Radiation Shielding at High Energy Electron Accelerators

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Regulatory and Advisory Agencies

◆In the European Union the regulations laying down the commissioning and operation of any facility with the radiation risk for population and workers are subject to the Council Directive 2013/59/Euratom of 5 December 2013. Member State shall bring into force the law by 6 February 2018

◆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.

Regulatory and Advisory Agencies

Advisory Agency

IAEA

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

ICRU

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.

ICRP

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

Regulatory and Advisory Agencies

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 (workers and general public) outside the shield, at a reasonable cost and without compromising the utility of the apparatus for its design purposes.

Shielding should be designed for normal operation at the maximum energy and power with allowance for occasional and rare high beam losses

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

Such goals are obtained in the following stages

- Specification of required dose equivalent (rate) outside the shielding
- Determination of the source term
- Design of the shield with adequate attenuation to achieve the required dose equivalent (rate) limitation

The following topics shall be considered

Radiation environment

that is particle yields reported in term of physical distribution such

- type of radiation
- energy
- fluence
- angle of emission

bremssstrahlung;
neutron;
muons;
pions;
kaons;
any other particle (charged particles, ions, nuclear fragments and delayed radiation)

Parameter to be considered

- **Maximum beam energy and intensity**
- **Average beam power**
- **Schedule and mode of operation**
- **Area classification**
- **Area occupancy**
- **Beam losses**
- **Annual dose limit for workers and member of the public**
- **Environmental radiological impact**

Availability of space

Induced radioactivity

Shielding materials

Cost

Regulatory limits

Trend in regulatory limits

Not always is possible to shield
Some times Is necessary to combine active and passive systems

Electron accelerators

The thickness of the shielding depends from the attenuation of prompt radiation 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 **now 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 lower than the limits above recommended.

Constraint 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

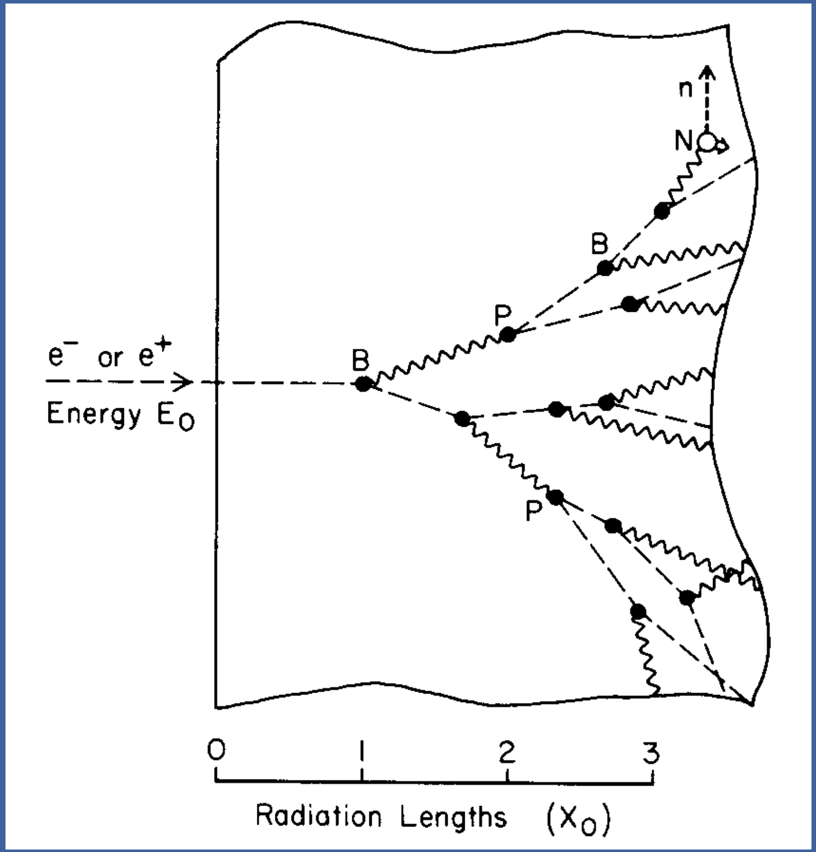
Our licensing authorities, referring to FLAME project, remembered recently to us that the shielding design must ensure an effective dose for the members of the public outside the shielding of 10μSv/y!!

Electrons

At “electron accelerators” of all energies bremmstrahlung dominate the secondary radiation field via the electromagnetic cascade.

Collision with: Atoms= soft collisions; Electrons- delta rays

Radiative interaction consists in electrons decelerated in the electric field of the nucleus



- Threshold energy is 1.022 MeV (= 2mc2)

Brems ➡ pair ➡ brems … the EM cascade

$E=E_0 e^{-x/X_0}$

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

X_0 = radiation length (distance in which an electron energy reduced to 1/e)

Multiplication stops when E_e drops below E_c

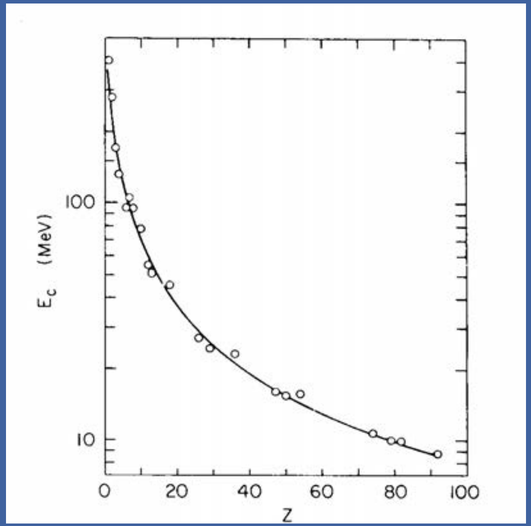
$$\frac{1}{X_o} = 4\alpha Z^2 r_o^2 \ln\left(183Z^{-1/3}\right) \quad \mathrm{cm^2 g^{-1}}$$

Critical energy E_c:

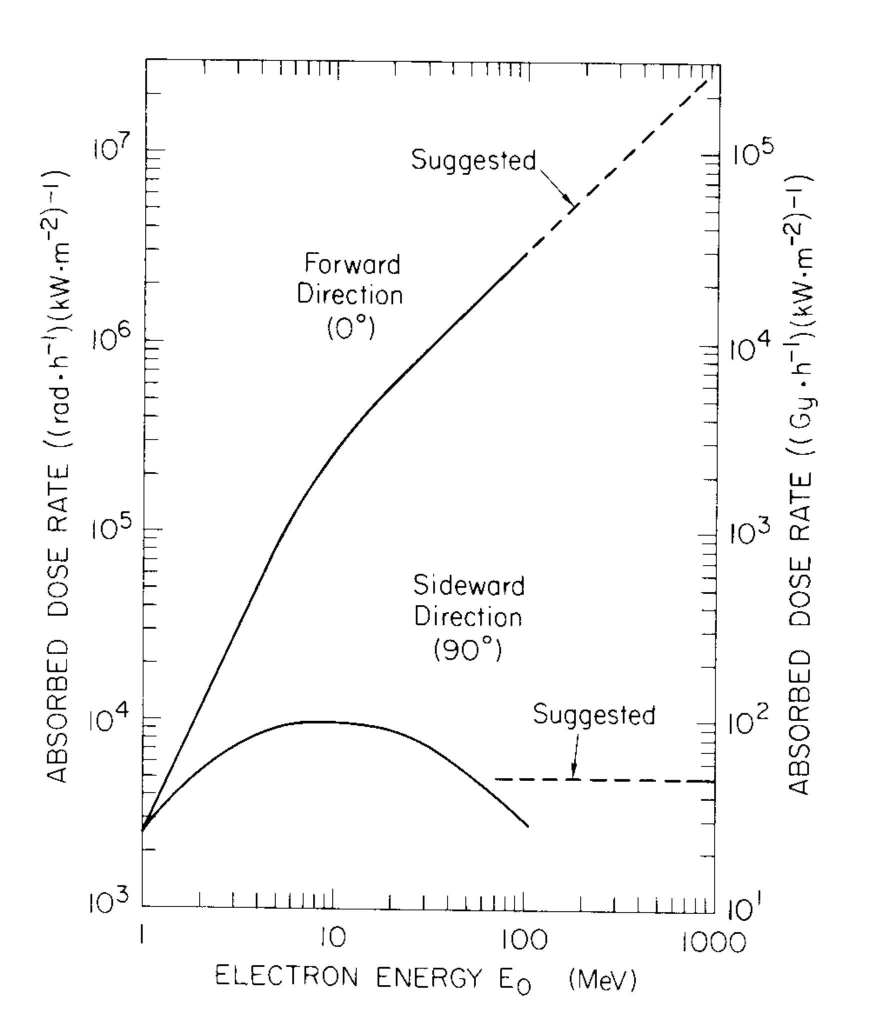
$dE/dx|_{col} = dE/dx|_{rad}$

E_c [MeV] = 800/(Z + 1.2)

	E_c [MeV]
Pb	9.51
Fe	27.4



Electrons



Rules of thumb:(for thick high-Z targets)

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

At 90º, E_0 > 100 MeV:

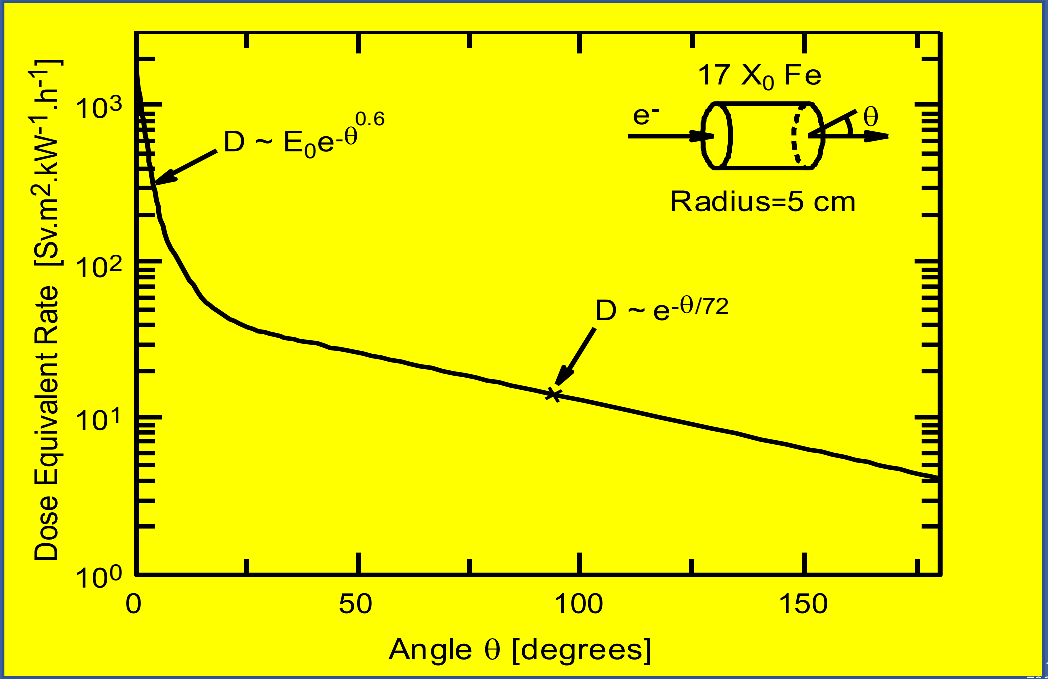
$$\dot{D}[Gy.h^{-1}.kW^{-1}.m^{2}] \approx 50$$

100

100

Forward-peaked:

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



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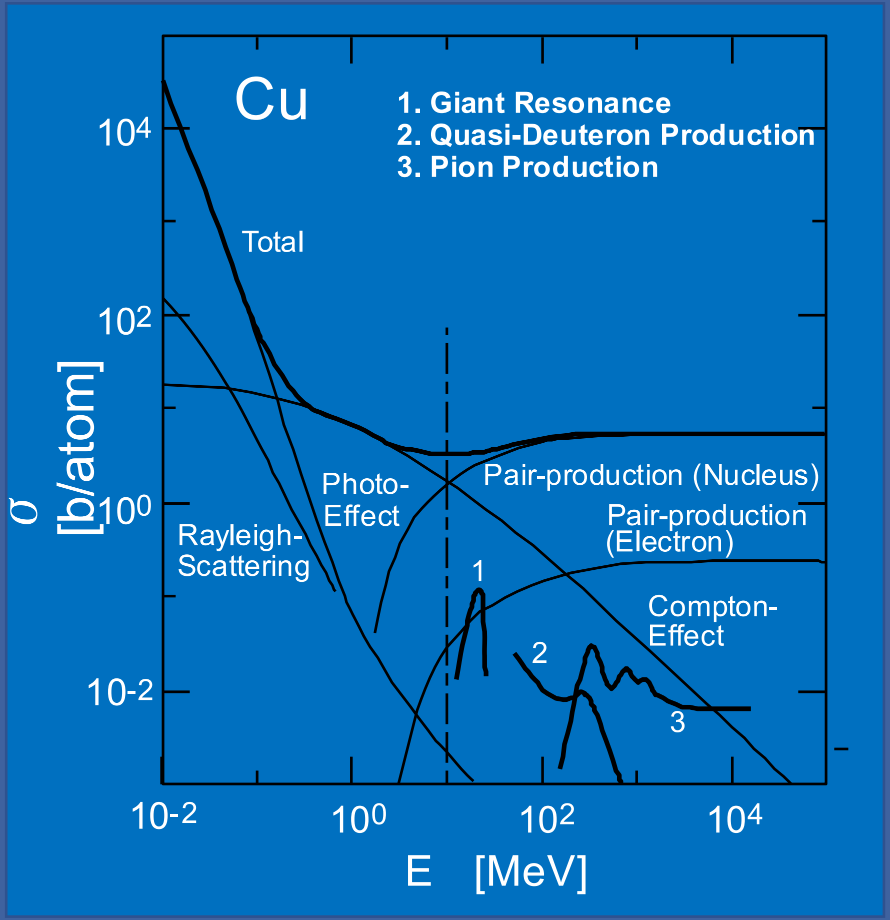
Electrons

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



Giant Resonance

Peak at 20-23 MeV for A< 40, 13-18 MeV for heavier nuclei

Quasi-Deuteron Production

Photons interact with a p-n pair

Pion Production

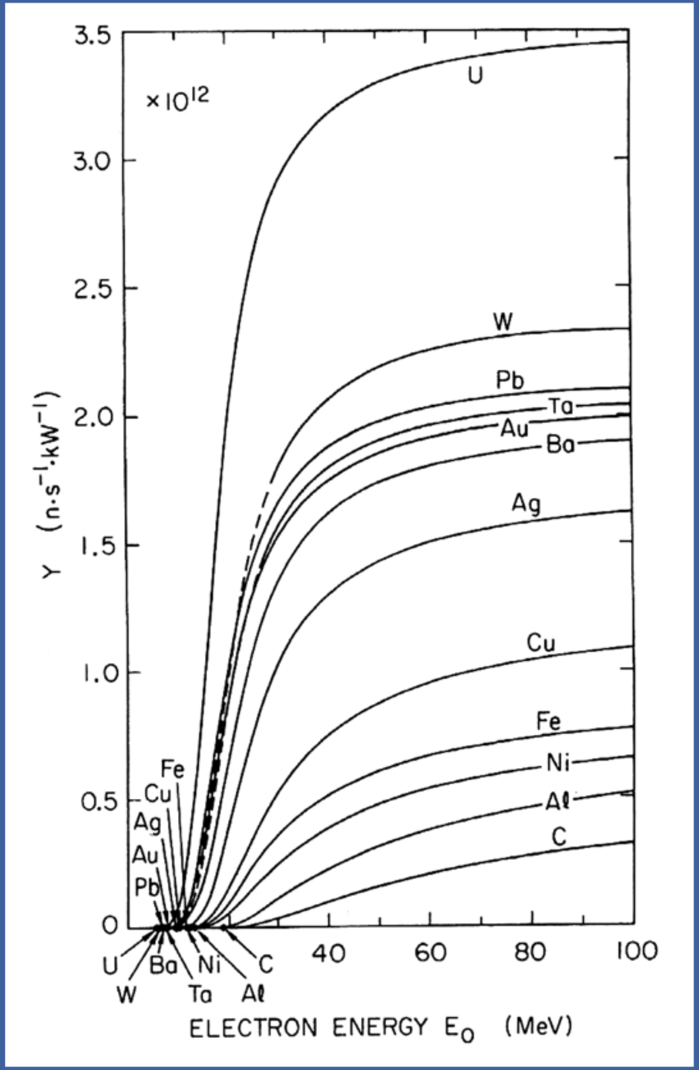
At electron energies > 140 MeV, pions can be produced; pions then generate neutrons

Largest resonance at E ~300 MeV, $\sigma \approx$ const in GeV region)

Most penetrating, generate spallation , evaporation and capture "following" in their path "equilibrium" neutron spectra behind thick shielding

Electrons

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



Giant resonance neutrons

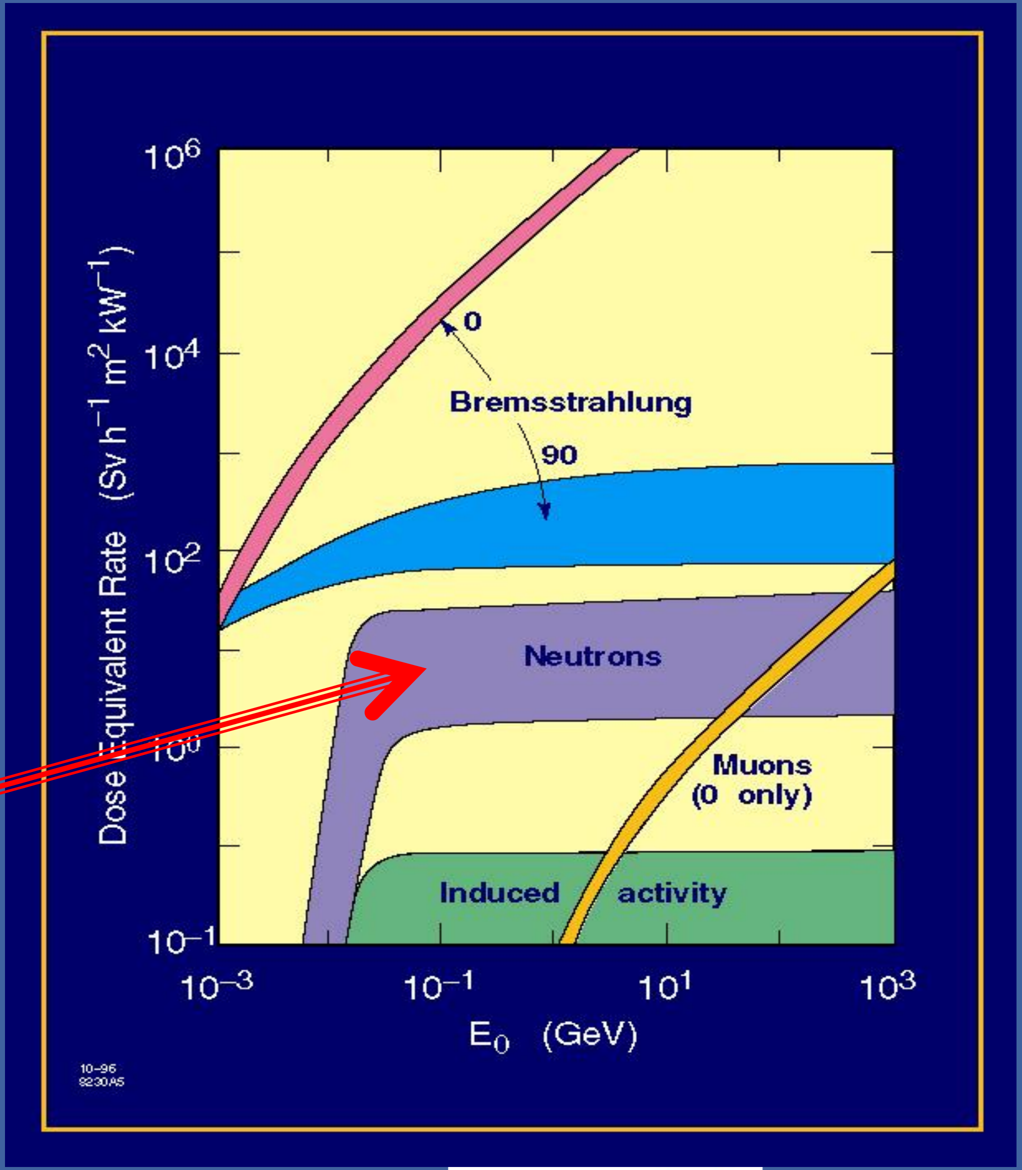
$$Y = 1.21 \times 10^{11}\ Z^{0.66}\ n\,s^{-1}\,kW^{-1}$$

High energy neutrons (E>25MeV)

For 400 MeV of electrons
between 0° - 30° 2.5×10^{-4} n sr^{-1}/e^{-}
between 30° - 60° 2.1×10^{-4} n sr^{-1}/e^{-}
between 60° - 120° 1.2×10^{-4} n sr^{-1}/e^{-}

Electrons

Source term for thick target per unit power



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

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.

- μ^+/μ^- pair will occur with a much lower probability than e^+/e^- pair. $(m_\mu/m_e)^2 \approx 4.10^4$

- 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 μ^+/μ^- pair production

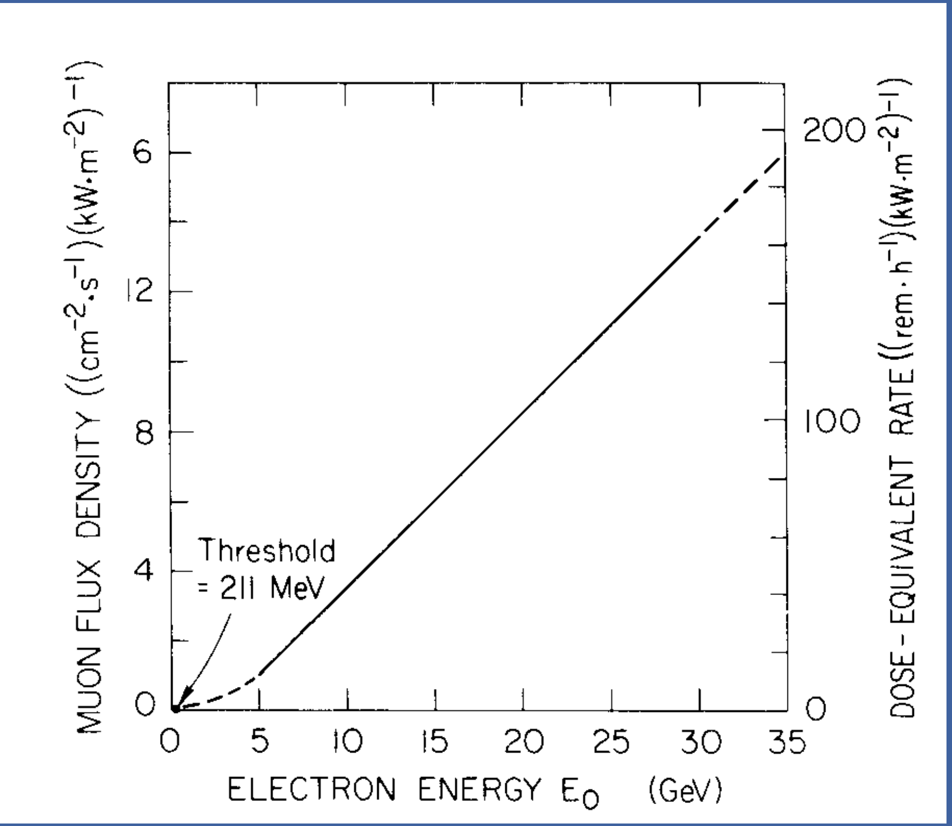
- Muon angular distribution is extremely forward-peaked, and this distribution narrows further with increasing energy.

- Important above E_0 ~ 1 GeV

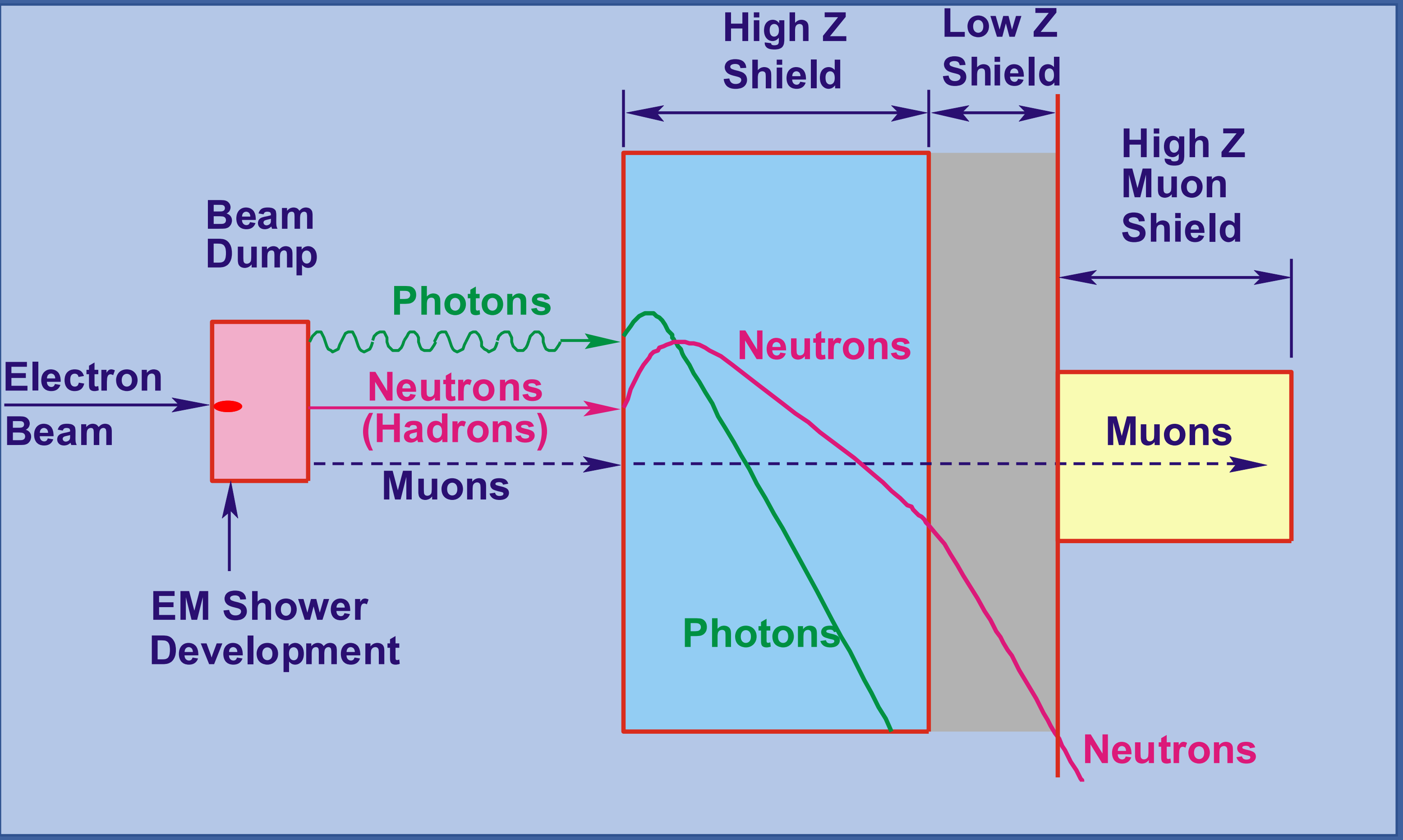
- Energy loss only by ionization

- Yield ~ 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.



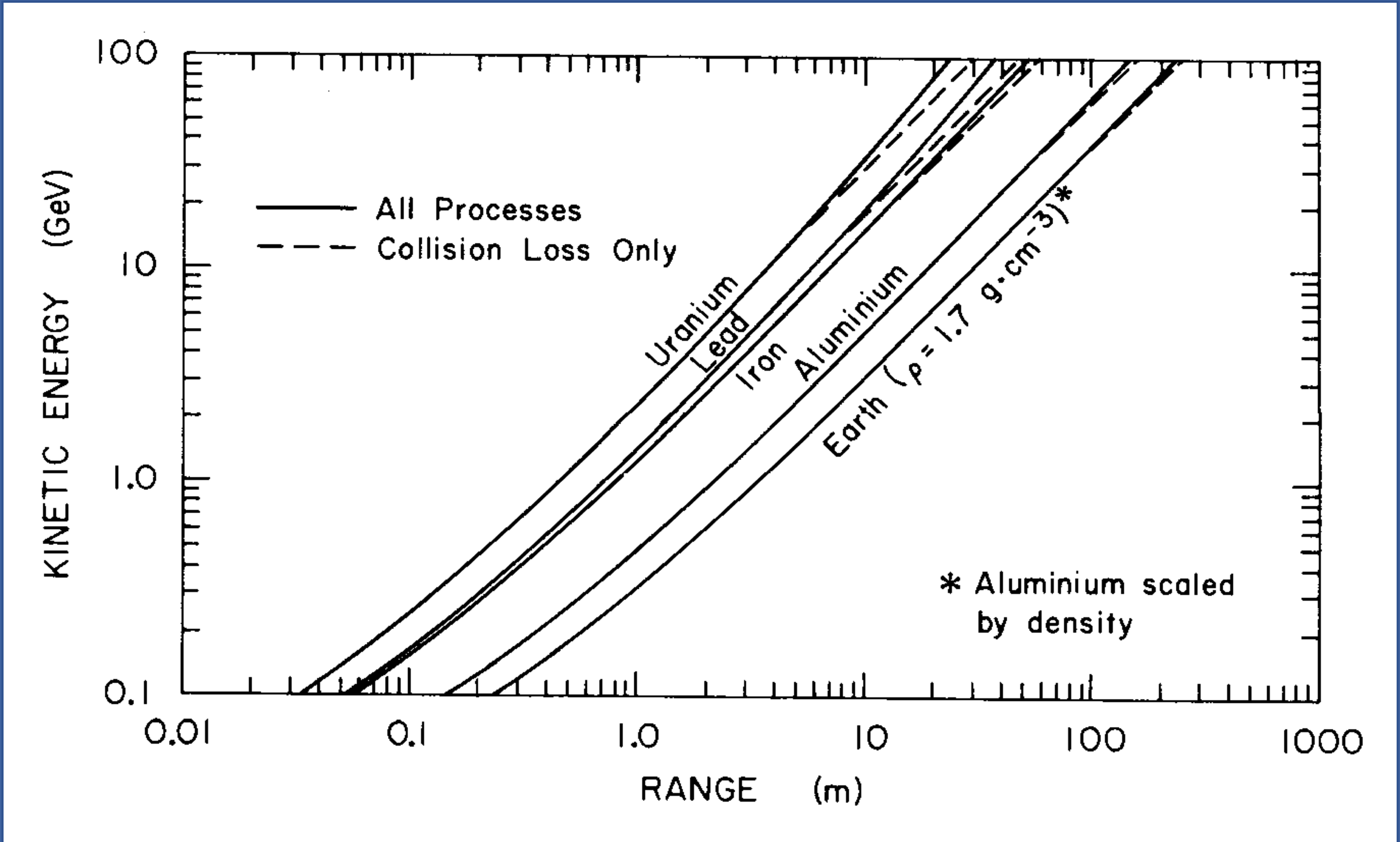
Electrons



high inelastic cross sections in high-*Z* materials to reduce the neutron energy by *(n,xn)*

At very high energies completely ranging out muons may be impractical.

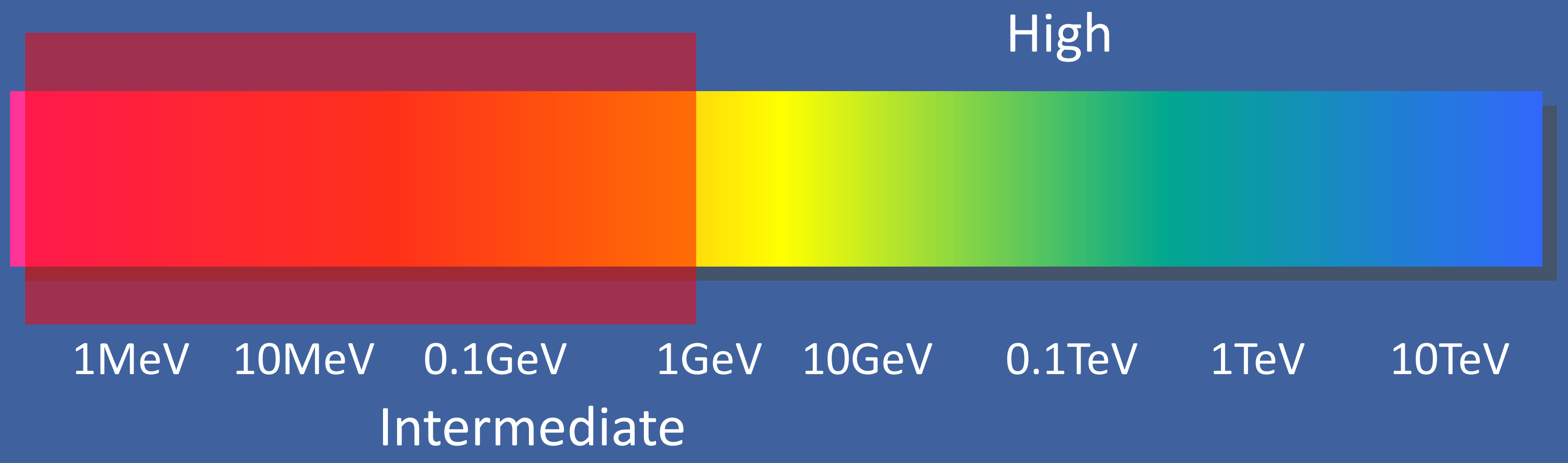
Muon Range



100
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
100
1000
RANGE (m)

Protons

Energy scale for proton accelerators:



Protons

Generation of prompt radiation

Interactions of protons with matter

- Direct interactions
- Pre-equilibrium
- Equilibrium → evaporation

Low energies: energy loss by ionization

Higher energies: energy loss by nuclear interactions

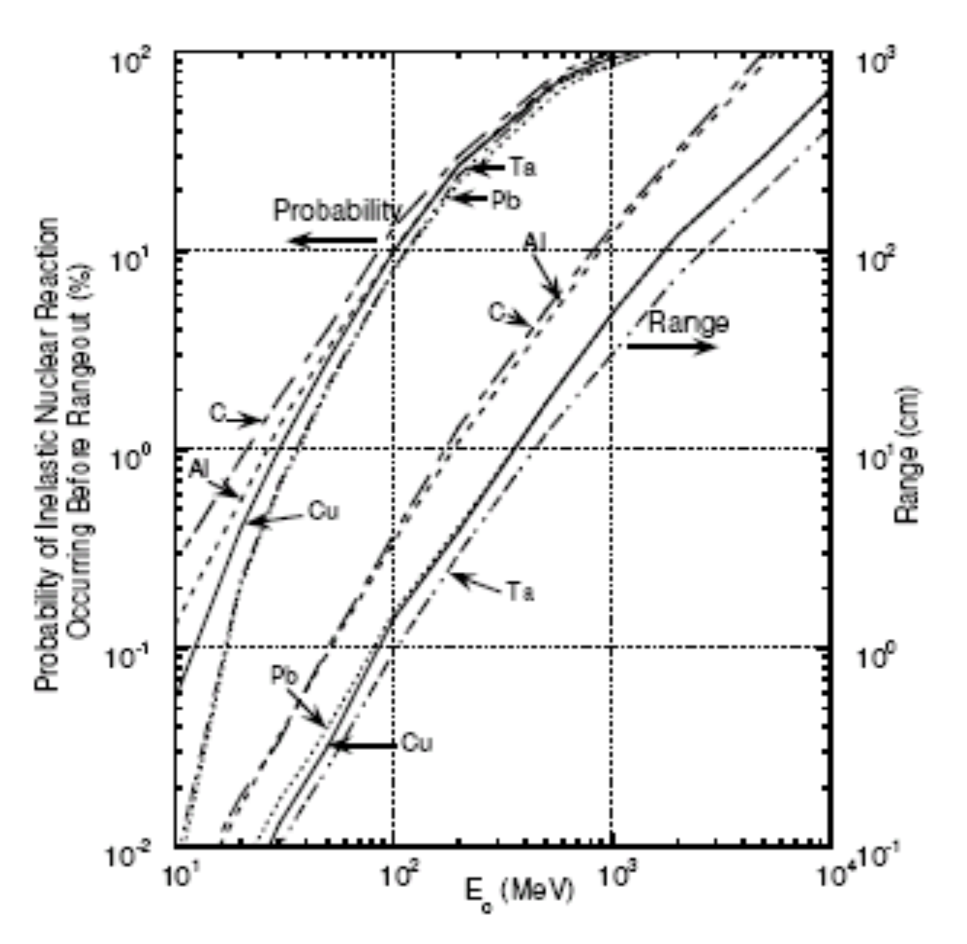
Range in iron:

$$R = 1.1 \times 10^{-3} E_p^{1.6}$$

At the highest energies the proton range is no longer a useful concept

For other materials:

$$R = R_{Fe} \frac{\rho_{Fe}}{\rho} \frac{\sqrt{A}}{\sqrt{A_{Fe}}}$$



Generation of prompt radiation

◆In contrast to electromagnetic cascade, in which the two dominant processes have nearly constant cross section, the situation in hadronic cascade 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

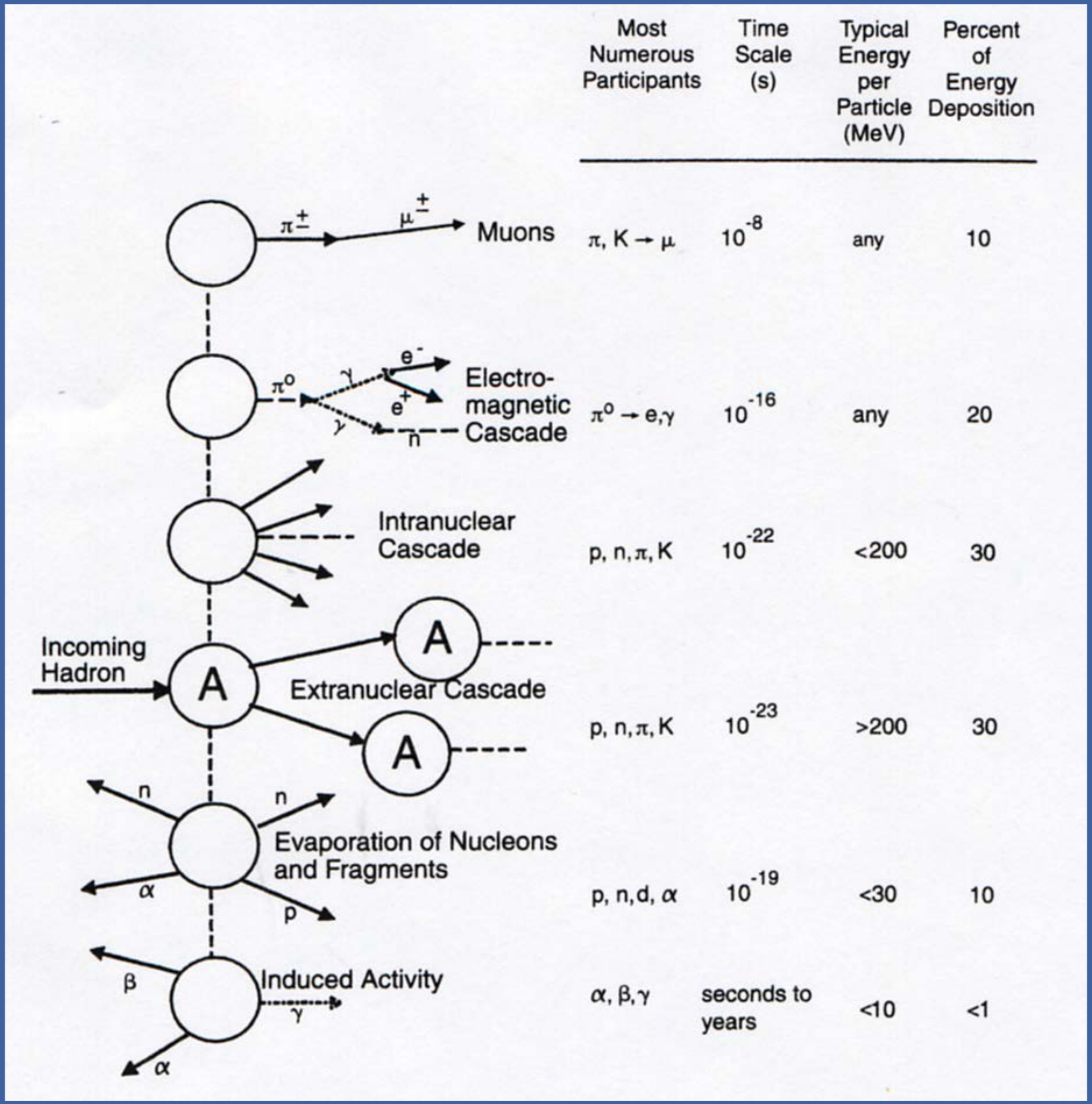
◆The main means of energy transfer is due to the interaction of high-energy nucleon that is hadrons with energy higher than 150 MeV, that serve to propagate the cascade.

◆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.

◆Charged π mesons (but only Kaons) decay into muons plus neutrinos

◆Neutral π mesons produce high energy photons, responsible of electromagnetic cascade

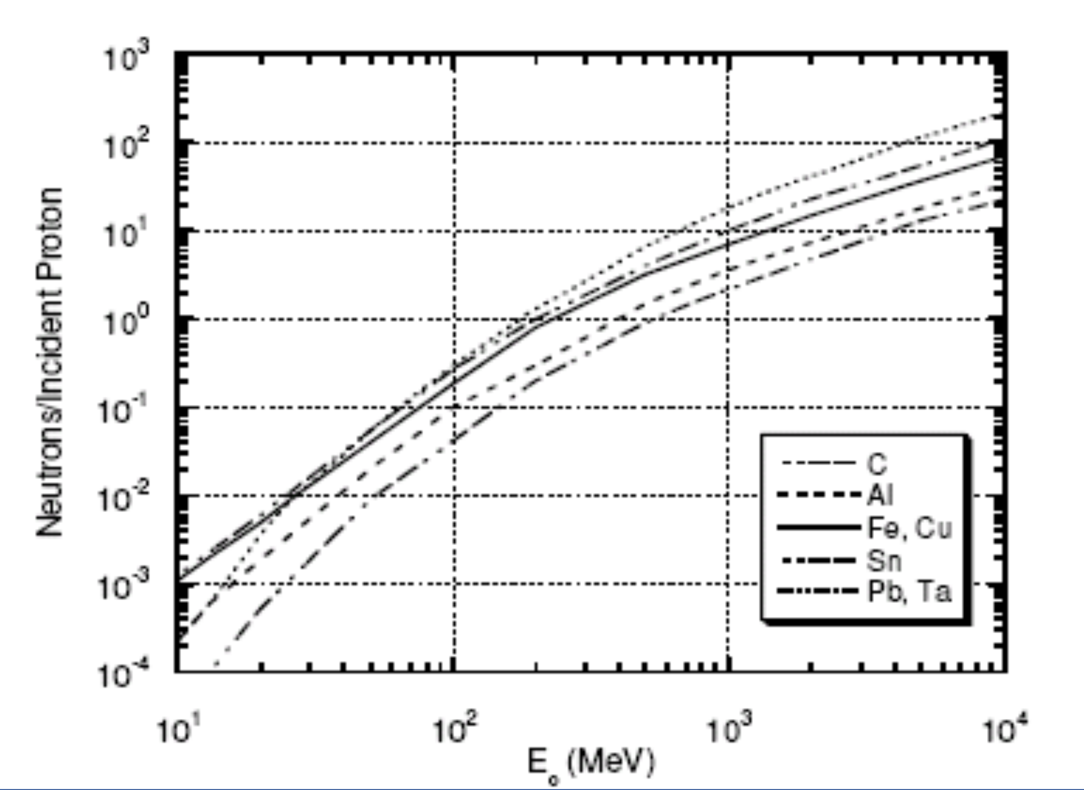
◆Neutrons dominate the prompt radiation field outside the thick shield.



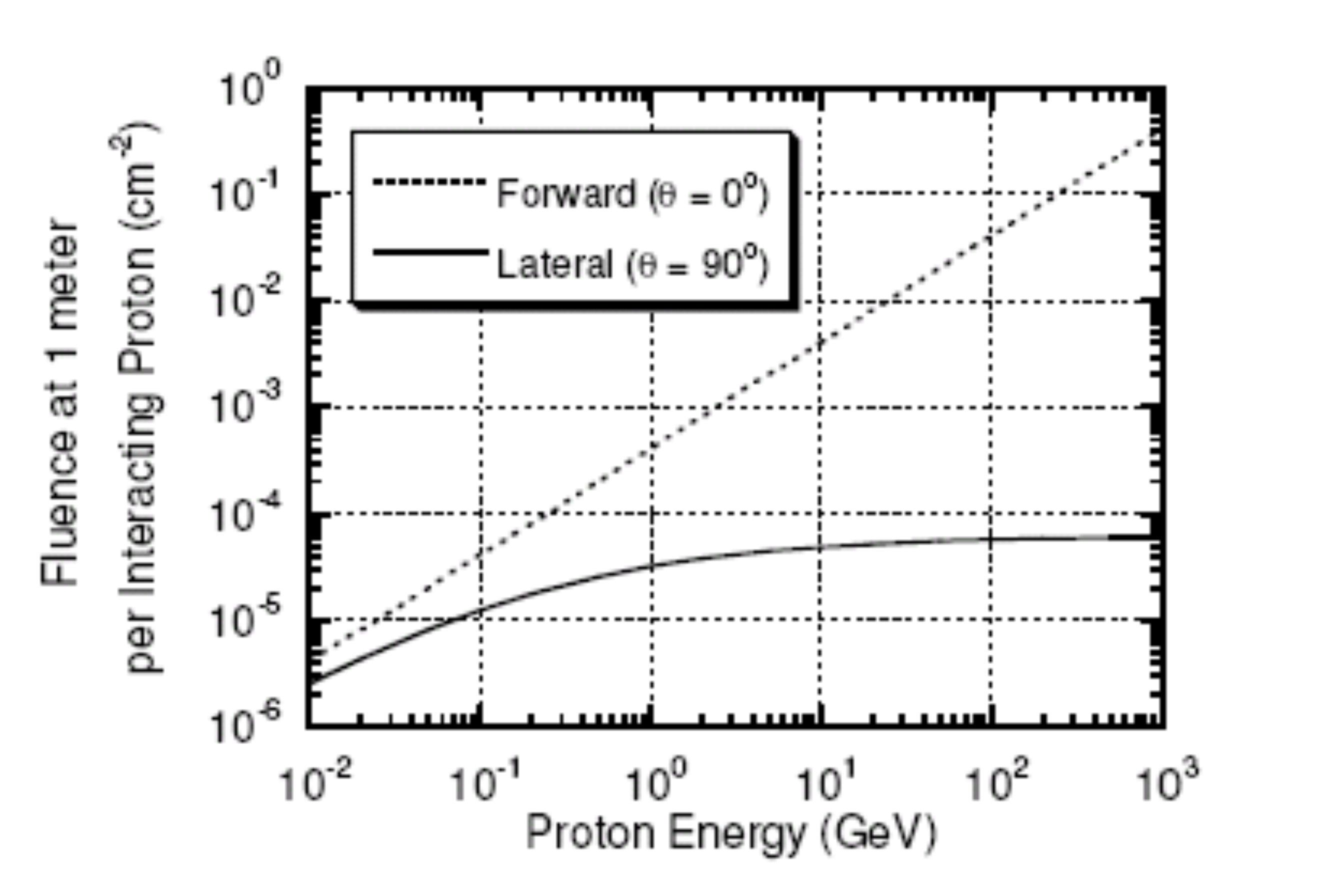
Source Terms

- 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)



Fluence of neutrons



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

Accelerator shielding-Symmetric cascades

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

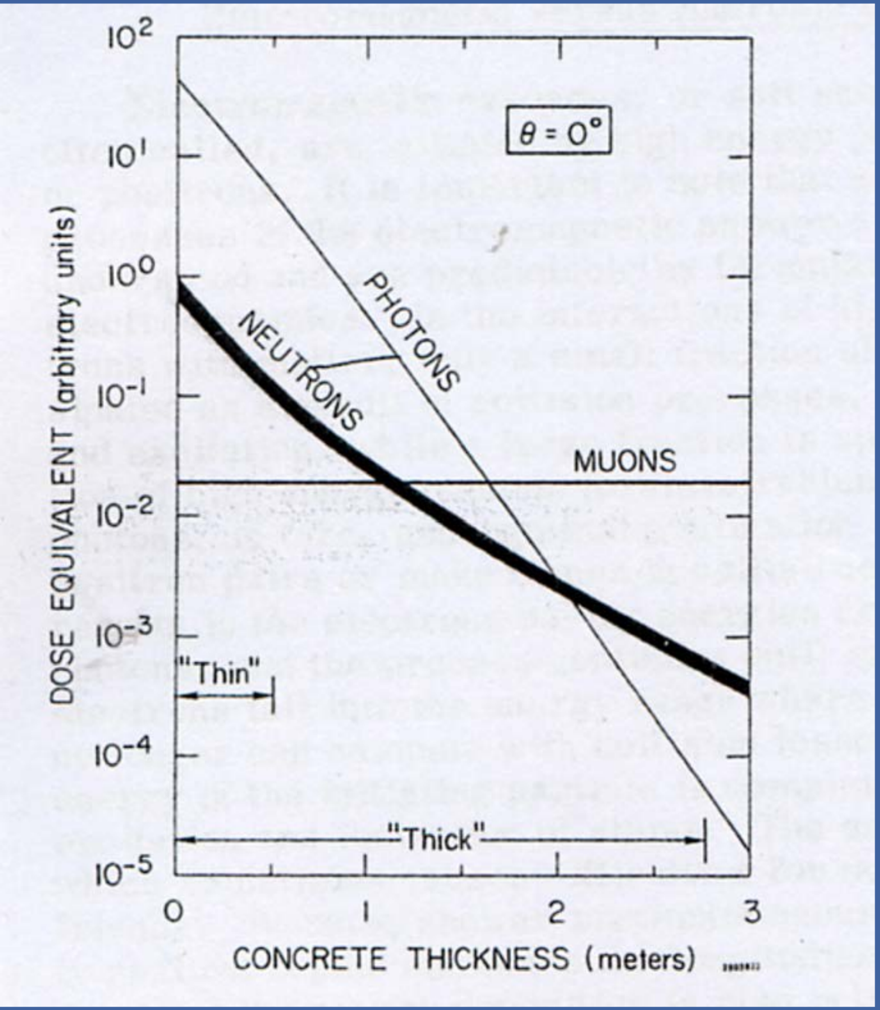
A multiplying “shower” is the result of both

The electromagnetic cascade produce a hadronic cascade

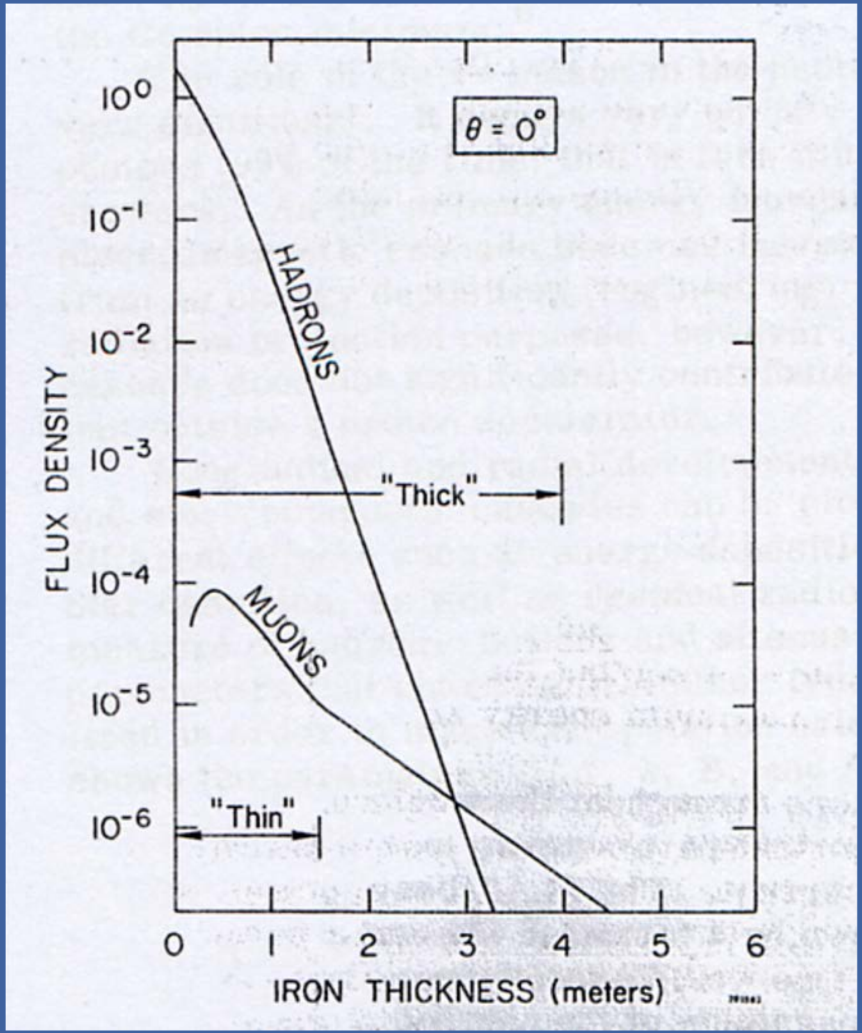
The hadronic cascade produce cascade an electromagnetic cascade

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

Accelerator shielding-Symmetric cascades



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



Shielding

$$\frac{H}{H_0} = e^{-d/\lambda} = 2^{-d/\lambda_2} = 10^{-d/\lambda_{10}}$$

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

$$\sum \dot{H}_i = \sum_i \frac{S}{r^2} e^{-d/\lambda i} * f_i$$

Conversion coefficients

E≅2 MeV $f_{NRG} = 2.87 \mu Sv/h/ncm^2 s^{-1}$

$f_{NHE} = 1.8\ \mu Sv/h/ncm^2 s^{-1}$

λ = attenuation length

λ_2 = half-value layer

λ_{10} = tenth-value layer

$$\lambda = \frac{\lambda_2}{\ln 2} = \frac{\lambda_2}{0.693} = \frac{\lambda_{10}}{\ln 10} = \frac{\lambda_{10}}{2.30}$$

Shielding - Attenuation lenghts

e^-

Bremsstrahlung

Material	Density (g/cm^3)	Angle (gradi)	Attenuation length λ (cm)
Concrete	2.35	0°	20.4
Concrete	2.35	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

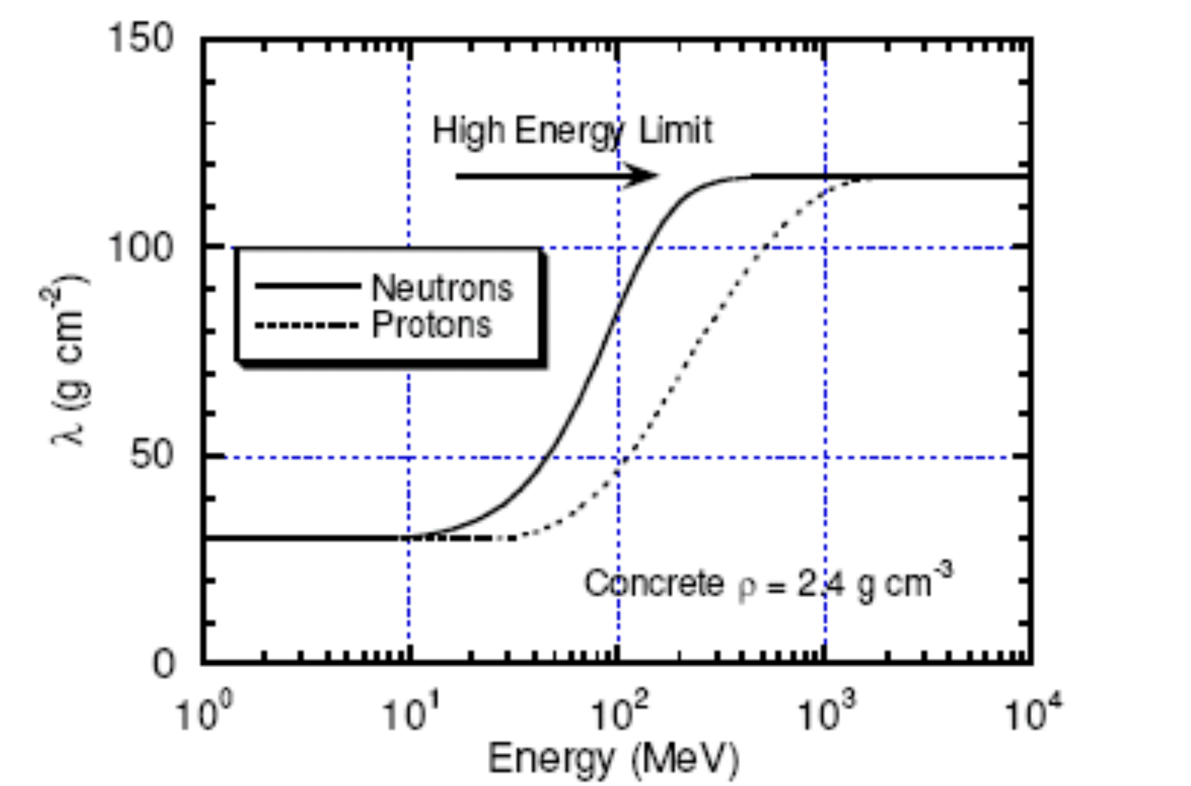
Material	Density (g/cm^3)	Attenuation length λ (cm)
Lead	11.35	18.30
Concrete	2.35	17.4
Heavy concrete	3.4	11.7
Earth	1.6	52.8
High Density Polyethylene	1.01	6.36

High energy neutrons (E>25MeV)

Material	Density (g/cm^3)	Attenuation length λ (cm)
Lead	11.35	16.8
Concrete	2.35	48.9
Heavy concrete	3.4	33
Earth	1.6	56.3
High Density Polyethylene	1.01	61.4

p

Attenuation Length in Concrete



Neutron Shielding Materials

If the cost and convenience were no criteria, any material in sufficient quantity may be used for shielding against radiation

Many practical constraints limit materials to those most commonly used in construction

- Concrete
- Steel
- Earth

Other materials may be more advantageous under certain circumstances but the following factor should be evaluated

- Thickness and weight
- For shielding and structural purposes
- Effective against photons and neutrons
- Uniformity consistency homogeneity
- Permanence of capability of shielding
- Cost of material
- Cost of installation of material
- Possibility of inducing radioactivity

Aggiungere materiali

TABLE 4.8—*The elemental composition of representative soils.*[a]

Element	Global Average[b] (Chilton *et al.*, 1984) (percent)	Wilson and Karcher (1966) Average[c] (percent)
Oxygen	43.77	50.2 ± 2.2
Silicon	28.1	26.5 ± 9.2
Aluminum	8.24	6.7 ± 2.9
Iron	5.09	5.5 ± 9.0
Manganese		0.07 ± 0.06
Titanium		0.45 ± 0.43
Calcium	3.65	5.0 ± 6.6
Magnesium	2.11	1.3 ± 1.5
Potassium	2.64	1.4 ± 0.7
Sodium	2.84	0.6 ± 0.5

[a] Based on a dry-weight percentage basis. The total does not add to 100 percent.

[b] This is a mixture approximating the relative abundance of the eight most common elements in Earth's crust.

[c] These are means and standard deviations of compositions of 28 soils selected from throughout the United States.

TABLE 4.9—*Typical compositions of representative concretes after curing (Chilton et al., 1984).*

Concrete Type	Ordinary	Magnetite[a]	Barytes[b]	Magnetite and Steel	Limonite and Steel[c]	Serpentine[d]
Density ($g\ cm^{-3}$)	2.35	3.53	3.35	4.64	4.54	2.1
Element	Partial Density ($g\ cm^{-3}$)					
Hydrogen	0.013	0.011	0.012	0.011	0.031	0.035
Oxygen	1.165	1.168	1.043	0.638	0.708	1.126
Silicon	0.737	0.091	0.035	0.073	0.067	0.460
Calcium	0.194	0.251	0.168	0.258	0.261	0.15
Carbon						0.002
Sodium	0.04					0.009
Magnesium	0.006	0.033	0.004	0.017	0.007	0.297
Aluminum	0.107	0.083	0.014	0.048	0.029	0.042
Sulfur	0.003	0.005	0.361			
Potassium	0.045		0.159		0.004	0.009
Iron	0.029	1.676		3.512	3.421	0.068
Titanium		0.192		0.074		
Chromium		0.006				0.002
Manganese		0.007				
Vanadium		0.011		0.003	0.004	
Barium			1.551			

[a] Magnetite ($FeO{\cdot}Fe_2O_3$) as aggregate.

[b] Barytes, a $BaSO_4$ ore, as aggregate.

[c] Limonite, a hydrated Fe_2O_3 ore, plus steel punchings, as aggregate.

[d] Serpentine ($3MgO{\cdot}2SiO_2{\cdot}2H_2O$) as aggregate; a concrete usable at high temperatures with minimal water loss.

Environmental radiological aspects

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 du to the accelerator operation

neutron skyshine

$$\Phi(r) = \frac{Q.e^{-r/\lambda}}{r^2}$$

$$H(r) = \frac{3 * 10^{-15} e^{-r/\lambda}}{r^2} \quad (Sv / n)$$

λ 300-850 m

Radiation Protection at LNF: the laser based accelerators

◆ 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.

◆ 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 part of my presentation is to focus some radiological protection aspects, that a project manager should take into account in designing a facility for lasers from hundreds terawatt to hundred petawatt peak power.

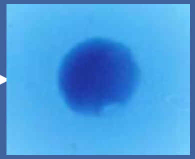
But why Laser-Plasma accelerators?

Laser-Plasma accelerators

ENERGY SOURCE: Laser

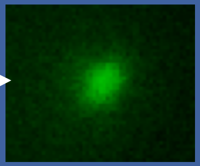
Laser focusing and control

OVERDENSE PLASMA Laser-solid interactions

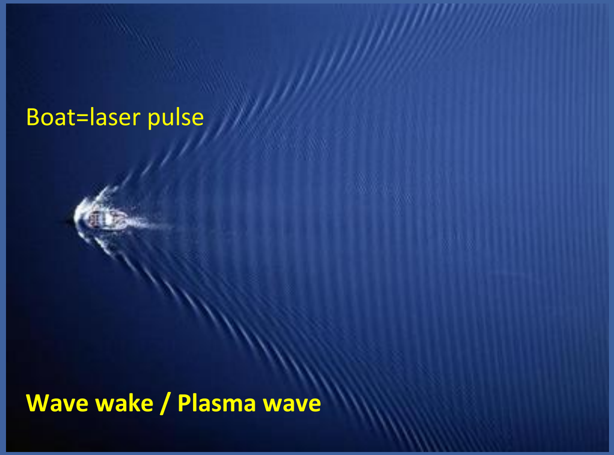


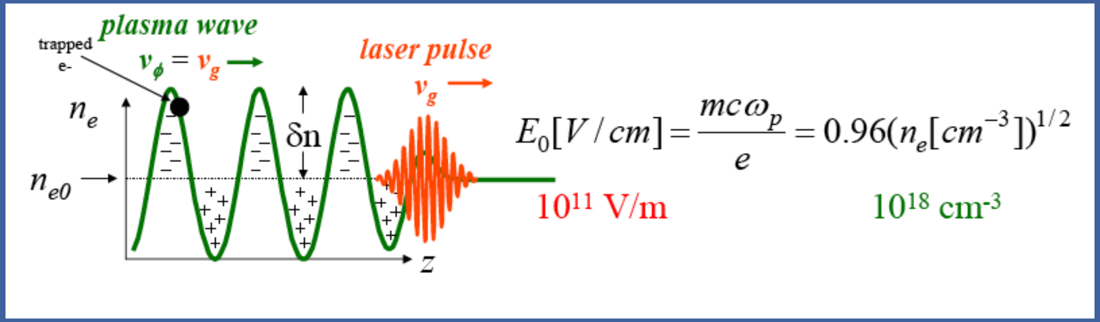
Protons, ions, e^-, e^+, broad spectrum, lower E,

UNDERDENSE PLASMA Laser-gas interactions



e^-, e^+, narrow spectrum, GeV energy





Surfer=particle

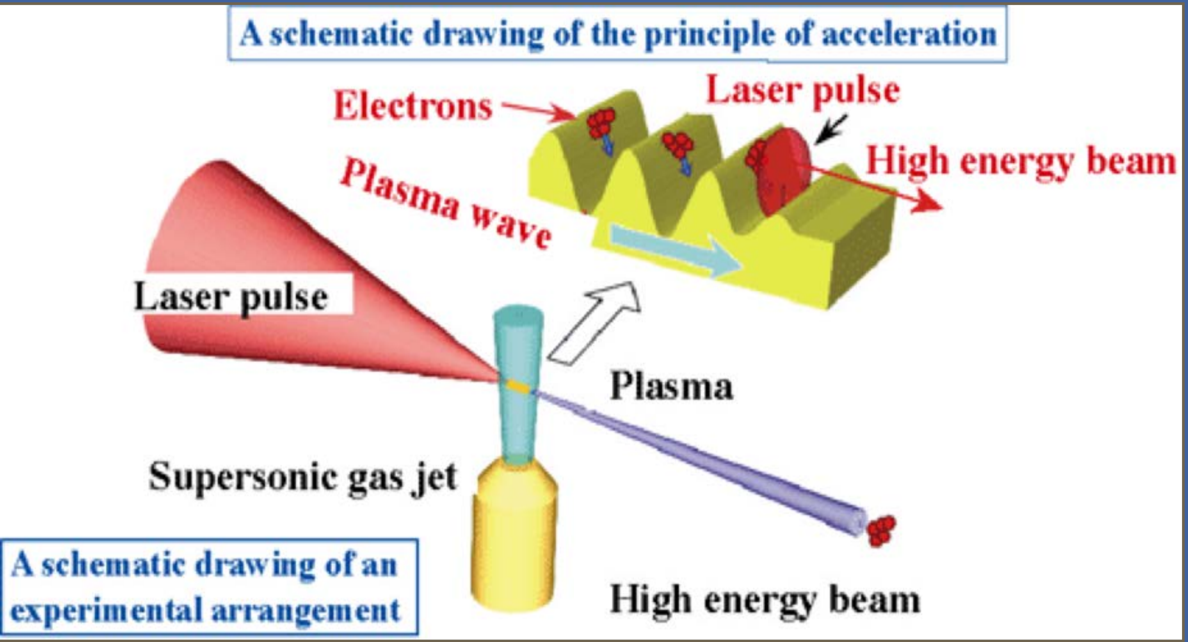
Laser-Plasma accelerators

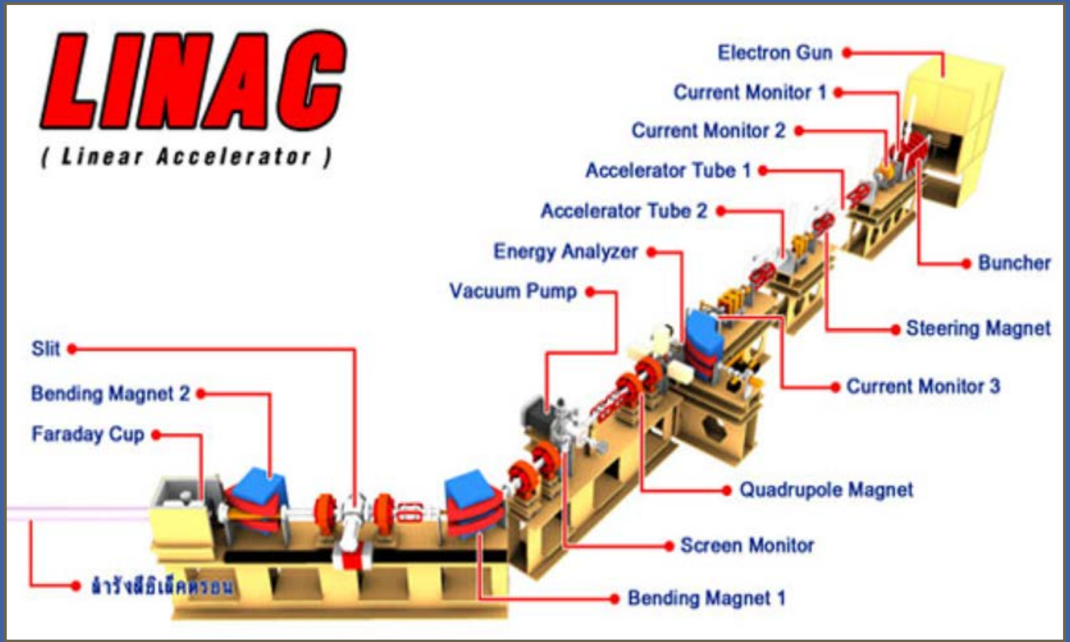
◆ **CONVENTIONAL ACCELERATORS:**

- 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





Laser-Plasma accelerators

well known for accelerators

The source term

open **question** for accelerator laser based facilities

◆Measurements on existing facilities up to 1 PW

Not easy task

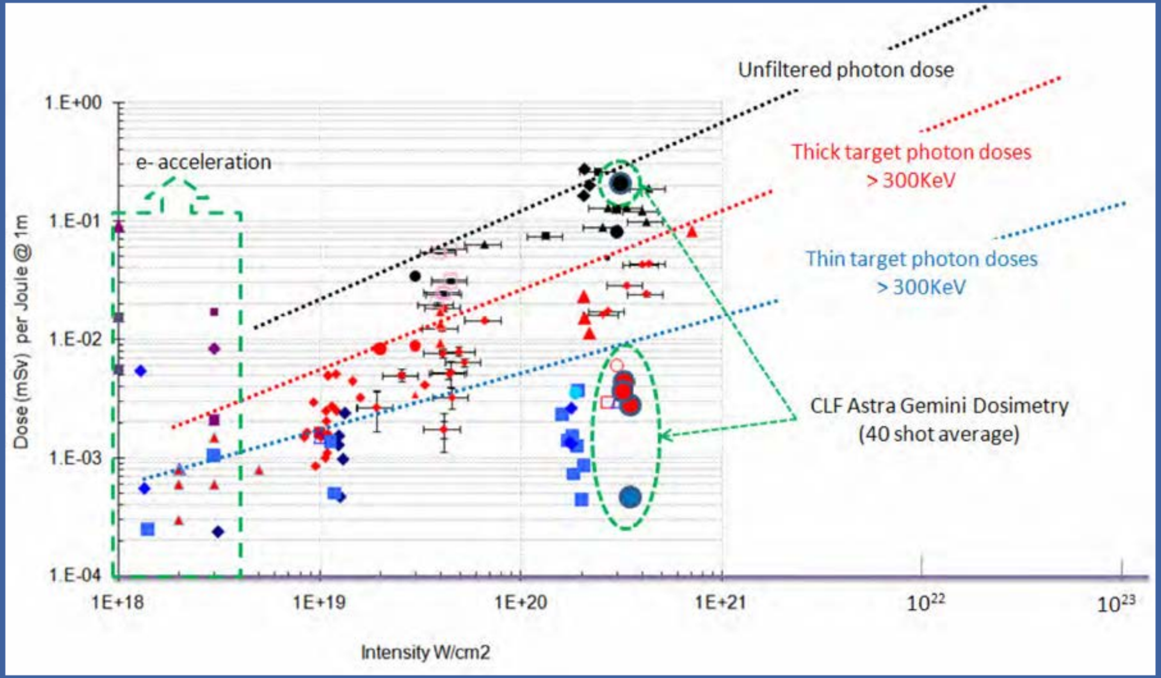
▪because the modality of production of particles (pulsed radiation);

▪because of the availability of instruments able to measure very short pulses.

◆Only dosimetric evaluation are available

◆Any extrapolation to power higher 100 PW is quite impossible

From ELI White book



Determination of the source term

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;

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).

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

N_i^T the total number of particle per steradiant N_j^G

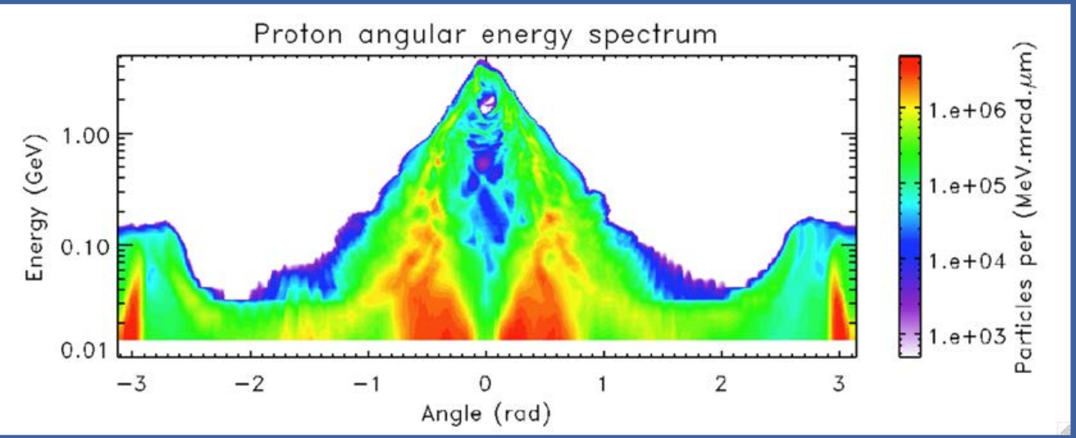
T_i temperature in MeV

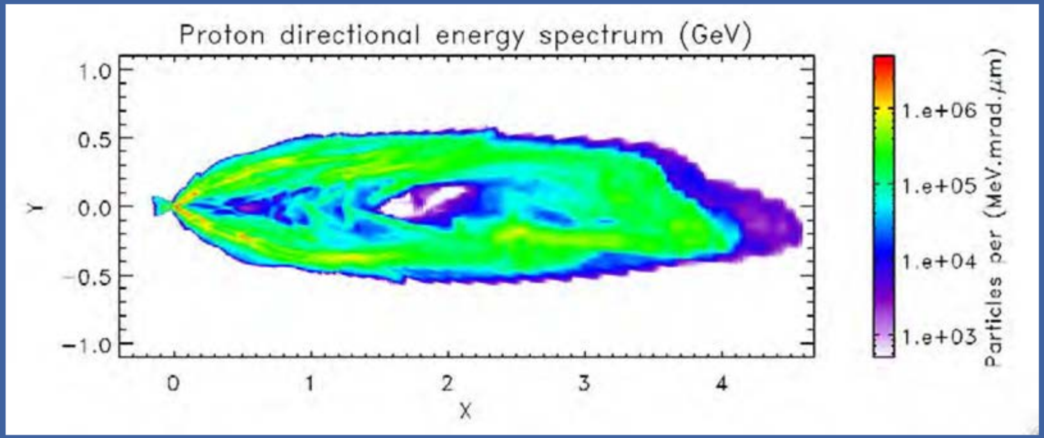
E_j^G the central energy in MeV

thermal component quasi-monochromatic component

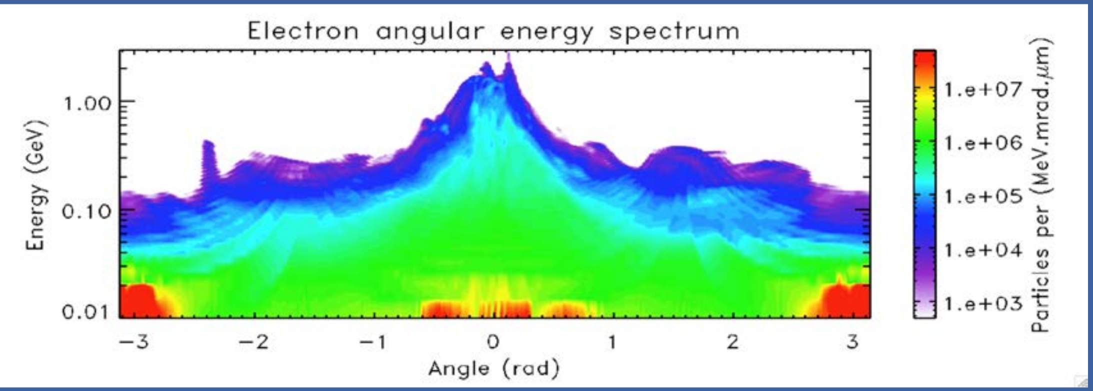
Determination of the source term

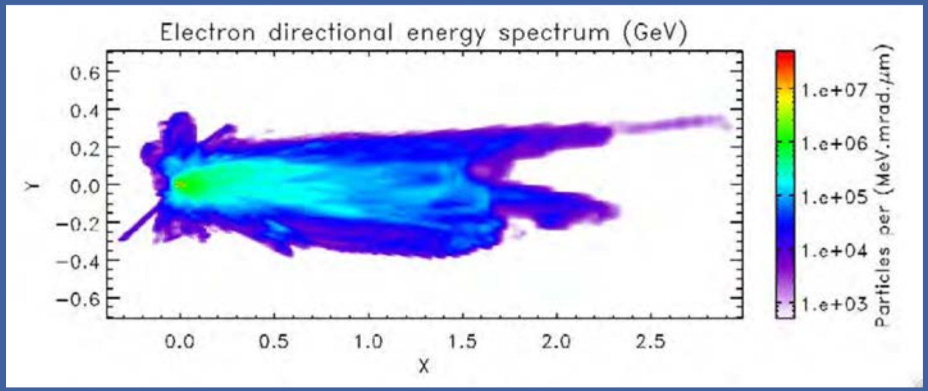
Target Thickness 1 µm   Material H   Density 0.088 g/cm^3 2kJ 15 fs   1.6x10^{23} *W/cm^2*





From ELI-PP Mid Term Report





The only way to define a source term is to use analytical estimations, numerical simulations and sometimes scaling laws

LNF FLAME Project

The number of the new facilities, equipped with multi-terawatt laser, used for studies in ultra-high intensity laser interaction with solid, gases and plasmas, as well as for high energy gradient acceleration technique, knows a continuous increase in the world.

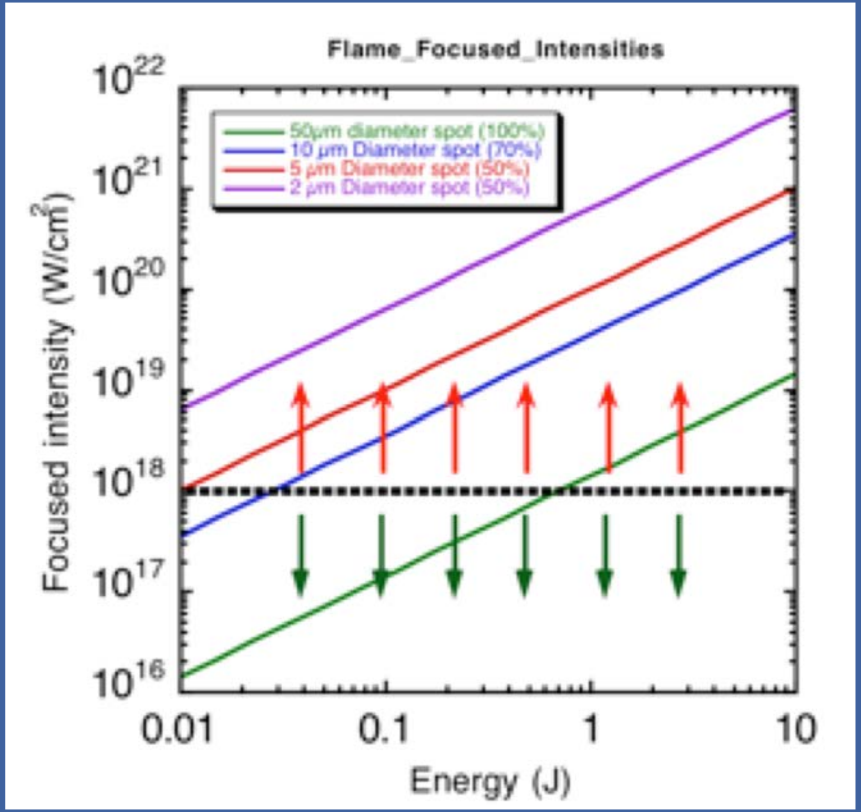
At National Laboratories of Frascati (LNF) is under commissioning the FLAME Laser (Frascati Laser for Acceleration and Multidisciplinary Experiments) whose main parameters are

Peak power 300 TW Output energy 8 J

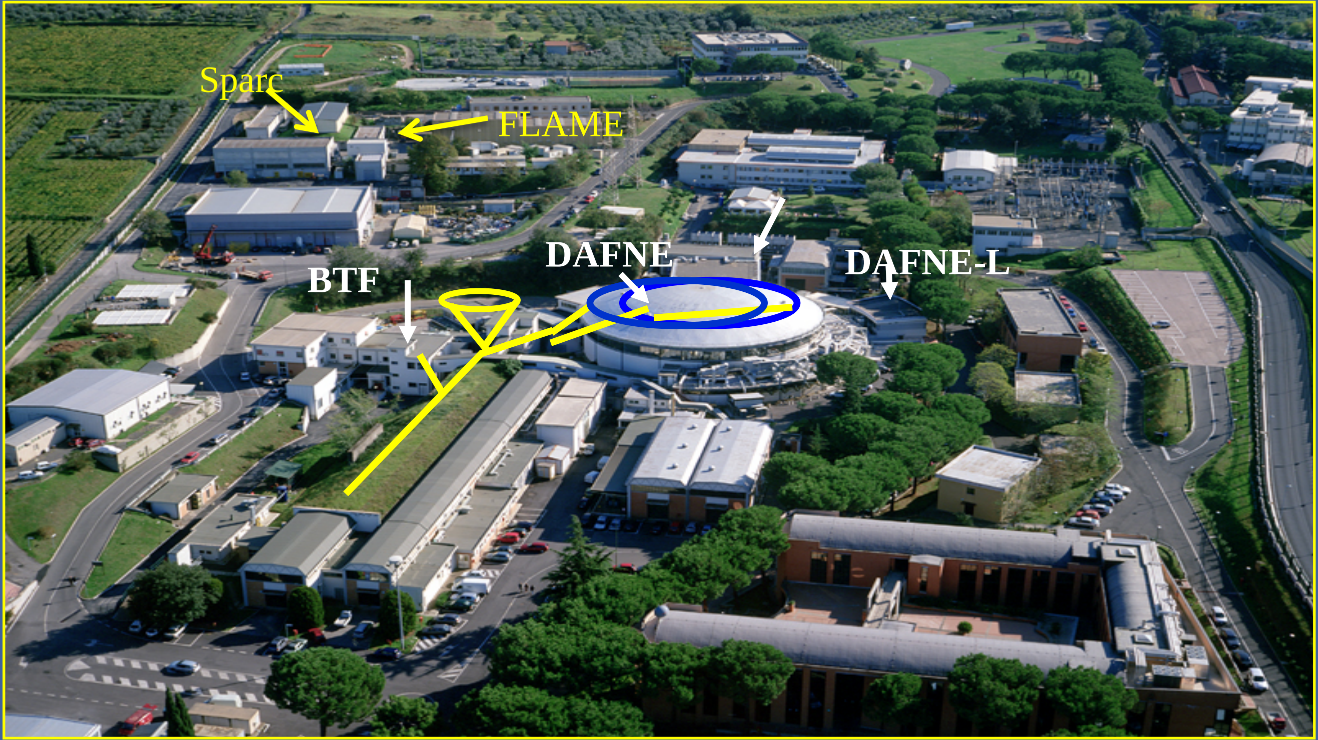
Pulse duration 20 fs Repetition rate 10 Hz

Up to 10^{20} W cm^{-2}

At laser interaction intensities of greater than 10^{17} W cm^{-2} a considerable part of laser energy is converted into generation of radiation.



Frascati Laser for Acceleration and Multi-disciplinary Experiments

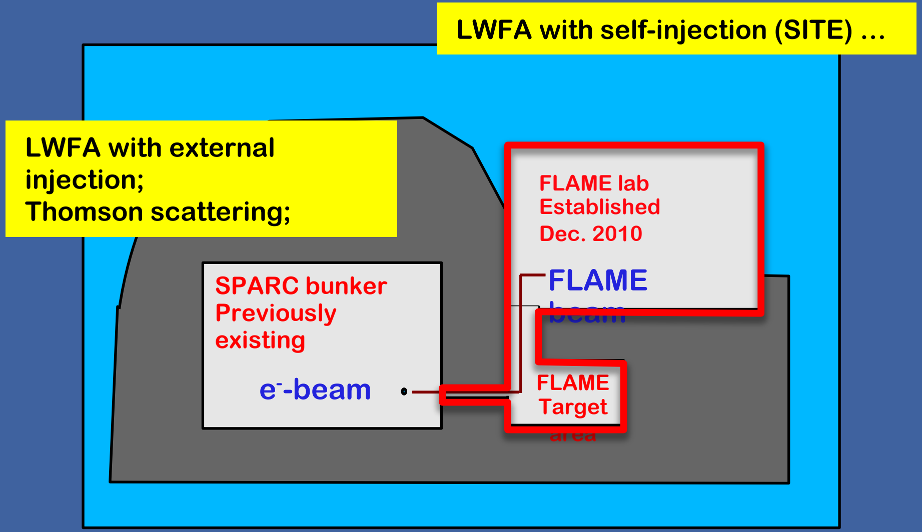


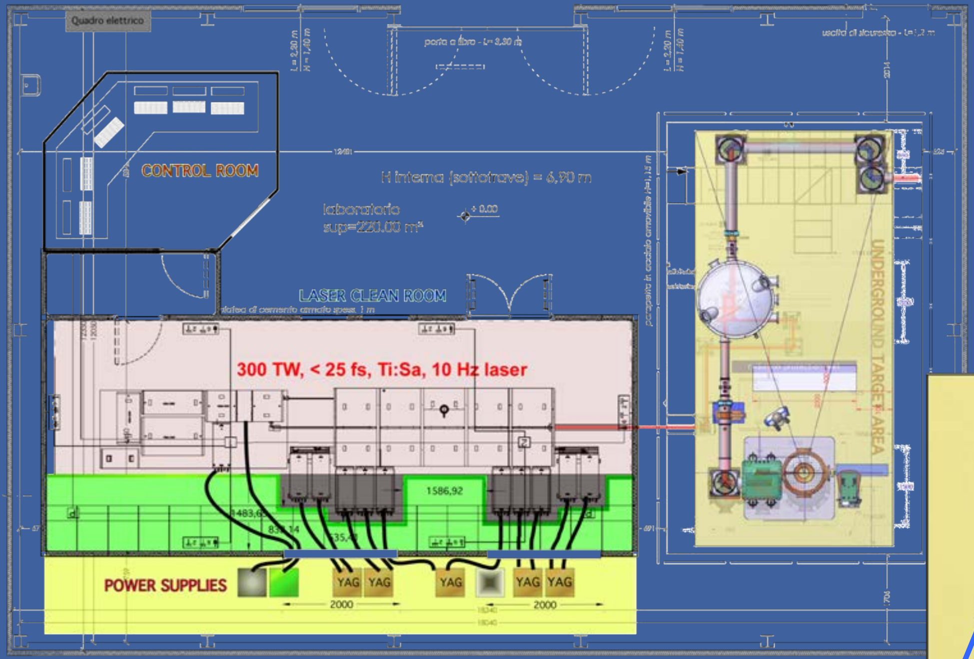
SPARC (Sorgente Pulsata Auto-amplificata di Radiazione Coerente, pulsed self-amplified source of coerent radiation)

E_{max} 150 MeV
I_p 200A
Pulse duration 10ps
Repetition Rate 10Hz

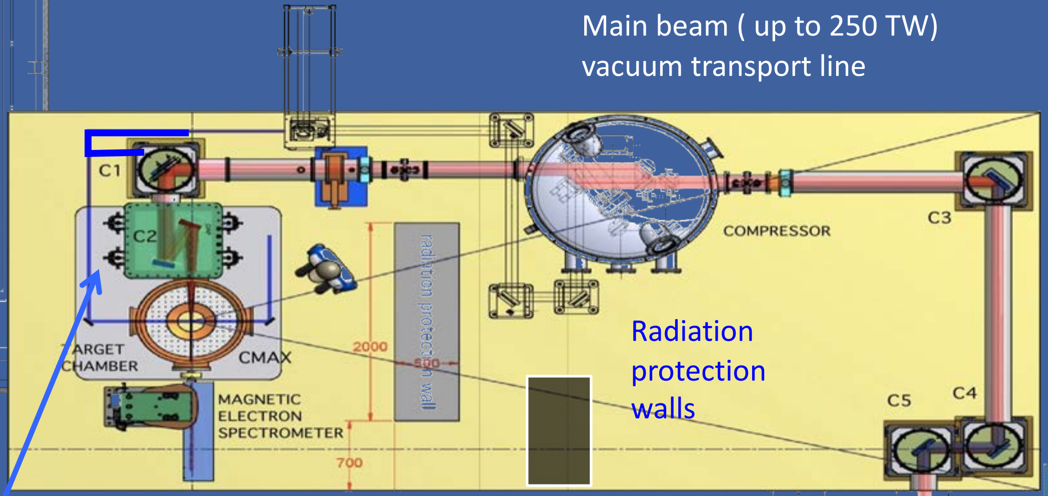
FLAME

nominal peak power 300 TW	
pulse length	≥ 20fs
repetition rate	10 Hz
output energy	8J
laser intensity	~ 10^{20} Wcm^{-2}





Main beam (up to 250 TW)
vacuum transport line

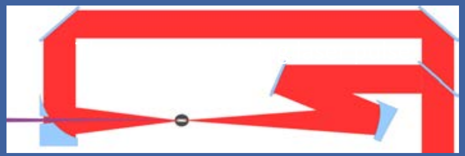


Aux "probe" beam up to 100 mJ

To SPARC bunker

Plasma acceleration

Thompson source



γ-rays

splitter

Main laser pulse
from FLAME

For the shielding evaluation

We reported only the values obtained in most conservative case from the point of radiation protection view (200 MeV, 1 nC/shot, 10Hz)

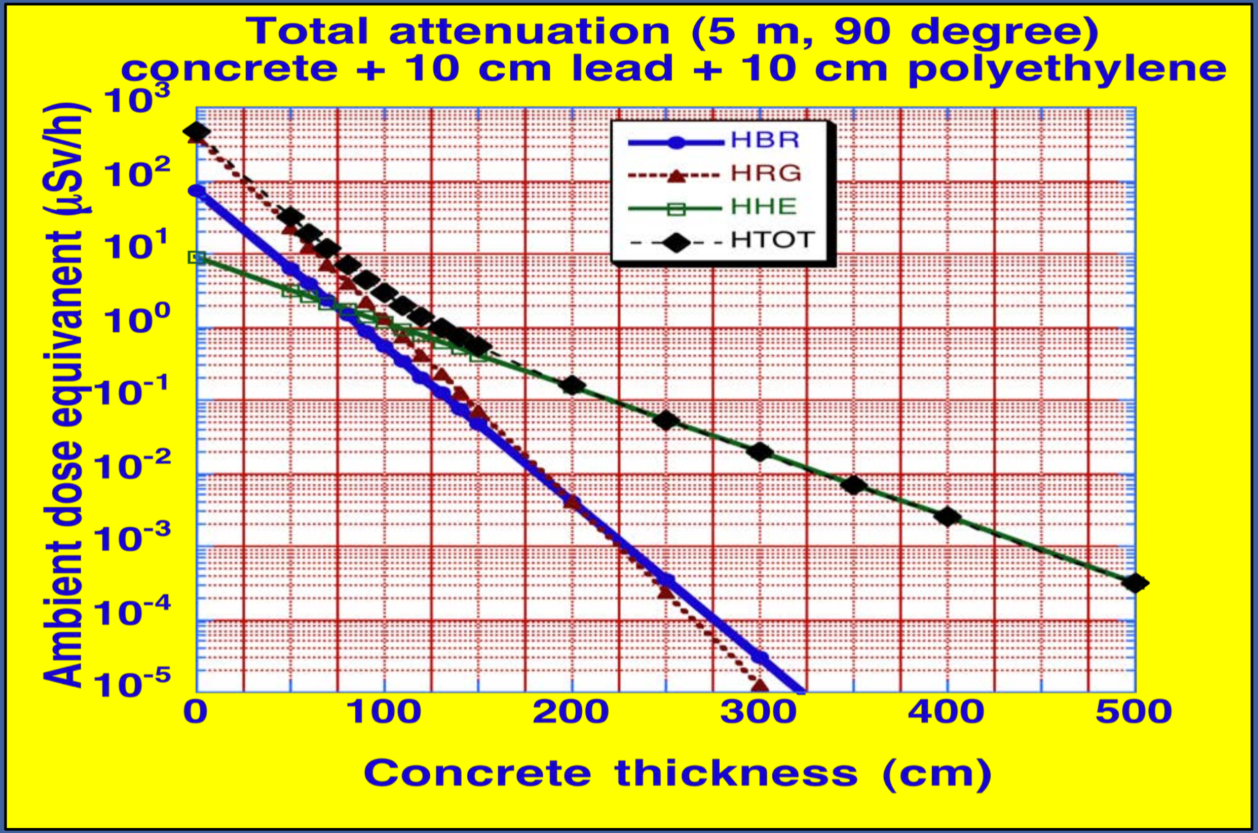
$$\sum \dot{H}_i = \sum_i \frac{S_i}{r^2} e^{-d/\lambda i}$$

250 h/year

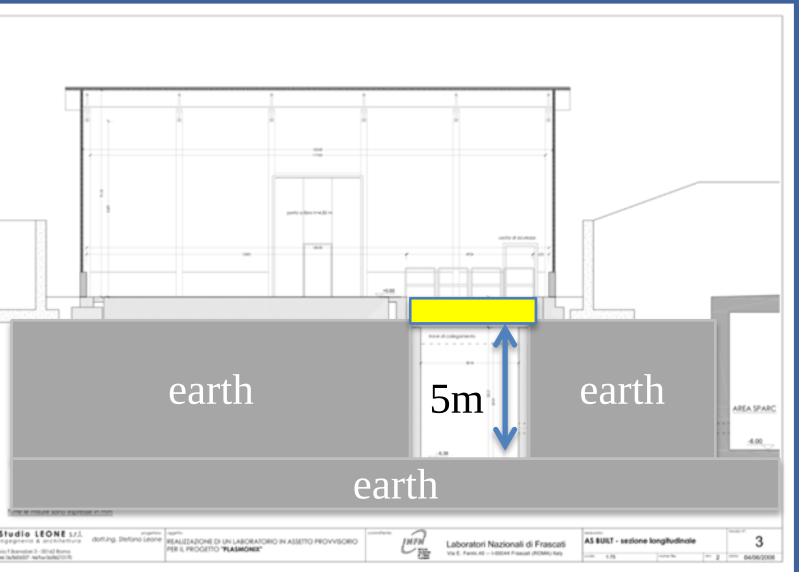
↓

ambient dose equivalent rate

H*(10) < 1mSv/year

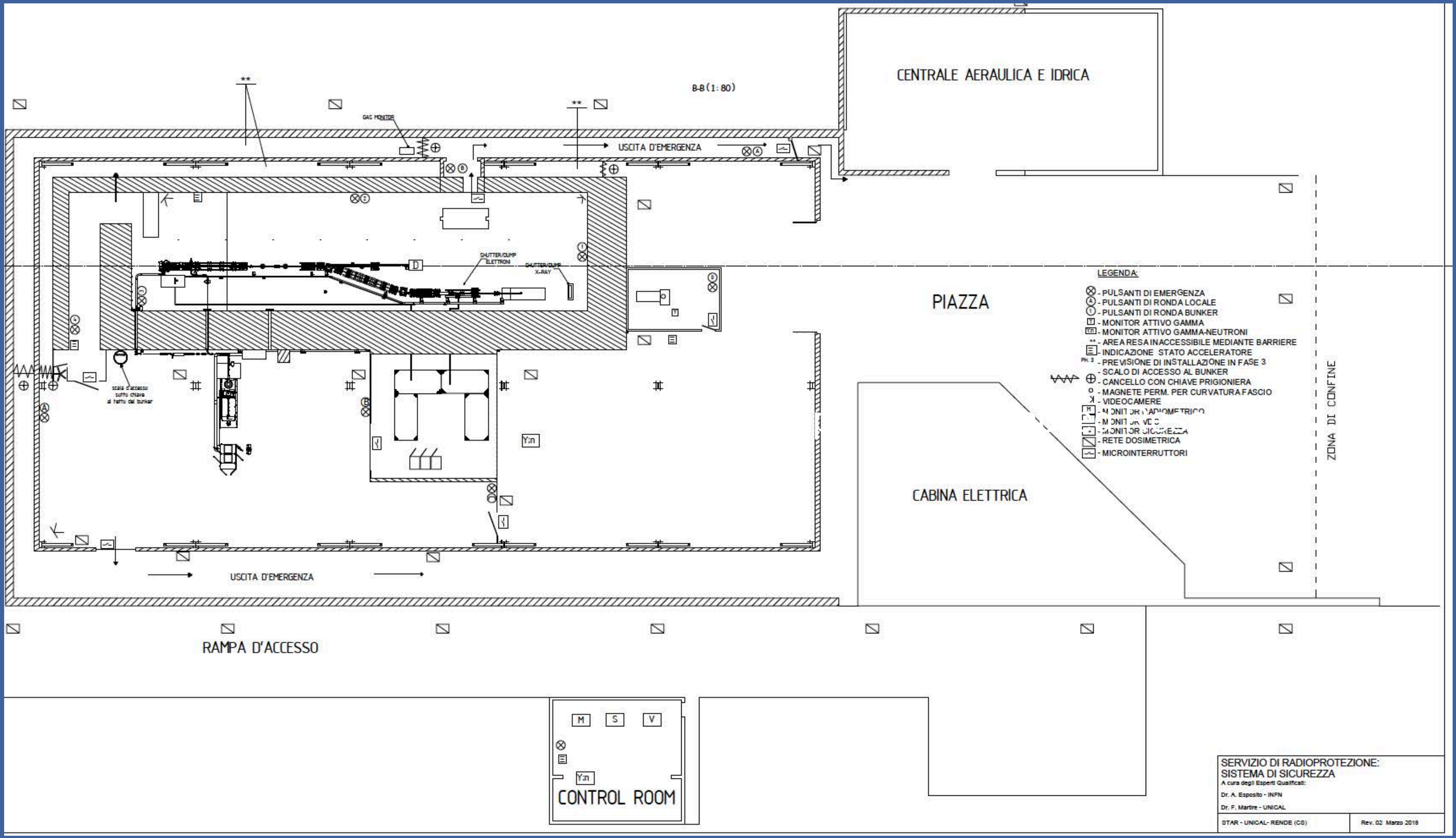


The ambient dose equivalent rate was evaluate only at 90°



È appena il caso di evidenziare che il normale funzionamento previsto sia in fase di “commissioning” che in fase di esercizio sarà a “single shot” da 200 MeV, 1 nC, 20 fs, massimi parametri raggiungibili. Sono previsti 10000 shot al giorno per 100 giorni anno.
In tali condizioni diventano del tutto trascurabili i ratei di equivalente di dose sul piano di calpestio.

The STAR Facility (Southern Europe Thompson Backscattering Source for Applied Research)



STAR is a typical Thomson Source for X-ray generation in the 20 −100 keV range, devoted to radiological imaging of pre-clinical studies and cultural heritage studies: electron recoil effects are absolutleynegligible in this case, where X-ray flux and moderate bandwidth are the key factors (hence maximum luminosity)

Obbiettivi di progetto

- Gli obiettivi di progetto prevedono, nelle normali condizioni di lavoro, che le dosi nelle aree esterne del bunker, cioè nell'hangar, dove si può trovare il personale operatore, siano mantenute entro 0,3 – 0,5 mSv/anno.

- Eventuali eccedenze oltre questi limiti comporteranno la classificazione delle aree come “zone sorvegliate/controllate” con conseguente limitazione dei tempi di permanenza.

- Nelle normali condizioni di lavoro, il rateo di equivalente di dose nelle aree dell'hangar abitualmente frequentate dai lavoratori, non dovrà superare 0,25 μSv/h e, solo in particolari ed eccezionali situazioni, per un breve periodo di tempo, potrebbe raggiungere qualche μSv/h.

- Resta inteso che eventuali valori superiori verranno controllati e automaticamente bloccati dal sistema di controllo radiometrico. Il contributo di dose ai membri della pubblico dovuto al funzionamento di STAR non dovrà eccedere 10 μSv/anno.

Il progetto STAR prevede tre fasi operative.
La prima fase prevede il funzionamento degli impianti fino ad una energia massima degli elettroni pari a 60 MeV. La successiva fase a 85 MeV, fino al raggiungimento dell'energia massima (3^ fase) di 350 MeV.

6000 ore anno di operazione

2000 ore anno di lavoro degli addetti

Da un punto di vista delle valutazioni di radioprotezione, le caratteristiche di funzionamento fondamentali per le tre fasi sono di seguito riportate:

Fase 2

Elettroni

Energia massima all'uscita della regione di accelerazione: 85 MeV

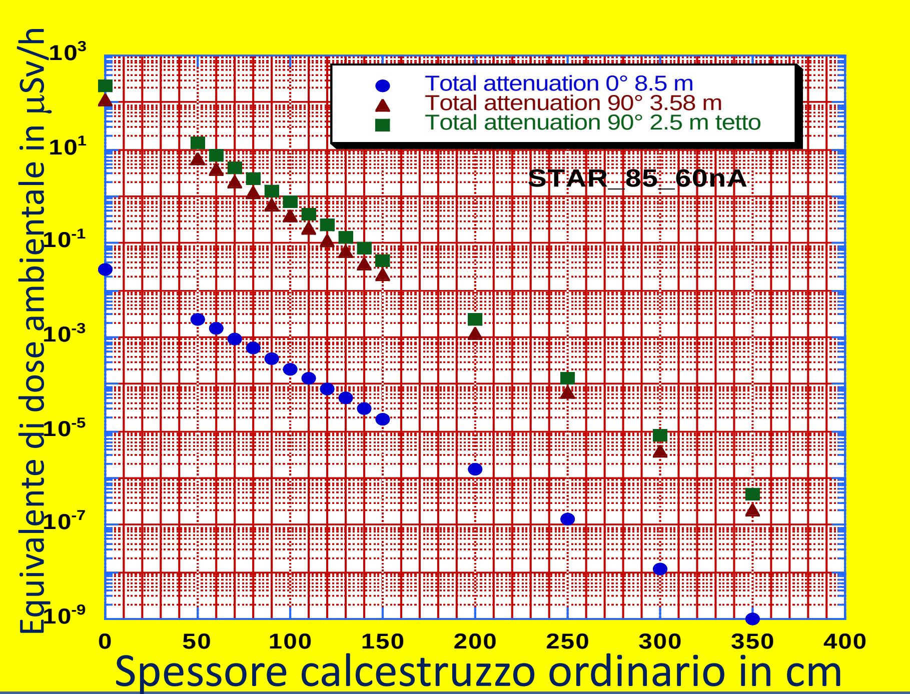
Corrente media 150 nA, corrente di buio inclusa (100nA)

Perdita di fascio lungo la linea da vuoto: 50 nA prima della prima sezione acceleratrice
40 nA prima dell'inizio della dogleg

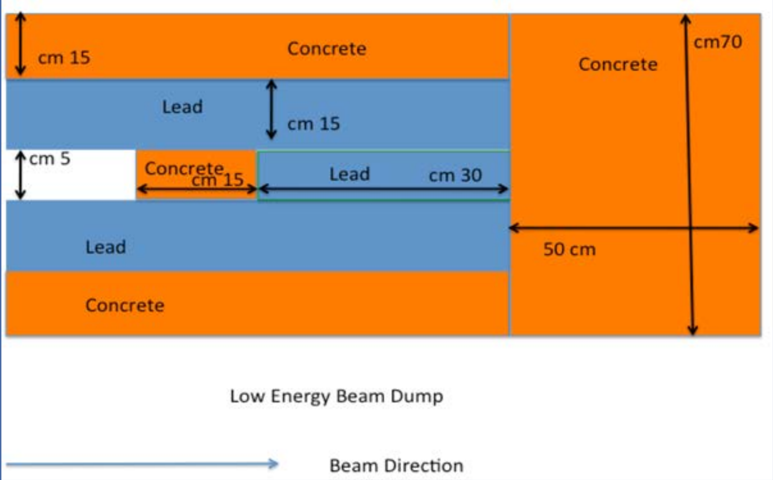
Fotoni

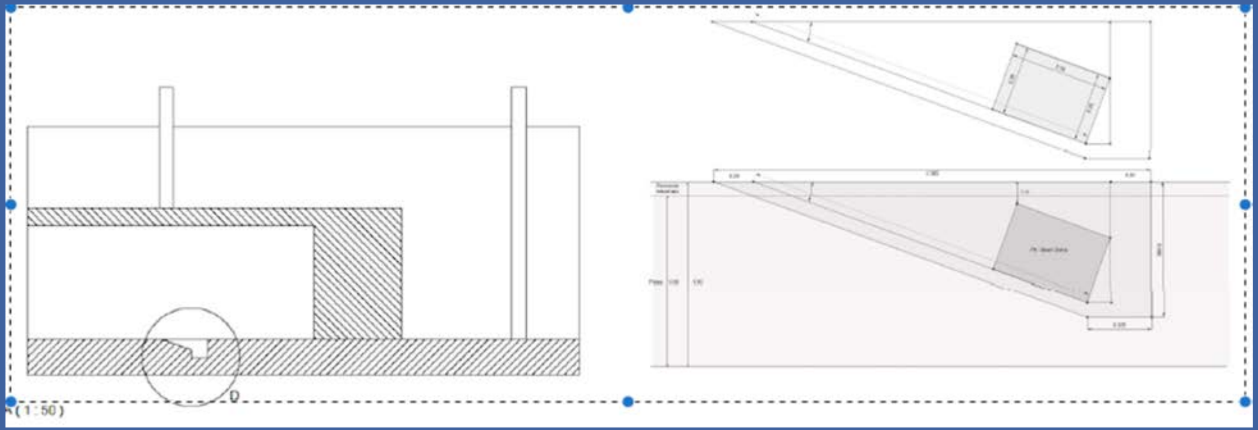
Intervallo energetico: 7 – 240 keV

Flusso: $5x10^{12}$



Star-andamento dell'attenuazione totale del fascio dopo l'interazione con il beam dump a varie distanze dal punto sorgente





Dump orizzontale

Che si fa una volta avuto il nulla osta all'impiego?

Si procede con la prima verifica dell'Esperto Qualificato che consiste nelle verifiche sul

- sistema di sicurezza segnalazione ed emergenza relativo all'area sottoposta a prove
- sistema di controllo radiologico
- sistema di controllo accessi ove fosse previsto
- nonche' sulla rispondenza delle schermature con quelle di progetto

Se i controlli effettuati danno tutti esito positivo si prosegue con l'accensione impianto facendolo portare a raggiungere l'energia e la corrente di esercizio, cosi' come indicato nel nulla osta all'impiego.

E si prosegue con la misura dei campi di radiazione all'esterno delle schermature.

Sulla base dei controlli e delle misure effettuate l'Esperto Qualificato da' il suo benestare al funzionamento, indicandone anche il periodo di validita', trascorso il quale dovra' provvedere ad effettuare tutte quelle misure e verifiche di competenza alla fine delle quali rinnovarlo. E cosi' via

Grazie

Neutron Shielding Materials

- Many shielding materials produce capture gamma rays or photons from inelastic scattering interactions. These can be minimized by adding lithium or boron to the shield. Lithium-6, which has a large (n thermal, α) cross section of 941 barn does not yield capture gamma rays by neutron absorption, and the helium and tritium atoms, that are formed, are easily absorbed.

- Natural boron contains 20% ^{10}B and is a very effective shielding material for thermal neutrons through $^{10}B(n, \alpha)^{7}Li$ reactions. About 96% of the ^{7}Li atoms created in these reactions are in an excited state which is relieved promptly by emission of a 0.48 MeV gamma ray, but these are easier to shield than the 2.225 MeV gamma rays from hydrogen capture and boron is commonly used in neutron shields.

- *Hydrogenous materials* such as paraffin and water make efficient neutron shields because of the effectiveness of elastic scattering with hydrogen atoms but not without potential problems. Paraffin is flammable, water can leak and evaporate, and thermal neutron capture produces 2.225 MeV gamma rays. When H_20 is used as a neutron shield, it is necessary to prevent leakage, minimize corrosion, and keep contaminants out, which is generally done by demineralization.

- *Metals* such as lead, iron, tungsten, and depleted uranium are relatively poor shield materials for neutrons; however, they are often used as a gamma shield, especially around nuclear reactors, and their neutron shielding properties are important because of such uses. Lead and iron can produce capture gamma rays of 7.4 and 7.6 MeV, respectively, although with low probability and (n, γ) interactions in ^{58}Fe produce radioactive ^{59}Fe ($T_{1/2}$= 44.51 d), which emits 1.1 and 1.29 MeV gamma rays. Metals are used in a mixed material shielding sandwhich to absorb high energy neutrons

- *Tungsten* is dense and is almost as effective as lead as a gamma shield. It is much better than lead for neutron attenuation, although secondary gamma radiation is produced due to capture reactions.

- *Depleted uranium*, which is readily available from nuclear fuel enrichment processes, is very dense (ρ = 19 g/cm^3) and is the best attenuator available on a volume basis for gamma rays. Neutron attenuation in U is about the same as in lead, and even though it doesn't produce significant capture gamma rays, fast fission reactions may yield gamma-emitting fission products.

- **Lithium and Boron are often incorporated into neutron shields because of its absorption cross section ^{6}Li (760 barn) and the large (n,γ) cross section of ^{10}B (3840 barn).**

- **The alpha particles from ^{10}B reactions are easily absorbed and the 0.48 MeV gamma rays from the excited ^{7}Li product, which occurs in 96% of the interactions, is not too difficult to shield.**

- **Borax (sodium borate) is a crystalline powdery material that is easily shaped into various shield configurations, is not subject to leakage, and is cheap and effective.**

- **Borated water and borated polyethylene are useful, as are boron oxide, boric acid, and boron carbide (B_4C). A sandwich material called boral is available that consists of an Al-B_4C mixture clad in aluminum. Boron has also been added to various steels to absorb thermal neutrons and reduce activation products and associated gamma rays.**

- *Polyethylene* is a pure hydrocarbon that contains 18% more hydrogen per unit volume than water (about 8 x 10^{22} atoms of H/cm^3 versus 5.98 x 10^{22} atoms of H/cm^3 for H_2O). Unfortunately, it softens at about 100 ºC and will burn; a more dense (p = 0.96 g/cm^3) variety is available that softens at about 200 ºC but with slightly diminished neutron removal properties. Boron can also be added to polyethylene to absorb thermal neutrons from hydrogen interactions. Water extended polyethylene (or WEP) is a special formulation of polyethylene that is an especially effective neutron shield.

- *Lithium hydride* contains about 12.6% H by weight and is a very effective material for neutron attenuation. It is, however, difficult to fabricate into solid shields. It also actively combines with water, and because of this property needs to be protected from water by encapsulation or other means. Lithium hydroxide is often mixed with water to absorb thermal neutrons and has been used as a burnable reactivity shim in nuclear reactors or added to water shields to absorb thermal neutrons after they are slowed down. Capture reactions in lithium do not produce gamma rays, but absorption of neutrons by ^{6}Li in natural lithium produces tritium, which can be minimized by using lithium depleted in ^{6}Li.

- Cadmium has a high (n, γ) neutron capture cross section (2450 barn) and is frequently used as a neutron absorber, but like hydrogen has the disadvantage of emitting energetic 9.05 MeV capture gamma rays, which themselves require shielding.