From Conventional to Laser-Plasma Acceleration: New and Old Radiation Protection Issues

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Electron accelerators @LNF

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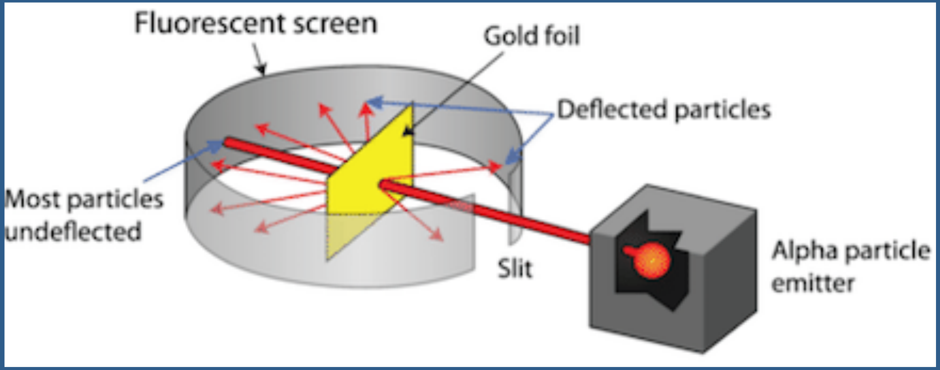
Sources of Particles

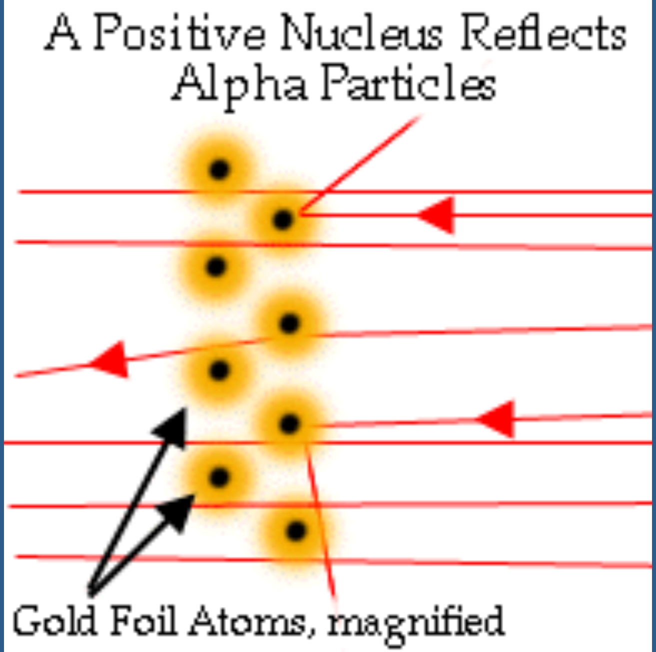
- Radioactive Decays
  - Modest Rates
  - Low Energy
- Cosmic Rays
  - Low Rates
  - High Energy
- Accelerators
  - High Rates
  - High Energy

Rutherford's Scattering

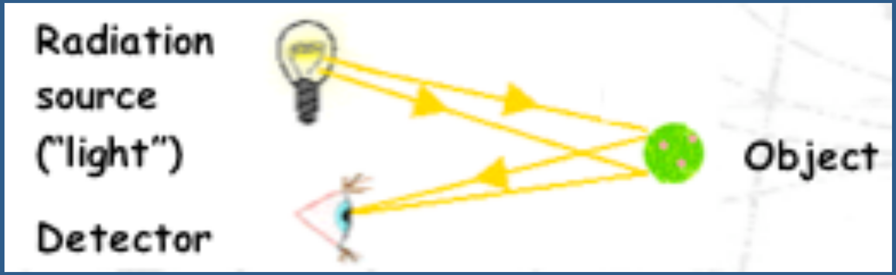


Results

1911

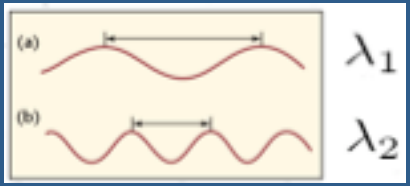


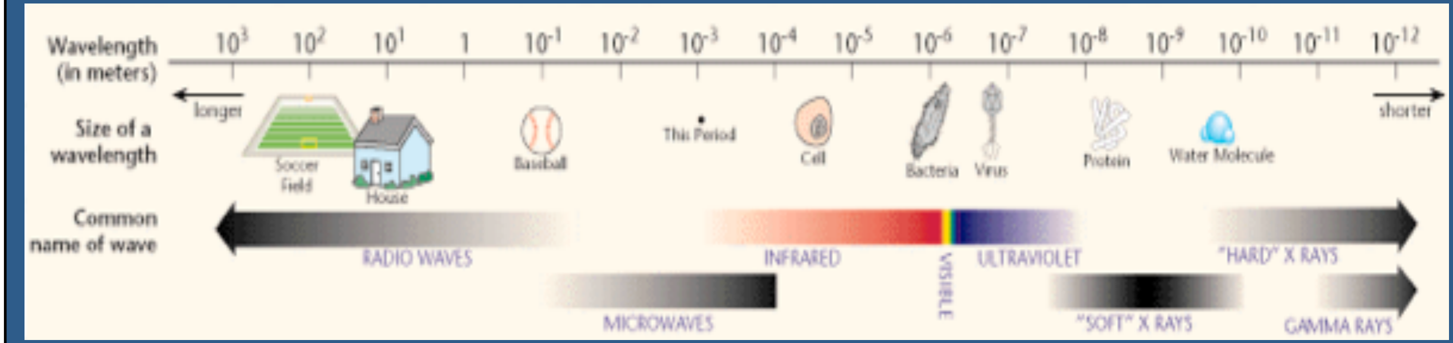
- Radiation source
- Target
- Detector



Resolution defined by wavelength

$$\Delta r \propto \lambda$$

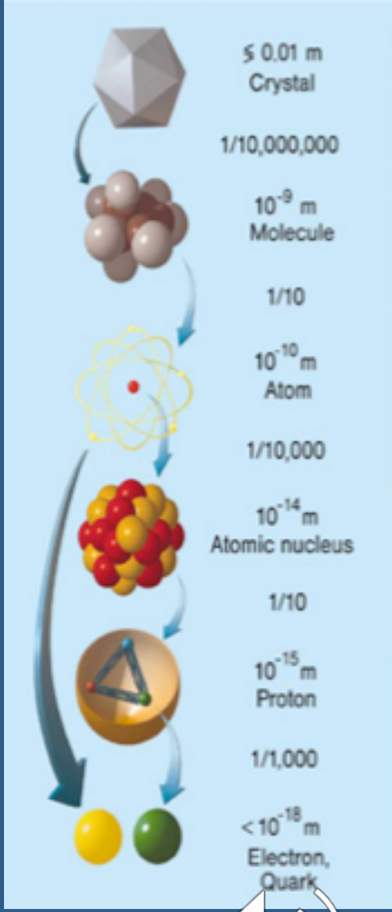




Particles are waves

$$\Delta r \propto \lambda = h/p$$

1 MeV=10^{-12} m
1 GeV=10^{-15} m
1 TeV=10^{-18} m



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Accelerators started with some theoretical work in the early 1920s, with the first accelerator producing nuclear reaction in 1931. Thus it is approximately 90 years of history!

Types of Conventional Accelerators

- Linear Accelerator (one-pass)
- Storage Ring (multi-turn)

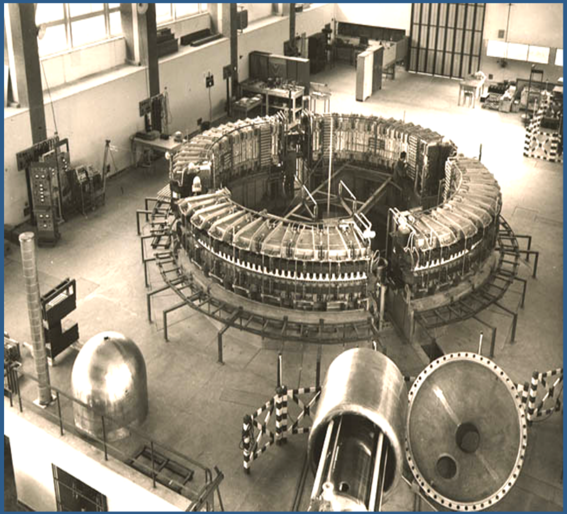
- Fixed Target (one beam into target)
- Collider (two beams colliding)

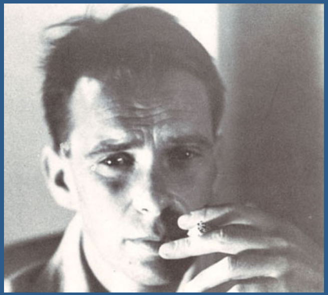
- electrons (e^+e^-)
- protons (pp or pp)

- Static Accelerators
- Cockroft-Walton
- Van-de Graaff
- Linear
- Cyclotron
- Betatron
- Synchrotron
- Storage Ring

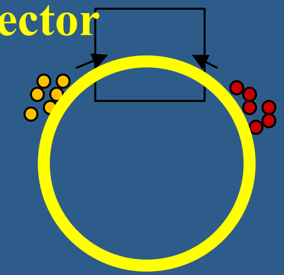
The history of LNF electron accelerators 1

The Frascati Electron *Synchrotron*
1959-1975

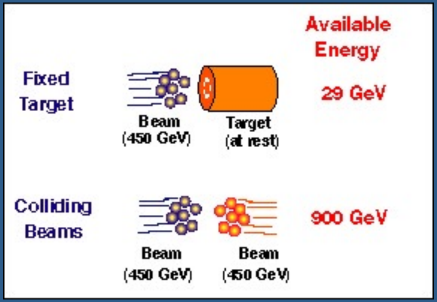




Bruno Touschek,
Frascati, 1960

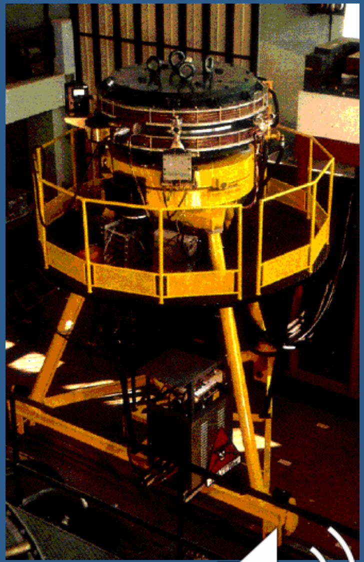


Accumulation ring

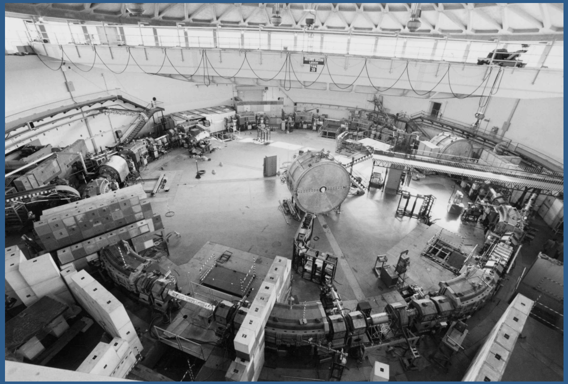


			Available Energy
Fixed Target	Beam (450 GeV)	Target (at rest)	29 GeV
Colliding Beams	Beam (450 GeV)	Beam (450 GeV)	900 GeV

ADA
1961-1964



Adone storage ring 1967-1993



DAΦNE collider1996

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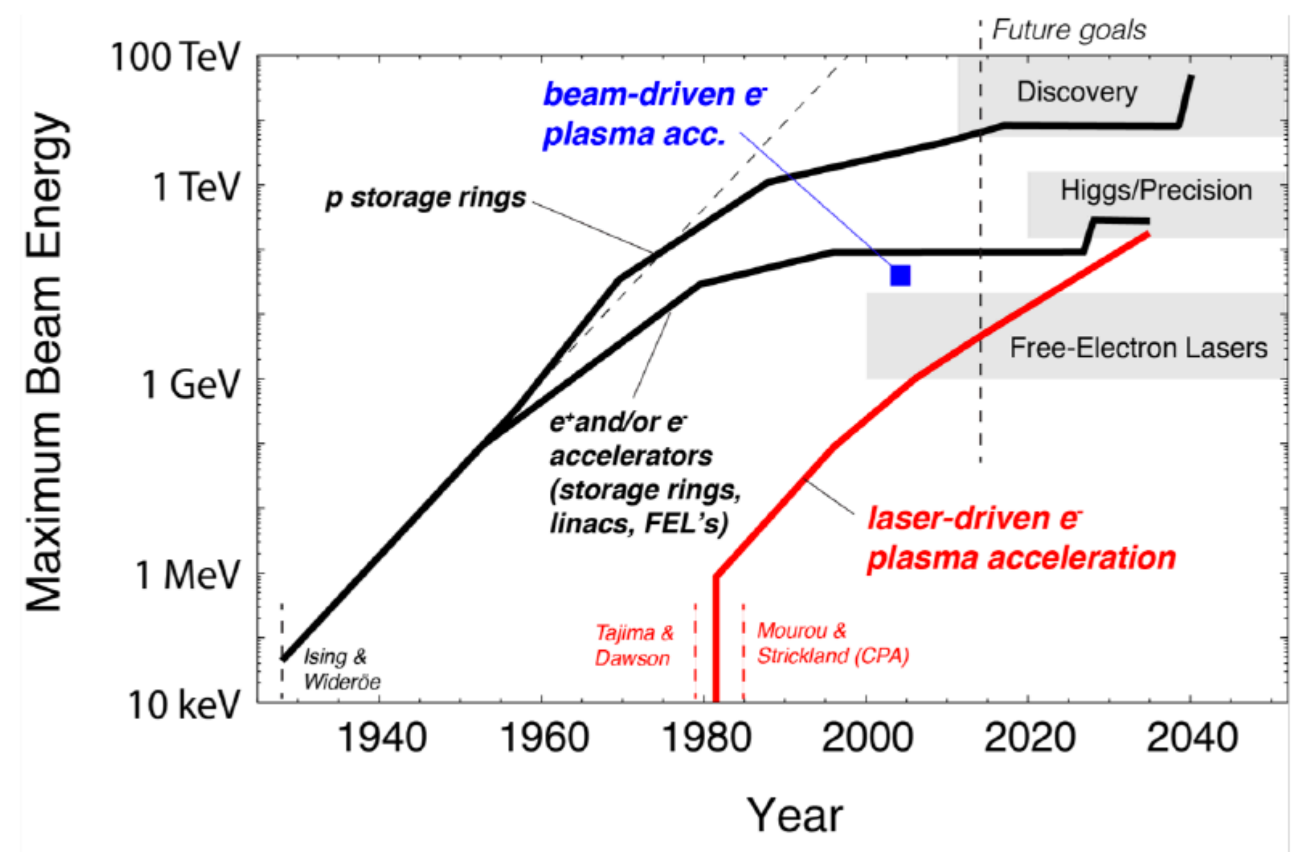
Any advancement in particle physics has historically been linked with the availability of particle beams of energy or intensity ever increasing . For more than three decades the collision energy in particle colliders has increased exponentially in time as it is described by the so-called Livingston curve.



It is evident that the exponential increase of beam energy with time has leveled off in conventional RF accelerators since the 1980s

It is also evident that at the same time a new technology emerged, based on the revolutionary proposal of plasma accelerators by Tajima and Dawson in 1979, and the invention of amplified chirped optical pulses (CPA) by Mourou and Strickland in mid 1980s

Laser Electron Accelerator
T. Tajima and J. M. Dawson
Phys. Rev. Lett. 43, 267 –
Published 23 July 1979

Donna Strickland and Gerard Mourou, (1985). *Compression of amplified chirped optical pulses. Optics Communications. V.* ***56*** *(3): 219–221*

Chirped pulse amplification (CPA) is a technique for amplifying an ultrashort laser pulse up to the petawatt level, with the laser pulse being stretched out temporally and spectrally, then amplified, and then compressed again. The stretching and compression uses devices that ensure that the different color components of the pulse travel different distances.

An intense electromagnetic pulse can create a weak of plasma oscillations through the action of the nonlinear ponderomotive force. Electrons trapped in the wake can be accelerated to high energy. Existing glass lasers of power density 10^{18}W/cm^2 shone on plasmas of densities 10^{18} cm^{-3} can yield GeV of electron energy per centimeter of acceleration distance. This acceleration mechanism is demonstrated through computer simulation. Applications to accelerators and pulsers are examined.

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Plasmas are created via ionization, which can occur in several ways: through collisions of fast particles with atoms; through photoionization by electromagnetic radiation; or via electrical breakdown in strong electric fields. The latter two are examples of field ionization, which is the mechanism most relevant to the plasma accelerator context. To get some idea of when field ionization occurs, we need to know the typical field strength required to strip electrons away from an atom.

At the Bohr radius

$$a_\mathrm{B} = \frac{\hbar^2}{me^2} = 5.3 \times 10^{-9}\ \mathrm{cm}$$

the electric field strength is

$$E_\mathrm{a} = \frac{e}{4\pi\varepsilon_0 a_\mathrm{B}^2} \simeq 5.1 \times 10^9\ \mathrm{V\,m^{-1}}$$

The atomic intensity I_a represents a threshold

$$I_\mathrm{a} = \frac{\varepsilon_0 c E_\mathrm{a}^2}{2} \simeq 3.51 \times 10^{16}\ \mathrm{W\,cm^{-2}}$$

A laser intensity of $I_L > I_a$ guarantee ionization for any target material

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

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

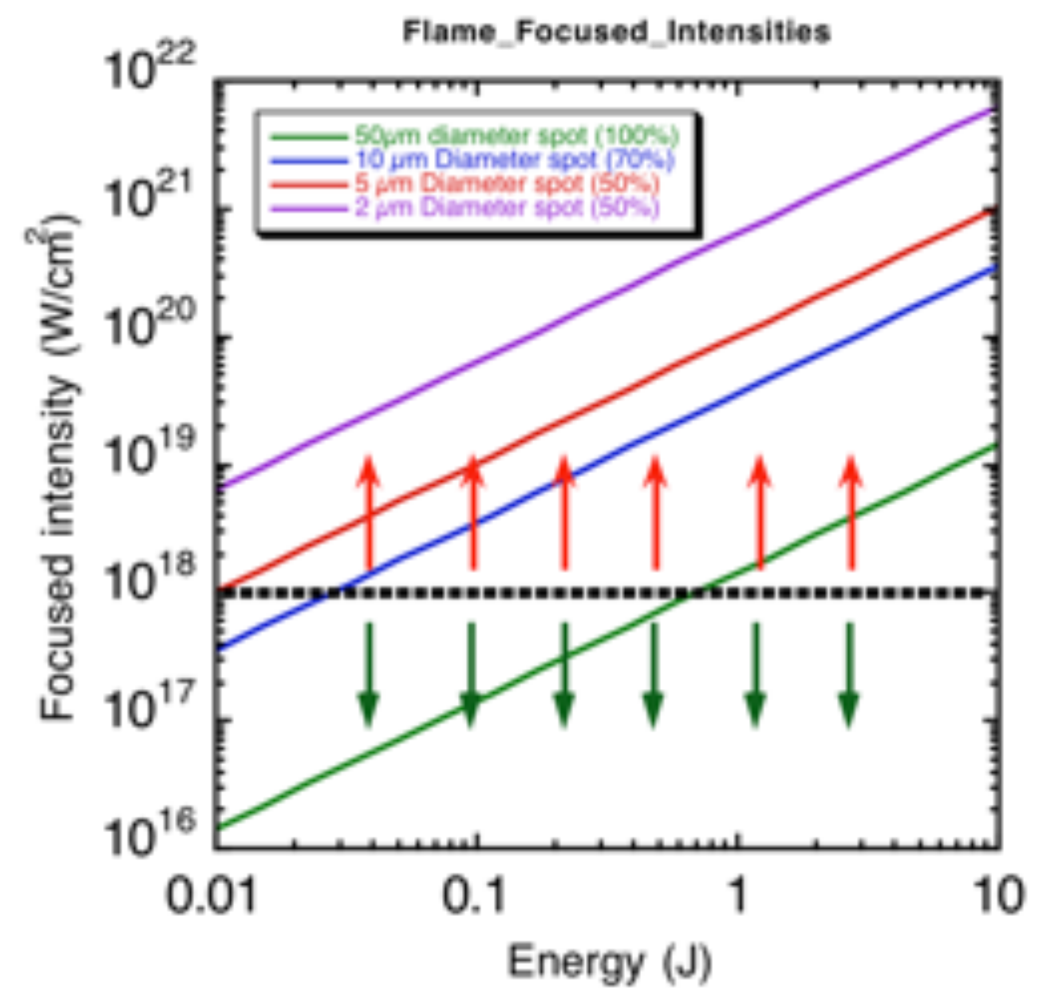
Peak power 300 TW

Pulse duration 20 fs

Repetition rate 10 Hz

Output energy 8 J

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



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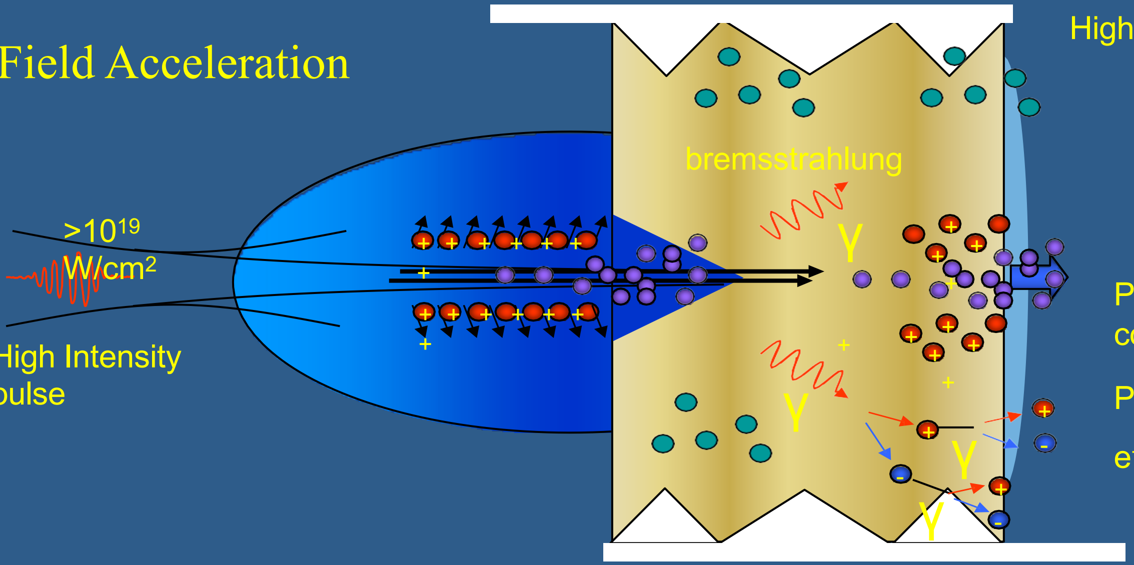
◆ CONVENTIONAL ACCELERATORS:

- 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 Wake-Field Acceleration



High energy neutron emission

> 100 MeV electrons

> 50 MeV protons

Photoelectron conversion,

Pair production

e^+ - e^- - shower

muon, pion etc…

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Istituto Nazionale di Fisica Nucleare

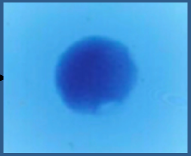
Laser-Plasma accelerators

Laser Wake-Field Acceleration

ENERGY SOURCE: Laser

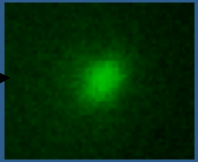
Laser focusing and control

OVERDENSE PLASMA
Laser-solid interactions

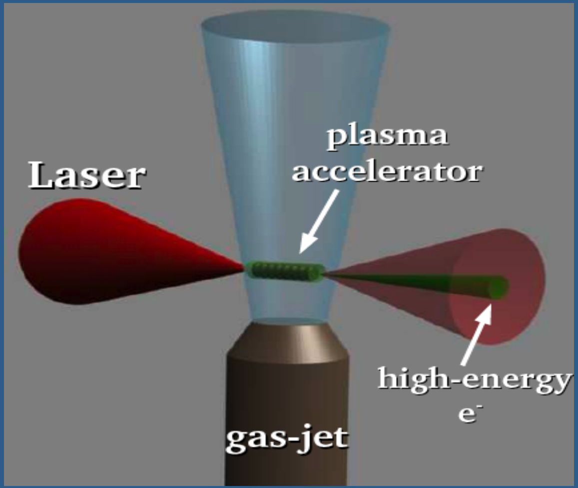


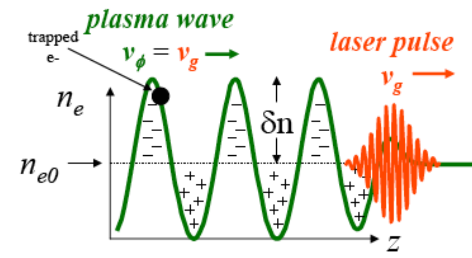
Protons, ions, e^-, e^+, broad spectrum, lower E,

UNDERDENSE PLASMA
Laser-gas interactions



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

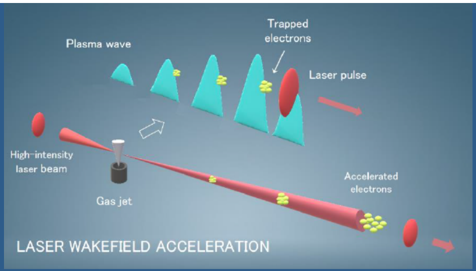




$$E_0[V/cm] = \frac{mc\omega_p}{e} = 0.96(n_e[cm^{-3}])^{1/2}$$

10^{11} V/m

10^{18} cm^{-3}



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The history of LNF electron accelerators 2

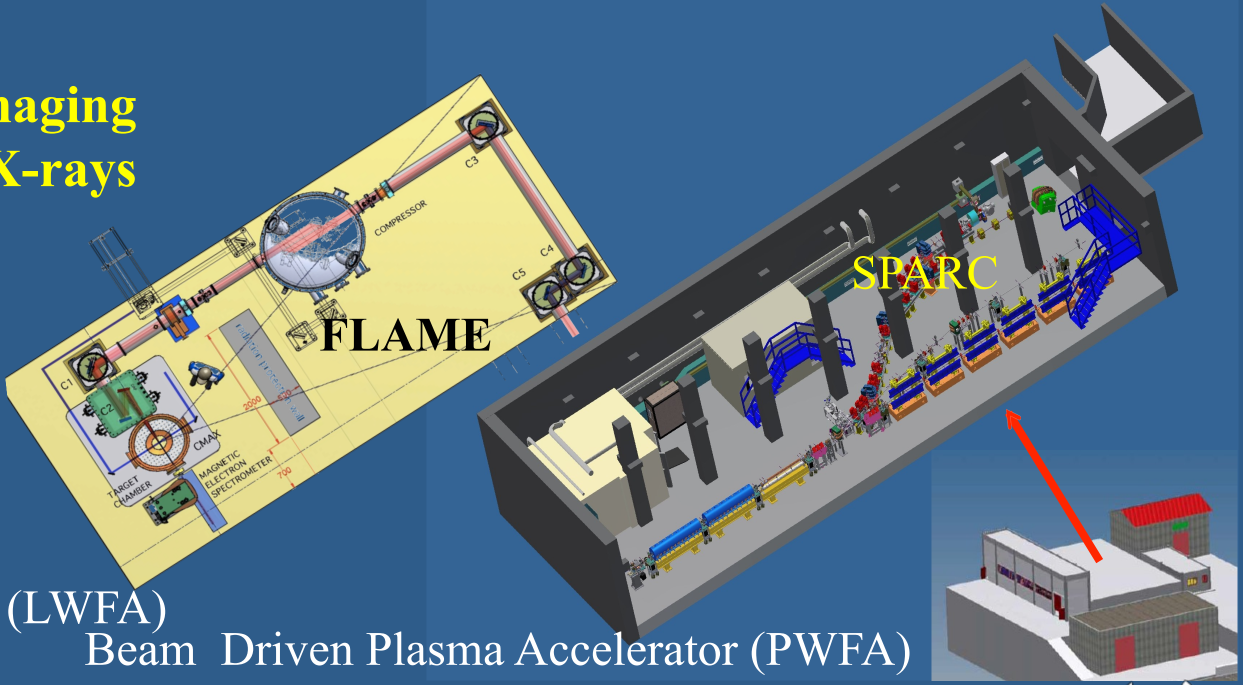
- self-injection of electrons in plasma waves driven into the bubble regime by FLAME pulses - into supersonic gas-jets;

- external injection of ultra-short SPARC electron bunches into plasma waves driven by FLAME pulses;

- ions/protons production by FLAME pulses onto metallic foils;

- development of a monochromatic and tuneable X-ray source in the 20-1000 keV range, based upon Thomson scattering of laser pulses by relativistic electrons

-advanced radio-logical imaging with mono-chromatic X-rays from Thomson source

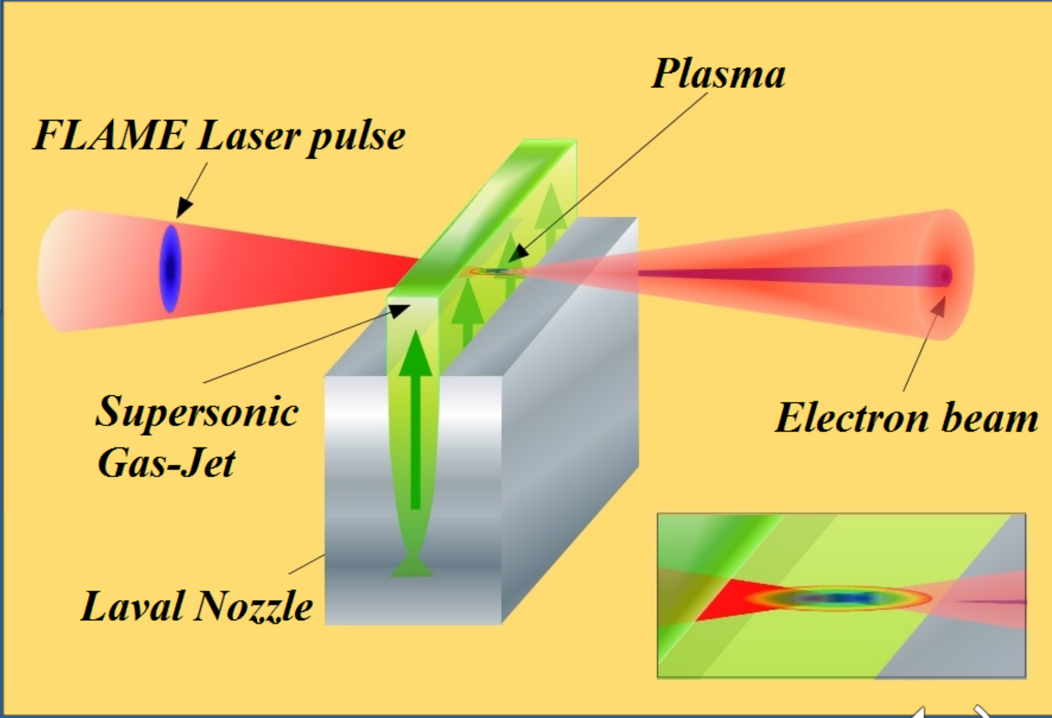


Laser Driven Plasma Accelerator (LWFA)

Beam Driven Plasma Accelerator (PWFA)

In a self injection test experiment - current target configuration we obtained electron with energies up to 500 MeV and more with only 10mm

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



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EuPRAXIA is the first European project that develops a dedicated particle accelerator research infrastructure based on novel plasma acceleration concepts and laser technology.

EuPRAXIA is the first European project that develops a dedicated particle accelerator research infrastructure based on novel plasma acceleration concepts and laser technology. It focuses on the development of electron accelerators and underlying technologies, their user communities, and the exploitation of existing accelerator infrastructures in Europe.

The EuPRAXIA Consortium has formed around an EU-funded Horizon 2020 conceptual design study to develop the concept of a ’European Plasma Research Accelerator with eXcellence In Applications’. It serves as an open innovation platform bringing together 16 participants and 25 associated partners from Europe, Asia, and the United States.

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The EuPRAXIA project aims at the construction of an innovative electron accelerator using laser- and electron-beam-driven plasma wakefield acceleration that offers a significant reduction in size and possible savings in cost over current state-of-the-art radiofrequency-based accelerators. The foreseen electron energy range of one to five gigaelectronvolts (GeV) and its performance goals will enable versatile applications in various domains, e.g. as a compact free-electron laser (FEL), compact sources for medical imaging and positron generation, table-top test beams for particle detectors, as well as deeply penetrating X-ray and gamma-ray sources for material testing.

The EuPRAXIA facility for beam-driven plasma acceleration (PWFA) is proposed to be constructed in Frascati, Italy, and is ready to proceed. The host lab is INFN-LNF, and the electron beam driver will rely on the most compact RF technology available, namely, X-band structures developed at CERN.

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The Frascati site of EuPRAXIA will build on the investments in beam-driven plasma acceleration at SPARC_LAB.

The proposal also reflects on the Italian interest in an FEL user facility that combines a 1 GeV RF-based FEL option with a plasma-based advanced FEL setup at possibly higher energy. EuPRAXIA@SPARC_LAB would be the first FEL on the Frascati site.

EuPRAXIA@SPARC_LAB installation area

User applications for EuPRAXIA@SPARC_LAB will focus on a 1 GeV free-electron laser with an upgrade to 2–5 GeV, an inverse Compton scattering photon source, high-energy positron beams, and test beams.

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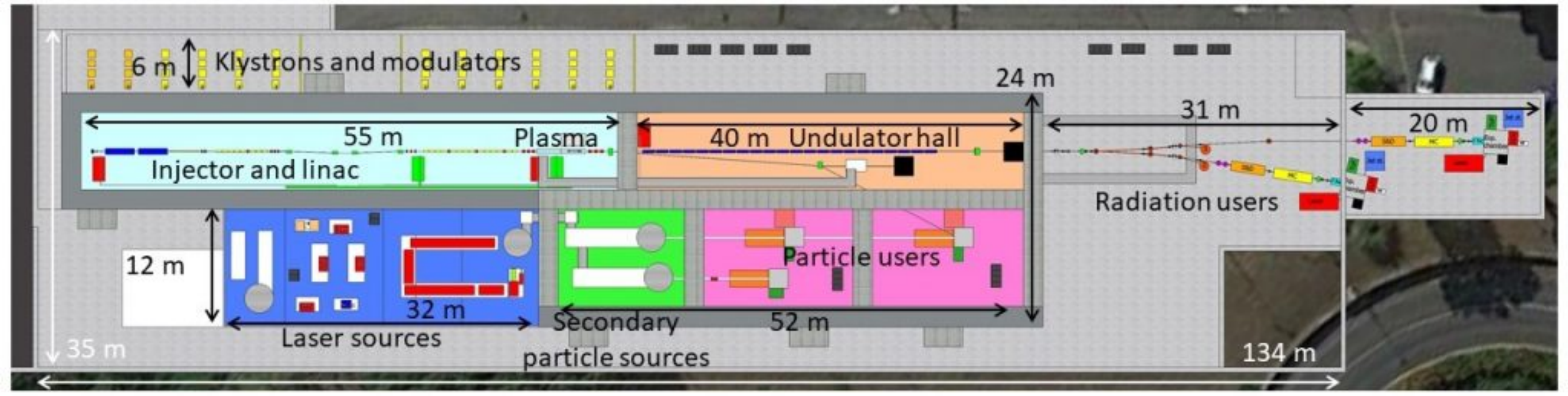
Construction Site for Beam-Driven Plasma Acceleration **EuPRAXIA@SPARC_LAB**

Energy [GeV]	**1.2**	**5**
Q [pC]	500	50
Peak Current [kA]	3	3
Rep. Rate [Hz]	100	100
Average Current [nA]	50	5
Beam Power [W]	60	25



Among the new ESFRI project (European Strategy Forum on Research Infrastructures) there is

EuPRAXIA - European Plasma Research Accelerator with Excellence in Applications, a distributed, compact and innovative accelerator facility based on plasma technology, set to construct an electron-beam-driven plasma accelerator in the metropolitan area of Rome, followed by a laser-driven plasma accelerator in European territory. (ESFRI ROADMAP 2021)

Radiation protection issues

The steps needed to arrive at a preliminary understanding of radiological impact of the any accelerator facility are below listed:

- specification of design parameters
  - type of particles accelerated;
  - beam characteristic;
  - maximum energy and current;
  - duty cycle;

That is the source term

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Radiation protection issues

- specification of assumptions on expected operation
  - operation time per year;
  - occupational factor for different building and location;
- determination of applicable radiation protection goals;
- assessment radiological risk for workers and general public;
  - under normal working condition;
  - under accident condition;
- estimation of radiation source strength;

That is the dose constraints and radiation protection goals

The higher the energy of particle accelerated, the more complex the characteristic of the prompt radiation field, that exist only while the accelerator is in operation.

- primary particles production (electrons, protons, ions)
- prompt radiation production
    - bremssstrahlung, neutrons, muons, pions, kaons
    - any other particle (charged particles, ions, nuclear fragments and delayed radiation);

The determination of a source term for laser- based accelerator is not an easy task

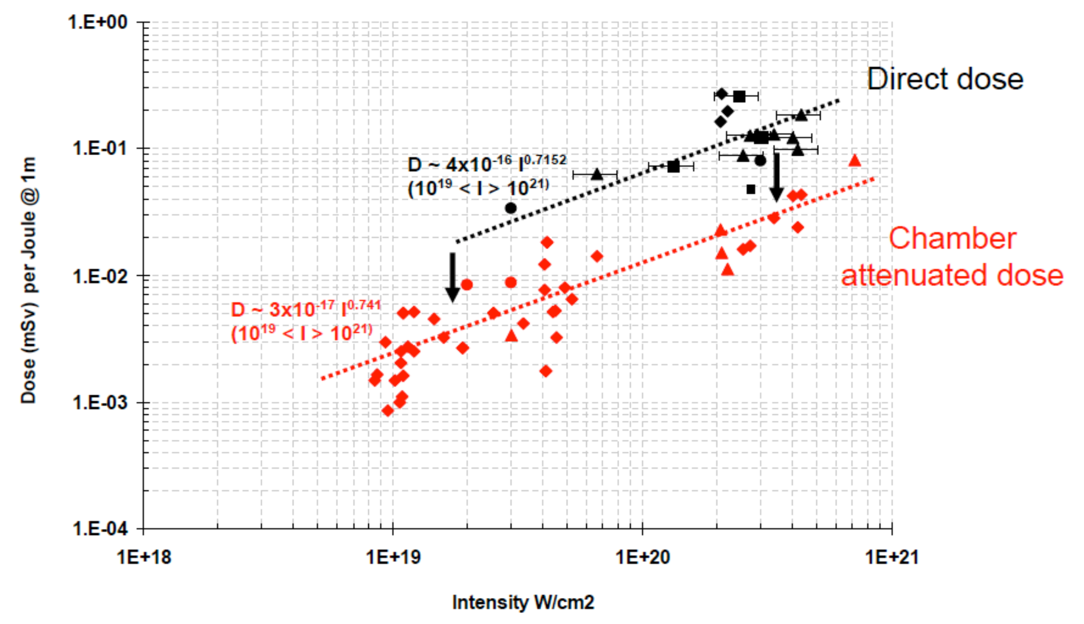
◆Measurements on existing facilities up to 1 PW

Not easy task

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

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

◆Only dosimetric evaluation are available



◆Any extrapolation to power higher 100 PW is quite impossible

An estimation of the primary radiation in laser gas-interaction can be mainly obtained using computer code

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>

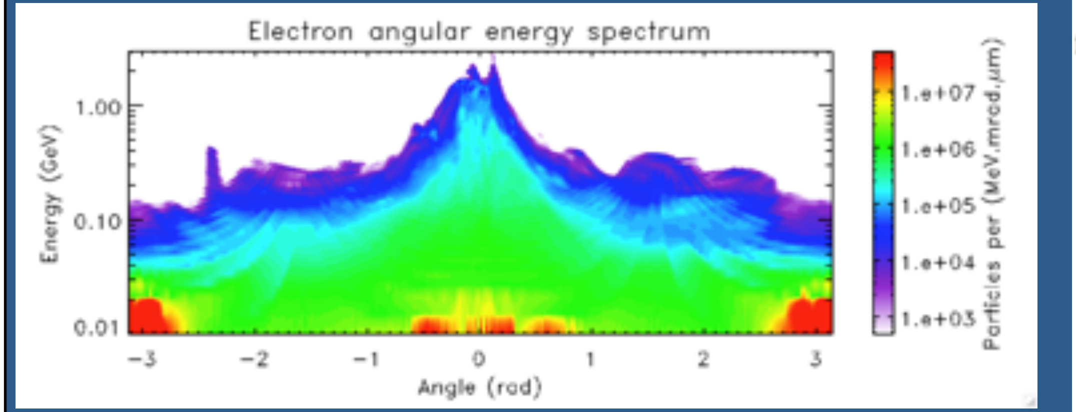
N_j^G

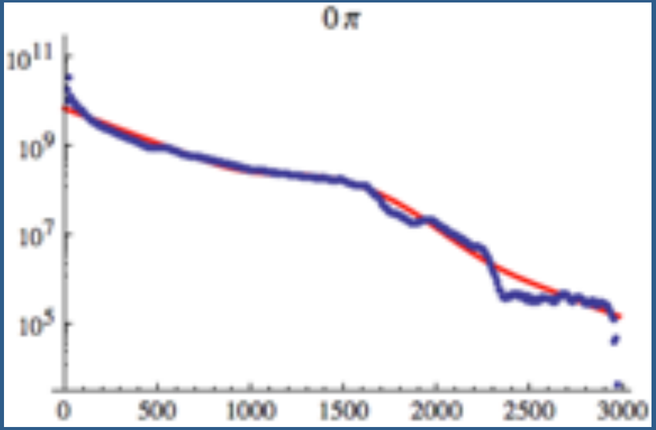
T_i temperature in MeV

E_j^G the central energy in MeV

thermal component quasi-monochromatic component

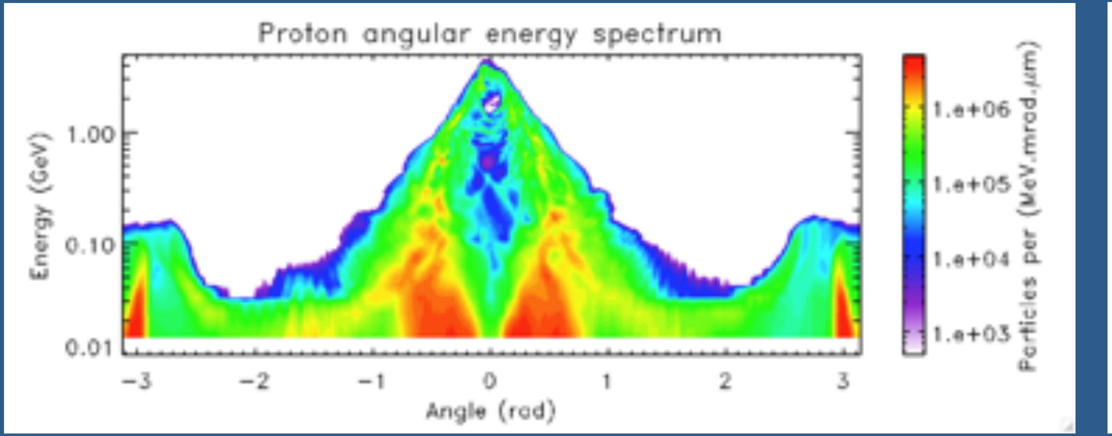
Target Thickness 1 µm Material H Density 0.088 g/cm^3 2kJ 15 fs 1.6x10^{23} *W/cm^2*

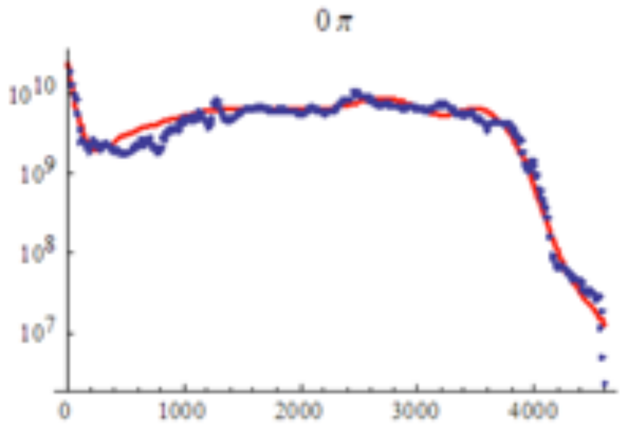




MeV

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





MeV

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Are alse possible some analytical estimation of the source term (0.1 Hz and 10 Hz beamlines)**:**

- ✓ Reference: *W. Lu et al., Phys. Rev. S.T. Accelerators and Beams 10 (2007) 061301*
- ✓ Electron Energy:

$$\Delta E[GeV] \cong 1.7\left(\frac{P[TW]}{100}\right)^{\frac{1}{3}}\left(\frac{10^{18}}{n_p[cm^{-3}]}\right)^{\frac{2}{3}}\left(\frac{0.8}{\lambda[\mu m]}\right)^{\frac{4}{3}}$$

- ✓ Electron Beam Charge:

$$N = 2.5 \times 10^{9}\frac{\lambda[\mu m]}{0.8}\sqrt{\frac{P[TW]}{100}}$$

➢Electron beams (gas-targets)
- 0.1 Hz, 300 J
- 10 Hz, 50 J

Values calculated and used by Anna Ferrari and Daniele Margarone

E_{e-} = 50 GeV   1.3nC

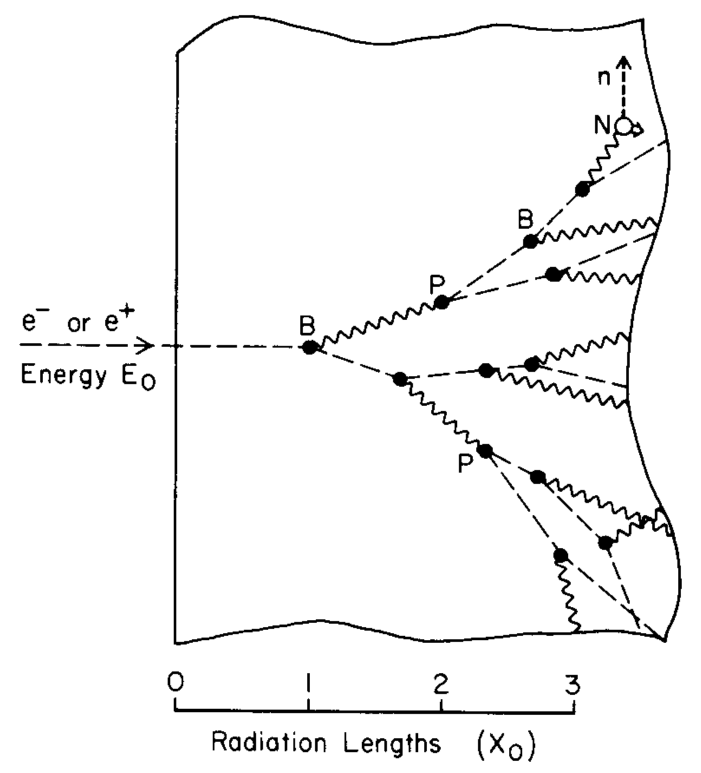
E_{e-} = 5 GeV   1nC

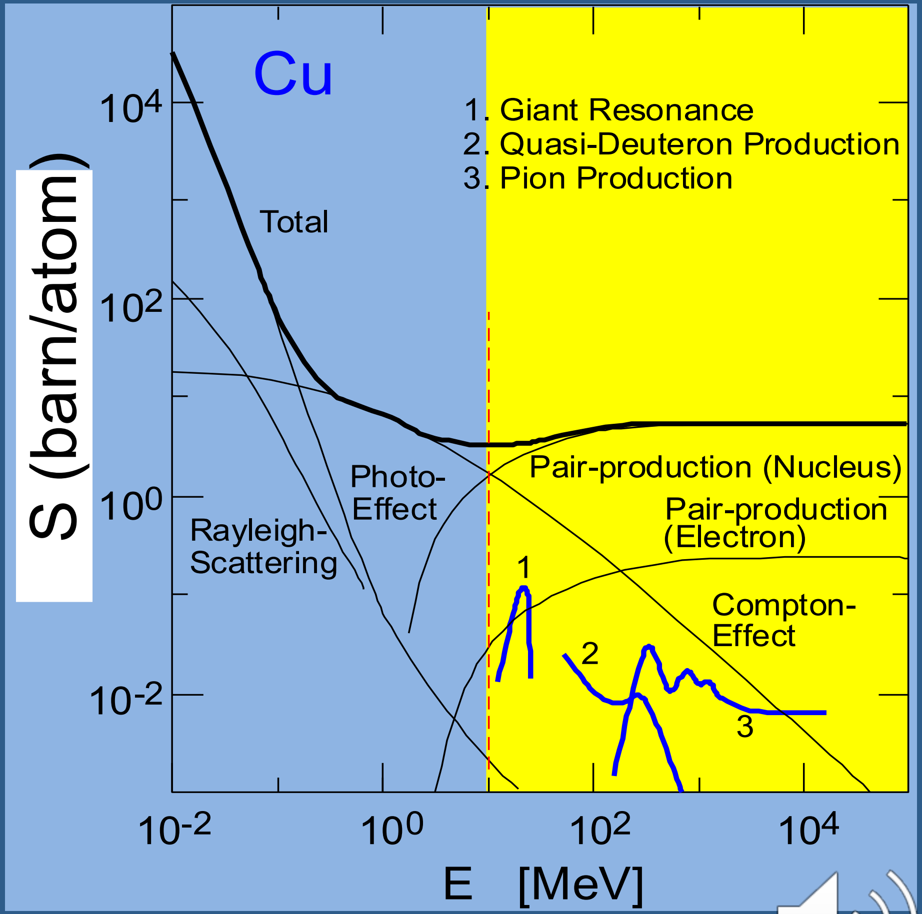
SHIELDING ASSESSMENT AT THE ELI BEAMLINE FACILITY (Czech Republic)

Anna Ferrari[1] & Daniele Margarone[2]
[1]*Institute of Safety Research and Institute of Radiation Physics, FZD Dresden-Rossendorf, Germany*
[2]*Institute of Physics of the Czech Academy of Science, Prague , Czech Republic*

Electrons

For shielding evaluation purposes, three components of radiation field which are produced when an electron beam, with energies of hundreds MeV, hits a thick target or the thin wall of the vacuum chamber under a small angle have to be considered.





Bremsstrhlung

Giant resonance neutrons

High energy neutrons

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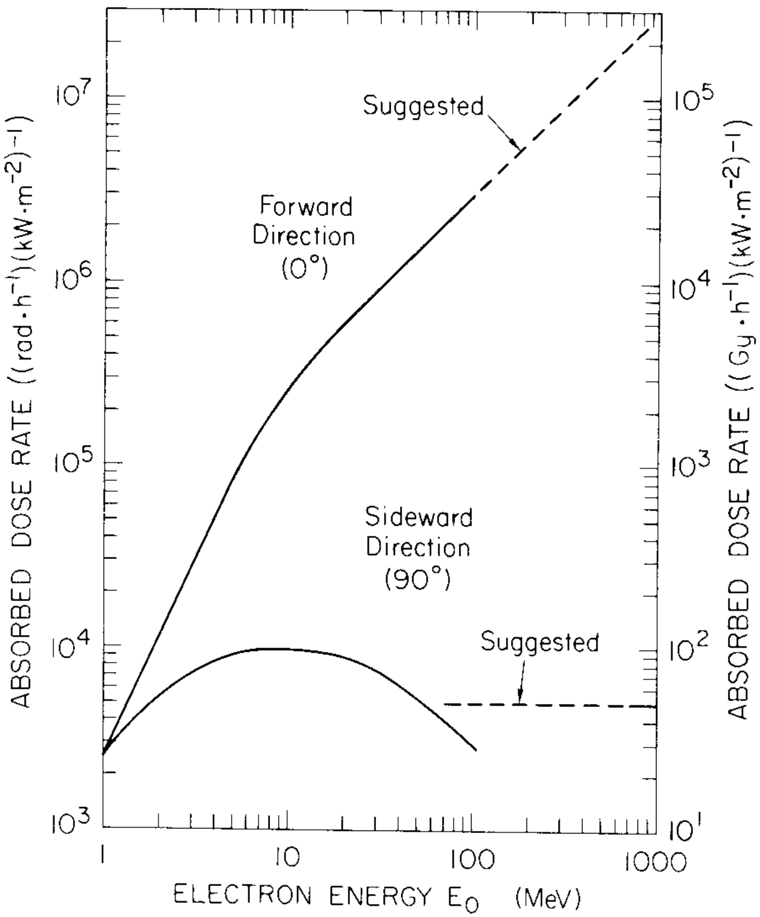
Electrons

Bremsstrhlung source term



Swanson's 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:

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

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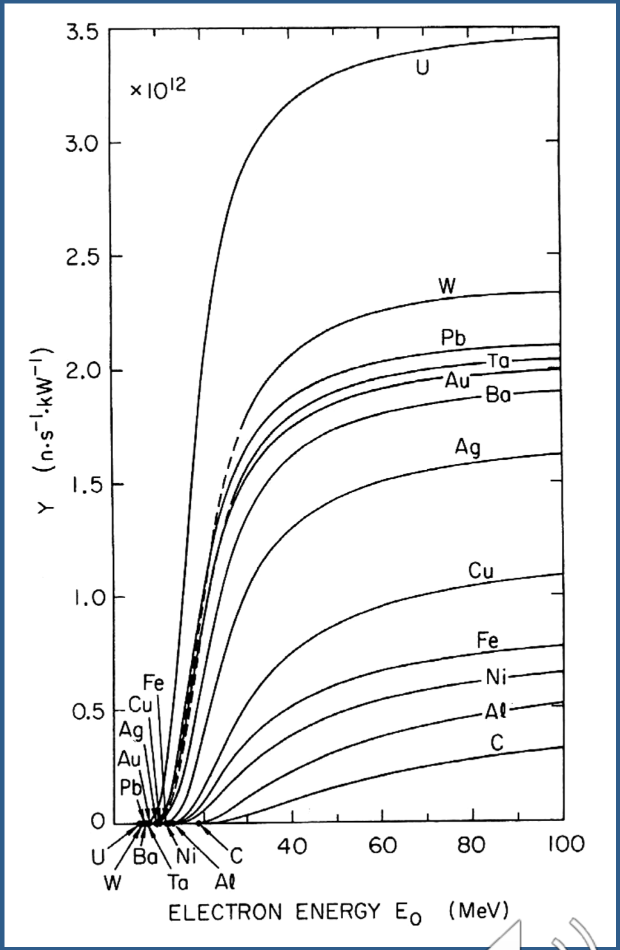
Electrons

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



Giant resonance neutrons

$$Y = 1.21\times10^{11}\, Z^{0.66}\, n\, s^{-1}\, kW^{-1}$$

Evaporation (Maxwell – dominant) and
direct emission (higher E tail)

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

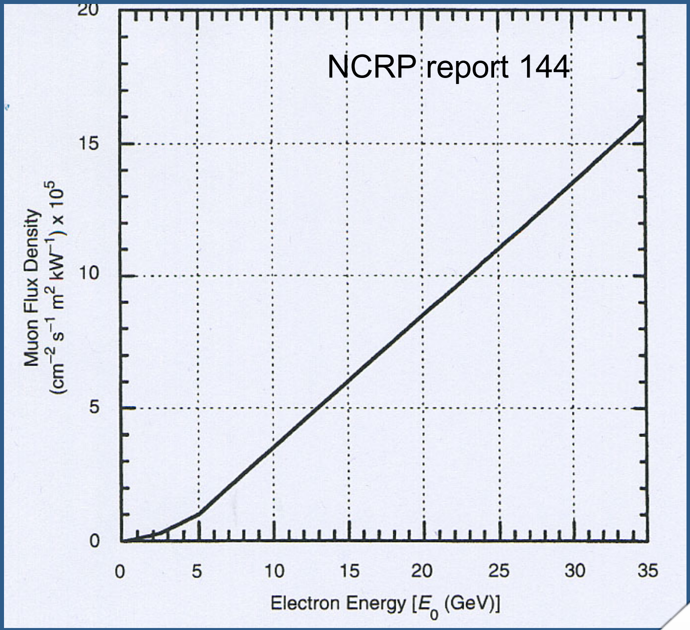
High energy neutrons (E>25MeV)

For 6.3 GeV of electrons
between 0° - 30° 2.3×10^{-2} n sr^{-1}/e^{-}
between 30° - 60° 1.5×10^{-2} n sr^{-1}/e^{-}
between 60° - 120° 8.1×10^{-3} n sr^{-1}/e^{-}

For 20 GeV of electrons
between 0° - 30° 5.1×10^{-2} n sr^{-1}/e^{-}
between 30° - 60° 2.7×10^{-2} n sr^{-1}/e^{-}
between 60° - 120° 1.9×10^{-2} n sr^{-1}/e^{-}

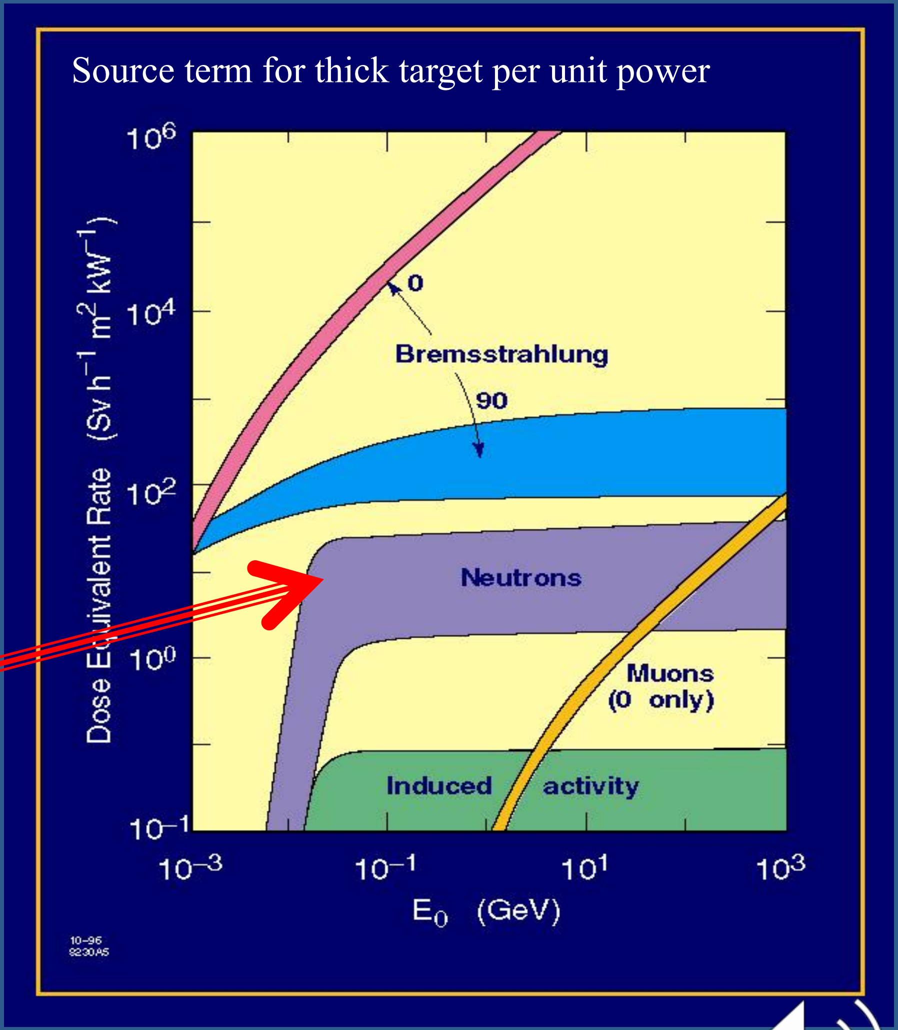
Electrons - muon production

- Muon production is analogous to e^+/e^- pair production by photons in the field of target nuclei when photon energy exceeds the threshold $2m_mc^2 \approx 211$ 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
- 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 0° direction.



Electrons

Dose equivalent rates per unit primary beam power, produced by various types of secondary radiation from an electron target, as a function of primary beam energy, if no shielding is present (qualitative). The width of the bands suggests the degree of variation found, depending on such factors as target material and thickness.



Source term for thick target per unit power

$E_{threshold}$ ~ 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

Shielding assessment

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

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

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

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

Material	Radiation Components	Attenuation length (cm)
Concrete	Bremsstrahlung	20.4 (0°)
Concrete		18.7 (90°)
Lead		2.2
High Density Polyethylene		69.3
Concrete	Giant resonance neutron	17.4
Lead		18.30
High Density Polyethylene		6.36
Concrete	High energy neutron	8.9
Lead		16.8
High Density Polyethylene		61.4

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Shielding materials

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

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

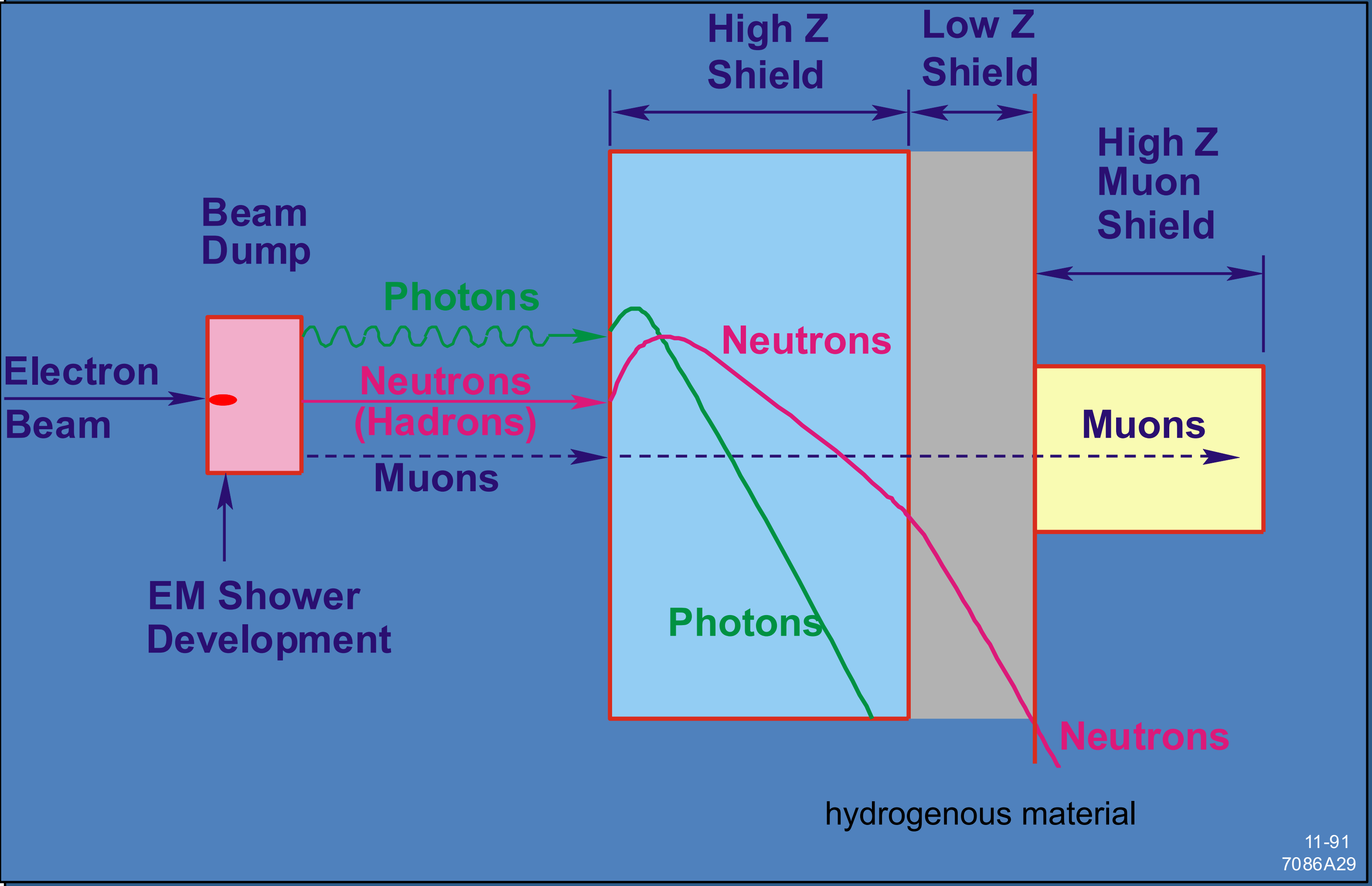
Stability of shielding

Cost including installation and maintenance

Possibility of induced radioactivity

Shield design must be integrated with all other aspects of an accelerator facility

Electrons



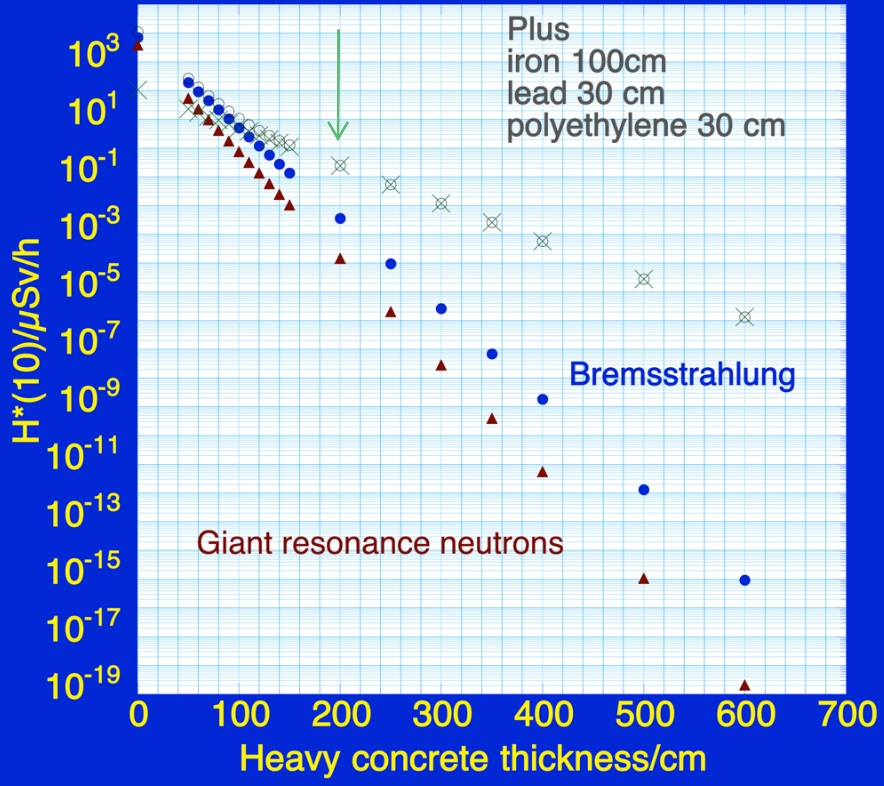
high inelastic cross sections in high-*Z* materials to reduce the neutron energy by *(n,xn)*

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

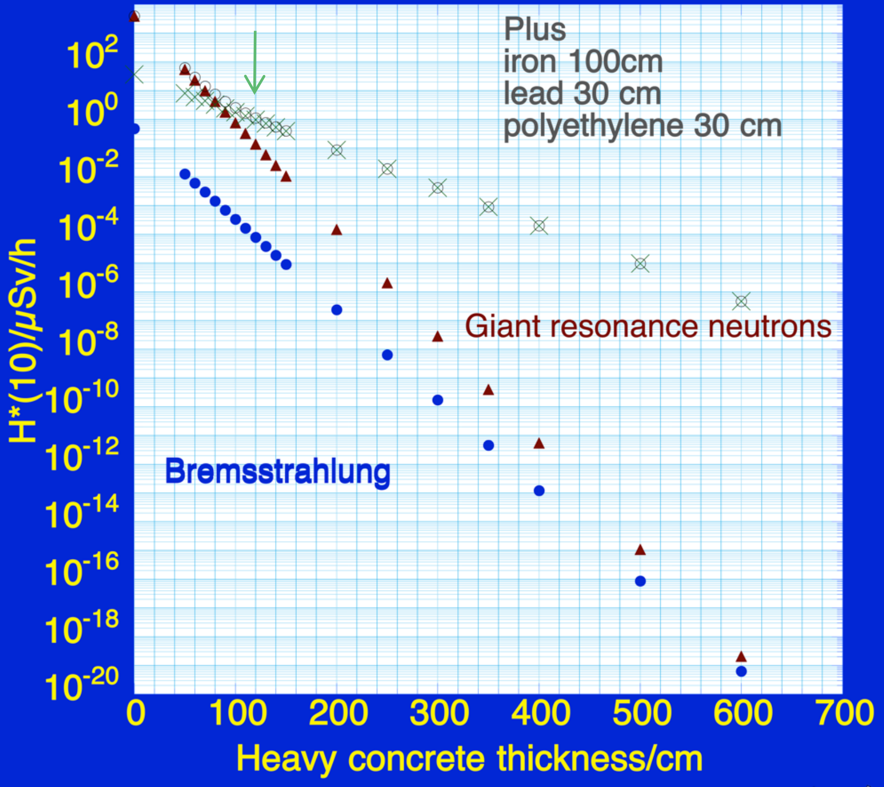
Shielding assessment – total attenuation

E_{e-} = 5 GeV   1nC 10 Hz 50 J (gas - target)

Total Attenuation 0 ° 5GeV



Total Attenuation 90° 5GeV



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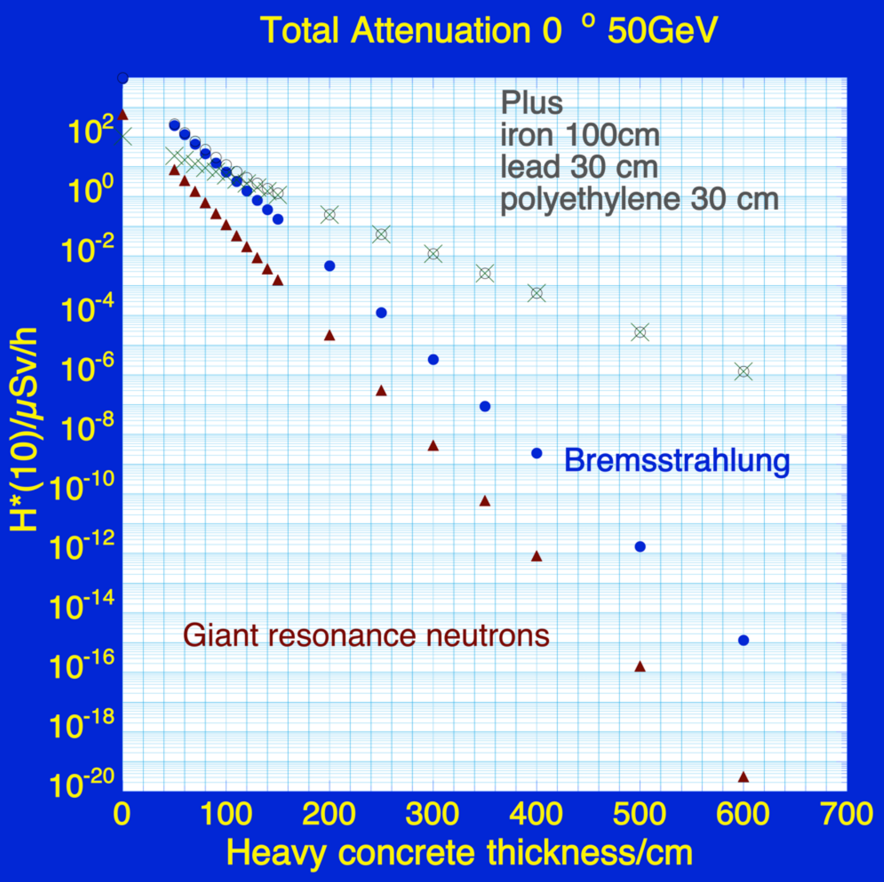
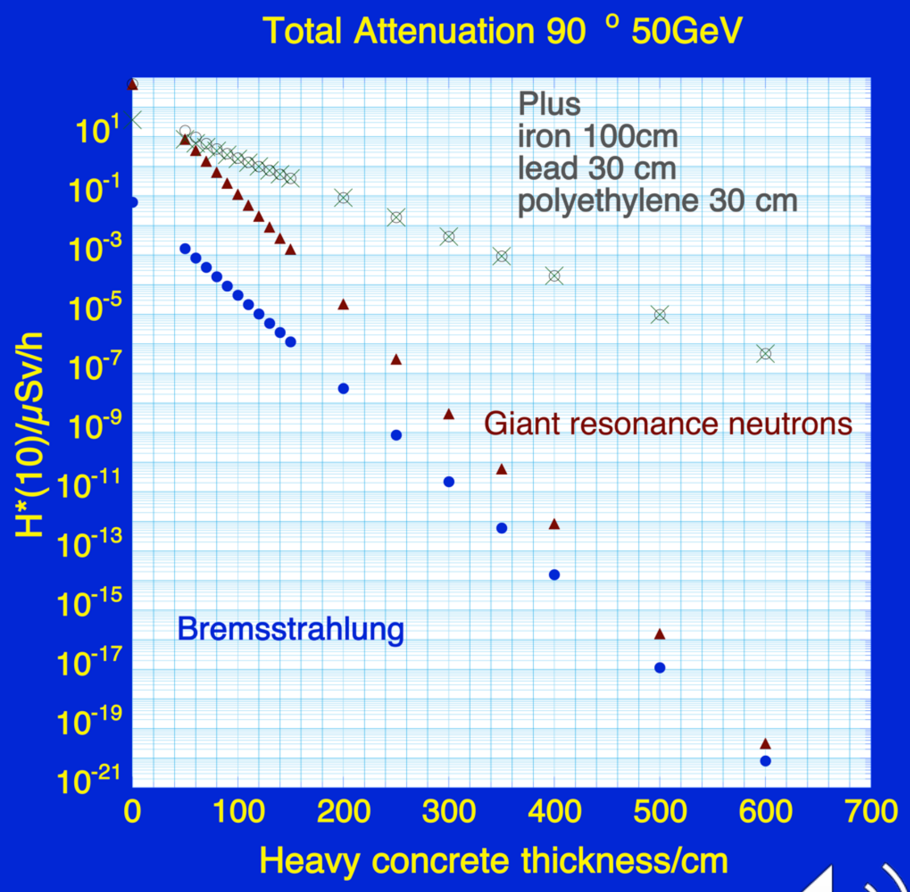
Shielding assessment – total attenuation

E_{e-} = 50 GeV 1.3 nC 0.1 Hz 300 J (gas - target)





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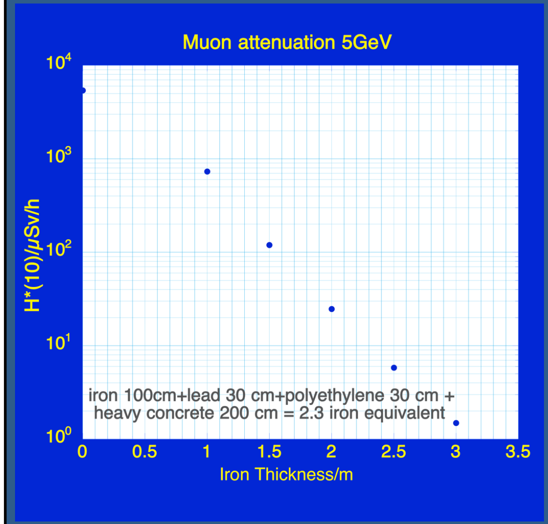
Shielding assessment – muon attenuation



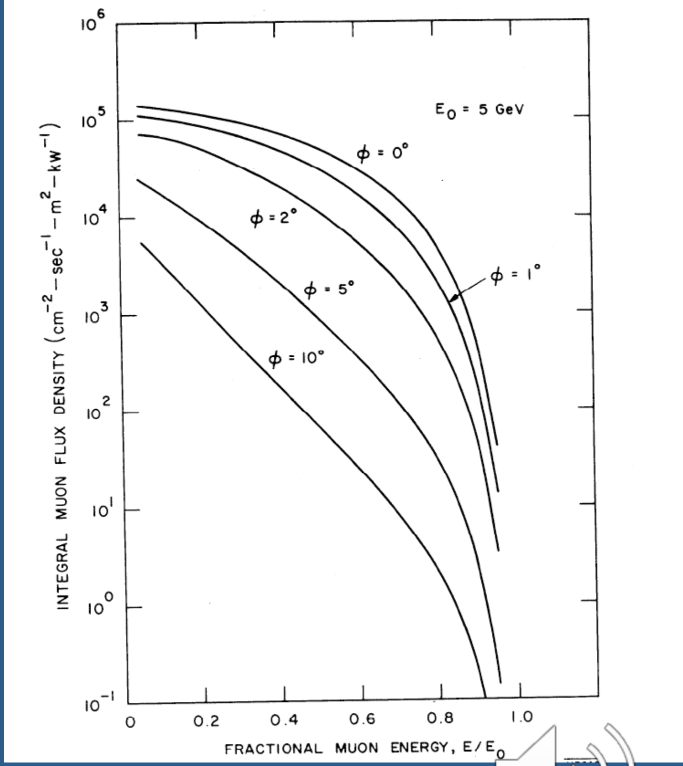
Adapted from Sullivan

$3x10^{-4}$μSv cm^2

Conversion factor from Pelliccioni

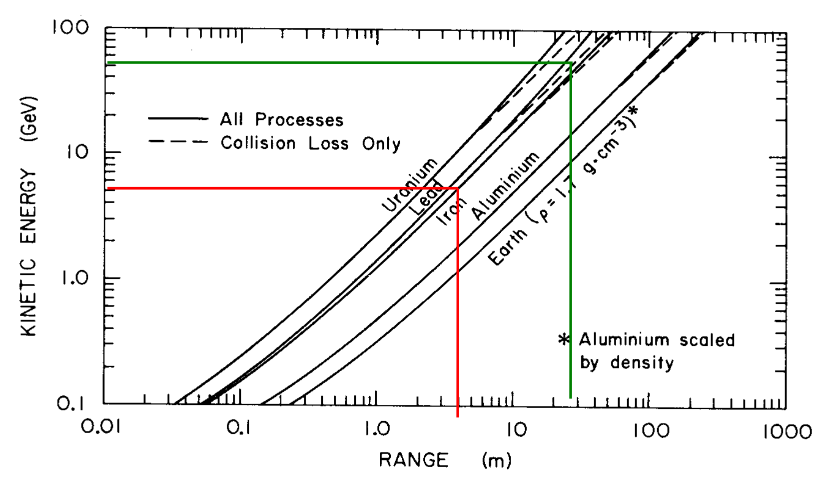
Material	*Density/gcm^{-2}*	*Relative range*
Water	1	5.7
Earth	1.8	3.6
Concrete	2.35	2.6
Aluminium	2.7	2.6
Baryte	3.2	2.4
Iron	7.4	1
Copper	8.9	0.86
Lead	11.3	0.79
Uranium	19	0.46
Tungsten	19.3	0.43

$(S/\rho)_{min} \cong 2$ MeV/g cm^{-2}



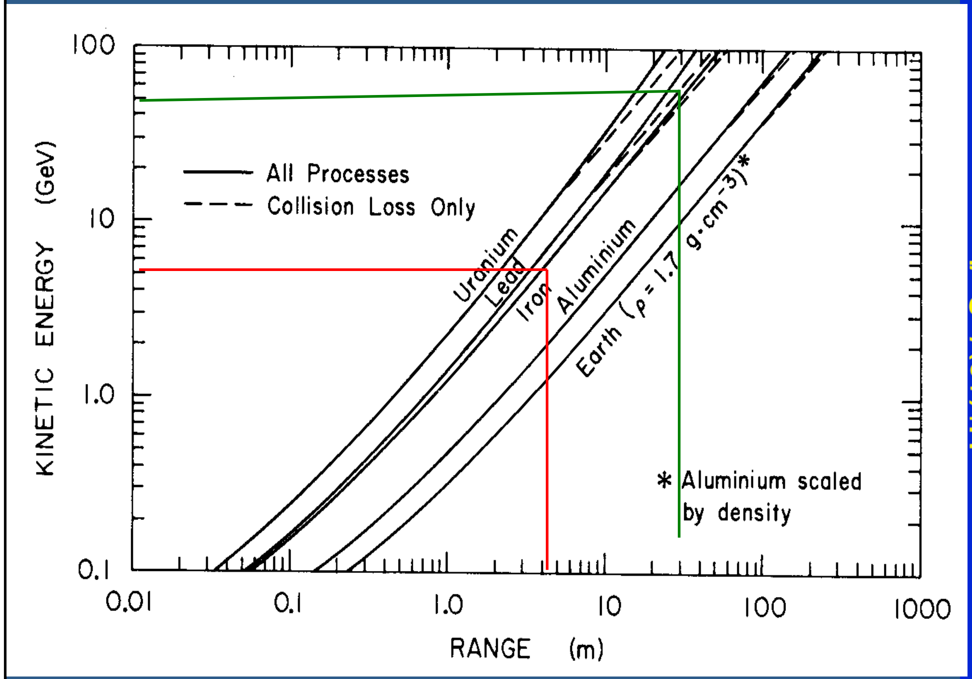
The shield used to reduce the ambient dose equivalent rate to less than 1 μSv/h is able to shield also the muon component because is equivalent to 2.3 m of iron.

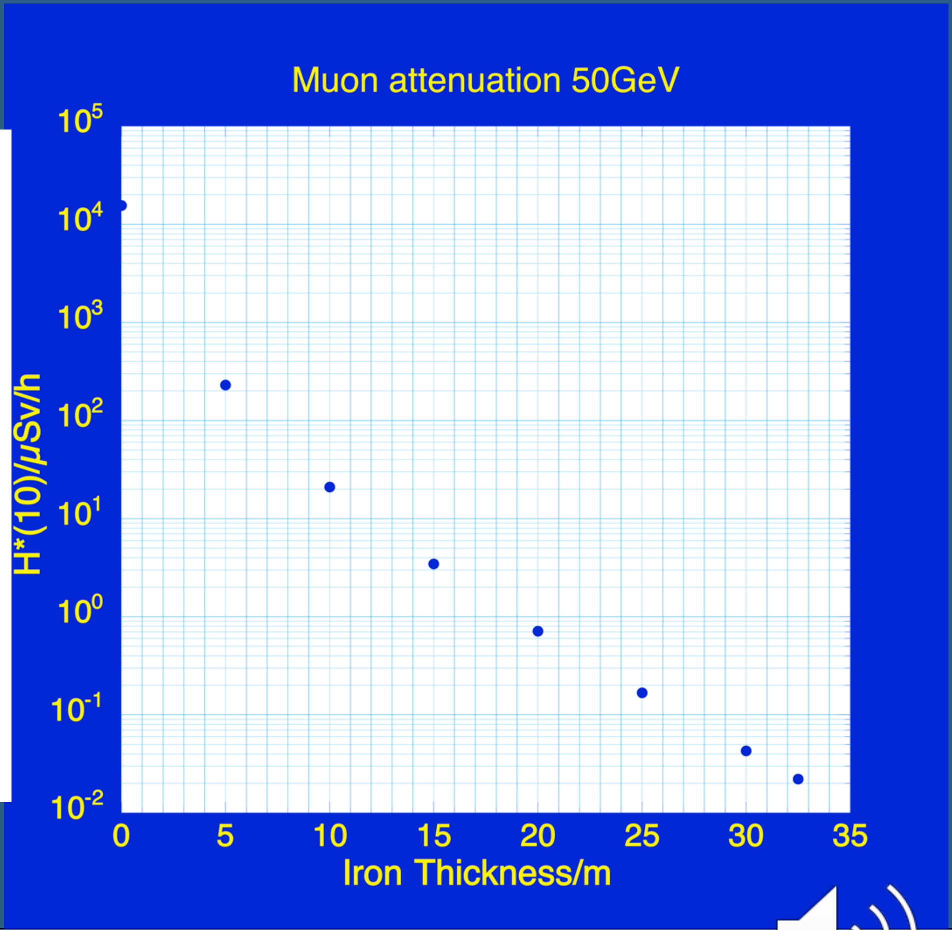
The muon dose rate on beam axis and behind a beam dump could be approximated by exp(-10 t/E)/(t*t) where E is the energy in GeV (>3 GeV) and t is the thickness of iron traversed in the range 0.1E-0.65E m of iron from Sullivan



Shielding assessment – muon attenuation

It is quite impossible ranging out 50 GeV muons unless you use at least 20 m of iron or you install underground the experimental chamber.





Beam time – radiation protection policy

Shielding 2m of heavy concrete+1m Iron+ 30 cm polyethylene`+ 30 cm lead

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E_{e-} = 5 GeV 1nC 10 Hz 50 J (gas - target)

60 h/year of operation

0° 15 µSv/year

90° 5 µSv/year

µ 480 µSv/year

E_{e-} = 50 GeV 1.3 nC 0.1 Hz 300 J (gas - target)

90 h/year of operation

0° 22 µSv/year

90° 8 µSv/year

µ 42 mSv/year

Dosimetry at laser-plasma accelerators is a challenge due to the complexity of the radiation fields which, in ultra-short mode, contain many components with high instantaneous fluxes and dose rates. One difficulty lies in the fact that the secondary radiation field will be composed of a combination of different types of radiation and energies following interactions of the primary beam with the surrounding materials, including shielding

Conventional instruments

Active	Passive
Ionization Chamber	TLD
Proportional counter	Track etch detectors
Scintillation detectors	Nuclear emulsions
Solid state detectors	Activation detectors
Tissue equivalent proportional counter	Bubble detector
Bonner Spheres	Bonner Spheres

Problems

Mixed field dosimetry (γ, n, μ. p etc.)

Pulse duration fs

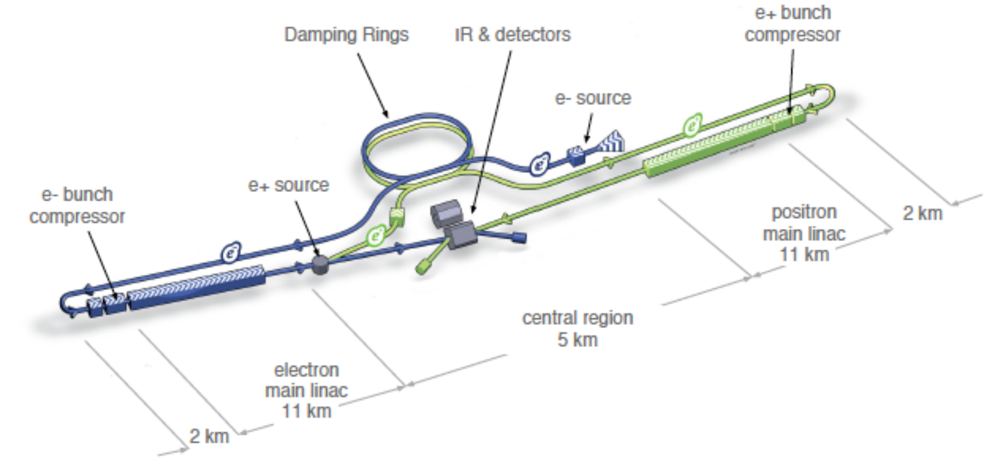
Operation shot by shot

The future of accelerator will be dominated by laser-based accelerator

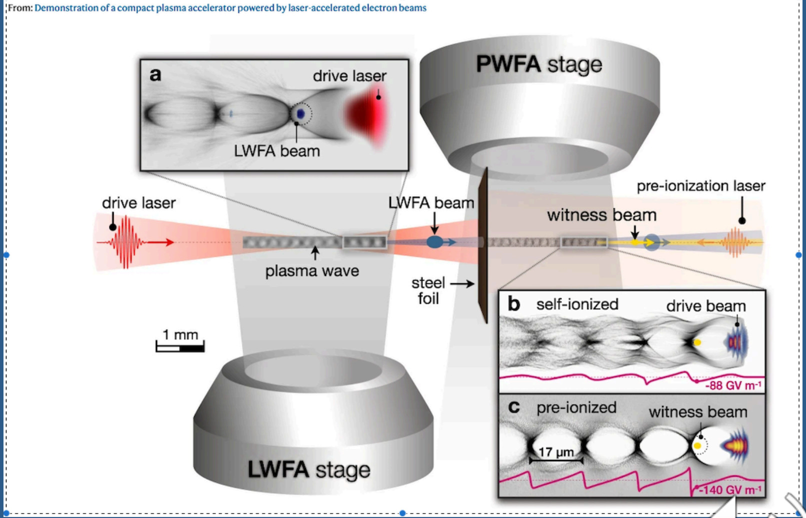
PWFA beam driven

LWFA laser driven

International Linear Collider



Kurz, T., Heinemann, T., Gilljohann, M.F. *et al.* Demonstration of a compact plasma accelerator powered by laser-accelerated electron beams. *Nat Commun* **12,** 2895 (2021). https://doi.org/10.1038/s41467-021-23000-7


From: Demonstration of a compact plasma accelerator powered by laser-accelerated electron beams

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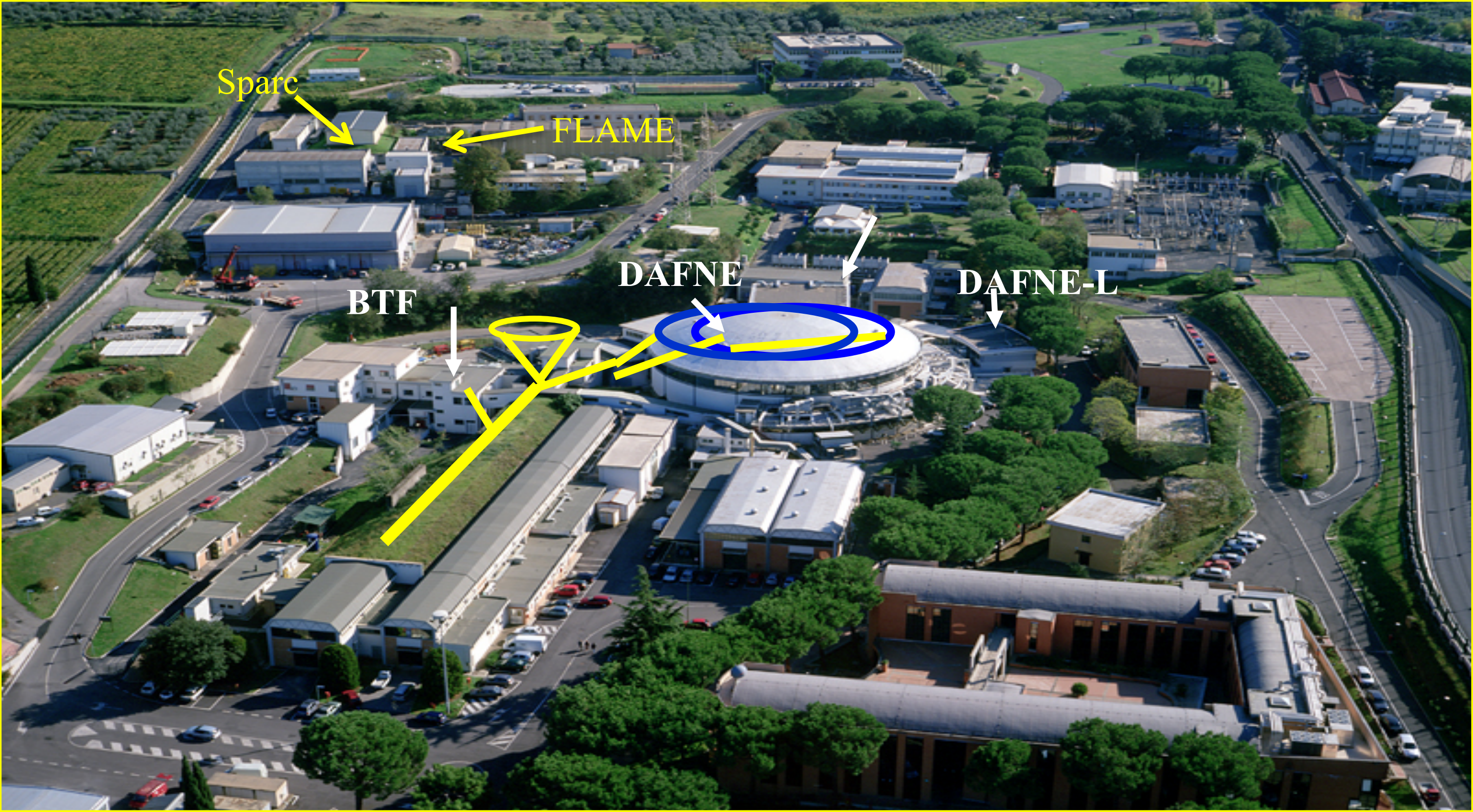
In conclusion

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



Thank you

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