Radiation protection issues for laser based accelerators and commissioning of LNF FLAME project

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Introduction

◆Radiations and particles have many applications in several field of human activities.

In addition to their continued application to fundamental research they are in fact widely applied in all field of science (medicine, material science, chemistry, food sterilization, health care product sterilization and so on).

◆Up to today the radiation were produced by the conventional radiation sources (accelerators, X-ray tube, radioactive sources), with the well-known associated problems of costs, parameters achievable and safety.

◆The generation and acceleration of charged particles using lasers, able to focus ultra-short high intensity pulses onto targets, is opening new perspectives in laser acceleration as well as in nuclear physics and attosecond science.

◆ 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.

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Introduction

The aim of this presentation is

◆to focus the radiological protection aspects, 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", that a project manager should take into account in designing a facility for laser based accelerators.

◆to describe the status of art of the LNF Flame project

◆to report preliminary tests, experiments and results

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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 the Directive 96/29/Euratom of 13 May 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 restrictive policies.

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Regulatory and Advisory Agencies

Advisory Agency → IAEA

Advisory Agency → ICRU

Advisory Agency → ICRP

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

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.

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

The last basic consideration on radiation protection were stated in Publication 103 of 2007

The ICRP Publication provides

the biological aspects of radiation protection;
the quantities used in radiological protection;
the system of radiological protection of humans

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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

- Determination of the source term
  - well known for accelerators
  - open question for accelerator laser based facilities
- Specification of required dose equivalent (rate) outside the shield
- 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

Environmental radiation | Shielding materials | Trend in regulatory limits

and so on

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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.

When a very powerful laser interacts with a gas jet or a solid target electrons, protons, ions or photons are produced.

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

That is

- **bremssstrahlung;**
- **neutrons;**
- **muons;**
- **pions;**
- **Kaons;**
- **any other particle (charged particles, ions, nuclear fragments and delayed radiation)**

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Accelerator shielding

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	15 mSv
Skin[c,d]	500 mSv	50 mSv
Hands and feet	500 mSv	–

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 a value of 10µSv/y!!

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

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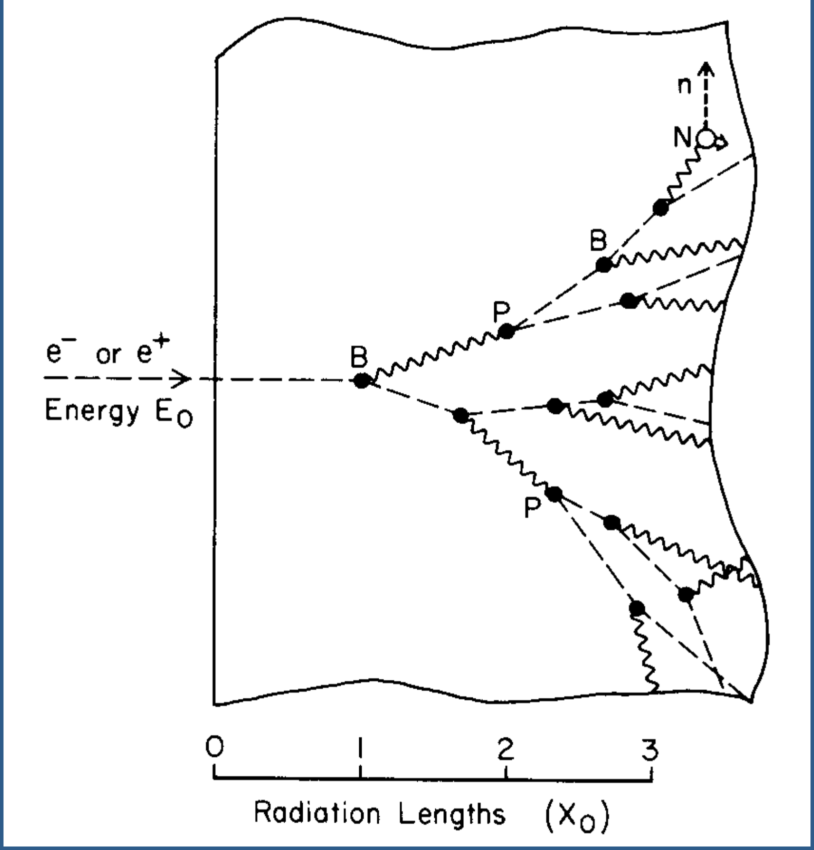
Electrons

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, ~9/7X_0 for photons

X_0 = radiation length (e^- energy reduced to 1/e)

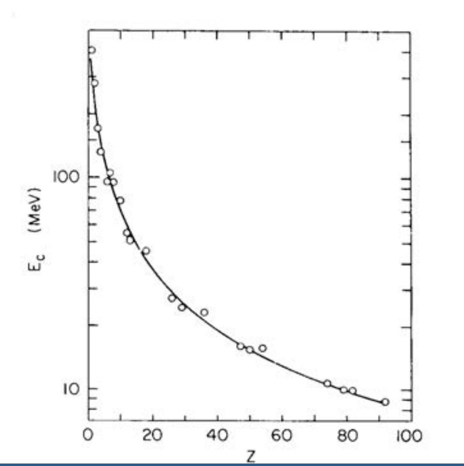
Multiplication stops when E_e drops below E_c

Critical energy $\boldsymbol{E_c}$:

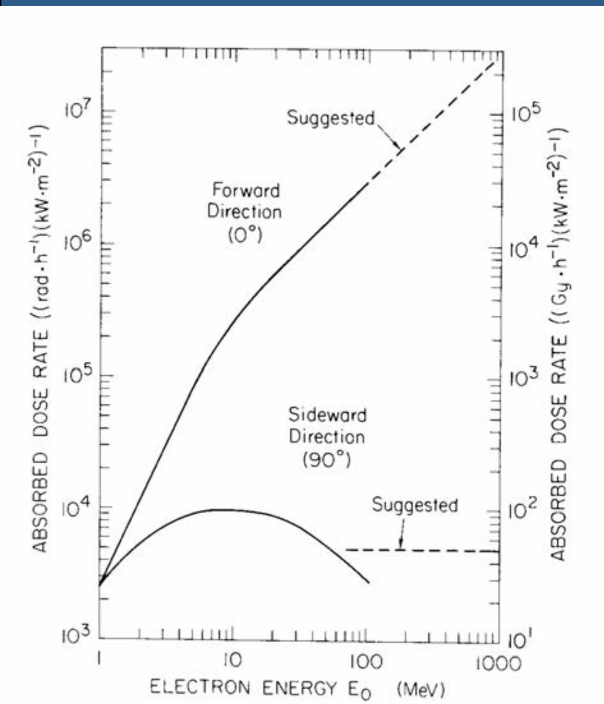
$dE/dx|_{col} = dE/dx|_{rad}$

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

	E_c [MeV]
Pb	9.51
Fe	27.4



Electrons

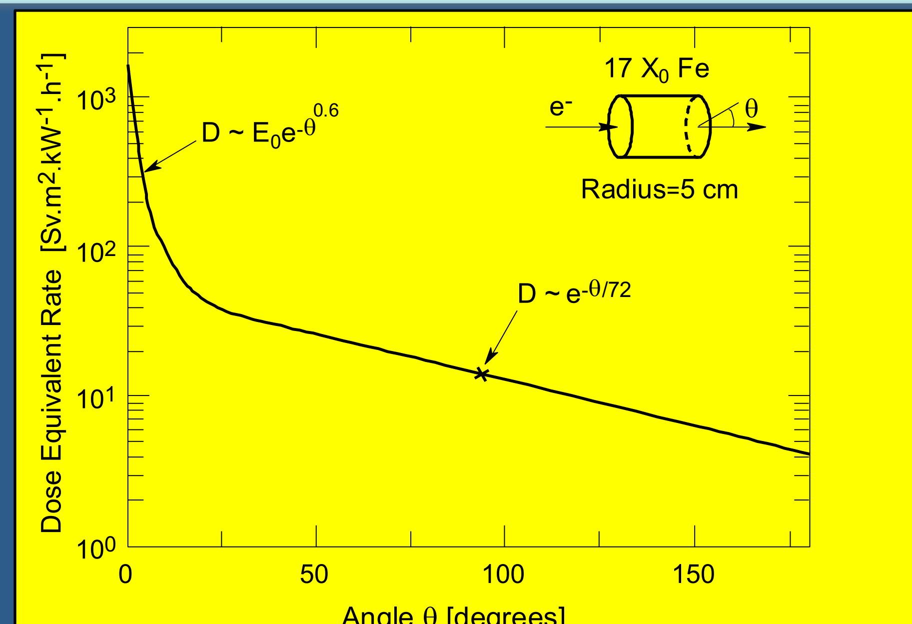


Rules of thumb:(for thick hi-Z targets)

At 0°, E_0 > 20 MeV: $\dot{D}\left[\mathrm{Gy.h^{-1}.kW^{-1}.m^{2}}\right] \approx 300E_0$

At 90°, E_0 > 100 MeV: $\dot{D}\left[\mathrm{Gy.h^{-1}.kW^{-1}.m^{2}}\right] \approx 5$

100



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

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

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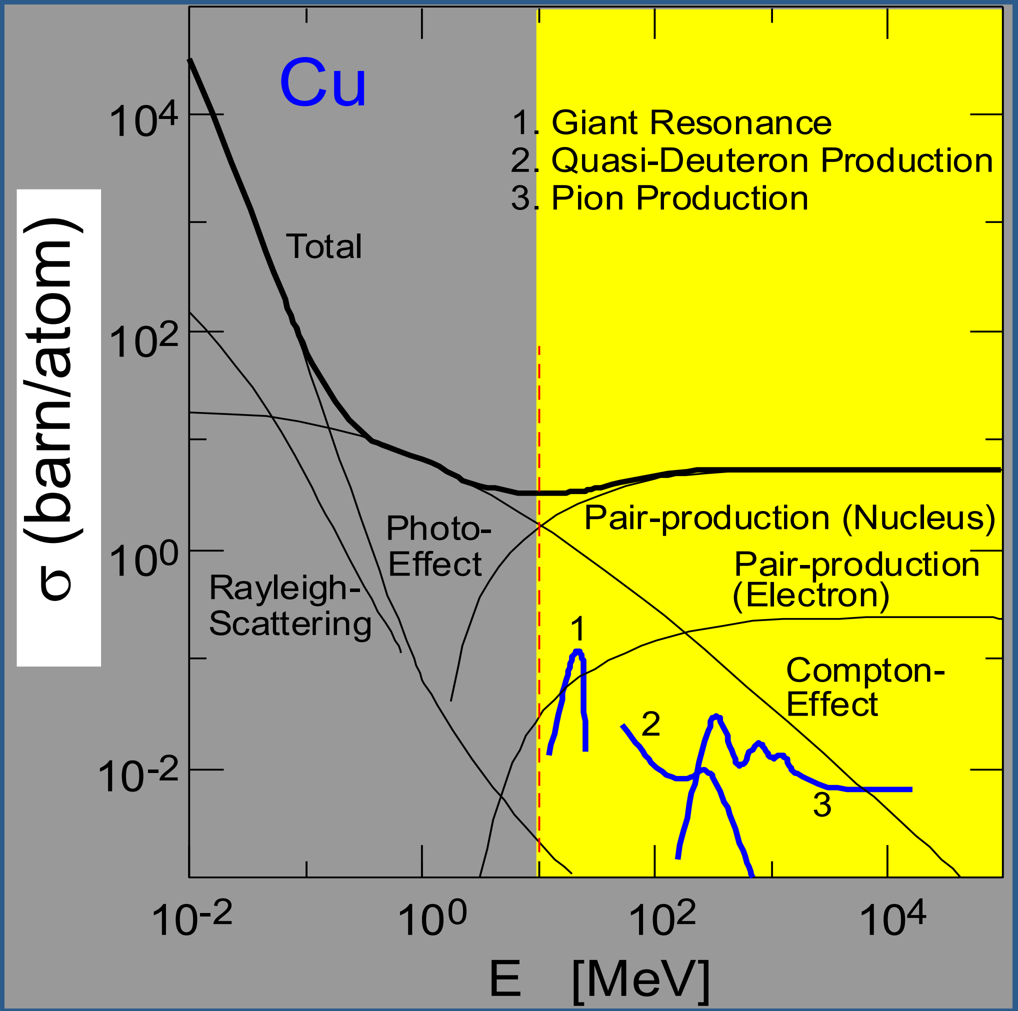
Electrons

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



Electrons

Giant resonance neutrons

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

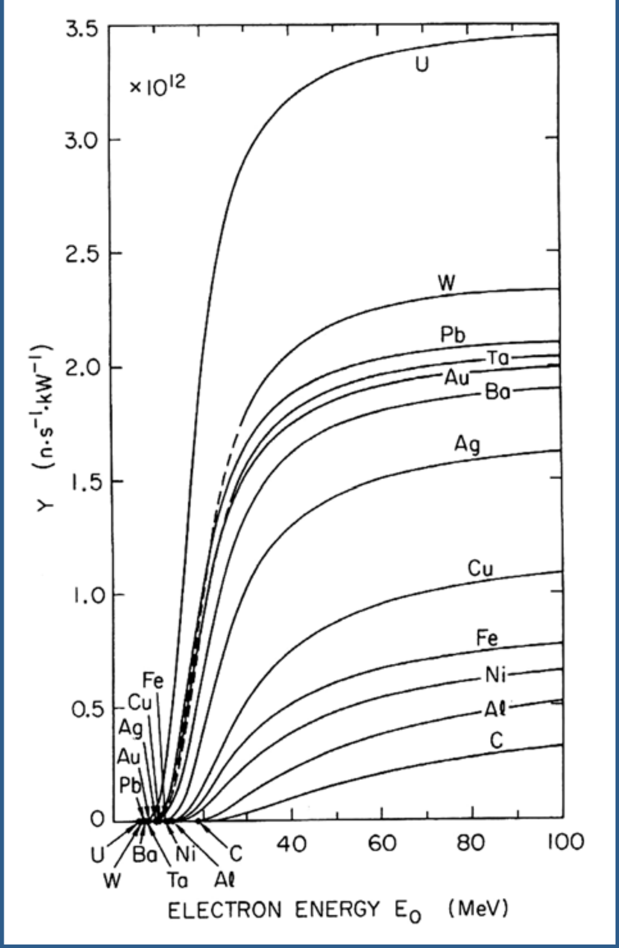
$E_{threshold}$ ~ 6-13 MeV
for most materials

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

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^{-}

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



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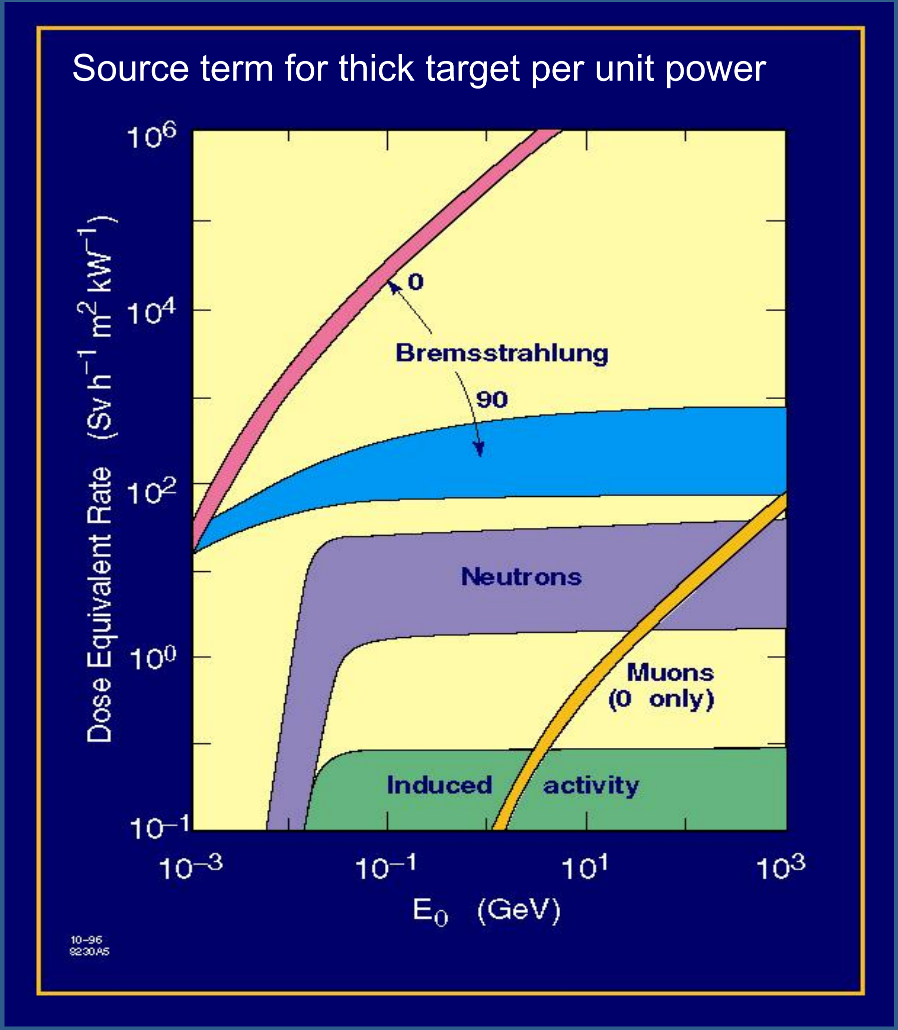
Electrons

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.



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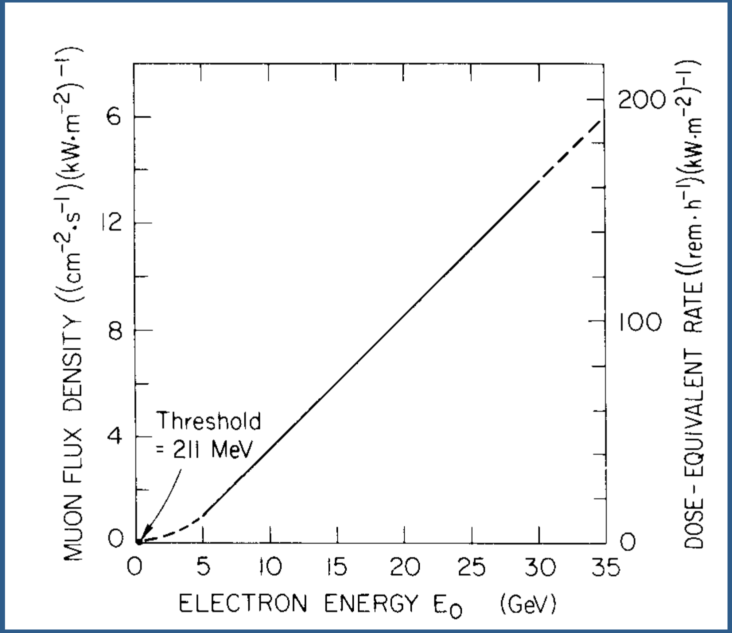
Electrons - muon production

- Muons production is analogous to e^+/e^- pair production by photons in the field of target nuclei when photon energy exceeds the threshold $2m_mc^2 \approx 211$ MeV.
- μ^+/μ^- pair will occur with a much lower probability than e^+/e^- pair.
- 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
- Muons 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
- Yield ~ E_0 (per unit beam power)
- Muons 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 0° direction.



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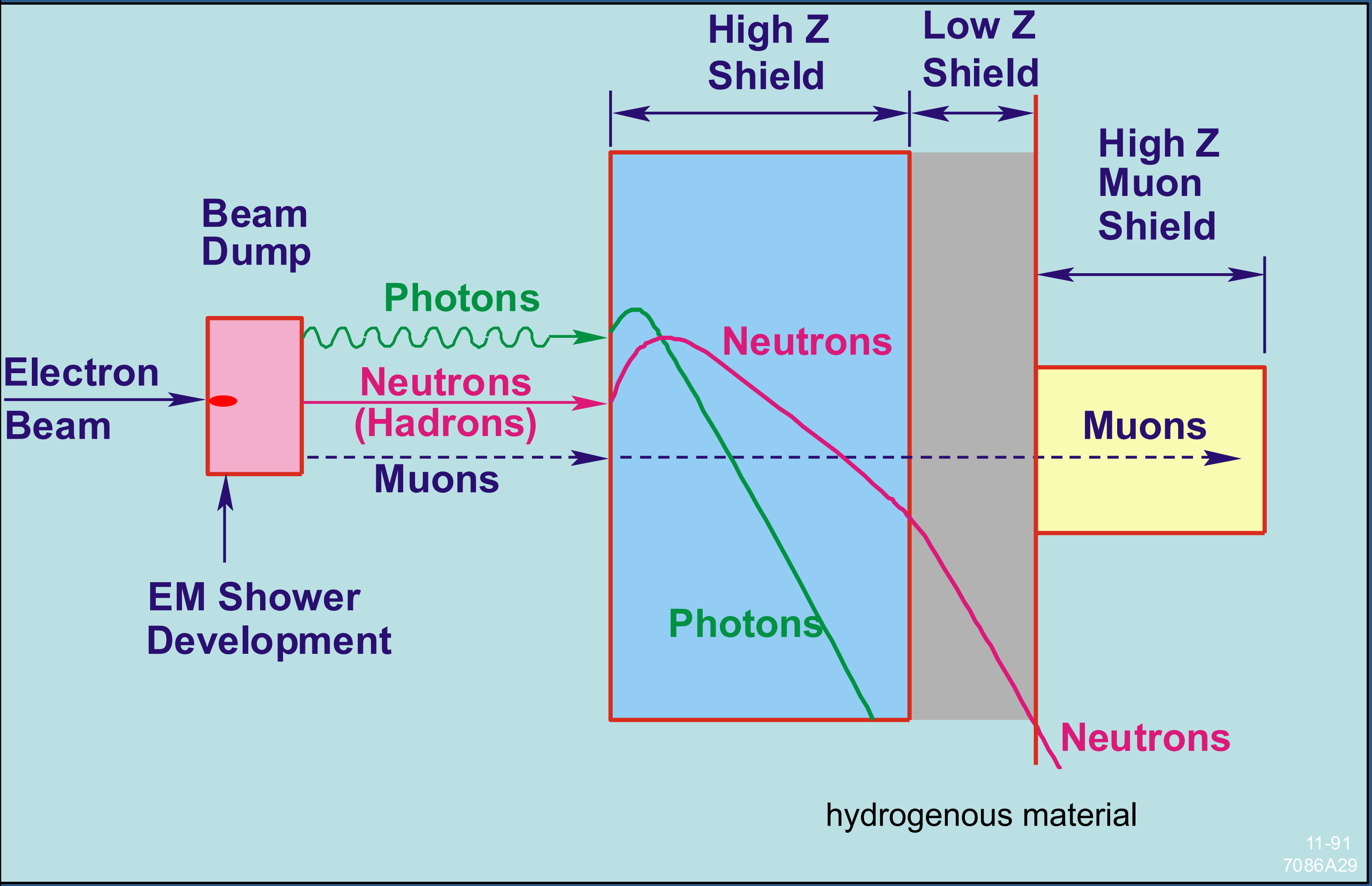
Electrons



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.

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Protons

◆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

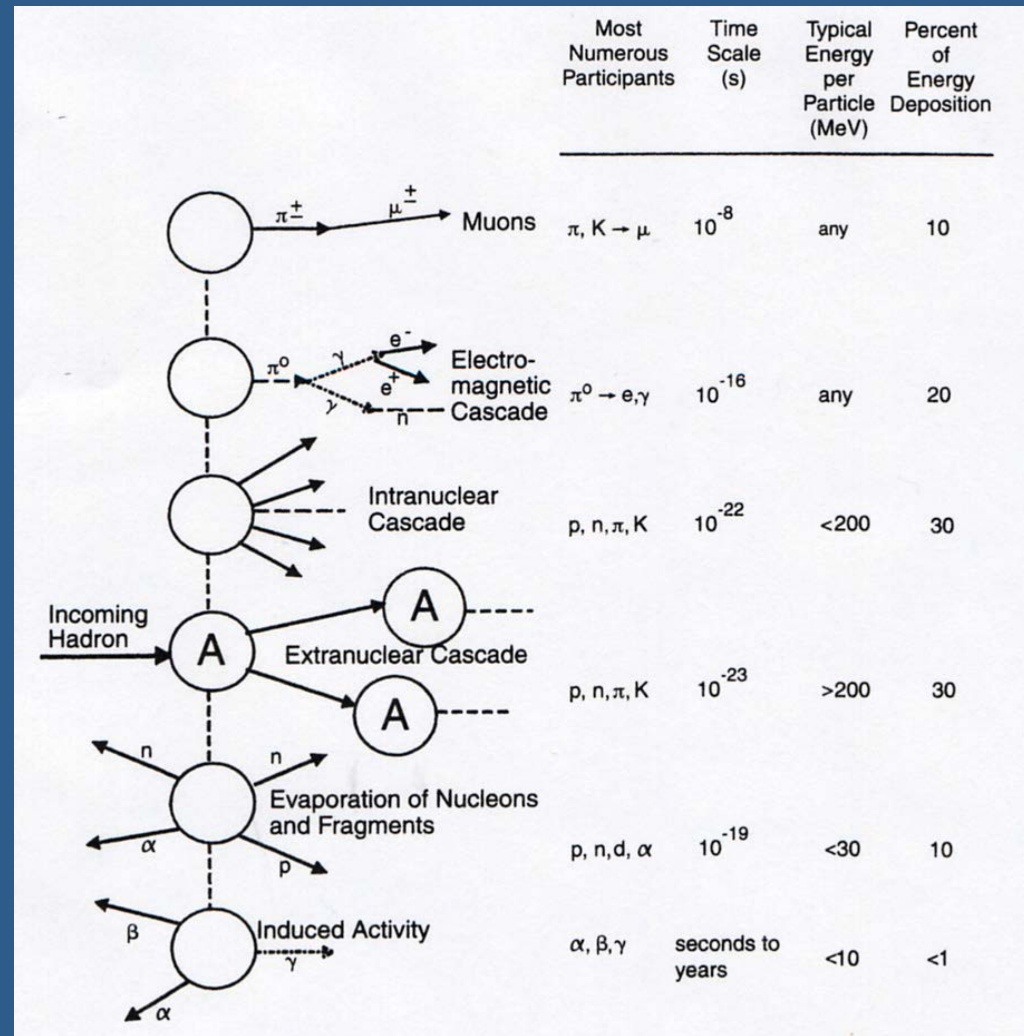
◆The main means of energy transfer is due to the interaction of high-energy nucleon that is hadrons with energy higher than 150 MeV, that serve to propagate the cascade.

◆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.



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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

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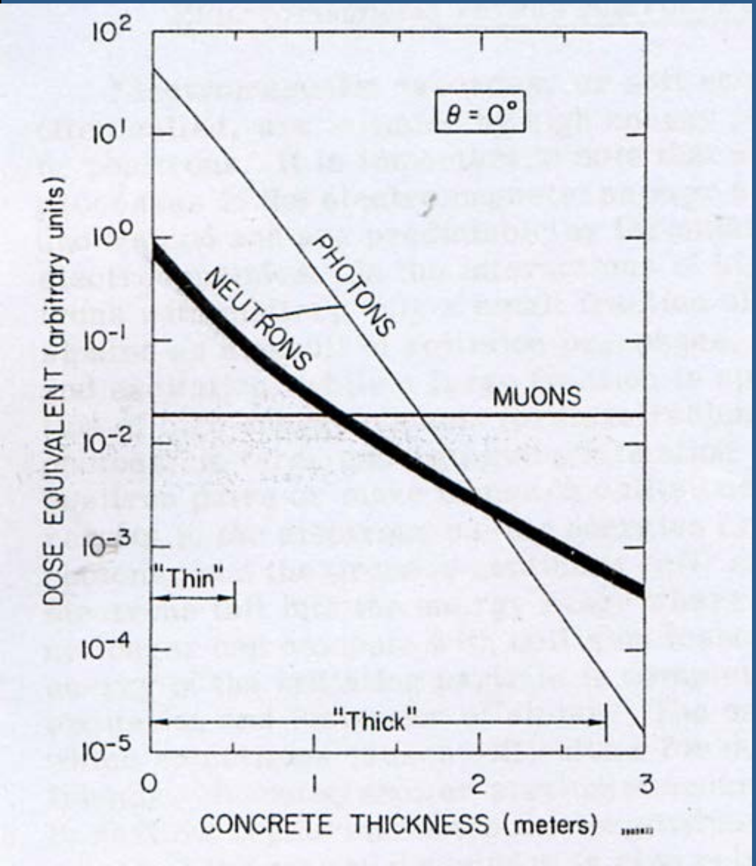
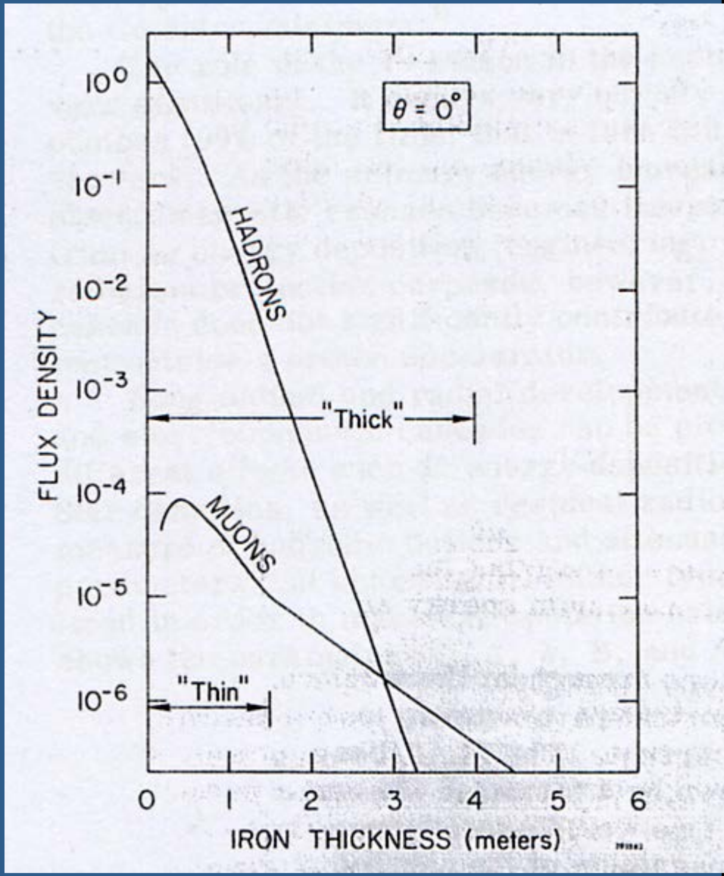
Accelerator shielding-symmetric cascades





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.

Shielding materials

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

However, for practical reason, only material commonly used in constructions are used

Ordinary concrete	aggregates	Heavy concrete	Steel	Earth
2.35 gcm^{-3}	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}		

Main factors used for selecting a shielding material

Possibility of shielding against X , γ and neutrons

Required thickness and weight

Multiple use for shielding and structural purposes

Homogeneity of shielding

Stability of shielding

Cost including installation and maintenance

Special materials

Lead   Lead alloys   Tungsten   Depleted Uranium

Hydrogenous materials

wood

polyethylene

water

Hydrogen is very important for neutron attenuation 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.

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Shielding

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

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

Conversion coefficients

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

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

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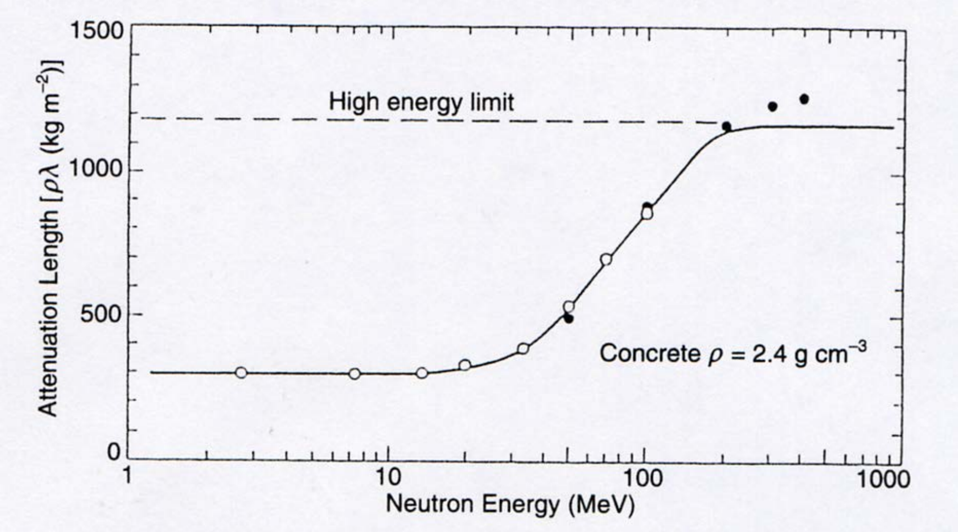
Shielding - Attenuation lenghts

Bremsstrahlung

e-

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

p



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
Terra	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
Terra	1.6	56.3
High Density Polyethylene	1.01	61.4

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Induced Activity

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

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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 and scattered radiation.

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

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

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

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

(Sv / n)

λ 300-850 m

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Environmental radiological aspects

- 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);

- noxious gas production O_3, NO, NO_x;

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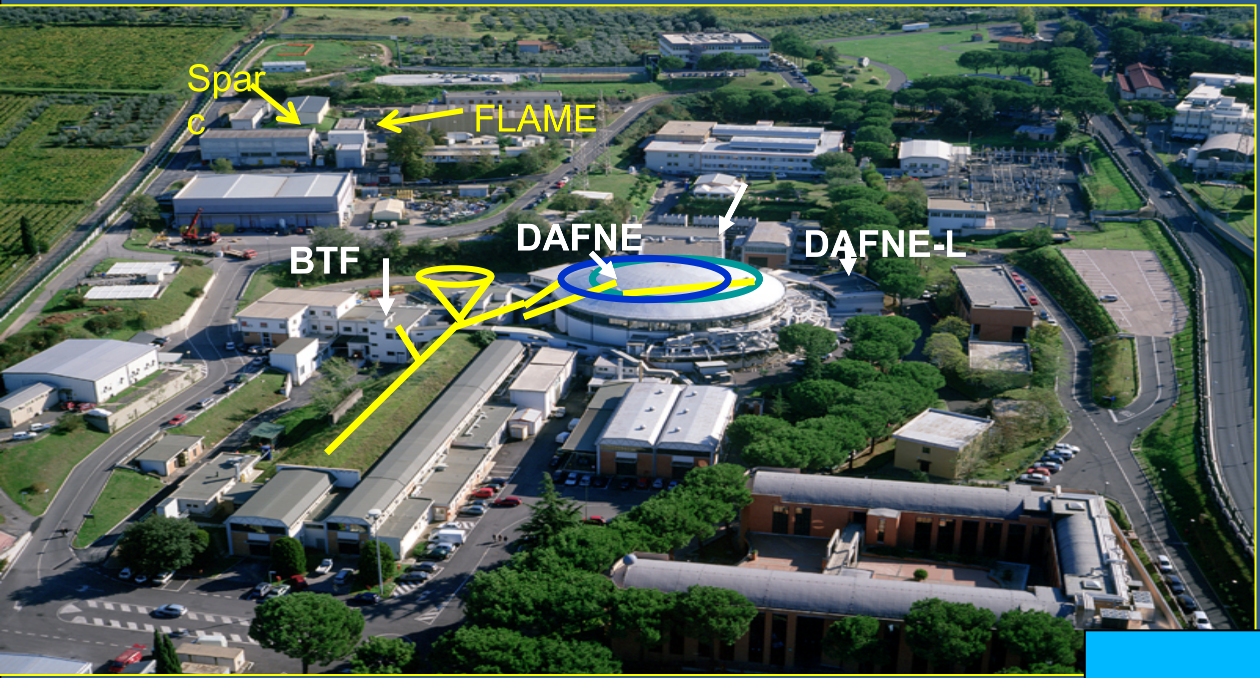
Frascati Laser for Acceleration and Multi-disciplinary Experiments

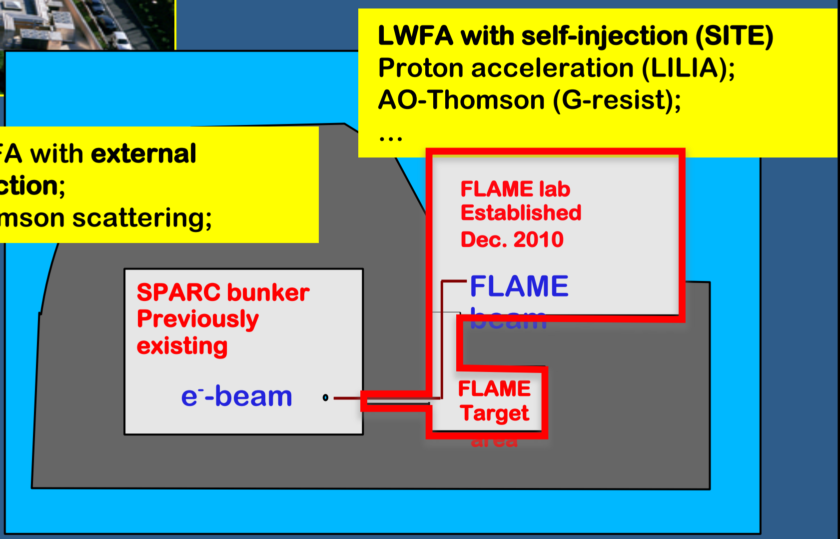


SPARC (Sorgente Pulsata Auto-amplificata di Radiazione Coerente, pulsed self-amplified source of coerent radiation)

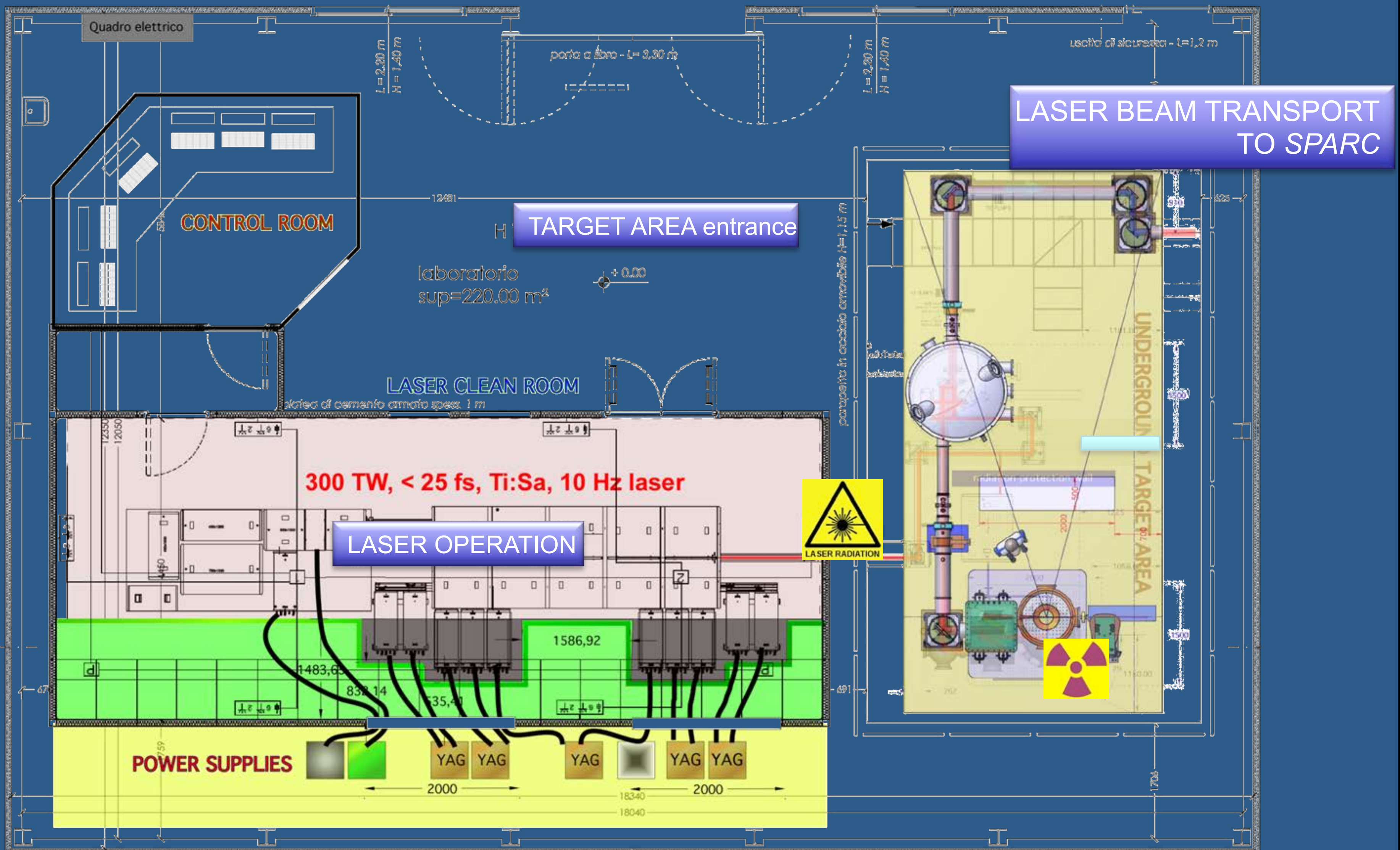
E_{max} 150 MeV
I_p 200A
Pulse duration 10ps
Repetition Rate 10Hz

FLAME

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



FLAME – Overview



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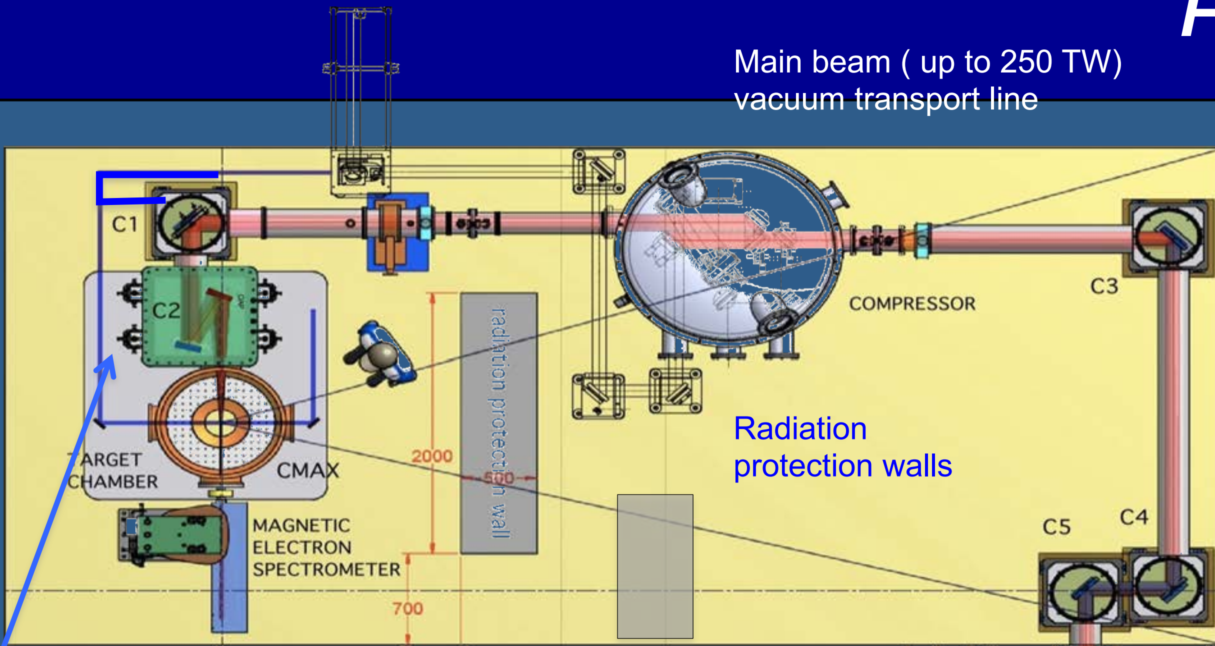
FLAME Target Area

Main beam (up to 250 TW)
vacuum transport line



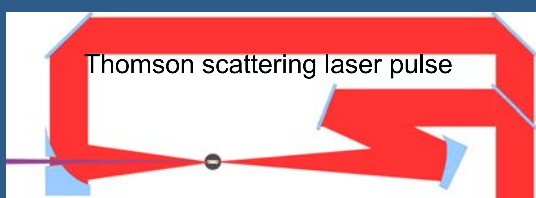
Radiation
protection walls

Aux “probe” beam up
to 100 mJ

To SPARC
bunker

Plasma acceleration

Thompson source



γ-rays

splitter

Main laser pulse
from FLAME

Plasma Acceleration laser pulse

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For the shielding evaluation

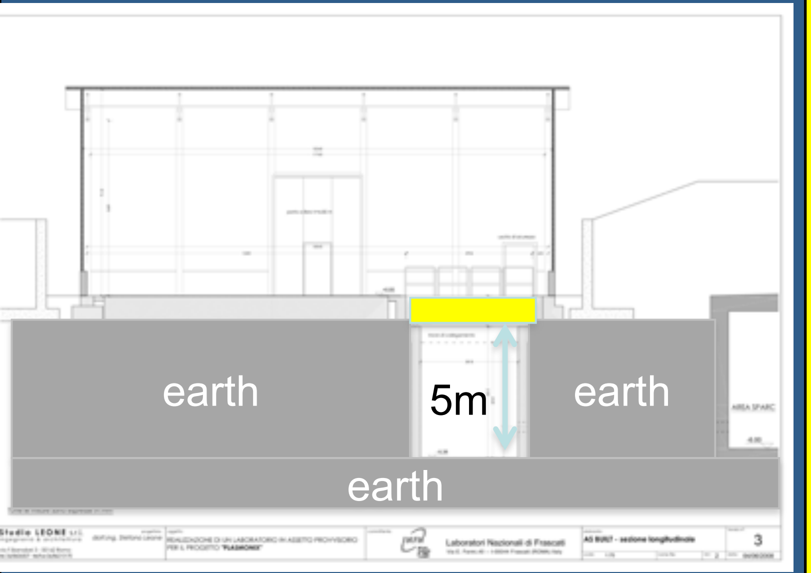
We reported only the values obtained in most conservative case from the point of radiation protection view (200 MeV, 1 nC/shot, 10Hz)

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

↓

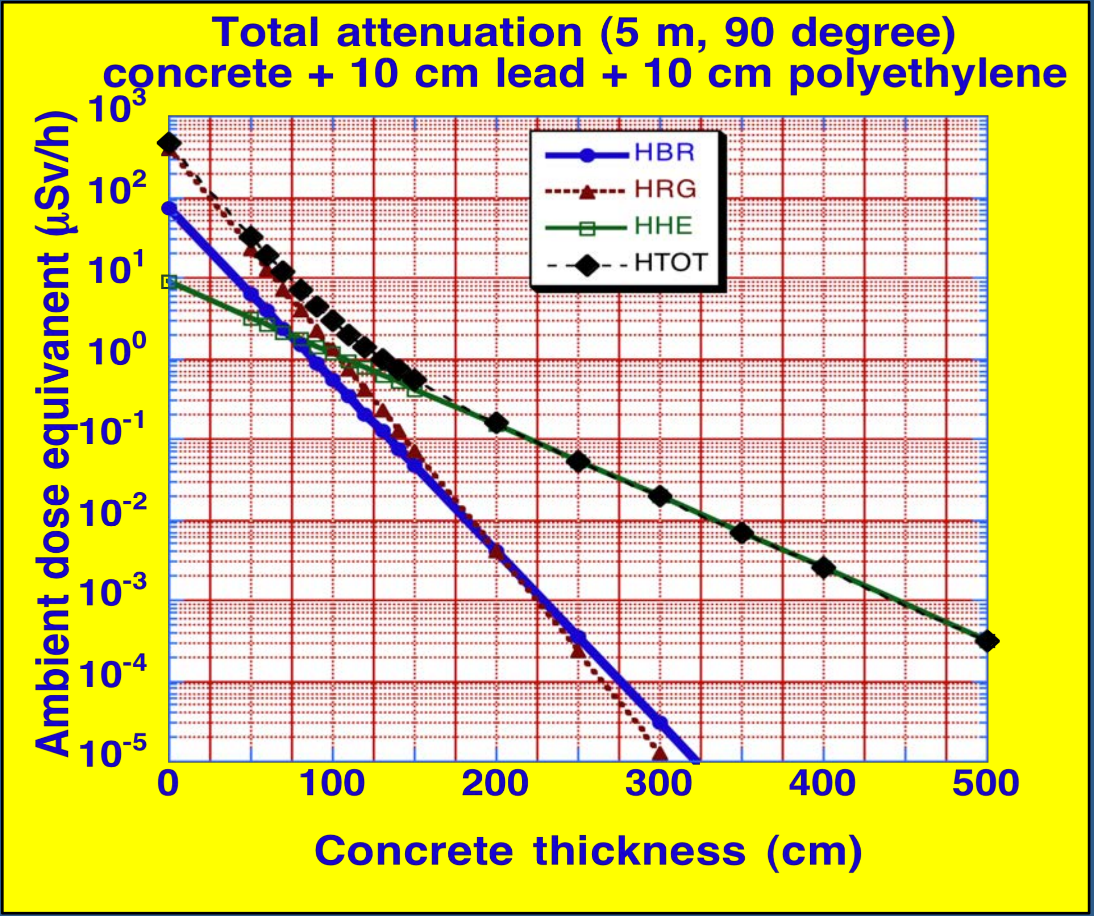
ambient dose equivalent rate

The ambient dose equivalent rate was evaluate only at 90°



H*(10) < 1mSv/year

250 h/year



Interlock design and feature

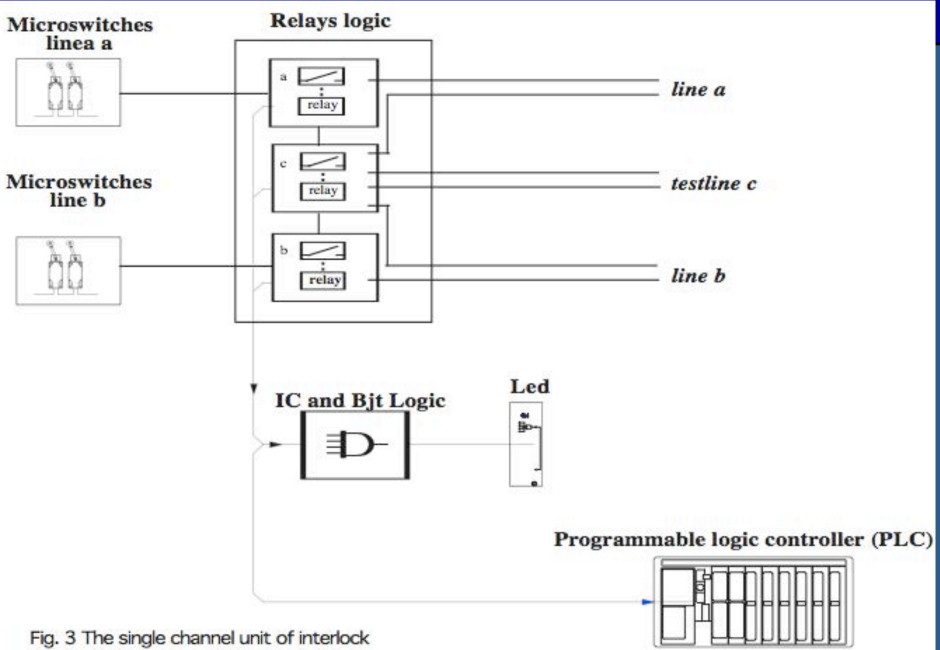


Fig. 3 The single channel unit of interlock

The door of FLAME experimental area is equipped with a lock with a key imprisoned. The access door is equipped with two independent chains of interlocks, each interlock consisting of two microswitches in series and each microswitch consisting of two contacts.

Emergency-off buttons, clearly visible in the darkness and readily accessible, are installed inside and outside the pit area . The reset of emergency-off buttons must be done locally.

Warning lights and audible warning are given inside radiation areas when the laser is ready to give a shot.

Any violation of the radiation areas must cause the stop of the machine. In this case
a shutter is inserted along the main laser beam transport;
a valve is inserted between the compressor and the interaction chamber;
a mirror in the compressor is rotated to avoid any transport of the main beam to experimental chamber. Start again require a new area search.

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Radiological risk for the workers and the members of public from the prompt radiation.

Normal working condition

The ambient dose equivalent rates in the various areas of FLAME laboratory as well as in the external areas are quite negligible and however difficult to measure with the radiation protection instruments used in routine monitoring.

Accident condition

The only accident condition consists in the irradiation of person close to the target area during the FLAME operation. This event is quite unlikely taking into account of the redundancy of the radiation safety system. The evaluation of the effective dose is not an easy job because of the impossibility to take into account the distance from the source, the condition of the exposition, the numbers of shots and so on.

Only one shot can in principle give at 1m from the target an ambient dose equivalent of 3-4 mSv in the worst conditions

Area classification

Target area — **Controlled area during the operation. Access forbidden.**

Area interlocked @ laser on.
Free access area @ laser off unless of residual radioactivity

Control room and clean room — **Free access area. No restrictions or requirements from the radiation protection point of view**

Worker classification

All the workers will be classified “non exposed” workers

According with the Italian law in force the annual exposure limit for non exposed workers is 1 mSv equal to the limit for the members of public.

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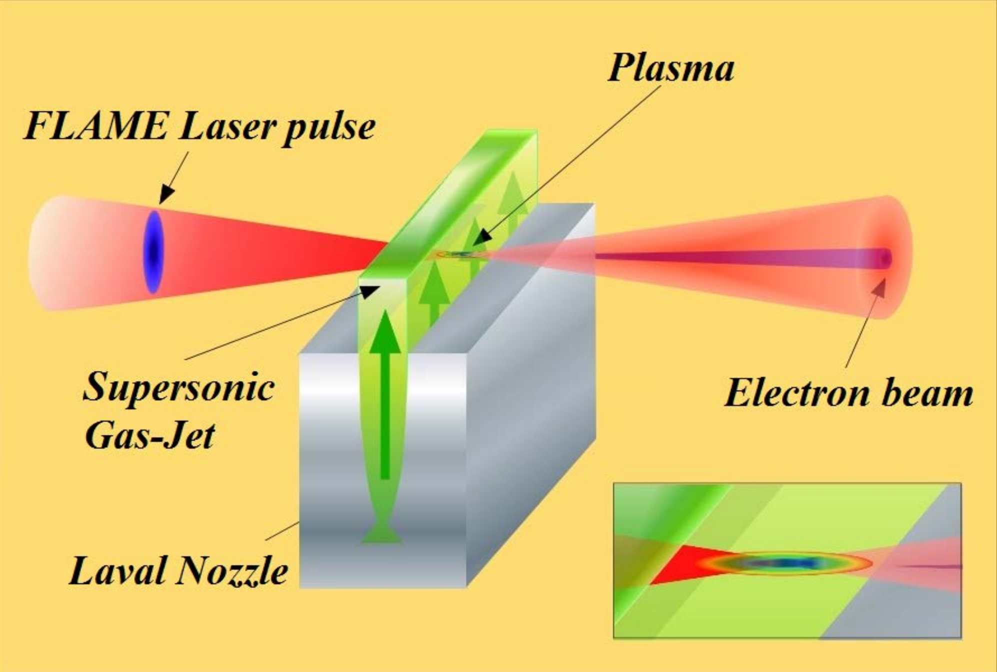
Self Injection Test Experiment - current target configuration

Laser peak power = 50 – 100 Terawatt
Lgasjet = 4 - 10 mm
Plasma density = 1 10^{18} -1 10^{19} cm^{-3}
Pulse duration = 25-30 fs
Laser intensity $\leq 5\ 10^{19}$ W/cm^2
Laser focal spot = 9 - 17 μm
Laser energy = 1.3 – 2.5 J



Goals:
-Demonstrate highest acceleration gradient
-Control of Self-Injection - Need of control of the injection process and separation of the injection stage from the acceleration stages.
-Extend acceleration length-multi-GeV energy range-Stable and long term 10Hz operation of a high charge,>1GeV, < 3% energy spread, <3mrad divergence
-Compactness, medium to high energy electrons
-Reliability (reproducibility and stability)
-Moderate to small energy spread

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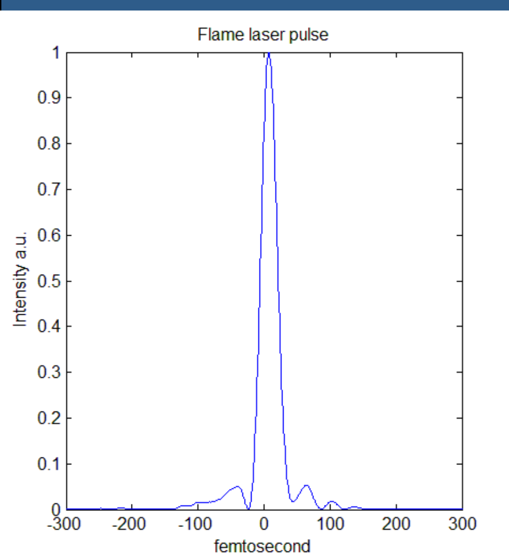
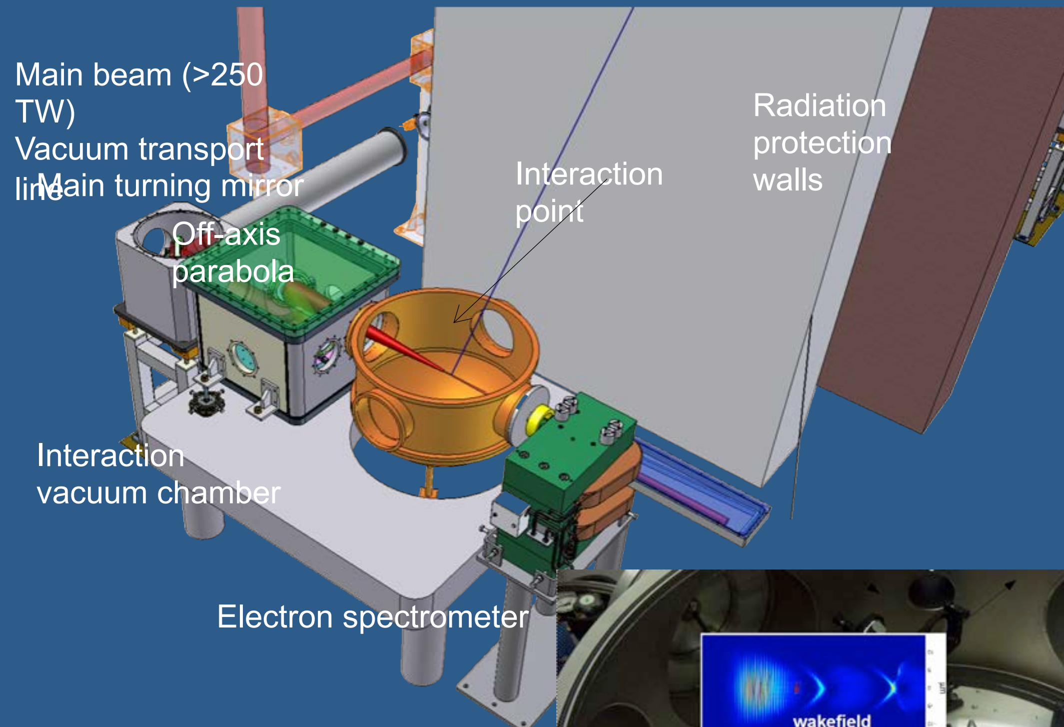
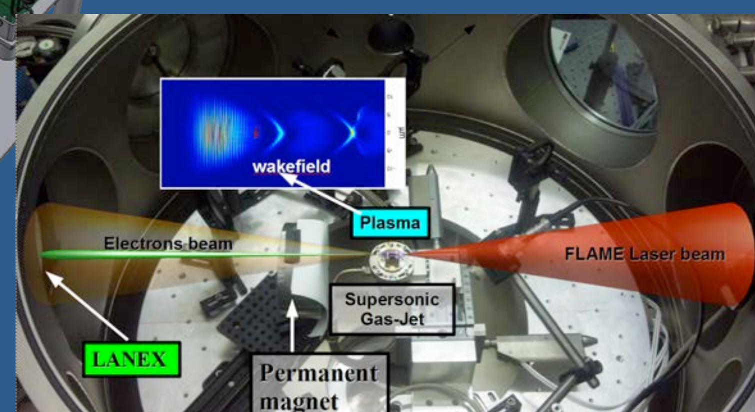
In order to characterize the radiation field of FLAME laboratory the Radiation Protection Group of LNF installed a network of passive detectors mainly inside but also outside radiation shield. In each positions were installed different TLD detectors (TLD 400 bulb detectors, TLD 600, TLD 700, from Thermo Company previous Harshaw Company) plus a stack of PADC detectors.

Detectors were exposed
from July 25th 9:00 am
up to July 27th 4:00 pm.
55 hours
For a 2980 effective shots
(~10shot/min) plus 10% for
setting







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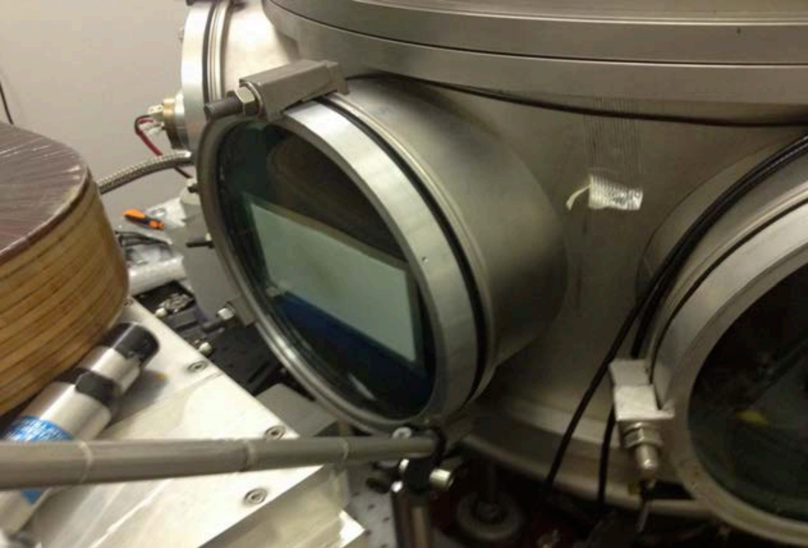

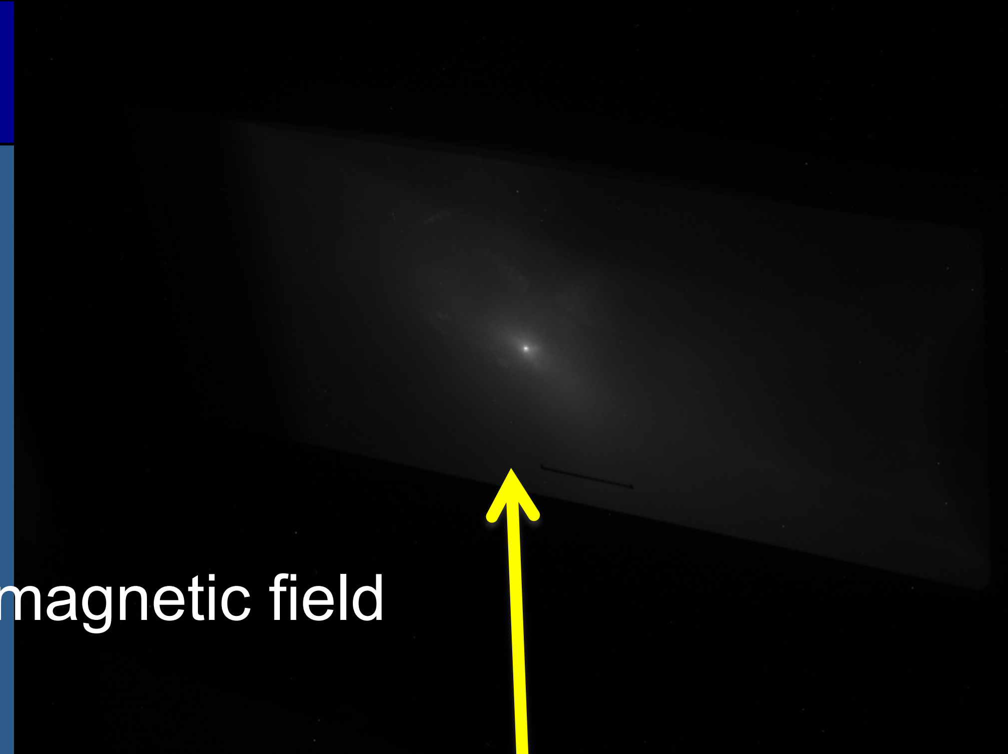

Lanex screen with and without magnetic field

Electron beam divergence about 1 mrad

Electron energy dispersion with a 0.9 Tesla of permanent magnetic dipole

Estimation of electron energies ranges up to 500 MeV and more. Work is in progress in order to obtain the energy spectrum.

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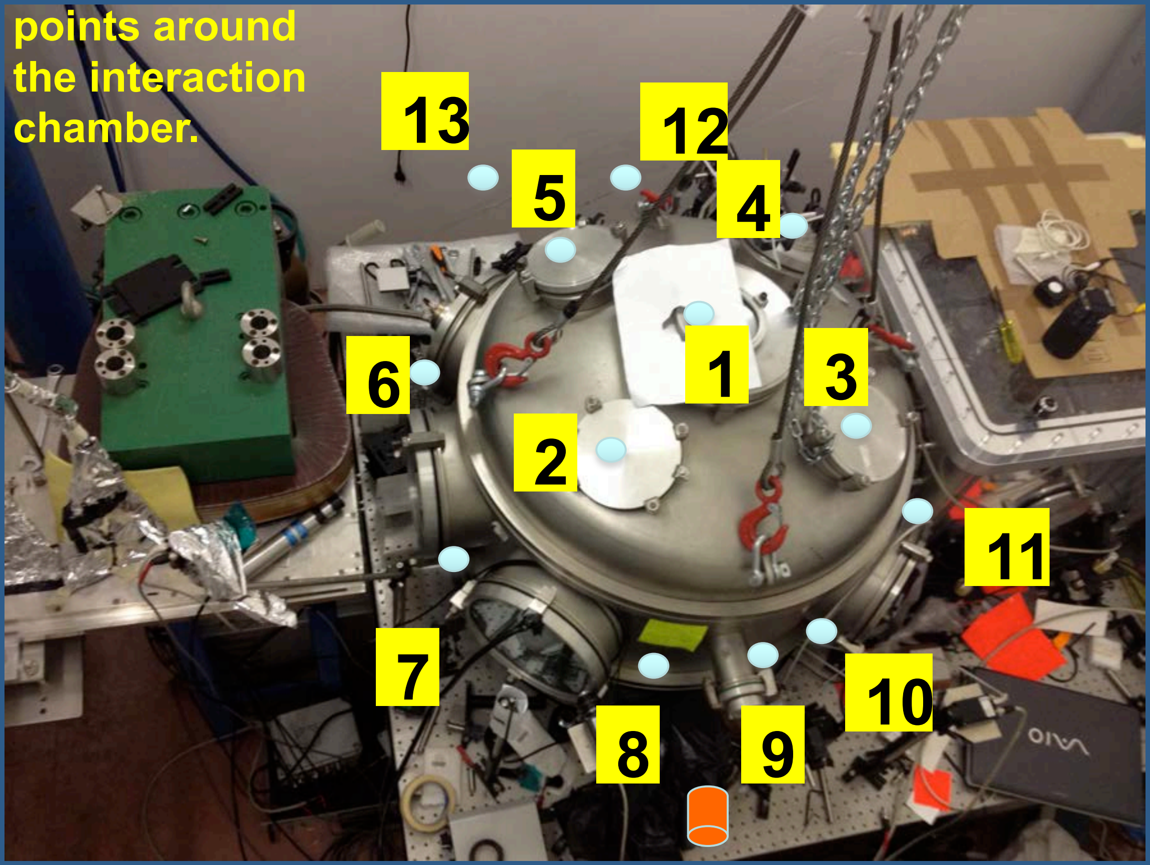
In about 2 days of exposition were obtained from TLD 400 and 700 the values reported in a table.

Outside flame pit only background was measured ranging from 0.05 to 0.07 mSv.

Automess Scintillator Probe 6150AD-b

Measurement points around the interaction chamber.



Measurement positions	Ambient dose equivalent (mSv)	Ambient dose equivalent (mSv)
1	0.55	0.84
2	0.84	1.99
3	0.56	1.01
4	0.34	0.56
5	1.05	2. 31
6	611	497.22
7	65	174.00
8	4.8	1.29
9	3.27	1.35
10	2.3	0.99
11	1.3	0.52
12	0.06	0.04
13	0.05	0.04
Uncertainties	10%	up to 20%

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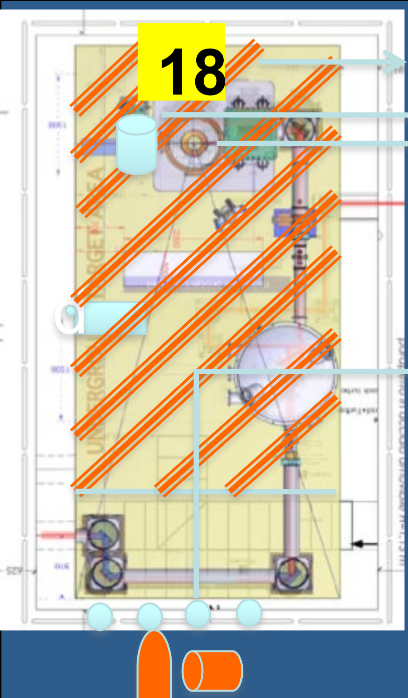
The Automess Scintillator Probe 6150AD-b in integration mode of operation measured a value of 1 microSievert in an hour of operation at a rate of about 10 shots per minute. The value is consistent with the value obtained with TLD 400 and 700, taking into account the different position and size of both detectors



Half a meter of ordinary concrete

Passive network detectors before half a meter of ordinary concrete

14 15 16 17

Flame pit entrance equipped with two stairs

Gamma and neutron active detectors

Measurement positions	Ambient dose equivalent (mSv)	Ambient dose equivalent (mSv)
14	0.05	0.04
15	0.06	0.04
16	0.06	0.04
17	0.06	0.04
18	0.07	0.04

A person close to interaction chamber (point 6) during the operation in such conditions could receive in one minute about 2 mSv. This value is consistent with maximum credible accident.

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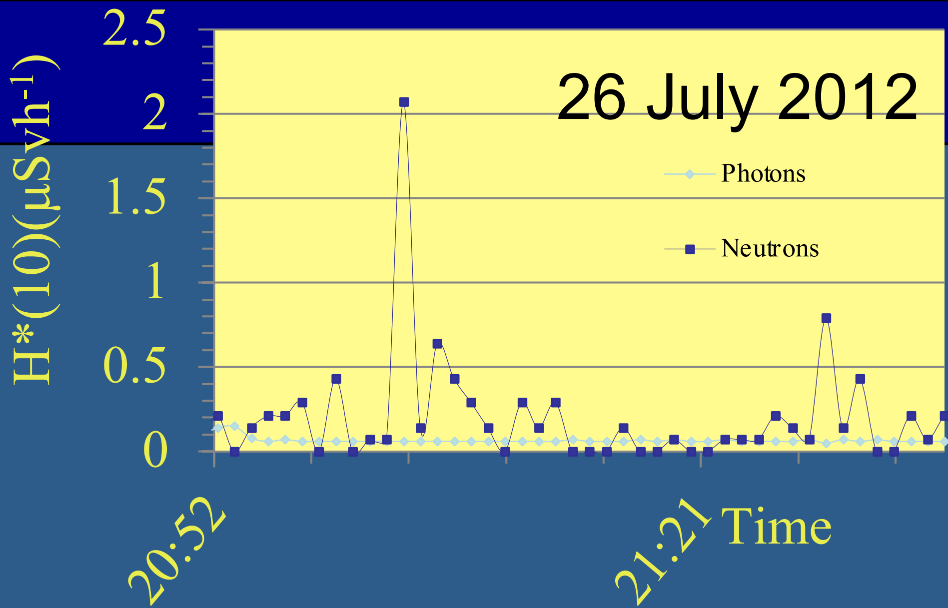
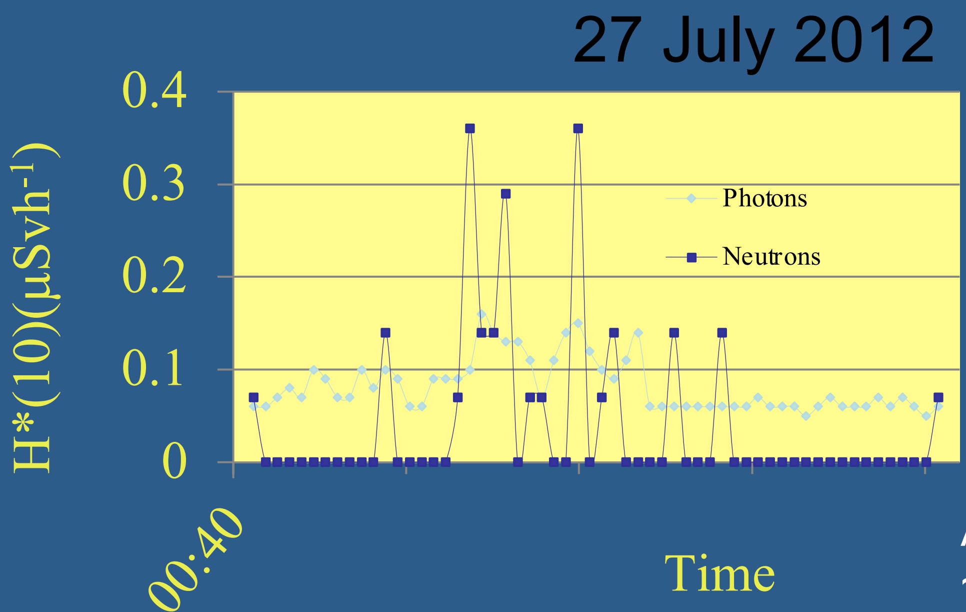


Ambient dose equivalent rate just outside FLAME pit as shown in the previous figure.

Each point represents the ambient dose equivalent obtained averaging samples on each minute of operation and scaling for an hour.



A contemporary gamma and neutron emission not always were detected.

Neutron background is negligible in practice, while photon background is ~0.06 μSv/h

Annual exposure to natural radiation sources is ~3.3mSv equal 0.38 μSv/h.

Conclusion

◆The FLAME project has been completely commissioned during the last year, including laser, target area, beam transport, access control system, passive radiation detectors network and radiation protection control system.

◆A measurement campaign for demonstration of stable operation and GeV range, was organized at the end of July 2012.

◆Preliminary results after the campaign were reported and discussed.

◆The work to obtain the final and complete results is still in progress.

◆ In conclusion the commissioning and the operation of FLAME laser don't pose particular problems of radiation protection outside the shield.

◆All the same a considerable effort should be made to study and improve the response of the actual active and or passive instruments to such radiation field.

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Thank you for your attention

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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.

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Thank you for your attention

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