# Radiation protection for laser-based accelerators

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# Summary

First of all, why laser-based accelerators?

How to derive the term-source

How to design the radiation protection project

# Introduction

- Radiations and particles have many application in several fields of human activities. In addition to their confirmed application to fundamental research they are in fact widely applied in all fields of science, medicine, chemistry, material science and so on. Up to today radiations have been produced by radiation sources (conventional accelerators, X-ray tube, radioactive sources, etc.) with the well-known connected problems of costs, parameters and safety.

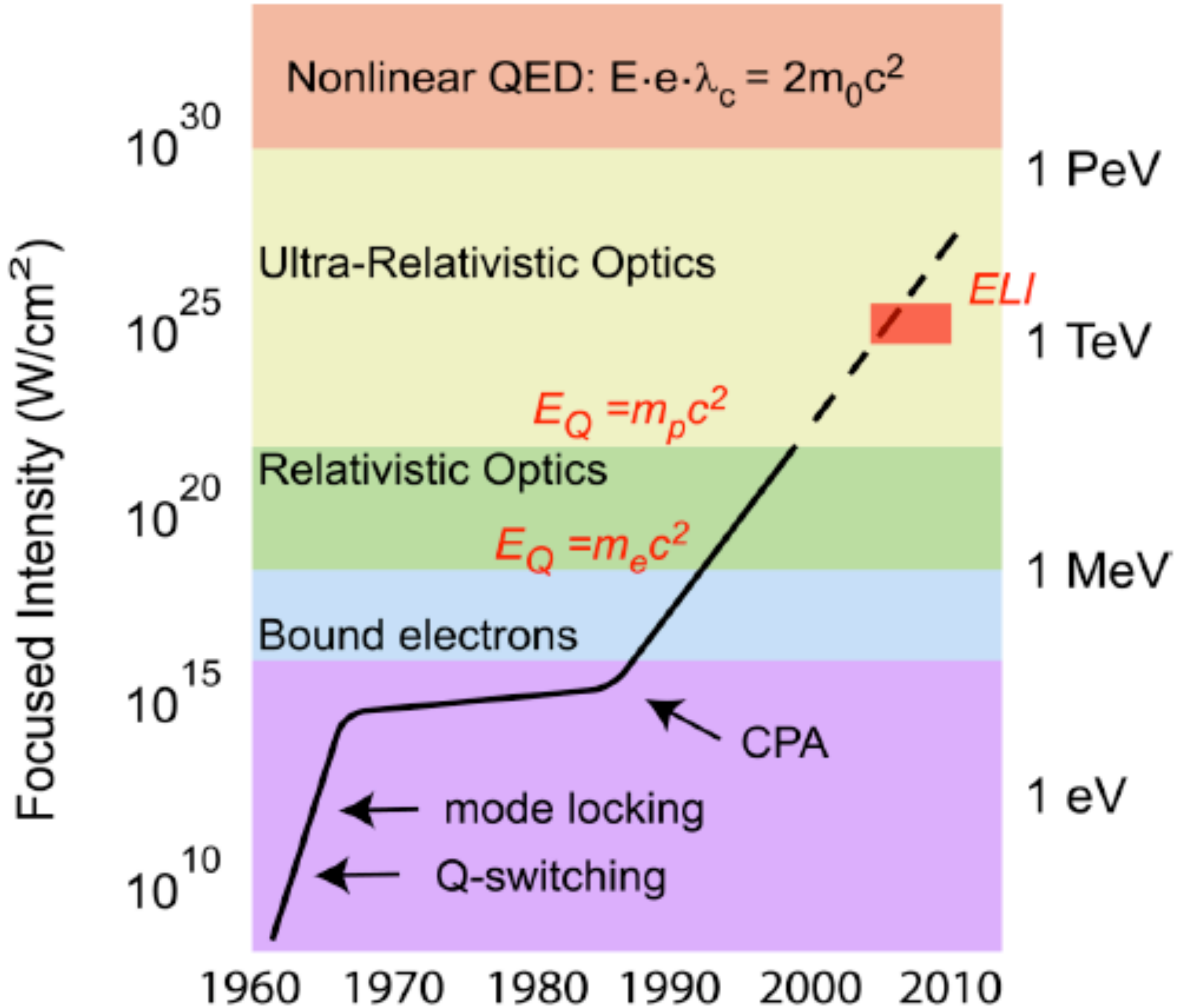
- Since few years, following the development of lasers able to focus ultra-short high intensity pulses onto targets, became possible the generation and acceleration of charged particles, opening new perspectives namely in high energy beam facilities.

*Gérard Mourou nobel price 2018*

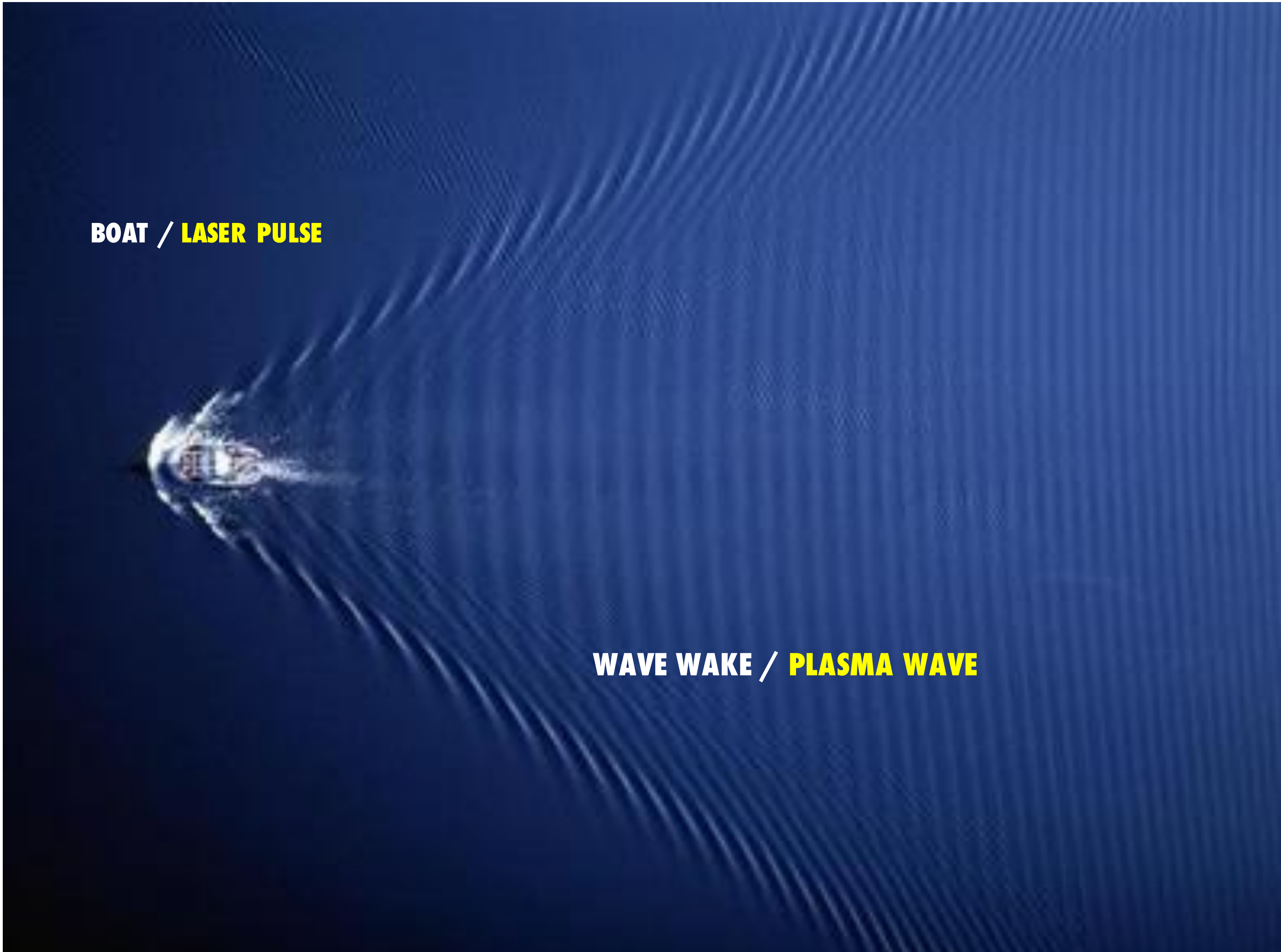
*"Chirped pulse amplification"*

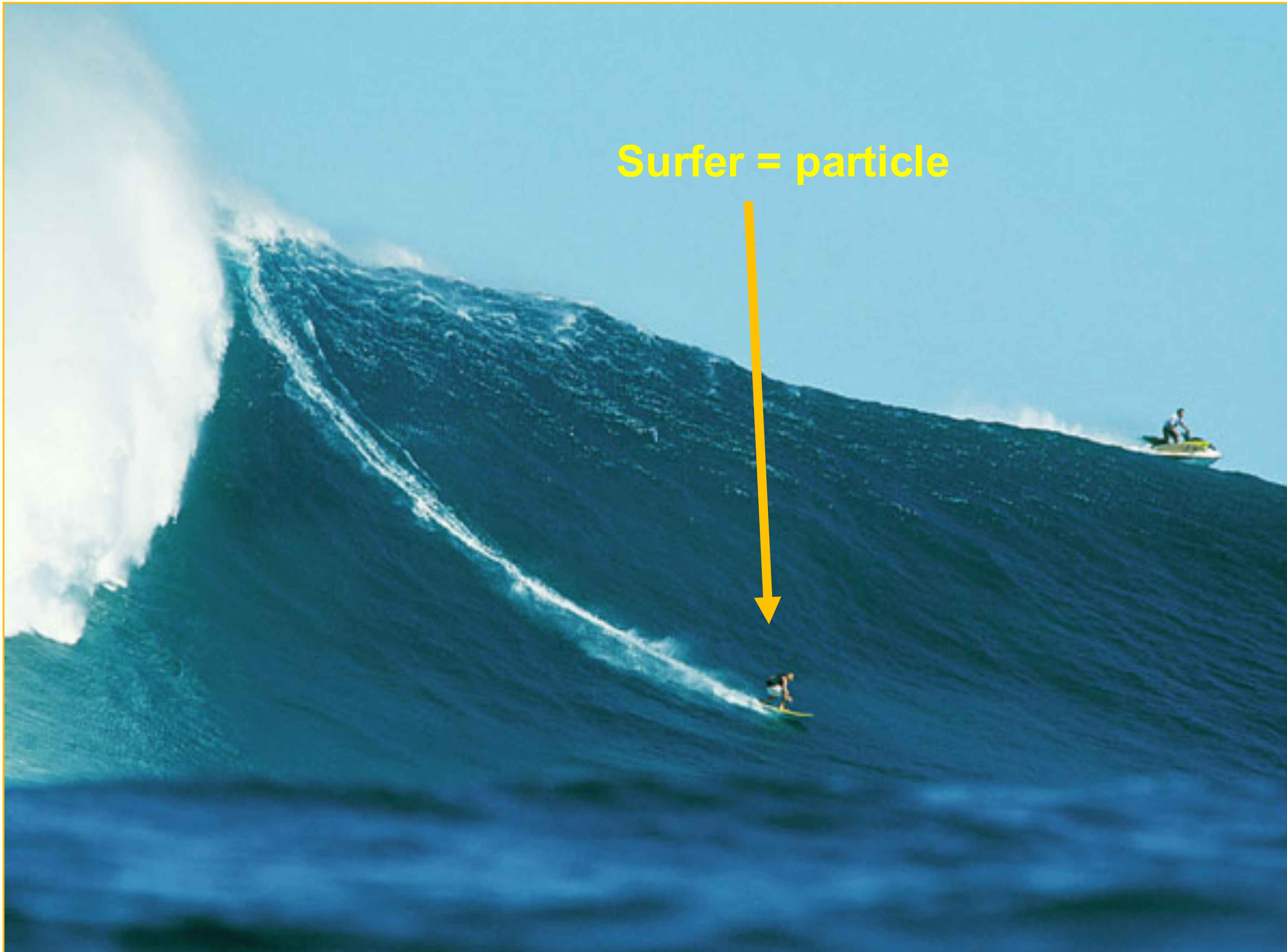
*Nobel prize motivation: "for their method of generating high-intensity, ultra-short optical pulses."*

At intensities of $10^{18}$ W/cm$^2$ the laser matter interaction is governed by electron relativistic behavior producing a lot novel effects as X and gamma ray production electron and proton acceleration, neutron and positron production and so on




***"Chirped pulse amplification"***

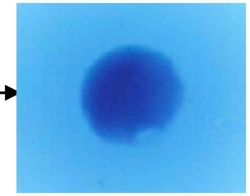

BOAT / LASER PULSE
WAVE WAKE / PLASMA WAVE


Surfer = particle

Energy Source: Laser

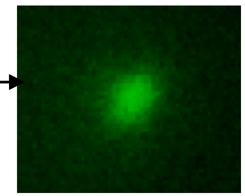
Laser focusing and control

**Overdense Plasma**
*Laser-solid interactions*

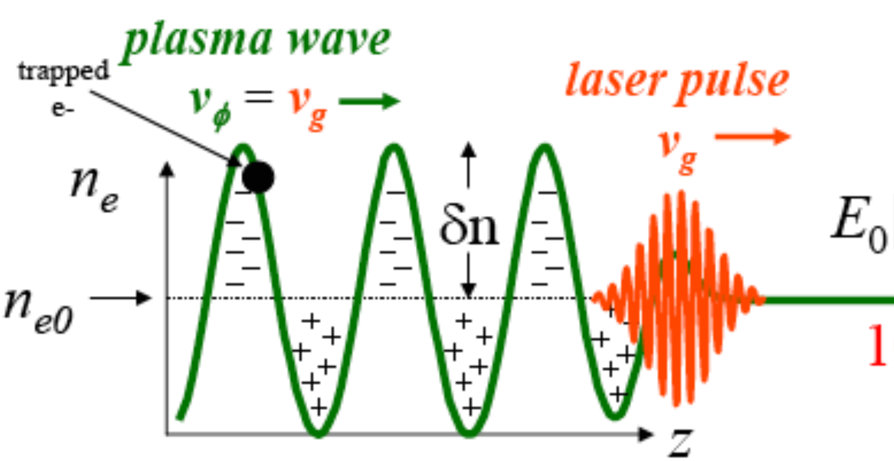


Protons, ions,
e-, e+,
broad spectrum,
lower E,

**Underdense Plasma**
*Laser-gas interactions*



e-, e+,
narrow spectrum,
GeV energy



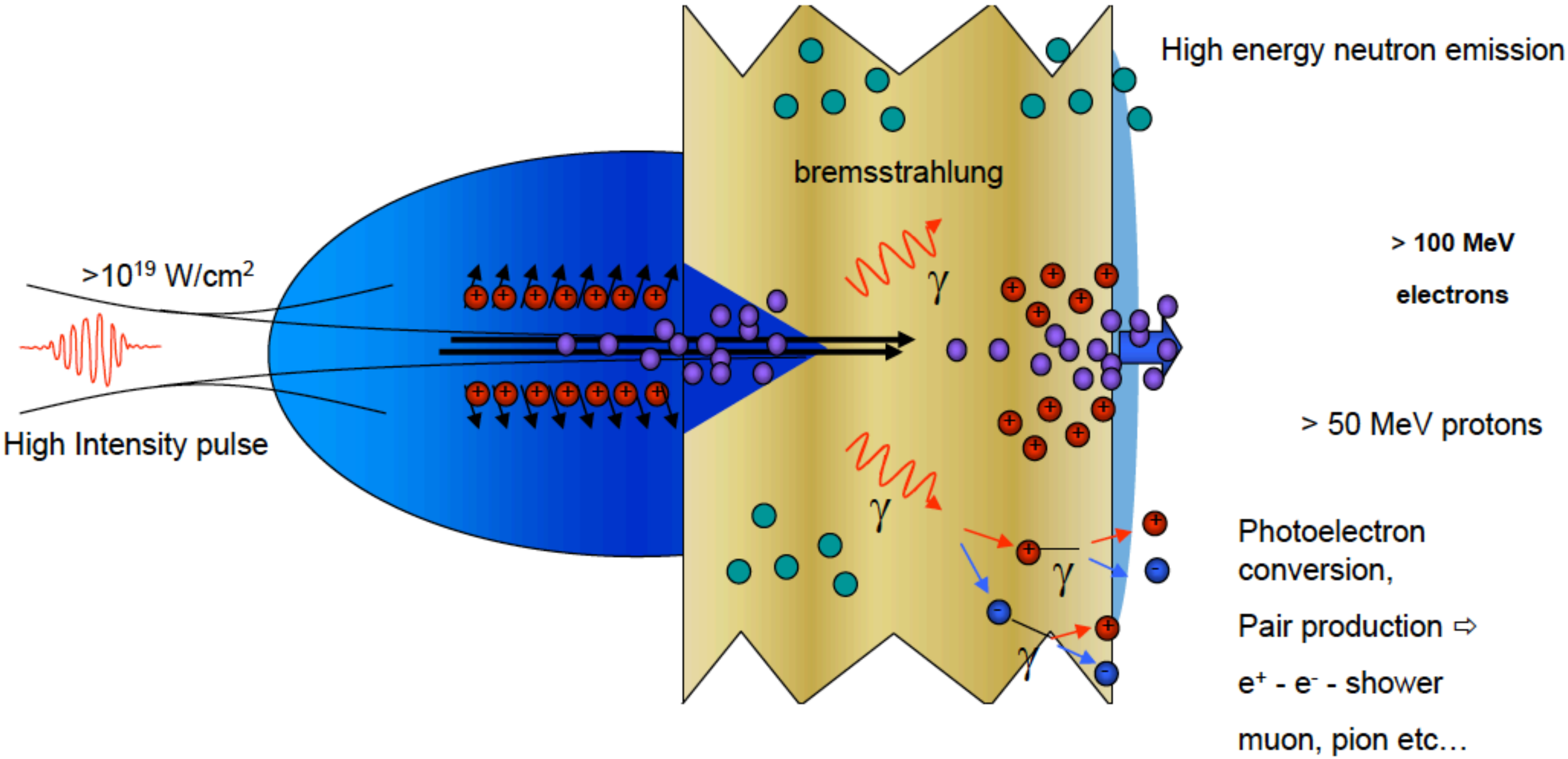

**Plasma frequency**

$$E_0[V/cm] = \frac{mc\omega_p}{e} = 0.96(n_e[cm^{-3}])^{1/2}$$

$10^{11}$ V/m

$10^{18}$ cm$^{-3}$

**Plasma density**



High energy neutron emission
bremsstrahlung
$>10^{19}$ W/cm$^2$
High Intensity pulse
γ
γ
γ
γ
**> 100 MeV**
**electrons**
> 50 MeV protons
Photoelectron
conversion,
Pair production ⇨
$e^+$ - $e^-$ - shower
muon, pion etc…

# Why a plasma to accelerate electrons ?

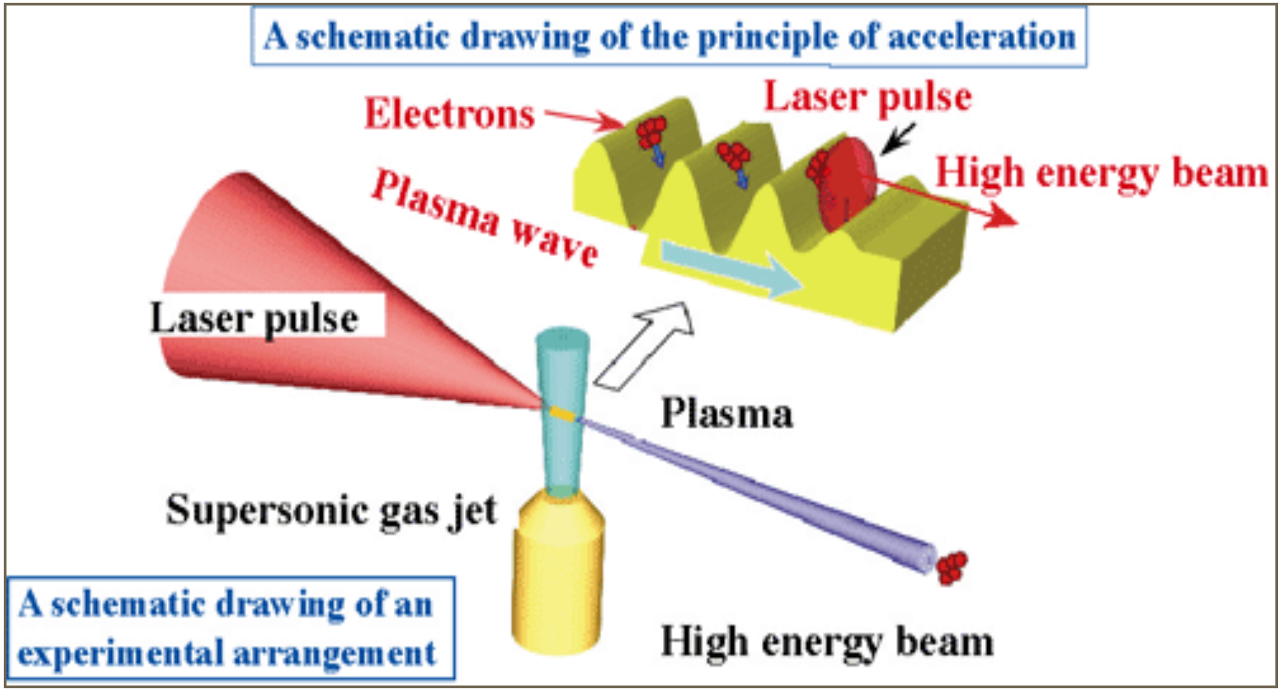
- no limits to the accelerating electric fields
- electron plasma waves fit requirements for particle acceleration:
  - intense longitudinal electric fields
  - phase velocity very close to the speed of light c

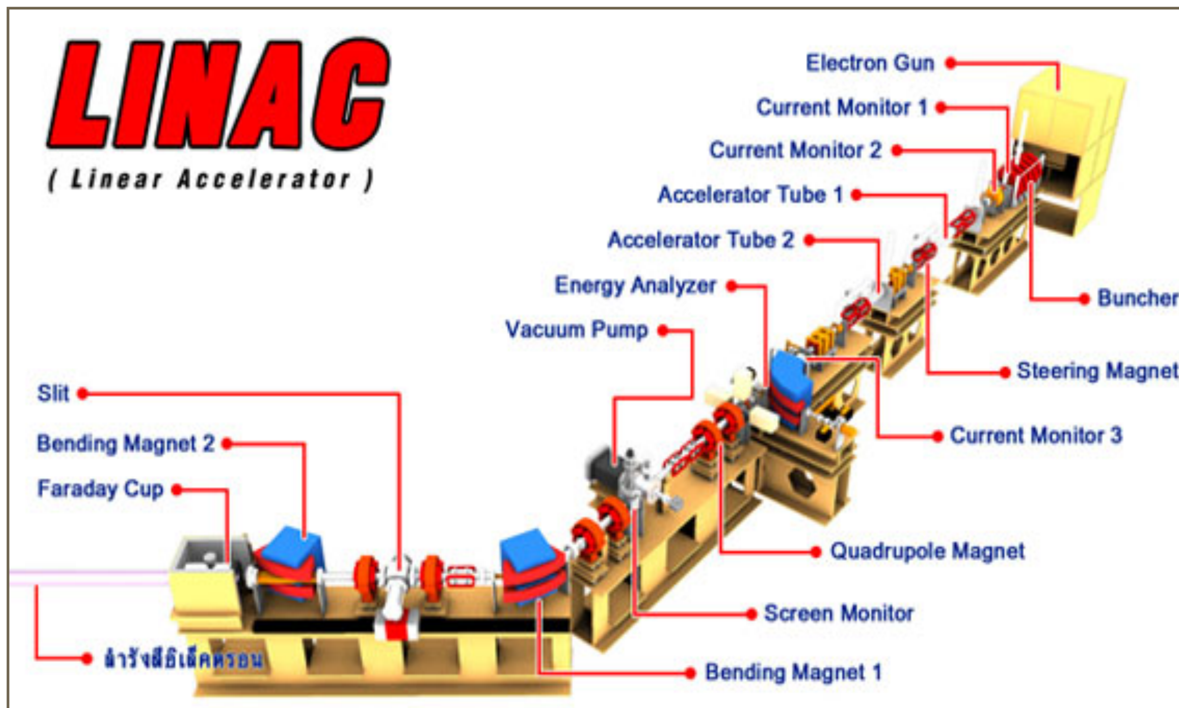
**Conventional Accelerators**

- electron gun (photocathode) + accelerating cavities (RF)
- accelerating fields **<100 MV/m**

**Laser-Plasma Accelerators**

- plasma medium (gas …) + electron plasma waves (intense laser)
- accelerating fields **>100 GV/m**


A schematic drawing of the principle of acceleration
Electrons
Laser pulse
High energy beam
Plasma wave
Laser pulse
Plasma
Supersonic gas jet
A schematic drawing of an experimental arrangement
High energy beam


LINAC
( Linear Accelerator )
Electron Gun
Current Monitor 1
Current Monitor 2
Accelerator Tube 1
Accelerator Tube 2
Energy Analyzer
Vacuum Pump
Slit
Bending Magnet 2
Faraday Cup
Buncher
Steering Magnet
Current Monitor 3
Quadrupole Magnet
Screen Monitor
Bending Magnet 1
ลำรังสีอิเล็คตรอน

Numerical examples of the electron beam energy scaling (W. Mori et al, UCLA)

| P(PW) | $\tau$ (fs) | $n_e$($cm^{-3}$) | $W_0$ (μm) | L(m) | E(J) | Q(nC) | E(Gev) |
|---|---|---|---|---|---|---|---|
| 0.12 | 30 | 2e18 | 15 | 0.009 | 3.6 | 1.3 | 1.12 |
| 1.2 | 100 | 2e17 | 47 | 0.28 | 120 | 4 | 11.2 |
| 12 | 300 | 2e16 | 150 | 9 | 3.6k | 13 | 112 |
| 120 | 1000 | 2e15 | 470 | 280 | 120k | 40 | 1120 |

A huge number of projects in EU

LASERLAB EUROPE

The Integrated Initiative of European Laser Research Infrastructures

http://www.laserlab-europe.net/

**ELI would be the first infrastructure dedicated to the fundamental study of laser-matter interaction in a new and unsurpassed regime of laser intensity: the ultra-relativistic regime ($I_L > 10^{23}$ W/cm$^2$)**

**attosecond science**

**laser-plasma interaction**

**laser plasma accelerators**

**laser-produced X-ray beam**

**high energy physics**

**nuclear physics and astrophysics**

**Extreme Light Infrastructure (ELI)**

http://www.hiper-laser.org/

HiPER is a proposed European High Power laser Energy Research facility dedicated to demonstrating the feasibility of laser driven fusion as a future energy source.

◆ From than on all practices concerning the use of laser in relativistic and ultra relativistic regime have been regarded as practices with radiation risk and consequently treated.

◆ The aim of this paper is to focus the radiological protection aspects, mainly

- *licensing requirements,*
- *prompt radiation production*
- *residual radiation production,*
- *radiation shielding*
- *shielding materials*
- *radiation monitoring*
- *determination of any environmental impact*
- *specific operational requirements of an "accelerator facility",*

that a project manager should take into account in designing a facility for laser based accelerators from hundreds terawatt to hundred petawatt peak power.

- **In the European Union the regulations laying down basic safety standard for protection against the danger arising from exposure to ionizing radiation are into the Council Directive 2013/59/Euratom of 5 December 2013 1996.**

- **Such Directive, taking into account the recommendations of *International Advisory Bodies*, lays down basic safety standards for the protection of the health of workers and general public against the danger arising from ionizing radiation.**

- **Each State of the European Union may adopt more restictive policies.**

Advisory Agency

IAEA

The IAEA is the world's center for cooperation in the nuclear field.

ICRU

Radiometric quantities

The ICRU, has as its principal objective to develop and promulgate internationally accepted recommendations on radiation related quantities and units, terminology, measurement procedures, and reference data for the safe and efficient application of ionizing radiation to medical diagnosis and therapy, radiation science and technology, and radiation protection of individuals and populations.

Dosimetric quantities

ICRP

Radiation protection quantities

The ICRP is an advisory body providing recommendations and guidance on all aspects of protection against ionizing radiation.

-basic dosimetric quantities

-dose limitation quantities

**The basic consideration of radiation protection were stated in Publication 26 (1977), reiterated in Publication 60 (1990) and in Publication 103 of 2007.**

**The last publication provides**

- ***the biological aspects of radiation protection;***
- ***the quantities used in radiological protection;***
- ***the system of radiological protection of humans included a system of dose limitation***
  - **justification;**
  - **optimization of protection;**
  - **application of dose limits**
- ***the implementation of commission's recommendations***
- ***as well as medical exposure and protection of the environment***

# Accelerator shielding

**The aim of an efficient accelerator shielding design is to attenuate the prompt radiation produced to levels that are acceptable to humans outside the shield, at a reasonable cost and without compromising the utility of the apparatus for its design purposes.**

**Such goal is obtained in the following stages**

- **Specification of required dose equivalent (rate) outside the shielding**

***well known for accelerators***

- **Determination of the source term**

***open question for accelerator laser based facilities***

- **Design of the shield with adequate attenuation to achieve the required dose equivalent (rate) limitation**

**Taking into account factors as e.g.**

**Availability of space** **Induced radioactivity** **Regulatory limits** and so on

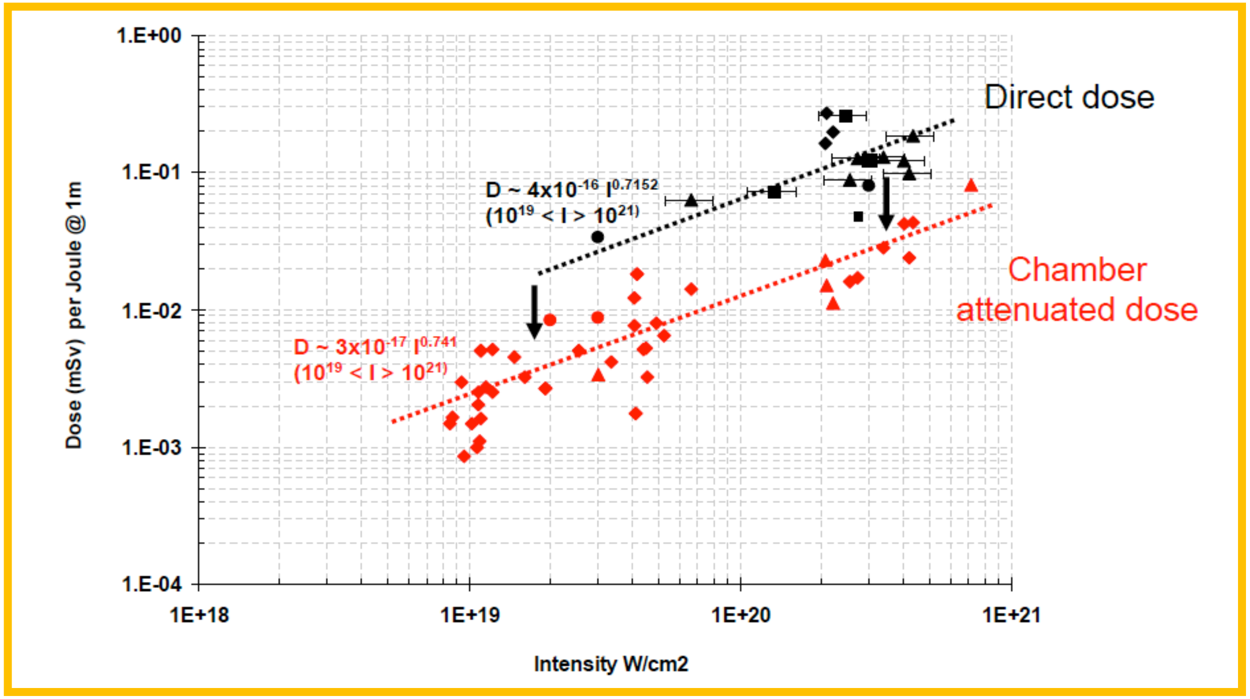
**Environmental radiation** **Shielding materials** **Trend in regulatory limits**

- **Measurements on existing facilities up to 1 PWatt**

**Not easy task**

- **because the modality of production of particles (pulsed radiation);**
- **because of the availability of instruments able to measure very short pulses.**

- **Only dosimetric evaluation are mainly available**




**From Rob Clarke**
***Radiation Protection Supervisor***
**CLF High Power Lasers**
**STFC Rutherford Appleton Laboratory**

- **Any extrapolation to higher power it's not easy and is quite impossible for power higher than 100 PWatt,**

# Determination of the source term

❖ ***To obtain the source term that is particle yields reported in term of physical distribution***
***such***

***type of radiation***
***energy***
***fluence***
***angle of emission***

***only numerical simulation are possible with the well known problems of code validation.***

**In order to simulate or calculate (analytically) the source term a simple description of the experiment and the target is necessary according to the following items**

- **type of target, like thin Al foil or He gas jet;**
- **characteristic of the laser, i.e. energy, pulse length, focal spot, wavelength;**
- **experimental layout, i.e. angle of incidence, focal number f/5, polarization of the laser;**

# Determination of the source term

**The main code used for such calculation is**
R. A. Fonseca *et al.*, "OSIRIS: A Three-Dimensional, Fully Relativistic Particle in Cell Code for Modeling Plasma Based Accelerators", Lecture Notes in Computer Science 2331, p.342-351, Springer Berlin / Heidelberg, (2002).

$$N(x) = \begin{cases} 0 & \text{for } x \geq E^{max} \\ \sum_i \frac{N_i^T}{T_i} \exp\left(\frac{x}{T_i}\right) + \sum_i 2\frac{N_j^G}{\Delta E_j^G} exp\left[-4ln2\sqrt{\frac{2\,ln2}{\pi}}\left(\frac{x-N_j^G}{\Delta E_j^G}\right)^2\right] & \text{for } x < E^{max} \end{cases}$$

thermal component

quasi-monochromatic component

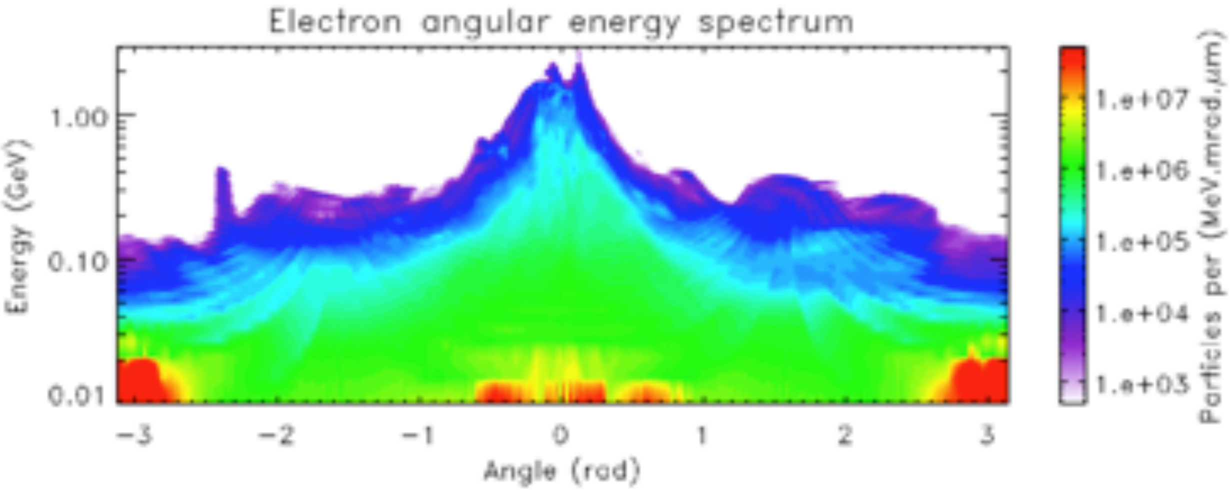
$N_i^T$ the total number of particle per <u>steradiant</u> $N_j^G$

$T_i$ temperature in MeV

$E_j^G$ the central energy in MeV

# Determination of the source term

Target Thickness 1 μm Density 0.088 g/cm³ 2kJ 15 fs $1.6 \times 10^{23}$ *W/cm²*
Material H

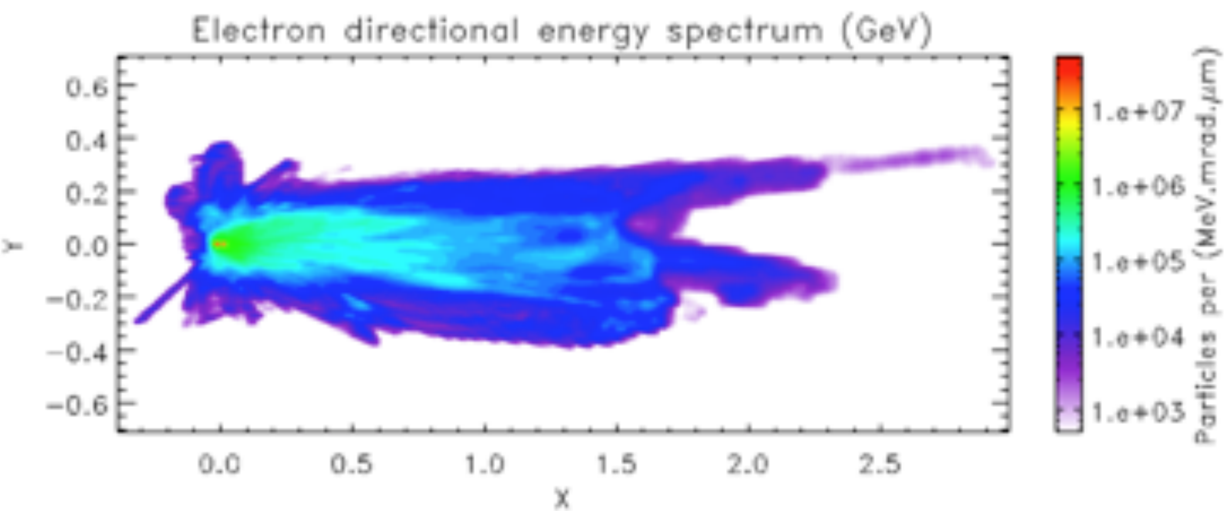



$N_i^T$=1.9e$^{12}$e$^-$/sr

$T_i$=270 MeV

$E^{max}$=3000 MeV

2D generated data




$N_j^G$ =7.5e$^{10}$e$^-$/sr

$E_j^G$=1330 MeV

# Determination of the source term

The higher the energy of particles accelerated the more complex the characteristic of the prompt radiation

Electrons, protons, ions or photons are produced when a very powerful laser interacts with a gas jet or a solid target

Such radiation, after the interaction with the experimental chambers walls and/or the shielding materials, will generate, via electromagnetic or hadron cascade, the so-called prompt radiation.

That is

bremssstrahlung;
neutron;
muons;
pions;
kaons;

any other particle (charged particles, ions, nuclear fragments and delayed radiation)

**The thickness of the shielding depends from the attenuation of such particles and from the radiation protection policy chosen.**

**According to the recommendations of ICRP, to the European Directives as well as the laws in force in such matter, the recommended dose limits are listed in the following table.**

Table 6. Recommended dose limits in planned exposure situations[a].

| Type of limit | Occupational | Public |
|---|---|---|
| **Effective dose** | 20 mSv per year, averaged over defined periods of 5 years[e] | 1 mSv in a year[f] |
| **Annual equivalent dose in:** | | |
| Lens of the eye[b] | 150 mSv ***20 mSv*** | 15 mSv |
| Skin[c,d] | 500 mSv | 50 mSv |
| Hands and feet | 500 mSv | – |

The radiation protection policy would suggest to adopt radiological requirements ***reasonably*** lower than the limits above recommended.

**The constraints and reference levels for members of the public in planned exposure situation should be smaller than the public dose limits, and would typically be set by the national regulatory authorities**

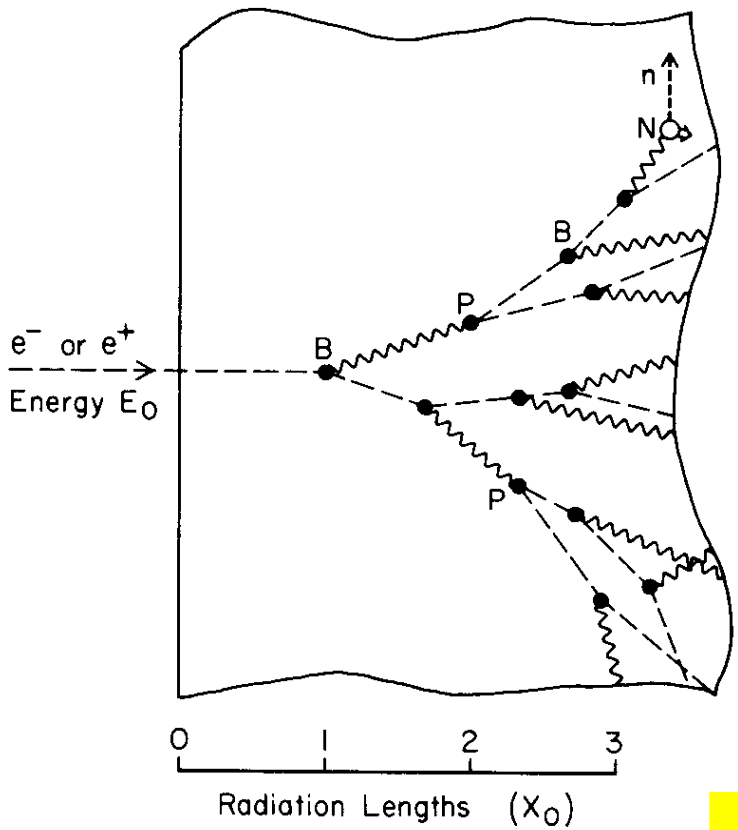
**Our licensing authorities remembered recently to us that the shielding design must ensure an effective dose for the members of the public beyond the boundary of the radiological installation of 10µSv/y!!**

**That is a so called trivial dose equal few percent of the annual dose limit for public exposure equal annual risk of death of $10^{-7}$ ( ICRP 104)**

**Impossible to measure!! And used also for prompt radiation**

# Electrons

**At "electron accelerators" of all energies bremstrahlung photons dominate the secondary radiation field via the electromagnetic cascade.**




**Brems ➡ pair ➡ brems …**

**1 step ~1 $X_0$ for electons, ~9/7$X_0$ for photons**

**$X_0$ is that distance in which an electron loses 1/e its energy by emitting x-rays**

**Multiplication stops when $E_e$ drops below $E_c$**

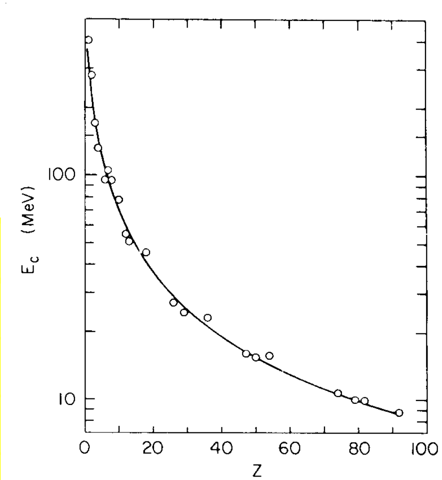
**Critical energy $E_c$:**

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

$$E_c\ [\text{MeV}] = 800/(Z + 1.2)$$

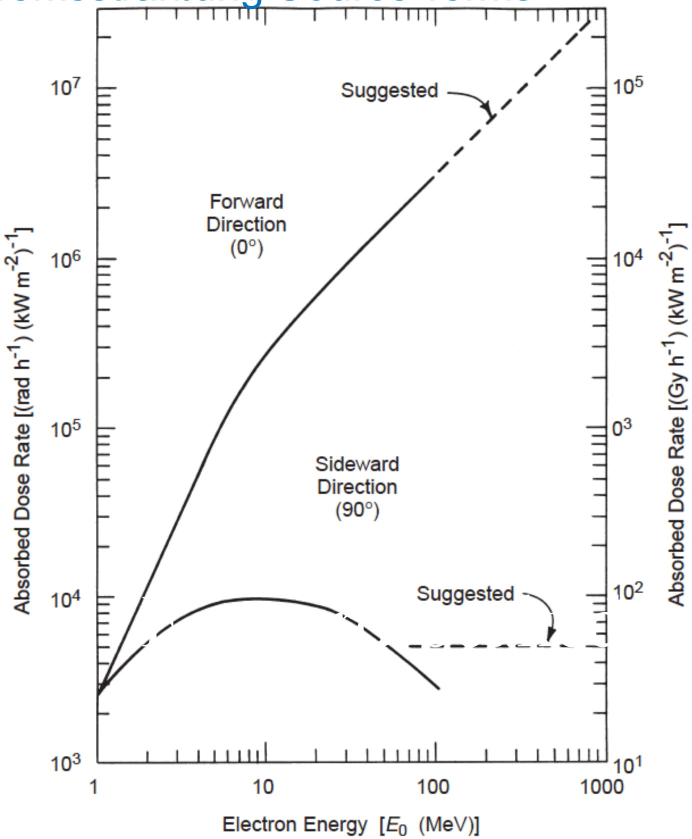
$$\frac{1}{X_0} = 4\alpha Z^2 r_0^2 \ln\left(183 Z^{-1/3}\right) \quad \text{cm}^2\text{g}^{-1}$$

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



## Electrons

Bremsstrahlung Source Terms




Forward-peaked:

$$\theta_{1/2}(^\circ) = 100 / E_0(MeV)$$

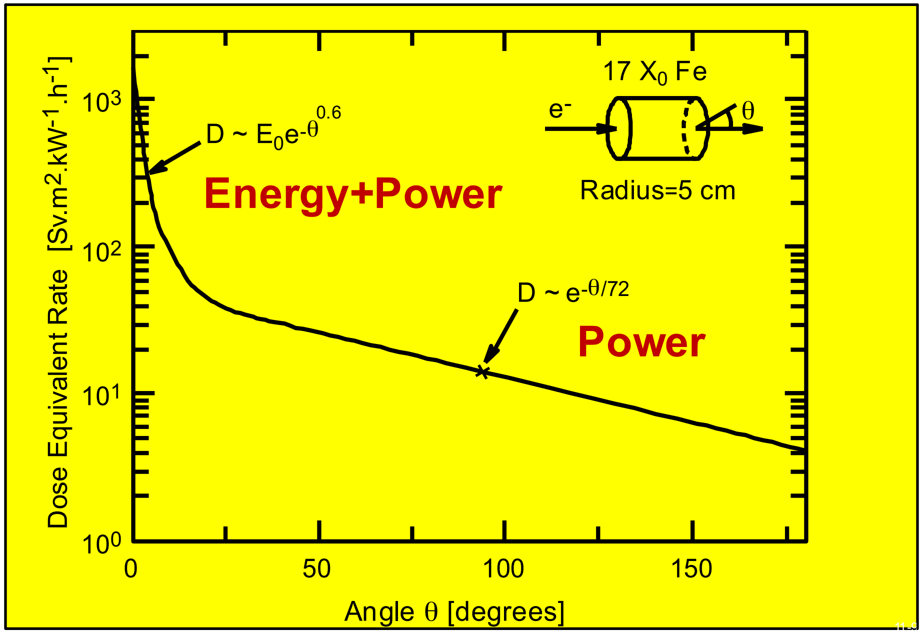
## Rules of thumb:(for thick hi-Z targets)

**At 0°, $E_0$ > 20 MeV:**

**$dD/dt = 300\ E_0\ (Gy\ h^{-1})\ (kW\ m^{-2})^{-1}$**

**At 90°, $E_0$ > 100 MeV:**

**$dD/dt = 50\ (Gy\ h^{-1})\ (kW\ m^{-2})^{-1}$**



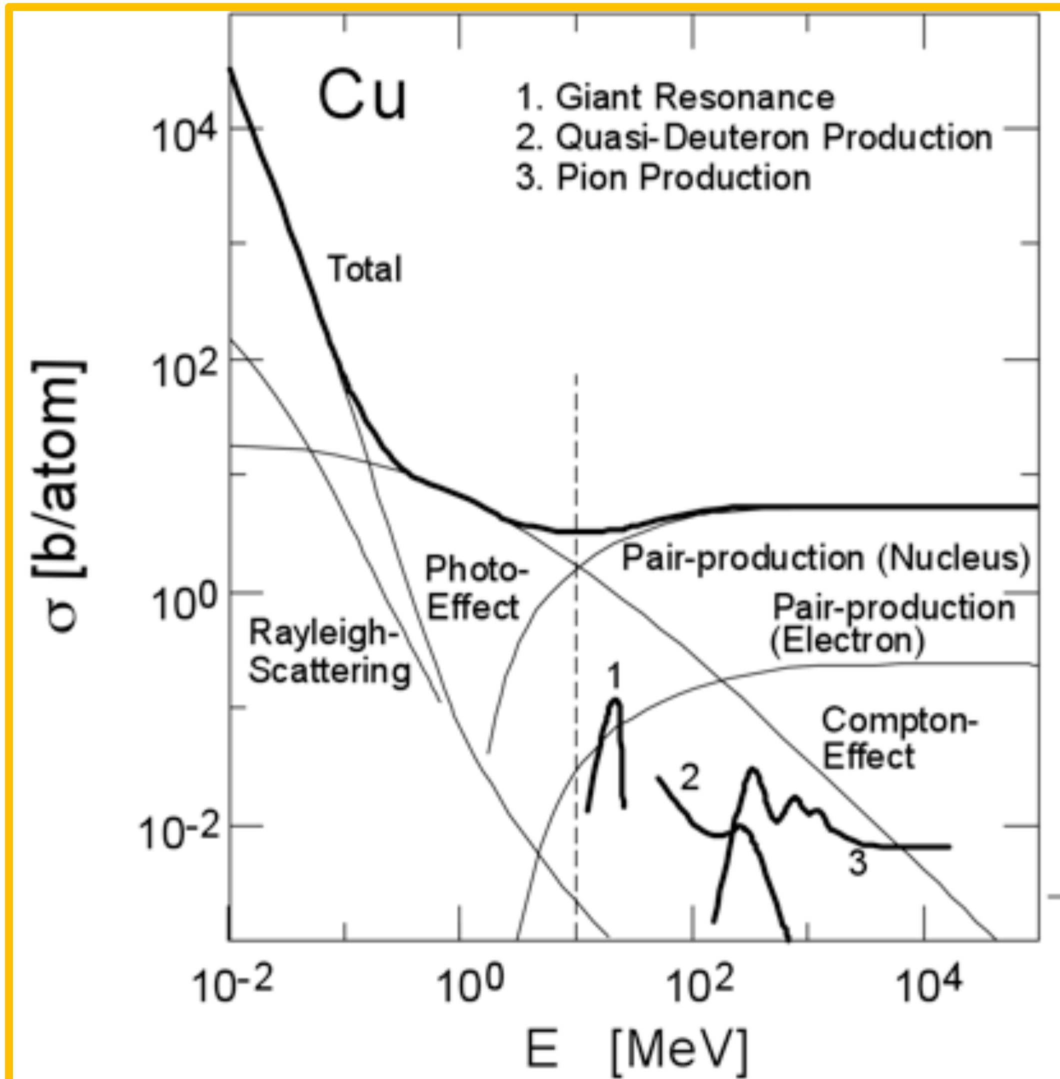

**$\theta_{1/2}$ = 1° for 100 MeV, 0.01° for 10 GeV**

# Electrons_Photoneutrons

**Cross-sections of major photon interactions in copper as function of energy.**

- **1 Peak at 20-23 MeV for A< 40, 13-18 MeV for heavier nuclei**
- **2 Photons interact with a p-n pair**
- **3 For E > 140 MeV, pions can be produced; pions then generate neutrons**

**Largest resonance at E ~300 MeV,**
**σ≈const in GeV region**



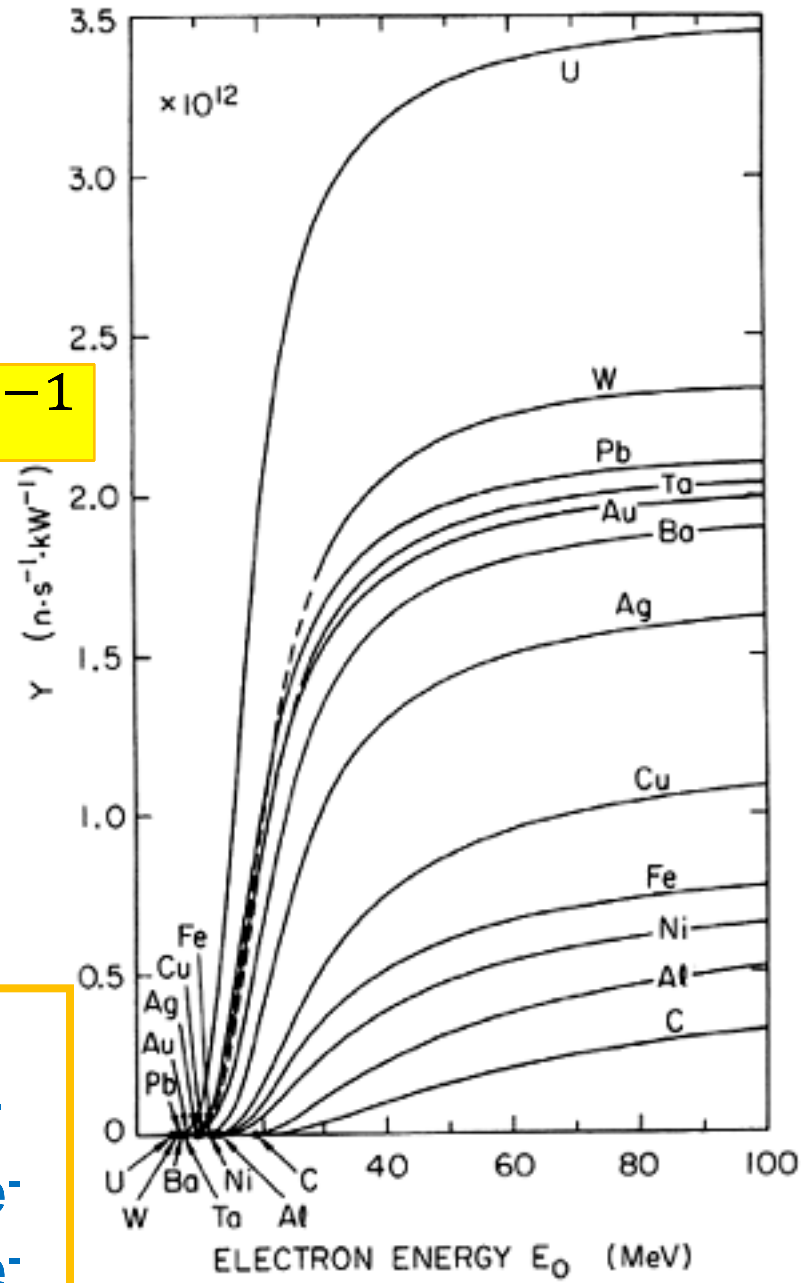

**The most penetrating component**

# Electrons

## Giant resonance neutrons

Neutron yields from infinitely thick targets, per kW of electron beam power

$$Y = 1.21 * 10^{11} Z^{0.66}\, ns^{-1} kW^{-1}$$




**High energy neutrons (E>25MeV)**

**For 400 MeV of electrons**

between 0˚ - 30˚ $2.5 \times 10^{-4}$ n $sr^{-1}/e^-$

between 30˚ - 60˚ $2.1 \times 10^{-4}$ n $sr^{-1}/e^-$

between 60˚ - 120˚ $1.2 \times 10^{-4}$ n $sr^{-1}/e^-$

# Electrons - muon production

- Muon production is analogous to $e^+/e^-$ pair production by photons in the field of target nuclei when photon energy exceeds the threshold $2m_m c^2 \approx 211$ MeV.

- $\mu^+/\mu^-$ pair will occur with a much lower probability than $e^+/e^-$ pair.

$$\frac{\sigma(e^+,e^-)}{\sigma(\mu^+,\mu^-)} \approx \left(\frac{m_\mu}{m_e}\right)^2 = 4*10^4$$

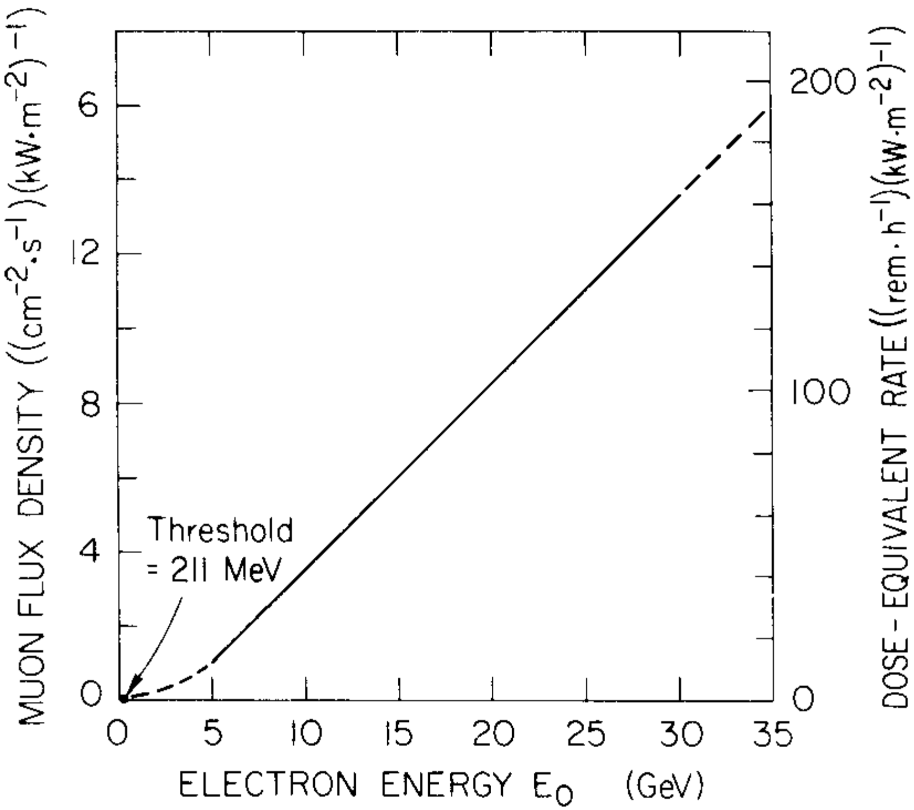
- Muon are also produced by the decay of pions and/or kaons, but the magnitude of fluences is small compared to the fluences from direct $\mu^+/\mu^-$ pair production

- Muon angular distribution is extremely forward-peaked, and this distribution narrows further with increasing energy.

- Important above $E_0 \sim 1$ GeV

- Energy loss only by ionization very penetrating and forward peaked

- Yield $\sim E_0$ (per unit beam power)

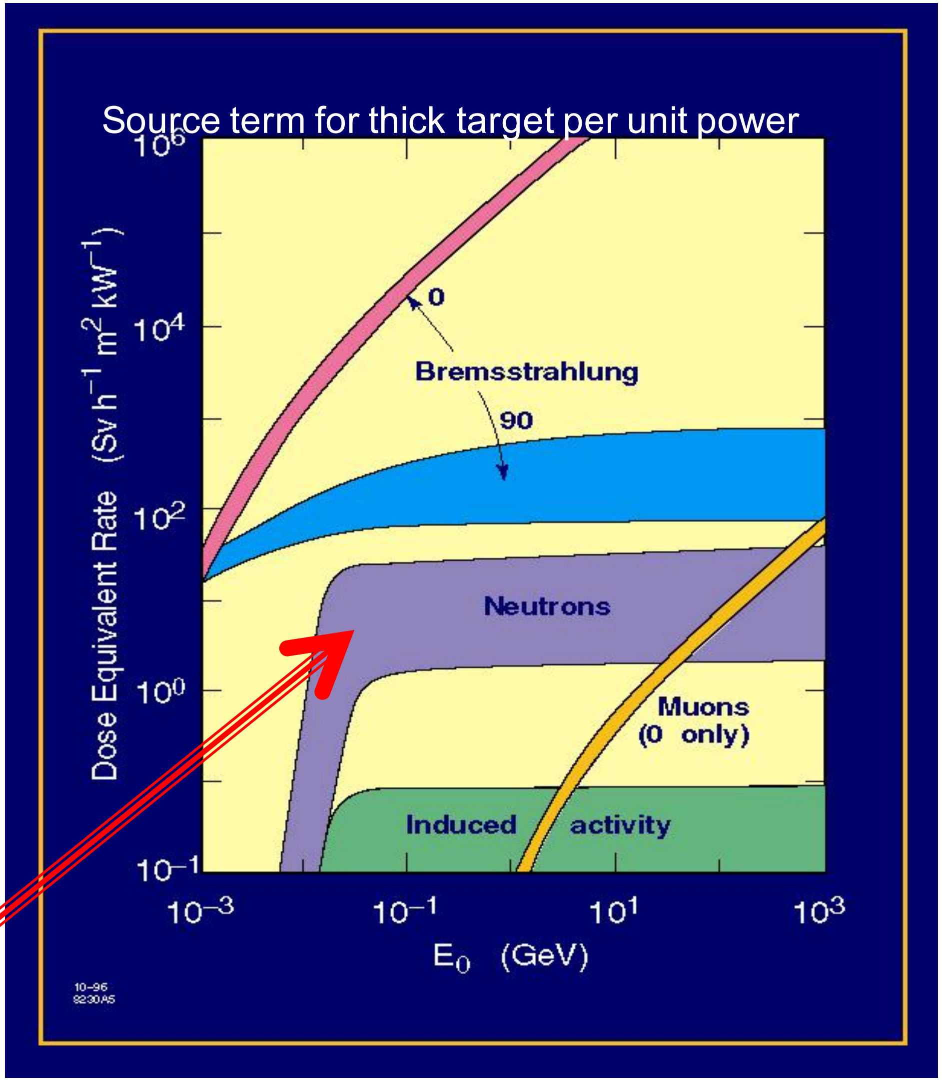



- Muon generally become a problem at higher energies mainly behind beam dumps, and only within a narrow cone of a few degrees, depending on energy, around the 0º direction.

# Electrons

**Dose equivalent rates per unit primary beam power, produced by various types of secondary radiation from an electron target, as a function of primary beam energy, if no shielding is present (qualitative).**

**The width of the bands suggests the degree of variation found, depending on such factors as target material and thickness.**

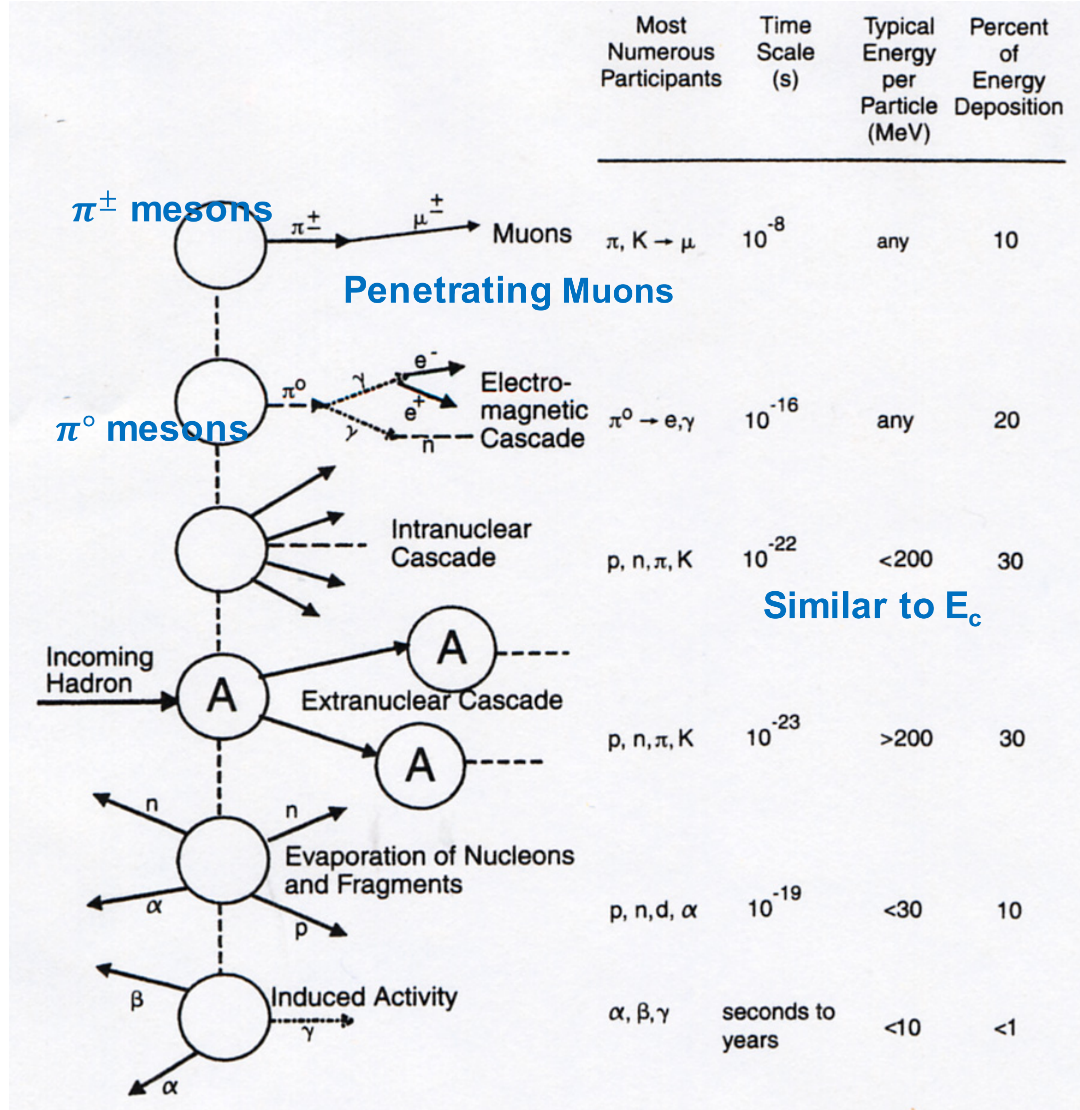



| | | |
|---|---|---|
| $E_{threshold}$ ~ 6-13 MeV | | |
| for most materials | | |
| but for | D, | $E_{th}$ = 2.23 MeV |
| | $^9$Be | 1.67 MeV |
| organic materials | $^{12}$C | 18.72 MeV |
| air, water | $^{16}$O | 15.67 MeV |

- In hadronic cascade the situation is much more complicated

The collision of high energy nucleon with a nucleus gives rise to a large numbers of particles, mainly nucleons, pions and kaons

The main means of energy transfer is due to the interaction of high-energy nucleon that is hadrons with energy higher than 150 MeV, that serve to propagate the cascade.




- Nucleons in the energy range 20-150 MeV also transfer their energy mainly via nuclear interaction but at these energies charged particles are rapidly stopped by ionization and thus only neutrons predominate at lower energies.

- Neutrons dominate the prompt radiation field outside the thick shield.

# Accelerator shielding-Symmetric cascades

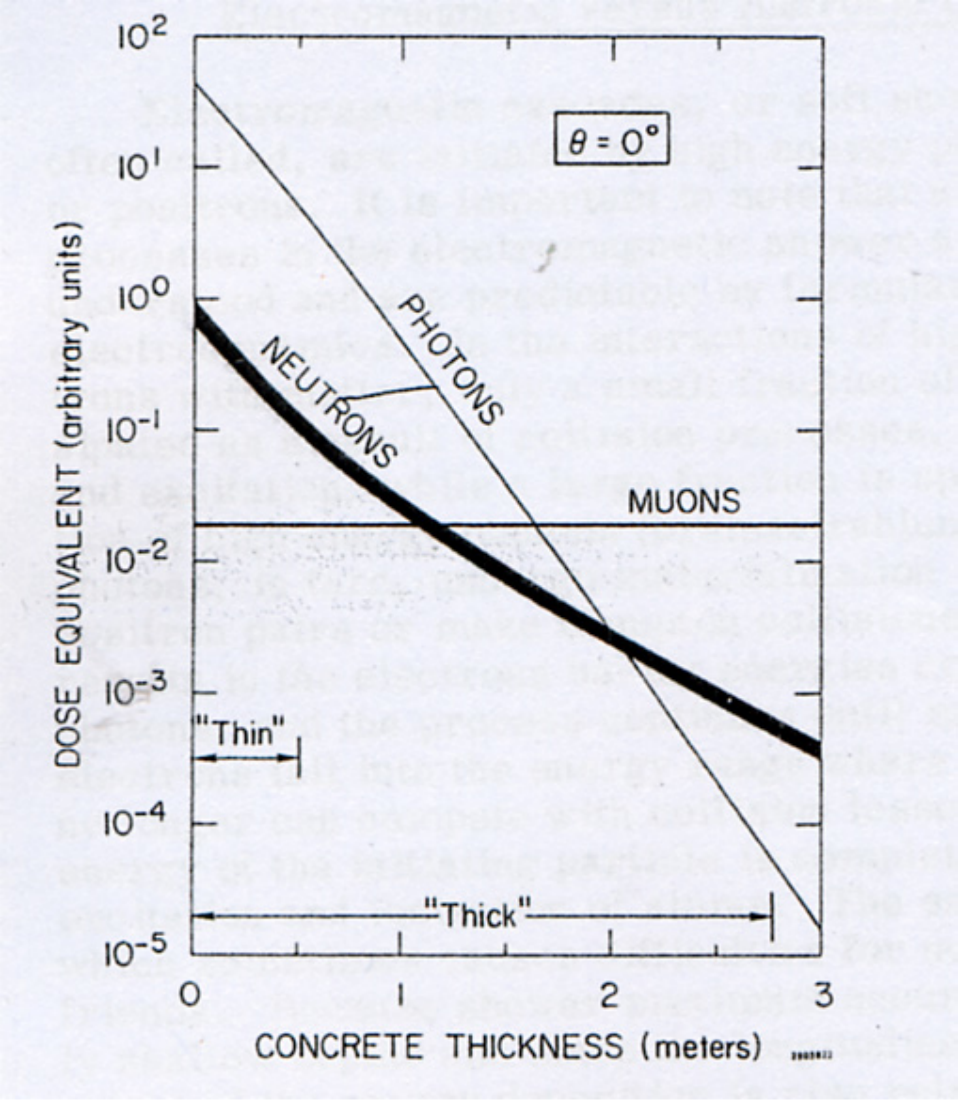
**As previously shown the radiation environments of high energy electron and proton accelerators have interesting similarities and differences**

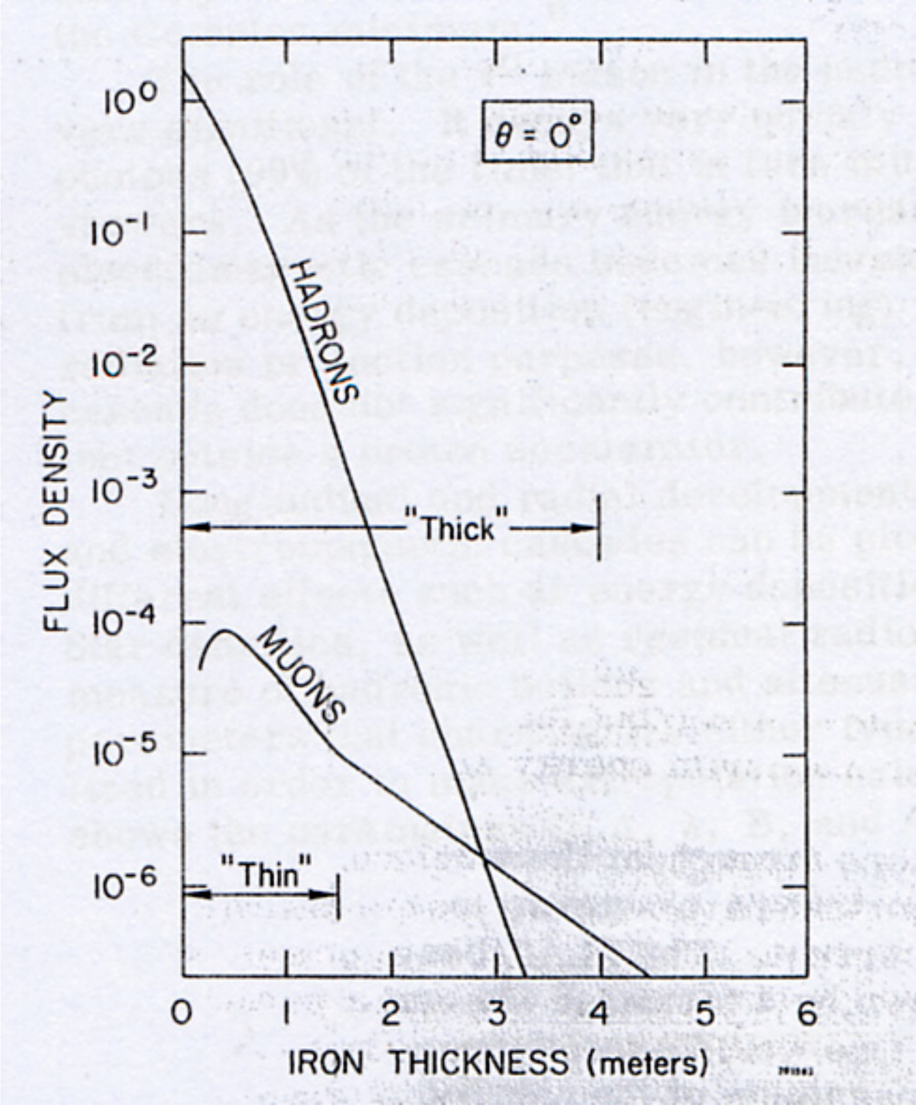
**A multiplying "shower" is the result of both**

**The electromagnetic cascade produce a *hadronic cascade***

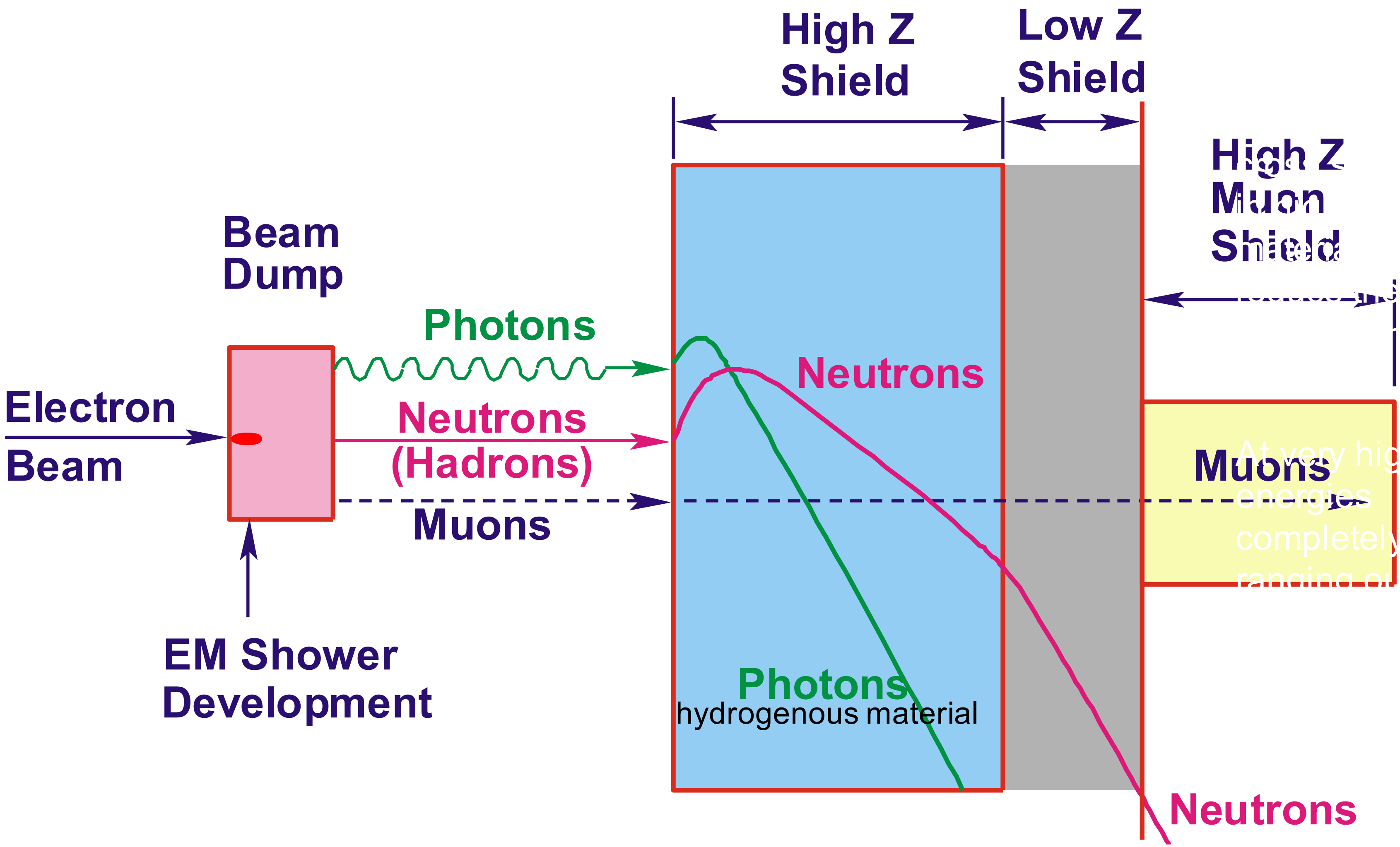
**The hadronic cascade produce *an electromagnetic cascade***

**But**
**the electromagnetic cascade is much shorter and less penetrating**
**A thick shielding is governed by the hadronic one**




The overall conclusion is that thick shielding situations are similar, although not necessarily comparable in magnitude unless the electron machine operates at high beam power.



High Z
Shield
Low Z
Shield
High Z
Muon
Shield
Beam
Dump
Photons
Electron
Beam
Neutrons
(Hadrons)
Muons
Neutrons
Muons
EM Shower
Development
Photons
hydrogenous material
Neutrons

# Shielding materials

**Any material in sufficient quantity may be used for shielding against accelerator radiation**

**Ordinary concrete**

**2.35 $gcm^{-3}$**

| Aggregates | Heavy concrete | Steel | Earth |
| --- | --- | --- | --- |
| Magnetite | 3.53 $gcm^{-3}$ | 7.8 $gcm^{-3}$ | 1.7-2.35 $gcm^{-3}$ |
| Barytes | 3.35 $gcm^{-3}$ | | |
| Magnetite + steel | 4.64 $gcm^{-3}$ | | |

## Special materials

Lead    Lead alloys    Tungsten    Depleted uranium

Hydrogenous materials    wood
water    polyethylene

Hydrogen is thus important for neutron dosimetry because one-half of the energy of intermediate and fast neutrons is transferred to the recoiling hydrogen atoms. This energy transfer relationship also explains why hydrogenous materials are so effective in slowing down (or moderating) high-energy neutrons.

Main factors used for selecting a shielding material

Possibility of shielding against X , g and neutrons

Multiple use for shielding and structural purposes

Required thickness and weight

Stability of shielding    Homogeneity of shielding

Cost including installation and maintenance

# Ambient dose equivalent rate

$S_i$= source term

r = distance of interest

d = thickness interposed

λ = attenuation coefficient

$f_i$= conversion coefficients for use in radiological protection against external radiation

$$\sum \dot{H}_i = \sum_i \frac{S_i}{r^2} e^{-\mathrm{d}/\lambda_i} * f_i$$

Conversion coefficients

$$f_{GRn} = 2.87 \frac{\frac{\mu Sv}{h}}{\frac{Neutrons}{cm^2 s^{-1}}}$$

$$f_{HEn} = 1.8 \frac{\frac{\mu Sv}{h}}{\frac{Neutrons}{cm^2 s^{-1}}}$$

# Bremsstrahlung

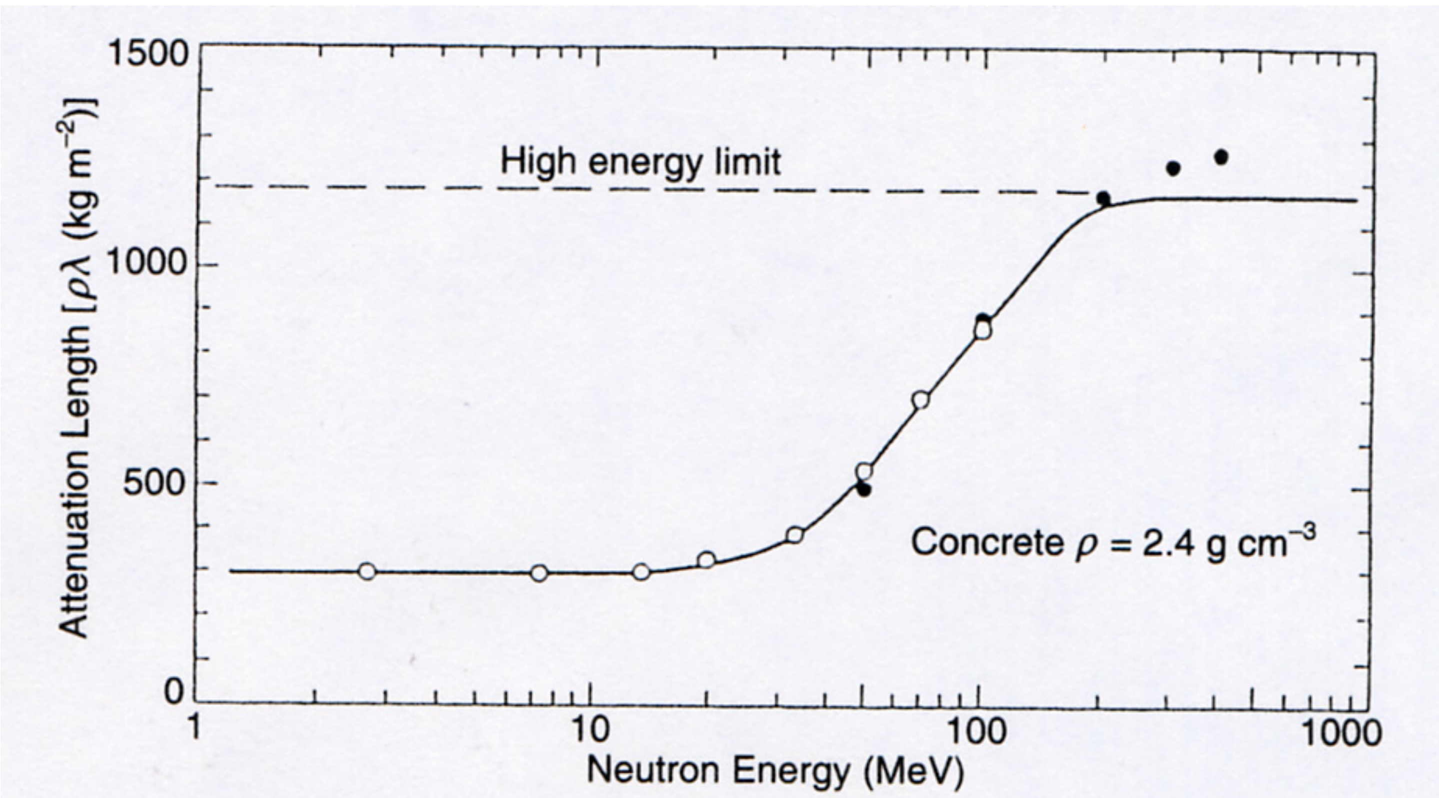
| Material | Density ($g/cm^3$) | Angle (gradi) | Attenuation length λ (cm) |
|---|---|---|---|
| Concrete | 2.3 | 0° | 20.4 |
| Concrete | 2.3 | 90° | 18.7 |
| Heavy concrete | 3.4 | 0° | 13.8 |
| Heavy concrete | 3.4 | 90° | 12.6 |
| High Density Polyethylene | 1.01 | | 69.3 |
| Lead | 11.35 | | 2.2 |
| Iron | | | 4.76 |
| Earth | | | 43.8 |

# Giant resonance neutrons

| Material | Density ($g/cm^3$) | Attenuation length λ (cm) |
|---|---|---|
| Lead | 11.35 | 18.30 |
| Concrete | 2.3 | 17.4 |
| Heavy concrete | 3.4 | 48.9 |
| Earth | 1.6 | 52.8 |
| High Density Polyethylene | 1.01 | 6.36 |

# High energy neutrons (E>25MeV)

| Material | Density (g/cm$^3$) | Attenuation length λ (cm) |
|---|---|---|
| Lead | 11.35 | 16.8 |
| Concrete | 2.3 | 8.9 |
| Heavy concrete | 3.4 | 33 |
| Earth | 1.6 | 56.3 |
| High Density Polyethylene | 1.01 | 61.4 |



Radioactivity can be induced in solid components, air and water at particle accelerators.

The three photonuclear reactions previously described are responsible for most of the produced activity in the electrons machine components

Furthermore, neutrons resulting from these reactions can activate surrounding materials (*e.g.* soil and air and cooling water )

The produced activity in a proton accelerator structure will be related to the number of inelastic interactions produced by the proton and its cascade in the material of interest (n,xn), (p,xn), and some from spallation, fragmentation and capture.

**According to their susceptibility to activation around high energy machines, it is possible to classify various materials in following categories:**

**Low:** lead, ordinary concrete, aluminum, wood, plastics

**Moderate:** iron (steel, ferrites), copper

**High:** stainless steel, tungsten, tantalum, zinc, gold, manganese, cobalt, nickel

**Fissionable:** uranium, plutonium, thorium

# Induced Activity

$$A_R(t) = \lambda_R N_R(t) = \sigma_{B,R}\varphi N_B\left(1 - e^{-\lambda_R t}\right)$$

$$A_R(t, Tc) = A_{RS}\left(1 - e^{-\lambda_R t}\right) e^{-\lambda_R T_c}$$

| | |
|---|---|
| $A_R$ | is the activity |
| $\varphi$ | is the fluence rate |
| $\sigma_{BR}$ | is the activation cross section |
| $N_B$ | is the number of atoms of type B in the target material |
| $N_R$ | is the number of radioactive atoms produced after t irradiation time |
| t | is the irradiation time |
| Tc | is the cooling time |

# Radiation measurements

The radiation field around accelerators or laser based accelerators are complex:

many different ionizing radiation over a broad range of energies, energy distribution

fs

many different distribution in space and time

Radiation dosimetry is necessary mainly for the following reasons

✦routine radiological protection survey;
✦individual monitoring;
✦beam intensity measurements;
✦investigation of radiation accidents;
✦radiation field monitoring;
✦environmental monitoring.

# The radiation dosimetry it is not an easy task!

## Quantities in Radiological Protection

## Primary Physical Quantities

*Calculation using*
*$W_R$ , $W_t$ and*
*anthropomorphic phantom*
*interaction coefficients for energy absorption*

*Calculation for simple phantom (spheres or slab) validation by measurement*

fluence, $\Phi$
energy fluence, $\Psi$
air kerma, $K_a$
exposure, X

## Operational quantities

ambient dose equivalent, H*(d)
directional dose equivalent, H' (d,Ω)
personal dose equivalent, Hp (d)

## Protection quantities

absorbed dose, D
equivalent dose, $H_T$
effective dose, E

*Related by calibration and calculation*

*Estimation by measurements and calculation using usando $w_R$ and anthropomorfic phantom*

Monitored quantities

*Instruments response*

# Conventional instruments

## Active

Ionization Chamber

Proportional counter

Scintillation detectors

Solid state detectors

Tissue equivalent proportional counter

Bonner Spheres

## Passive

TLD

Track etch detectors

Nuclear emulsions

Activation detectors

Superheated drop or Bubble detecto

Bonner Spheres

## Problems

## Mixed field dosimetry

## Pulse duration

The environmental impact and exposure of Members of the Public is due to the **prompt radiation field**, included **skyshine** component, and to the residual radioactivity mainly **airborne and groundwater radionuclides**;

At large distance the radiation field due to the accelerator operation comprises two components ***direct*** or and ***scattered radiation***.

The terms "skyshine" refers to all radiation whether scattered by (the ground), air or (neighbouring buildings) - concern for boundary dose

photon skyshine

The skyshine field is dominated by neutrons for both high-energy electron and proton accelerator

**Experience has shown that for high energy accelerator skyshine may represent the largest contribution to the exposure of the general public due to the accelerator operation**

neutron skyshine

$$\Phi(r) = \frac{Q.e^{-r/\lambda}}{r^2} \qquad \boxed{H(r) = \frac{3*10^{15} e^{-r/\lambda}}{r^2}}$$

(Sv x n) λ 300-850 m

- **radionuclides produced in air**
  - **radionuclides produced directly in air**
    **(H-3; Be-7, C-11, N-13, 0-15, Ar-41, Cl-38)**
  - **radionuclides produced in dust;**
    **(Be-7, Na-24, P-32)**

- **radionuclides produced in earth shielding and groundwater**
  **(H-3, Be-7,Na-22, P-32, Ca-45, Ca-47, Sc-46, Sc-47, Cr-51 Mn-54, Fe-55, Fe-59, Co58, Co-60, Eu-152);**

- **environmental impact and exposure of Members of the Public is due to the prompt radiation field, included skyshine component, and to the residual radioactivity mainly airborne and groundwater radionuclides;**

- **noxious gas production $O_3$, NO, $NO_x$;**

**The elements of an operational radiation safety program consist in**

- the operational organization of the installation;

  It is necessary to indicate the chain of responsibilities.

  Usually the Director has prime responsibility for safety. This responsibility is normally met by the delegation of duties and function for safety down through the laboratory's administrative structure to managers and supervisors and ultimately every individual;

- the program for training and qualifying workers ( operators, users, maintenance technicians) in respect of the operation and of the operational maintenance of the facility;

- the security and safety systems;

- a plan showing the location, perimeters, areas, structures and system of the facility

# Operational Radiation Safety Program

- general standards used in the project for buildings systems, structures of the facility in order to avoid any inadvertent exposure of personnel;
- description of activities carried out in different part of the facility;
- classification and delimitation of areas;
- classification of exposed workers;
- internal rules of radiation protection;
- radiological safety system (interlock and warning devices)
- access control system;
- emergency egress requirements.
- external and internal radiation exposure control;
- radioactive waste management;
- monitoring and control of radioactive material.

# Quality assurance for the safety program

- **The quality assurance program for the activity to be licensed**
- **The worker health and safety policies and procedure**
- **The environmental monitoring program**
- **The program to inform stakeholder.**

**An internal safety review system must be established and maintained to periodically assess and document the condition of the facility, equipment and engineered safety system.**

**Appropriateness and implementation of procedures, administrative controls and personal training and qualification must be periodically reviewed and documented by the internal safety review system.**

# Radiation safety system

The prompt radiation hazards associated with the accelerator operation can be high. The primary goal of the Radiation Safety System of an accelerator facility is to protect people from prompt radiation hazards with a ***fully interlocked, engineered passive/active system*** that is ***reliable, redundant, and fail-safe***.

**A personnel protection system can be considered as divided into two main parts:**

- an access control system intended to prevent any unauthorised or accidental entry into radiation areas

the access control system is composed by physical barriers (doors, shields, hutches), signs, closed circuit TV, flashing lights, audible warning devices, including associated interlock system, and a body of administrative procedures that define conditions where entry is safe

- a radiation alarm system.

the radiation alarm system includes radiation monitors, which measure radiation field directly giving an interlock signal when the alarm level is reached.

# Interlock design and feature

All circuits and component must be fail safe

**Two independent chains of interlocks must be foreseen, each interlock consisting of two microswitches in series and each microswitches consisting of two contacts.**

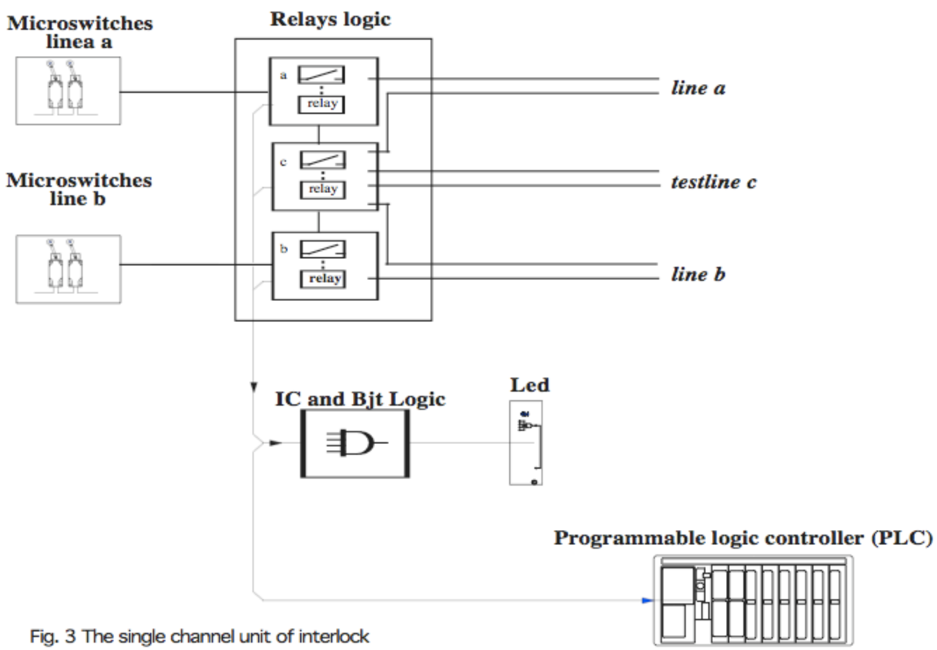



Fig. 3 The single channel unit of interlock

Emergency-off buttons must be clearly visible in the darkness and readily accessible. The reset of emergency-off buttons must be done locally.

Warning lights must be flashing and audible warning must be given inside radiation areas before the accelerator is turned on

Before starting with the accelerator a radiation area must be searched.

**Any violation of the radiation areas must cause the stop of the machine. It is possible to start again with the operation only after a new search.**

◆The generation and acceleration of charged particles by lasers is opening new perspectives namely in high energy beam facilities.

◆The use of laser in relativistic and ultra relativistic regime have to be regarded as practices with radiation risk and consequently treated.

**◆The talk tried to summarize the radiological protection aspects that a project manager and /or project engineers should take into account in designing a facility for lasers of hundreds petawatt , focusing mainly**

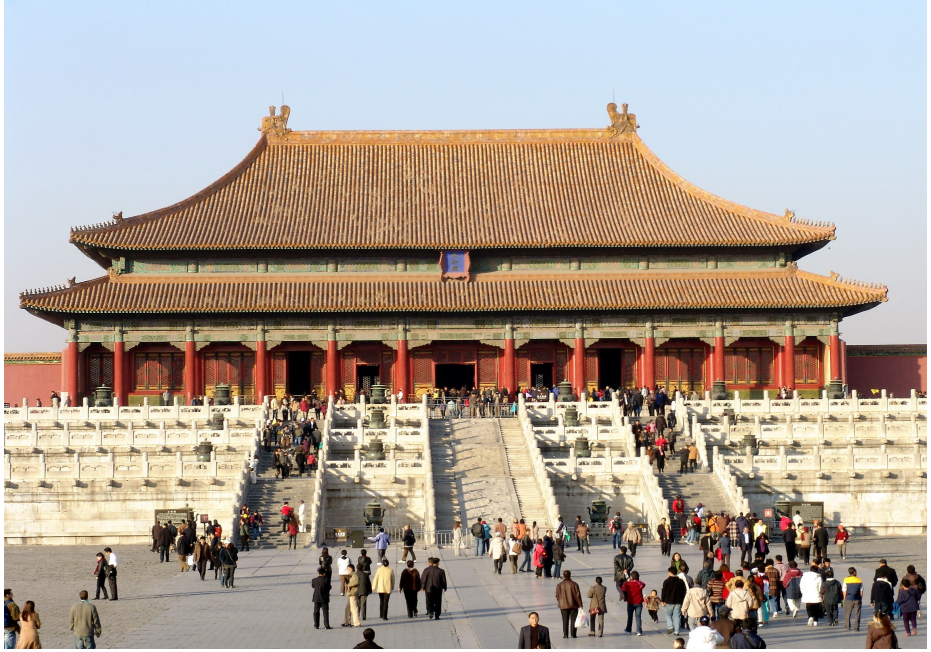
- **licensing requirements,**
- **prompt and residual radiation fields,**
- **shielding of radiations produced,**
- **shielding materials,**
- **radiation monitoring,**
- **determination of any environmental impact**
- **and other specific operational requirements of an “accelerator facility”,**

**◆Apart the difficulties in the calculation of the source term as well as the measurements of particles produced the commissioning and the operation of a multipetawatt laser don’t pose particular problems of radiation protection and shielding**

Thank you

谢谢

Grazie



# List of reports, books and or scientific papers used for the presentation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★Council Directive 96/29/Euratom of 13 May 1996;
★Annals of ICRP Publication 26, 60,
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★ A.Esposito
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