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Goodwyn

Important Concepts in Radiobiology Dosimetry

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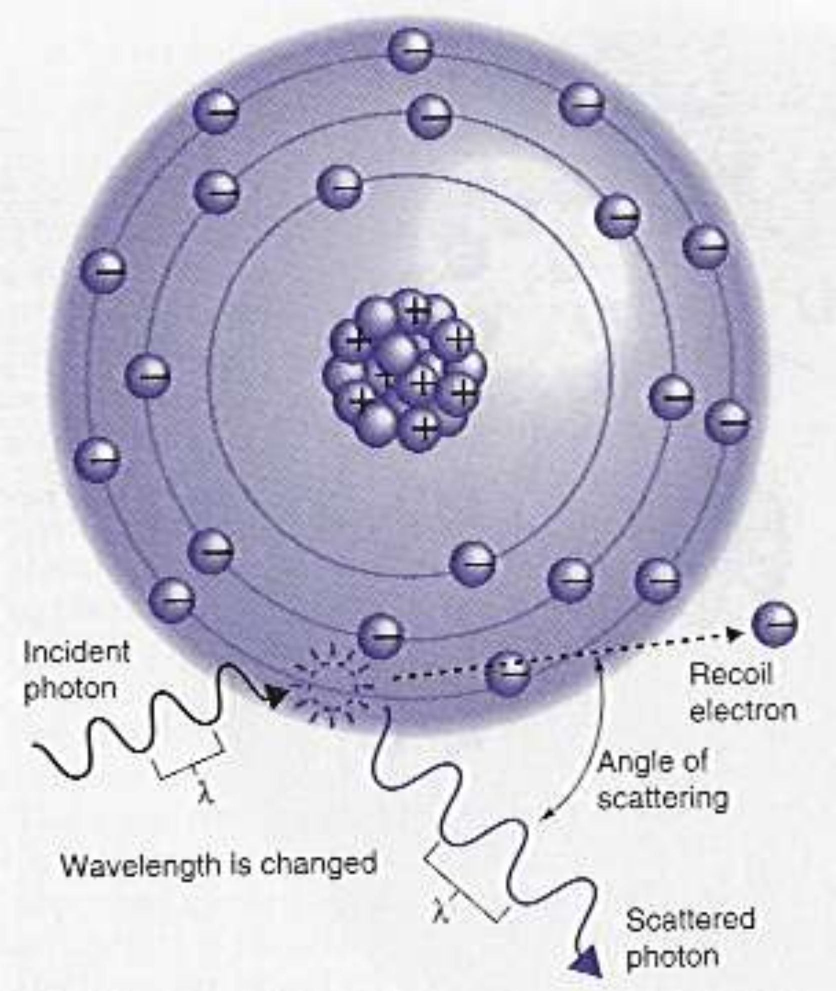
What is an Ionization?

-An event that results in positively and negatively charged particles.

-Radiation with enough energy to disrupt atomic structure by ejecting orbital electron is called:

"**Ionizing Radiation**"



Ionizing Radiation

- Directly ionizing radiation
  - Charged particles (e^-, β^+, p^+, α^{++}, etc.)
  - Deposit energy (Dose) by many low energy interactions (ionizations)
    - Definite range (shallow depths)
- Indirectly ionizing radiation
  - Uncharged radiation (photons – x & γ rays, neutrons)
  - Two step process:
    - Large energy transfer to directly ionizing radiation.
    - Directly ionizing radiation delivers dose
    - Exponential attenuation (deeper depths)

Ionizing Radiations used in Radiobiology

- **X rays**
  - Grentz ray — < 20 kV
  - Contact — 20 < kV <50
  - Superficial — 50 < kV < 150
  - Orthovoltage — 150 < kV < 300
  - Megavoltage (Linac) — 4 < MV < 25
- **Gamma rays**
  - ^{60}Co — 1.25 MeV
  - ^{137}Cs — 662 keV
  - ^{125}I & ^{103}Pd — 20 – 35 keV
- **α emitters** — 4 – 9 MeV
- **protons** — ≤250 MeV
- **other**

Ionizing Radiation Quantities

Exposure,
Absorbed Dose,
Relative Biological Effectiveness, RBE

Ionizations occurs,
Energy is absorbed,
Relevant Biological damage is done

EXPOSURE: A bunch of photons interact in a small mass of air, creating electrons which then cause a bunch of ionizations. **Count the ions**

DOSE: Some of the energy transferred is absorbed some re-irradiated. Dose represents the **energy** ultimately **absorbed**.

Relative Biological Effectiveness (RBE)

$$\mathrm{RBE} = \frac{\text{Dose from Standard Radiation}}{\text{Dose from Test Radiation}} \text{ for same biological effect}$$

RBE depends radiation type (LET), dose rate, fraction size, and biological effect

What is the standard radiation?

- Historically: 250 kVp x rays
- Recommended today: ^{60}Co gamma rays
- RBE of ^{60}Co is 10 – 20% lower than for 250 KVP

Ionizing Radiation Units

Quantity	Classical unit	SI Unit	Relation
Exposure	Roentgen [R]	Coulomb/kg	100 R ≈ 100 rad
Dose	rad	Gray 1 J/kg	100 rad = 1 Gy
RBE	rem = RBE*dose	Sievert?	100 rem = 1 Sievert

Photon interactions

Photoelectric absorption :

Compton Scatter:

Pair Production:

Photon Interaction Coefficients

Attenuation coefficient:

μ [probability of an interaction per unit path length]

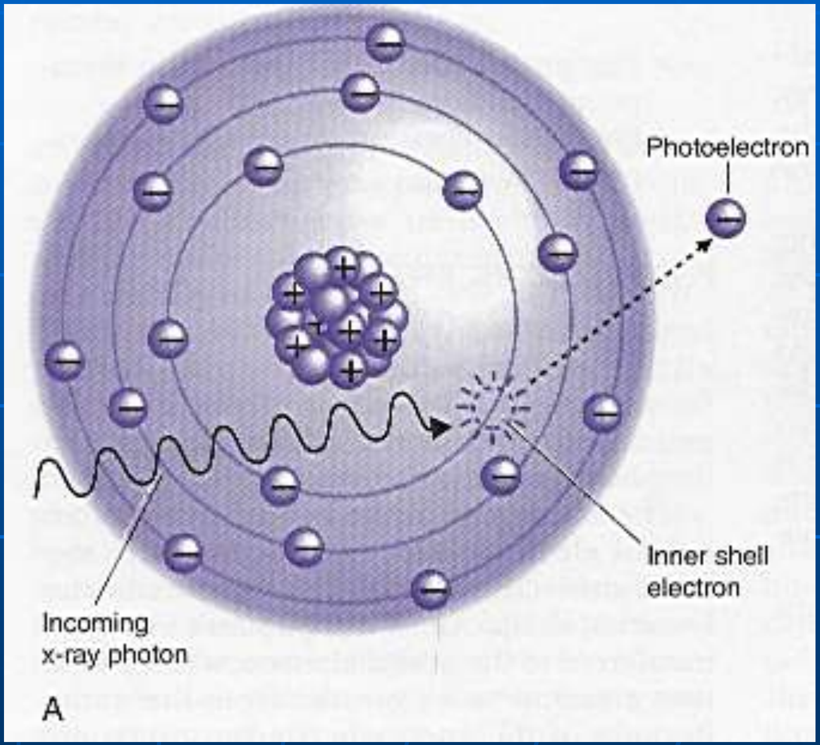
$$I = I_o e^{-\mu \bullet x}$$

Mass Energy absorption coefficient: **proportional to Dose**

μ_{en}/ρ [fraction of energy absorbed per unit path length]

Photoelectric absorption:

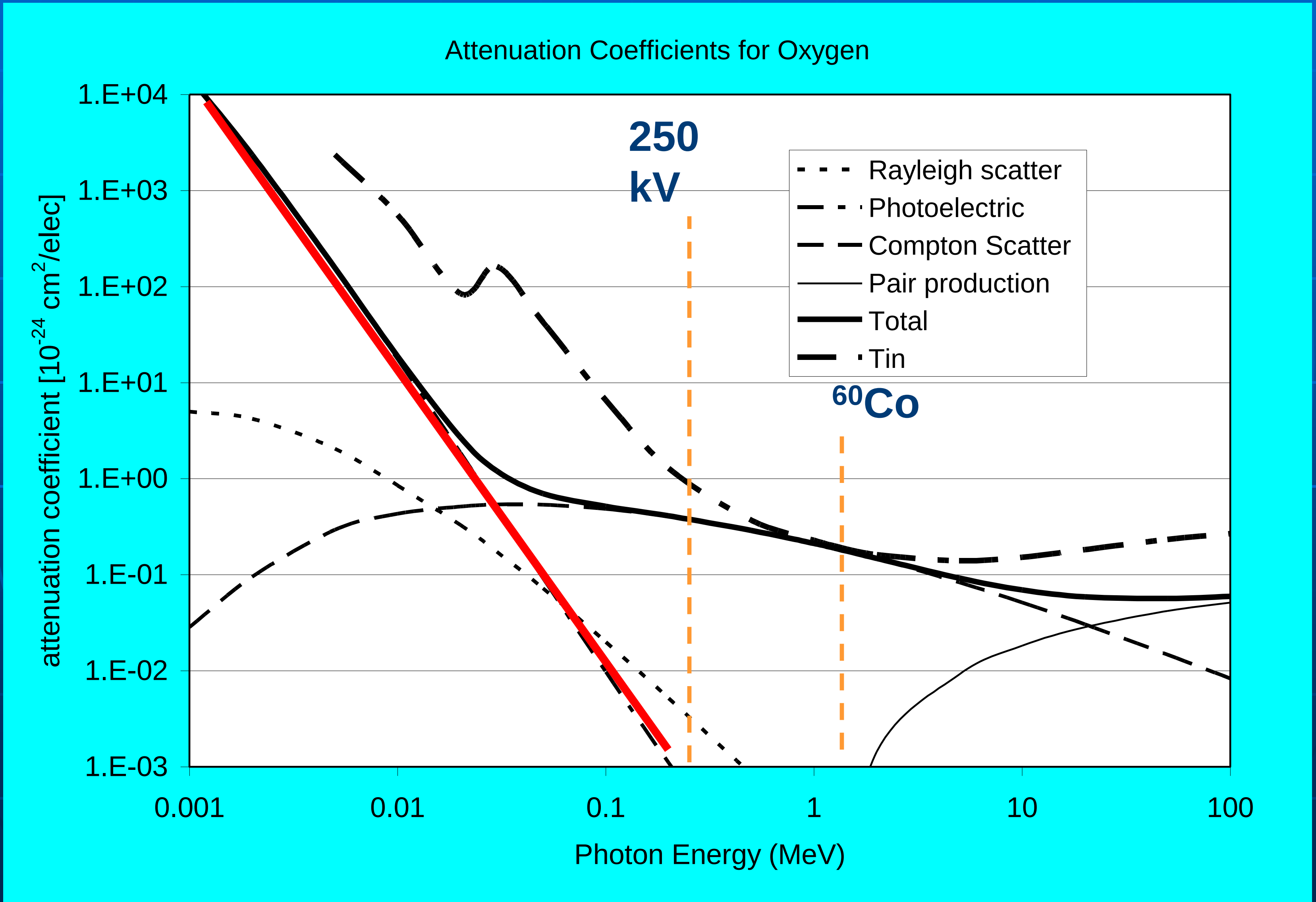
- Photon interacts with a single orbital e^-, ejecting it from the atom (ionization).
- **Dominant interaction** at low energies and high Z materials



Photoelectric Effect:

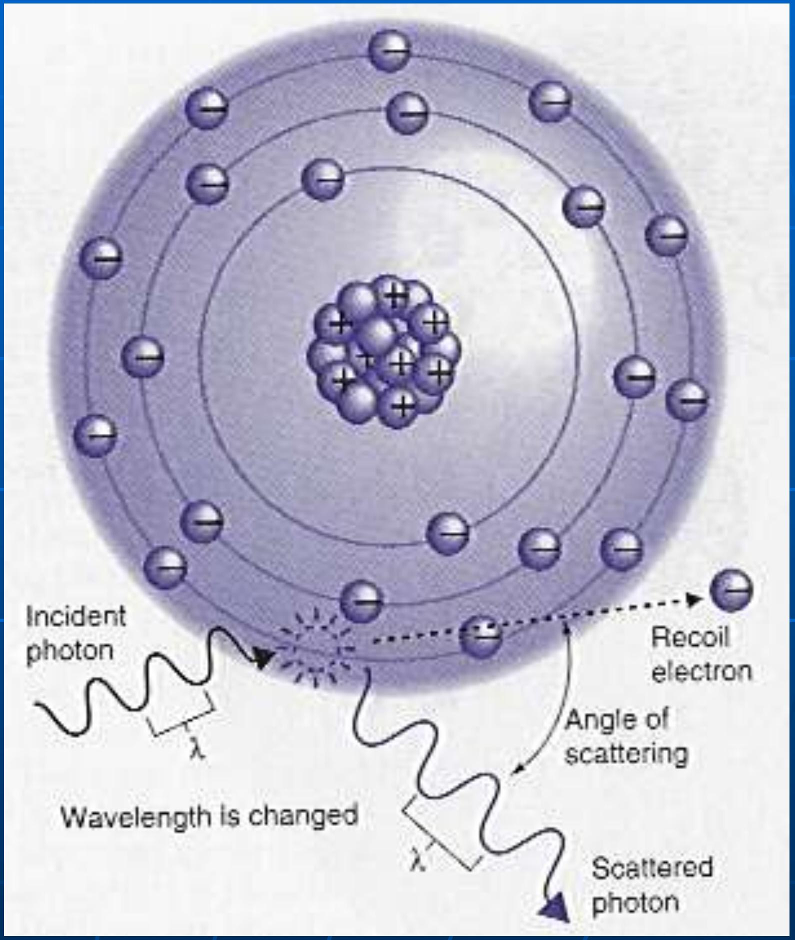
Attenuation falls very rapidly with increasing energy

Attenuation increases dramatically with increasing Z $\propto (Z/E)^3$

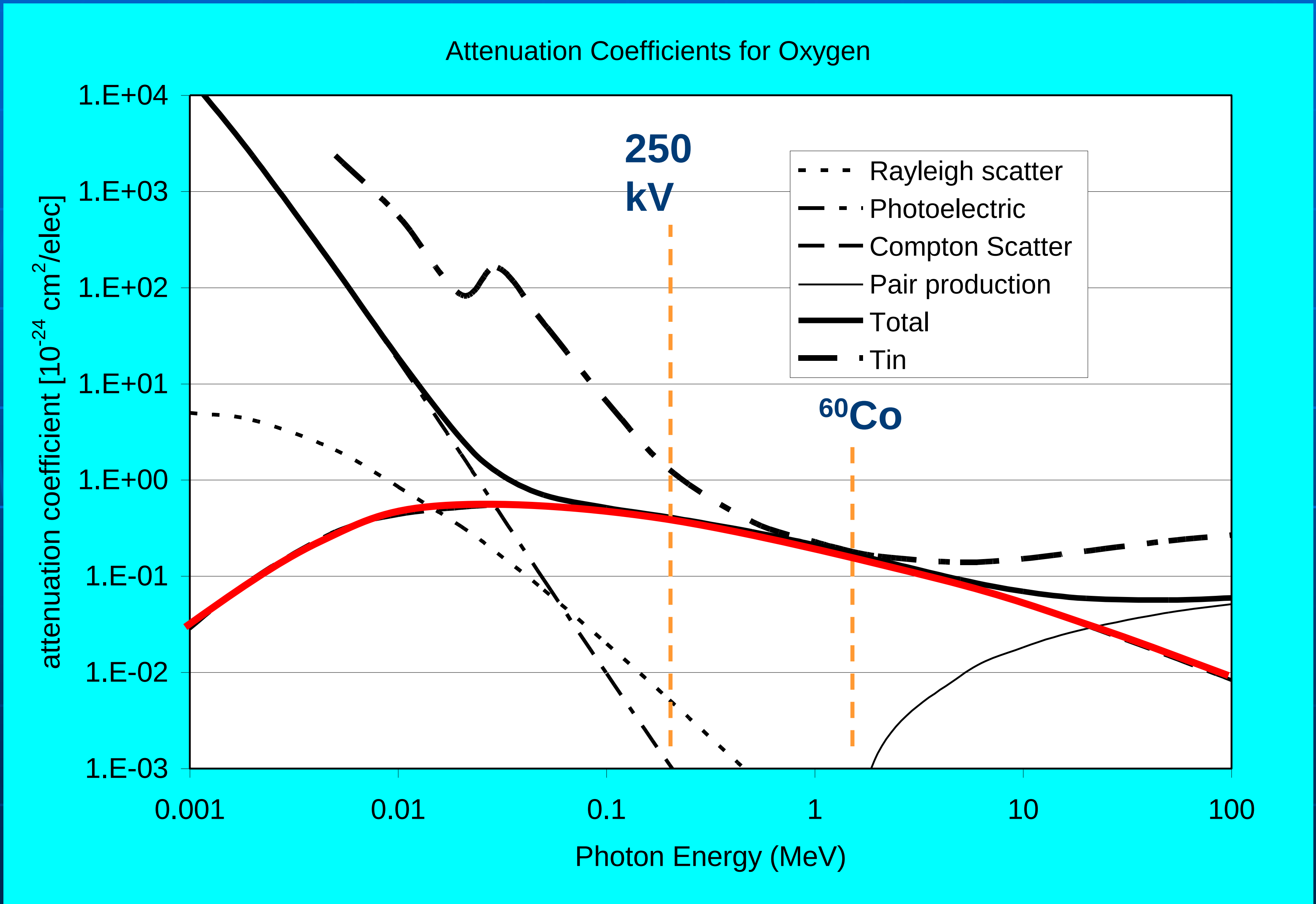


Compton Scatter:

- **Dominant** interaction in radiotherapy.
- Photon interacts with a single orbital e^-
- Some energy transferred to e^- , some energy retained in scattered photon
  - e^- to create ionizations
  - Photon to go on to interact with another atom



Compton scatter: Probability of the interaction is virtually independent of energy and Z.



Important Concept for Conventional x rays

- Photoelectric effect:
  - very efficient energy transfer process

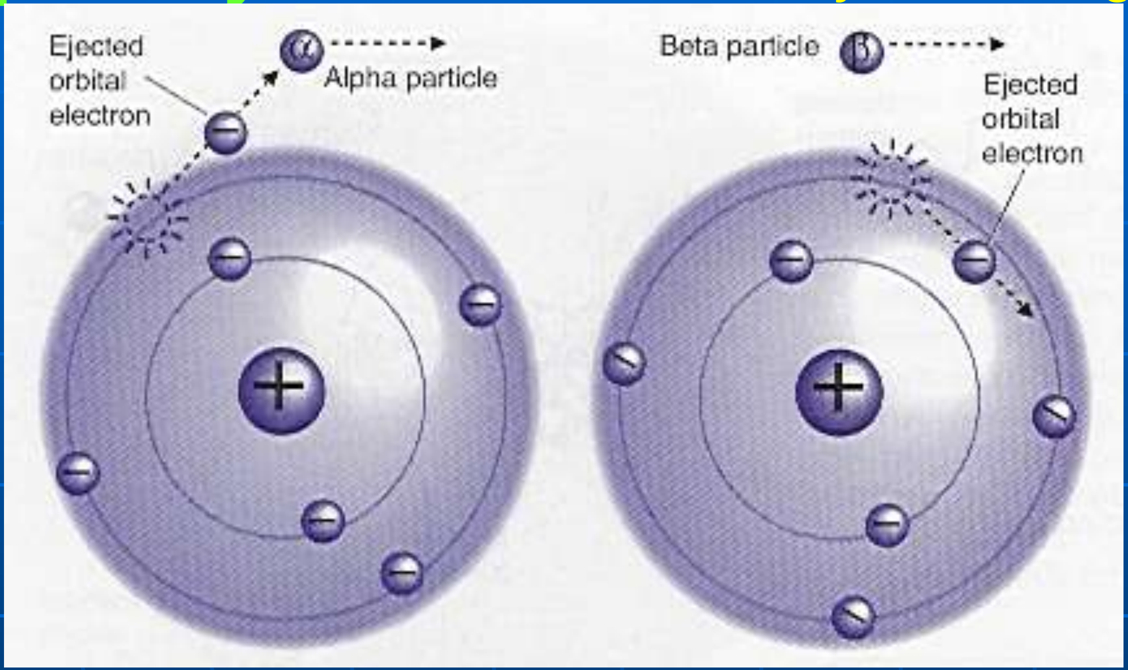
- Compton Scatter:
  - Low energy – poor energy transfer process – much of the hν energy retained in scattered hν
  - High energies – better energy transfer process.

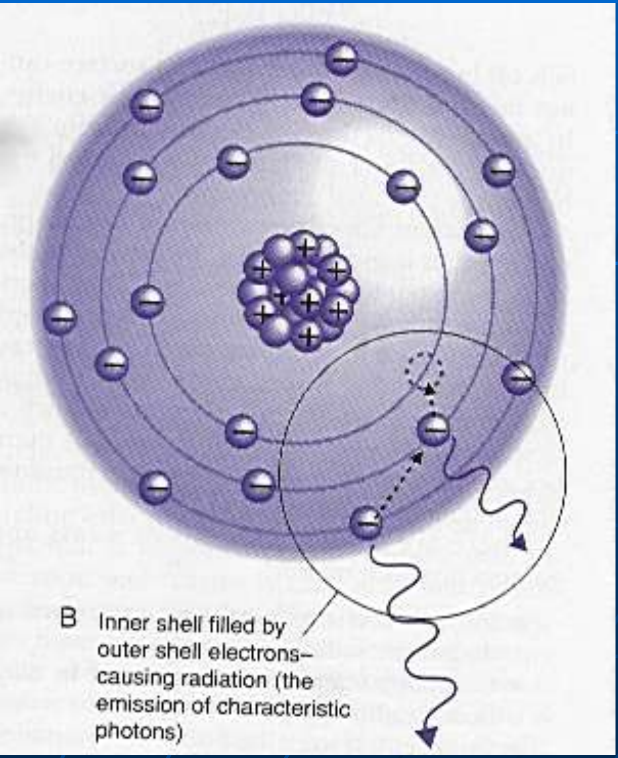
- In kVp x-ray range scattered photons have lots of energy, so dose from scatter is high, both back scatter and side scatter.

Charged particle interactions:

- Interact with **outer shell** electron –

primary interaction - many low energy transfer – ionizations.





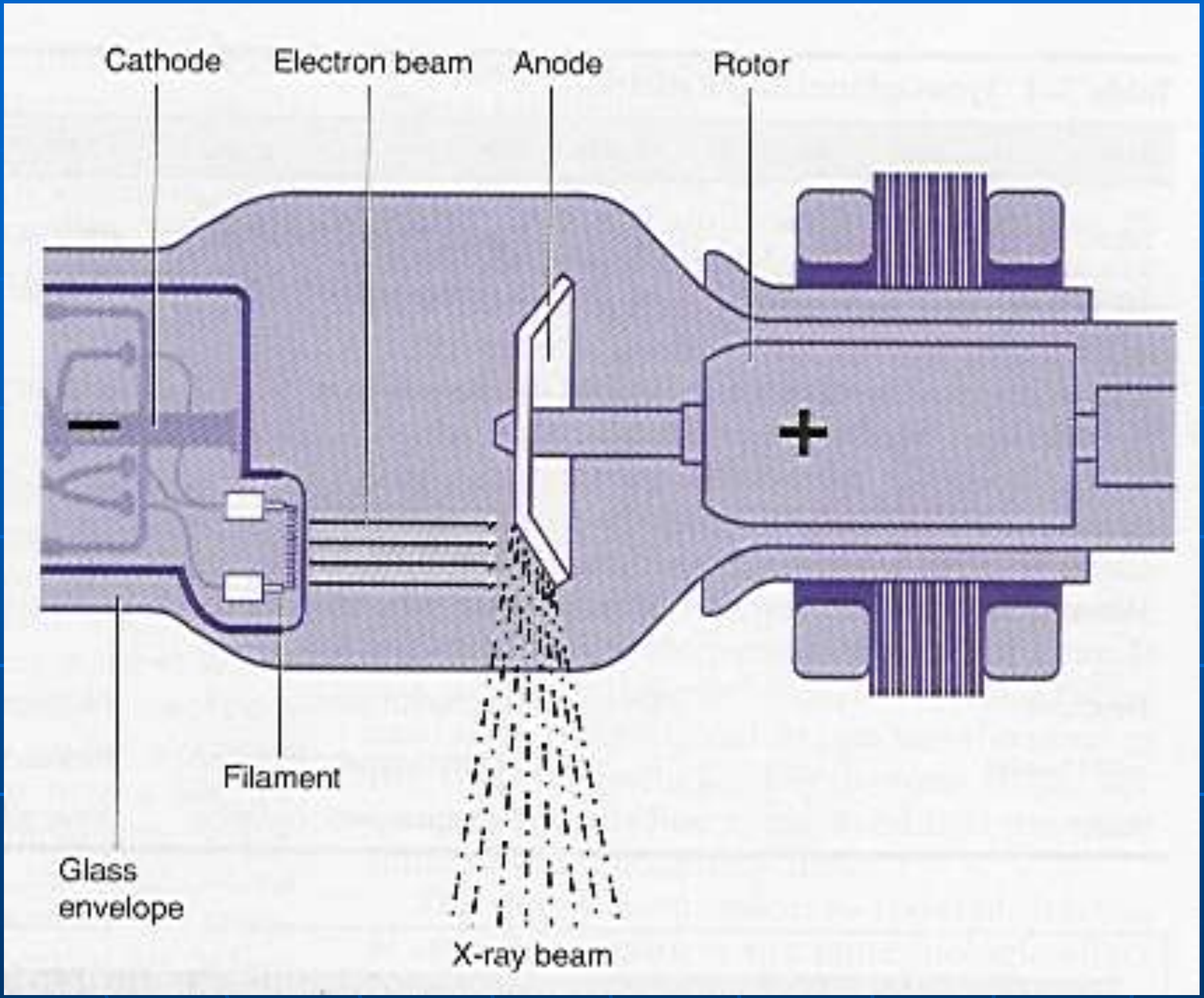
- Interact with **core electron – characteristic x ray.**
- Interact with nucleus – **bremsstrahlung (x ray).**

Collision – ionization-

creates the radiobiological effect

- breaking molecular bonds,
- molecule may recover from a single break
- Multiple breaks in a DNA molecule - serious damage.
    - densely ionizing radiations are more biologically damaging.
    - End of path higher density ionization

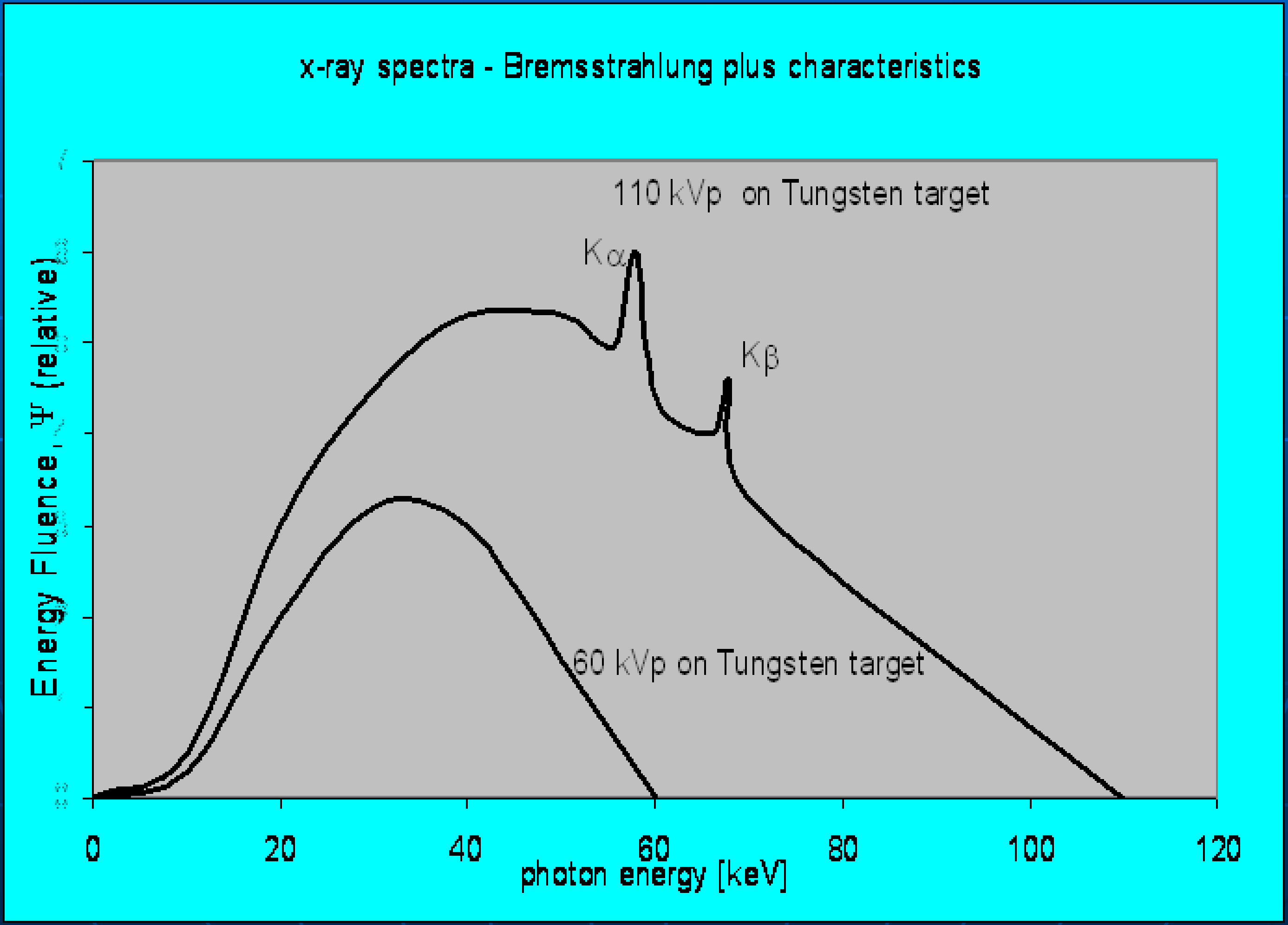
Formation of X-rays



e^- accelerated through a potential of 1 volt gains energy of 1 eV
So electron accelerated through 80 kV has an energy of 80 keV

Conventional X ray spectrum

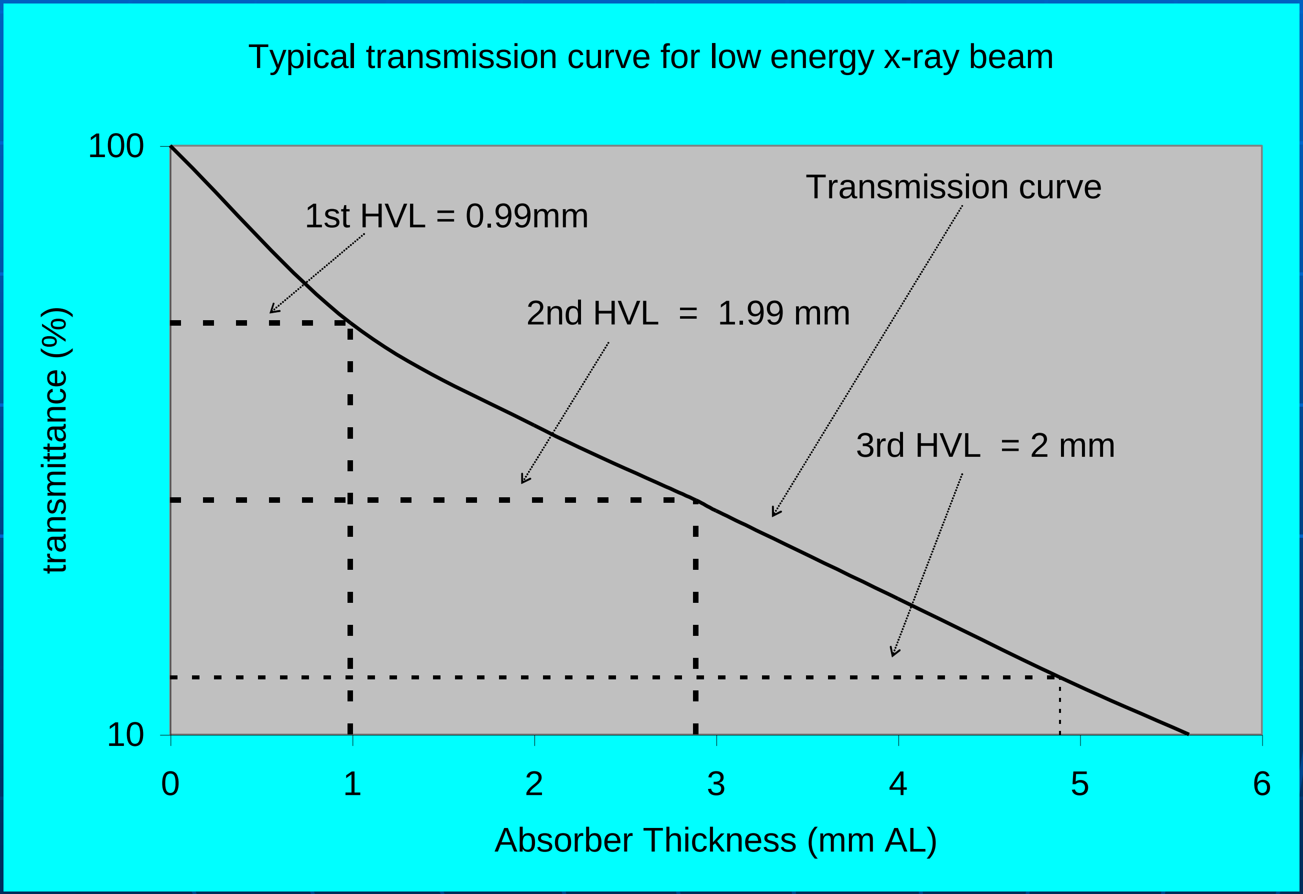
- Maximum energy of x rays therefore is the accelerating potential, KV
- Average energy ~ 1/3 (0.3 - 0.4) maximum energy
- Low energy x rays selectively absorbed by photoelectric process
- Characteristic x-rays if KV is greater than binding energy of core electrons



X ray beams characterized by their ability to penetrate through metals

Half value Layer, **HVL,** (in mm of Al or Cu) is the thickness to reduce radiation intensity to ½ of its initial value

Specify beam by 1st HVL and Homogeneity Coefficient, HC



$$HC = \frac{1^{st}\ HVL}{2^{nd}\ HVL}$$

60 KV beam

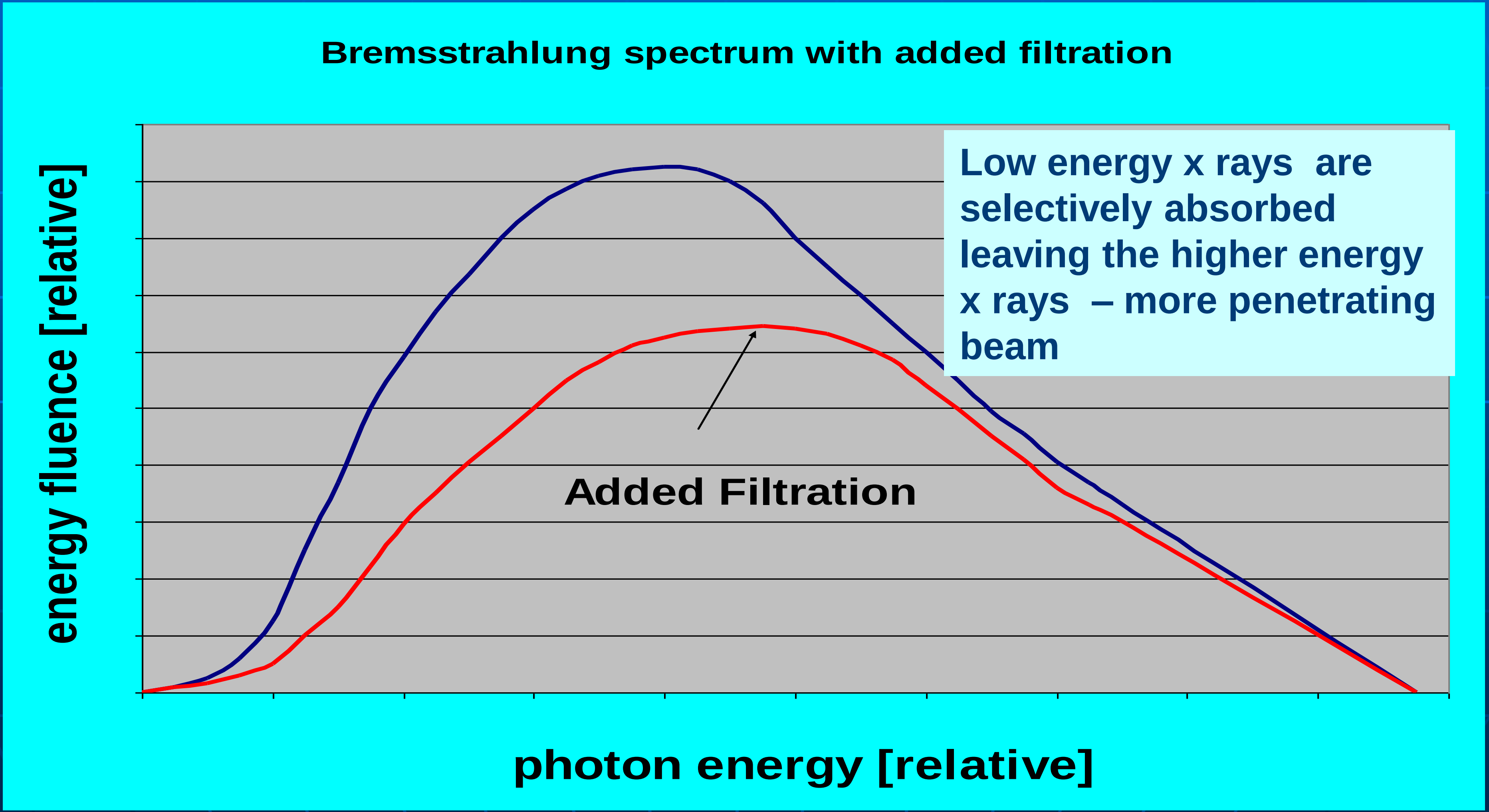
Eff. E ~ 20 KeV

HC ~ 0.5

HVL ~ 1.0 mm Al

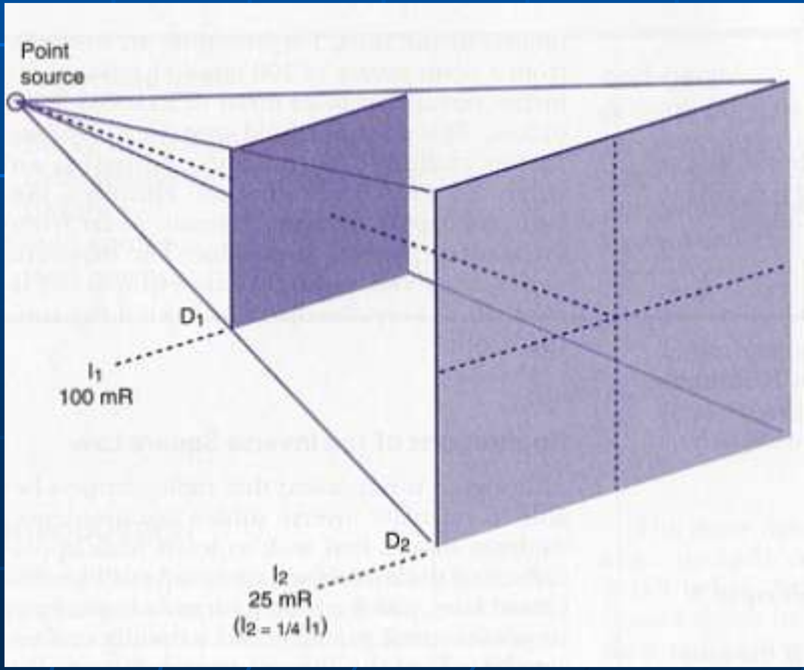
X-ray spectra with added external filter

Typical filters are Al at low energies,
Cu + Al at medium energies, and
Sn, + Cu + Al at high energies.



Dose as a function of distance (depth)

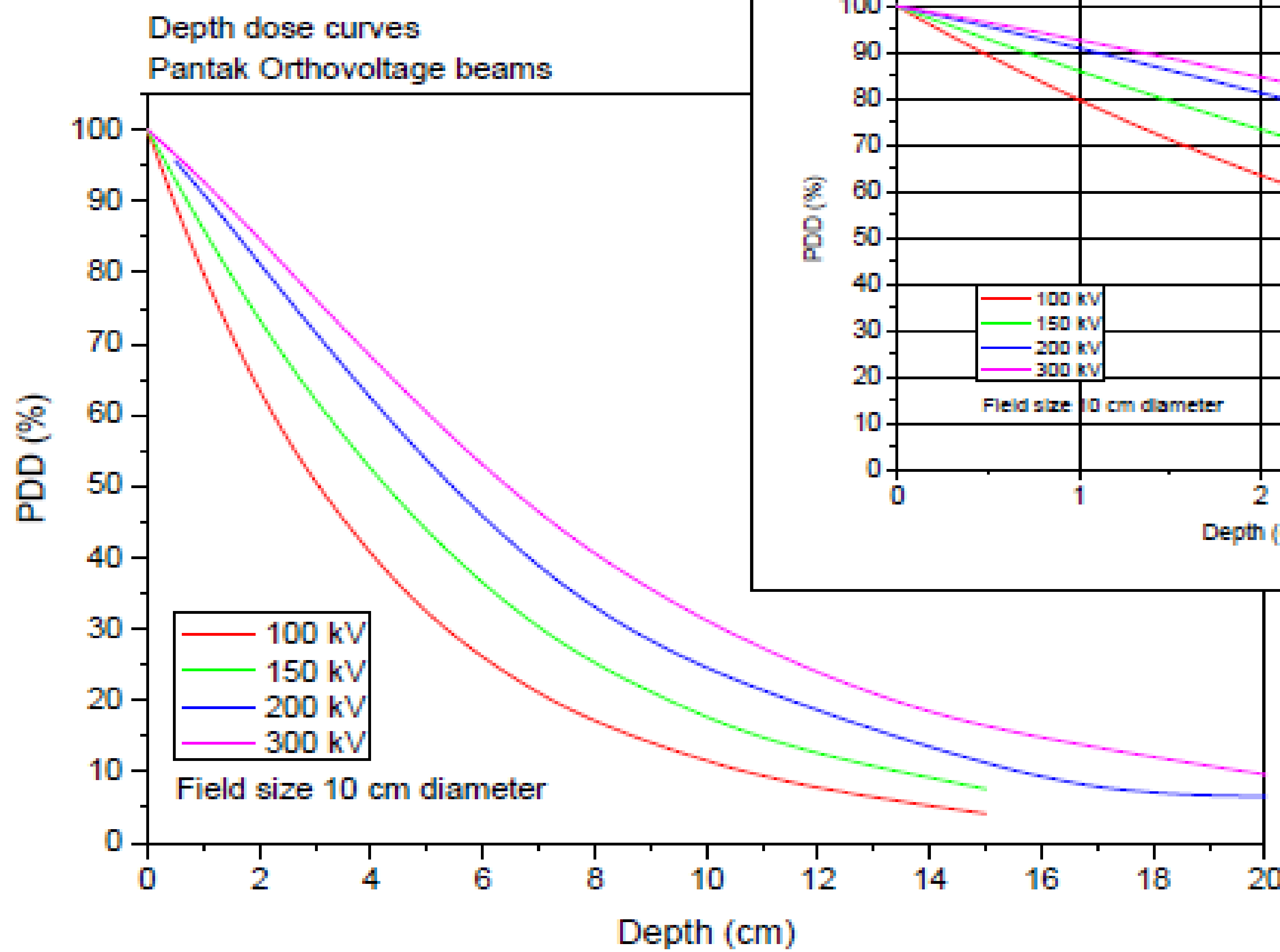
- Dose (rate) varies as
  - Distance from source
  - Attenuation due to penetrating matter
  - Scatter from target or surrounding materials
- Distance from the source
  - Point source: $1/r^2$: external beam and internal sources
  - Infinite line source: $1/r$: internal sources and blood irradiators

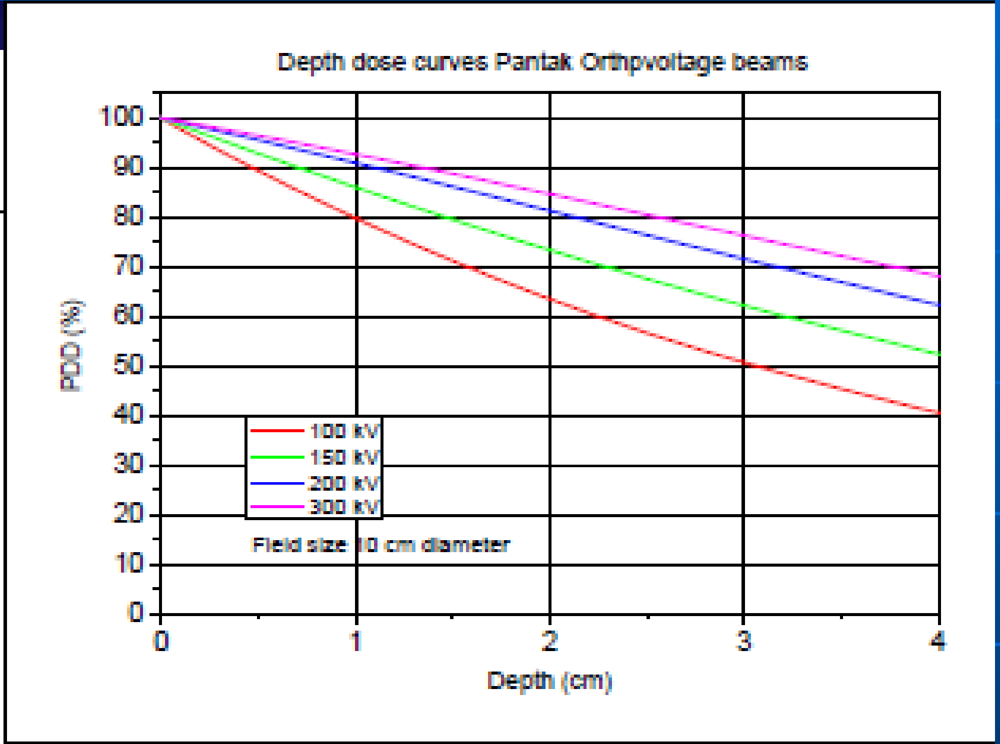


Depth dose:

- Strongly field size dependent: scattered photons
- Strongly distance dependent: $1/r^2$
- Strongly energy dependent: attenuation coefficients:

Orthovoltage Depth dose for 10 cm diameter field





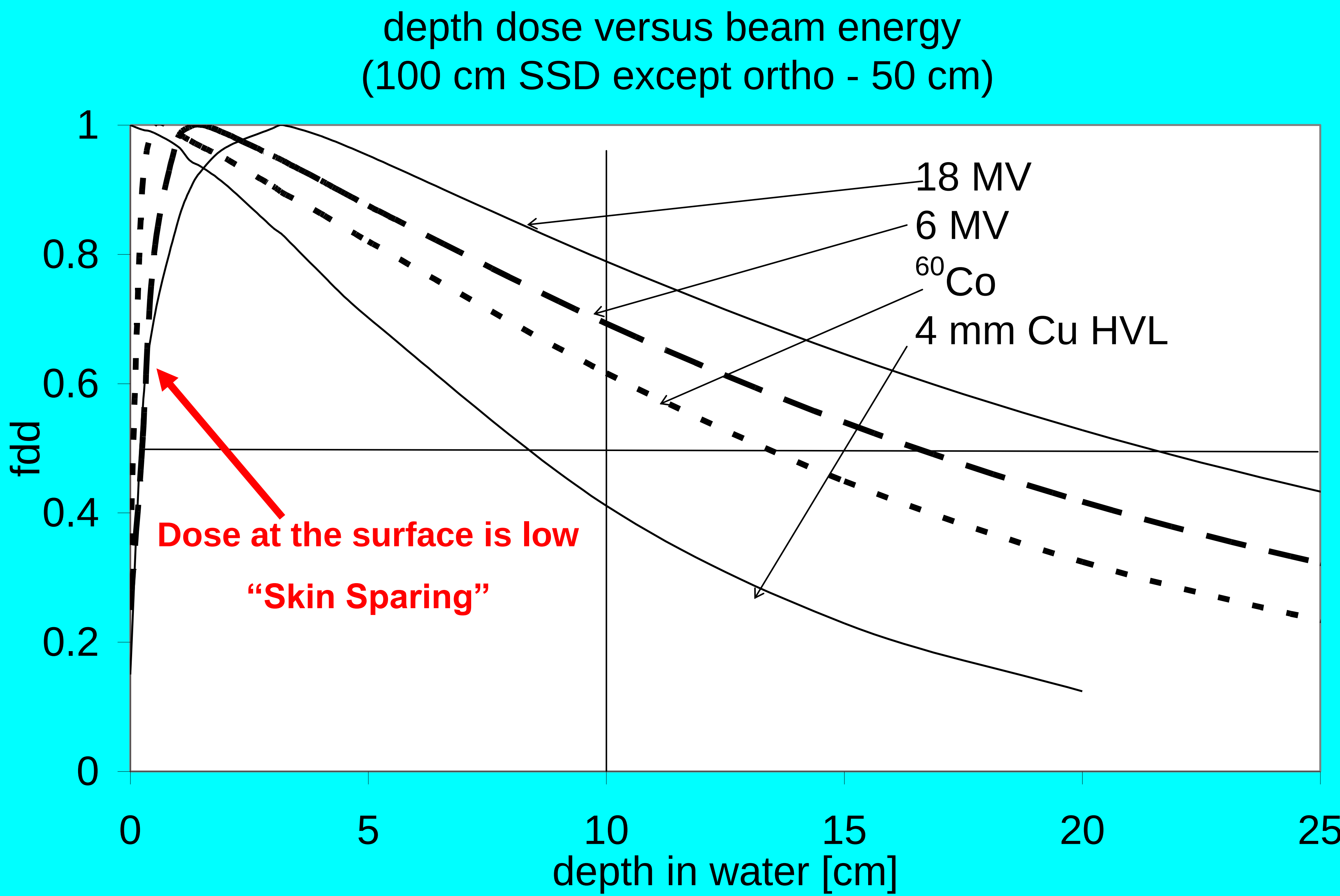
Depth dose for 10cm diameter field

Orthovoltage: All representative values

HVL	kV	%dd 0.5 cm	%dd 3 cm
1 mm Al	60 kV	83% 30 SSD	32% 30 SSD
4 mm Al	100 kV	95% 30 SSD	67% 30 SSD
0.5 mm Cu	140 kV	98.5% 50 SSD	77% 50 SSD
3 mm Cu	250 kV	~100% 50 SSD	92% 50 SSD

Conventional x rays

- Photon Scatter is very high
  - Side scatter – Dose depends upon how tightly packed your mice are in the radiation jig
  - Polystyrene not a good phantom material. (15% error in blood irradiator)
  - Back scatter very high (20 -30% for 10 square) so important what your Petri dish sets on
- Dose falls off fairly rapidly at conventional x ray energies.
  - The thickness of media in a Petri dish is critical


depth dose versus beam energy
(100 cm SSD except ortho - 50 cm)
1
0.8
0.6
0.4
0.2
0
fdd
0
5
10
15
20
25
depth in water [cm]
18 MV
6 MV
60Co
4 mm Cu HVL
Dose at the surface is low
"Skin Sparing"

Photon Skin sparing

- What is depth of Maximum dose (soft tissue)
  - Cs 137 0.3 cm
  - Cobalt 60 0.5 cm
  - 6 MV 1.5 cm
  - 18 MV 3.5 cm
  - Conv. x rays surface (?)

You may need to bolus small animals in ^{137}Cs & ^{60}Co

Be Careful there is some skin sparing at Orthovoltage energies:

- TLD powder in heat seal bags – under-responds.

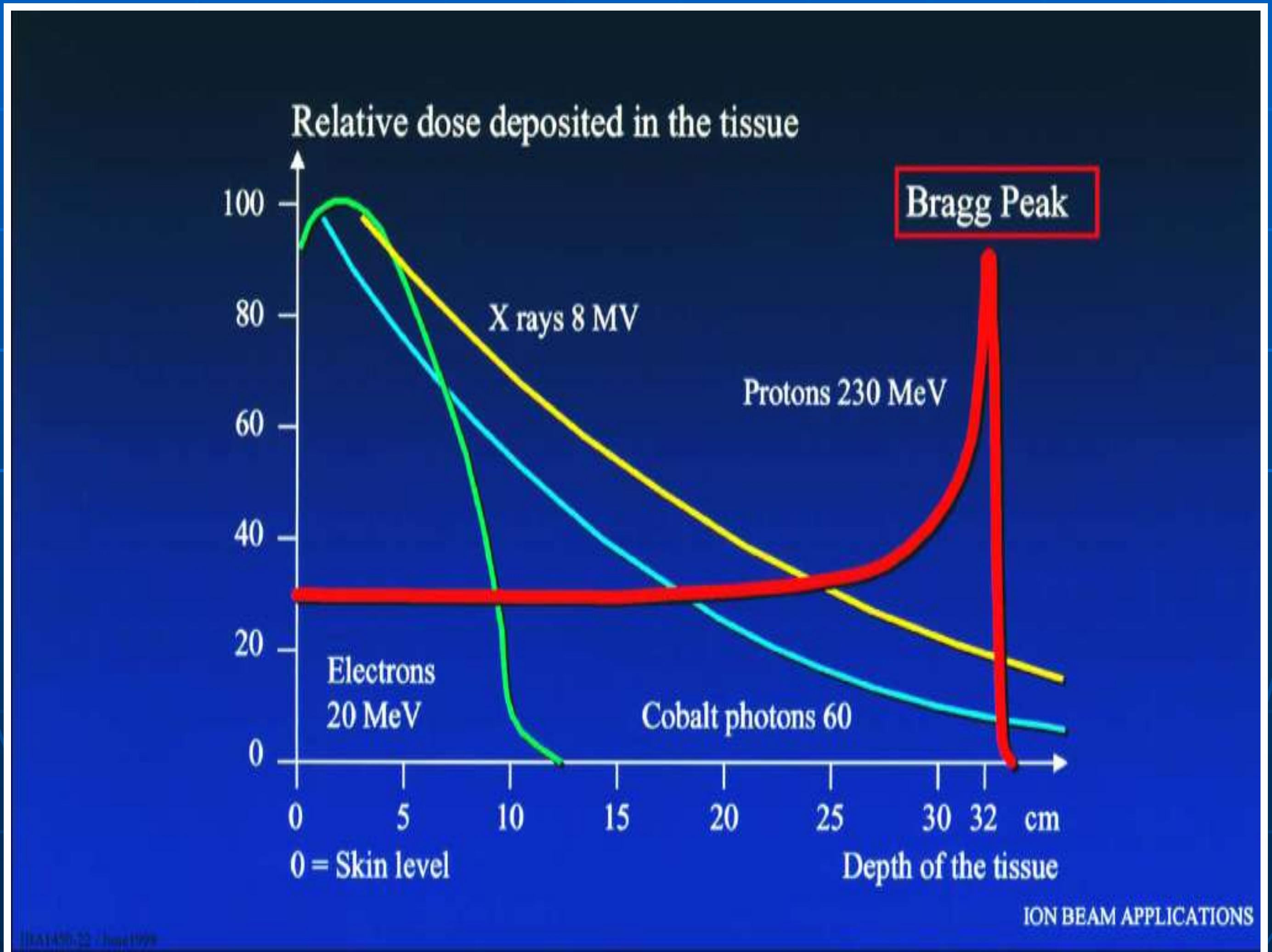
Depth Dose of Heavy charged particles:

Particle loses energy constantly by many ionizations (CSDA)

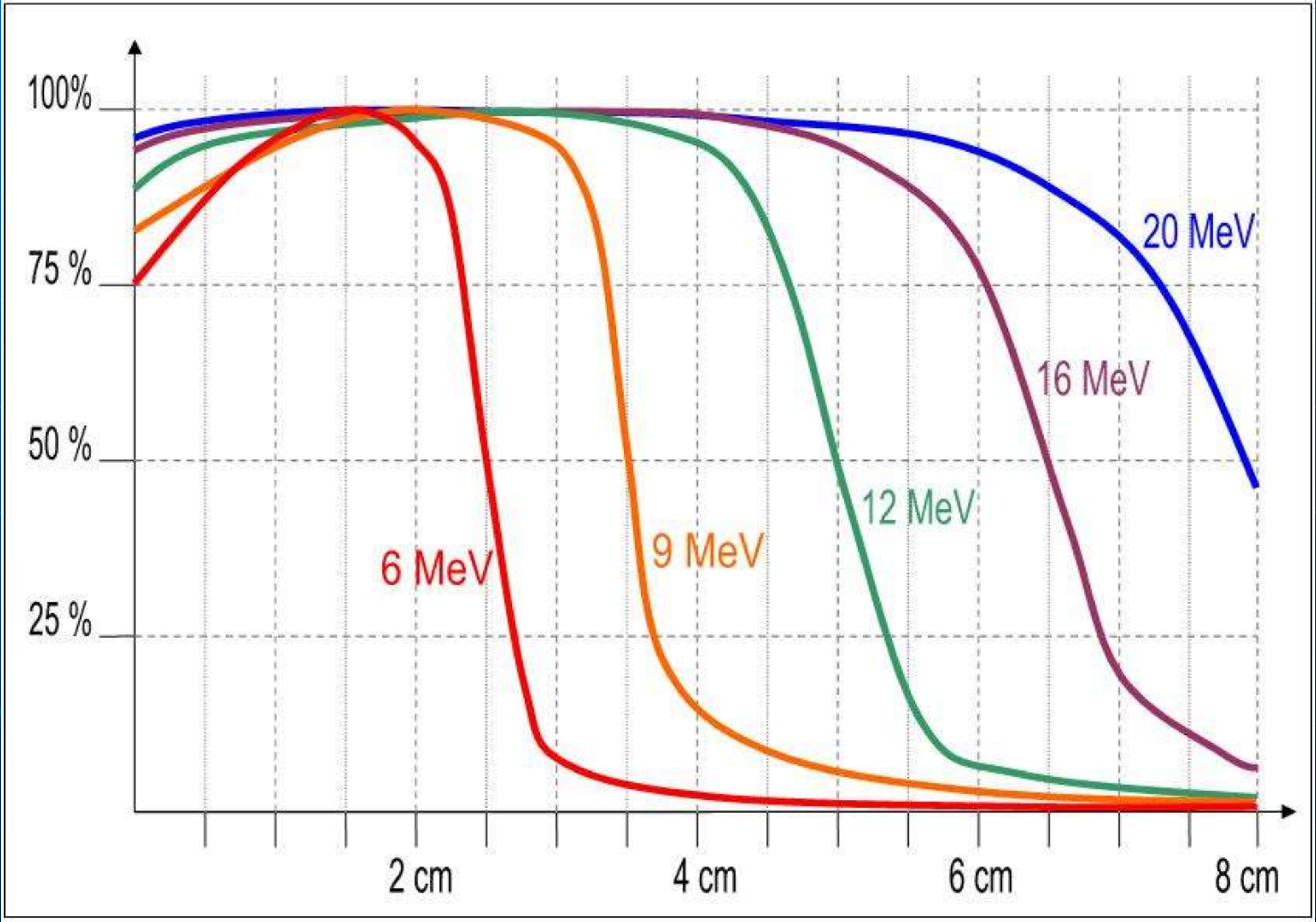
High energies stopping power is nearly constant with energy

Low energies stopping power rises dramatically with reduced energy.

Dose proportional to stopping power



Dose builds up inside the surface, sharp fall off at depth, bremsstrahlung tail
Electrons have limited and distinct range -- in tissue lose ~ 2 MeV / cm
Rule of thumb: range [cm] in water/tissue ~ E[MeV] / 2



Which x ray beam to be used?

- Parameters that effect this choice
  - Energy,
    - Using a filter can increase the HVL so get better penetration.
      - less dose gradient over the animal
      - reduces the dose rate
    - Reducing the KV allows the use of higher current, maybe higher dose rate.
- Beam flatness:
  - flattening filter can improve this
    - reduces output (not much)
    - Delivers more uniform dose over the field

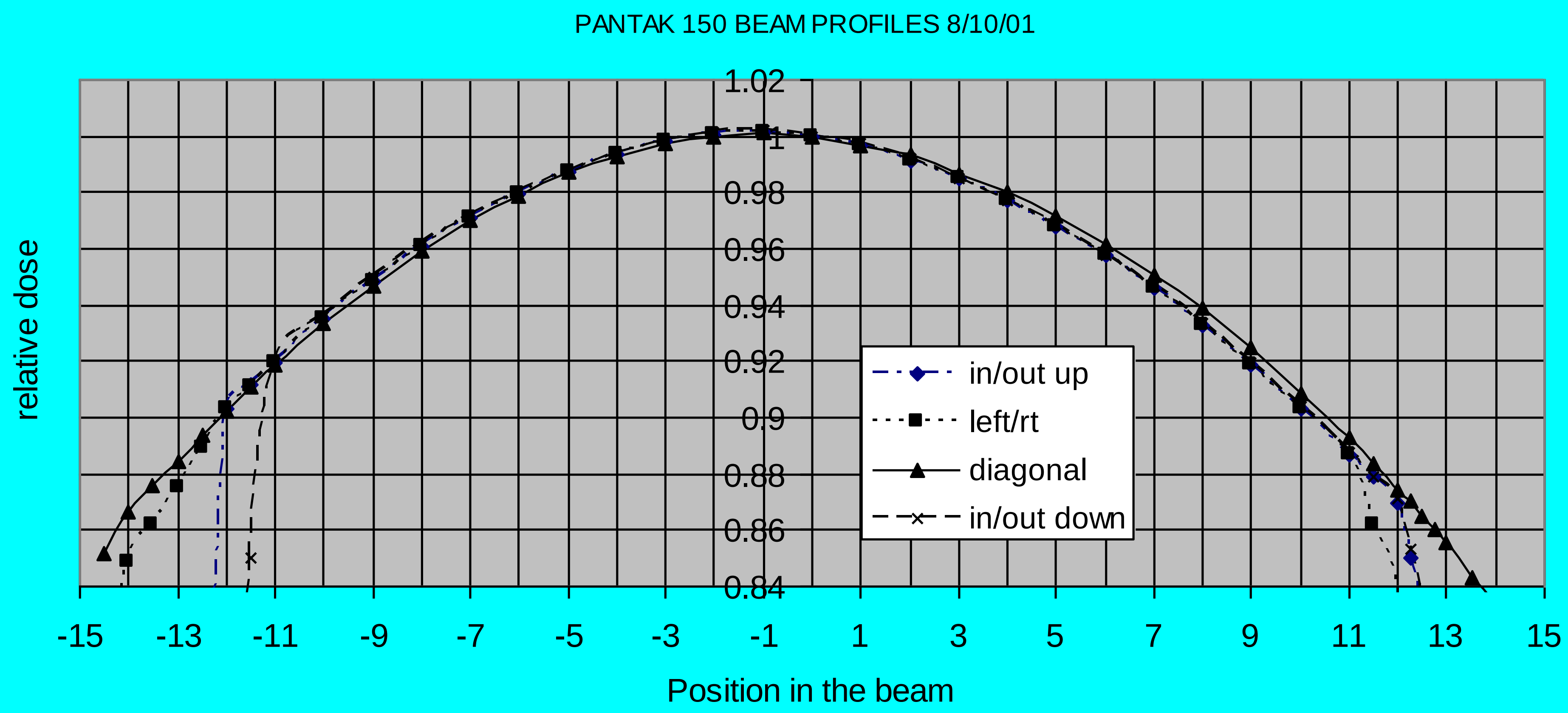
On our 300 KV unit we chose the 300 KV beam with 9 mA and minimal additional filtration. This gave us a very low HC of 0.63 but it gave us a dose rate of 1.3 -1.9 [Gy/min] for our routine use of the machine.

Techniques to obtain more uniform dose throughout the target

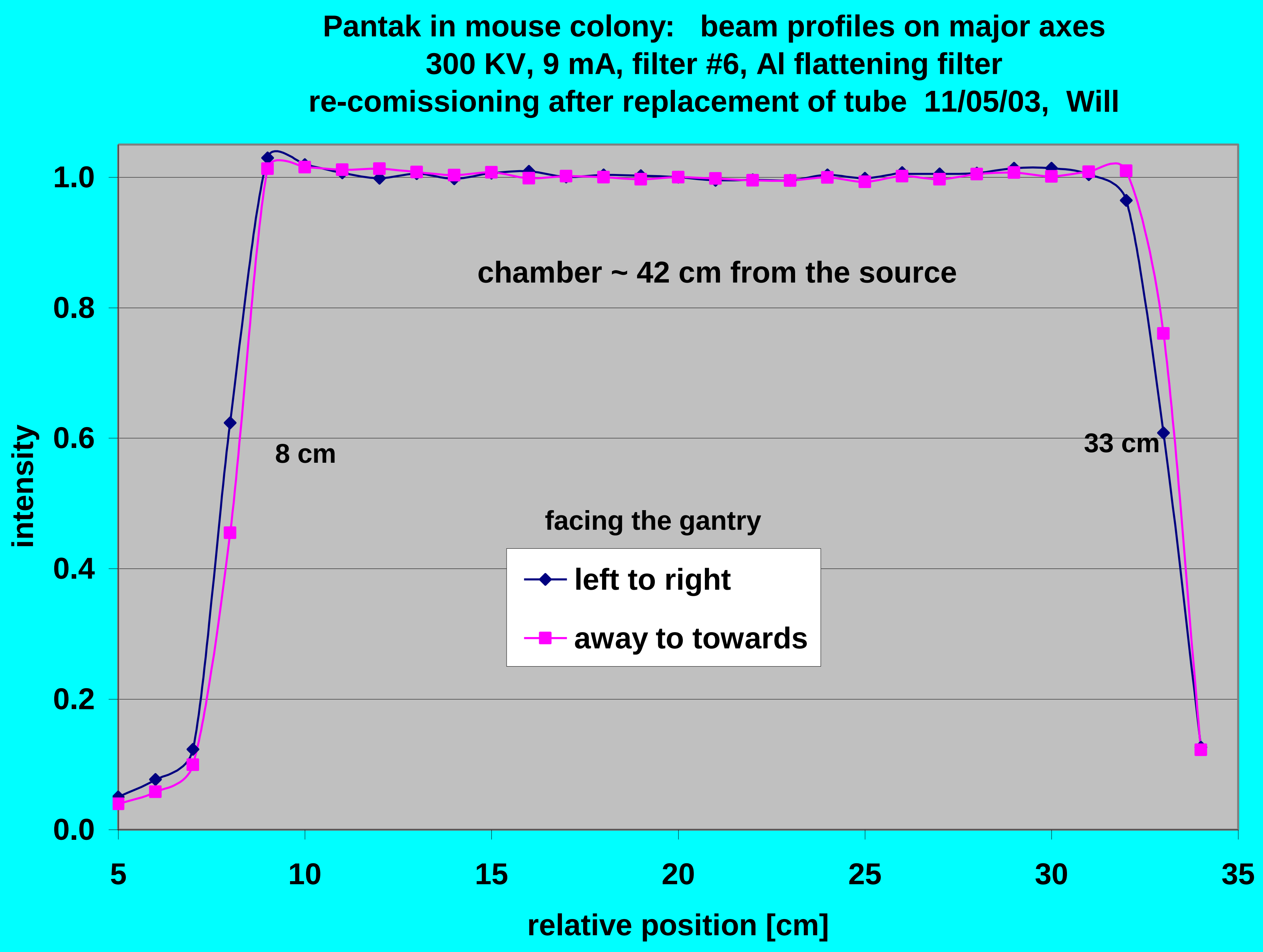
- Beam flattening filters
- Parallel Opposed treatment
- Verify beam flatness in anatomical phantom (film)
- Make walls of irradiation chamber very low Z

Design a flattening filter

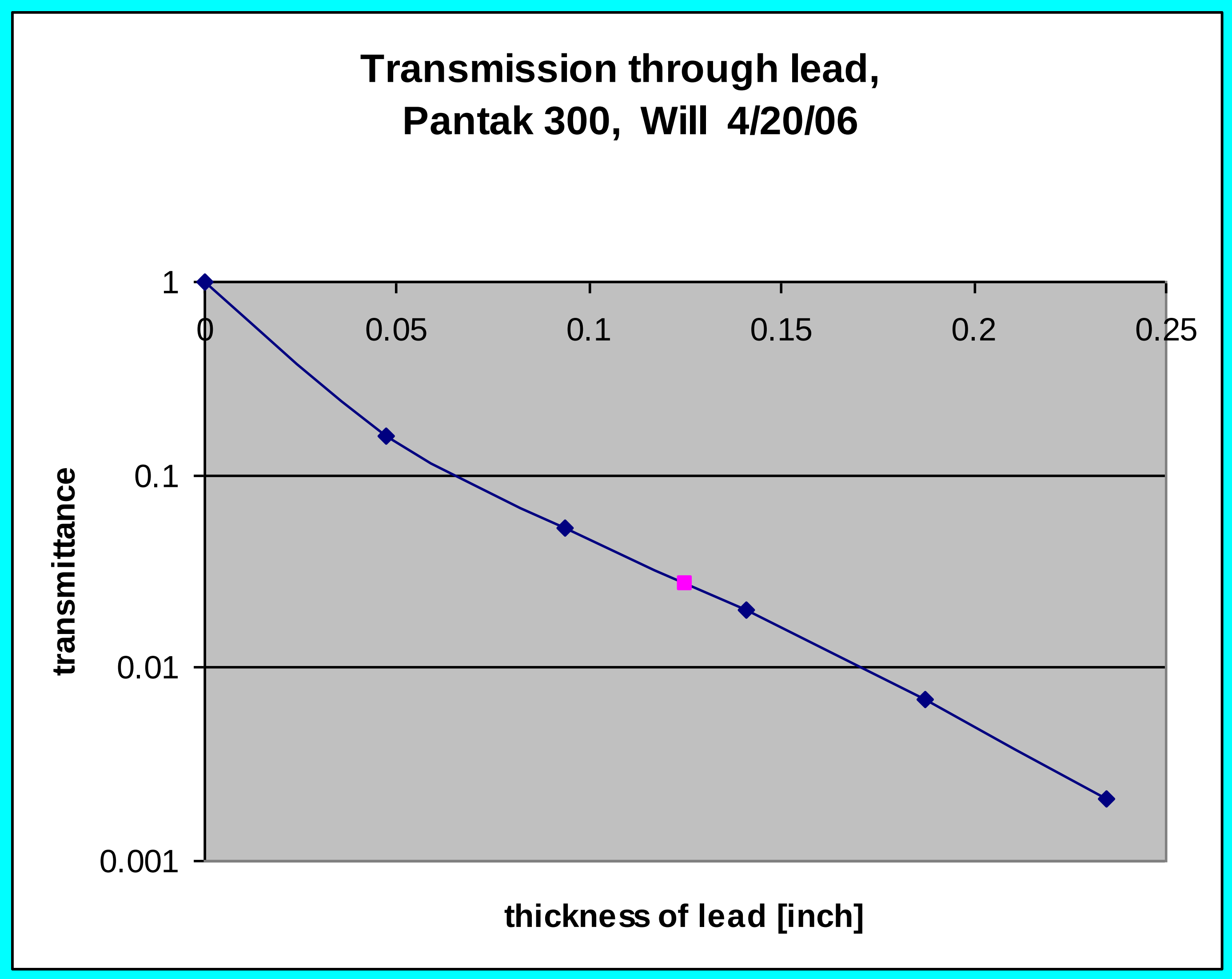
MDACC does this on all of its external beam animal irradiators; Cobalt and Orthovoltage



Result: dose uniform within 2% over whole beam



At conventional x ray energies photoelectric effect so strong, very important to measure the transmission through your lead (or other alloy) shields

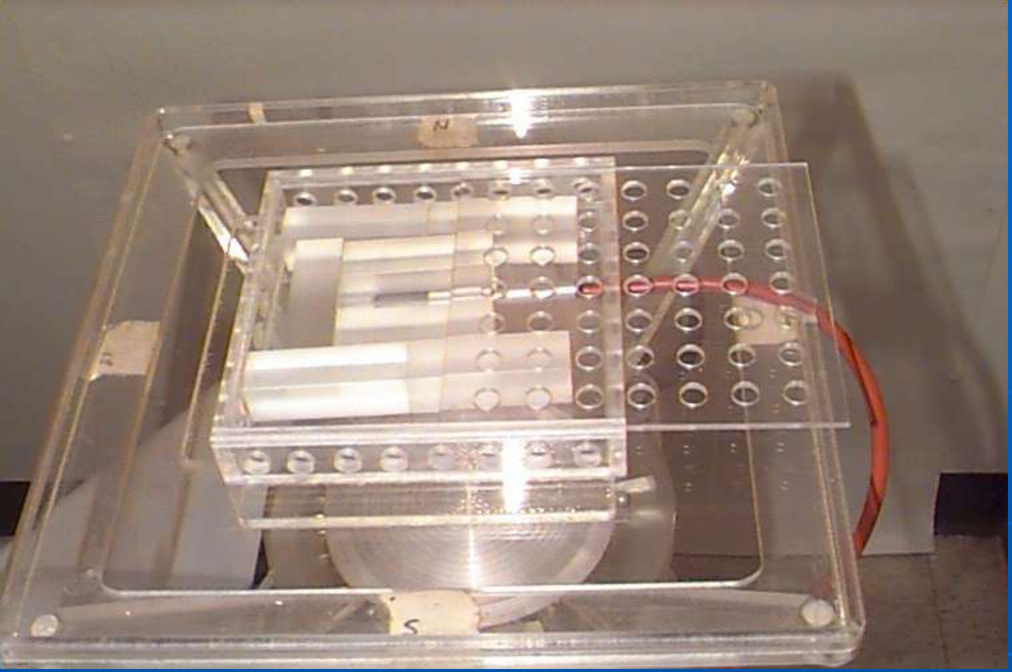


Dose uniformity over animal

- Whole body mouse irradiation:
  - Measured dose at top of PMMA mouse and at bottom of mouse with TLD.   Total gradient ± 15% at 150 kV, 250 kVp, and 300 kVp
  - Redundant check: BJR #17 data using 10 cm^2 square field calculated ± 12% at 30 cm SSD for all 3
  - Does BJR verify TLD measurements considering the constraints?
    - You bet it does.

$1/r^2$ accounts for ½ the effect (±7%)

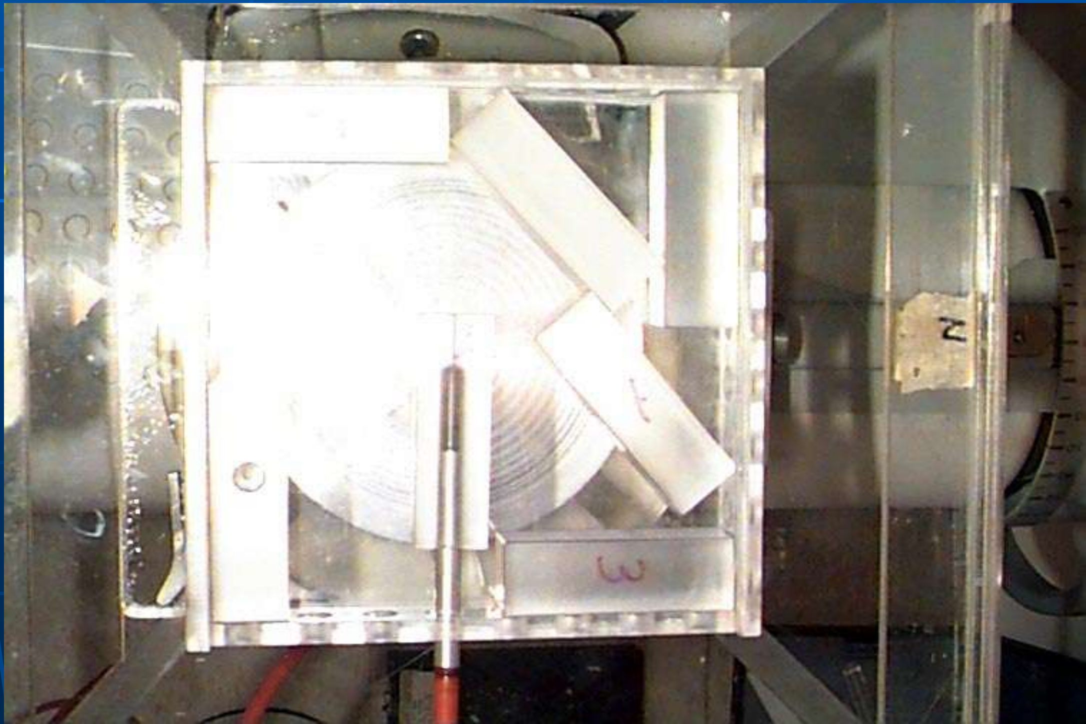
300 KV Pantak
Whole body mouse irradiation



Whole Body Mouse jig
8 mice ordered

Whole Body Mouse jig
5 mice random

Constancy irradiation



Redundancy

- Have someone else make selective measurements to verify.
- Verify ion chamber measurements with TLD - Std TLD calibrated in same beam with well known geometry.
- Verify using standard dosimetry data, BJR 17 or BJR 25 for orthovoltage
  - How do you extrapolate to small field sizes and thin animals (incomplete side and backscatter) and unusual SSD or other geometry.

Redundancy continued

Do not be afraid to use biological dosimeters:

- New Machine:
- Physics Staff: Calibrate unit
- Radiobiologists:
  - Very confident in their dose response curve for mouse Crypt cells.
  - Sacrificed some mice to run a dose response curve
  - Told Physics that calibration off by 15%
- Physics staff: verified 15% discrepancy, primarily a communication problem.
- Radiobiology staff occasionally challenged Physics (me), we discussed and resolved.

Petri dish dosimetry

- We saw how rapidly the depth dose drops at low energies
- Dose rate drops even faster at short SSD.
- Thickness of media over the cells is critical
- Backscatter at Orthovoltage is high:
  - Backscatter from “treatment table” is critical. (30%)

Stomach education

On average it takes ~ **30 eV** of energy to remove one electron from an atom.

A **100 keV** electron creates something like **3,000** ionizations

Not very many ionizations do biological damage

$$\frac{\overline{W}}{e} \approx 30 \; {}^{eV}\!\!\big/_{i.p.}$$

$$\frac{100\; keV\; e^{-}}{30\,[eV/i.p.]} = \approx 3 \bullet 10^{3}\;[i.p.]$$

Accurate Dose Delivery is Essential