NERS 555

Radiological Physics and Dosimetry

Introduction to the course

Introduction to the course

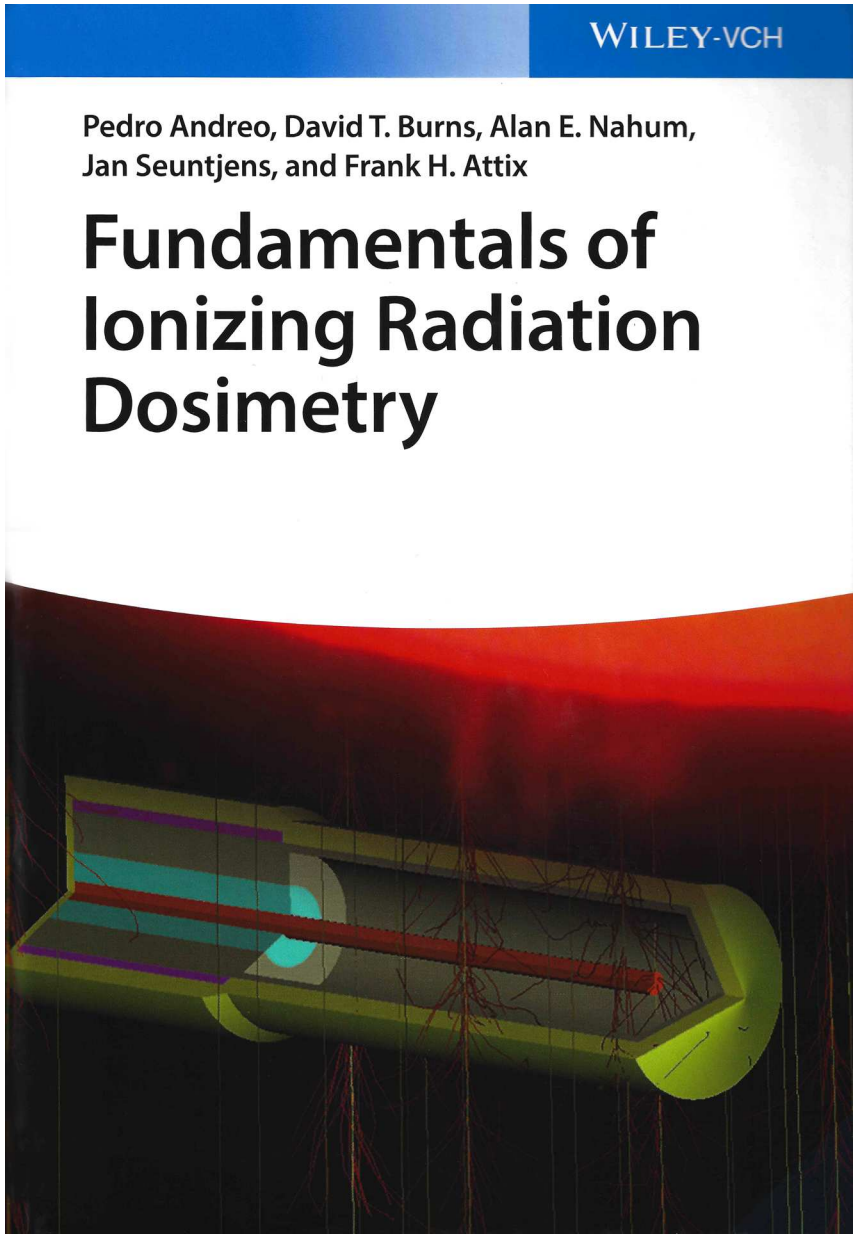
Website: `www.umich.edu/~nersb590/`
(Don't worry! The 590b is an historical artifact!)
(This really is NERS 555.)
Please go to this site before every lecture.
Read the assigned material, at least once before lecture.

There will be a weekly quiz associated with the assigned reading material that carries a 1% graded course weight. The scope of the quiz will be clearly communicated to you before lecture.

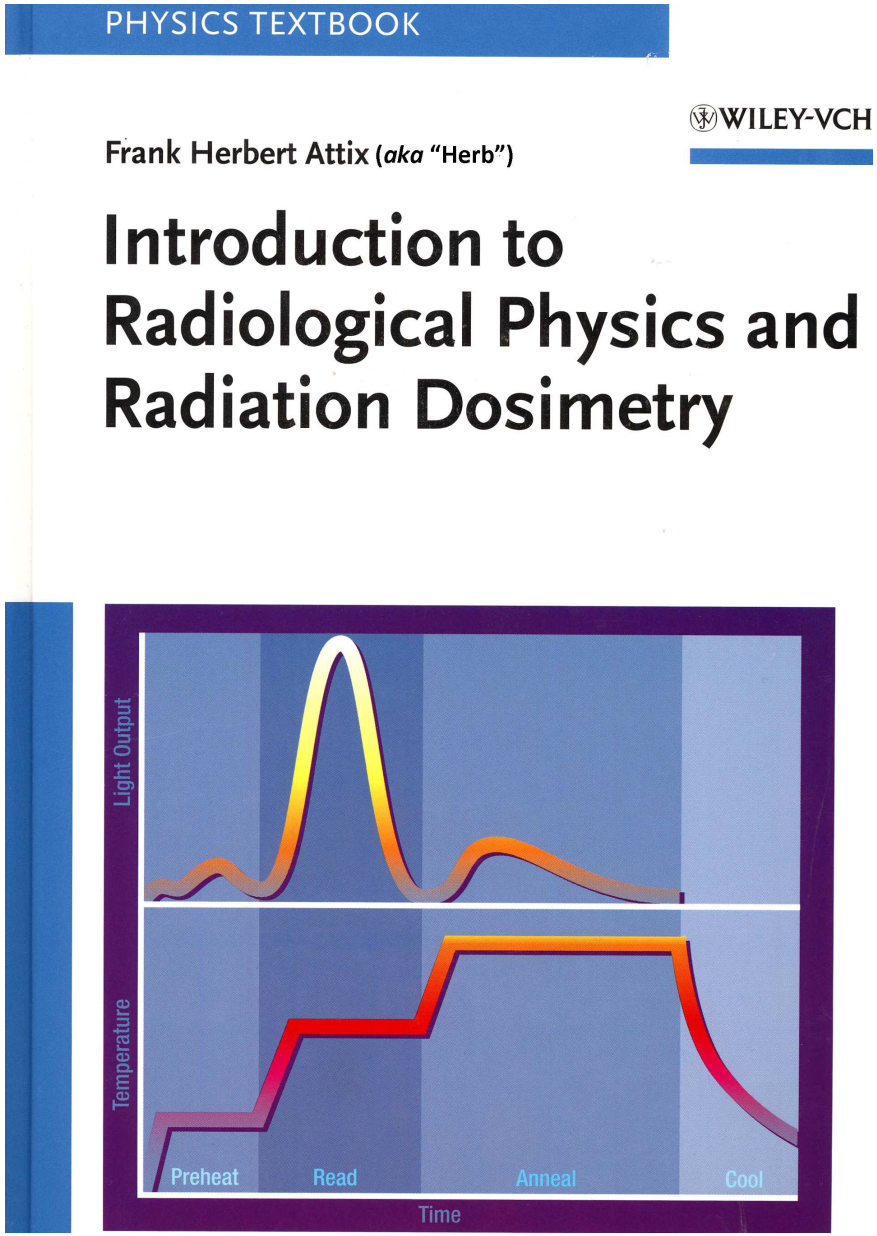
Class Policy: Please see the course website. (Also attached below)

Class Schedule: Ditto on the above.

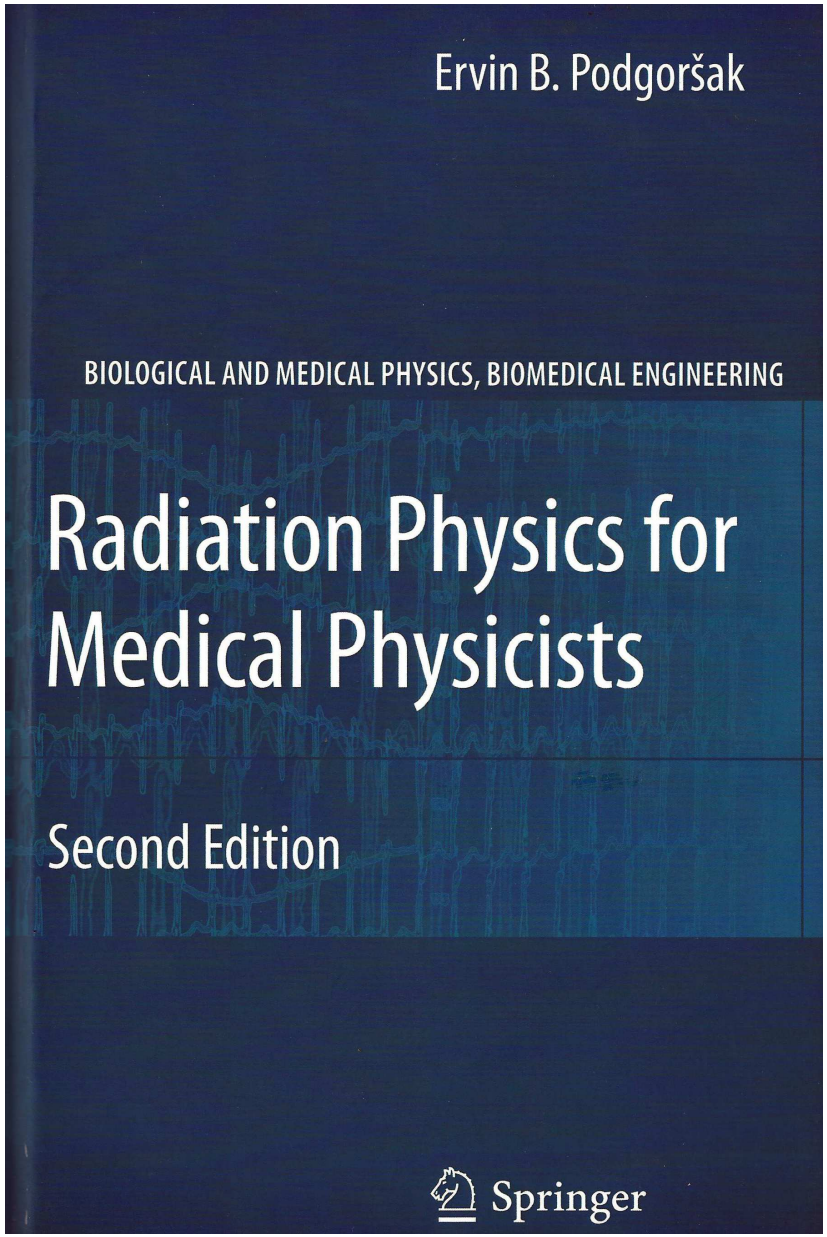
The best book on Radiological Physics and Radiation Dosimetry



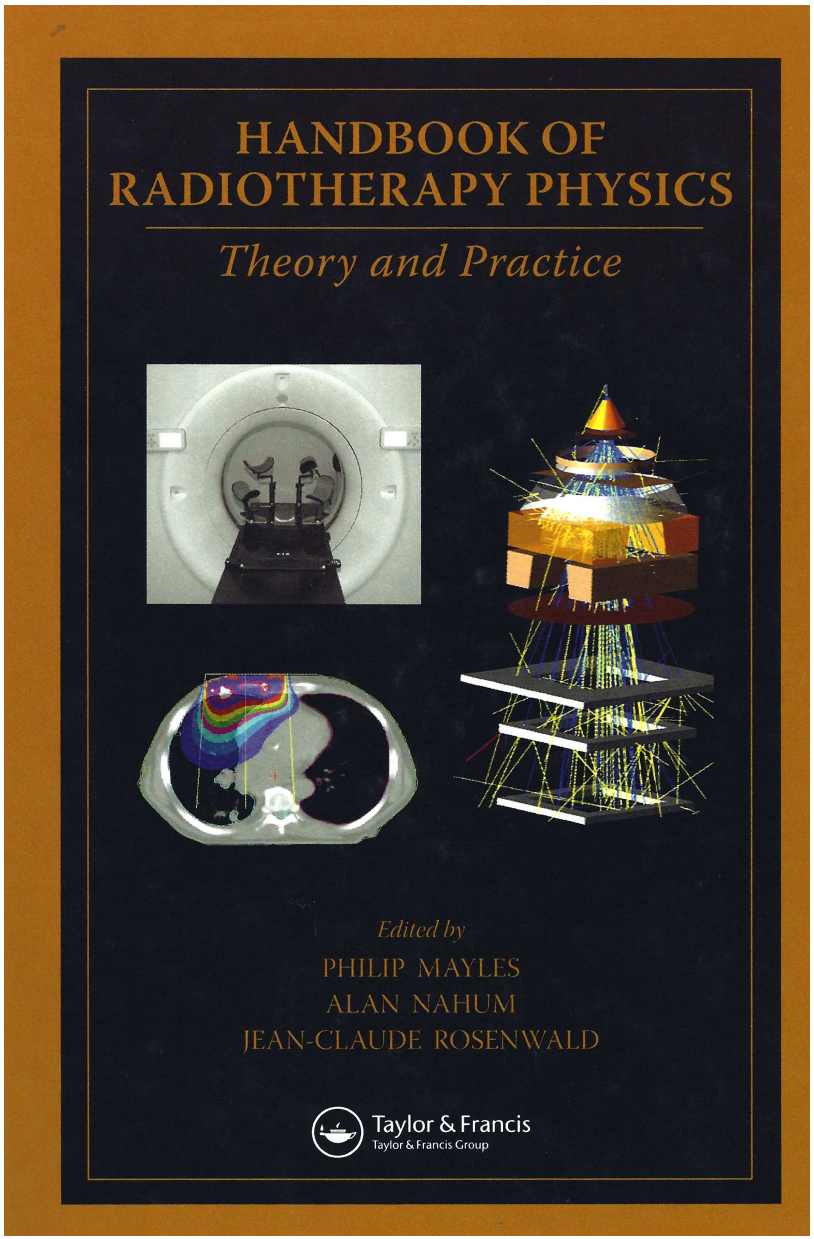
that replaced the following (still good) book



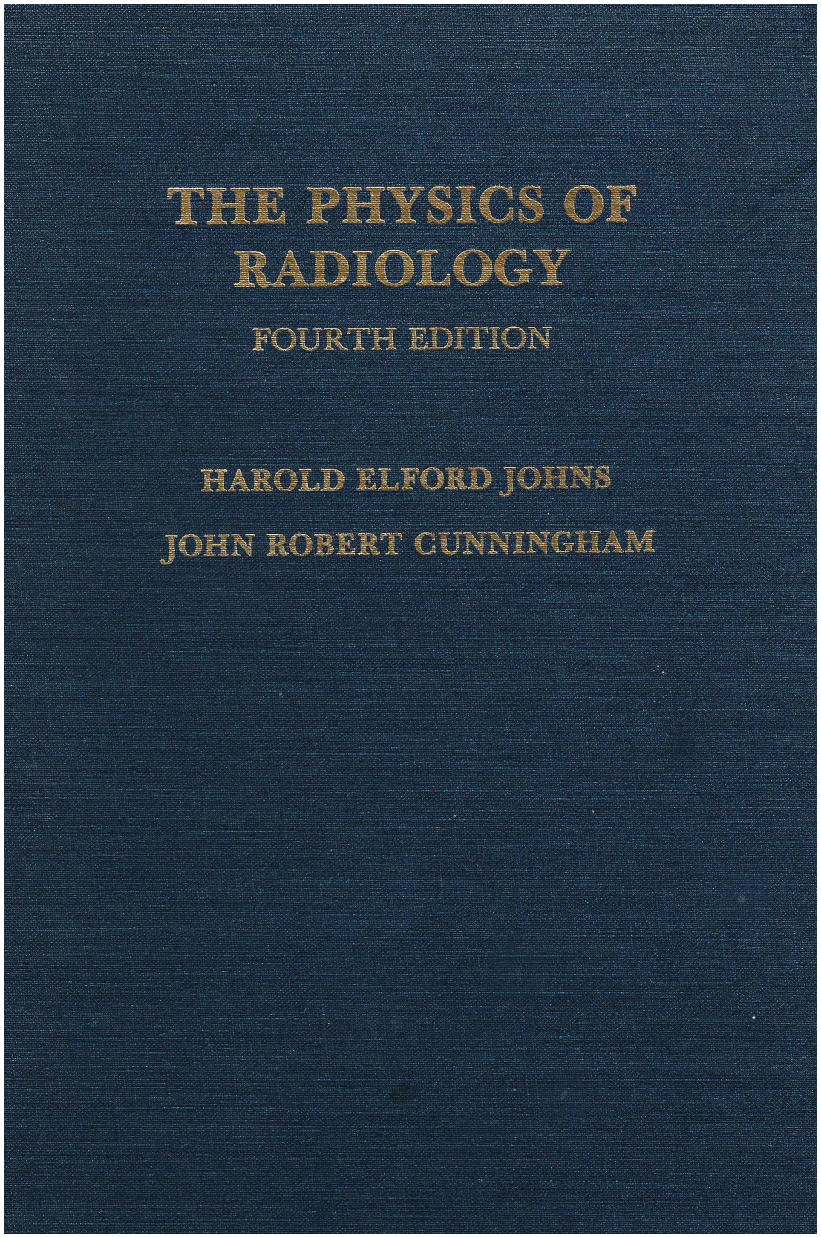
The 2nd best book



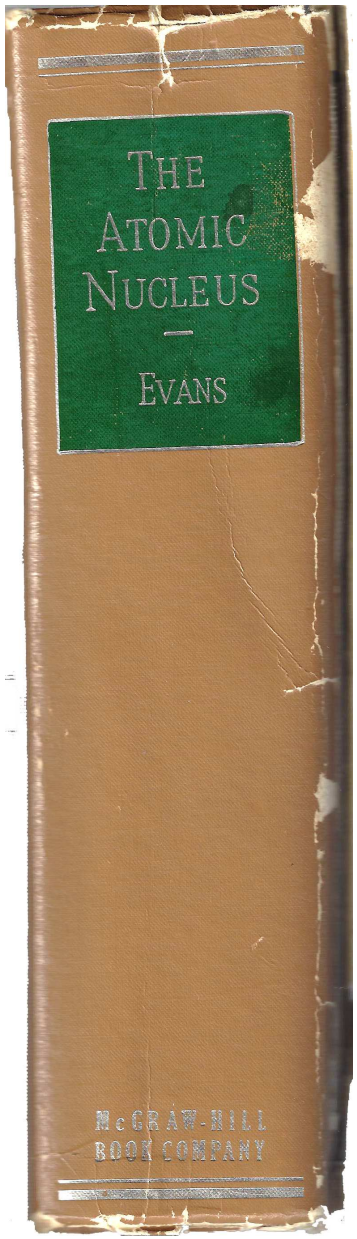
The 3rd best book



The 4th best book

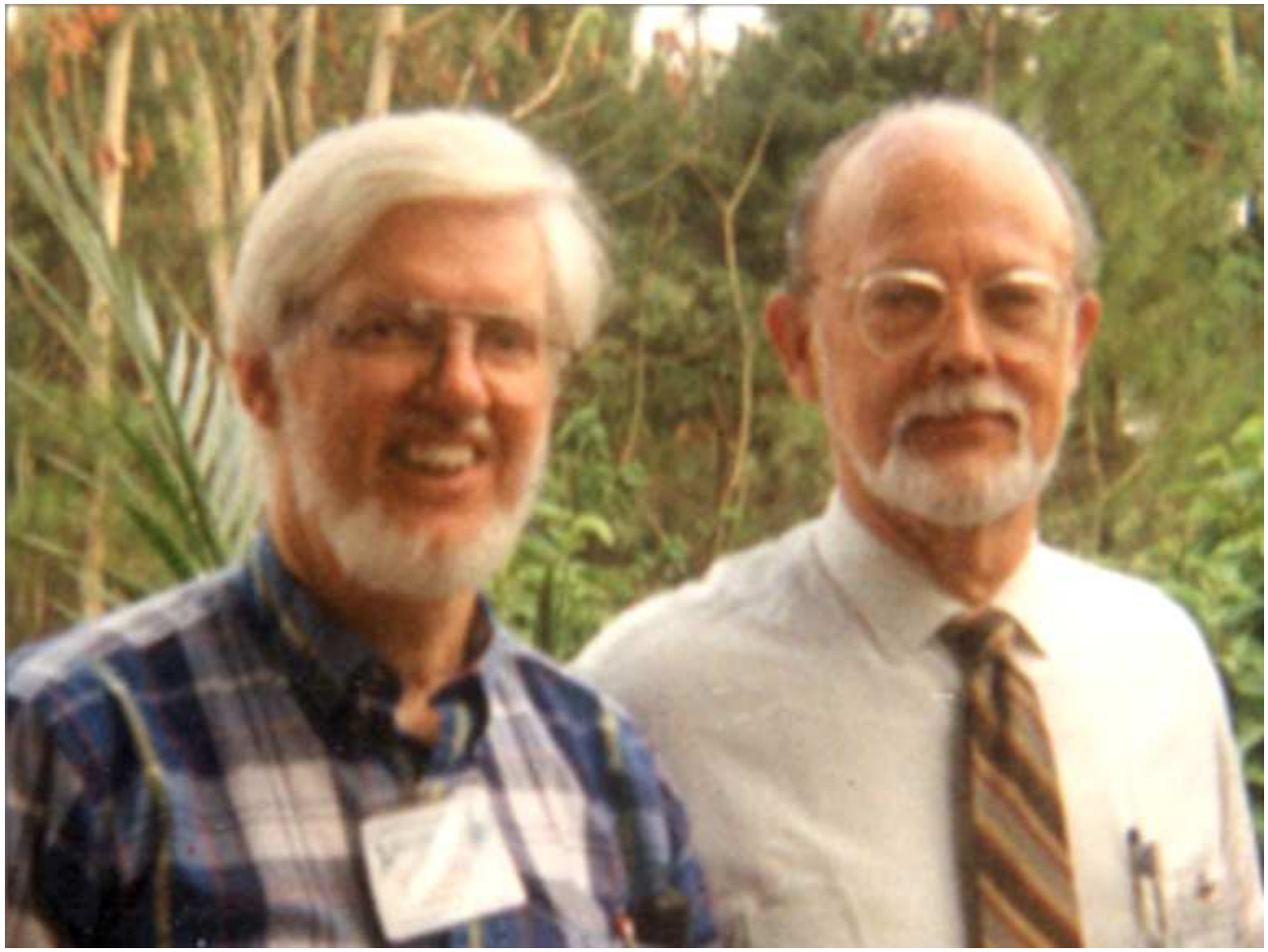


Special mention for those interested in Radiation Interactions



Left to right:
Harold E. Johns, ^{60}Co-treatment inventor, founder of modern medical physics
Charles C. Burkell, Director of Saskatoon clinic (hired the right people)
Sylvia Fedoruk, researcher on the ^{60}Co project, co-discoverer of CT imaging

John S. Laughlin, Director of the Memorial-Sloan Kettering Cancer Clinic, ushered in modern medical physics in the USA



Left to right:
John R. Cameron, one of the founders of medical physics in the USA
Frank H. Attix (*a.k.a.* Herb), best medical physics professor ever (U Wisconsin)

What is Radiological Physics?

As stated eloquently in: `www.radiologicalphysicsinc.com/faqs.html`

Radiological physics is primarily an applied branch of physics. It is concerned with the application of physical energy to the diagnosis and treatment of human disease. It encompasses those branches of medical physics that are generally referred to as diagnostic radiological physics, therapeutic radiological physics, and medical nuclear physics.

How does radiation impact life?

Radiation interacts with DNA in two ways, in approximately equal proportion.

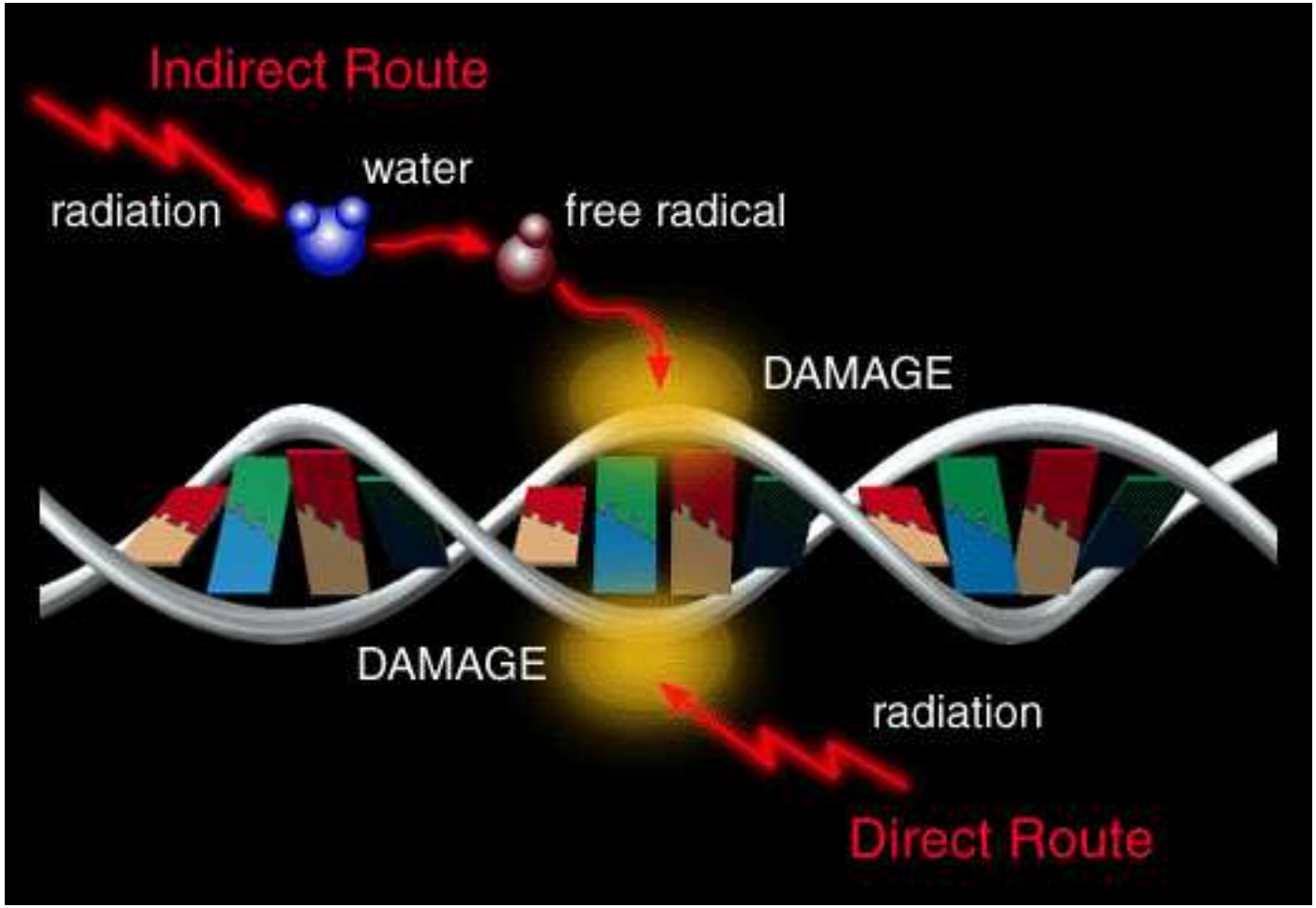


Figure 1: Direct and indirect damage on DNA. Image courtesy of `www.windows2universe.org/earth/Life/cell_radiation_damage.html`. That website offers some nice quantitative descriptions of radiation damage.

The areas of damage are called "lesions"

Two lesions, however close to each other, are usually repaired within about 5 minutes.

Three lesions, within 10 base pairs, is usually lethal.
i.e. The DNA does not replicate and the cell dies.
Depictions of a 10 base-pair segment of DNA are shown on the next page.

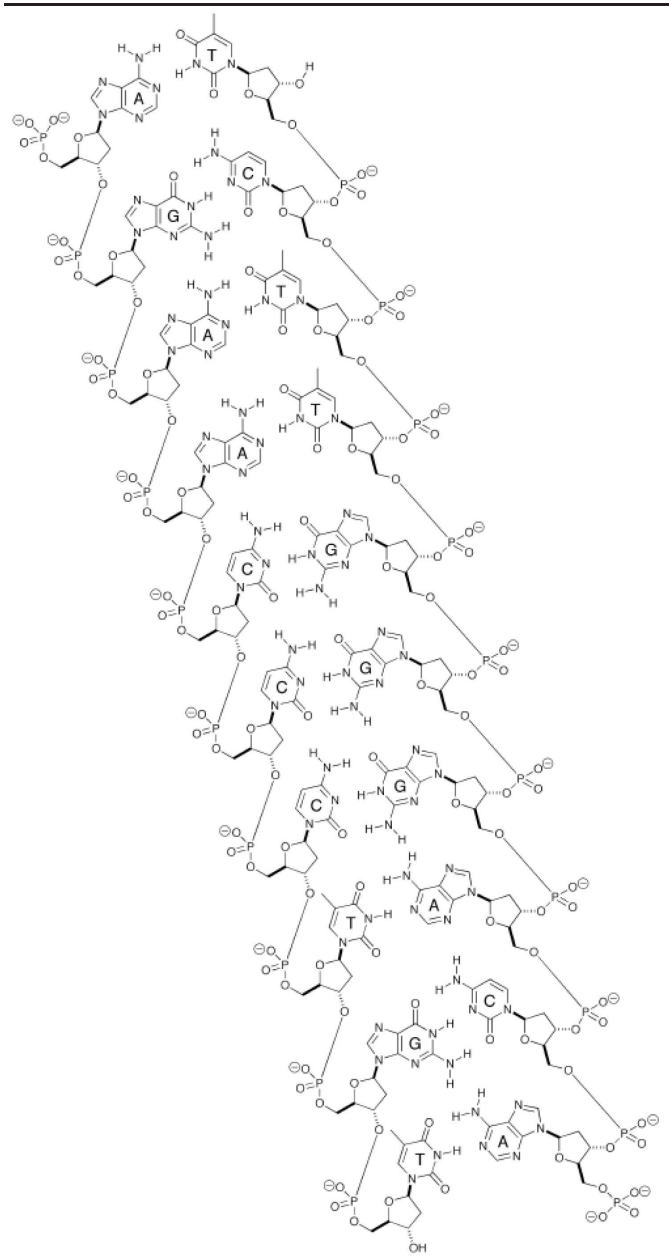
How are lesions formed?

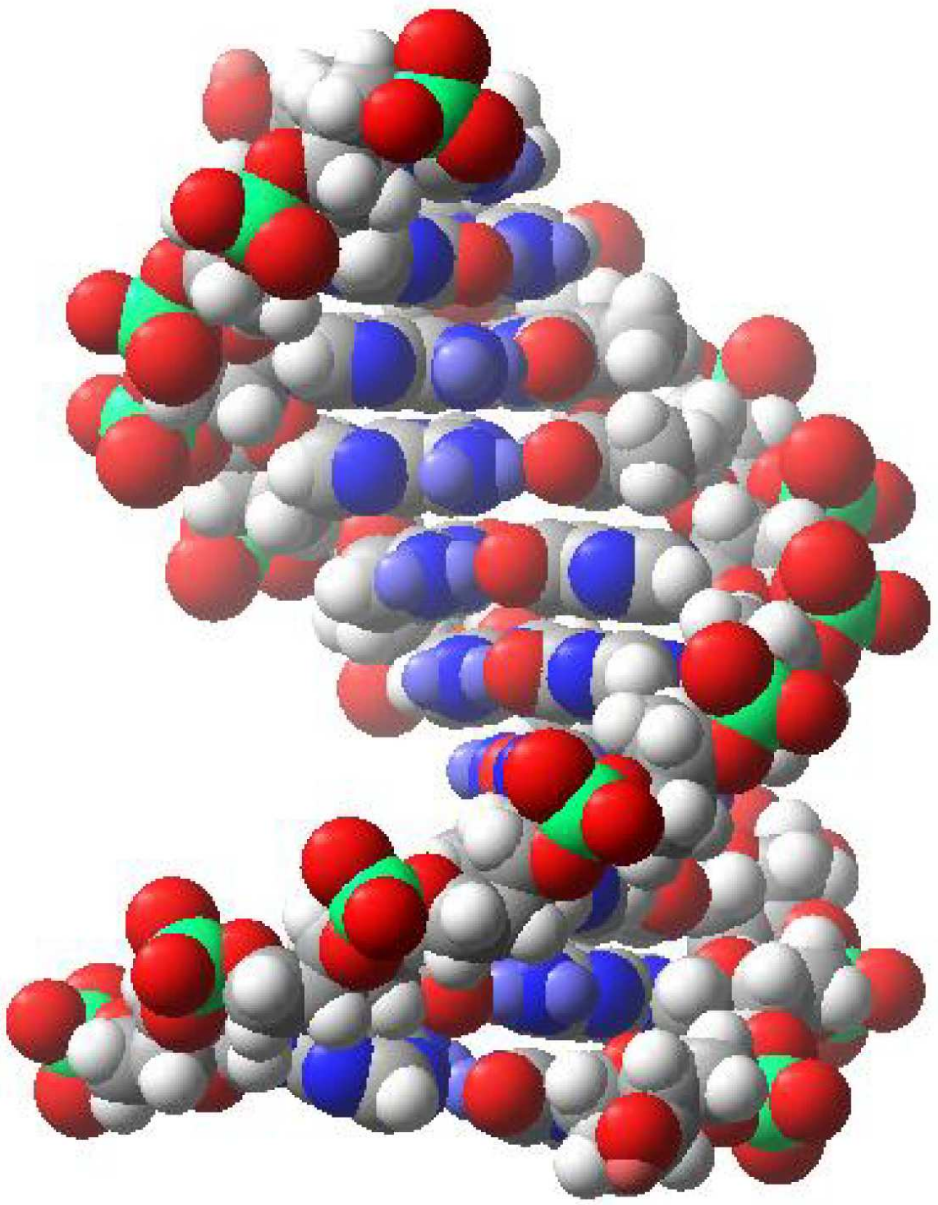
Direct impact of ionizing radiation ionization, excitation, or ions (from chemicals in the body) on DNA cause lesions.

Indirect damage can occur when ionization causes a water radical to form.
These radicals can diffuse with the cell and damage DNA.

Both the above processes occur in approximately equal proportion.

10 base pairs, schematic representation and folded realistically





Basic track structure

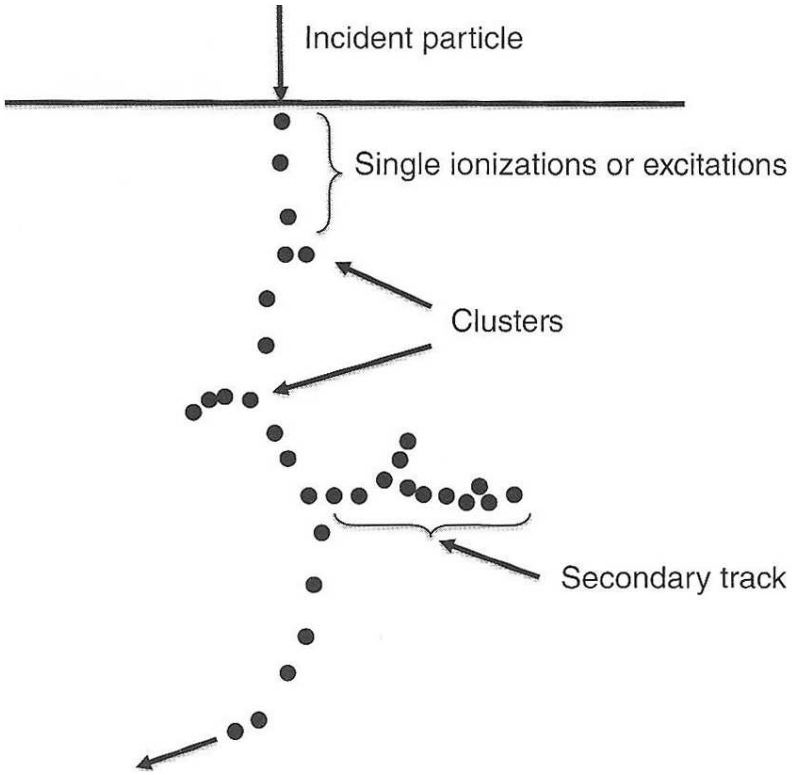
All dose is deposited by electrons in biological materials, irrespective of the incident radiation, so long as the interaction is electromagnetic in nature, *e.g.*γ, $e^{\pm}$, p, n, α and so on.

At the nanoscopic level, the interactions are stochastic in nature, governed by random interactions, setting into motion copious numbers of secondary interactions through inelastic collisions with the atoms and molecules of the target.

For example, a 1 MeV e^{-} in water loses

- 65% of its energy to initial spurs,
- 15% to blobs, and
- 20% to short tracks.

The physical stage



During $0 \rightarrow 10^{-16}$ s $(0.1$ fs$)$ the track is formed, comprised of spurs, blobs and short tracks, characterized by the energy deposited.

spurs	6	–	100	eV per event
blobs	100	–	500	eV per event
short tracks	500	–	5000	eV per event

Above 5000 eV, the tracks are considered to be independent. (Also, much rarer.)

The physical stage

Inside the spurs, blobs and short tracks are also comprised of spurs, the initial events that trigger the later chemical reactions are caused by inelastic collisions between water molecules and electrons.

$H_2O \longrightarrow H_2O^+ + e^-$: ionization of water
$H_2O \longrightarrow H_2O^*$: molecular excitation

Early chemical reactions

During $\approx 10^{-16}\mathrm{s} \rightarrow 10^{-12}$ s (1 ps)

Pre-diffusion

$$
\begin{array}{lcllcll}
 & e^- & \longrightarrow & e^-_{\mathrm{aq}} & & & : \text{formation of solvated electron and thermalization} \\
H_2O^+ + & H_2O & \longrightarrow & H_3O^+ & + & OH & : \text{formation of hydronium radical and hydroxyl} \\
 & H_3O^+ & \longrightarrow & H^+ & + & H_2O & : \text{dissociation of hydronium radical} \\
 & H_2O^* & \longrightarrow & H & + & OH & : \text{formation of hydrogen and hydroxyl}
\end{array}
$$

At the end of the early chemical reaction phase, diffusion starts. An e^- moves about 2 nm before thermalizing and transforming into an e^-_{aq}, while the H and OH have moved about 2 molecular diameters, 0.5 nm apart apart.

The width of a DNA molecule is from 2–12 nm.
The width of a water molecule is 0.275 nm.

Diffusion and spur chemistry

During $\approx 10^{-12}\mathrm{s} \rightarrow 10^{-7}$ s the spur expands while undergoing numerous chemical reactions. The most important ones are:

$$
\begin{aligned}
H + H &\longrightarrow H_2 && : \text{hydrogen molecule formation} \\
H + OH &\longrightarrow H_2O && : \text{recombination} \\
OH + OH &\longrightarrow H_2O_2 && : \text{peroxide formation} \\
e^-_{\mathrm{aq}} + OH &\longrightarrow OH^- && : \text{hydroxide formation} \\
e^-_{\mathrm{aq}} + H^+ &\longrightarrow H + H_2O && : \text{recombination}
\end{aligned}
$$

During this diffusion phase, many of the chemical species are being returned to water, though reactants are still being produced. It is during this phase that much of the DNA damage is occurring.

The end of this phase ends the notion of independent spurs, as now spurs are beginning to overlap (in condensed materials).

$G(x)$-values

At 10^{-7} s spur is mature, though chemistry still proceeds as above.

At the time, the species produced are described as follows:

G(species)	Number of species per 100 eV
$G(e^-_{\mathrm{aq}})$	2.7
$G(\mathrm{H}^+)$	2.8
$G(\mathrm{H})$	0.55
$G(\mathrm{H_2})$	0.45
$G(\mathrm{OH}^-)$	0.1
$G(\mathrm{OH})$	2.75
$G(\mathrm{H_2O_2})$	0.7

Note that the G values change with time as well as the quality of radiation that started the chemical reactions.

All of the chemical species participate in the disruption of DNA, described below.

DNA disruption, repair and mis-repair

The DNA in **every cell** in our body is disrupted (one lesion) on average **once per second**.

The disruptions are caused by natural in unnatural radiation in the our environments, and will as from the 70,000 harmful ingredients we consume each day.

These are faithfully repaired within 5 minutes.

Double lesions, even those within 10 base pairs are also repaired, mostly.

Occasionally, double lesions are mis-repaired.

These DNA may reproduce, but are usually harmless.

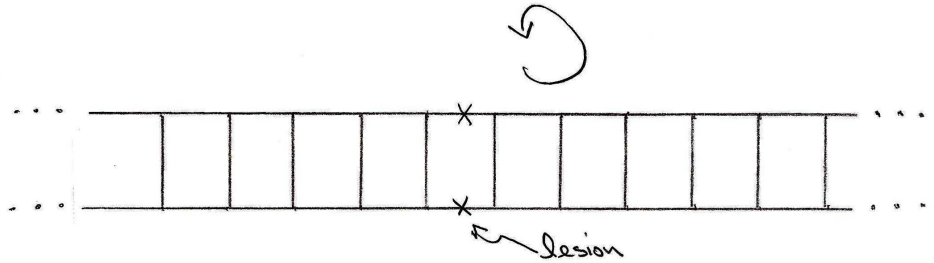
Very occasionally, the mis-repair generates a cancerous cell (oncogenesis).

Three lesions usually lead to non-viable DNA, but can also lead to oncogenesis.

Mis-repairs on multiple lesions less than 10 base pairs apart

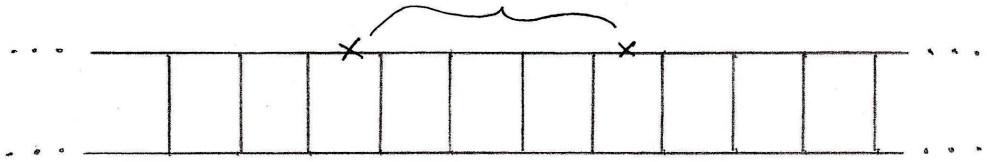
2 lesions on different sides

flips and reattaches



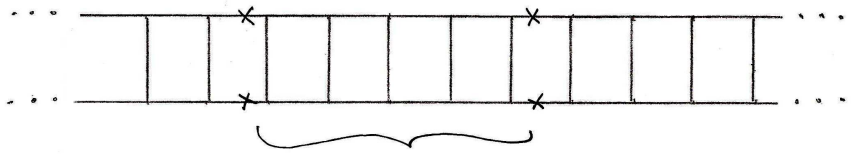
2 lesions on the same side

breaks off, flips and reattaches



4 lesions

breaks away, reorients, and attaches



Mis-repairs on two lesions less than 10 base pairs apart

Rarely, one of these bad repairs leads to a cell that is viable (lives, can reproduce), but it is not functionally useful to the collective.

Reproducing, without check, leads to cancer. (oncogenesis)

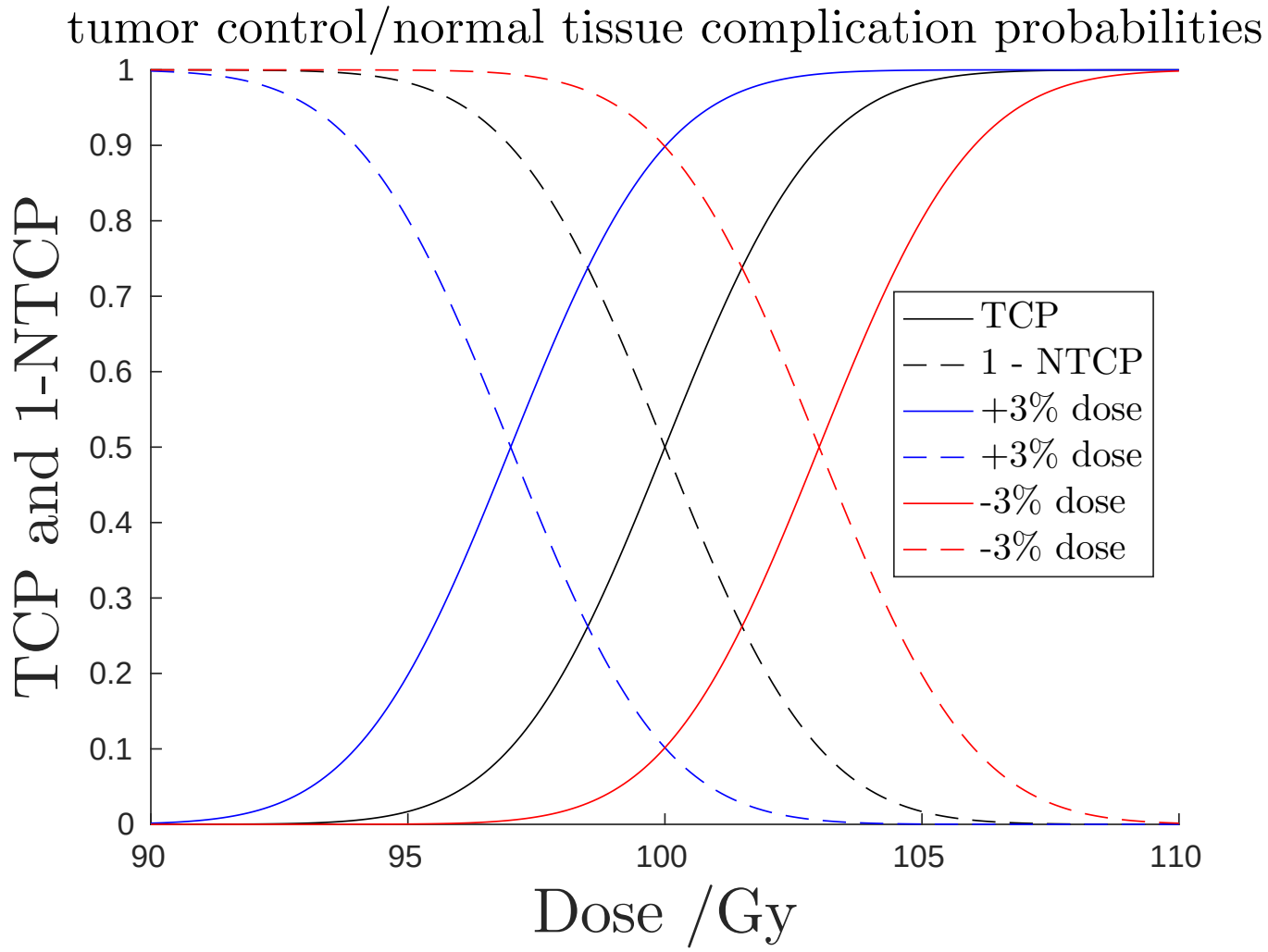
Radiotherapy, an important branch of medical physics, aims to kill cancer cells, using beams of particles (usually bremsstrahlung photons, but high energy electrons, protons, α-particles, and heavy ions are used as well) directed at cancerous tumors.

Healthy cells are killed (meaning that they cease to reproduce) as well.

It is a very delicate balance.

3% wrong dose has therapeutic outcomes:
3% too high $\Longrightarrow$ normal tissue complication
3% too low $\Longrightarrow$ cancer not eradicated, will grow back
Some nomenclature:
Tumor Control Probability (TCP) (higher $\Longrightarrow$ better clinical outcomes)
Normal Tissue Complication Probability (NTCP) (higher $\Longrightarrow$ worse clinical outcomes)
1 - NTCP, opposite of NTCP, what is plotted below (higher $\Longrightarrow$ better outcomes)

That delicate balance



If the prescribed dose (100 Gy) is exact, then, in this depiction, there is equal probability of cure and damage, dose 3% too high, the probabilities change to cure/damage = 0.9/0.10, 3% too low, cure/damage = 0.1/0.90.

What this course is all about

Clearly, *dosimetry i.e.* measurement of radiation is critical, and **that** is what this course is all about.

The topics covered:

1. Dosimetry
2. Definition and applications of *fluence*, as well as other radiometric quantities, *e.g. kerma*, *exposure* and *dose*
3. Definition and applications of *radiation equilibrium*
4. How to think about radiation microscopically (radiation physics, radiation interactions)
5. How kerma, exposure and dose are measured
6. How hospitals (and other industrial users of radiation) guarantee the consistency of their dose delivery
   - *i.e.* How the international community of radiation users have agreed on standards
   - How it is measured absolutely in National Standards' Laboratories
   - How the absolute measurement gets transmitted to Secondary Standards Dosimetry Laboratories (SSDLs), hospitals and other users

Radiation "Quality"

Radiation *quality* refers to:

- the particle species (γ, $e^{\pm}$, p, n, α-particle, π $\cdots$) in a radiation *field*. The jargon *field* means that there are so many particles, that their distributions are assumed to be continuous (allowing deterministic mathematical developments to be developed using calculus) (calculus is a very useful fiction) (spacetime is not continuous!)
- their distributions in energy
- spatial distribution (collimation, perhaps)
- angular distributions
- temporal distributions (if any)

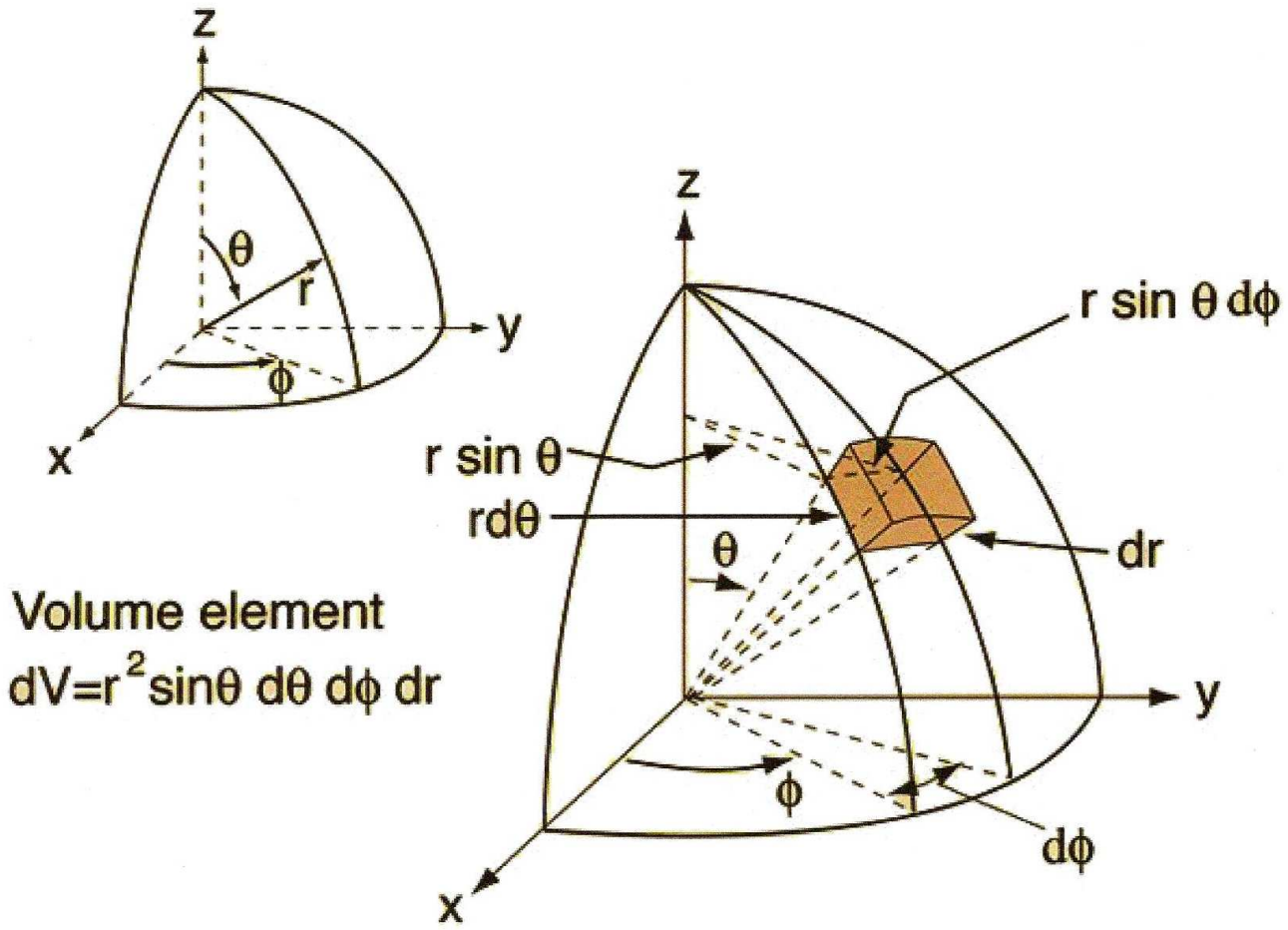
Radiation quality is represented by a macroscopic, continuous function:

$n_i(\vec{x}, \vec{\Omega}, E)$ (we will ignore time, since most of our applications do not employ it), where:

i	:	particle index indicating species (γ, $e^{\pm} \cdots$)
$\vec{x}$	:	space vector for position in space
$\vec{\Omega}$	:	direction vector, $\vec{\Omega} = (u, v, w) = (\sin\theta\cos\phi, \sin\theta\sin\phi, \cos\theta)$
θ	:	polar angle, $0 \leq \theta \leq \pi$, $\hat{z} \cdot \vec{x} = r\cos\theta = z$
ϕ	:	azimuthal angle, $0 \leq \phi \leq 2\pi$
E	:	kinetic energy, usually expressed in MeV or keV

Solid angle, polar coordinates

Definitions used in the rest of this course:



Dosimetry

is the science of the measurement of *dose* in a radiation field because dose is an excellent predictor of radiological damage. Dose has units E/M and is given in J/kg. Dosimetry can also refer to measurements of other radiometric quantities, such as *kerma*, or *exposure* (defined later).

Given a detector with dose response function $d_i(\vec{x}, \vec{\Omega}, E)$, we may write a symbolic equation for the dose measured, D, as:

$$D = \mathcal{N} \otimes \mathcal{D} \equiv \sum_{i=1}^{N_\mathrm{p}} \int_{\mathcal{D}} \mathrm{d}\vec{x}\, \mathrm{d}\vec{\Omega}\, n_i(\vec{x}, \vec{\Omega}, E) d_i(\vec{x}, \vec{\Omega}, E)$$

where N_p is the number of particle species that the detector is sensitive to, and the integral is over the volume of space and the radiation direction in the sensitive volume of the detector, $\mathcal{D}$. In the compact form, $\mathcal{N} \Rightarrow$ radiation quality, $\mathcal{D} \Rightarrow$ detector response, and $\otimes \Rightarrow$ sum and integration above.

There are two branches of calibration dosimetry, absolute and indirect.

Absolute dosimetry

Absolute dosimetry measures dose directly and absolutely.

Absolute dosimetry is only done in Primary Standards Dosimetry Laboratories (PSDLs), such as the USA's National Institutes of Standards and Technology or Canada's National Research Council of Canada (NRCC).

These two countries fully respect each other's absolute dosimetry standards, so that clients in both countries can utilize the services of either.

The national institutions maintain radiation *standards*. These "standards" really refer to the devices (ionization chamber, for example) that are extremely well characterized.

The radiation beams at PSDLs are not perfectly known (though they have a really good idea, particularly e^- beams. So, through a complete understanding of $\mathcal{D}$, they determine D to an absolute accuracy of about 0.5%. The cost of maintaining absolute standards are quite high, and the value of such importance to welfare and commerce, that these efforts are undertaken by governments.

Reference dosimetry

Reference dosimetry is a less expensive way of determining dose from, say, a linear accelerator in a hospital setting. Neither the hospital's radiation measuring device is all the well characterized, nor the $n()$ from its accelerators. With the assistance of NRLs or SSDLs, absolute dosimetry can be achieved through comparison with the national standard.

There are several two very interesting models for achieving this.

The itinerant primary standard model ...

The national standard instrument travels from hospital to hospital!

The standard detector, labeled $\mathcal{D}_{\rm S}$ and the hospital's secondary standard detector, labeled $\mathcal{D}_{\rm H}$, are both exposed to identical beams at the hospital facility, beams that are typical of those used in cancer therapy treatments.

The standard chamber gives absolute dose, and the ratio of the two doses, allows a measurement of dose in the hospital beam, to be referred back to the primary standard. First the calibration is performed:

$$D_{\rm S} = \mathcal{N}_{\rm H} \otimes \mathcal{D}_{\rm S} \quad \textit{(dose to the standard instrument in the hospital's beam)}$$
$$D_{\rm H} = \mathcal{N}_{\rm H} \otimes \mathcal{D}_{\rm H} \quad \textit{(dose to the hospital secondary standard in the hospital's beam)}$$
$$C = \frac{\mathcal{N}_{\rm H} \otimes \mathcal{D}_{\rm S}}{\mathcal{N}_{\rm H} \otimes \mathcal{D}_{\rm H}} \quad \textit{(calibration factor relating the two)}$$

The power of this approach is that C is only weakly dependent on the radiation quality of the hospital beam.

... The itinerant primary standard model ...

When the secondary instrument is used for routine calibration of the hospital beam, the following measurement is performed:

$\mathcal{N}'_{\rm H} \otimes \mathcal{D}_{\rm H}$ *(hospital instrument measured in the hospital's beam)*

$$\mathcal{N}'_{\rm H} \otimes \mathcal{D}_{\rm H} = \mathcal{N}'_{\rm H} \otimes \mathcal{D}_{\rm H} \left[\frac{\mathcal{N}'_{\rm H} \otimes \mathcal{D}_{\rm S}}{\mathcal{N}'_{\rm H} \otimes \mathcal{D}_{\rm S}} \right] \quad \textit{(multiplied by unity)}$$

$$\mathcal{N}'_{\rm H} \otimes \mathcal{D}_{\rm H} = \mathcal{N}'_{\rm H} \otimes \mathcal{D}_{\rm S} \left[\frac{\mathcal{N}'_{\rm H} \otimes \mathcal{D}_{\rm H}}{\mathcal{N}'_{\rm H} \otimes \mathcal{D}_{\rm S}} \right] \quad \textit{(reorganized)}$$

$$\mathcal{N}'_{\rm H} \otimes \mathcal{D}_{\rm H} = \mathcal{N}'_{\rm H} \otimes \mathcal{D}_{\rm S} \left[\frac{1}{C'} \right] \quad \textit{(C' is very close to the calibration factor C)}$$

Thus,

$$\begin{aligned} D' &= C' \left[\mathcal{N}'_{\rm H} \otimes \mathcal{D}_{\rm H} \right] \\ &\approx C \left[\mathcal{N}'_{\rm H} \otimes \mathcal{D}_{\rm H} \right] \ \textit{(C can replace C'since C' is very close to the calibration factor C)} \end{aligned}$$

The interpretation of the above equation is that $\mathcal{N}'_{\rm H} \otimes \mathcal{D}_{\rm S}$ is a prediction of the response of the hospital chamber in the PSDLs beam (that we call D'), referenced absolutely to the PSDLs standard chamber's measurement in the hospital's beam via a correction factor.

... The itinerant primary standard model

Advantages

- Most direct
- Simplest

Disadvantages

- Cost
- Risk to the primary standard instrument
- Variability of clients' laboratories

No one uses this approach anymore, though New Zealand had a close approximation to it.

The itinerant secondary standard model ...

This is the way most of the world does it now.

In this case, the hospitals ship their internal secondary standard instrument to the PSDL. The PSDL does a direct comparison of the customer's instrument with the primary standard, and provides a calibration factor, $C_{\rm S}$:

$$C_{\rm S} = \frac{\mathcal{N}_{\rm S} \otimes \mathcal{D}_{\rm S}}{\mathcal{N}_{\rm S} \otimes \mathcal{D}_{\rm H}}$$

that is, the ratio of the primary standard over the customer's secondary standard.

When the hospital is doing its routine calibrations, it makes the following measurement:

$$\mathcal{N}_{\rm H} \otimes \mathcal{D}_{\rm H} \qquad \textit{(hospital instrument measured in the hospital's beam)}$$

$$\mathcal{N}_{\rm H} \otimes \mathcal{D}_{\rm H} \; = \; \mathcal{N}_{\rm H} \otimes \mathcal{D}_{\rm S} \left[\frac{\mathcal{N}_{\rm H} \otimes \mathcal{D}_{\rm H}}{\mathcal{N}_{\rm H} \otimes \mathcal{D}_{\rm S}} \right] \qquad \textit{(multiplied by unity)}$$

Identify $D = \mathcal{N}_{\rm H} \otimes \mathcal{D}_{\rm S}$ as the dose since it refers $M_{\rm H} = \mathcal{N}_{\rm H} \otimes \mathcal{D}_{\rm H}$, the hospital measurement to the PSDL standard.

... The itinerant secondary standard model

Reorganizing,

$$
\begin{aligned}
D &= M_{\mathrm{H}} \left[\frac{\mathcal{N}_{\mathrm{H}} \otimes \mathcal{D}_{\mathrm{S}}}{\mathcal{N}_{\mathrm{H}} \otimes \mathcal{D}_{\mathrm{H}}} \right] \\
&= C_{\mathrm{S}} M_{\mathrm{H}} \left[\left[\frac{\mathcal{N}_{\mathrm{H}} \otimes \mathcal{D}_{\mathrm{S}}}{\mathcal{N}_{\mathrm{H}} \otimes \mathcal{D}_{\mathrm{H}}} \right] \Bigg/ \left[\frac{\mathcal{N}_{\mathrm{S}} \otimes \mathcal{D}_{\mathrm{S}}}{\mathcal{N}_{\mathrm{S}} \otimes \mathcal{D}_{\mathrm{H}}} \right] \right] \quad \textit{(multiplied and divided by } C_{\mathrm{S}}\textit{)} \\
&= C_{\mathrm{S}} M_{\mathrm{H}} \left[\left[\frac{\mathcal{N}_{\mathrm{H}} \otimes \mathcal{D}_{\mathrm{S}}}{\mathcal{N}_{\mathrm{S}} \otimes \mathcal{D}_{\mathrm{S}}} \right] \Bigg/ \left[\frac{\mathcal{N}_{\mathrm{H}} \otimes \mathcal{D}_{\mathrm{H}}}{\mathcal{N}_{\mathrm{S}} \otimes \mathcal{D}_{\mathrm{H}}} \right] \right] \quad \textit{(reorganized)}
\end{aligned}
$$

Hence,

$$
\begin{aligned}
D &= C_{\mathrm{S}} M_{\mathrm{H}} A \quad \textit{where } A \textit{ is defined as} \\
A &\equiv \left[\frac{\mathcal{N}_{\mathrm{H}} \otimes \mathcal{D}_{\mathrm{S}}}{\mathcal{N}_{\mathrm{S}} \otimes \mathcal{D}_{\mathrm{S}}} \right] \Bigg/ \left[\frac{\mathcal{N}_{\mathrm{H}} \otimes \mathcal{D}_{\mathrm{H}}}{\mathcal{N}_{\mathrm{S}} \otimes \mathcal{D}_{\mathrm{H}}} \right]
\end{aligned}
$$

A is an additional factor, completely theoretical, that accounts for the differences in ratios of responses of the primary and secondary standard, for different hospital beams. Generally, $0.95 \leq A \leq 1.05$. It is small, but it is important.

We shall visit this factor later in the course.

International system of radiation standards (from TRS-398)

2.1. The International Measurement System

The International Measurement System (IMS) for radiation metrology provides the framework for consistency in radiation dosimetry by disseminating to users calibrated radiation instruments which are traceable to primary standards (see Fig 2.1).

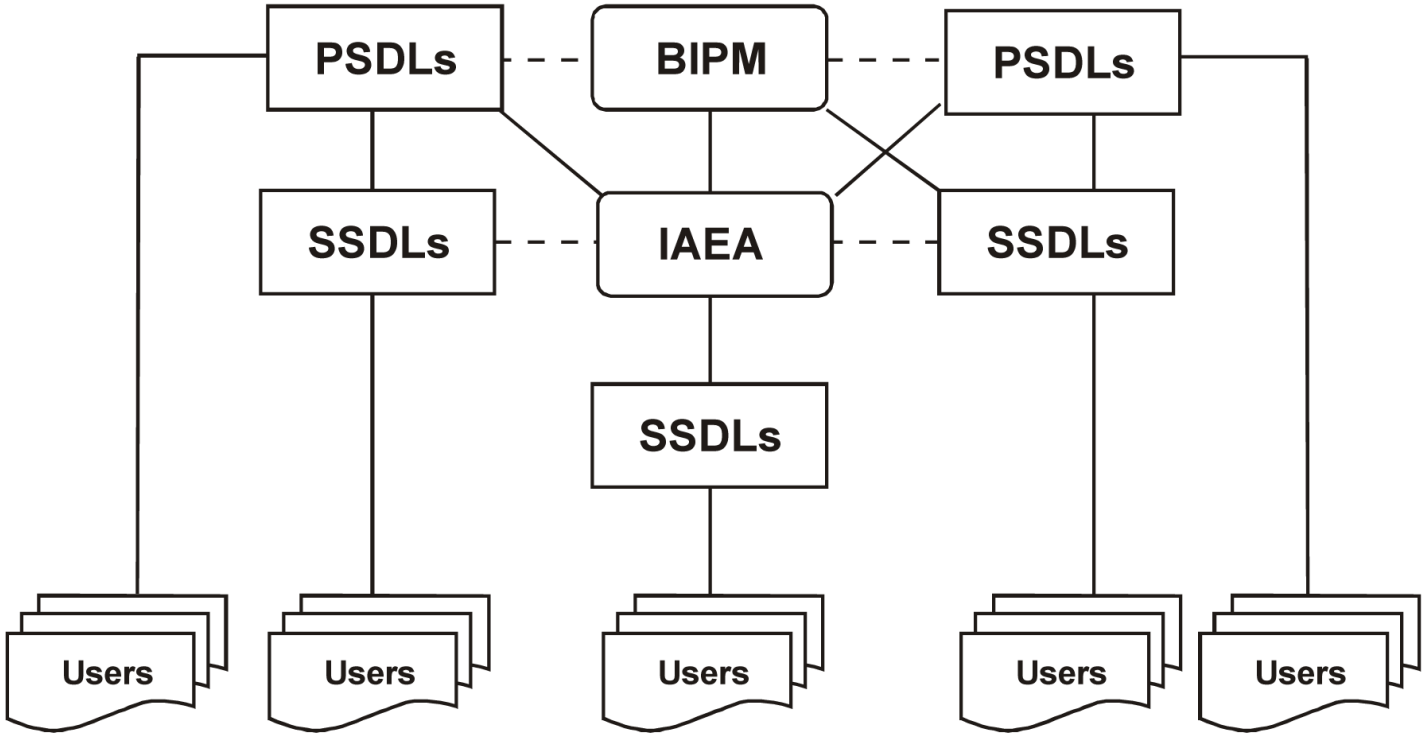


Fig 2.1. The International Measurement System (IMS) for radiation metrology, where the traceability of user reference instruments to Primary Standards is achieved either by direct calibration in a Primary Standard Dosimetry Laboratory (PSDL) or, more commonly, in a Secondary Standard Dosimetry Laboratory (SSDL) with direct link to the BIPM, a PSDL or to the IAEA/WHO network of SSDLs. Most SSDLs from countries not members of the Metre Convention achieve the traceability of their standards through the IAEA. The dashed lines indicate intercomparisons of primary and secondary standards.

Radiation species for radiotherapy and how they are produced

The "i" in previous slides have been devoted to the species of the radiation type. The ones used directly for radiotherapy are:

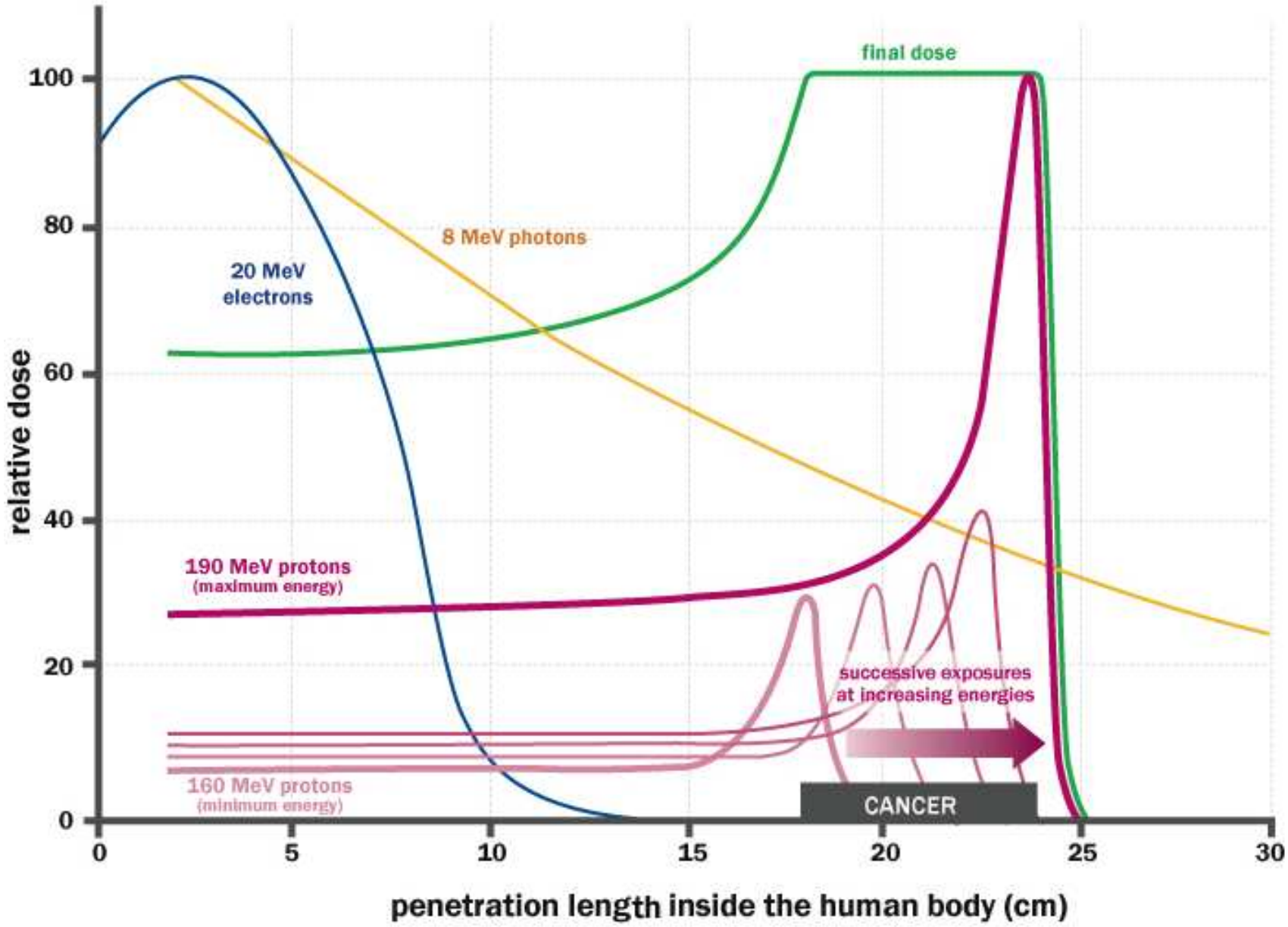
Symbol	particle names	generation method
γ	X-rays, γ-rays	Bremsstrahlung radiators (e^- induced), radioisotopes
e^-	electrons	linear accelerators (LINACs)
p	protons	Cyclotrons (mostly)
n	neutrons	Reactors, thermal and epithermal
α	alpha particles	Accelerators, and radiopharmaceutical delivery
${}^{A}\mathrm{X}$	heavy particles	Mostly ${}^{12}\mathrm{C}$ using accelerators
π^-	pion therapy	Accelerator based *a.k.a.* hadron therapy

γ's account for $\approx$ 85% of radiation treatments, while e^-'s account for $\approx$ 10%.

Hence, we shall focus on these modalities for the remainder of the course.
(Excellent web resources exist for the others.)

Energy ranges: $6 \longrightarrow 21$ MeV (most common), though
$2 \longrightarrow 50$ MeV (are/have been) in existence.

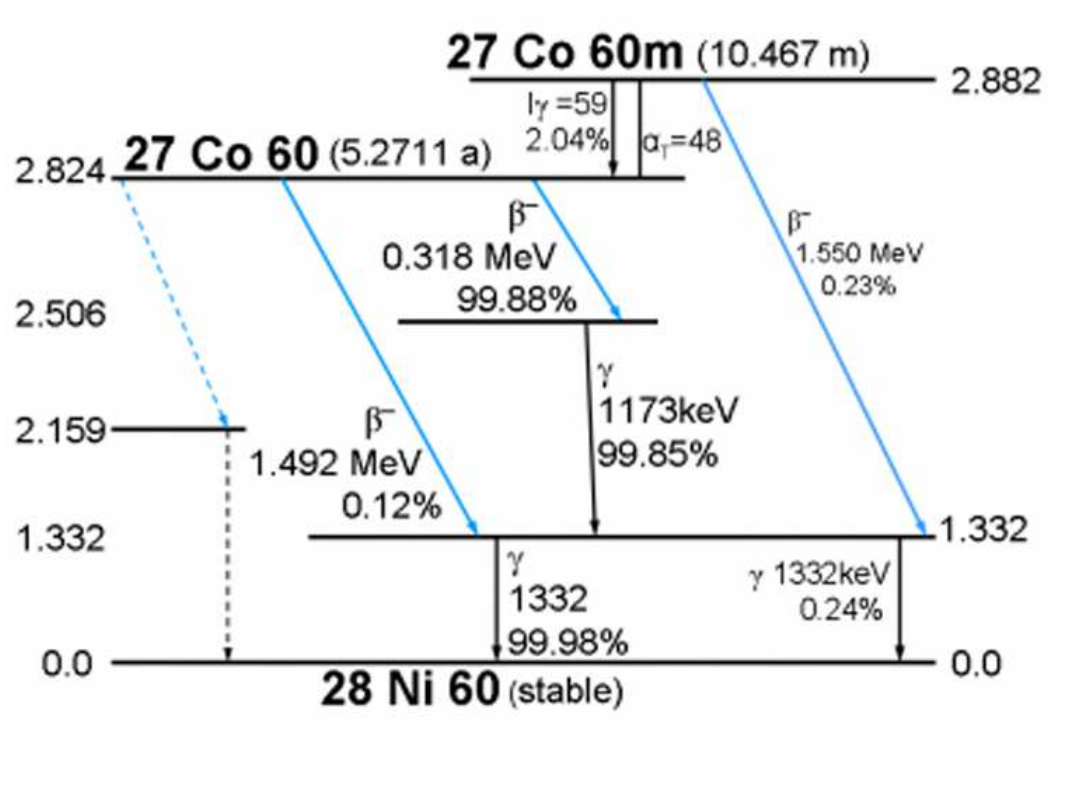
Therapeutic comparisons of γ, e^-, and p beams



^{60}Co γ beams, the nanoscopic process

Therapy-class γ photons can be produced by radioactive decay, *esp.* ^{60}Co, that has a half-life of 5.2714y.

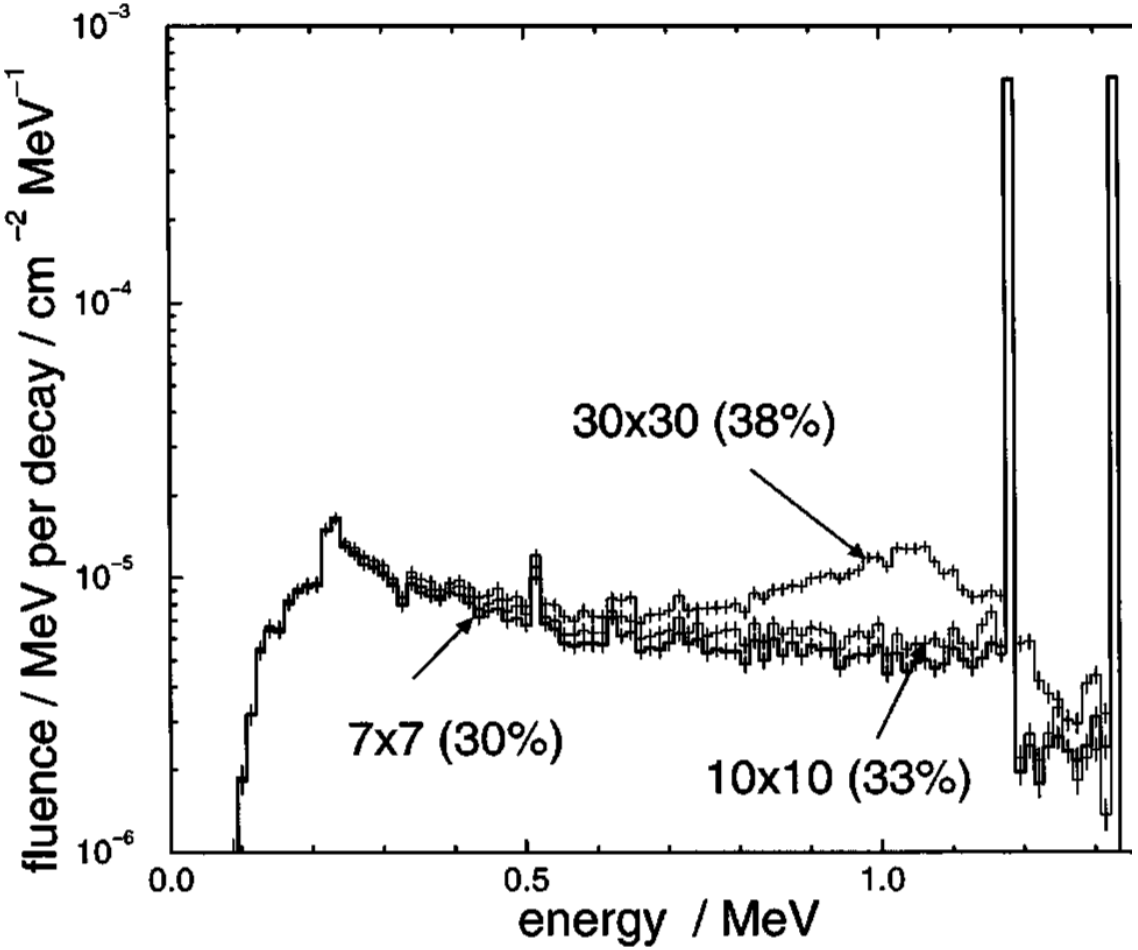
The decay scheme is:



The dominant γ-decay mode is comprised of almost equal amounts of 1.173 MeV and 1.322 MeV γs, an almost completely monoenergetic source of 1.25 MeV photons.

^{60}Co γ beams, the macroscopic process

For practical uses, ^{60}Co γs must be encapsulated, and the encapsulated source contained within a protective housing, and collimated. As shown in the figure below, there is a non-negligible continuous spectrum component that arises from internal (predominantly Compton) scatter in the encapsulation and collimation. Note the field-size dependence!

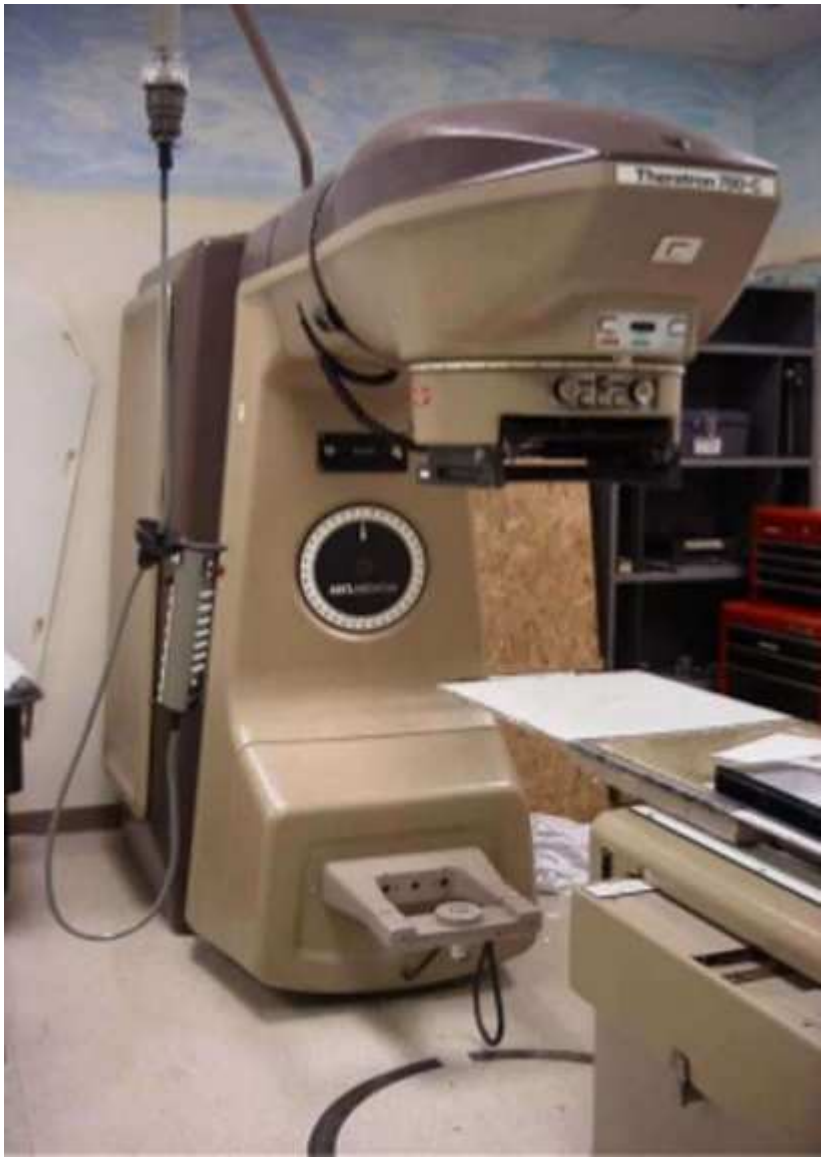


^{60}Co γ beams, historical medical delivery devices

The Theratron Junior was one of the first practical treatment devices.

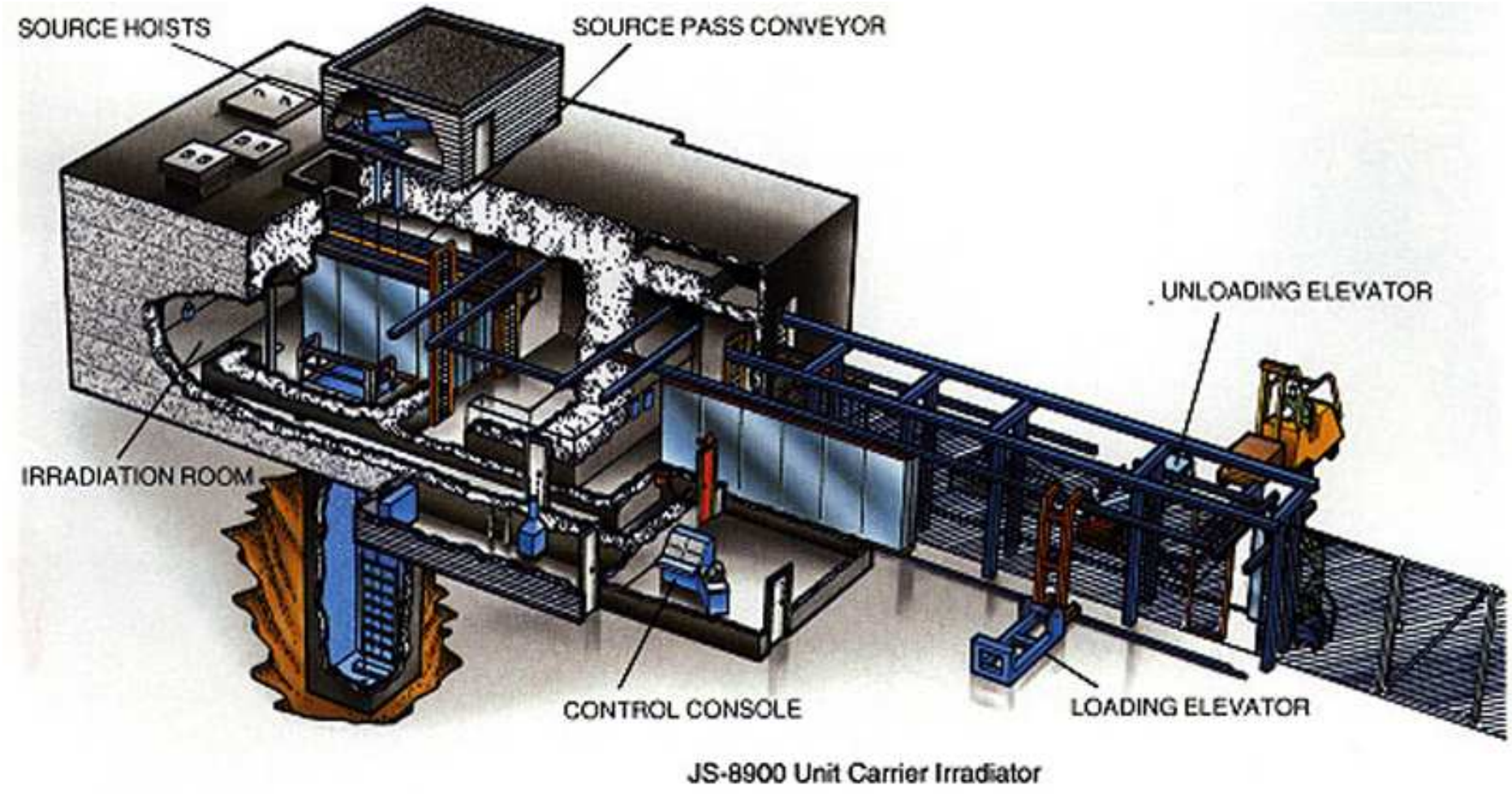
^{60}Co γ beams, modern medical delivery devices

Medical ^{60}Co irradiators evolved to a more modern appearance.



^{60}Co γ beams have other industrial uses

An industrial ^{60}Co beam irradiator sterilizer/processor:



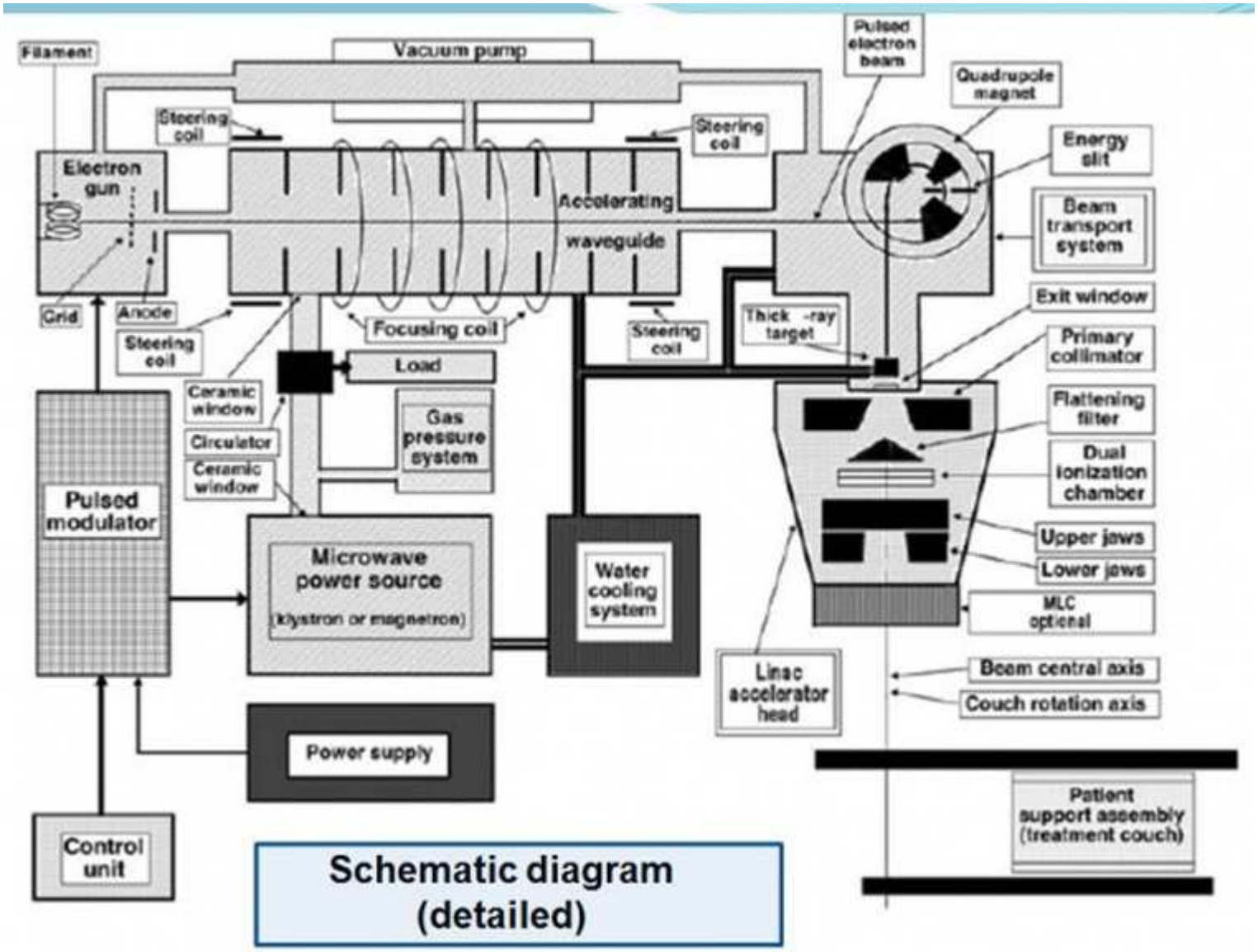
Applications: Food, medical devices, pharmaceuticals, combination drug/device products, animal husbandry, archives, cosmetics and toiletries, horticultural supplies, packaging ...

First use of a LINAC for treatment in the USA

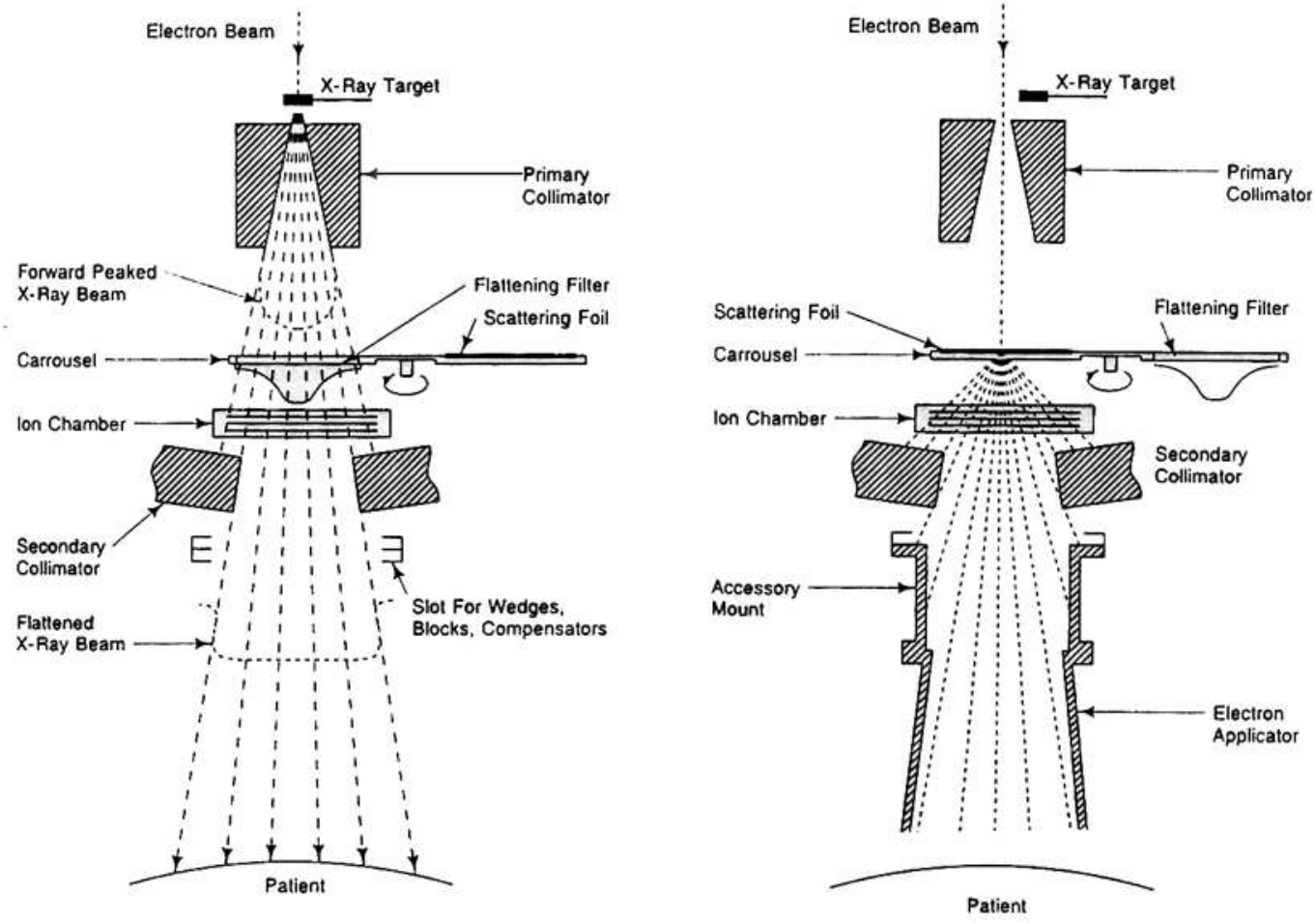
LINACs provide sources of high-energy electron and photon beams for radiotherapy.

This is the first use of a medical accelerator in the USA, at Stanford University Hospital by Dr. Henry Kaplan, in 1957. Gordon Isaacs was treated for retinoblastoma using a 6 MeV e^- beam, and his left eye retained normal vision.

Modern Medical LINAC Design



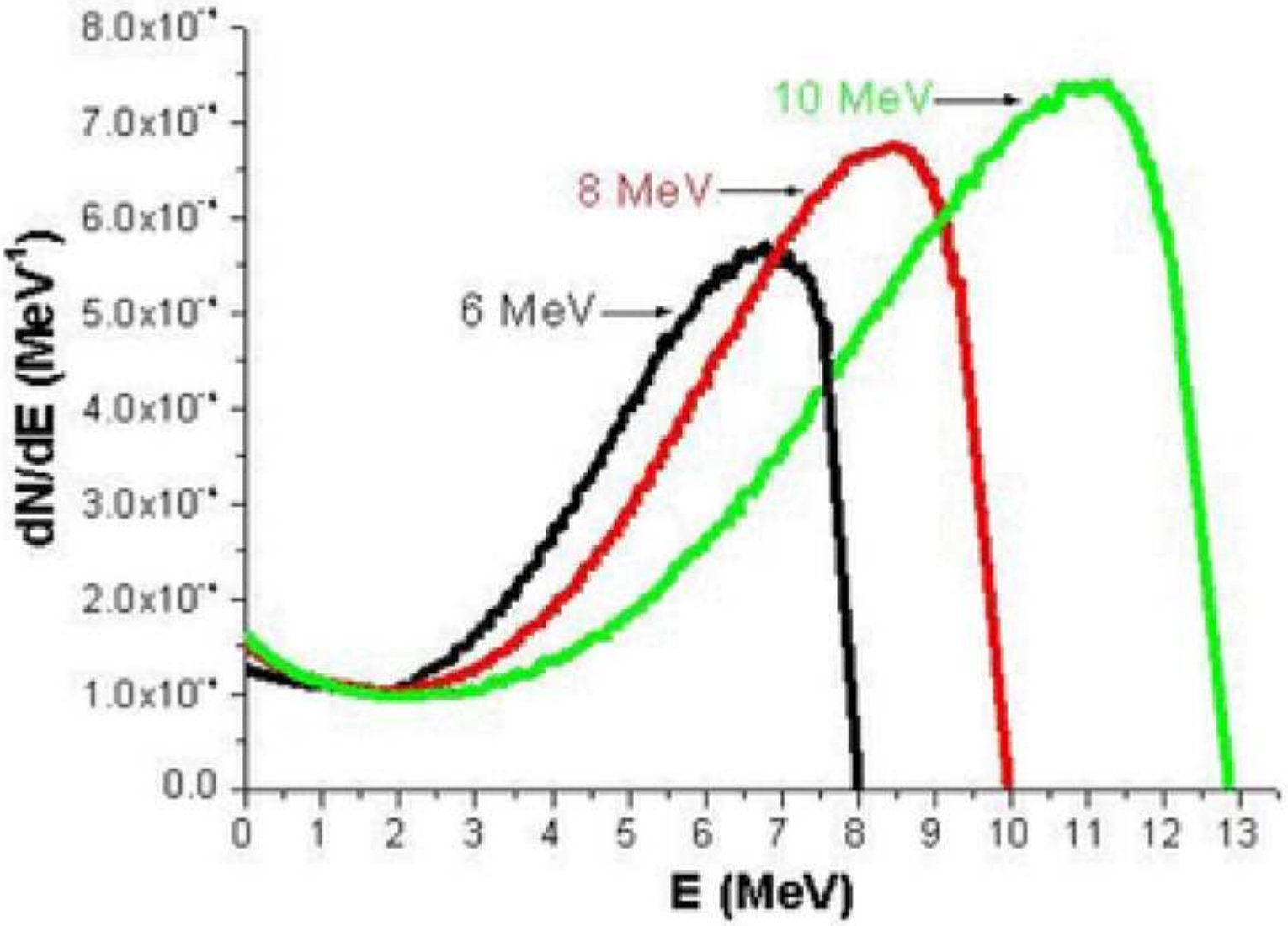
Modern Medical LINAC Collimation System



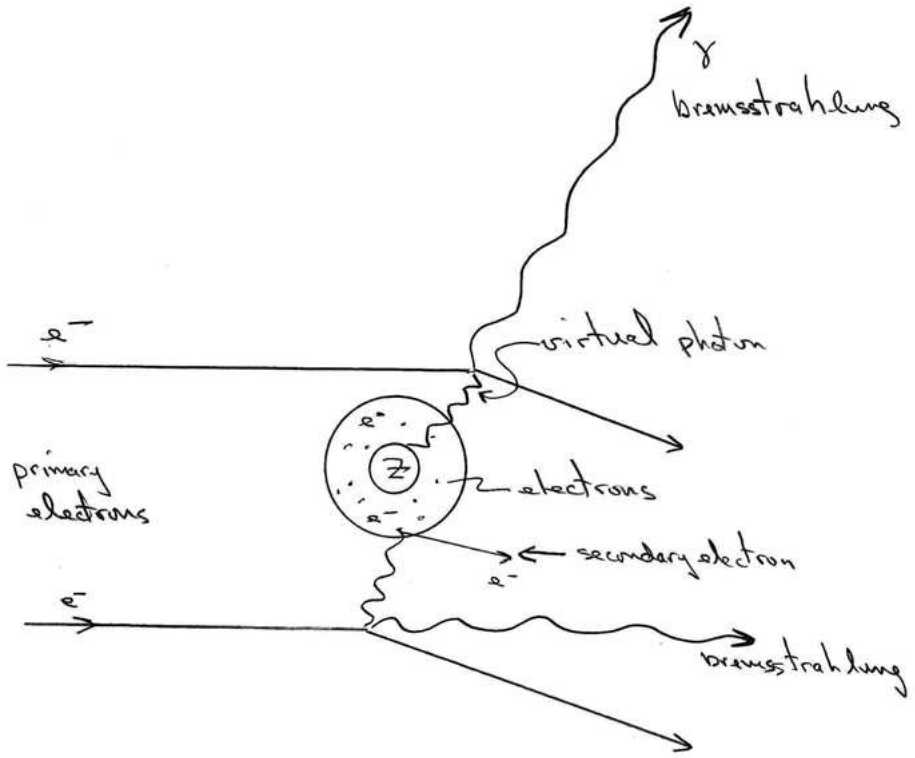
On the left is shown a schematic of a photon treatment, and on the right, an electron treatment.

e^- beams, the source for γ and e^- treatments

e^- beam that emerges from the LINAC (specifically, at the end of the collimator):



Bremsstrahlung γ beams, the nanoscopic process

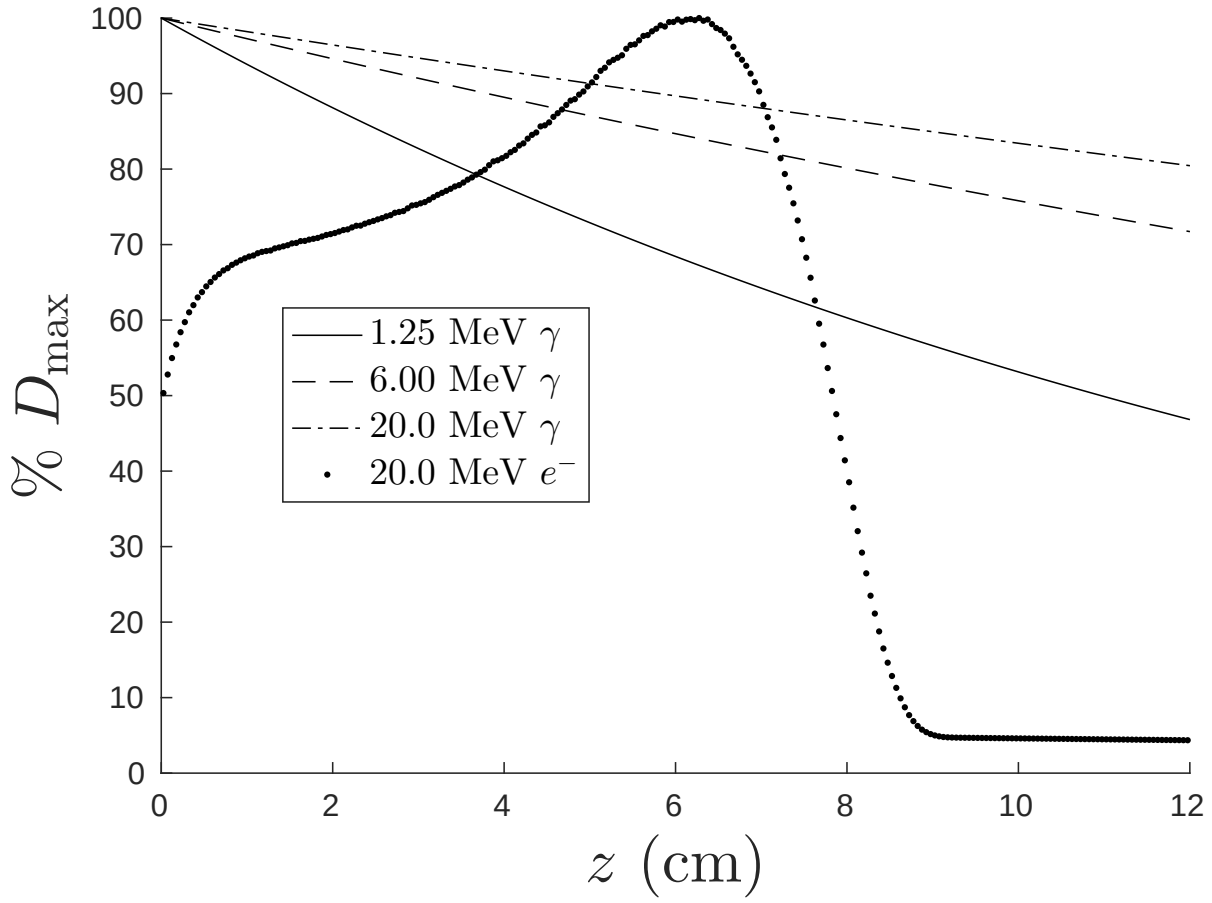


Therapy-class γ photons are produced by high-energy e^- interacting with atoms (usually in high-Z targets, *esp.* ^{74}W)

In the upper half of the figure, the dominant interaction is with the nucleus.

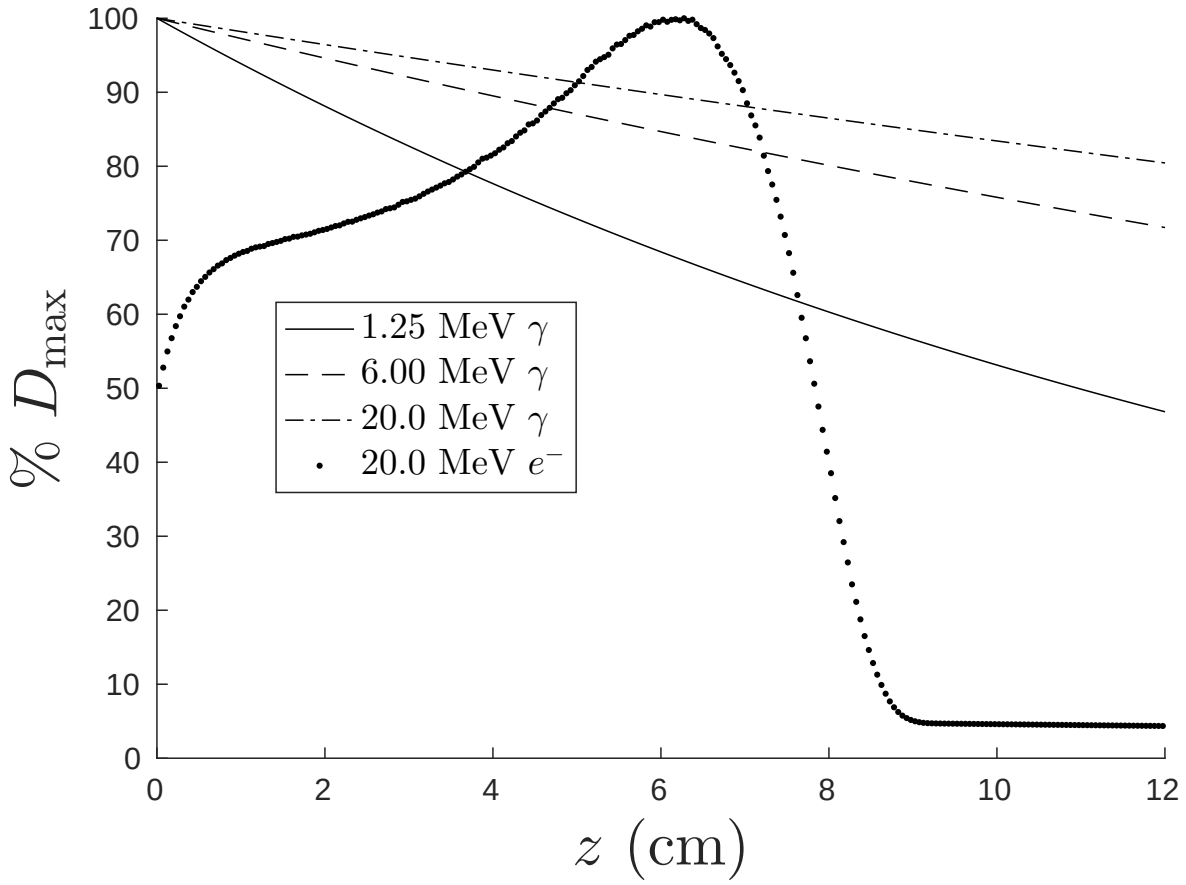
The lower half of the figure depicts a secondary source, with an atomic e^- providing the necessary recoil.

Motivation for the Development of Medical LINACs ...



In the above figure, note that for ^{60}Co source (1.25 MeV), about half the beam has attenuated by 12 cm, risking surface dose to health tissue for deep-seated tumors. LINACs can better this by producing higher dose fractions deeper in the patient.

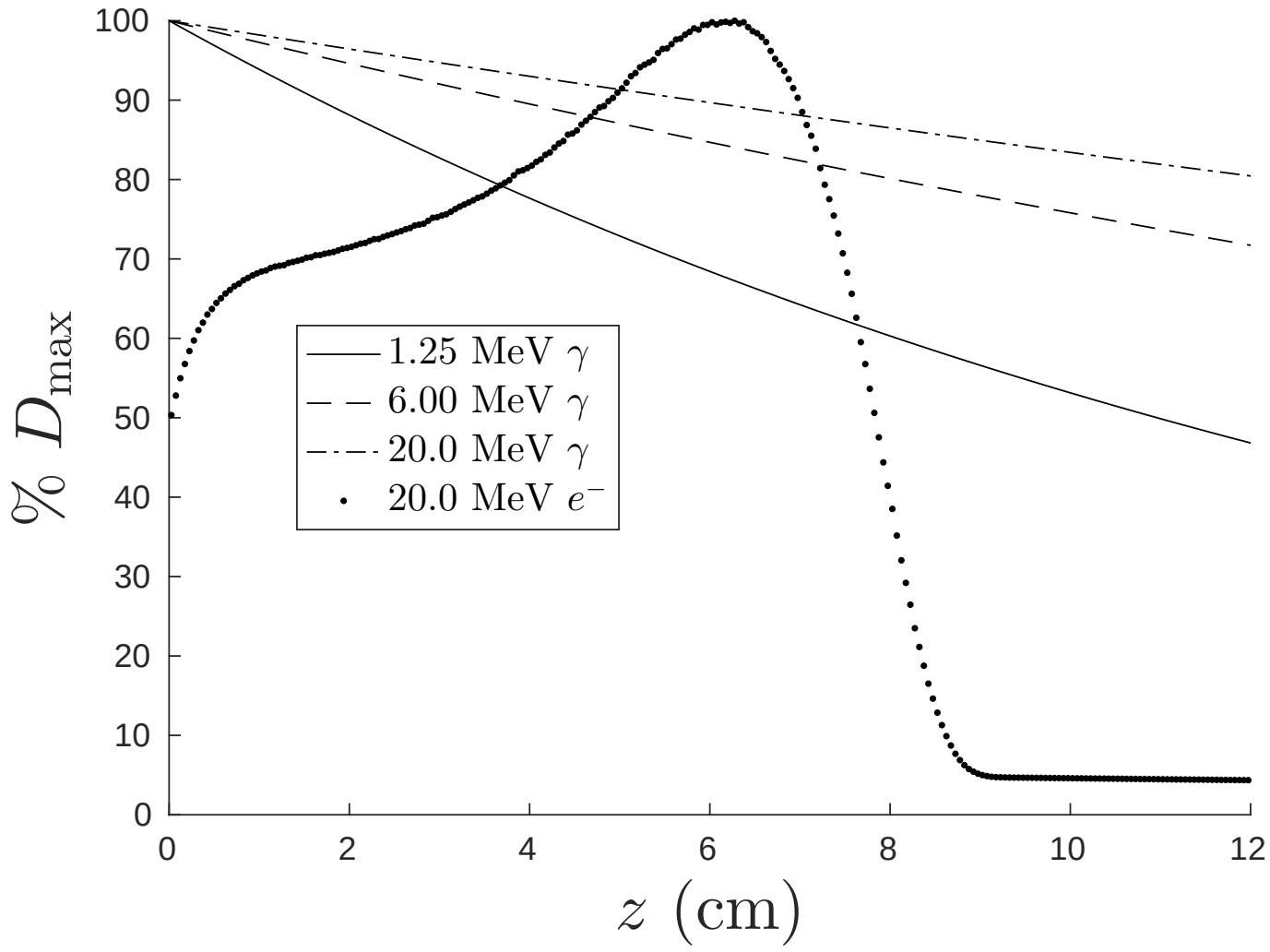
... Motivation for the Development of Medical LINACs ...



The mean-free paths for the 3 photon qualities are:

monoenergetic γ energy (MeV)	mean free path in water (cm)
1.25	15.82
6.00	36.10
20.0	55.16

... Motivation for the Development of Medical LINACs

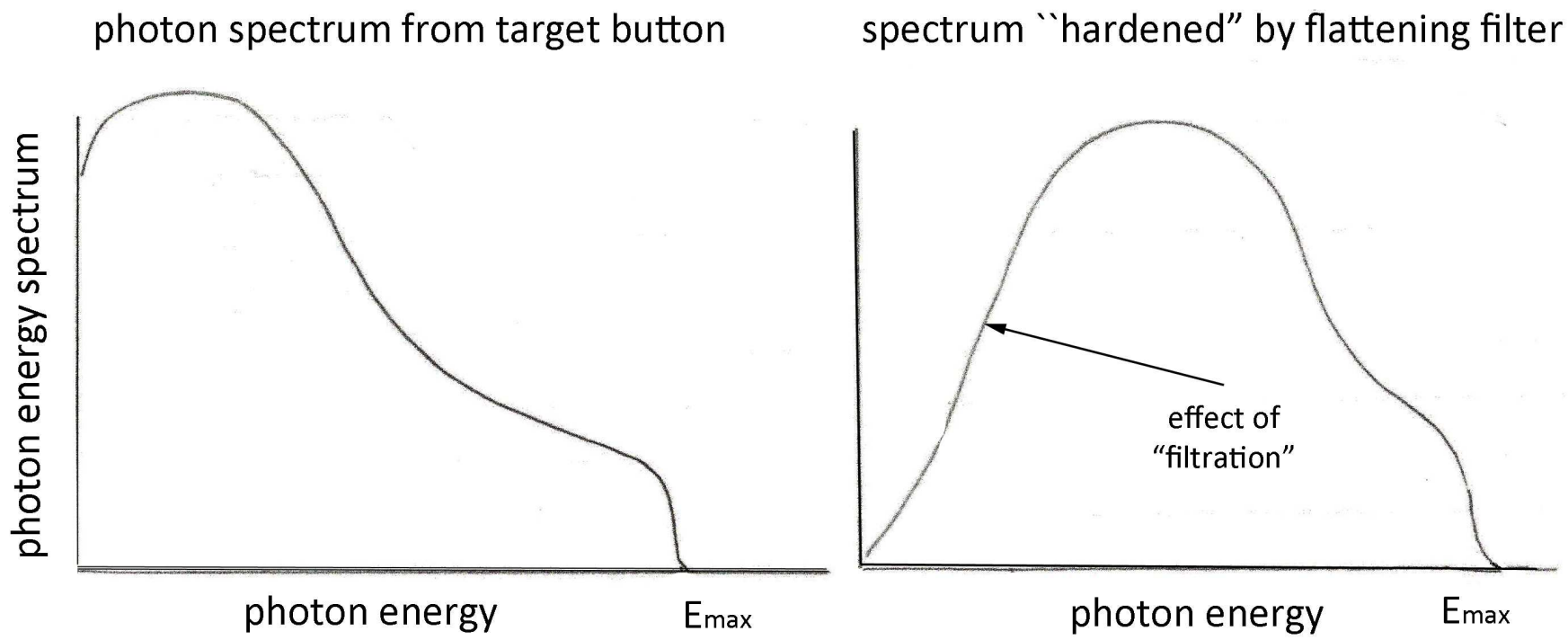


Electron beam have a finite range, about 10 cm in water for 20 MeV. They can be used effectively for shallow tumors, and spare healthy tissue beyond the electron range.

Modern Medical LINAC Installation

Location: Lahey Medical Center, Peabody, Massachusetts

Beam "hardening" ...

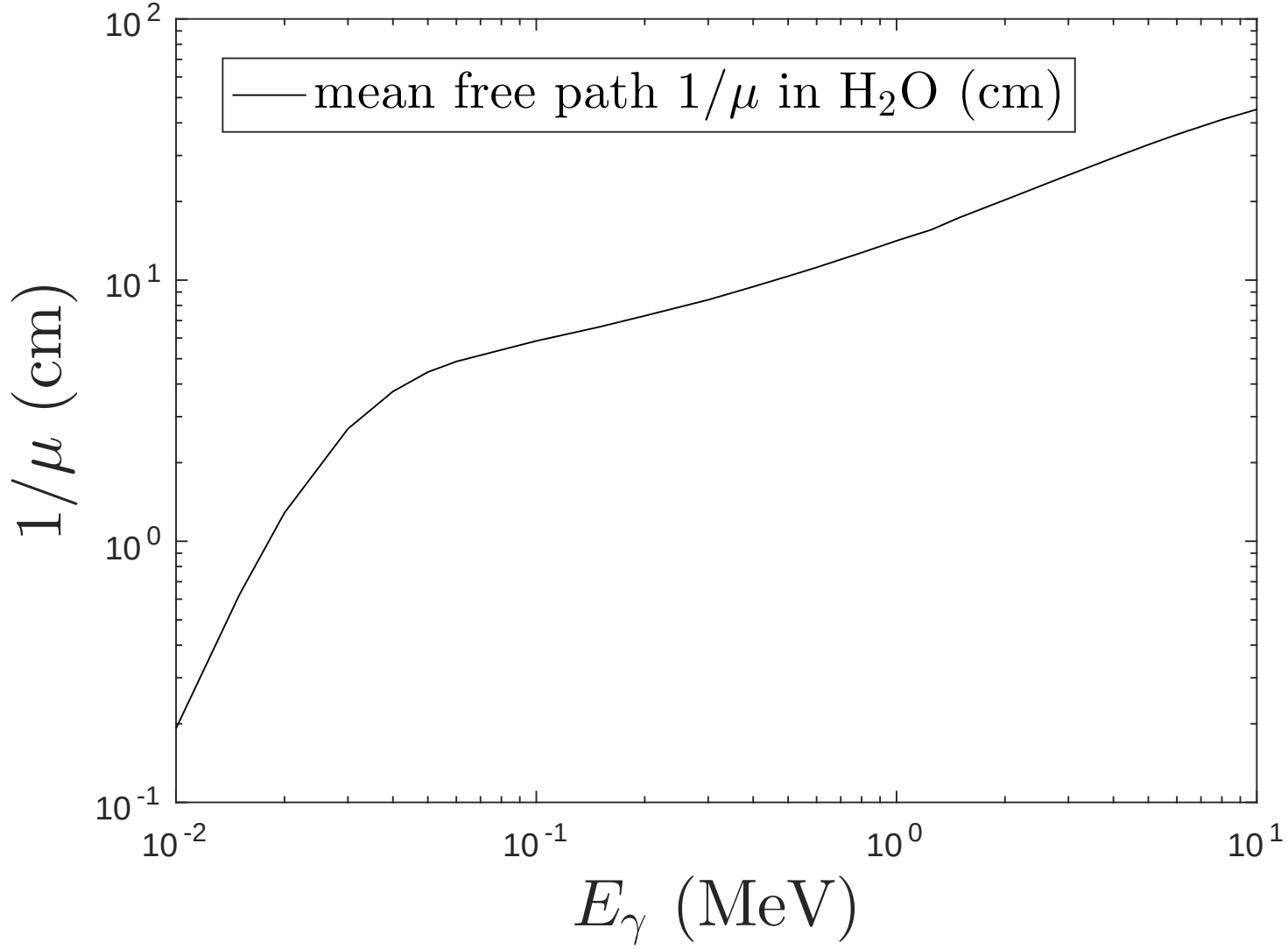


Photon beams "harden" as they go through material because lower energy photons are attenuated more in the attenuation law:

$$I(z) = I_0 e^{-\mu z}$$

where $I(z)$ is the beam intensity at depth z, I_0 is the intensity at the surface, and μ is the attenuation coefficient. $1/\mu$ is called the "mean free path".

... Beam "hardening" ...



```
%{
   This Matlab script file was used to create the plot on the previous page
   using LaTeX labeling. If the download does not work properly, you can
   probably cut-and-paste from here.
%}
clear all, close all

E = [ ...
   0.01   0.015   0.02   0.03   0.04   0.05   0.06   0.08 ...
   0.10   0.15    0.2    0.3    0.4    0.5    0.6    0.8  ...
   1.0    1.25    1.5    2.0    3.0    4.0    5.0    6.0    8.0    10. ];
mumu = [ ...
   5.21   1.6     0.778  0.371  0.267  0.225  0.205  0.185 ...
   0.171  0.151   0.137  0.119  0.106  0.0966 0.0894 0.0785 ...
   0.0707 0.0641  0.0575 0.0493 0.0396 0.0340 0.0303 0.0277 0.0243 0.0222];
mutr = [ ...
   4.79   1.28    0.512  0.149  0.0677 0.0418 0.0320 0.0262 ...
   0.0256 0.0277  0.0297 0.0319 0.0328 0.0330 0.0329 0.0321 ...
   0.0311 0.02975 0.0284 0.0262 0.0229 0.0209 0.0195 0.0185 0.0170 0.0162];
muen = [ ...
   4.79   1.28    0.512  0.149  0.0677 0.0418 0.0320 0.0262 ...
   0.0256 0.0277  0.0297 0.0319 0.0328 0.0330 0.0329 0.0321 ...
   0.0309 0.02955 0.0282 0.0260 0.0227 0.0206 0.0191 0.0180 0.0166 0.0157];

figure(1)
loglog(E,mumu,'k-',E,mutr,'k--',E,muen,'k-')
xlabel('$E_{\gamma}$ (MeV)','Interpreter','LaTex','FontSize',20)
ylabel('$\mu, \mu_{tr}, \mu_{en}$ for H$_2$O','Interpreter','LaTex','FontSize',20)
legendHandle = legend('$\mu$','$\mu_{tr}$','$\mu_{en}$');
set(legendHandle,'Interpreter','LaTex','FontSize',20)

figure(2)
loglog(E,1./mumu,'k-')
xlabel('$E_{\gamma}$ (MeV)','Interpreter','LaTex','FontSize',20)
ylabel('$1/\mu$ (cm)','Interpreter','LaTex','FontSize',20)
legendHandle = legend('mean free path $1/\mu$ in H$_2$O (cm)');
set(legendHandle,'Interpreter','LaTex','FontSize',16)
```