Center for Medical Countermeasures Against Radiation

Neutron Irradiations and Dosimetry

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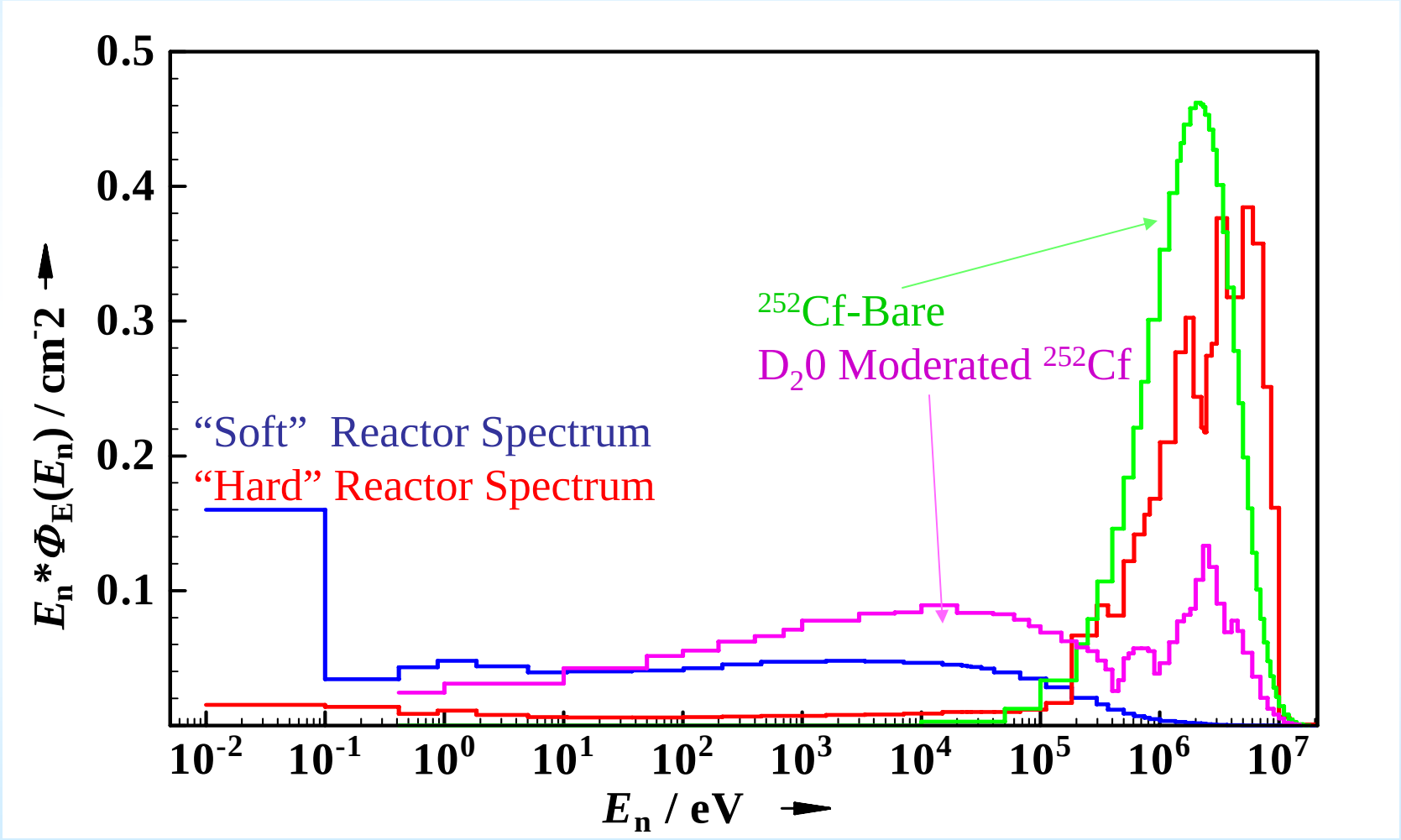
Goal: Introduce you to …

- Challenges in Neutron Dosimetry
- How we can determine dosimetric quantities of interest
- Neutron irradiations available at Duke

Facts and Challenges

- Neutrons ionize indirectly, via secondary charged particles: protons and heavier cp
- Neutron energies span many decades
- Their biological effects vary greatly with energy

Example of Neutron Spectra



Quantities (quick recap)

- **Fluence**: $\Phi = dN/da$ [cm^{-2}] ; dN is number of particles impinging on a sphere around point of interest, with great-circle area da *(particles/cm^2)*

- **Exposure** X [Roentgen] – *Obsolete, not for neutrons;* replaced by “Kerma in air”

- **Kerma** $K = d\varepsilon_{tr}/dm$ [Gy=$J.kg^{-1}$] or [rad] **…**where ε_{tr} is energy tranferred by *indirectly ionizing* radiation (neutrons, γ)

Quantities

- **Absorbed Dose** $D = d\varepsilon/dm$ [Gy= $J.kg^{-1}$ = 100 rad] where ε is energy imparted (to a small volume of mass *dm*)

- **Dose Equivalent** $H = D.Q$ [Sv=$J.kg^{-1}$] where $Q=f(LET)$ is the quality factor

- Linear Energy Transfer: LET [$keV.\mu m^{-1}$] – how densely is energy imparted; much higher for protons than electrons

N vs γ: Biological effects

- For same energy deposited, neutrons much more effective (~10x) in damaging cells
- Neutron secondaries: high LET (mostly p^+)
- Photon products: low LET (e^- and e^+)
- 1 MeV e^- range in H2O: 4.3 mm
- 1 MeV p^+ range in H2O: 0.023 mm
- Ionization density much higher for p^+

Quantities

- **Equivalent Dose** $H_T = \Sigma w_R D_R$ [Sv=J.kg^{-1}]
- **Effective Dose** $E = \Sigma w_T H_T$ [Sv=J.kg^{-1}]
- **Dose-Equivalent Index** H_I
  [Sv=J.kg^{-1}] i.e. max. Dose-Equivalent in an ICRU tissue sphere (30 cm diameter).

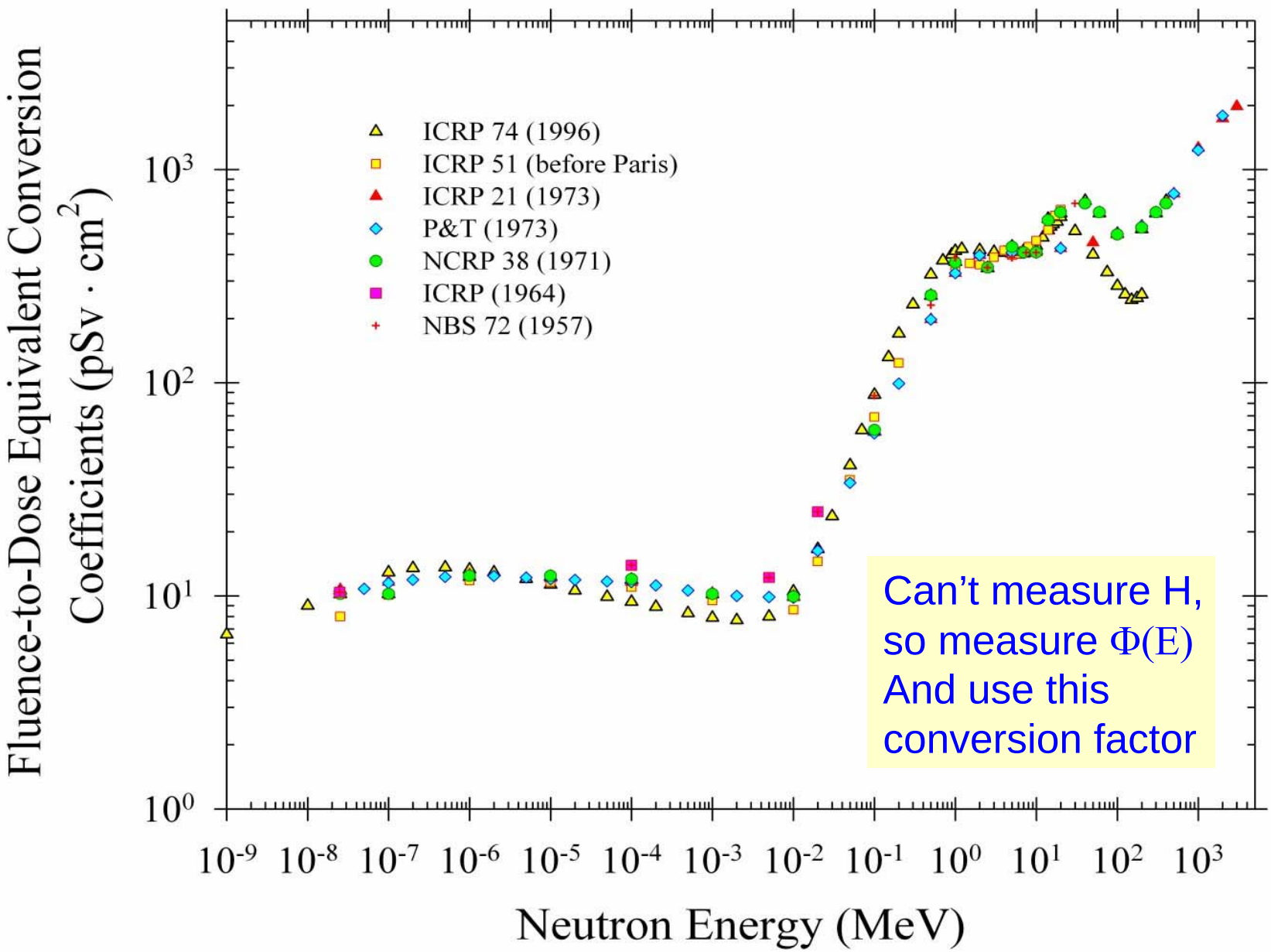
Quantities

- Fluence, Abs. Dose and Kerma are purely **physical = measurable** quantities
- H, H_T, E, EDE …must be estimated or calculated from measured **Φ(E), D(LET)**,…
- “Measurable” (not really) quantity: Ambient Dose Equivalent (similar to Dose-Equivalent Index in 30 cm sphere)

Underground Quantity Definitions

- Exposure is a quantity that everybody can measure, but nobody wants
- Dose equivalent is a quantity that everybody wants, but nobody can measure
- Ambient Dose Equivalent – The dose equivalent received by a 30-cm diameter spherical man….if he weren't there

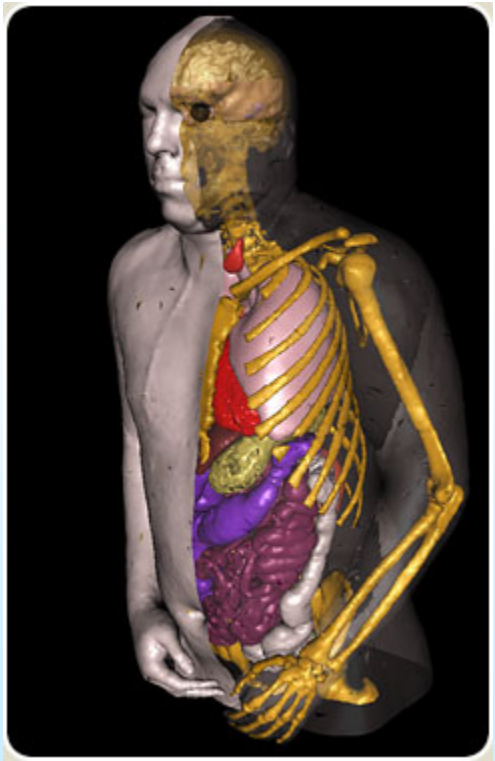
Loosely after J. McDonald

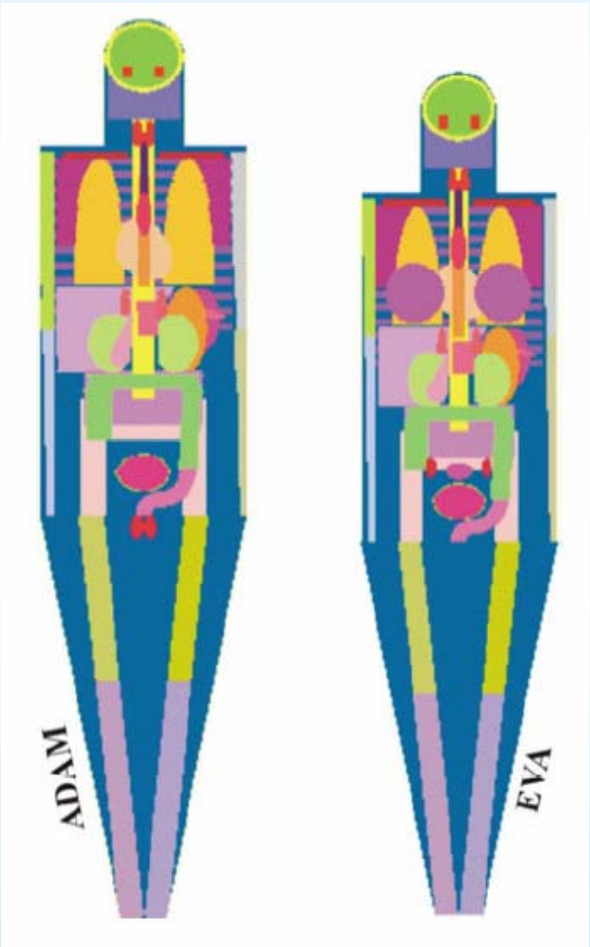

Fluence-to-Dose Equivalent Conversion Coefficients (pSv · cm^2)
ICRP 74 (1996)
ICRP 51 (before Paris)
ICRP 21 (1973)
P&T (1973)
NCRP 38 (1971)
ICRP (1964)
NBS 72 (1957)
10^3
10^2
10^1
10^0
10^{-9} 10^{-8} 10^{-7} 10^{-6} 10^{-5} 10^{-4} 10^{-3} 10^{-2} 10^{-1} 10^0 10^1 10^2 10^3
Neutron Energy (MeV)
Can't measure H, so measure Φ(E) And use this conversion factor

Conversion Factors

- Calculated for humans (not mice) using Monte-Carlo codes and increasingly complex phantoms

VIP-Man, based on the Visible Human Project

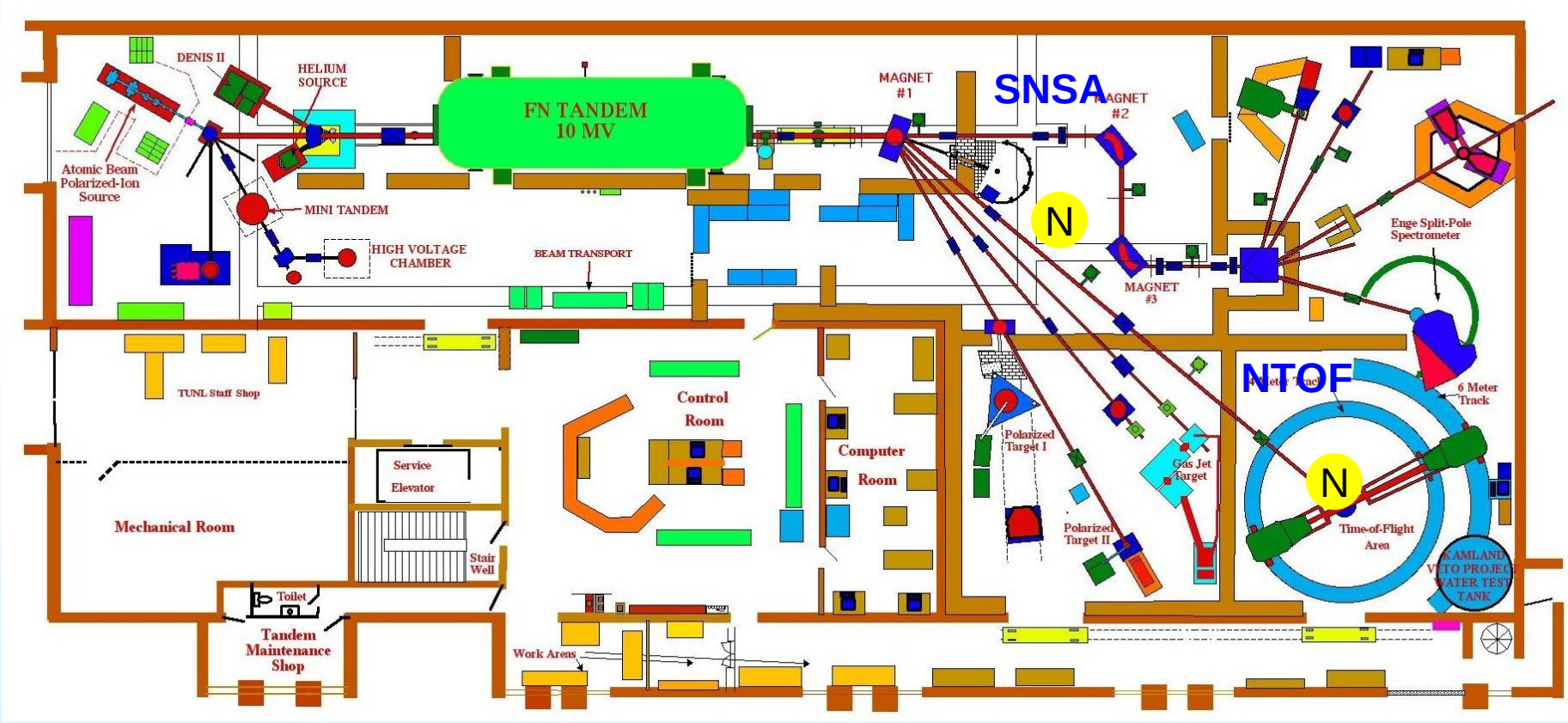




MIRD Phantoms

Triangle Universities Nuclear Lab

- Two areas for neutron irradiations in TUNL



TUNL

- Charge particle beams at TUNL

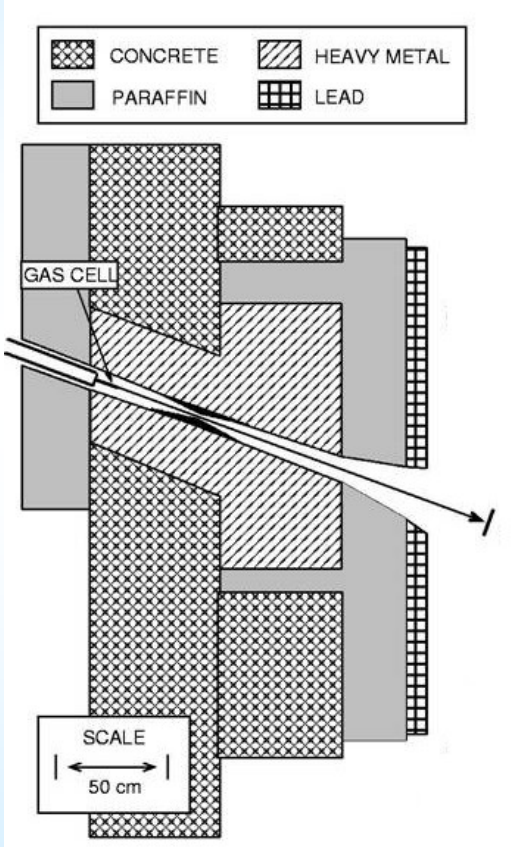
Parameter	Performance Specifications
Nominal energy range	1.5 to 19.0 MeV [(a)]
Beam pulse repetition rate	DC to 2.5 MHz with 1.5 ns wide pulses [(b)]
Particle types	p, d, ^{3}He, ^{4}He and heavier ions [(c)]
Maximum current on target	
unpolarized protons and deuterons	2 μA pulsed and 5 μA dc [(d)]
polarized protons and deuterons	2 μA
^{3}He and ^{4}He	500 nA
Heavy ions	50 nA
Energy spread	less than 500 eV

Neutron production at TUNL

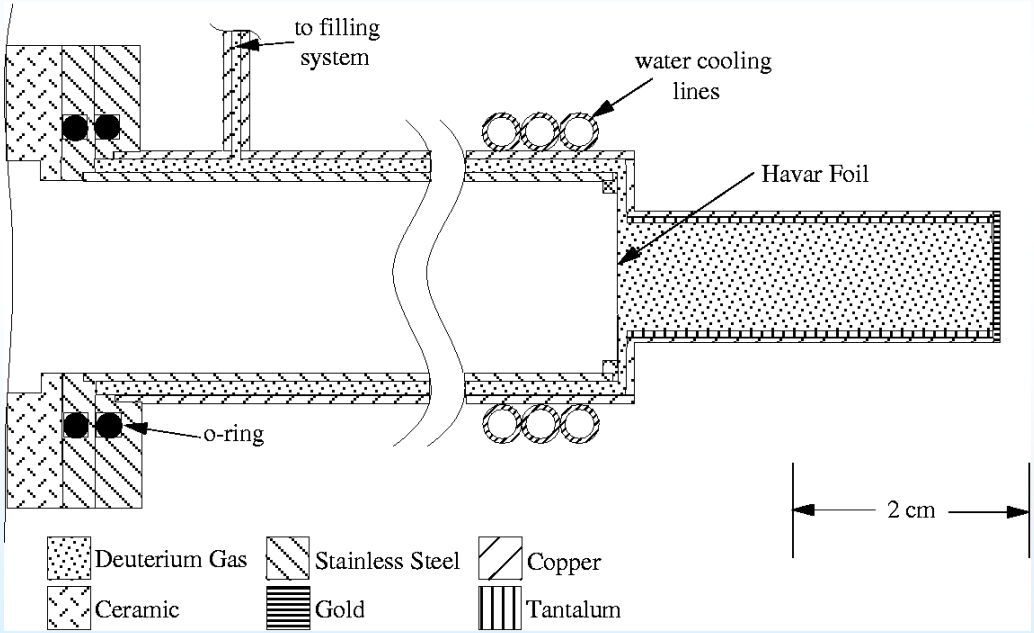
- Reactions: $^{2}H(d,n)^{3}He$, $^{3}H(p,n)^{3}He$, $^{7}Li(p,n)^{7}Be$
- High-flux yield from protons or deuterons on ^{9}Be:

Dose-equivalent rates from 5 micro-A deuterons on 9-Be target		
En [MeV]	Sv/h	rem/h
0.5	1.13	112.7
3.2	7.13	713.3
8	2.84	283.8
14	0.12	12.3

Neutron production at TUNL



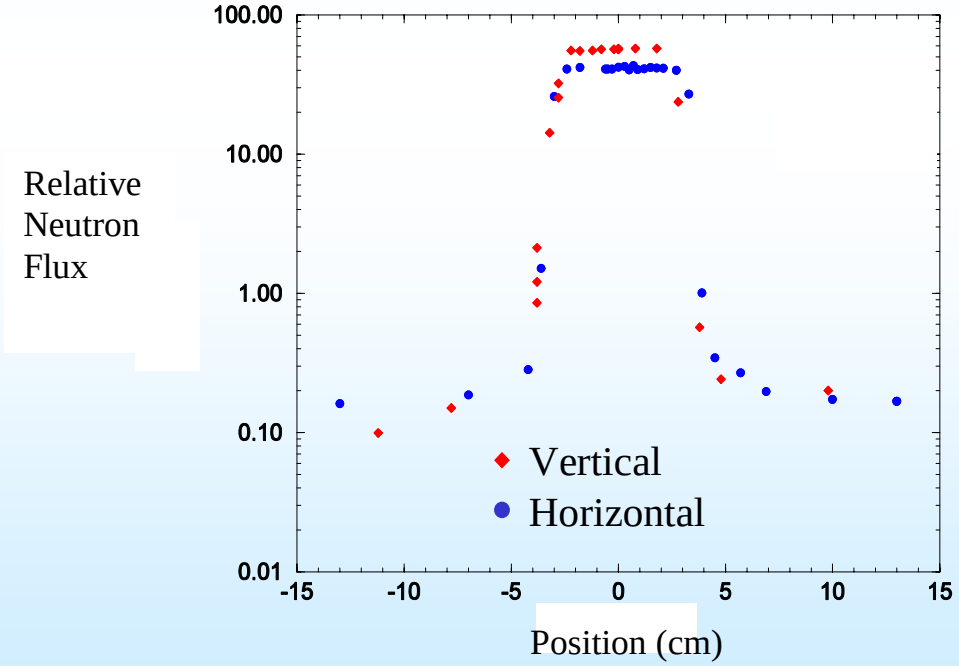
Shielded Neutron Source

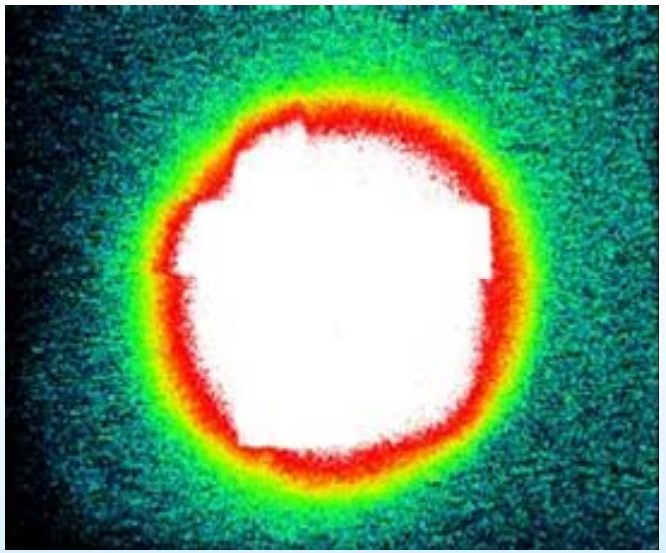


Deuterium gas target

TUNL

- Beam profile at Shielded Neutron Source Area with circular collimator





Dosimetry Goals at TUNL

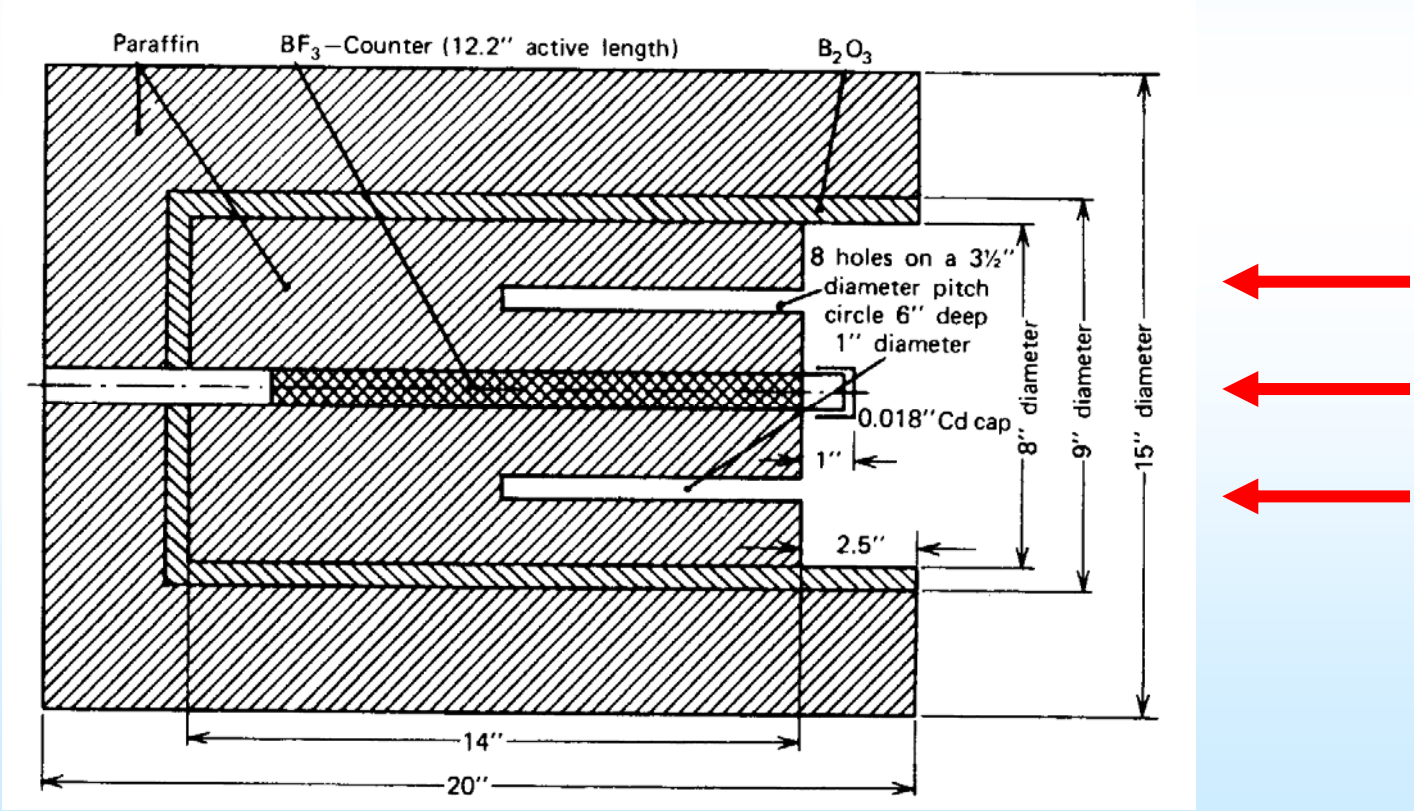
- Measure neutron fluence and its energy distribution $\Phi(E)$
- Establish the photon contamination of neutron beams: D_G
- Measure (and calculate) distribution of dose as a function of LET.

Neutron Beam Characterization

- Time-Of-Flight measurements for energy
- Long-counter for fluence
- Bonner spheres for fluence and energy
- Ionization Chambers for tissue Kerma
- TEPC for Dose as function of LET (micro-dosimetry)
- Monte Carlo calculations for specific phantom: spatial distribution of D(LET)

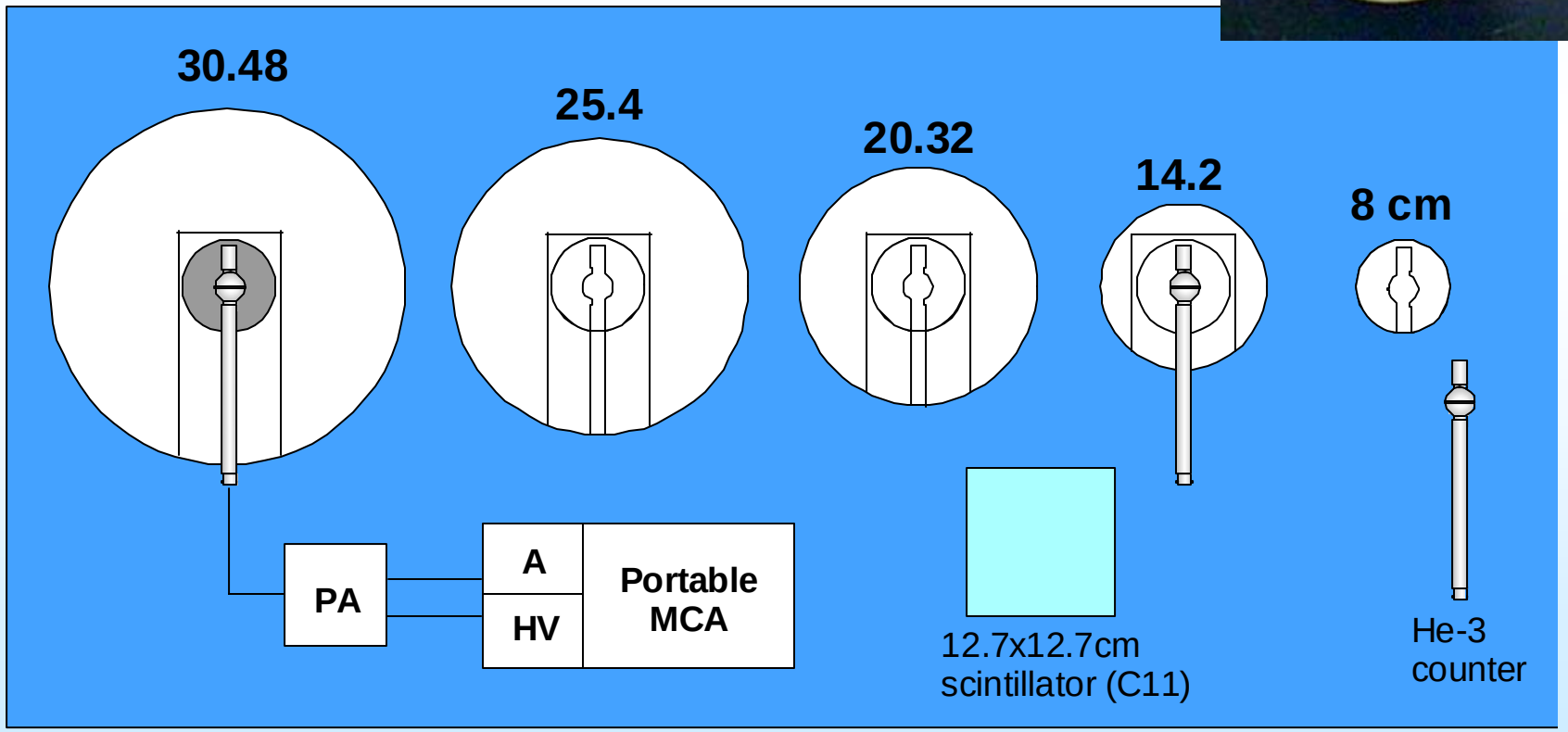
“Long Counter”

- Secondary standard for neutron fluence measurements



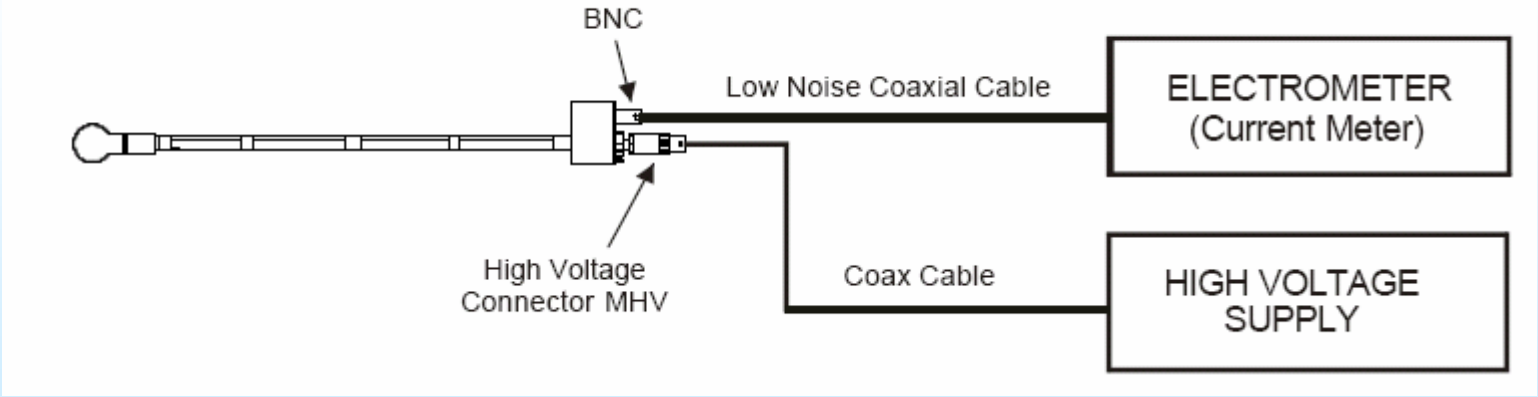
Duke Bonner Spheres

Measurements of primary and scattered neutron spectra in room using "spectra unfolding" technique



Twin Ionization Chambers

- Tissue-equivalent and graphite



Twin Chamber Technique

- There are no pure neutron fields, photon (gamma) always present: $D_{tot} = D_N + D_G$

- Goal: separate D_N and D_G using two ionization chambers (IC):
  - Tissue-equivalent IC (T): equally sensitive to N and G
  - Carbon IC (U): very low sensitivity to N

Twin Chamber Technique

- Response of TE IC:

$$R_T = k_T D_N + h_T D_G$$

- Response of graphite IC:

$$R_U = k_U D_N + h_U D_G$$

- k_T, h_T … sensitivity of TE IC to N and G, resp.
- k_U, h_U … sensitivity of graphite IC to N and G, respectively (formalism of AAPM Report No. 7, Protocol for Neutron Beam Dosimetry)

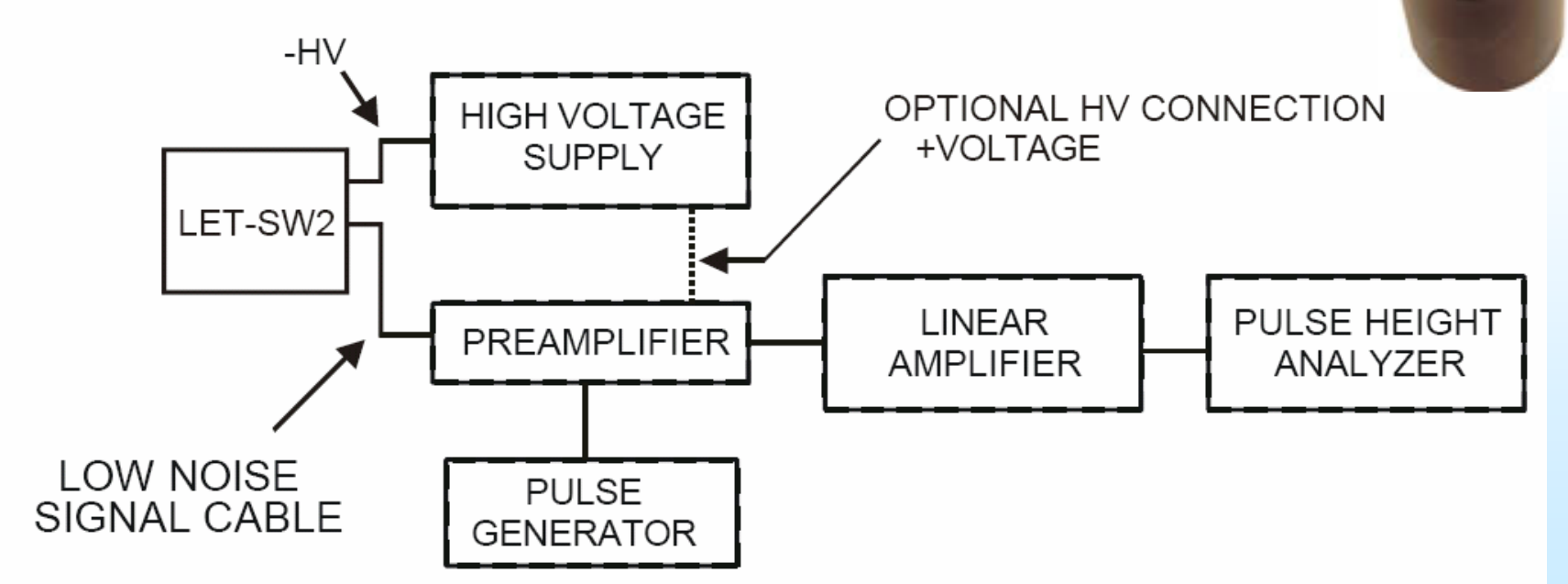
Twin Chamber Technique

- Then D_N and D_G can be easily obtained from measured R_T and R_U:

$$D_N = \frac{h_U R_T - h_T R_U}{h_U k_T - h_T k_U} \qquad D_G = \frac{k_U R_U - k_U R_T}{h_U k_T - h_T k_U}$$

TEPC

- Tissue-equivalent Proportional Counter: measures Dose as function of LET



Monte Carlo Calculations

- Predict contribution of scatter in experiment
- Calculate energy deposition patterns in great detail, including spatial and energy distributions of secondary charged particles in specific small animal phantoms
- Establish conversion fluence-to-dose factors for mice or other small animals

Development of a 4D Digital Mouse Phantom for Molecular Imaging Research

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MONTE CARLO

Suitable voxel-based phantoms may be developed using data from micro-CT and NMR, or possibly imported from computer models developed for other purposes (Duke, ORNL).

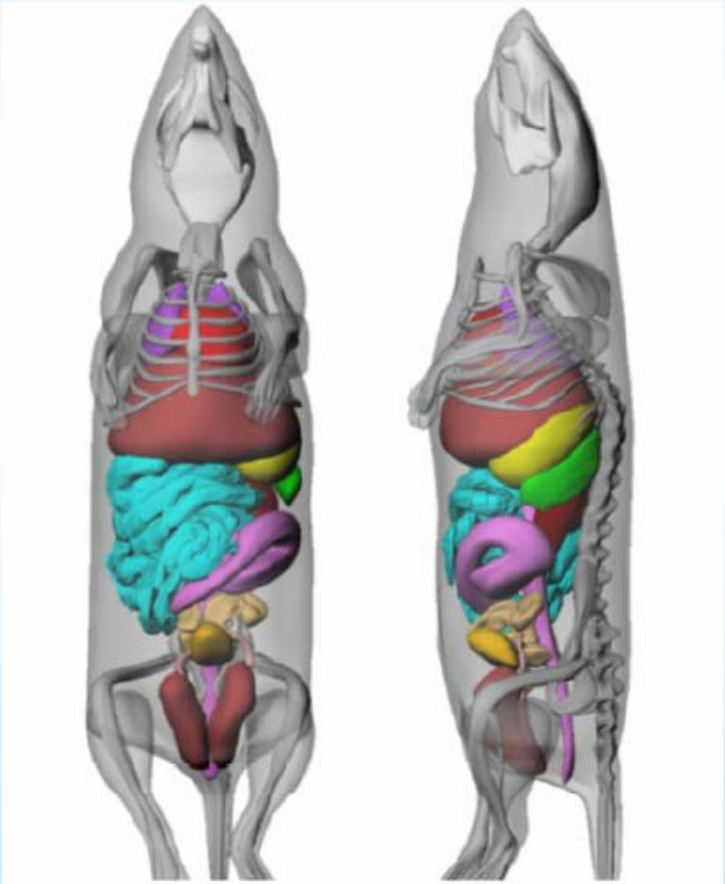

Figure 12: Anterior (left) and lateral (right) views of the digital mouse phantom.