Neutrons Secondary to Proton Therapy;

Problems & Solutions

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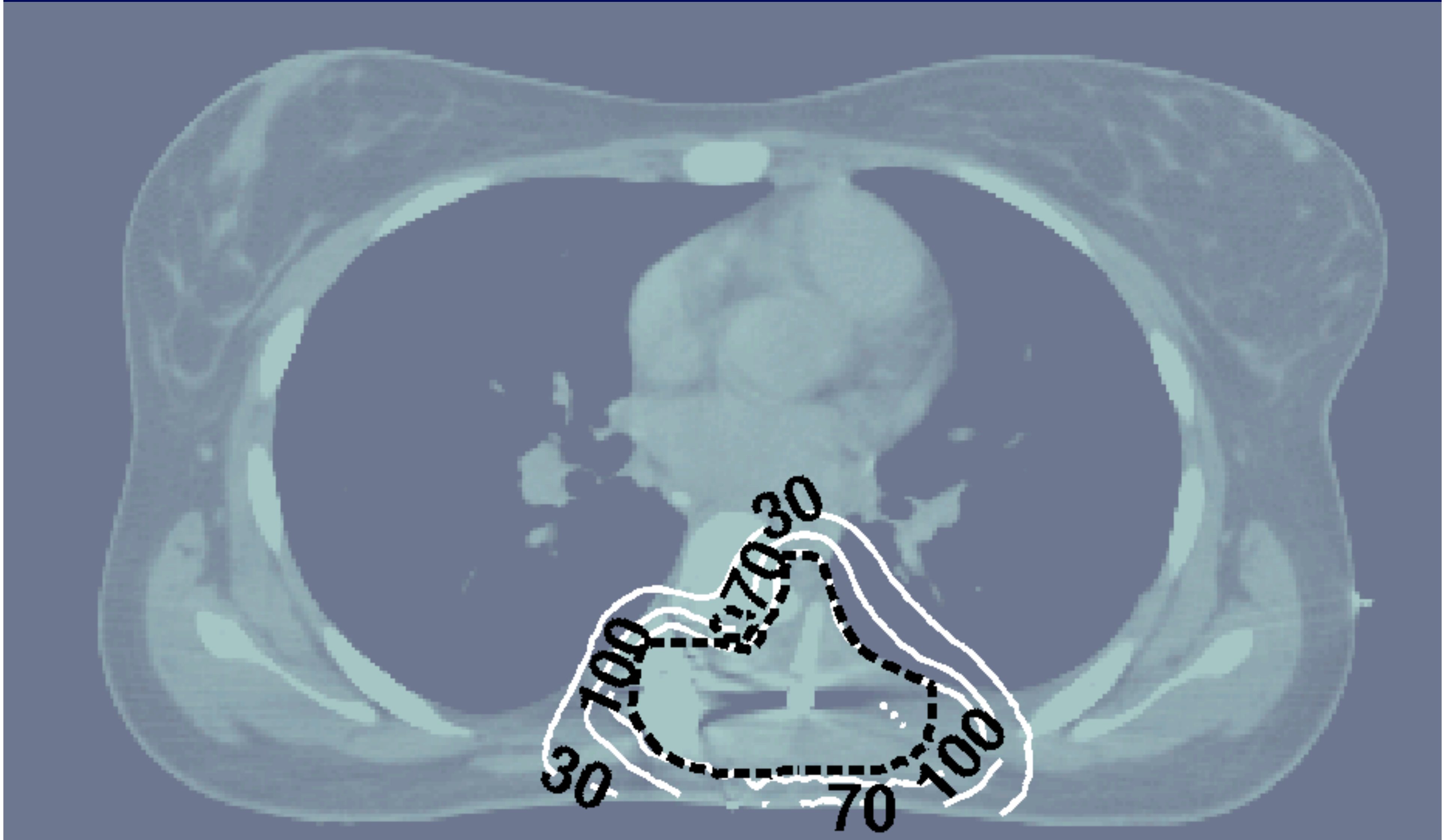
Radiation:
The Two-Edged Sword

- Radiation therapy can cure cancer
- Radiation can induce cancer

PROTONS

- Because they have a limited range and deposit most energy in the Bragg peak, Protons are the logical next step in improving dose distributions, i.e. to maximize the dose to the tumor and minimize dose to normal tissue.

Proton IMPT, 3 Scanned Pencil Beams



(Courtesy of Dr. Thomas DeLaney)

Epithelioid Sarcoma Close to Vertebrae

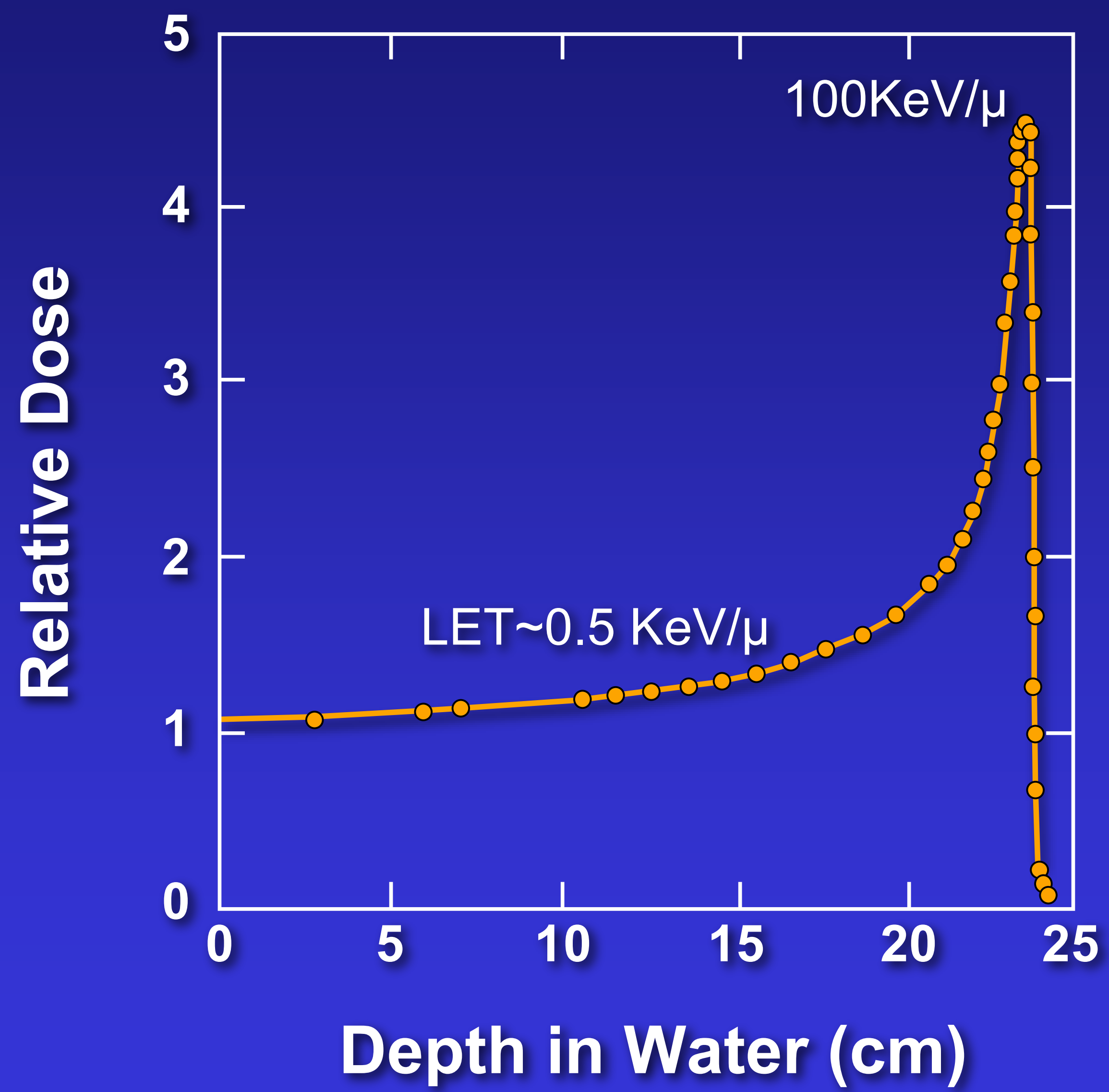
The Herman Suit Doctrine

- Normal Tissues that are not Irradiated cannot develop Late Effects of Any Sort
  - Fibrosis
  - Cancer

PROTONS

- Radiation-induced cancers outside the treatment volume (the problem with IMRT) should be essentially eliminated because of the reduction in the volume of normal tissues exposed.
- However...........

RBE 1.1 of ^{60}Co or Linac



Protons

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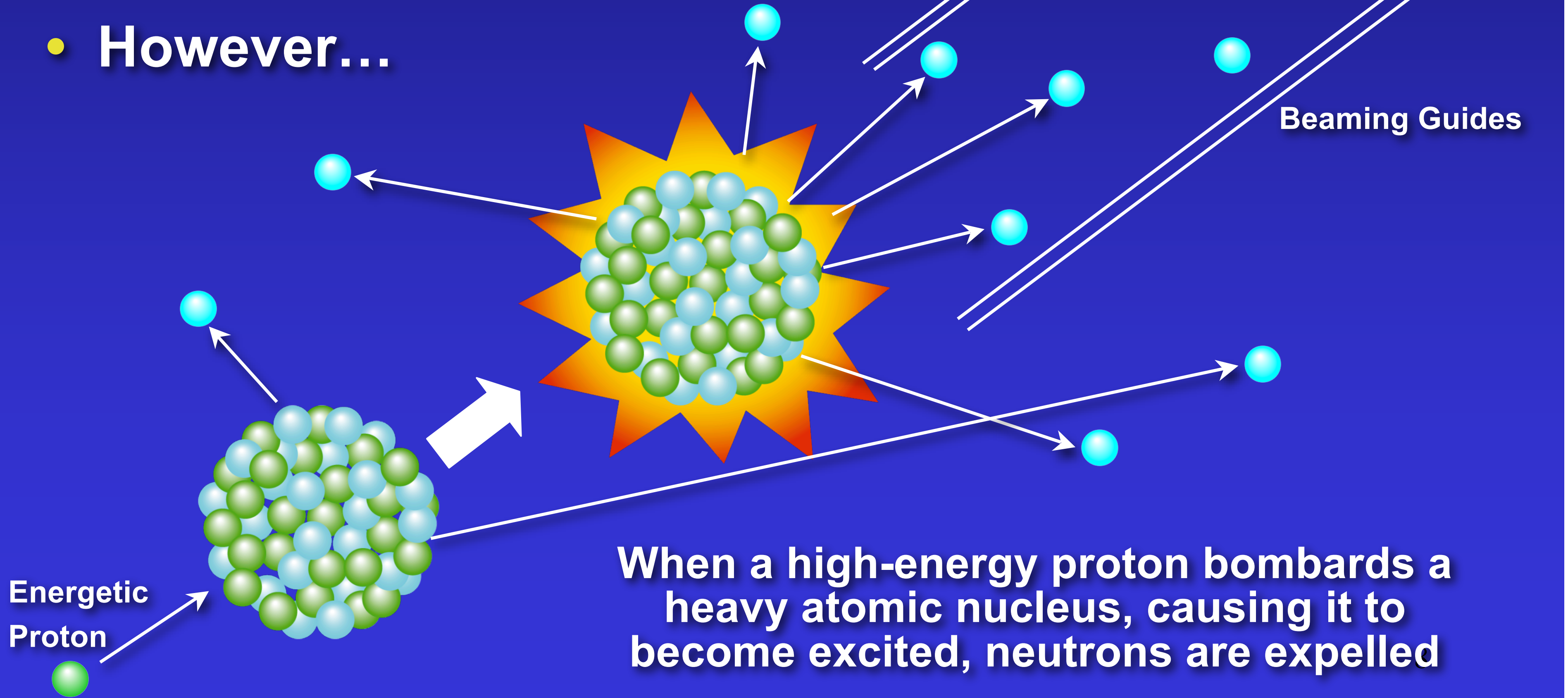
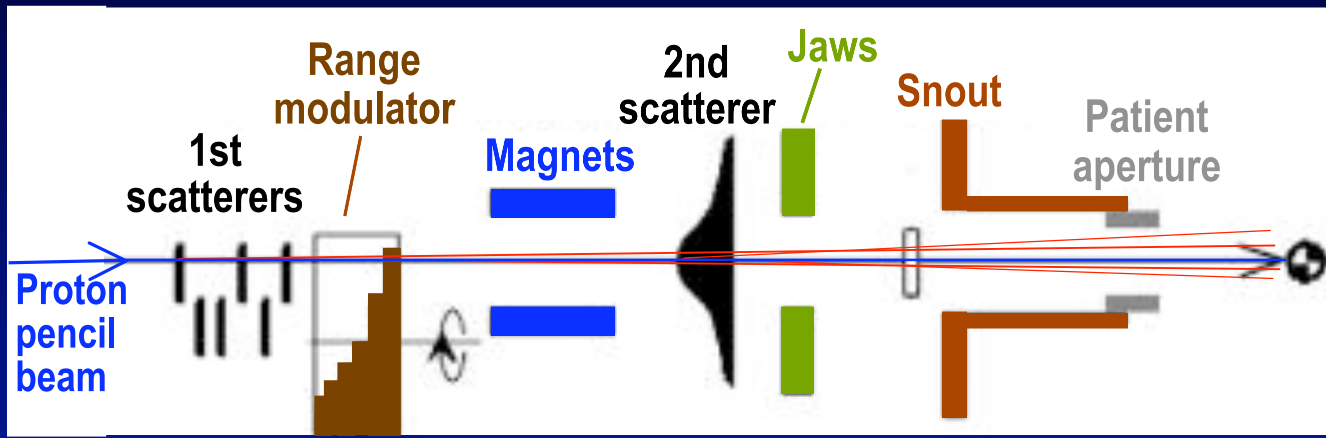
- However…

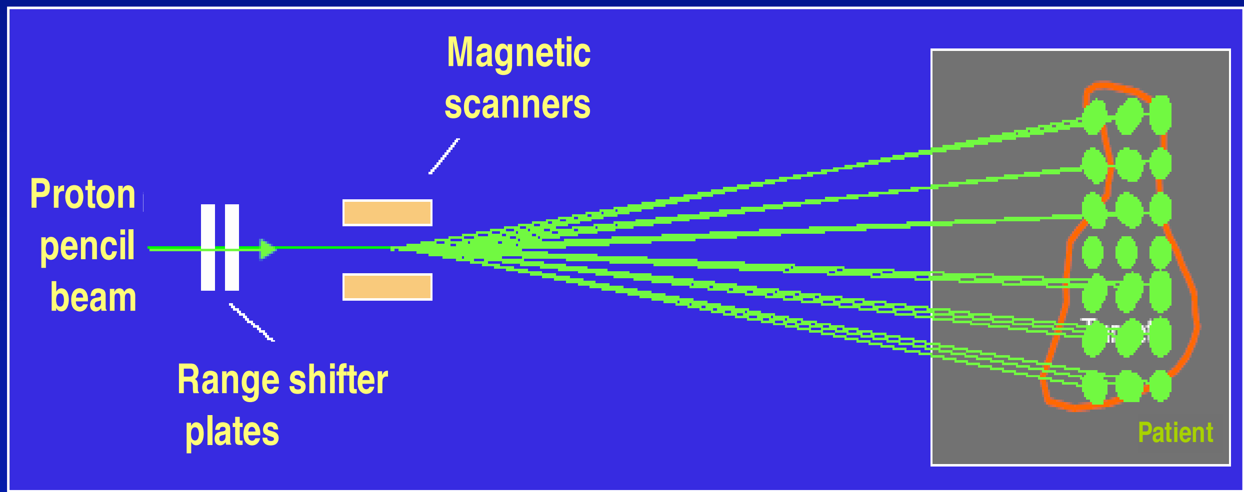


How to scan pencil proton beams over a large target…

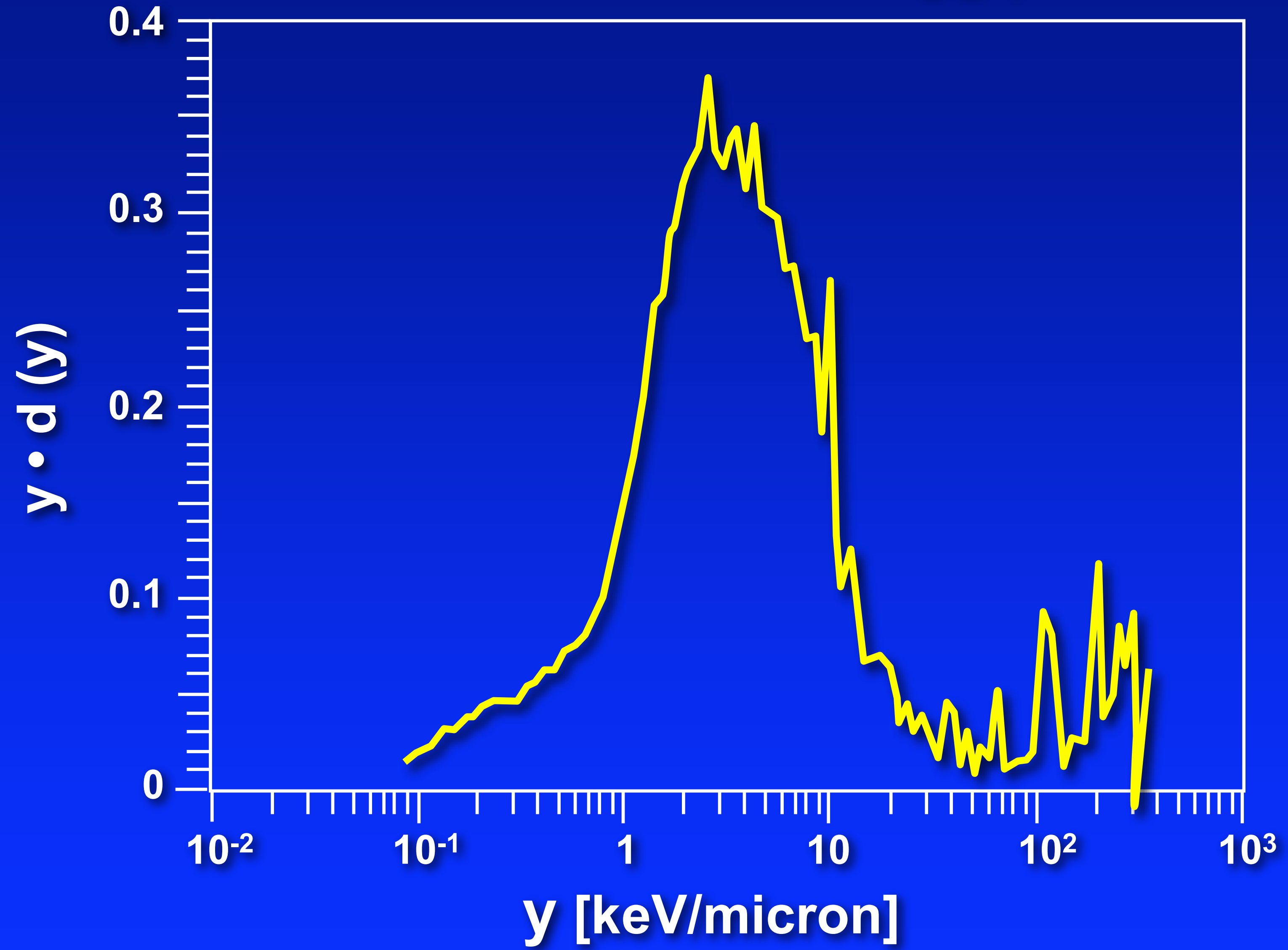
Passive scanning



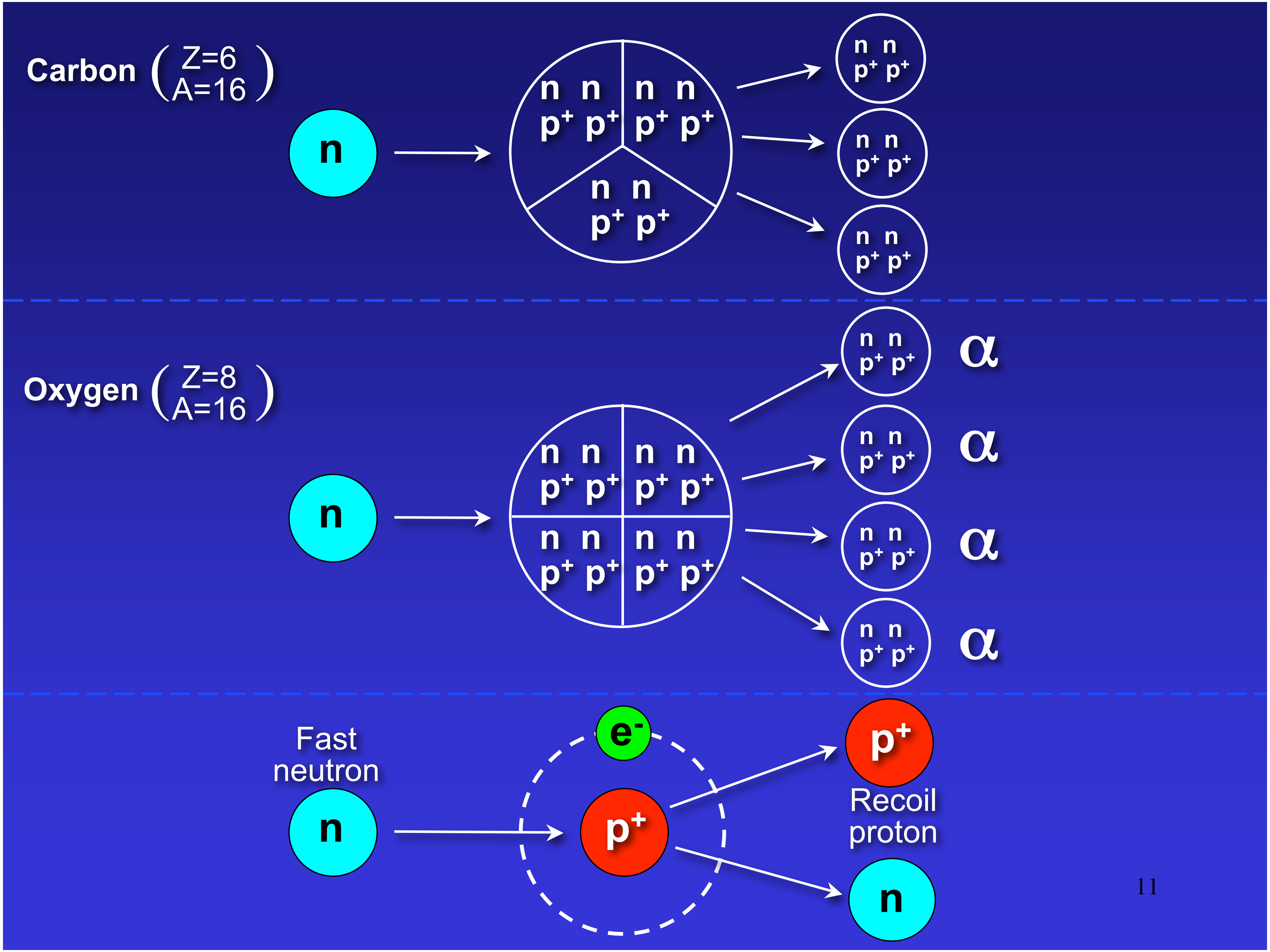
Active scanning



Rear of extended Bragg peak

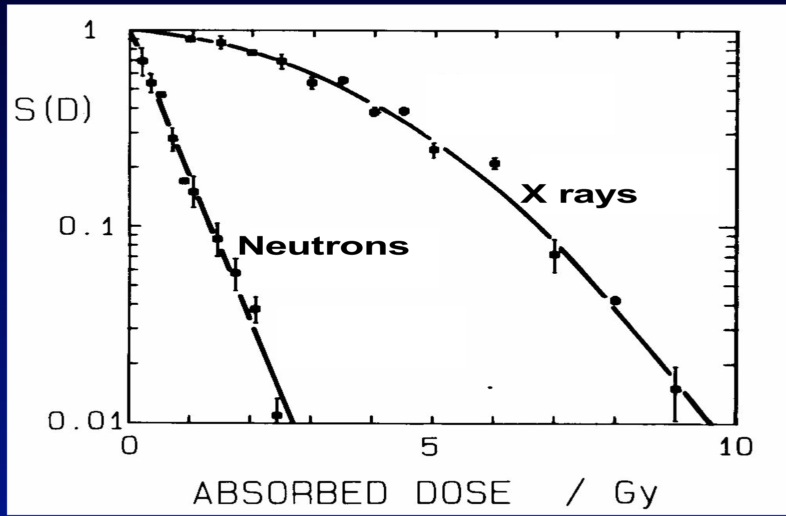


The RBE of 160 MeV protons KLIAUGA & Rossi
IJROBP 4, 1001 1978

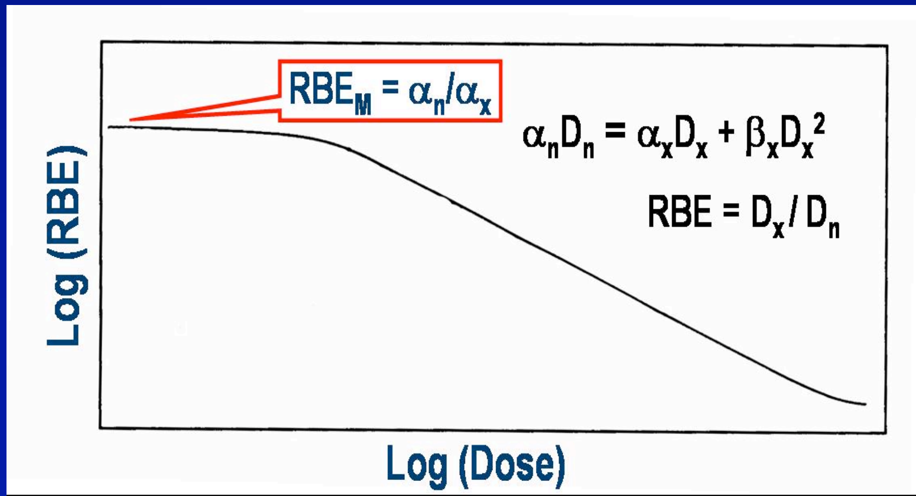

Carbon (Z=6 A=16)
n
n n p+ p+
n n p+ p+
n n p+ p+
Oxygen (Z=8 A=16)
α
α
α
α
Fast neutron
e-
p+
Recoil proton
n

Neutron RBE

Photons have curved dose-response relations, while those for neutrons are straighter



It follows that the neutron RBE is dose dependent, with a constant maximal value (RBE_M) at low doses

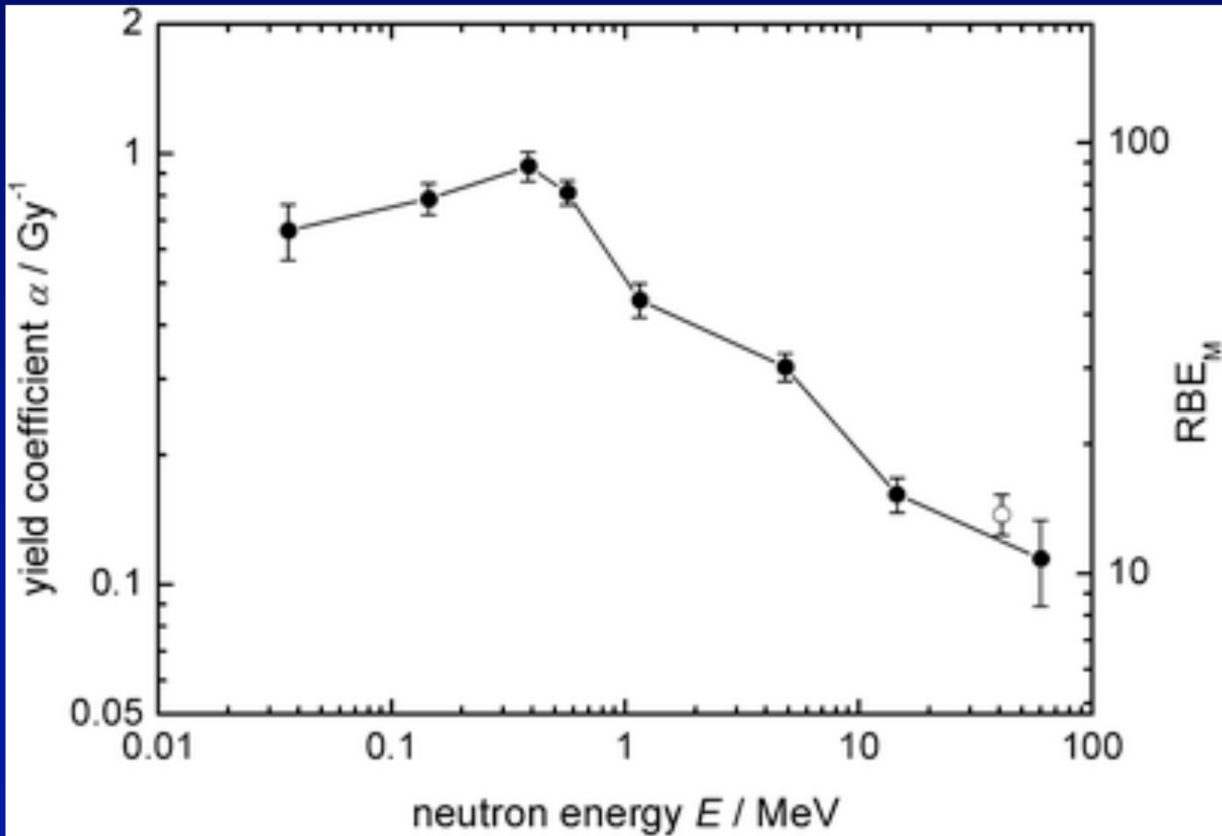


Estimated low-doses RBE values for fission-neutron induced carcinogenesis in mice

Data from Ullrich et al.

Mouse strain / Endpoint	Measured RBE_M
RFM / Thymic lymphoma	27 ± 26
RFM / Pituitary	59 ± 52
RFM / Harderian gland	36 ± 10
RFM / Lung tumor	6 ± 3
BALB/c Lung adenocarcinoma	19 ± 6
BALB/c Mammary carcinoma	33 ± 12
Overall	*30 ± 17*

Neutron RBEs – Dicentrics in Human Lymphocytes

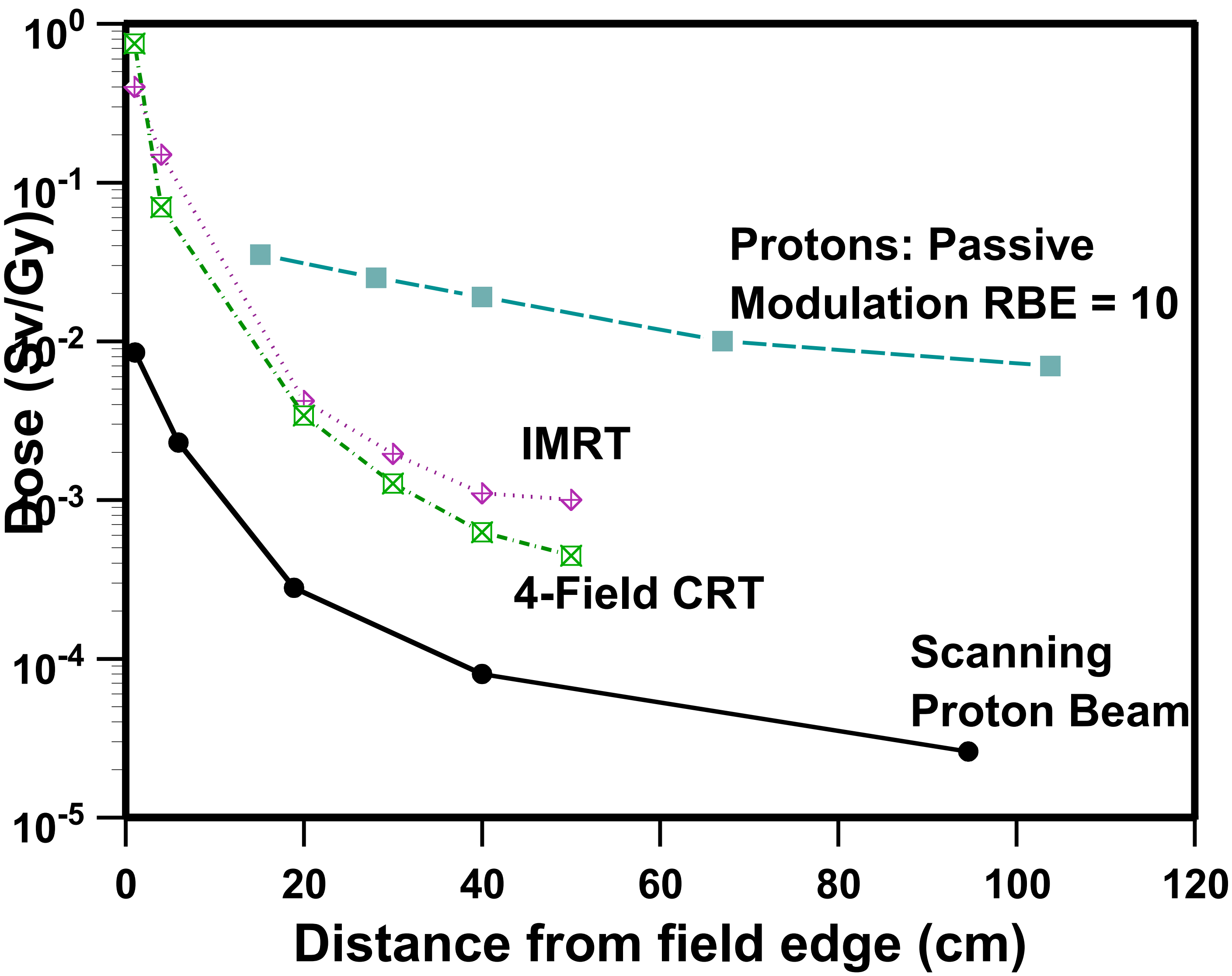


Nolte et al., Radiation and Environmental Biophysics (2005)

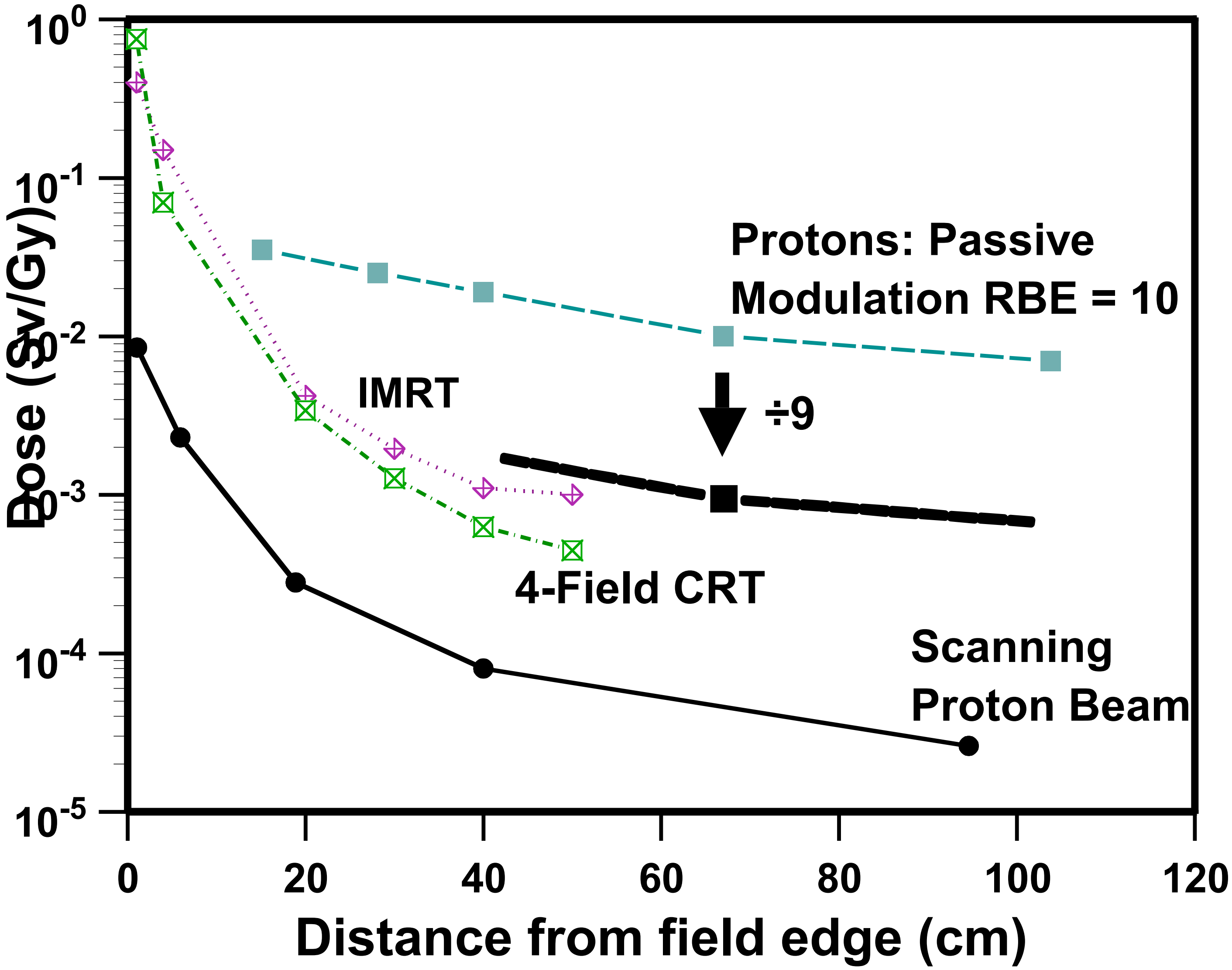
Neutron RBE

Must assume a value of 20 to 30

- Fission Neutrons in A-bomb Survivors; RBE=100 (Lower Limit 25)
- Fission Neutrons in Mice; variety of Cancers; Mean RBE=30
- Chromosome Aberrations in Lymphocytes for a Neutron Spectrum Similar to MD Anderson; RBE=100 ??



Dose (Sv/Gy)
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
0
20
40
60
80
100
120
Distance from field edge (cm)
Protons: Passive
Modulation RBE = 10
IMRT
4-Field CRT
Scanning
Proton Beam



Protons: Passive
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÷9
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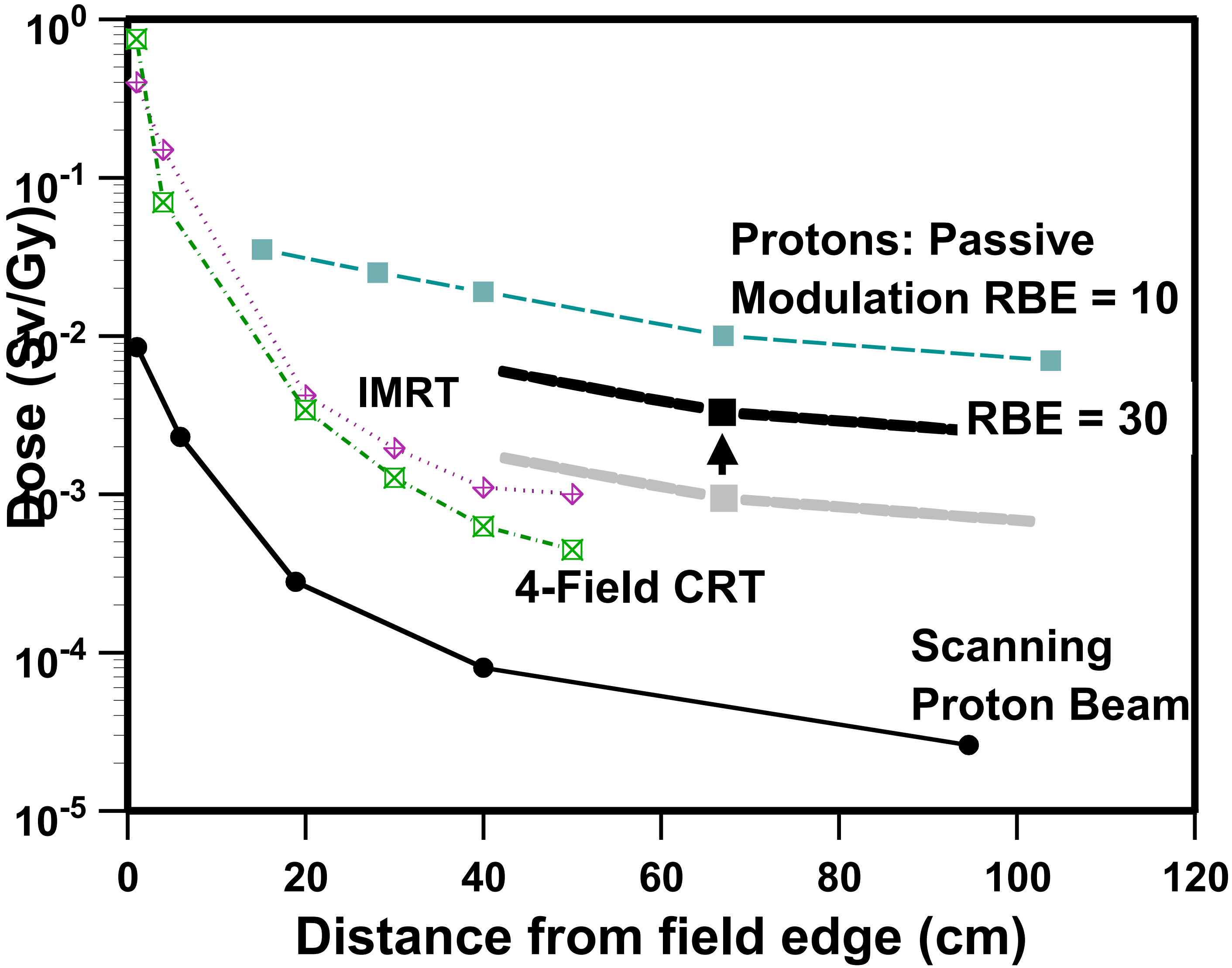

Dose (Sv/Gy)
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RBE = 30
IMRT
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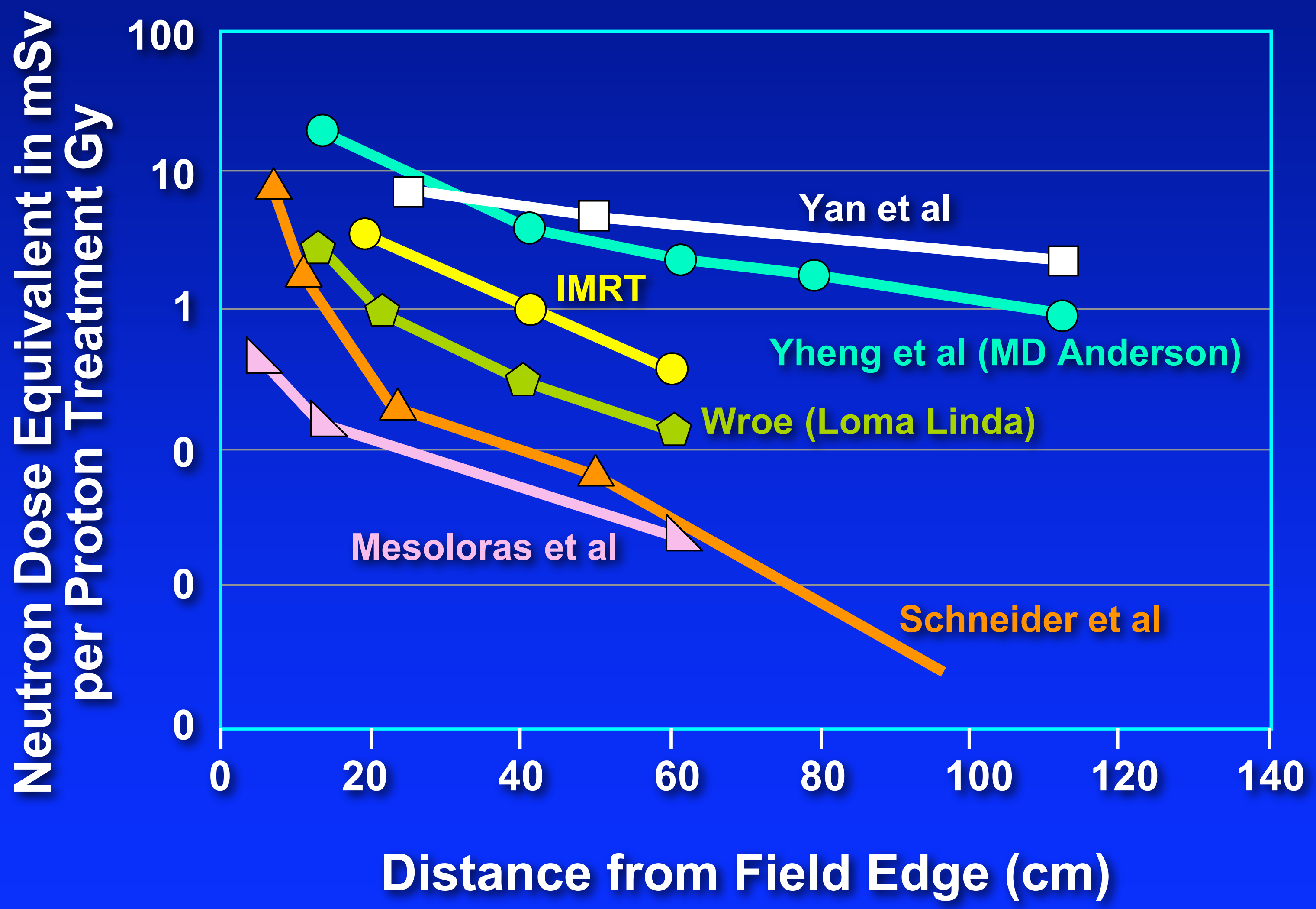
120
Distance from field edge (cm)

Neutron Dose Equivalent vs. Distance from Field Edge



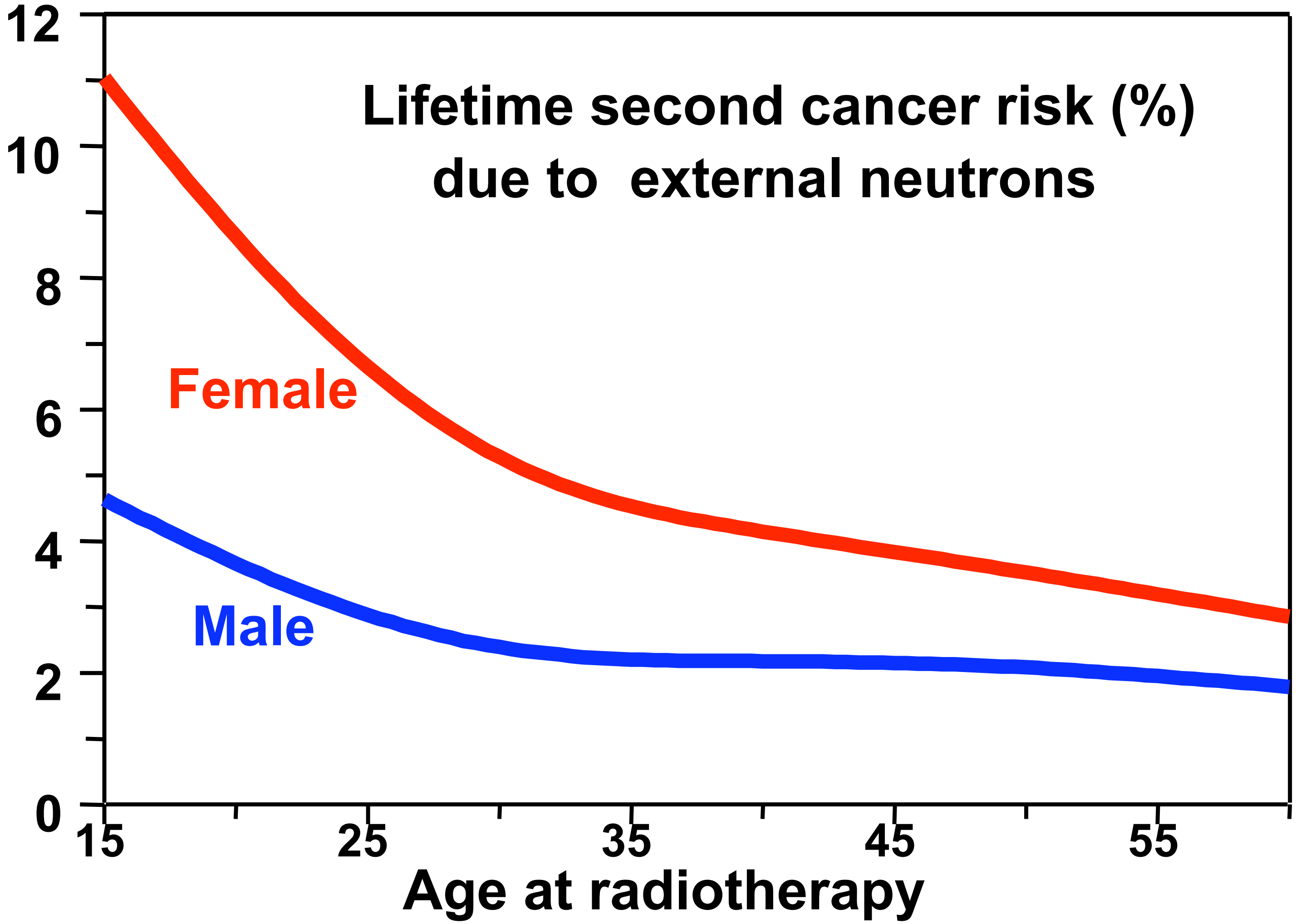
Northeast Proton Therapy Center

- Patient treated for lung cancer (72 Gy)
- Monte Carlo calculations to arrive at neutron organ doses (Paganetti et al. Phys Med Biol 2005)
- Cancer Risks calculated for External neutrons. Neutron RBE assumed to be 25 (Brenner & Hall 2007)

Calculated neutron organ doses for a three-field proton therapy plan at the passively-modulated NPTC facility, treating a lung tumor with a planned 72 Gy GTV dose

	Neutron dose (mGy)	
Organ	*Internal*	*External*
Red bone marrow	28	16
Colon	0	4
Lung (out of field)	39	34
Stomach	0	20
Bladder	0	3
Breast	1	24
Liver	1	32
Esophagus	2	29
Thyroid	1	32
Brain	0	12
Kidney	0	19
Pancreas	0	22

- **Doses derived from detailed Monte-Carlo simulations of the NPTC beamline by Paganetti and colleagues**



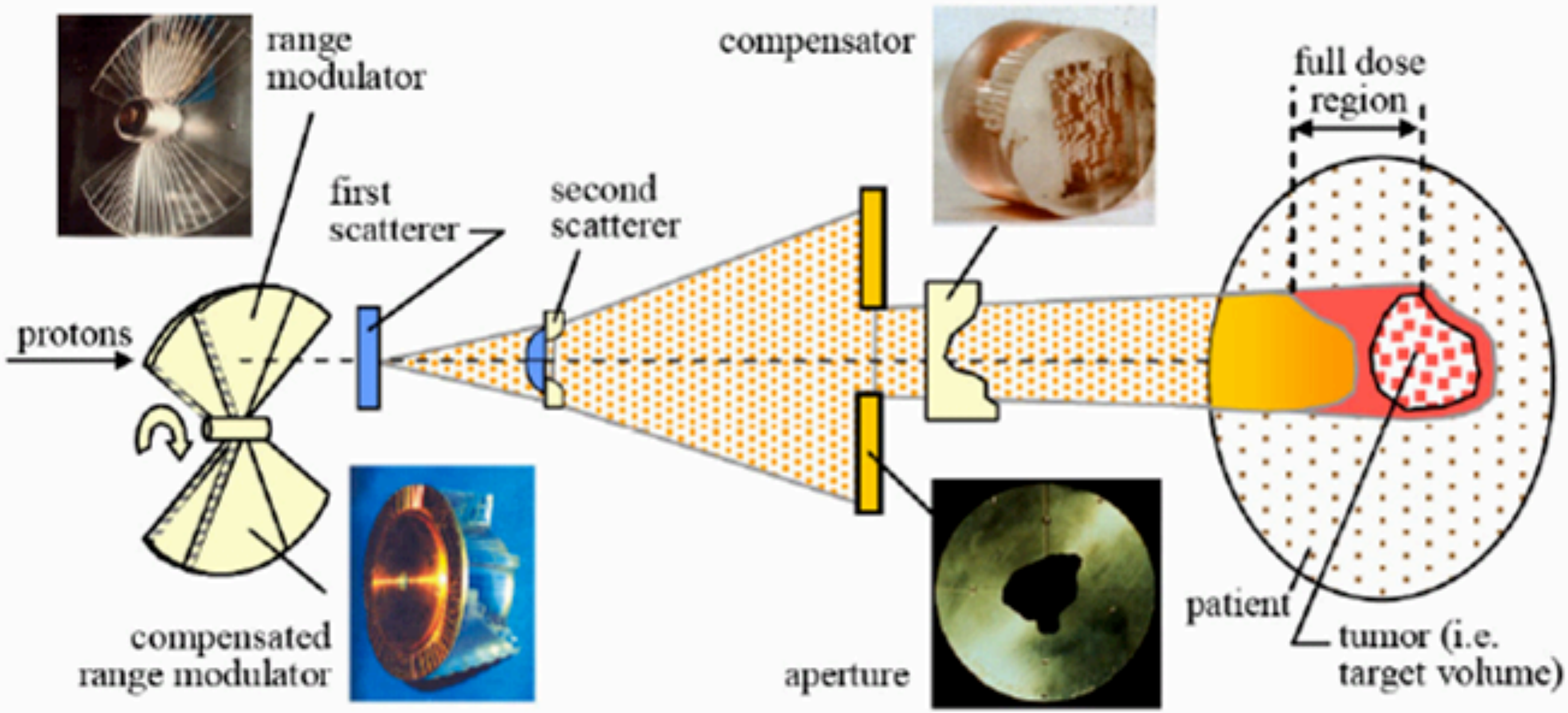
- For a 72 Gy proton therapy lung-tumor plan at the passively-modulated NPTC facility, assuming the patient is cured of his / her primary tumor.
- Doses derived from detailed Monte-Carlo simulations of the NPTC beamline by Paganetti and colleagues
- RBE assumed: 25

Paganetti, Suit, and colleagues are quite right….

"The major secondary dose contributors are neutrons from the proton treatment nozzle. These external neutrons account for a much higher secondary dose (by about two orders of magnitude) than the internal neutrons."

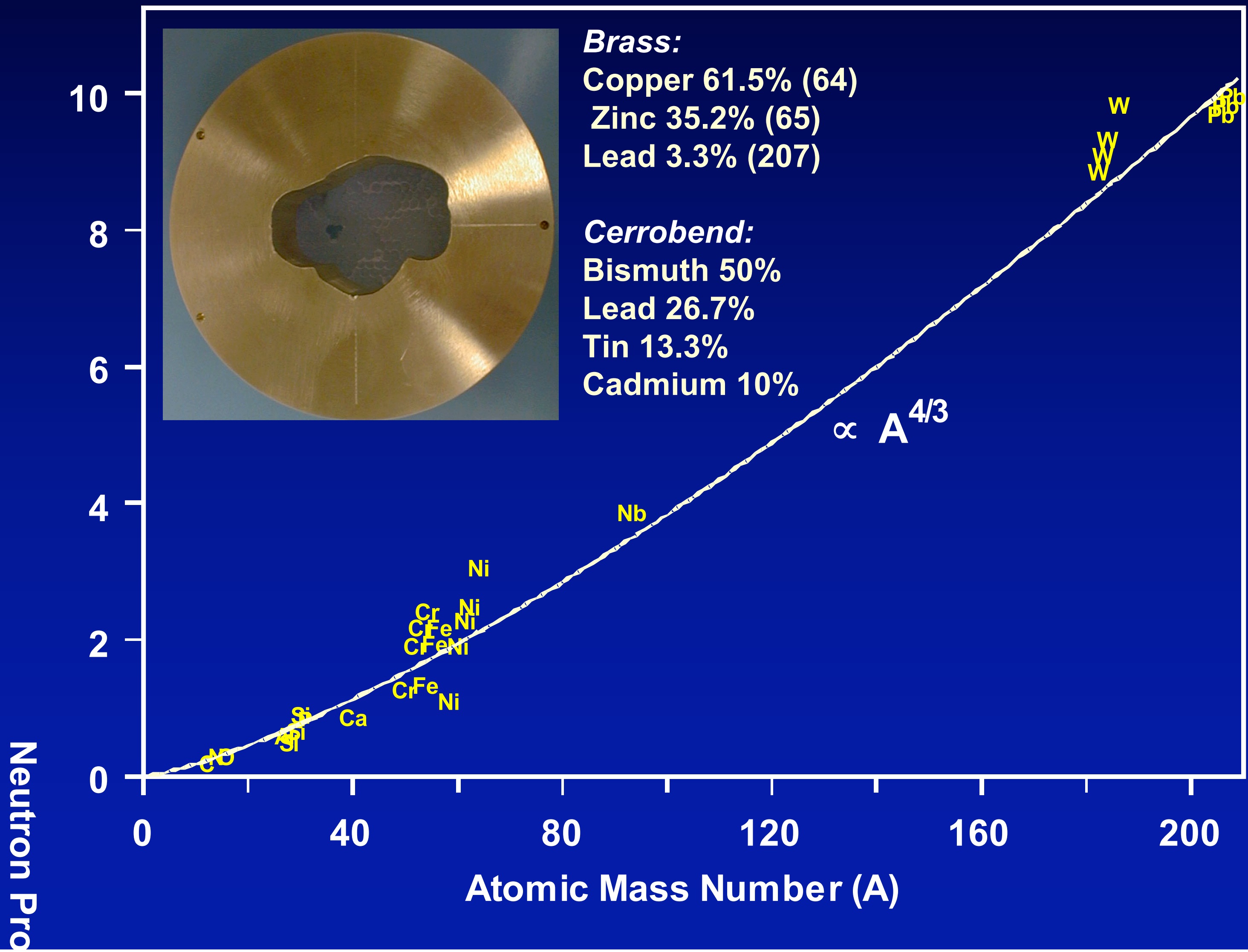
Jiang, Wang, Xu, Suit and Paganetti (2005)

Treatment nozzle for a passive scattering proton therapy beamline

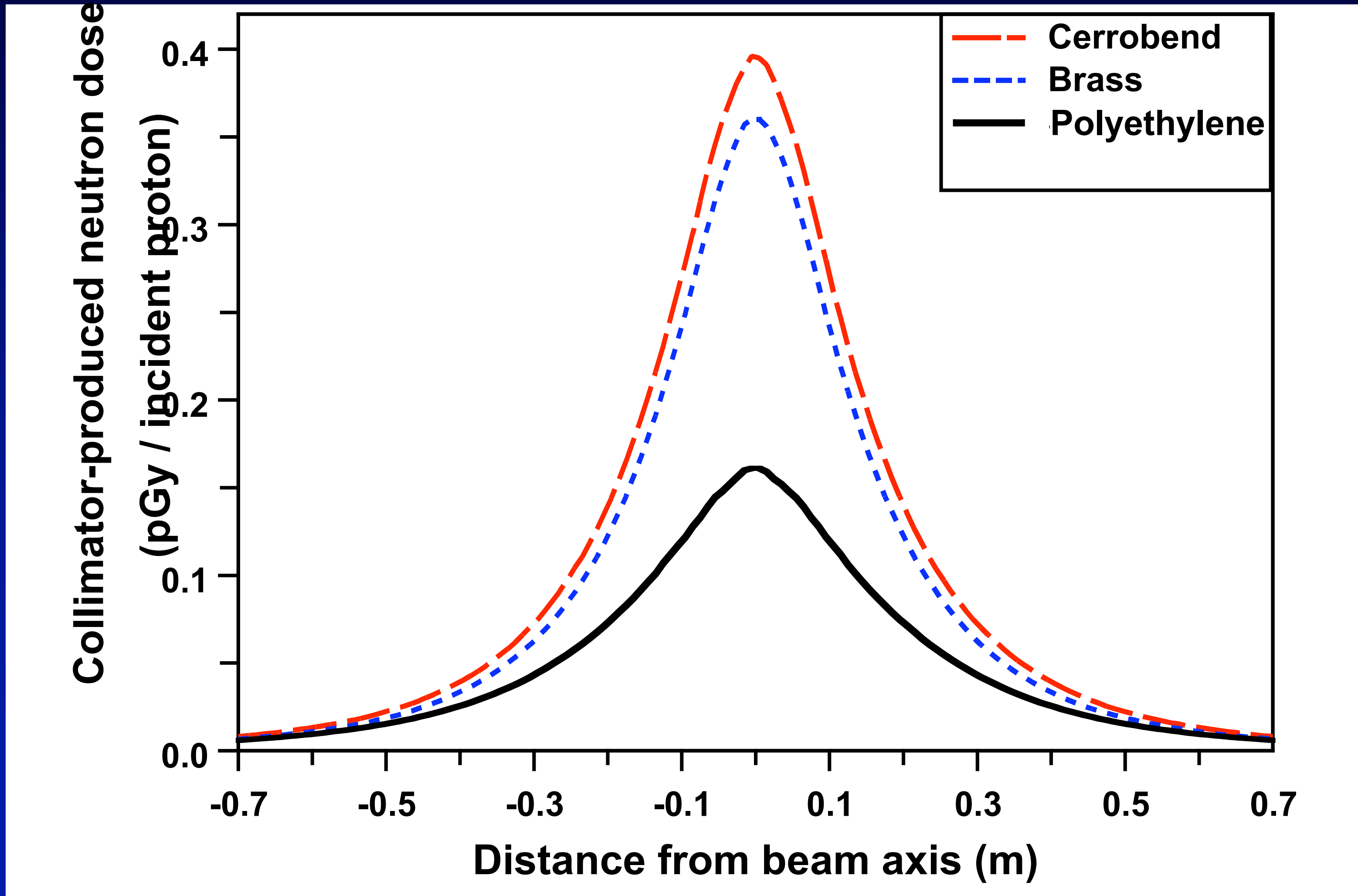


MASSACHUSETTS GENERAL HOSPITAL
RADIATION ONCOLOGY

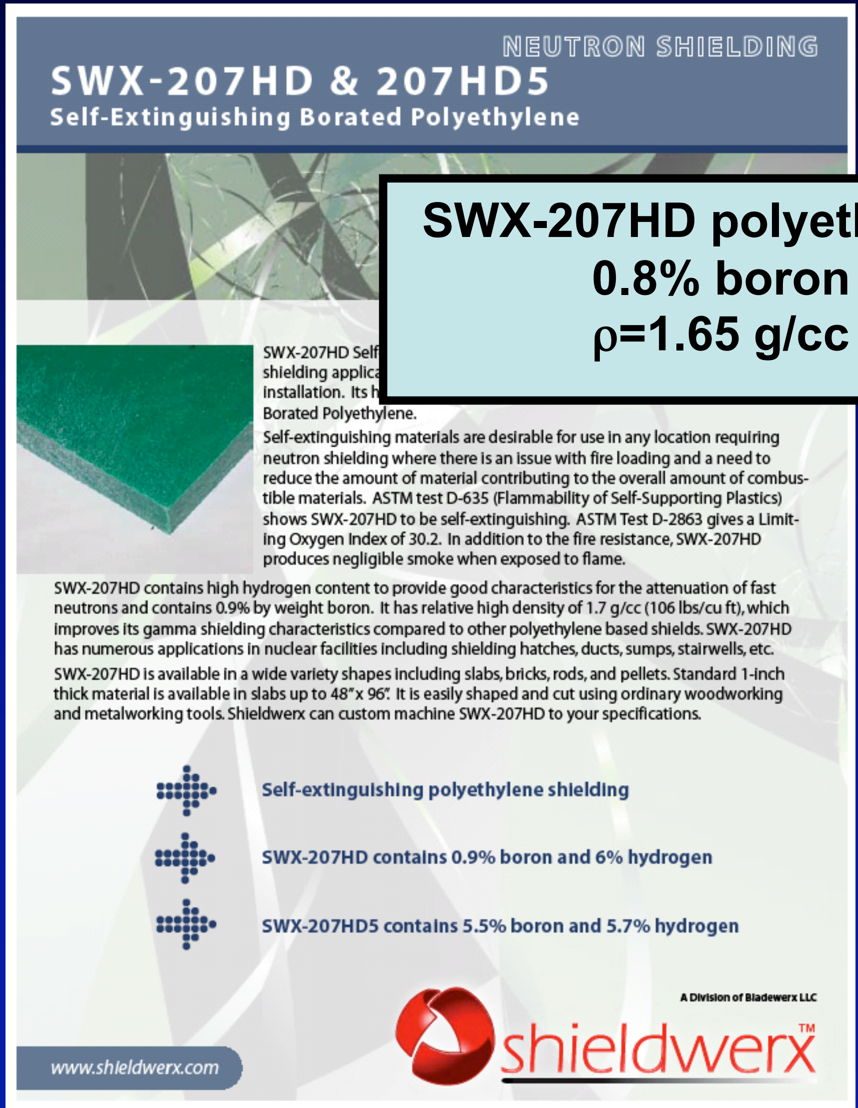
Evaluated neutron production cross sections for 150-MeV protons



A polyethylene collimator (ρ=0.94 g/cc) will result in a significant reduction in the secondary neutron dose But it would have to be ~14” thick.



But a polyethylene (ρ=0.94 g/cc) collimator would have to be ~14" thick, which would be problematic



NEUTRON SHIELDING

SWX-207HD & 207HD5

Self-Extinguishing Borated Polyethylene

SWX-207HD Self...
shielding applica...
installation. Its h...
Borated Polyethylene.

Self-extinguishing materials are desirable for use in any location requiring neutron shielding where there is an issue with fire loading and a need to reduce the amount of material contributing to the overall amount of combustible materials. ASTM test D-635 (Flammability of Self-Supporting Plastics) shows SWX-207HD to be self-extinguishing. ASTM Test D-2863 gives a Limiting Oxygen Index of 30.2. In addition to the fire resistance, SWX-207HD produces negligible smoke when exposed to flame.

SWX-207HD contains high hydrogen content to provide good characteristics for the attenuation of fast neutrons and contains 0.9% by weight boron. It has relative high density of 1.7 g/cc (106 lbs/cu ft), which improves its gamma shielding characteristics compared to other polyethylene based shields. SWX-207HD has numerous applications in nuclear facilities including shielding hatches, ducts, sumps, stairwells, etc.

SWX-207HD is available in a wide variety shapes including slabs, bricks, rods, and pellets. Standard 1-inch thick material is available in slabs up to 48" x 96". It is easily shaped and cut using ordinary woodworking and metalworking tools. Shieldwerx can custom machine SWX-207HD to your specifications.

- Self-extinguishing polyethylene shielding
- SWX-207HD contains 0.9% boron and 6% hydrogen
- SWX-207HD5 contains 5.5% boron and 5.7% hydrogen

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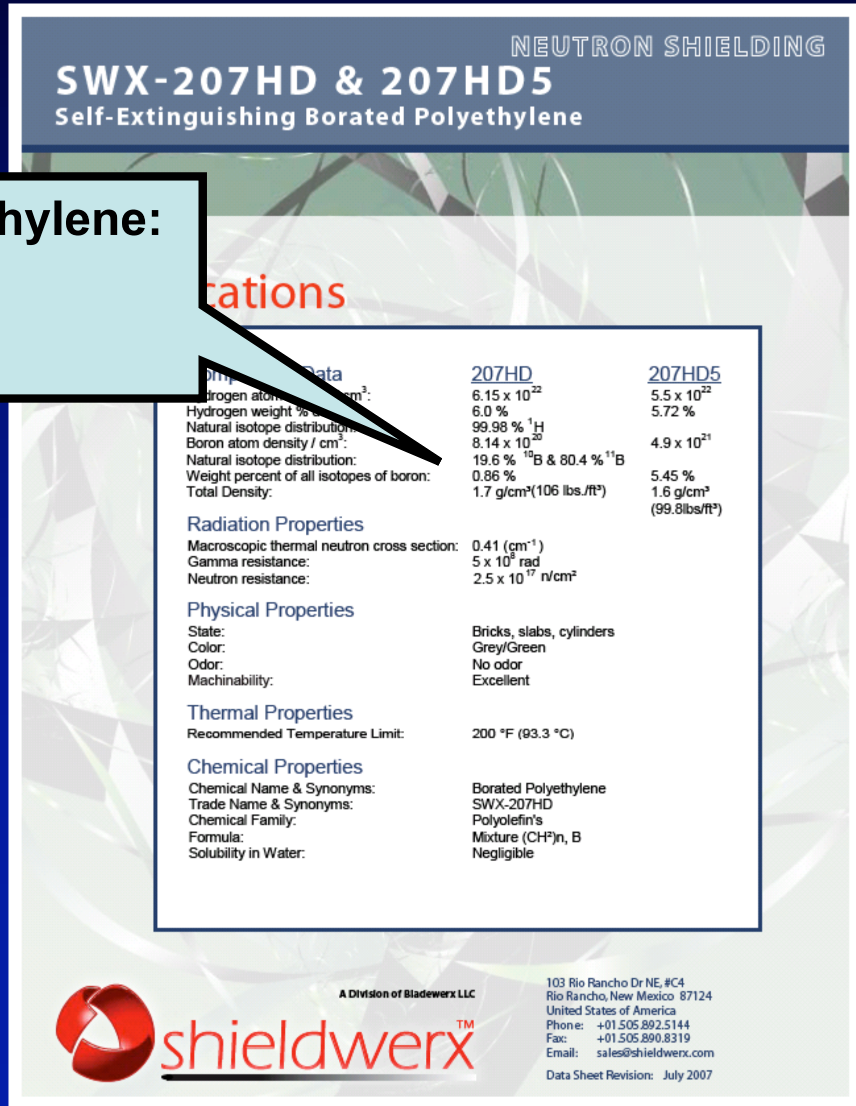
shieldwerx™

www.shieldwerx.com

SWX-207HD polyethylene:
0.8% boron
ρ=1.65 g/cc



NEUTRON SHIELDING

SWX-207HD & 207HD5

Self-Extinguishing Borated Polyethylene

...cations

...Data	207HD	207HD5
...drogen ato... cm^3:	6.15 x 10^{22}	5.5 x 10^{22}
Hydrogen weight % ...	6.0 %	5.72 %
Natural isotope distributio...	99.98 % ^{1}H	
Boron atom density / cm^3:	8.14 x 10^{20}	4.9 x 10^{21}
Natural isotope distribution:	19.6 % ^{10}B & 80.4 % ^{11}B	
Weight percent of all isotopes of boron:	0.86 %	5.45 %
Total Density:	1.7 g/cm³(106 lbs./ft³)	1.6 g/cm³ (99.8lbs/ft³)

Radiation Properties

Macroscopic thermal neutron cross section:	0.41 (cm^{-1})
Gamma resistance:	5 x 10^8 rad
Neutron resistance:	2.5 x 10^{17} n/cm²

Physical Properties

State:	Bricks, slabs, cylinders
Color:	Grey/Green
Odor:	No odor
Machinability:	Excellent

Thermal Properties

Recommended Temperature Limit:	200 °F (93.3 °C)

Chemical Properties

Chemical Name & Synonyms:	Borated Polyethylene
Trade Name & Synonyms:	SWX-207HD
Chemical Family:	Polyolefin's
Formula:	Mixture (CH²)n, B
Solubility in Water:	Negligible

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shieldwerx™

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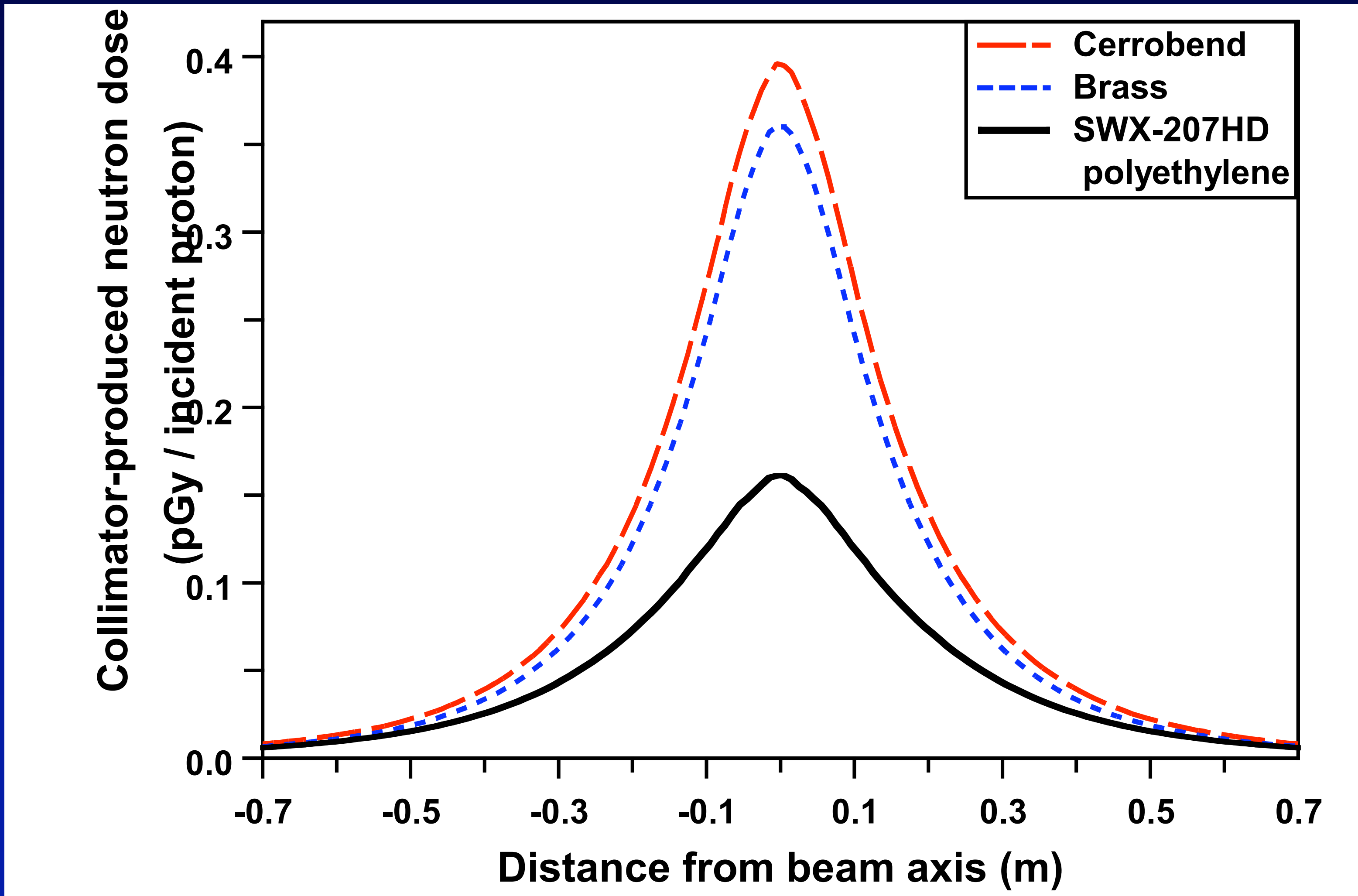
Data Sheet Revision: July 2007

Using a 7½“ thick SWX-207HD polyethylene collimator (0.8% boron: density =1.65 g/cc) will result in a significant reduction in the secondary neutron dose



A 7½" thick collimator....

... may still be problematic, if it degrades the lateral penumbra

Solution 1:

Taper the inside walls of the collimator

(Polyethylene is very easy to machine)

Problems and Solutions. The Problem

- Having spent about $125 million on a proton facility to reduce dose to normal tissues, does it make sense to spray the patient with a total body dose of neutrons, the RBE of which is poorly known, and end up with a second cancer risk similar to IMRT ?

Problems and Solutions. Solutions;

- Use a Scanning Beam and avoid the problems of Passive Modulation…… ……However this is technically difficult, and introduces problems of its own
- Replace the Brass collimator with a collimator made of SWX-207HD Polyethylene (containing Boron), or a Hybrid collimator, made of part brass and part polyethylene.(Brenner, Hall & Paganetti, in press)

NASA Space Radiation Laboratory

- At the 1GeV/nucleon Iron Ion beam at Brookhaven National Laboratory, the neutron contamination is minimized by the use of a massive collimator consisting of layers of LUCITE, ALUMINUM and POLYETHYLENE. This sort of technology could replace Brass in the clinical facilities.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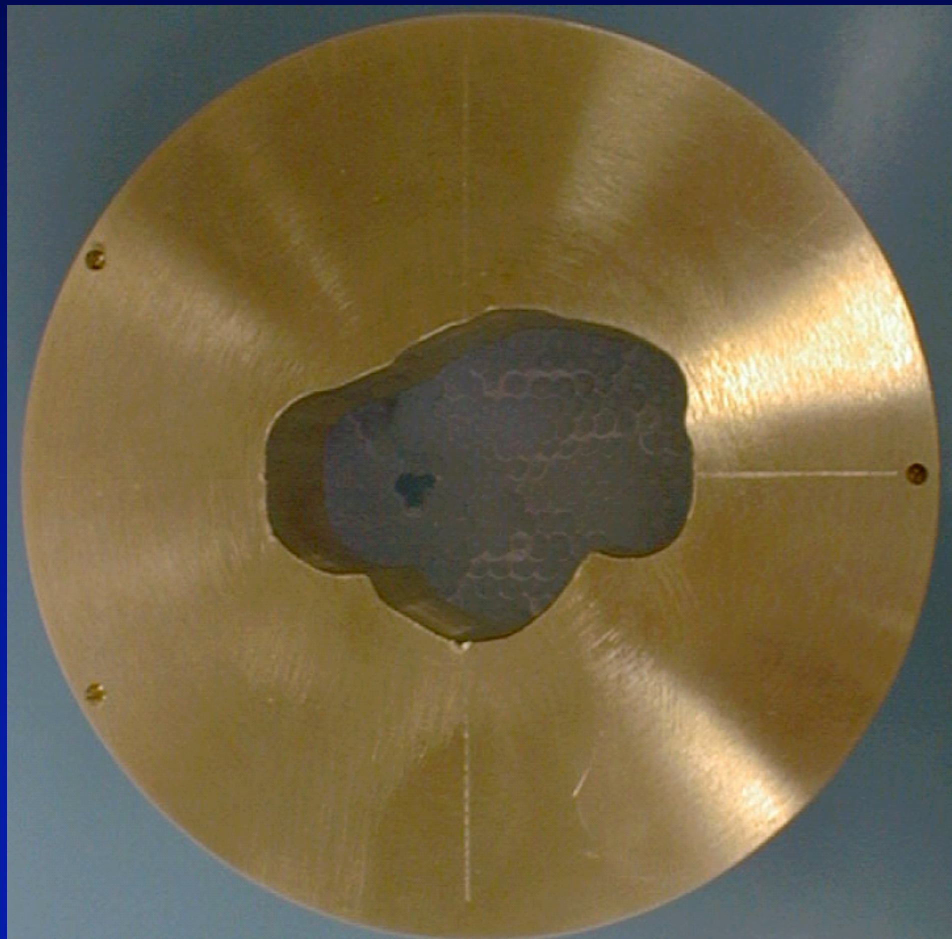
2006

In most clinical configurations, almost all the external neutron dose comes from the final brass (or cerrobend) patient-specific collimator



Brass:
Copper 61.5%
Zinc 35.2%
Lead 3.3%

Cerrobend:
Bismuth 50%
Lead 26.7%
Tin 13.3%
Cadmium 10%