3rd EPS-TIG Hands-on Workshop
Petrovac na Moru, Montenegro
July 07 - 09, 2023

Extreme Light Infrastructure

What is ELI ERIC?

Mateusz Rebarz

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project supported by:
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What is ELI ?

The **Extreme Light Infrastructure** is the world's largest and most advanced high-power laser infrastructure and a global technology and innovation leader in high-power, high-intensity, and short-pulsed laser systems.

ELI is the first European Strategy Forum on Research Infrastructures (ESFRI) Landmark constructed in the Central Eastern European Member States. Three world-class high-power, high-repetition-rate laser facilities have been established in Czech Republic (ELI Beamlines), Hungary (ELI-ALPS) and Romania (ELI-NP)

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ELI Facilities

ELI BEAMLINES

Czech Republic, Dolní Břežany (outskirts of Prague)
(in ERIC since April 2021)

ELI ALPS

Hungary, Szeged
(in ERIC since April 2021)

ELI NP

Romania, Magurele (outskirts of Bucharest)
(in ERIC soon)

Extreme peak power: 10 PW

- Particles acceleration
- X-ray sources

Extreme pulse duration: 166 as

- Attosecond physics
- Few-cycle pulses from THz to UV

Extreme photon energy: 19 MeV

- Photonuclear physics
- Gamma sources

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What is ERIC ?

The **E**uropean **R**esearch **I**nfrastructure **C**onsortium (ERIC) is a legal framework created by the European Commission to allow the operation of Research Infrastructures of Pan-European interest.

Construction was possible with European Structural Investment Funds

The Czech Republic,
Host of Seat

Hungary,
Host

Italian Republic

ESIF

Lithuania

Federal Republic of Germany
Observer

Bulgaria
Observer

European International Organisation Established in 2021

Member countries support ELI ERIC jointly with national funding

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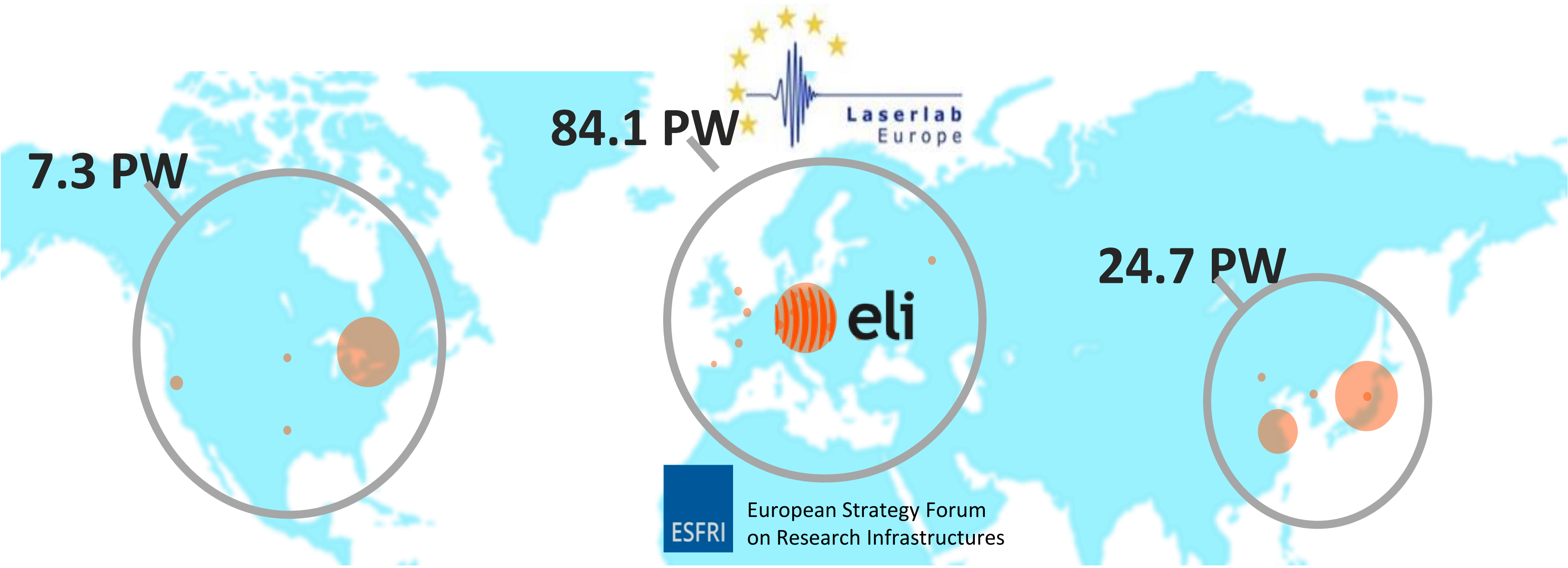
Petawatt-class lasers worldwide

Europe leads the world in laser production and installation, especially state-of-the-art systems

- **Investment** in high-power laser systems in Europe is connected to **a strong and relatively consolidated** community in Laserlab Europe beginning in 2001.
- **The ELI Facilities** are introducing **> 33 PW (3x10PW @10Hz systems)**



SOURCE: Courtesy of J.L. Collier, CLF RAL, UK

ELI vs Synchrotrons

Accelerator based sources

- ⊕ Reliability
- ⊕ Tuneability
- ⊕ Flux
- ⊖ Limited temporal resolution
- ⊖ Synchronization

Laser-driven sources

- ⊕ Synchronization
- ⊕ Temporal resolution
- ⊕ Flexibility (pump-probe)
- ⊖ Limited tuneability
- ⊖ Flux

High complementarity between synchrotrons and ELI infrastructure

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Available end-stations

Optical stations

- UV-VIS-IR Transient Absorption
- Stimulated Raman Spectroscopy
- Time-Resolved Ellipsometry
- Transient Current Technique

Soft X-ray stations

- Electron and Ion Time of Flight
- Coherent Diffractive Imaging
- VUV Ellipsometry

Hard X-ray stations

- Time-Resolved X-ray Diffraction
- Time-Resolved X-ray Absorption

Acceleration stations

- Laser-Plasma Electron Accelerator
- Laser-Plasma Ion Accelerator

Others

- Nonlinear THz Spectroscopy
- Photoemission electron microscopy (PEEM)

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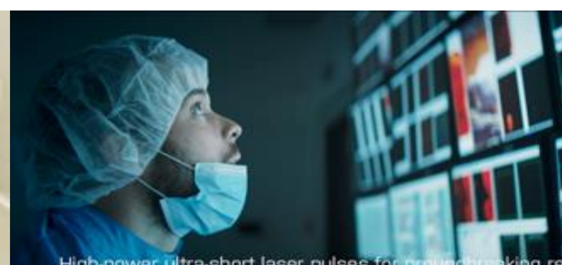
Access to ELI Infrastructure

ELI ERIC is Open to the World

A user facility with three access modes

- **Excellence-Based Access** – Evaluation of proposals by international peer-review panels. ***Results of experiments published and open.***
- **Mission-Based Access** – Thematic research granted on the basis of scientific missions pursuing challenges. Proposals reviewed by international panels. ***Results published and open.***
- **Proprietary Access** – Paid access for industrial or other users. ***Results are retained by the user,*** consistent with ELI ERIC's Data and IPR Policy.



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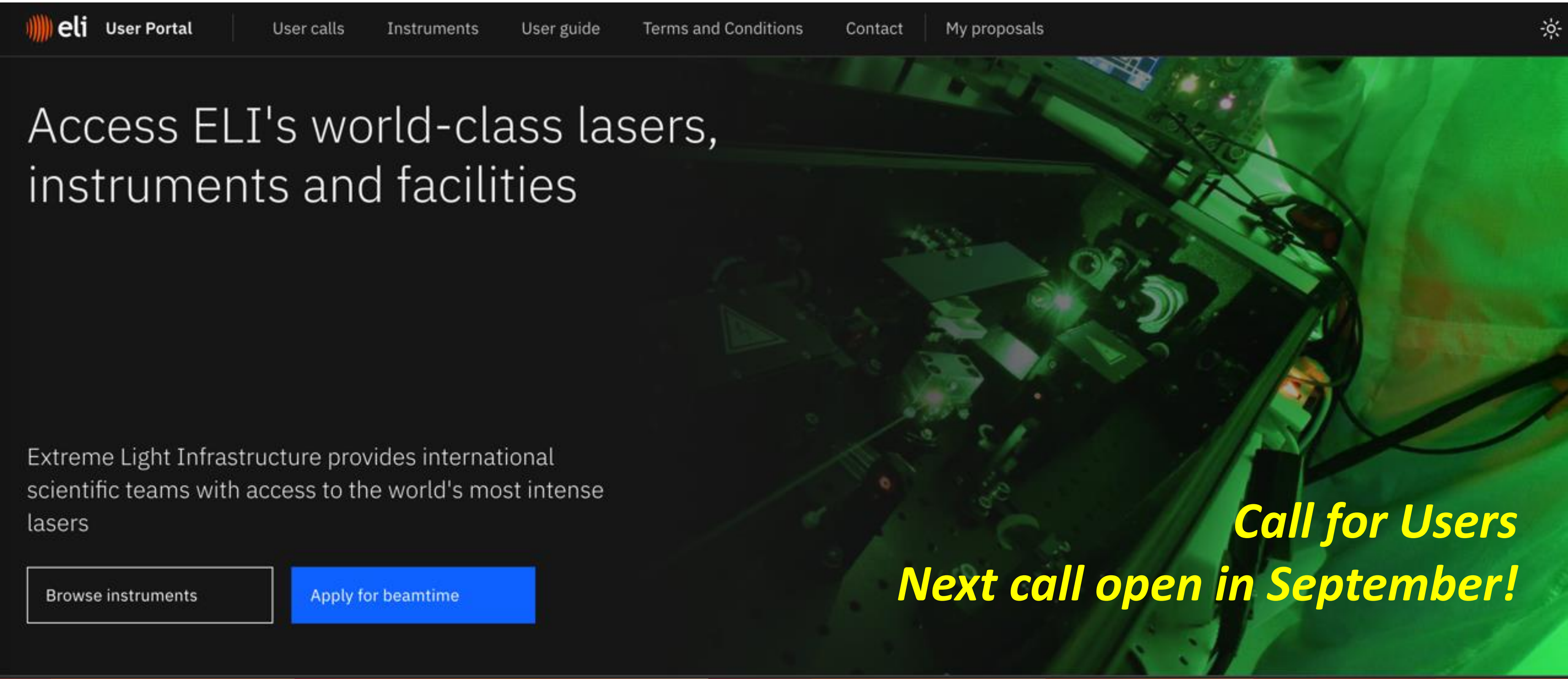
Calls for Users

User Portal: ***https://up.eli-laser.eu/***



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Extreme Light

What does it mean?

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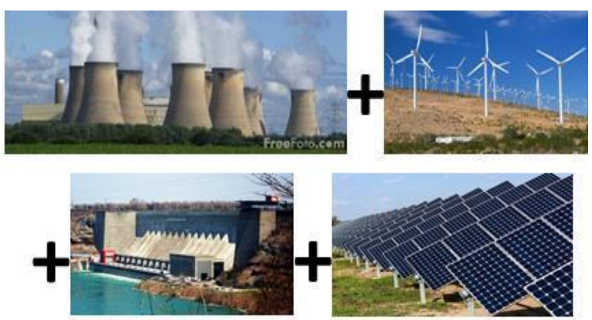
Ultra-high power
(up to 10 PW)

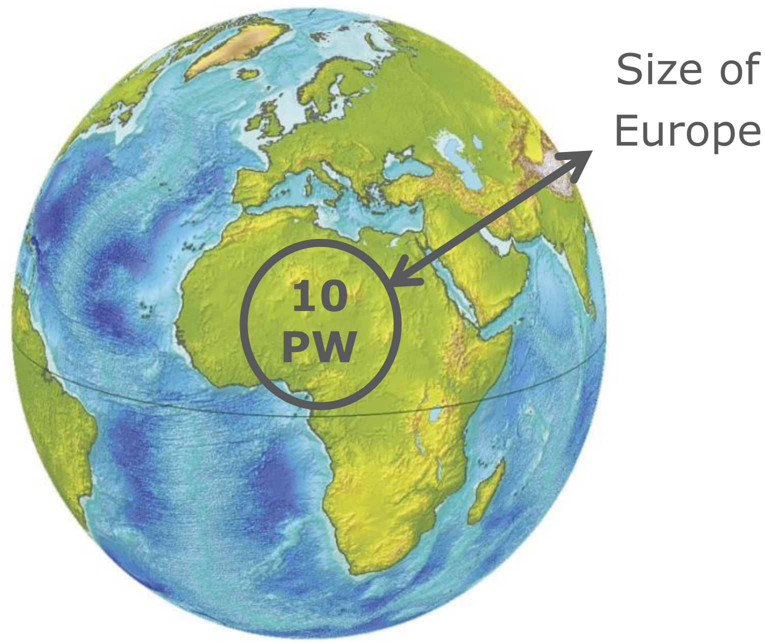
10 PW = 10^{16} W =
= 10 000 000 000 000 000 W

Total electricity generating capacity:

All World: 0.0053 PW
U.S. + EU: 0.0019 PW



Sun power shining on Earth:
174 PW



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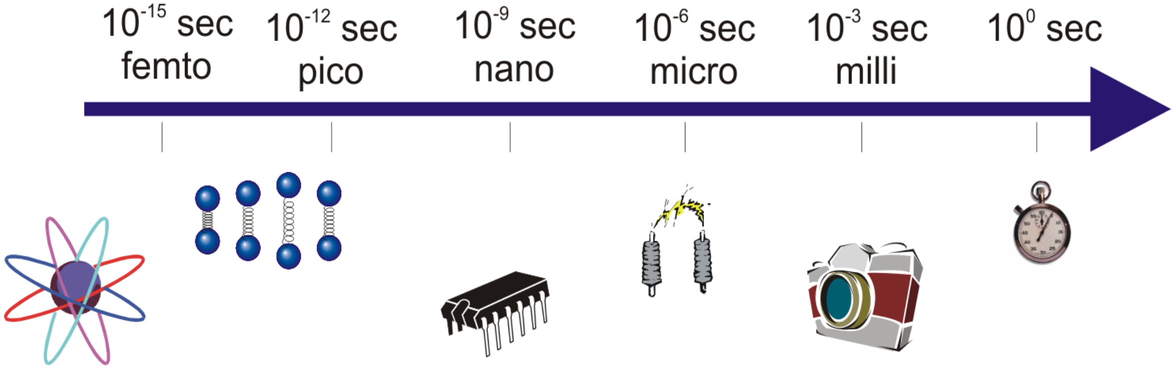
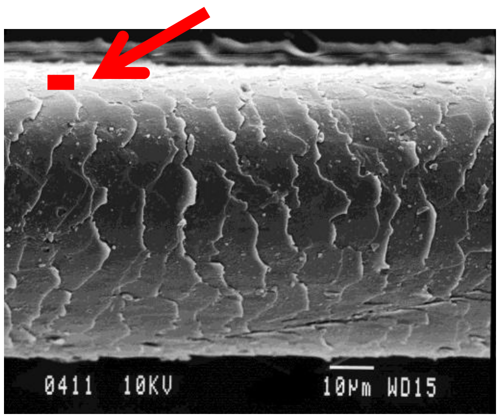
Ultra- short pulses
(100 as - 100 fs)

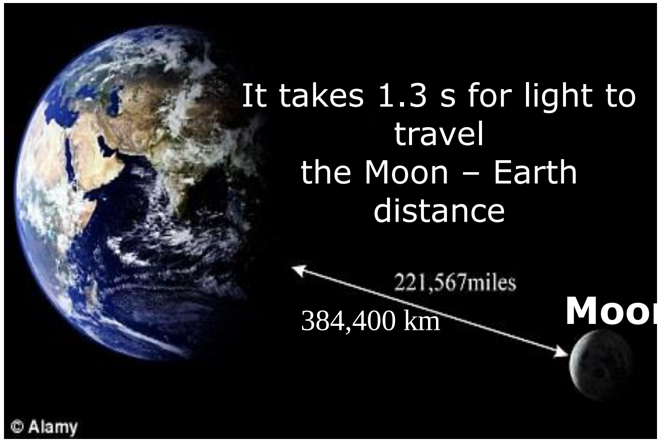


ELI Beamlines lasers
10 fs = 10^{-14} s =
0.000 000 000 000 01 s

3 µm = 0.003 mm



Light speed ~ 300 000 km/s



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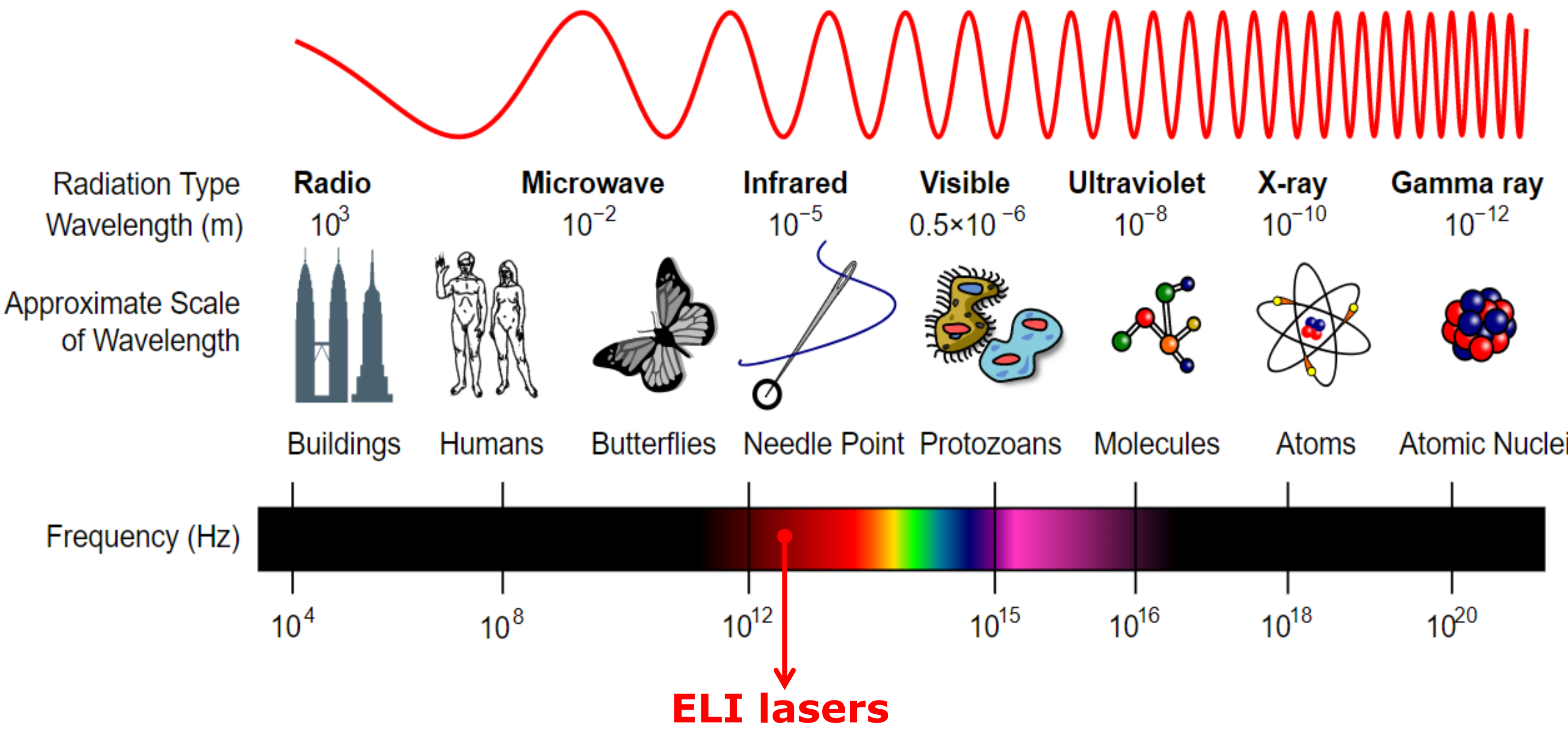
Ultra-broadband spectrum
(Radio…Gamma)



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Experimental Science at ELI

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Experimental science at ELI

Particle acceleration

Plasma physics

X-ray sources

Exotic physics

Bio/molecular and material science

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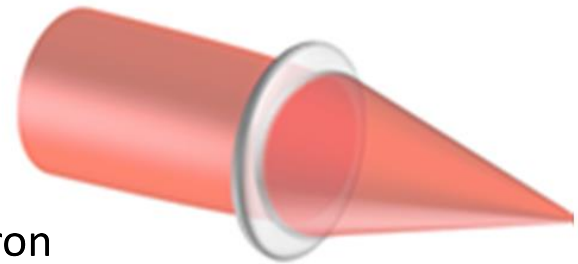
Exotic Physics

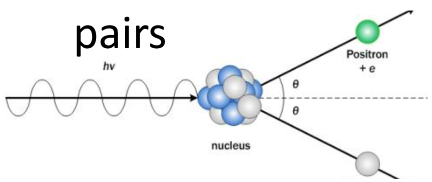
Relativistic regime: ultrahigh intensity interactions occurring in the laser field **> 10^{18} W/cm^2**

10 PW

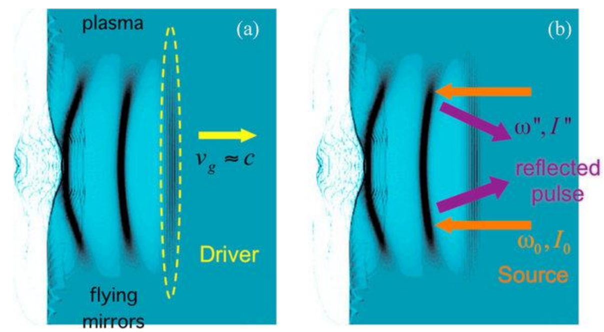


1 μm → **10^{24} W/cm^2**

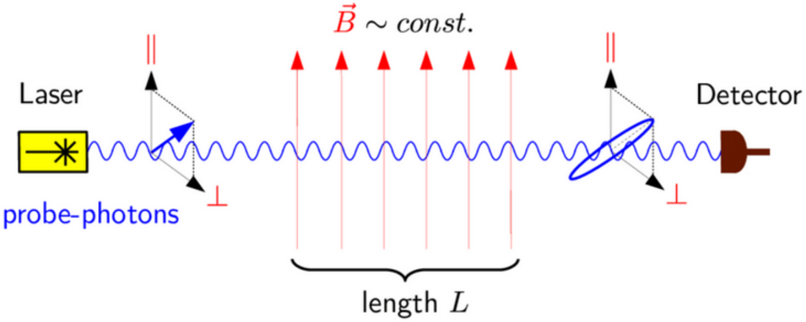
electron-positron pairs



Relativistic flying mirror



Vacuum birefringence



the focusing of a 10 PW laser pulse requires the use of sophisticated ellipsoidal plasma mirror setups (solid-state-based optics is not useful due to damage threshold)

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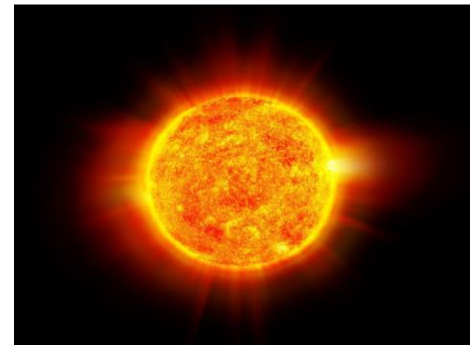
Plasma Physics

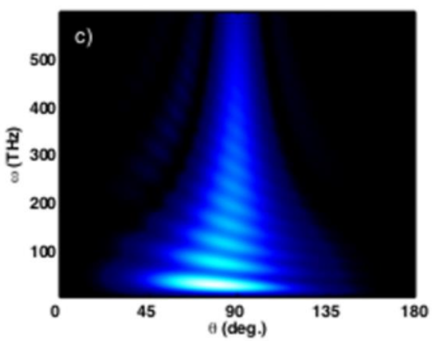
Plasma: fundamental state of matter representing most of the non-dark matter in the universe (electrons + ions + neutral atoms)

Laboratory astrophysics

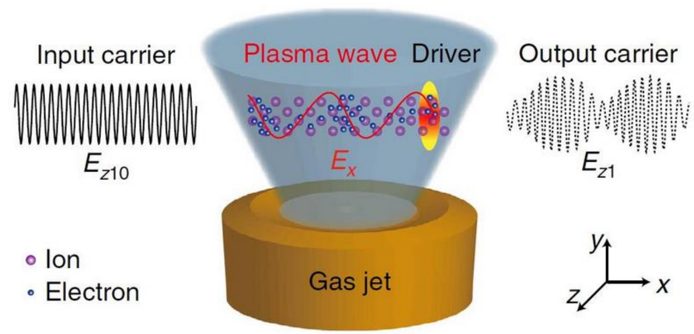
Thermonuclear fusion



Gravitational waves



Plasma optics



High-energy density plasma: pressures > 1 Mbar, energy densities > 10^{11} J/m^3.
Lasers are the only way to create such conditions in a controlled way in the laboratory.

Particle acceleration

Plasma physics

X-ray sources

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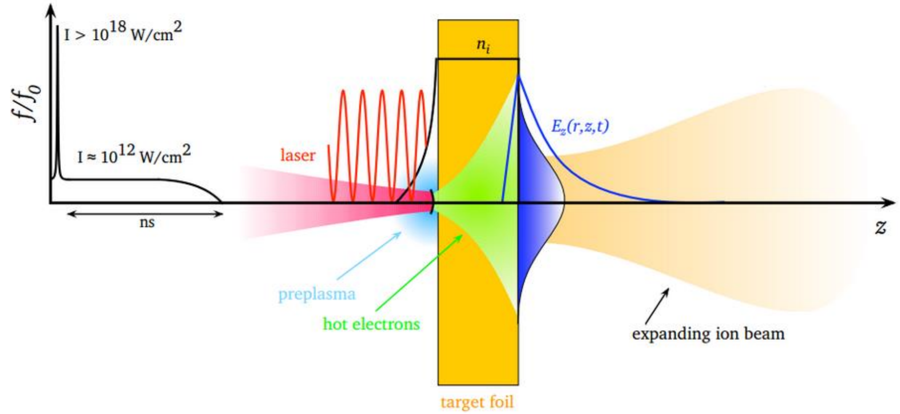
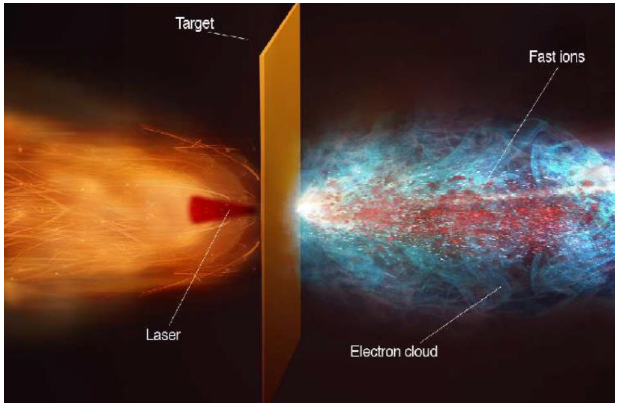
Ions acceleration

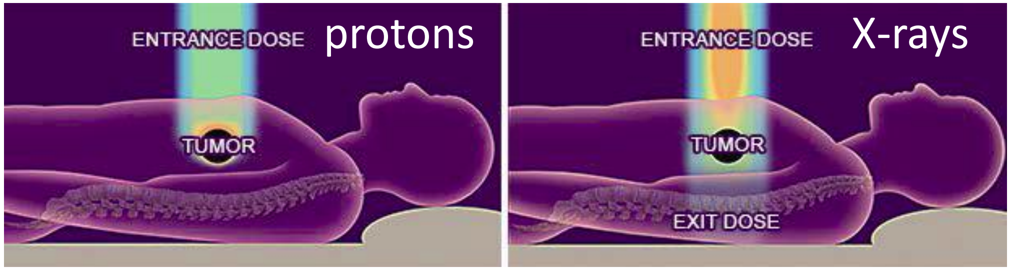
Target Normal Sheath Acceleration: laser generated collective displacement of a large number of electrons at the rear surface of **thin solid** target creates the field accelerating ions

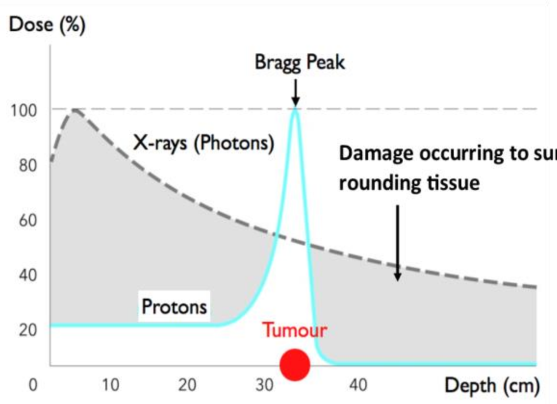
Rev. Mod. Phys. 85, 751





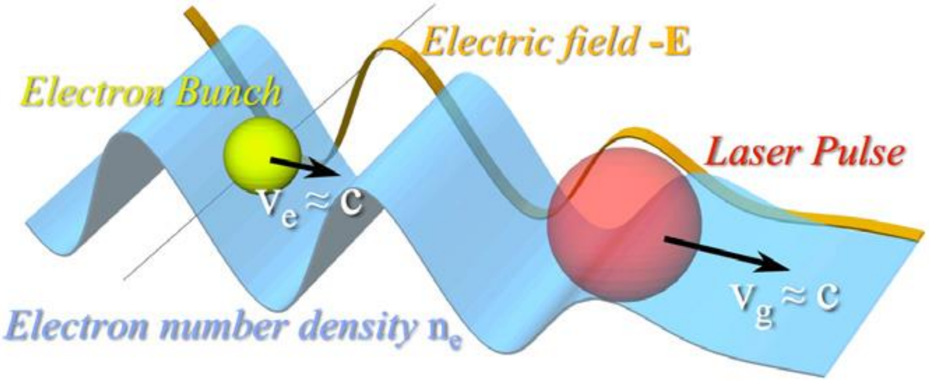
Application: Hadron therapy
method of a treatment of tumors using accelerated ions



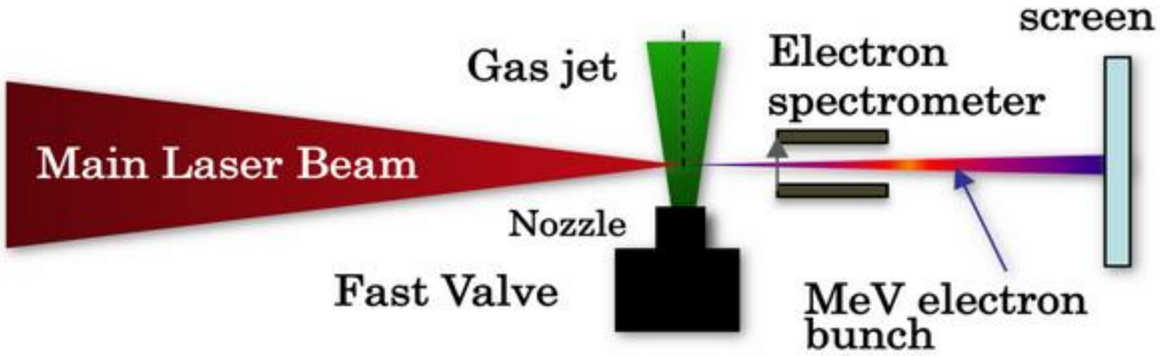


Electrons acceleration

Laser wakefield acceleration: laser pulse propagating through the **plasma** produces a wave behind which the electrons are accelerated



Plasma Phys. Control. Fusion 56 (2014) 084015



Application: LWFA sources x-rays are generated by the oscillations of energetic electron beams

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Experimental science at ELI Beamlines

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Exotic physics

Bio/molecular and material science

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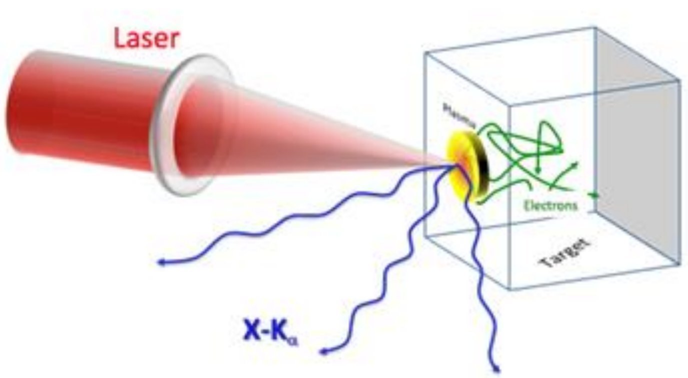
Laser driven X-ray sources

Focusing laser on the specific target

Plasma Source

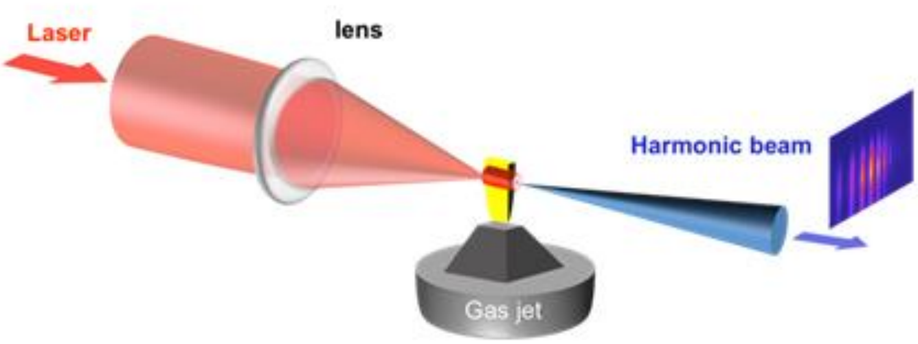


4-30 keV

100 fs

incoherent

High Harmonics



10-250 eV (5 -120 nm)

< 20 fs

coherent

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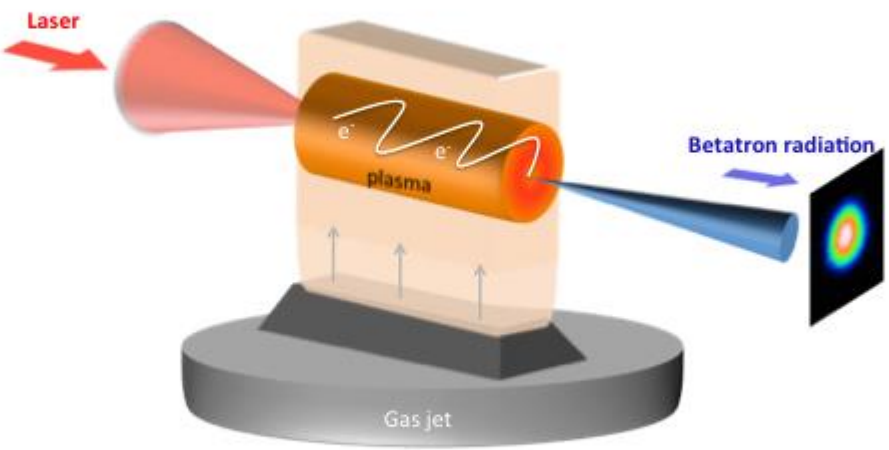
Laser driven X-ray sources

Oscillating Relativistic Electron Beams

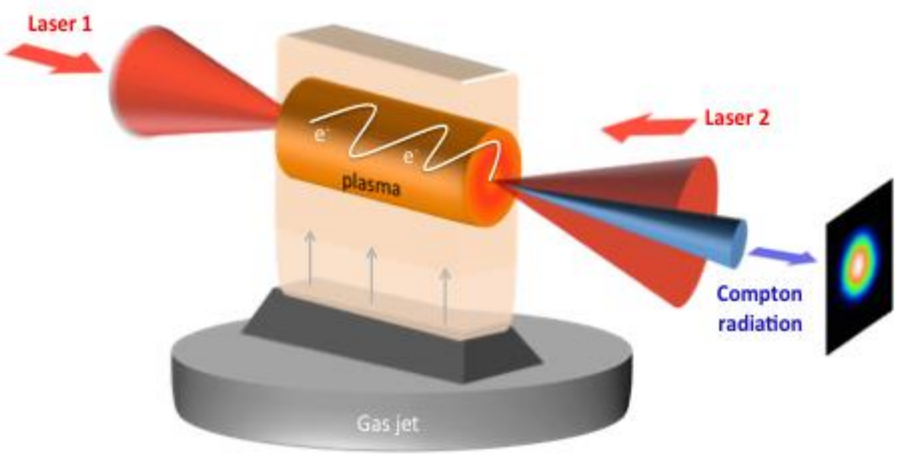
Betatron Source



1-100 keV

10 fs

Compton Source



100 keV - 5 MeV

10 fs

output pulses inherit the temporal profile of the laser-plasma electron bunch

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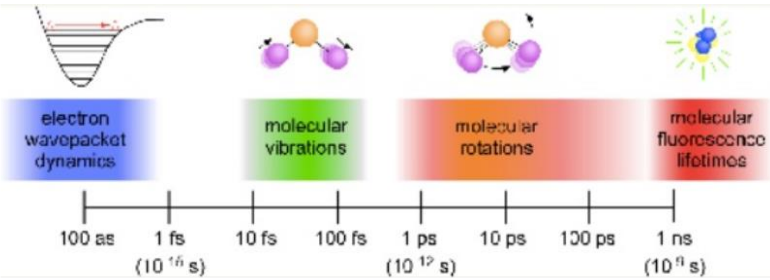
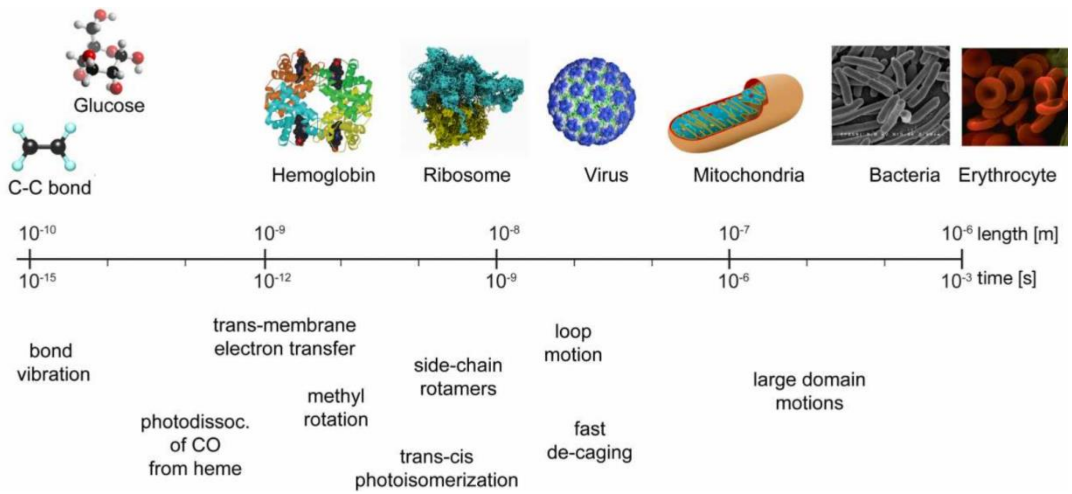
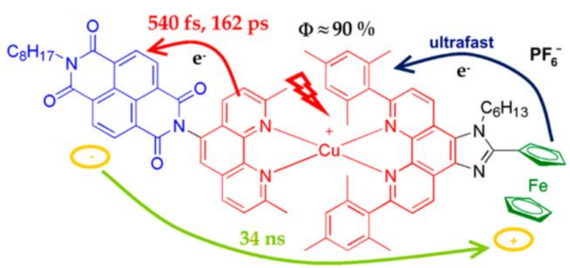
Bio/Molecular & Material Science

Time-resolved spectroscopy: any technique that allows to measure the temporal dynamics and the kinetics of photophysical processes

Photophysics Photochemistry Photobiology







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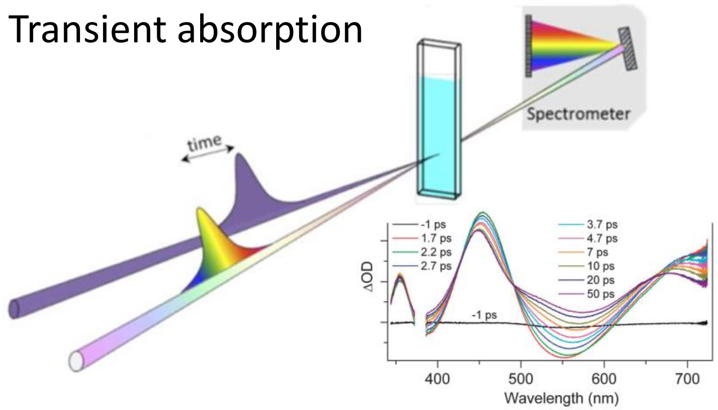
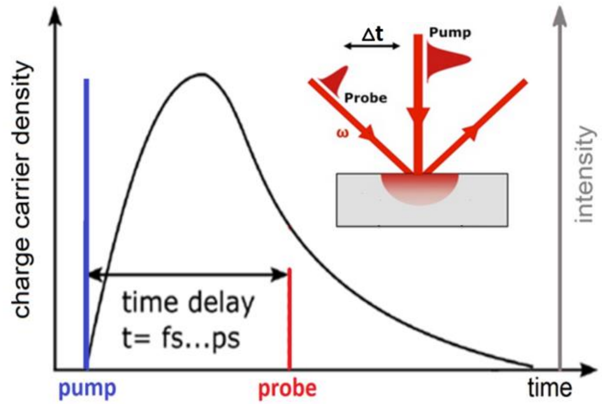
Pump-probe techniques at ELI

Transient absorption

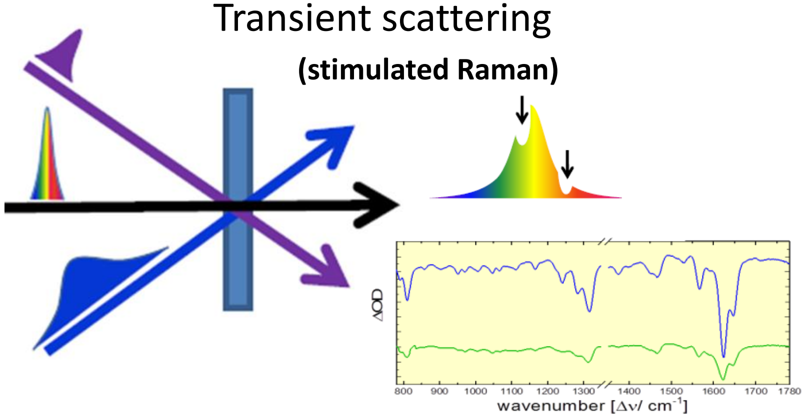


Transient reflection



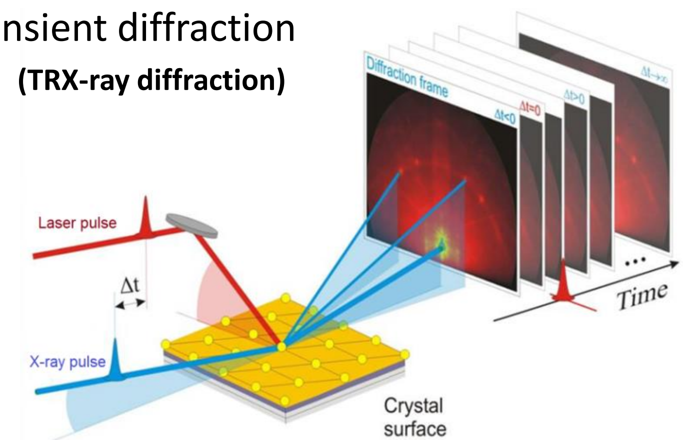
Transient scattering

(stimulated Raman)



Transient diffraction

(TRX-ray diffraction)



New values for society

New scientific challenges for technology development:

- Biomedical — Cancer treatment, new drug development
- Material — New materials, nanomaterials
- Molecular — New generation of chemical compounds
- Energetics — Laser fusion system, new energy sources

Technical solutions for industrial users:

- 3D imaging and diffraction of unique complex biological structures
- Extreme field conditions
- Optical spectroscopy and molecular dynamics
- Pump & probe experiments

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Ultrashort laser pulses

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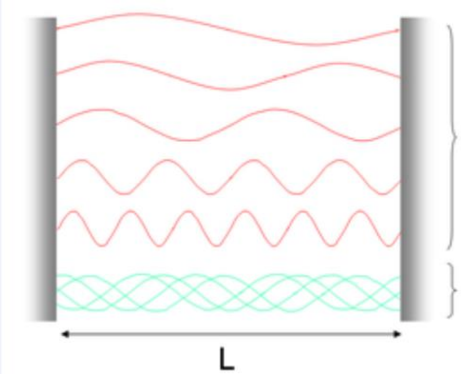
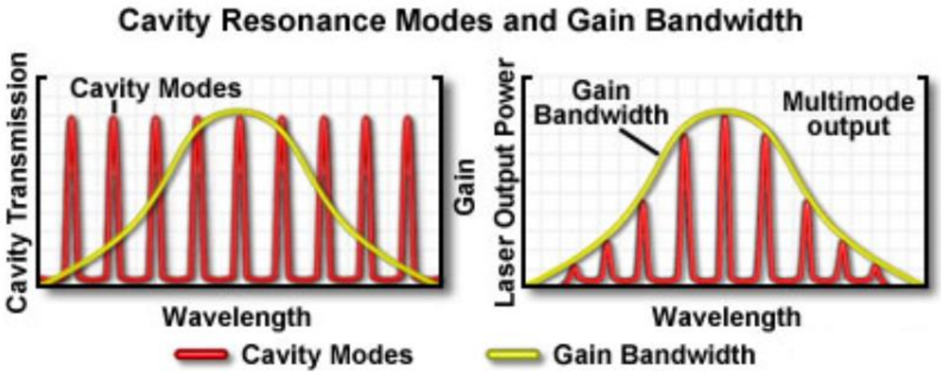
How to generate fs laser pulse ?



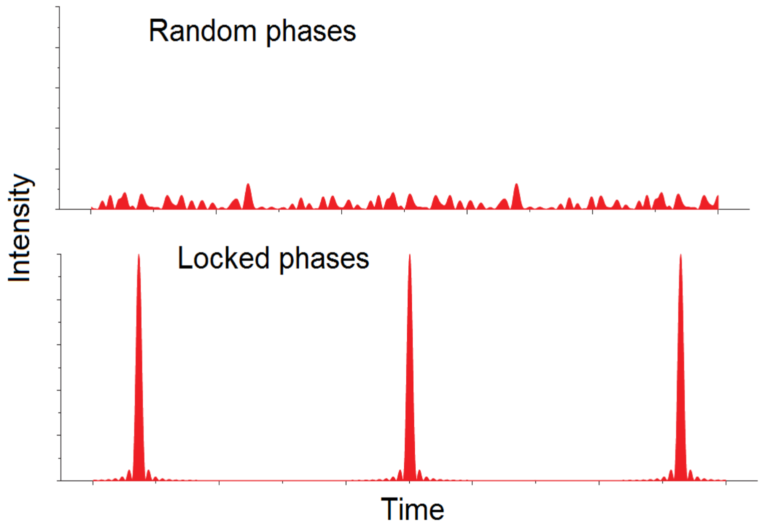
resonant modes

$$2L = q\lambda$$

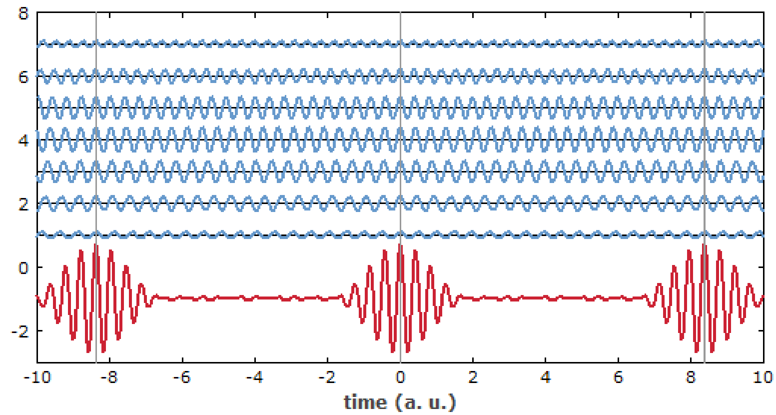
non-resonant modes



micro.magnet.fsu.edu

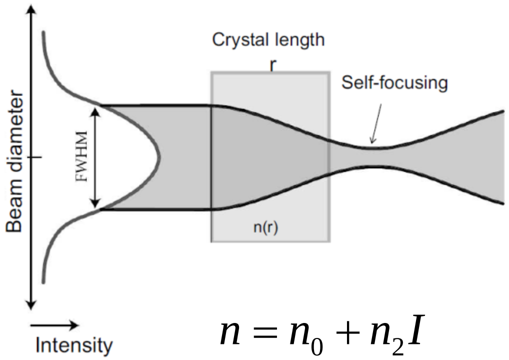


modelocking



How to generate fs laser pulse ?

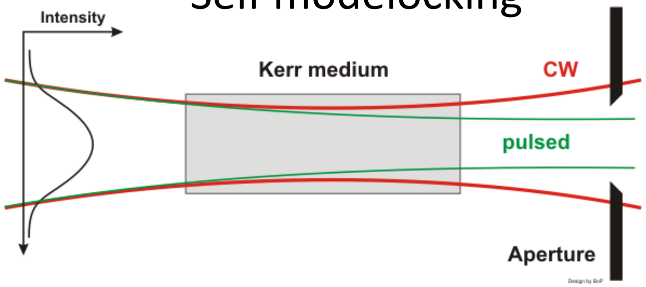
Optical Kerr effect – self-focusing



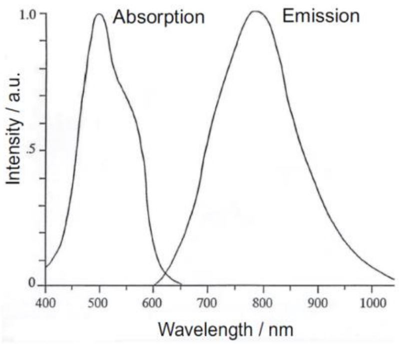
$$n = n_0 + n_2 I$$

self-focusing in air

Self modelocking



Ti:sapphire (Sapphire crystal doped with Titanium (Ti^{3+}) ions)



Absorption: 400 – 600 nm

Emission: 600 – 1000 nm

Actual tunability: 750 – 850 nm

Output of Ti:sapphire oscillator:

E ~ 5 nJ
λ ~ 800 nm
Δλ ~ 100 nm
Δt ~ 15-35 fs
Reprate ~ 80 MHz

$$\Delta t \geqslant K \frac{\lambda_0^2}{\Delta\lambda \cdot c}$$

Gauss-shape: K=0.44

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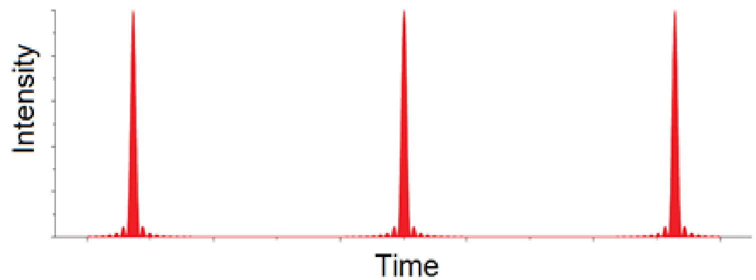
CPA technology

Femtosecond oscillator



Δt ~ 15 fs
λ ~ 800 nm
E ~ 5 nJ

Nobel Prize 2018
Gérard Mourou and Donna Strickland

Chirped Pulse Amplification

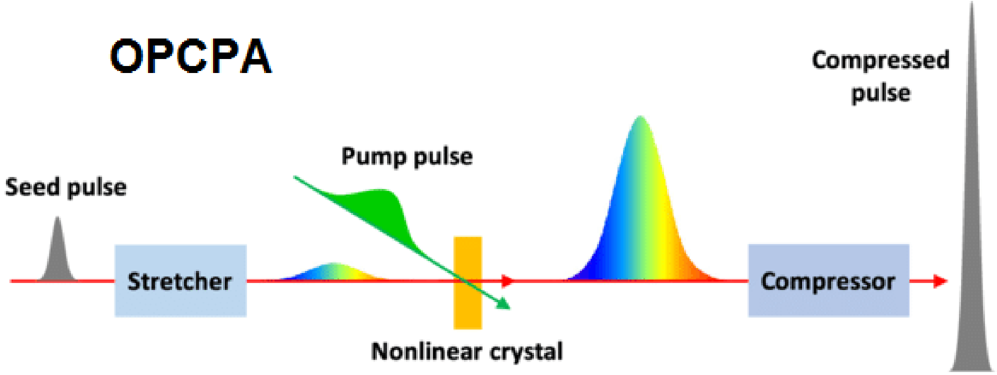
We start with a weak pulse → Result is an amplified short pulse

ELI Lasers

ELI Beamlines

L1	L2 *	L3	L4
5 TW	100 TW	1 PW	10 PW
100 mJ	2 J	30 J	1.5 kJ
15 fs	25 fs	30 fs	150 fs
1 kHz	50 Hz	10 Hz	0.01 Hz

* target in 2026



Technologies

DPSSL
Diode Pumped Solid State Laser
OPCPA:
Optical Parametric Chirped-Pulse Amplification

3rd EPS-TIG Hands-on Workshop
Petrovac na Moru, Montenegro
July 07 - 09, 2023

ELI Beamlines

Mateusz Rebarz

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ELI Beamlines

ELI Beamlines is an international user facility for fundamental and applied research using ultra-intense laser and particle beams

Beamline	L1	L2	L3	L4
Peak power	>5 TW	PW	≥PW	10 PW
Energy in pulse	100 mJ	≥15 J	≥30 J	≥1.5 kJ
Pulse duration	<20 fs	≤15 fs	≤30 fs	≤150 fs
Rep rate	1 kHz	10 Hz, >10 Hz	10 Hz	1 per min

- Department of Laser Systems

Experimental departments

- Department of Plasma Physics and Ultra-high Intensity Interactions
- Department of Radiation Physics and Electron Acceleration
- Department of Ion Acceleration and Applications of High Energy Particles
- Department of Structural Dynamics

Czech Republic
Dolní Břežany (on the outskirts of Prague)

www.eli-beams.eu

ELI Beamlines

Laser building

16,500 m²

Laboratories

4,500 m²

Offices

4,400 m²

Multifunction areas

2,300 m²

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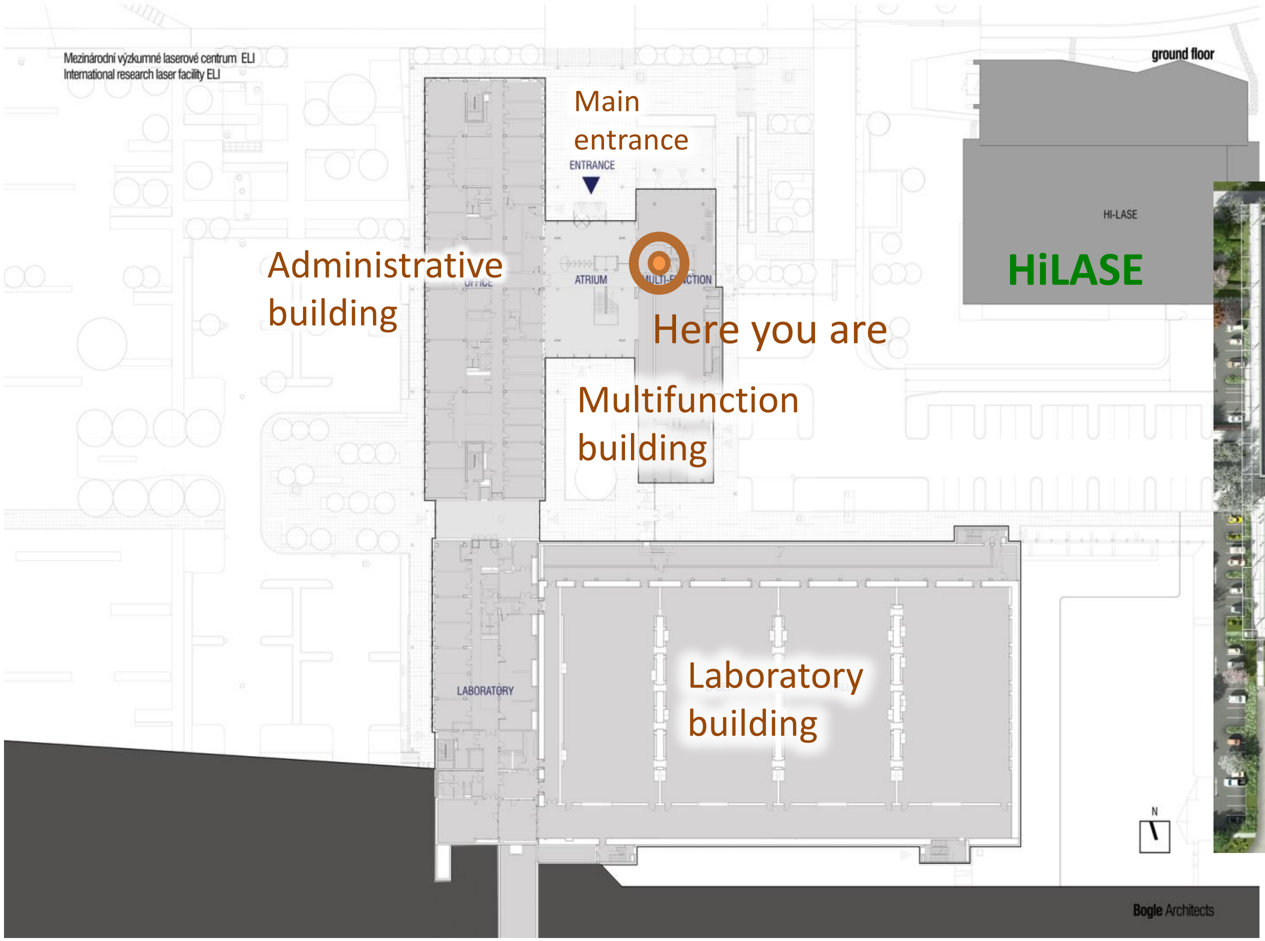
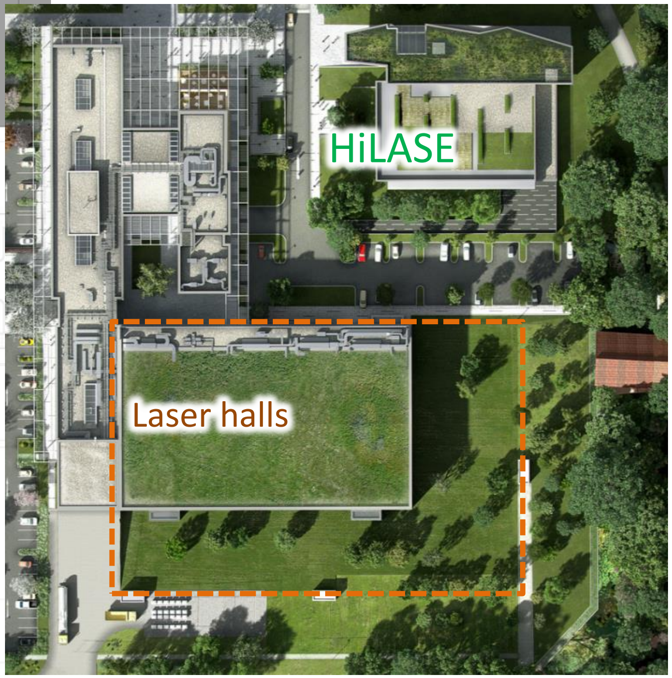
ELI Beamlines





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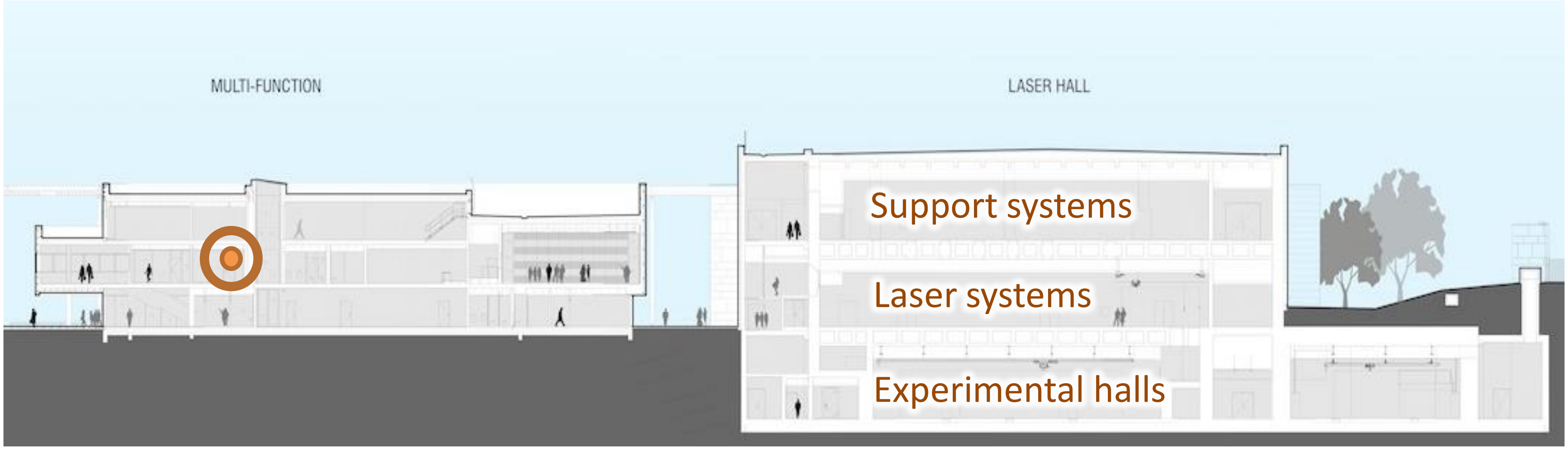
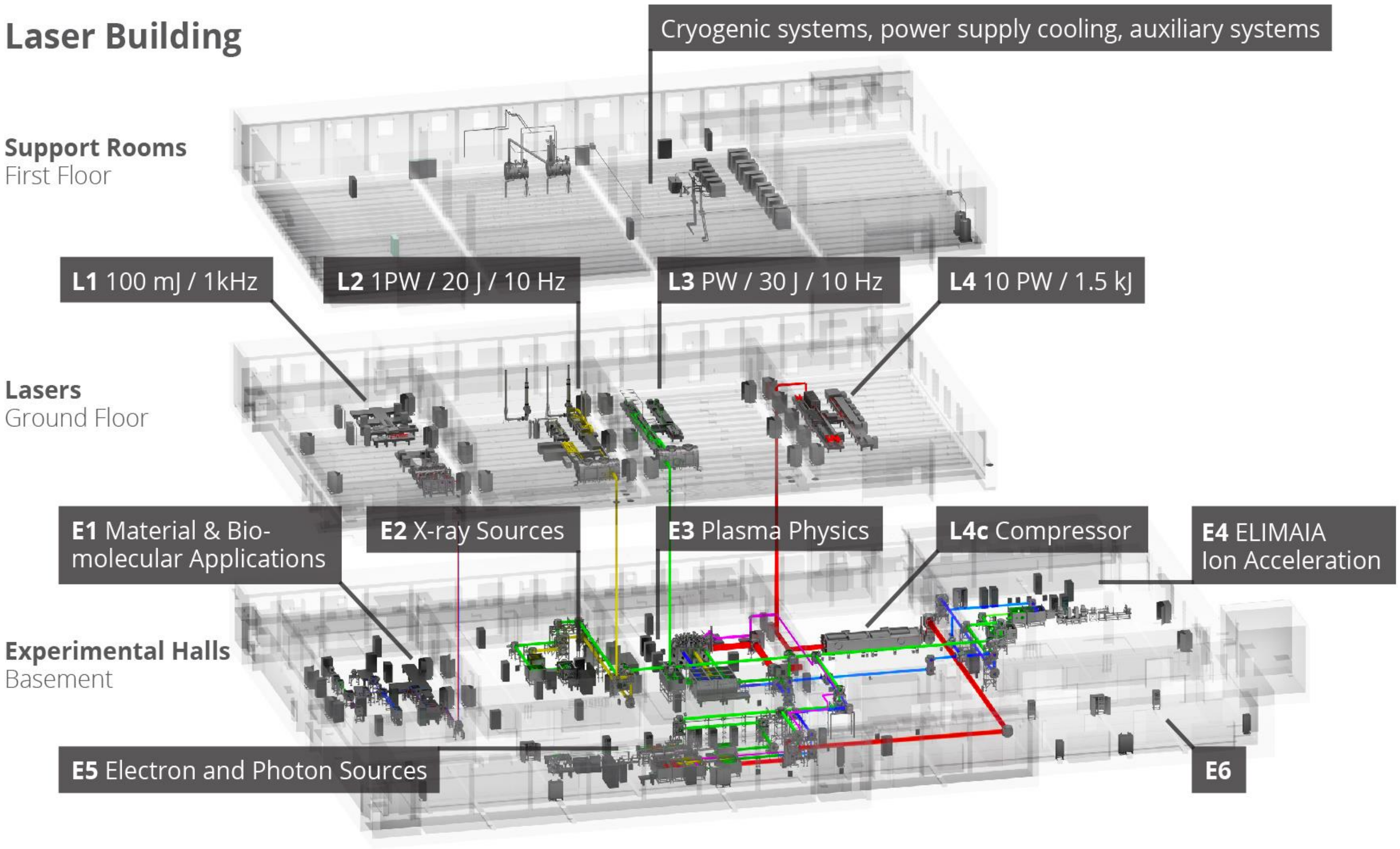


ELI Beamlines



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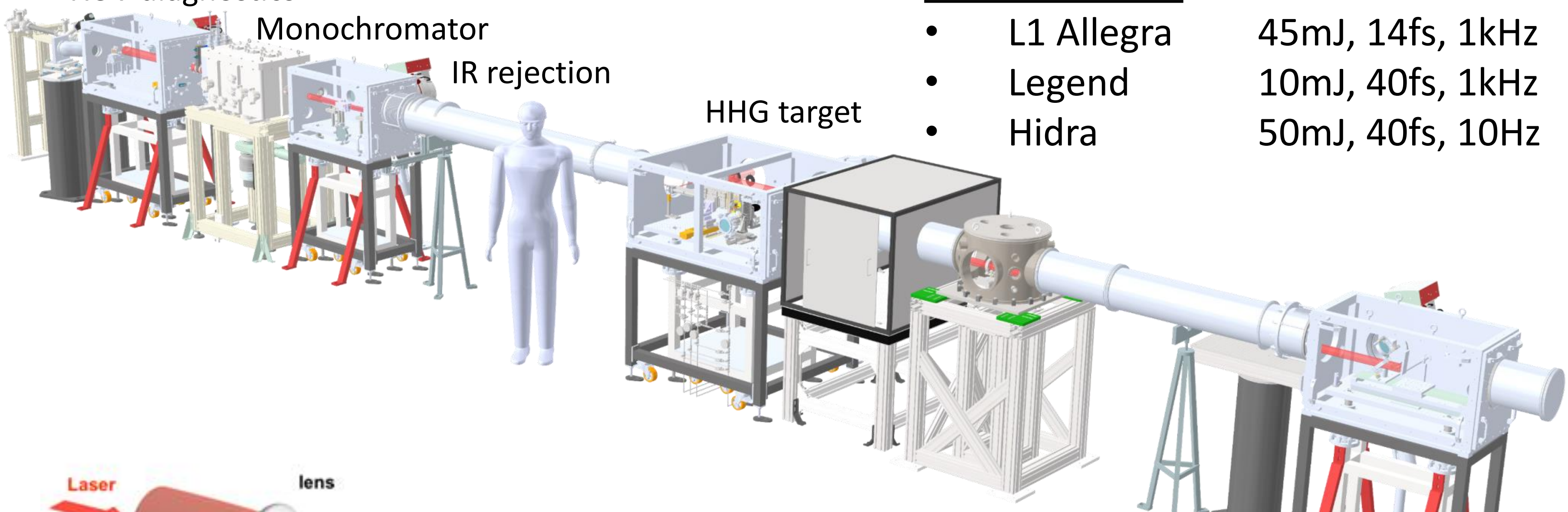
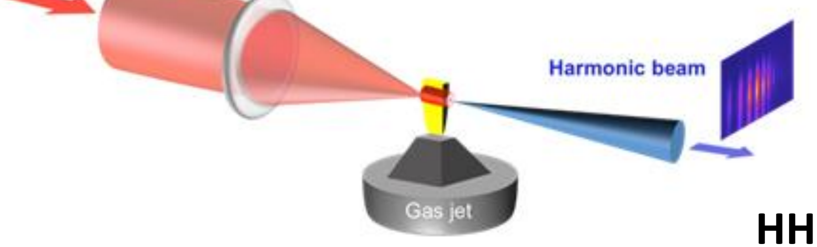
Experimental Hall

High Harmonics Generation (HHG)



<u>Available lasers</u>

- L1 Allegra 45mJ, 14fs, 1kHz
- Legend 10mJ, 40fs, 1kHz
- Hidra 50mJ, 40fs, 10Hz



HHG - High-order Harmonic Generation, in gas
10-120 eV, 20-35 fs, resolution <1 eV

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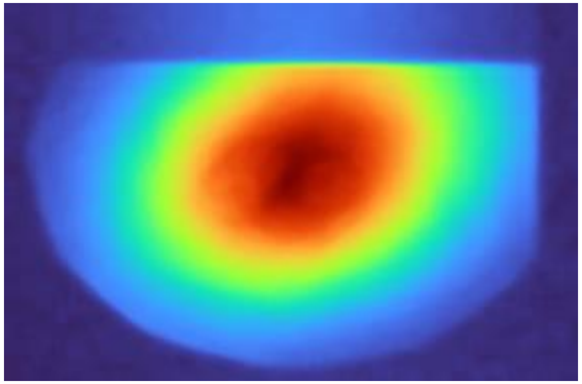
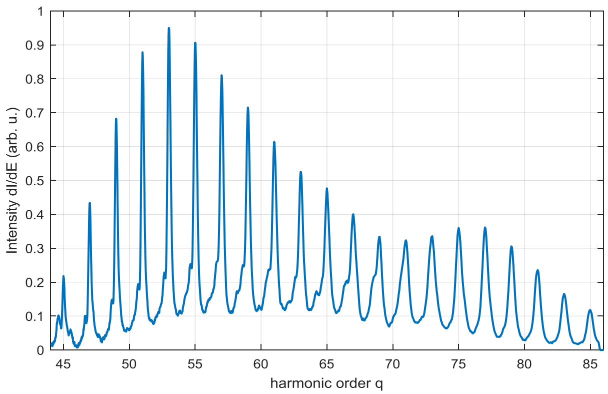
High Harmonics Generation (HHG)

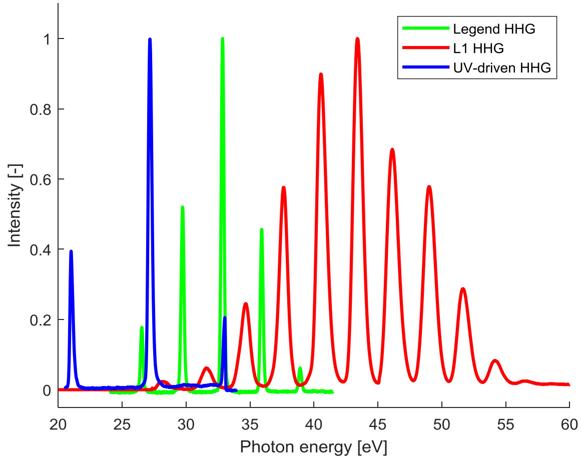
Measured XUV beam profile

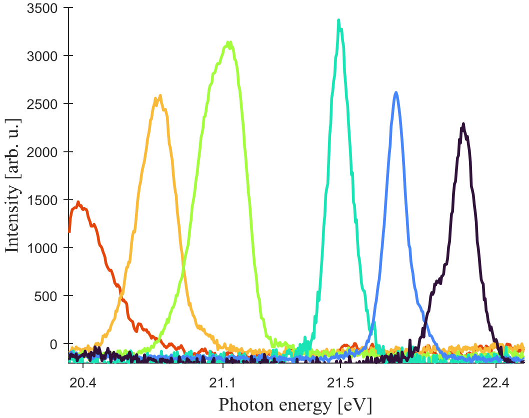


Gas	λ_{XUV} (nm)	Estim. XUV energy (μJ)
Xenon	≥50	2
Argon	≥30	0.2
Neon	≥13	0.02
Helium	≥10	0.02

neon







L1: λ=830 nm, τ=15 fs, 10 mJ

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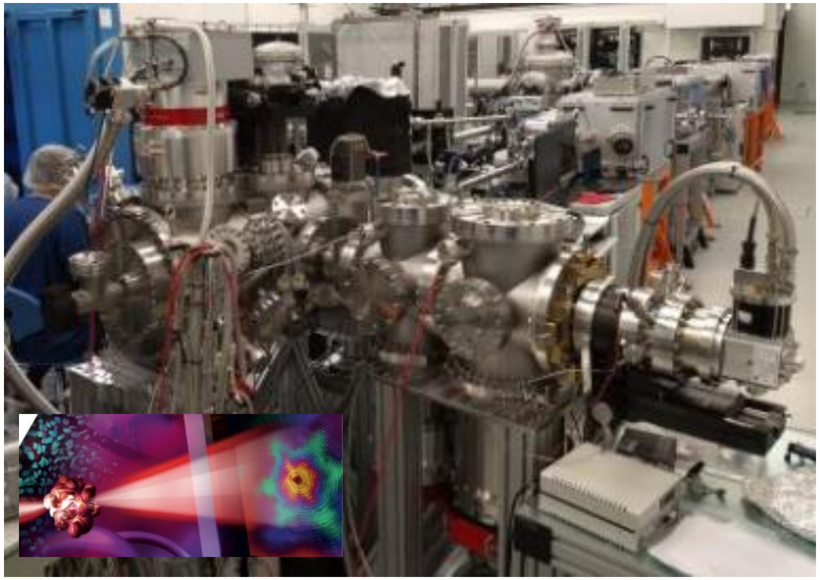
MAC chamber & AMO science



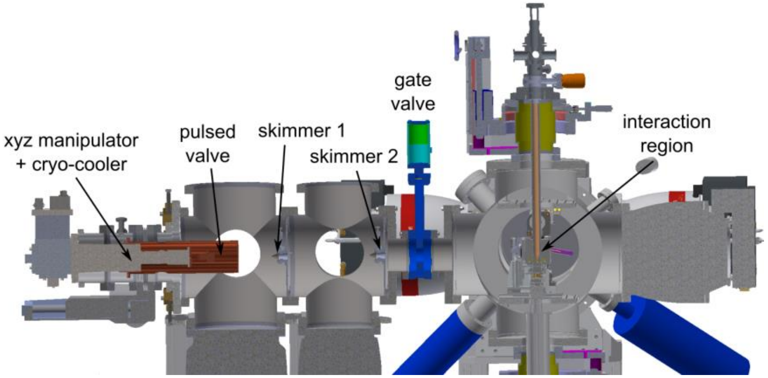
MAC: Multi-purpose chamber for AMO (Atomic, Molecular, Optical) and CDI (Coherent Diffractive Imaging) science.

Detectors: Electron and Ion Time of Flight spectrometer (in-house development)
Velocity Map Imaging (VMI 75 mm MCP with a phosphor screen and ns gated imaging detector)

Samples delivery: Cluster source – for rare-gas and water clusters with sizes from few to 100 nm. Molecular source (5 KHz), aerosol injection.

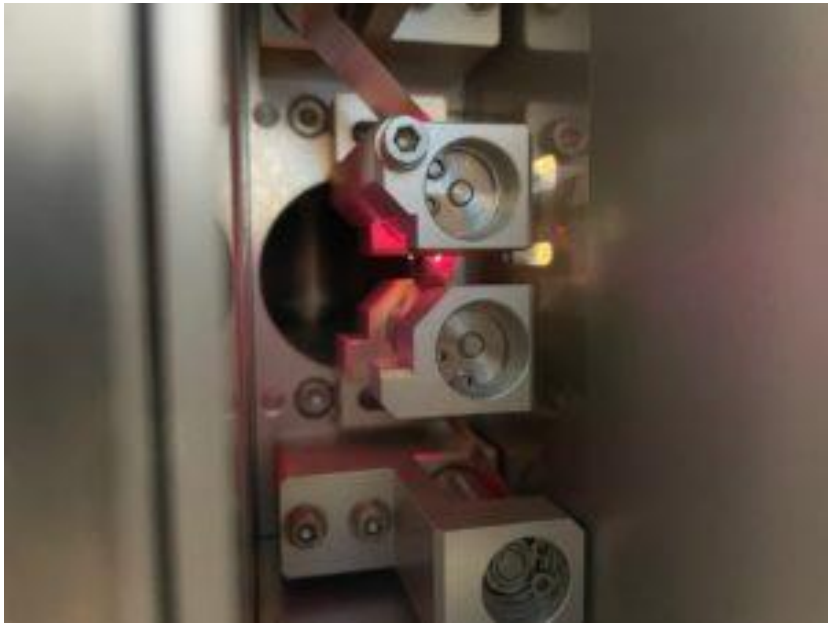
Cluster source

- Rare-gas clusters and He nanodroplets
- Based on a cryo-cooled Even-Lavie valve
- Cooling: Sumitomo RDK408E2 cryo-cooler
- Double skimmer setup
- Cluster size is tuned by temperature and pressure behind the nozzle
- Upgrade: doping of He nanodroplets

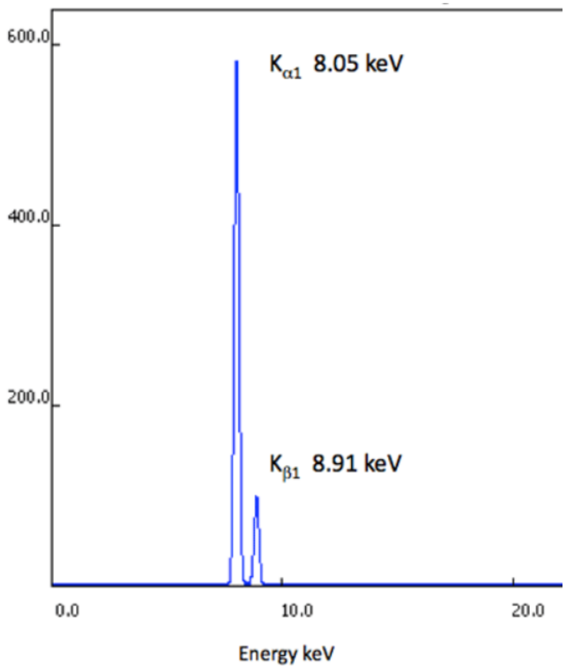


Plasma X-ray Source (PXS)

Cu-tape source: ~ 8 keV X-rays



2.9e10 ph/(shot*sr) @ 1 keV bandwidth



3-30 keV Bremsstrahlung (continuum)

Complementary CW sources: Cu and Mo anodes – 10^8 ph/sec

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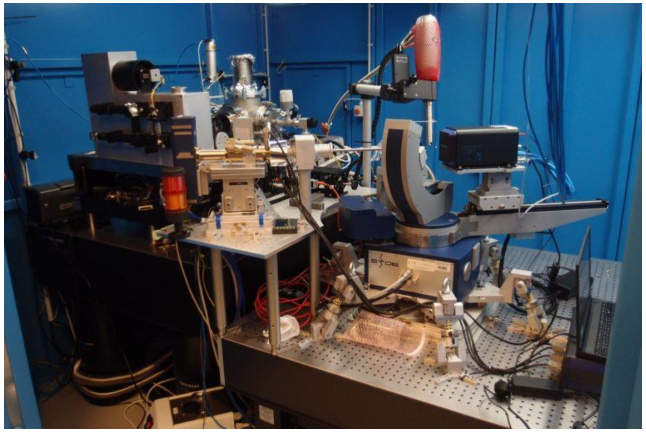
X-Ray Diffraction & Spectroscopy (XRD/XAS)

Hard X-ray Diffraction



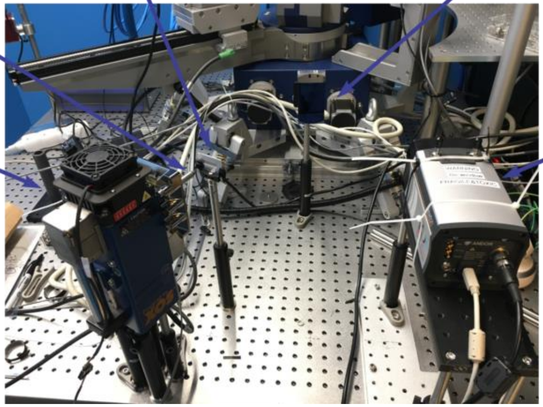
Euler cradle goniometer

simultaneously rotating the investigated sample at 360° and positioning the X-ray detector at desired angle and distance.

Detection

recording of the diffracted and scattered X-ray photons by a single photon counting hybrid pixel 3 kHz detector (Eiger X 1M, Dectris)

Hard X-ray Spectroscopy



Spectrometer

von Hamos design with gratings from 4 to 12 keV

Detection

custom designed CCD (Andor) with greater acceptance angles and beryllium window filtering background illumination

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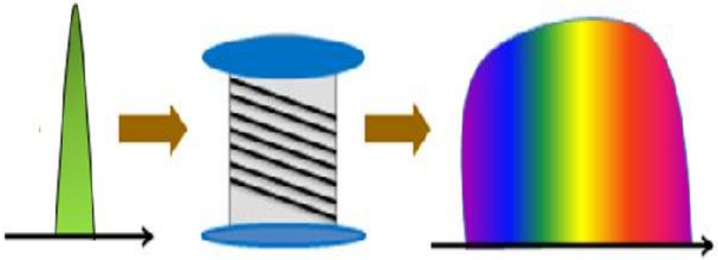
Optical Spectroscopy Stations

UV-VIS-IR Transient Absorption: monitoring excited and transient states of molecules, atoms and materials

Stimulated Raman Spectroscopy: monitoring Raman vibrational spectra of molecules to follow structural changes with high time resolution

TR Ellipsometry: measures the polarization response of samples providing optical constants of the material in an excited states and during the time evolution of these states



Light sources

Ti:saph - fs lasers (800 nm, 20-35 fs, 1 kHz)
OPA - Optical Parametric Amplifiers (0.25-2.5 μm)
HCF - Hollow Core Fiber (5 fs, 250 - 1100 nm)

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Compressor for 10 PW laser

3rd EPS-TIG Hands-on Workshop
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July 07 - 09, 2023

Experiment 1

Optical spectroscopy

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Spectroscopy

What is spectroscopy?
Spectroscopy is a technique used to study the **interaction between matter and light** across a wide range of wavelengths.

Why is spectroscopy important?
Spectroscopy is used in various fields of science and technology, including chemical analysis, environmental monitoring, material characterization, medical diagnostics, and astronomical studies.

What do we measure?
Spectrum = the intensity (or flux) of radiation as a function of wavelength

What properties of incident or generated light can we measure?

- Absorption
- Reflection
- Emission
- Scattering
- Polarization, refraction and many others

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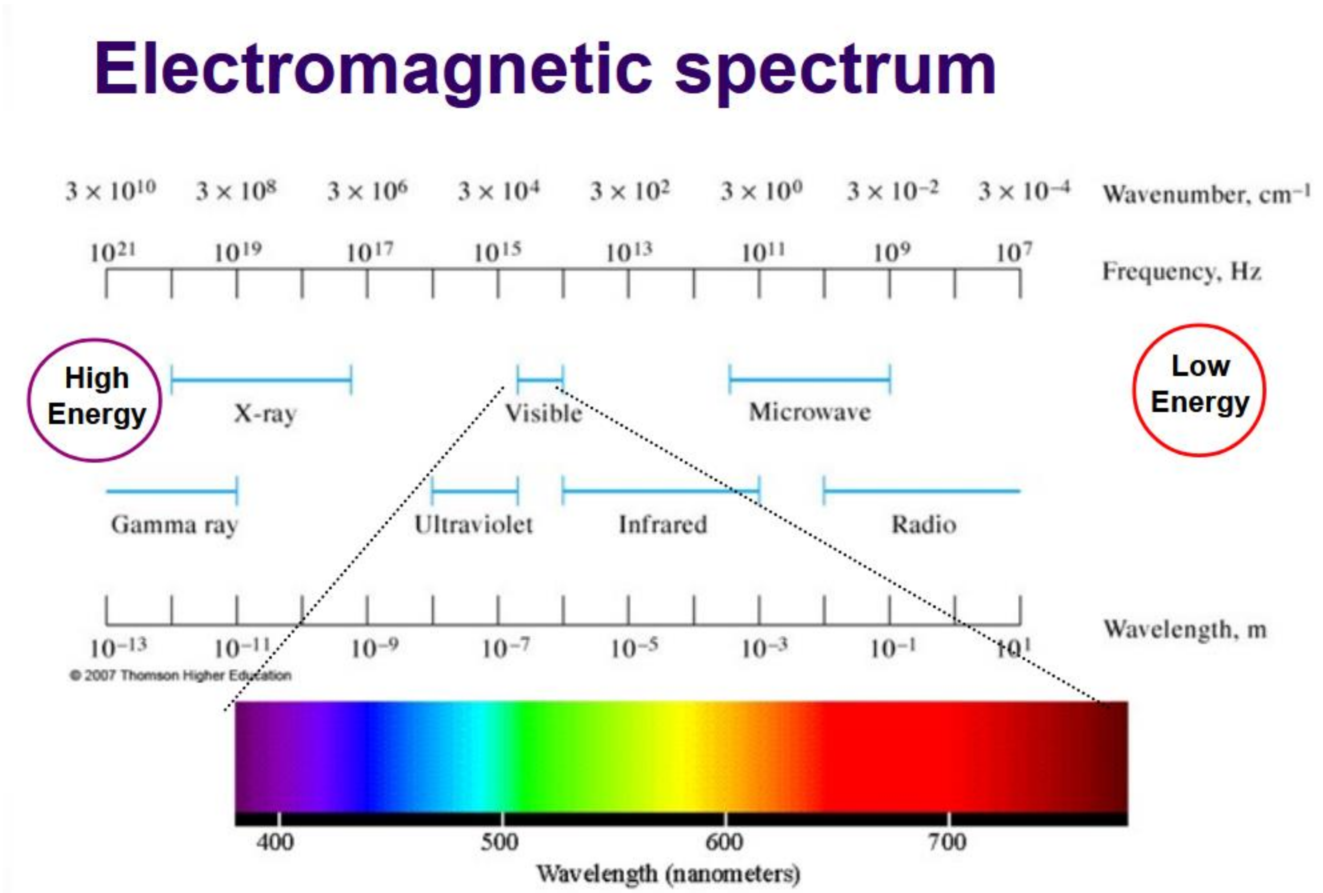
Optical spectroscopy



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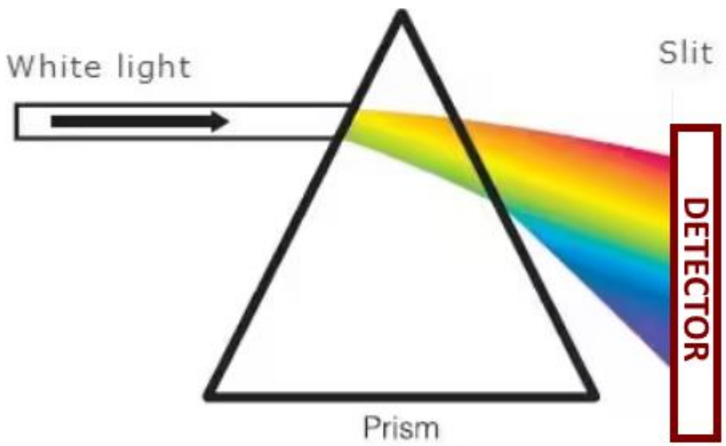
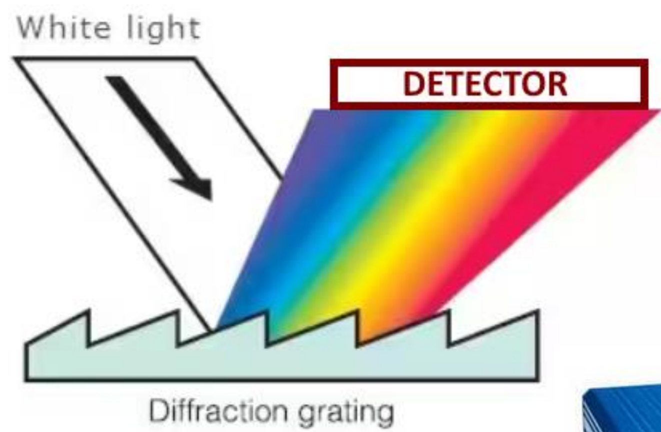
Spectrometer

What is a spectrometer?

A spectrometer separates an incoming light source into its spectral components, while measuring the outgoing light intensity emitted by a substance over a broad spectral range. The incident light from the light source can be transmitted, absorbed or reflected through the sample. It is widely used for spectroscopic analysis of sample materials.





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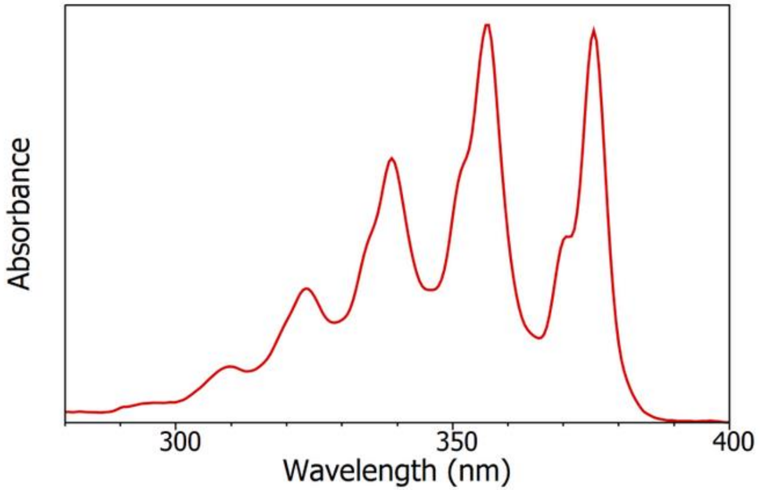
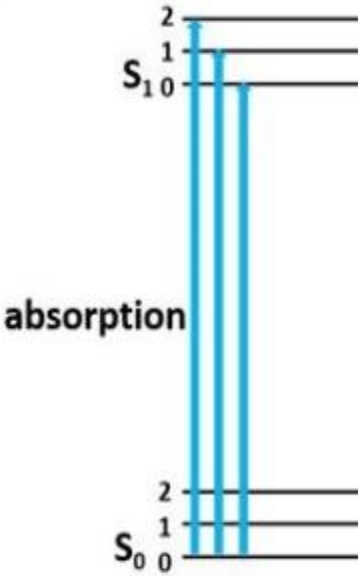
Absorption spectroscopy

Absorption spectra (also known as UV-Vis spectra, absorbance spectra and electronic spectra) show the change in absorbance of a sample as a function of the wavelength of incident light . The intensity of light transmitted through the sample, I_{sample} (such as an analyte dissolved in solvent) and the intensity of light through a blank, I_{blank} (solvent only) are recorded and the absorbance of the sample calculated using:

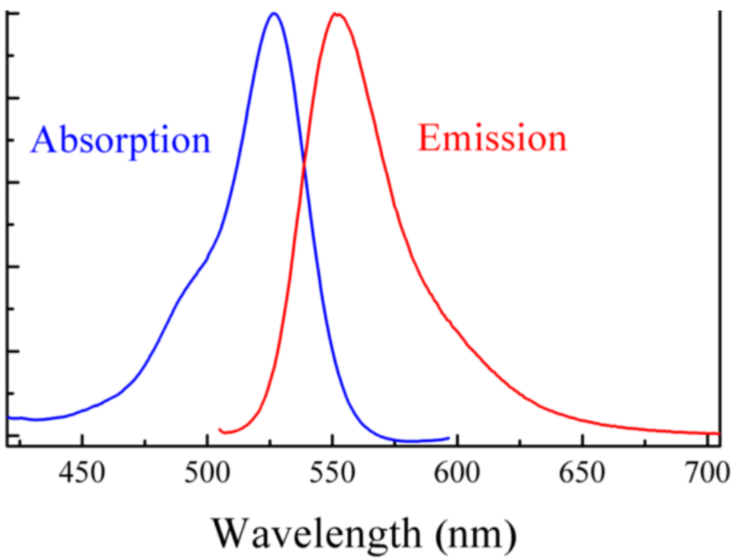
$$A = \log\left(\frac{I_{blank}}{I_{sample}}\right)$$

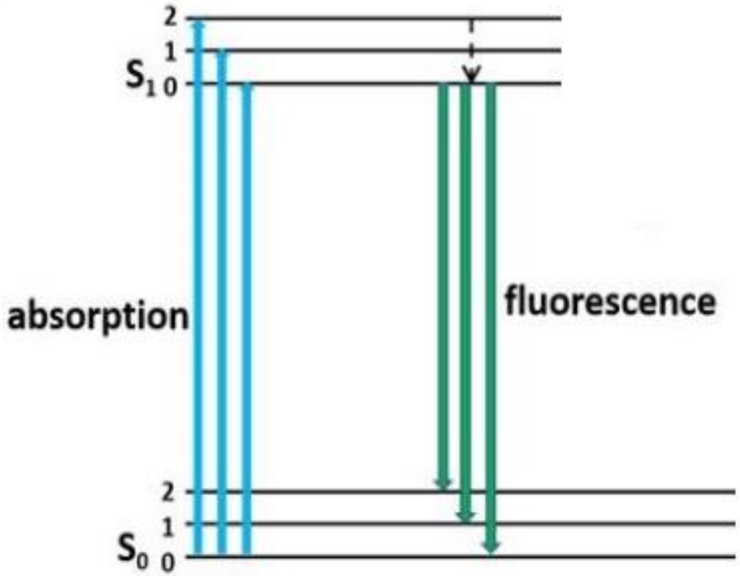




Emission spectroscopy

In emission spectroscopy, a sample is illuminated with monochromatic light (typically ultraviolet or visible) with an energy the sample compounds can absorb. The sample absorbs these excitation photons, exciting the molecule from its ground state to an excited electronic state (absorption). The molecule then falls back to the ground state, and the resulting energy is emitted as a photon—causing the molecule to fluoresce. The intensities and frequencies of these photons are detected and analyzed.





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Experimental setup