Challenges and requirements for neutron dosimetry at laser-driven accelerators

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Neutron Beams at High Energy : Applications and Metrology
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A bit of history

LASER: **Light Amplification by Stimulated Emission of Radiation**

- 1960: first laser by Theodore Maiman at Hughes Research Laboratory

  Maiman, T., "Stimulated Optical Radiation in Ruby" *Nature* **187**, 493–494 (1960

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- 1979: first idea of laser driven acceleration

  Tajima, T., Dawson, J. M., (1979), "Laser electron accelerator", PRL 43, 267

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- 1985: Development of Chirped Pulse Amplification

  Strickland, D., Mourou, G., "Compression of amplified chirped optical pulses", Optics Communications, 56, 3 (1985)

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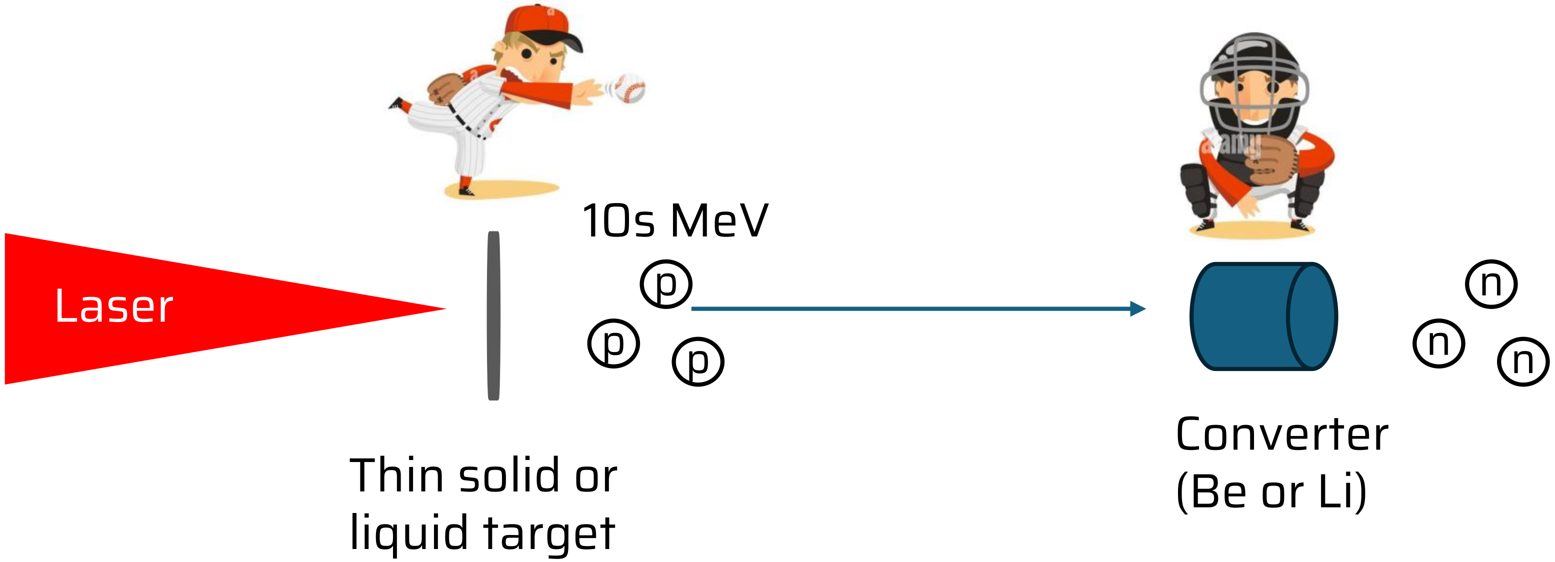
Laser Driven Neutron Sources

- Laser Driven Neutron Sources (LDNS) use a pitcher-catcher scheme based on
  - **Target Normal Sheath Acceleration**

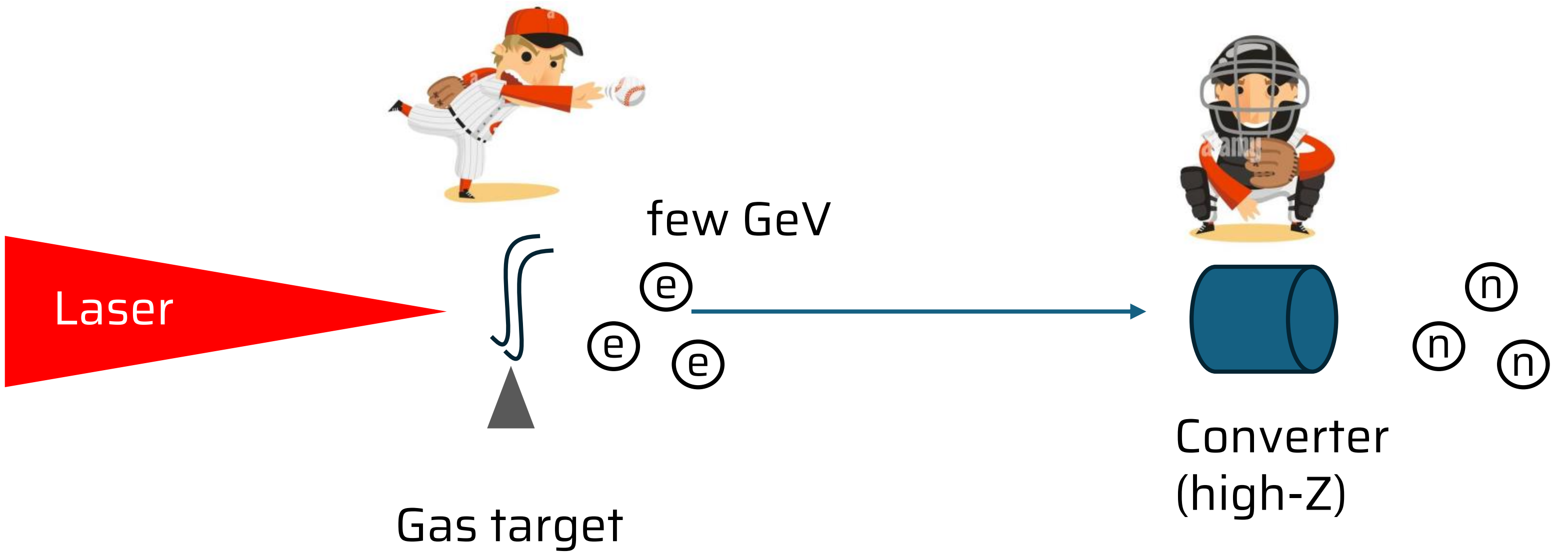


The spectrum is exponentially decaying toward its maximum energy, which is similar to the ion cutoff energy for (p,n) reaction

Laser Driven Neutron Sources

- Laser Driven Neutron Sources (LDNS) use a pitcher-catcher scheme based on

or **Laser Wake Field Acceleration**



The isotropic emission and neutron spectrum, peaks around 1 MeV

LDNS: Key Features

The key features that distinguish LDNS are:

- **Ultra-short neutron pulses**:
  - Temporal widths of the neutron pulses are in the ps range.
- **High peak flux**:
  - Total yields up to $10^{10\text{-}11}$ n/sr per laser shot under optimized conditions.
- **Mixed-field composition**:
  - The radiation field in laser-driven environments is strongly mixed, comprising high-energy neutrons, gamma rays, scattered protons, and secondary electrons, posing significant challenges for detector development and calibration.
- **Compactness:**
  - The actual particle acceleration happens in the μm to m scale. The entire system is several 10s m.
- **Tunability**:
  - Control over beam parameters is through target engineering (e.g., double-layer foils, gas-foil targets) and laser pulse shaping.
- **High repetition rate potential:**
  - Although presently limited by laser (the higher the power the lower the rate) and target system, repetition rates up to 10 Hz are feasible for PW class lasers

LDNS: Applications

1. Fundamental & Applied Nuclear Physics
- Neutron-induced reactions
- Cross-section measurements and nuclear data
- Validation of simulation codes and theoretical models .

2. Space & Aviation Applications
- Simulation of cosmic-ray-induced neutron fields relevant to avionics and astronaut safety .
- Evaluation of Single Event Effects (SEE) and Displacement Damage in electronics .

3. Material Science & Non-Destructive Testing
- Fast neutron imaging for dense or shielded objects (e.g., explosives, spent nuclear fuel, concrete defects) .
- Thermal/epithermal neutron radiography and tomography for hydrogenous materials and corrosion analysis .

4. Archaeometry & Cultural Heritage
- Neutron activation analysis (NAA) and resonance spectroscopy for elemental and isotopic composition in ancient artifacts .

5. Security & Nuclear Safeguards
- Differential die-away analysis (DDAA) and neutron interrogation for detecting fissile materials in cargo and waste .

6. Medical Applications (Future-Oriented)
- Radiobiological studies using ultrashort high-fluence neutron pulses .
- Feasibility of radiation therapy applications (e.g., boron neutron capture therapy) once stable beams are available .
- Isotope production (e.g., Mo-99 for Tc-99m) with high-flux sources .

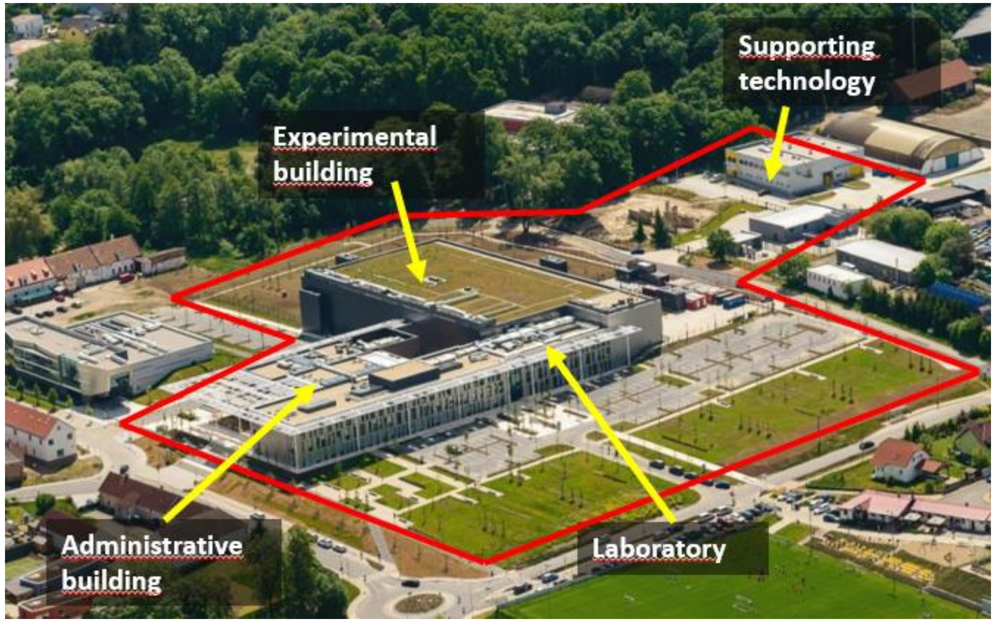
LDNS: Laser Parameters

- Laser parameters (along with target materials) have direct impact on LDNS production

- Key laser parameters for LDNS are:
  - Pulse energy (the higher the better)
  - Pulse duration (the short the better?? … in some applications, yes)
  - Repetition rate (the higher the better)

- Petawatt (PW) and multi-PW lasers, such as the ones at ELI Beamlines, have the **potential** of providing similar fluxes as established neutron production facilities in a cost-effective way.

ELI Beamlines

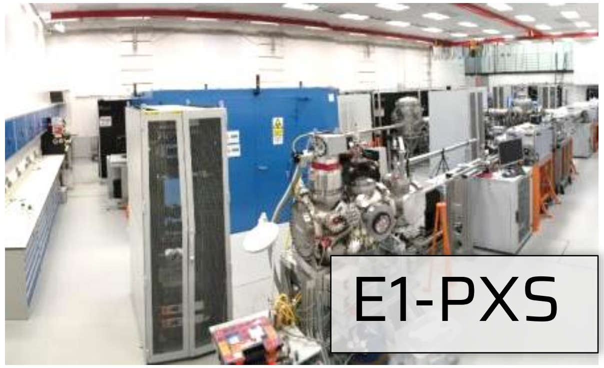


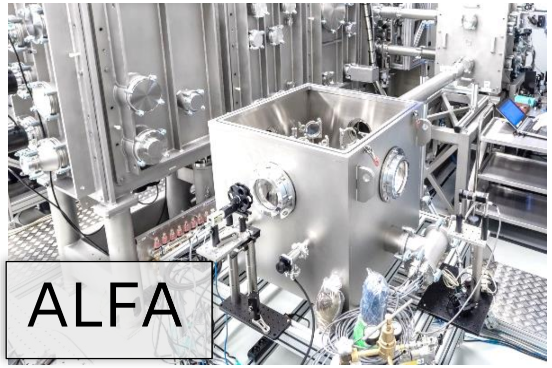
- ELI Beamlines, part of the Extreme Light Infrastructure ERIC, is a laser driven user facility located just south of the city of Prague.
  - It aims at investigating high-field high-density physics, developing high-brightness sources of X-rays, as well as secondary proton, electron, and ion beams, for interdisciplinary applications in physics, medicine, biology, and material sciences
- The experimental building houses four main laser systems labeled L1 (ALLEGRA), L2 (AMOS), L3 (HAPLS), and L4 (ATON)

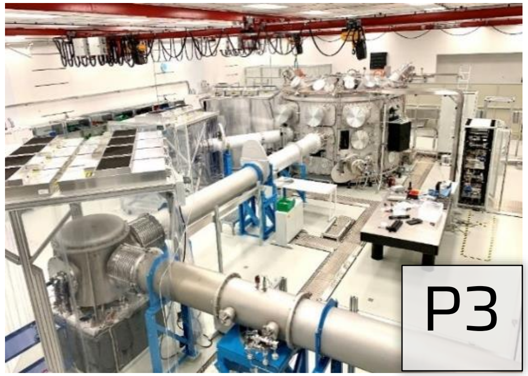
Target Parameters – Lasers are still in commissioning

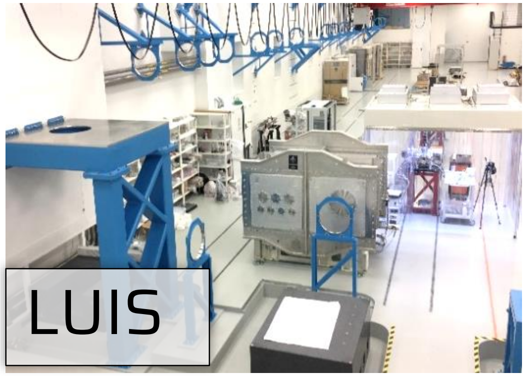
Laser	Energy [J]	Power [TW]	Rate [Hz]
L1 (ALLEGRA)	0.1	5	10^3
L2 (AMOS)	2	10^3	50
L3 (HAPLS)	30	10^3	10
L4 (ATON)	$2\cdot10^3$	10^4	0.1

ELI Beamlines Experimental Stations

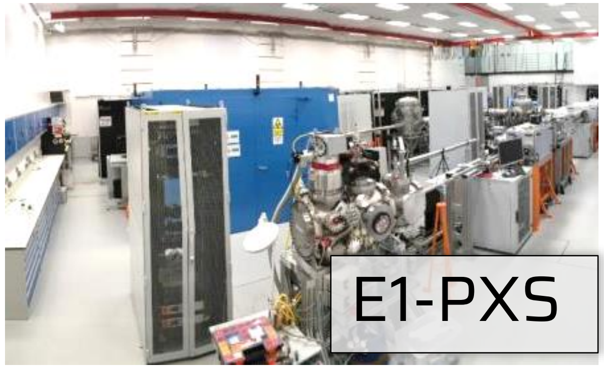


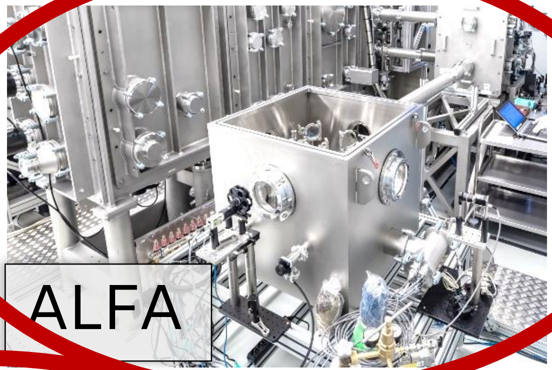


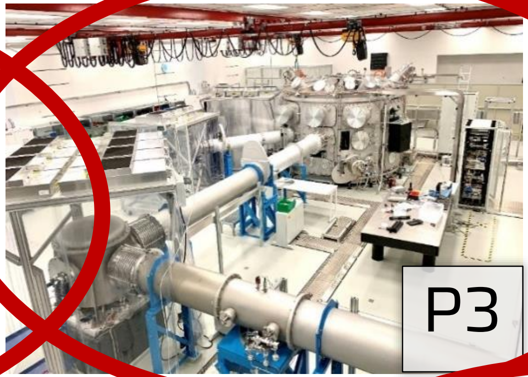




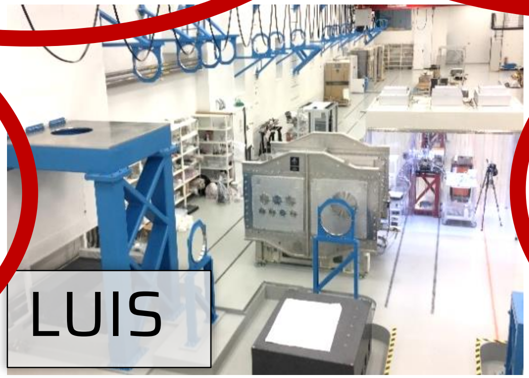
ELI Beamlines Experimental Stations







Neutron
Production!!



Neutron Dosimetry @ ELI Beamlines

- **Mainly for Radiation Protection**

- **LB 6419**
  - Used in high and medium occupancy areas (control rooms and corridors)
  - Dual-detector system: Combines a moderated ^{3}He proportional counter with a plastic scintillator
  - Wide energy range: Sensitive to neutrons from thermal energies up to >20 MeV
  - Designed for pulsed and continuous fields:
    Effective in mixed radiation environments, including pulsed neutron sources
  - Time-resolved measurements: Based on the detection of decay products from short-lived activation nuclides (e.g., ^{12}B, ^{8}Li)

- **MDN-01 Ionization chambers**
  - Used in low occupancy areas (technology service areas)
  - Proportional He-3 counter inside a polyethylene sphere moderator (25 cm diameter).

Neutron Dosimetry @ ELI Beamlines

- Passive detectors were used in a handful of experiments when a higher neutron production was anticipated.
  - Track-Etched Detectors
  - Li-6 enriched TLDs
  - Bubble detectors

@ Bubble Technology Industries

- Results from one of these campaigns have been published
  - Olšovcová, V. et al., Neutron dose assessment in laser-generated ultra-short pulsed fields, *Radiation Protection Dosimetry*, Volume 199, Issue 15-16, October 2023, Pages 1910–1916, https://doi.org/10.1093/rpd/ncac221
  - The publication highlights the challenges of neutron dose assessment at laser facilities.

Problematics

The same characteristic that make LDNS interesting and unique pose significant challenges for accurate neutron dose measurements.

- No currently available neutron detectors has truly developed for laser facilities.
- Lack dosimetry standards for ultra-short (ns) and ultra-intense (10^{10}-10^{11} n/sr) neutron bursts.
- Lack of accredited calibration facilities that replicate the harsh radiation environments of laser facilities (ultra-short pulsed, high-dose rate mixed radiation fields). This affects:
  - Calibration and testing of neutron detectors .
  - Monte Carlo benchmarking neutron production.

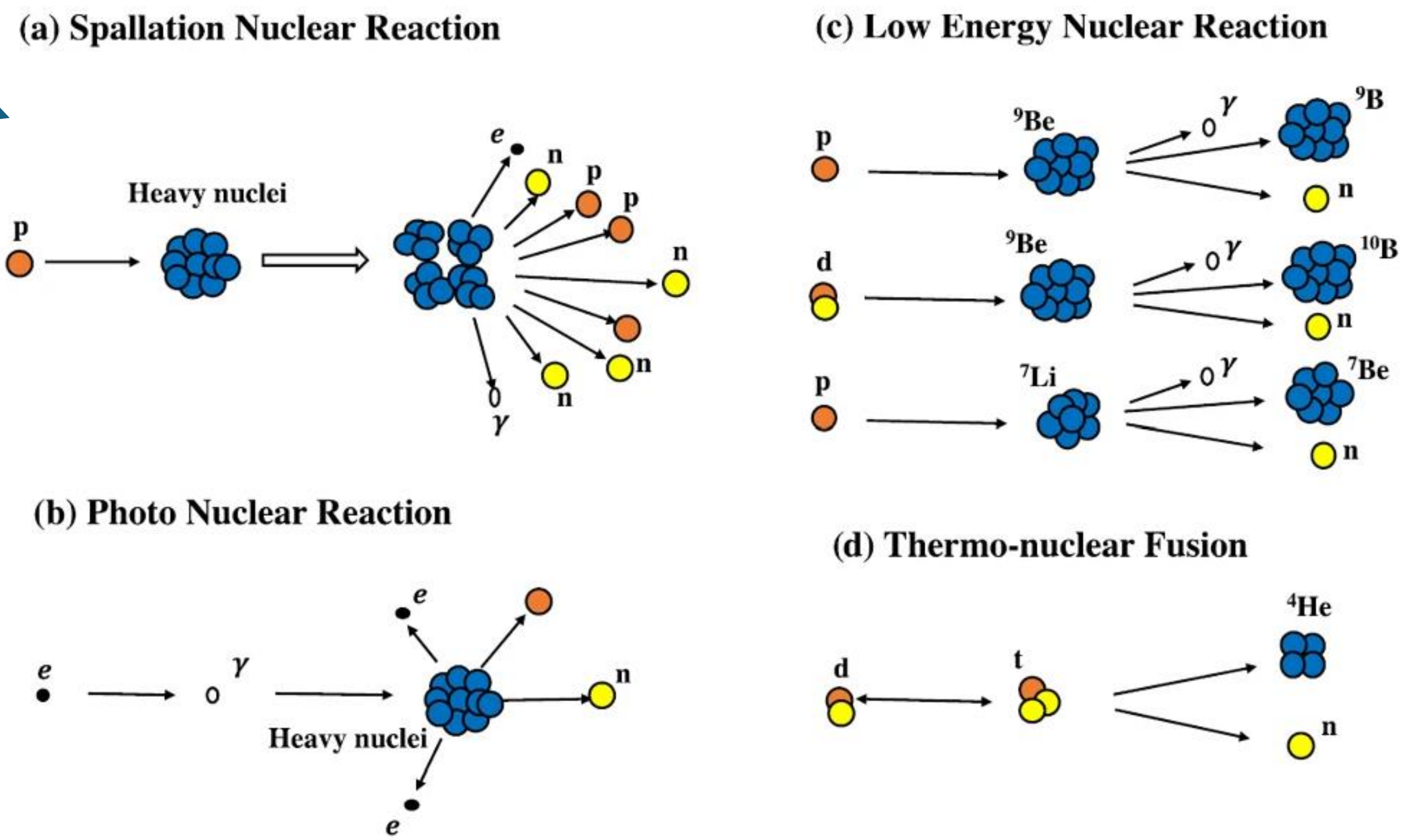
Areas affected:

Radiation Protection
Dosimetry (fundamental for any future medical application)
Accelerator technology development (needed to support machine design)
Simulation and Monte Carlo development

BACKUP

Neutron Generation

This requires GeV protons!



Neutron generation processes driven by accelerators and high-power lasers. **a** Spallation nuclear reaction, **b** photo-nuclear reaction, **c** low-energy nuclear reaction, **d** thermo-nuclear fusion.

Yogo, A., Arikawa, Y., Abe, Y. *et al.* Advances in laser-driven neutron sources and applications. *Eur. Phys. J. A* **59**, 191 (2023). https://doi.org/10.1140/epja/s10050-023-01083-8

Target Normal Sheath Acceleration

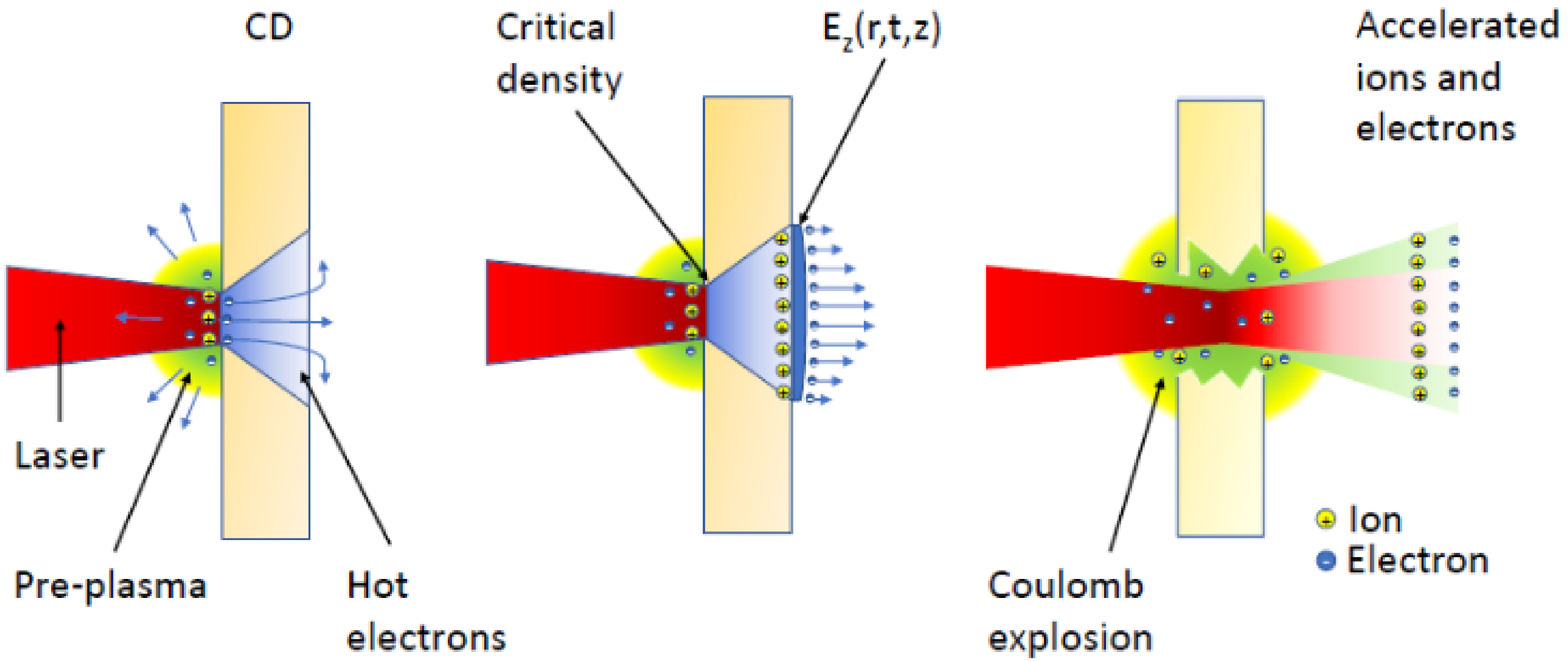
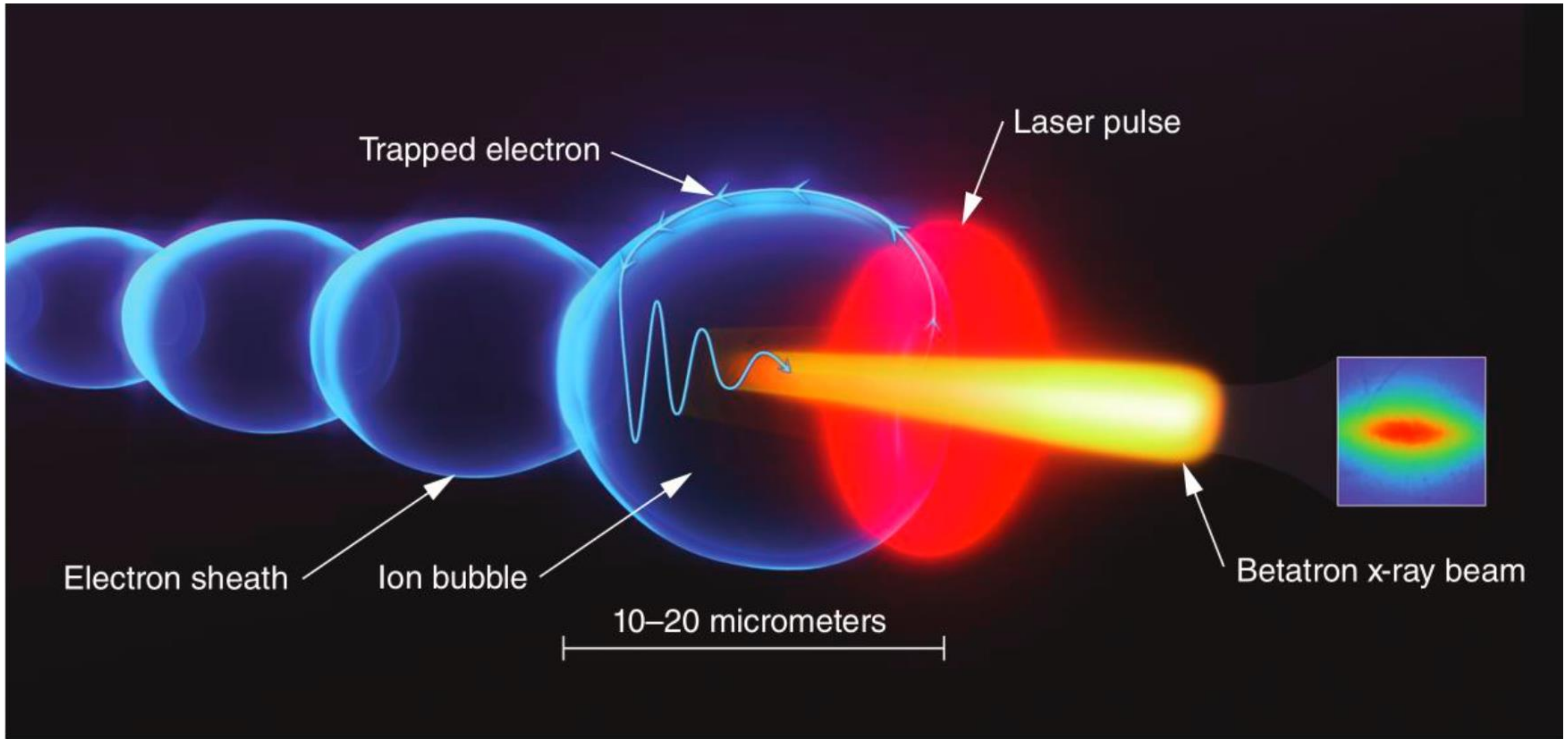


Figure 2.1: The process of laser-driven ion acceleration. A laser pulse impinges on a target and creates a plasma. Energy is transferred to the electrons which create a sheath at the rear surface. This charge separation creates a strong electric field that is capable of accelerating ions from the surface. If the target is thin enough the laser can

From: https://doi.org/10.25534/tuprints-00012996

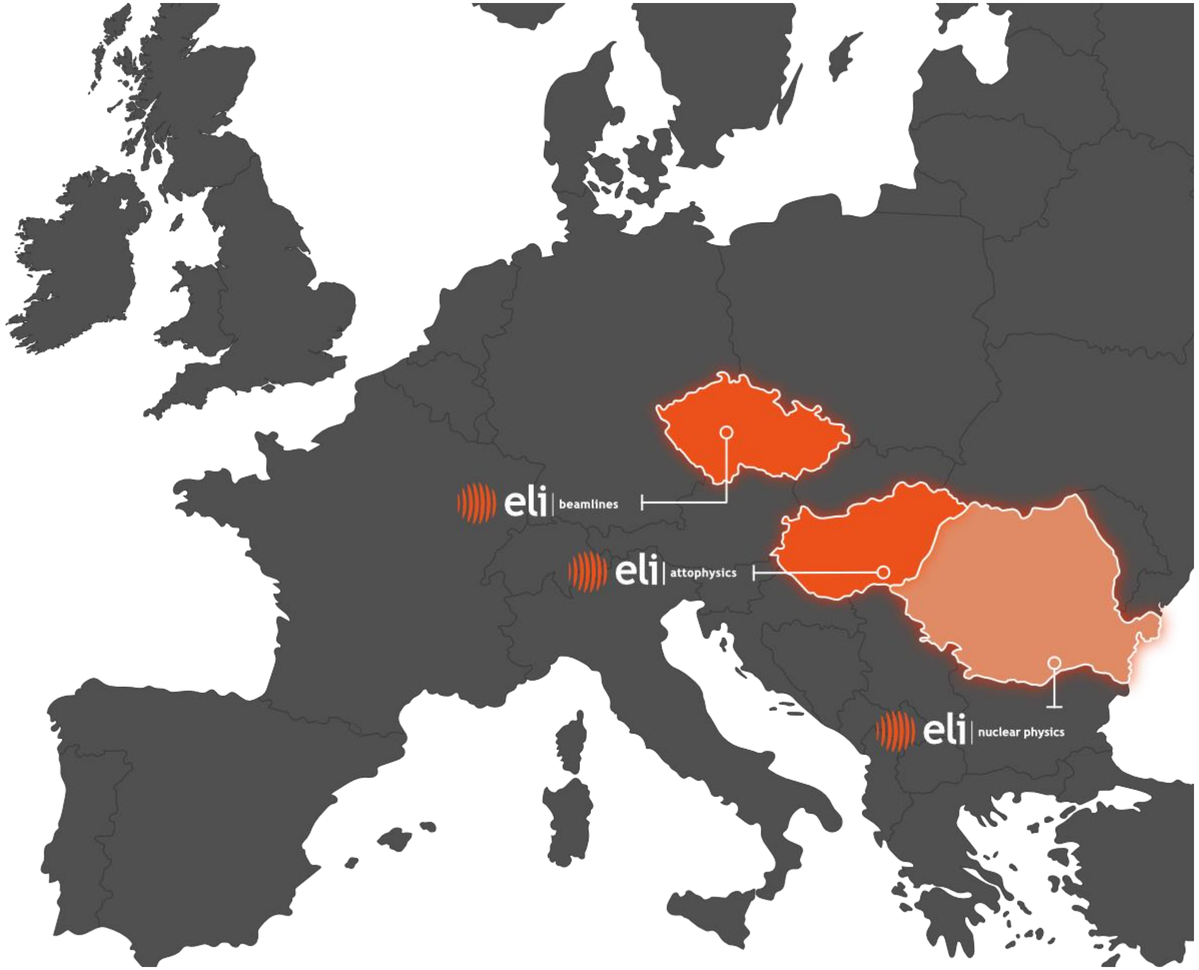
Laser Wake Field Acceleration



- Laser Wake Field Acceleration (LWFA)
  - high intensity (PW-class) ultra-short (fs) lasers propagate inside a gas ionizing it and expelling the plasma electrons
  - a wake is created behind the laser in which acceleration gradients of up to **hundreds of GV/m** can be achieved.

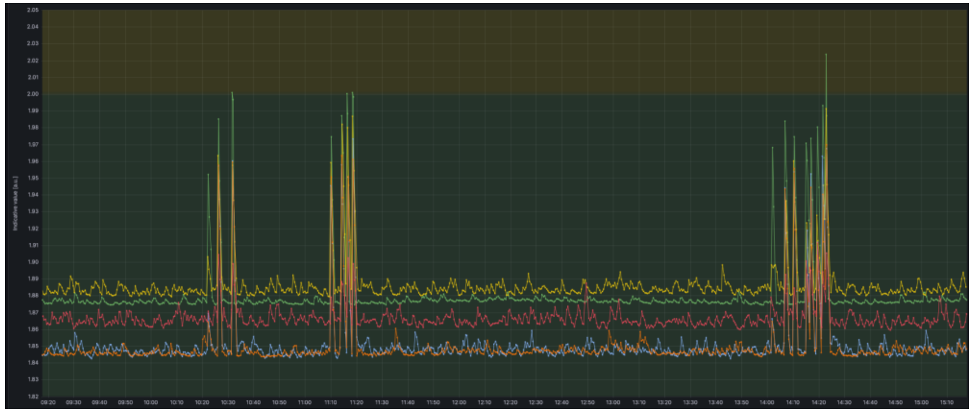
ELI Sites

- **ELI ALPS - Hungary**
  - Ultrafast physical processes
  - Attosecond measurement techniques
- **ELI Beamlines – Czech Republic**
  - Secondary sources
  - Medical imaging and diagnostics, radiotherapy
- **ELI NP – Romania**
  - Photonuclear Physics
  - Exotic nuclei



RP Standard Measures

- Monte Carlo assessment
- People not allowed in the experimental area
  Personal Safety Interlock in place
- Monitoring system of ionizing radiation



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