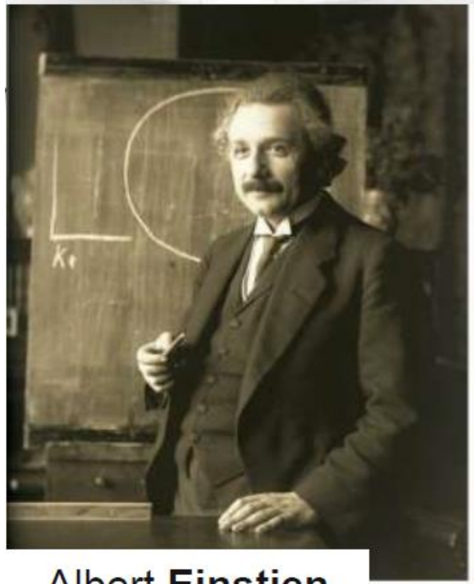
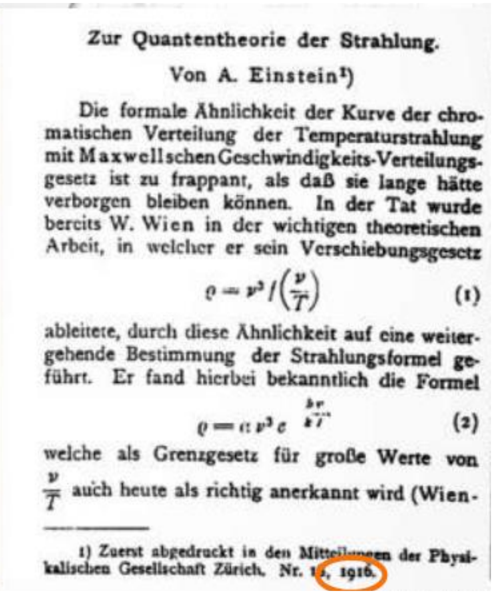
ELI ERIC: Development of a large scale laser facility

ELI Summer School
August 29th 2023

In the beginning....

Light Amplification by Stimulated Emission of Radiation





Zur Quantentheorie der Strahlung.

Von A. Einstein[1])

Die formale Ähnlichkeit der Kurve der chromatischen Verteilung der Temperaturstrahlung mit Maxwellschen Geschwindigkeits-Verteilungsgesetz ist zu frappant, als daß sie lange hätte verborgen bleiben können. In der Tat wurde bereits W. Wien in der wichtigen theoretischen Arbeit, in welcher er sein Verschiebungsgesetz

$$\varrho = \nu^3 f\left(\frac{\nu}{T}\right) \qquad (1)$$

ableitete, durch diese Ähnlichkeit auf eine weitergehende Bestimmung der Strahlungsformel geführt. Er fand hierbei bekanntlich die Formel

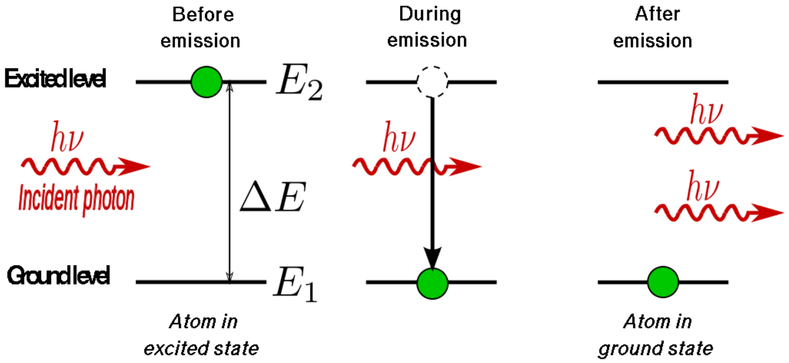
$$\varrho = \alpha \nu^3 e^{-\frac{h\nu}{kT}} \qquad (2)$$

welche als Grenzgesetz für große Werte von $\frac{\nu}{T}$ auch heute als richtig anerkannt wird (Wien-

1) Zuerst abgedruckt in den Mitteilungen der Physikalischen Gesellschaft Zürich, Nr. 18, 1916.

Albert Einstien

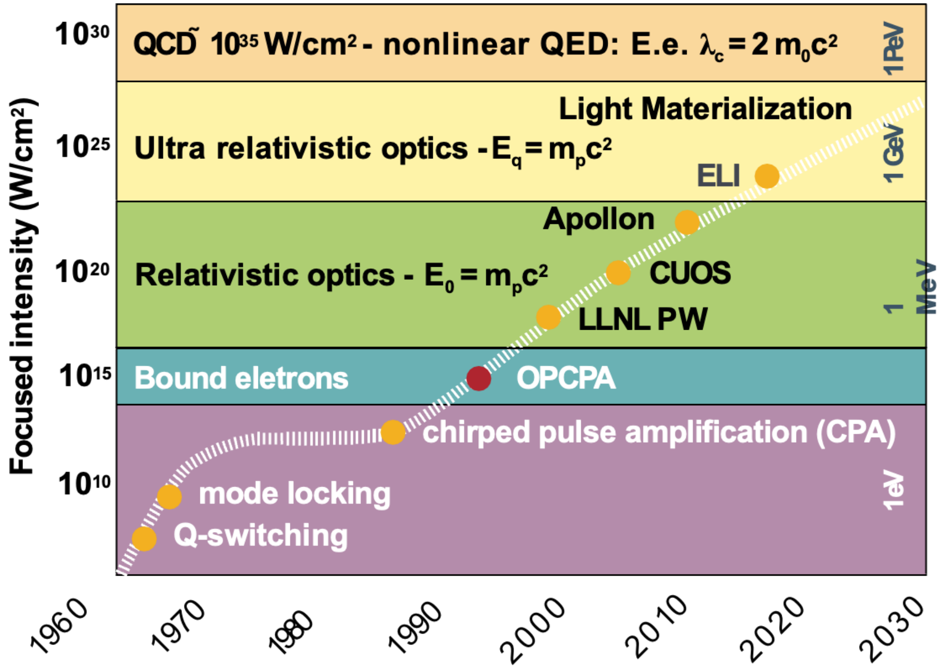
1916.

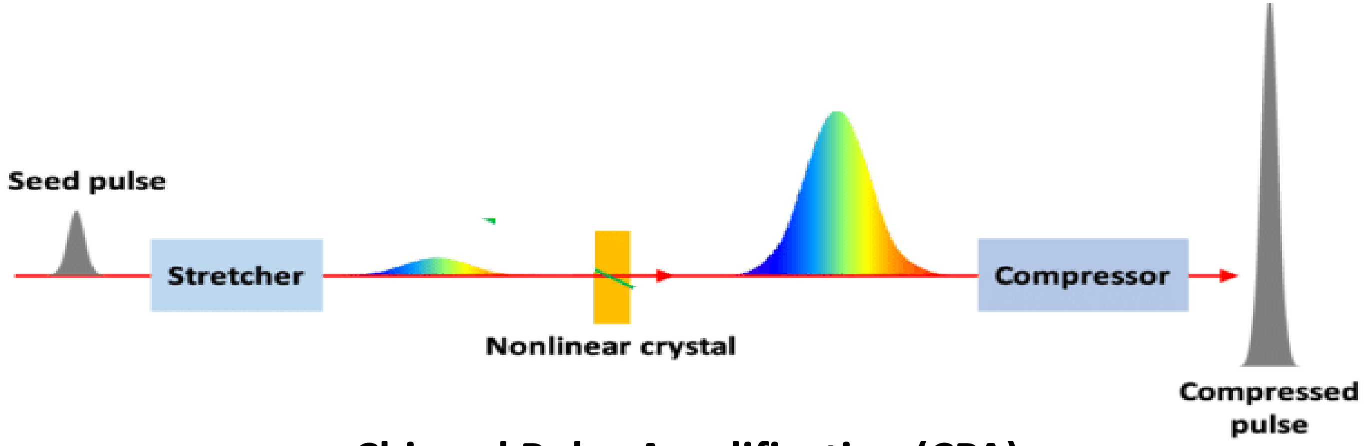


$$E_2 - E_1 = \Delta E = h\nu$$

From Nobel Prize to Extreme Light

A Technological Breakthrough Enables ELI

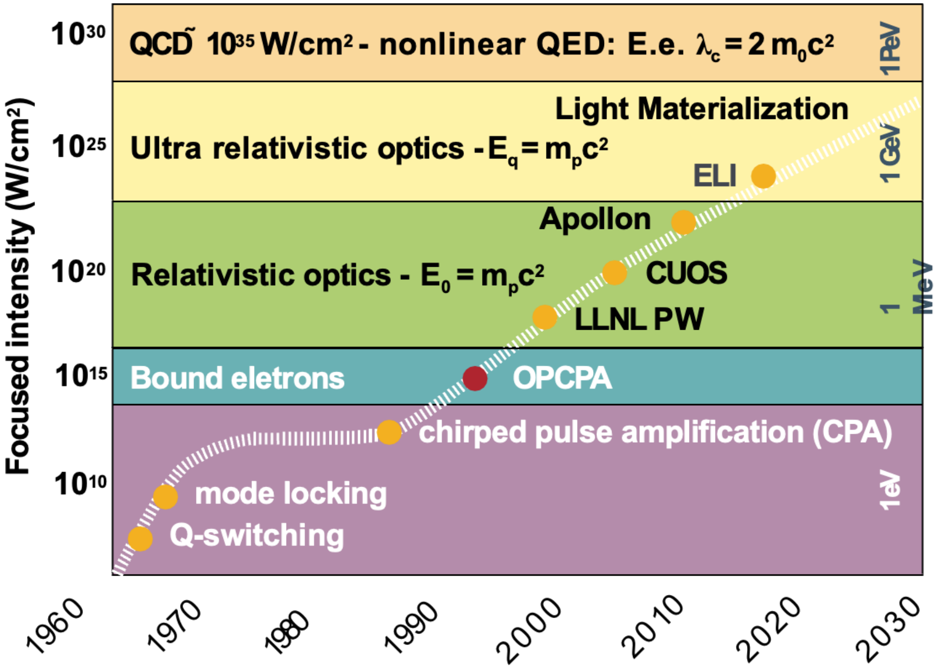




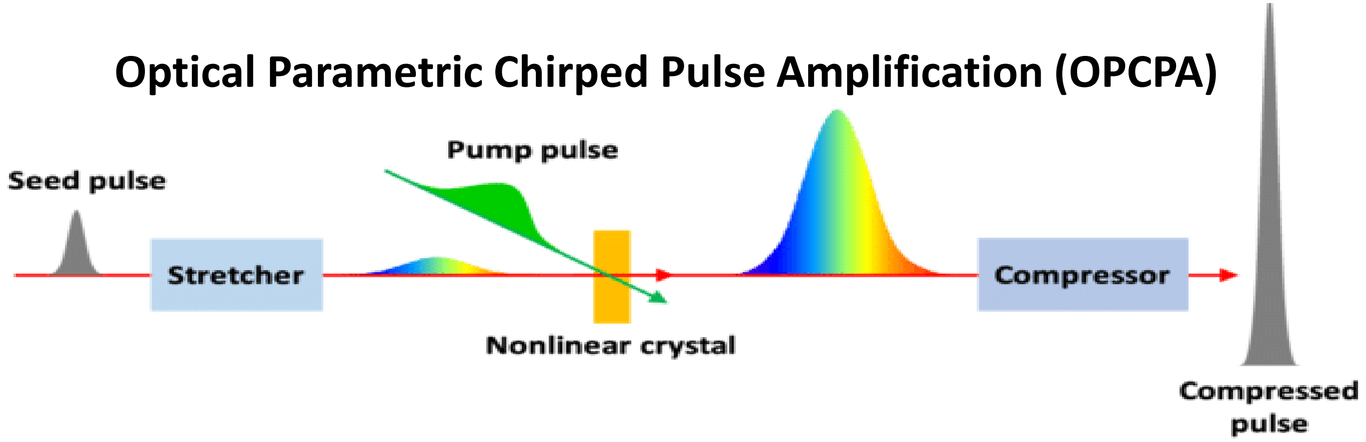
Chirped Pulse Amplification (CPA)

From Nobel Prize to Extreme Light

A Technological Breakthrough Enables ELI



Optical Parametric Chirped Pulse Amplification (OPCPA)



Gérard Mourou and Donna Strickland *won the* ***2018 Nobel Prize for Physics*** *for proposing* ***"Chirped Pulse Amplification"*** *for high-power, ultrafast, extremely intense lasers.*

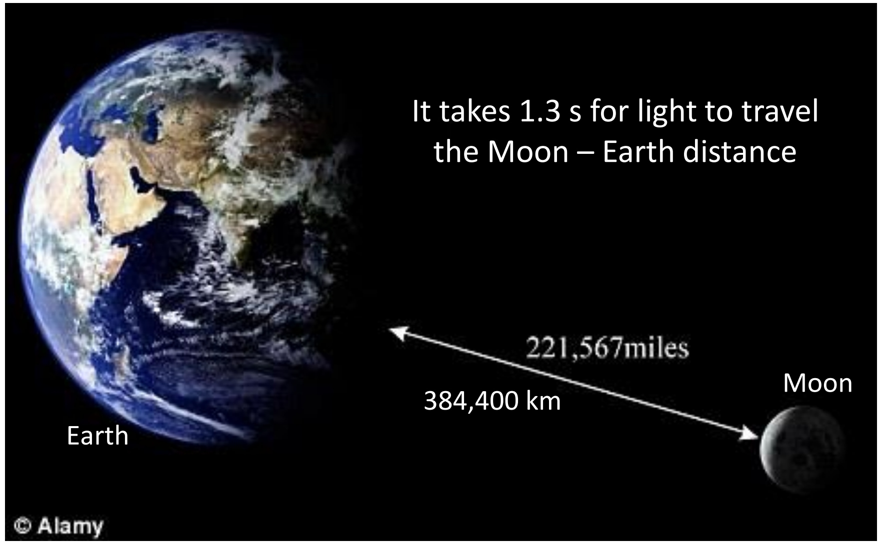
Mourou, *et al* proposed ELI in 2004, and from 2007-2010 initial research including 15 institutions and € 7.9M from the Seventh Framework Programme.

Femtosecond-class Laser ?

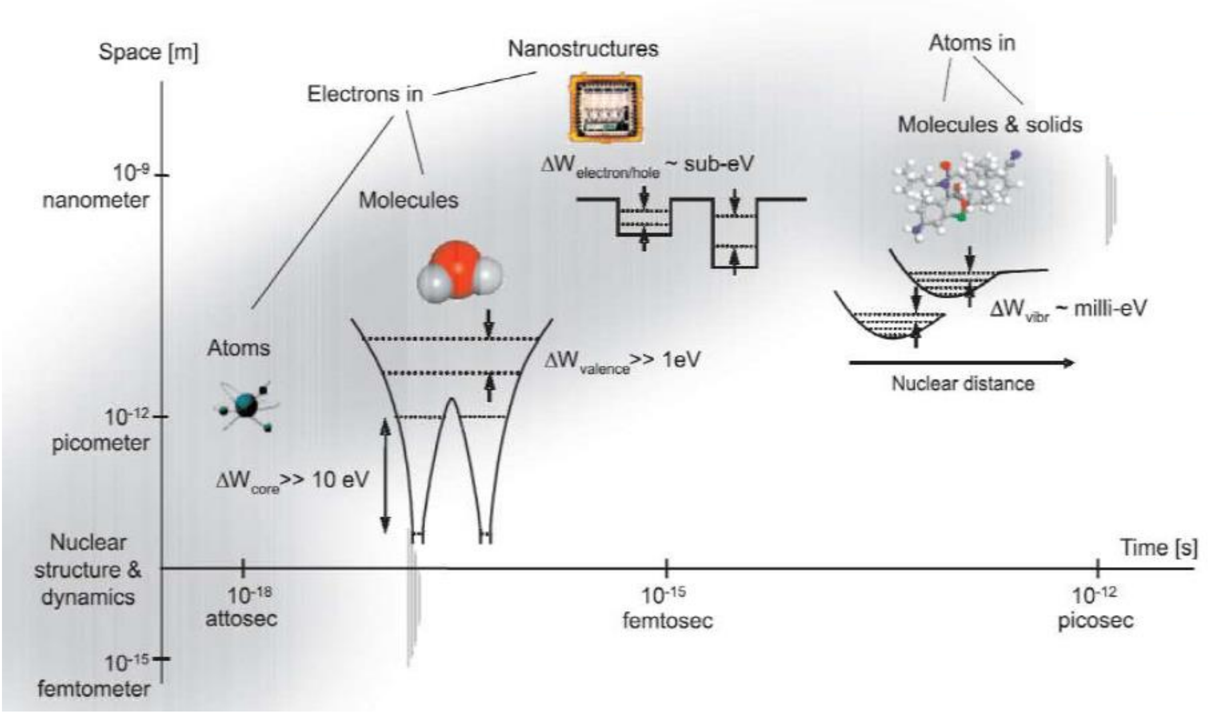
10-100 fs

10 fs = 10^{-14} s

Speed of Light: 300 000 km/s



10 fs pulse → 3 μm path



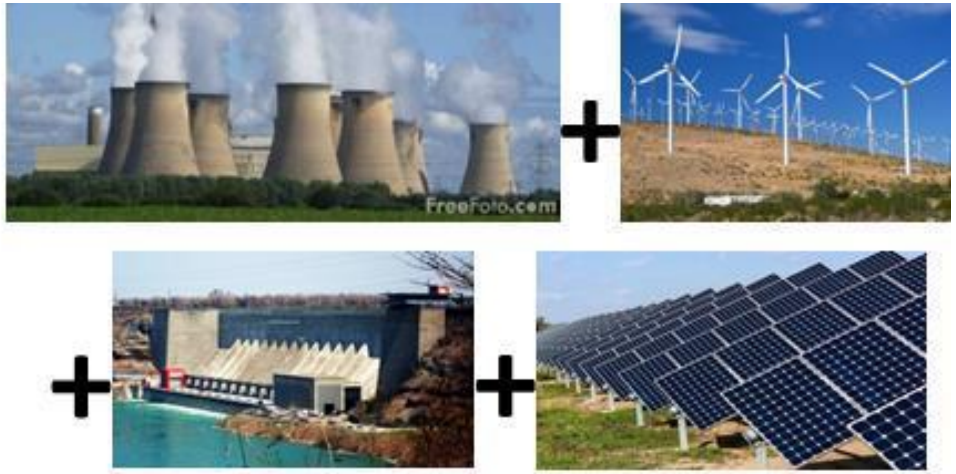
fs and **sub-fs** timescale – electronic motion
in atoms and molecules

PetaWatt-class Laser ?

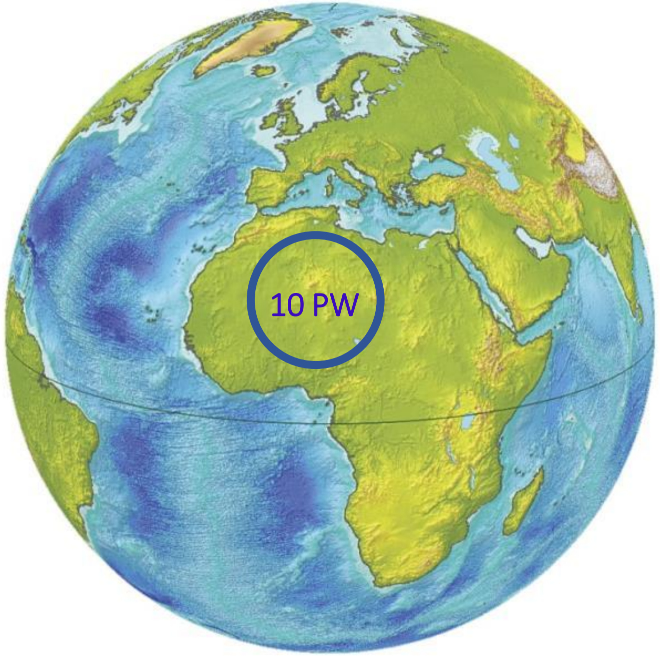
1-10 PW (in 10-100 fs)

1 PW = 10^{15} W

Total global electricity generating capacity is ‘only’ 10 TW = **0.01PW**



Sun power shining on Earth: 174 PW



1 PW in 10 fs pulse = 10^{15} x10^{-14} = 10 J - which is not a huge amount of energy. If we want to use lasers to drive processes that need significant energy we need to increase the repetition rate….

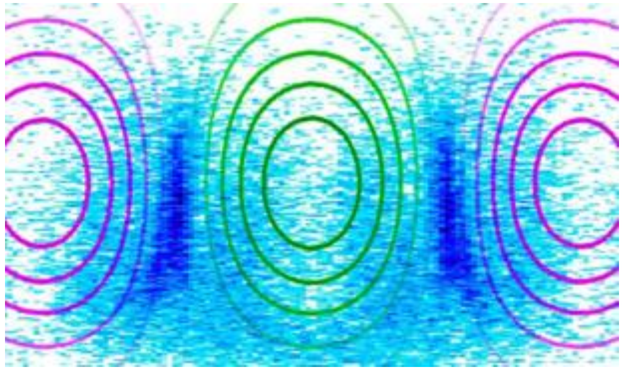
eli Democratising science using high-performance lasers

Applications in Material Science and Biology – structure and dynamics to attosecs

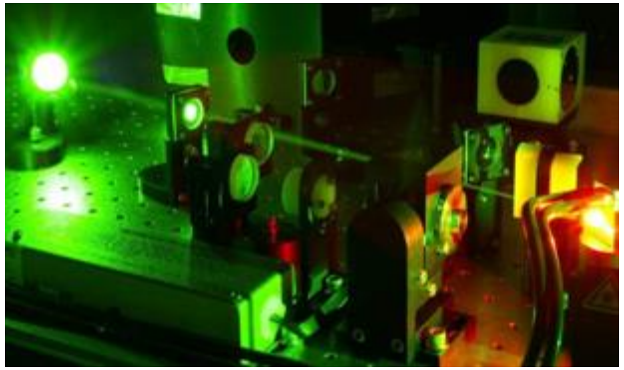
Particle Acceleration
250 MeV Ions Acceleration by lasers

Radiation Physics and Electron Acceleration
Soft to hard x-rays, GeV electrons

Plasma Physics and High Energy Density, Astrophysics, Nuclear Photonics

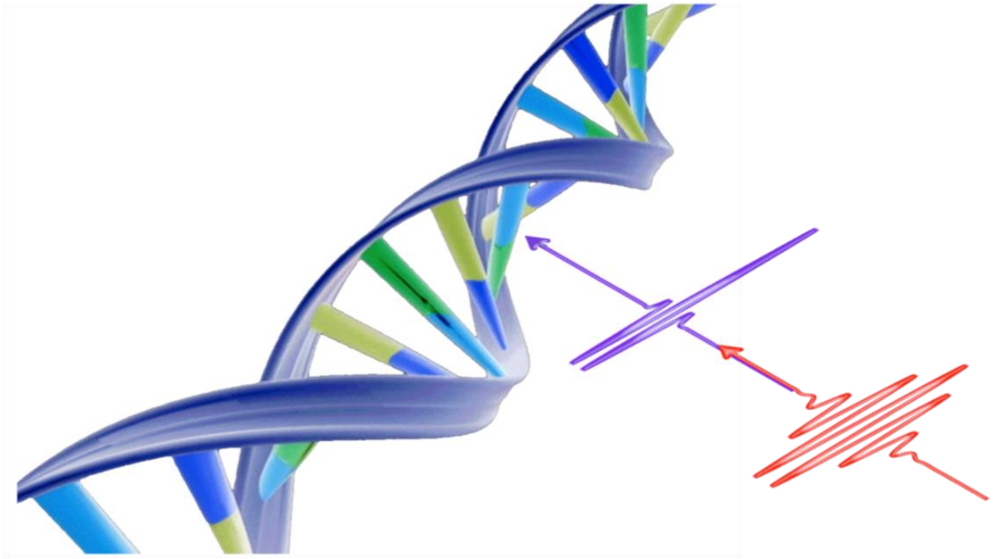


Ultra High Intensity Interactions
High-field physics and theory



Laser Development

Pump-probe studies of chemical and biochemical processes

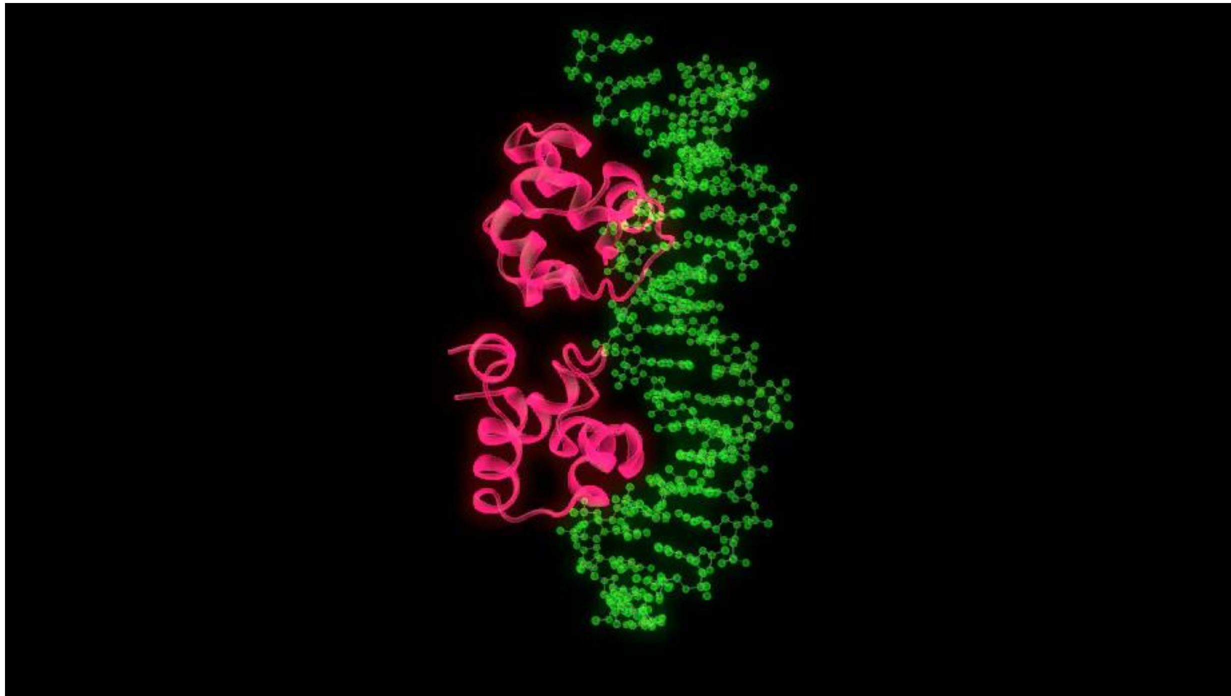


Ultrafast, intense laser pulses can drive **secondary sources** of even faster (sub-fs – attosecond) pulses

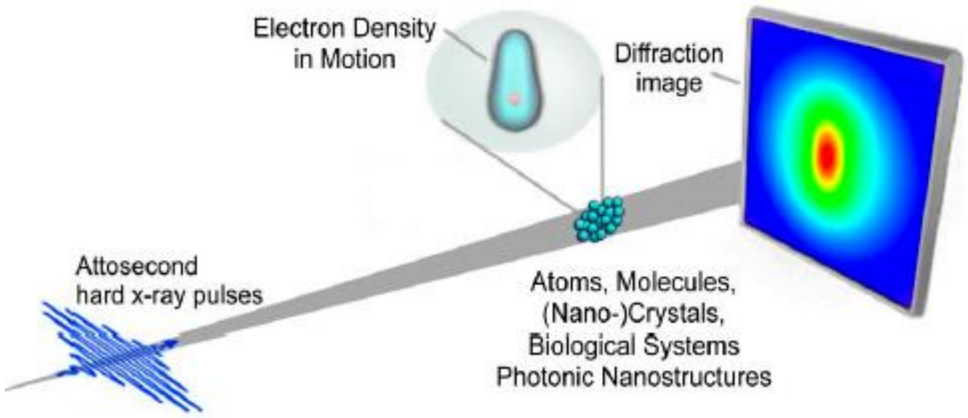
Induce changes in the electronic configuration with a stimulating pulse of light - the **pump**

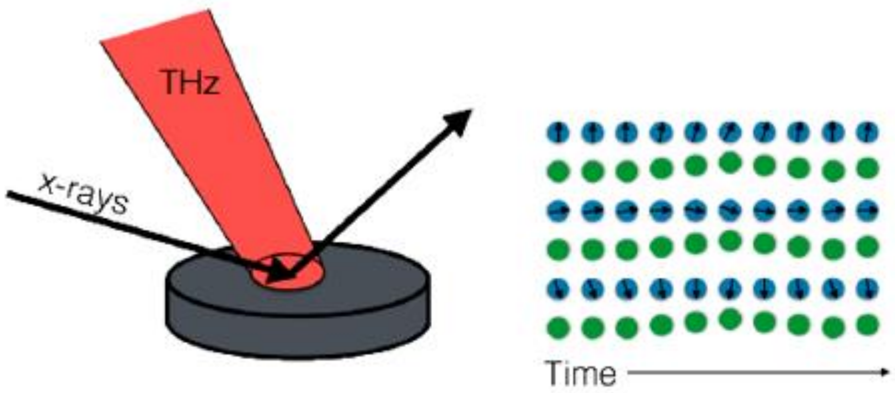
Probe the global structural-rearrangement as a function of time delay between pump and probe

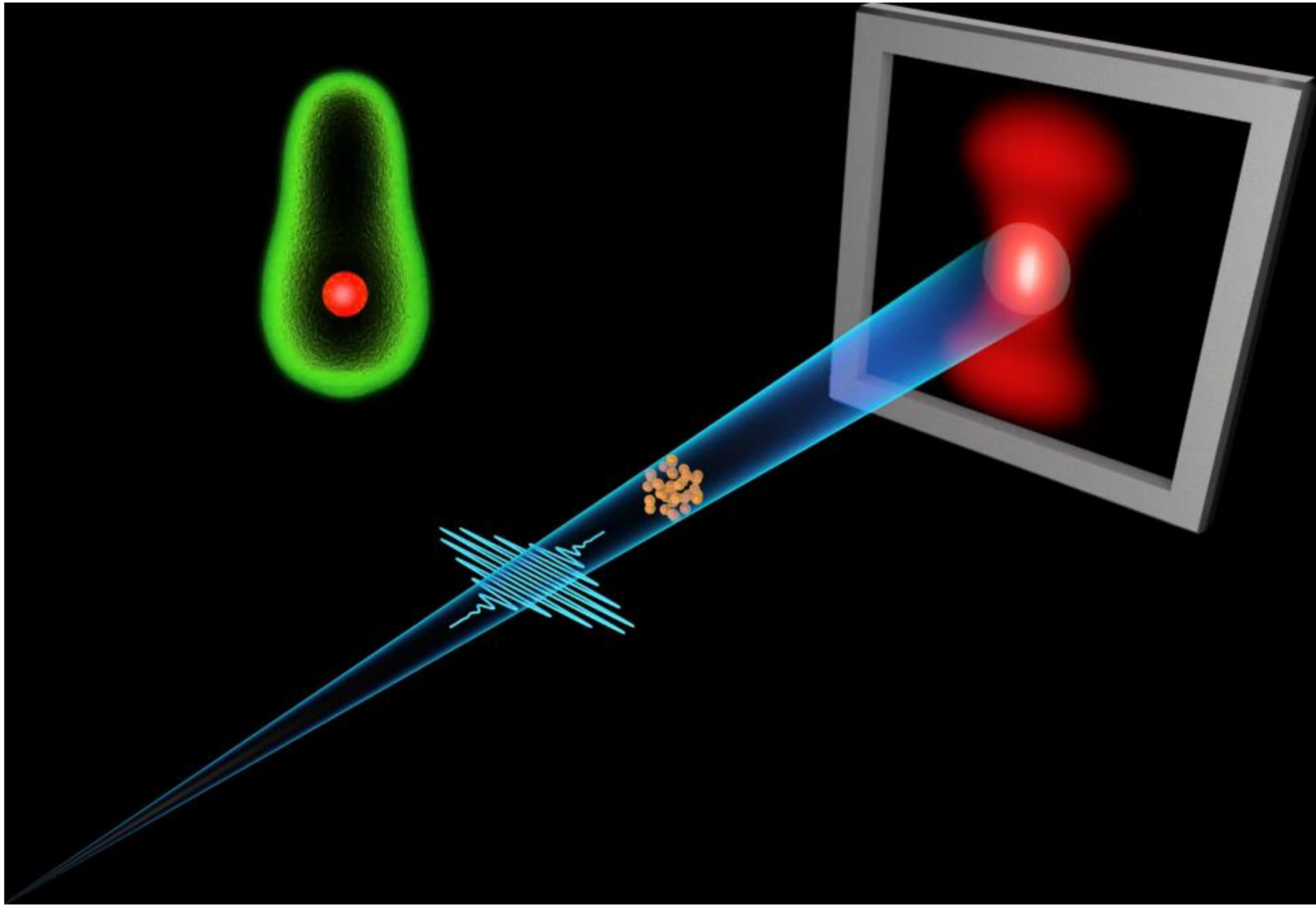
Repeat at a high rate to build up statistics (>KHz) and produce a much stronger signal – plus combine with other probes, e.g. mass-spectrometry



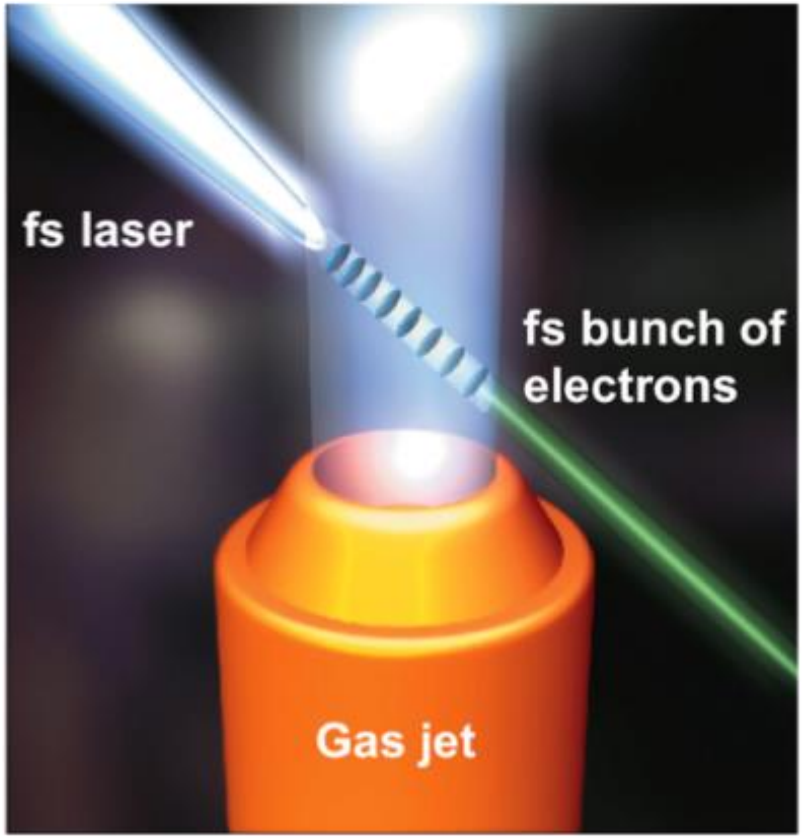
Attosecond X-Ray structures

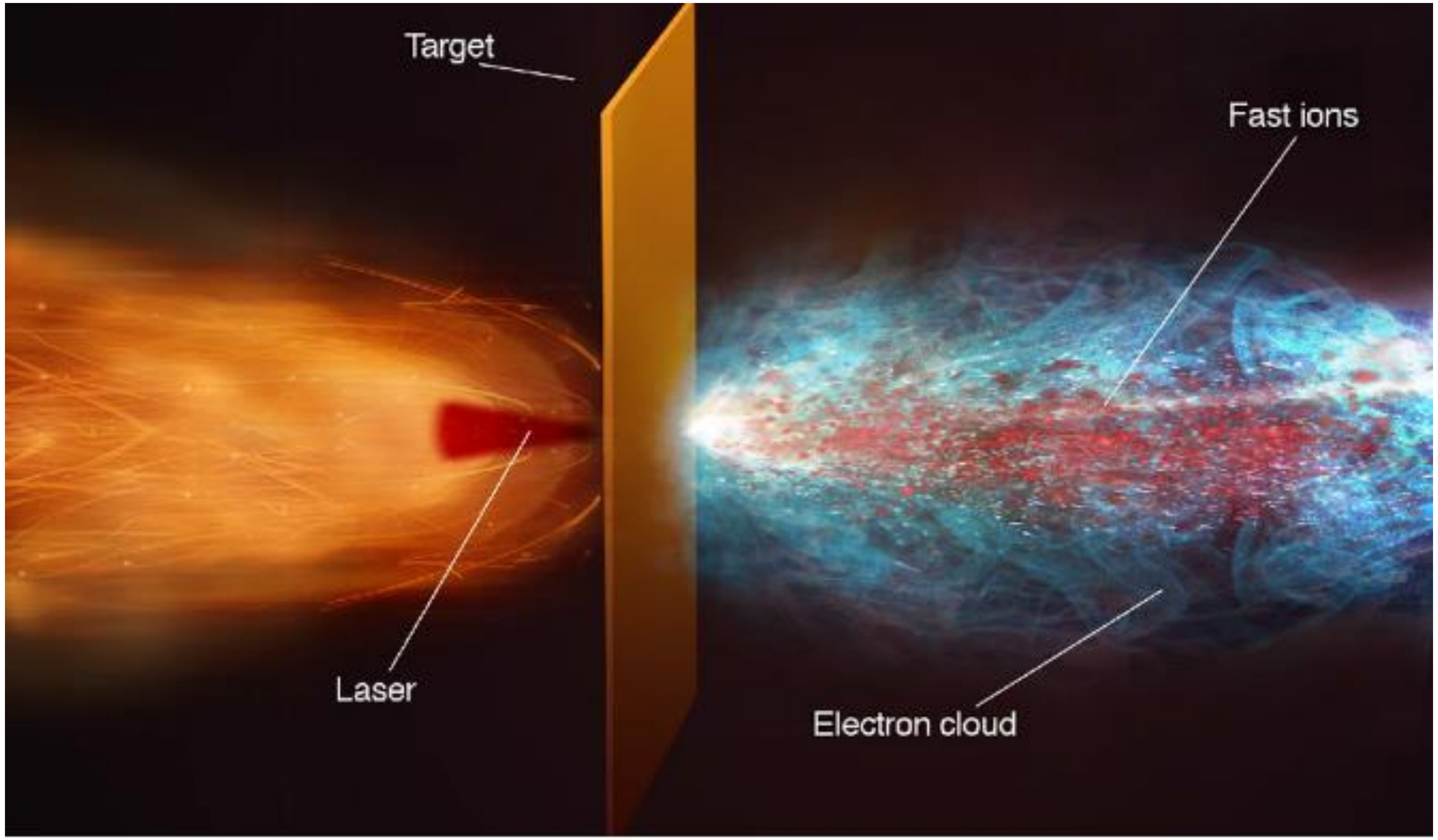




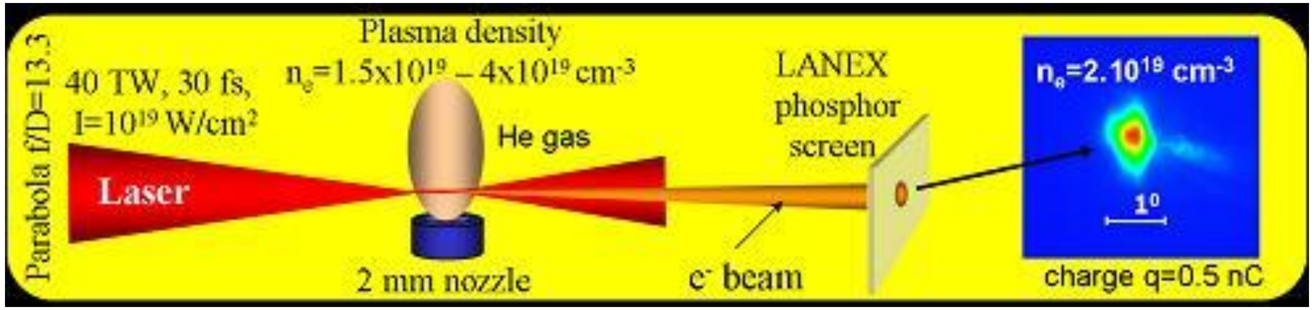


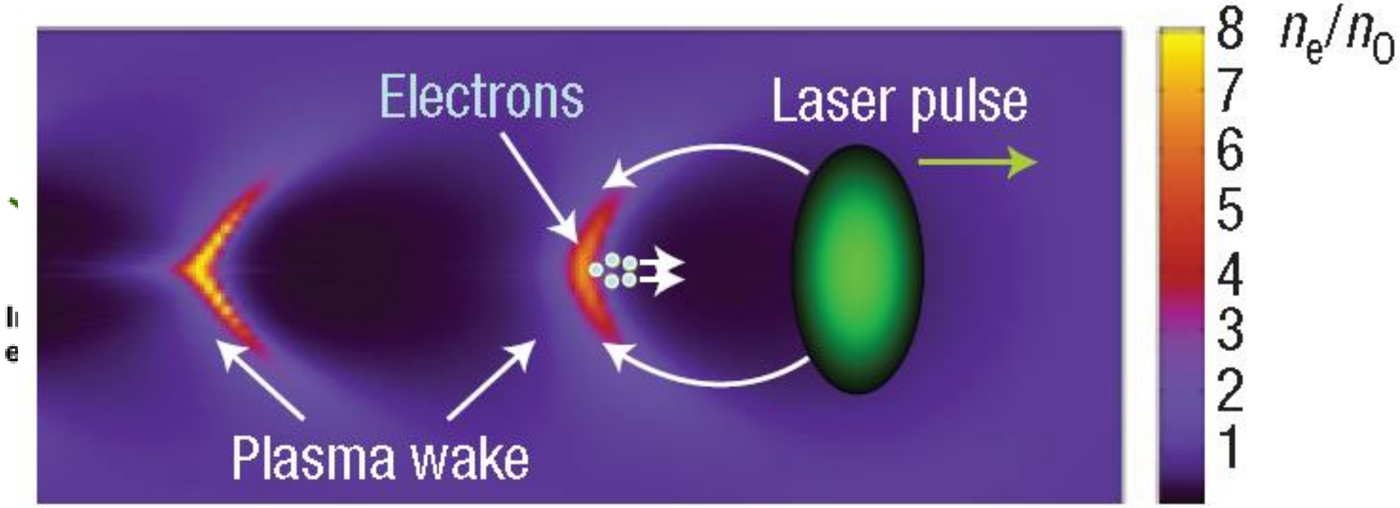
Secondary sources: X-rays and particle beams





Laser-Plasma Electron Acceleration





Intense laser pulse ionizes gas, with separated electrons dragged in its wake producing X-ray source and high-energy electron beam

REVIEW PAPERS:

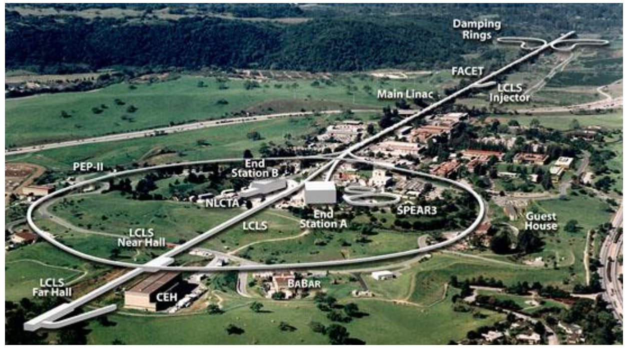
- *Esarey et al., Rev. Mod. Phys. 81 (2009) 1229*
- *Leemans & Esarey, Phys. Today 62 (2009) 44*
- V. Malka et al., Nature Phys. 4 (2008) 447

Laser Wakefield Electron Acceleration

Conventional accelerators limited by dielectric breakdown: max E-field ≈ 10’s Mev/m

Laser wakefield driving field orders (3) of magnitude higher

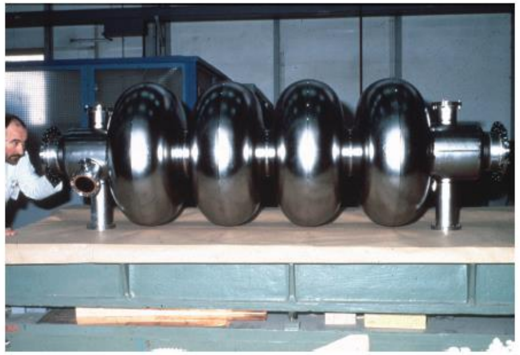
SLAC linear accelerator



electron energy: 50 GeV

3 km long!

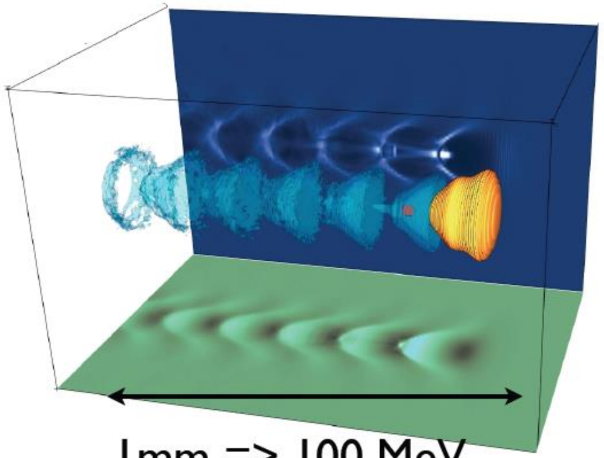
RF Cavity



1 m => 100 MeV Gain

Electric field < 100 MV/m

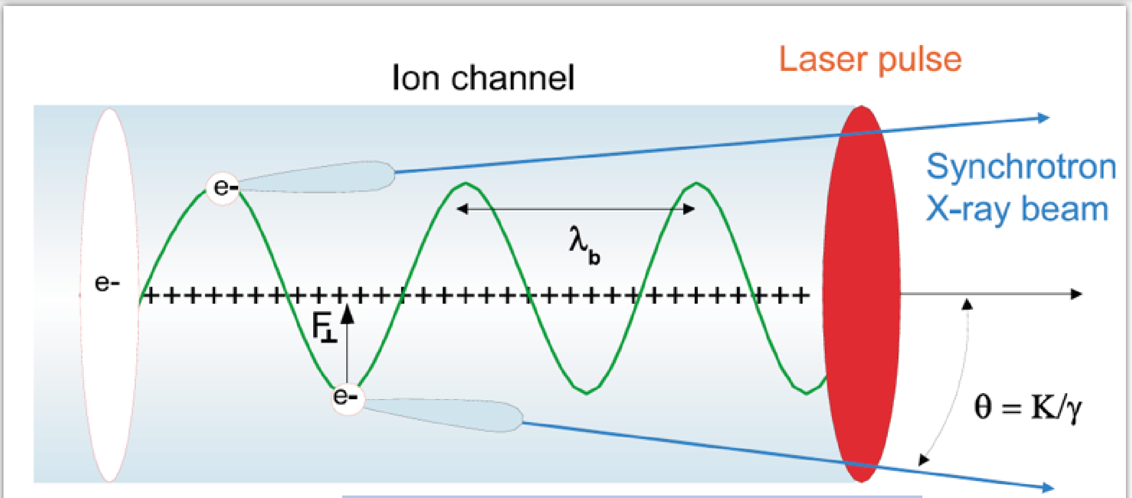
Plasma Cavity



1mm => 100 MeV

Electric field > 100 GV/m

LWFA betatron X-ray source



A. Rousse *et al.*, ***Phys. Rev. Lett.*** **93**, 135005 (2004)

'Hard' photon energy - E_{crit} > 25 keV
investigating dense material, biological materials

Small source size (~ µm)
intrinsically high resolution / exhibits spatial coherence

Small divergence (~ 10 mRad)
makes beam line

Short pulse (~ 10s fs)
suitable for ultrafast dynamics

Bright (>10^9 photons per shot)
suitable for single shot imaging

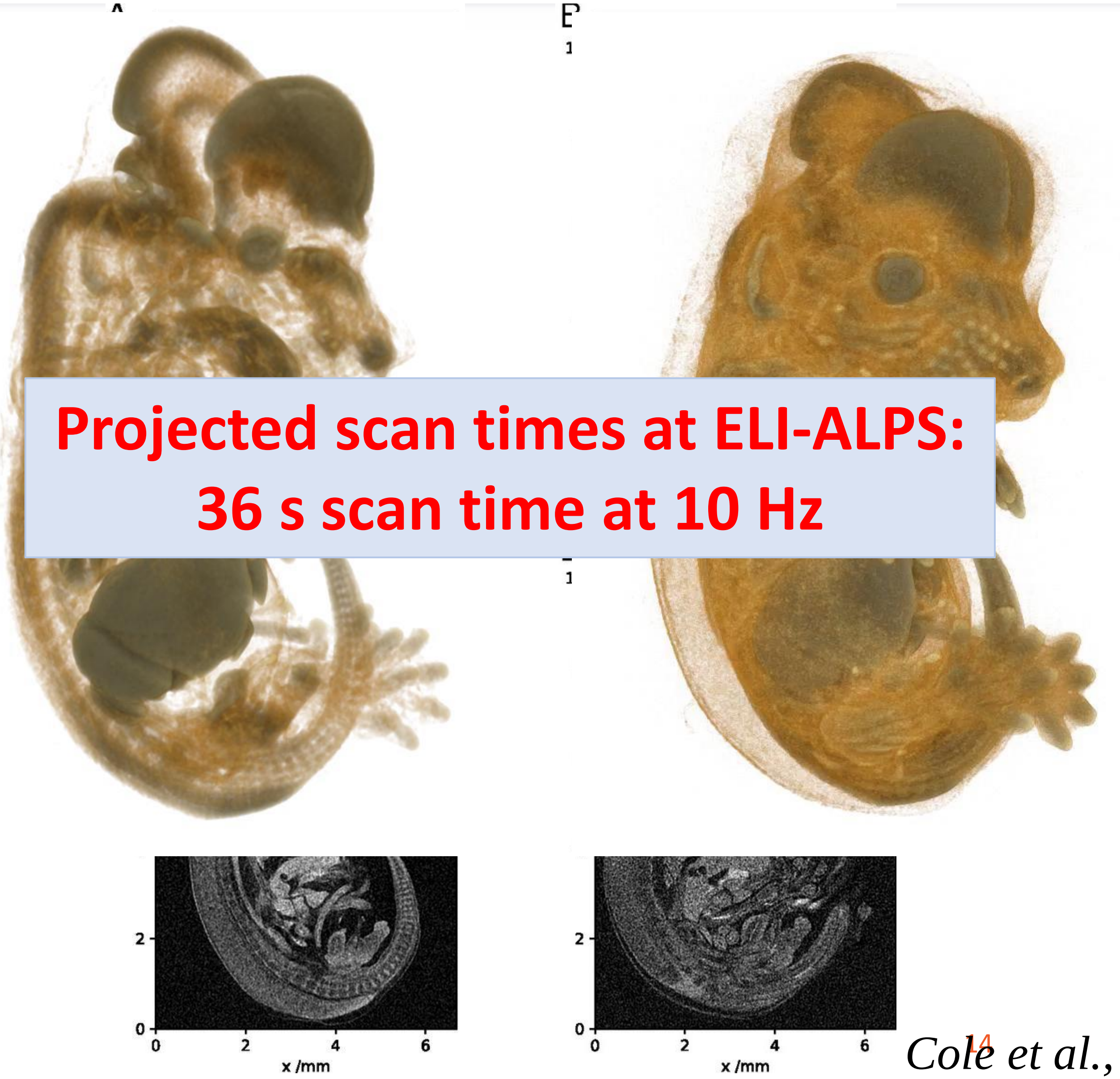
Accelerated micro computed tomography

Astra laser,
85 keV X-ra
3 µm sourc

2e10 photo

Laser shot e
360 project

2 hours s



ize

sec

on
ns

an

Projected scan times at ELI-ALPS:
36 s scan time at 10 Hz

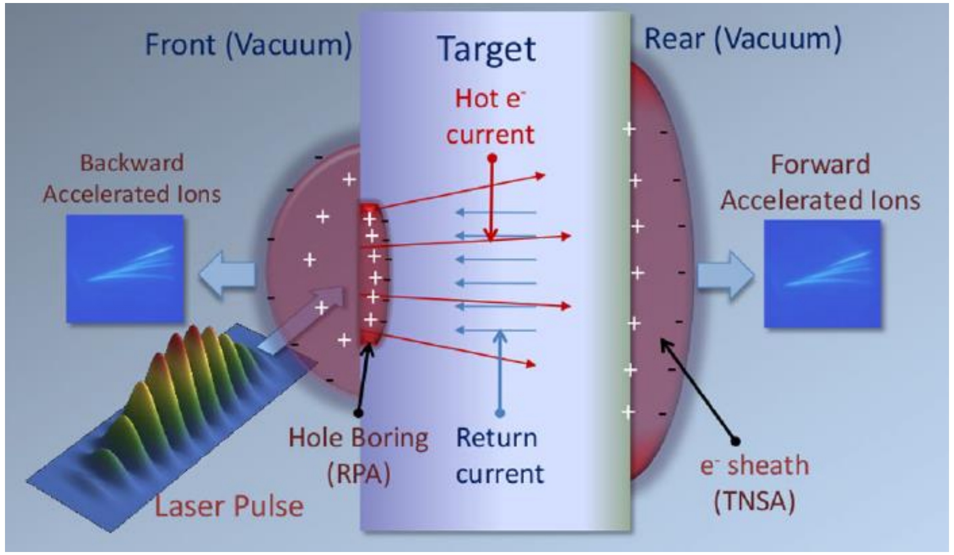
Cole et al., PNAS 2018

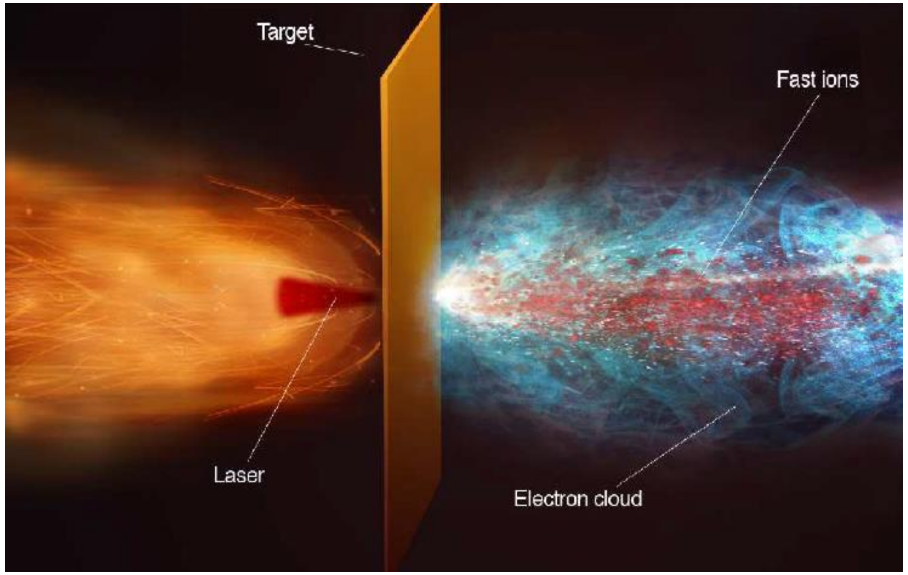
Laser-Plasma Ion Acceleration

Laser pulse hits a thin foil and produces accelerated charged particles: energy gain ~100MeV in ~μm

Target Normal Sheath Acceleration

0.1-10 μm long





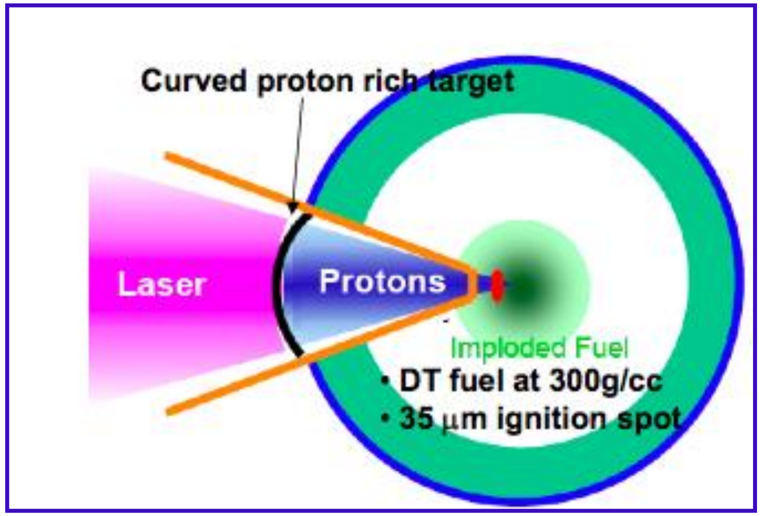
REVIEW PAPERS:

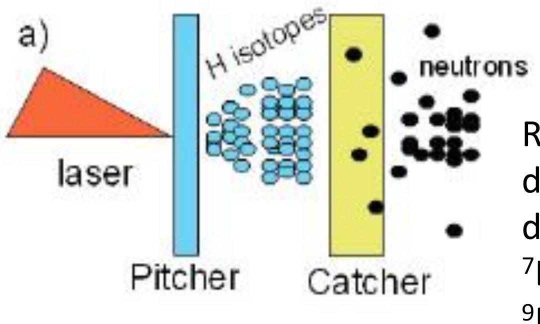
- *Macchi, Borghesi, Passoni, Rev. Mod. Phys. 85 (2013) 751*
- *Borghesi et al, Springer Proc. Phys. 231 (2019) 143*

Applications of laser driven ions

unique beam features

Fast Ignition (Inertial Confinement Fusion)

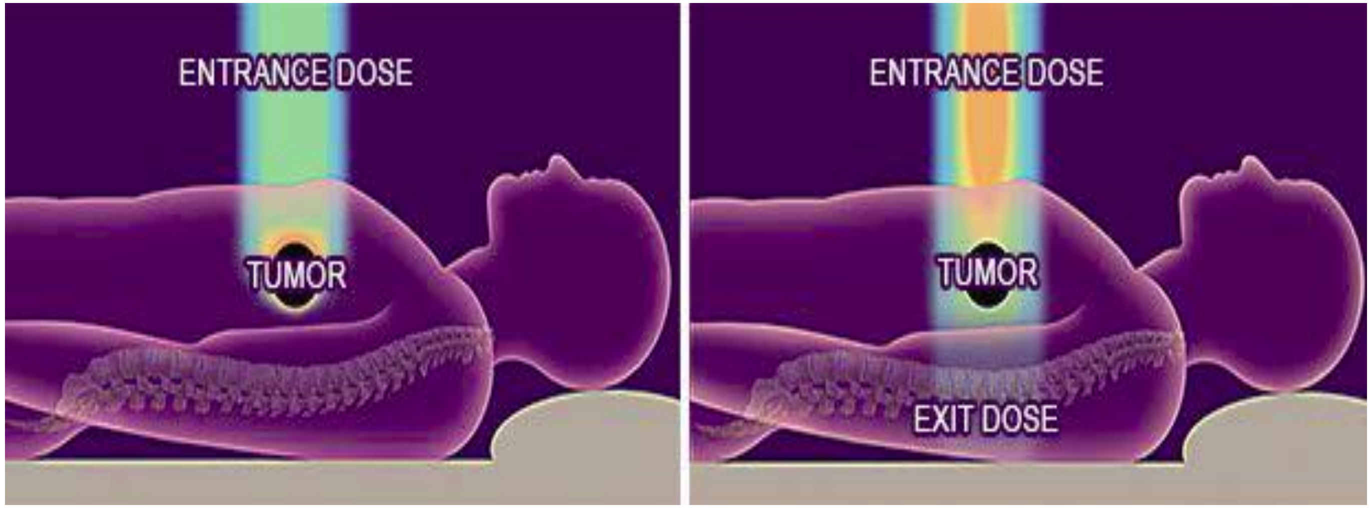


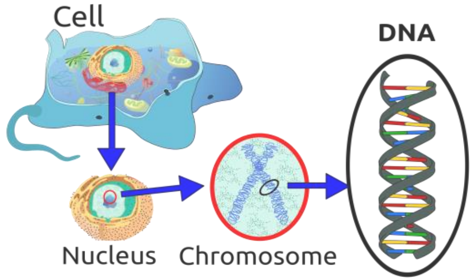


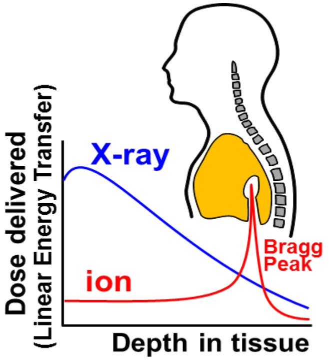
Reactions:
$d(d,n)^3He$
$d(p, n+p)^1H$
$^7Li(p,n)^7Be$
$^9Be(p,n)^9B$
.....

Neutron generation (H ions on converter materials)

Particle therapy of cancer (hadrontherapy – almost nothing in Central Europe)

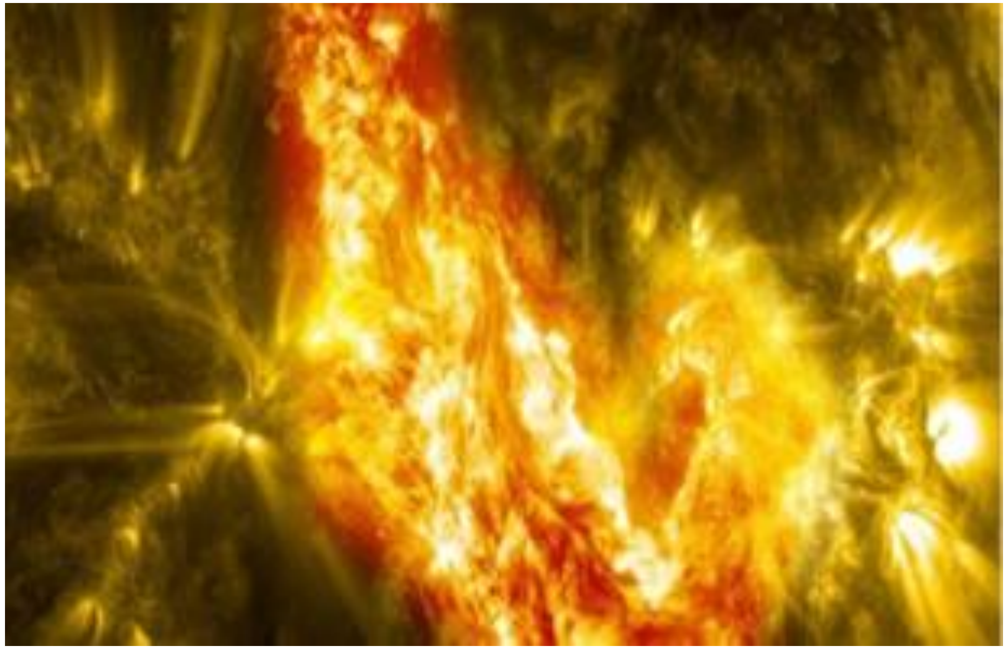




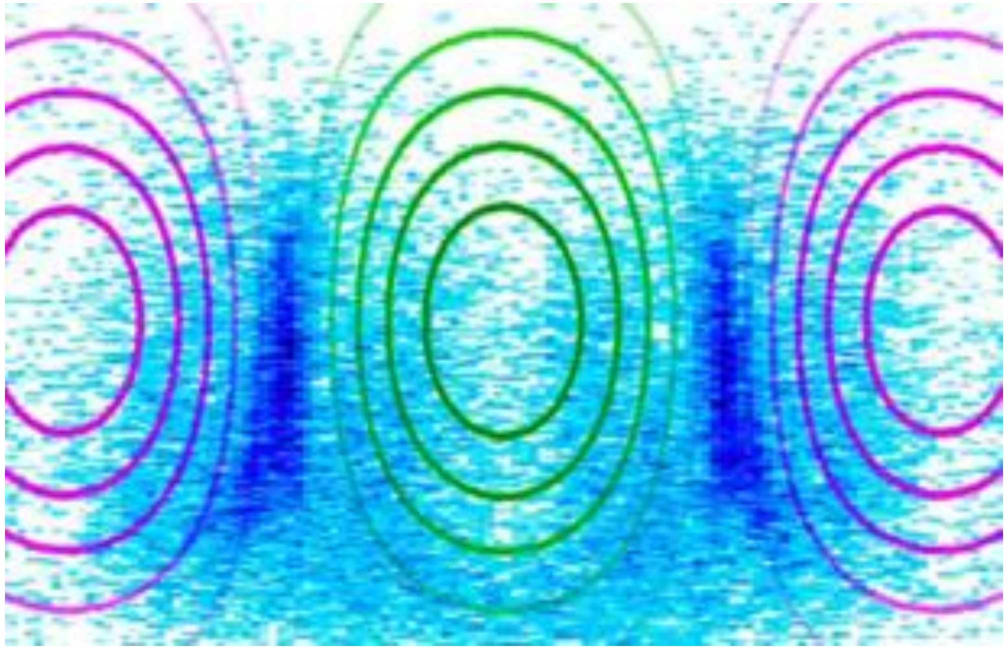


Radiobiology (ns-ps ultra-intense dose gives non-linear 'Flash' effects)

Physics in ultra-high electromagnetic fields



Plasma Physics and High Energy Density,
Astrophysics, Nuclear Photonics

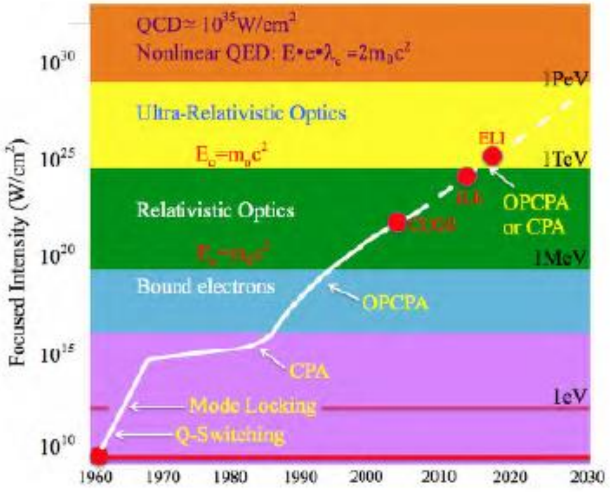


Ultra High Intensity Interactions
High-field physics and theory

Matter (and absence of matter) under extreme electromagnetic fields

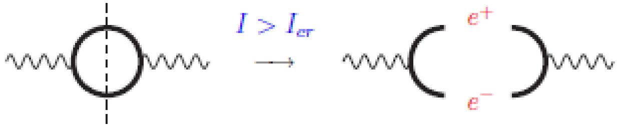
Plasma physics

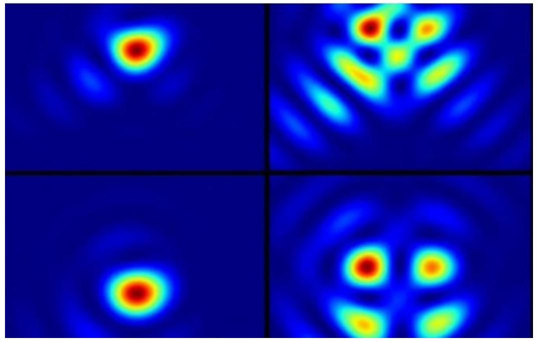
- High energy density physics, inertial confinement fusion, shock physics, development of plasma optics at ultra-high light intensities and energy densities



Explore vacuum structure

- Strong-field QED and production of matter-antimatter pairs, dispersive and absorptive photon propagation processes in ultra-high laser fields - vacuum birefringence and diffraction





Extreme Light Infrastructure for Europe

3 distributed branches set up as user facilities using European Structural Funds:

- **Attosecond Laser Science**, exploring ultra-fast processes with uniquely high time resolution (atto – a billion, billionth of a second) *(ELI Attosecond Light Pulse Source (ALPS), Szeged, HU)*
- **High-Energy Beamlines Facility**, developing and applying *very* short pulses of ultra-intense radiation to explore extreme conditions or produce high-energy particles and radiation *(ELI Beamlines, Prague, CZ)*
- **Nuclear Physics Facility** with ultra-intense lasers and brilliant gamma beams to produce and explore new nuclear states or generate neutron beams *(ELI NP, Magurele, RO)*

A European Research Infrastructure Consortium

A European International Organisation Established in 2021 brings together ALPS and Beamlines into one co-ordinated legal entity: ELI ERIC

The Czech Republic,
Host of Seat

Hungary,
Host

Italian Republic

Lithuania

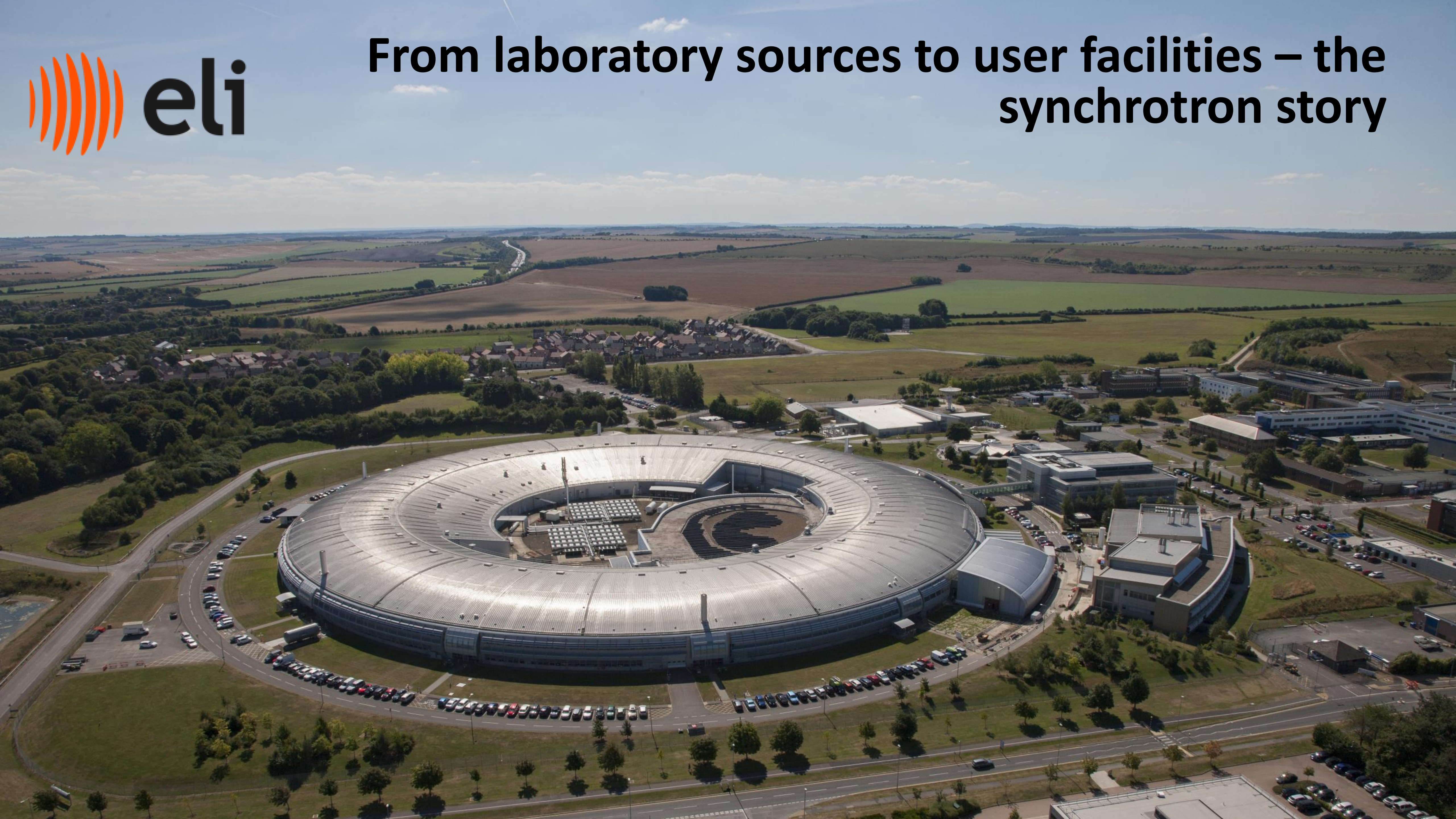
Federal Republic of Germany
Observer

Bulgaria
Observer

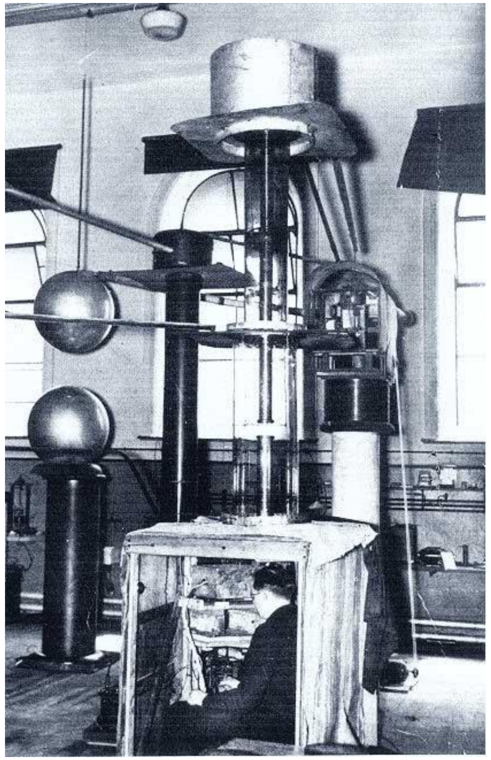
Horizon 2020 (INFRADEV) helps finance the integration of the joint user programme, as well as initial access pilots, flagship experiments

Member countries support ELI ERIC jointly with national funding.

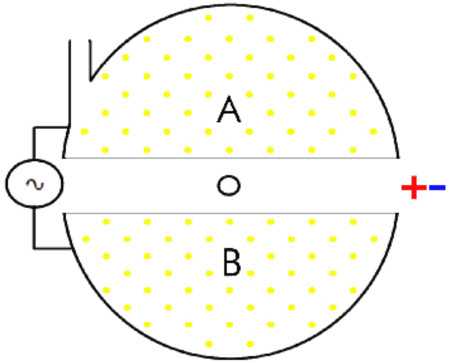
From laboratory sources to user facilities – the synchrotron story

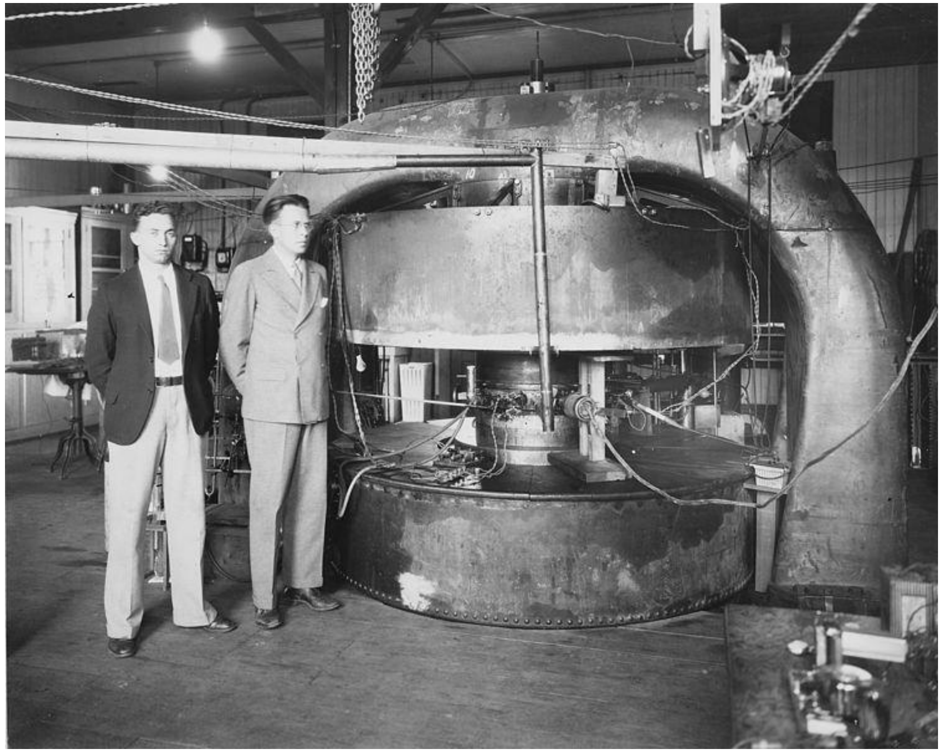


Origins



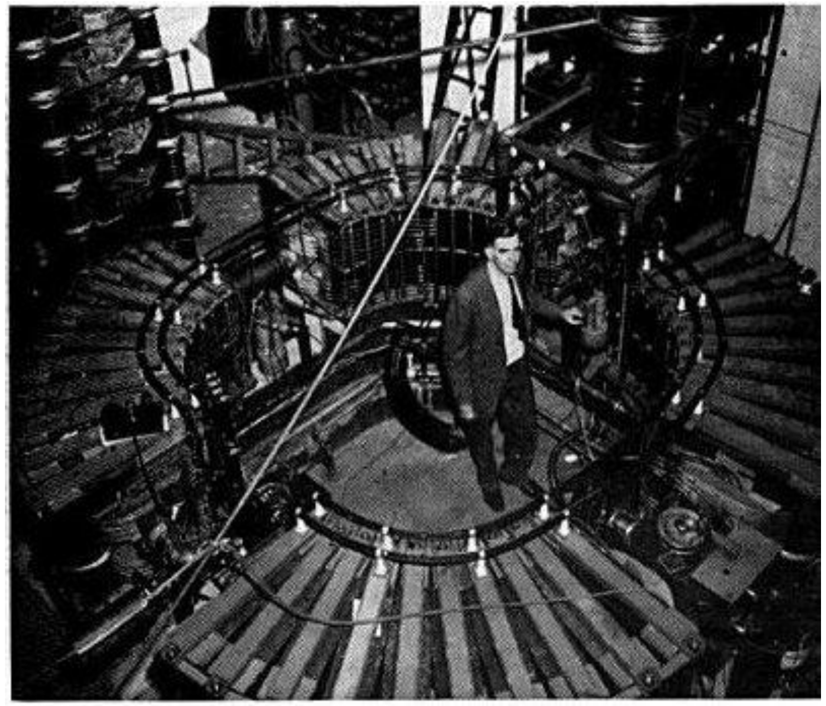
Cockroft and Walton – Cambridge 1930's





Lawrence – California – 1930's

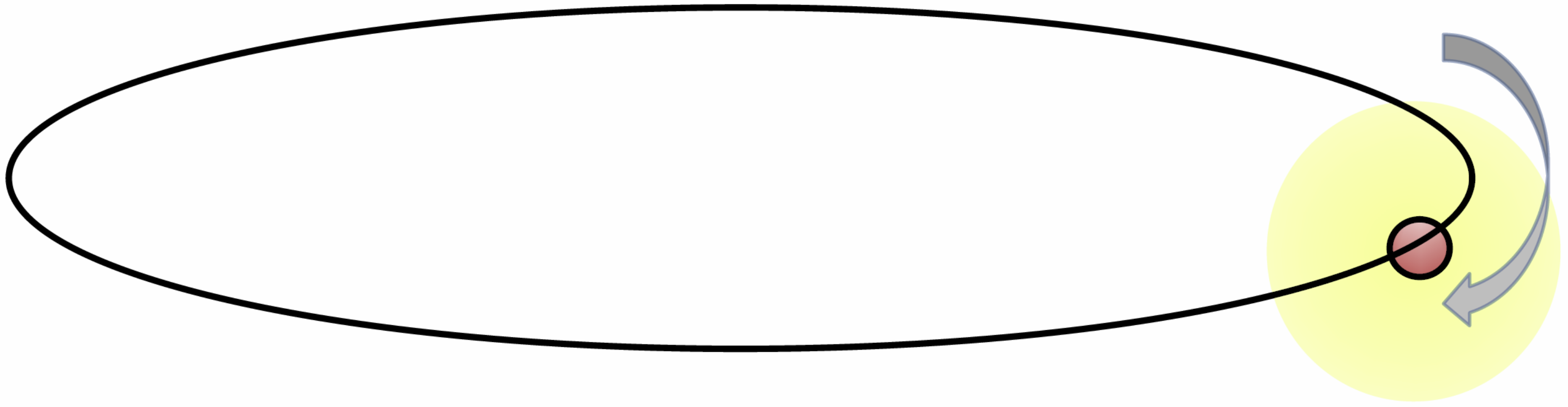
Ever increasing circles



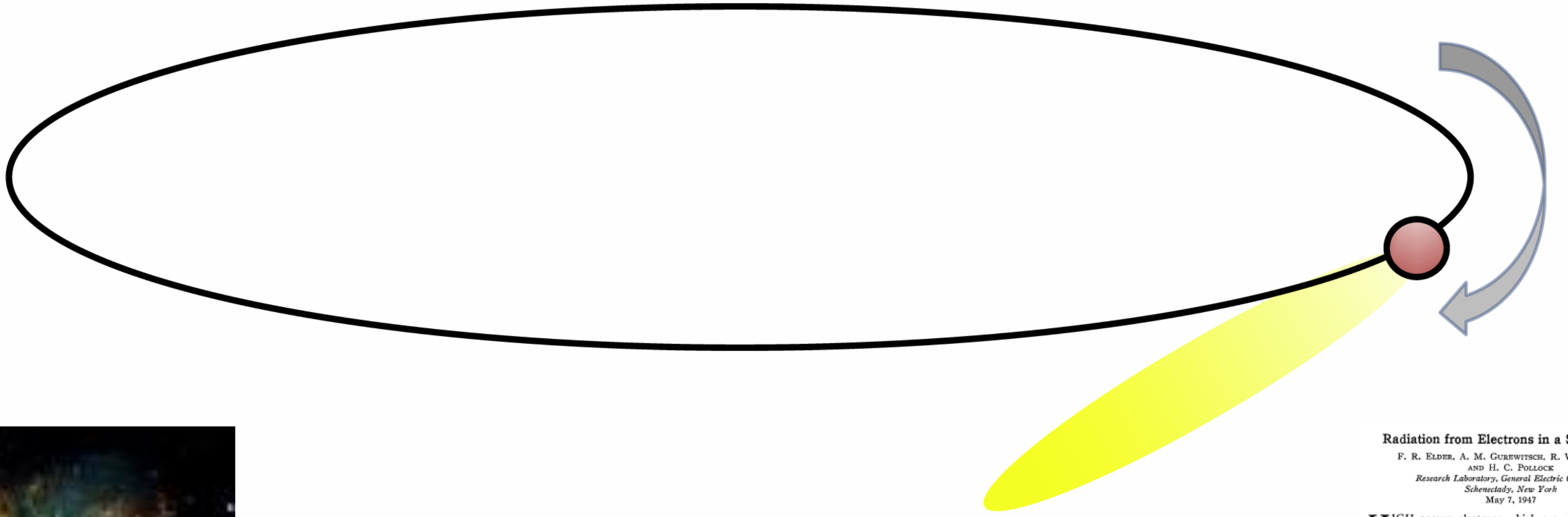
University of Michigan – 1949

CERN LHC from 2008

Unintended consequences



Unintended consequences

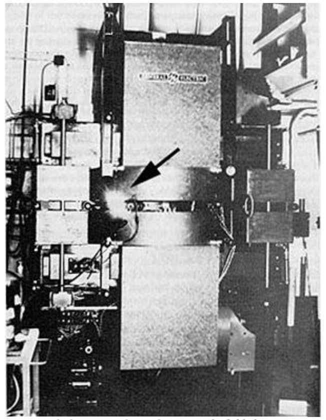


1946

Radiation from Electrons in a Synchrotron

F. R. Elder, A. M. Gurewitsch, R. V. Langmuir, and H. C. Pollock
Research Laboratory, General Electric Company, Schenectady, New York

May 7, 1947



HIGH energy electrons which are subjected to large accelerations normal to their velocity should radiate electromagnetic energy.[1–4] The radiation from electrons in a betatron or synchrotron should be emitted in a narrow cone tangent to the electron orbit, and its spectrum should extend into the visible region. This radiation has now been observed visually in the General Electric 70-Mev synchrotron.[5] This machine has an electron orbit radius of 29.3 cm and a peak magnetic field of 8100 gausses. The radiation is seen as a small spot of brilliant white light by an observer looking into the vacuum tube tangent to the orbit and toward the approaching electrons. The light is quite bright when the x-ray output of the machine at 70 Mev is 50 roentgens per minute at one meter from the target and can still be observed in daylight at outputs as low as 0.1 roentgen.

The synchrotron x-ray beam is obtained by turning off the r-f accelerating resonator and permitting subsequent changes in the field of the magnet to change the electron orbit radius so as to contract or expand the beam to suitable targets. If the electrons are contracted to a target at successively higher energies, the intensity of the light radiation is observed to increase rapidly with electron energy. If, however, the electrons are kept in the beam past the peak of the magnetic field and then expanded to a target, the intensity of the radiated light appears to be independent of the energy at which the electrons are removed from the beam. This is to be expected, for in a given machine the radiation is proportional to the fourth power of the electron energy. The light radiation is not observed if the beam is contracted before its energy is about 30 Mev. When the electron beam has been accelerated to the peak of the magnetic field and then decelerated to low energy, a rough measurement of the phase angle over which the light was visible gave a value of 90–100 degrees. The light was viewed through a slotted disk rotating at synchronous speed.

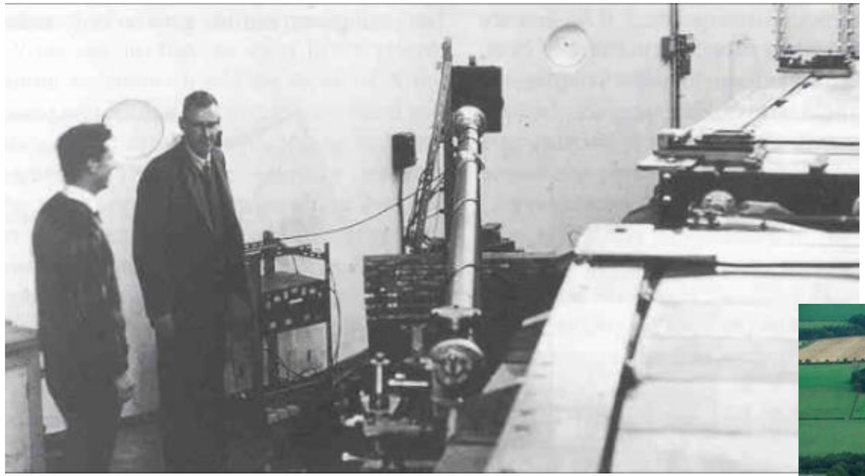
If the r-f resonator is turned off a short time before the peak of the magnetic field, the electron beam slowly contracts to a radius just larger than that of the interior target and then expands as the magnetic field decreases. In this case, the observer no longer sees a single point of light but a short line with extension in the plane of the orbit.

The light emitted from the beam is polarized with the electric vector parallel to the plane of the electron orbit. It disappears as the observer rotates a piece of Polaroid before the eye through ninety degrees. An investigation of the spectral distribution of the energy is in progress and will be reported.

This work has been supported by the Office of Naval Research under contract N5ori–178.

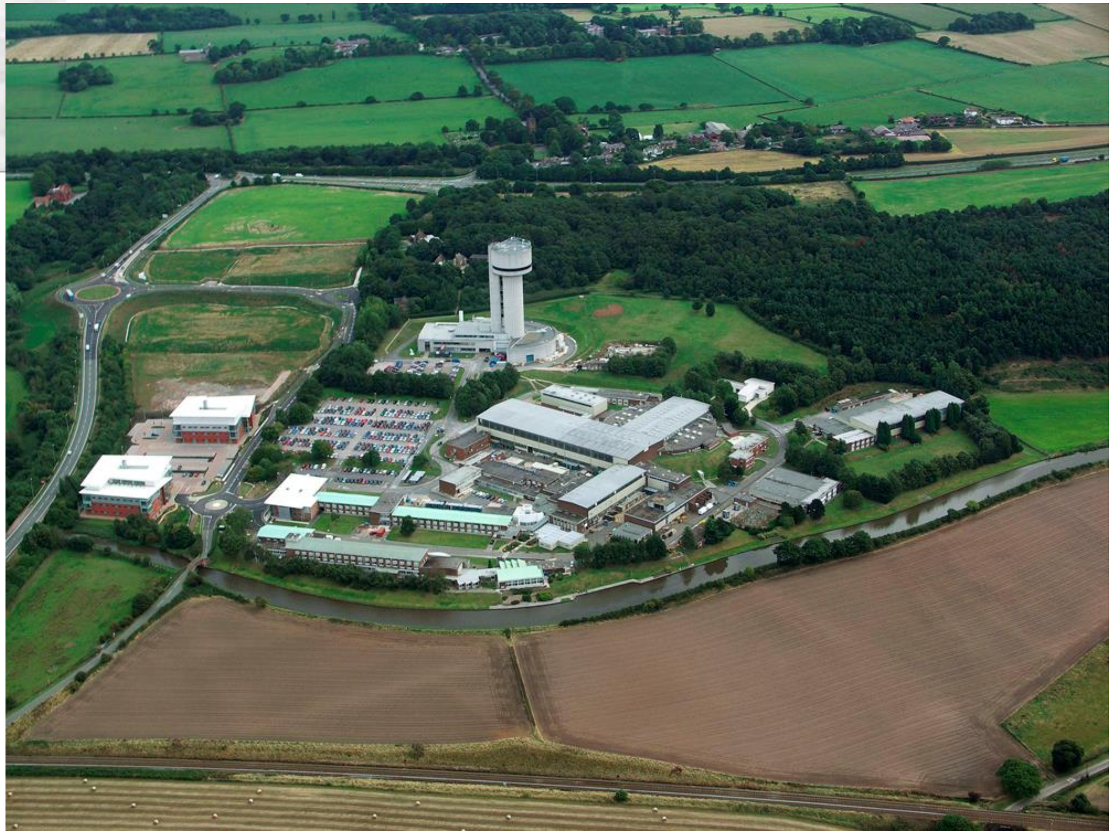
[1] D. Iwanenko and I. Pomeranchuk, Phys. Rev. **65**, 343 (1944).
[2] J. P. Blewett, Phys. Rev. **69**, 87 (1946).
[3] L. I. Schiff, Rev. Sci. Inst. **17**, 6 (1946).
[4] J. S. Schwinger, Phys. Rev. **70**, 798 (1946).
[5] H. C. Pollock *et al.*, Phys. Rev. **70**, 798 (1946).

Intended consequences



NINA, Daresbury
1960's

Synchrotron Radiation Source,
Daresbury, 1981 - 2008




1990's – 3rd generation sources
10,000s mostly non-expert users accessing the facility 24/6

ELI Beamlines
Dolní Břežany

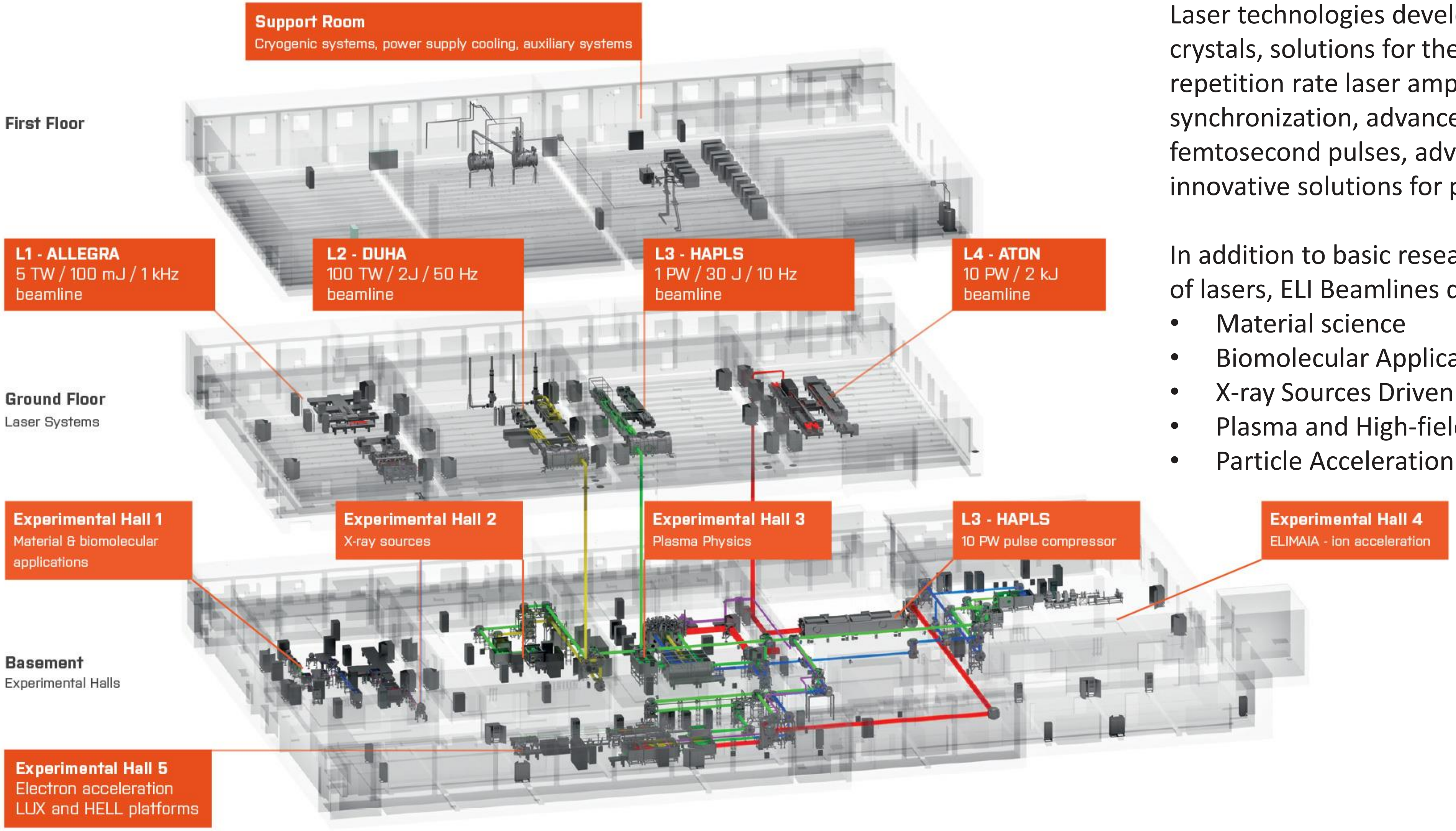
ELI Beamlines

Dolní Břežany

Mission profile

- Operate cutting edge, **high-power femtosecond laser** systems with **high energy**, **high repetition-rate** capability
- Explore interaction of **light with matter (plasma) at ultrahigh laser intensities**
- Offer **secondary sources (X-rays and accelerated particles)** with unique capabilities to users
- Enable **pioneering research** not only in plasma physics, high-field physics, nuclear fusion and laboratory astrophysics, but also in material science, biology, chemistry, medicine and other disciplines with strong **multidisciplinary application** potential

ELI Beamlines Facility Layout

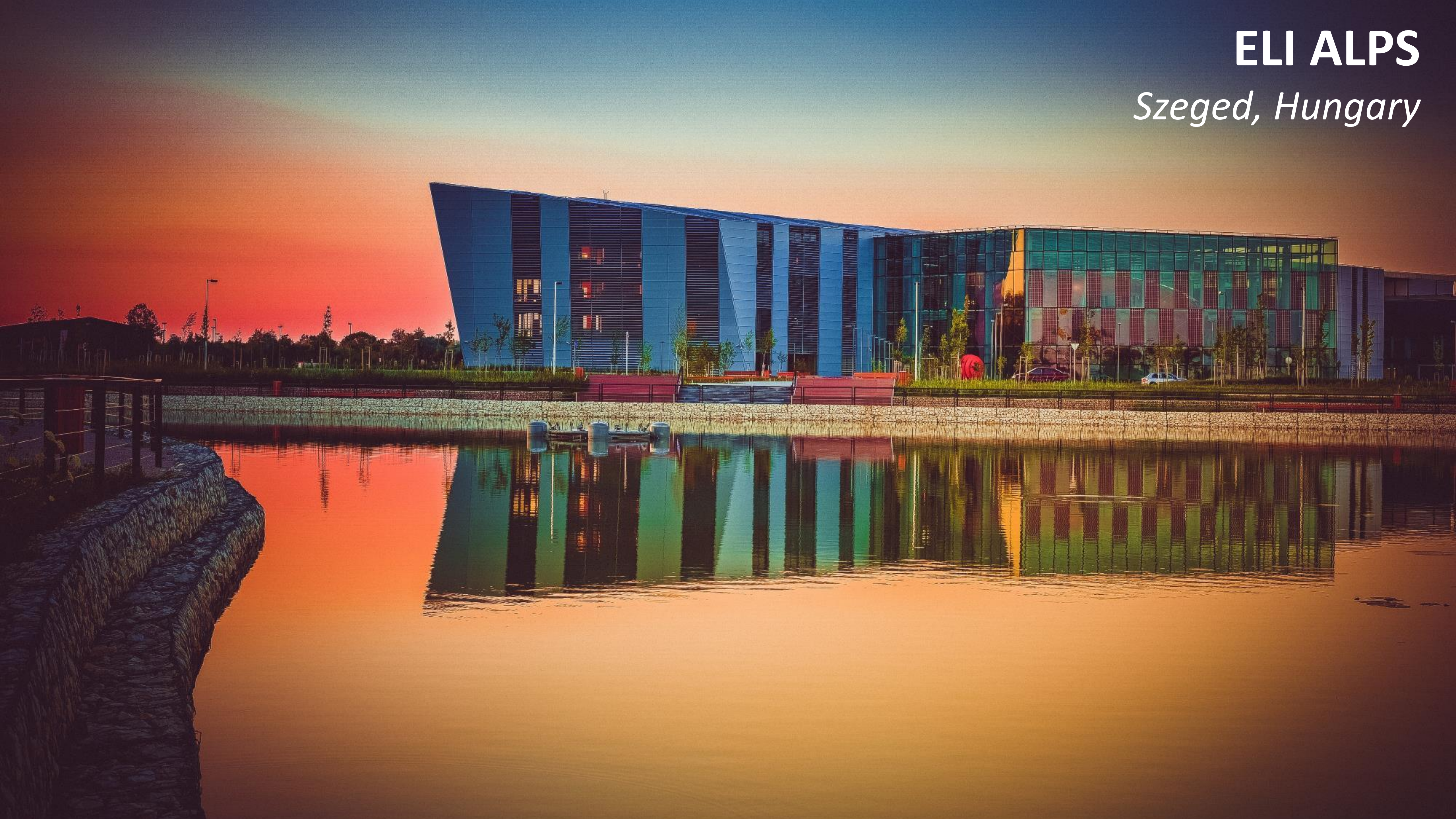


ELI Beamlines

Laser technologies developing new techniques for laser crystals, solutions for the cryogenic cooling of high-power repetition rate laser amplifiers, femtosecond synchronization, advanced repetition rate diagnostics of femtosecond pulses, advanced control systems, and innovative solutions for petawatt (PW) pulse compressors.

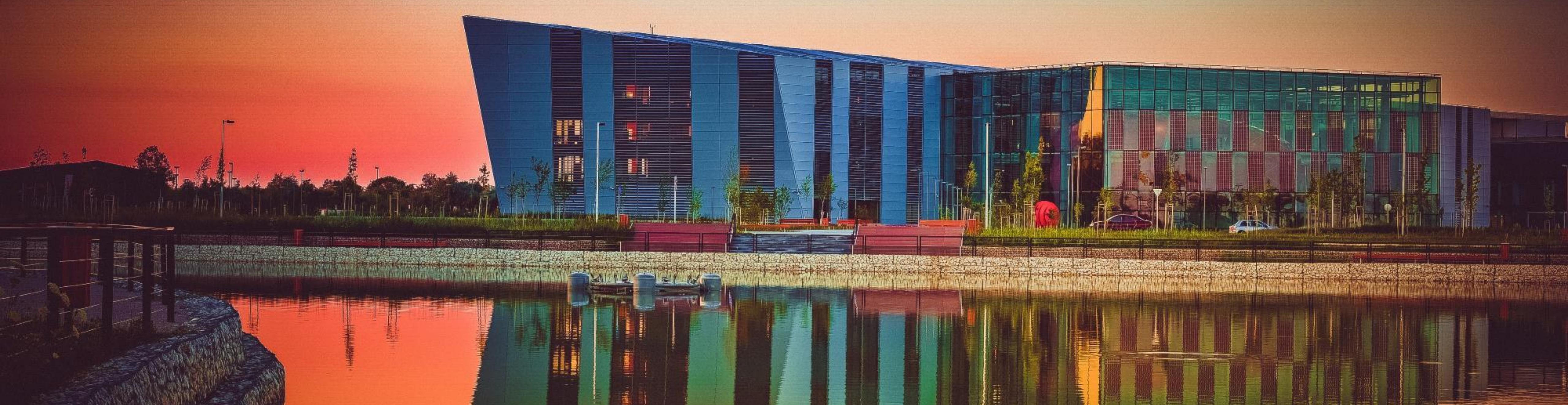
In addition to basic research and development in the field of lasers, ELI Beamlines deals with research:

- Material science
- Biomolecular Applications
- X-ray Sources Driven by Ultrashort Laser Pulses
- Plasma and High-field Physics
- Particle Acceleration


ELI ALPS
Szeged, Hungary

ELI ALPS

Szeged, Hungary



Mission Profile

To provide laser and secondary light and particle sources in the form of ultrashort bursts with high repetition rates. Energetic coherent light pulses of few optical cycles are available from the THz (10^{12} Hz) to the X-ray (10^{18} — 10^{19} Hz) frequency range

Dedicated to study extremely fast dynamics by taking snapshots in the attosecond scale of the electron dynamics in atoms, molecules, plasmas and solids

The parallel existence of these secondary sources and state of the art lasers including PW-class lasers within the same facility, offers unique time-resolved investigation possibilities for both nonrelativistic and relativistic interaction of light with all the four phases of matter

ELI ALPS Facility Layout

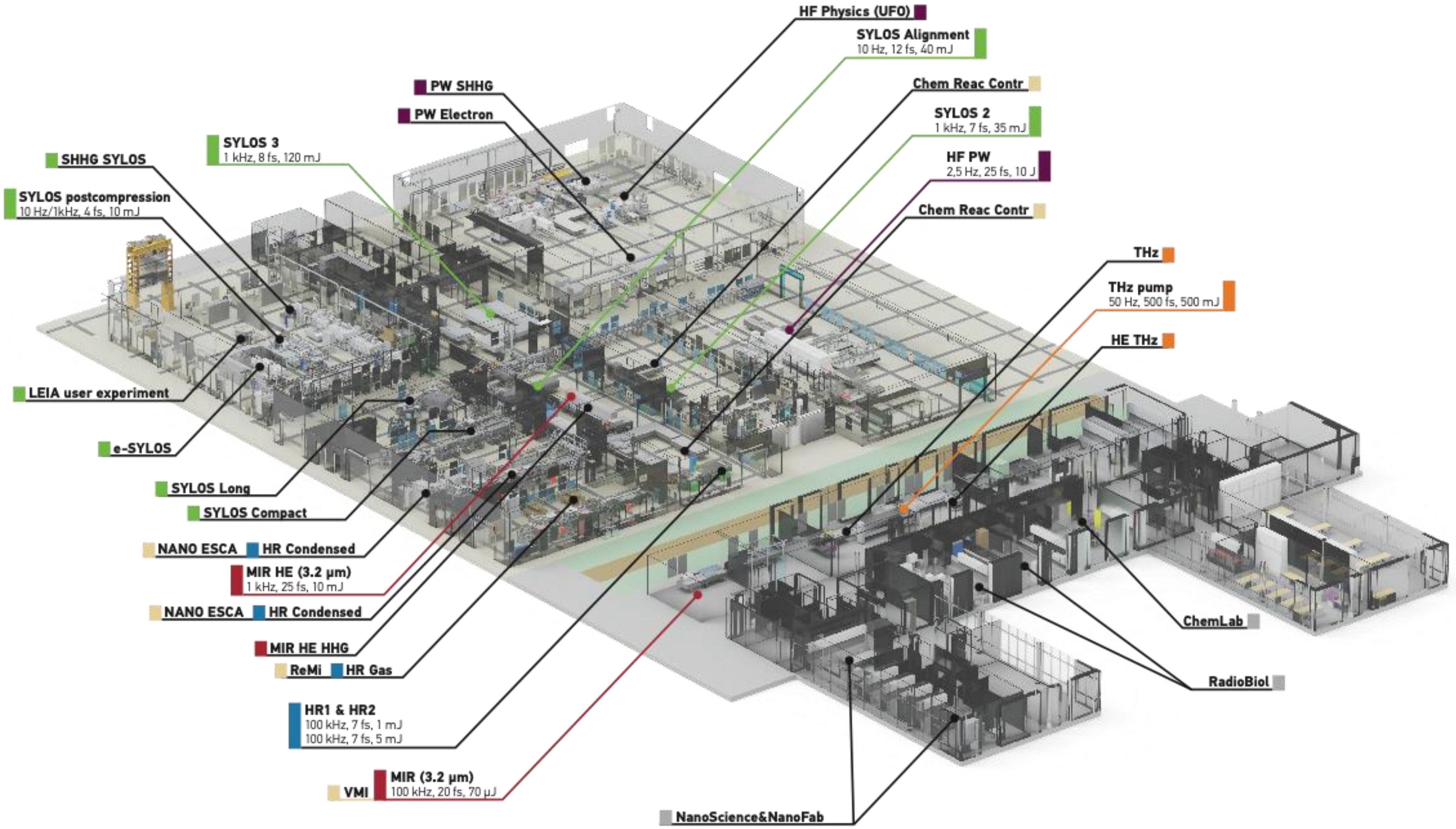
ELI ALPS

(Attosecond Light Pulse Source)

ELI ALPS is a leading research facility in ultrafast physical processes as well as a world-class centre for generating outstanding biological, chemical, medical and materials science results.

Research fields and applications:

- Development of attosecond light sources and measurement techniques
- Radiobiological applications
- Energy research: solar cells, artificial photosynthesis, transmutation of used nuclear fuels
- High-peak-power photonics
- Information technology, materials science and nanoscience
- Particle acceleration with few cycle laser pulses



ELI NP

Măgurele, Romania

Most advanced photonuclear physics facility in the world with 2 PW class lasers

Basic science

- Laser-driven nuclear physics, nuclear astrophysics and nucleosynthesis
- particle acceleration with high power lasers
- Strong field quantum electrodynamics (QED)

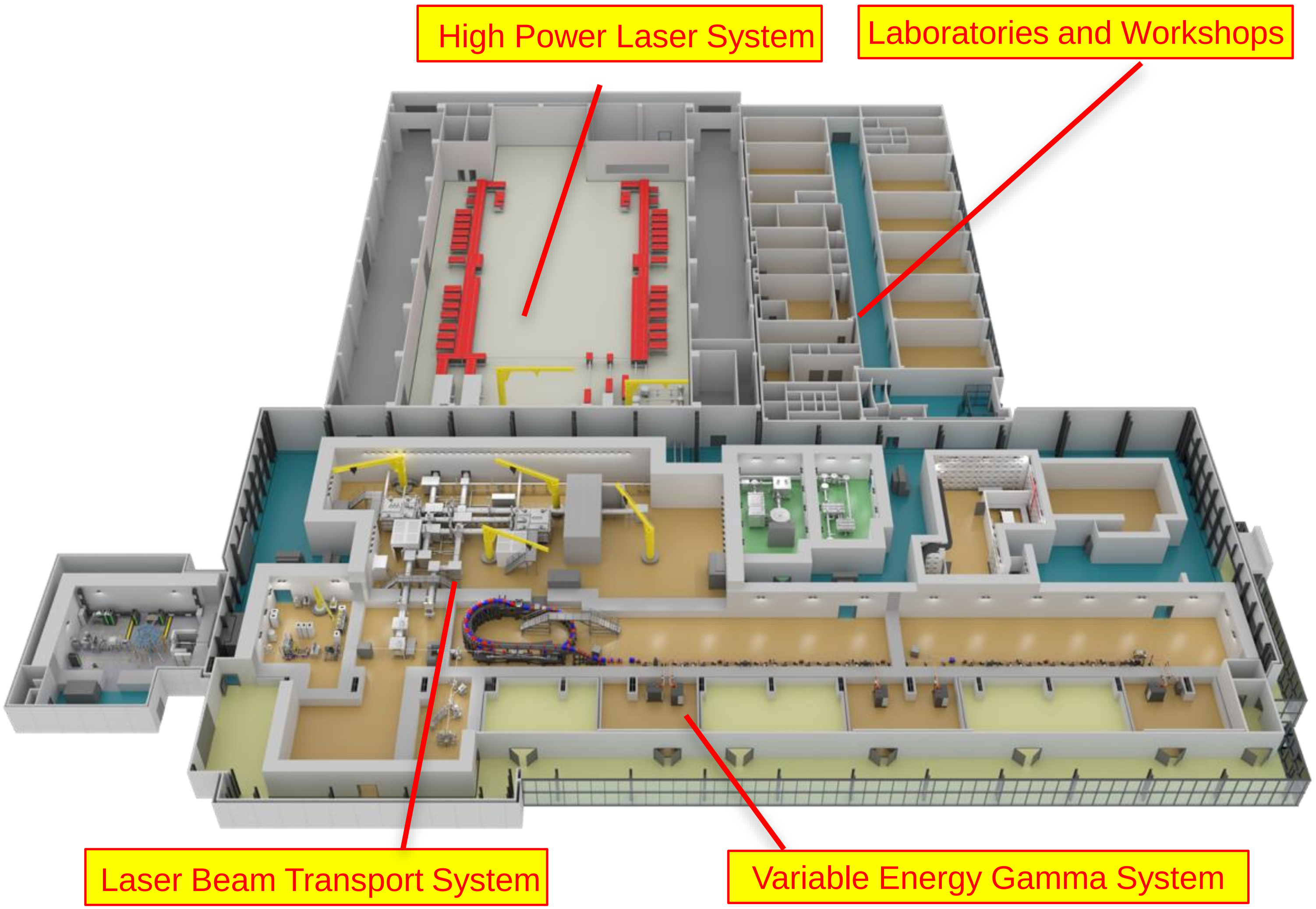
Technology development

- Medical applications (X-ray imaging, radioisotopes)
- Industrial applications (non-destructive studies)
- Materials and biological science in high radiation fields

ELI NP Facility Layout

World-unique combination of instrumentation

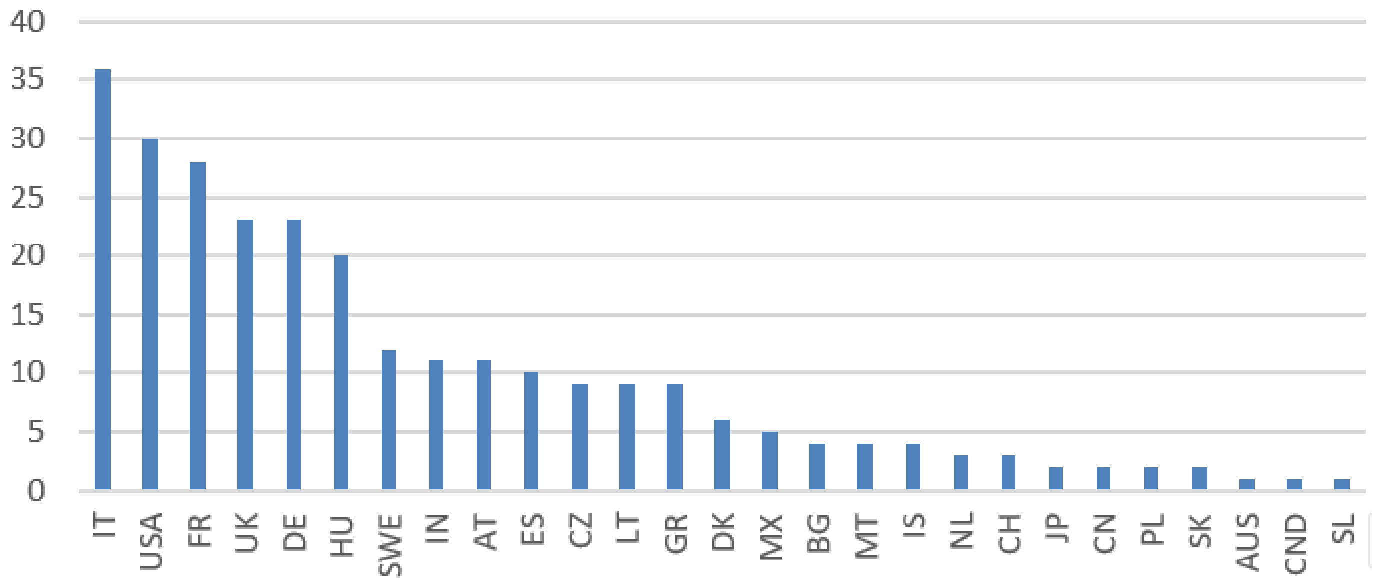
- 100 TW laser, 27 fs, 2.7 J @10 Hz (single shot available)
- 1 PW laser, 24 fs - 1 ps, 25 J @ 1 Hz (single shot available)
- 10 PW laser operational (**10.4 PW on target from April 2023** ! but only offered to users when experimental station complete
- Optics and chambers for nuclear physics and ultra-high-field physics (QED)
- Monochromatic γ-beam (tunable 0.2 – 19.6 MeV) under development

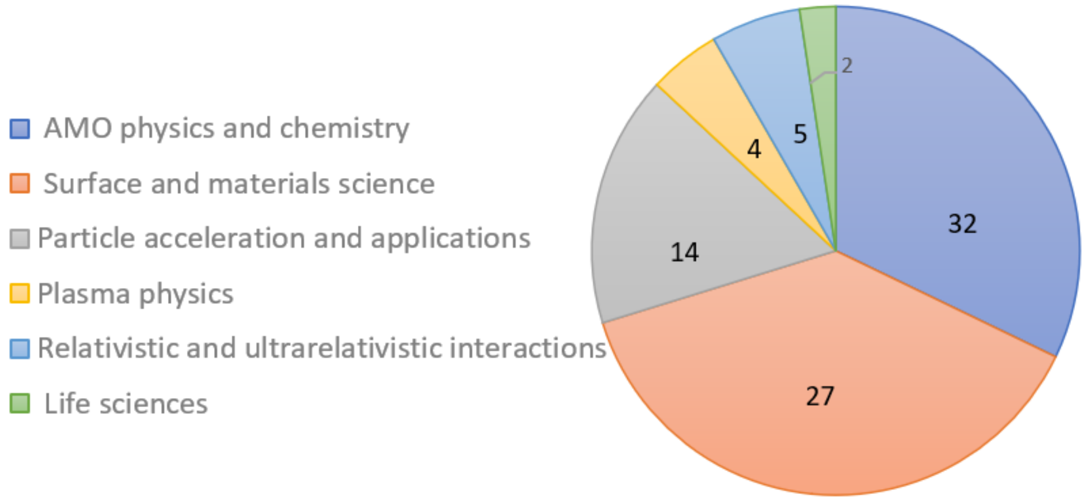


ELI User Calls

- 1st User Call launched June 2022 for experiments late 2022 to April 2023
  - 44 proposals accepted and evaluated for 10 beamlines/sources
- 2nd User Call launched Jan 2023 for experiments late 2023 to Feb 2024
  - 102 accepted and evaluated for 32 beamlines/sources
- 3rd User Call in mid-Sept Jan 2023 for experiments from Feb 2024
- Single point of access https://up.eli-laser.eu

2^{nd} ELI ERIC User Call





Nationality of institute to which all unique external investigators are affiliated for the 2^{nd} user call at ELI ERIC: 271 in total plus 51 unique investigators from ELI ALPS, and 39 from ELI Beamlines

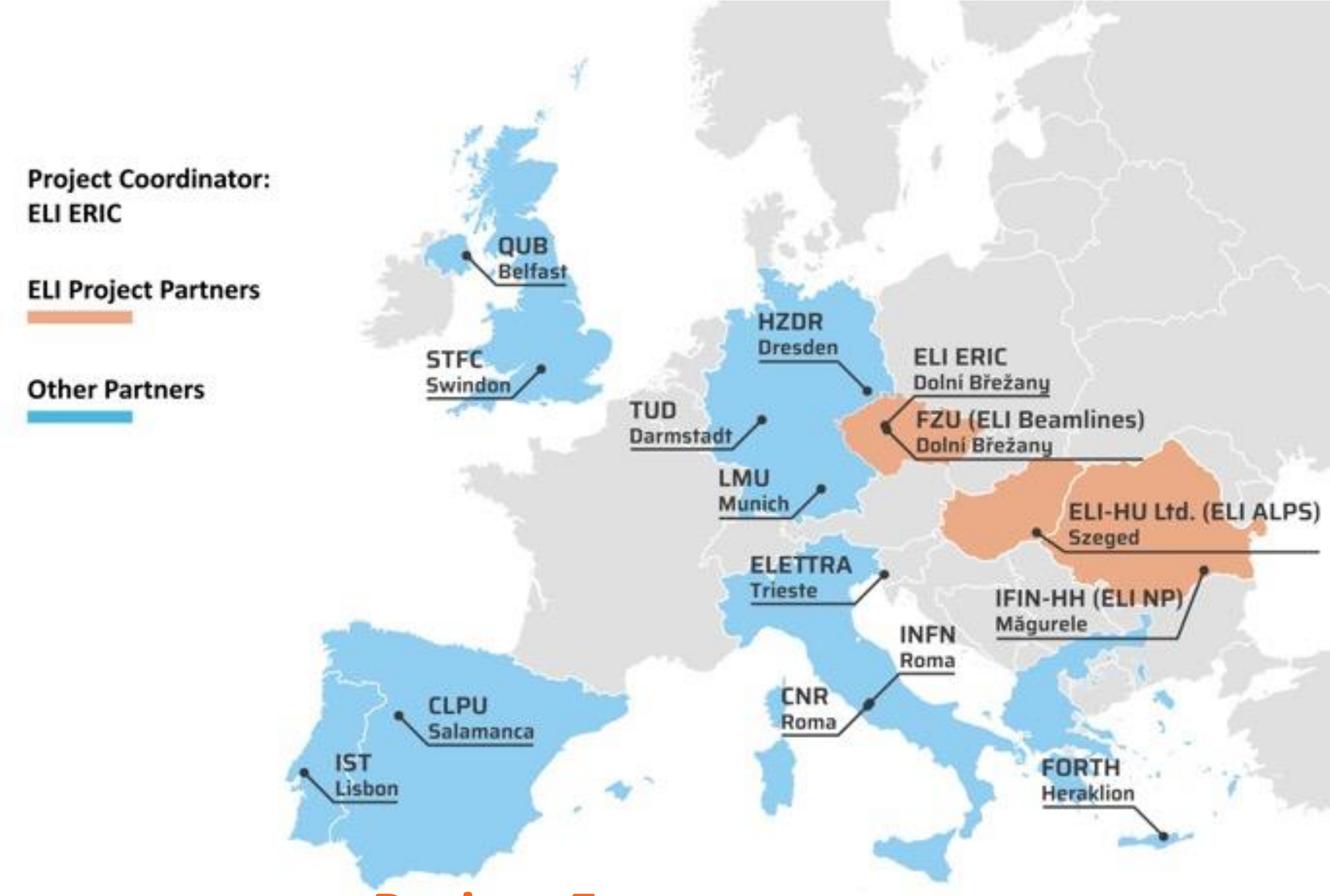
Integrating ELI's Facilities Requires Resources and a Plan.

Project Objectives

IMPULSE focuses on **achieving quick and effective transition of ELI ERIC from construction into sustainable operations** by **uniting the ELI facilities** and making them **accessible for users through one single, high-quality access point**.

IMPULSE addresses the **key scientific, technical, organisational,** and **management requirements** of this **integration**, **building user communities** and **expanding the ELI member consortium.**

https://impulse-project.eu/



Project Facts

- **14 Partners**
- **9 Countries**
- **42 Months**
- **€19.9 Million**

IMPULSE is funded by the European Union's Horizon 2020 research and innovation programme under grant agreement No. 871161

ELI ERIC: Development of a large scale laser facility

ELI Summer School
August 29th 2023

ELI Attosecond Light Pulse Source

Szeged, Hungary

ELI ALPS is a world-class centre for :

- Ultrafast physical processes
- Chemical, medical and materials science analysis
- Attosecond measurement techniques
- Biological imaging technologies
- Artificial photosynthesis
- Nanoscience
- 270 international staff
- Area 30,000 m^2

ELI ALPS Facility Layout

ELI ALPS

(Attosecond Light Pulse Source)

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- High-peak-power photonics
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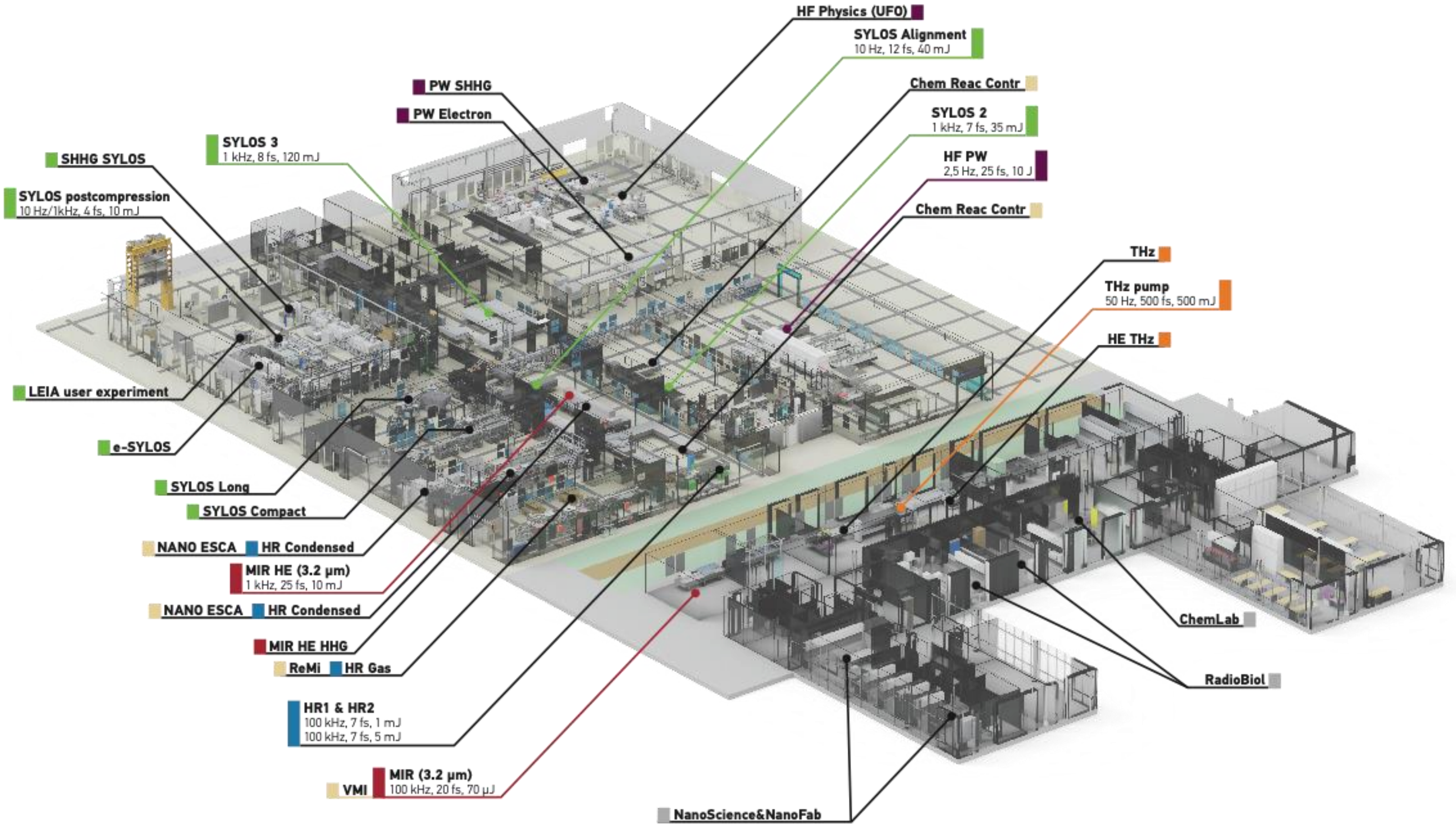
- Particle acceleration with few cycle laser pulses



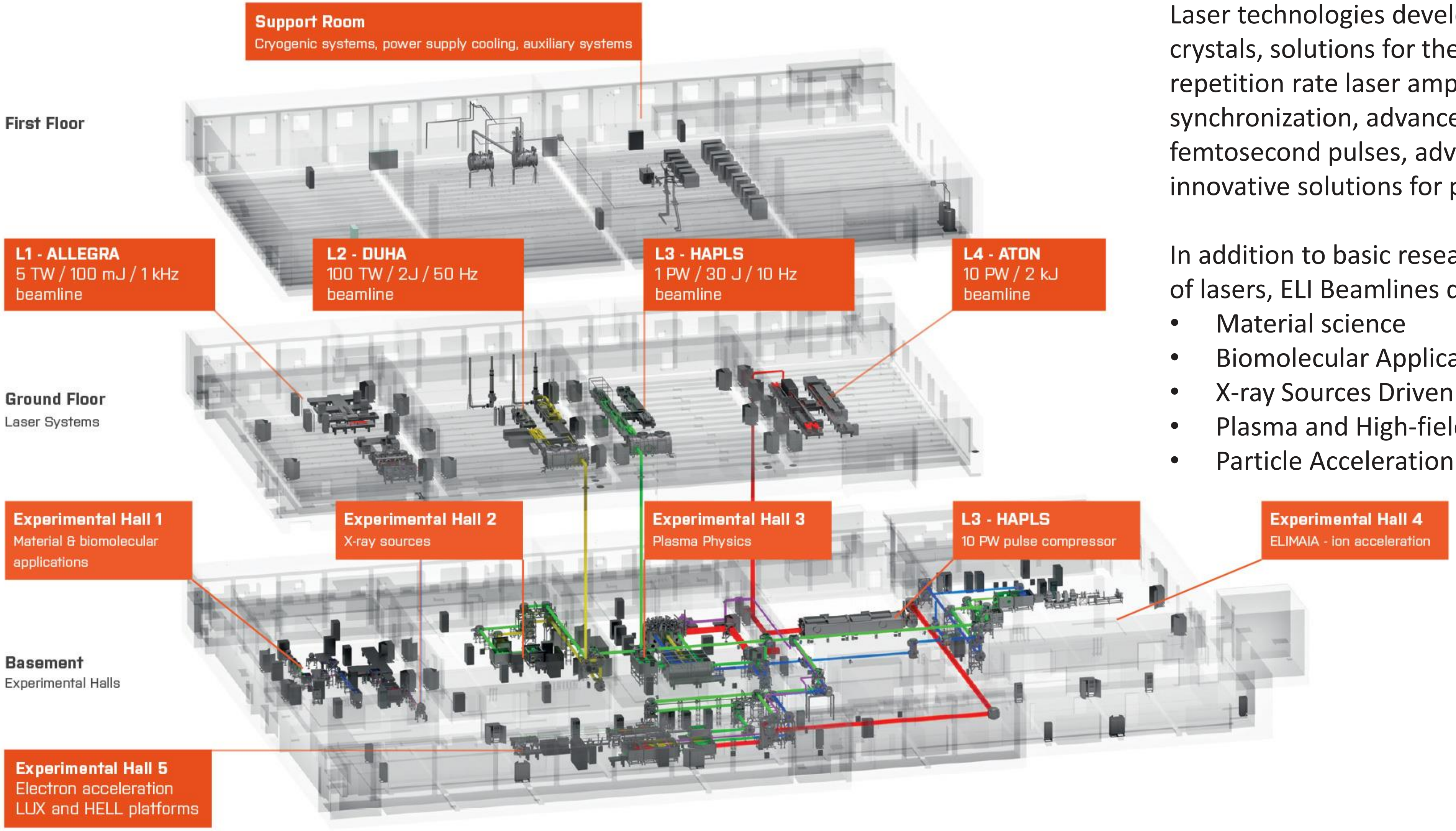
ELI Beamlines

Dolní Břežany, Czech Republic

ELI Beamlines is the world's most versatile laser center covering the broadest range of energy and frequency under one roof. We explore the interaction of light with matter at intensities 10 times higher than previously achievable.

- medical imaging and diagnostics, radiotherapy
- new materials
- X-ray optics
- Laser driven hadron-therapy
- High field
- Fusion
- 300+ international staff

ELI Beamlines Facility Layout



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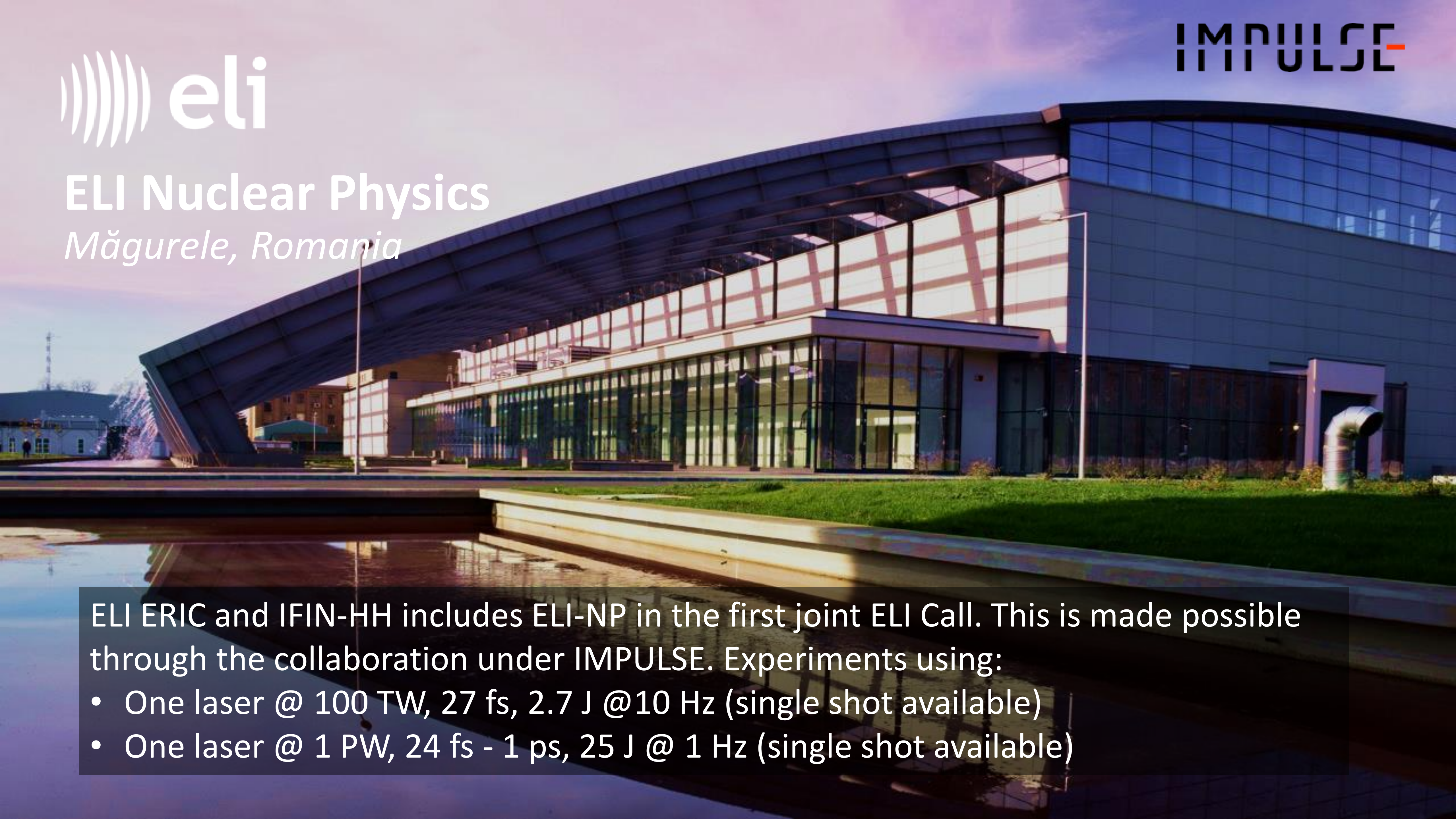


ELI Nuclear Physics

Măgurele, Romania

ELI ERIC and IFIN-HH includes ELI-NP in the first joint ELI Call. This is made possible through the collaboration under IMPULSE. Experiments using:

- One laser @ 100 TW, 27 fs, 2.7 J @10 Hz (single shot available)
- One laser @ 1 PW, 24 fs - 1 ps, 25 J @ 1 Hz (single shot available)

ELI-NP Research Infrastructure

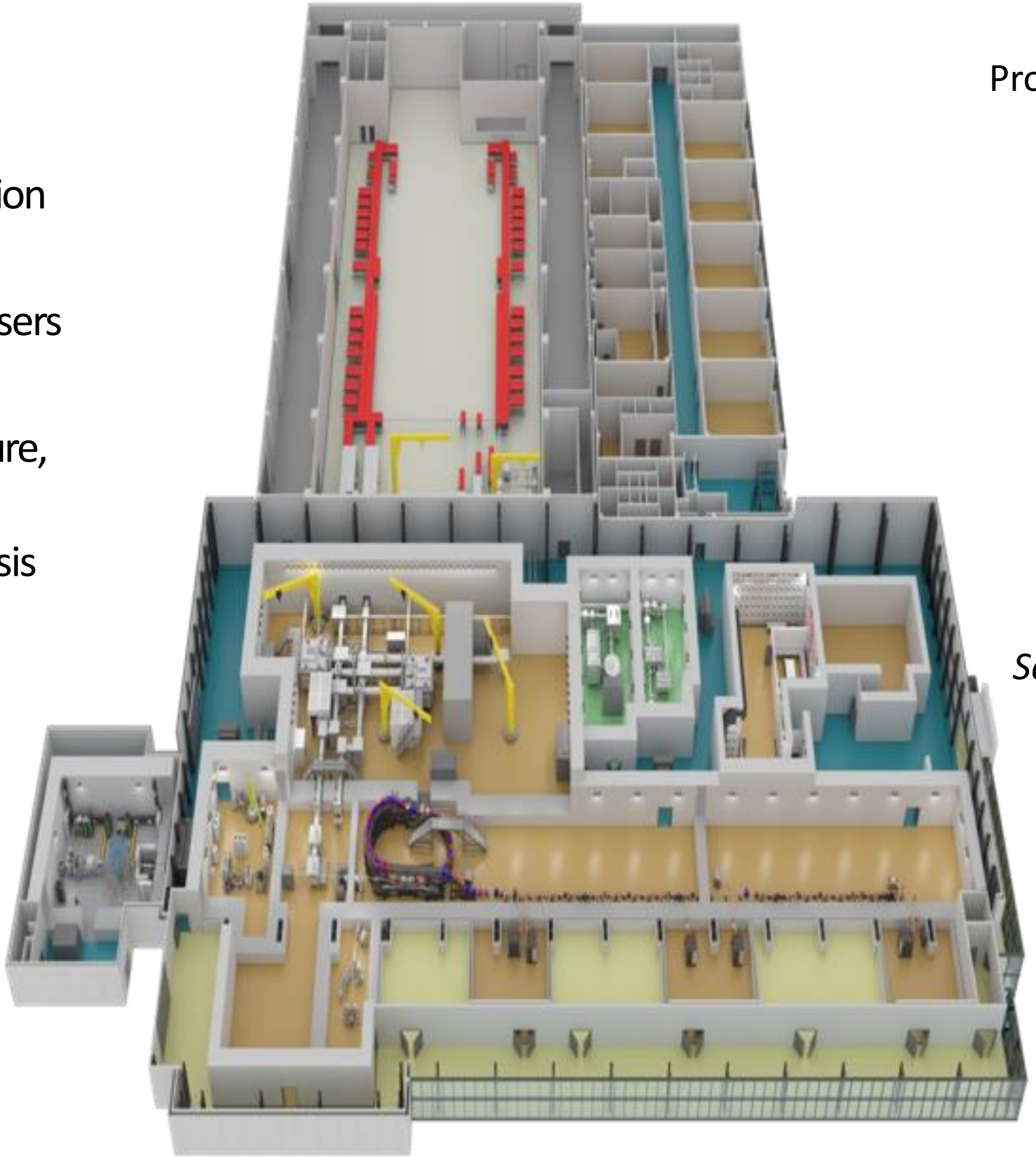
eli

Advanced studies in basic science ...

- characterization of laser-matter interaction with nuclear methods
- particle acceleration with high power lasers
- nuclear reactions in plasma
- photonuclear reactions, nuclear structure, exotic nuclei
- nuclear astrophysics and nucleosynthesis
- quantum electrodynamics (QED)

... and applications – developing technologies for:

- medical applications (X-ray imaging, radioisotopes)
- industrial applications (non-destructive studies with !)
- material studies with positrons
- materials in high radiation fields



Calin Ur
Project Director
ELI-NP

Sydney Galès
Science Director
ELI-NP

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.

IMPULSE

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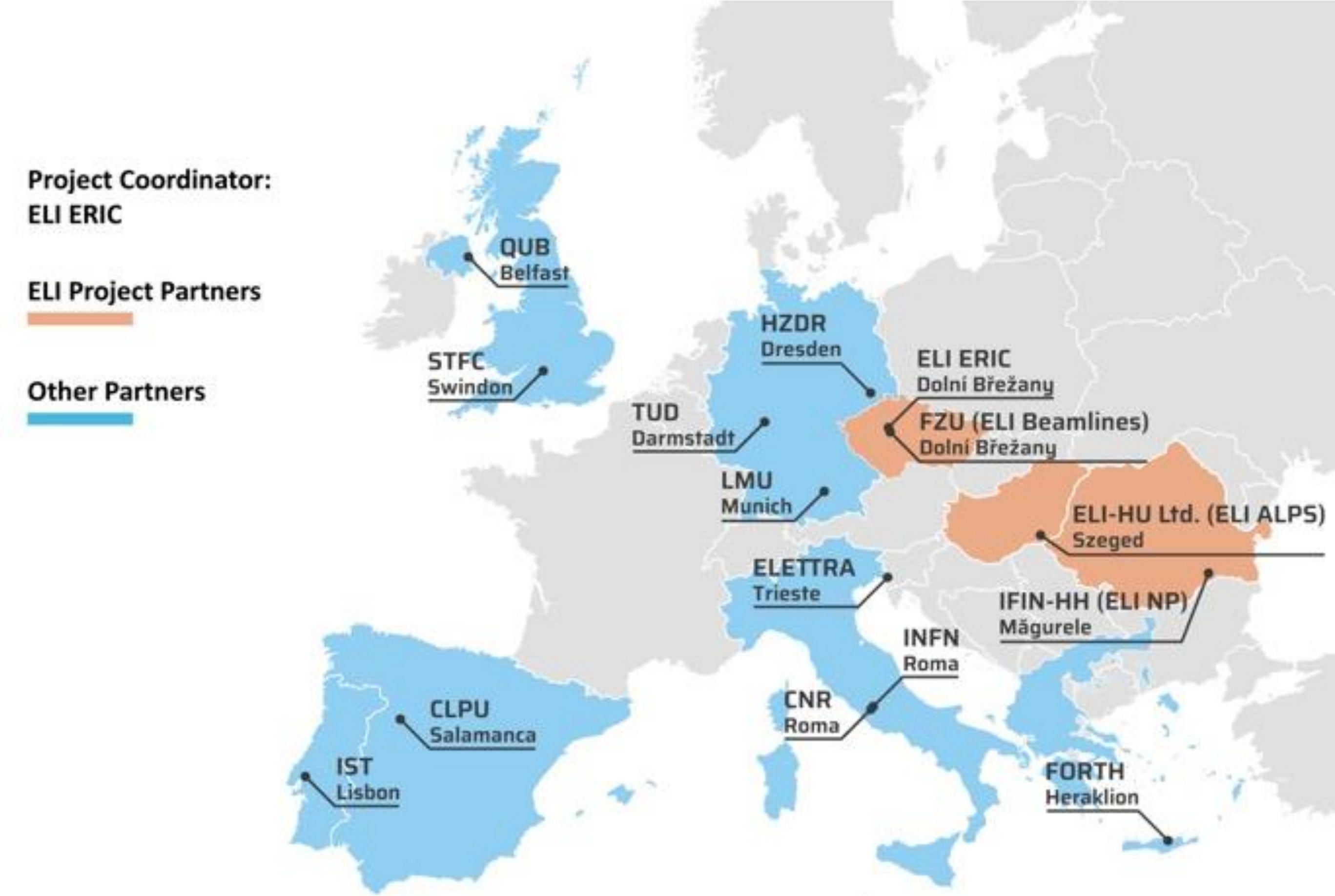

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