ICRS-13 & RPSD-2016

13th *International Conference on Radiation Shielding*
&
19th Topical Meeting of the *Radiation Protection & Shielding Division*
of the *American Nuclear Society* -2016

3rd Plenary invited talk:

Secondary Neutrons from Proton Radiation Therapy"

Dr. Rebecca M. Howell

University of Texas, USA

The author will present an overview of secondary neutrons in proton therapy. In particular, she will discuss the wide variability of data in the literature and focusing on the variability in measurement techniques used in different studies. Additionally the presentation will compare the secondary neutrons encountered in scanning beam and passive scatter proton therapy and high energy photon therapy.

Rebecca M. Howell, PhD, is a tenured Associate Professor at The University of Texas MD Anderson Cancer Center. Dr. Howell was elected Fellow of the American Association of Physicists in Medicine (AAPM) last year. She received her MS (2001) and PhD (2005) from the University of Texas Health Science Center San Antonio. Dr. Howell is certified by the American Board of Radiology and has 15 years of clinical experience. She has published 50 peer-reviewed papers and is Principal and Co-investigator on several funded research grants from the National Cancer Institute and other funding agencies. Her research focuses on out-of-field dose and late effects of radiation therapy.

Secondary Neutrons in Proton Therapy

Presented by:
Rebecca M. Howell
PhD, DABR, FAAPM

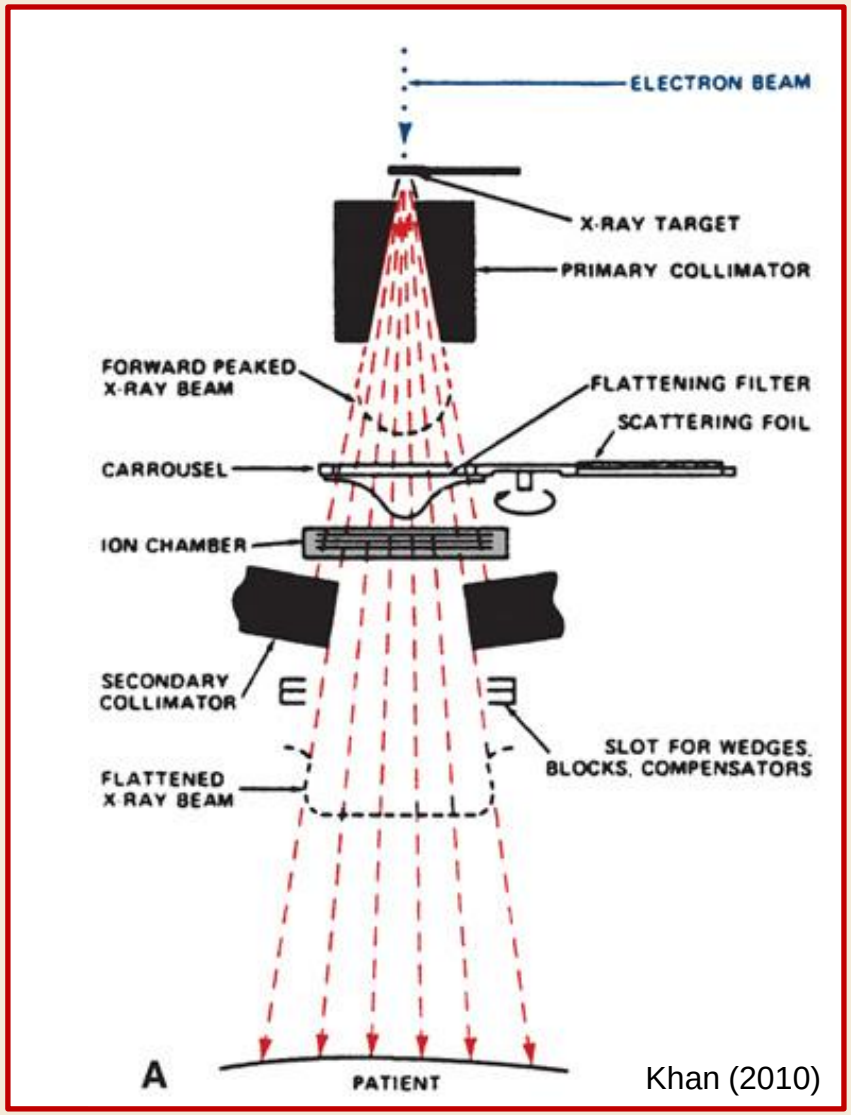
THE UNIVERSITY OF TEXAS
MD Anderson Cancer Center
Making Cancer History®

Background
Treatment Planning in Radiation Therapy

- **Standard of care: commercial TPS used to calculate patients' treatment plans (all RT types)**
- **Accuracy**
  - **High-dose regions and areas within the primary beam path are typically well described (accuracy ± 2%)**
  - **Low-dose regions**
    - **Accuracy beyond a few centimeters outside the treatment field edge is usually poor**
    - **Secondary neutrons are not considered**

Secondary Neutrons
Photon Therapy

External Neutrons in Photon Therapy



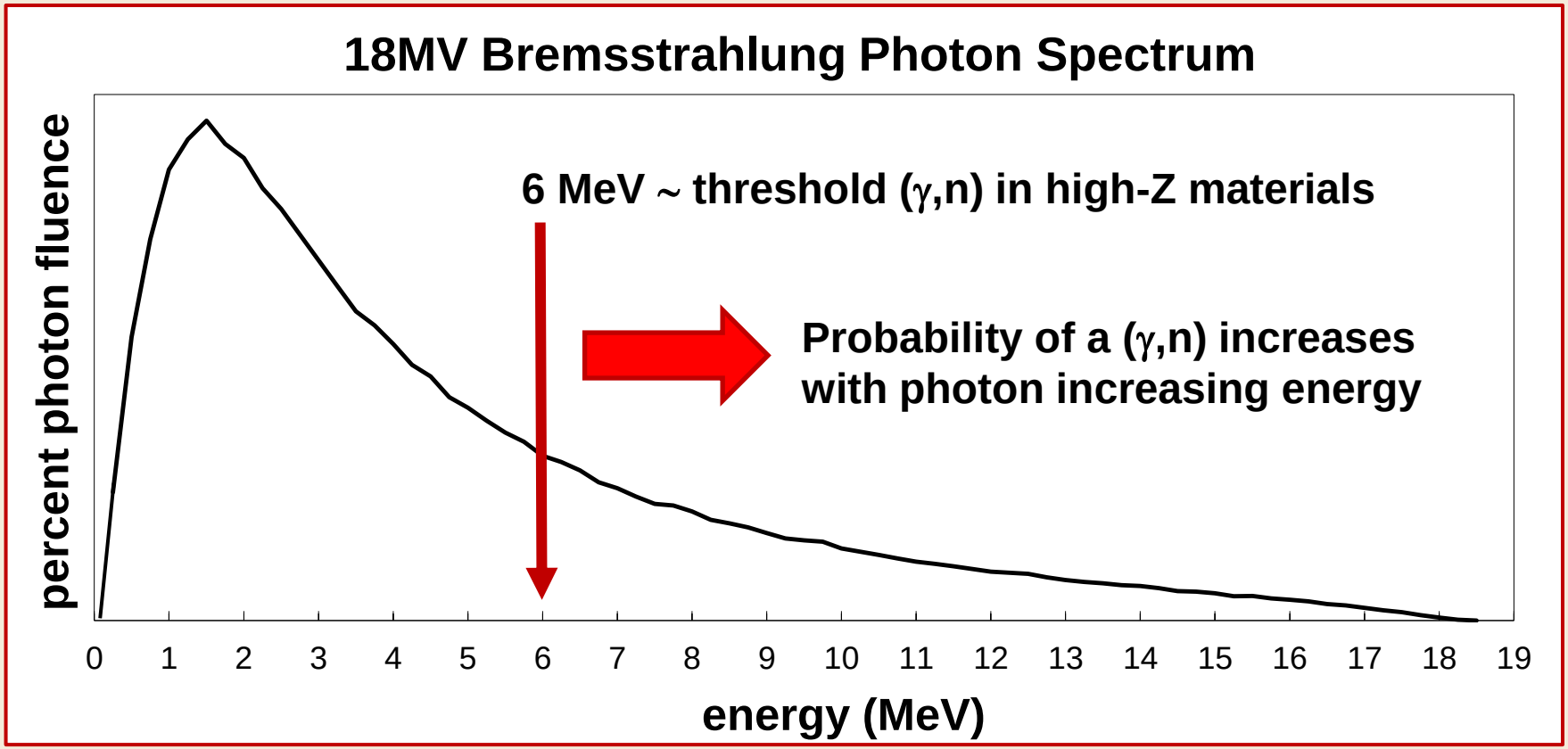
Khan (2010)

(γ,n) in High-Z Materials

- **Primary collimator**
- **Target**
- **Flattening filter***
- **Secondary jaws**
- **MLC****

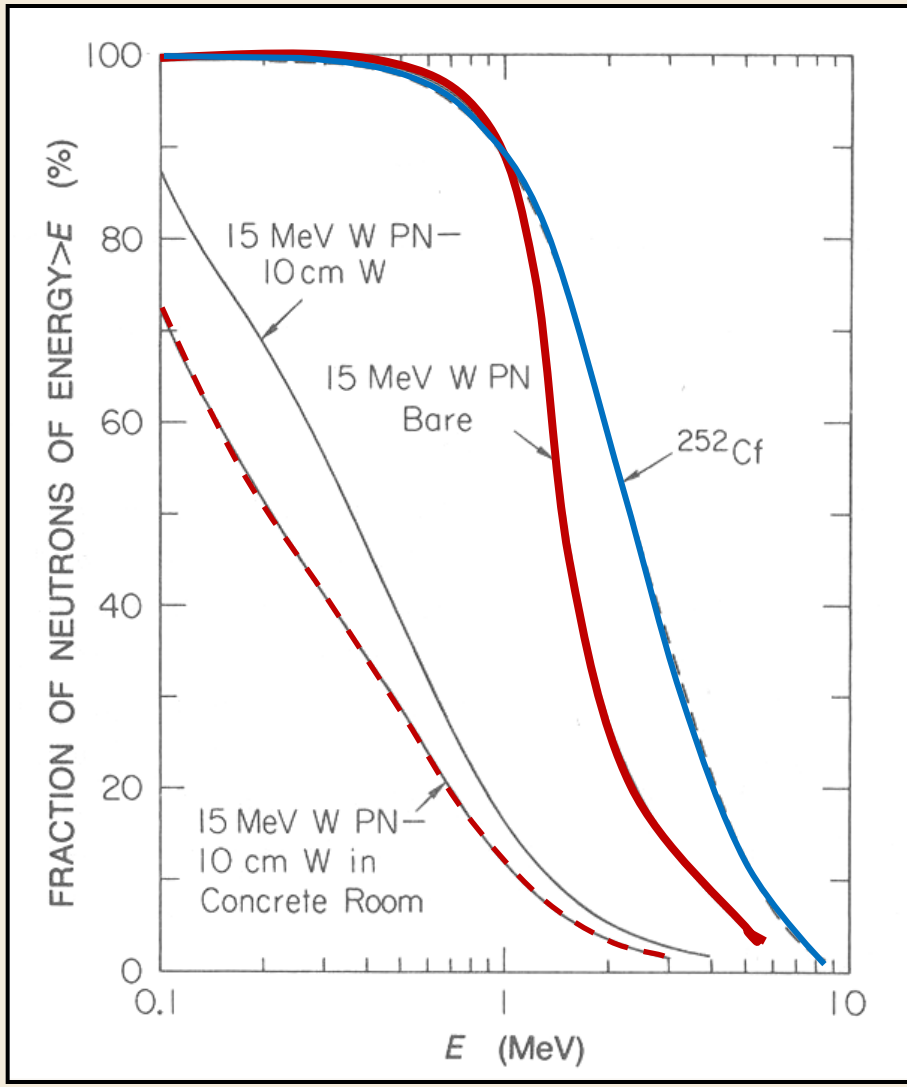
Photon Beam Energy Effect on Neutron Production

- **Bremsstrahlung photon beams**
  - **Wide distribution of energies**
  - **Max energy ≈ energy of electron beam on the target.**



Secondary Neutron Spectra from Clinical Photon beams

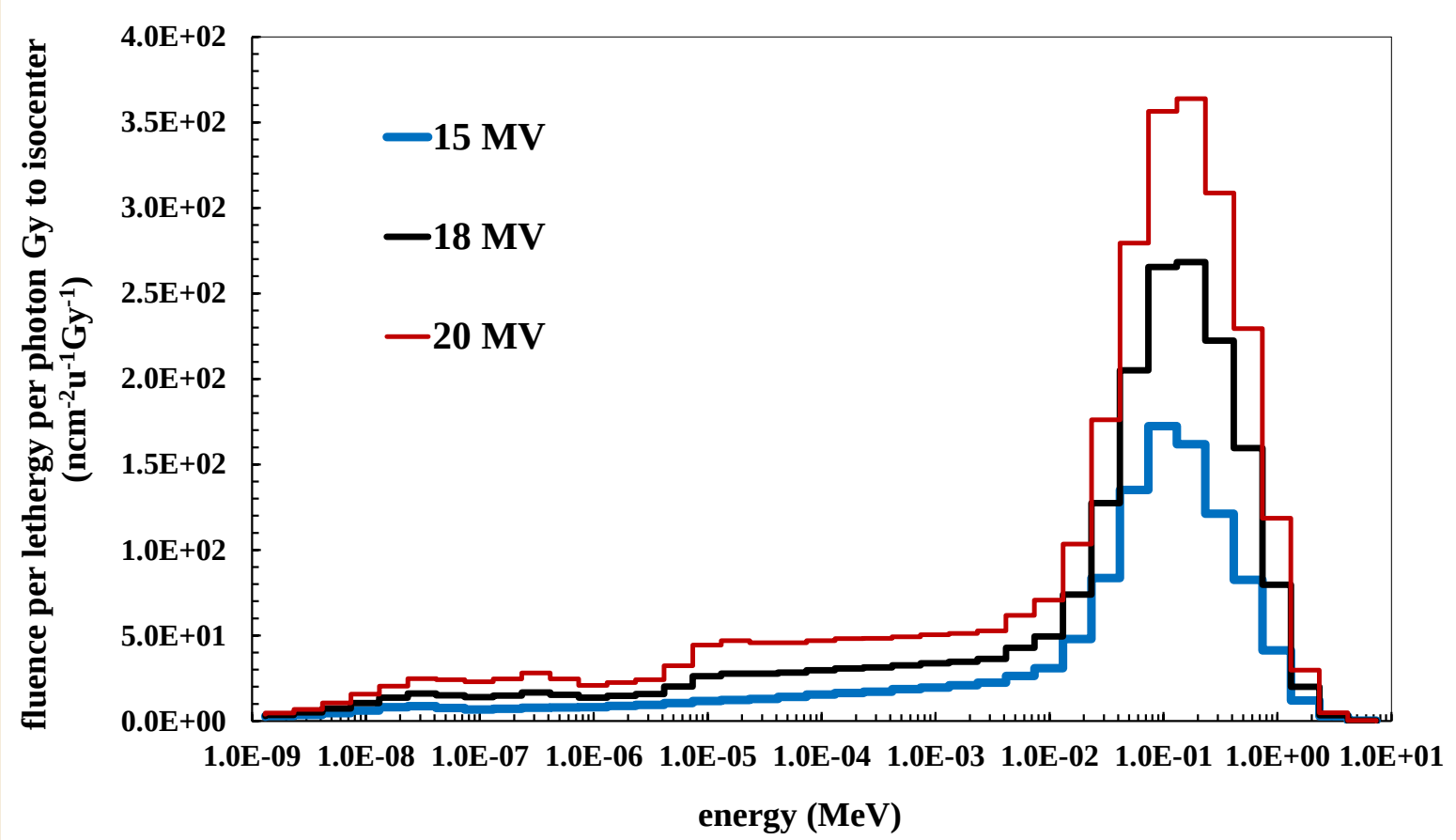
- **Energy distribution in the linac head ~ isotropic resembles a fission spectrum.**
- **Softens, as neutrons undergo interactions in the linac head, patient, and treatment vault.**



NCRP Report 79 (1984)

Secondary Neutron Spectra from Clinical Photon beams

- **Similar energy distribution for all photon beams**
- **Fluence increases with increasing photon beam energy**



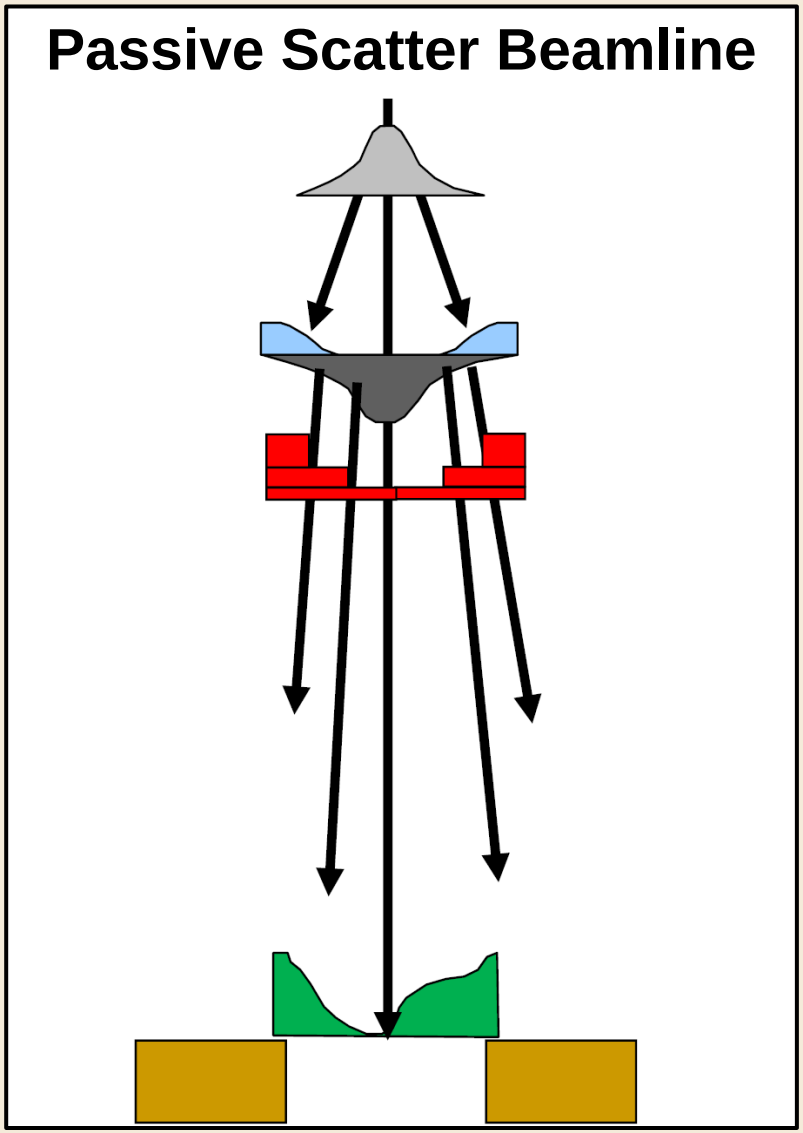
Howell *et al.*, Med Phys 36, (2009).

Internal Neutrons in Photon Therapy

- **(γ,n) in low-Z Materials is negligible compared to high-Z materials**
  - **Higher threshold energies:**
    - **^{16}O (17 MeV)**
    - **^{12}C (19 MeV)**
    - **^{14}N (8 MeV)**
  - **Lower x-sections (20X - 30X ↓)**
- **<u>Essentially no neutron production in patient</u>**
  - ***Exception high-z implants, e.g., hip prosthesis***

Secondary Neutrons
Proton Therapy

Background
External Neutrons in Proton Therapy

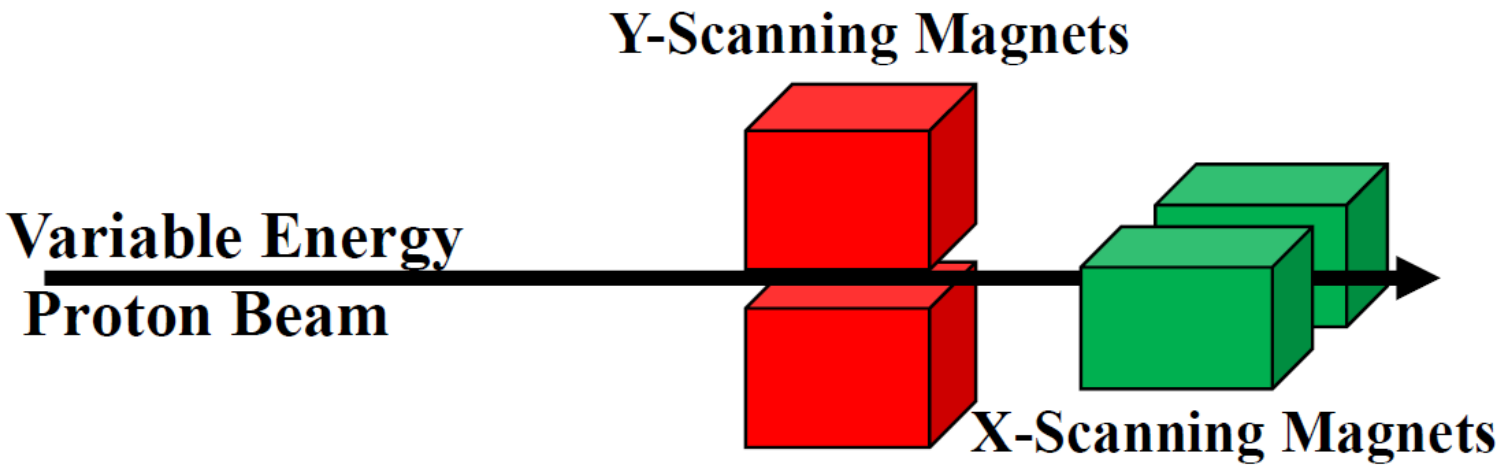


(p,n) in High-Z Materials

- Double scatterer
- Modulation wheel (SOBP)
- Compensator
- Field aperture

External Neutrons in Proton Therapy

Spot Scanned Beamline



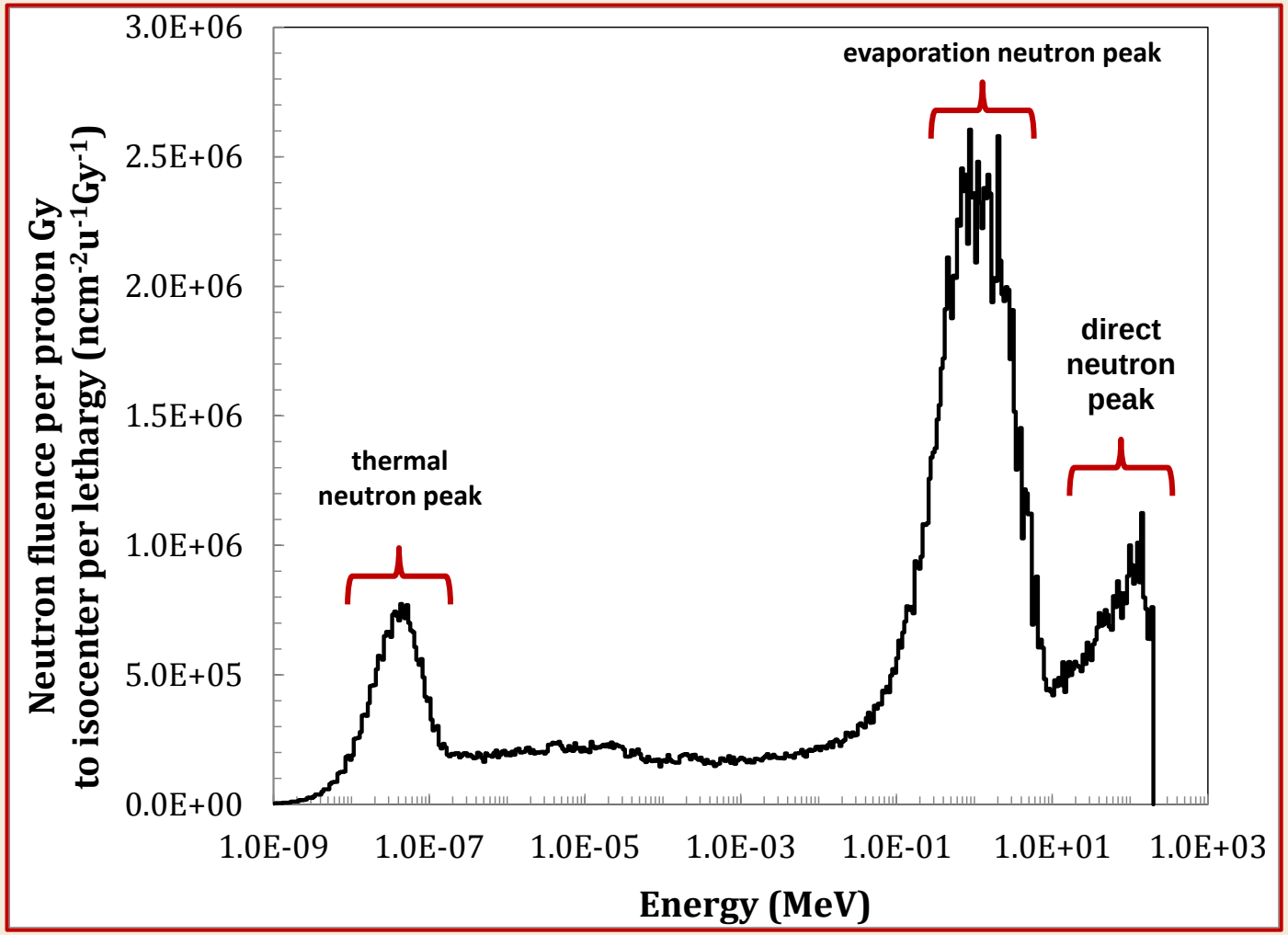
- **Less high-Z materials in beamline**
  - **Less neutron production**

Internal Neutrons in Proton Therapy

- **(p,n) in low-Z Materials is important and non-negligible downstream of the target and w/in 10 cm of field edge.**
  - **In passive scatter, can contribute ~ 50% of the dose equivalent.**
  - **In spot scanning, dominant source neutron dose.**
- **Internal neutron production ⬆ with:**
  - **Beam energy due to higher (p,n) cross sections.**
  - **Field size because the proton beam is incident on a larger volume of tissue.**

Secondary Neutron Spectra from Clinical Proton beams

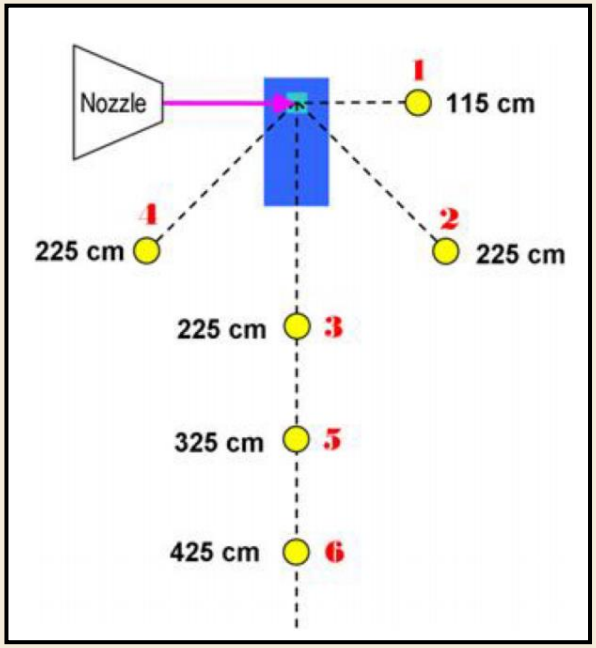
- **Similar energy distribution for all proton beams**

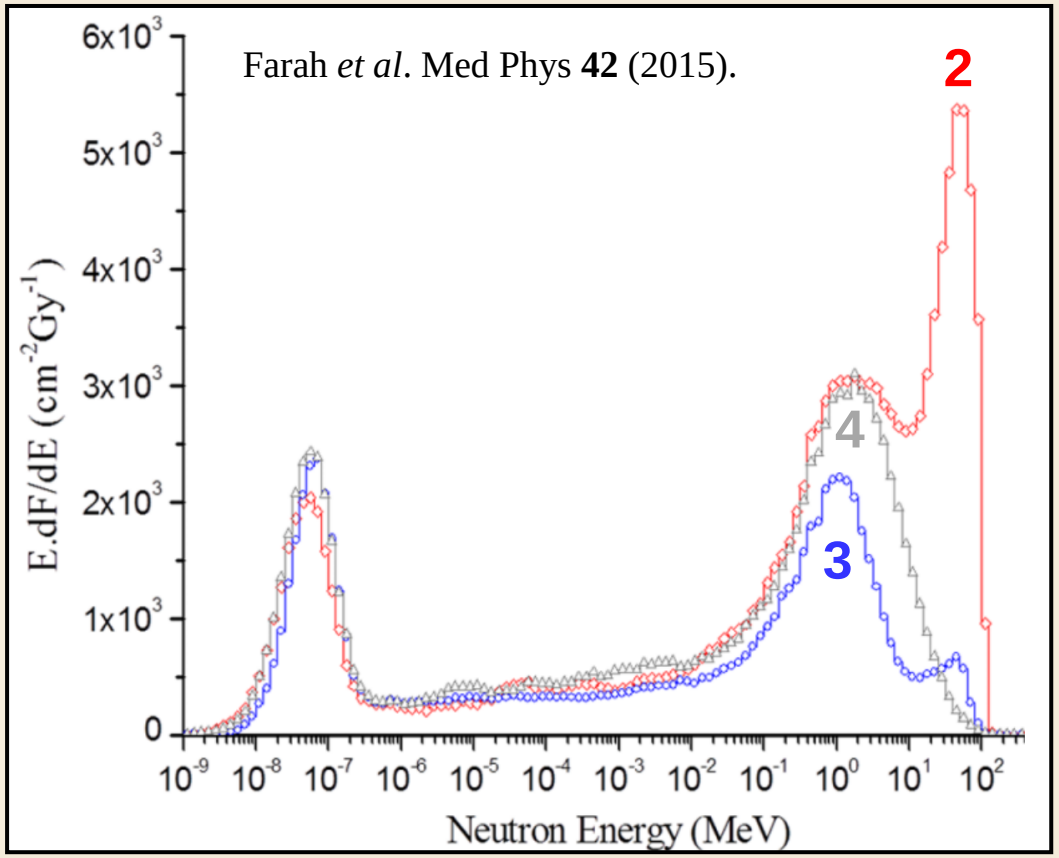


Howell and Burgett, Med Phys 41 (2014).

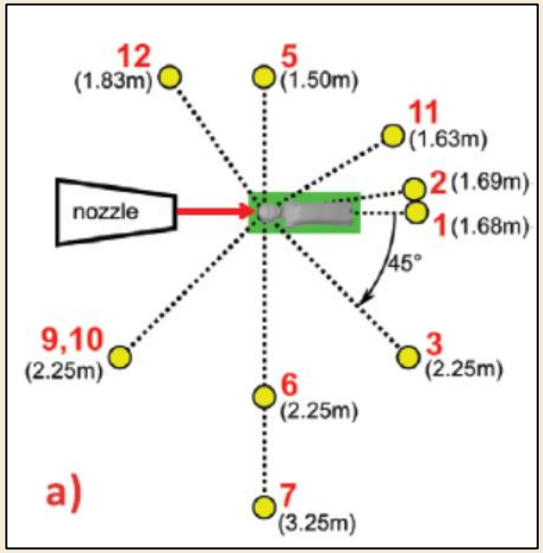
Location, location, location….

- **Relative peak heights differ at different relative positions from isocenter, as beam softens.**

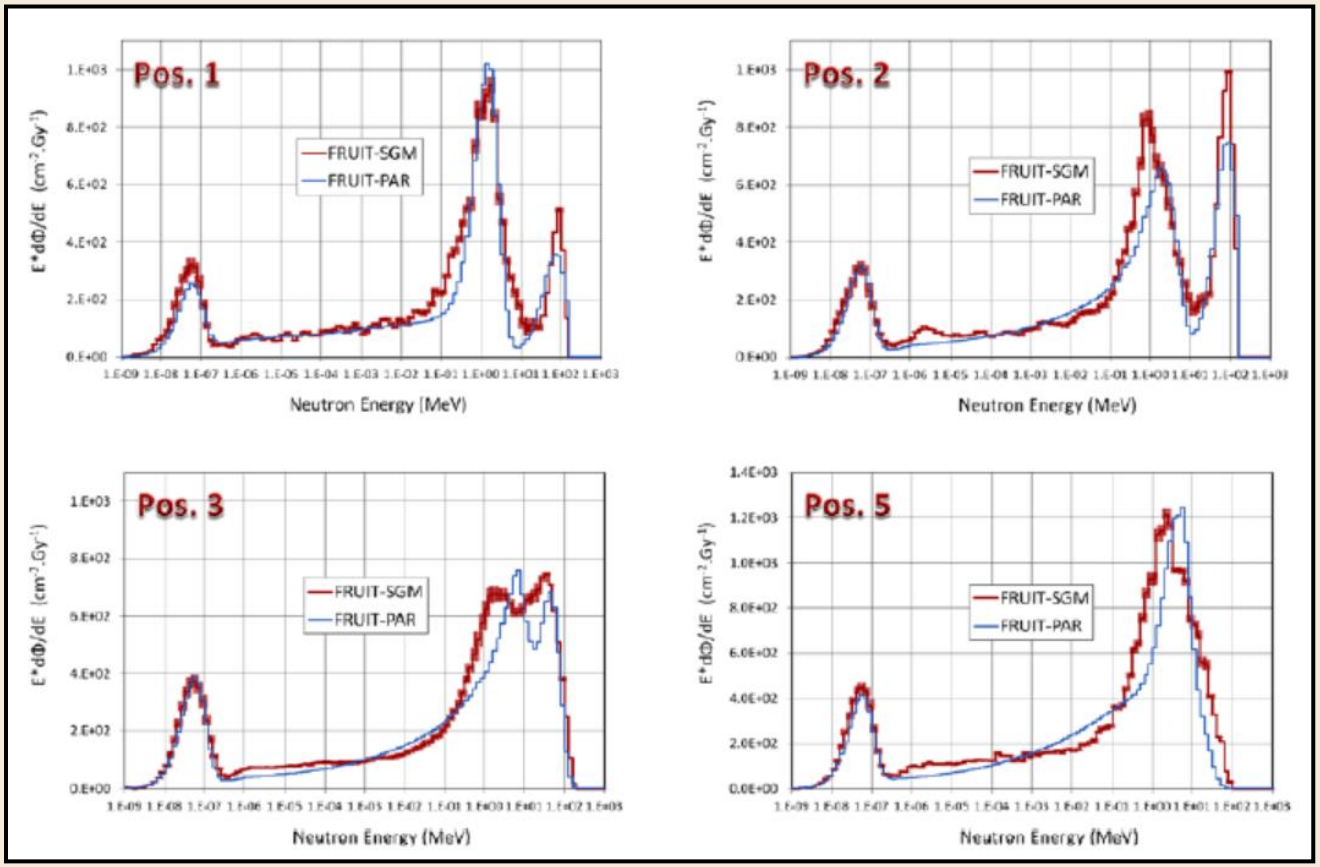




Scanning Beam Measurements - IBA



- **Greater high energy component**
  - **Along beam path (than off axis)**
  - **Closer to isocenter**

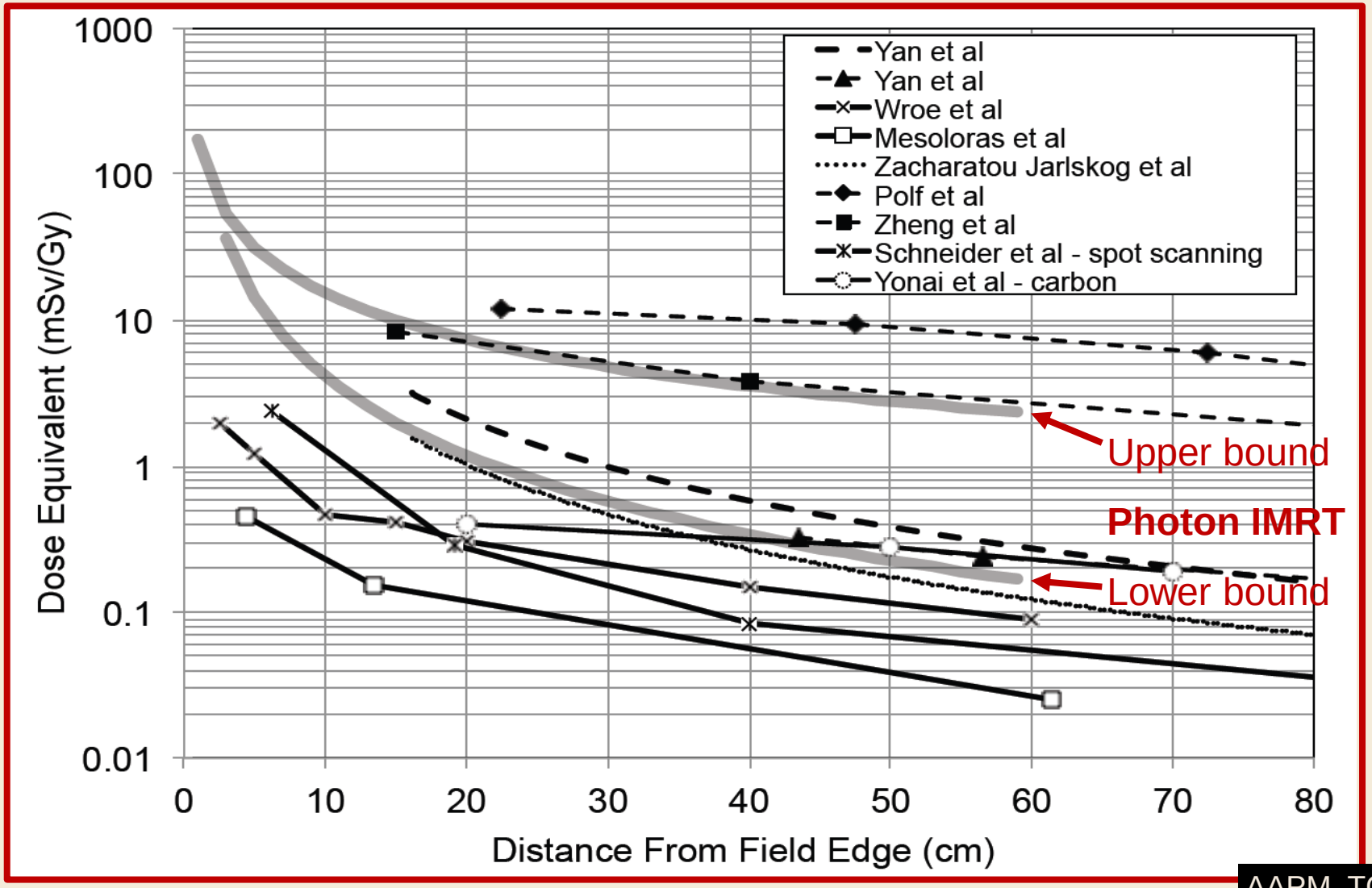


Mares *et al*,. 2016

Published Data
Secondary Neutrons in PRT

- **How much secondary neutron dose results from PRT???**
- **Substantial published data on out-of-field neutron dose from PRT.**
- **but data highly variable spanning orders of magnitude….**

Data Span Orders of Magnitude



AAPM, TG-158

General Questions to Consider when Evaluating Neutron Data

Measurements

- How were the data measured?
- Was the detector sensitive to neutrons over the entire energy range?
- If an active detector was used, was pulse pile-up a potential issue?
  - If yes, was it appropriately accounted for?
- If in phantom, was the change in spectrum with increasing depth taken into account?

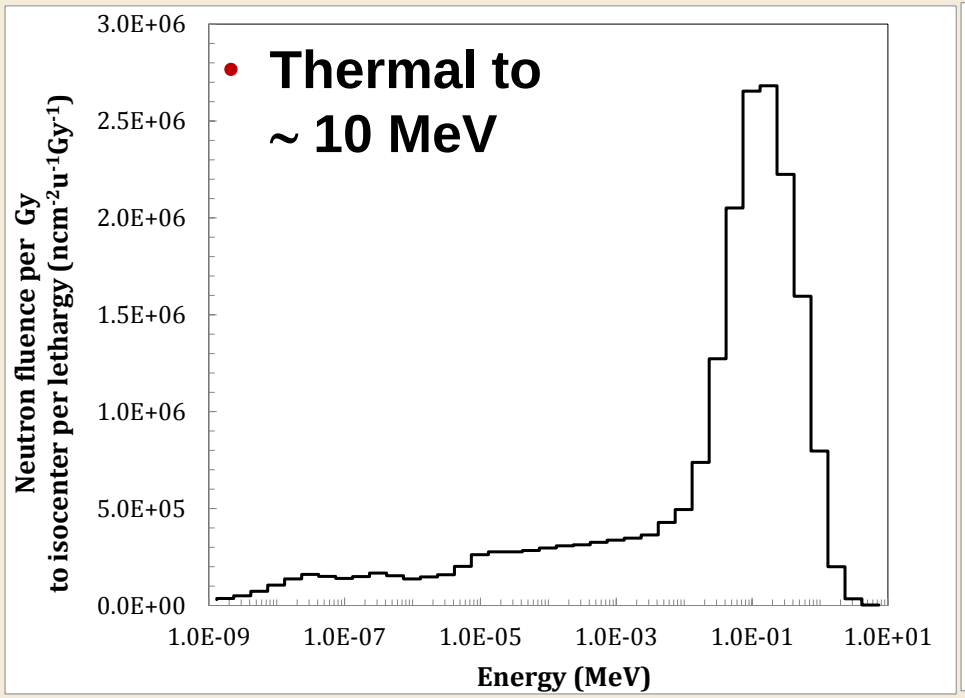
Simulations

- Was the model appropriately validated against “good” measurements?

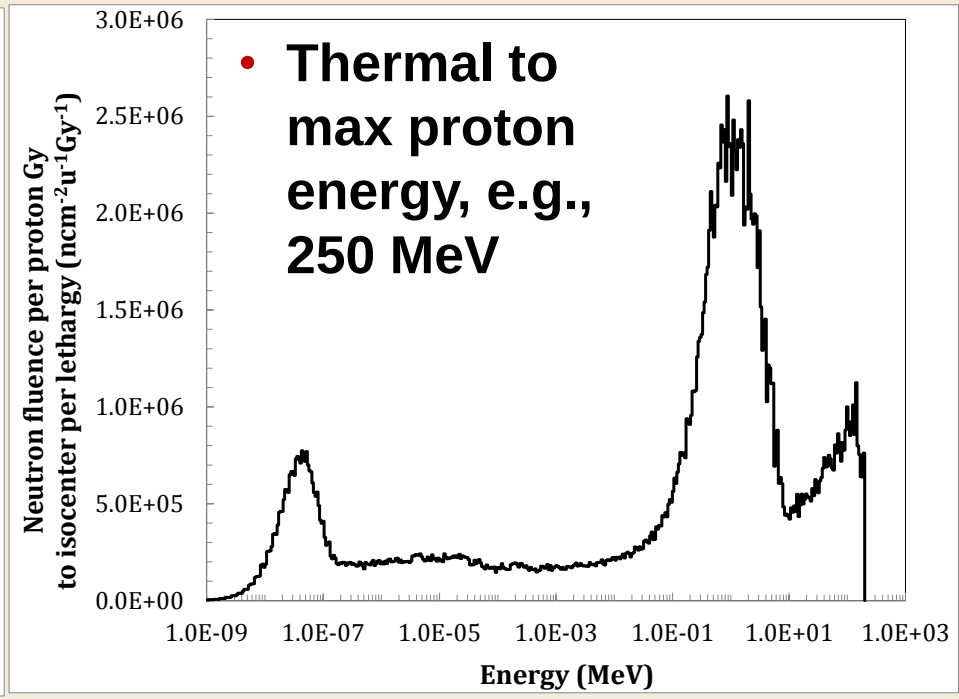
Neutron Measurement Techniques

Detector Energy Response
In the Context of Spectra being Measured

Photon Therapy



Proton Therapy

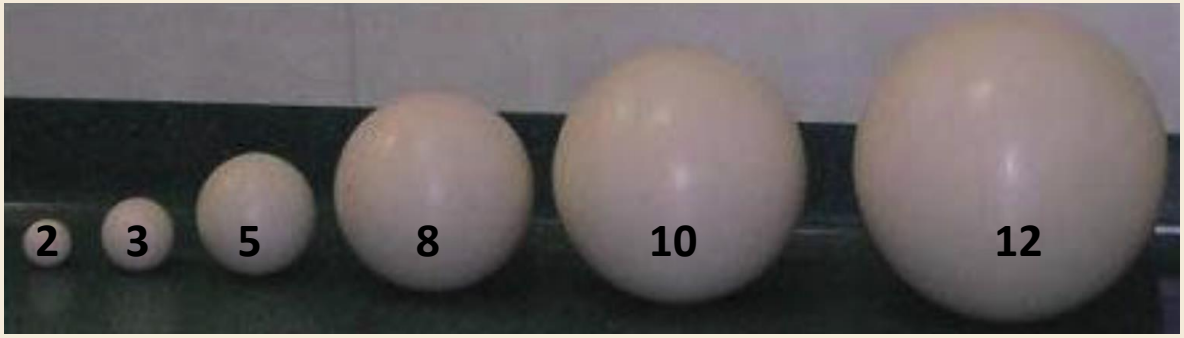


Neutron Detection Techniques

- **The vast majority of neutron detectors are only able to detect thermal neutrons.**
  - **Active Detection**
    - $^{10}B(n,\alpha)$
    - $^{6}Li(n,\alpha)$
    - $^{3}He(n,p)$
  - **Passive Detection**
    - **Thermoluminescent Dosimeters (TLD)**
    - **Activation Foils (^{198}Au and ^{111}In)**
- **Modified response based owhen embedded in various moderators (low-Z and high-Z).**

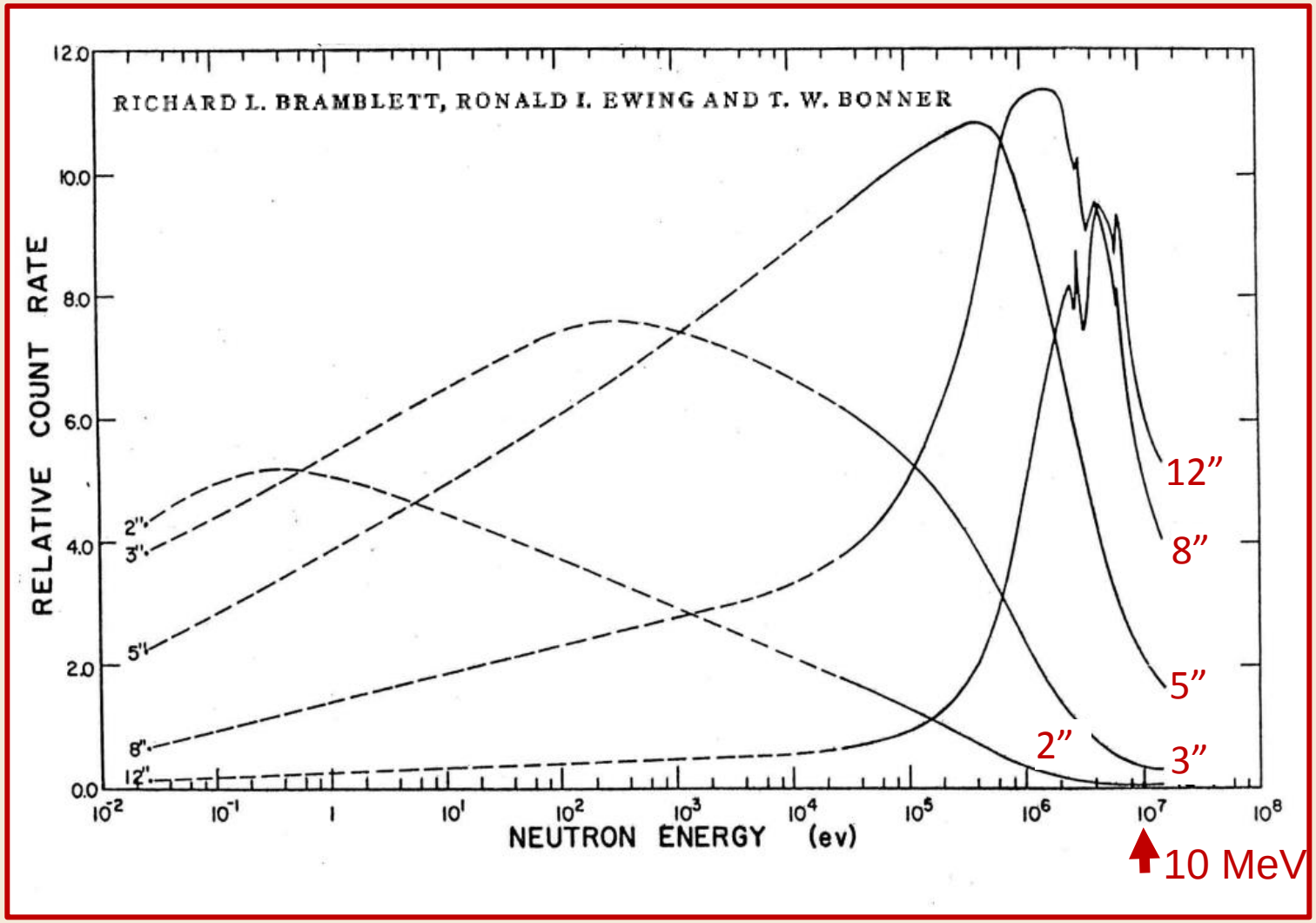
Systems of Moderators

- **By varying the thickness of this moderating material, the detector becomes optimized for specific neutron energy ranges.**



Tedious measurement system: **repeat measurements with each sphere and then de-convolve data to determine spectrum.**

Response Functions for 2” to 12” Moderators



- For all spheres response begins to drop above 10 MeV.
- Suitable for measuring secondary neutrons from photon therapy.

What about PRT???

Extended Range Bonner Spheres

- Increase sensitivity to high energy neutrons by adding high-Z materials with large (n,xn) cross sections.

1. NEMUS

B. WIEGEL and A.V. ALEVERA. “NEMUS – the PTB Neutron Multisphere Spectrometer: Bonner spheres and more. *Nucl. Instr. and Meth. Phys. Res.* A476, 52 (2002)

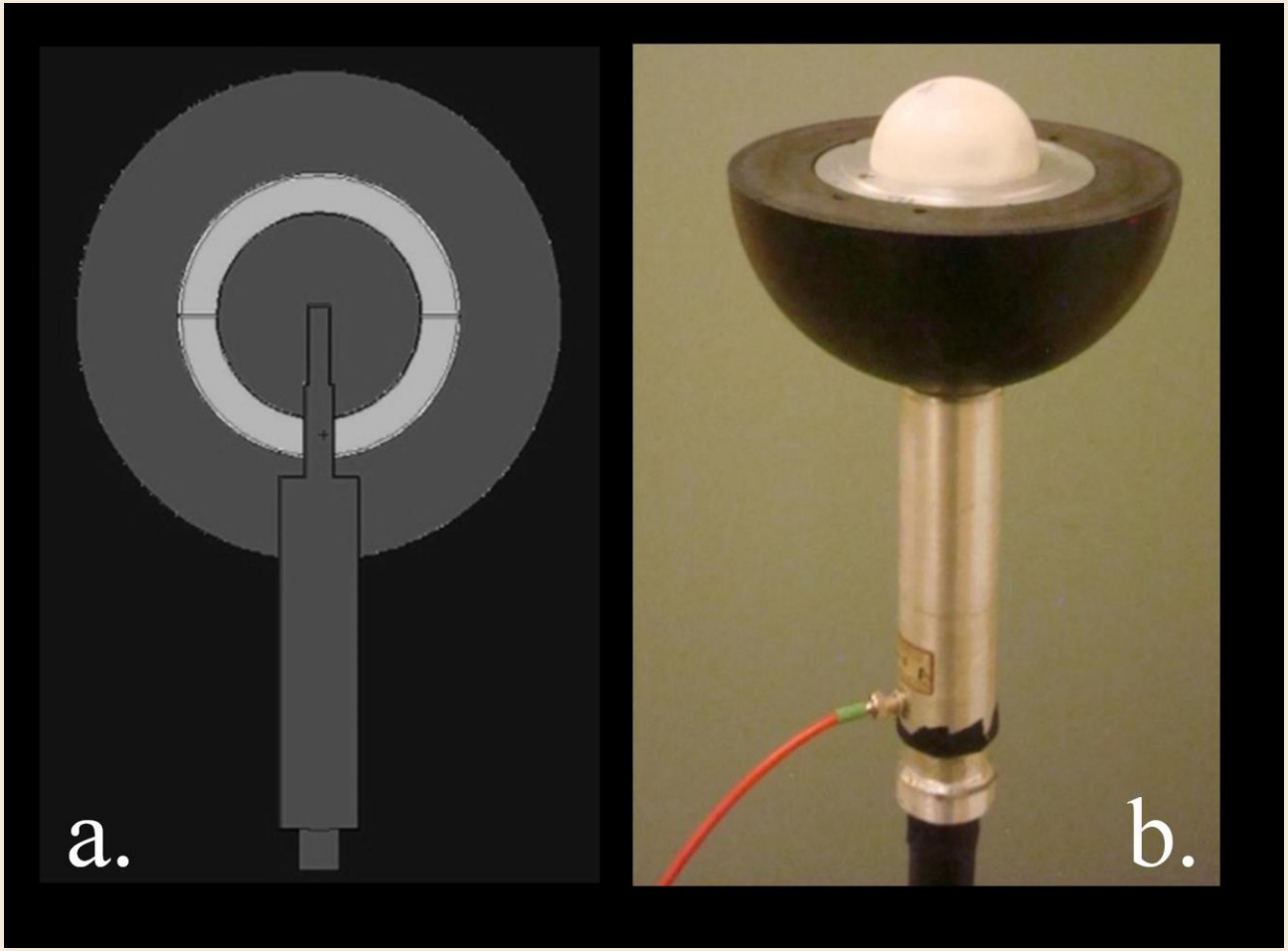
2. CERN

C. BIRATTARI, P. CAPPELLARO, A MITAROFF, and M. SILARI. Development of an extended range Bonner sphere Spectrometer. Proceedings of Monte Carlo 2000 – Advanced Monte Carlo for Radiation Physics, Particle Transport Simulation, and Applications, Lisbon (Portugal), 1157-1162 (2000)

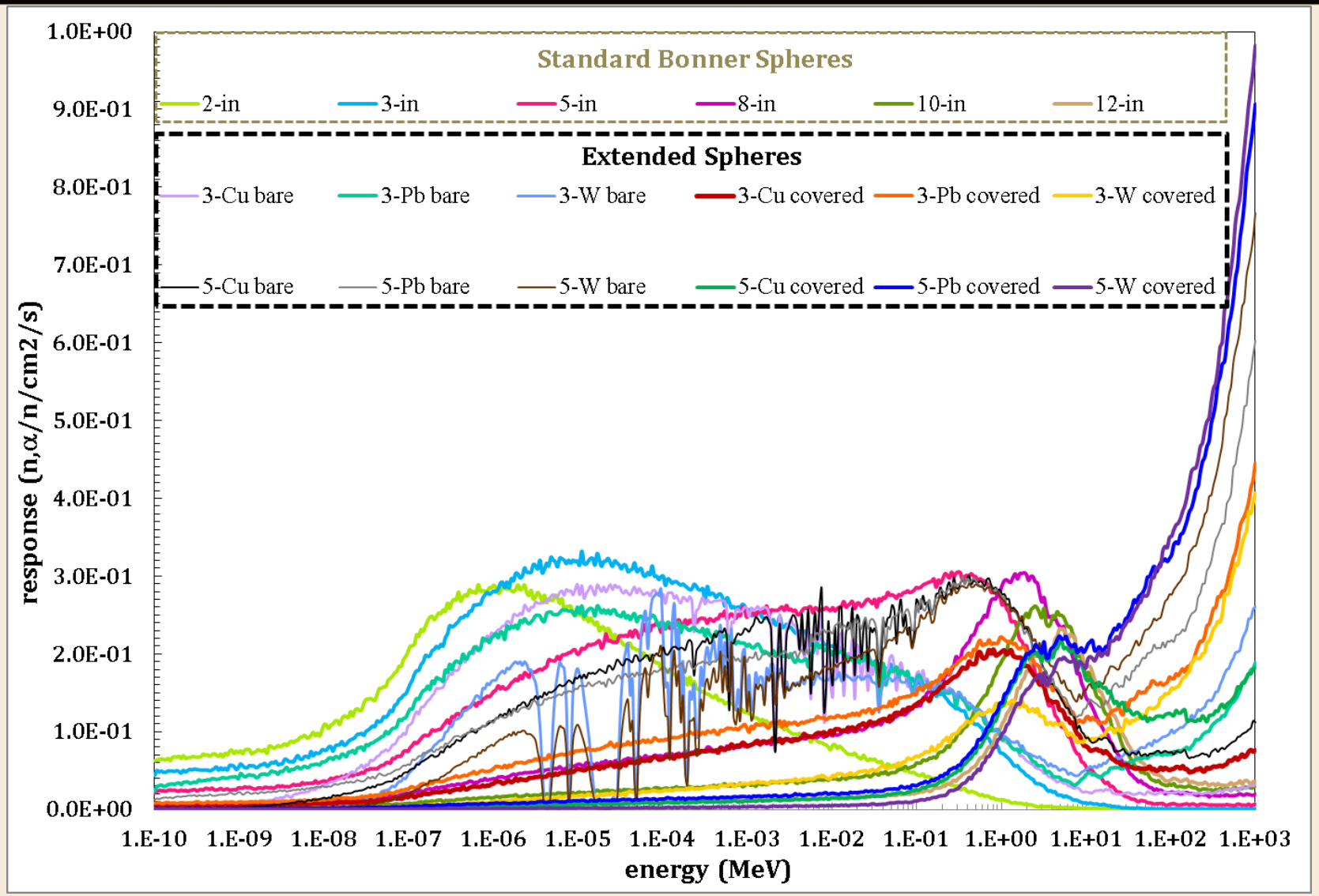
1. Bonner Sphere Extension

Howell RM, Burgett EA, Hertell NE, Kry SF, Wang Z and Salehpour M. Measurement of high-energy neutron spectra with a Bonner sphere extension. Nuclear Technology 168(2):333-339, 2009 and Howell RM, Burgett EA, Wiegel B, Hertel NE. Calibration of a Bonner sphere extension (BSE) for high-enegy neutron spectrometry. Rad Meas 45:1233-1237, 2010.

Bonner Sphere Extension

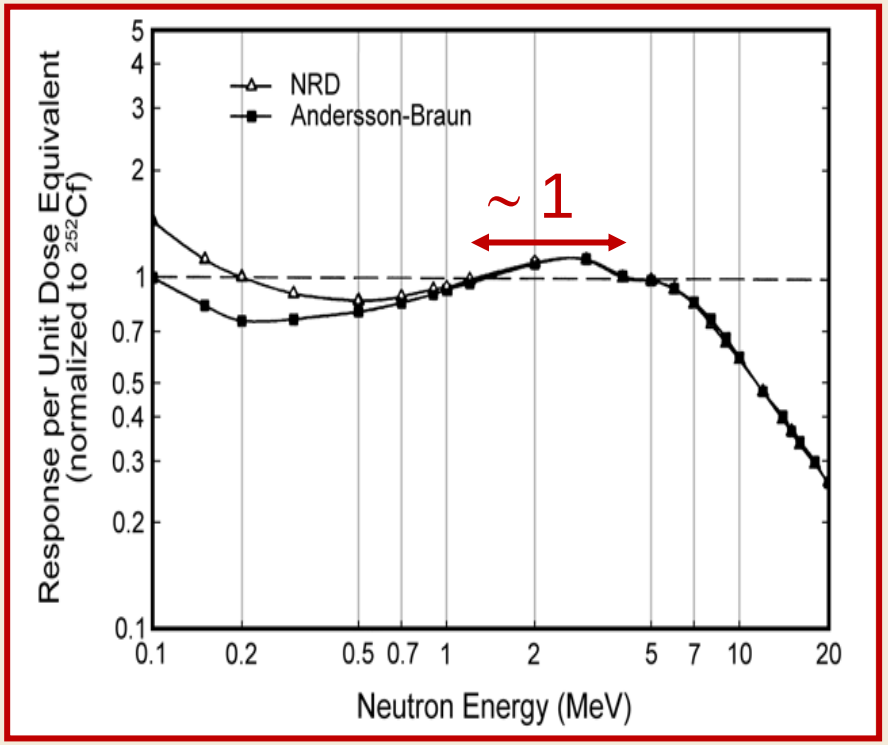


Response Functions for ERBSS



Neutron Survey Meters

- **Active thermal neutron detector (often BF_3) surrounded by a low-Z moderator.**



Energy Response

- **1 MeV, response ~1**
- **0.1 - 10 MeV, response 1.5 – 0.5**
  - **Under/over response within 50%**
- **> 10 MeV, response rapidly decreases with increasing energy.**
  - **underresponse ~6X at 100 MeV.**

For PRT, underestimate dose:

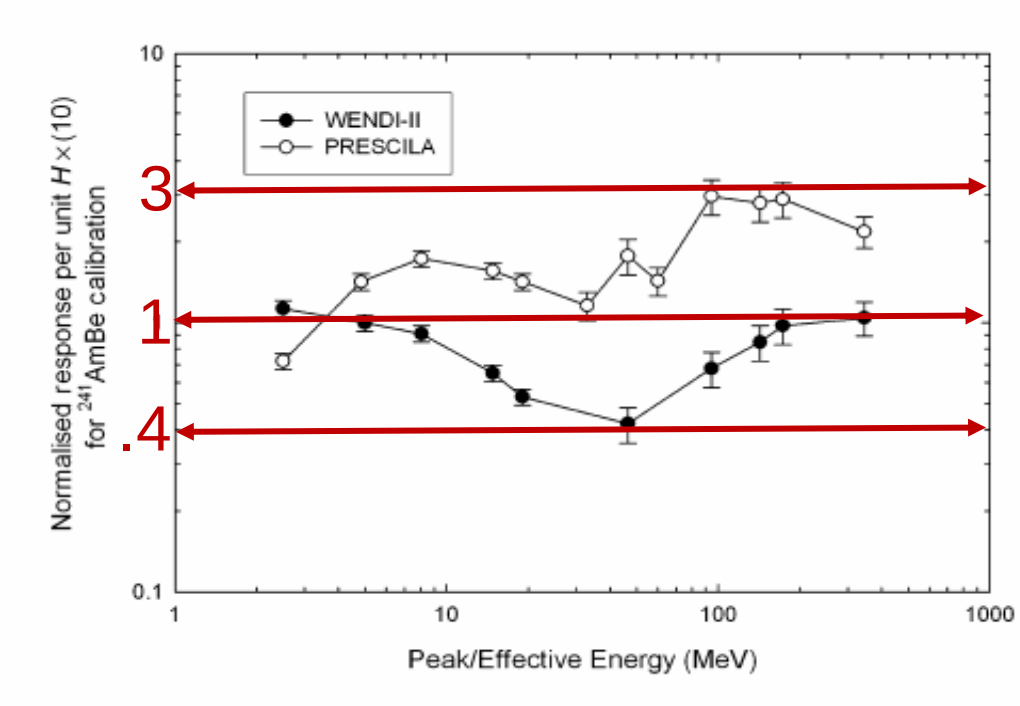
- **No response to neutrons from 10 MeV - max proton energy.**

Extended Range Neutron Survey Meters

- **Active thermal neutron detector surrounded by a low-Z moderator + Pb or W to extend high energy response.**

Energy Response

- **WENDI-II**
  - **2 – 10 Mev and 100 – 300 MeV, response ~ 1**
  - **10 – 100 MeV under-responds by as much as 40%**
- **PRESCILA generally over-responds**

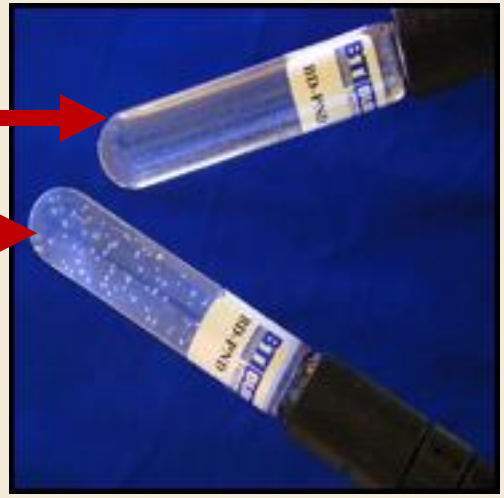


For PRT:

- **WENDI-II is reasonable detector, but still has uncertainty due to variable response, but generally within 50%.**

Fast Neutron Detectors
Bubble Detectors

- **Small sealed tube with superheated droplets of liquid dispersed throughout a polymer.**
- **When neutrons strike a droplet, 2°cp are emitted that vaporize the droplet, producing a bubble.**
- **Neutron dose determined by counting the bubbles and applying a calibration factor.**



BD-PND (BTI Bubble Technology Industries, Ontario Canada)

Advantages

- Easy to use
- High sensitivities
- Reusable
- Instantaneous reading

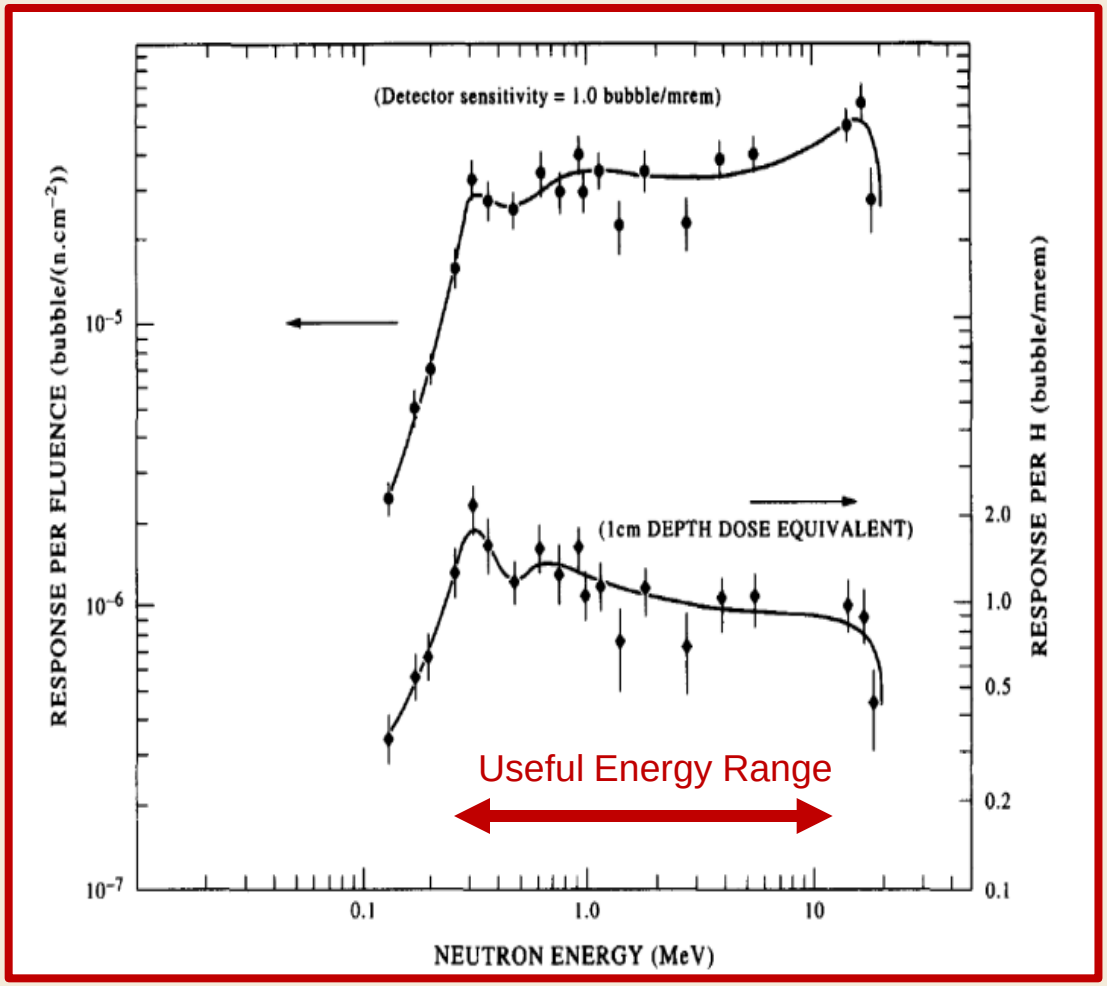
Fast Neutron Detectors
Bubble Detectors

Energy Response:

- Somewhat uniform response to neutrons over the energy range of 100 keV–10 MeV.
- At energies < and > this range, the response decreases rapidly.

For PRT, underestimate dose:

- No response to neutrons from 10 MeV - max proton energy.
- Further complicated In phantom neutrons lose energy rapidly limited response < 100 keV



Fast Neutron Detectors
Track Etch Detectors

- **Solid-state nuclear track etch detectors are made of polymers that include mainly H, C, and O, e.g, CR-39 polymer.**
- **When a neutron interacts in these materials, the recoil nuclei from the constituent materials leave behind microscopic damage trails, or tracks.**
- **Chemical processing (etching) is used to enlarge the tracks.**
- **The track density can then be scored and neutron dose determined using a calibration factor.**

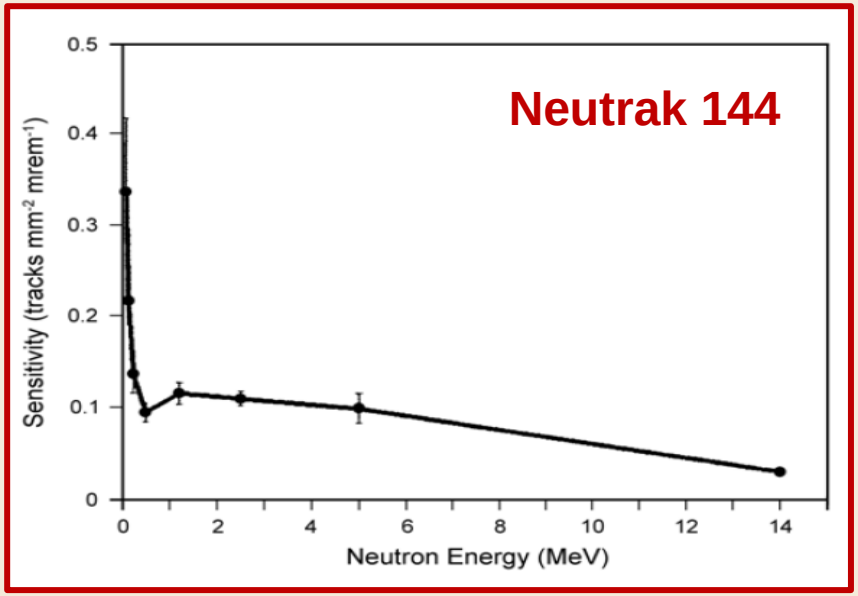
Fast Neutron Detectors
Track Etch Detectors

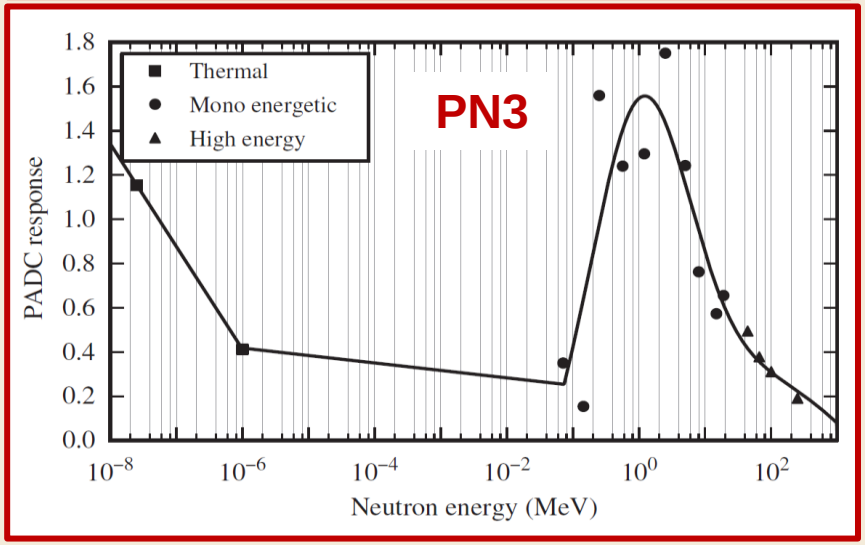
Energy Response:

- For most track etch detectors, response falls off above ~ 6 – 10 MeV.
- PN3 does respond above 10 MeV, but response is complexly energy dependent.

For PRT, underestimate dose:

- Most underestimate dose due to limited/no response to neutrons from 10 MeV - max proton energy.
- PN3 have successfully been used, but must account for energy dependence.



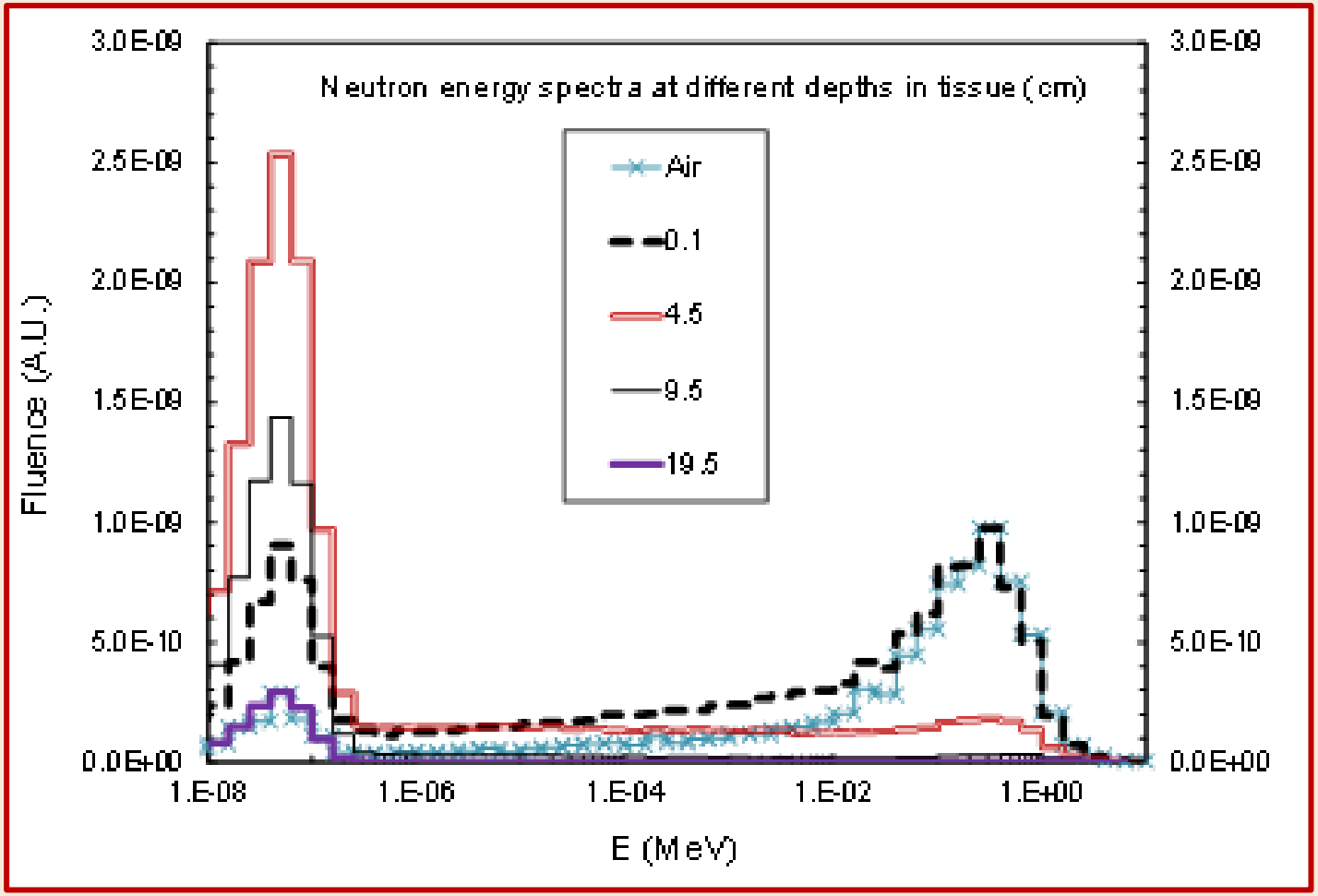


Special Considerations

In-phantom Measurement Challenges

- **Neutron detectors with moderators are too large for phantom measurements.**
- **But for those that are small enough….**
  - **Neutrons rapidly lose energy in phantom due to scatter with low-Z media.**
  - **Detector responses to different neutron energies can vary by several orders of magnitude.**
  - **Thus, incomplete consideration of the detector response or neutron spectrum being measured can easily result in errors of several orders of magnitude.**

Variations in the Neutron spectrum as a Function of Depth in Tissue



- **Let's consider the examples of TLD 600 & bubble detectors in the context of these data….**

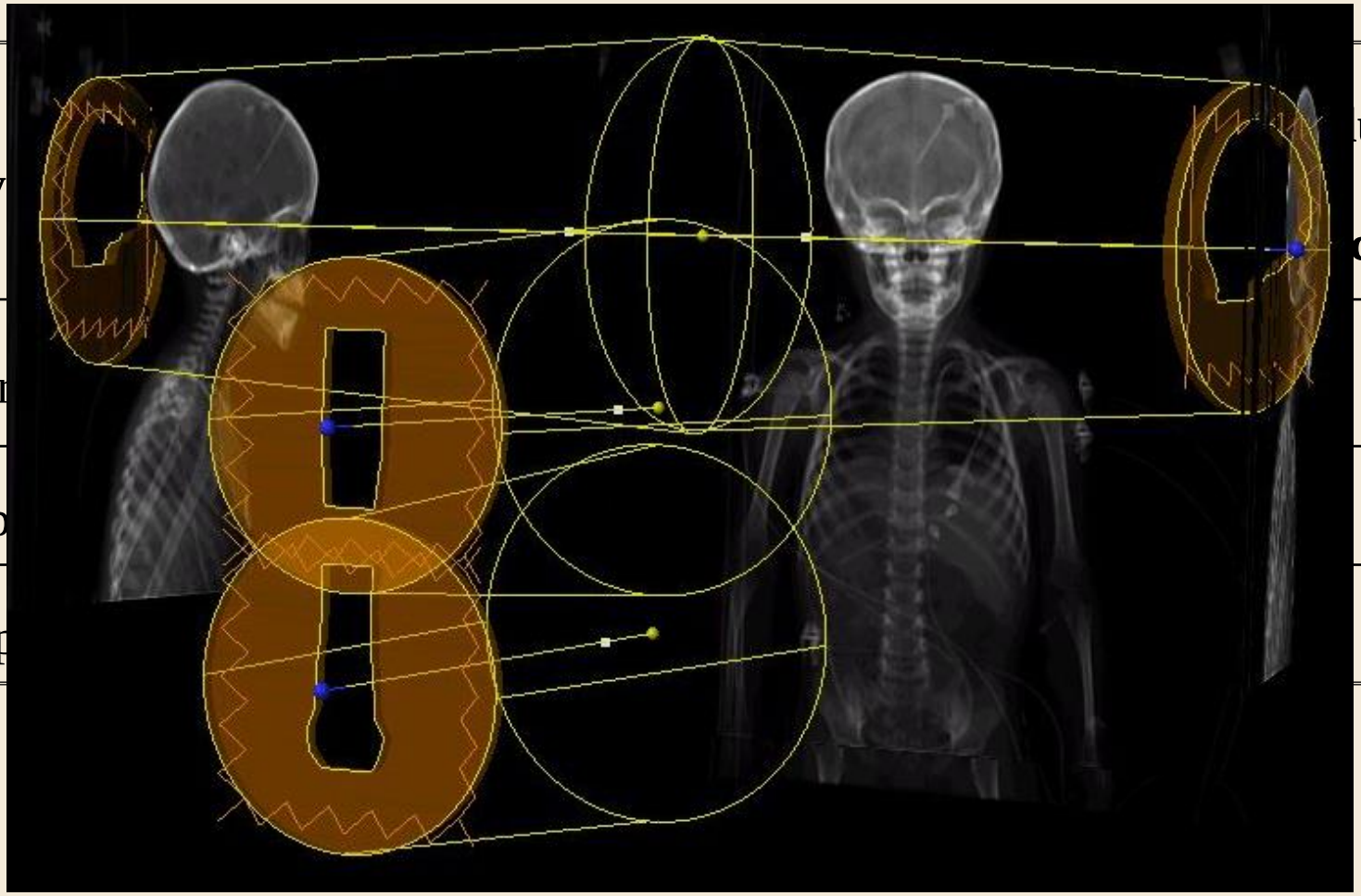
Clinical Proton Beam Therapy Cranial Spinal Irradiation

What about Clinical Scenarios??

- **Dose from secondary neutrons is of particular concern in proton CSI because:**
  - **almost universally utilized for children and adolescents,**
  - **who often survive many decades following diagnosis, and**
  - **are at significant risk of RT-related late effects.**

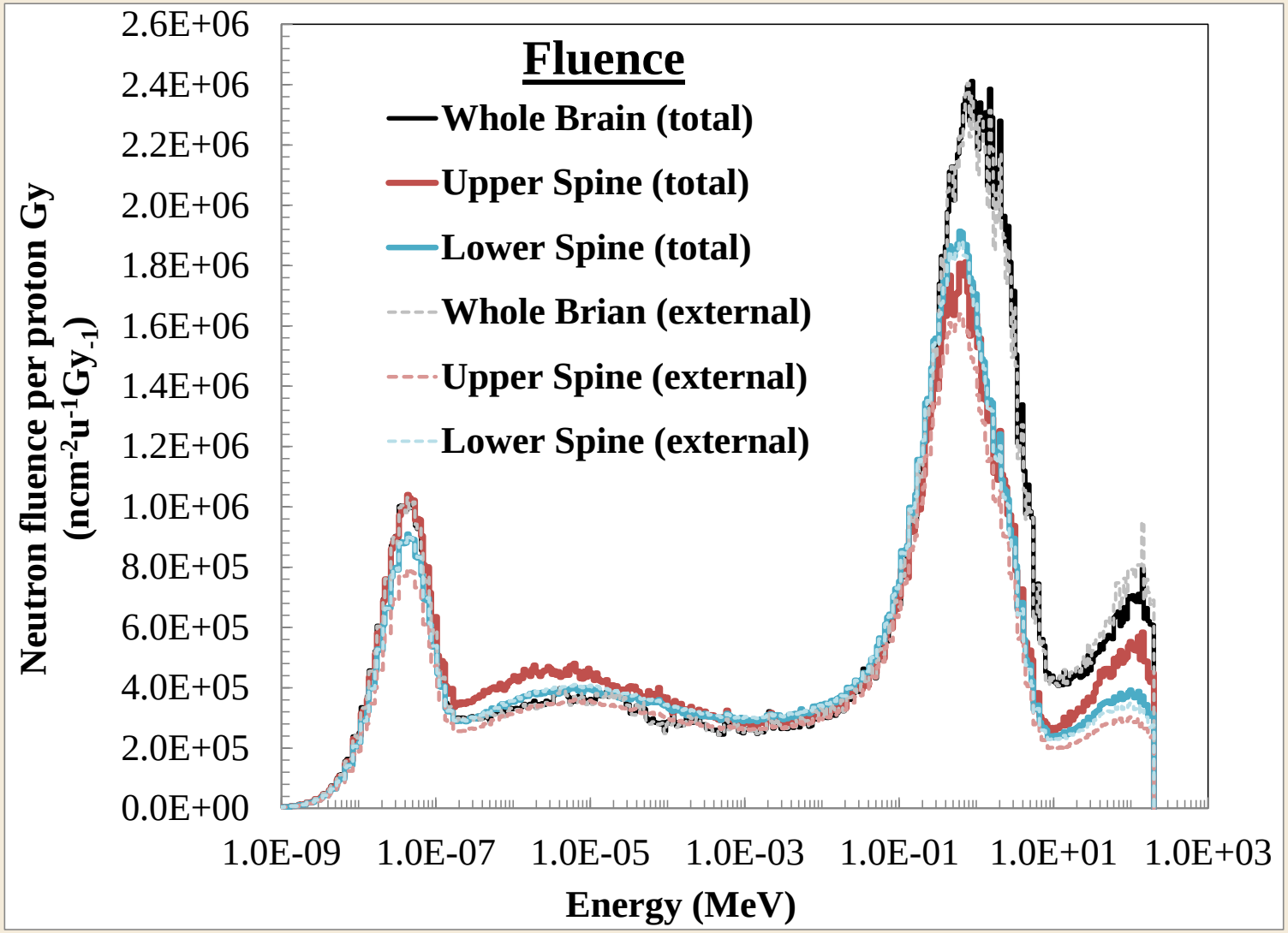
Passive Scatter Beamline - Mevion

- **Measure Clinical Scenarios**

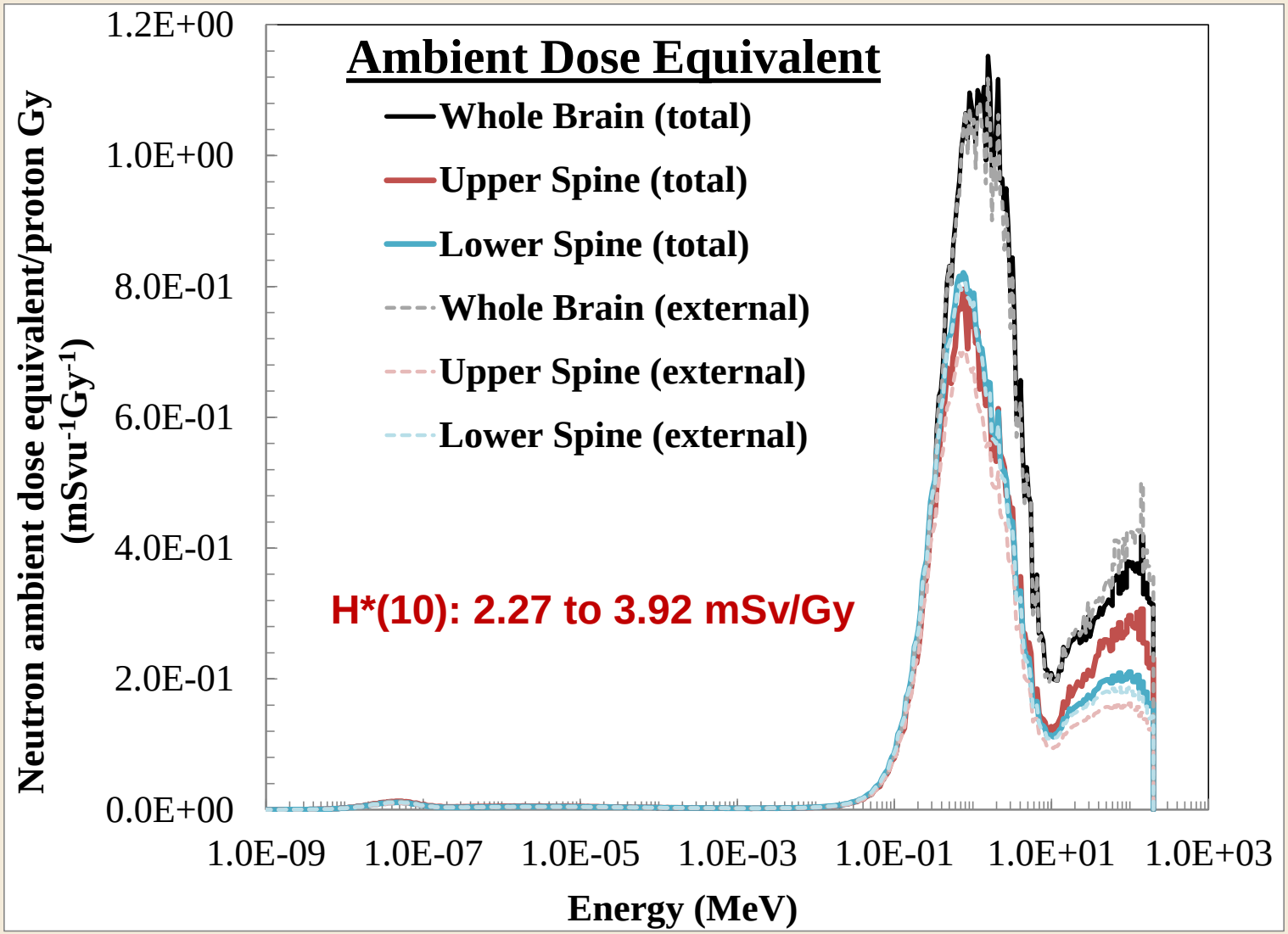


Field ty	ulation cm)
Whole br	16
Upper sp	8
Lower Sp	8

Passive Scatter Beamline - Mevion



Passive Scatter Beamline - Mevion



What about Scanning Beam?

How much lower are the neutron doses compared to passive scatter?

- **EURADOS WG 9 Comprehensive Study**
- **IBA beamline (Krakow, Poland)**
  - **measured 10 spectra**
  - **Two proton energies 100 and 144 MeV**
  - **2 different ERBSS**
  - **High value: 2.7μSv/Gy at 1.6 m**
  - **Low value: 0.52 μSv/Gy at 3.35 m**

Passive Scatter versus Scanning Beam

External Neutrons

- Doses from neutrons generated external to the patient are highly dependent on the
  - proton beam incident on the patient, which depends on:
    - the design of the proton therapy machine itself and
    - treatment-specific devices within the beamline.

Internal Neutrons

- Doses from neutrons generated within the patient increase with:
  - beam range and
  - treatment volume irradiated (i.e., field size).

mSv/Gy versus μSv/Gy

Secondary Neutrons
Protons versus Photons

Photons versus Protons

Protons

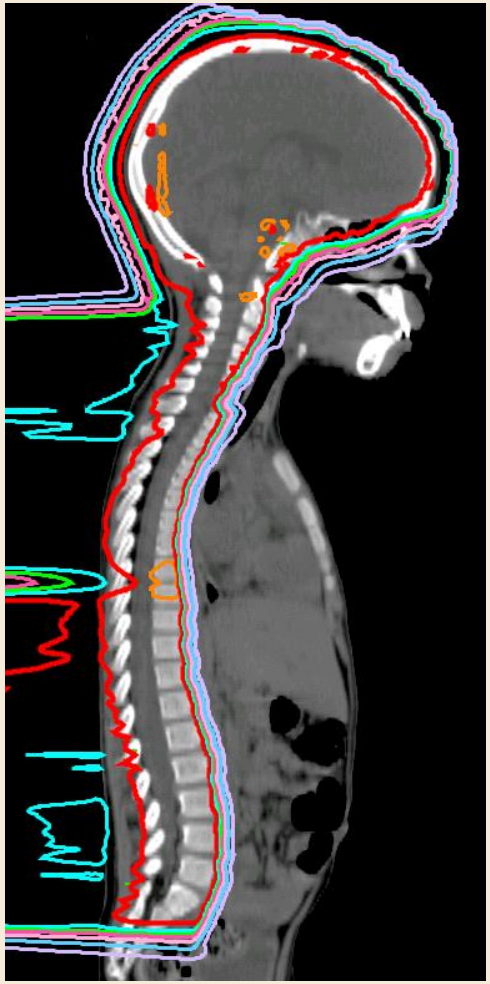
- Narrow proton energy distribution
- Higher primary energies: 180 MeV, 200 MeV, 250 MeV
- (p,n) in both high-Z and low-Z
  - External and Internal neutron production
- Patient dose:
  - μSv – mSv per Gy

Photons

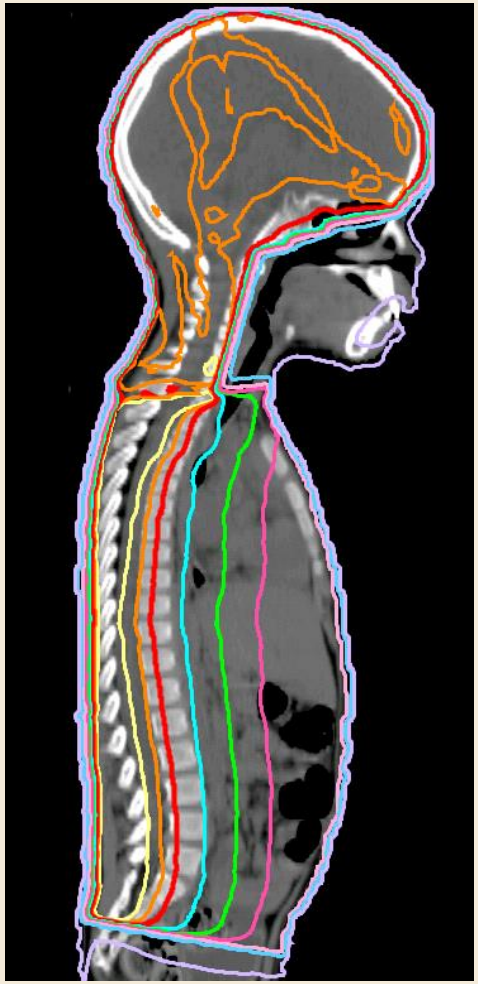
- Wide photon energy distribution
- Lower primary energies: 15 MV, 18 MV, 20 MV
- (γ,n) in high-Z
  - External neutrons
- No (γ,n) in low-Z
  - No internal neutrons
- Patient does
  - mSv/Gy (varies over ~3X for CRT, IMRT, FFF)

The Bigger Picture

Proton CSI



Photon CSI

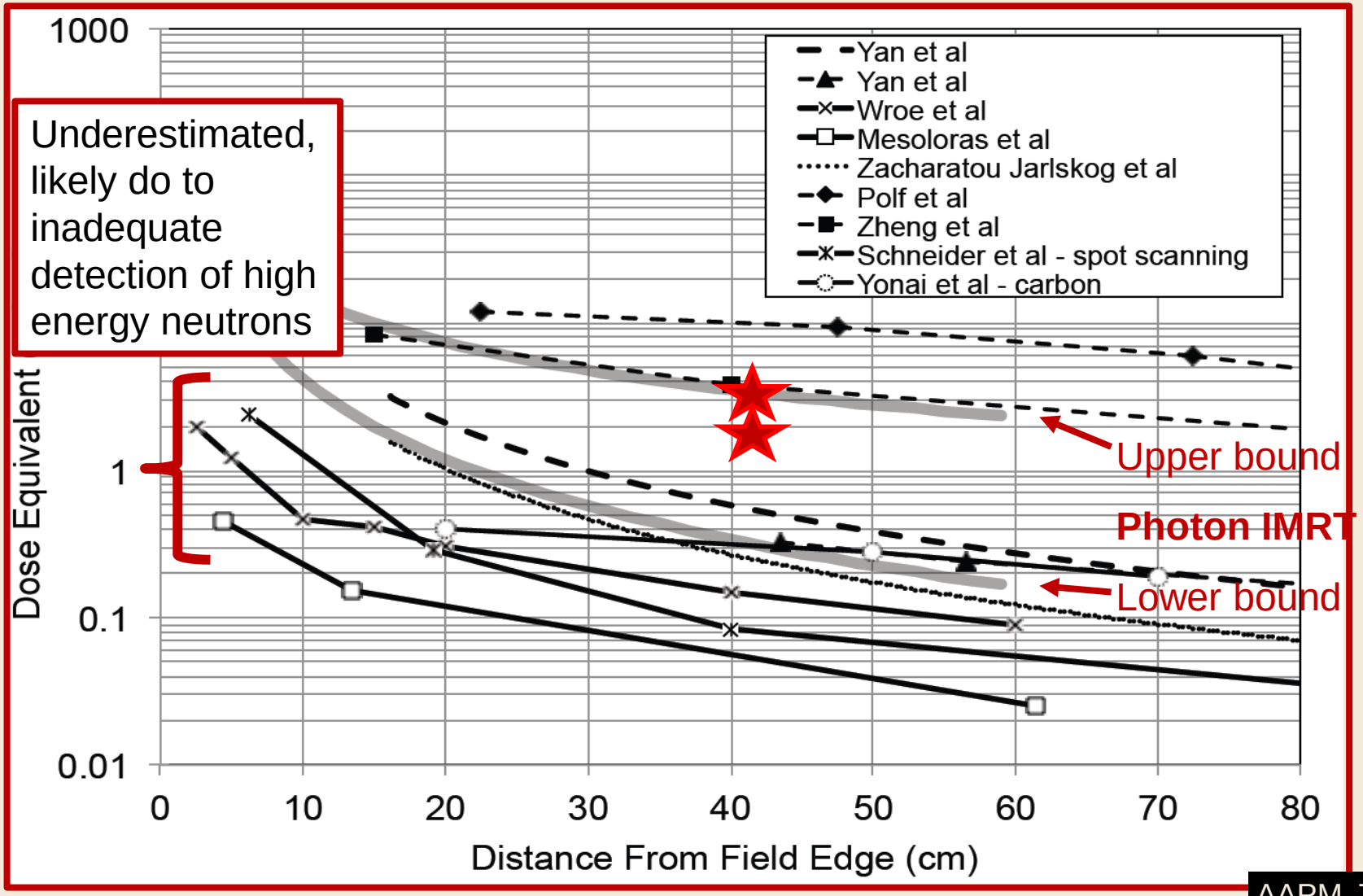


Dose (%)
110
105
100
90
80
70
50
25
5

Compare 21Gy RX

- For a PRT example of 5 mSv/Gy → **10.5cSv**
- For CRT FIF plan, entire abdomen is covered by 50% isodos line, i.e., **10 Gy**

Data Span Orders of Magnitude



AAPM, TG-158

What's Recommended?
American Association of Physicists in Medicine

For Neutron Research

1. Optimal neutron dosimetry consists of in air spectra measurements
2. Monte Carlo is well-suited for in-patient/phantom neutron dose calculations, but the model must be first validated against in-air neutron measurements
3. Neutron measurements in-patient/phantom, particularly those based on thermal neutron detection, should account for the spatial variations in the neutron energy spectrum
4. **Low-energy neutron detectors (e.g., standard Bonner spheres, most track etch detectors, bubble detectors, etc.) should not be used in proton beams. Appropriate detectors include extended-range Bonner sphere systems, SWENDI detectors, and TEPCs**

What's Recommended?
American Association of Physicists in Medicine

For Clinical Concerns Regarding Neutrons

- Neutron dosimetry requires high levels of expertise and is prone to very large errors if techniques are performed incorrectly.
- Neutron measurements should only be conducted when there is a thorough understanding of neutron dosimetry and the dosimeter being used (particularly the spectrum being measured and the energy response of the detector).
- In lieu of this, **previously published data should be used to get a reasonable estimate.**

What’s needed?

- **A comprehensive measurement campaign of the various PRT beamlines, several beamlines with similar (as possible) experimental design as possible…..**

Thank you

- **and stay tuned for……**
- AAPM TG 158: Measurement and calculation of doses outside the treated volume from external-beam radiation therapy

Memories from ICRS-10

References

- NCRP, Report 79 - Neutron Contamination from Medical Electron Accelerators. (National Council on Radiation Protection and Measurements, Bethesda, Md., 1984).
- R.M. Howell, S.F. Kry, E. Burgett, N.E. Hertel, D.S. Followill, "Secondary neutron spectra from modern Varian, Siemens, and Elekta linacs with multileaf collimators," Med Phys 36, 4027-4038 (2009).
- S.F. Kry, R.M. Howell, M. Salehpour, D.S. Followill, "Neutron spectra and dose equivalents calculated in tissue for high-energy radiation therapy," Med Phys 36, 1244-1250 (2009).
- R.M. Howell, E.A. Burgett, "Secondary neutron spectrum from 250-MeV passively scattered proton therapy: Measurement with an extended-range Bonner sphere system," Med Phys 41 (2014).
- F. Khan The Physics of Radiation Therapy 4th Ed. (2010)
- J. Fontenot, P. Taddei, Y. Zheng, D. Mirkovic, T. Jordan, W. Newhauser, "Equivalent dose and effective dose from stray radiation during passively scattered proton radiotherapy for prostate cancer," Phys Med Biol 53, 1677-1688 (2008).
- J. Farah, V. Mares, M. Romero-Exposito, S. Trinkl, C. Domingo, V. Dufek, M. Klodowska, J. Kubancak, Z. Knezevic, M. Liszka, M. Majer, S. Miljanic, O. Ploc, K. Schinner, L. Stolarczyk, F. Trompier, M. Wielunski, P. Olko, R.M. Harrison, "Measurement of stray radiation within a scanning proton therapy facility: EURADOS WG9 intercomparison exercise of active dosimetry systems," Med Phys 42, 2572-2584 (2015).
- PAPER
- V. Mares1, M. Romero-Expósito, J. Farah, S. Trinkl, C. Domingo, M. Dommert, L. Stolarczyk, L. Van Ryckeghem, M. Wielunski, A comprehensive spectrometry study of a stray neutron radiation field in scanning proton therapy
- Physics in Medicine and Biology, 61 (2016)

- B. Gottschalk, "Neutron dose in scattered and scanned proton beams: in regard to Eric J. Hall (Int J Radiat Oncol Biol Phys 2006;65:1-7)," International journal of radiation oncology, biology, physics 66, 1594; author reply 1595 (2006).
- H. Paganetti, T. Bortfeld, T.F. Delaney, "Neutron dose in proton radiation therapy: in regard to Eric J. Hall (Int J Radiat Oncol Biol Phys 2006;65:1-7)," International journal of radiation oncology, biology, physics 66, 1594-1595; author reply 1595 (2006).
- C.Z. Jarlskog, H. Paganetti, "Risk of developing second cancer from neutron dose in proton therapy as function of field characteristics, organ, and patient age," Int J Radiat Oncol 72, 228-235 (2008).
- D. Hecksel, V. Anferov, M. Fitzek, K. Shahnazi, "Influence of beam efficiency through the patient-specific collimator on secondary neutron dose equivalent in double scattering and uniform scanning modes of proton therapy," Med Phys 37, 2910-2917 (2010).
- C. Zacharatou Jarlskog, C. Lee, W.E. Bolch, X.G. Xu, H. Paganetti, "Assessment of organ-specific neutron equivalent doses in proton therapy using computational whole-body age-dependent voxel phantoms," Phys Med Biol 53, 693-717 (2008).
- U. Titt, Y.S. Zheng, O.N. Vassiliev, W.D. Newhauser, "Monte Carlo investigation of collimator scatter of proton-therapy beams produced using the passive scattering method," Phys Med Biol 53, 487-504 (2008).
- H. Jiang, B. Wang, X.G. Xu, H.D. Suit, H. Paganetti, "Simulation of organ-specific patient effective dose due to secondary neutrons in proton radiation treatment," Phys Med Biol 50, 4337-4353 (2005).