A high repetition laser-plasma proton accelerator for medical radioisotope production

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INTERNATIONAL CONFERENCE ON MEDICAL ACCELERATORS AND PARTICLE THERAPY

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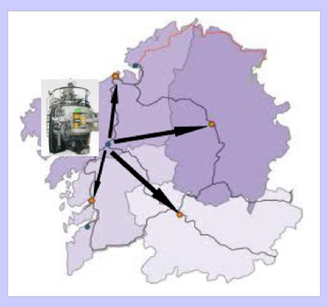
Motivation

POSITRON EMISSION TOMOGRAPHY (PET) IMAGING.

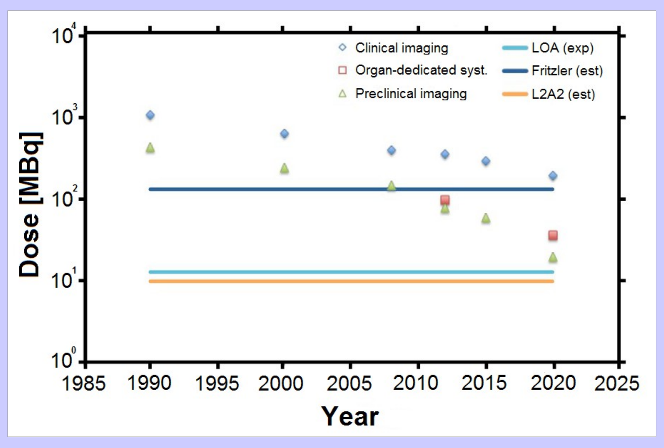
- Detection of 511 keV gamma-rays from the annihilation of positrons produced by short-lived β^+ radioisotopes.
- Most accurate 3D technique in medical diagnosis.
- Over 2M treatments/year and an increase of about 7% each year.



WHY LASER-INDUCED PRODUCTION OVER CONVENTIONAL ACCELERATOR PRODUCTION?

- Cheaper and more compact.
- Localized production over general production.
- Radioisotopes with shorter half-lifes.

Radioisotope	Half life
^{11}C	~20 min
^{13}N	~10 min
^{15}O	~2 min
^{18}F	~110 min

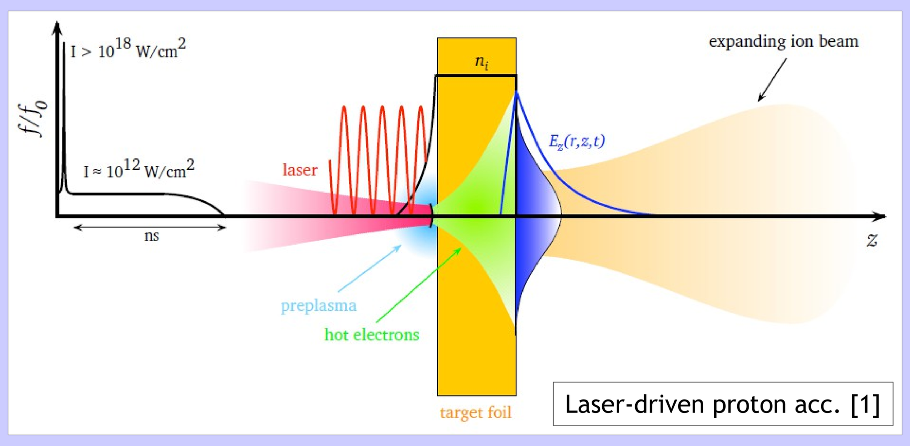


Proton/Ion acceleration

LASER-DRIVEN PROTON ACCELERATION.

Multiple mechanisms involved that scale with laser intensity:

- Plasma generation on target surface due to ASE/prepulses.
- Laser-plasma interaction → Generation of electron bunch (~MeV).
- *Target Normal Sheath Acceleration* (TNSA) → Generation of a proton/ion beam (~MeV, ~ps).



ISOTHERMAL PLASMA EXPANSION MODEL [2,3].

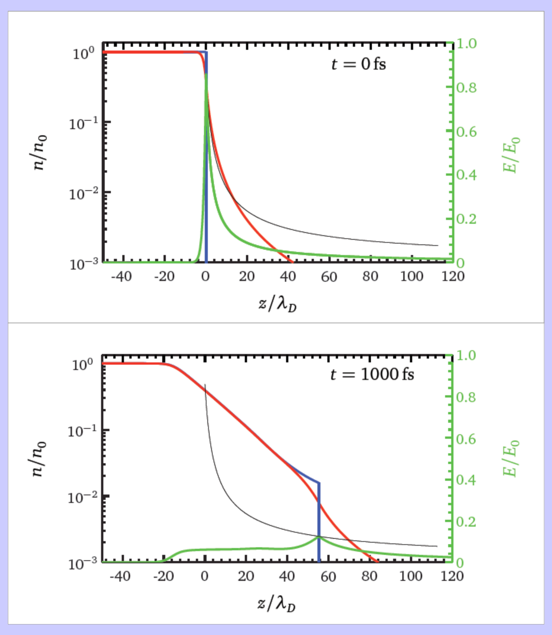
- Electron cloud at rear side with constant temperature T_e.
- Analytical description of the electric field (~TV/m) and the particle distributions.
- Acceleration time limited to fs - ps.

$$\frac{dN}{dE} = \frac{N_0}{\sqrt{2ZK_BT_eE}}e^{-\sqrt{\frac{2E}{ZK_BT_e}}}$$

$$E_{max} = 2K_BT_e\ln^2\left(\tau+\sqrt{1+\tau^2}\right)$$

$$N_0 = n_{e0}c_s\tau_{acc}$$

$$\tau = \omega_{pi}\frac{\tau_{acc}}{\sqrt{2e}}$$



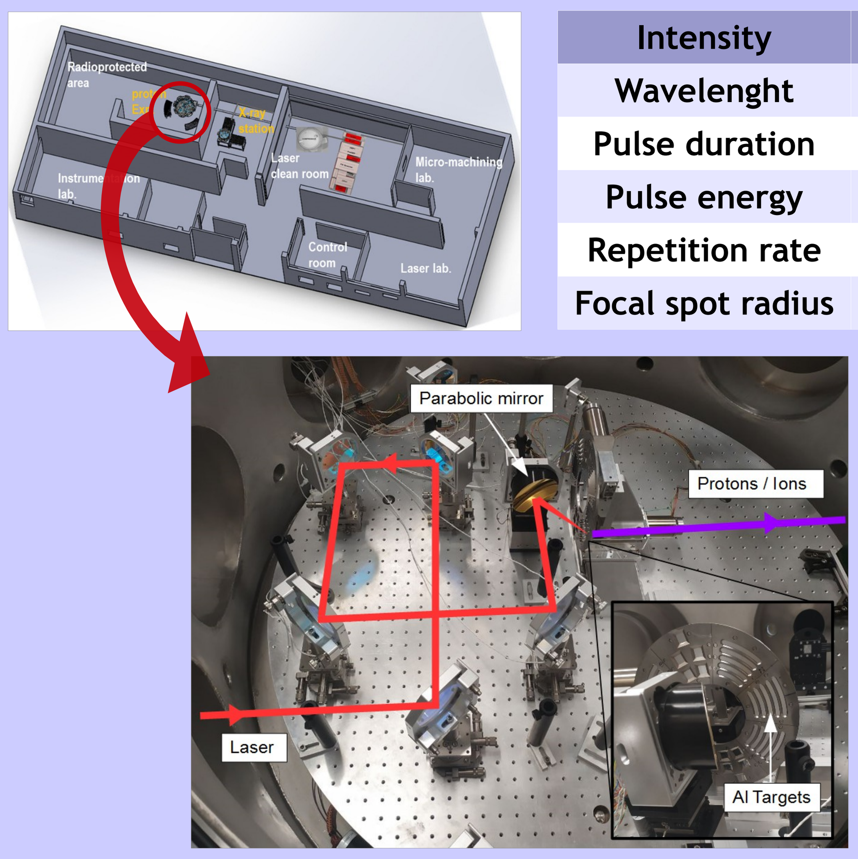
Left: Temporal evolution of the electric field (green) and the ion (blue) and electron (red) densities at the rear side of the target [1].

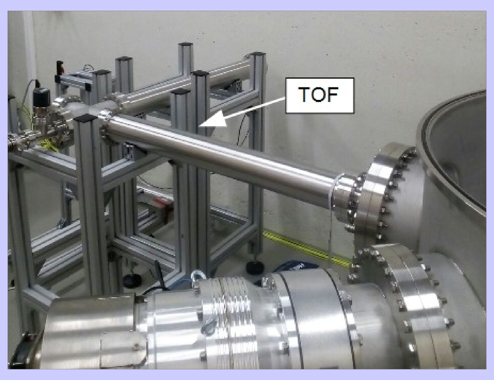
Experimental set-up @ L2A2

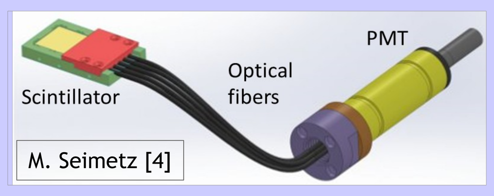
THE LASER LABORATORY FOR ACCELERATION AND APPLICATIONS.

At the L2A2 of the Universidad de Santiago de Compostela, Spain, a high repetition rate femtosecond laser is used for proton acceleration and radioisotope production.

Intensity	~10^{19} W/cm^2
Wavelenght	800 nm
Pulse duration	25 fs
Pulse energy	1.2 J
Repetition rate	10 Hz
Focal spot radius	≥2 µm







DETECTION AND DIAGNOSIS TOOLS.

Advanced radiation detector systems for the precise characterization of the proton/ion beam:

- *Time-of-Flight* (TOF): Beam energy data.
- Thomson parabola: Ion discrimination (p, C$^+$, C^{+2}, etc.).

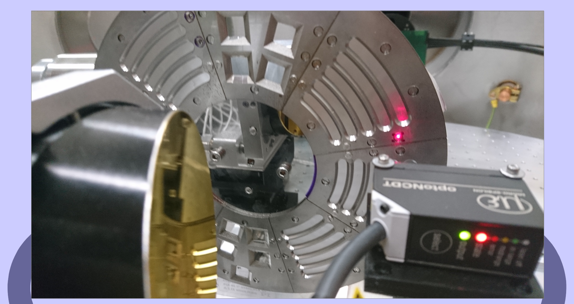
TARGET SYSTEM.

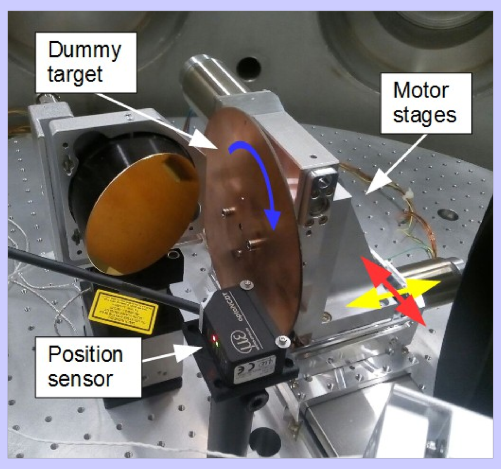
Aluminium and mylar sheets of 2 - 12 µm thickness are placed in a wheel-like holder which allows hundreds to thousands shots in a row at 10 Hz.

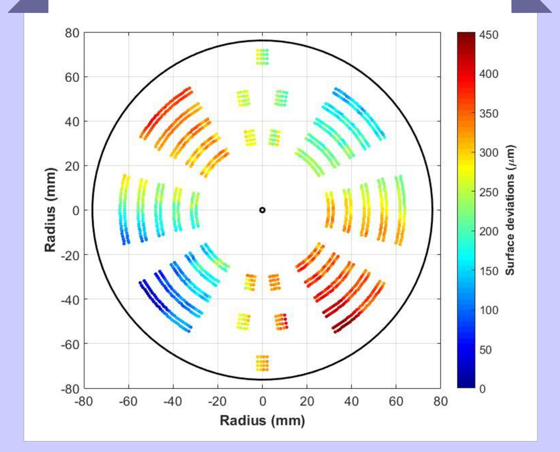
CONTROL AND CORRECTION SYSTEM.

Accurate movement of the target assembly shot-by-shot for the target material refreshment and positioning at the laser focal spot (20 nm, 20 µdeg precision).

Focal correction is done by previously generating a target surface map with a optical laser-position sensor (~1 µm repeatibility). Deviation reduction from hundreds to a few µm.







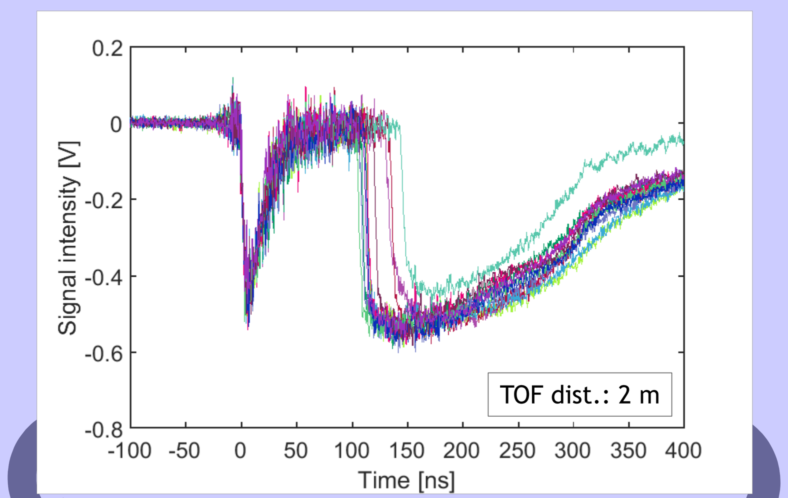
Measurements and results

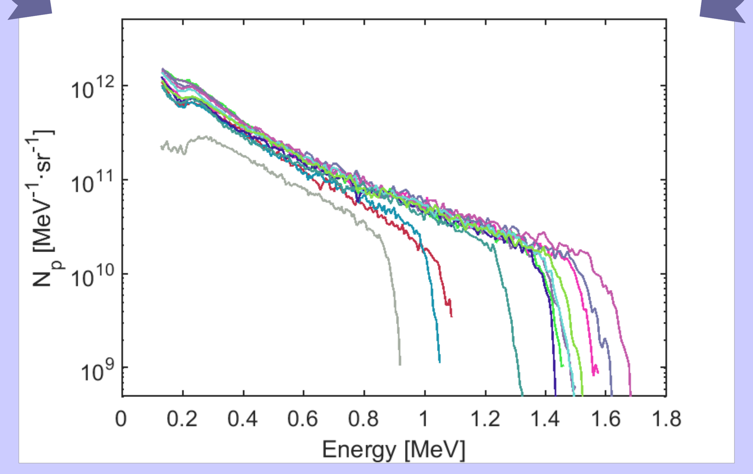
EXPERIMENTAL MAIN RESULTS.

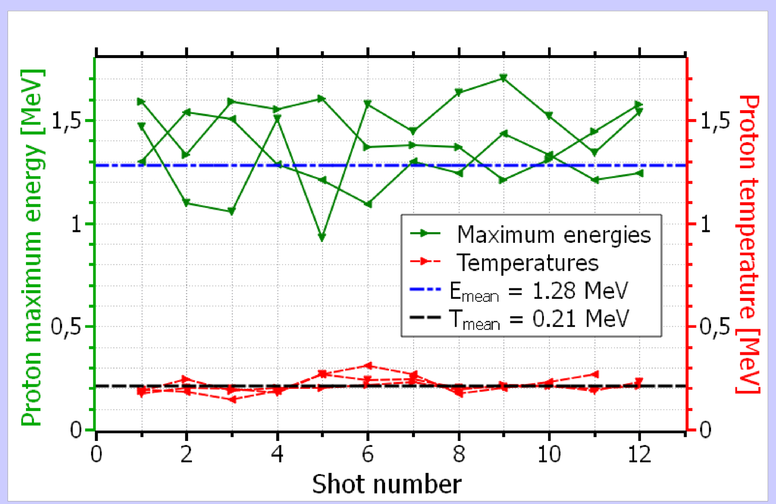
December 2018 and April 2019 campaigns:

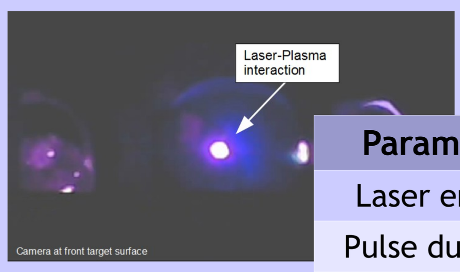
- Multishot operation at 10 Hz.
- High stability (~12%) both in cut-off energy and temperature.
- Proton energies up to 2 MeV.

Proton spectra are reconstructed from TOF signals and compared with calculations given by the isothermal expansion model.



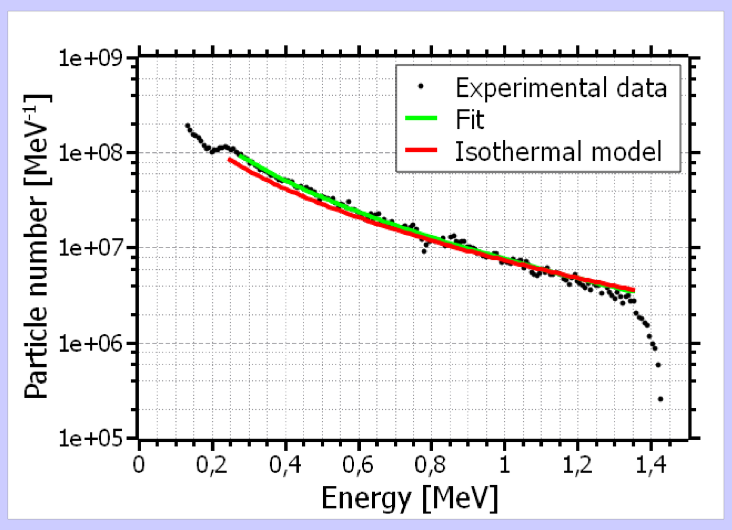






Isothermal expansion model calculation parameters.

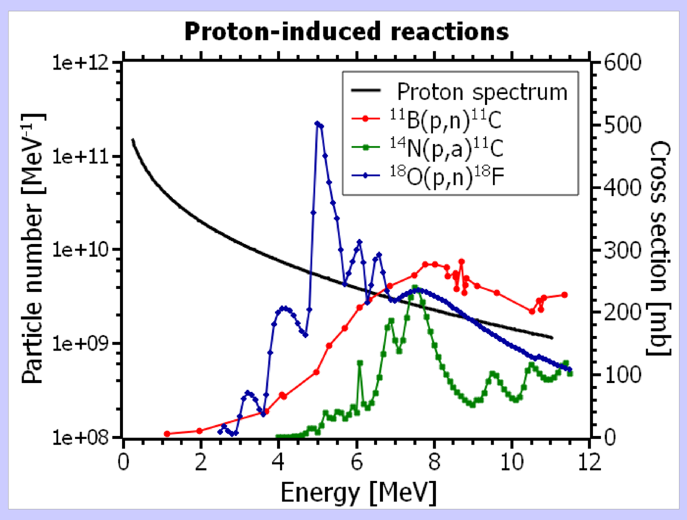
Parameter	Value
Laser energy	1.0 J
Pulse duration	50 fs
Focal spot radius	9.8 µm
Intensity	6.6·10^{18} W/cm^2
Target thickness	12 µm



Production estimates

PROTON ACCELERATION ESTIMATES.

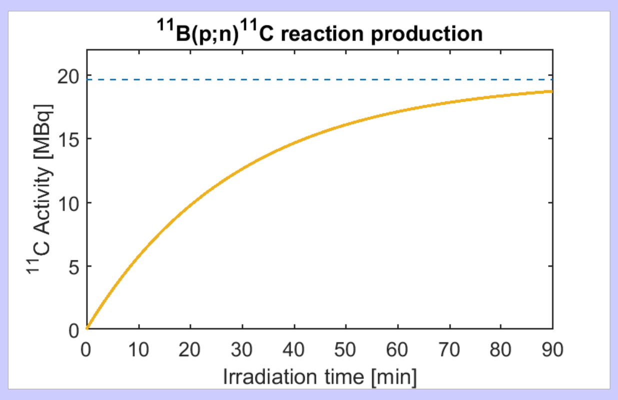
For optimized L2A2 experimental parameters, isothermal expansion model calculation gives a proton spectrum with cut-off energy of 11.03 MeV → Higher than some radioisotope production cross section thresholds!



PET RADIOISOTOPE PRODUCTION ESTIMATES.

Radioisotope activities estimated after 1h of irradiation at 10 Hz:

Producion reaction	Activity [MBq]
^{11}B(p;n)^{11}C	16.33
^{10}B(d;n)^{11}C	5.06
^{14}N(p;α)^{11}C	8.02
^{14}N(d;n)^{15}O	5.04
^{18}O(p;n)^{18}F	3.38



Required doses for PET imaging:

- Preclinical: 10 - 30 MBq. → Almost there!
- Clinical: 200 MBq - Gbq. → Achievable at 100 - 200 Hz.

WHAT'S NEXT?

- Optimization of experimental parameters: target thickness, positioning precision and focal spot radius, to achieve proton energies up to 10 MeV at 10 Hz.
- Stable production of ^{11}C and study its application for preclinical PET imaging.

References

[1] M. Roth, M. Schollmeier, *CERN Yellow Reports* 1, 231 (2016). **[2]** P. Mora, *Phys. Rev. Lett.* 90, 185002 (2003). **[3]** J. Fuchs *et al.*, *Nature Physics* 2, 48-54 (2006). **[4]** M.Seimetz *et al.*, *IEEE Trans. Nuc. Sci.* 62, 6 (2015).

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