International Neutron Scattering Instrumentation School

INFN—Laboratori Nazionali di Frascati
Rome, Italy
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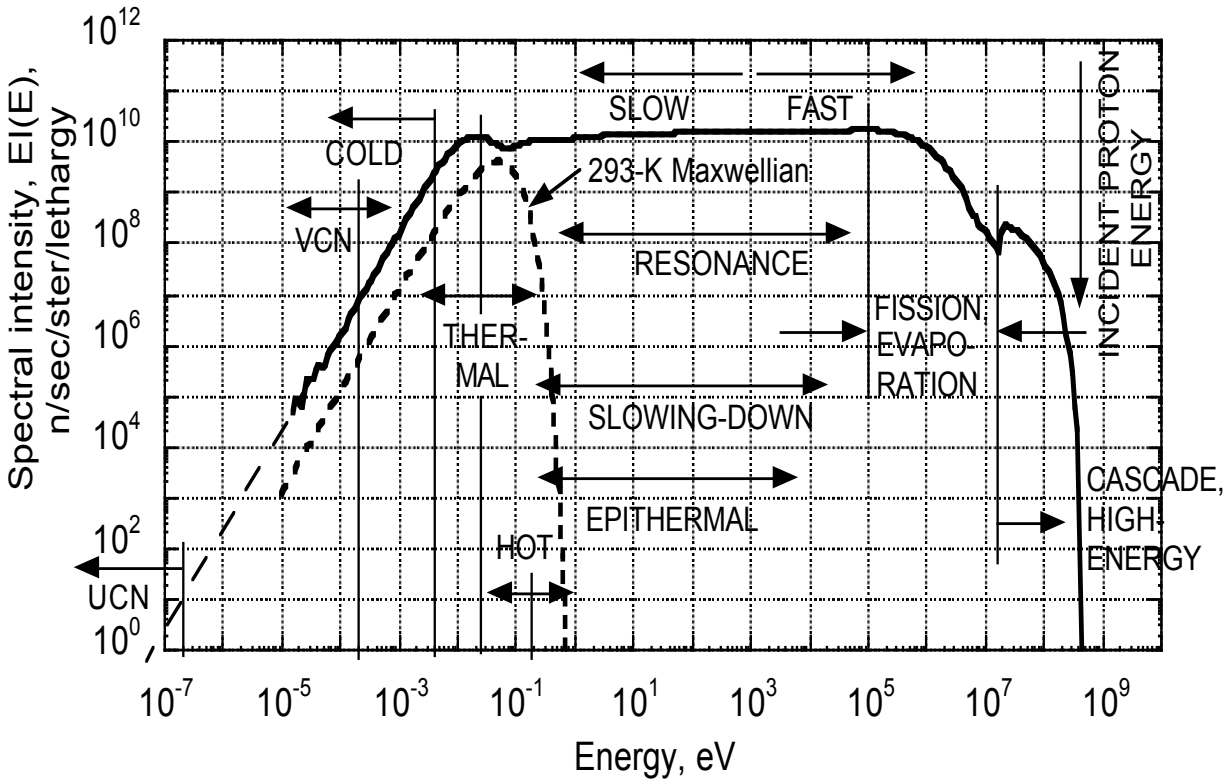
Perspectives on Future Neutron Sources

John M. Carpenter, IPNS, SNS

Fast and slow neutrons, etc.



Existing Research Neutron Sources

- Fission reactors—cold and hot sources—ILL, FRM-2, JRR3, HFIR …

- Accelerator-based spallation sources
  - Pulsed—RT and cold—ISIS, ISIS TS-2, SNS, JSNS, LANSCE, (ESS)
  - Steady—RT and cold moderator—SINQ

- Reactivity-pulsed reactor—RT and cold moderators—IBR-2, (Sorgenta Rapida = SORA, … —1960s)

- e^- Bremsstrahlung photoneutron sources—Hokkaido, RPI, …

- Low-energy particle-driven compact accelerator-based source(s)–LENS, (CPHS, Bilbao, …)

  —UCANS-III will meet in Bilbao in August 2012—substantial efforts, ~12 involved laboratories—watch these

Existing Research Neutron Sources

- The first group serve as major neutron scattering research installations
- The electron linacs serve as centers for component testing and development of components and techniques
- The Compact Accelerator-based Neutron Sources (CANS) are under development as small, inexpensive sources for testing, training, and low-flux applications, and for prototyping of large sources.

Neutron-producing mechanisms

- Fission Reactors ~160 MeV heat per neutron
- Spallation Proton accelerators ~30 MeV heat per neutron
- (γ,n) Electron linacs ~2800 MeV heat per neutron

  Evaporation spectrum, ~ 2-MeV neutrons

- (D,T) Low-energy D on TiT_2 ~24000 MeV heat per neutron

  14.MeV neutrons

- (D,D) Low-energy D on D_2O even worse

  2. 2MeV neutrons

- p and D on light atoms: LENS See following data

Exotic ideas

- (D,T) Fusion devices ? heat per neutron

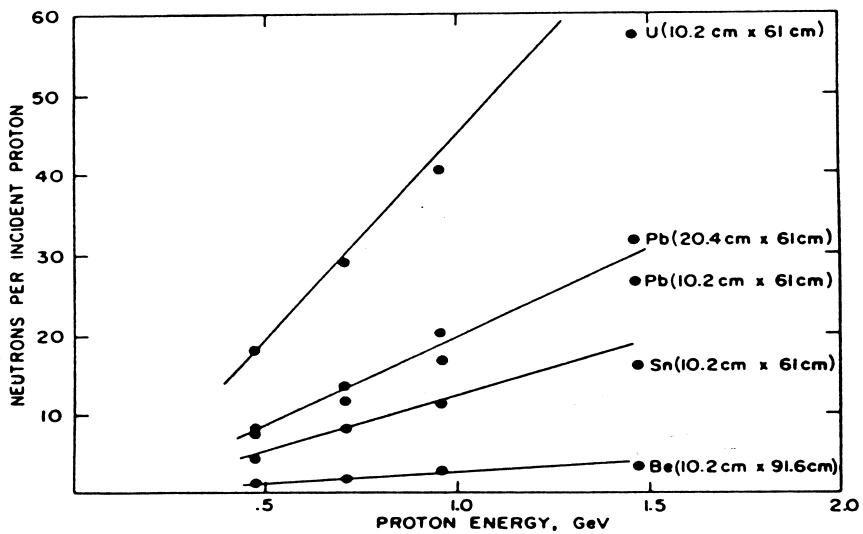
  14.MeV neutrons

- (γ,n) 15-MeV ICS γσ ον Τα ~600 MeV heat per neutron

  Λασερ βαχκσχαττερινγ φρομ ενεργετιχ ελεχτρονσ: εωαπορατιον

Fraser Spallation Neutron Yield Data

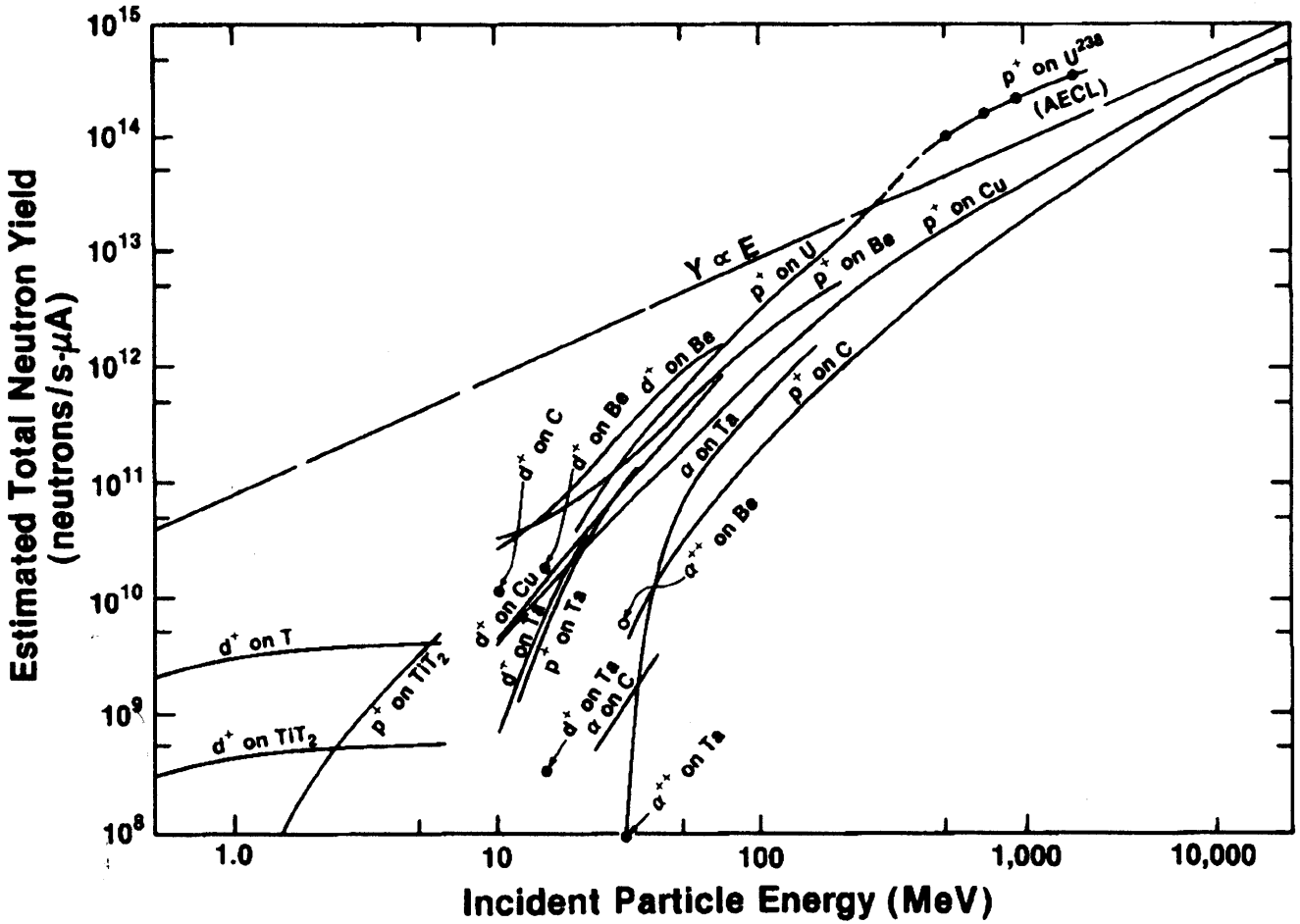
In the mid-1960s, John Fraser and his colleagues, in support of the Canadian ING project, carried out seminal, systematic measurements of thick-target (where incident particles lose all their energy and stop in the target) spallation neutron yields [Fraser et al. 1965].



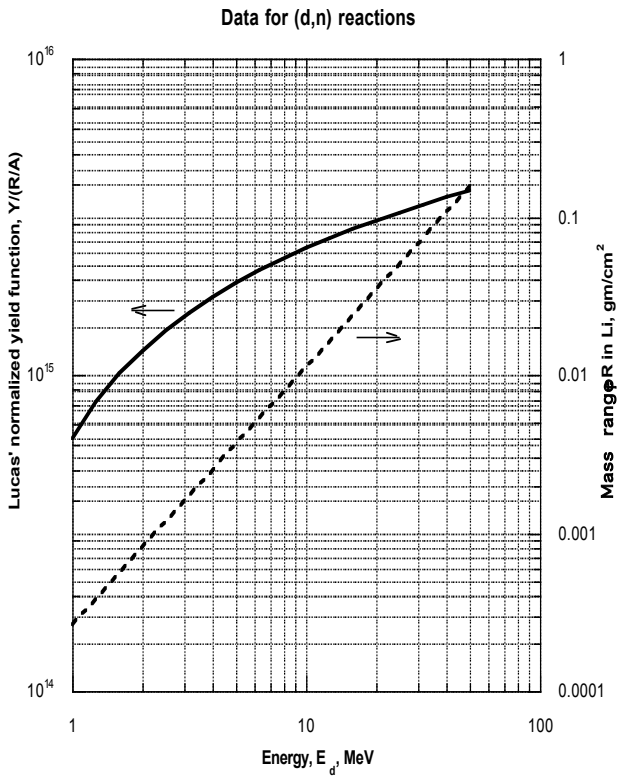
A function that reasonably well correlates the Fraser data is

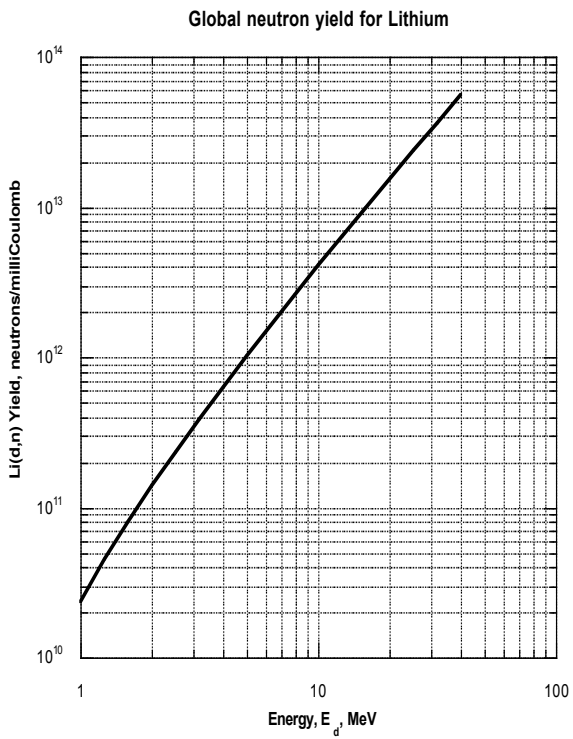
$$Y(E,A) = \begin{cases} 0.1(E_{GeV} - 0.120)(A + 20), & \text{except fissionable materials;} \\ 50.(E_{GeV} - 0.120), & {}^{238}\mathrm{U}\,. \end{cases}$$

Neutron yields vs. particle energy

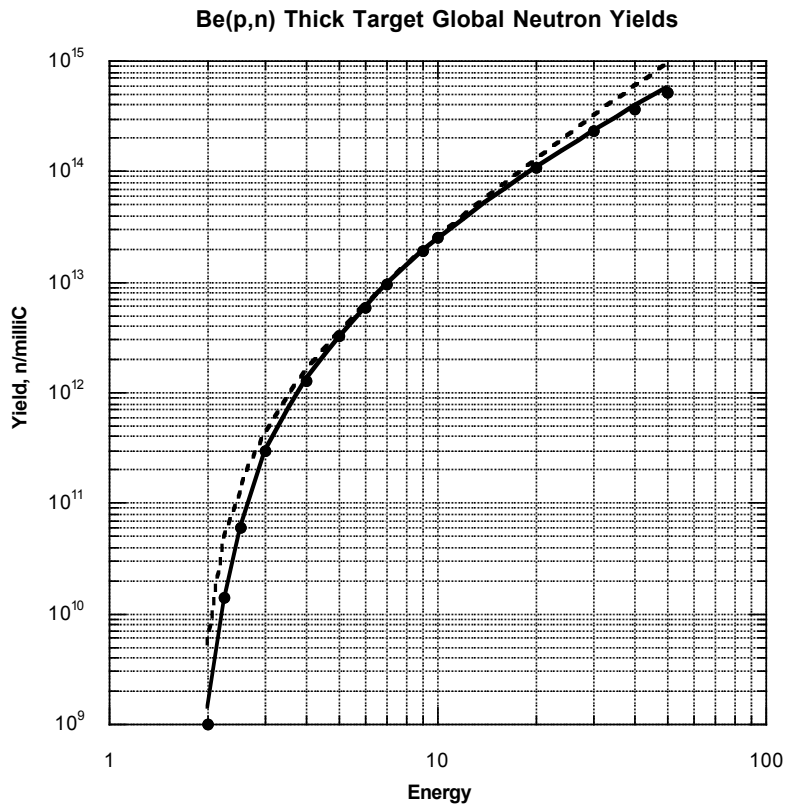


(D,n) Neutron yields





Be (p,n) Neutron Yields

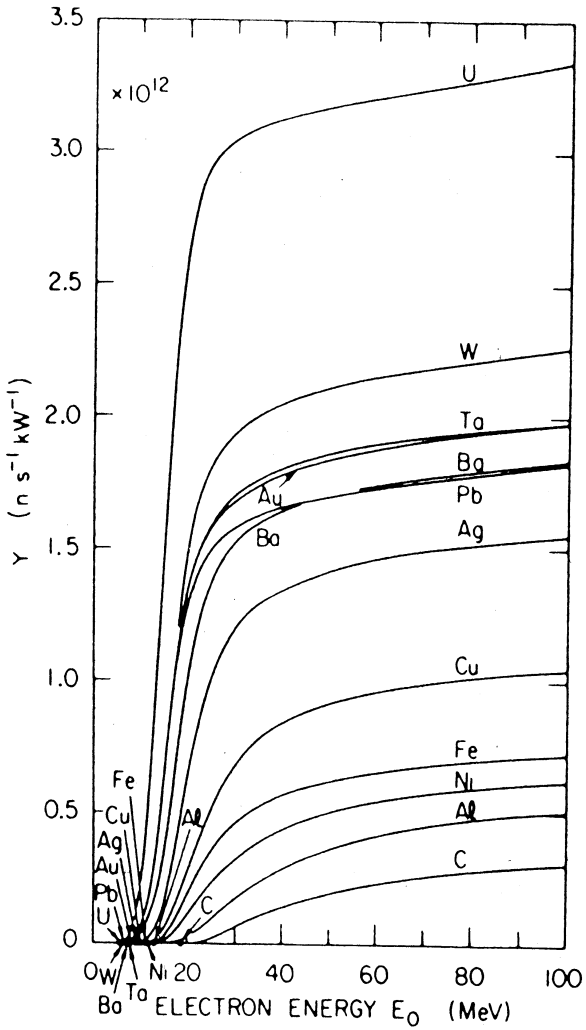


Nann [Lavelle et al. 2007] has proposed a simple function to fit the Be(p,n) data, which fits the data reasonably well,

$$Y(E_p) = 3.42\text{x } 10^8 (E_p - 1.87)^{2.05}$$

neutrons per millicoulomb.

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

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

Problems of neutron source design

Target design

Heat dissipation

- Use energy-efficient production process (spallation wins)
- Distribute heat (rotating target, liquid target)
- Pulsed operation (short heat pulse, slow heat removal)
- Low-afterheat target material (W better than Ta)
- Cavitation mediation (in liquid targets)
- Radiation damage

Safety

- Replacement, storage and disposal of spent components
- Remote handling, inspection

Problems of neutron source design

- Moderator design
  - Optimize spectra and pulse widths (integral part of instruments)
  - Maximize flux (geometric design, O/P ratio) (ISIS TS-2 example)
  - Material choice (CH_4, C_6H_3-3(CH_3),other HCs; H_2O, O/P LH_2)
  - Temperature (cooling He @100K, @25K, …)
  - Heat removal (flow vs. stationary,99.999% pure Al, Cu)
  - Radiation damage (material deterioration, burping, H_2 release, O/P conversion and maintenance, poison burnup)

Work on new ideas—theory, calculation and tests

– macroscopic: grooves; crystal-guided; SANS-based funnels …

– microscopic: anisotropic scatterers, e.g. oriented $(CH_2)_n$

– consult and join in community efforts

Spend time on methods for neutron beam characterization and modeling, including collimation and guide performance. Maintain design codes and measuring capabilities long into operation.

Problems of neutron source design

- Shielding
  - Biological—relatively easy
  - Background control —difficult, spend effort on calculations and materials choices; re ISIS TS-2
    - Spend time on materials choices
    - Refer to existing prototypes
    - Realize that the as built facility behaves uniquely—be prepared to chase backgrounds for a long time
  - Tangential beam ports

    Can get away with radial arrangement with curved guides and guide bunkers as in SINQ
  - Remember undesirable properties of materials—Cd, Gd and ^{10}B emit gamma rays
  - Lithium is nice but realize that most commercial material is depleted in ^{6}Li

Conjectural Neutron Source Ideas

- A number of novel ideas for neutron sources have recently come to light:
  - Laser fusion sources
  - Inverse Compton Scattering photoneutron sources
  - Halo nuclei
  - Laser plasma proton spallation sources

Laser Plasma Proton Spallation

- Recent tests of laser-driven neutron sources have shown interesting results. [Zagar et al. 2005] Extremely short (~ps), acutely focused pulses of laser light (~kJ), produce tiny volumes (~μm^3) of high temperature (~10^{10} K) material in thin (Al) foil targets, resulting in beams of energetic (~10-50 MeV) protons that emerge from both sides of the foil. When these fall on heavy-element (Pb) targets, they produce short (~ns) pulses of (~10^9) neutrons by spallation reactions.

- One scheme is the laser-driven inertial fusion scheme of Taylor et al. [2007]. Pulsed laser beams brought to focus on a D,T pellet produce an intense source of 14-MeV neutrons. Moderators Nearby (not too near!) provide neutron beams for research purposes.

- Advances in pulsed laser technology, two-stage pulsing, and fusion target design might achieve a neutron source several orders of magnitude more powerful than any existing facility. Work spanning several decades, pursued on behalf of fusion energy applications, will be required to bring about this development, which receives lavish funding for fusion energy purposes.

Inverse Compton Scattering Photoneutrons

- Relativistic electrons collide head-on with laser photons, whereby the photon gains a significant fraction of the electron kinetic energy—Inverse Compton Scattering (ICS) . The process can produce photons in the gamma-ray range with electron machines of ~ GeV energy. For example, a 0.06-J, 1-μm-wavelength laser pulse colliding with a bunch of $2x10^9$ 875 MeV electrons could produce photons of 14-MeV energy. [Moncton 2011] These, exciting heavy nuclei through the giant dipole resonance reaction (GDR) lead to substantial production of evaporation (~ 1-MeV) neutrons.
- The process is more more efficient than bremsstrahlung photoneutron production because it avoids the intermediate, inefficient step of bremsstrahlung radiation and consequent target heating. A 1-kW-s beam of 15-MeV photons incident on a small tantalum target would produce about 10^{13} neutrons [Micklich 2011]. This amounts to about 600 MeV heat per neutron.
- Requires an electron storage ring similar to those that already exist in synchrotron light sources and in ones for other purposes.

Halo Nuclei

- *Halo nuclei* are nuclear isomers in the mass number range 40 <A < 80 or 140 < A< 180 , in which the last neutron, loosely bound, approaches zero binding energy. They can now be produced using Compton backscattering gamma rays off brilliant electron beams. Having half-lives in the range of 100 ps to microseconds, these would have small neutron separation energies, from which neutrons could be released by a second low-energy, pulsed, polarized intense photon beam to produce a low-energy, pulsed, polarized neutron beam. Habs, Böni, et al. [2011] have evaluated this idea.

Prospects

- These ideas all are interesting and deserve attention. Plus others, when they come along.

- A less conjectural idea which has attractive prospects is that of a dedicated Very Cold Neutron source, which we have evaluated in some depth, and which I will describe in the following.

Very Cold Neutrons

- Very Cold Neutrons, VCNs, are those with "Rule of 2" parameters that might be produced from moderators at the temperature of superfluid He (2.2 K) in a broad range around and thereabout
    - Energies ~ 200 micro-eV
    - Wavelengths ~ 20 Å
    - Speeds ~ 200 m/s.

  Neutron optical devices work better at long wavelengths than at conventional wavelengths, because refractive indices are proportional to $(\text{wavelength})^2$, as is gravity droop, and 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.

Prospects for a Very Cold Neutron Source

VCNS

VCNS: Preliminary Considerations

- "As cold as is realistic" means 2-4 K, that is, a moderator at the temperature of liquid helium.
- Preliminary studies lead to Pb as target material and as fast-neutron shield, and to a 2-to-4 K pebble-bed of D_2O ice, solid D_2 or CD_4 moderator cooled by flowing L-He.
- The response time of a 2-K D_2O moderator, about 4 msec, indicates a "long-pulse" operating mode. Practical use of long-wavelength (~ 20 Å) neutrons requires long interpulse intervals, therefore a low pulsing frequency.
- We assume 1.5-MW proton beam, 4-msec pulse width and 5-Hz pulsing frequency, indicating a linac accelerator driver.

VCNS: Safe Observations

- Production of large quantities of mm-scale, solid pellets (CO_2, CH_4, NH_3, D_2, …) is an established technology
- Target technology presents no overwhelming challenges.
- A prolific source of Very Cold Neutrons with wavelengths ~ 20 Å, energies ~ 100 μeV will serve applications in studies of large structures and slow motions: nanotechnology and biological sciences

VCNS: Challenges

- Neutronic simulations require scattering kernels that don't exist for the temperatures of interest—developing these kernels requires considerable effort.

- Data on low-temperature thermal conductivities and specific heats of candidate moderator materials are sparse, yet essential to evaluating static and dynamic effects of moderator heating.

- Heat transfer calculations for L-He cooling is a special field, e.g. in superconducting accelerator components.

VCNS: Challenges, more

- There is little or no experience with neutron scattering instruments suitable for the expected scientific applications and for use of very cold neutrons in the long-pulse mode.

- ANL convened a Workshop on Application of a VCNS held 21-24 August 2005. See Proceedings of the Workshop on Applications of a Very Cold Neutron Source ANL report ANL05/42.

- Instruments are likely to rest heavily on neutron optical devices all of which work better at long than at short wavelengths. Beam modulation and spin-echo methods loom large.

- Concepts need to be developed and demonstrated.

- No prototype of VCNS yet exists on which to demonstrate the target, moderator or the instrument concepts, except at ILL PF2.

VCNS: Design Challenges

- The main problem to be overcome in the design is to reduce the nuclear heating (neutron and γ) in the moderator medium while maintaining a high Very Cold neutron flux in the moderator. The fundamental constraints are the low heat transport rates and low heat capacities of cryogenic materials.

- A new (to present day SPSS aficionados) aspect of the problem is that the instantaneous heating of the moderating medium can raise the temperature during the pulse to unacceptable levels.

- Need to avoid gamma heating of the moderator due to capture in the shielding, premoderator, reflector and moderator.

VCNS: Design Approach

- Because nuclear heating (fast n and γ 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.

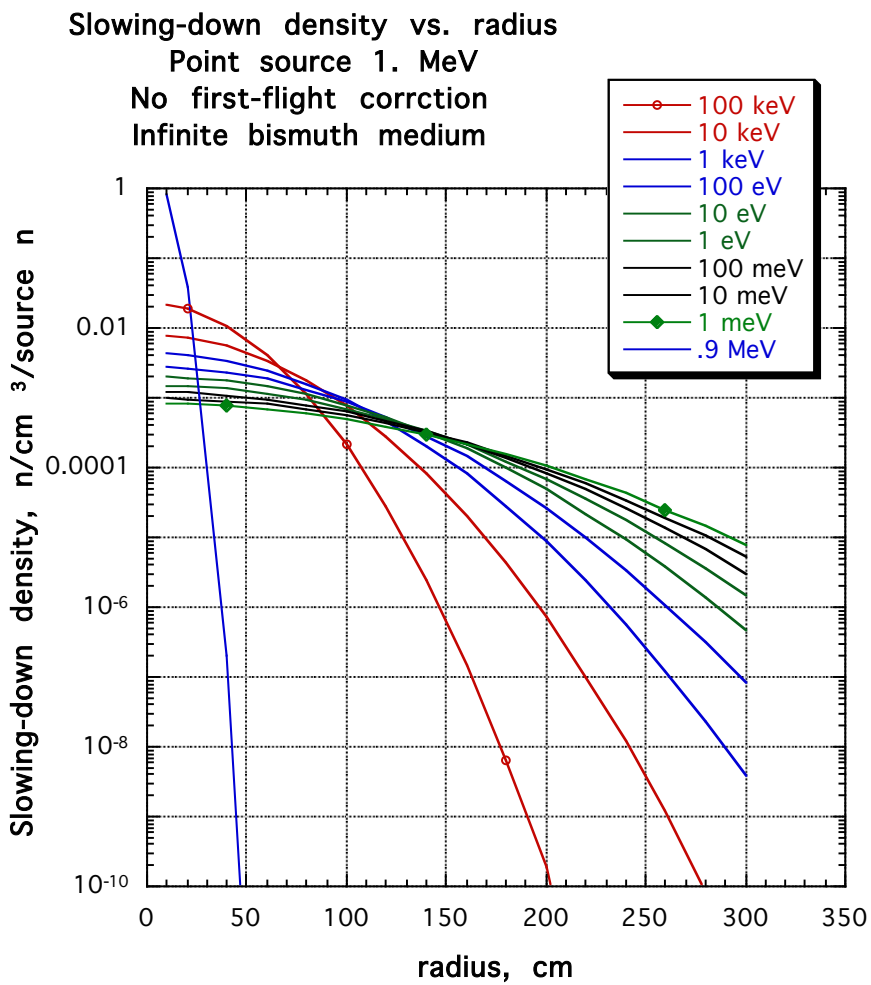
VCNS: Optimization

- The parameter to be optimized is the ratio of cold neutron flux 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.
- Moderator heating at large distances from the source seems to be predominantly due to capture gamma rays that originate in the shielding material.
- Optimizable parameters are the distance of the moderator from the source, the choice and layering of shielding materials, and the source power and pulsing frequency. The tool is MCNPX.

Feasibility of the VCNS Concept

- Whether it is feasible to build a VCNS rest on three key questions
  - Are there scientific applications that would use these long-wavelength neutrons?
  - Can we build instruments that can take advantage of the unique characteristics of the proposed source?
  - Will the performance of the source in practical terms enable the kinds of research that we hope to attract?
- Studies of neutron source performance are the key to answering the last question and fundamental to answering the second question.
- Most of this presentation deals with the source.

VCNS: Analytical Results



The figure shows the slowing-down density, q(r,E), of neutrons from a point source in an infinite medium of bismuth, calculated from classical theory.

Slow (~ 1. meV) neutrons survive at large radii, while fast neutrons and gammas that contribute to nuclear heating diminish substantially beyond radii of about 1 meter.

The flux per unit energy is related to the slowing-down density as $\Phi(r,E) = q(r,E)/\xi\Sigma_s E$.

Relevant Activities Elsewhere

ISIS TS-II

—optimization of TMRS using MCNP imbedded in an optimization routine.

ESS

—development of ideas for instruments for long-pulse neutron sources.

PSI Spallation Ultra-Cold Neutron Source (SUNS)

—development of scattering data for very cold moderator materials, operation of a UCN source. PSI hosted a workshop on Applications of VCNs in February 06.

Biennial meetings on UCN and cold neutron source technology are held in Russia (last meeting, St. Petersburg, June, 2012)

The PF2 UCN/VCN beam is uniquely available as a testing venue.

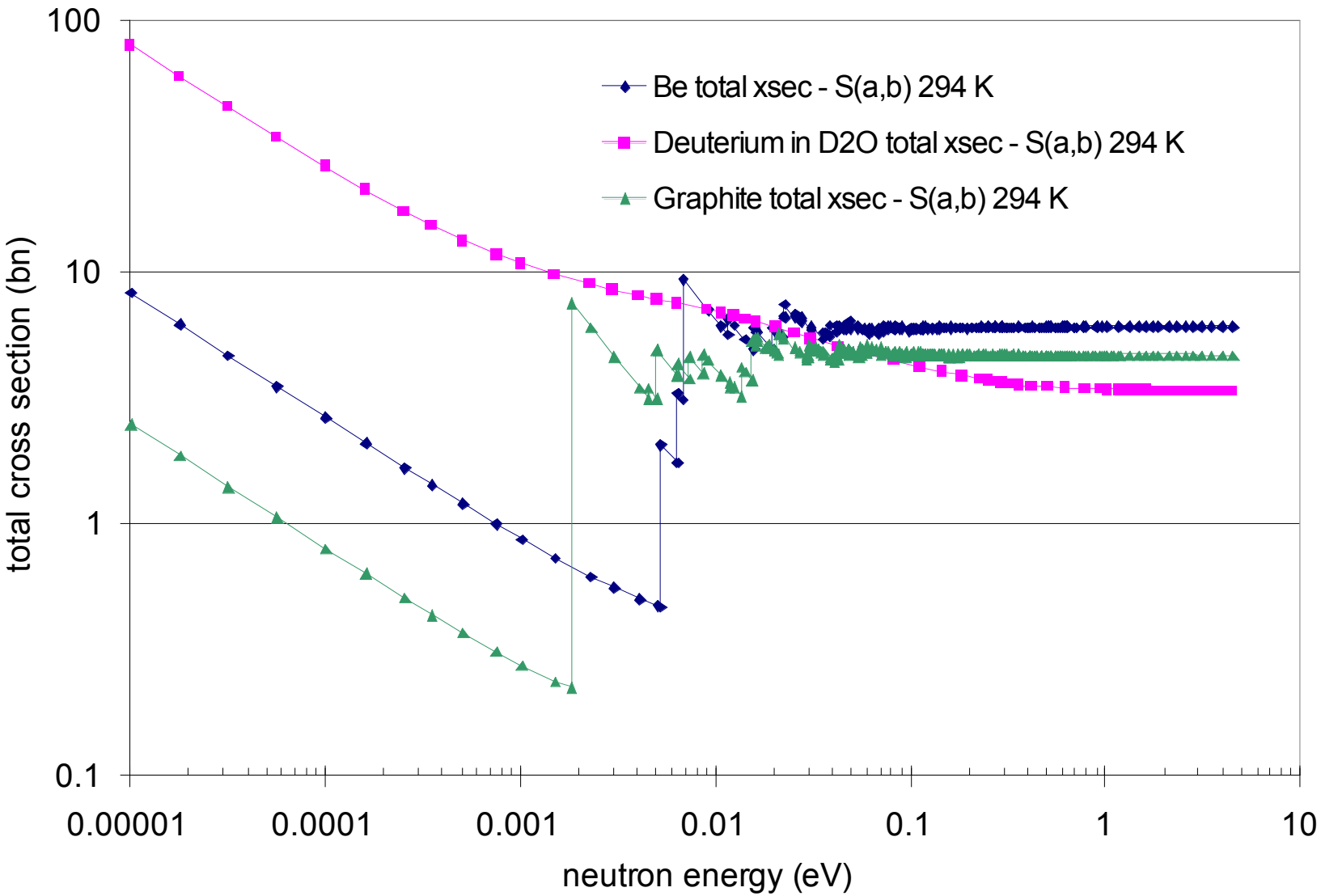
VCNS Accelerator System

- We have worked out the conceptual design of an accelerator system to drive the VCNS.
  - 1-GeV proton linac
  - Instantaneous current, 75 mA.
  - Pulse length, 4 msec
  - Energy per pulse 300 kJ
  - Pulsing frequency, 5 Hz.
  - 1.5-MW time-average beam power.
- The linac components are ones common in modern high-power proton linac technology.
- The VCNS will complement the capabilities of the SNS in the very cold neutron regime. The SNS accelerator system is not capable of driving the conceived VCNS.

Materials Selection

- Target
  - Need high Z, low neutron absorption
  - Candidates: Hg (some n absorption), Bi (^{210}Po production), Pb
  - Radiogenic lead (low in ^{204}Pb, ^{207}Pb) could reduce moderator heating due to gamma generation
- Warm moderator
  - D_2O (H_2O neutron absorption much higher)
  - Beryllium, graphite, lead?
- Cold/Ultra-cold moderator
  - Rely on D (D_2, D_2O, CD_4, etc.) rather than H
  - Need a material with incoherent scattering at low temperatures & neutron energies
  - Be, graphite (Bragg edges make these poor choices)

Cross Sections for Candidate Moderators



Radiogenic Lead

- All natural lead (204,206,207,208) is either "primordial" (i.e. produced directly in the supernova 4.56 Gy ago), or "radiogenic," i.e. the stable products of the three natural actinide decay chains. The Th-232 chain gives Pb-208; the U-238 chain gives Pb-206; the U-235 chain gives Pb-207. Lead-204 is only primordial.

- Different U and Th mines produce different isotopic ratios of lead as byproduct, which are advantageously depleted in the neutron-capturing isotopes ^{204}Pb and ^{207}Pb.

- For example, years ago, two varieties of radiogenic lead were feedstocks for ORNL Calutron production of isotope-separated reference lead materials. The table that follows compares the 2200-m/sec capture cross sections and the resonance capture integrals of the isotopes and example mixtures.

VCNS: Gamma Rays, Radiogenic Lead

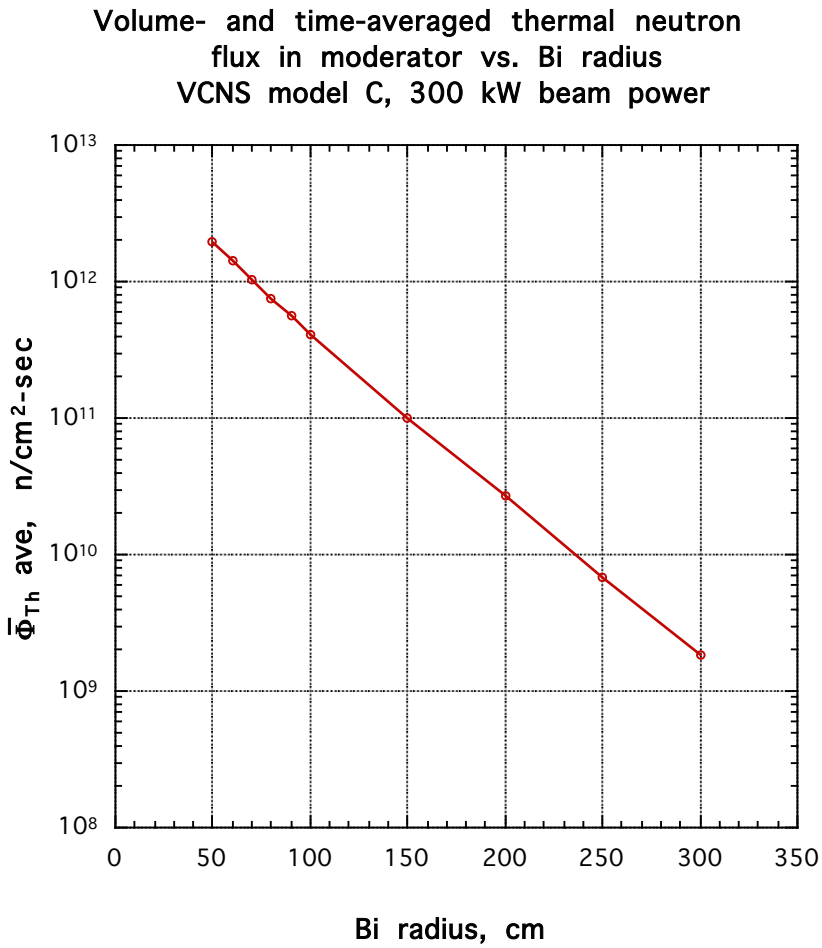
Gamma rays generated in the shielding dominate the heat production in the moderator. Radiogenic lead is available in isotopic compositions that reduce the capture rate in the shield.

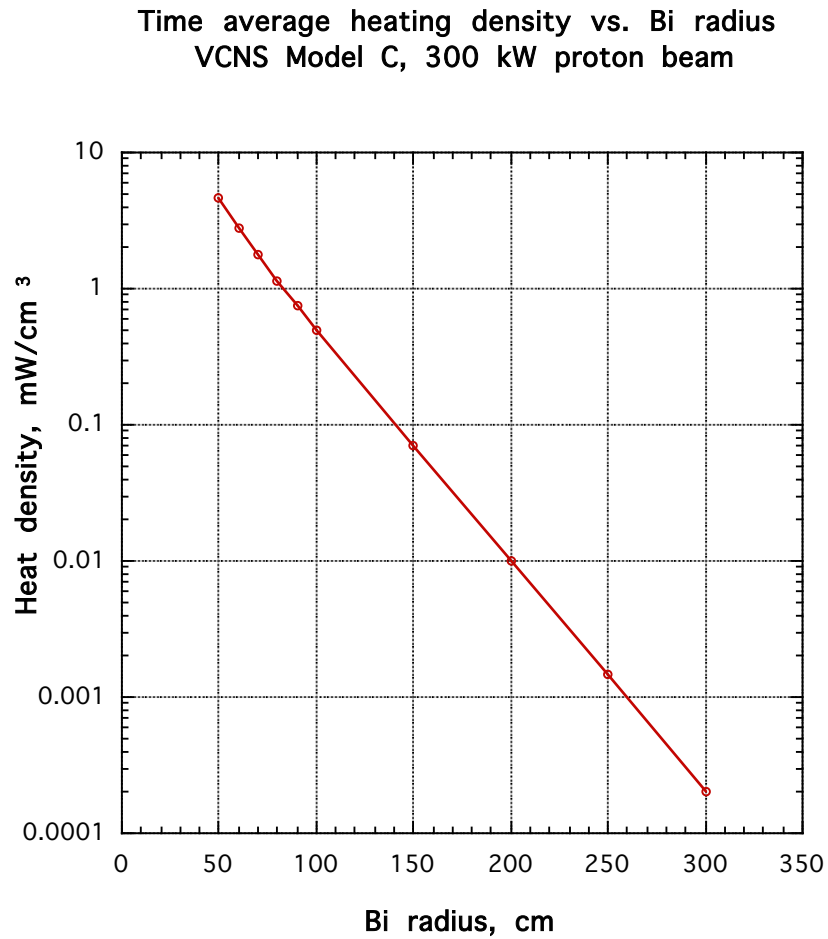
			Primordial Lead Standard Composition			Radiogenic Lead High-206 Lead			Radiogenic Lead High-208 Lead		
A	σ_γ, mb	I, mb	f, %	f σ_γ	f I	f, %	f σ_γ	f I	f, %	f σ_γ	f I
204	661.	1700.	1.4	9.2	24.	0.2	1.32	3.4	.024	.16	.41
206	30.5	200.	24.1	7.4	48.	87.8	26.8	176.	25.6	7.81	51.2
207	709.	400.	22.1	156.	88.	8.9	63.1	35.6	1.78	12.6	7.1
208	0.5	2.0	52.4	0.26	1.0	3.3	.017	.065	72.6	.36	1.45
				σ_γ	I		σ_γ	I		σ_γ	I
Averages				173.	161.		91.2	218.		20.9	73.2

Bismuth (monoisotopic), σ_γ = 34. Mb, I = 190 mb, is much superior to standard lead. However, the "high-208" radiogenic lead is better still.

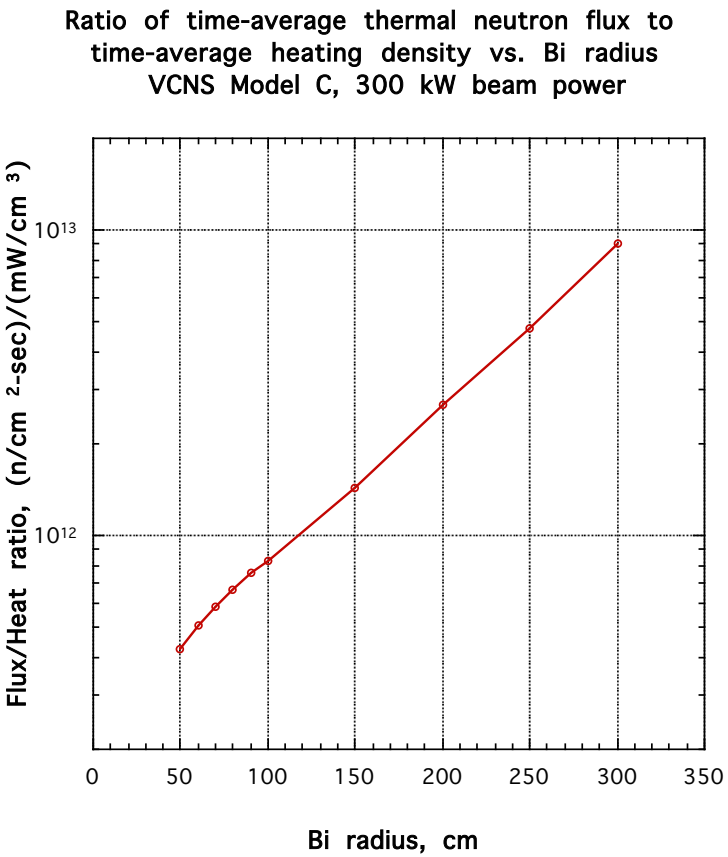
The average gamma energies emitted per capture are 5408, 6714, and 4663 keV for the three varieties of Pb, and 4604 keV for Bi.

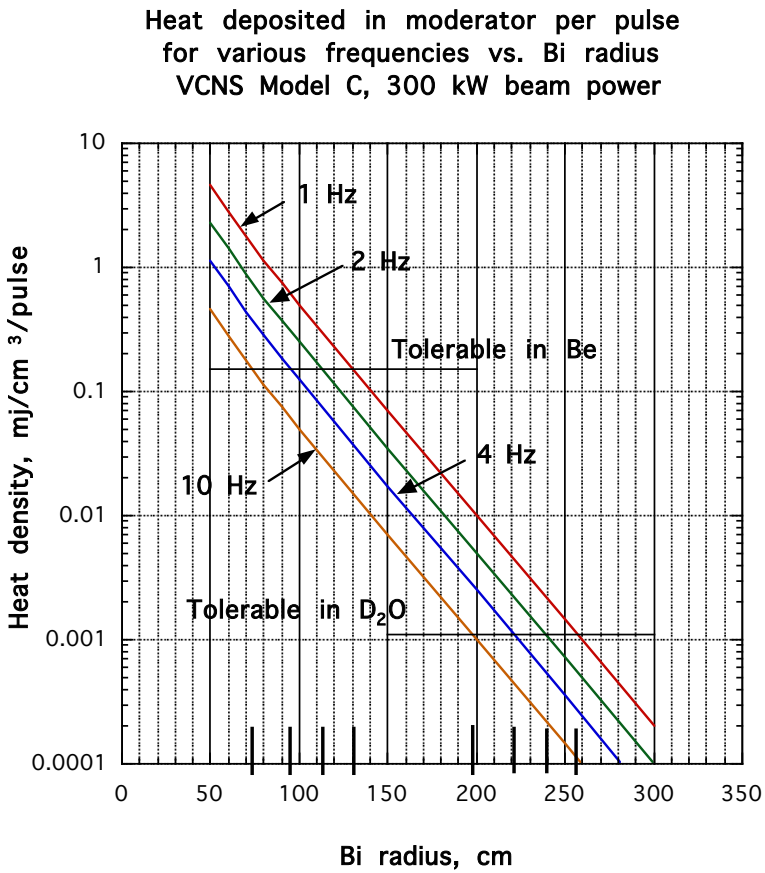
VCNS Monte Carlo Results first round





VCNS Monte Carlo Results



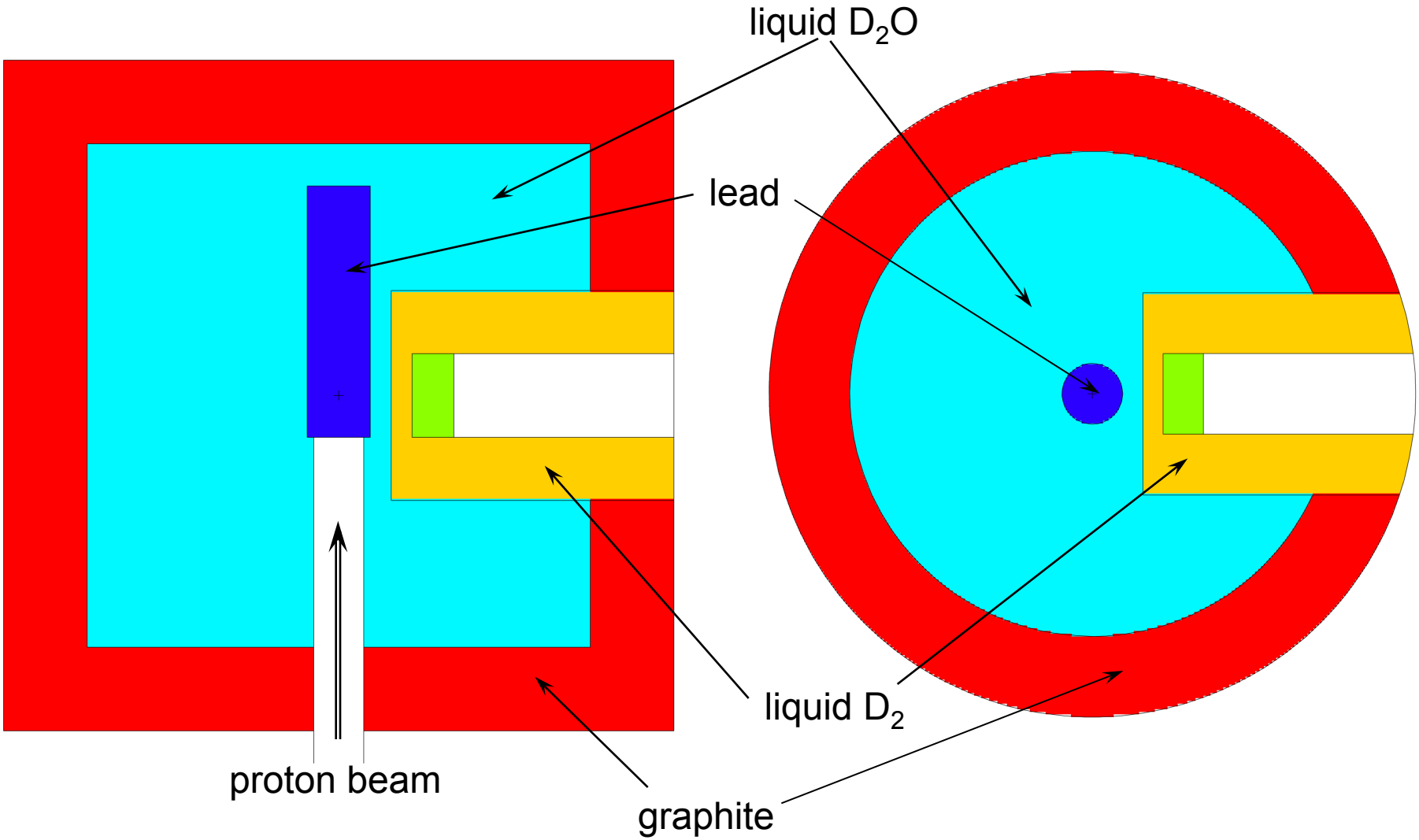


What Does a VCN/UCN Source Look Like?

- Typical UCN source configuration includes
  - Warm moderator (D_2O, ~ room temperature)
    - Choice of warm moderator affects rise/fall time of neutron pulse
  - Cold moderator (liquid D_2, ~ 20 K)
    - Some results have indicated that an intermediate temperature moderator is not necessary
  - Ultra-cold moderator (0.2 – 5 K)

- Study general properties of VCN source in warm moderator
  - Thickness
  - Location with respect to target
  - Target parameters

Representative VCN Source Model



Design Constraints

- Target heating
  - What will the target be (plates, liquid metal)?
  - Can we cool the entrance window and the high-energy portion of the target?
  - This consideration places a maximum limit on current density ($\mu A/cm^2$) during a pulse
- Moderator heating
  - Total energy deposition in moderator
  - Peak energy deposition in space and time
  - Can the moderator be cooled enough to prevent an unacceptable rise in temperature during a pulse?
  - Heat capacity and thermal diffusivity of materials are critical
  - This consideration places a limit on energy deposition in moderator
- Together these will limit the available neutron flux

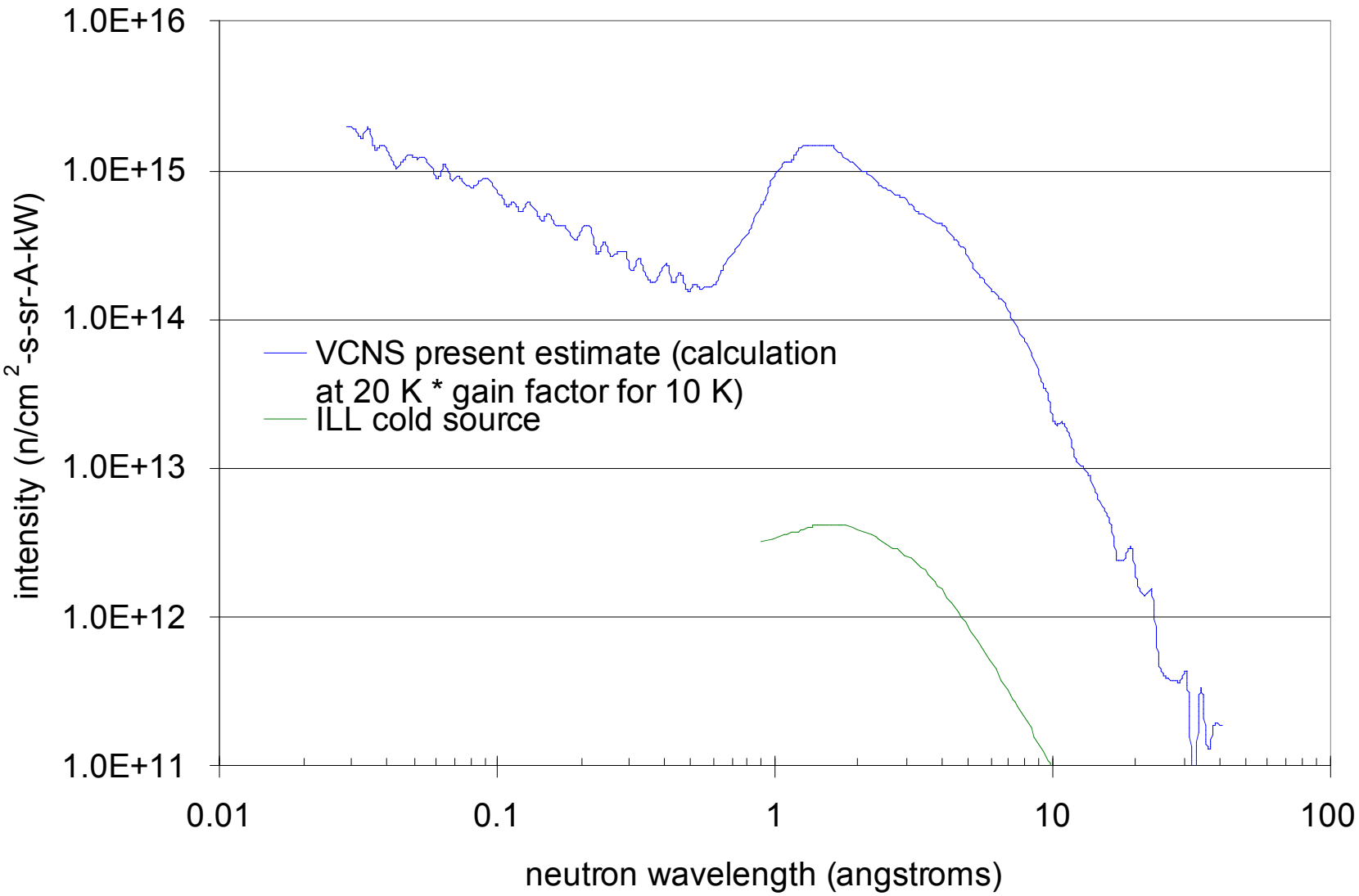
Requirements for Computation

- Code
  - MCNPX version 2.5.0
- Model
  - We use simplified geometric models
  - Both obvious and subtle effects will be left out
  - Real-world performance will be less
- Data
  - Good calculations require good data
  - Neutron scattering kernels do not yet exist for the materials, temperatures, and energies of interest
- How to proceed? We can either …
  - Perform simulations with free gas kernel (not 'wrong', just an approximation)
  - Calculate using known kernels and extrapolate from experiment

Preliminary Modeling

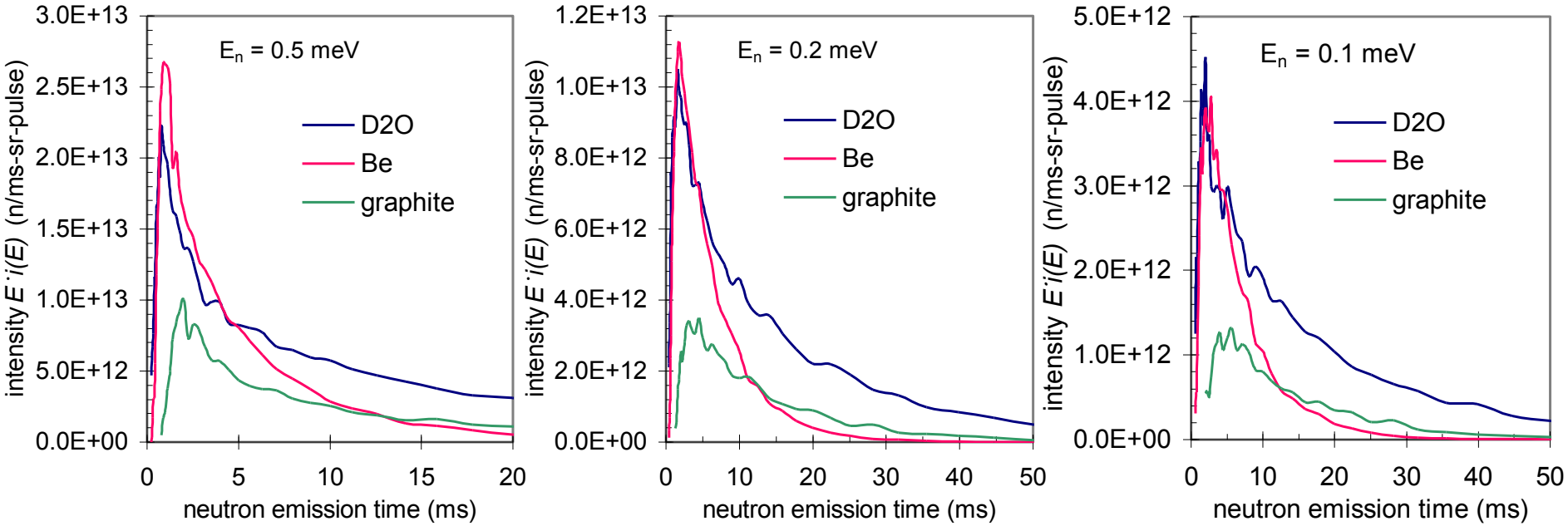
- Needed to get some idea of neutron emission spectra, intensities, and pulse widths
- These studies treated low-temperature scatterers as free gas
- Model highly generalized

Scaled Neutron Flux for VCNS Concept



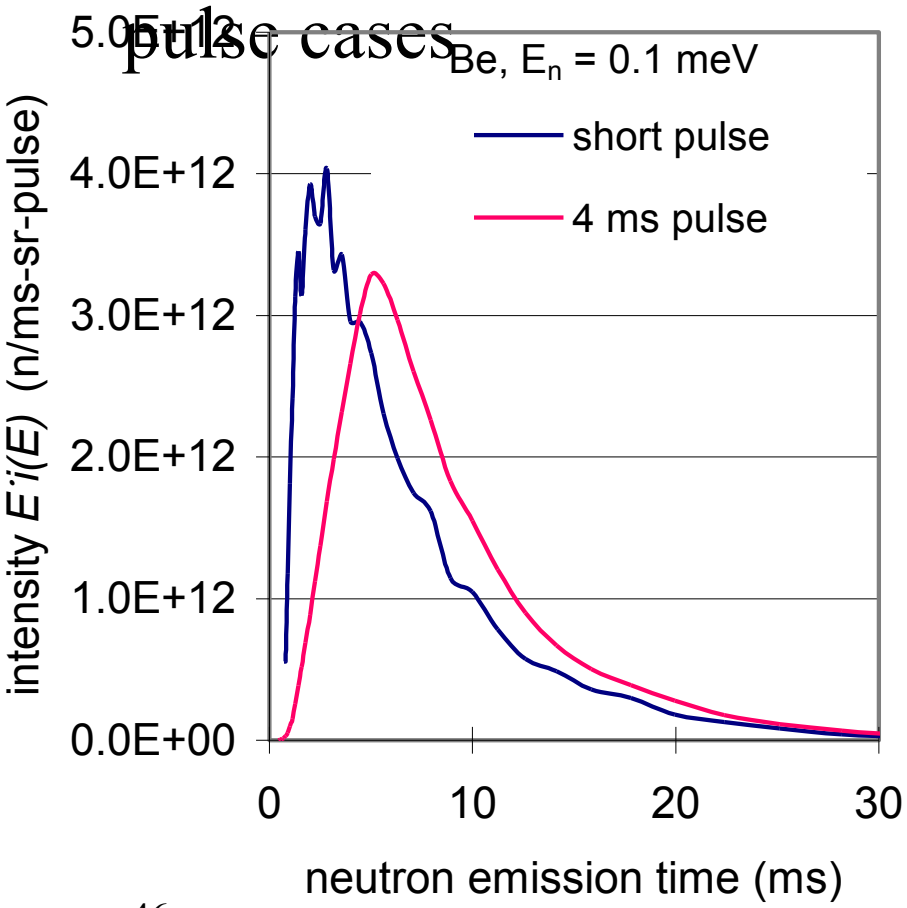
MCNPX Model A – Pulse Shapes

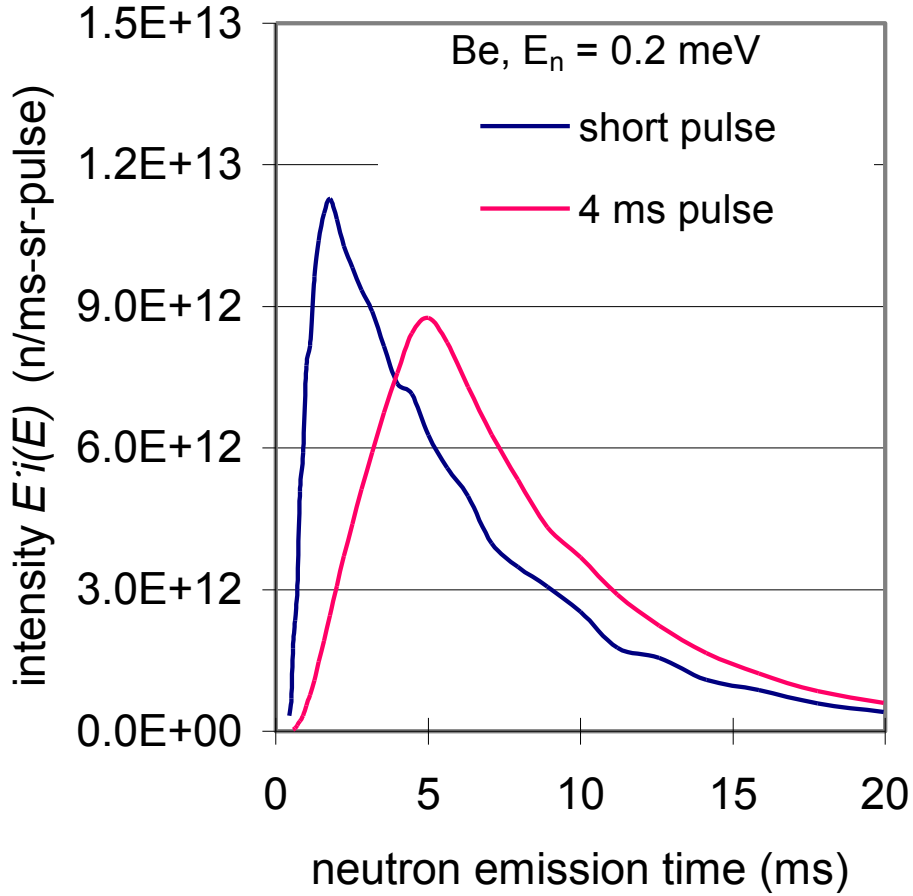
- Short-pulse time distributions



MCNPX Model A – Pulse Shapes

- Compare time distributions for short-pulse and 4-ms pulse cases





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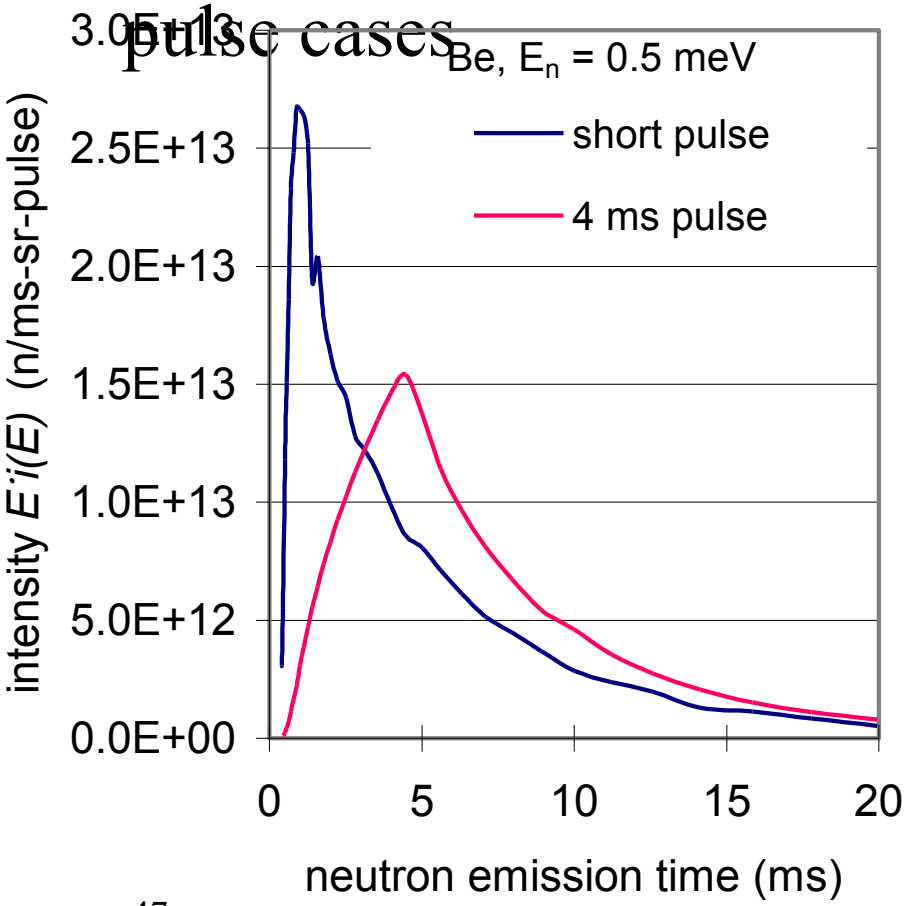
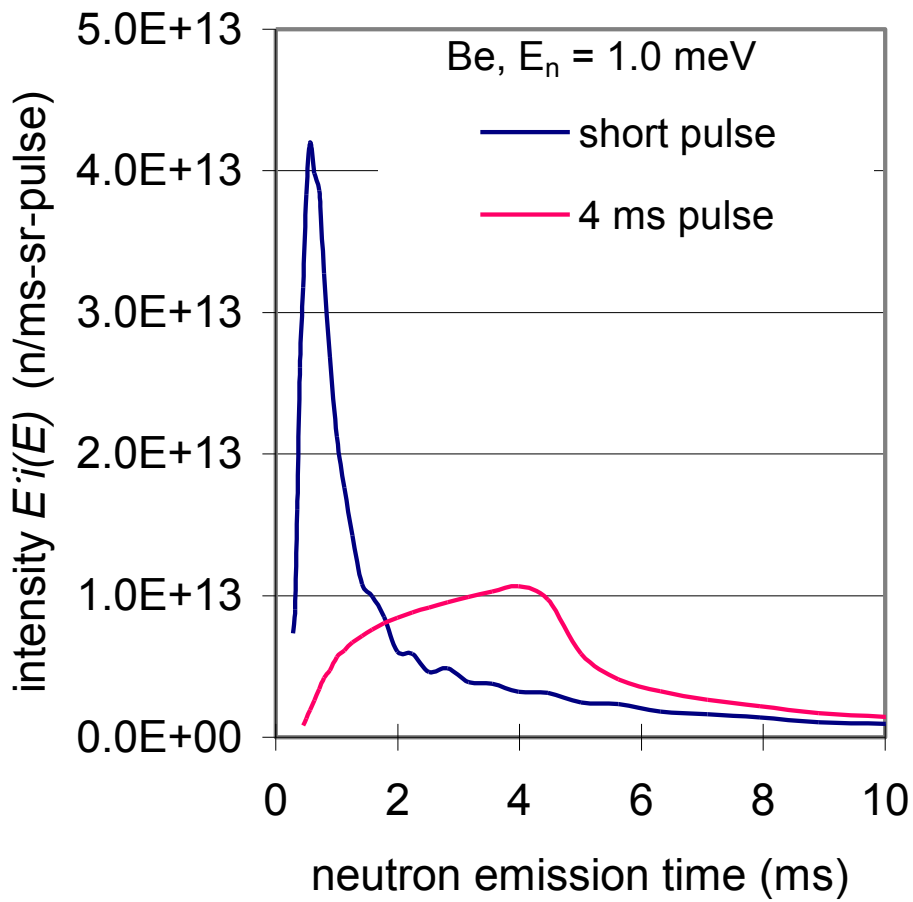
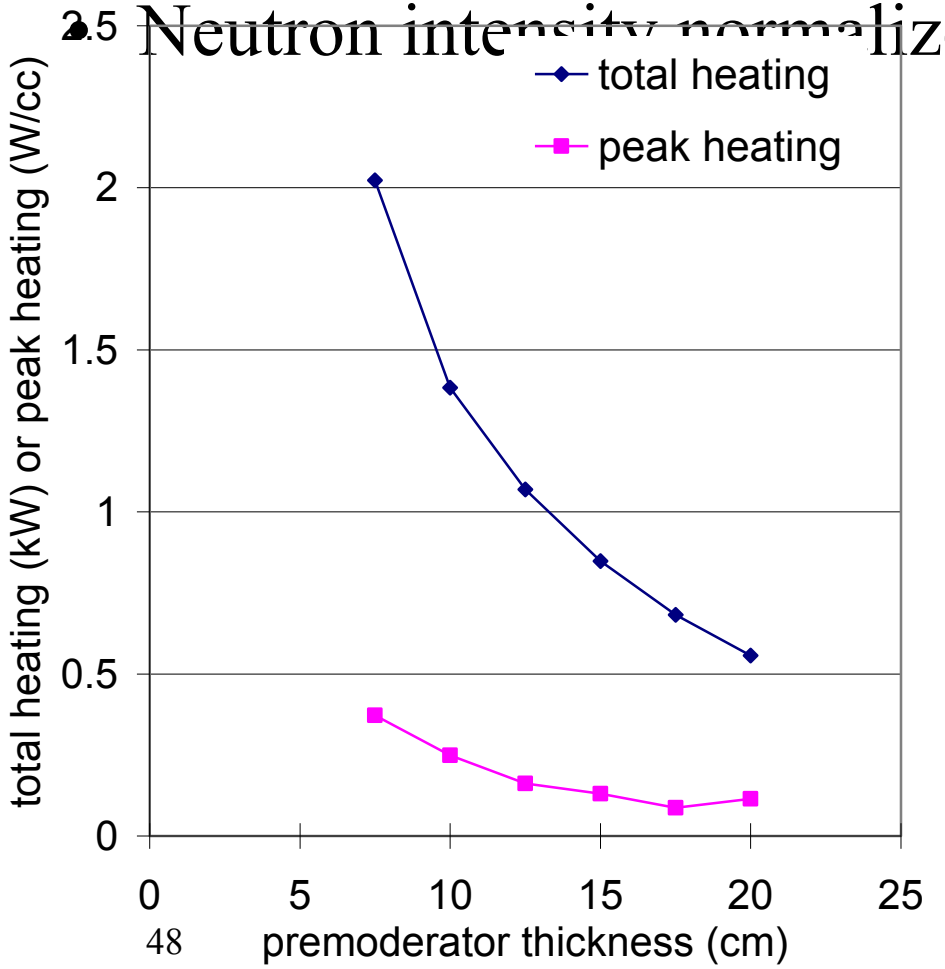
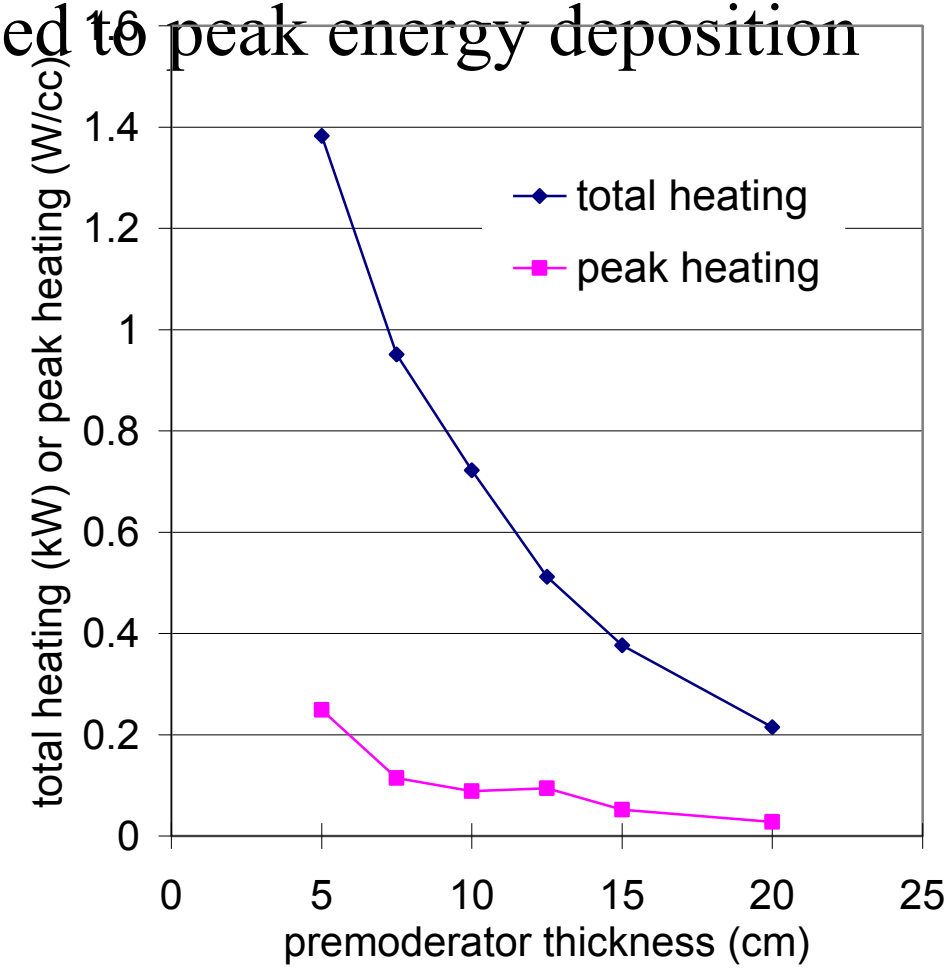




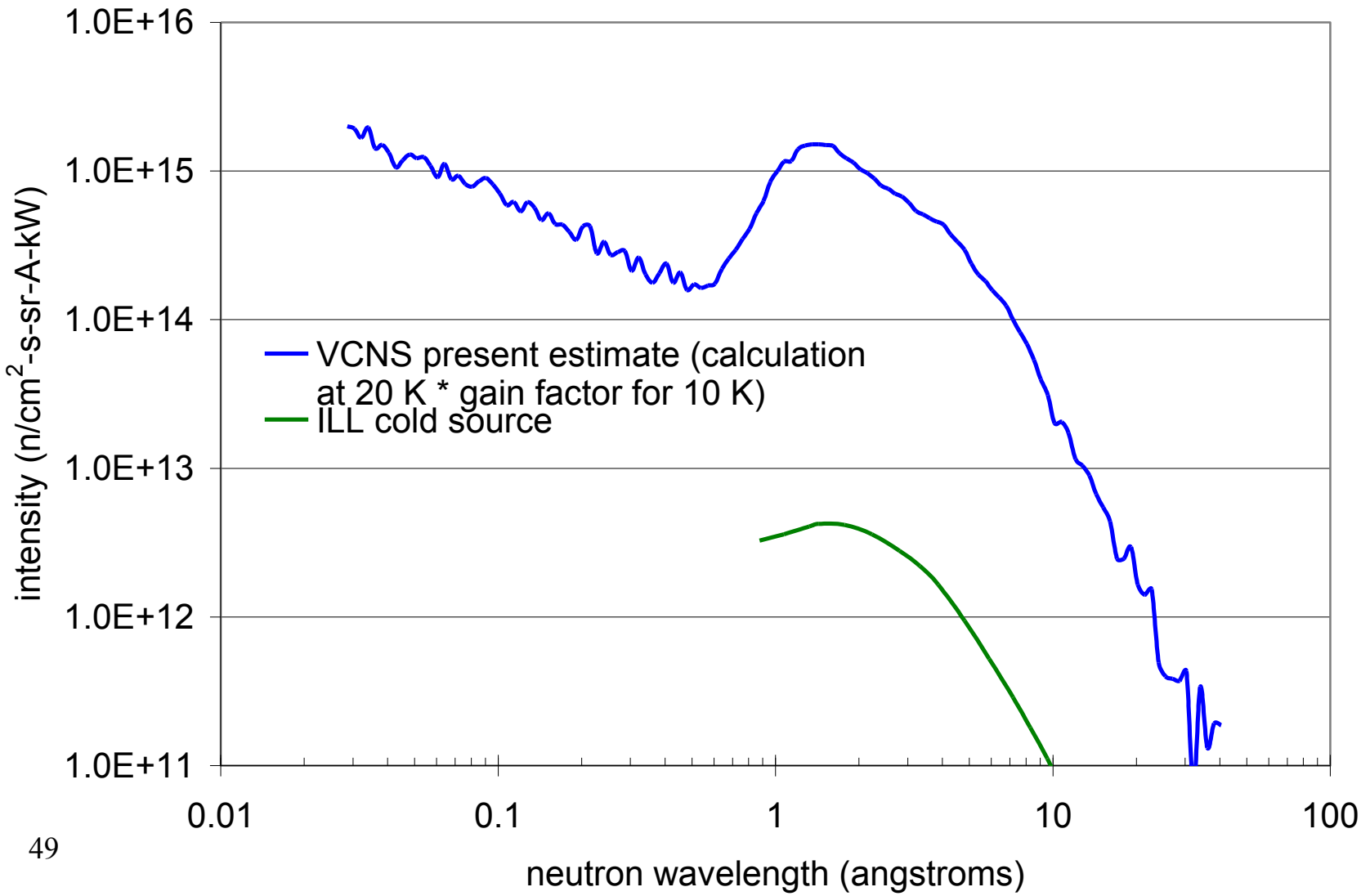
Cold Moderator Heating Results

- R_{target} = 10 cm, R_{beam} = 7.5 cm
- Neutron intensity normalized to peak energy deposition





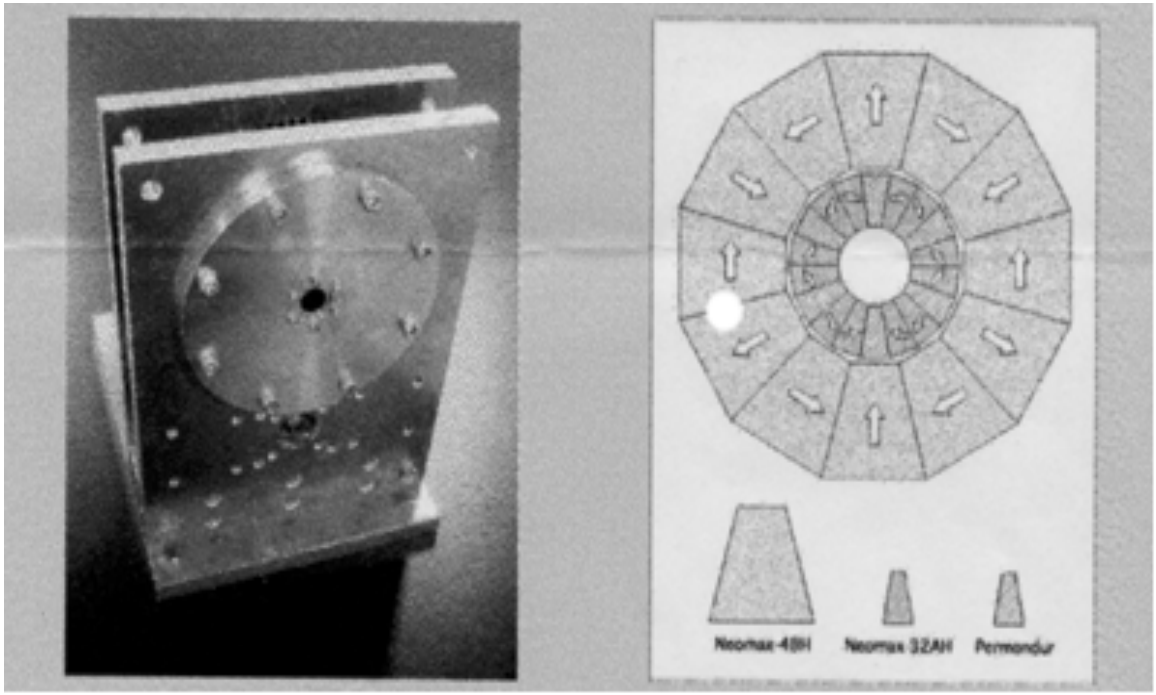
Scaled Neutron Flux for VCNS Concept



VCNS Workshop at Argonne

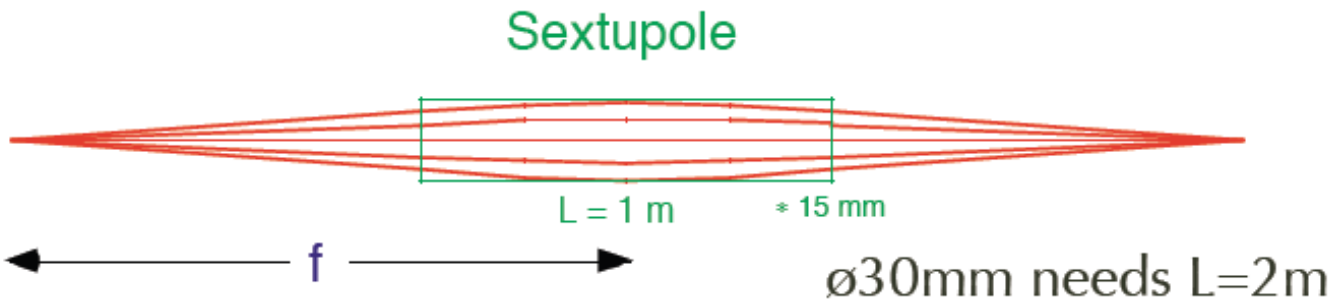
- A workshop to explore the interest from the scientific community in a VCNS was held at Argonne on 21-24 August 2005
- 39 workshop participants came from 12 US and international institutions
- Primary focus was to gauge interest in scientific applications of a facility delivering 30-1000 times the presently envisioned flux at 20 Å
- Participants received briefing materials beforehand
- Selected individuals gave prepared talks
- Participants came prepared to discuss the applications of the proposed facility

Shimizu's Sextupole Lens

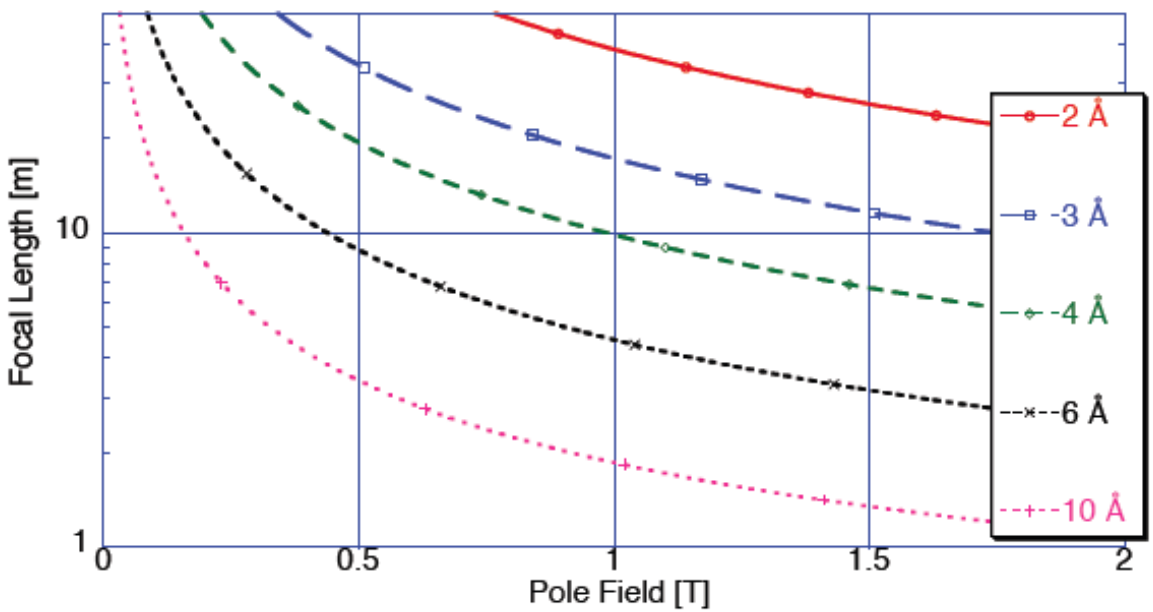


The outer ring rotates with respect to the inner ring, which varies the strength of the sextupole field. This can be synchronized so as to maintain the focal position according to the wavelength of the neutrons arriving at the lens.

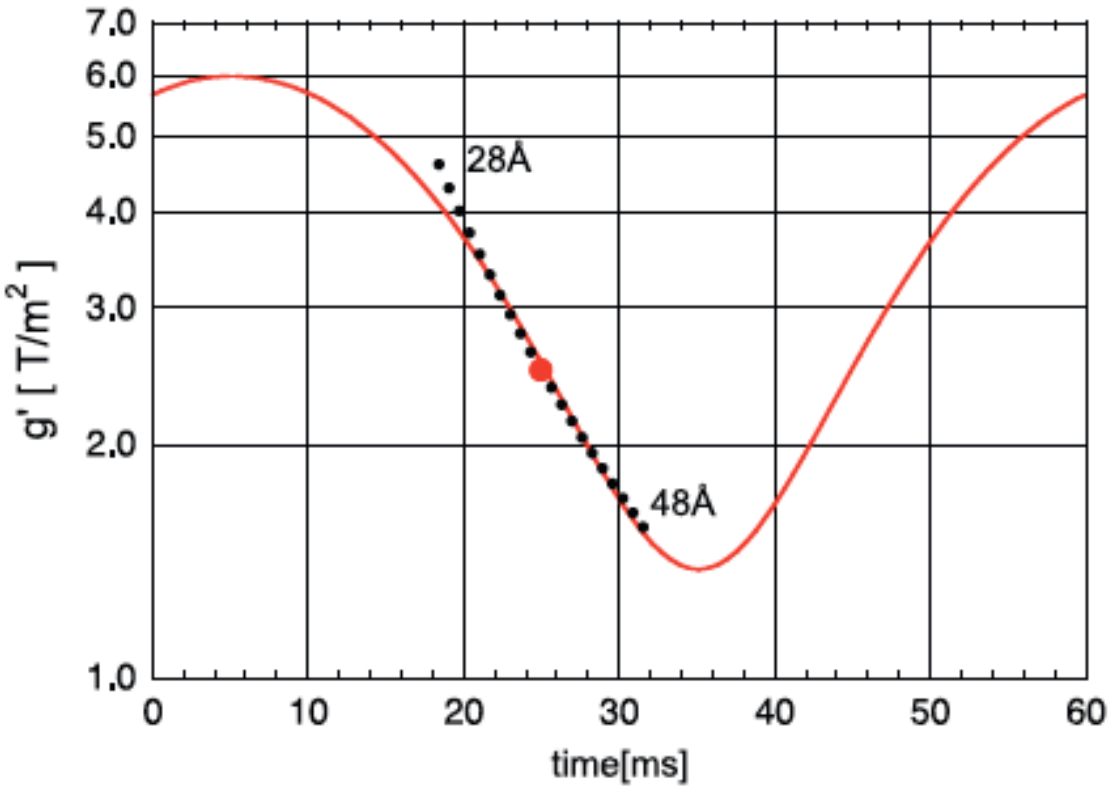
VCN focusing in a sextupole field



ø30mm needs L=2m

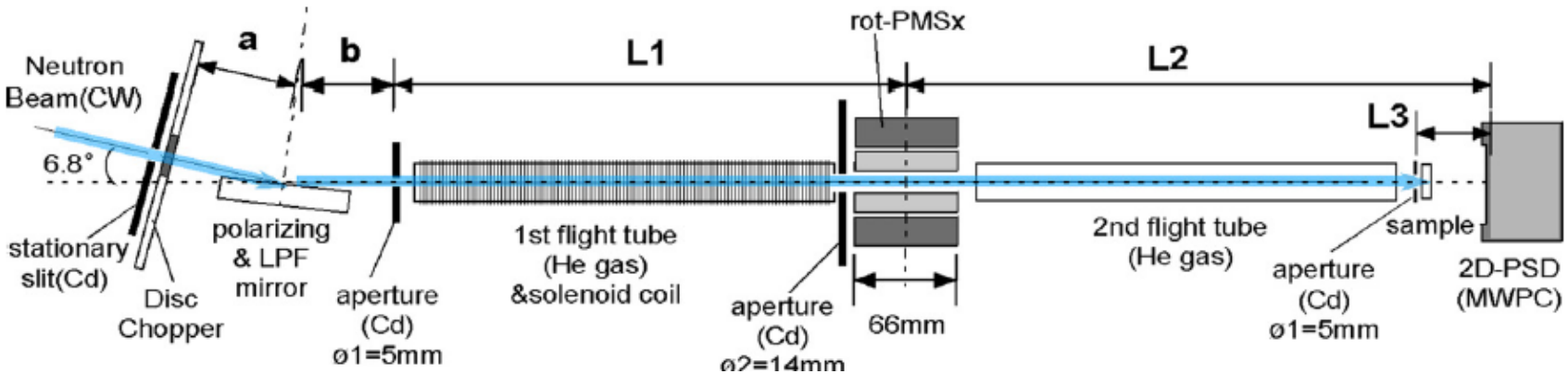


Performance of a magnetic lens in a Pulsed Beam

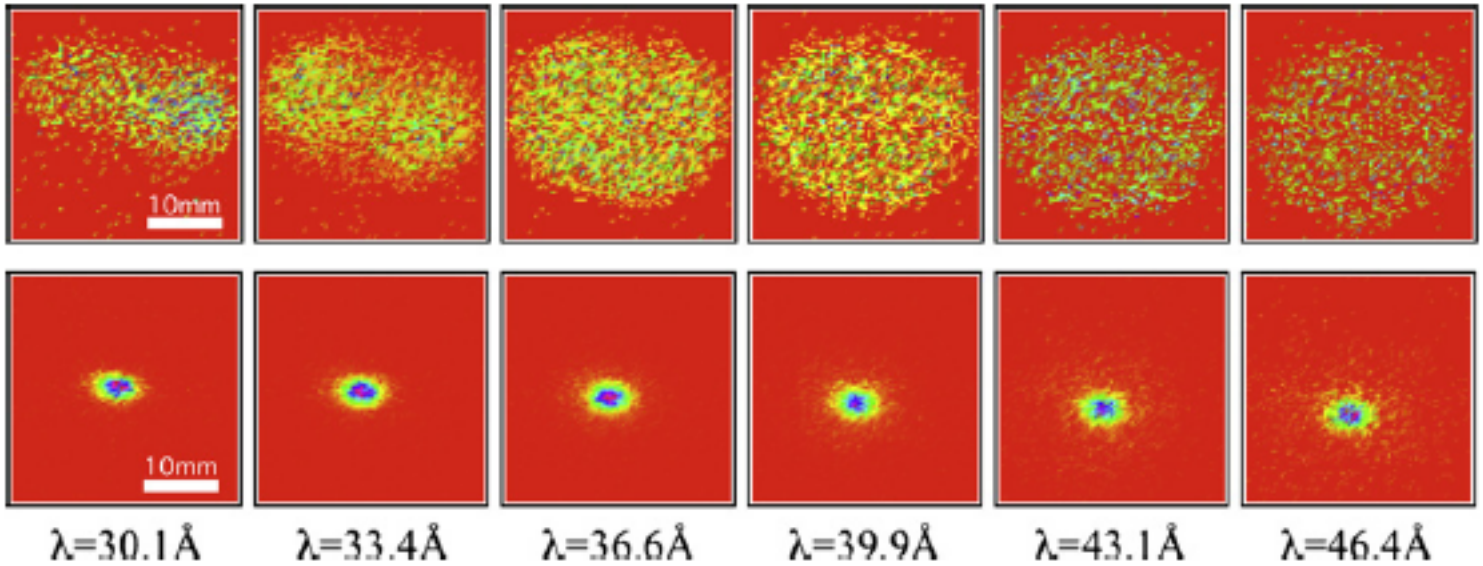


M. Yamada, et al. NIM 634 (2011) S156-S160

Test Focusing of Sextupole Lens

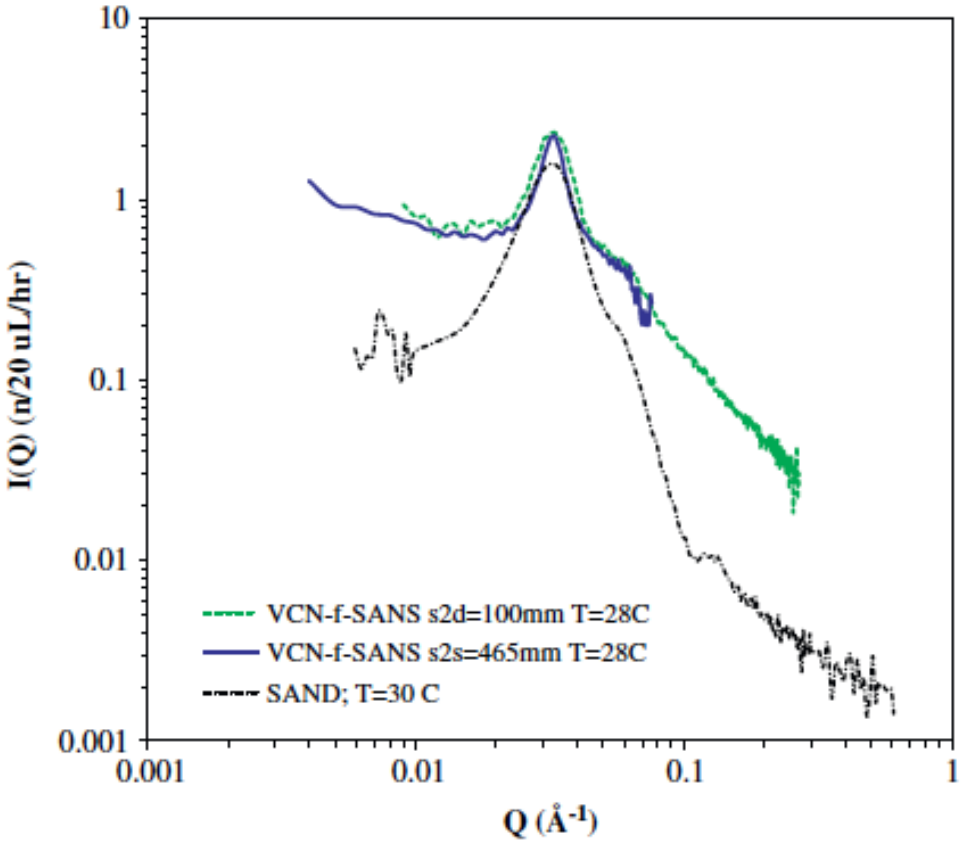


Focusing with the Sextupole Lens



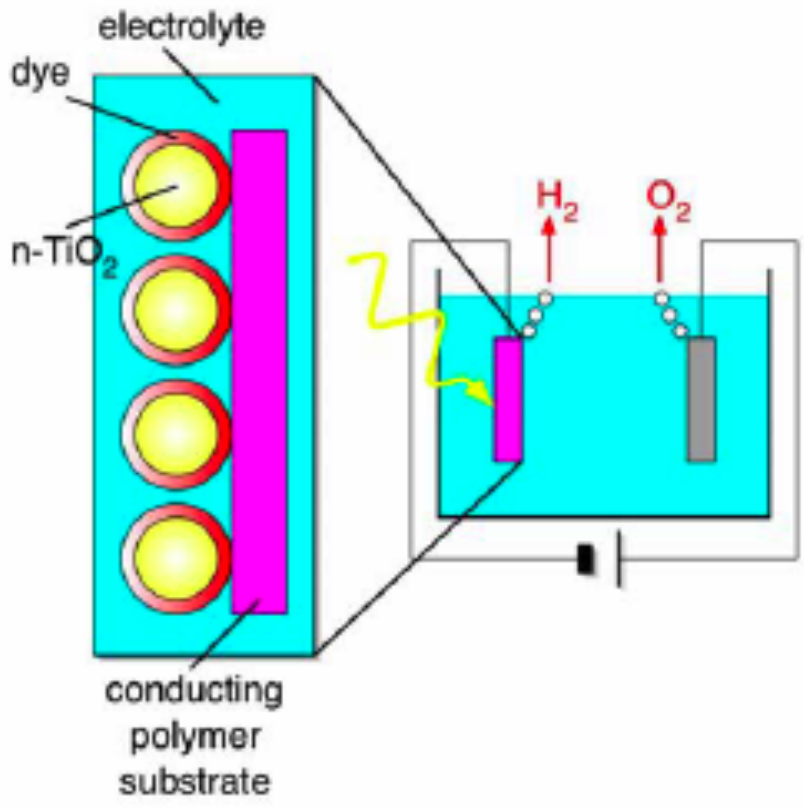
t-o-f SANS Measurement with Wavelength-Focused Sextupole Lens

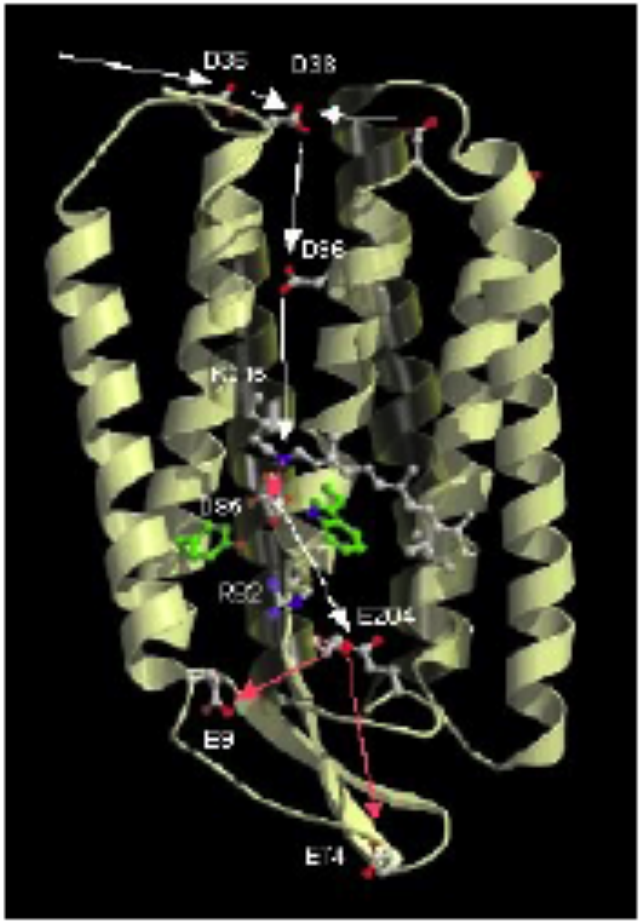
Background not satisfactory, but Q-scale seems correct



VCNS Applications

nanoscale-enhanced photocleavage of water



VCNS Applications

light-driven protein-based proton pump