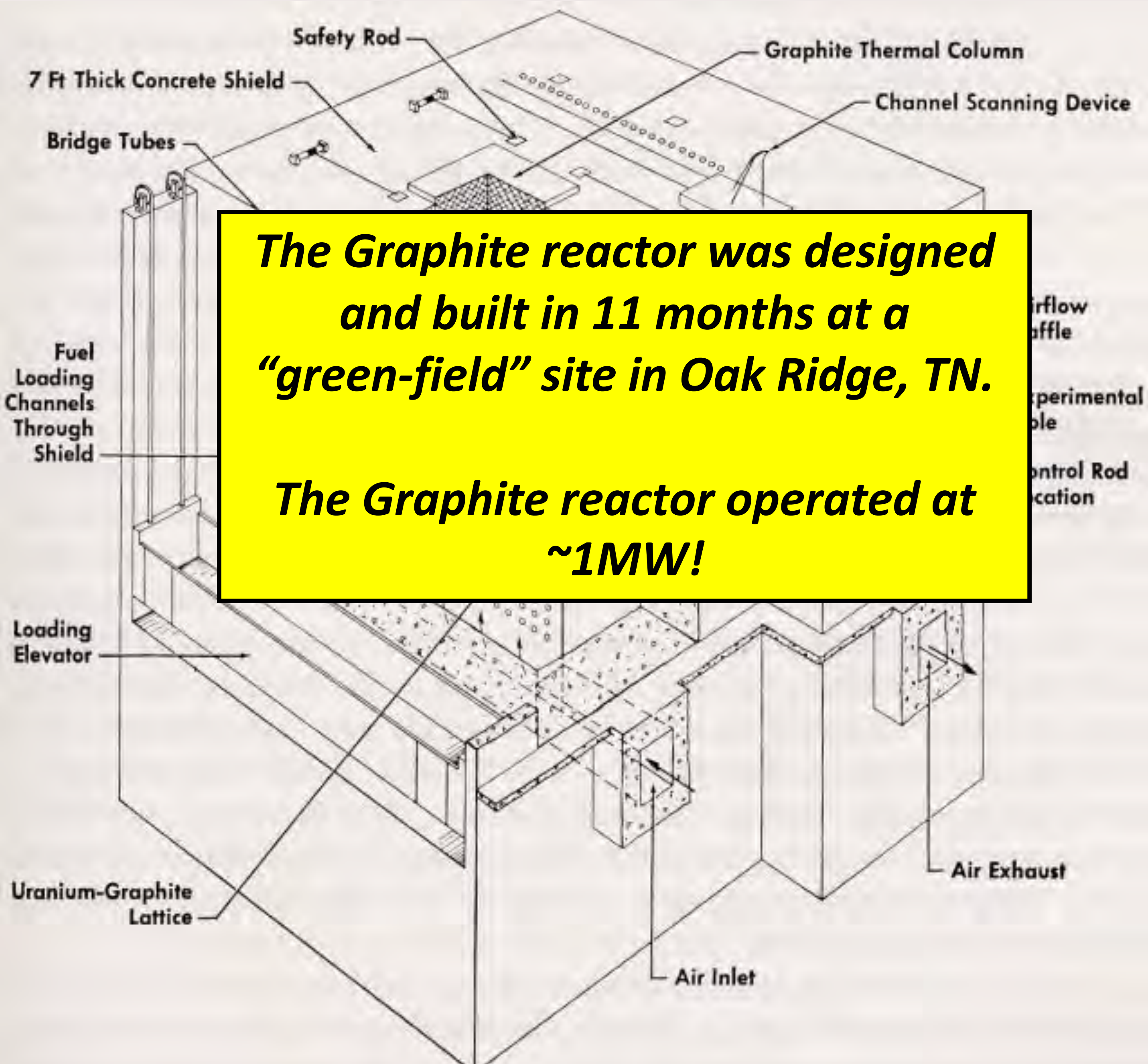

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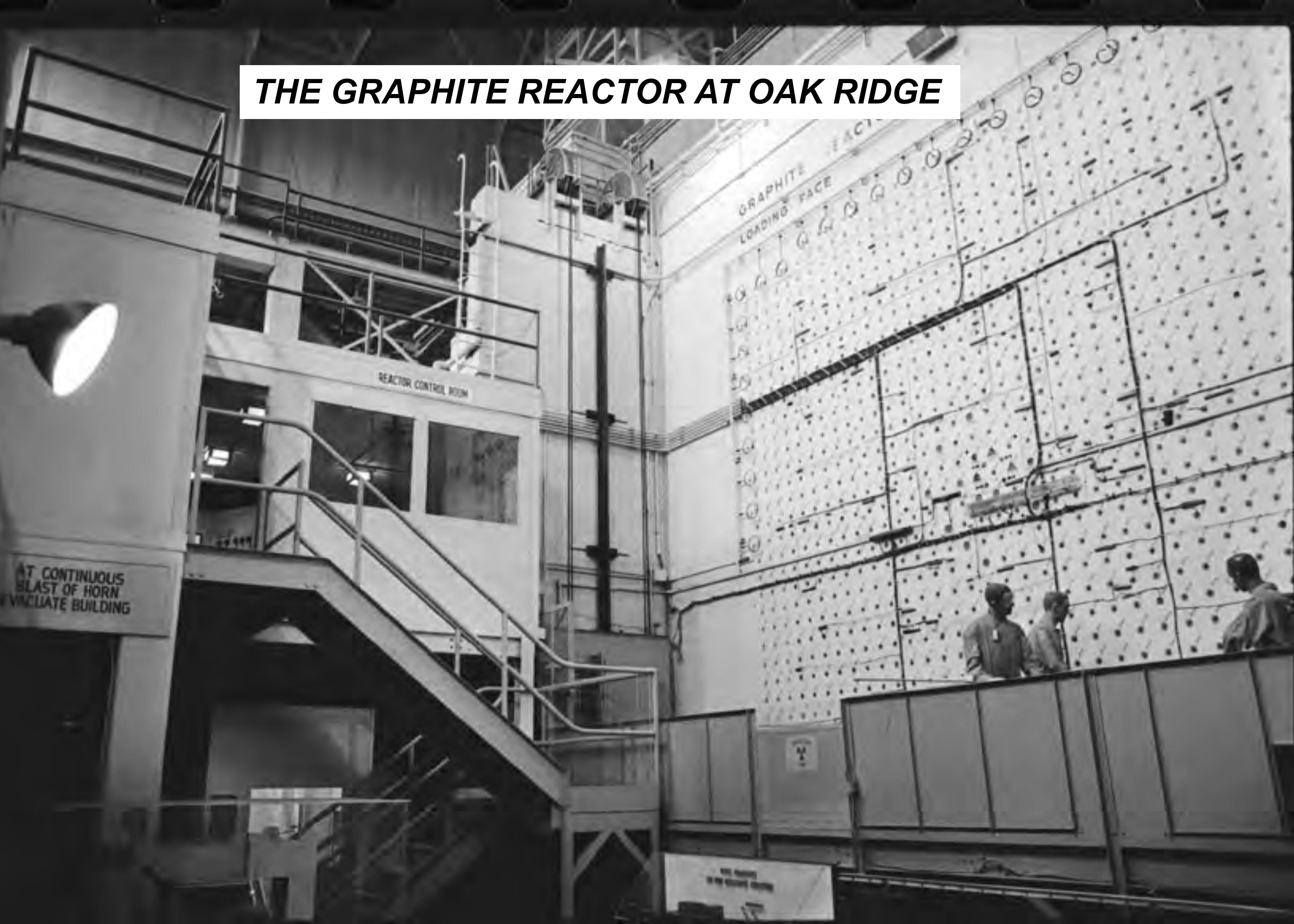

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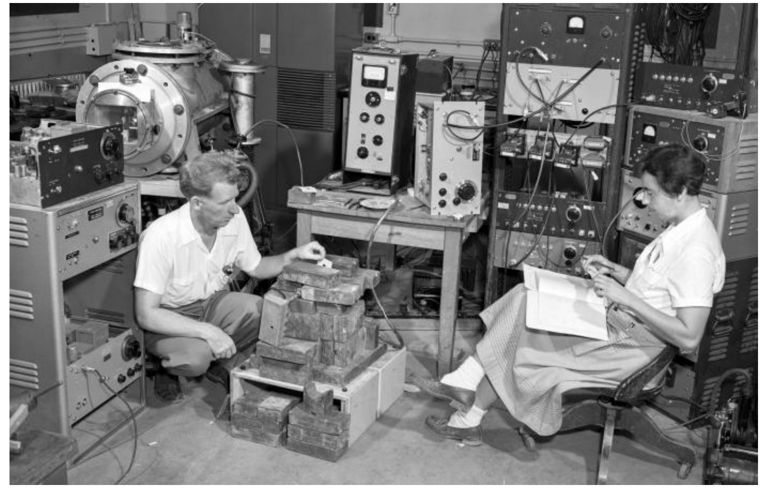
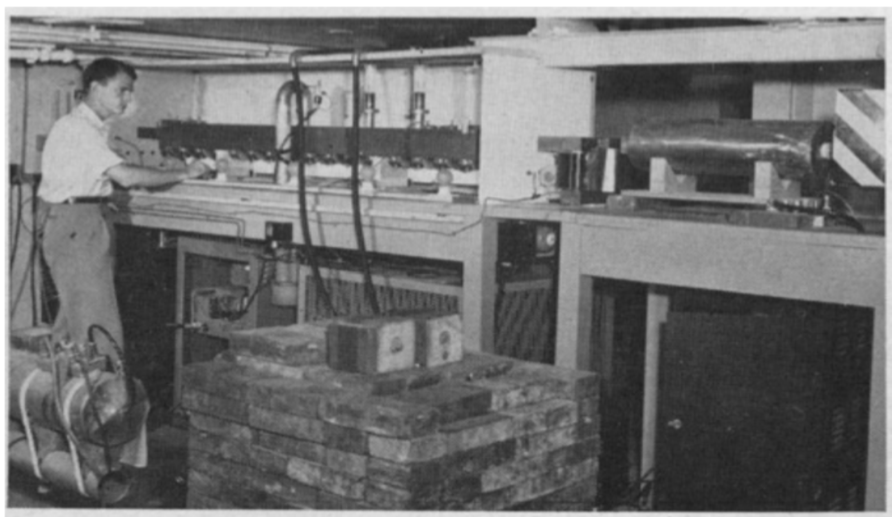
1st Neutron Scattering Experiment
Shull & Wollen (Nobel prize 1994)

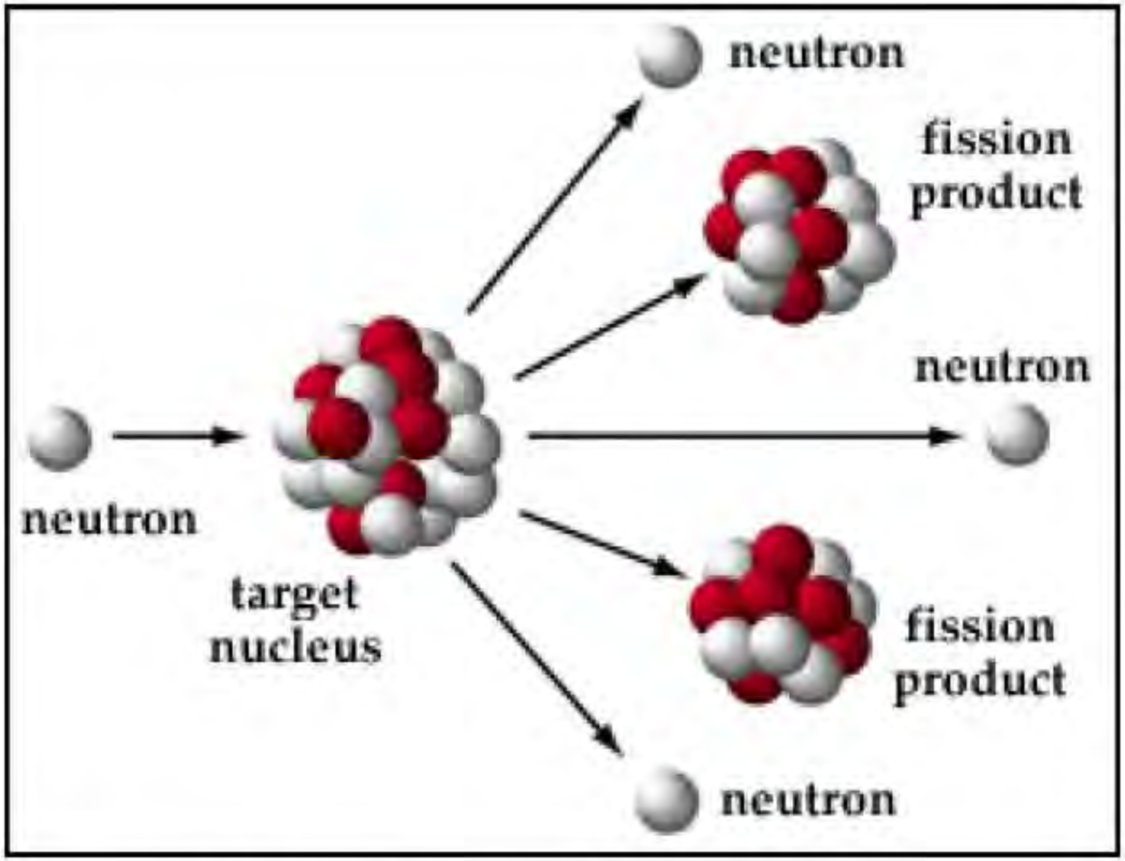


1st Observation of Neutron Decay
Snell & Pleasonton



1st Neutron Electric Dipole Search
Ramsey, Purcell, & Smith (Nobel Prizes 1952 & 1989)

Each Fission Event Produces ~200Mev and ~1.5 "Useful" Neutrons



Nuclear Fission

Some Essential Features of a High Flux Reactor

Figure of Merit is the Peak Neutron Flux at the Core n/cm^2/s

Key Design Features:

1. **High Power Density**
2. **Compact Core**
3. **Highly Enriched Fuel**
4. **D_2O Moderation and Cooling**
5. **Cryogenic Cold Source(s)**

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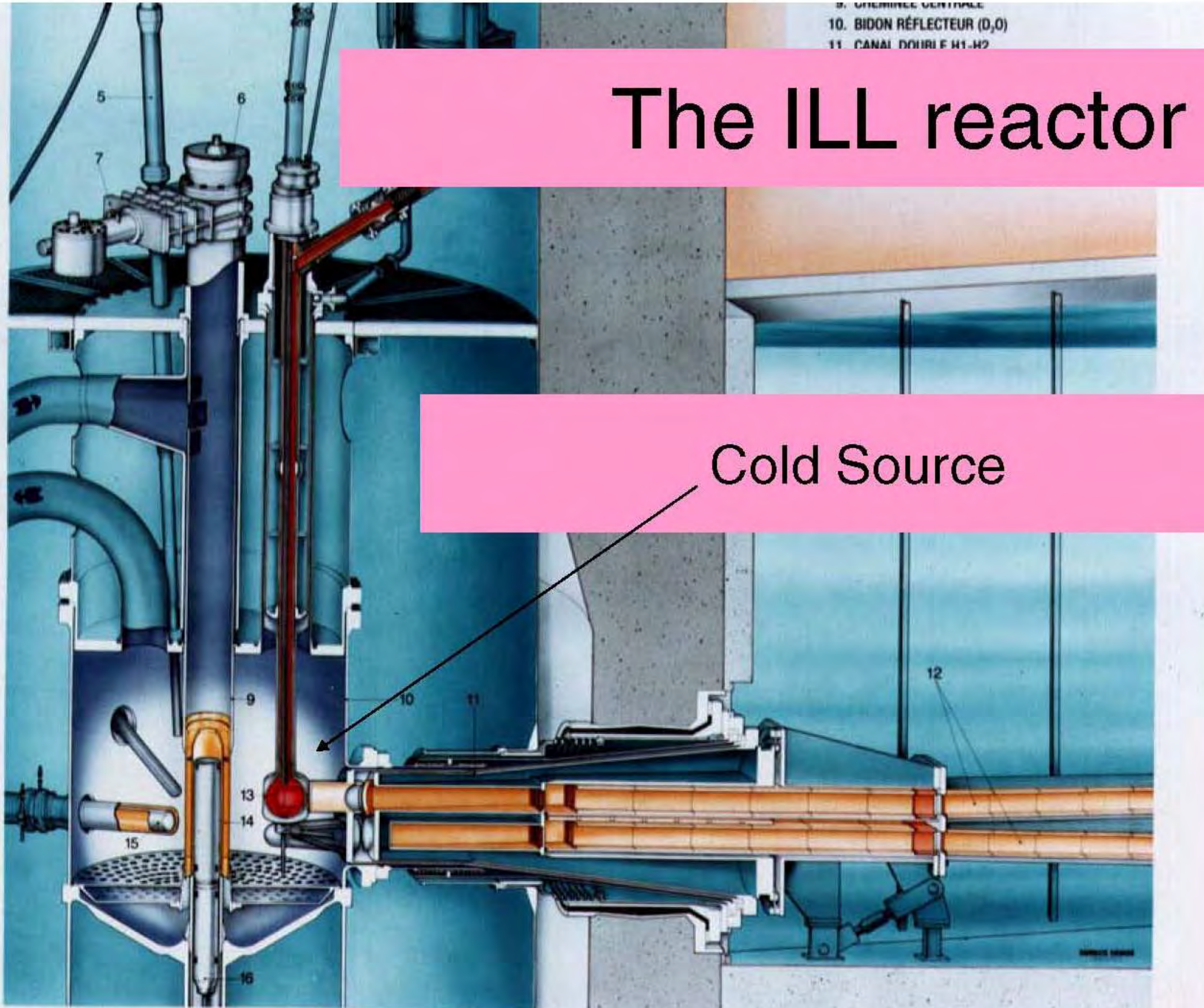
Ultimate engineering limitation is ability to remove heat from the compact core at ~100MW

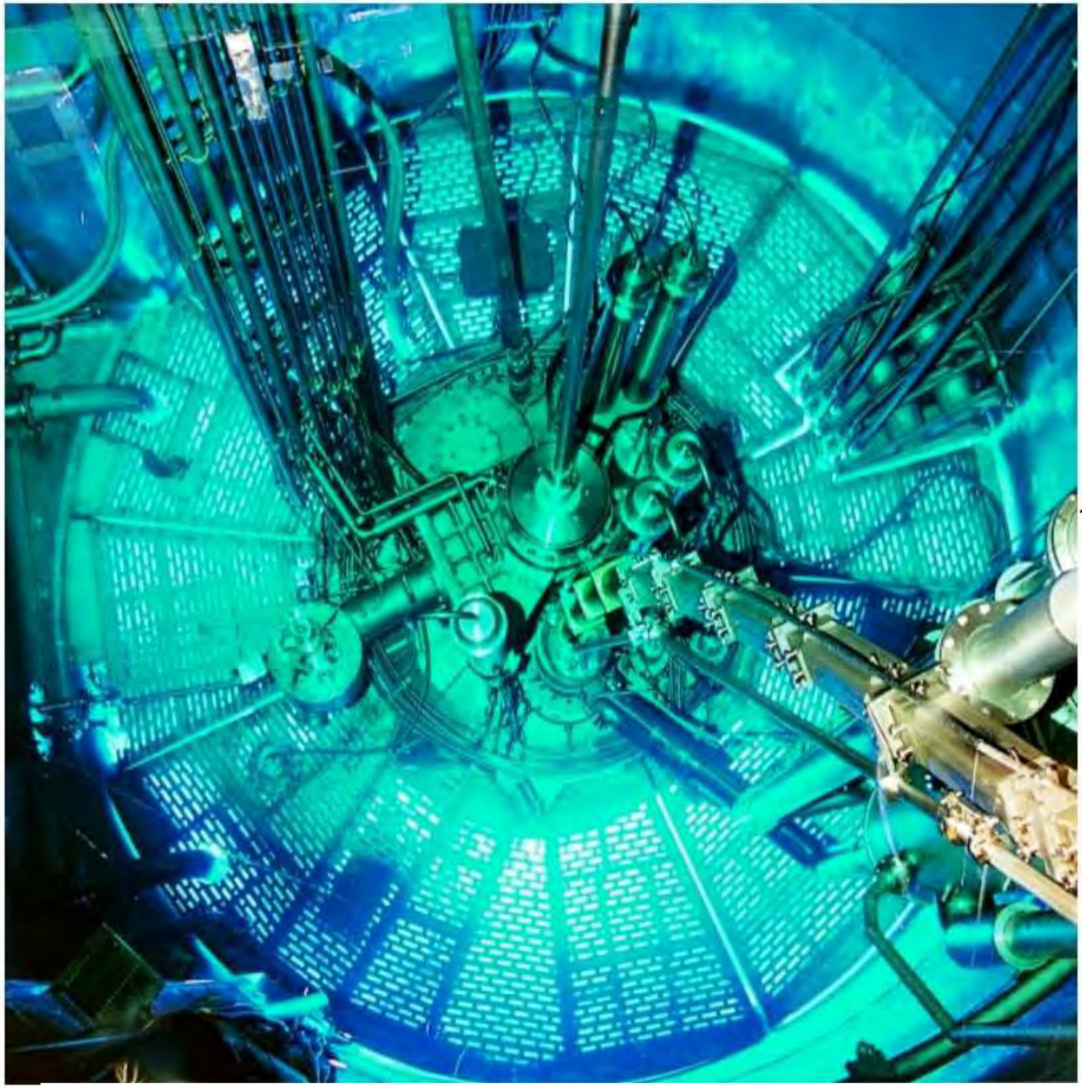
The Institute Laue Langevin, Grenoble

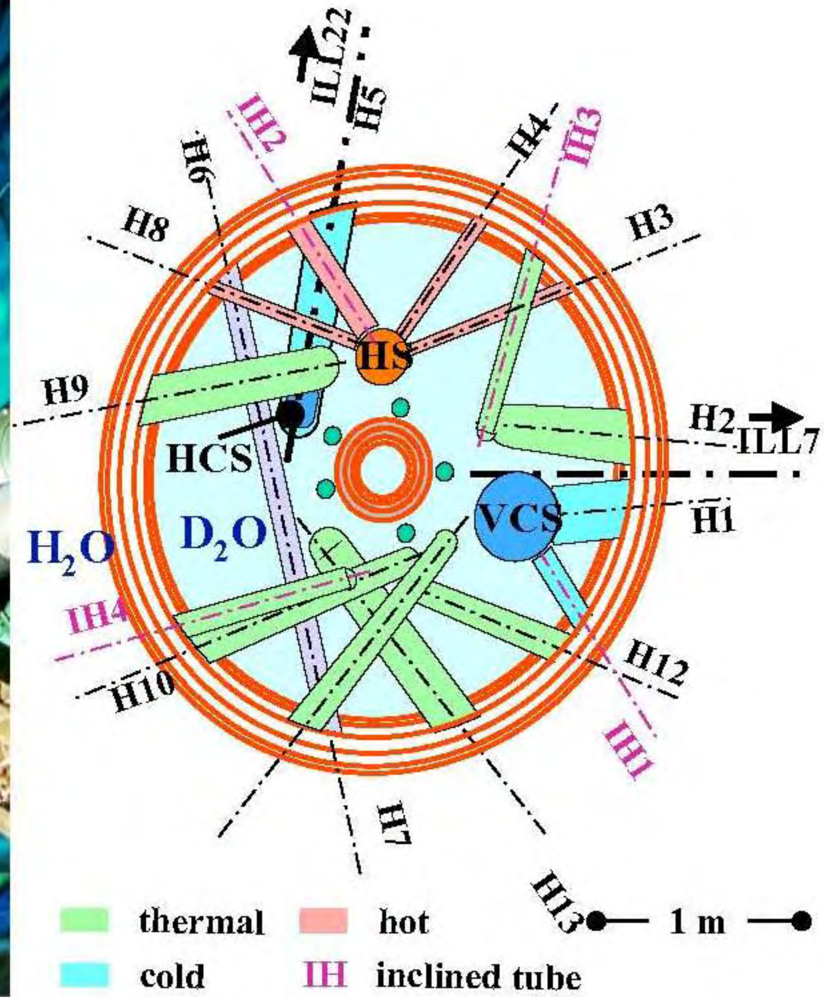
57 MW High Flux Reactor

The ILL reactor



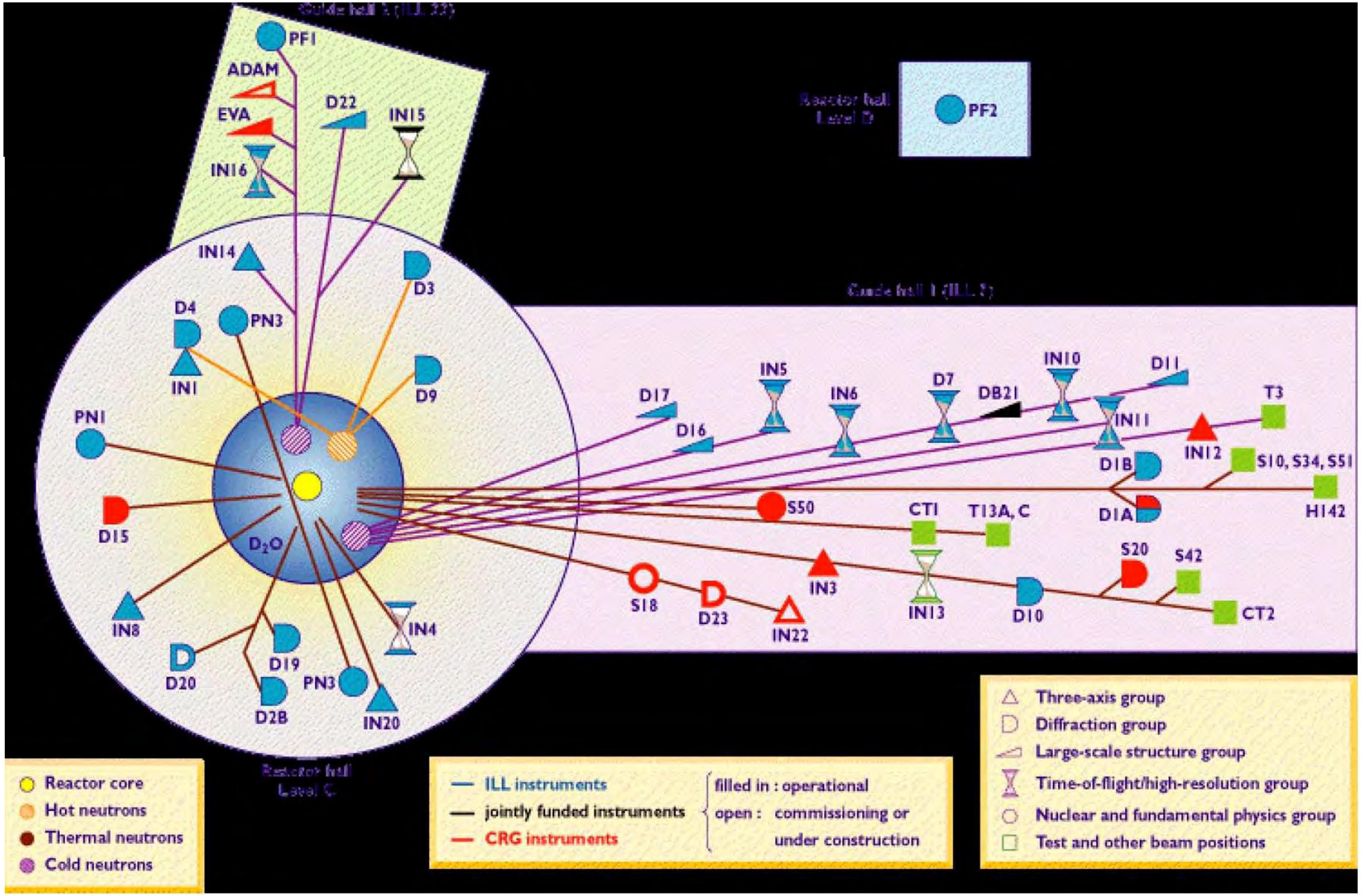
Most Neutron Sources Have Multiple Moderators





The High Flux neutron Source at the ILL

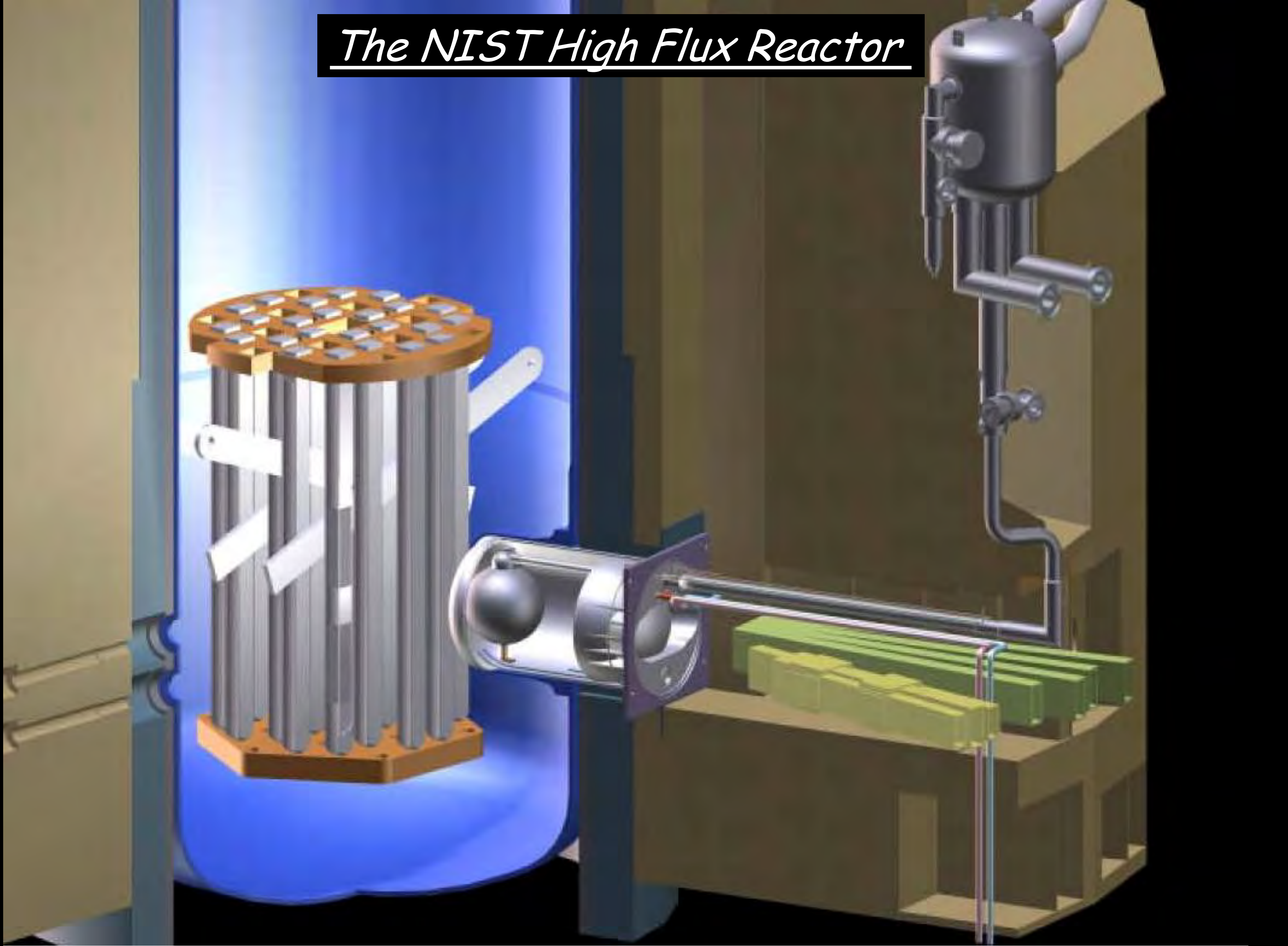
A Neutron Source Can Serve Many Neutron Instruments



Instrument Layout at the Institut Laue Langevin

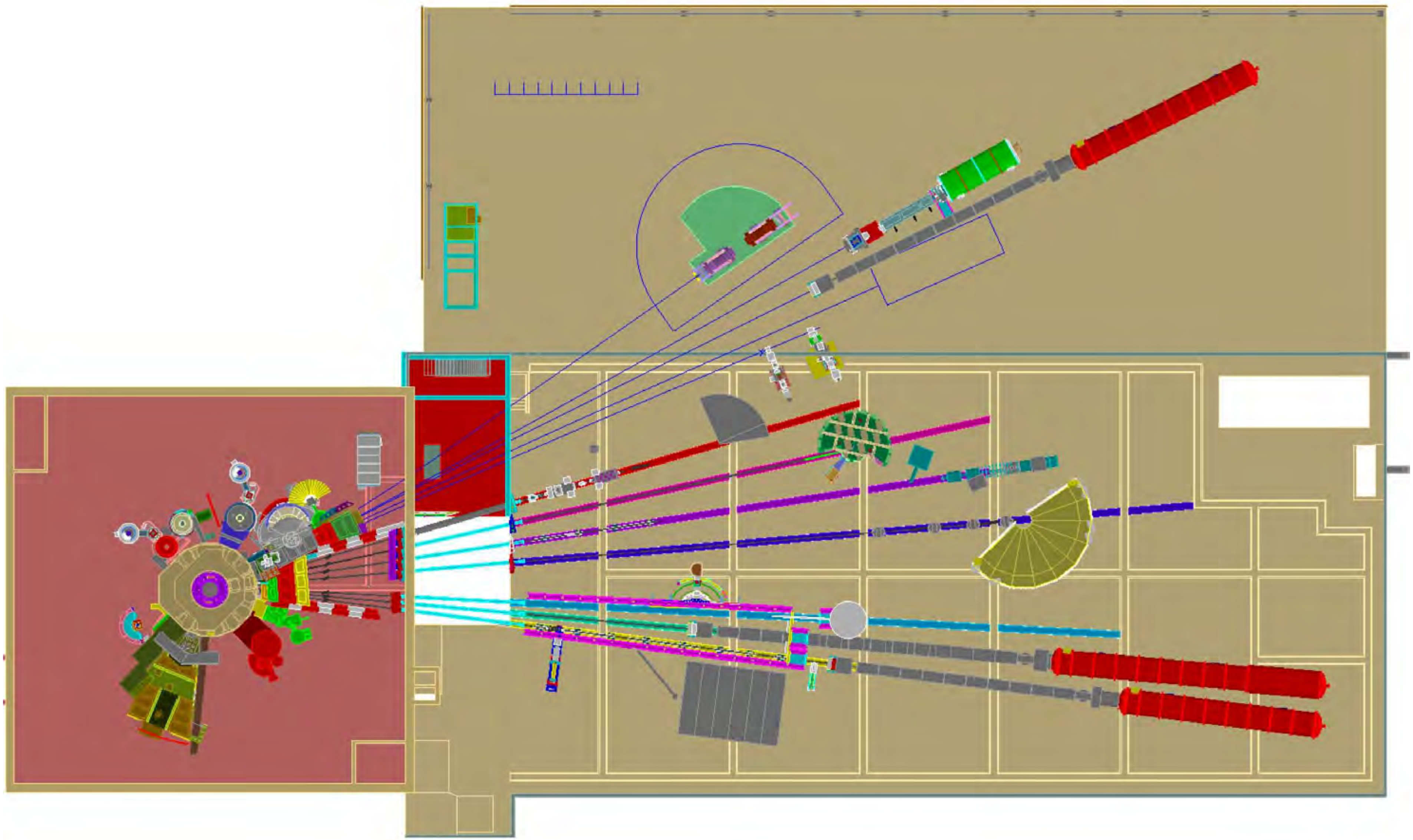
The Guide Hall at the ILL Houses ~30 Neutron Spectrometers

The NIST High Flux Reactor



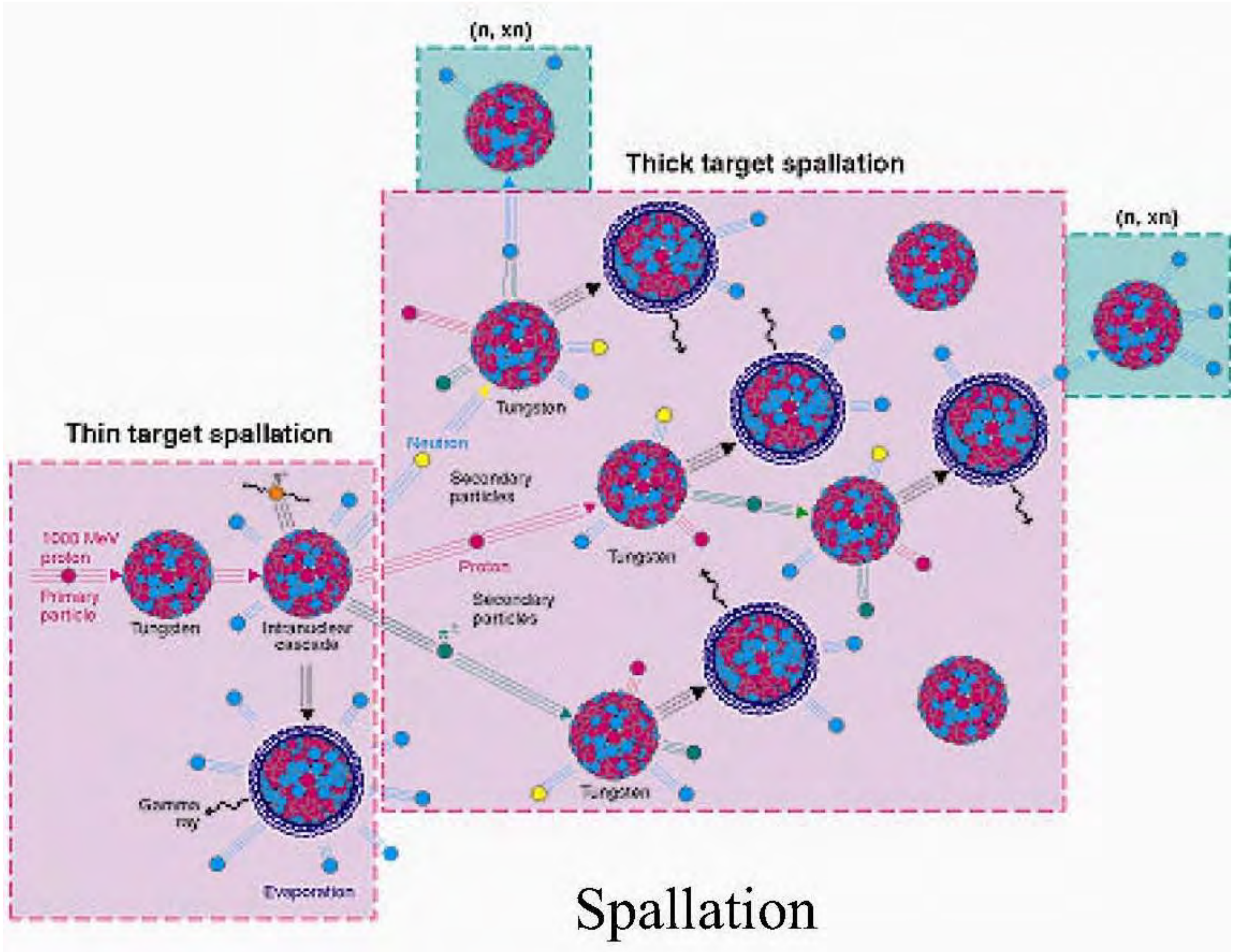
The NIST Cold Neutron research Center

The NIST Cold Neutron research Center

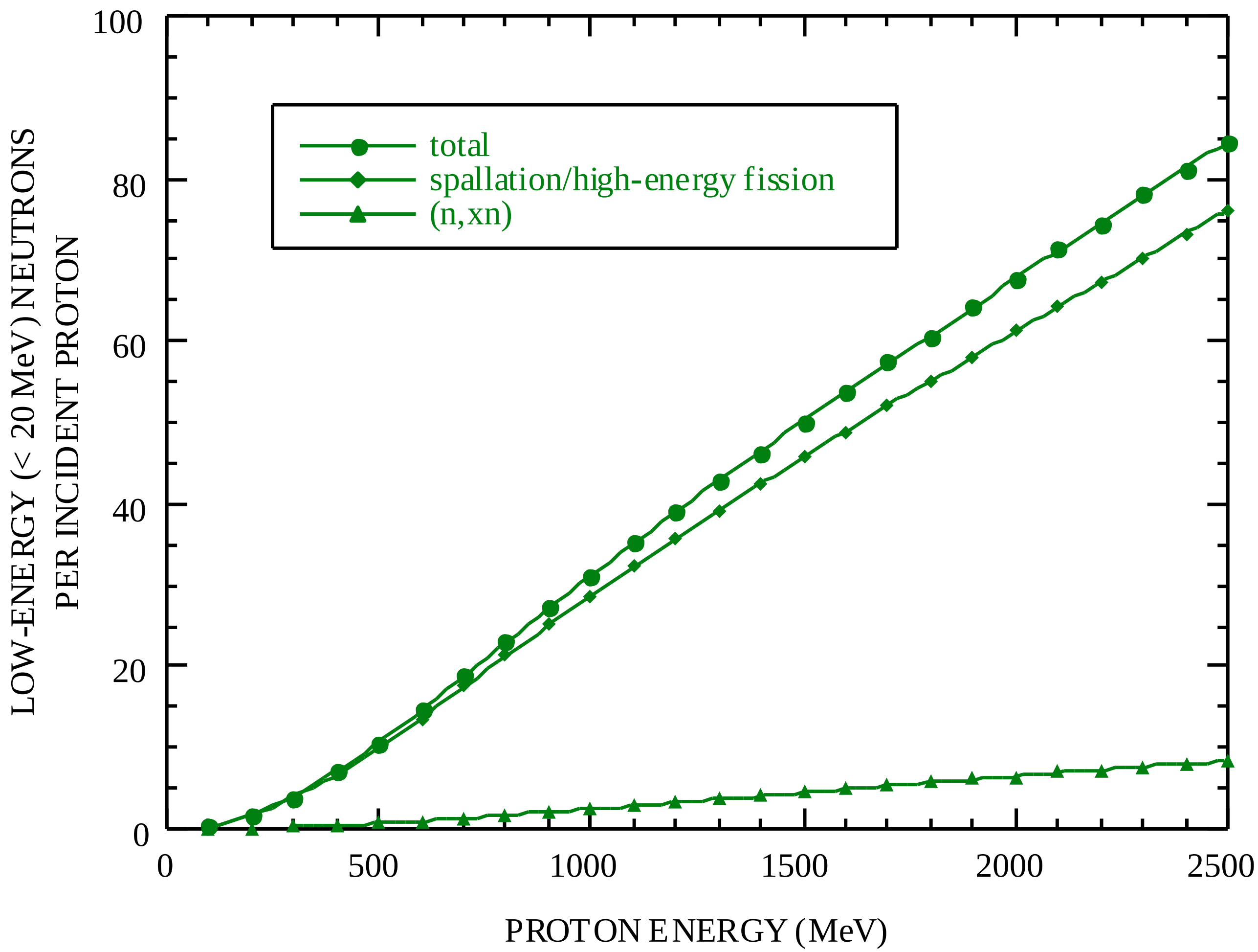


Spallation Sources

At ~1.4 GeV, Each Incident Proton Produce ~40 "Useful" Neutrons



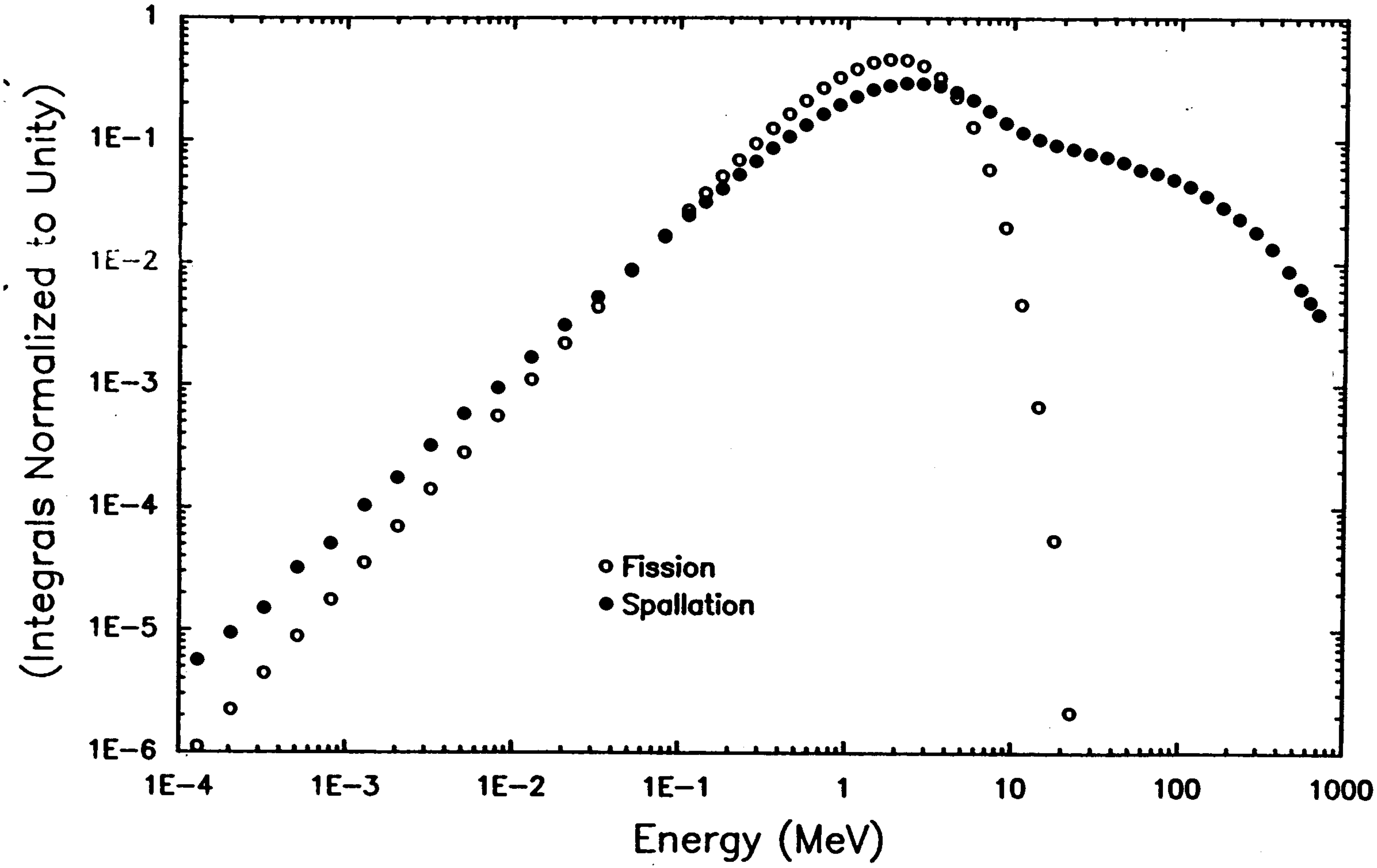
Neutron Production is Roughly Proportional to Power



NOTE: Spallation gives ~x10 more neutrons per MW

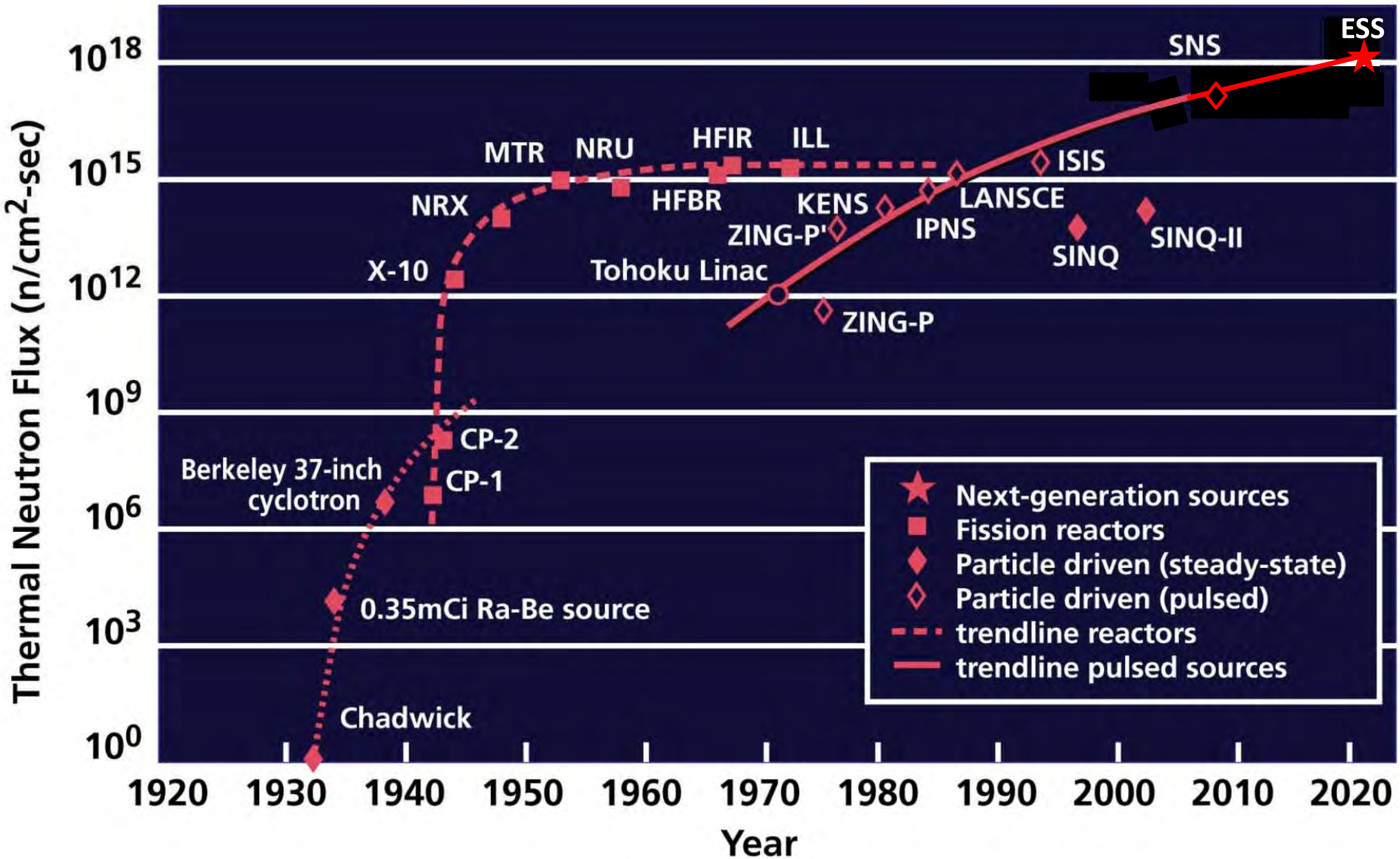
(Courtesy,Gary Russell)

The Spallation Neutron Spectrum is Broad



(Courtesy,Gary Russell)

Neutron Source Intensities Have Increased by Nearly 18 Orders of Magnitude Since Chadwick*



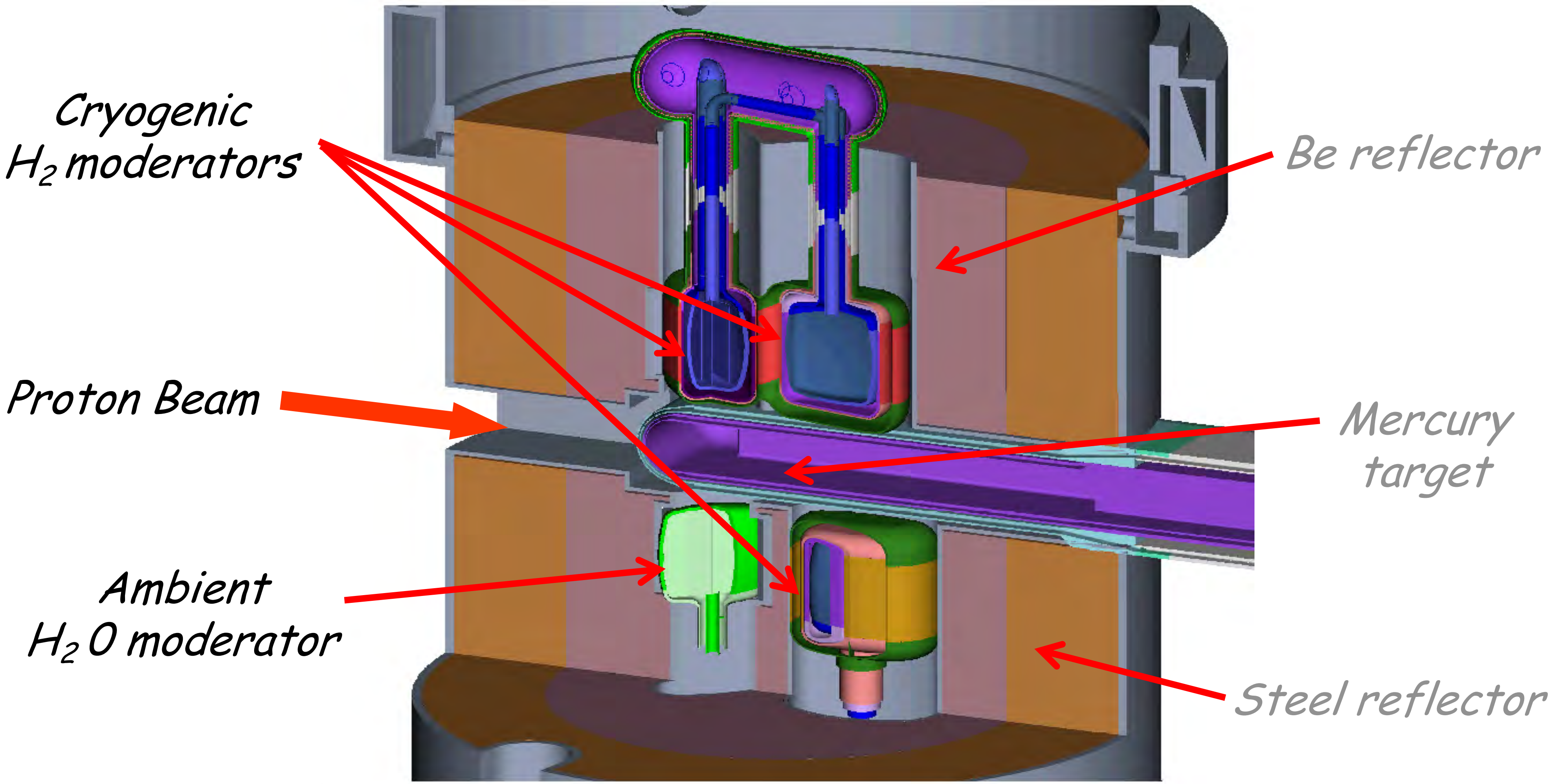
(Updated from *Neutron Scattering*, K. Skold and D. L. Price: eds., Academic Press, 1986)

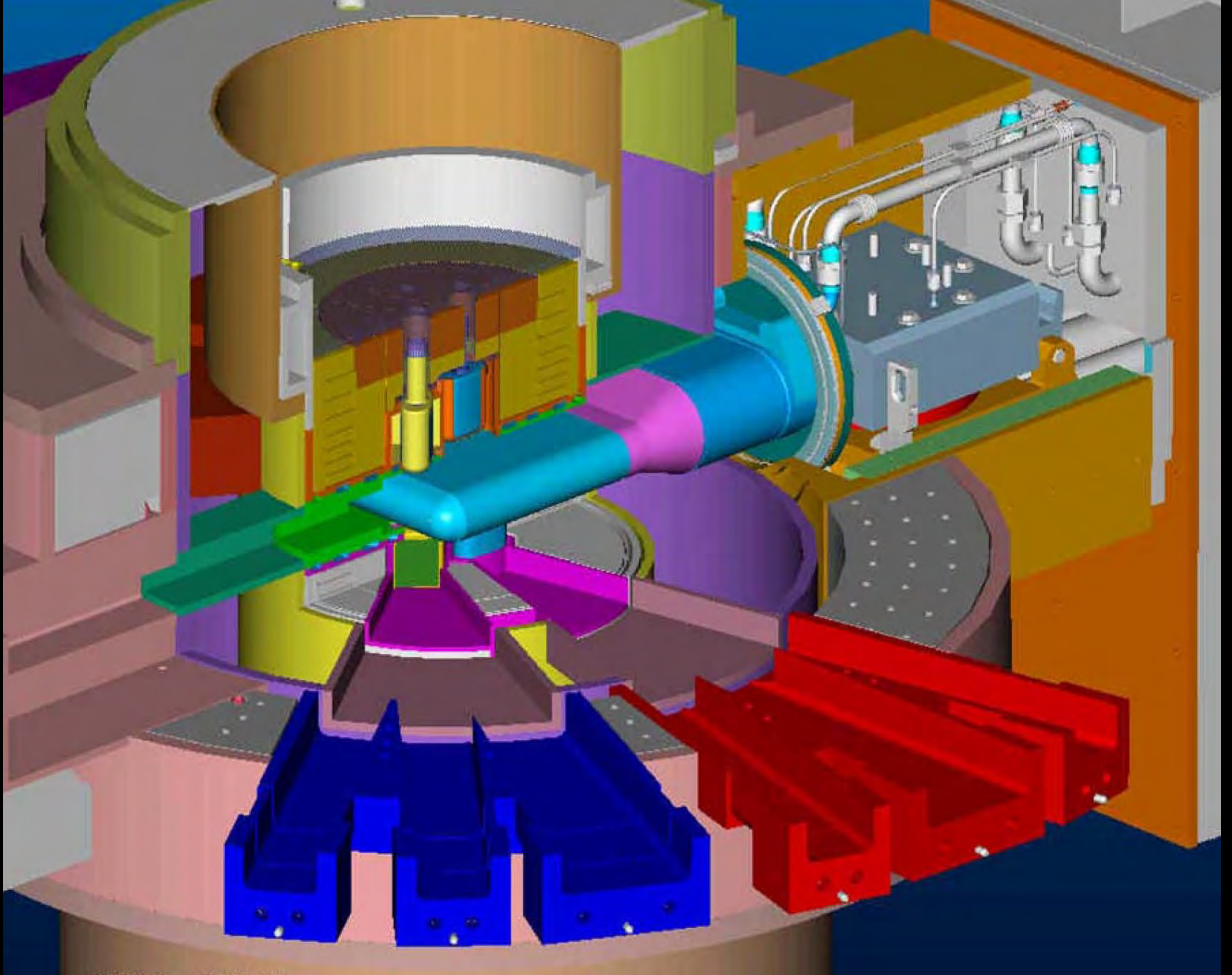
The Spallation Neutron Source

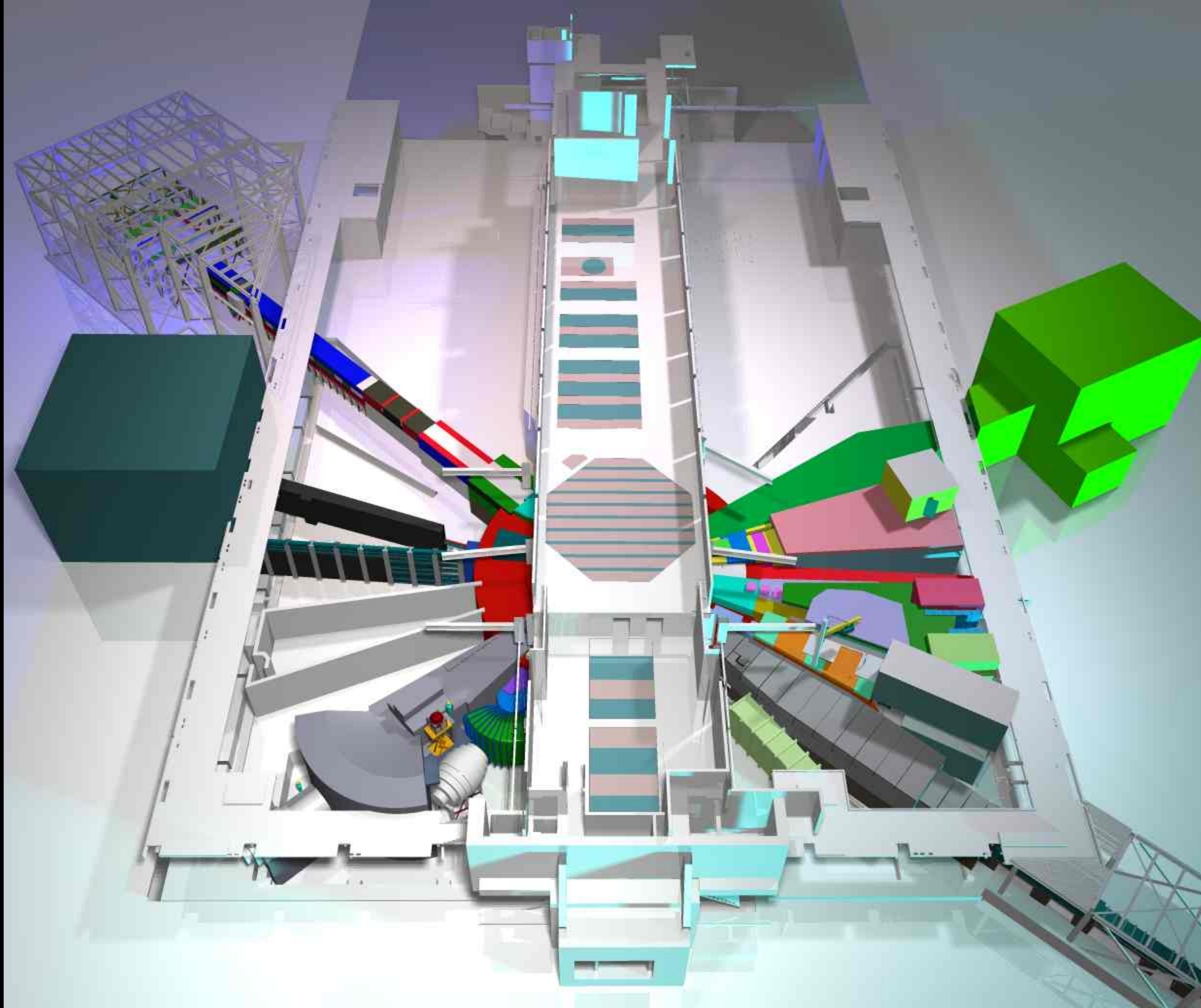

SNS-03671-2005


Front-End Systems
(Lawrence Berkeley)
Accumulator Ring
(Brookhaven)
Target
(Oak Ridge)
Linac
(Los Alamos and
Jefferson)
Instrument Systems
(Argonne and Oak Ridge)

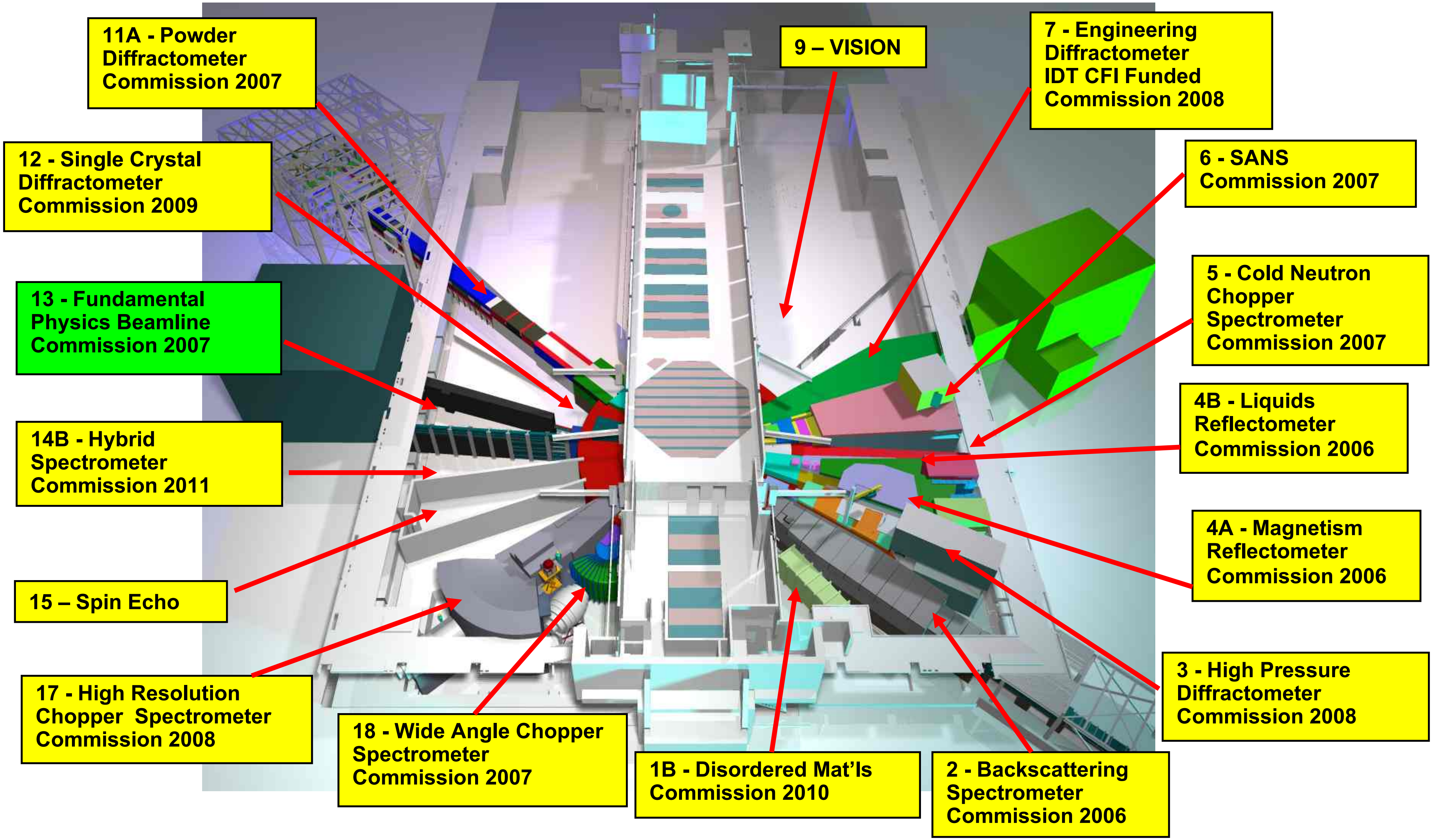
Target, Reflectors, and Moderators







Beamline 13 Has Been Allocated for Nuclear Physics



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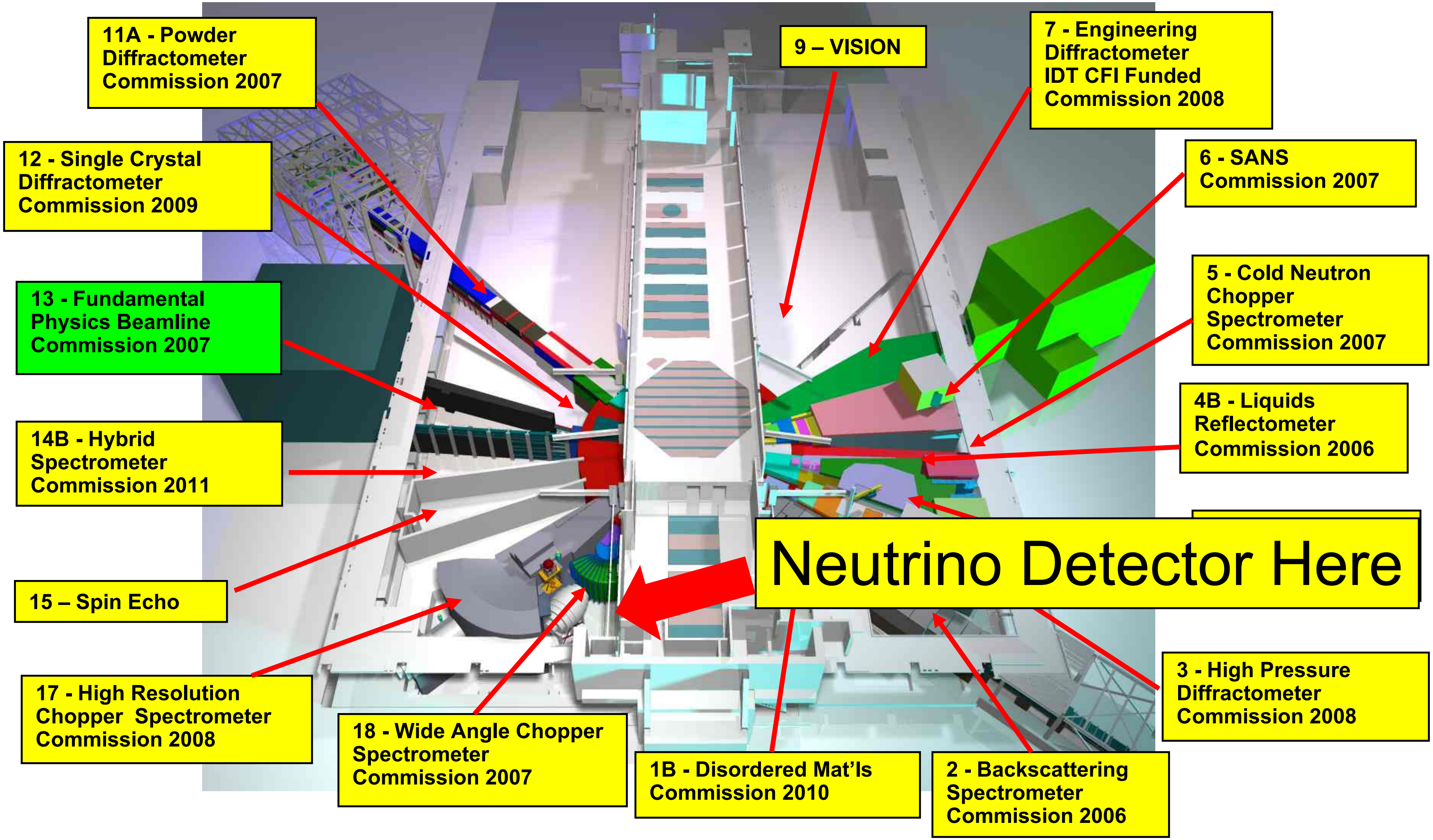
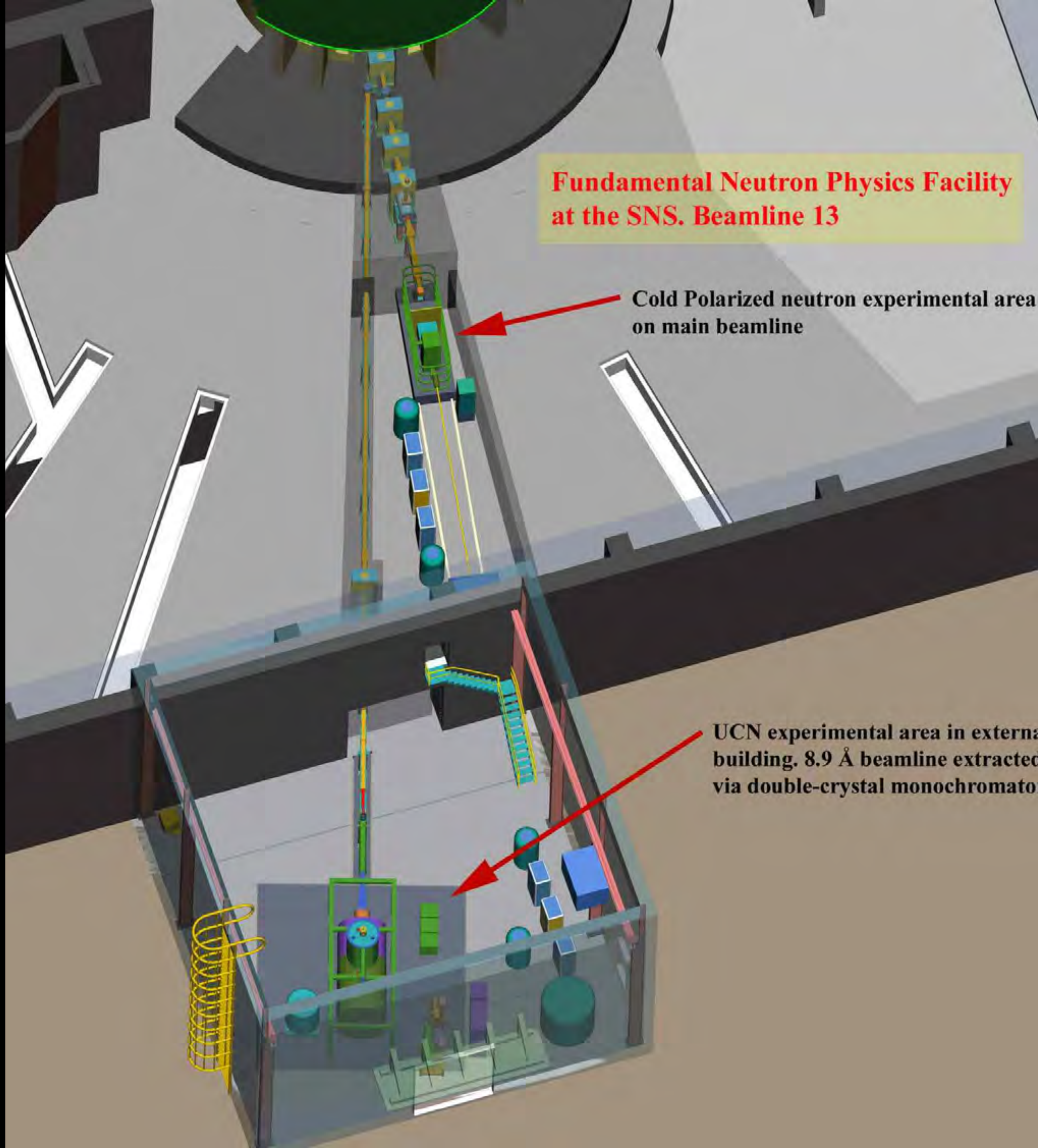
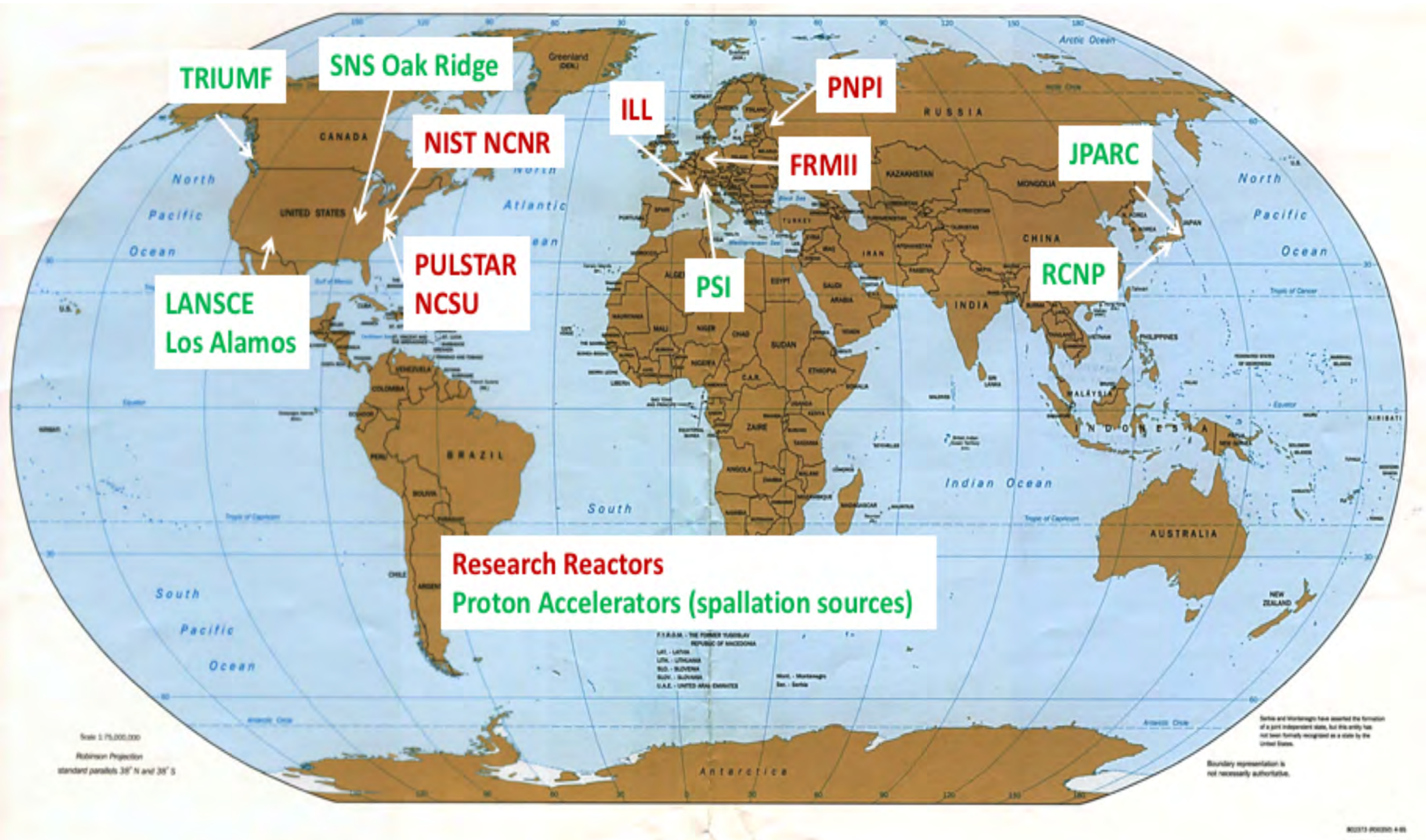


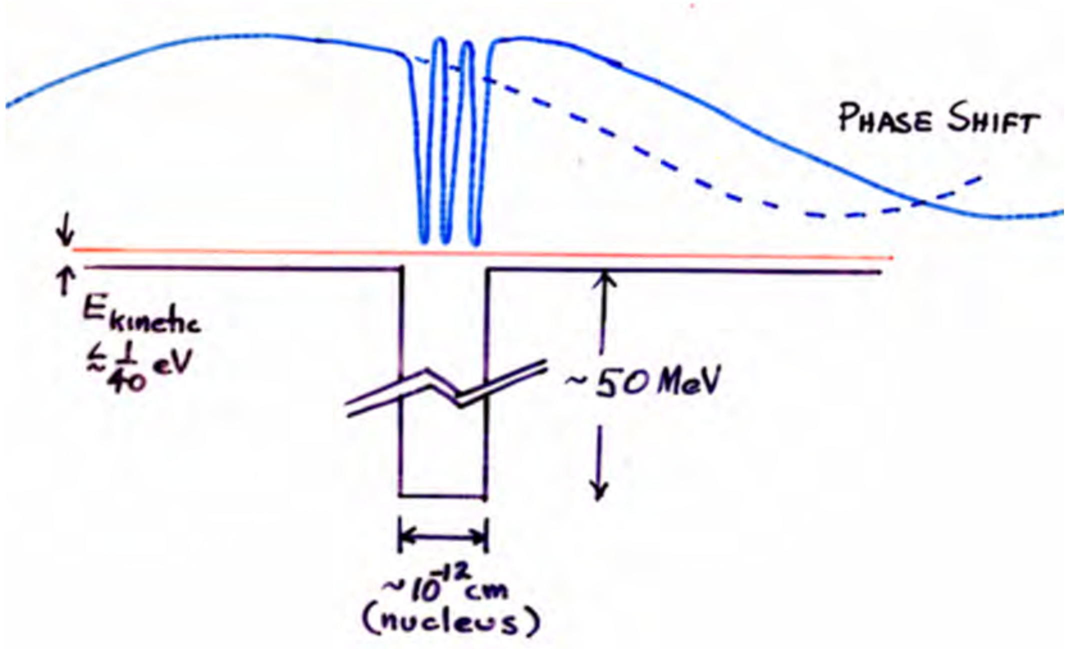

Fundamental Neutron Physics Facility
at the SNS. Beamline 13
Cold Polarized neutron experimental area
on main beamline
UCN experimental area in externa
building. 8.9 Å beamline extracted
via double-crystal monochromator

Sources for Fundamental Neutron Physics Research

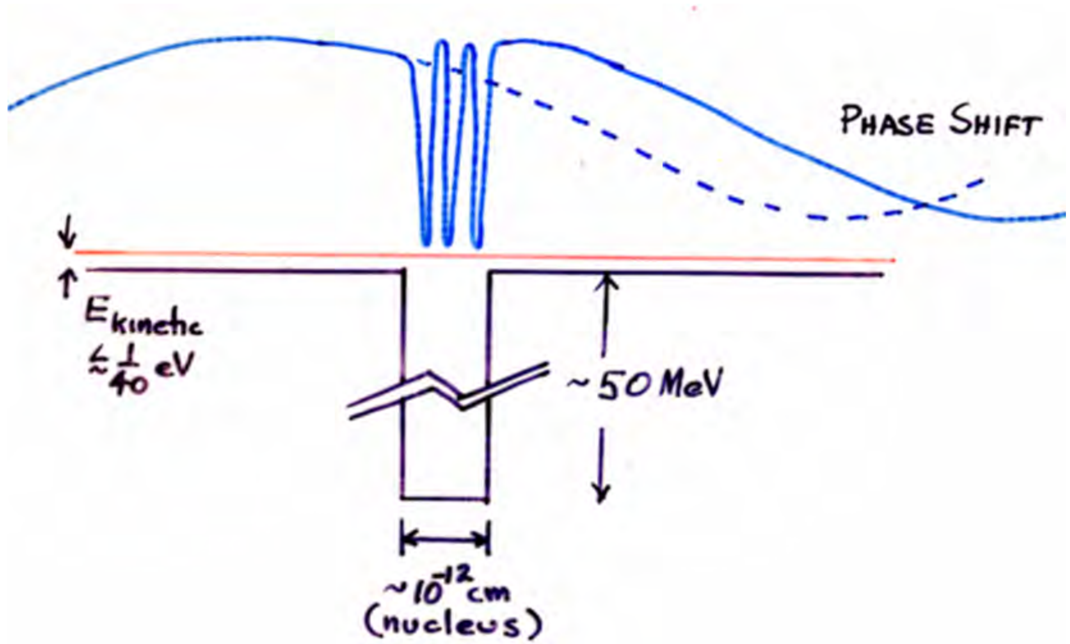


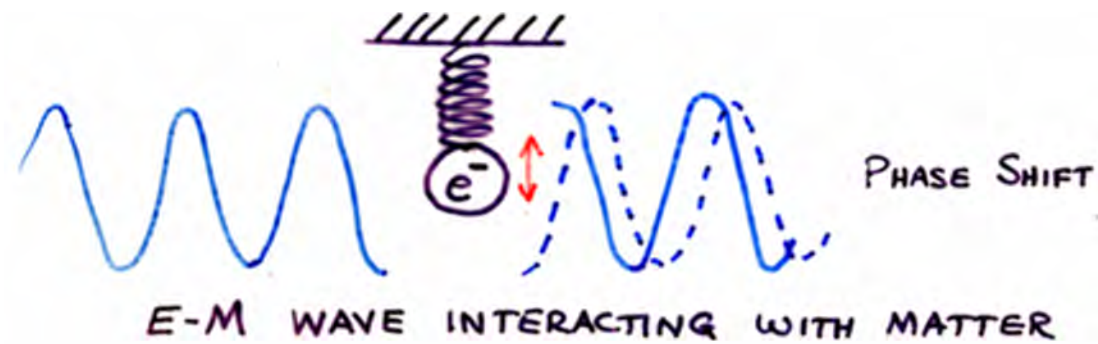
Neutron Guides
&
Ultracold Neutrons

Coherent ("Optical") Interaction Between Neutrons and Matter



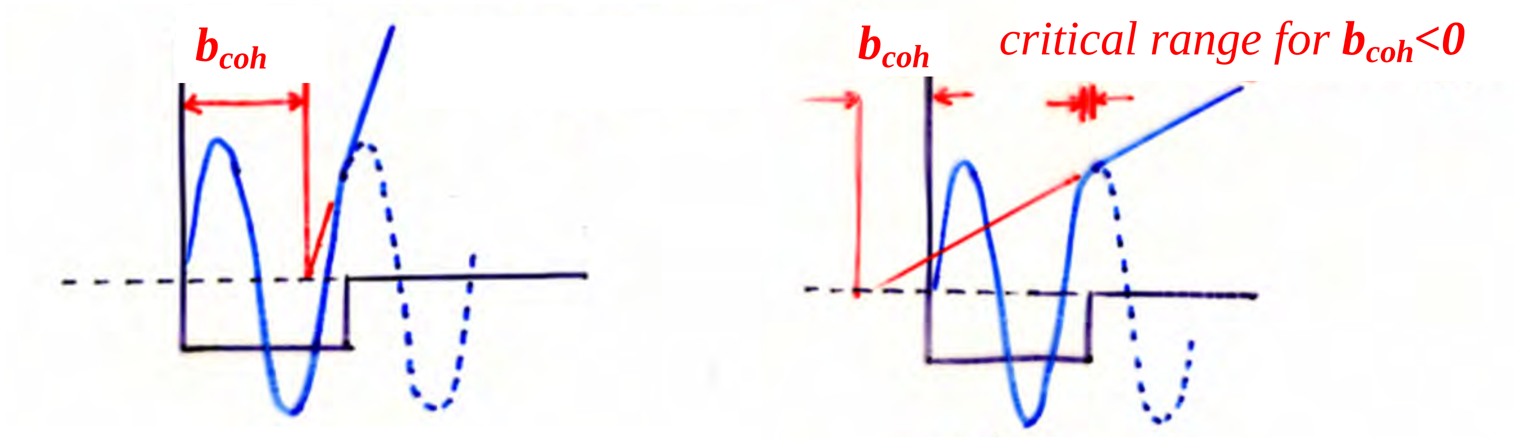
Coherent ("Optical") Interaction Between Neutrons and Matter





Phase shift leads to Index of Refraction

At low energies S-wave scattering dominates, phase shift is given by $\cot(\delta) = \frac{-1}{kb_{coh}}$



For most nuclear well depths and well sizes,
it is unlikely to obtain a positive coherent scattering length:

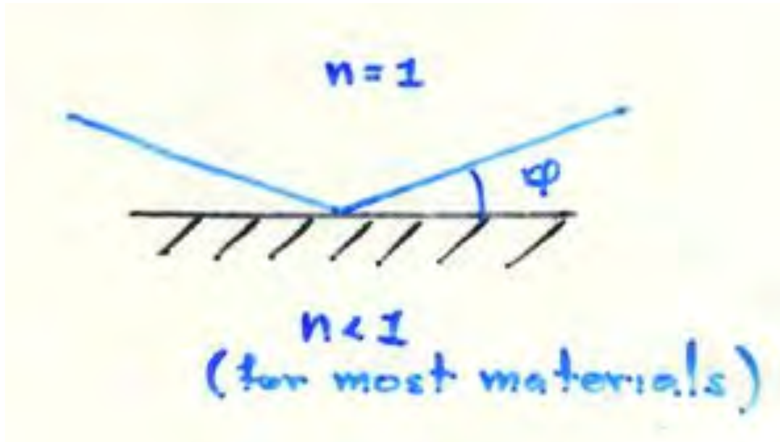
$$n = \sqrt{1 - \frac{N\lambda^2 b_{coh}}{\pi}}$$

*Index of refraction is therefore <1 for most nuclei **

**In the vicinity of A~50 (V,Ti,Mn) nuclear sizes are such that* $b_{coh}<1$ *and thus n>1*

Neutron Reflection from Matter

$$n^2 = 1 - \frac{\lambda^2 N b_{coh}}{2\pi} \longrightarrow \cos\theta_{crit} = n$$



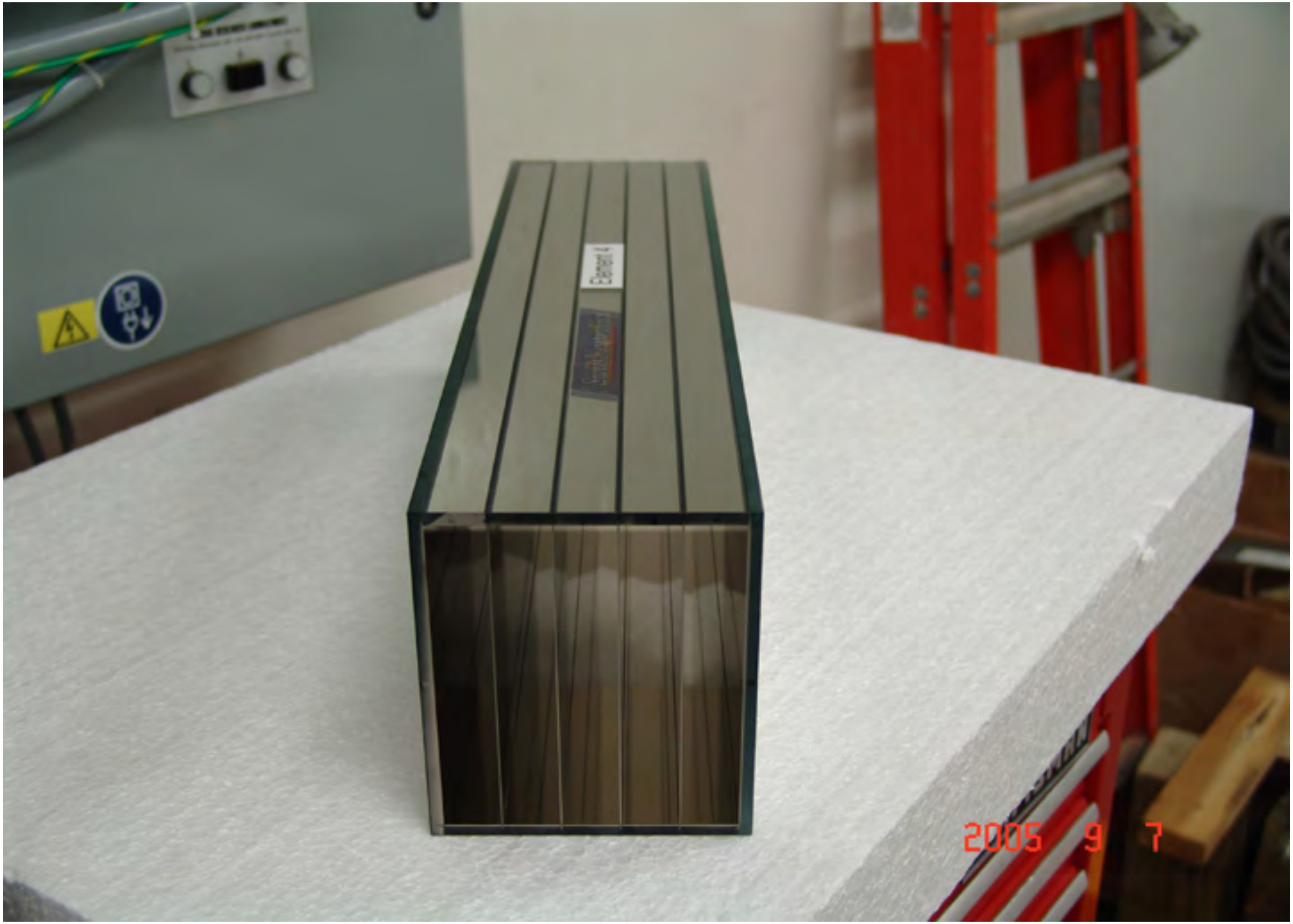
Neutrons will undergo complete "external" reflection from a polished surface for most materials

Ni or ^{58}Ni are particularly useful as a neutron mirror material

$$\theta_{crit}(Ni) \approx 1.7x10^{-3} / \lambda(Angstrom)$$

For most neutron beams this means $\theta_{crit} \leq 10^{-2}$

Guide Section from SNS



Neutron Guides can be used to Focus Neutron Beams

Photo: Swiss Neutronics

Large Cross Section Guides are Commercially Available

Prototype Guide for SNS Ultracold Beam

A Single Moderator can Feed Multiple Neutron Guides

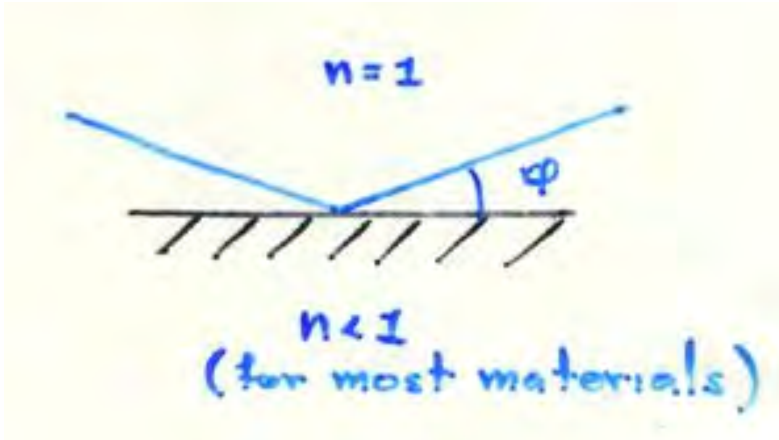
Photo: Institut Laue Langevin

Ultra Cold Neutrons

**see Golub, Richardson, Lamoreaux, Ultracold Neutrons*

Neutron Index of Refraction

$$n^2 = 1 - \frac{\lambda^2 N b_{coh}}{2\pi} \longrightarrow \cos\varphi_{crit} = n$$



For sufficiently large neutron wavelength, λ, n=0 and cosφ_{crit} =90°

This implies that neutrons will be reflected at all angles
and can be confined in a "bottle"

These are known as "Ultracold Neutrons."

Limits to Thermal UCN Production

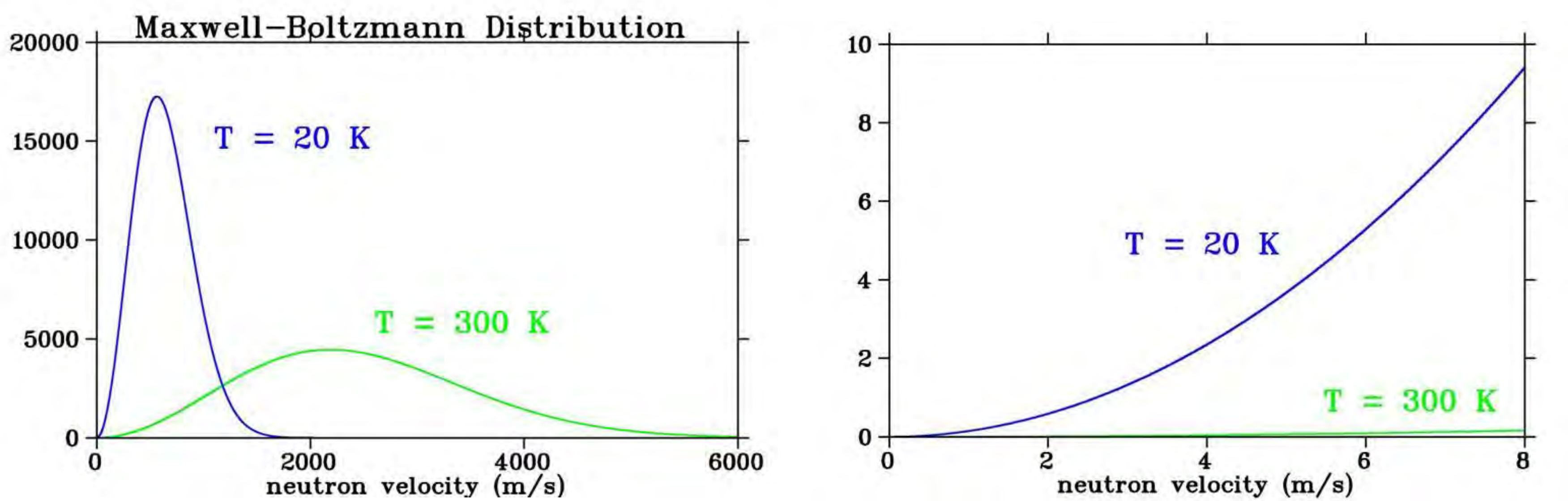
In thermal equilibrium: $\rho_{UCN} = \frac{2}{3}\frac{\Phi_0}{\alpha}\left(\frac{V}{k_B T_n}\right)^{3/2}$

Increase the Flux Φ_0*:*

Reactors are at the practical limit of heat transfer.

Only practical hope would be a 10-20 MW Spallation Source.

Lower the temperature T_n *(also reduces* α*):*



Practical limit for true moderator is about 20k which gives a density increase of ~x20

Practical Thermal Source Limit for UCN production: $\rho_{UCN} \approx 2 \cdot 10^3 cm^{-3}$

Ultracold Neutron Energies are Very Low

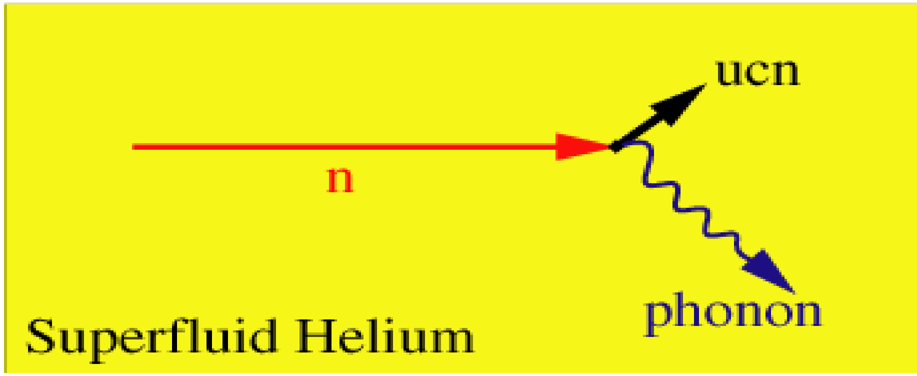
The Fermi "Pseudo-Potential" the most advantageous materials is ~ 100 neV

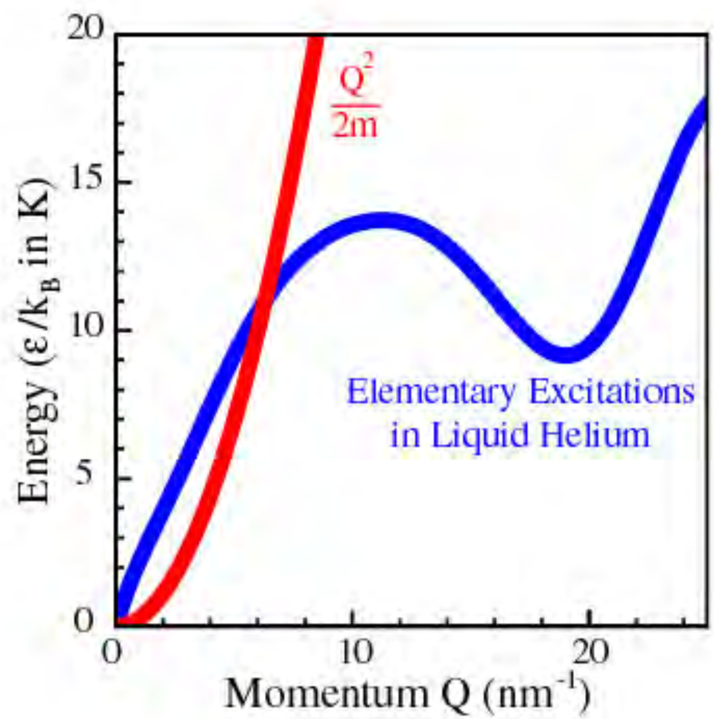
This corresponds to a:

Neutron Velocity	≈ 500 m/s
Neutron Wavelength	≈ 500 Å
Magnetic Moment Interaction	$\mu_n \cdot B \approx 100$ neV for B~1Tesla
Gravitational Interaction	$m_n g h \approx 100$ neV for h~1 m

Ultracold Neutron can be trapped in material, magnetic, or gravitational bottles

Super Thermal Source of UCN





- *Neutrons of energy E ≈ 0.95 meV (11 k or 0.89 nm) can scatter in liquid helium to near rest by emission of a single phonon.*

- *Upscattering by absorption of an 11 k phonon is a UCN loss mechanism. But population of 11 K phonons is suppressed by a large Boltzman Factor: ~ $e^{-11/T}$ where T~200 mk*

Golub and Pendlebury (1977)

Solid D_2 Superthermal UCN Source

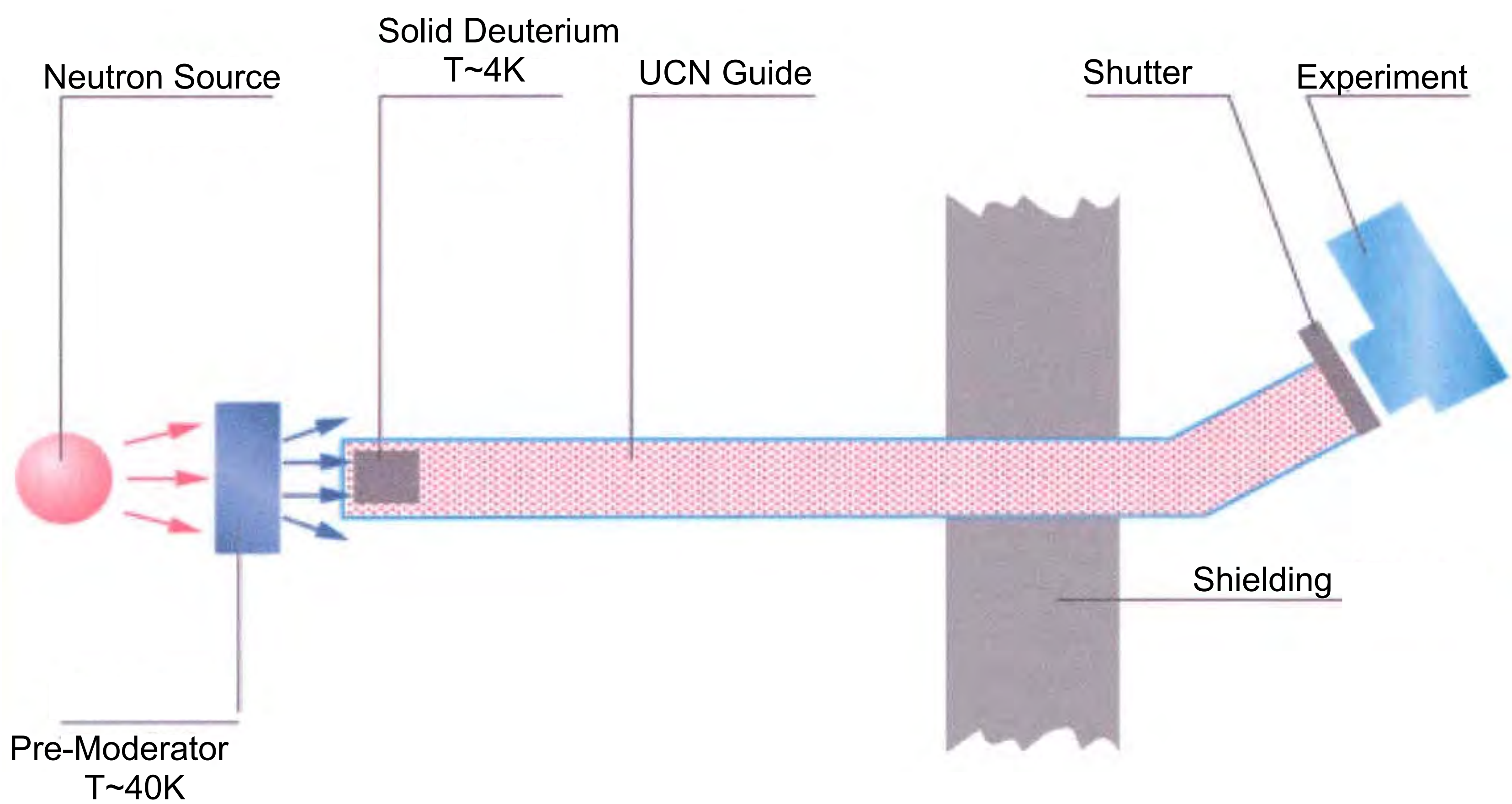
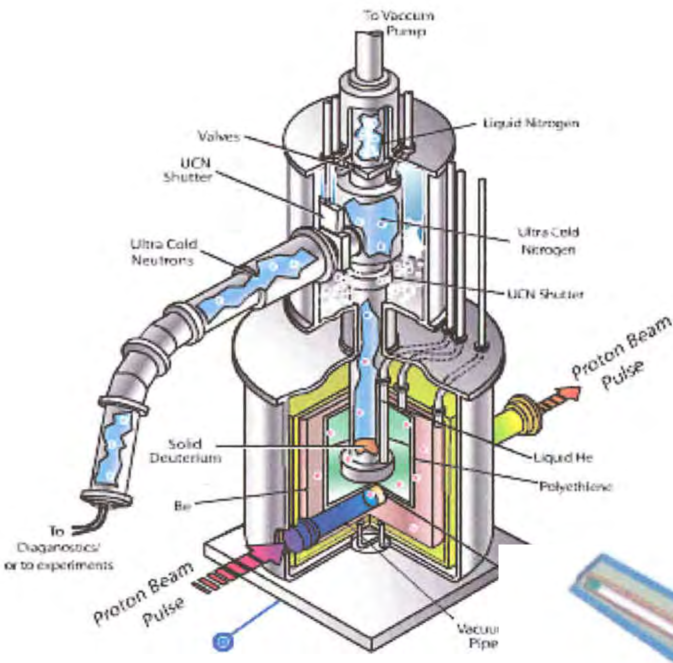


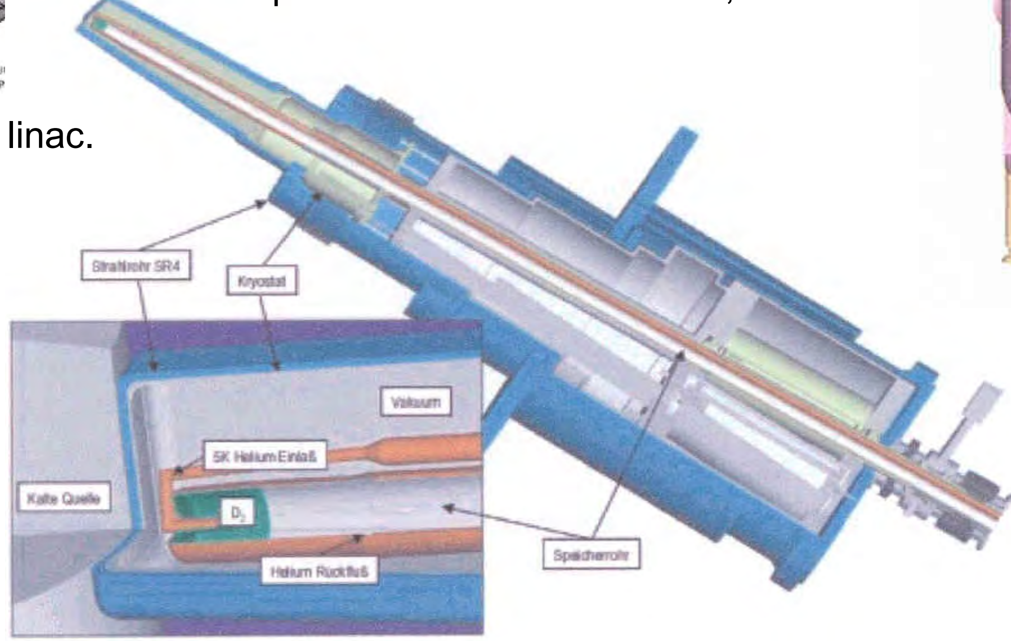
Figure courtesy FRM-11 webpage

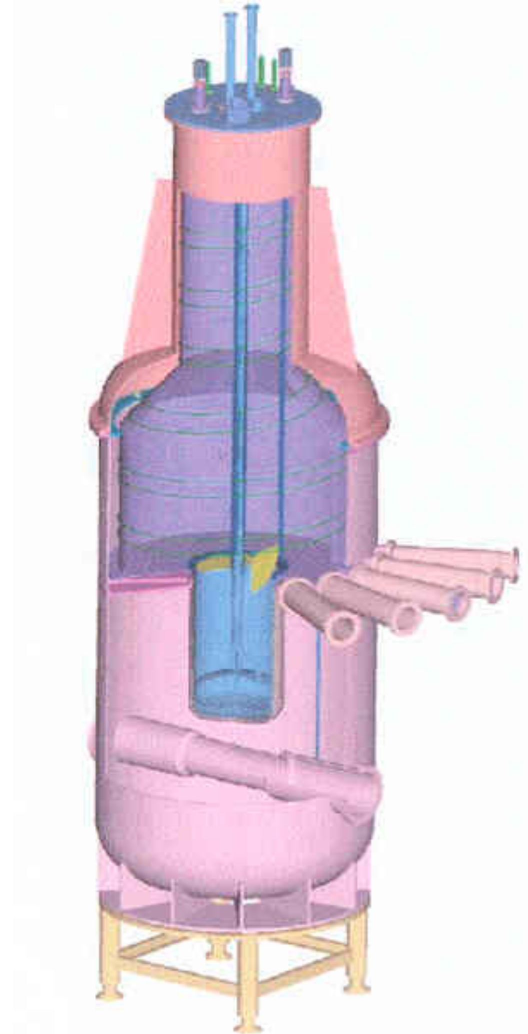
Solid D2 UCN Sources



Operational at the LANSCE linac.

Proposed at the FRM-II reactor, Munich





Operational at the PSI, Switzerland.

End of Lecture 2