The Laser Laboratory for Acceleration and Applications

3rd Topical Workshop on Novel Acceleration Techniques

Dresden, April 2014

José Benlliure

Universidad of Santiago de Compostela

UNIÓN EUROPEA
FONDO EUROPEO DE DESARROLLO REGIONAL
"Una manera de hacer Europa"

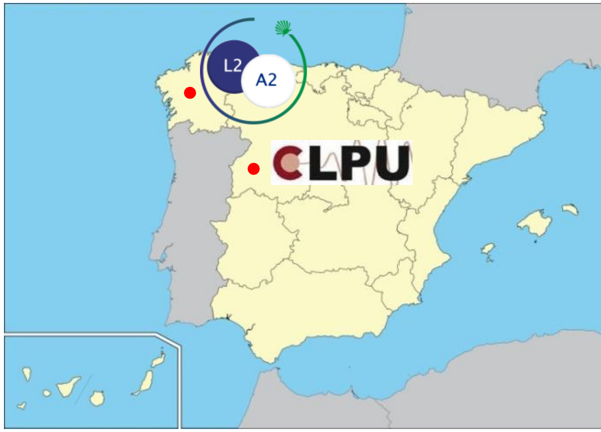
Laser Laboratory for Acceleration and Applications

A new laser facility for J and mJ ultra-short laser pulses generation

- low-energy particle acceleration: activation
- X-ray generation
- micro-machining, material modifications, microelectronics, photonics,…

A Ti:Sa compact laser system with two beam lines:

- front-end line: ~1 mJ, 1 kHz, 25 – 100 fs, ASE c.r. 10^{-6}
- amplified line: ~1.2 J, 10 Hz, 25 – 100 fs, ASE c.r. 10^{-10}



Research team

Laser physics

- J. Arines, C. Bao, M. Flores (USC)
- F. Cambronero, D. Nieto (L2A2)

Laser-matter interaction:

- C. Ruíz, A. Aragón (L2A2)
- A. Paredes (UVi)

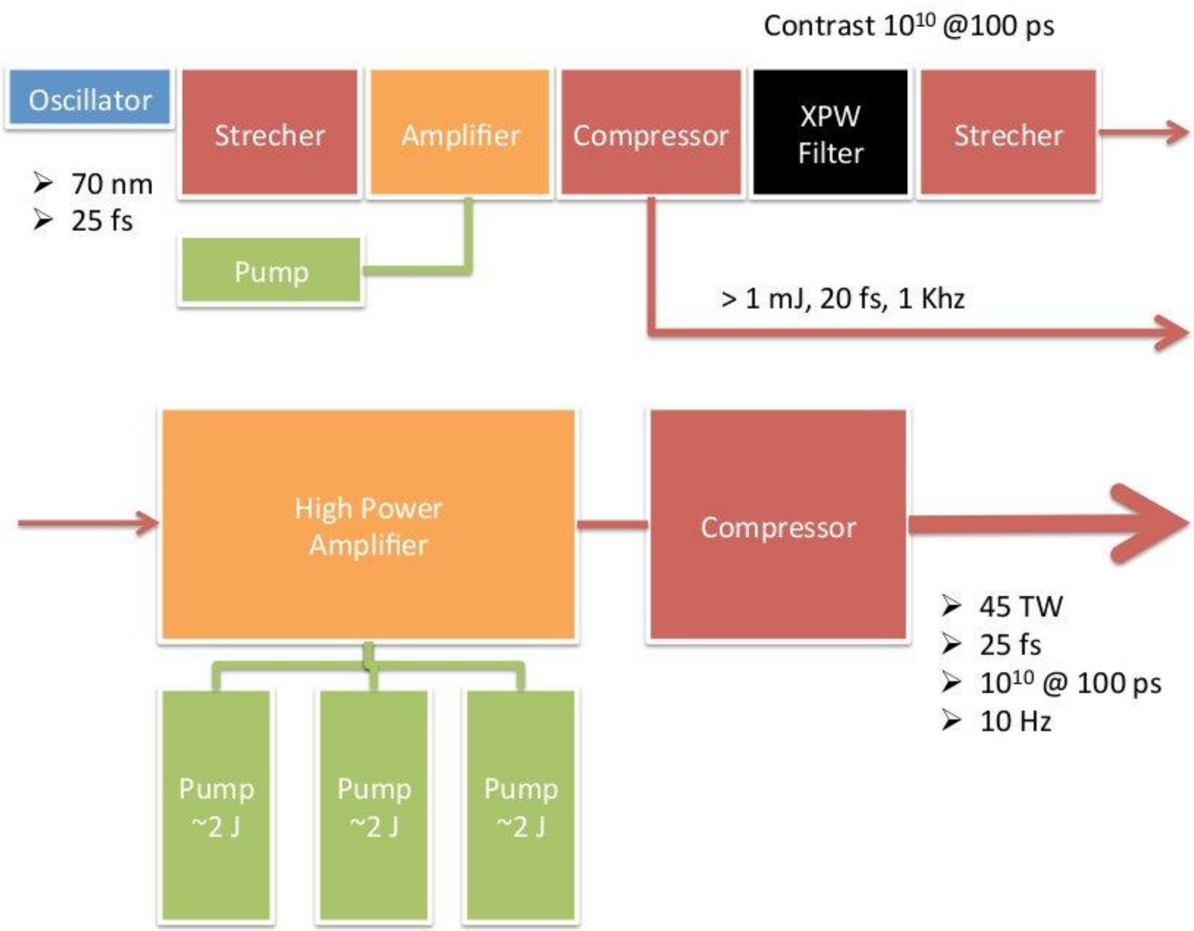
Nuclear and medical Physics:

- H. Alvarez, J. Benlliure, D. Cortina (USC)
- A. Iglesias, J. Llerena, J. Silva (L2A2)

Sensors and computing:

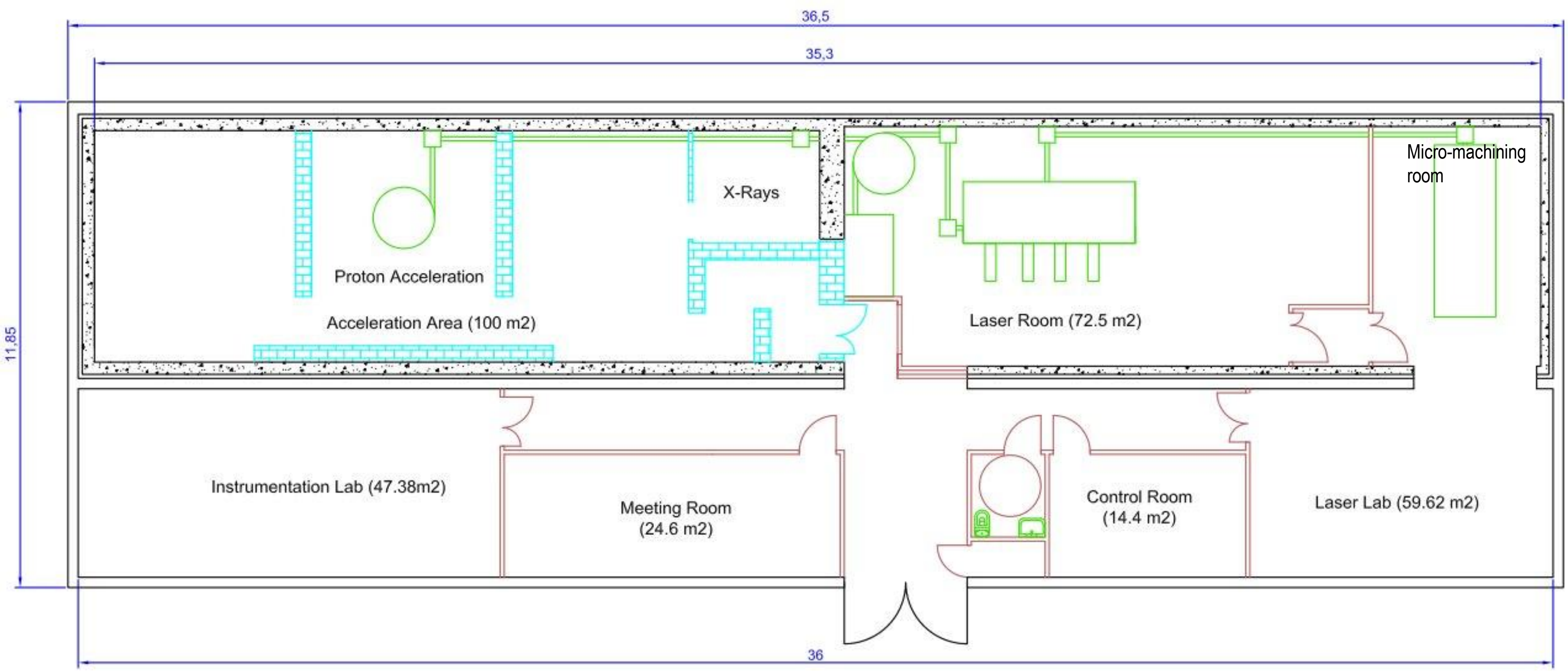
- D. Cabello, V. Sánchez, J. Vidal (USC)
- B. Blanco, D. Castro (L2A2)

L2A2 facilities: laser system



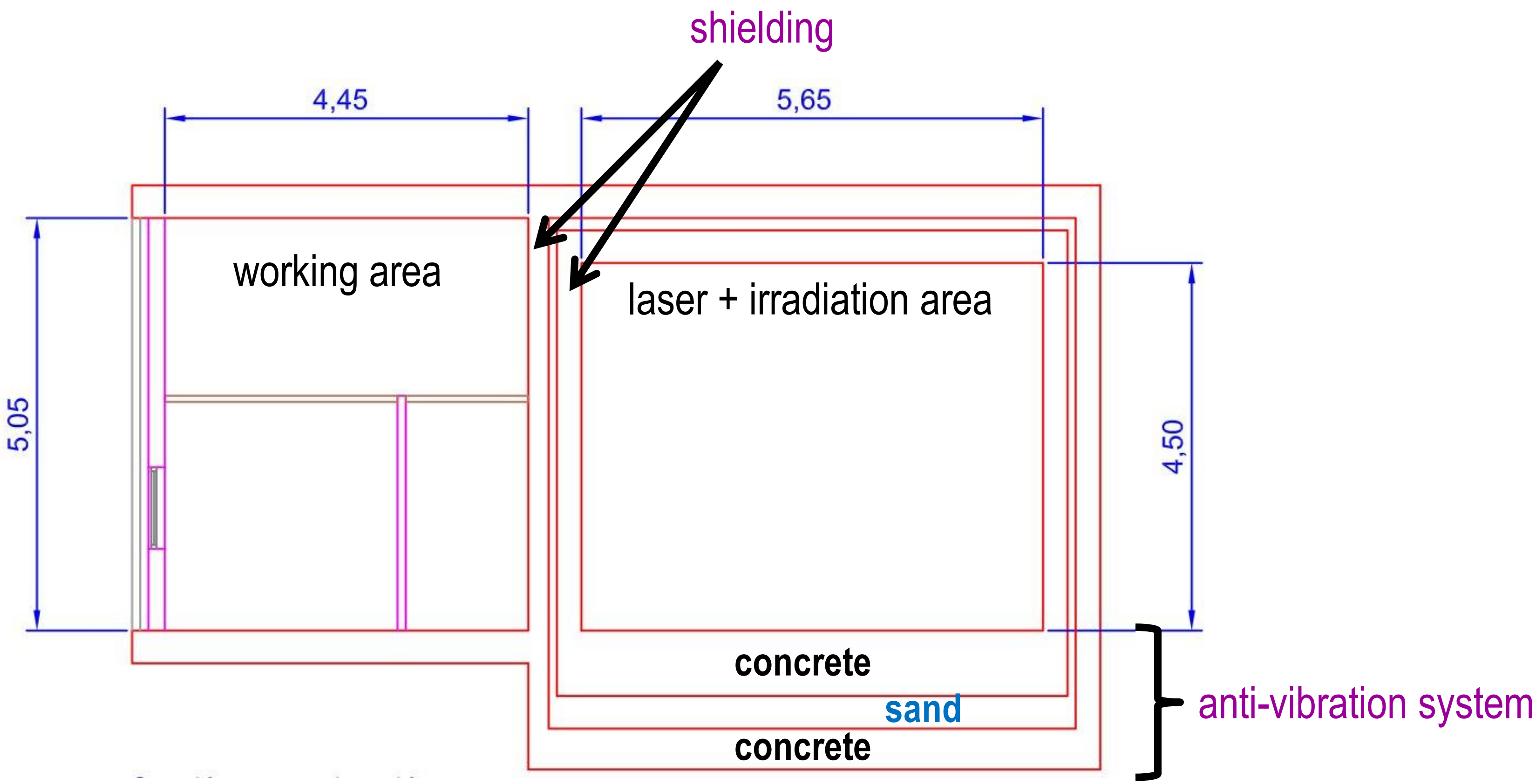
L2A2 facilities: building

- ✓ Laser room
- ✓ Acceleration area
- ✓ Instrumentation and laser labs



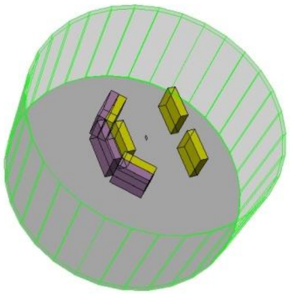
L2A2 facilities: building

Specific design to avoid vibrations in the laser and acceleration areas providing some shielding



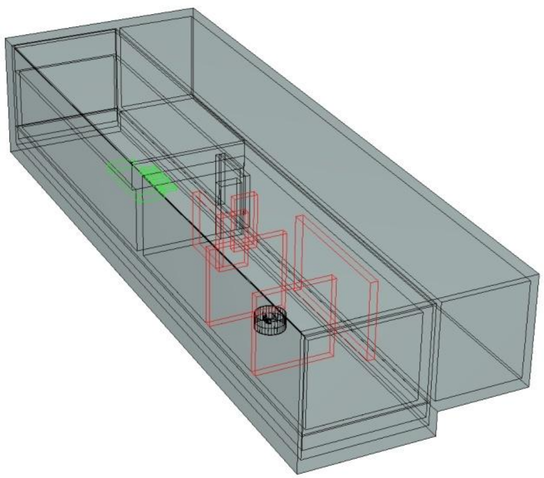
L2A2 facilities: radiation shielding

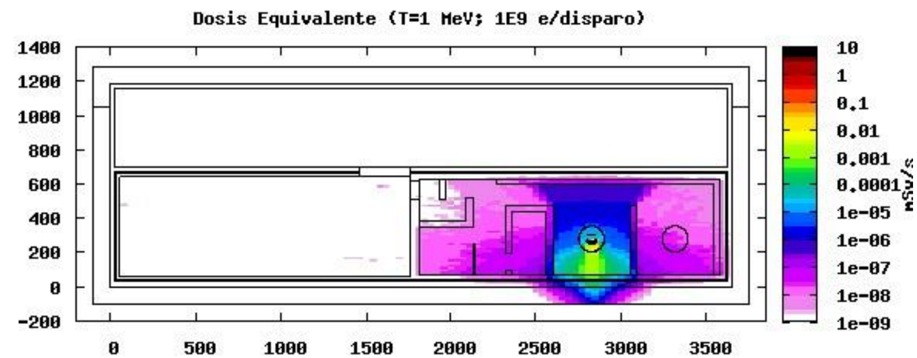
Multi-barrier system



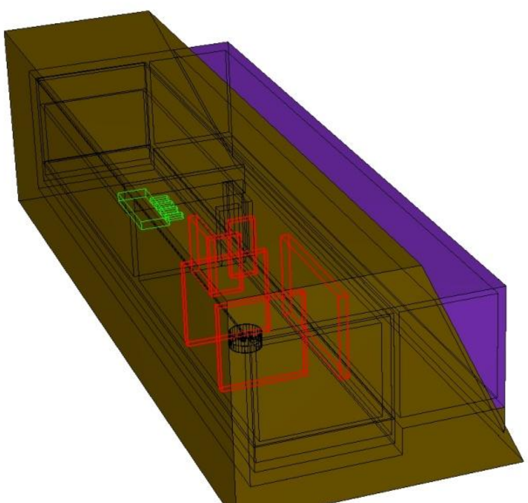
Close-to-target shielding

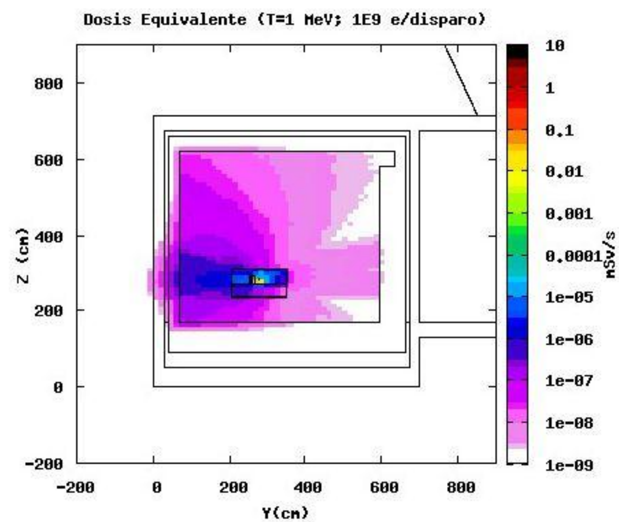
The three shielding barriers guarantees a radiation level below the natural one in the accessible areas





Mobile walls made of concrete blocks





Underground laboratory

L2A2 facilities: time schedule

	2013				2014				2015				2016			
	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4
Conceptual design	■	■														
Technical design			■	■	■											
Laser construction						■	■	■	■	■						
Building construction						■	■	■								
Experiment constru.						■	■	■	■	■	■					
Laser commissioning											■	■				
First experiments													■	■	■	■

L2A2 facilities: possible upgrades

Joule beam line:

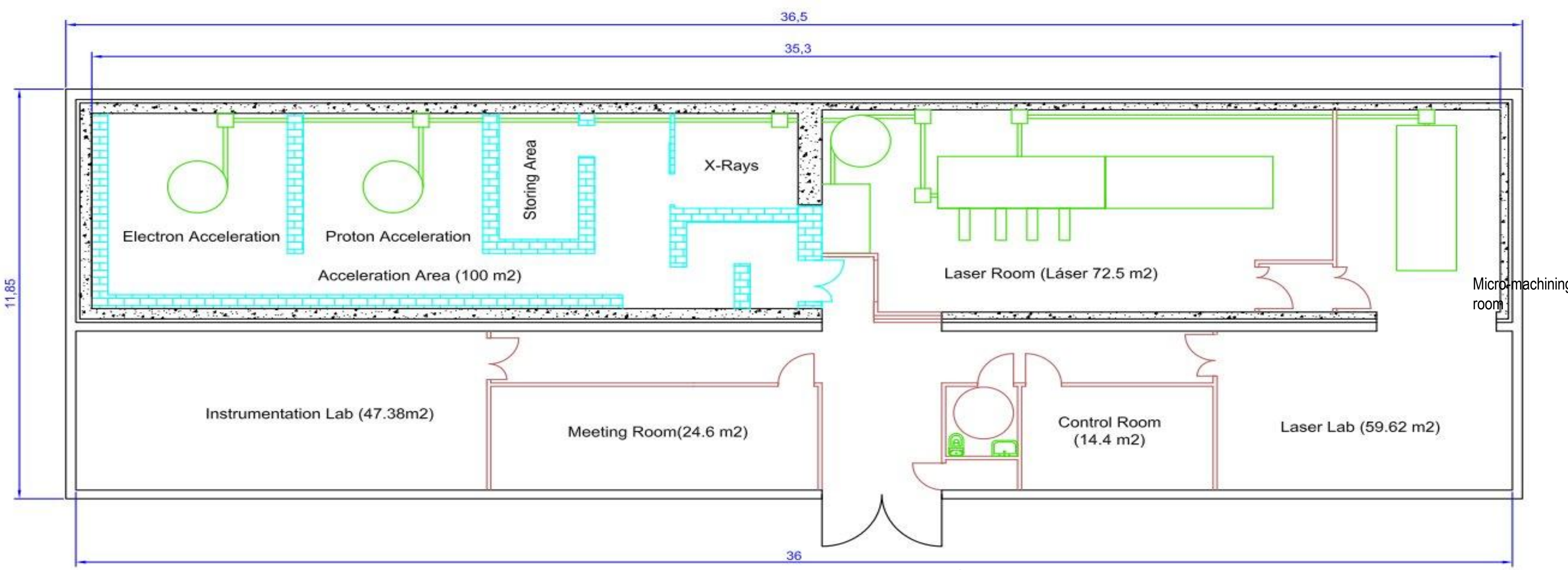
- ✓ Higher pulse energy: 1.2 J → 3 J @ 10 Hz
- ✓ Higher pulse rate: 10 Hz → 100 Hz

Milli-Joule beam line:

- ✓ Higher pulse energy; 1 mJ → 5 mJ @ 1 kHz
- ✓ Improved contrast

Additional acceleration stations:

- ✓ Gaseous targets for electrons



Research program

Low-energy proton acceleration

- ion acceleration processes
- production of medical-imaging radioisotopes

X-ray production:

- λ^3 acceleration regime
- incoherent X-ray source

mJ ultra-short laser pulses applications:

- micromachining
- surface texturing
- microfluidics
- .....

Medical-imaging radionuclides

The use of radionuclides in physical and biological scienc
can be broken down into three general categories:

-Radiotracers

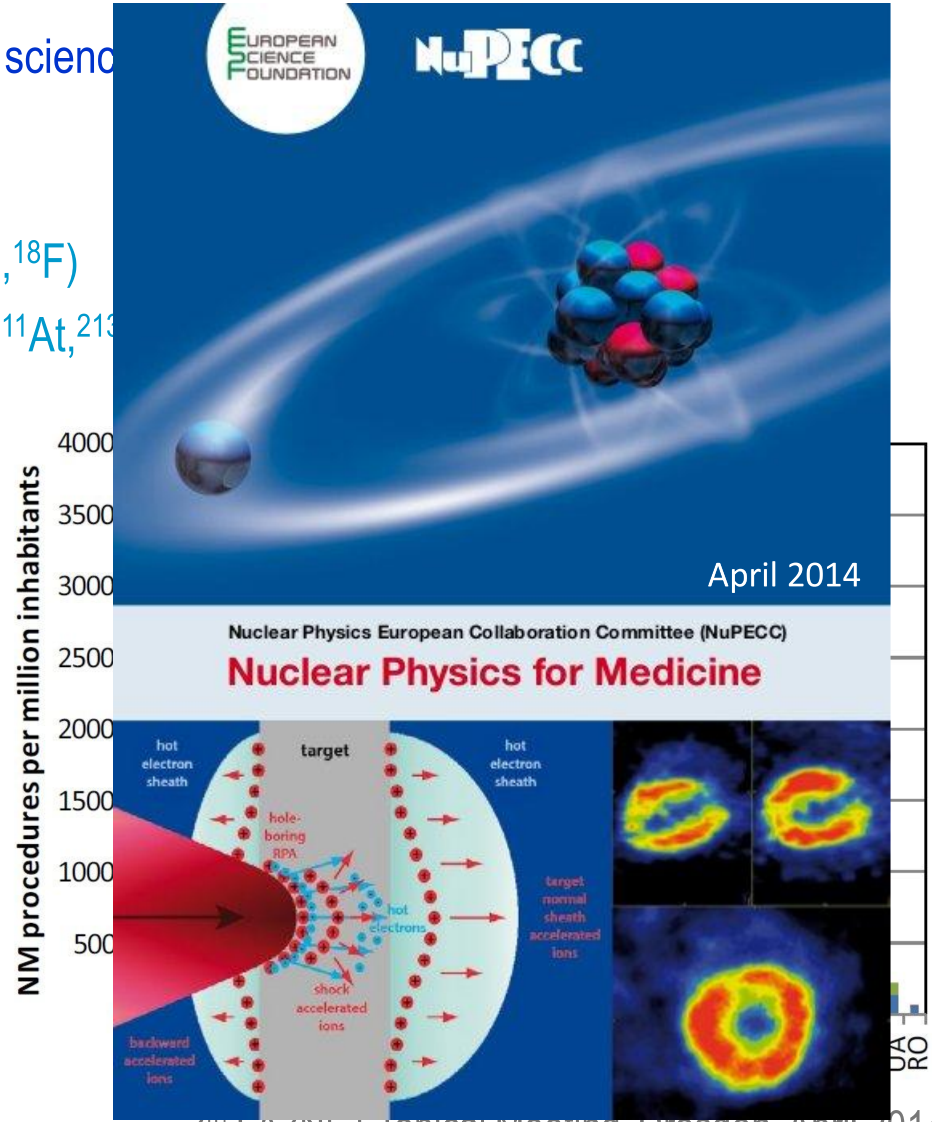
-Imaging: SPECT(^{99m}Tc,^{201}Tl,^{123}I), PET(^{11}C,^{13}N,^{15}O,^{18}F)

-Therapy: brachytherapy(^{103}Pd), targeted therapy(^{211}At,^{213}

Radionuclides world-wide demand is increasing exponentially

Radionuclides can be produced by:

- Nuclear reactors
- Particle accelerators
- Lasers may come into the game

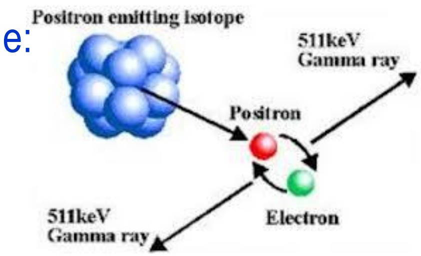


Medical-imaging radionuclides

Positron-emission tomography is considered the most accurate 3D imaging technique:

-Positrons emitted by specific β^+ radionuclides annihilate producing two photons

-The back-to-back emission of pairs of photons from a given volume made it possible its reconstruction using appropriate image reconstruction algorithms

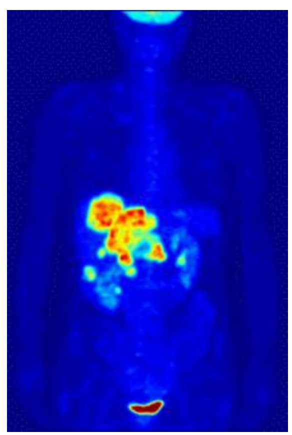


The production of β^+ radionuclides requires an accelerator with a complex infrastructure :

-The production strategy is based on a regional production center and distribution.

-Short-lived emitters can only be used close to the production center

Radionuclide	Half-live	reaction	E_{min} (MeV)	E_{beam} (MeV)
^{11}C	20.3 min.	$^{14}N(p,\alpha)$ $^{11}B(p,n)$ $^{10}B(d,n)$	3.13 3.02 0	11-19 10 10
^{13}N	9.97 min.	$^{16}O(p,\alpha)$ $^{13}C(p,n)$	5.55 3.23	19 11
^{15}O	2.03 min.	$^{15}N(p,n)$ $^{14}N(d,2n)$ $^{16}O(p,pn)$	3.77 0 14.28	11 6 >26
^{18}F	110 min.	$^{18}O(p,n)$ $^{20}Ne(d,\alpha)$	2.57 0	11-17 8-14
^{64}Cu	12.7 h	$^{64}Ni(p,n)$ $^{68}Zn(p,\alpha n)$ $^{nat}Zn(d,\alpha xn)$	2.49 8.65 9.31	15 30 19
^{124}I	4.14 d	$^{124}Te(p,n)$ $^{125}Te(d,2n)$	3.97	13 25



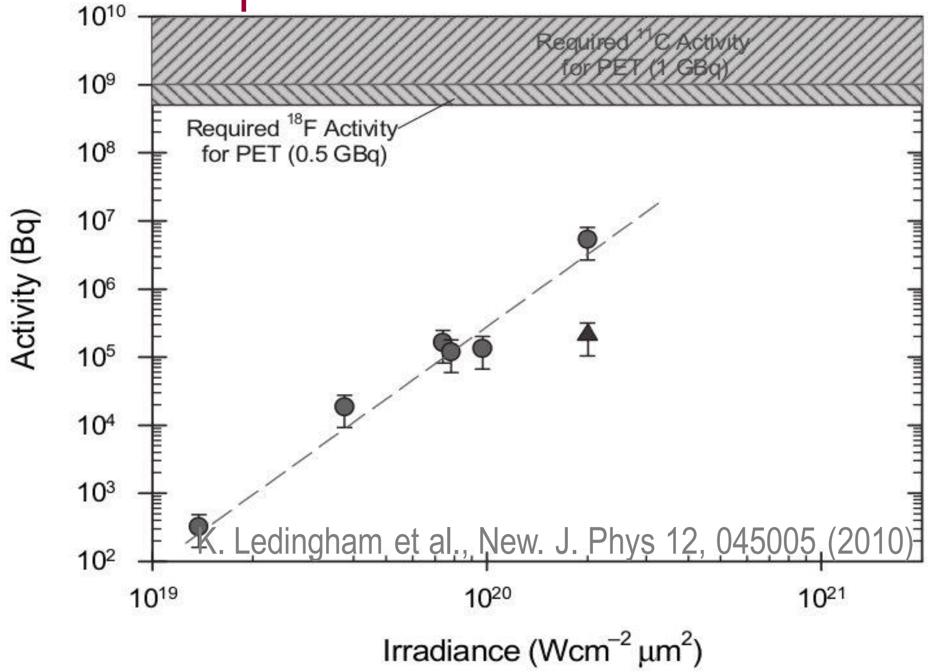
Medical-imaging radionuclides

$^{11}C/^{18}F$ production with laser-accelerated protons

- 120 J, ~1 ps (10^{20} W/cm^2), CR ~10^6
  ^{11}C activity/shot ~ 200 kBq
  I. Spencer et al., NIMB 183, 449 (2001)

- 20-30 J, 0.3 – 0.8 ps (1-6 10^{19} W/cm^2), CR <10^6
  ^{11}C activity/shot ~ 1 MBq
  J. Fuchs et al., PRL 94, 045004 (2005)

- 0.8 J, 40 fs (6 10^{19} W/cm^2), CR <10^6
  ^{11}C activity/shot ~ 1.2 kBq
  S. Fritzler et al., App. Phys. Lett. 83, 3039 (2003)

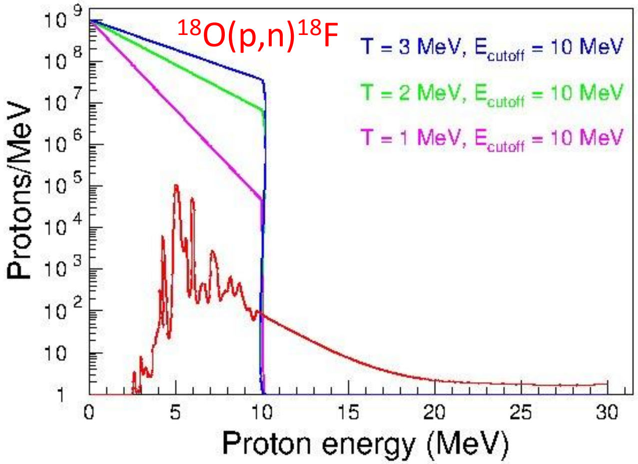


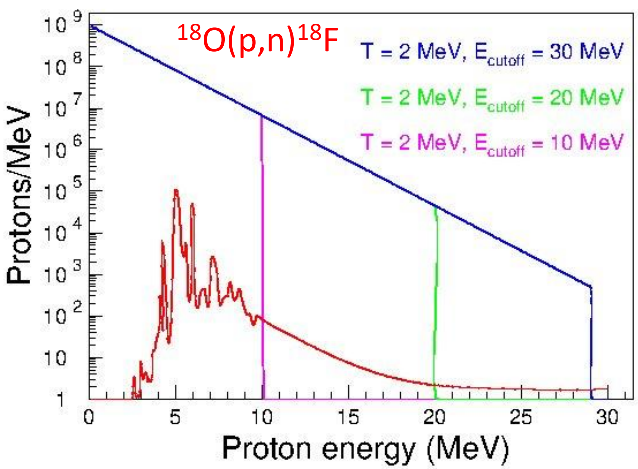
Present laser technologies are limited by the pulse repetition rate for clinical applications but

- acceleration targets could be optimized (i.e. multi-shot targets)
- pre-clinical doses could be produced
- alternative reactions may be used e.g. $^{10}Be(d,n)^{11}C$
- clinical doses are being reduced and laser systems at 100 Hz are not too far

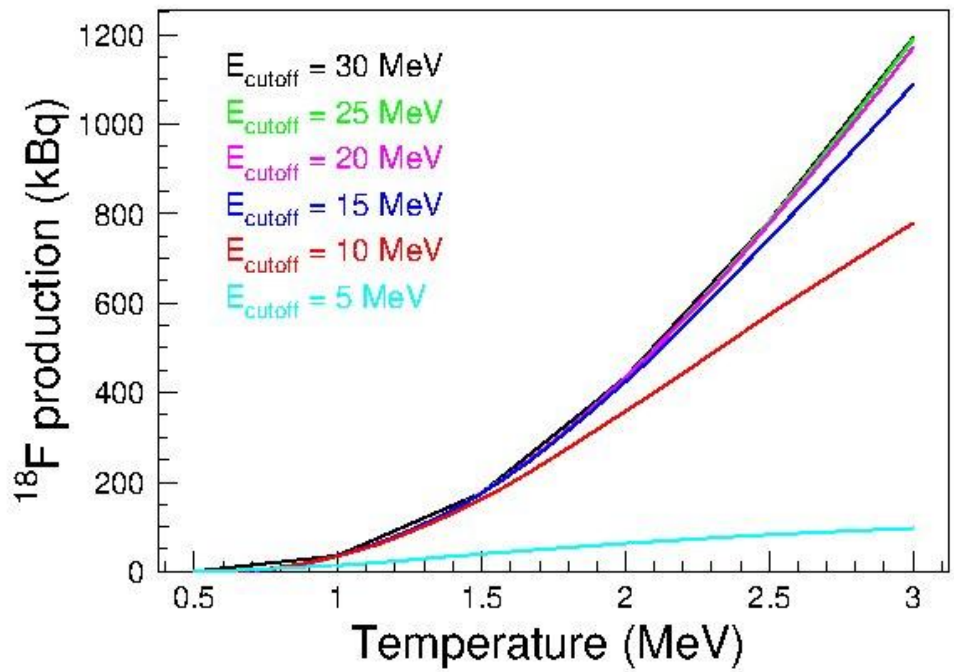
Medical-imaging radionuclides

Radioisotope production with laser





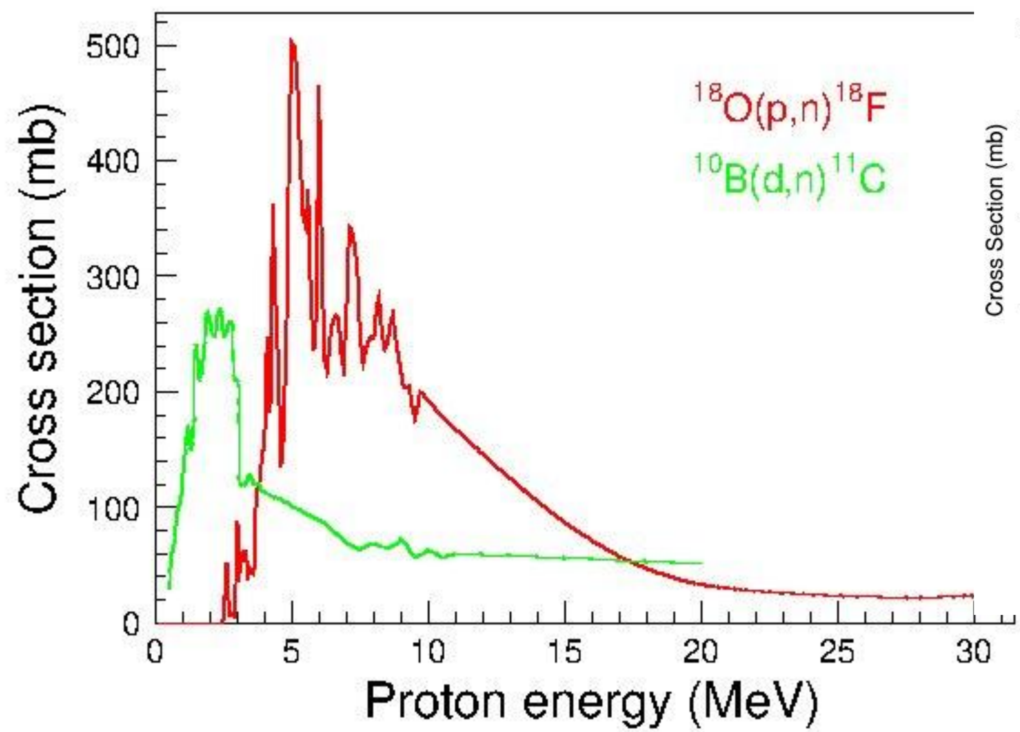
Optimum proton energy spectrum

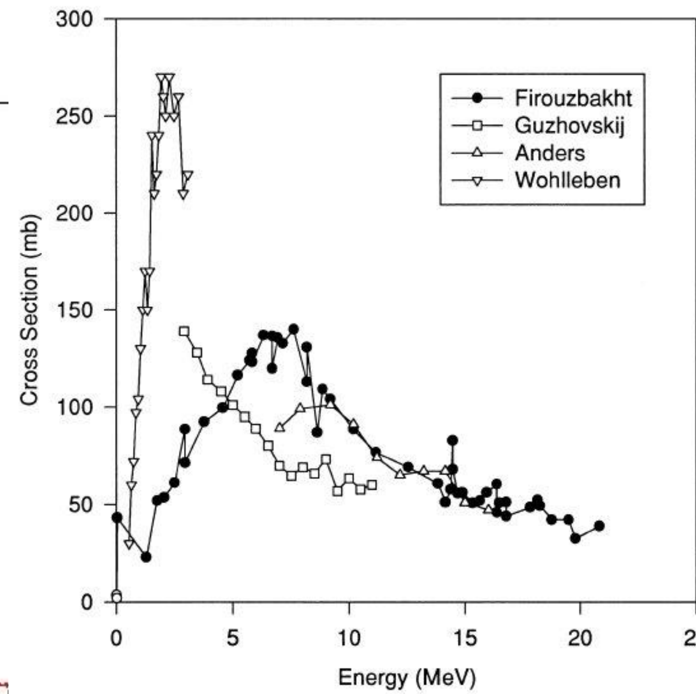


- The production depends strongly on the temperature for cutoff energies well above the reaction threshold
- Protons with energies above the maximum production cross sections do not contribute much

Medical-imaging radionuclides

Production cross sections





The energy dependence of the production cross sections defines the minimum energy for the beam particles

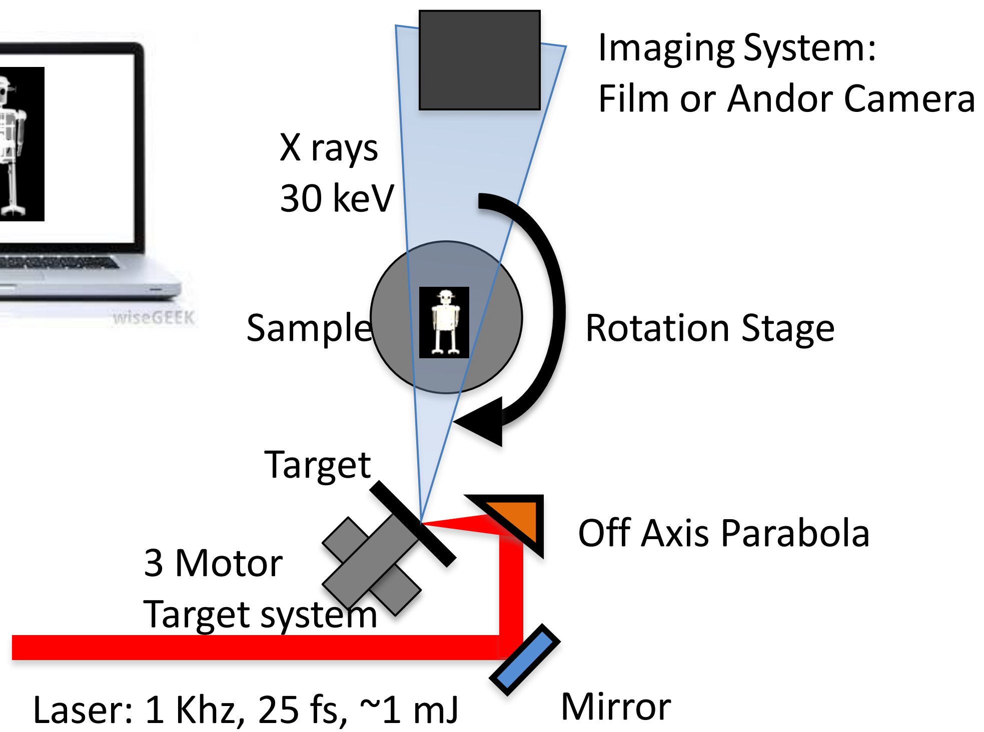
In some cases the cross sections are not sufficiently well known

λ3 incoherent X-ray production for imaging

A Khz X-ray source for imaging based on the λ^3 regime

- ✓ Laser parameters: ~ 1 mJ, 25 fs, 1Khz.
- ✓ Expected X-ray source: 10-20 KeV Temp, 1 μm source size, low divergence.

Proposed application: X ray tomography and/or phase contrast imaging.



Applications with mJ ultra-short laser pulses

- **Surface texturing:** Several industrial applications can benefit from engineered solid-fluid interface behaviour, including drag reduction, anti-ice surfaces or cavitation control.

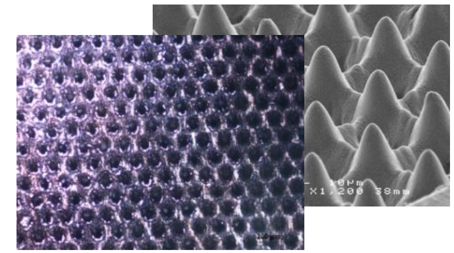
- **Photovoltaics:** Laser processing of thin films for photovoltaics applications.

- **Biomedical devices:** material properties remain the same as before processing (stents).

- **Photonic devices:** manufacture of optical waveguides for photonic integrated circuits and other telecommunications devices.

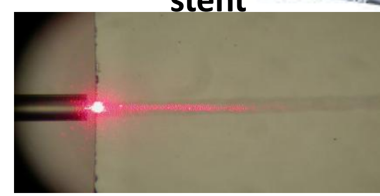
- **Microfluidics:** Fentosecons pulse can generate clean and precise channels on transparent materials

- **Displays (touch screens):** Fentosecond laser can generate accurate tracks increasing the resolution. Laser-based selective elimination of thin films (ITO).

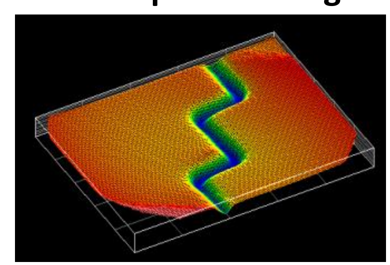


Surface texturing

stent



Optical waveguide

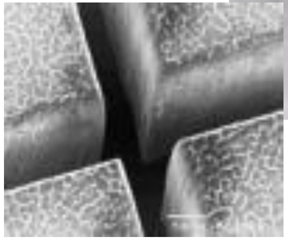


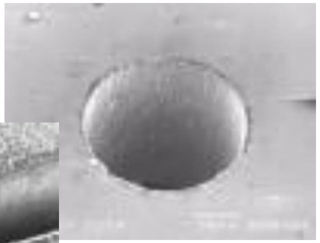
microfluidics

Applications with mJ ultra-short laser pulses

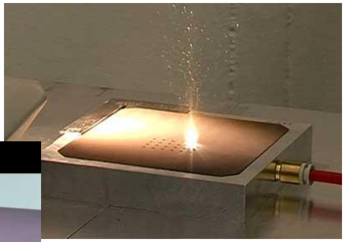
- **Micromachining:** Laser processing: marking, cutting and scribing of wide ban gap materials to create new arquitectures easy to fabricate. Drilling diesel injector nozzles or other mechanisms applied to machining high precision. Micro-optical machining of micro-lenses or diffractive optical elements in materials with high quality surface finish.
- **Microelectronics**: miniaturization of components, laser structuring of conducting films on transparent substrates for electronics devices.
- **Joining dissimilar materials** for obtaining cost-effective materials and to improve the resistance to mechanical and thermal stress. Wide ban gap materials joined to metal or other host surfaces .
- **Nanoparticles generation** In vacuum, generation of nanoparticle aerosols and colloids from solid targets, Laser printing.
- **Fundamental research** on short pulse laser-material-ambient interactions.
- **High harmonic generation.** High stabilized harmonic generation, hard X-ray radiation from laser-produced plasma, soft X-ray radiation.

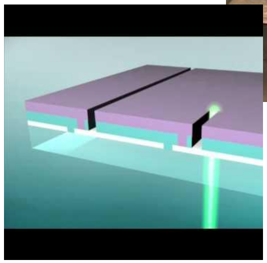
Cutting





Drilling





Summary

✓ A new facility for plasma-laser particle acceleration and other applications of ultra-short laser pulses is under construction at USC.

✓ The facility is based on a Ti:Sa compact laser with two beam lines:

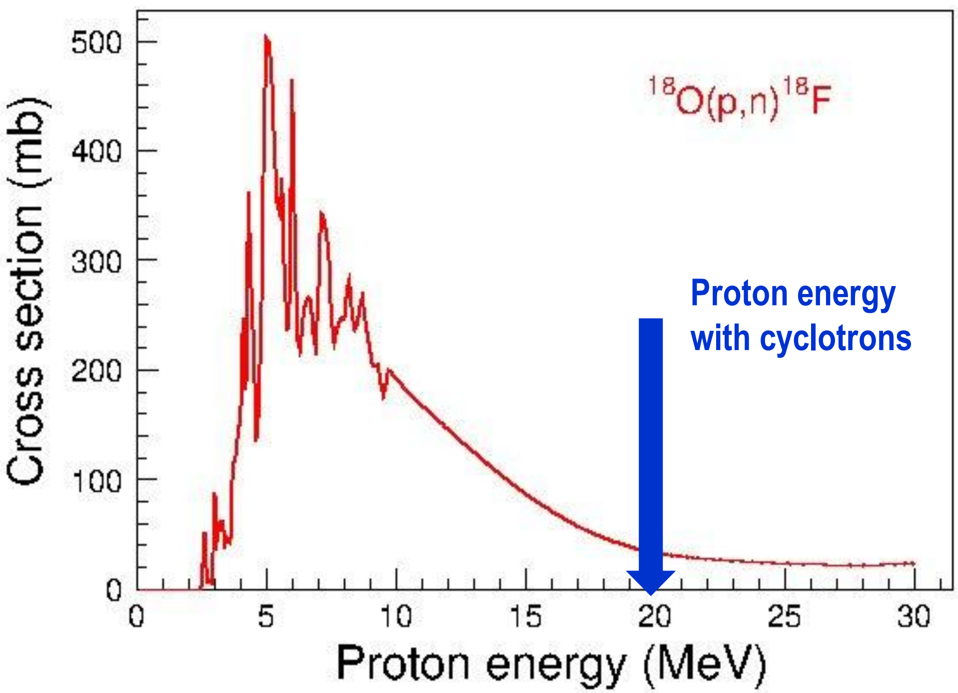
- 1 mJ, 1 kHz, 25 – 100 fs and 10^{-6} ASE contrast ratio
- 1 J, 10 Hz, 25 – 100 fs and 10^{-10} ASE contrast ratio

✓ The main lines of the research program are:

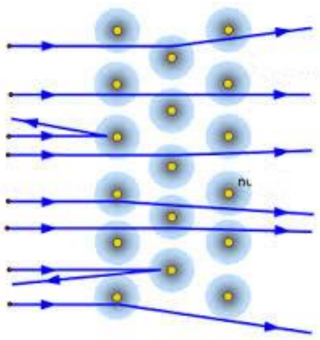
- proton acceleration: radionuclide production for medical imaging
- incoherent X-ray production for tomography
- other applications of femtoseconds laser pulses: micromachining, surface texturing, …..

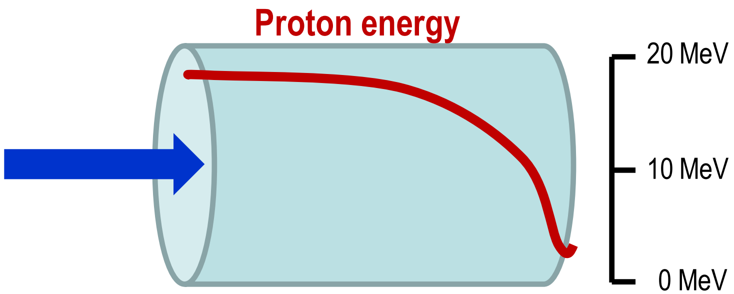
Medical-imaging radionuclides

Radioisotope production with cyclotrons



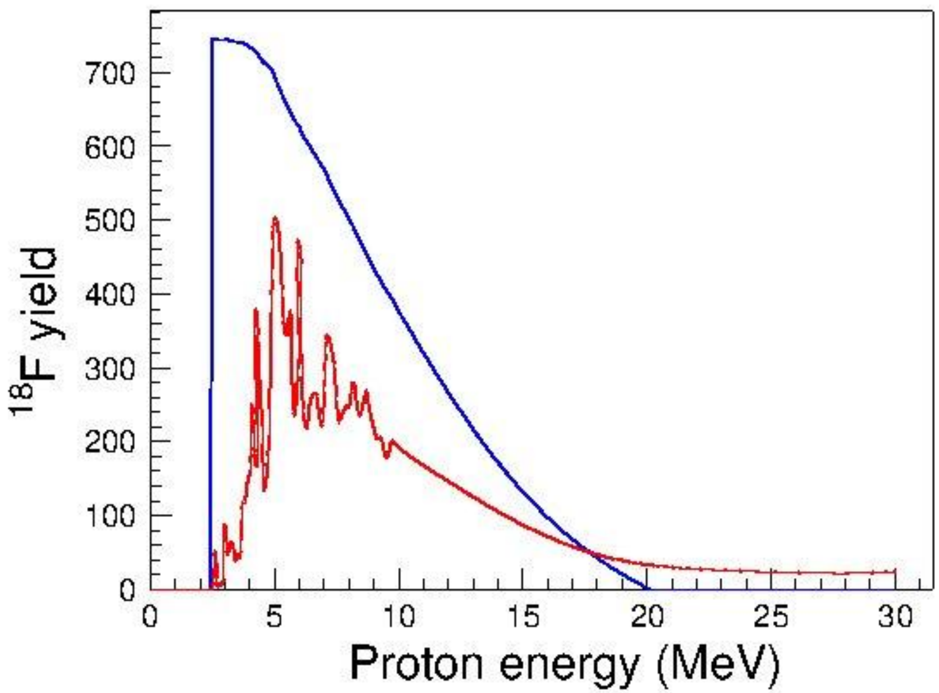
Nuclear and electromagnetic excitations



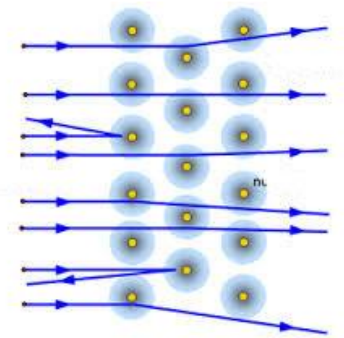


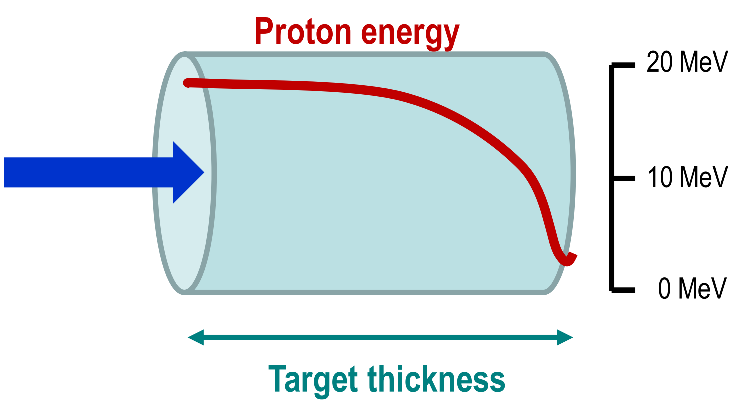
$$\frac{dE}{dx} \propto k_1 \frac{z^2 Z_{tar} \rho_{tar}}{v^2} \ln(k_2 v^2)$$

Radioisotope production with cyclotrons



Nuclear and electromagnetic excitations

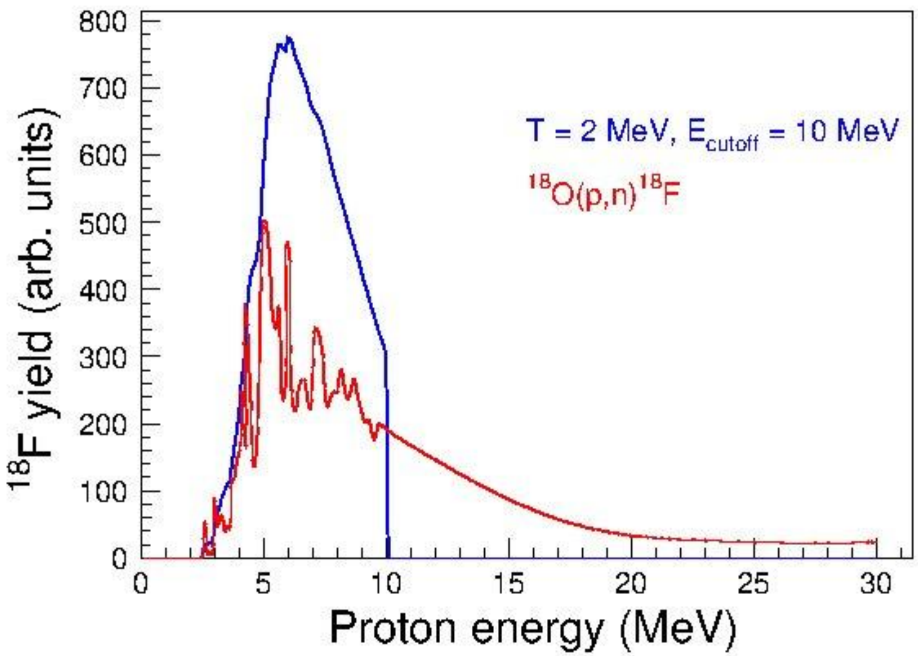




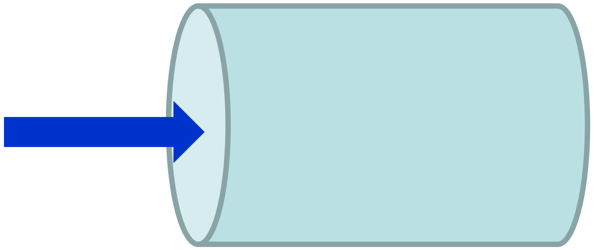
$$\frac{dE}{dx} \propto k_1 \frac{z^2 Z_{tar} \rho_{tar}}{v^2} \ln(k_2 v^2)$$

Medical-imaging radionuclides

Radioisotope production with laser



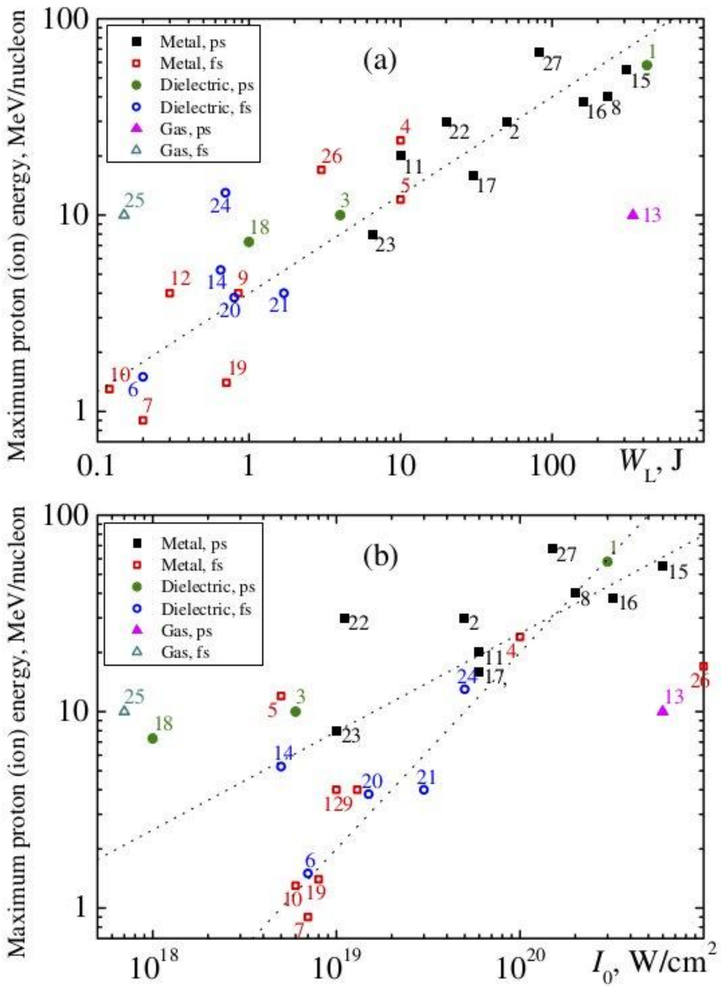
$$N^{18O} = N^{proy.} N^{tar.} \sigma$$



The final radioisotope production will depend on the number of protons produced by laser shot, but also on the shape of the energy spectrum of these protons.

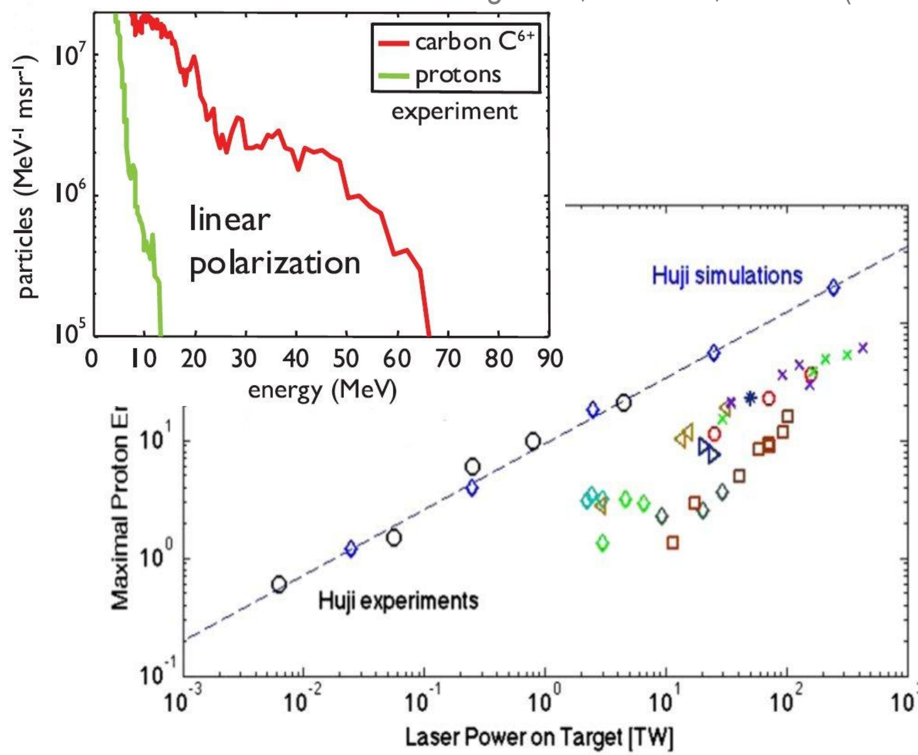
Conditions for the laser-based radioisotope production

Maximum proton energy



H. Daido et al., Rep. Prog. Phys. 75, 056401 (2012)

A. Henig et al., PRL 103, 245003 (2009)

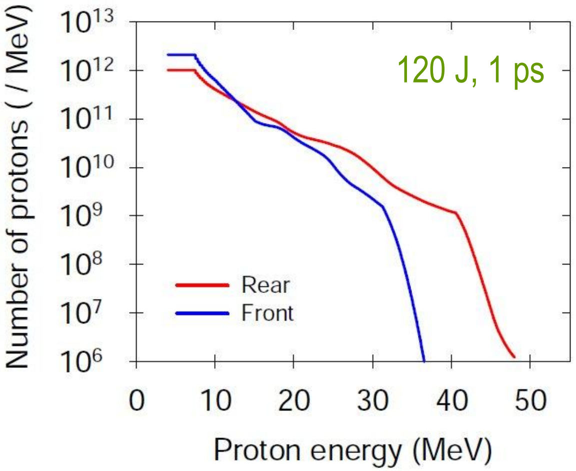


A. Ziegler et al., PRL 110, 215004 (2013)

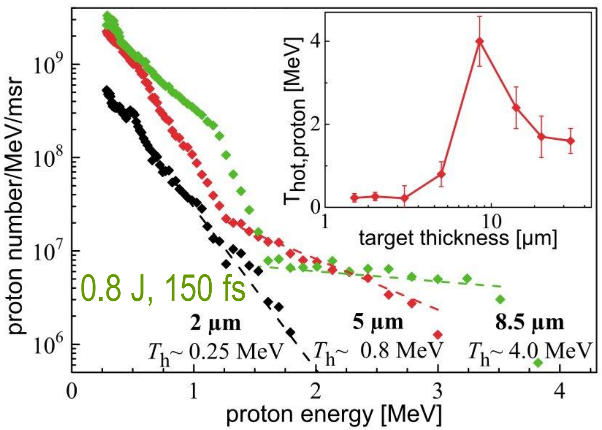
The maximum proton energy scales with the energy/intensity of the laser pulse. However, improved contrast ratio or specific target designs also contribute to produce higher energies

Conditions for the laser-based radioisotope production

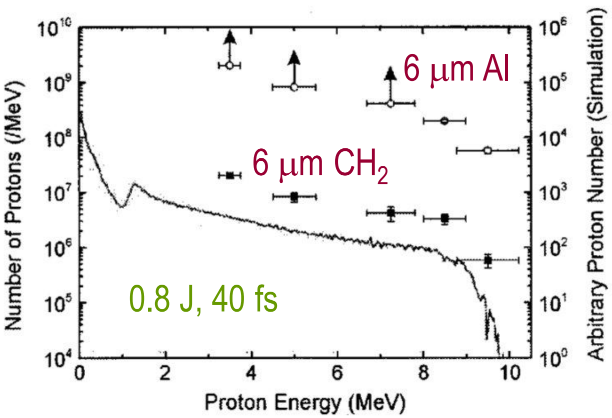
Proton energy spectrum



I. Spencer et al., NIMB 183, 449 (2001)



M. Kaluza et al., PRL 93, 045003 (2013)



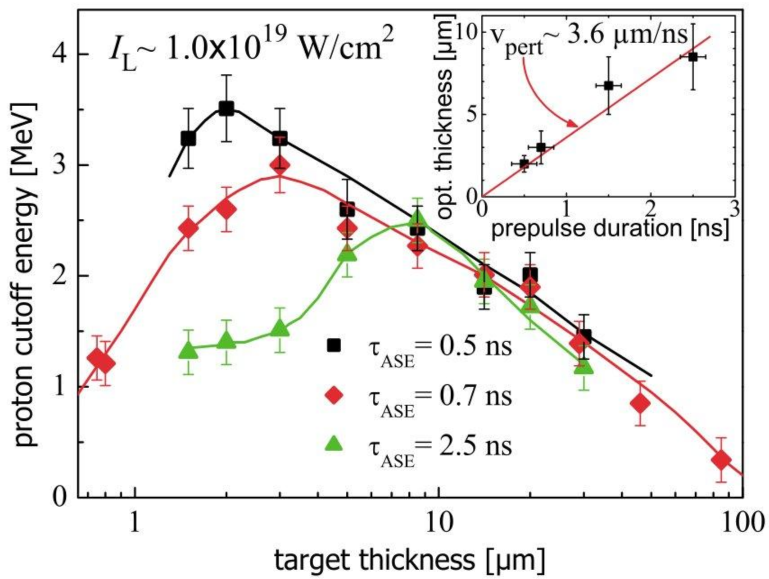
S. Fritzler et al., APL 83, 3030 (2003)

The shape (temperature) of the energy spectrum seems to be affected by the pre-pulse plasma heating.

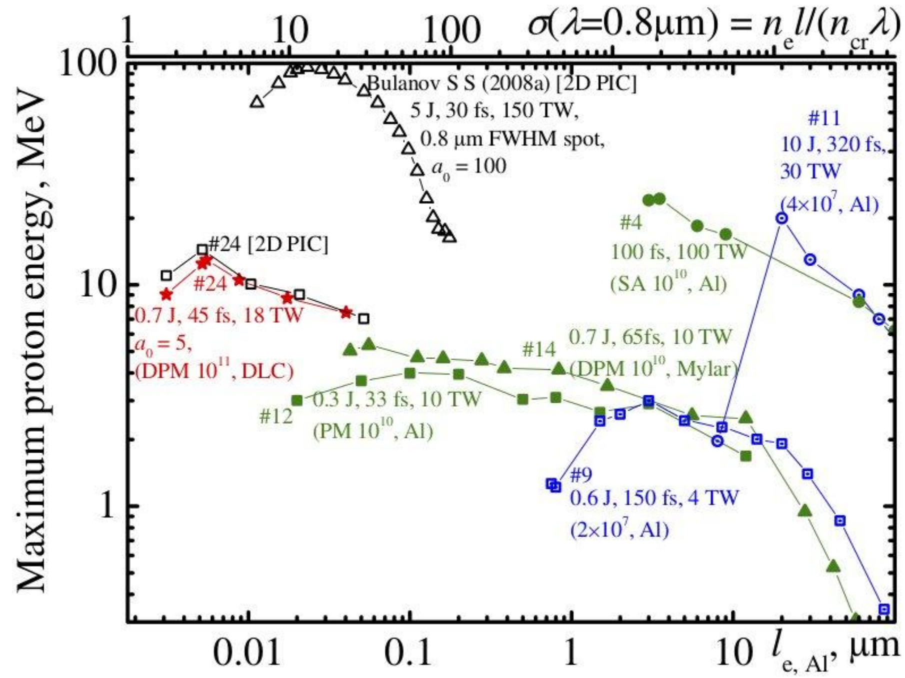
In general, rear-surface acceleration shows larger temperature and energy cutoff values.

Conditions for the laser-based radioisotope production

Target thickness



M. Kaluza et al., PRL 93, 045003 (2013)



H. Daido et al., Rep. Prog. Phys. 75, 056401 (2012)

The laser pre-pulse (contrast ratio) defines two regimes for the optimum target thickness:

-normal contrast (~10^8): optimum thickness around tens µm

-high contract (~10^{10}): optimum thickness around tens of nm