Machine-Learning Optimization of Laser-Driven Electron Accelerators

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Extreme Light Infrastructure (Beamlines Facility)

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Content

eli

Acknowledgements

ELI Beamlines (Czech. Rep.)

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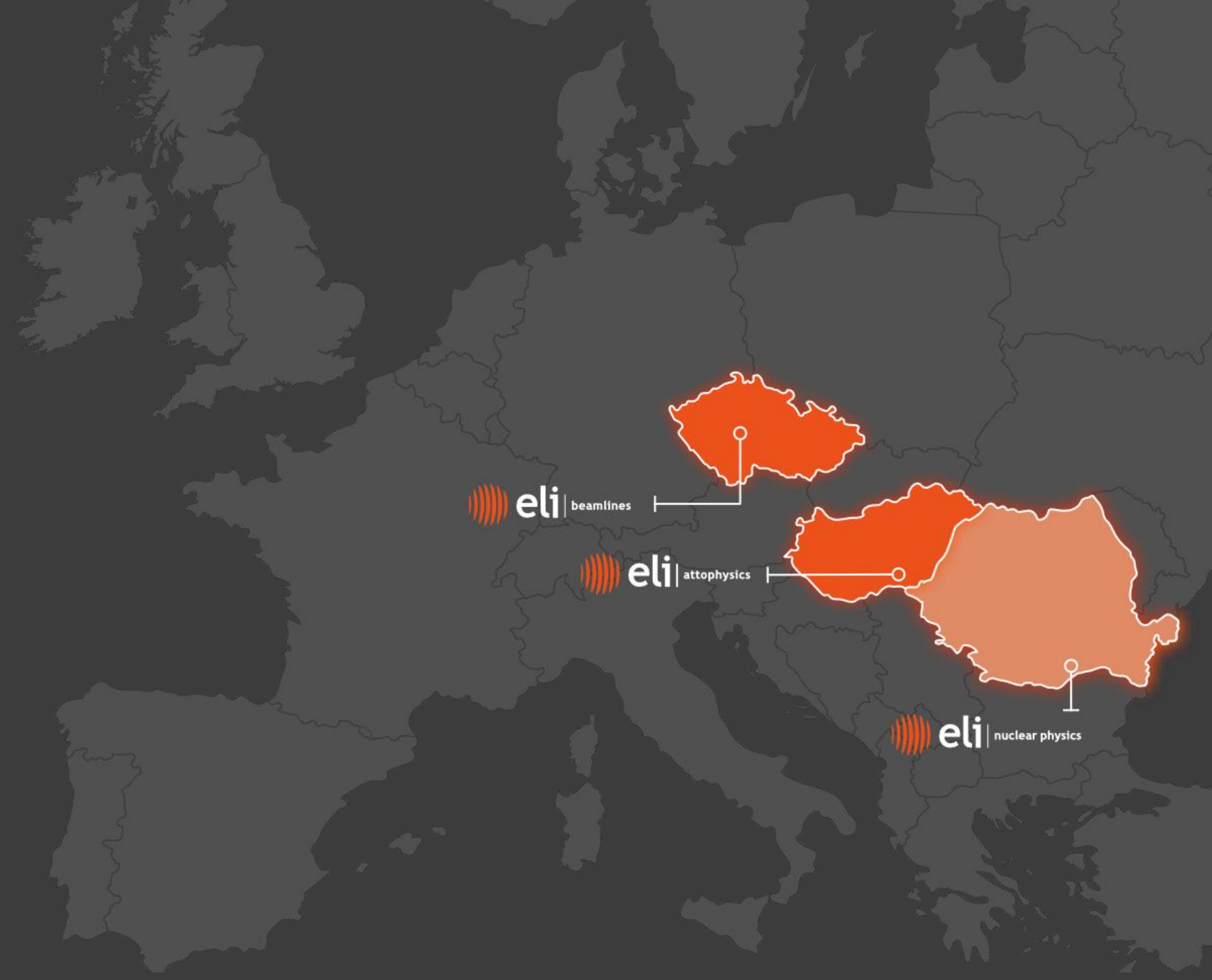
Map of ELI Facilities

ELI facilities are strategicaly located in 3 European countries:

ELI Beamlines facility is located in Dolní Břežany, right next to Prague, the capital of the Czech Republic.

ELI Attophysics facility is located in Szeged, third largest city in Hungary.

ELI Nuclear Physics is located in Magurele, on the outskirts of Bucharest, the capital of Romania.



eli | beamlines

- Sources of high-energy photons, electrons, protons, neutrons, and muons.
- Materials science, biomedicine, medical imaging, and radiotherapy.
- Plasma physics, high-field physics, laboratory astrophysics, and nuclear fusion.
- Cryogenic cooling for laser amplifiers, fs pulse diagnostics and synchronization.

eli | attophysics

- Attosecond light sources and measurement techniques.
- Radiobiological applications, ultrafast physical processes, biological imaging technologies.
- Artificial photosynthesis, transmutation of used nuclear fuels, materials science and nanoscience.
- Particle acceleration with few-cycle laser pulses.

eli | nuclear physics

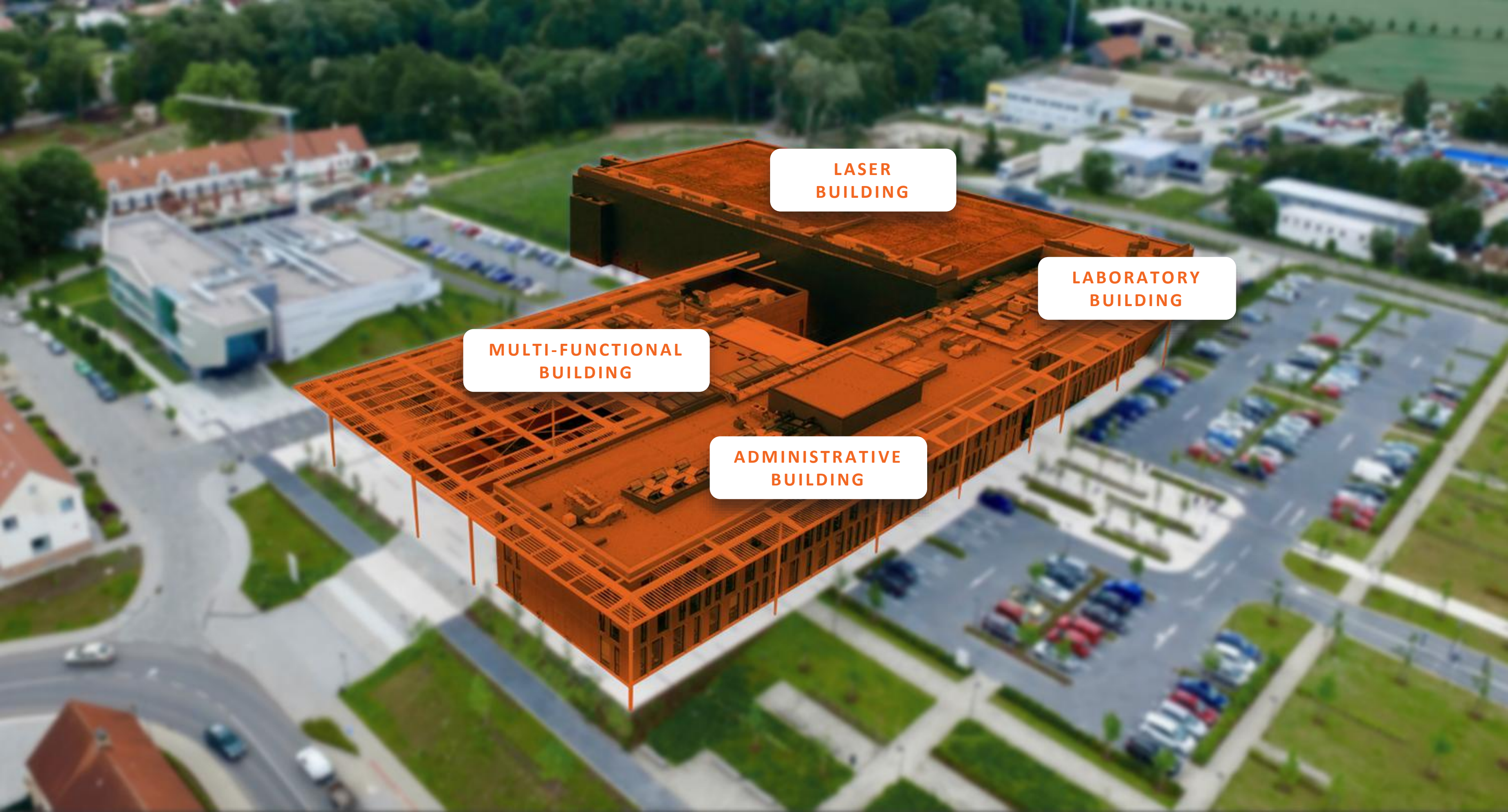
- Photonuclear reactions, nuclear structure, exotic nuclei, nuclear astrophysics and nucleosynthesis.
- Brilliant energy tunable gamma-ray beam system.
- Quantum electrodynamics, high-field physics.
- Particle acceleration with high-power lasers.
- Material studies with positrons, materials in high radiation fields.

ELI Beamlines Facility

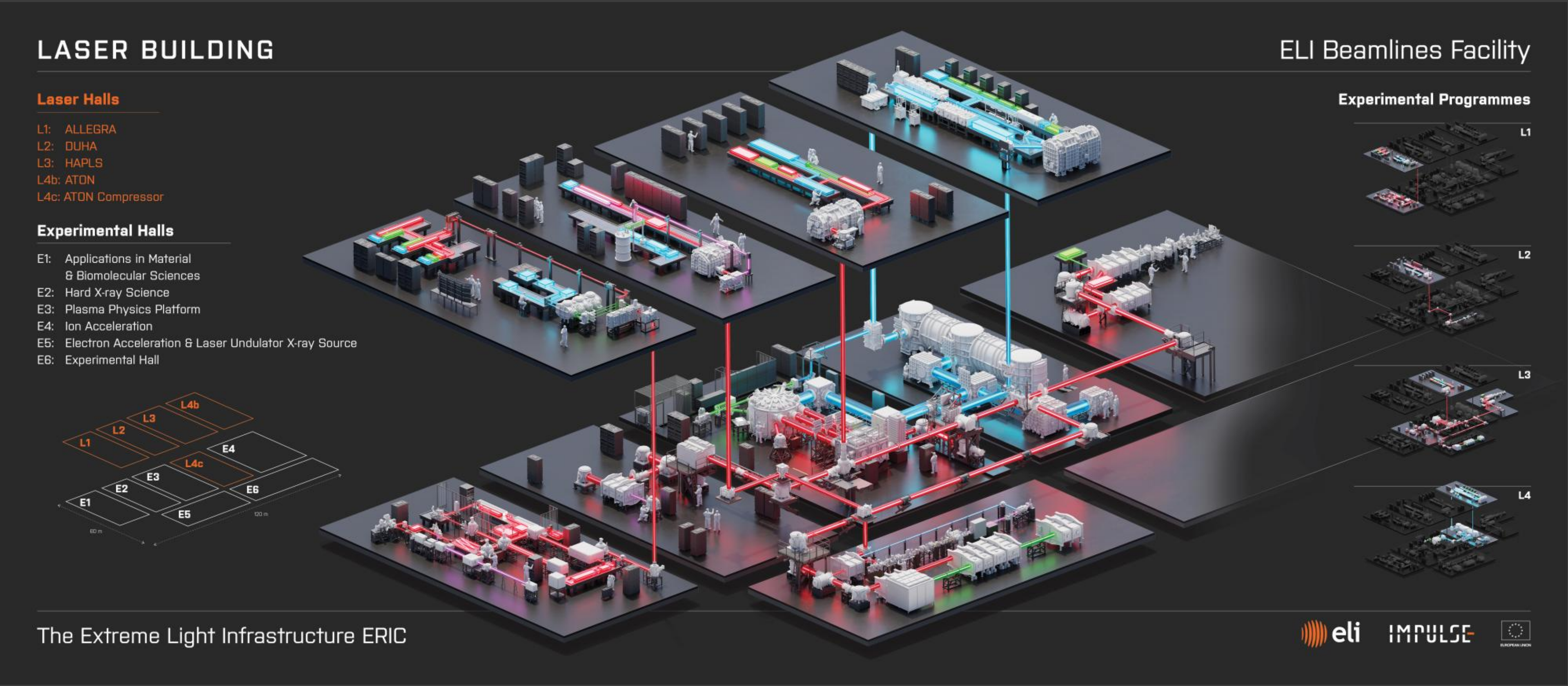
The ELI Beamlines Facility investigates the interaction of light with matter at intensities 10 times higher than ever before, pushing the boundaries of laser physics and technology.

It develops secondary sources of particles and radiation for use in molecular, biomedical, and material sciences, as well as plasma physics, high-field physics, laboratory astrophysics, and nuclear fusion.

As a user facility, ELI Beamlines operates 4 world-class laser systems, 7 secondary sources, and 10 end-stations. The site covers 28,000 m^2 and brings together 350+ international staff.

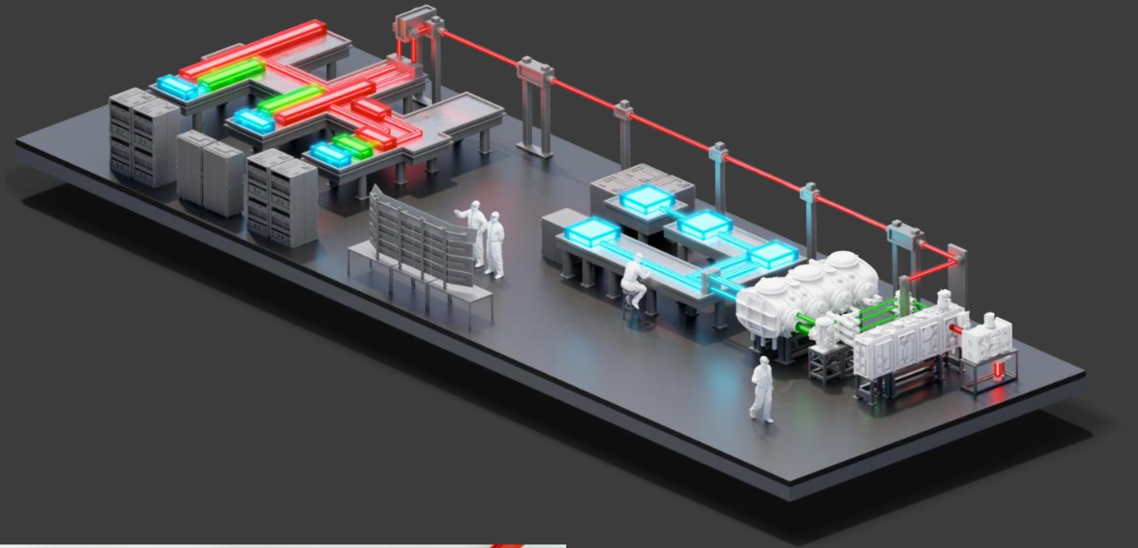

LASER BUILDING
LABORATORY BUILDING
MULTI-FUNCTIONAL BUILDING
ADMINISTRATIVE BUILDING

LASERS AND EXPERIMENTAL HALLS



L1: ALLEGRA

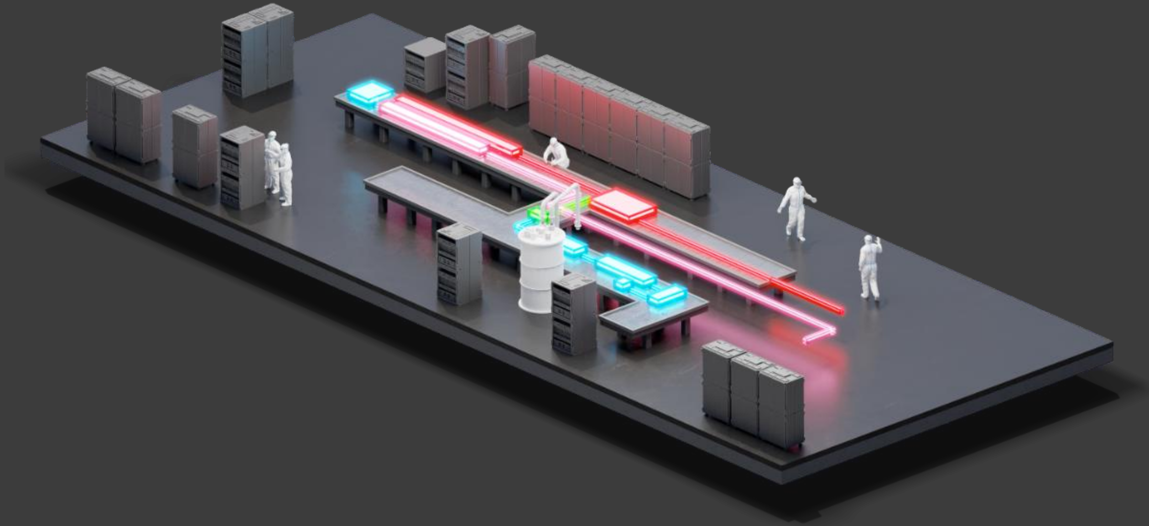
The L1 laser is being developed in-house by the ELI Beamlines laser team. Its design is based on the amplification of frequency-chirped picosecond pulses using an optical parametric chirped pulse amplification chain composed of seven amplification stages, enabling precise control of pulse duration and energy.



Peak power	5 TW
Pulse energy	100 mJ
Pulse duration	20 fs
Repetition rate	1 kHz

L2: DUHA

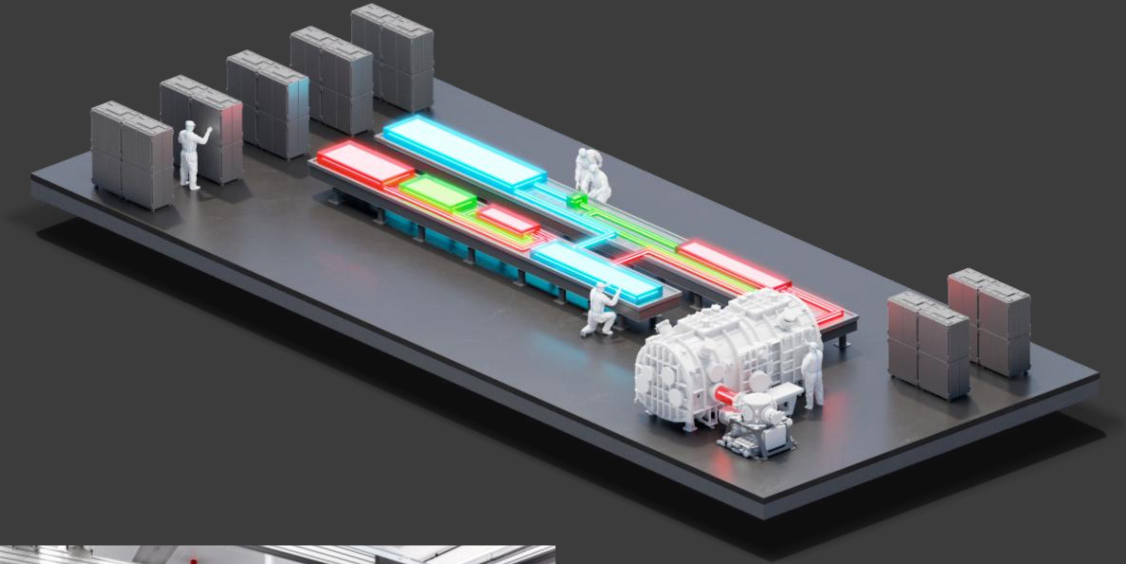
The L2 laser is developed in-house by the ELI Beamlines laser team. It features cryogenically cooled Yb:YAG multi-slab technology for pump laser amplification and employs a hybrid short-pulse amplifier, combining picosecond and nanosecond optical parametric chirped pulse amplification stages pumped by diode-pumped solid-state lasers.



Peak power	120 TW
Pulse energy	3 J
Pulse duration	25 fs
Repetition rate	50 Hz

L3: HAPLS

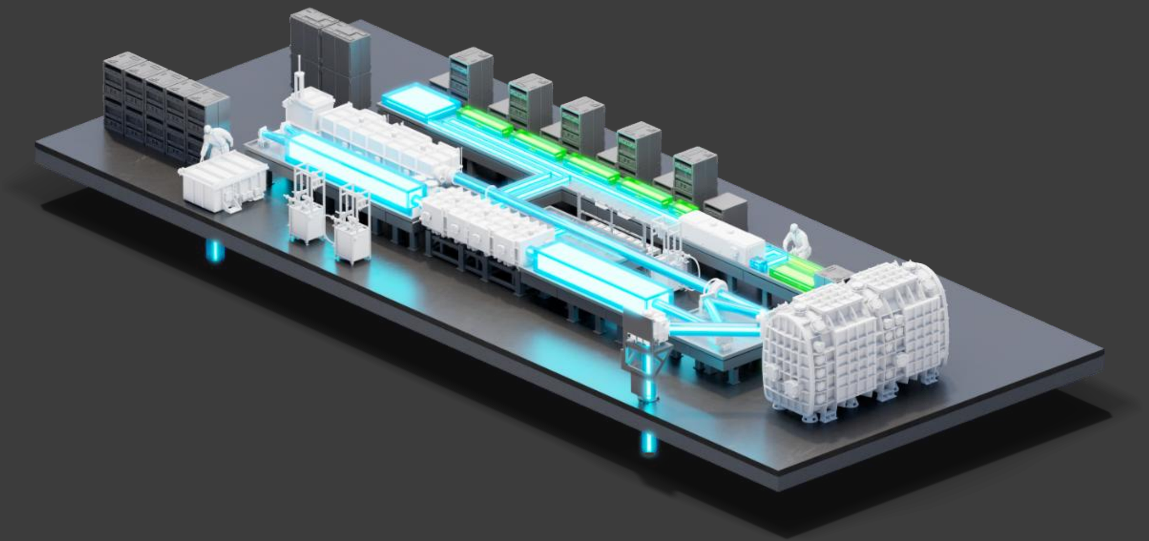
The L3 laser was developed at the Lawrence Livermore National Laboratory in collaboration with ELI Beamlines. The system generates femtosecond pulses in a titanium-doped sapphire amplifier, delivering exceptional pulse quality and stability.



Peak power	1 PW
Pulse energy	30 J
Pulse duration	30 fs
Repetition rate	10 Hz

L4: ATON

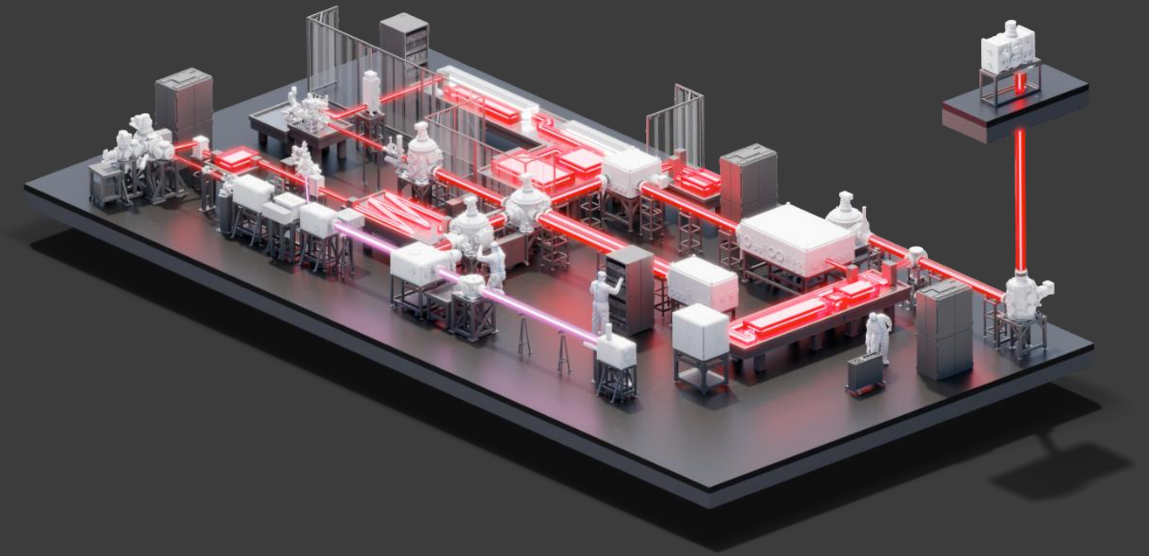
The L4 laser was built by a consortium of National Energetics (USA) and EKSPLA (Lithuania), with major contributions from ELI Beamlines. Its architecture is based on chirped pulse amplification in several optical parametric stages, followed by direct amplification in Nd:glass laser discs.

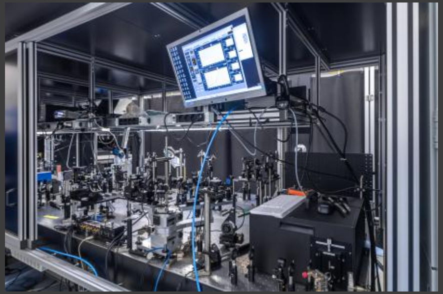


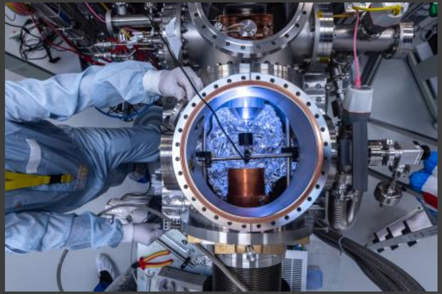
Peak power	10 PW
Pulse energy	1.5 kJ
Pulse duration	150 fs
Repetition rate	0.017 Hz

E1: Material and biomolecular applications

The E1 experimental hall hosts laser-driven secondary sources and experimental end-stations for studies in molecular, biomedical, and materials sciences. Experiments in E1 utilize synchronized laser and photon beams in the VUV and X-ray ranges, generated through high-harmonic generation or plasma X-ray sources, enabling ultrafast, high-resolution investigations of matter.

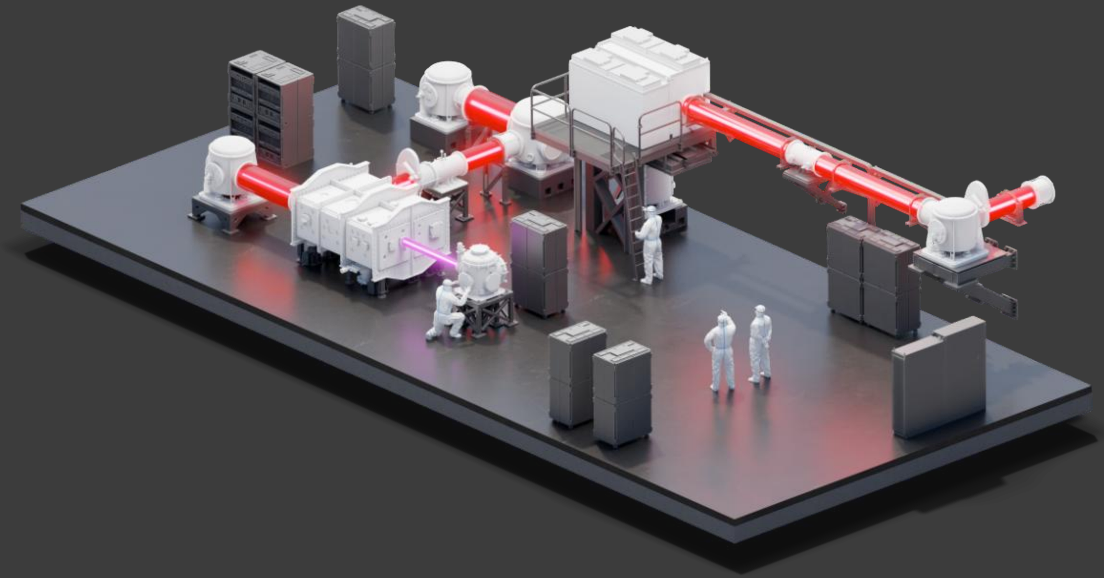






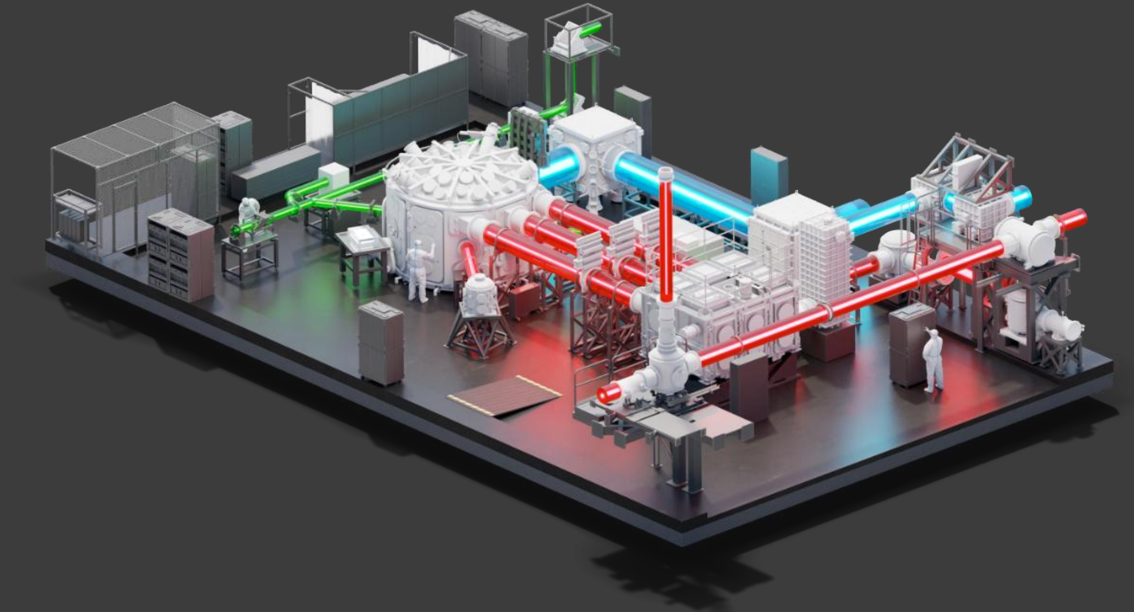
E2: Hard X-ray science

The E2 experimental hall is dedicated to producing ultrafast, high-brightness hard X-ray beams via betatron and Compton scattering mechanisms. These beams support advanced phase-contrast imaging and research on warm dense matter, providing insights into extreme states of materials and plasma dynamics.



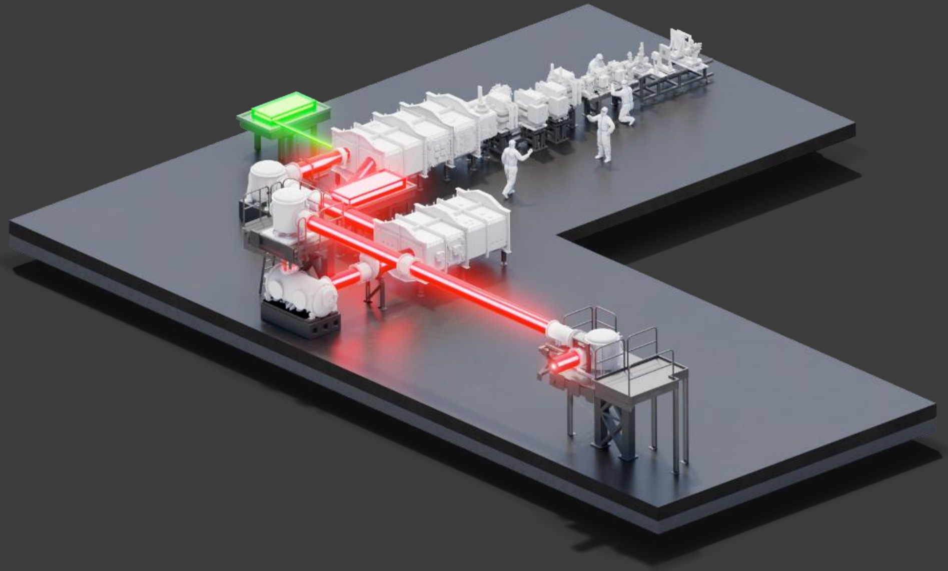
E3: Plasma physics platform

The E3 experimental hall is a versatile research facility focused on high-energy-density physics, warm dense matter, plasma optics, laboratory astrophysics, and inertial fusion. It features the P3 large vacuum chamber and synchronized high-intensity laser beams, offering a unique platform for studying laser–plasma interactions under extreme conditions.



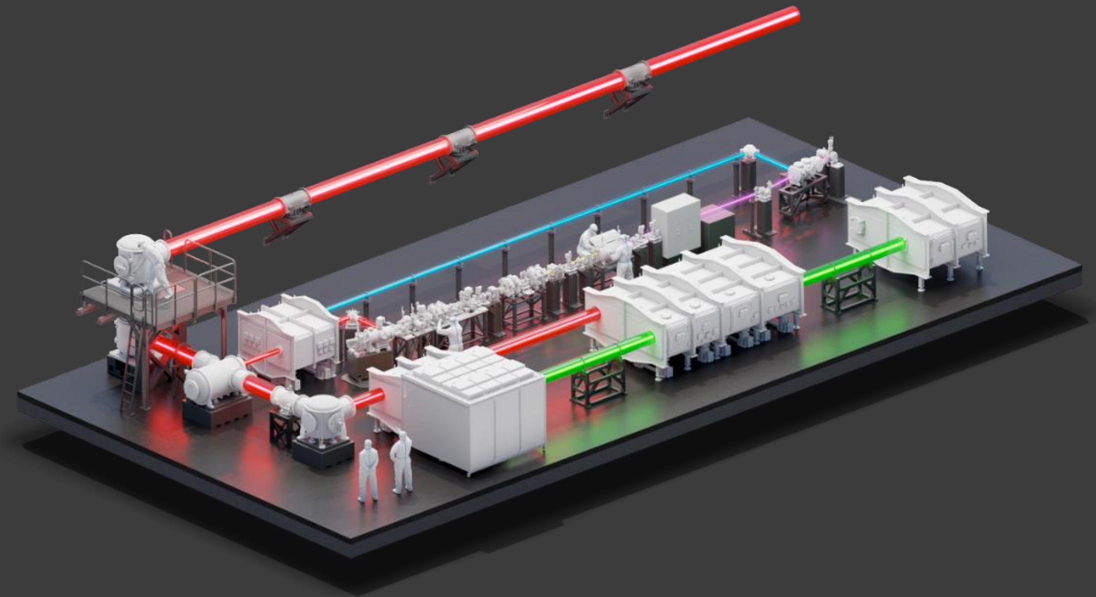
E4: Ion acceleration

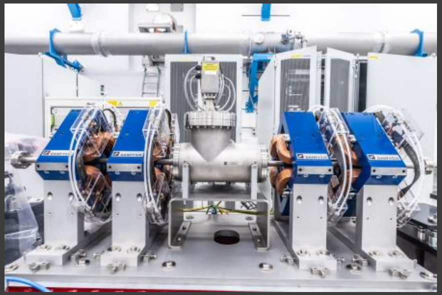
The E4 experimental hall supports experiments using laser-accelerated ion sources across a range of disciplines, including non-destructive material testing and biomedical applications. Its flexible interaction chamber enables the exploration of innovative ion acceleration schemes, advancing the development of compact and tunable ion beam systems.

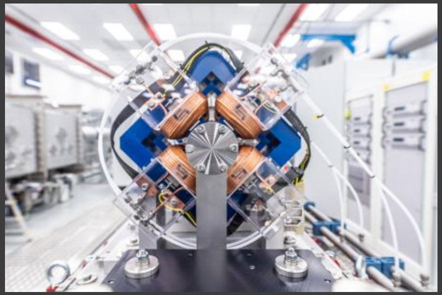


E5: Electron acceleration

The E5 experimental hall focuses on laser-accelerated electron sources and high-energy radiation generation. It accommodates setups with very long focal lengths, allowing experiments on multi-stage electron acceleration and magnetic undulators, paving the way toward laser-driven X-ray free-electron laser concepts.







Electron acceleration group

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Illia Zymak

Diagnostics

Leonardo Vilanova

Diagnostics

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Gas targetry

Matej Jech

Data

Michal Nevrkla

Instrument responsible

Jiri Sisma

Operator

Filip Vitha

Operator

Radio-frequency electron acceleration

- High-energy electron accelerators use electromagnetic fields oscillating at radio-frequencies to accelerate electron beams.
- Linear Accelerators (Linacs): high-energy, high-quality electron beams accelerated along a straight path that can extend over several km.
- Circular Accelerators (Synchrotrons): more compact, as electrons circulate multiple times to gain energy, but efficiency is limited because electrons lose energy through radiation emission (synchrotron radiation).
- Acceleration gradients in radio-frequency accelerators are limited by dielectric breakdown, restricting the maximum electric field to 10s of MV/m. Achieving very high energies requires large and costly facilities.

Why we need electron accelerators?

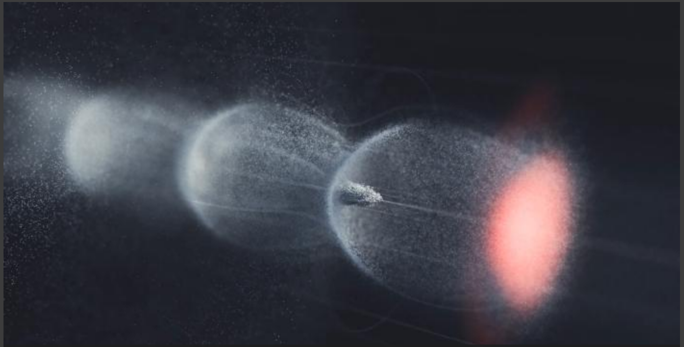
- Production of high-energy X-rays or electrons for cancer treatment.
- Generation of intense X-rays for crystallography, nanostructure analysis, chemical studies, and non-destructive material testing.
- Production of short-lived isotopes for diagnostic medical imaging.
- Sterilization and processing of medical equipment, food products, and industrial or environmental waste.
- Injectors for free electron lasers to study molecular dynamics and biological structures in real time.

SLAC National Accelerator Laboratory (USA)
50 GeV, 3.2 km length
Photo taken from https://www.mercurynews.com

European Synchrotron Radiation Facility (France)
6 GeV, 850 m circumference
Photo taken from https://www.filinchuk.com

Laser-driven electron acceleration

- First proposed in [T. Tajima et al., *Phys. Rev. Lett.* **43**, 267–270 (1979)], now known as laser wakefield acceleration (LWFA).
- When intense laser pulse interacts with a gas, it ionizes the medium and creates a plasma.
- As the laser pulse propagates through plasma, its ponderomotive force (radiation pressure) pushes electrons outward from the high-intensity region, leaving behind a positively charged ion cavity (referred to as a “bubble”).
- The resulting charge separation generates a restoring electric field that pulls electrons back toward their original positions, causing them to oscillate. This process forms a plasma wave, consisting of ion cavities surrounded by thin, dense electron layers.
- The maximum accelerating gradient is limited by plasma wave breaking, reaching up to 100 GV/m, over 3 orders of magnitude higher than that achievable in conventional radiofrequency accelerators. This offers a pathway to significantly more compact electron accelerators.
- As of 2025, the record electron energy achieved is 10 GeV (Lawrence Berkeley National Laboratory, University of Texas at Austin) over acceleration lengths of 10s of cm.



Animation of laser wakefield acceleration
Video taken from https://kaldera.desy.de

Analogy to laser wakefield acceleration
Photo taken from https://features.boats.com

Why is LWFA optimization challenging?

LWFA at the stage of fundamental research.

Key aspects of the underlying physics not fully understood.

Complexity of LWFA:

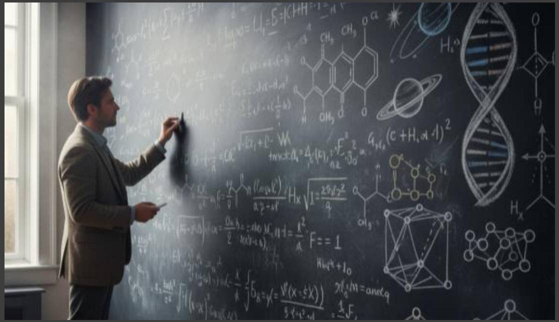
1. Multi-physics: interconnected dynamics of electromagnetic fields, plasmas, and relativistic particles,
2. Multi-scale: from micrometer laser wavelengths to centimeter-scale acceleration lengths,
3. Multi-parametric: small variations in input lead to large changes in outcome due to strong nonlinearity.

LWFA optimization methods

Experiment: limited by capabilities of laser systems (energy, power, repetition rate), optics (spot size), diagnostics.

Simulation: large number of high-fidelity simulations computationally very expensive.

Theory: rely on simplifying assumptions (reduced dimensionality, non-evolving pulse, low-amplitude limit).



AI/machine learning: navigate high-dimensional parameter space, reduce time/computational cost.

Motivation of our work

Project OPEN-34-34: Bayesian optimization of laser-driven electron accelerator.

Goal: For a given laser energy maximize the cut-off energy of the electron beam (without regard to other parameters) and identify the corresponding input laser and plasma parameters.

Method: computer simulations (particle-in-cell method) + machine learning (Bayesian optimization).

Possible application: LWFA-driven muon production for muon radiography or nuclear activation.

Assumptions

1. Laser energy and wavelength given (10 mJ and 1 μm).
2. Gaussian laser pulse, linear polarization, constant spectral phase.
3. Laser spot size and amplitude set according to matching conditions [W. Lu et al., *Phys. Rev. Lett.* **96**, 165002 (2006)].
4. Self-guiding in a uniform-density plasma.
5. External electron injection.

Under these assumptions, the problem is fully described only with 4 free parameters:

- laser pulse duration, τ_0, laser pulse amplitude, a_0, laser pulse spot size, w_0, and plasma density, n_e.

Maximum possible electron energy not necessarily achieved under these assumptions:

- non-Gaussian pulses [e.g., D. Oumbarek et al., *Sci. Rep.* **13**, 18466 (2023)],
- chirped pulses [e.g., H. T. Kim et al., *Sci. Rep.* **7**, 10203 (2017)],
- tailored plasma targets [e.g., E. Guillaume et al., *Phys. Rev. Lett.* **115**, 155002 (2015)],
- strongly mismatched regime [e.g., K. Poder et al., *Phys. Rev. Lett.* **132**, 195001 (2024)].

Reducing number of free parameters

Matching conditions [W. Lu et al., *Phys. Rev. Lett.* **96**, 165002 (2006)]:

- provide self-guiding through plasma over long distances keeping the laser profile unchanged,
- found by balancing ponderomotive force with plasma restoring force (factor of 2 inferred from simulations),
- laser spot size is $w_0 = 2c\sqrt{a_0}/\omega_p$ and laser amplitude is $a_0 = 2(P_0/P_{cr})^{1/3}$.

4 parameters are reduced into 2:

$$a_0 = 2(P_0/P_{cr})^{1/3} \quad (3)$$

$$w_0/\lambda_0 = \frac{\sqrt{2}}{\pi}\left(2\sqrt{\pi \ln 2}/\tau_0\omega_p\right)^{1/3}(P_0/P_{cr})^{-1/6}(\varepsilon_0/\bar{\varepsilon})^{1/3} \quad (4)$$

$$\tau_0/T_0 = \sqrt{\ln 2/\pi}\left(2\sqrt{\pi \ln 2}/\tau_0\omega_p\right)^{-2/3}(P_0/P_{cr})^{-1/3}(\varepsilon_0/\bar{\varepsilon})^{1/3} \quad (5)$$

$$n_e/n_{cr} = \left(2\sqrt{\pi \ln 2}/\tau_0\omega_p\right)^{-2/3}(P_0/P_{cr})^{2/3}(\varepsilon_0/\bar{\varepsilon})^{-2/3} \quad (6)$$

where P_0/P_{cr} is the normalized laser power and $\tau_0\omega_p$ is the normalized laser duration.

Reducing range of free parameters

Laser power less than crit. power for self-focusing, $P_0 < P_{\mathrm{cr}}$ [G. Z. Sun et al., *Phys. Fluids* **30**, 526 (1987)]:

- Diffraction, acceleration not efficient.

Laser power much higher than crit. power for self-focusing, $P_0 \gg P_{\mathrm{cr}}$ [N. M. Naumova et al., *Phys. Rev. E* **65**, 045402 (2002)]:

- Risk of filamentation instability, soliton formation, acceleration not efficient.

Ratio of laser power to critical power for self-focusing:

$$\frac{P_0}{P_{\mathrm{cr}}} \approx 4.84 \times 10^{-24} \frac{\mathrm{cm\ s}}{\mathrm{J}} \frac{\lambda_0^2\, \varepsilon_0\, n_e}{\tau_0} \approx 1 \qquad (1)$$

Optimal pulse duration for wakefield generation (1D, Gaussian pulse, low-amplitude, circ. pol.) [W. Leemans et al., *IEEE Trans. Plasma Sci.* **24**, 331–342 (1996)] can be calculated as $\bar{\tau} = 2\sqrt{2\ln 2}\, /\, \omega_p$.

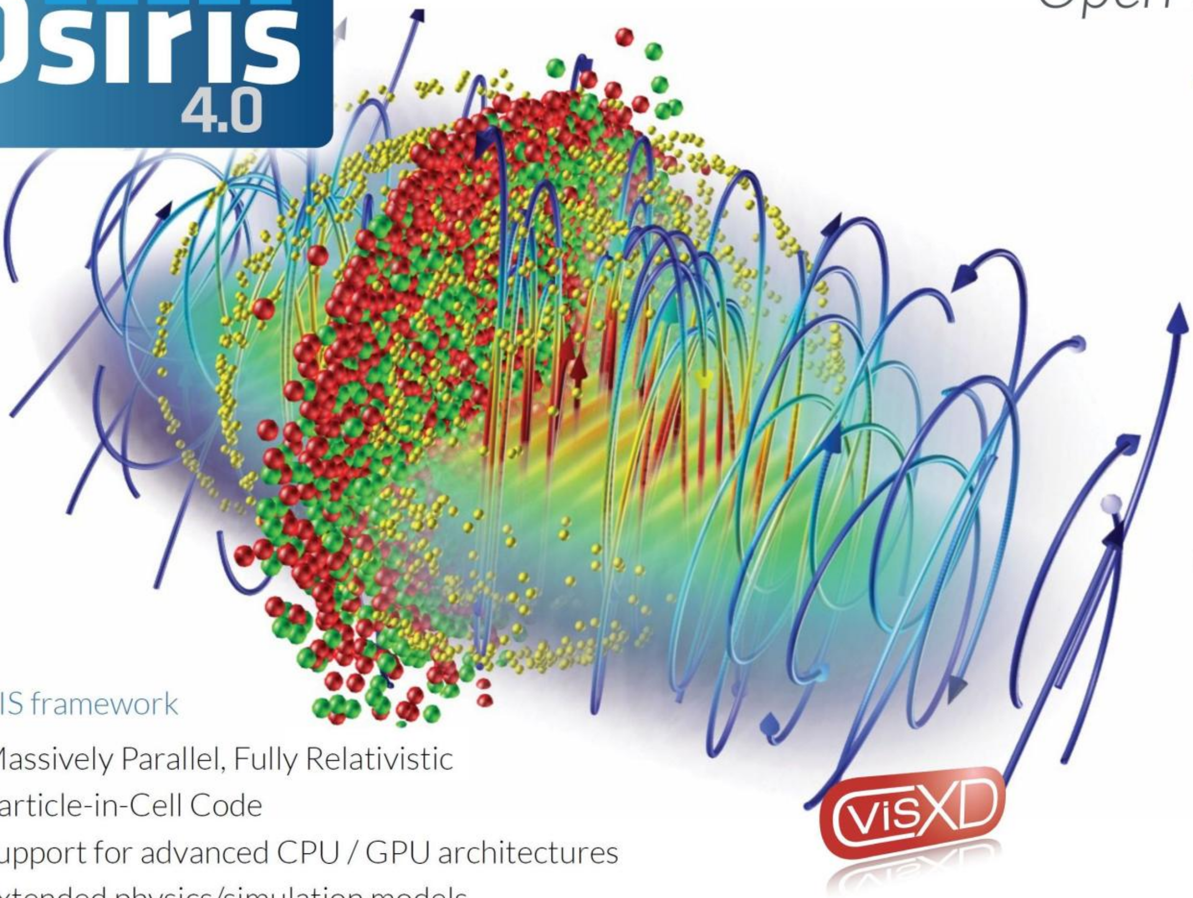
Ratio of laser pulse duration to optimal duration for wakefield generation:

$$\frac{\tau_0}{\bar{\tau}} \approx 1.7 \times 10^4 \frac{\mathrm{cm}^{3/2}}{\mathrm{s}}\ \tau_0\, n_e^{1/2} \approx 1 \qquad (2)$$

We select $P_0/P_{\mathrm{cr}} \in [1, 5]$ and $\tau_0 \omega_p \in [1, 5]$.

Osiris 4.0

Open-source version available



OSIRIS framework

- Massively Parallel, Fully Relativistic Particle-in-Cell Code
- Support for advanced CPU / GPU architectures
- Extended physics/simulation models
- AI/ML surrogate models and data-driven discovery

Open-access model

- 40+ research groups worldwide are using OSIRIS
- 400+ publications in leading scientific journals
- Large developer and user community
- Detailed documentation and sample inputs files available
- Support for education and training

Using OSIRIS 4.0

- The code can be used freely by research institutions after signing an MoU
- Open-source version at:

https://osiris-code.github.io/

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Optimization setup

Particle-in-cell (PIC) simulations:

- Numerical method for modeling plasma physics processes.
- Uses quasi-particles (representing groups of real particles) that move under the Lorentz force within electromagnetic fields computed on a static spatial grid.
- Using OSIRIS, massively parallel PIC code [R. A. Fonseca et al., *Computational Science - ICCS 2002*, 342–351 (2002)].
- Parallelization: MPI + OpenMP + AVX.
- Advanced numerical techniques (quasi-3D geometry - decompositions of electromagnetic fields into azimuthal Fourier modes, Moving window, Lorentz-boosted frame).

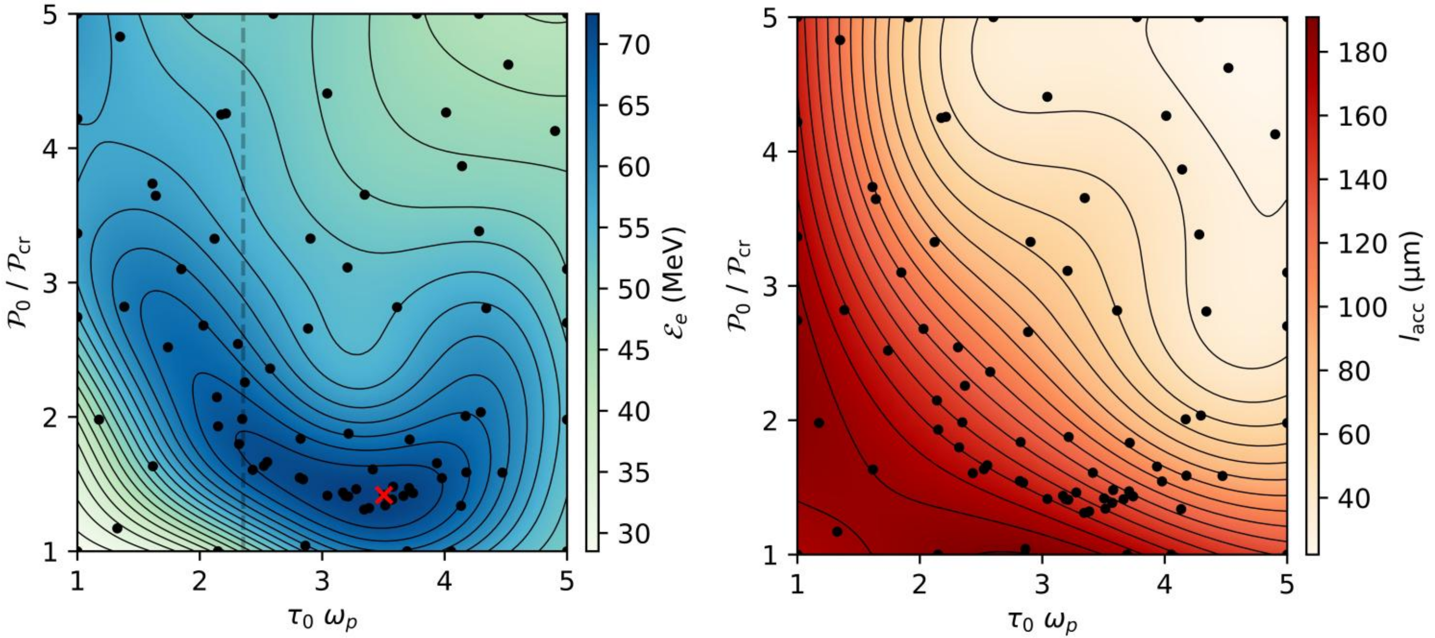
Bayesian optimization (BO):

- Machine learning method to optimize expensive-to-evaluate black-box functions while minimizing number of evaluations.
- Using OPTIMAS, a Python library for highly scalable optimization on supercomputers [A. Ferran Pousa et al., *Phys. Rev. Accel. Beams* **26**, 084601 (2023)].
- Gaussian process surrogate model with radial basis function kernel (objective function infinitely differentiable).
- Monte-Carlo based batched upper confidence bound acquisition function (trade-off between exploration and exploitation, multiple points selected and evaluated concurrently).

Typical job configuration (Project OPEN-34-34):

- Workload: 80 PIC simulations executed on Karolina CPU nodes.
- Resource allocation: 17 nodes in total (1 manager node – coordinates parameter generation and result collection, 16 worker nodes – run 8 simulations in parallel, asynchronously to handle non-uniform runtimes).
- Parallelization: each simulation uses 2 nodes, with 32 MPI processes and 4 OpenMP threads per node.
- Queue: qcpu with 48-hour walltime.

Optimization results for $10\ \mathrm{mJ}$ laser



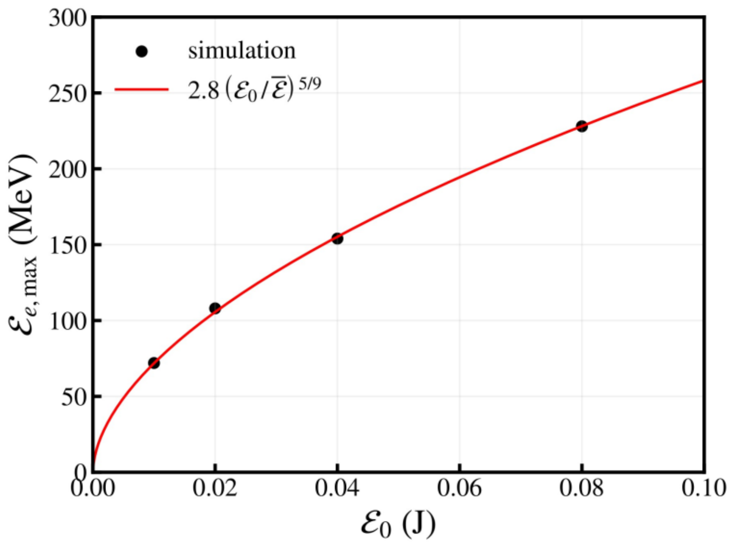
$\varepsilon_{e,\max} \approx 72\ \mathrm{MeV}$
$l_{acc} \approx 143\ \mu\mathrm{m}$

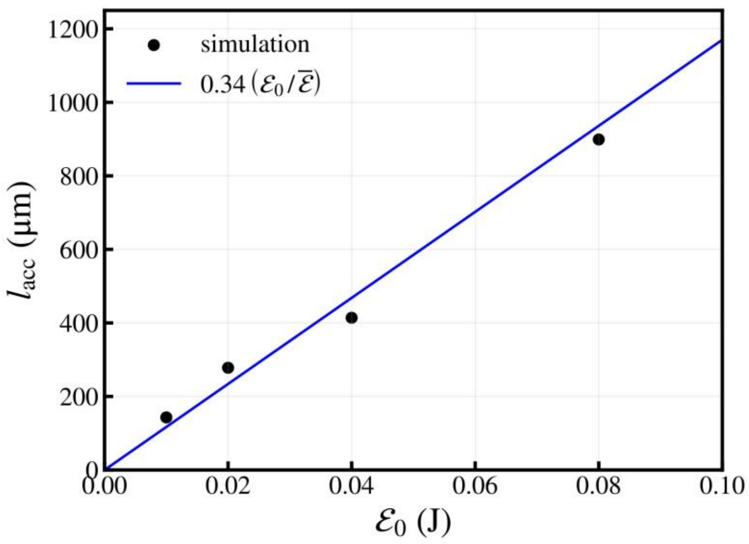
$P_0/P_{cr} \approx 1.42$
$\tau_0\ \omega_p \approx 3.50$

$\tau_0 \approx 9.5\ \mathrm{fs}$
$w_0 \approx 3\ \mu\mathrm{m}$
$a_0 \approx 2.3$
$n_e \approx 3 \times 10^{19}\mathrm{cm}^{-3}$

P. Valenta et al., *Physical Review Accelerators and Beams* **28**, 094601 (2025).
P. Valenta et al., *Proc. SPIE 13534, Laser Acceleration of Electrons, Protons, and Ions VIII*, 1353406 (2025).

Optimized scaling of laser-driven electron accelerators



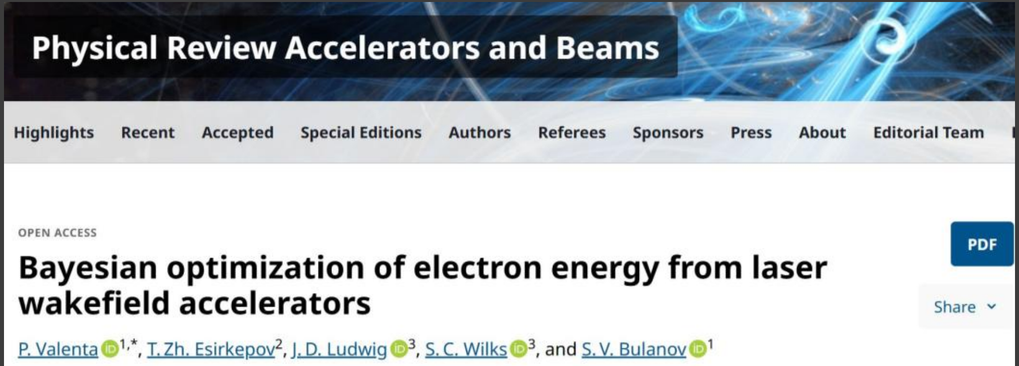


- **L1 laser (100 mJ):** 260 MeV, 1.2 mm
- **L2 laser (3 J):** 1.7 GeV, 3.5 cm
- **L3 laser (30 J):** 6.1 GeV, 35 cm
- **L4 laser (1.5 kJ):** 54 GeV, 18 m

P. Valenta et al., *in preparation.*

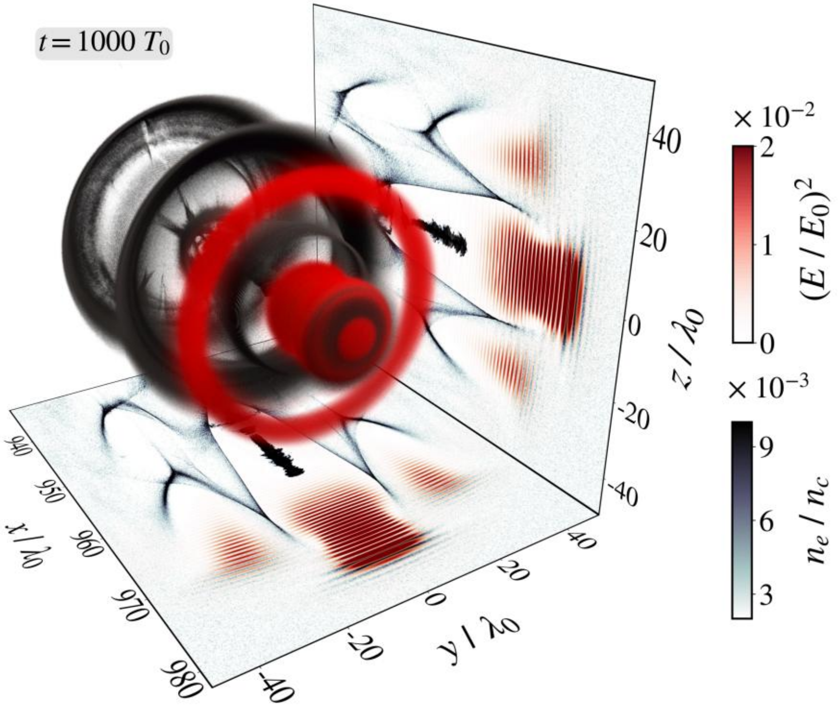
Conclusion

- With PIC simulations and BO we demonstrate that 10 mJ laser pulse can accelerate electrons to > 70 MeV over < 150 μm.
- We found that for given laser energy, there exists an optimal laser amplitude (power) for LWFA. Increasing amplitude (power) beyond this optimal value does not increase electron energy.
- Ultimate goal is to formulate scaling laws for electron energy and corresponding acceleration distance that:
  1. are expressed in terms of laser energy,
  2. are optimized (i.e., for given laser energy they must give maximum possible electron energy),
  3. are expressed along with the full set of input parameters, that enable the scaling.
- More details (including preformed plasma channel) in [P. Valenta et al., *Phys. Rev. Accel. Beams* **28**, 094601 (2025)]:

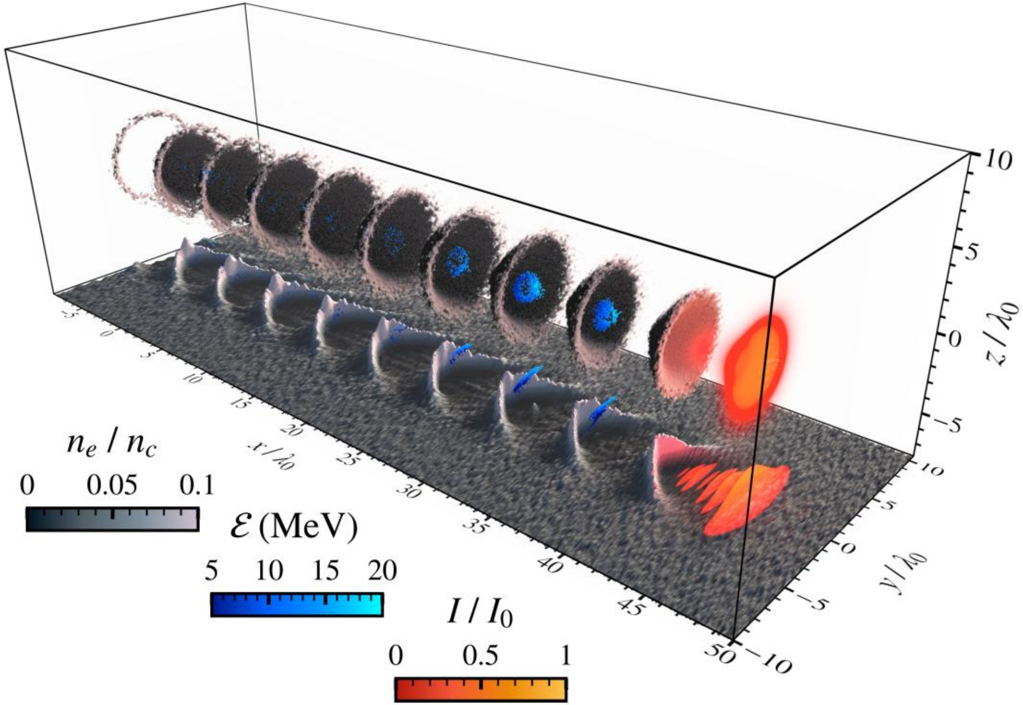


Data analysis and visualization

The following figures were created using the combination of the following software: `Python, matplotlib, Blender, Bheappe`



Published in P. Valenta et al., *Physics of Plasmas* **28**, 122104 (2021).



Published in C. M. Lazzarini et al., *Physics of Plasmas* **31**, 030703 (2024).

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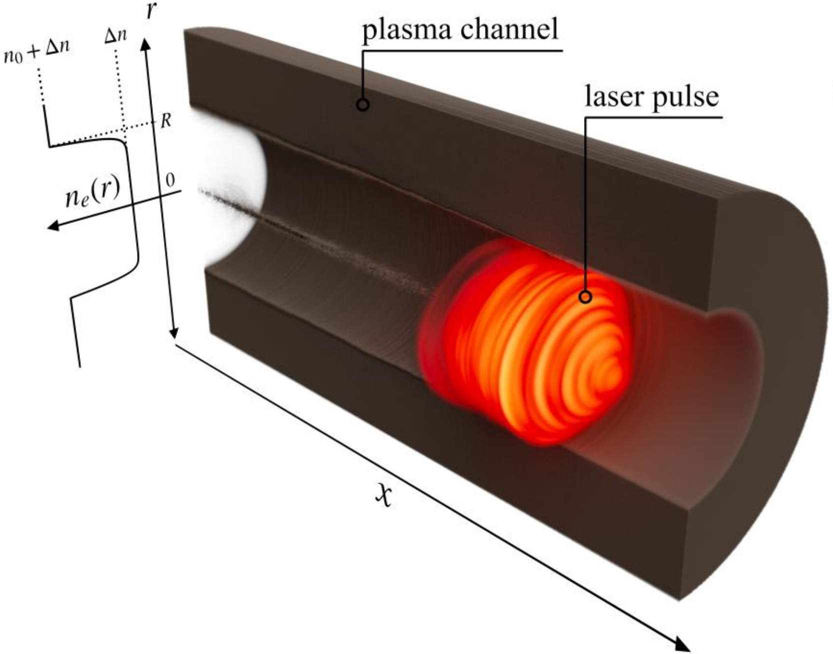

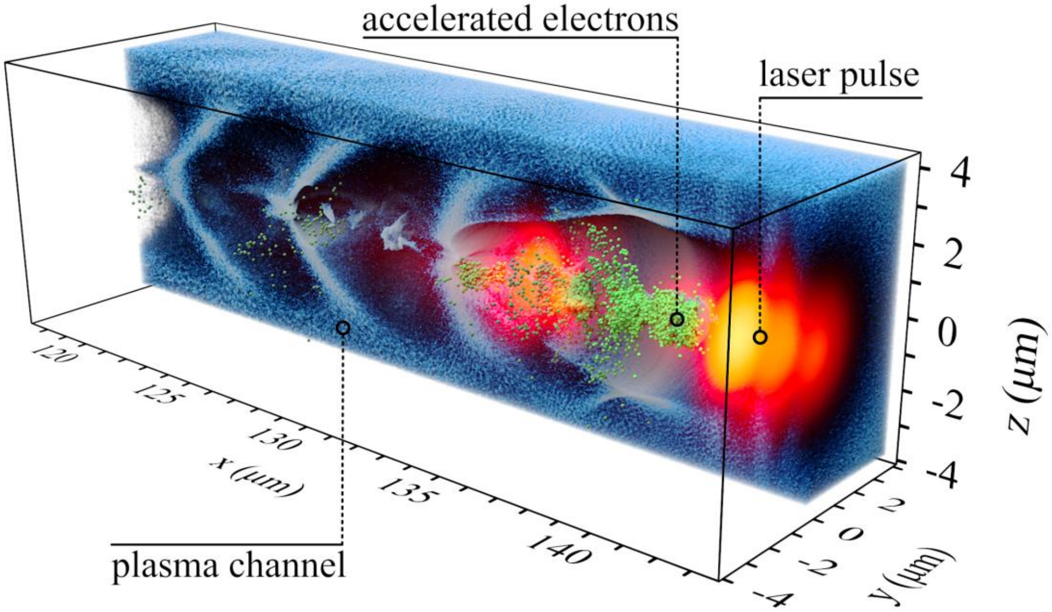

Published in P. Valenta et al., *Physical Review E* **109**, 065204 (2024).

Published in P. Valenta et al., *Physical Review Accelerators and Beams* **28**, 094601 (2025).

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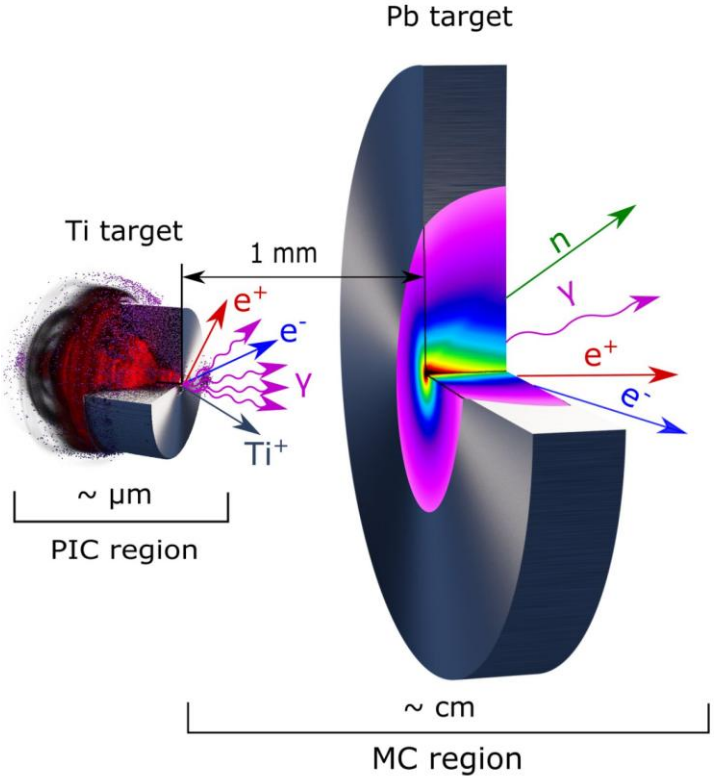
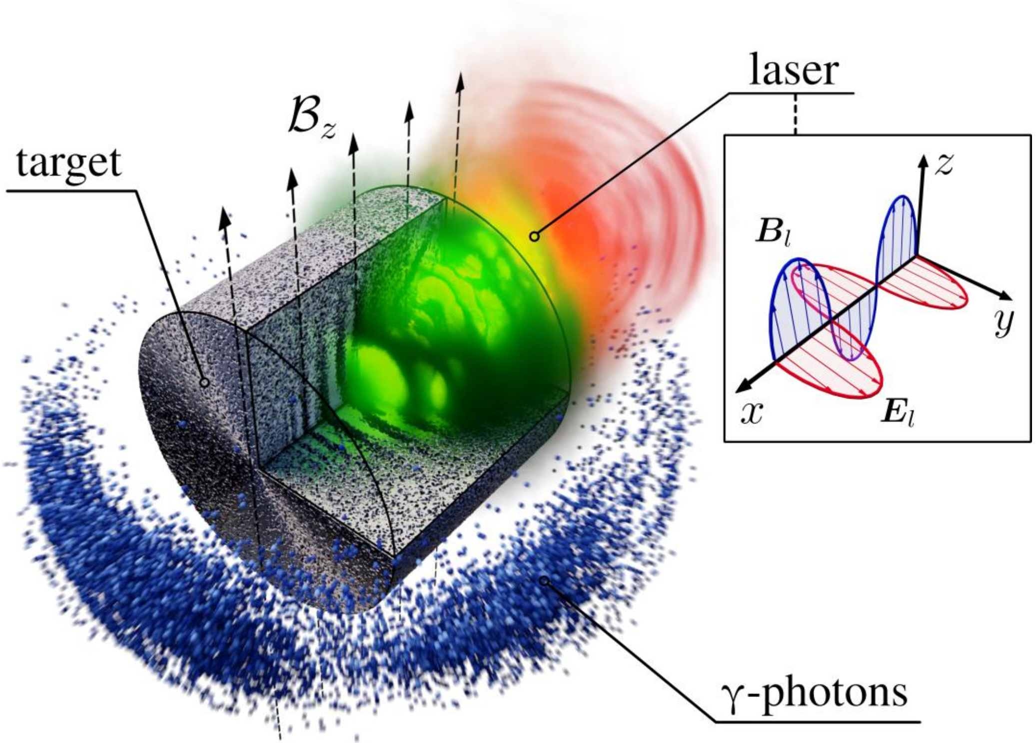


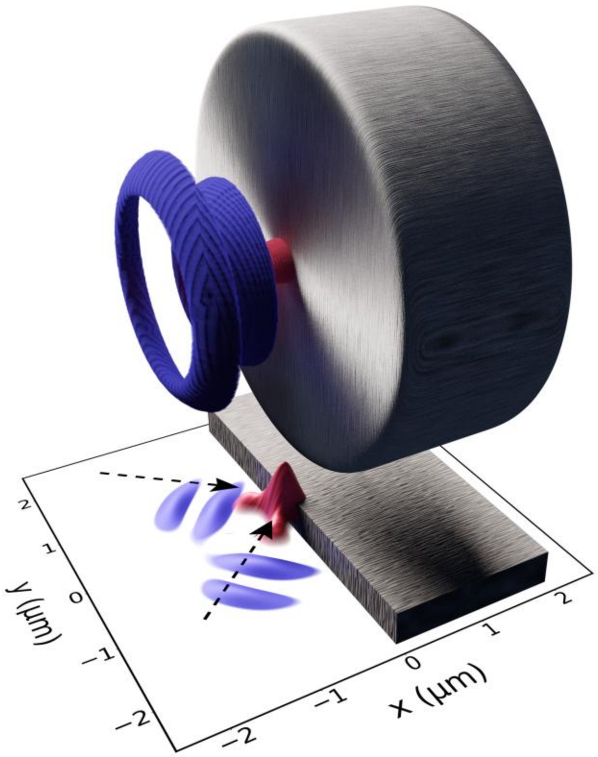
Published in D. Kolenaty et al., *Physical Review Research* **4**, 023124 (2022).

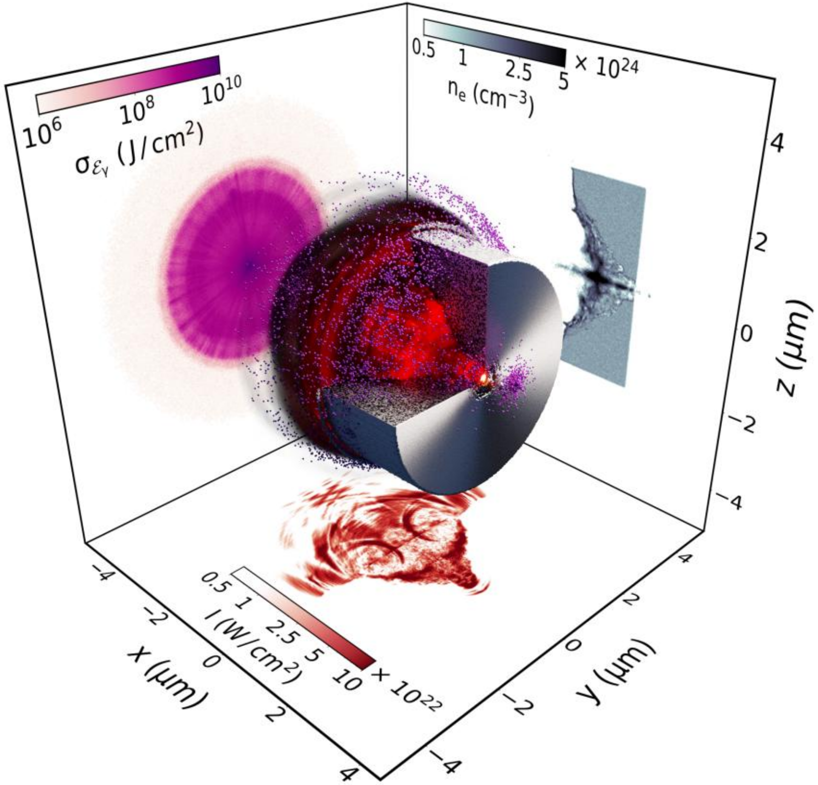


Published in P. Hadjisolomou et al., *Physical Review Research* **5**, 043153 (2023).

Data analysis and visualization

The following figures were created using the combination of the following software: `Python`, `matplotlib`, `Blender`, `Bheappe`





Published in P. Hadjisolomou et al., *Physical Review E* **104**, 015203 (2021).

Projects and publications

Principal Investigator of the following projects:

Project ID	Period	Title	Allocation
OPEN-34-34	2025 - 2026	Bayesian optimization of laser-driven electron accelerator	22,600 node hours (Karolina CPU) + 13,400 node hours (Barbora NG)
OPEN-30-14	2024 - 2025	Intense and compact muon sources for science and security	35,000 node hours (Karolina CPU)
OPEN-26-49	2022 - 2023	Laser-driven electron acceleration at kHz repetition rate	19,000 node hours (Karolina CPU)
OPEN-21-32	2021	Relativistic Mirrors in Laser-Plasma Interaction IV	610,000 CPU hours (Salomon)
OPEN-18-40	2020	Relativistic Mirrors in Laser-Plasma Interaction III	645,000 CPU hours (Salomon)
OPEN-15-50	2019	Relativistic Mirrors in Laser-Plasma Interaction II	400,000 CPU hours (Salomon)

Projects and publications

Publications in peer-reviewed journals:

[1] P. Valenta et al., *Physical Review Accelerators and Beams* **28**, 094601 (2025).

[2] P. Hadjisolomou et al., *Physical Review E* **111**, 025201 (2025).

[3] M. Matys et al., *New Journal of Physics* **27**, 033018 (2025).

[4] M. Matys et al., *Photonics* **12**, 436 (2025).

[5] P. Valenta et al., *Physical Review E* **109**, 065204 (2024).

[6] C. M. Lazzarini et al., *Physics of Plasmas* **31**, 030703 (2024).

[7] T. M. Jeong et al., *Reviews of Modern Plasma Physics* **8**, 9 (2024).

[8] P. Hadjisolomou et al., *Physical Review Research* **5**, 043153 (2023).

[9] M. Matys et al., *Photonics* **10**, 61 (2023).

[10] P. Hadjisolomou et al., *Journal of Plasma Physics* **88**, 905880104 (2022).

[11] D. Kolenaty et al., *Physical Review Research* **4**, 023124 (2022).

[12] P. Hadjisolomou, et al., *Physical Review E* **104**, 015203 (2021).

[13] P. Valenta et al., *Physics of Plasmas* **28**, 122104 (2021).

[14] P. Valenta et al., *Physical Review E* **102**, 053216 (2020).

[15] P. Valenta et al., *Physics of Plasmas* **27**, 032109 (2020).

[16] J. Mu et al., *Physical Review E* **102**, 053202 (2020)

[17] J. Mu et al., *Physics of Wave Phenomena* **27**, 247-256 (2019).

Publications in conference proceedings:

[1] P. Valenta et al., *Proc. SPIE 13534, Laser Acceleration of Electrons, Protons, and Ions VIII*, 1353406 (2025).

[2] M. Lamac et al., *Proc. SPIE 13534, Laser Acceleration of Electrons, Protons, and Ions VIII*, 1353408 (2025).

[3] M. Matys et al., *Proc. SPIE 13535, Research Using Extreme Light Infrastructures: New Frontiers with Petawatt-Level Lasers VI*, 1353503 (2025).

[4] P. Valenta et al., *Proc. SPIE 12580, Research Using Extreme Light: Entering New Frontiers with Petawatt-Class Lasers V*, 1258002 (2023).

[5] P. Valenta et al., *Proc. SPIE 11779, Laser Acceleration of Electrons, Protons, and Ions VI*, 14-22 (2021).

[6] P. Valenta et al., *Proc. SPIE 11037, Laser Acceleration of Electrons, Protons, and Ions V*, 57-65 (2019).

[7] J. Mu et al., *Proc. SPIE 11039, Research Using Extreme Light: Entering New Frontiers with Petawatt-Class Lasers IV*, 9-13 (2019).

Thank you for your attention.

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