Radiation Shielding at High-Energy Electron and Proton Accelerators

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Introduction

- Radiation source terms in high-energy (> several tens of MeV) electron and proton accelerators and their shielding by common shielding materials using analytical and semi-empirical methods
- Audience : professionals new to accelerator shielding
- Objective: cover general aspects

Shielding Goals

- Protect workers, general public, and the environment against unnecessary prompt radiation
- Protect workers from potential exposure to the induced radioactivity in the machine components
- Reduce unwanted background in experimental detectors
- Protect equipment against radiation damage
- Attenuate the radiation fields to acceptable levels with appropriate thickness, types of shield materials, locally or as part of the structure

General Considerations

- Radiation Environment
  - High-energy, high intensity particles: mix of photon, neutrons, electrons, pions, muons, kaons...
- Parameters to be considered include:
  - maximum beam energy and intensity, average beam power
  - normal and abnormal beam losses
  - schedule and modes of operations
  - area classification and area occupancy
- Shielding should be designed for maximum normal operation with allowance for occasional high beam losses.
- Maximum capability of the accelerator should be considered for targets and dumps.

General Considerations – Cont.

- In addition to an annual dose limit for normal beam losses, a maximum dose rate limit should be established for high, but occasional, beam losses
- Dose limits for radiation workers and the members of public should be considered
- Environmental radiological impact from beam operations should be considered
- The shielding design should be an integral part of the overall safety design of the accelerator.

General Considerations-Cont.

- Cost and/or space could prohibit shielding for full capability of an accelerator, or for full beam losses at all locations
- Combination of passive and active systems
- Active systems, e.g.,:
  - Current monitors: monitor and limit the beam current that is allowed to enter a beamline
  - Radiation monitors placed inside and/or outside of the shielding wall to detect and terminate unexpected, high radiation levels.

Checklist for shielding specification

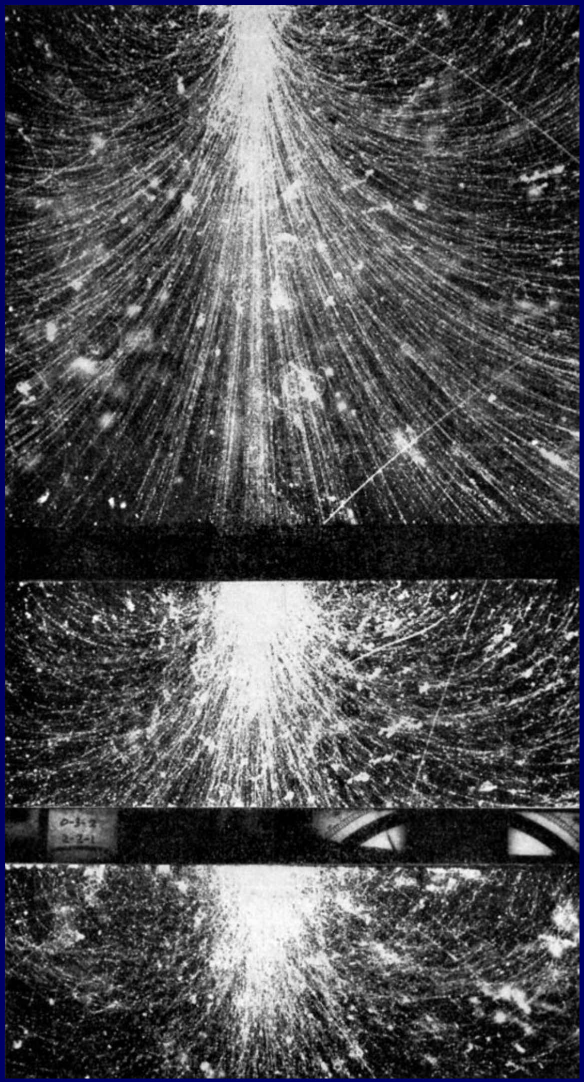
- Assess the physical lay-out, subdivide the facility according to functional and constructional requirements
- Define the primary and secondary radiation sources
- Specify an overall safety factor in the source definition considering possible future use and operations
- Define the maximum dose/year and the maximum dose rates in areas outside the projected shielding
- Specify the attenuation needed for all sources and areas
- Estimate the shielding
- Define a tentative shielding layout
- Assess the overall attenuation obtained and check for conflicting interests before proceeding with the design of the final layout

Shielding of Electron Accelerators

Sources of Prompt Radiation

- Bremsstrahlung
- Electromagnetic shower
- Neutrons
- Muons
  - Underlying process is the electromagnetic shower
- Synchrotron Radiation (covered elsewhere)

Electromagnetic Cascade



- This is an example of a shower produced in a cloud chamber by a cosmic-ray electron (from R. B. Leighton, Principles of Modern Physics (McGraw-Hill, 1959))
- A single, very high-energy electron enters the cloud chamber from the top, where it interacts within in a sheet of Pb (not shown)
- The charged particles are rendered visible by the cloud chamber, but neutral particles (e.g., photons) cannot be seen
- An external magnetic field (0.75 kG) has been applied (vertical to the viewing plane) to bend the charged particles
- Two additional Pb sheets in the chamber cause shower regeneration to occur

Electron Interactions

- When electrons (+ or –) traverse matter, three interaction processes dominate
  - Interactions with atoms as a whole in which the atoms themselves are left in *excited* and (sometimes) ionized states – called *soft* collisions
  - Interactions with orbital electrons in which the collision is *hard* and the knock-on electron (or delta ray) has a track of its own
  - Radiative interactions in which the primary electron is scattered by the field of nuclei with emission of x-rays (called bremsstrahlung)

Radiative Interactions

- Radiative interactions are inelastic scattering in which x-rays are produced when an electron *decelerates* under the influence of the electric field of the nucleus – hence, the name bremsstrahlung (German for "braking radiation")
- Radiative-loss mechanism becomes more important as the energy increases
- EM showers are essentially the result of two high-energy processes that feed one another:
  - X-rays produced by electrons (+ or –)
  - Pairs produced by photons
    - **Usually occurs in the field of a nucleus**
    - **Threshold energy is 1.022 MeV (= 2mc^2)**
    - **Pair production is the dominant way photons interact above 10 MeV in Pb (or 100 MeV in water)**

Radiation Lengths

- We have seen that, starting with a single high-energy electron or photon, the number of particles (e^-,e^+ and γ) increases with depth into the medium – the so-called longitudinal development
- A special unit of length, called the radiation length, makes it significantly easier to plot these longitudinal shower curves
- That is, we can make showers in different materials (Al, Pb, etc.) scale so that they all fit on the same plot – i.e., they look more or less alike
- The key is knowing that radiative processes dominate at high energies
- We define the radiation length, X_o, as that distance in which an electron loses 1/e[th] its energy by emitting x-rays
- Using the bremsstrahlung cross section we can show that

$$\frac{1}{X_o} = 4\alpha Z^2 r_o^2 \ln\left(183 Z^{-1/3}\right) \quad \mathrm{cm^2 g^{-1}}$$

Radiation Lengths (cont.)

- The natural unit of thickness in EM shower is the radiation length X_o defined as the distance in which an electron loses 1/eth its energy by emitting x-rays

$$\frac{1}{X_o} = 4\alpha Z^2 r_o^2 \ln\left(183 Z^{-1/3}\right) \quad \mathrm{cm^2 g^{-1}}$$

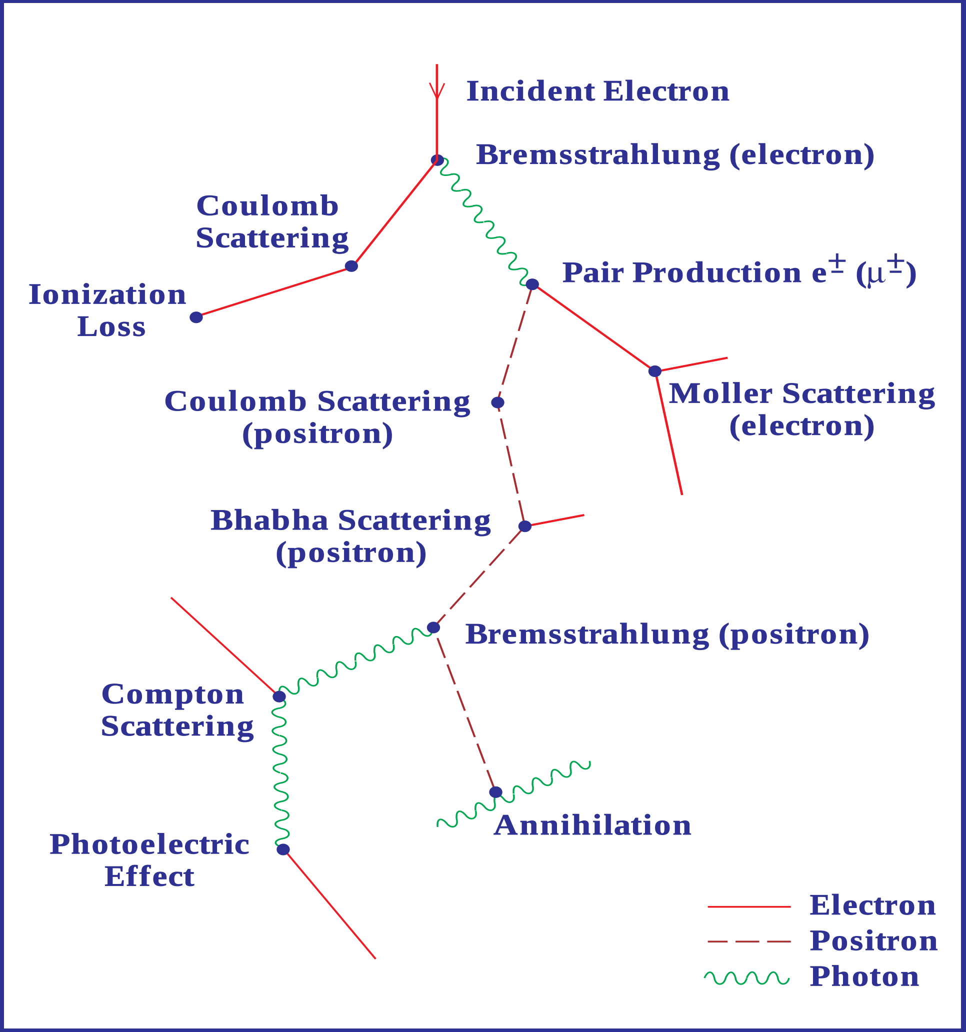
- Multiplication stops when *energy* drops below Critical Energy *Ec*

$$dE / dx|_{col} = dE / dx|_{rad}$$

$$Ec\ [\mathrm{MeV}] = 800/(Z + 1.2)$$

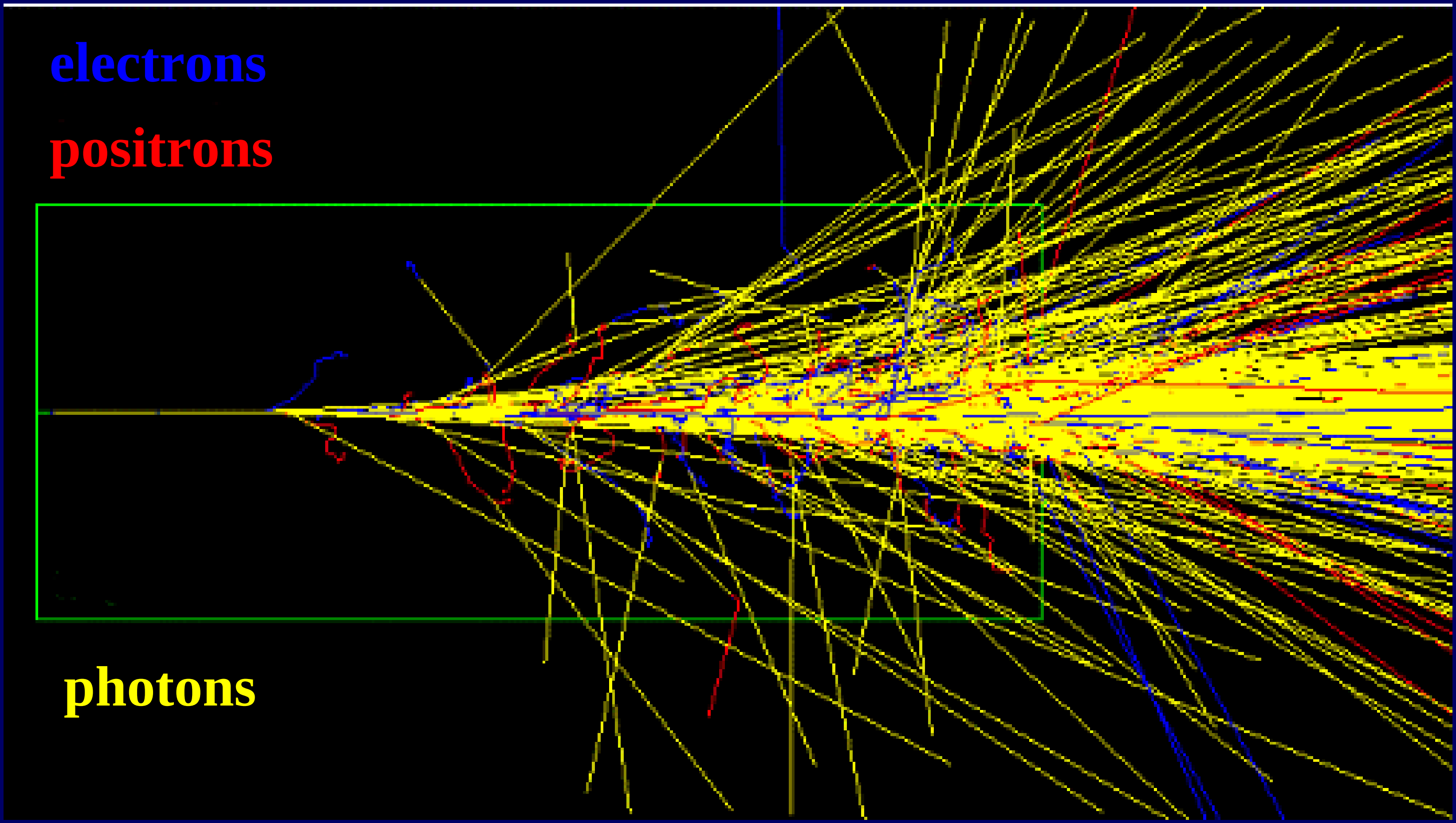
Material	**X_0 (cm)**	**E_c (MeV)**
Pb	0.56	9.5
Cu	1.4	25
Al	8.9	51
Water	36	92

The Electromagnetic Cascade Processes



EM Shower in W (E_0 = 10 GeV)

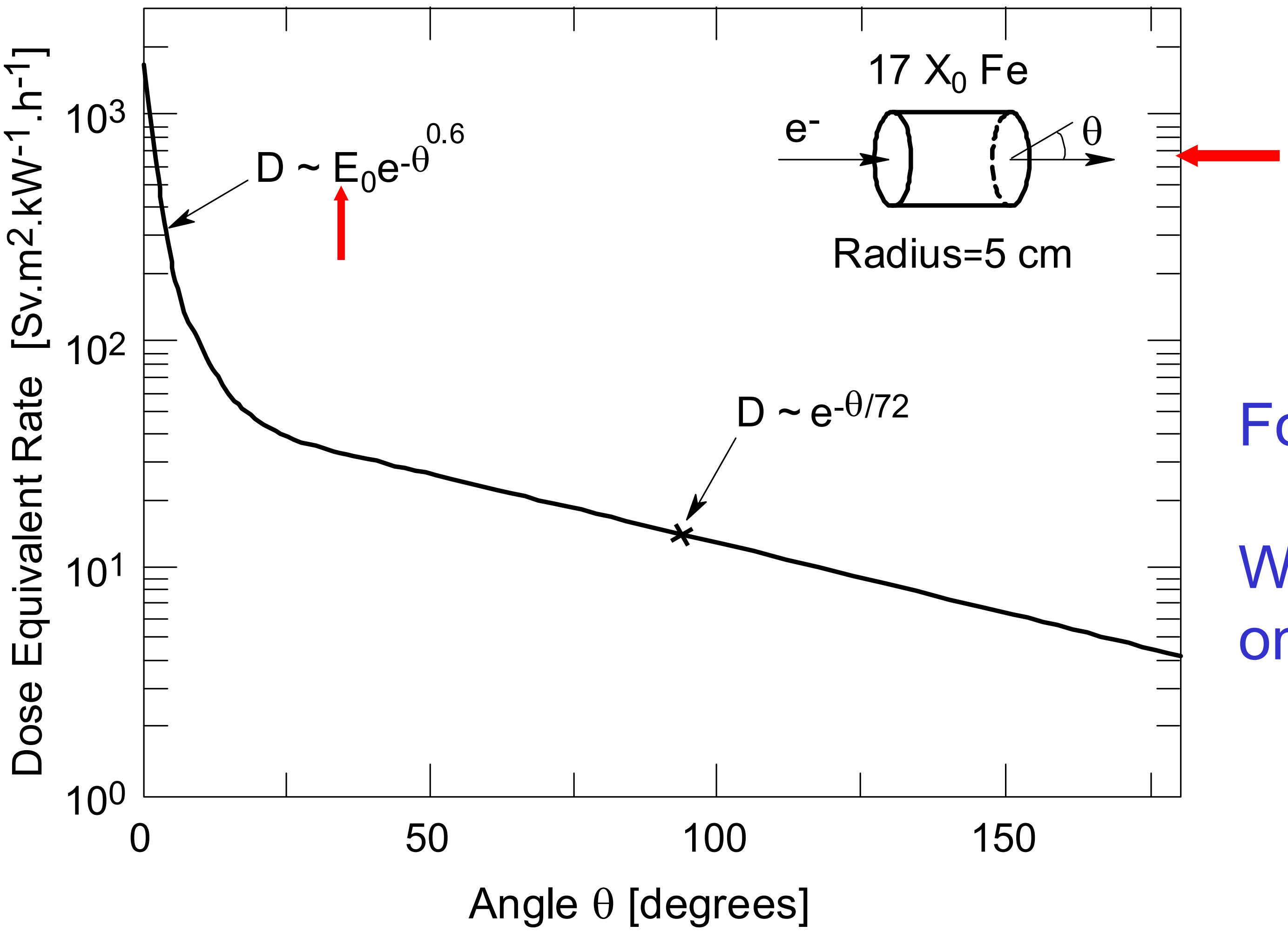
EGS4 simulation



Bremsstrahlung

- Highest radiation hazard near target or with thin concrete shield
- Forward-peaked: $\theta_{1/2}\left(^{\circ}\right) = 100 / E_0\left(MeV\right)$
- $\theta_{1/2}$ = 1° for 100 MeV, 0.01° for 10 GeV
- Two components: sharp forward at small angles, mild variation at wide angles

Bremsstrahlung Angular Distribution

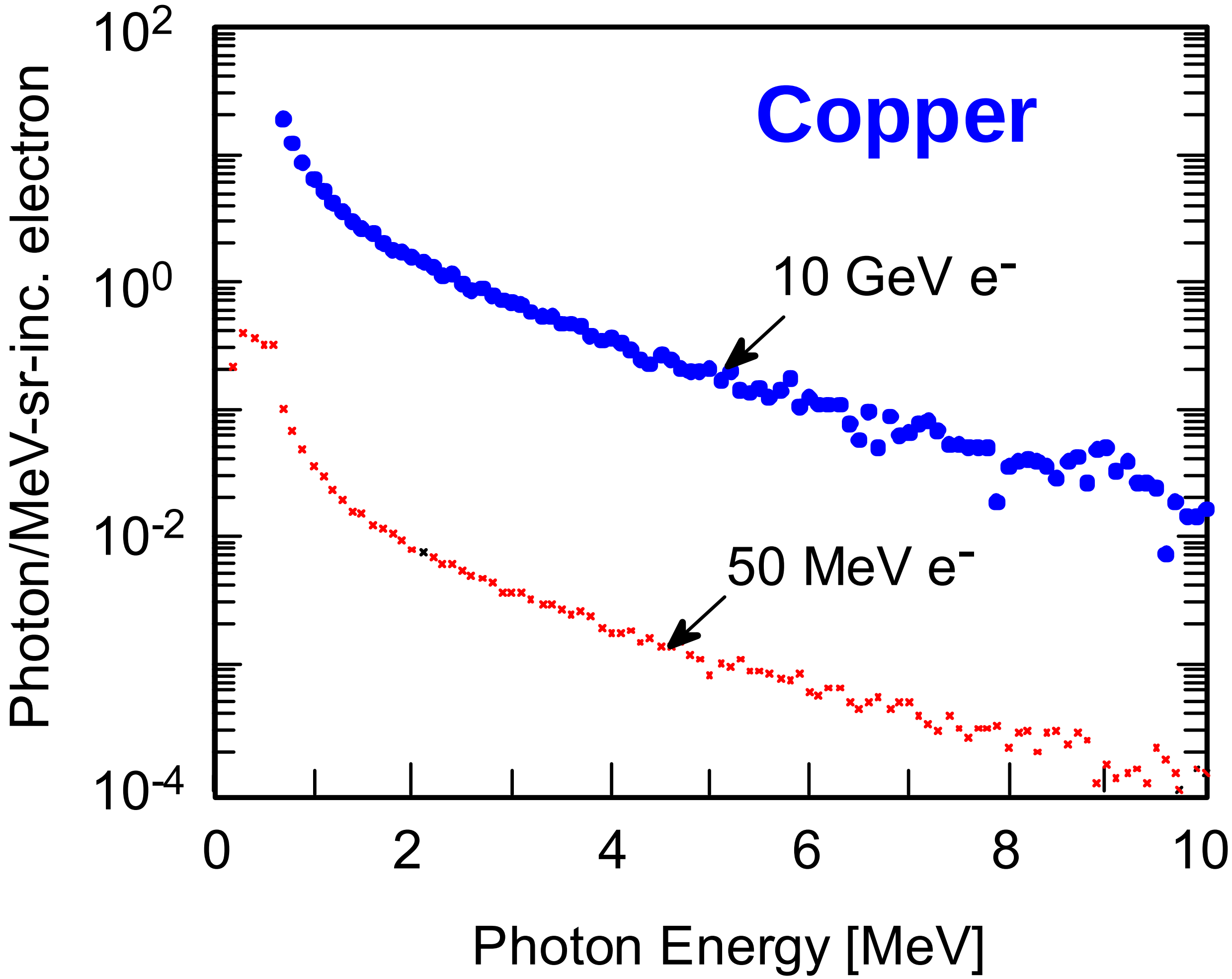


Thick target

Forward ~E.P

Wide angle only ~P

90º Bremsstrahlung



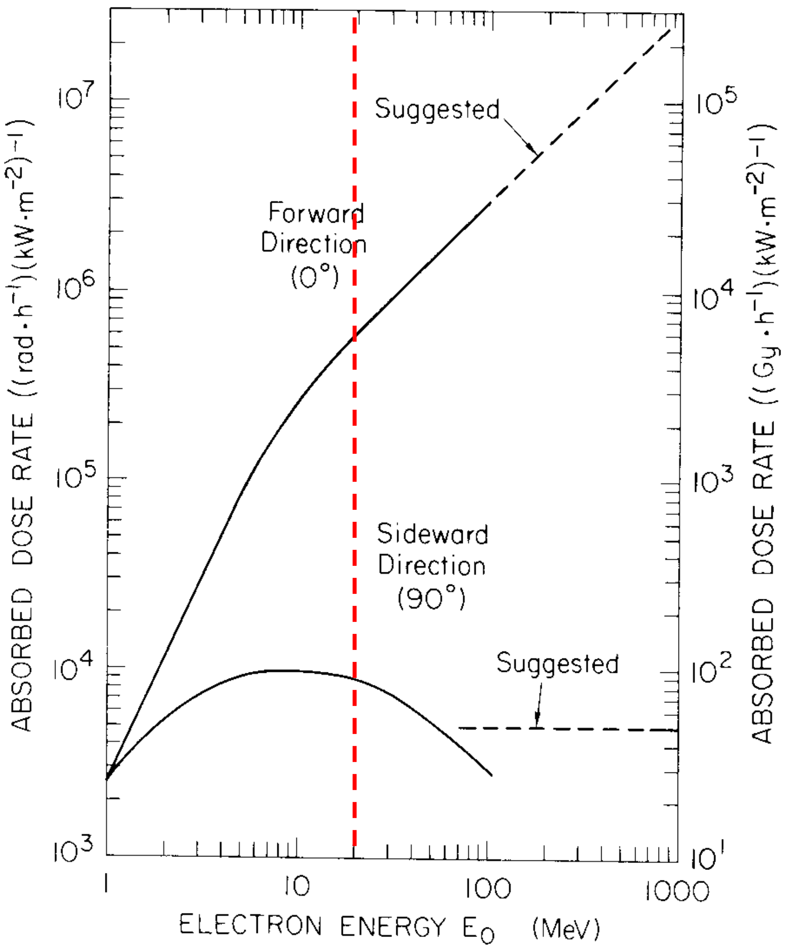
Mao *et al*

relatively soft spectra

90° Bremsstrahlung

- Shapes of spectra are independent of the incident electron energy
- 99.9% of photons have energies < 10 MeV
- Most photons with energies < 1.5 MeV are produced by Compton scattering
- Photons with 1.5 < E < 10 MeV are emitted by electrons at large angles (multiple scattering)

Bremsstrahlung Source Terms



Swanson's Rules of Thumb:
(for thick, high-Z targets)

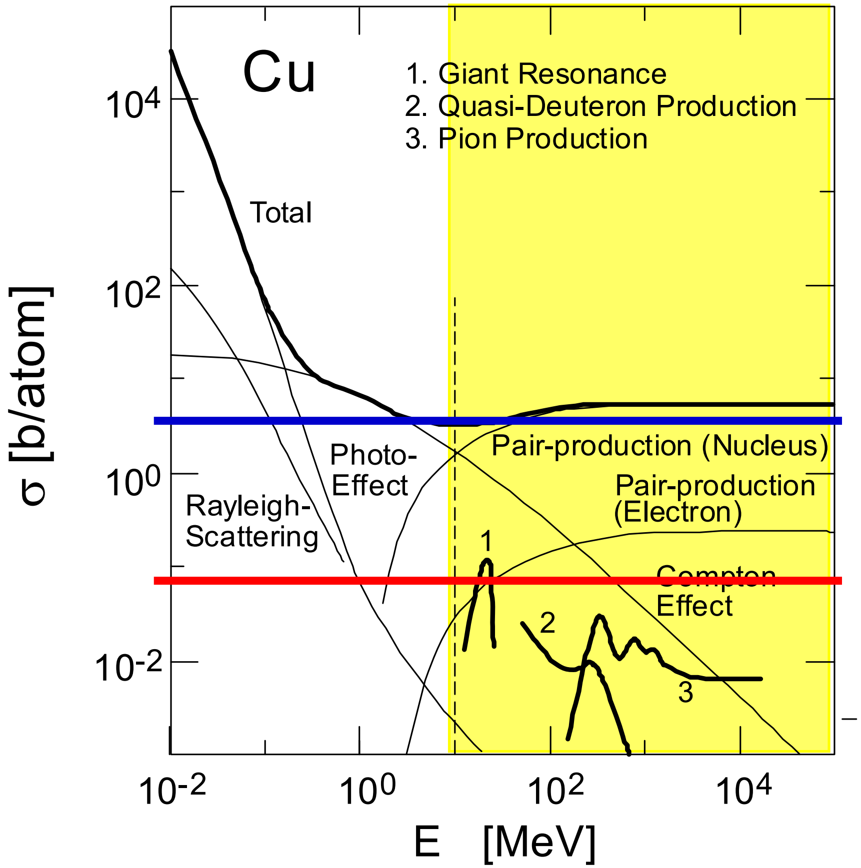
At 0º, E_0 > 20 MeV:

$$\dot{D}\left[\mathrm{Gy.h^{-1}.kW^{-1}.m^{2}}\right] \approx 300 E_0$$

At 90º, E_0 > 100 MeV:

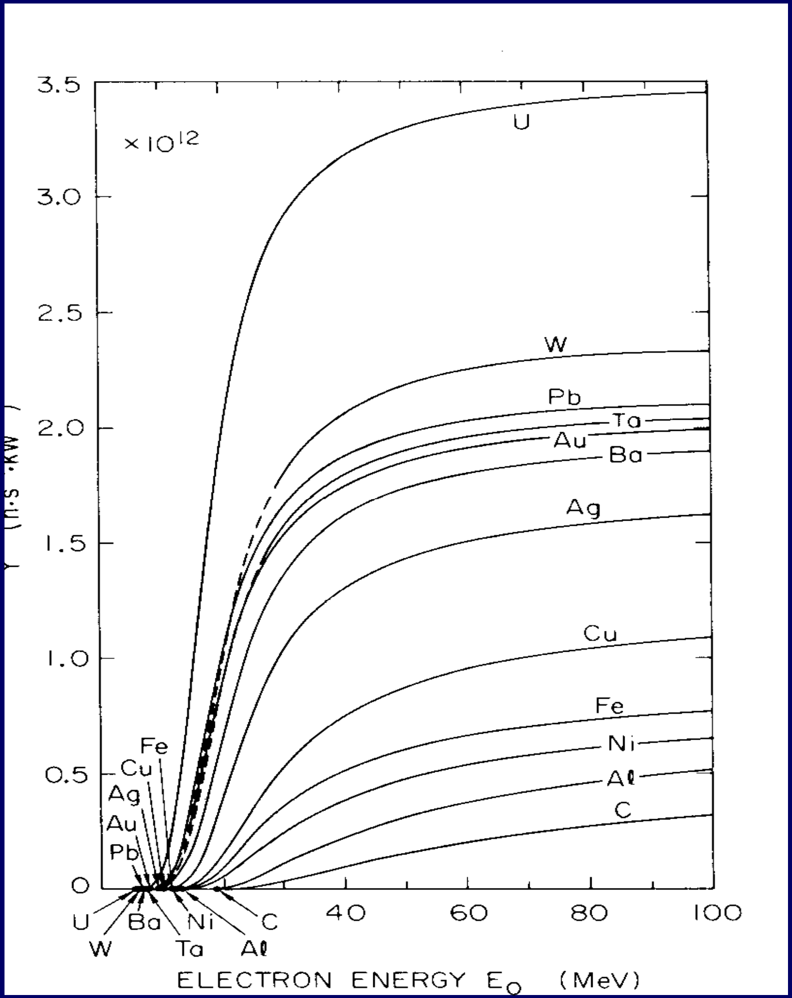
$$\dot{D}\left[\mathrm{Gy.h^{-1}.kW^{-1}.m^{2}}\right] \approx 50$$

Photoneutrons



- GRN: Peak at 20-23 MeV for A< 40, 13-18 MeV for heavier nuclei
- Pseudo-deutron: Photons interact with a p-n pair
- Photopoins: For E > 140 MeV, pions can be produced; pions then generate neutrons
  - Largest resonance at E ~300 MeV, $\sigma \approx$ const in GeV region)
  - Most penetrating, generate evaporation "following" in their path ➔ "equilibrium" neutron spectra behind thick shielding

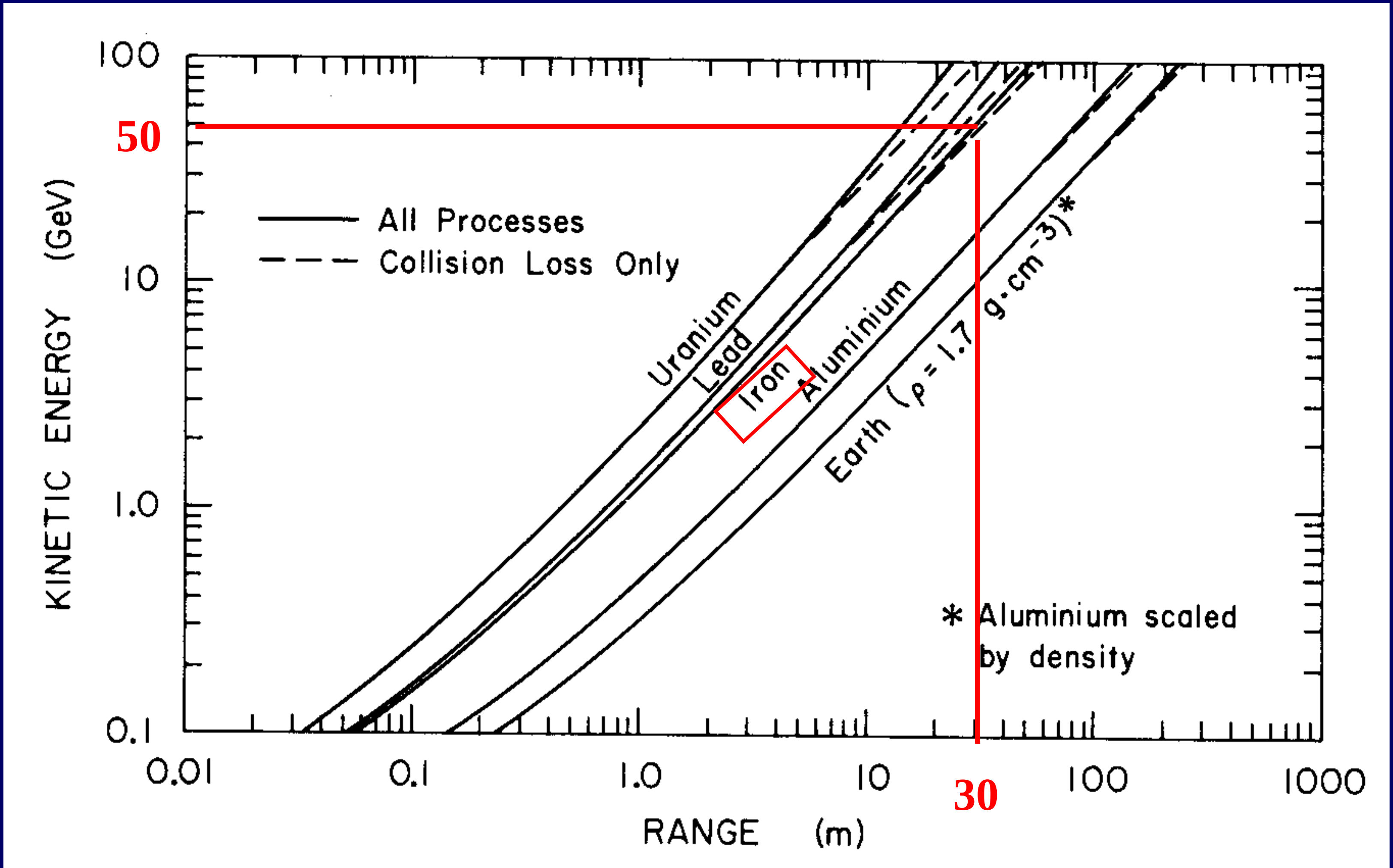
Neutron Yield versus Electron Energy for Various Materials



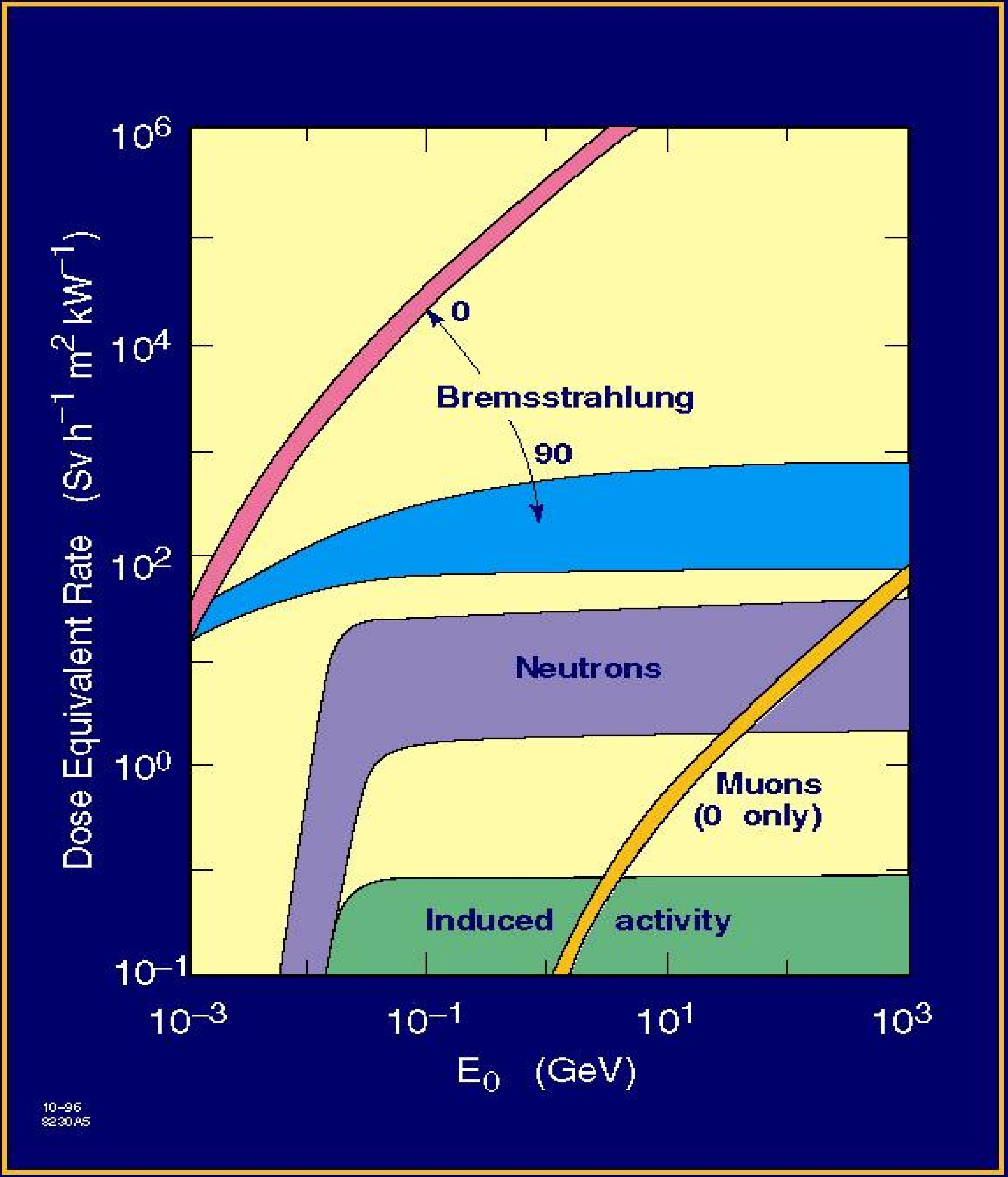
Muon Pair Production

- Possible for photon energy > 211 MeV
- $\sigma(e^+,e^-) / \sigma(\mu^+,\mu^-) \approx (m_\mu/m_e)^2 \approx 4.10^4$
- Important for electron beam energy E_0 above 1 GeV
- Energy loss only by ionization (< 100 GeV); very penetrating & forward peaked
- Yield ~ E_0 (per unit electron beam power)
- Problem mainly at ~0º behind beam dumps or targets

Muon Range



100
50
10
1.0
0.1
KINETIC ENERGY (GeV)
All Processes
Collision Loss Only
Uranium
Lead
Iron
Aluminium
Earth (ρ = 1.7 g·cm^{-3})*
* Aluminium scaled by density
0.01
0.1
1.0
10
30
100
1000
RANGE (m)



Dose Source Terms for Thick Target per unit Electron Beam Power

Prompt Radiation Source Terms

- "Source term" – normalized yield of secondary particles or dose rate for particular beam particle and target type
- Source terms
  - Low energy (< 100 MeV) machines: NCRP 51, IAEA 188 (electrons)
  - High energy machines: IAEA report 188 (electrons) and report 283 (protons), and Sullivan book

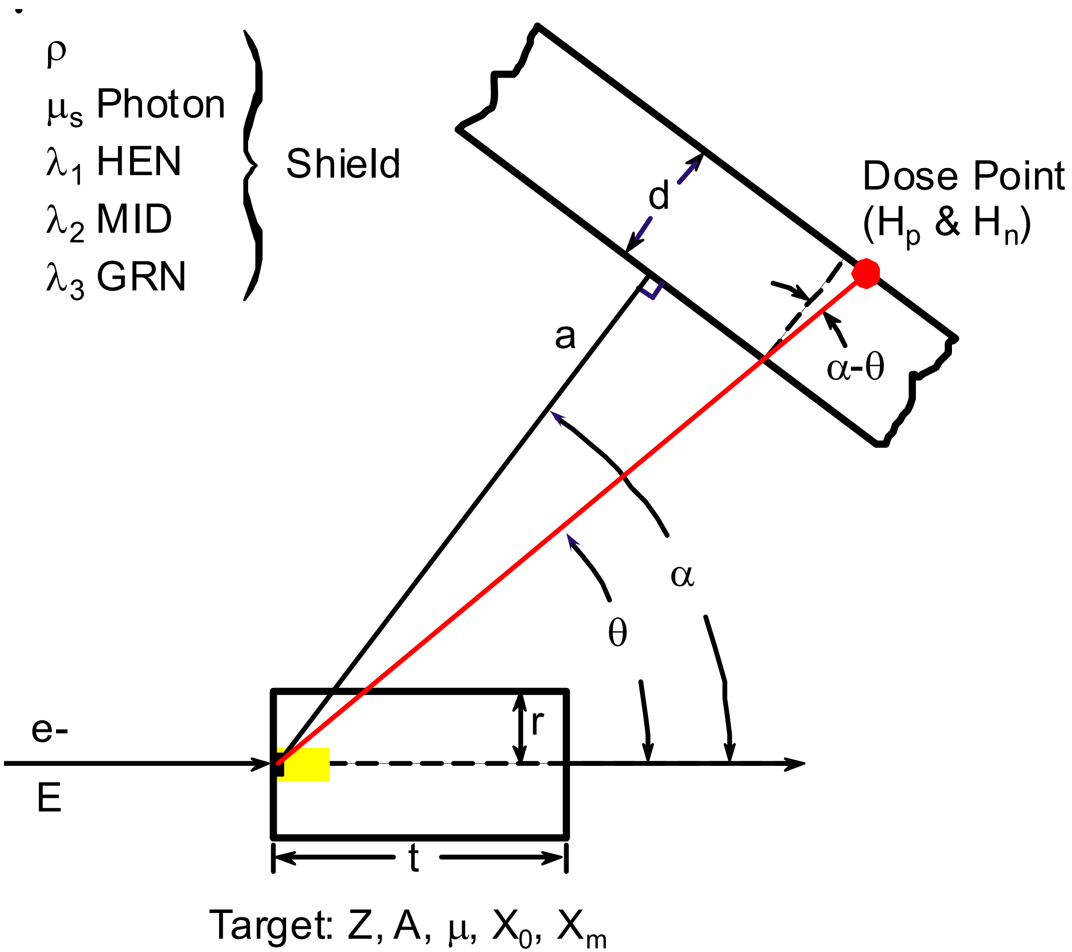
Calculation

- Simple cases: estimates of source terms and conservative attenuation lengths, semi-empirical approximations and “rules of thumb”
- Complex 3D problems and beam loss patterns: Monte Carlo codes (EGS4, FLUKA, MARS, MCNPX)
- Monte Carlo codes for accurate, complicated geometries
  - FLUKA (Fasso 2005), MARS15 (Mokhov 1995), EGS4 (Nelson et al. 1985), MCNPX (McKinney 2007), or PHITS (Iwase 2002)
- Analytic methods, formulae, recipes
  - NCRP 144, Radiation Protection for particle accelerator Facilities

SHIELD11 Code

- Semi-empirical analytic code (SLAC Nelson & Jenkins)
- Two photon components:
  - GamD (direct from bremsstrahlung)
  - GamI (indirect from HEN)
- Three neutron components: GRN, MID and HEN

SHIELD11 Code



SHIELD11 Code - Photons

$$H_p\left[\frac{Sv.m^2}{h.kW}\right] = 0.225\times\left[\frac{\cos(\alpha-\theta)}{a+d}\right]^2\times$$

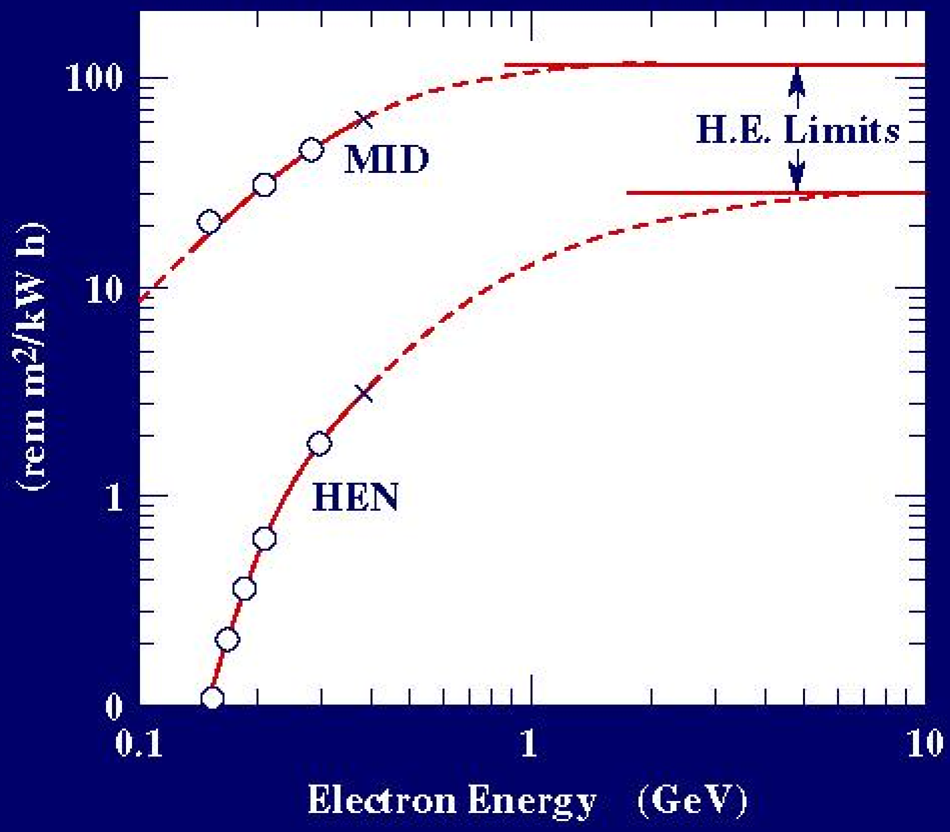
$$\left[\underbrace{\left(1.26\times 10^6\, E\times e^{-(t-0.01X_0)\mu}\times e^{-\theta^{0.6}}+230\times e^{-(r\mu-1.18)}\times e^{-\theta/72}\right)\times e^{-\frac{\mu_s d}{\cos(\alpha-\theta)}}}_{GamD} + \underbrace{\frac{0.27}{(1-0.72\cos\theta)^2}e^{-\frac{d\rho}{\lambda_1\cos(\alpha-\theta)}}}_{GamI}\right]$$

SHIELD11 Code - Neutrons

$$H_n\left[\frac{Sv.m^2}{h.kW}\right]=0.225\times\left[\frac{\cos(\alpha-\theta)}{a+d}\right]^2\times$$

$$\left[\underbrace{\frac{13.7\times e^{-\frac{d\rho}{\lambda_1\cos(\alpha-\theta)}}}{A^{0.65}\left(1-0.72\cos\theta\right)^2}}_{HEN}+\underbrace{\frac{44.3\times e^{-\frac{d\rho}{\lambda_2\cos(\alpha-\theta)}}}{A^{0.37}\left(1-0.75\cos\theta\right)}}_{MID}+\underbrace{4.94Z^{0.66}e^{-\frac{d\rho}{\lambda_3\cos(\alpha-\theta)}}}_{GRN}\right]$$

Effective Source Terms at 90° for a Thick Copper Target for MID and HEN Neutrons



Parameters Used in SHIELD Program

	Fe	Cu	Pb	Concrete
λ_γ	34	33	24	42
λ_1	145	152	200	120
λ_2	145	152	200	55
λ_3	47	53	97	30
X_0	13.84	12.86	6.37	26.7

1). $\lambda_\gamma = 1/(\mu/\rho)_{min}$

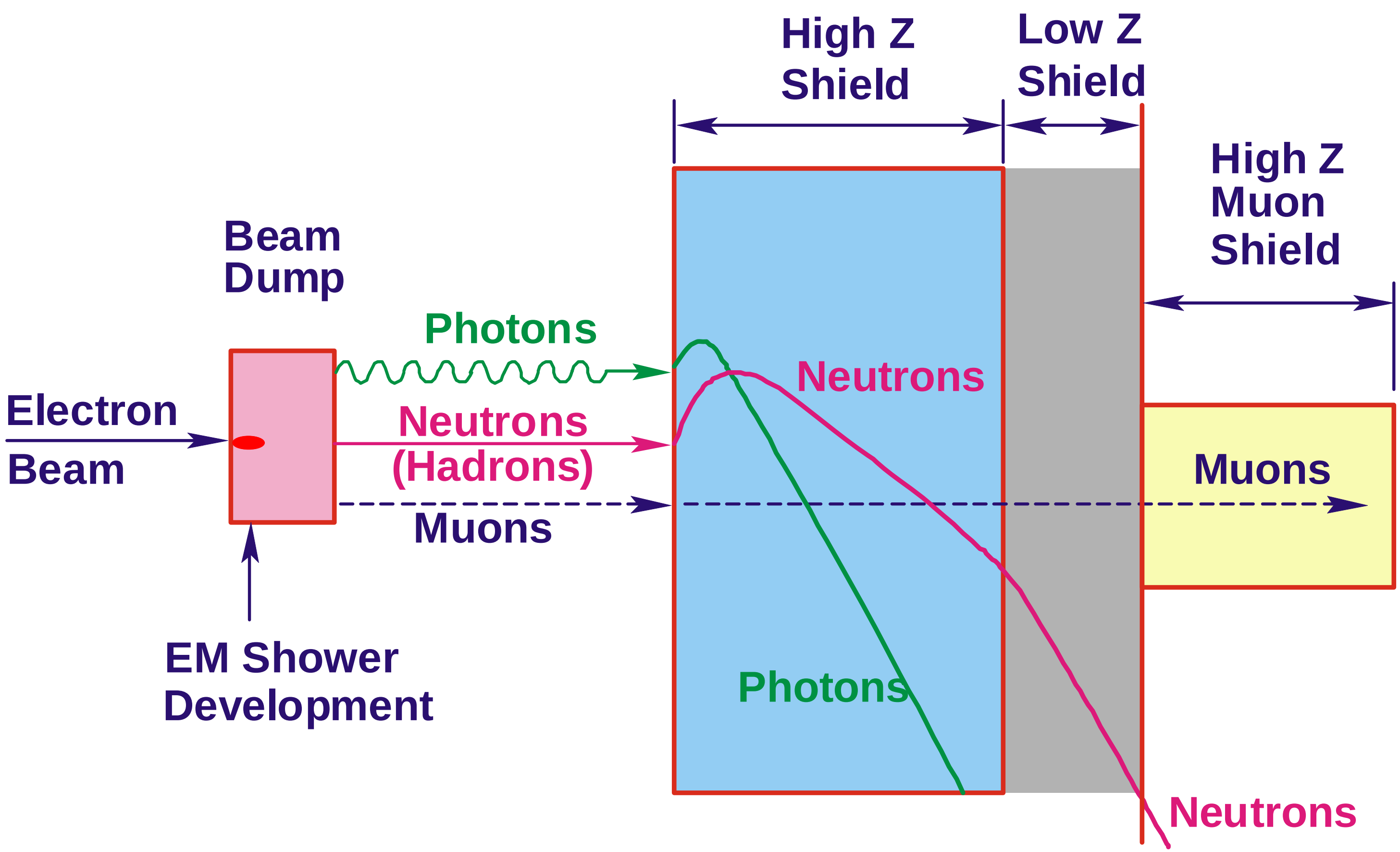
2). X_0 = Radiation Length, $X_m = 21.2X_0/E_c$

3). All numbers are in units of g cm^{-2}

Shielding for Electron Accelerators

- Photons and GRN dominate the fields with no or only moderate shielding
- High-E neutrons (and evaporation neutrons from shield) important with thick shielding
- High-E neutrons best shielded with high-Z material, followed by low-Z material
- Avoid EM shower in concrete shielding
- High Z for photons
- High hydrogen content for neutrons
- Usually steel or lead for photons
- Concrete for neutrons and photons
- Polyethylene (with boron) for low-energy neutrons
- High-Z muon shield at 0º - range out or scatter

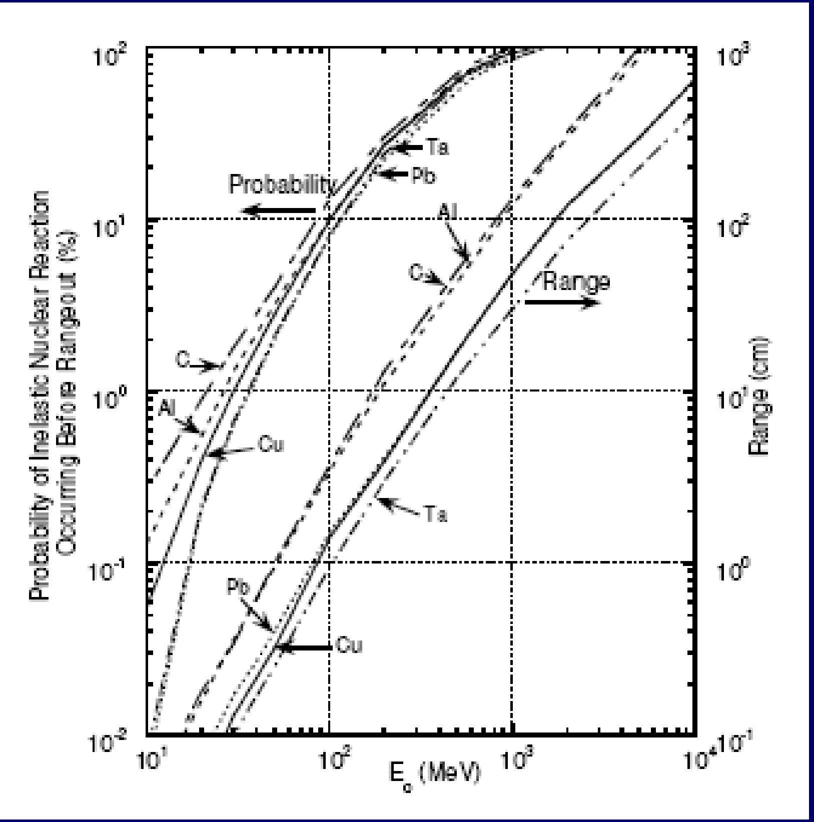
Shield behind High-Energy e⁻ Dump



Shielding of Proton Accelerators

Proton Interactions with Matter

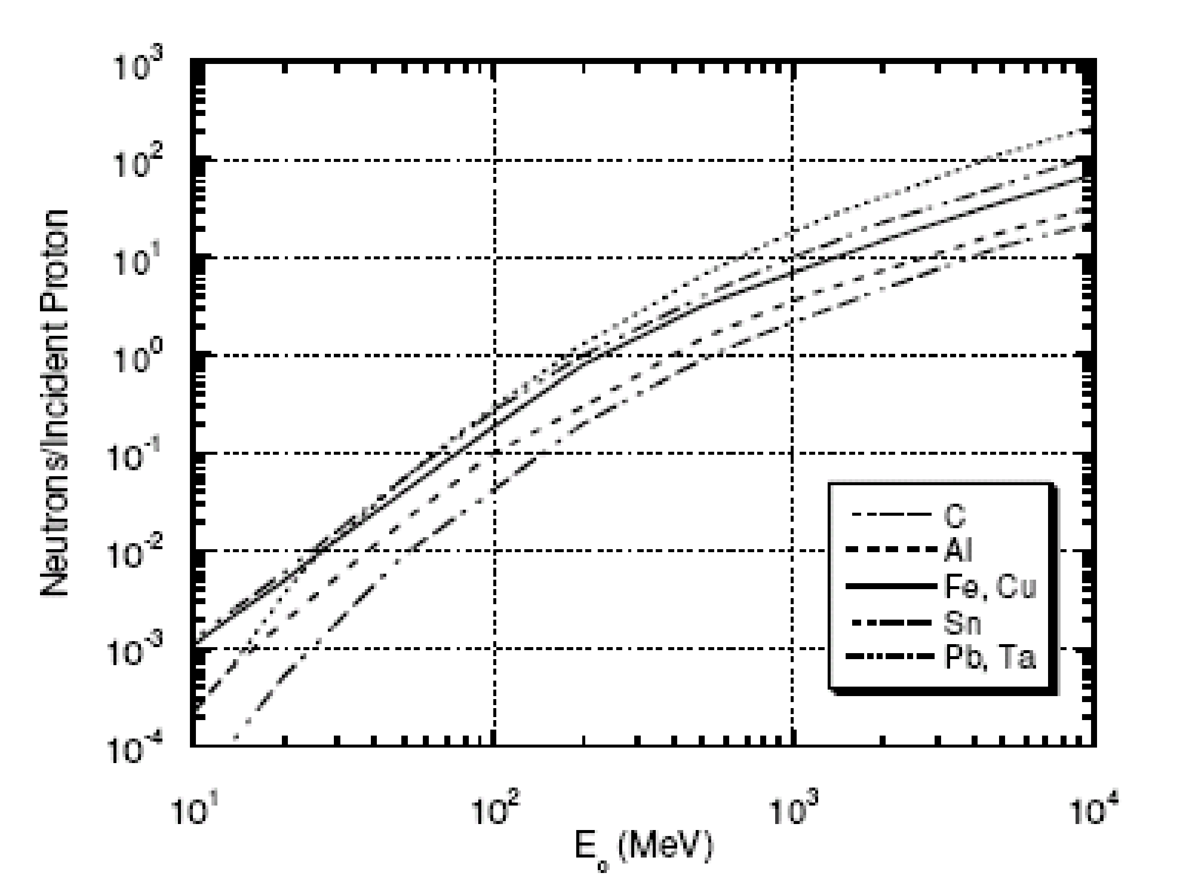
- Radiative processes are negligible
- Ionization range of a proton increases monotonically with energy
- Cross sections for inelastic interactions become nearly independent of energy
- Probability of interaction through inelastic nuclear reaction increases with energy (Te85).



Source Terms

- E < 10 MeV
  - (p,n) reaction are significant in low energies
    - 7Li(p,n)7Be, E_{th}=1.9 MeV, resonance structures
- 10 MeV < E < 1 GeV
  - Y ~ E^2 for 50<E<500 MeV
  - Y ~ E for E > 1 GeV
  - Evaporation neutrons ; boiling off of a nucleus, isotropic
  - Cascade neutrons; result directly from nuclear interactions, forward-peaked
- E > 1GeV
  - increased number of secondary particles

Total Neutron Yield per Proton, Thick Targets (Tesch 85)



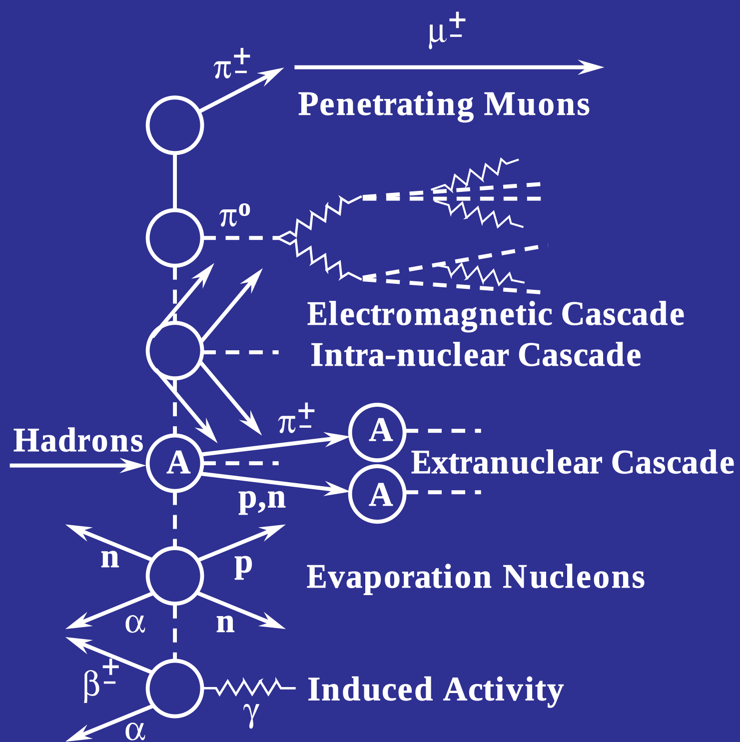
Hadronic Cascade

- At higher incident beam energies, hadronic cascade is initiated at proton accelerators
  - also at high energy electron accelerators
- Collision of a high energy nucleon with a nucleus produces a large number of neutrons
  - Evaporation neutrons originate as decays from excited states of residual nuclei and average a few MeV in energy. These neutrons tend to be isotropically distributed.
  - Cascade neutrons are emitted by direct impact and their spectrum extends in energy up to the incident energy with diminishing probability following a spectrum roughly characterized as having an energy dependence proportional to $1/E$.

Hadronic Cascade - Cont.

- As the proton kinetic energy increases, pion and kaon fragments of the struck nucleus play roles in the cascade
- Pions are absorbed with absorption lengths comparable in magnitude to those of protons. These particles also decay into muons. Because of their long ionization ranges and lack of nuclear interactions, muons provide a pathway for energy to escape the cascade.
- In general, neutrons E_n > 150 MeV are the principal drivers of the cascade
  - neutrons are produced in large quantities at large values compared with the forward-peaked pions

Six Levels of a Hadronic Cascade



	Most Numerous Participants	Time Scale/s	Typical Energy/Particle	Approx. Partition of Energy Deposition (%)
Penetrating Muons	$\pi^{\pm}$, K^{+} } $\mu^{\pm}$	10^{-8}	Any	10 (ionization only)
Electromagnetic Cascade	$\pi^{o} \rightarrow e^{\pm}\ \gamma$	10^{-16}	Any	20
Intra-nuclear Cascade	$p, n, \pi^{\pm}$	10^{-22}	< Few Hundred MeV	30
Extranuclear Cascade	$p, n, \pi^{\pm}$	10^{-23}	$\geq$ Few Hundred MeV	30
Evaporation Nucleons	n, p, d, α	10^{-19}	$\leq$ 30 MeV	10
Induced Activity	$\alpha, \beta^{\pm}, \gamma$	Seconds to Years	$\leq$ Few MeV	< 1

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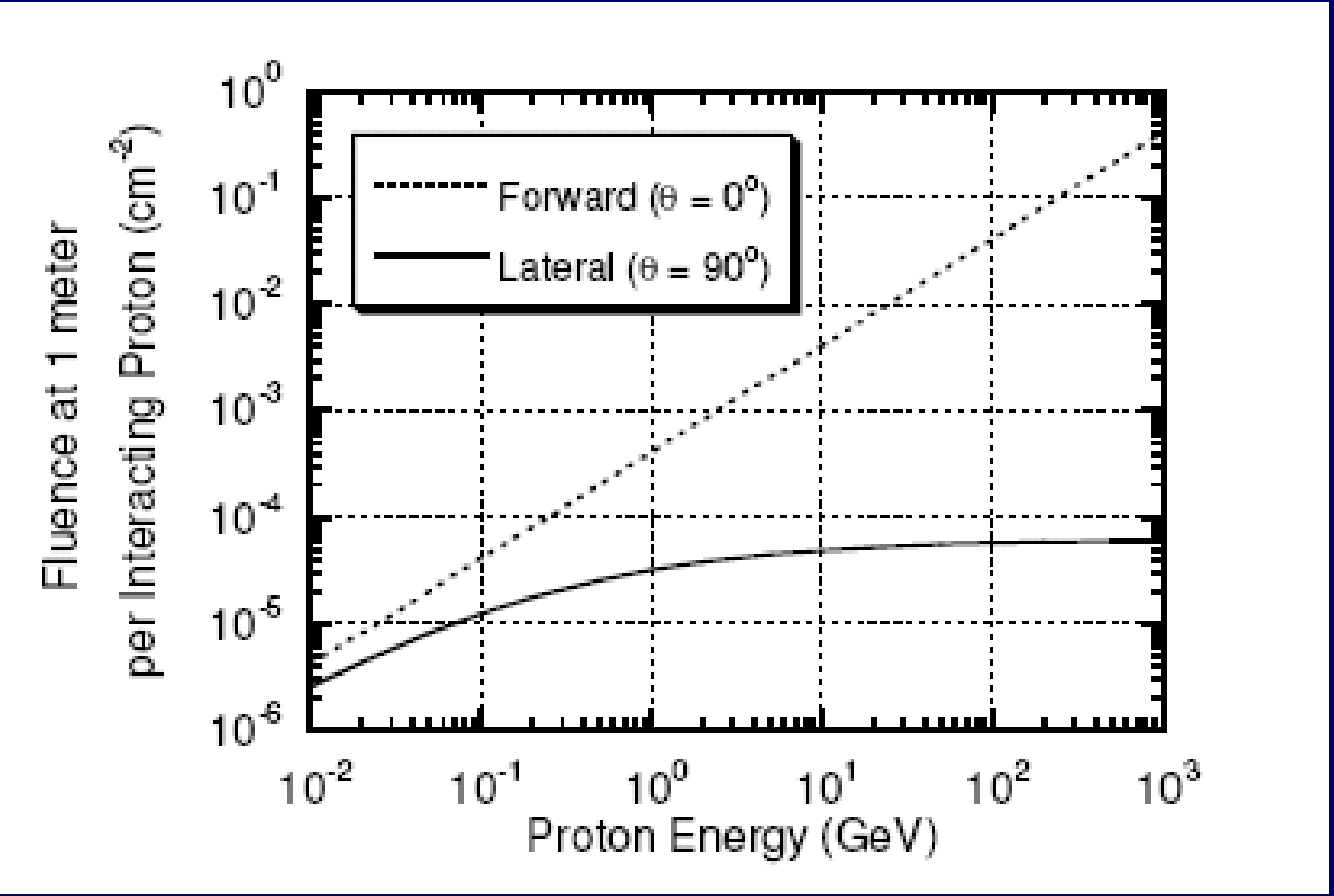
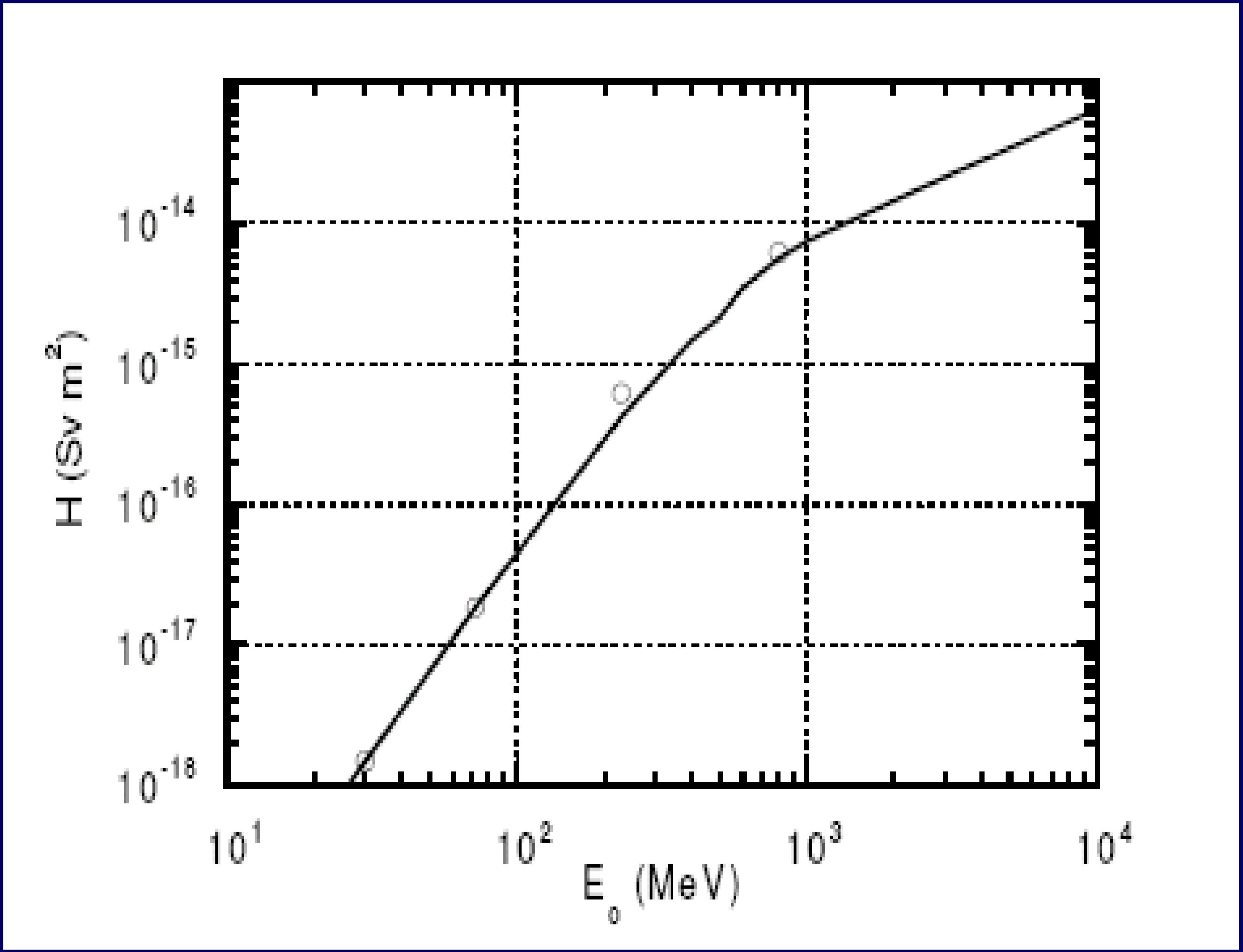
Fluence of neutrons



Copper target struck by protons in the energy region
0.05 < *Eo* < 5 GeV ; Sullivan (1989)

Dose Equivalent due to neutrons > 8 MeV at 90 degrees- beam on copper target



Tesch (1985)

Shielding of Low Energy Incident Protons (Eo < 15 MeV)

$$\mathrm{H}(t) = \Phi_o PG \exp\left(-\Sigma_r t\right),$$

- Φ_o fluence before the shielding
- P is the dose equivalent per fluence
- G is a "geometry factor"
  - $G = 1$, for parallel beams
  - $G = 1/r^2$, for an isotropic point source
- Σ_r is the macroscopic removal cross section

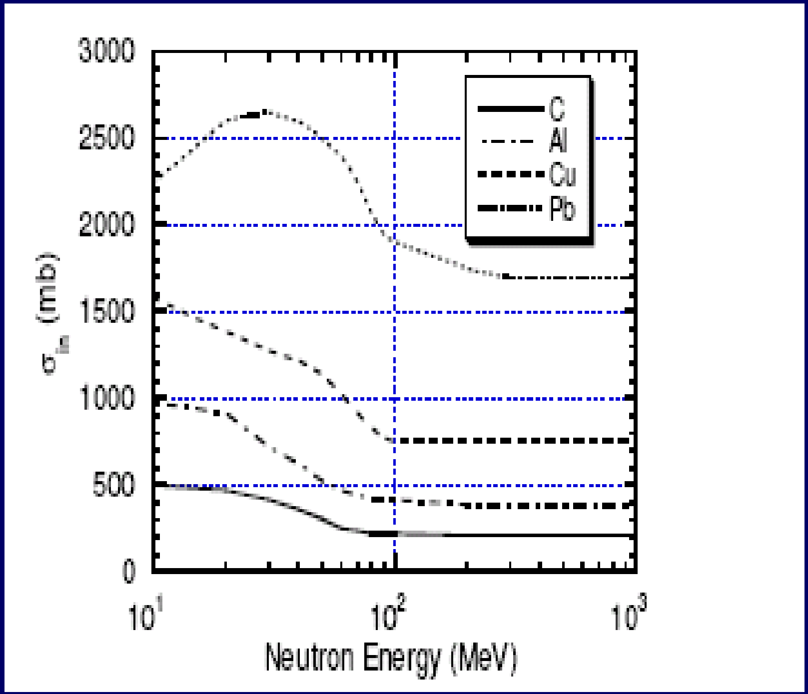
$$\Sigma_r = \frac{0.602\sigma_r \rho}{\mathrm{A}} \left(cm^{-1}\right), \qquad \sigma_r \approx 0.21\mathrm{A}^{-0.58} \left(barns\right)$$

- ρ is the density (g cm^{-3}), A is the mass number

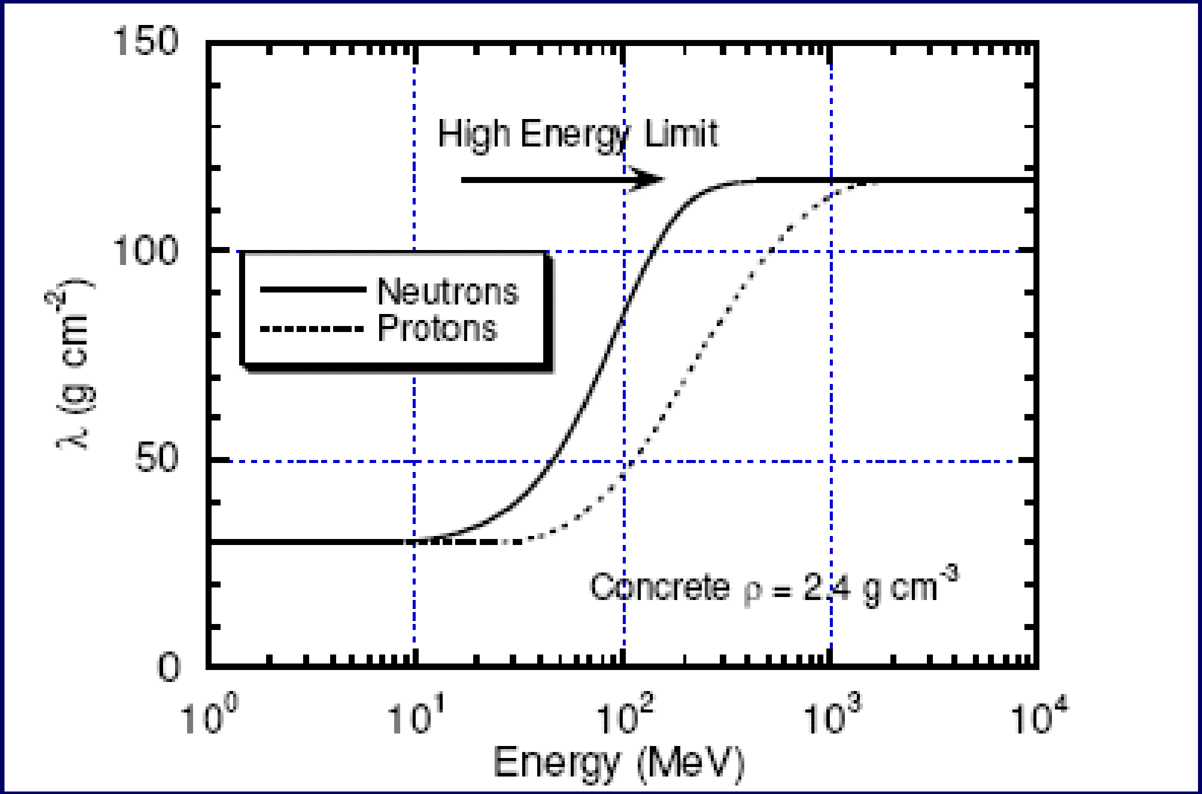
Attenuation Length

- Inelastic neutron cross sections is ~ constant at energies > 100 MeV
  - Important feature of shielding at high energy accelerators

$$\rho\lambda_{atten} = \frac{1}{N\sigma_{in}} \quad (cm)$$



Attenuation Length in Concrete



Transverse Shield

- Ideally, the transmission factor, $T(d)$, of a shield of thickness d can be expressed as

$$T(d) = \exp[-d/\lambda]$$

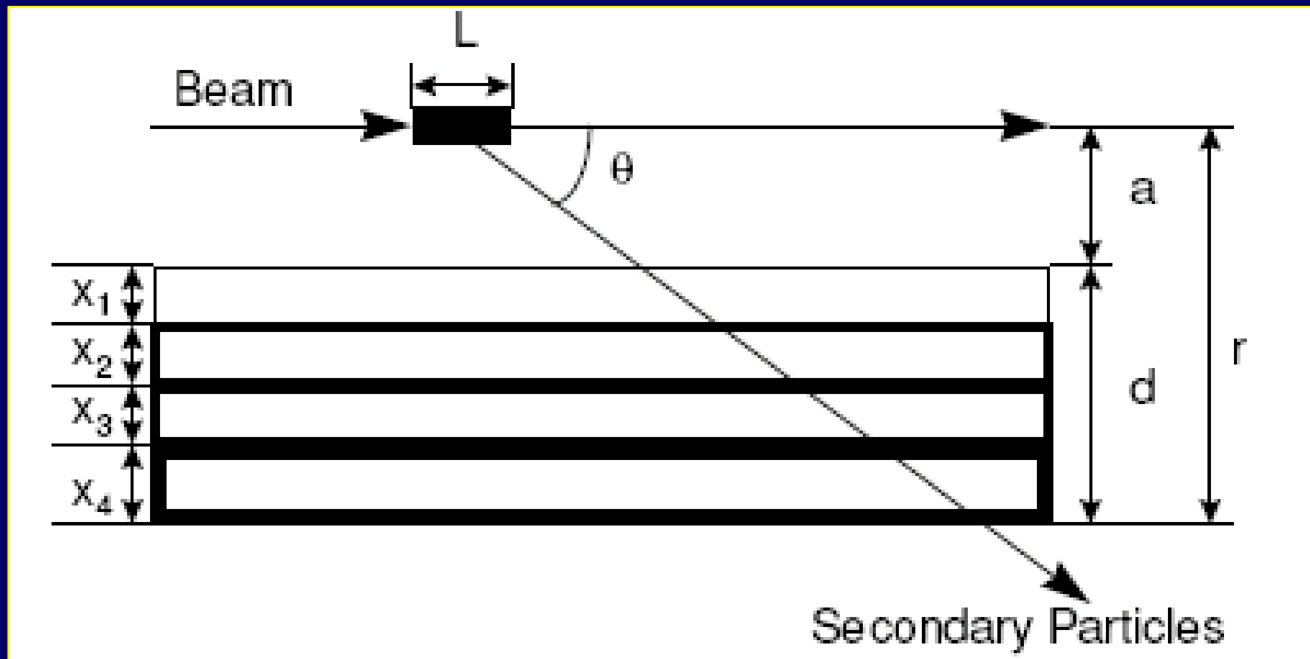
- For an effective source point, radiation levels outside the shield at a distance of (r) and angle (θ) can be expressed as

$$H(d,\theta) = r^{-2} H_\theta \exp[-d(\theta)/\lambda]$$

Moyer Model

- Developed by B. J. Moyer for Bevatron shielding
- An exponential approximation with constants fitted to actual data spanning the range of proton beam energies from 7.4 to 800 GeV
- Used for both point and line sources
- (Patterson 1973; Cossairt 2005; NCRP 2003; Thomas and Stevenson 1988)

$$H = \frac{H_{o}\left(\mathrm{E}_{\rho}\right) f\left(-\beta\, t\right) \exp\left(-\zeta \csc\theta\right)}{\left(r \csc\theta\right)^{2}}$$



$$H = \frac{H_o\left(\mathrm{E}_\rho\right) f(-\beta\ t) \exp\left(-\zeta\ \csc\theta\right)}{\left(r \csc\theta\right)^2}$$

$$\varsigma = \sum_{i=1}^{n} \frac{x_i}{\lambda_i}$$

$$H_o(E_\rho) = \left[\left(2.84 \pm 0.14\right) \times 10^{-13}\right] E_\rho^{(0.80 \pm 0.10)} \quad \left(\mathrm{Sv\ \ m^2}\right)$$

$$= 2.84 \times 10^{-8} E_\rho \left(\mathrm{mrem\ \ m^2}\right) = 2.8 \times 10^{-4} E_\rho^{0.8} \left(\mathrm{mrem\ \ cm^2}\right)$$

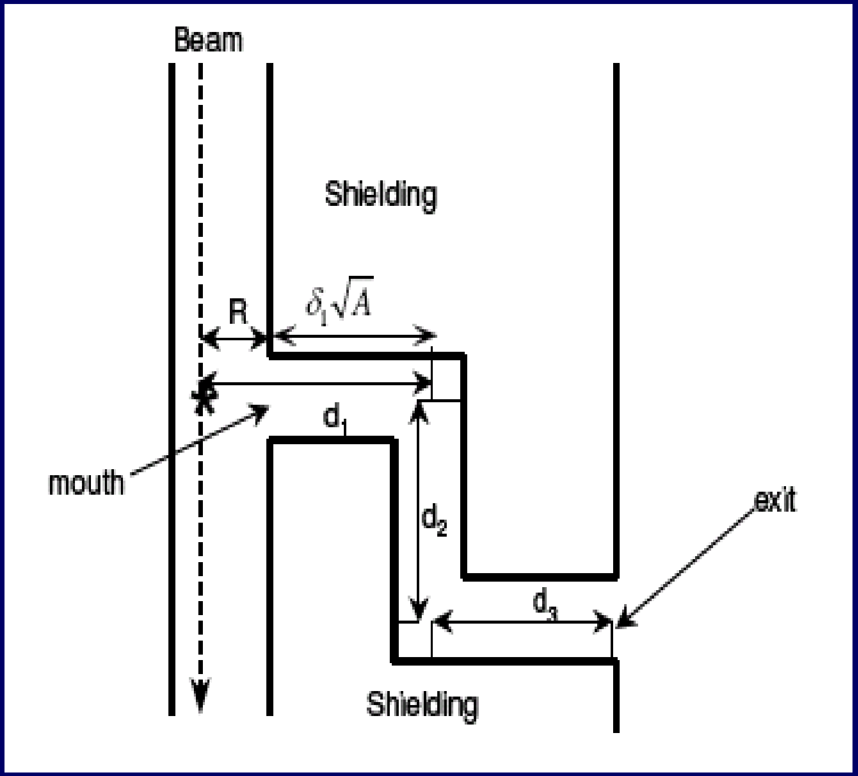
$$r = a + \sum_{i=1}^{n} x_i$$

Ducts

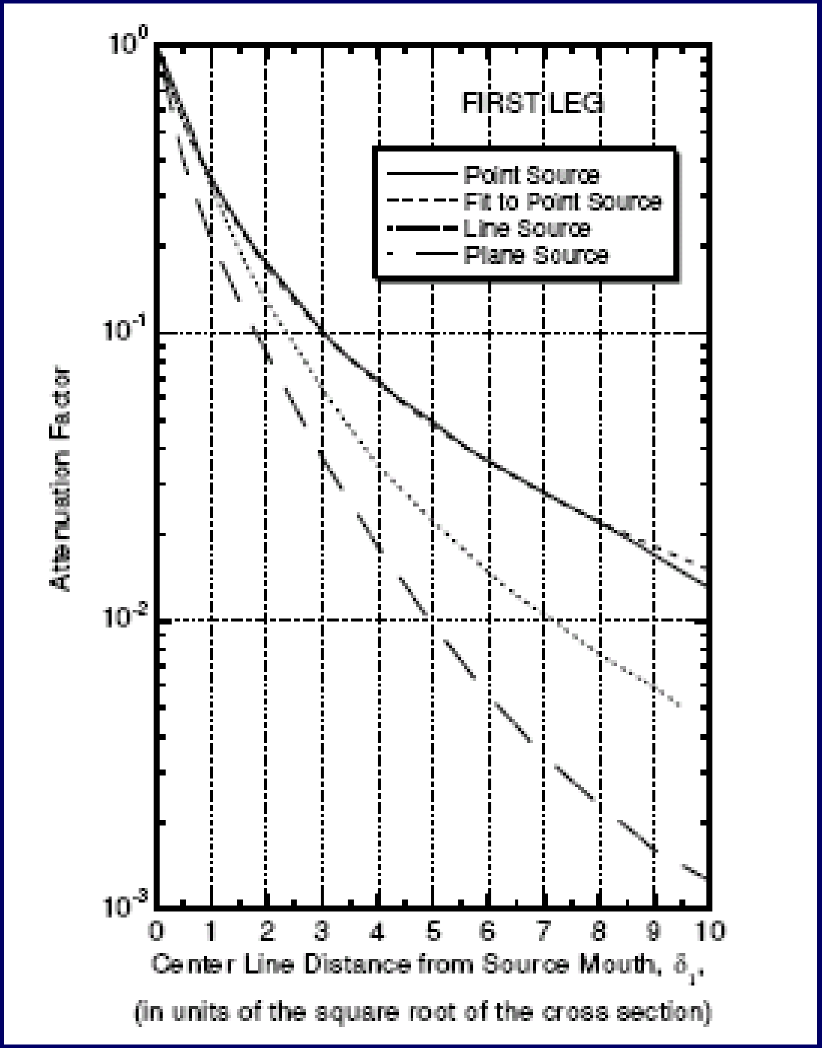
- Incident particle energy or particle type does not affect the results
- The data are usually presented in units of

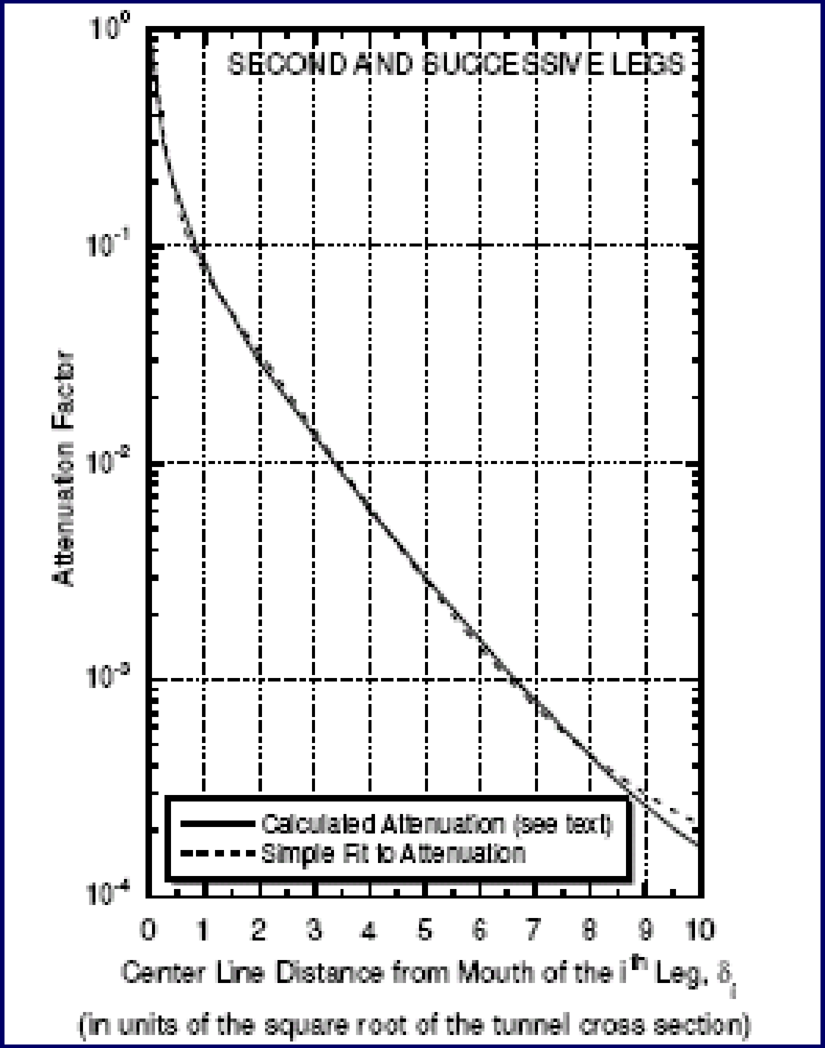
  $d/\sqrt{A}$

  where *d* is the distance from the source and *A* is the cross-sectional areas of the tunnel.
- The validity of scaling is for height/width ratio that lies between 0.5 to 2.



Universal Curves





Neutron Skyshine

- Neutrons escaping upwards and scattering in air to large distances – concern for site boundary dose
- Models: $$\Phi(r) = \frac{Q.e^{-r/\lambda}}{r^2}$$ or $$\Phi(r) = \frac{Q.e^{-r/\lambda}}{r}$$
- $1/r^2$ requires larger λ:

  Liu: λ =500 m ($1/r^2$), Jenkins λ =140 m (1/r)

Considerations for Shielding Materials (NCRP 2003)

- Required thickness and weight of the material
- Possibility of use as shielding against photons and neutrons
- Uniformity, consistency and homogeneity
- Cost, including cost of installation and maintenance
- Shield design must be integrated with all other aspects of an accelerator facility
- Possibility of induced radioactivity
- Concrete, earth, steel, lead, polyethylene

Shielding Materials

- Earth
  - Mostly SiO_2, effective shield for both photons and neutrons
    - density varies from 1.7 g cm^{-3} to as high as 2.25 g cm^{-3} depending on water content and the degree of compaction
- Concrete
  - Used for both photon and neutron shield, relative low cost, easy to cast to different shapes, good structural properties, modular and moveable
    - Portland concrete, density in the range of 2.3-2.4 g cm^{-3}
  - Heavy materials can be added in the concrete aggregate, barites or iron ore, to increase its density and average Z, density of heavy concrete can exceed 4.5 g cm^{-3}
- Water content of concrete shield (earth) may vary with time, changing its efficiency for use as shield against neutrons

Shielding Materials

- Iron
  - Density ~ 7.0 g cm^{-3}; steel density is typically around 7.9 g cm^{-3}
  - Steel, in conjunction with hydrogenous materials such as concrete, is used for shielding of high-energy neutrons (several tens of MeV)
  - 27.7 keV resonance and 73.9 keV resonance can result in large fluxes of soft neutrons outside iron shields
- Polyethylene
  - Density ~ 0.92 g cm^{-3}, large hydrogen content (~5% by weight), Thermal neutron capture in polyethylene can lead to a build up of 2.2 MeV photons, which can be mitigated by addition of a boron compound

Induced Activity

- Less of a problem in electron than proton accelerators
- Mainly exclusively external sources
- Due mostly to photonuclear reactions, and also subsequent activation by neutrons
- Estimates possible using data in literature: Saturated activity A_S per unit beam power
- In Air: ^{11}C, ^{13}N, ^{15}O, ^{41}Ar (with thermal neutron) plus ozone & other toxic gases

Susceptibility to Activation

- Low
  - lead, ordinary concrete, aluminum, wood, plastics
- Moderate
  - iron (steel), copper
- High
  - stainless steel, tungsten, tantalum, zinc, gold, manganese, cobalt, nickel
- Fissionable: uranium, plutonium, thorium

References

- IAEA Report 188, “Radiological safety aspects of the operation of electron accelerators” (1979)
- IAEA Report 283, “Radiological safety aspects of the operation of proton accelerators” (1988)
- A. H. Sullivan, *A Guide to Radiation and Radioactivity Levels near High Energy Particle Accelerators* (1992)
- NCRP Report 51, “Radiation Protection Design Guidelines for 0.1-100 MeV Particle Accelerator Facilities” (1977) and NCRP Report 144 “Radiation protection for particle accelerator facilities” (2005)
- Cossairt JD, Radiation physics for personnel and environmental protection. Rev. 9B. FNAL Report TM-1834; (2007)
- Patterson HW, Thomas R H. Accelerator health physics. (1973)