Concept for an Ultra-Cold Neutron Facility with CW Beams at 2 GeV

Dr. Bradley J. Micklich
Senior Physicist, Physics Division
Argonne National Laboratory

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Ultra-Cold Neutrons

- Ultra-cold neutrons have a very specific definition
  - Velocity < 7 m/s
  - Energy less than about 200 neV
  - Wavelength longer than 600 Å
  - Can be reflected from materials, and thus contained in material 'bottles'
- Ultra-cold neutrons are used in basic physics research to study
  - Neutron electric dipole moment (nEDM) (nature of baryon asymmetry)
    - Existence of a nEDM implies processes that violate CP symmetry. The standard model includes CP-violating processes but puts the upper limit on nEDM of $|d_n| \sim 10^{-32}$ e-cm. The current lower experimental limit is about $|d_n| \sim 10^{-26}$ e-cm.
  - Neutron half-life (nucleosynthesis, cosmic abundance of ^{4}He)
    - Neutron β-decay measurements (half-life and correlation coefficients) give information about the time scale for Big Bang nucleosynthesis and the cosmic abundance of ^{4}He.
- UCNs can be produced by two means
  - Thermal production in a solid-D_2 moderator (PSI UCN source)
  - Superthermal production by downscattering of 8.9-Å neutrons in He-II (KEK UCN source)

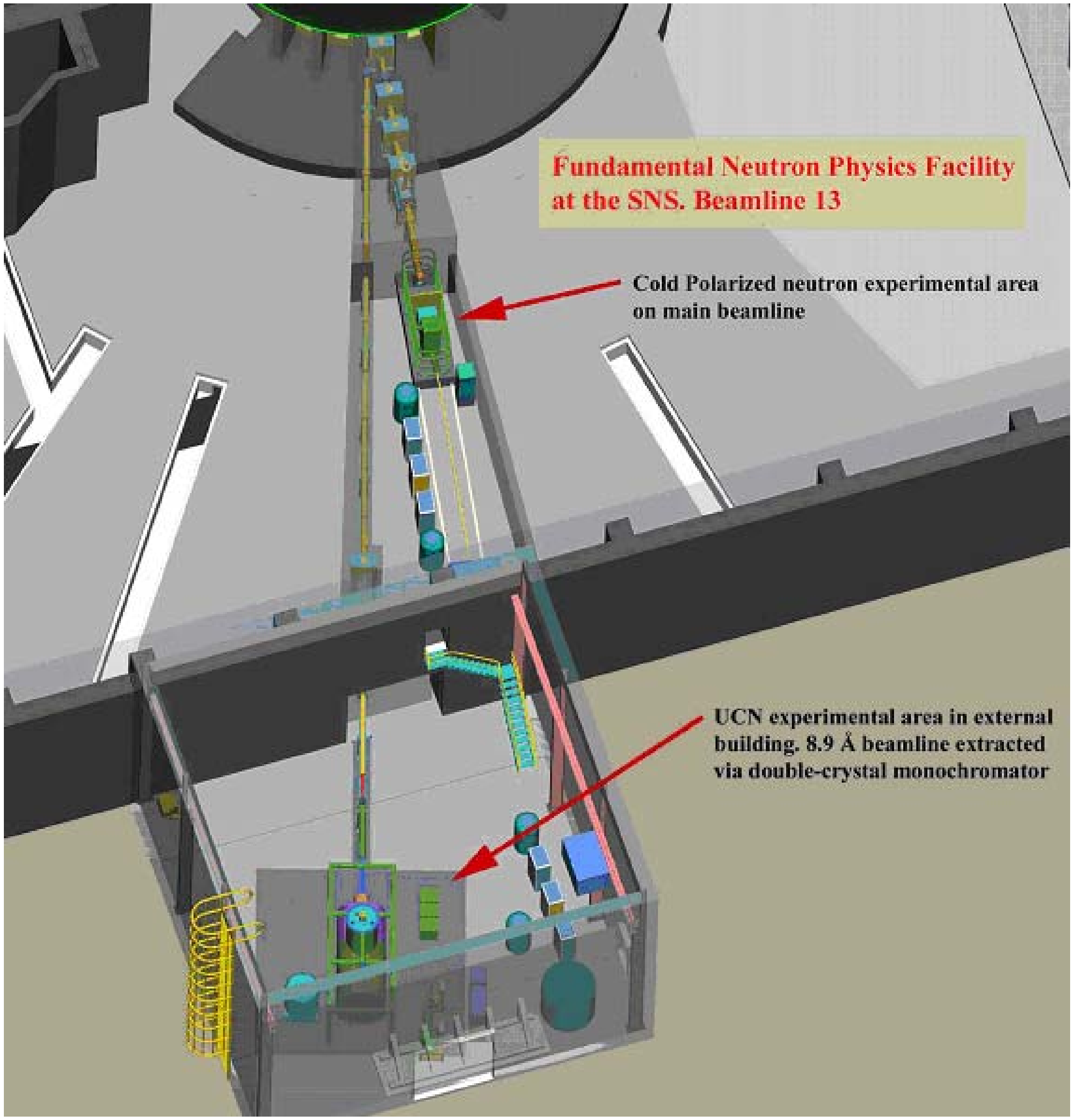
Ultra-Cold Neutrons

- Accelerators have several advantages for UCN production
  - Lower heat level in the system per unit neutron flux
  - Fewer gammas per neutron – less heating

- It is not clear which of the two methods of UCN production is 'better'
- Each one of the two methods is better for a particular class of experiments (nEDM vs. neutron lifetime)

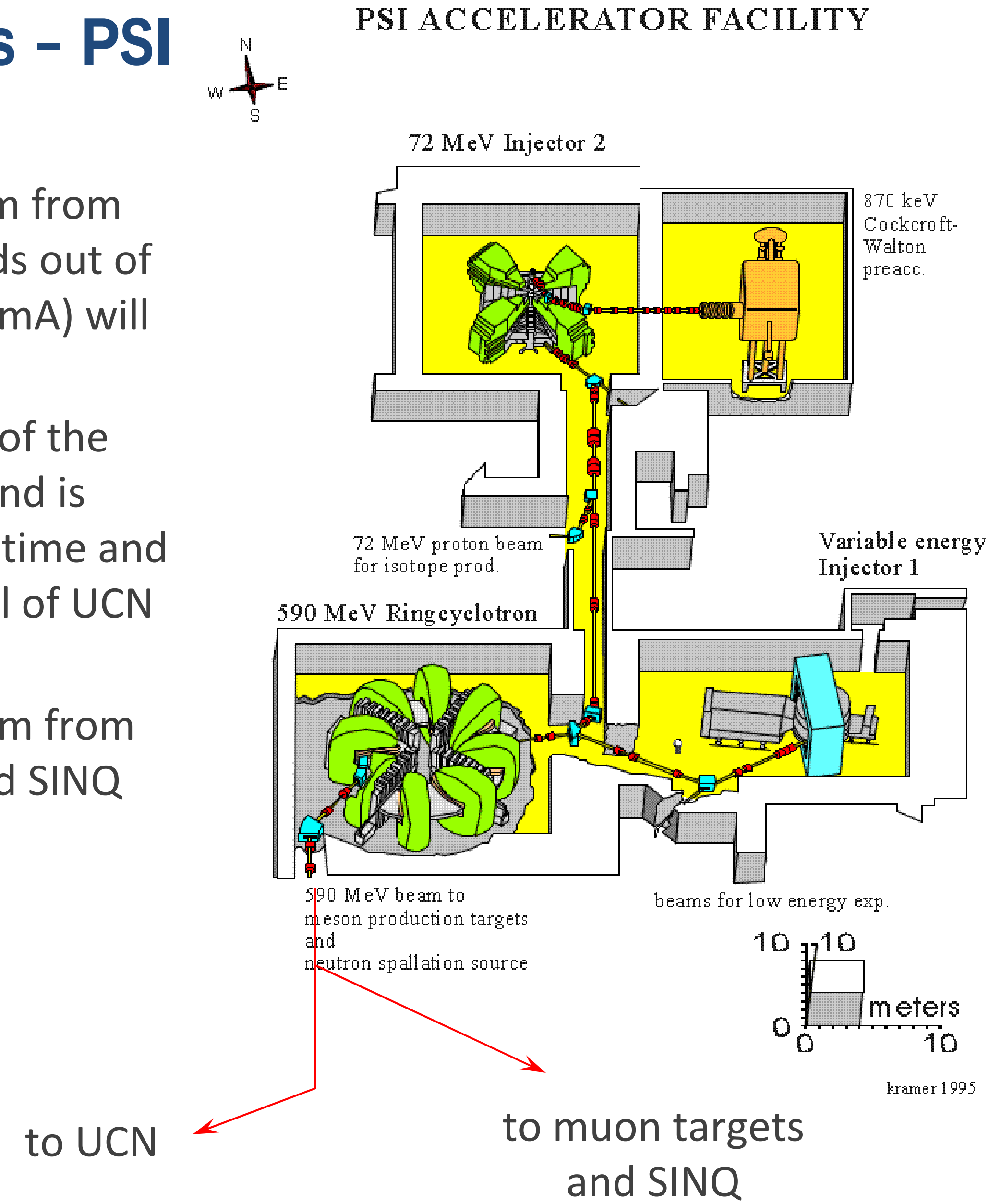
Fundamental Nuclear Physics Beamline at SNS

- Fundamental Physics beamline views the bottom downstream moderator, which is the fully coupled hydrogen moderator
- UCNs produced by scattering 8.9-Å neutrons from a double monochromator and then downscattering in He-II
- This moderator has peak flux at about 4 Å
- For UCN production, would love to have a moderator optimized for production of 8.9-Å neutrons
- This is not a UCN source!!



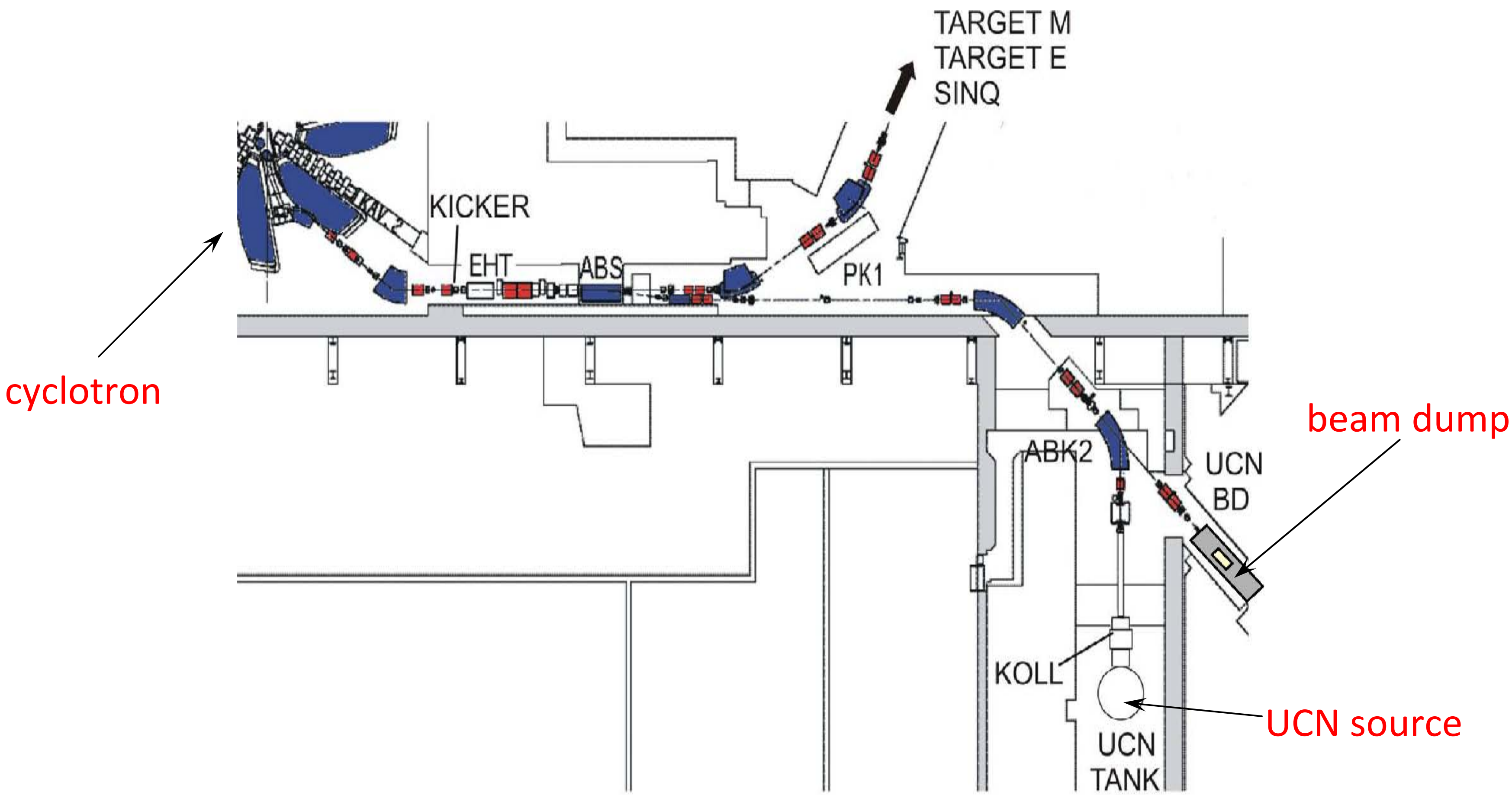
Ultra-Cold Neutrons – PSI

- A portion of the proton beam from the PSI cyclotron (4-8 seconds out of 800 seconds) (590 MeV, 2.2 mA) will be used to produce UCNs.
- Duty cycle allows re-cooling of the converter between pulses, and is consistent with the short fill time and long observation time typical of UCN experiments
- Only takes 1% of proton beam from muon production targets and SINQ



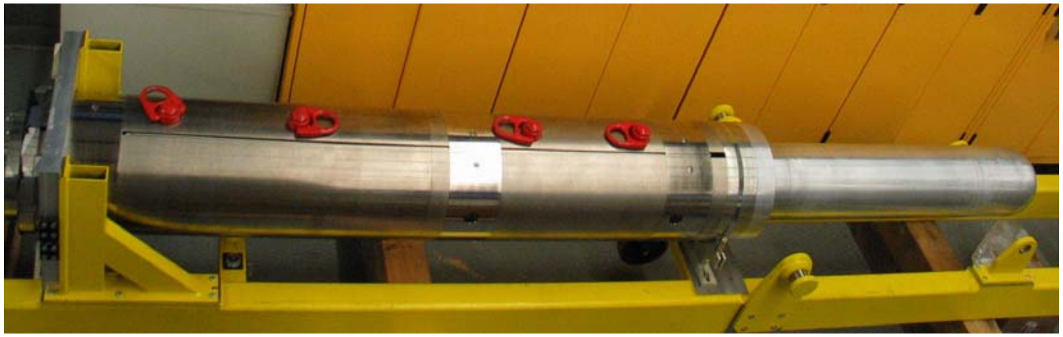
Ultra-Cold Neutrons – PSI

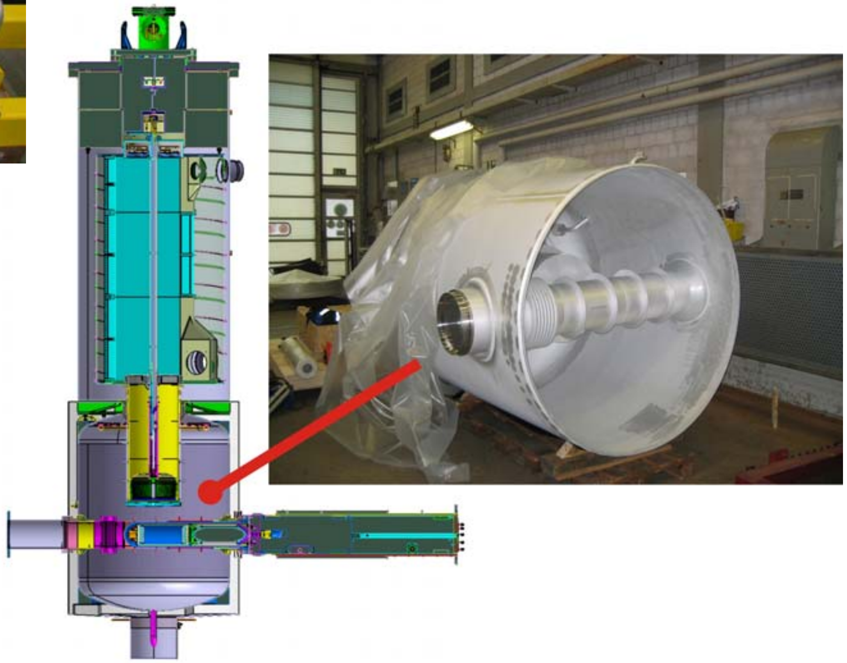
- Beam from the cyclotrons used to pass through this area to the medical physics area, which is now served by a dedicated accelerator



Ultra-Cold Neutrons – PSI

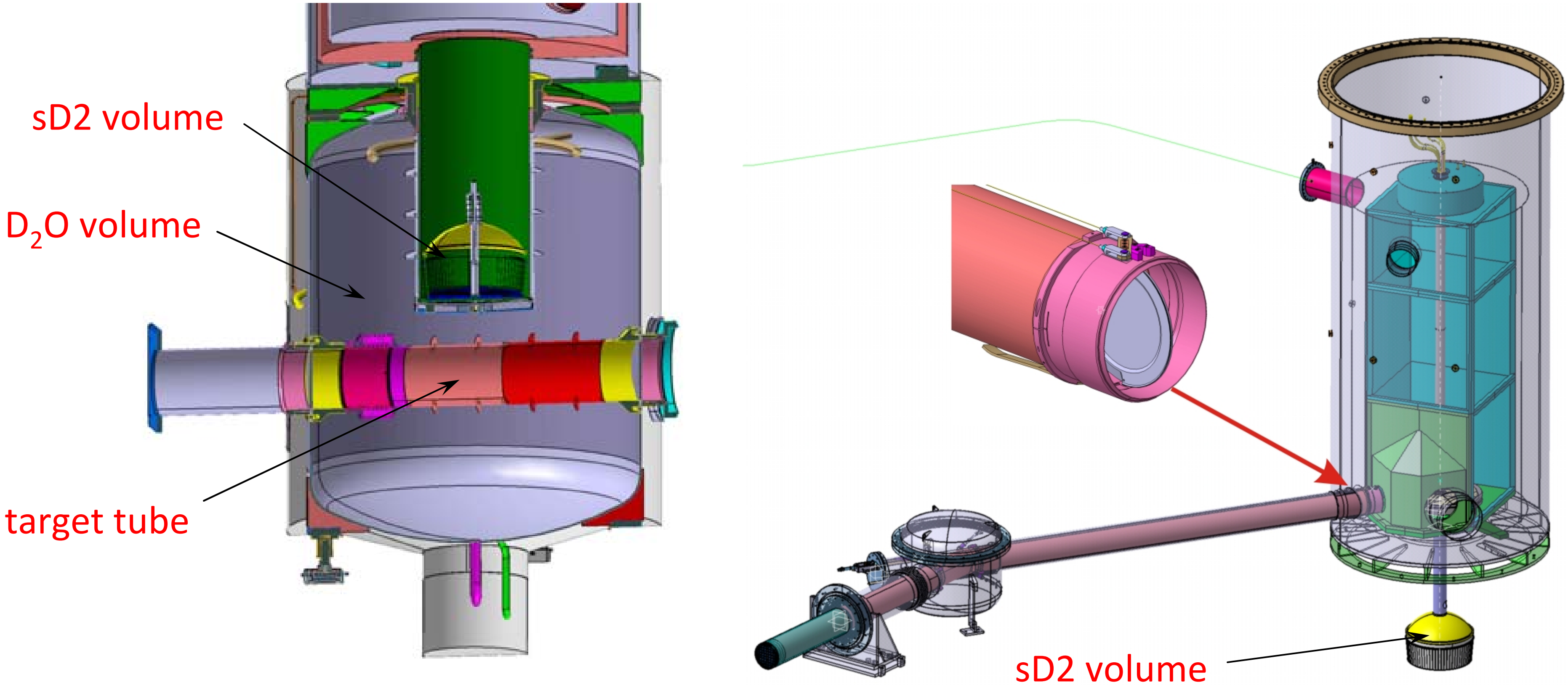
- Neutrons are produced in a canneloni-style target (lead inside Zircaloy tubes, 21 cm diameter and 55 cm long), and are then thermalized in an ambient-temperature heavy-water moderator





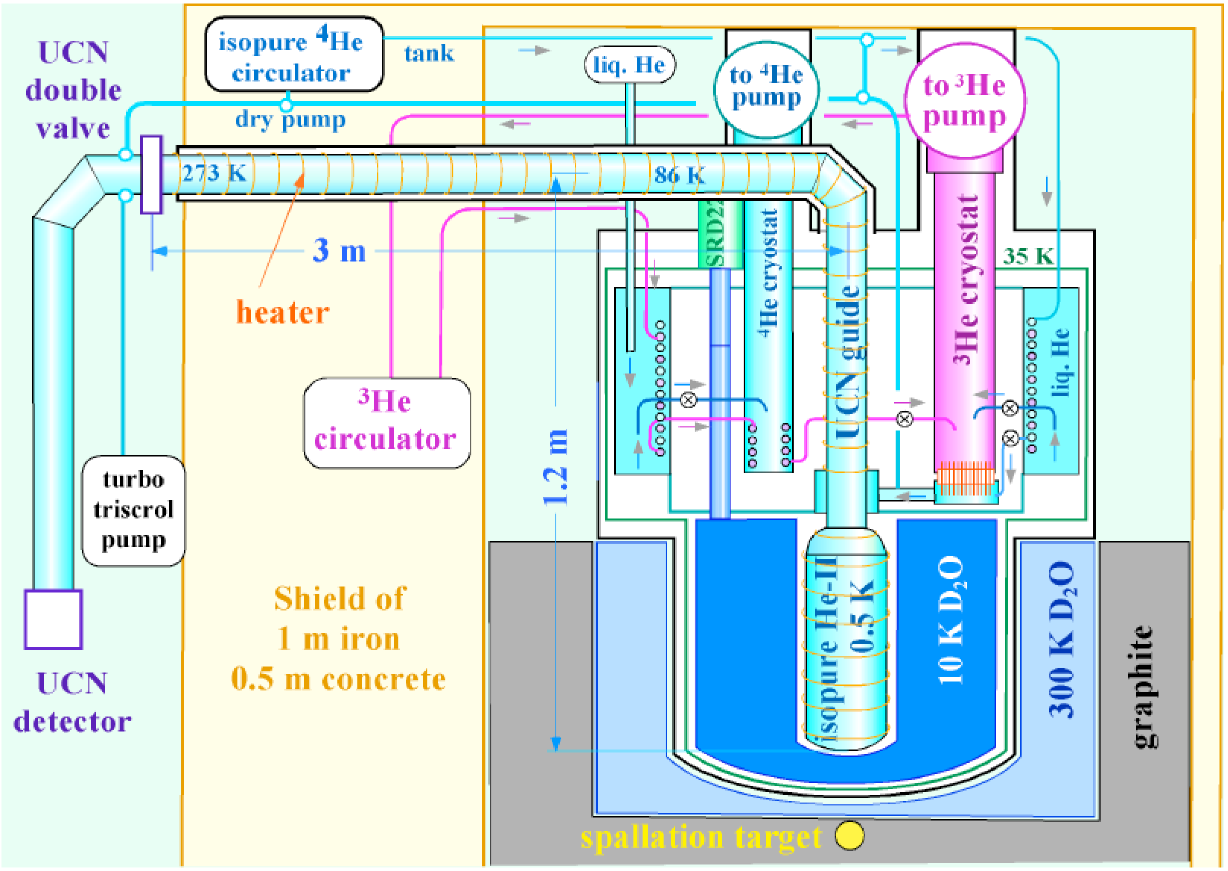
Ultra-Cold Neutrons – PSI

- The thermalized neutrons are further downscattered in a 30-liter volume of solid D_2 (50 cm diameter, 15 cm thick) cooled to 5 K
- Ultra-cold neutrons escape from the D_2 volume into a storage tank, from which they pass through guides to experimental areas



Ultra-Cold Neutrons – KEK (Japan)

- Neutrons produced by 200 nA of 392 MeV protons interacting in a 5-cm diameter, 20-cm long PB target
- Neutrons are moderated in ambient D_2O and cryogenic D_2O moderators
- UCNs produced by downscattering of 8.9-Å neutrons in 0.5-K He-II



What Would A UCN Facility Look Like at FNAL?

- Assume existence of a 2-GeV CW linac with available power 500-700 kW
  - Somewhat less power than available at PSI (1 MW)
  - Initial estimate – assumed same energy delivered to spallation target yields same UCN production – use higher (2%) duty factor to compensate
  - At PSI, 1 MW for 4 seconds ~ 4 MJ; at 500 kW, same energy delivered in 8 seconds
  - Power upgrades at PSI don't lead to increased UCN production, must reduce duty cycle at higher powers to prevent melting of sD_2
  - Higher energy spreads out neutron production in target – lower efficiency of UCN production?

- We are not thinking of a general-purpose neutron scattering facility (too expensive, and duplicative)
- Some results will also be presented for other proton energies

UCN Moderator Design Approach

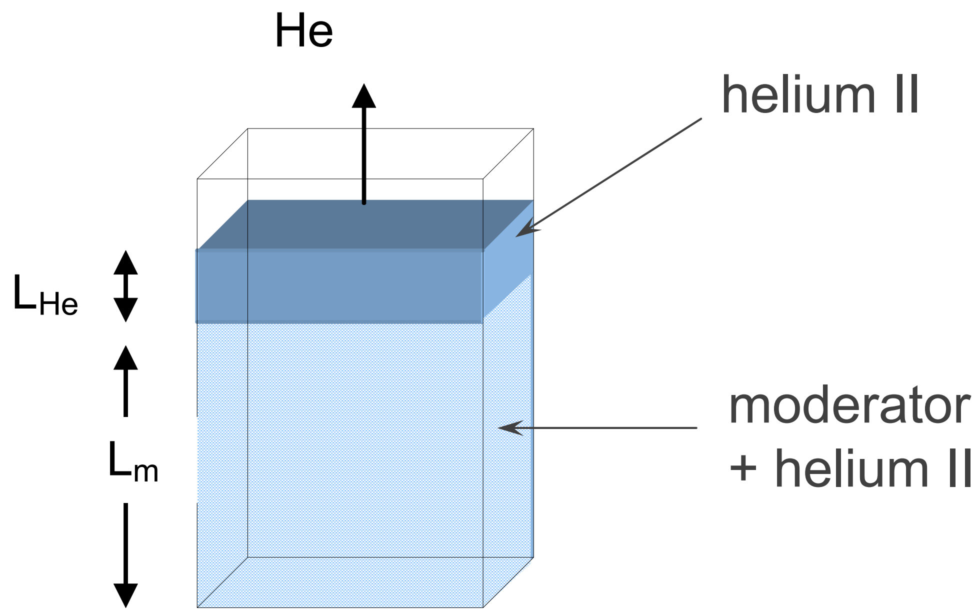
- Volumetric heating (mW/cc) in the UCN production region is the limiting factor
- The temperature of the moderator will rise during a pulse, and the heat must be carried away between pulses
- Because nuclear heating (fast neutrons and gamma rays from the source) decreases exponentially with distance from the source region, while neutrons, in the absence of absorption, are preserved in slowing-down, we expect to find a large radius at which the heating is acceptable and the cold neutron flux is as large as possible
- The source power in this approach is an adjustable parameter, which is a departure from convention in neutron facility design (we assume that we can take whatever fraction of the 500-700 kW we need, as long as it is not too large)
- The parameter to be optimized is the ratio of UCN production to nuclear heating in the moderator – this ratio improves with distance from the source, but at the sacrifice of ratio of cold neutron flux to source power

UCN Moderator Design Approach

- Perhaps the moderator physical form could be solid pellets cooled by superfluid helium
- Production of large quantities of mm-scale, solid pellets (CO_2, CH_4, NH_3, D_2, …) is an established technology. The same technology should be applicable to D_2O, which would produce low-density amorphous (LDA) ice

Moderator Cooling

- Can the heat be removed from the pellets without excessive temperature rise?
  - Rate of heat diffusion through pellet determined by size and thermal diffusivity $\alpha = k/\rho C_p$
  - Heat transfer into coolant determined by Kapitza resistance (mismatch of phonon spectra in moderator and coolant)
  - Enthalpy of He II between 1.8 K and 2.17 K is about 300 mJ/cm^3 – can absorb about 100 mJ/cm^3 (170 mJ/cm^3 of moderator)
  - Deposited energy must be removed before next pulse
- Preliminary heat transfer calculations in the liquid helium show that the heat conduction through the helium may be more of a limiting factor than the Kapitza resistance at the pellet surface (S. Van Sciver, Florida St.)
- Energy deposition may be limited by heat conduction to about 50 mW/cc



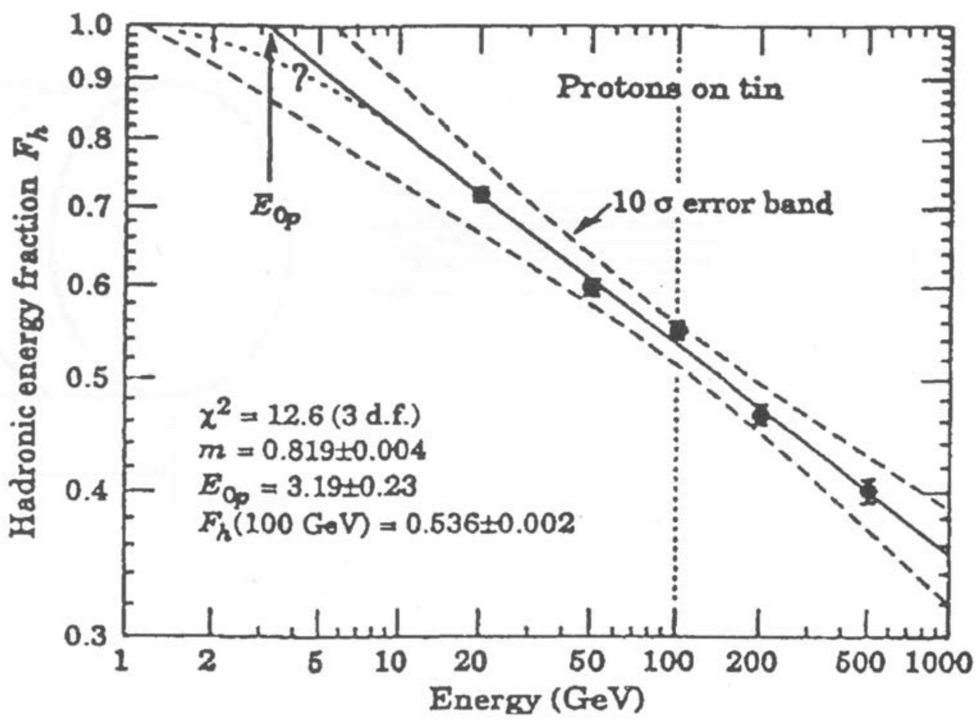
Summary of MCNPX Calculations for VCN/UCN Production

- Argonne studied concepts for a source of Very Cold Neutrons, for which the technology is very similar to that for UCN production
- A number of MCNPX simulations for a VCN source have applicability to UCNs

- Protons incident on bare target – neutron production and leakage vs. proton energy, target material
  - What proton energy and target material will maximize neutron yield?
- Target in heavy water moderator/reflector – determine best location for cold moderator
  - How do changes in the neutron production affect the neutron flux out in the moderator?
- Cold moderator inside heavy water moderator/reflector – long wavelength neutron emission vs. proton energy
  - How might selected proton beam energies affect UCN production?

Neutron Production from Spallation

- Optimum energy at or just above 1 GeV
- Calculations for higher energies, extrapolation to lower energies



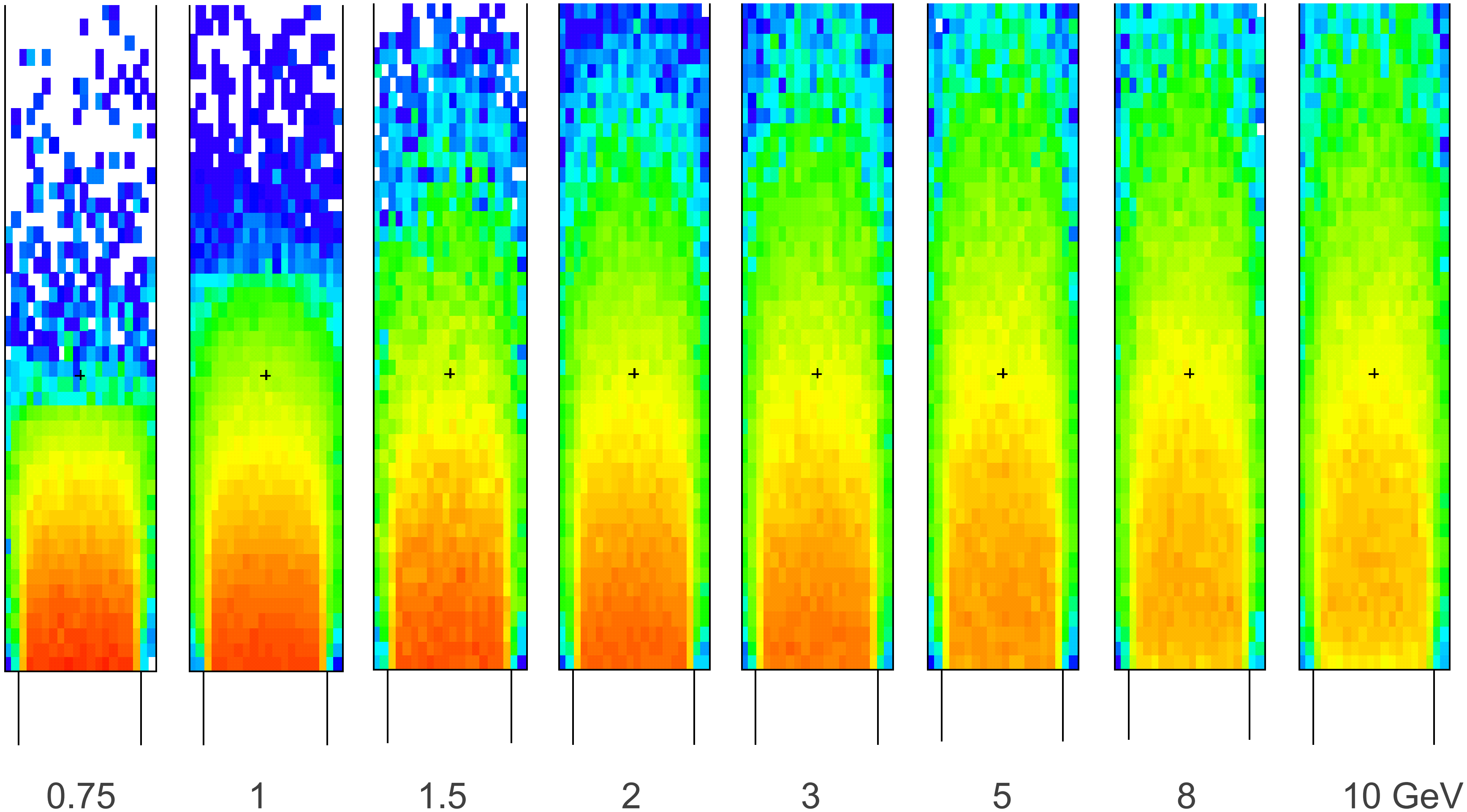
T. A. Gabriel et al., ANL-HEP-PR-93-69

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

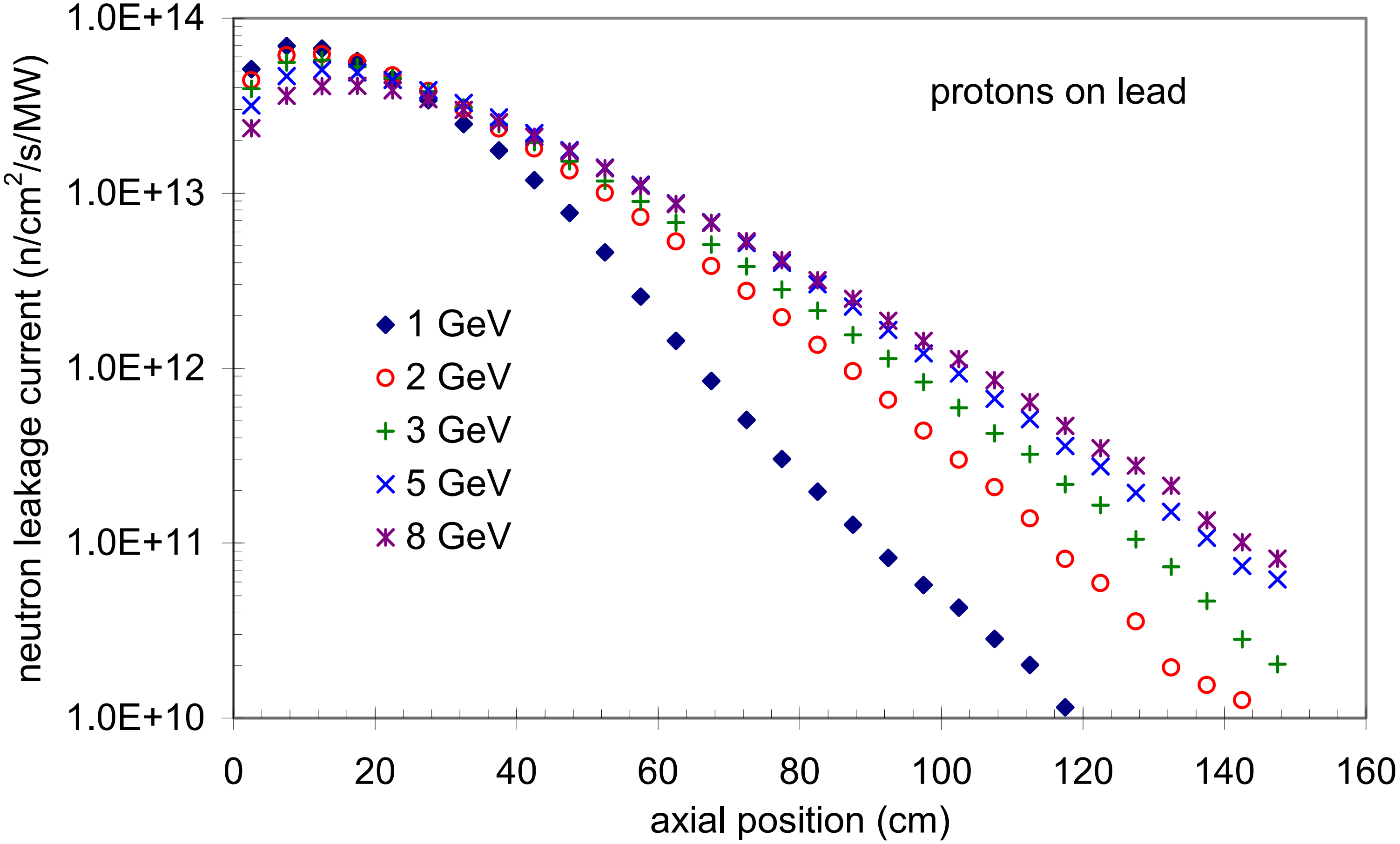
MCNPX Model – Target Neutron Production

- Proton energy varied from 0.75 to 10 GeV
- Lead target diameter 20 cm, length 200 cm; beam diameter 15 cm
- Color gradient the same for all proton energies



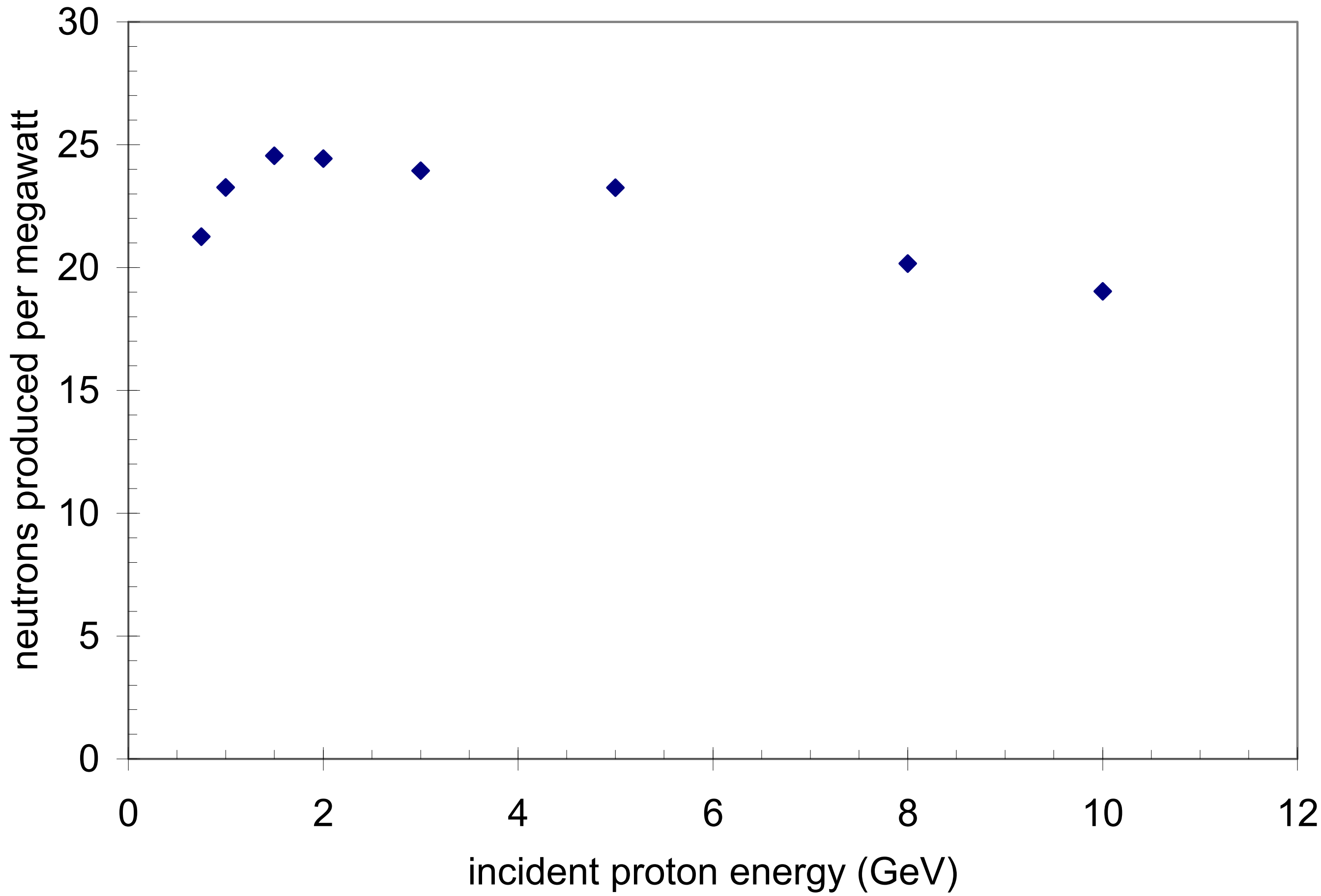
Neutron Leakage Current vs. Incident Proton Energy

- At higher proton energies, peak neutron emission is lower, broader, and shifted downstream



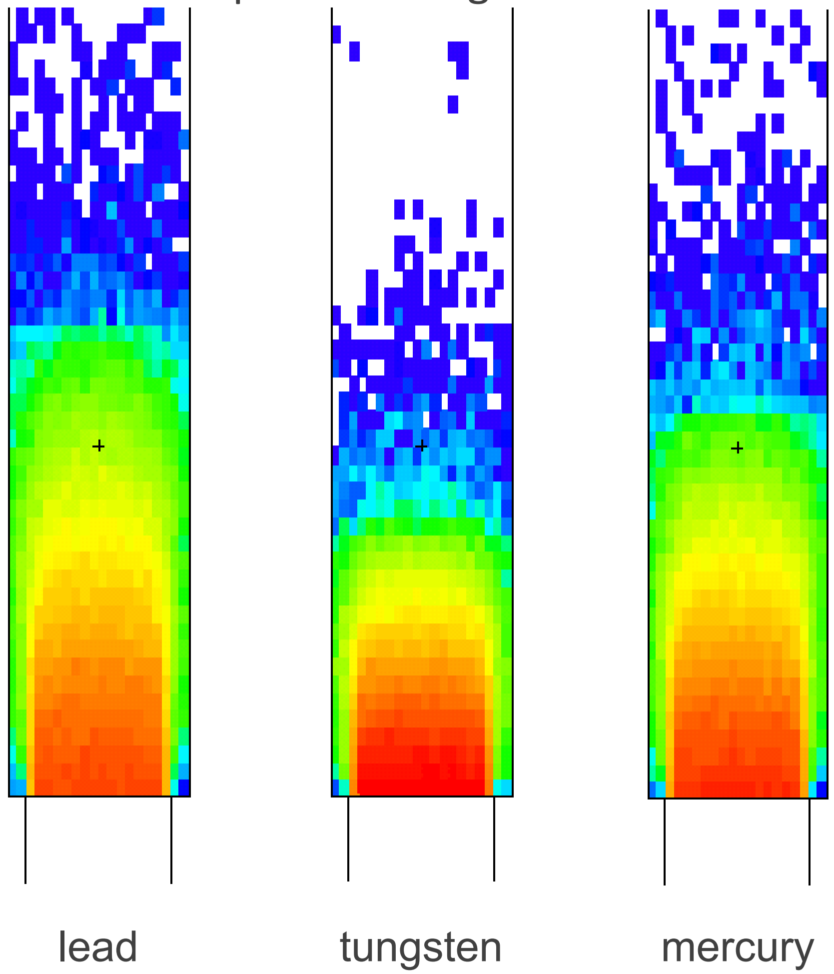
Neutron Production Efficiency vs. Incident Proton Energy

- Lead target diameter 20 cm, length 200 cm; beam diameter 15 cm
- Results consistent with measurements (geometry dependent)



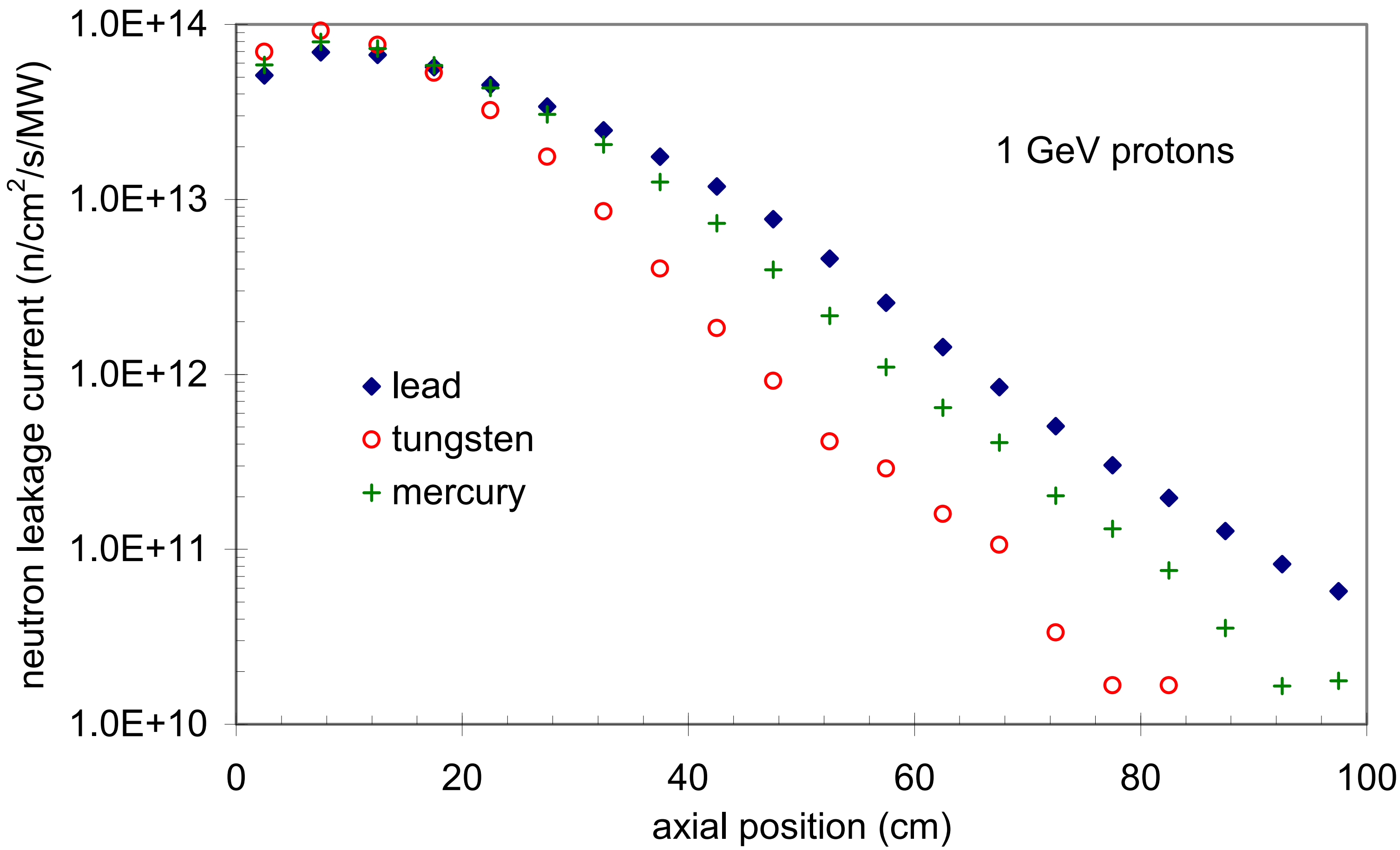
MCNPX Model – Target Neutron Production

- Considered lead, tungsten, mercury as target materials
- About the same neutron production in all three
- Color gradient the same for all proton energies



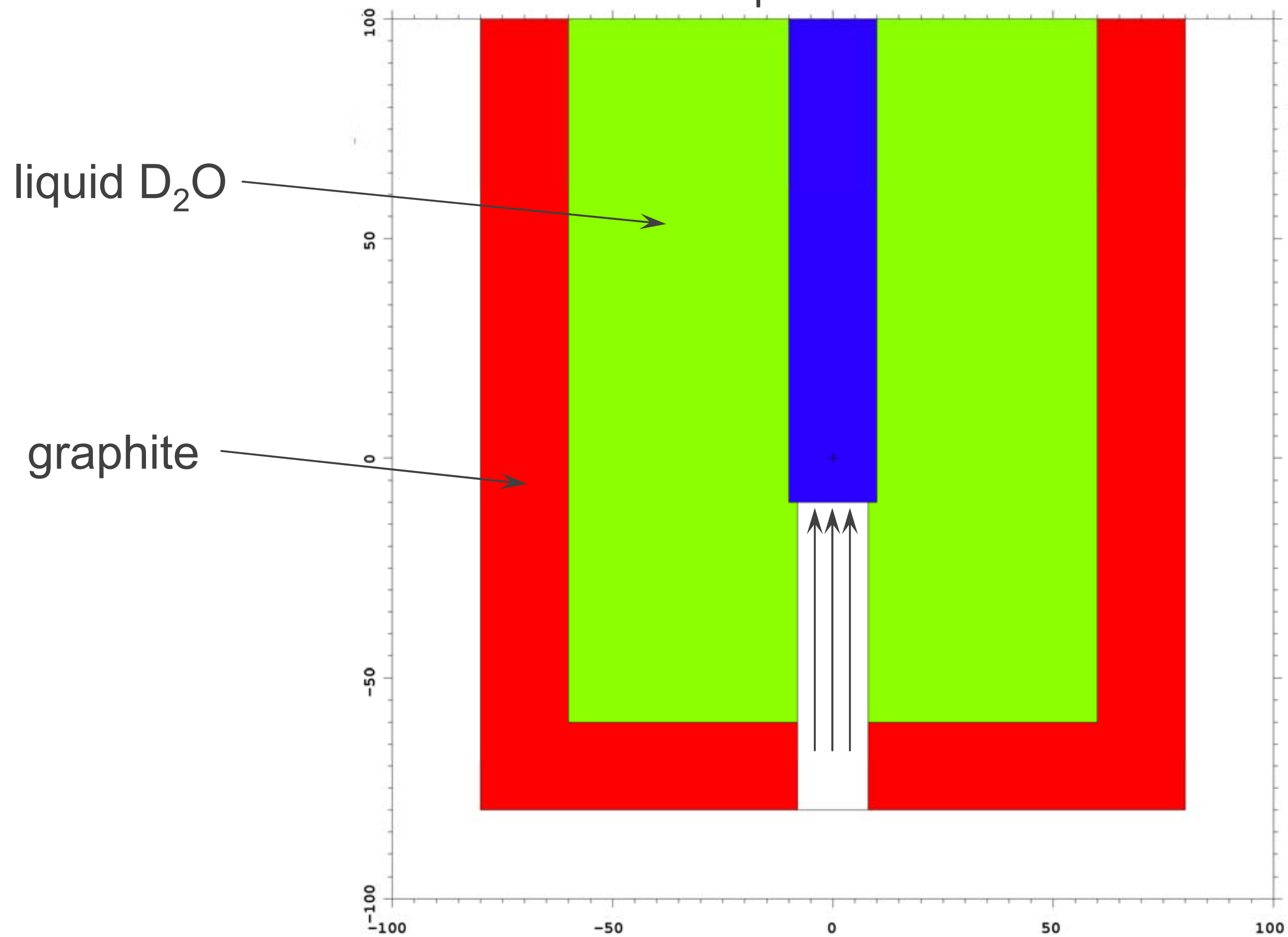
Neutron Leakage Current vs. Target Material

- For roughly constant Z, higher density leads to greater peak neutron emission which is narrower and shifted upstream

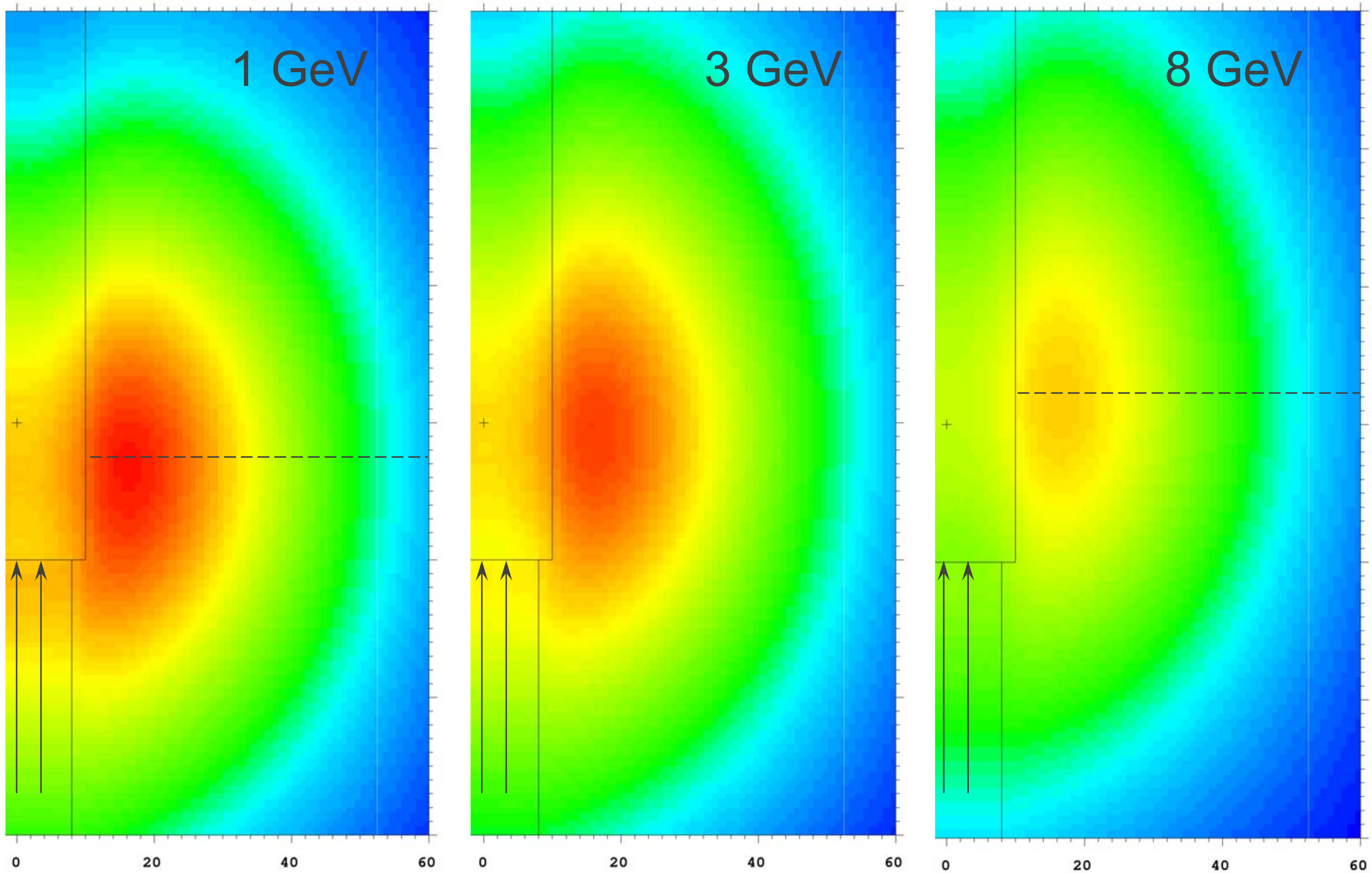


MCNPX Model - Moderator Neutron Flux Profile

- Lead target, proton energy varied from 0.75 to 10 GeV
- Calculate thermal neutron flux in liquid D_2O moderator/reflector
- This thermal flux is the 'source' for UCN production

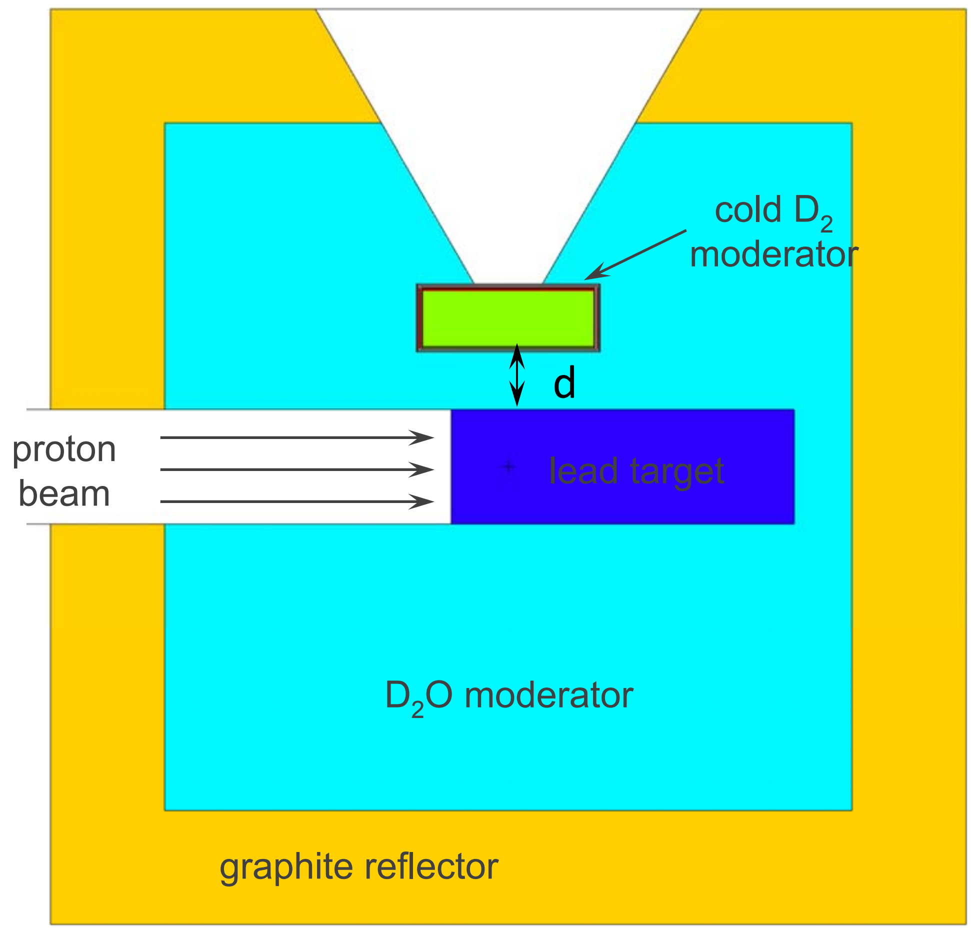


Neutron Thermal Flux vs. Accelerator Energy



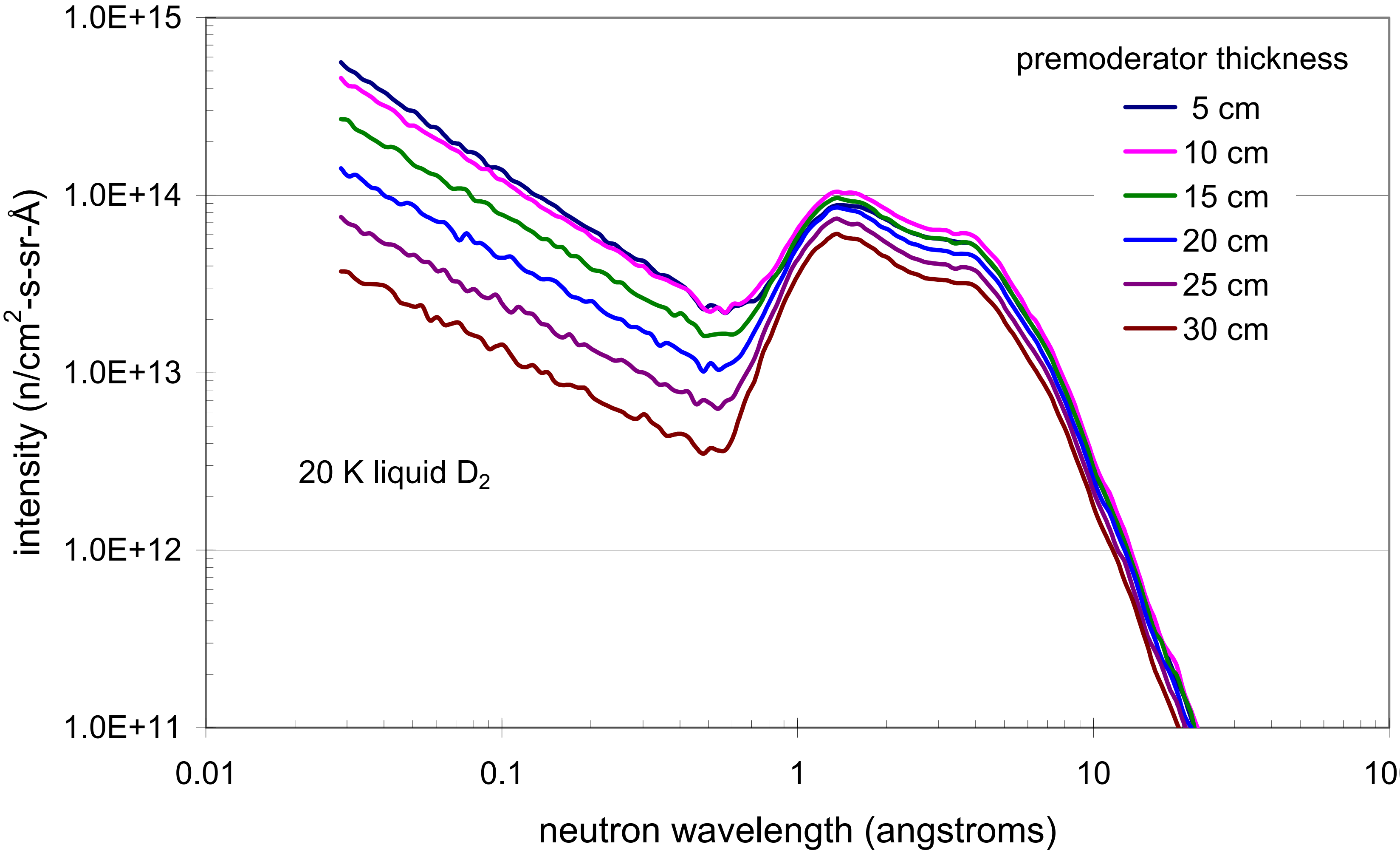
MCNPX Calculations for Cold Moderator

- For a given size of beam and target, vary cold moderator position (move further away)
- Calculate energy spectrum of neutrons emitted from surface of cold moderator
- Calculations use scattering kernel for liquid D_2 at 20 K



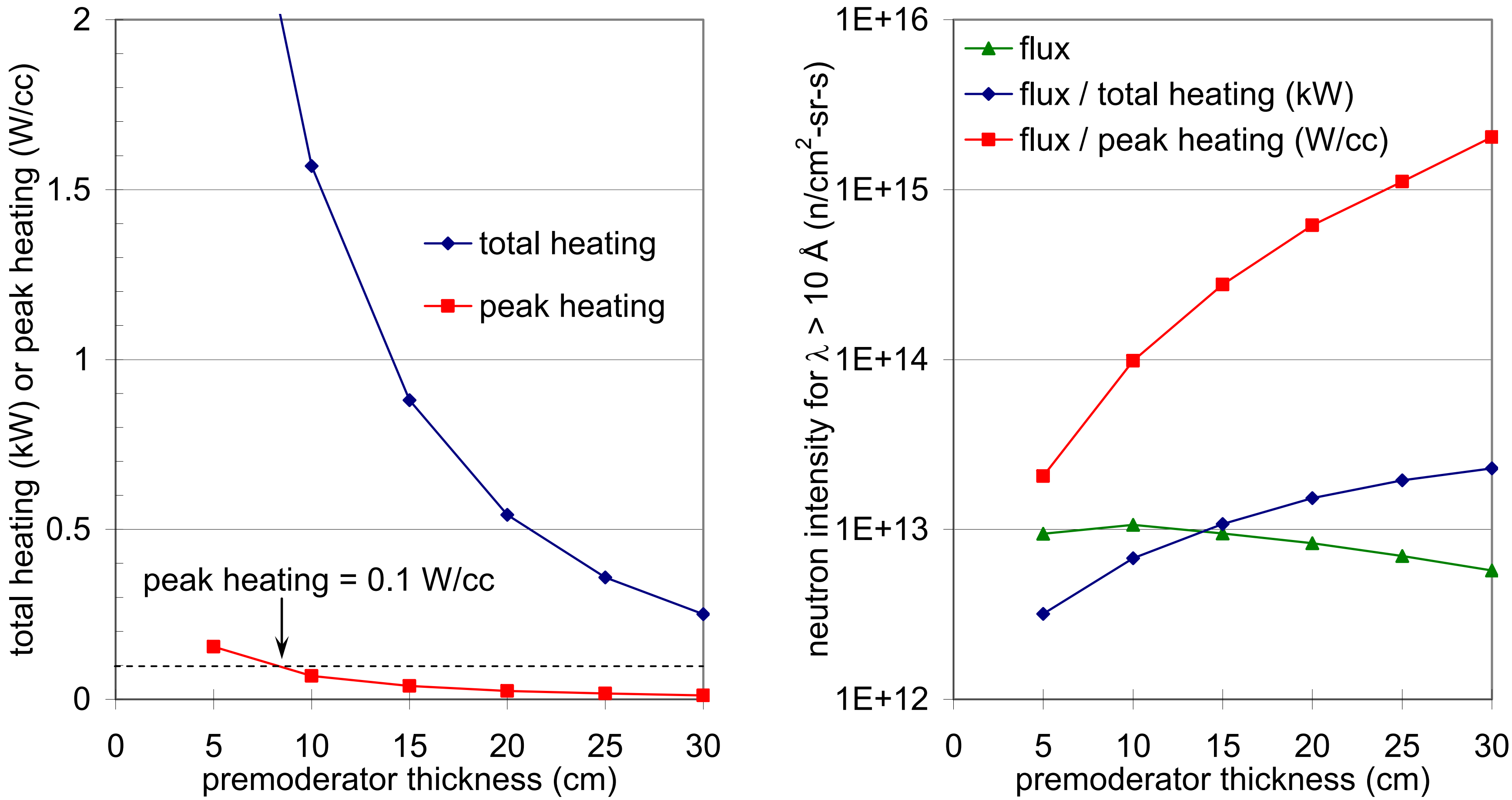
Modeling Results – Neutron Emission Spectra

- Premoderator thickness d varied from 5 to 30 cm (R_{target} = 10 cm)



Modeling Results - Neutron Intensity (λ ≥ 10 Å)

- Premoderator thickness varied from 5 to 30 cm (R_{target} = 10 cm)



Summary

- Accelerators have many desirable qualities for UCN production
  - Relatively low heating compared to reactors, favorable duty cycle possible
- UCN production will be limited by energy deposition in the moderator
- We can treat the accelerator power as an adjustable parameter
- The ratio of UCN flux to volumetric heating improves at larger distances from the spallation target

- Some serious study would be needed to determine whether UCN production at FNAL is viable
- Everything depends on the science case – what would this bring to the table that would be new – there are currently four nEDM experiments being planned (Greene)
- Need to take advantage of parasitic beam – no one will build an accelerator for UCN production alone
- How high can we push the UCN production?