MASTER DI II LIVELLO IN RADIOPROTEZIONE

The FLAME project of INFN-LNF

Adolfo Esposito

Data 18/04/2015

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DI ROMA

The FLAME project
of INFN-LNF

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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.

◆ 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 talk 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;

-to describe the status of art of the FLAME project

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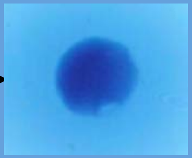
Laser-Plasma accelerators

ENERGY SOURCE: Laser

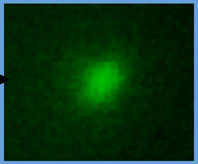
Laser focusing and control

OVERDENSE PLASMA
Laser-solid interactions

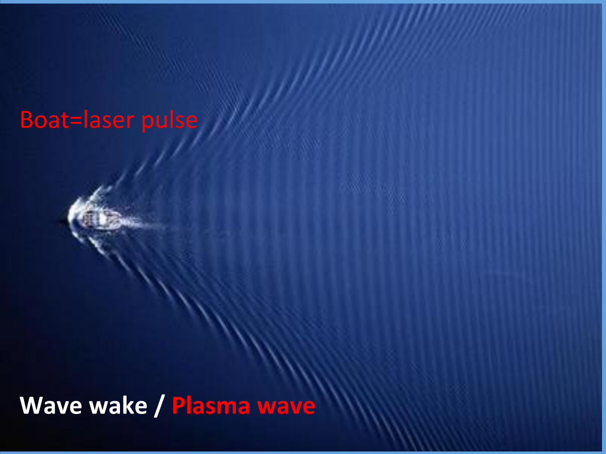


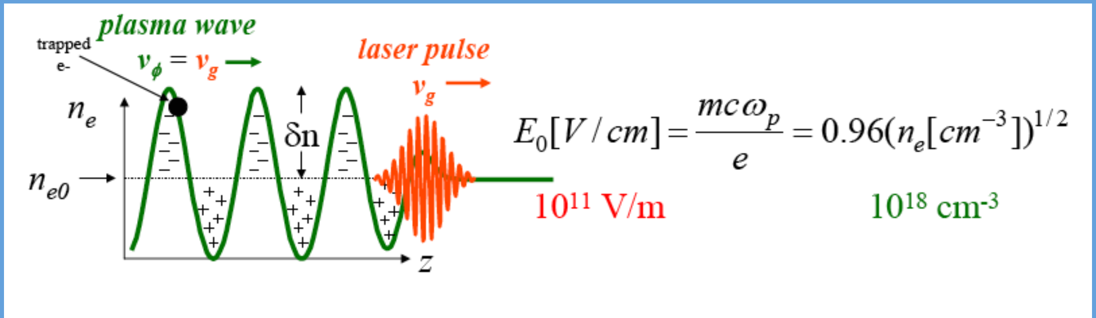
Protons, ions, e^-, e^+, broad spectrum, lower E,

UNDERDENSE PLASMA
Laser-gas interactions



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





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

Surfer=particle

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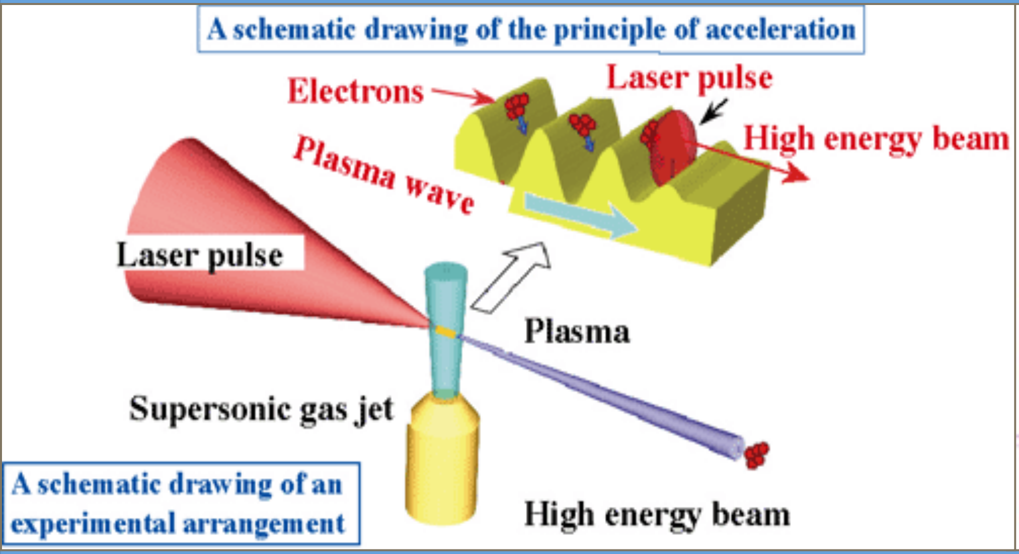
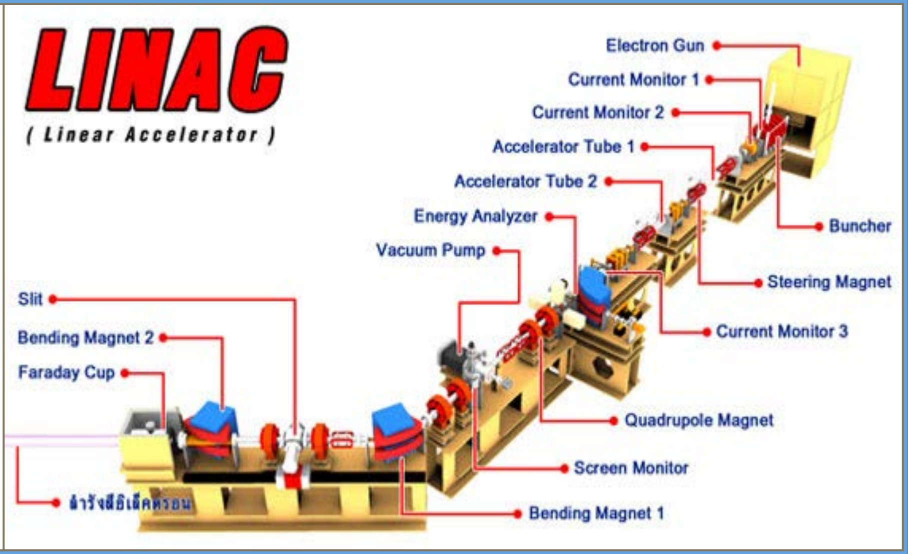
Laser-Plasma accelerators

- **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





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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

◆ 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

Environmental radiation | Shielding materials | Trend in regulatory limits

and so on

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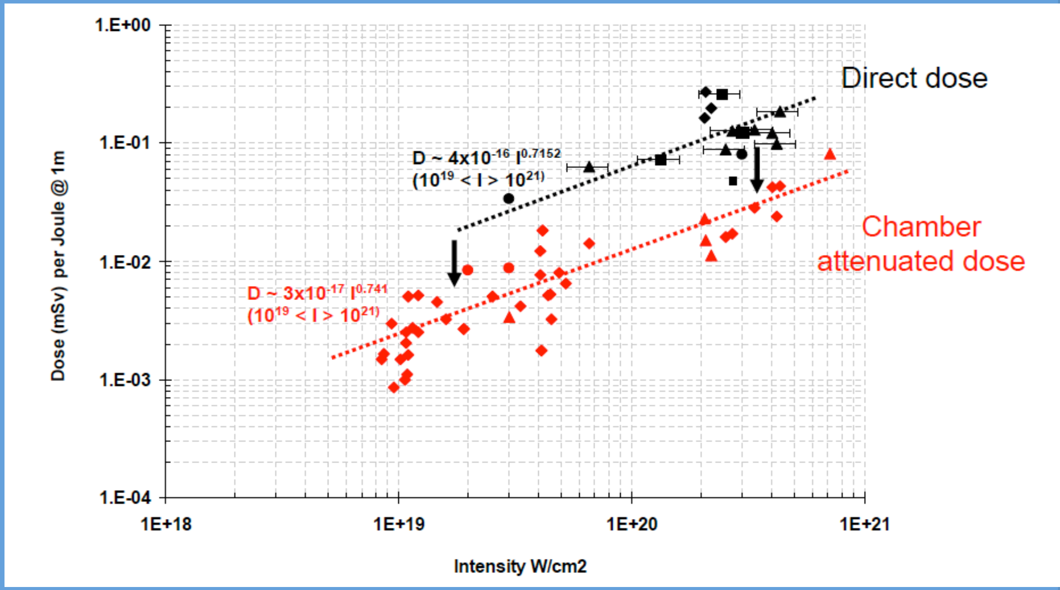
Determination of the source term

◆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



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

◆Any extrapolation to power higher 100 PW is quite impossible

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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.

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)

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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 <u>steradiant</u> N_j^G

T_i temperature in MeV

E_j^G the central energy in MeV

thermal component quasi-monochromatic component

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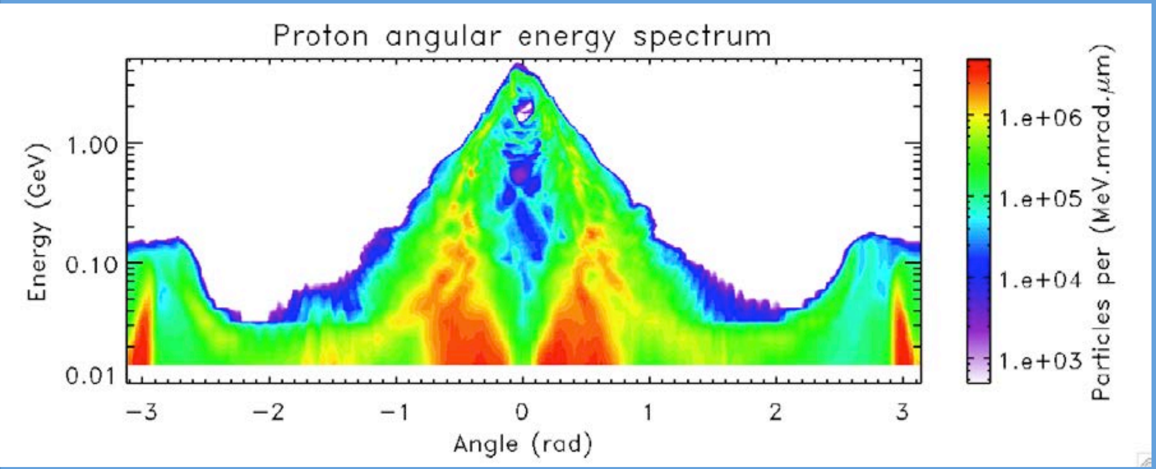
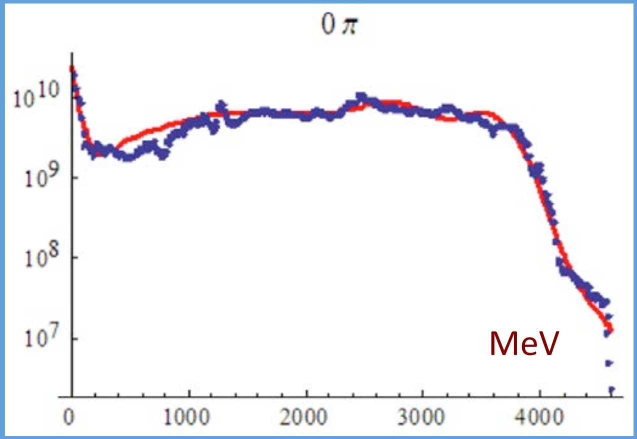
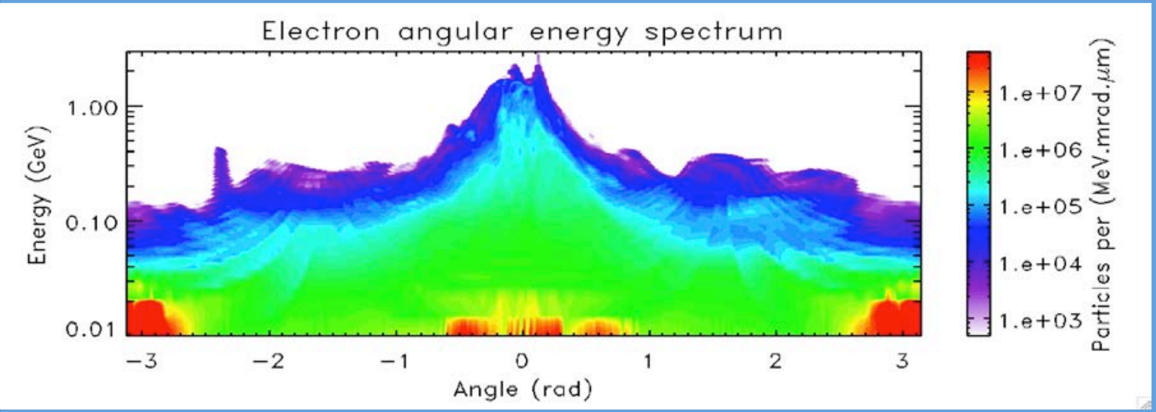
Determination of the source term

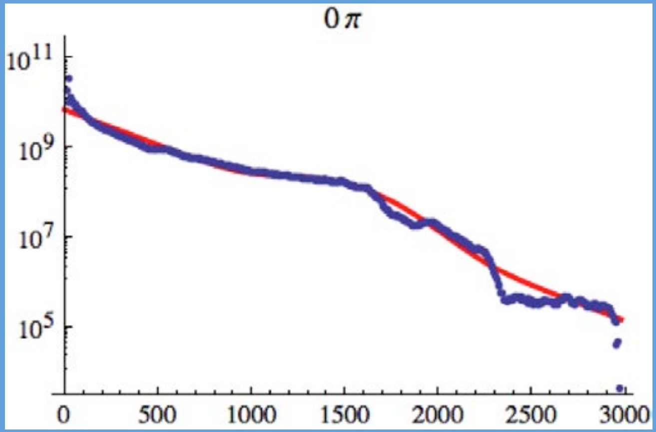
Target Thickness 1 µm   Material H   Density 0.088 g/cm^3 2kJ 15 fs   1.6x10^{23} *W/cm^2*





From ELI-PP Mid Term Report





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Accelerator shielding

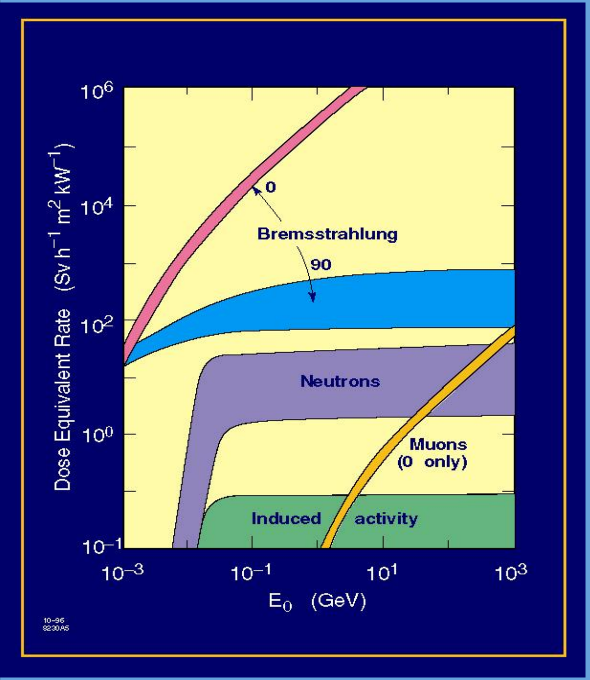
“electron accelerators”

bremstrahlung

giant resonance neutrons

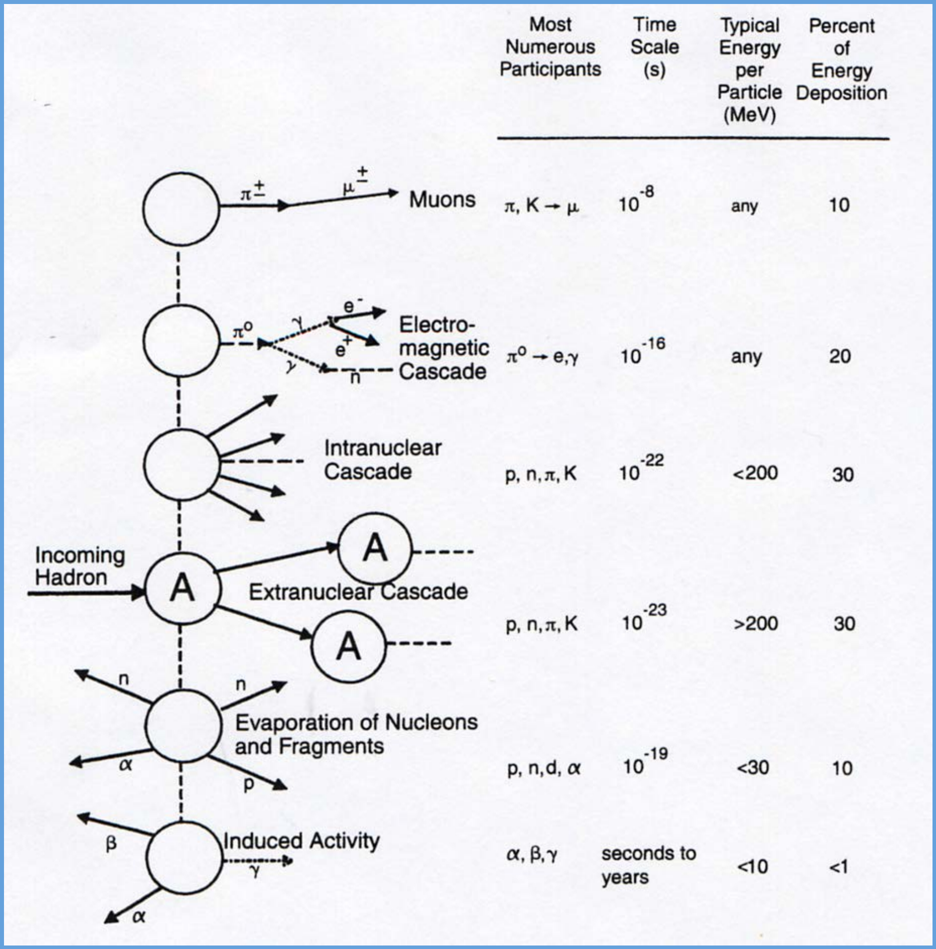
high energy neutrons (E>25MeV)

muon production



From Vylet adapted from Swanson

“proton accelerators”



From ICRU Report 28

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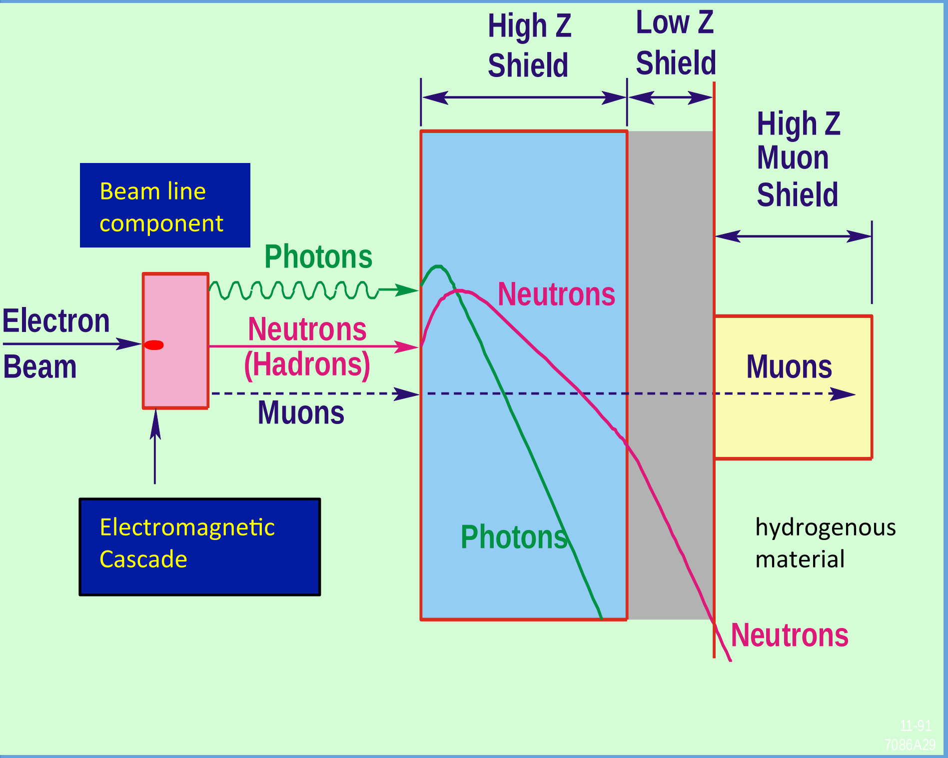
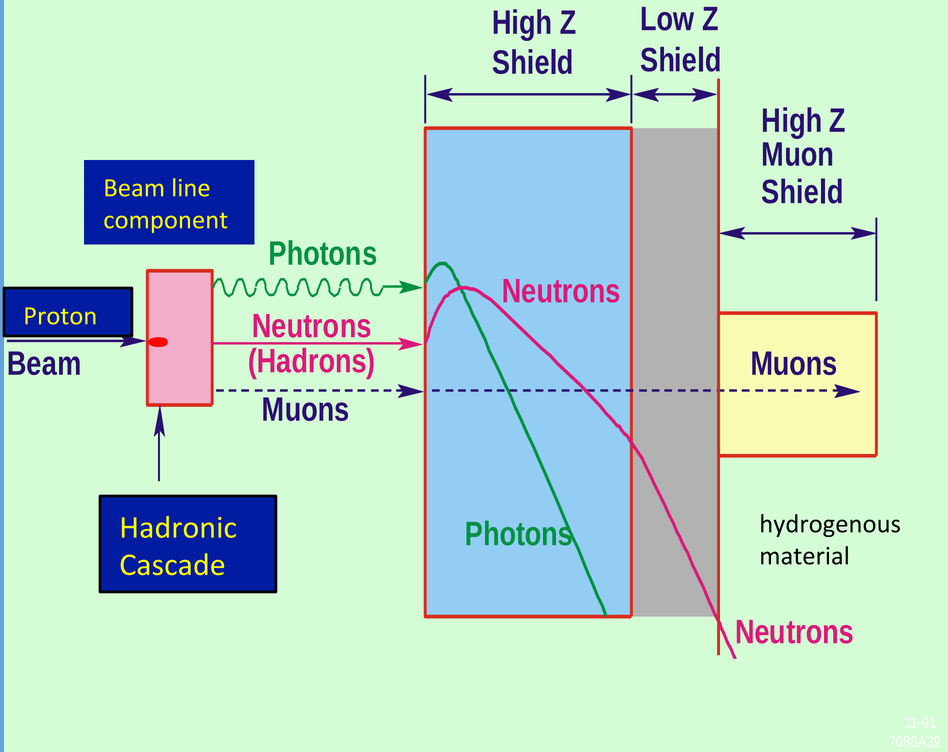
Accelerator shielding

"electron accelerators"



"proton accelerators"



adapted from Vylet

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.

A multiplying "shower" is the result of both cascades

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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LNF FLAME Project

As already said 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

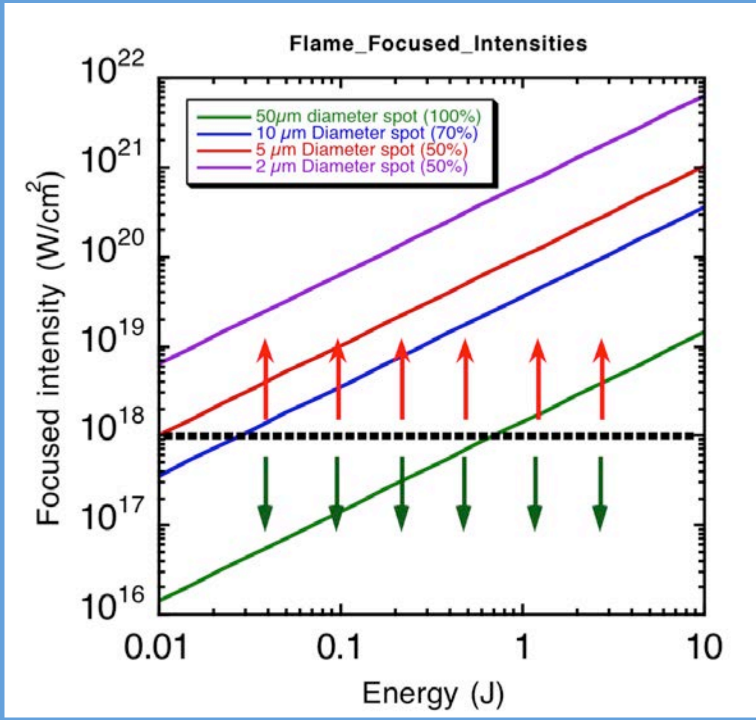
Peak power 300 TW

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.

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As already said 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.

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)

Extreme Light Infrastructure (ELI)

ELI is a European Project

attosecond science

nuclear physics and astrophysics

laser-produced X-ray beam

high energy physics

laser plasma accelerators

In the **Czech Republic**, Prague,the ELI pillar will focus on providing ultra-short energetic particle (10 GeV) and radiation (up to few MeV) beams produced from compact laser plasma accelerators to users.

In Hungary, Szeged, the ELI pillar will be dedicated to extremely fast dynamics by taking snap-shots in the attosecond scale (a billionth of a billionth of second) of the electron dynamics in atoms, molecules, plasmas and solids. It will also pursue research in ultrahigh intensity laser

In Romania, Magurele, the ELI pillar will focus on laser-based nuclear physics. For this purpose, an intense gamma-ray source is forseen by coupling a high-energy particle accelerator to a high-power laser.

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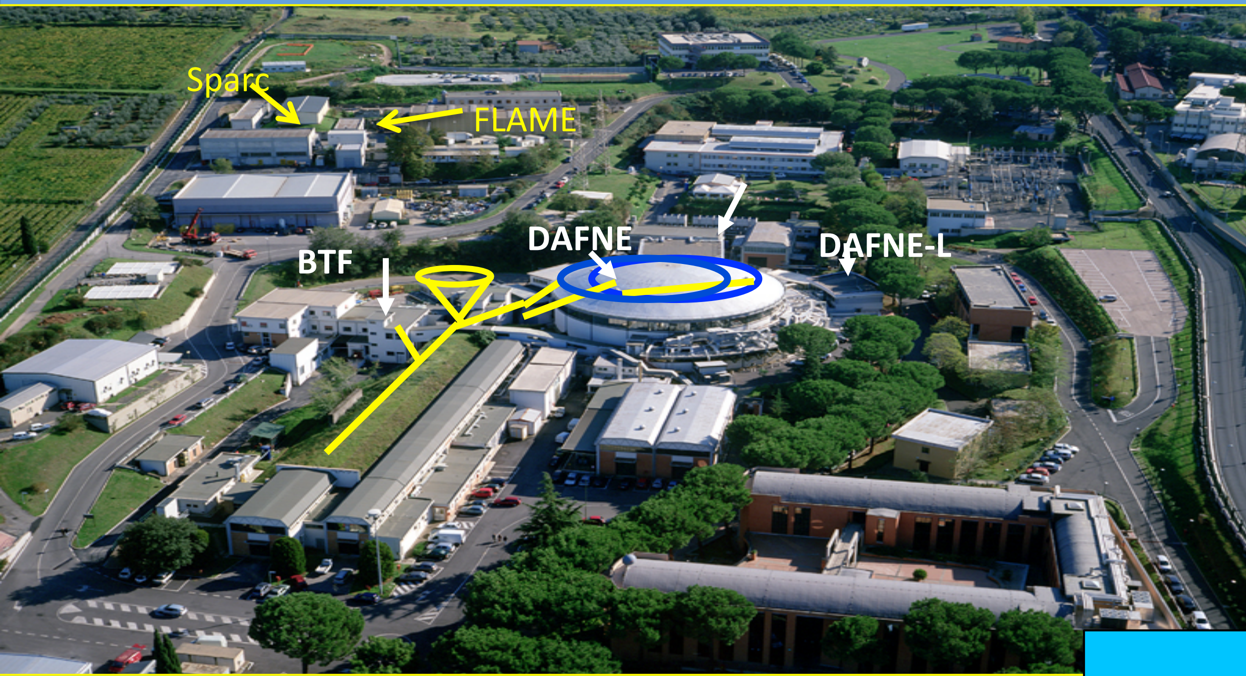
Frascati Laser for Acceleration and Multi-disciplinary Experiments



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

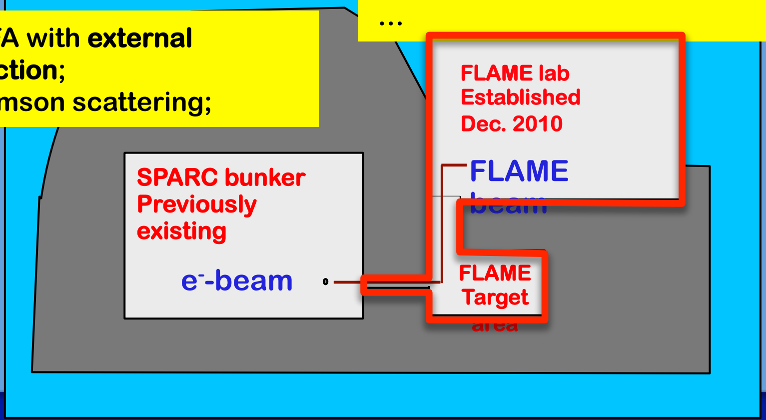
E_{max}	150 MeV
I_p	200A
Pulse duration	10ps
Repetition Rate	10Hz

FLAME

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

LWFA with self-injection (SITE)
Proton acceleration (LILIA);
AO-Thomson (G-resist);
…

LWFA with external injection;
Thomson scattering;



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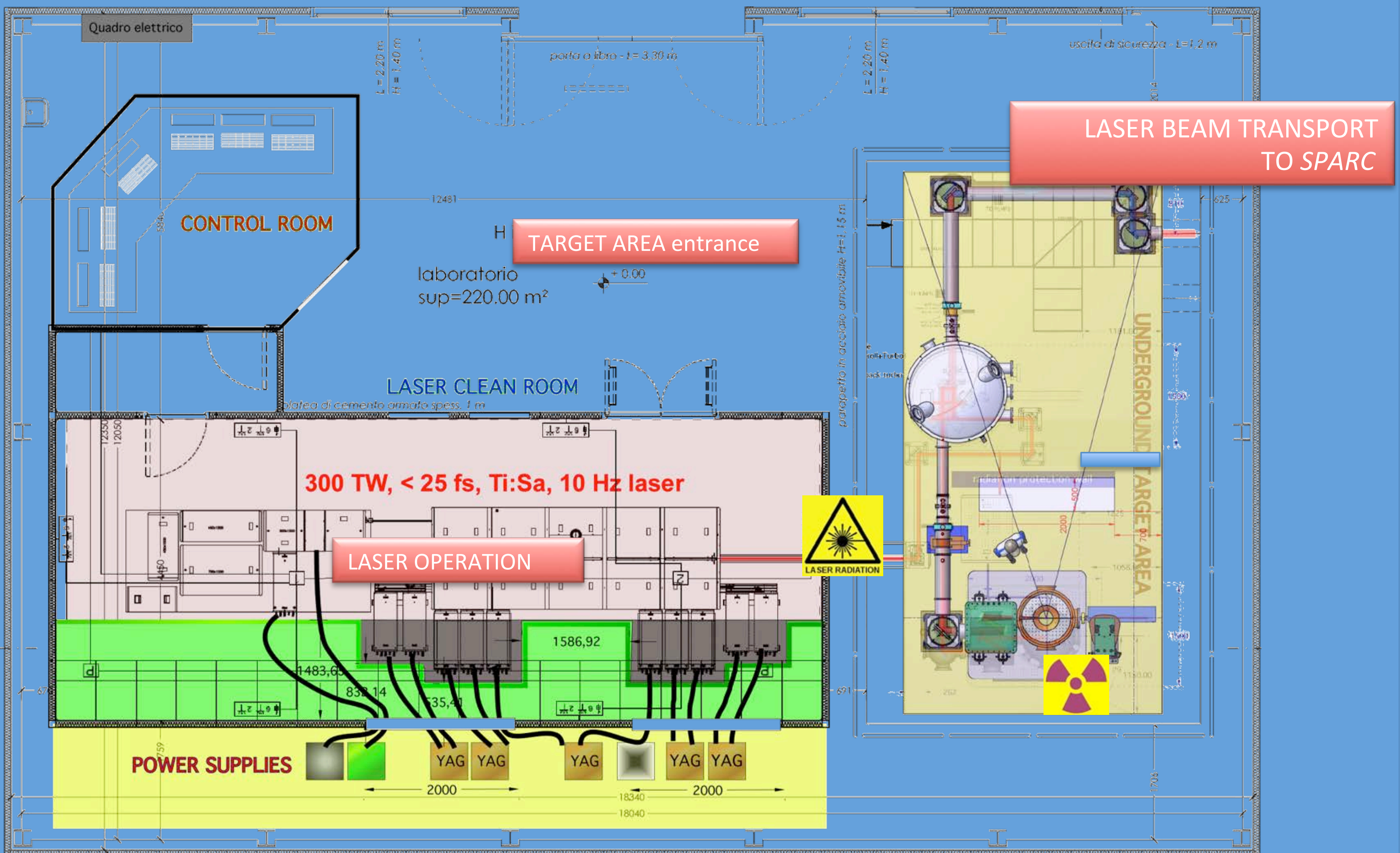
FLAME – Overview



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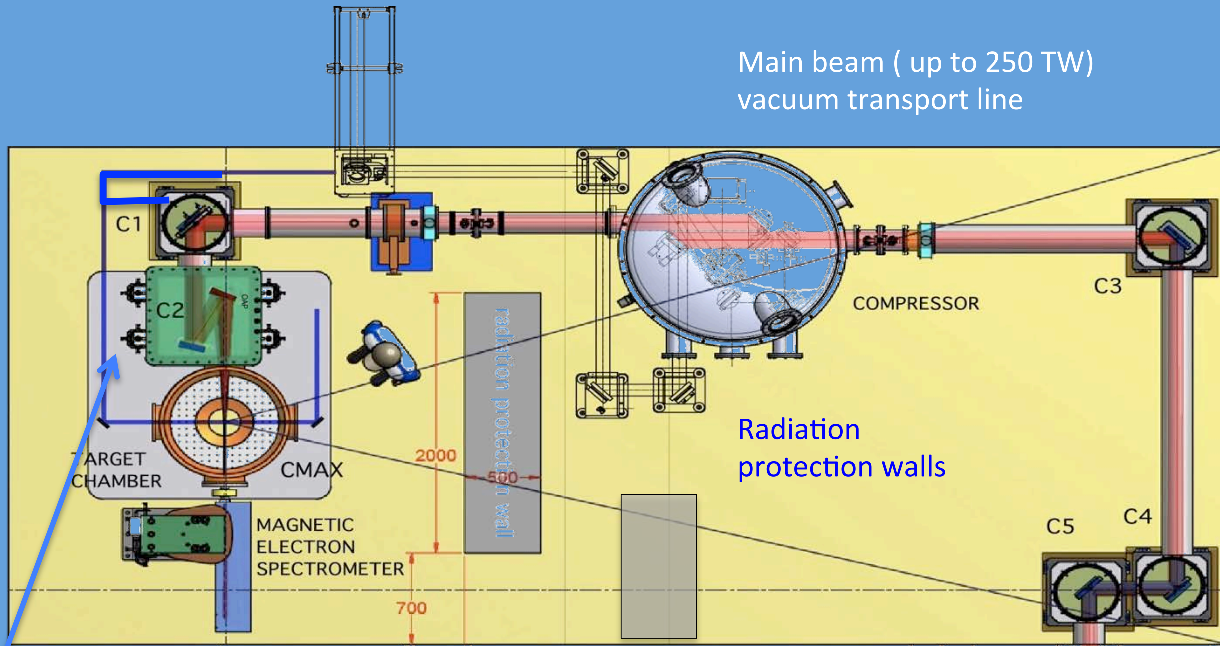
FLAME Target Area

Main beam (up to 250 TW)
vacuum transport line



Radiation
protection walls

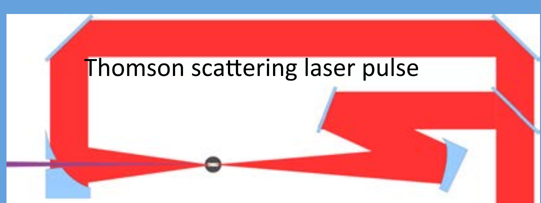
Aux "probe" beam up to
100 mJ

To SPARC
bunker

Plasma acceleration

Thompson source

γ-rays



splitter

Plasma Acceleration laser pulse

Main laser pulse
from FLAME

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Accelerator shielding

The thickness of the shielding depends from the attenuation of the so called prompt radiation (mainly bremsstrahlung X-rays and neutrons) 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 in Italy, 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	–

Equivalent dose limits for lens of the eye 20 mSv/y

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

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

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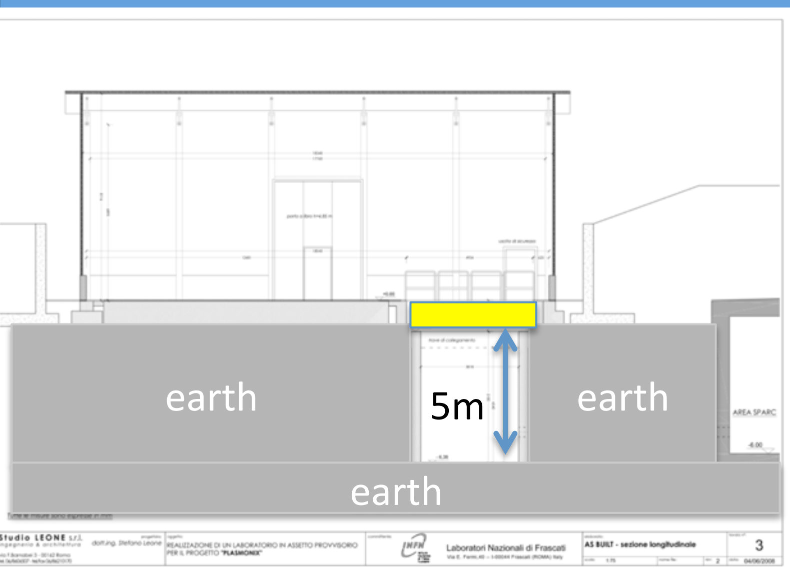
For the shielding evaluation

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

↓

ambient dose equivalent rate

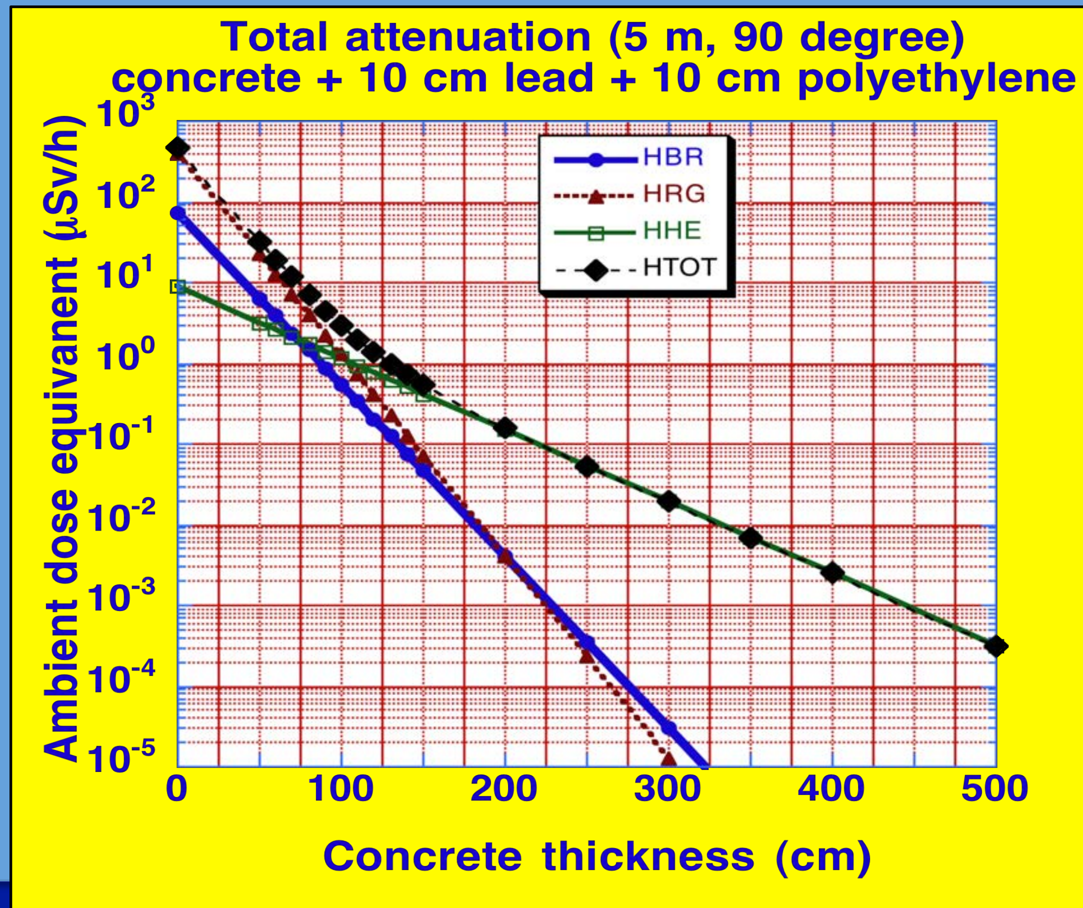
The ambient dose equivalent rate was evaluate only at 90°



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

250 h/year

H*(10) < 1mSv/year



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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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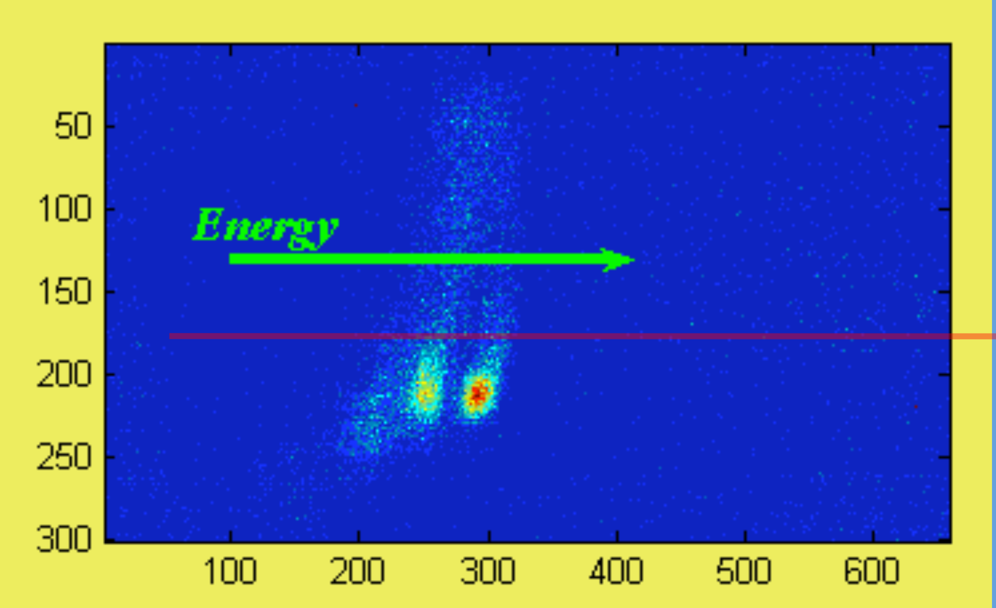
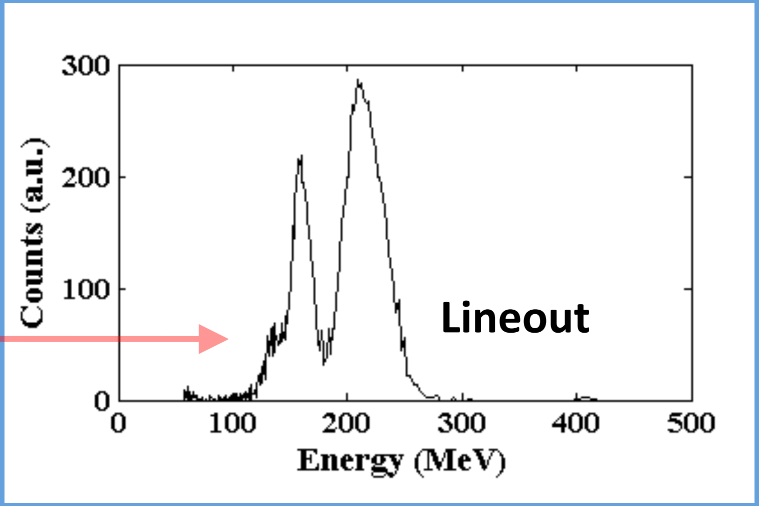
Pre-Preliminary test

Energy dispersion with a 0.9 T magnetic dipole

spectra acquired at 1 J laser energy on target and 35 fs: intensity at focus: 7×10^{18} W/cm^2

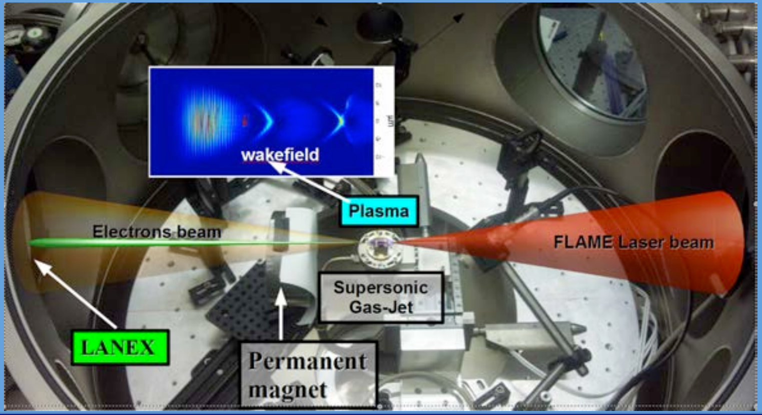


Pixel N.



Electrons at lanex screen

$Gd_2O_2S:Tb$ inorganic scintillator



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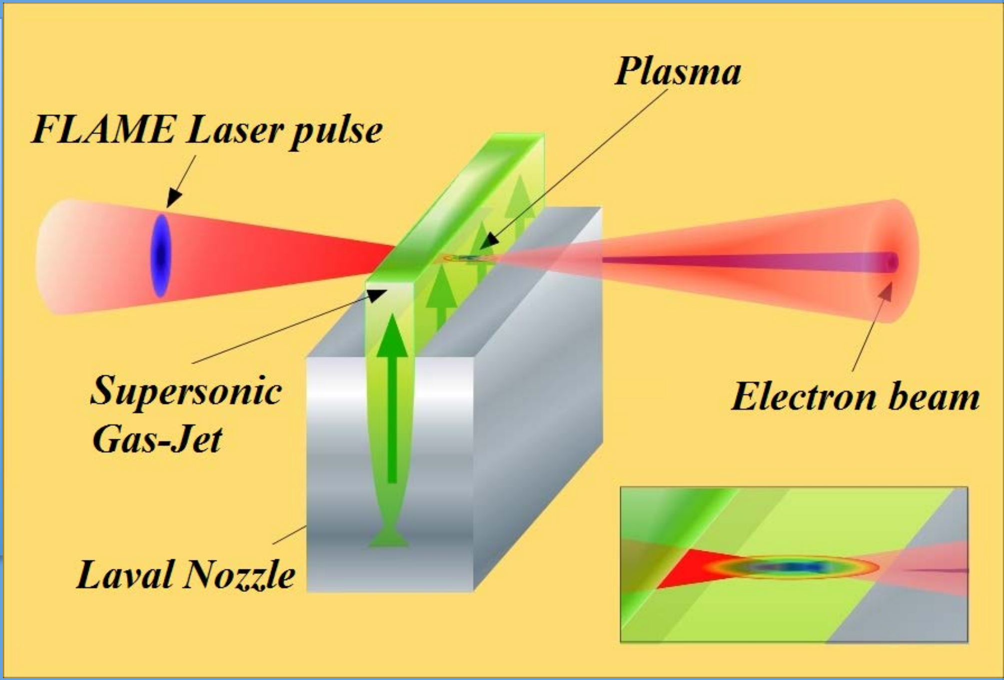
Self Injection Test Experiment - current target configuration

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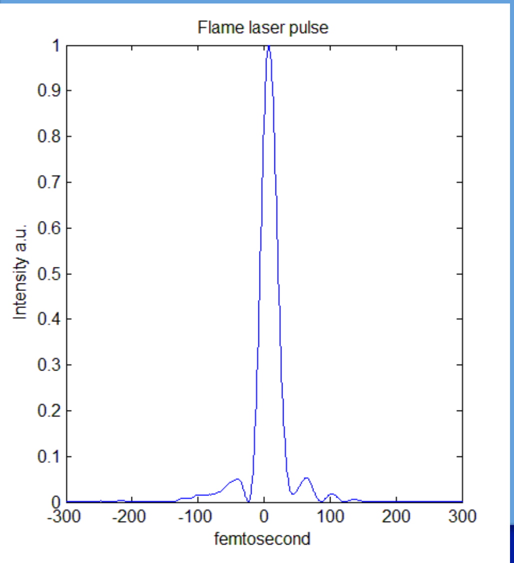
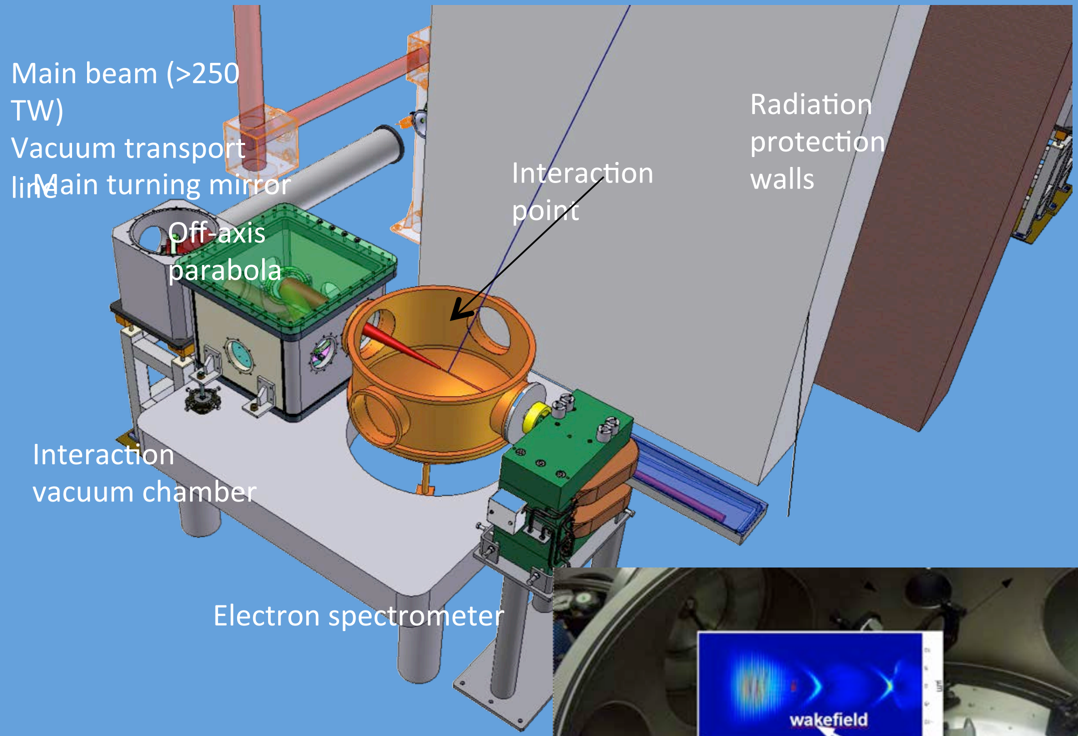
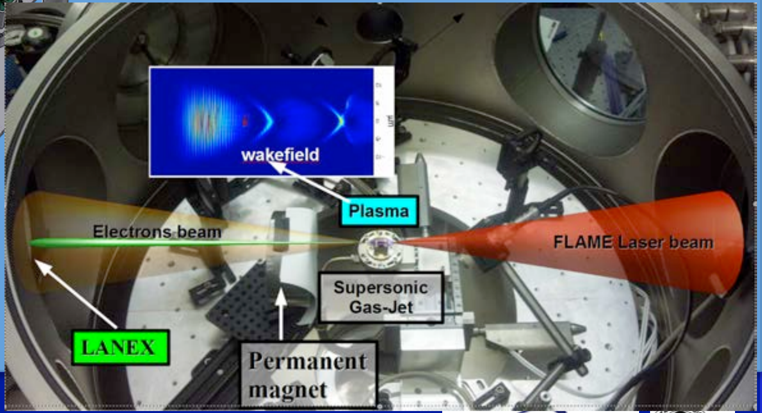
In order to characterize the radiation field of FLAME laboratory the Radiation Protection Group of LNF installed a network of passive detectors mainly inside but also outside radiation shield. In each positions were installed different TLD detectors (TLD 400 bulb detectors, TLD 600, TLD 700, from Thermo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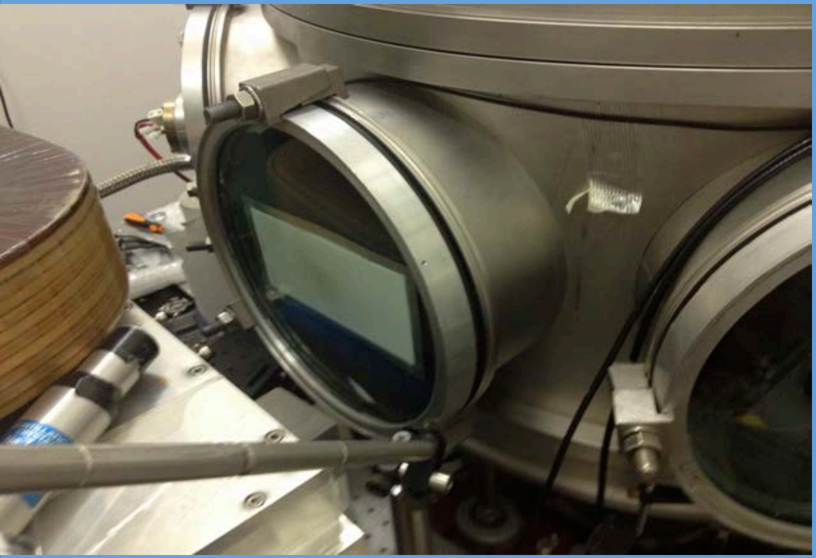
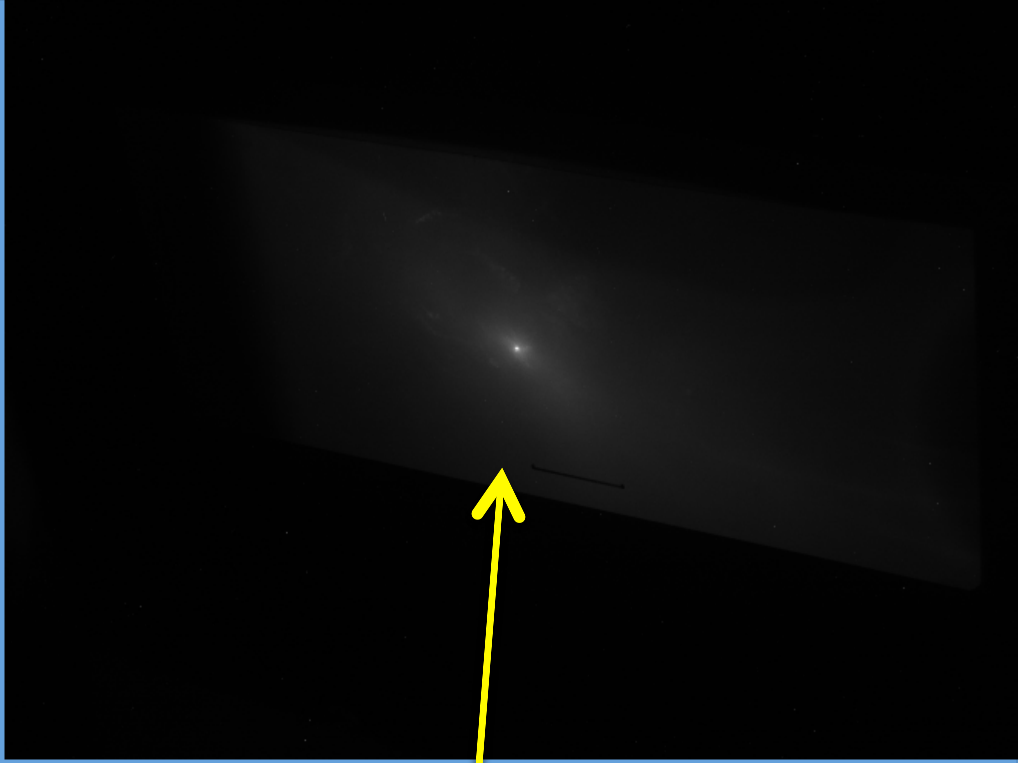


Lanex screen with and without magnetic field



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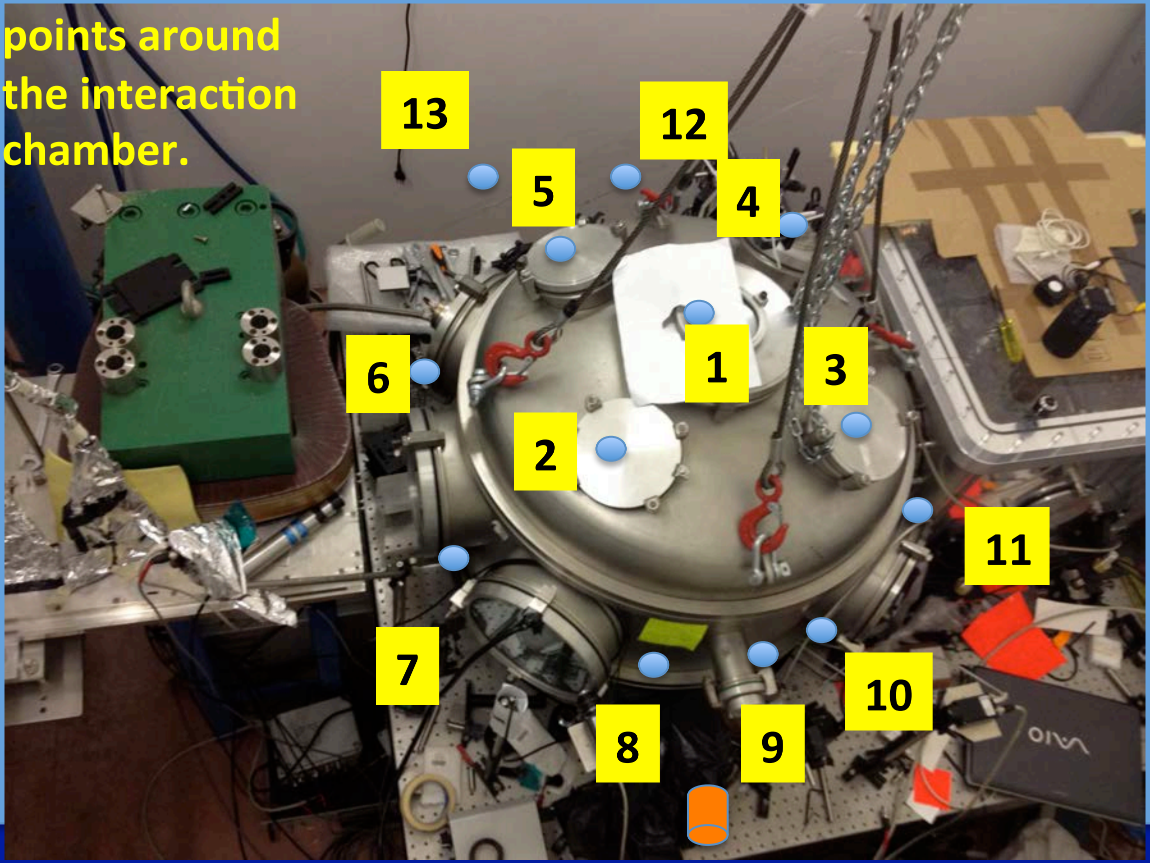
In about 2 days of exposition were obtained from TLD 400 and 700 the values reported in a table.

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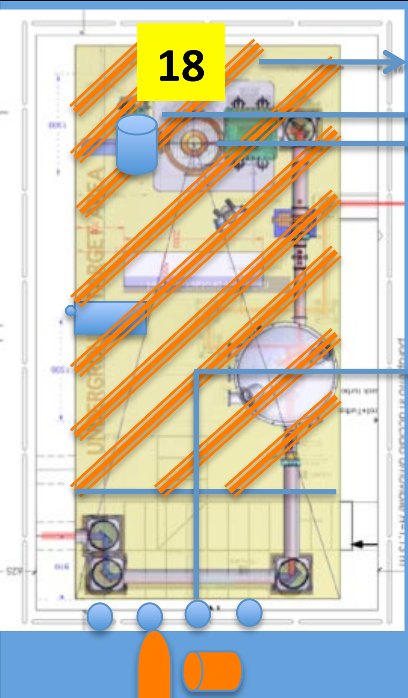
The Automess Scintillator Probe 6150AD-b in integration mode of operation measured a value of 1 microSievert in an hour of operation at a rate of about 10 shots per minute.
The value is consistent with the value obtained with TLD 400 and 700, taking into account the different position and size of both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



Half a meter of ordinary concrete

Passive network detectors before half a meter of ordinary concrete

14 15 16 17

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

Flame pit entrance equipped with two stairs

Gamma and neutron active detectors

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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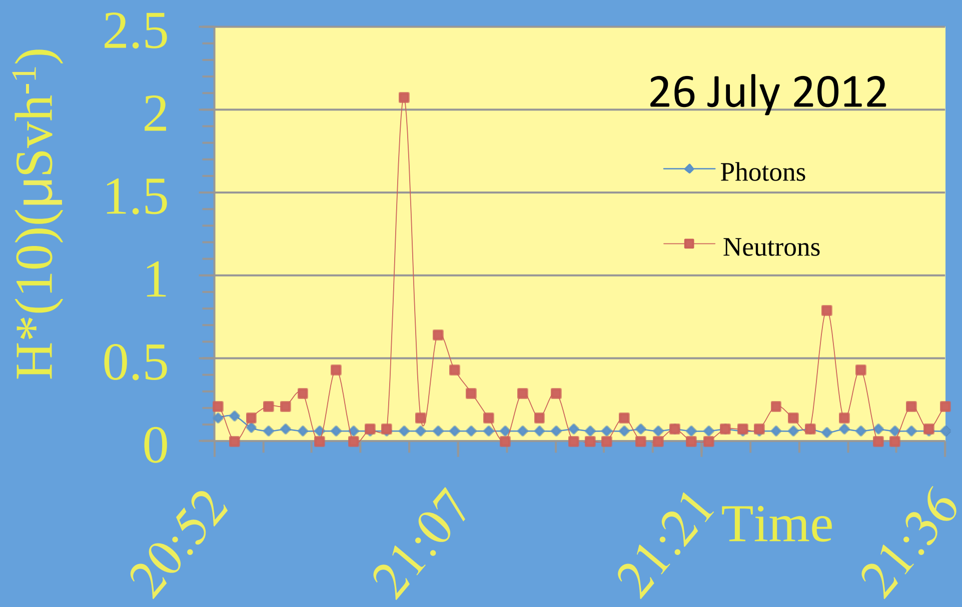
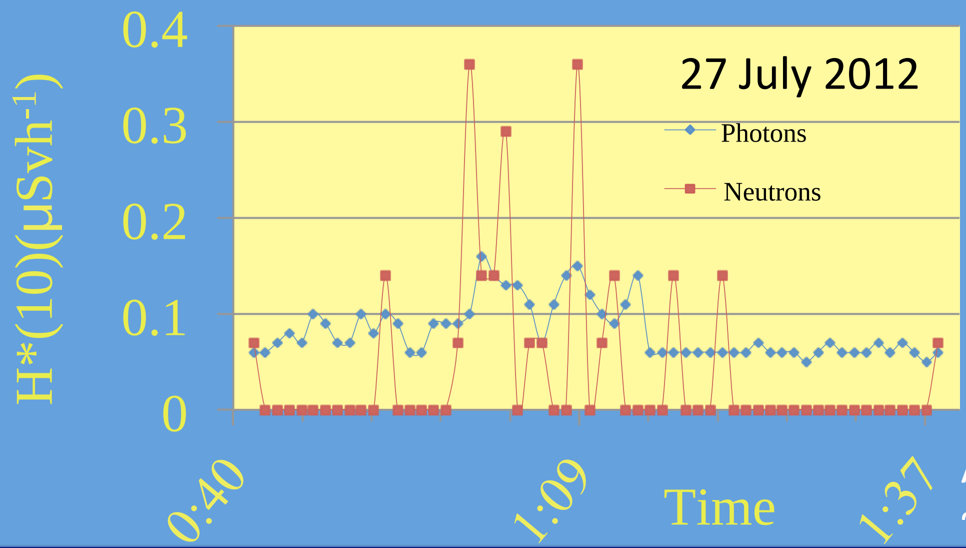


Ambient dose equivalent rate just outside FLAME pit as shown in the previous figure.

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.

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Conclusion

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

◆A first run (low laser energy, low peak laser energy and low laser intensity), was carried out in 2010 to demonstrate the feasibility of the operation and self acceleration of electrons.

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

◆Preliminary results after the present 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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