Fundamental research and applications with the EuPRAXIA facility at LNF, Frascati, 4-6 December 2024

Radiation from laser target interaction

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Outline

- Brief introduction to **laser-target interaction** (solid target) for particle and radiation production
- **Baseline mechanism**: target normal sheath acceleration (TNSA)
- Some recent result of interests for fundamental physics applications

  Overlaps with P. Tomassini talk, tomorrow at this workshop
- Remarks on existing and possible facilities at (LNF-)INFN

Laser matter interaction

- **Ionization:** from intensities order 10^{13} W/cm^2 the interaction between electromagnetic waves and matter is no longer resonant excitation of atomic states, but any material is readily ionized

- **Plasma oscillation**: after formation, plasma can further interact with a driving pulse providing intense electromagnetic fields

Laser-plasma coupling regimes

$$n_c = \frac{\pi\, m_e c^2}{e\, \lambda^2}$$

λ = 800 nm

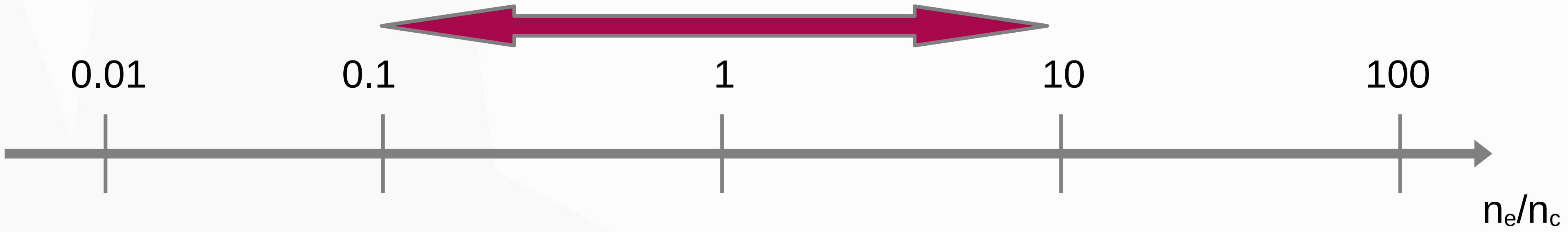
n_c = mg/cm^3

maximum density that a plasma should have in order to allow the propagation of an electromagnetic wave of a given wavelength

$n_e \ll n_c$ underdense plasma

$n_e \approx n_c$ near critical plasma
strong laser-plasma coupling

$n_e \gg n_c$ overdense plasma



GAS

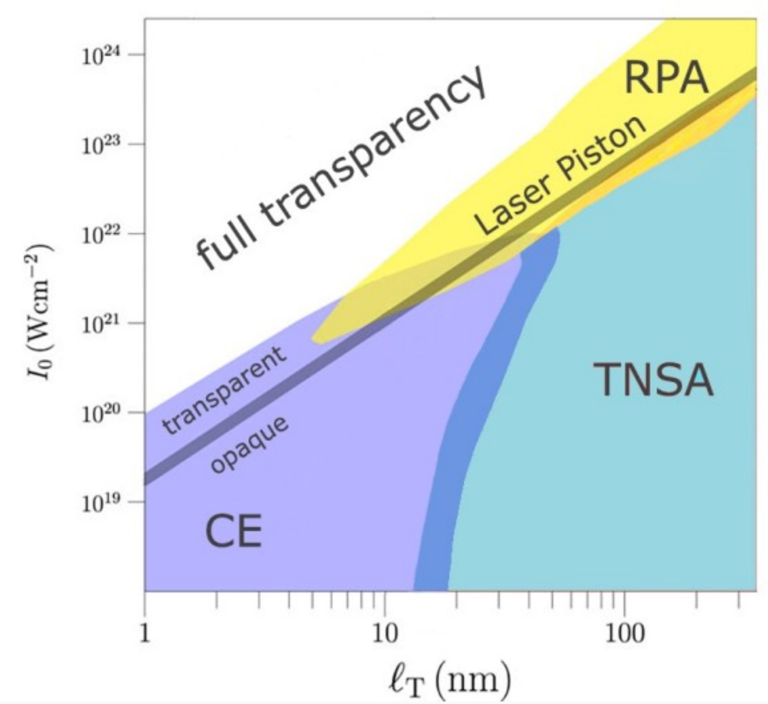
NEAR CRITICAL MATERIALS

- Very dense gas/criogenic jets
- Carbon nanotubes foams
- Carbon nanoparticle foams

SOLIDS

Laser-solid target interaction

Laser intensity and target thickness/manufacturing are key parameters



Plot from Tanaka et al., “Current status and highlights of the ELI-NP research program”, https://doi.org/10.1063/1.5093535

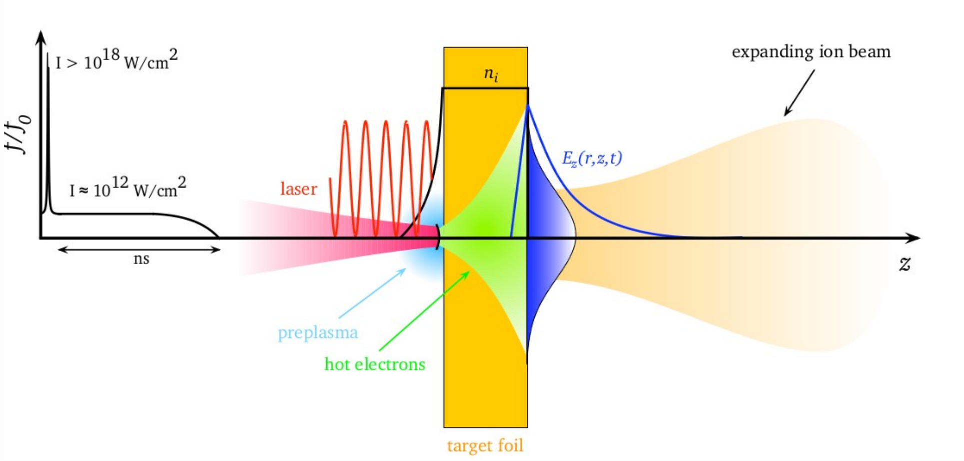
- **Chirped Pulse Amplification** (CPA) techniques provided short high energy laser pulses → laser energy in energetic particles
- **Multi-species production** (protons, ions, gammas, neutrons)
- Different mechanisms can interplay depending on the **laser intensity** and the **target thickness and composition**

Target Normal Sheath Acceleration: well modeled regime of interest for INFN laser facilities

TNSA - target normal sheath acceleration

- The laser prepulse creates a preplasma on the target's front side.
- The main pulse interacts with the plasma and accelerates MeV electrons, mainly in the forward direction.
- The electrons propagate through the target, leave the rear side, resulting in a dense sheath.
- An electric field due to charge separation is created (TV/m) and ionize the atom at the surface.
- Ions are then accelerated in this sheath field.

Picture from Roth, M., and M. Schollmeier. "Ion acceleration-target normal sheath acceleration." arXiv:1705.10569 (2017)



- short-duration, **high-flux proton beams**
- energy conversion efficiency ~ few %
- **broad**, Maxwellian-like energy spread
- maximum ion energy scale with laser energy

TNSA modeling

1) **Laser energy into hot electrons**

   •Knowledge of prepulse

   •Hydrodynamics of preplasma

   •Kinetic (PIC) modeling of interaction and electron production

2) **Hot electrons propagation trough the target**

   •Effect of cold return current

   •Target resistivity

   •Hybrid PIC/fluid modeling

3) **Ion expansion into the vacuum due to sheath electric field**

   •PIC modeling

   •Analytical models

Analytical modeling

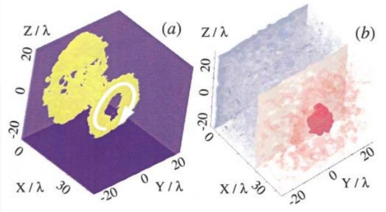
- **Fluid model** describing electron and ion expansion

  S Wilks, et al., PoP, 8,542 (2001);
  P Mora, Phys. Rev. Lett., 90, 185002 (2003)

- **Quasi-static field** by electrons and ions as test particles

  J Schreiber,et al., PRL, 97, 045005 (2006);
  M Passoni & M Lontano, Phys. Rev. Lett., 101, 115501 (2008)

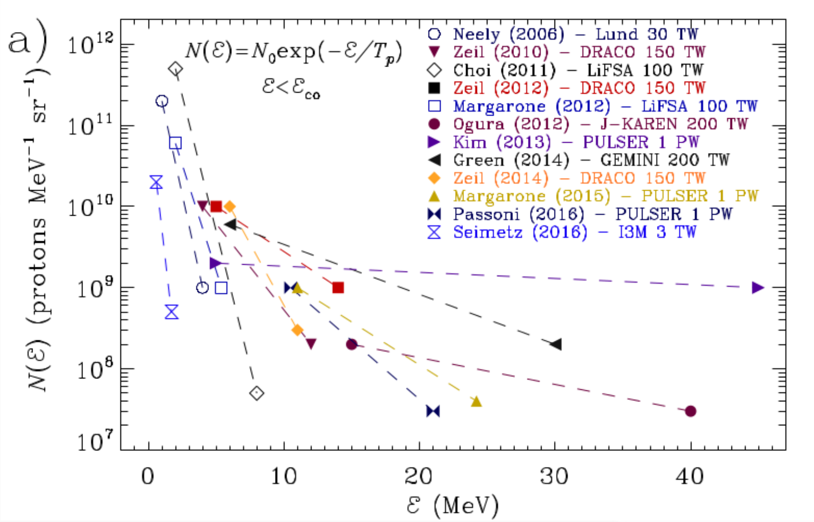
Particle-In-Cell (ab-initio modeling)



Pukhov, A. "Three-dimensional simulations of ion acceleration from a foil irradiated by a short-pulse laser." Physical review letters 86.16 (2001): 3562.

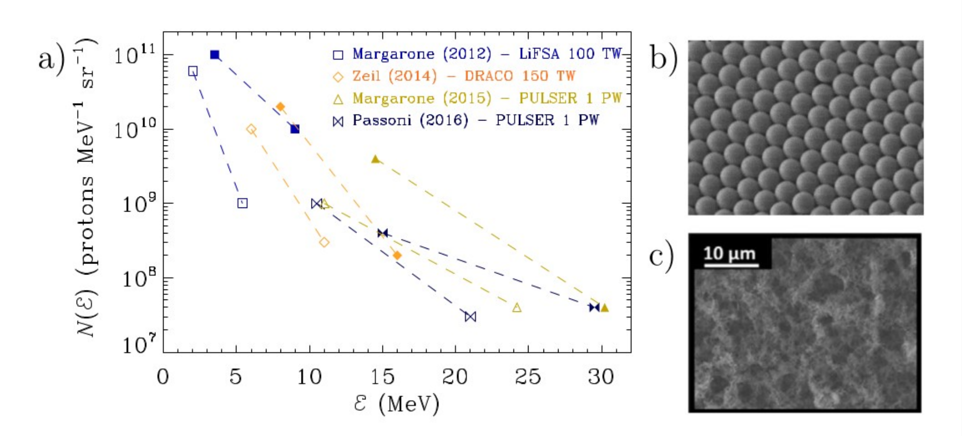
TNSA – scaling from experiments

Plots from Macchi, Andrea. "A review of laser-plasma ion acceleration." arXiv:1712.06443 (2017).



short pulses (25–40 fs)
solid targets (0.01–4.0 μm)

Laser energies in the plot almost compatible with the INFN laser facilities

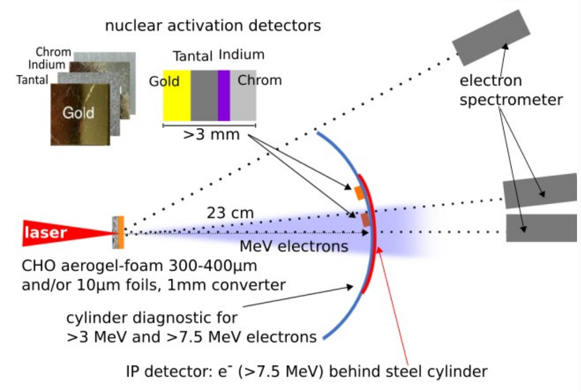


Energy enhancement in foam-covered targets

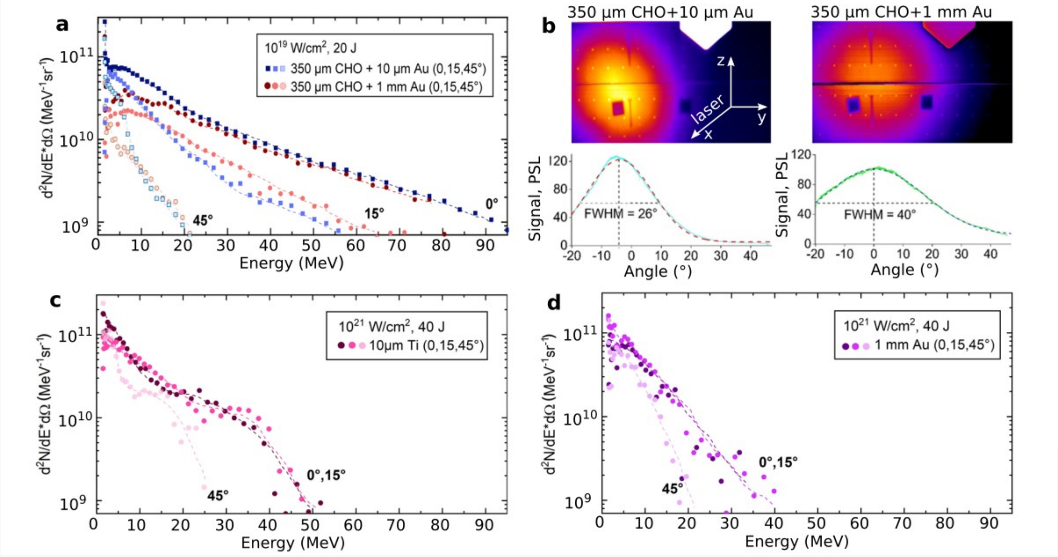
- field increases in near critical materials
- target with structured surface and shape can maximize hot electrons and laser coupling

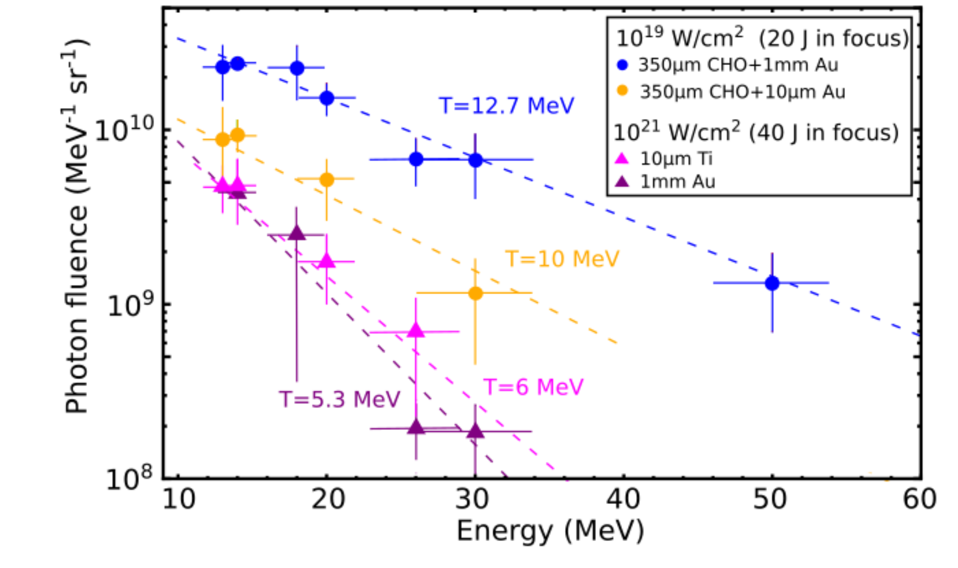
Laser on structured targets

If sub-picosecond laser pulse of relativistic intensity interacts with a pre-ionized polymer foam of near critical electron density → **Direct Laser Acceleration**



Günther, M. M., et al. "Forward-looking insights in laser-generated ultra-intense γ-ray and neutron sources for nuclear application and science." Nature Communications 13.1 (2022): 170.





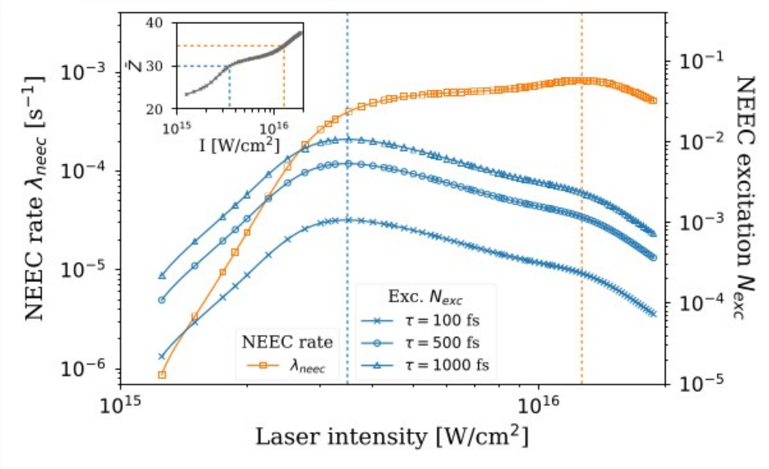
Nuclear Excitation by Electron Capture (NEEC)

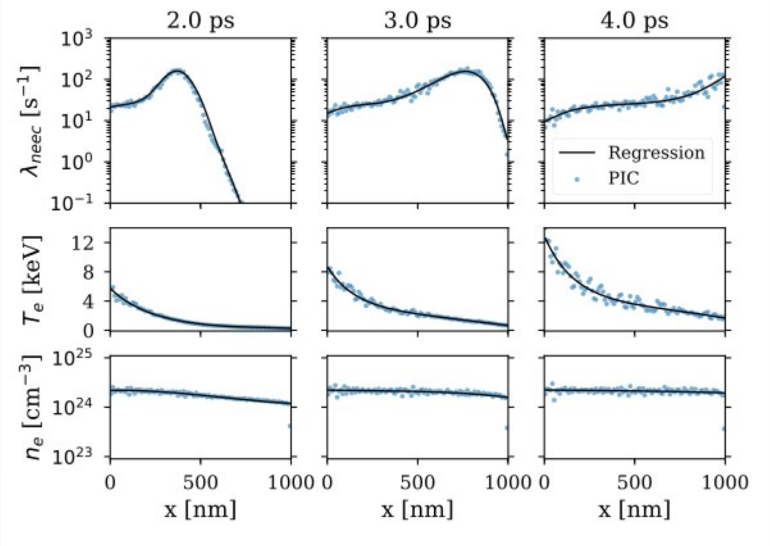
Wu, Yuanbin, et al. "Tailoring laser-generated plasmas for efficient nuclear excitation by electron capture." Physical review letters 120.5 (2018): 052504.

- strong optical laser that interacts with a solid-state target containing a fraction of nuclei in the isomeric state: **NEEC** and **photoexcitation** may occur in the generated plasma.

- Electron density, temperature and the NEEC rate based on PIC simulation as functions of target depth.

  I = 10^{18} W/cm^2 and λ = 800 nm

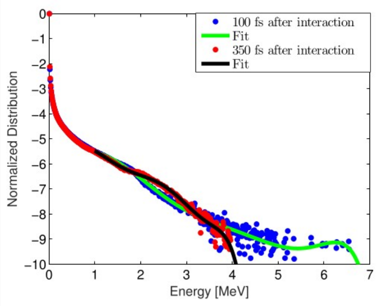




See B. Mishra talk at this workshop

Laser facilities @ INFN

- **FLAME** (Frascati Laser for Acceleration and Multidisciplinary Experiments)
- Up to 10^{20} W/cm^2
- **LWFA**, solid target **TNSA**, study of new radiation sources → **EuAPS**



Pompili, R., et al. "Femtosecond dynamics of energetic electrons in high intensity laser-matter interactions." Scientific reports (2016)

See F. Stocchi talk, this workshop

- **I-LUCE** (INFN Laser indUCEd radiation production)
- Two operational modes

  - Low power **50 TW** (nuclear fusion, nuclear physics, radioisotopes)

  - High power **350 TW** (proton, electron, neutron, gamma)


Eur. Phys. J. Plus (2023) 138:1038
https://doi.org/10.1140/epjp/s13360-023-04358-7
THE EUROPEAN PHYSICAL JOURNAL PLUS
Regular Article
Nuclear physics midterm plan at LNS

See P. Cirrone talk, this workshop

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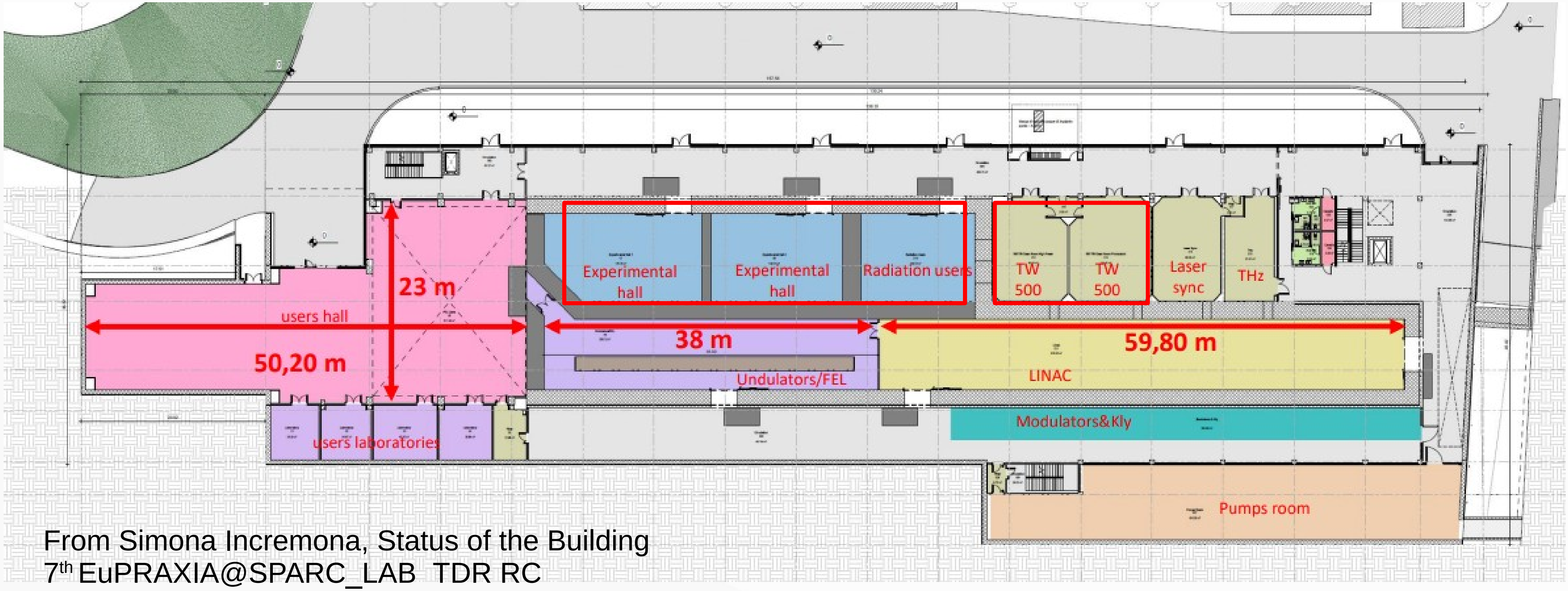

From Simona Incremona, Status of the Building
7th EuPRAXIA@SPARC_LAB TDR RC

- Only photocatode laser currently funded in the project
- Additional space in the building can eventually host laser system improvement
- Experimental hall space has been also accounted

Conclusions & Remarks

- **Laser-target interaction** can be **effective** in accelerating particles and producing radiation suitable for fundamental physics research.

- **Stable control** of laser systems as well as advanced engineering of the **targets** are key points for advances in the field.

- Interesting applications are (and can be) foreseeing at INFN.