attosecond

NEW SZÉCHENYI PLAN

ELI-ALPS
The Future Stronghold of Attoscience

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National Development Agency
www.ujszechenyiterv.gov.hu
06 40 638 638

HUNGARY'S RENEWAL

The projects are supported by the European Union and co-financed by the European Regional Development Fund.

OUTLINE

- What is ELI ?
- Science evolution from femtosecond to attosecond time domain
- ELI-ALPS: an international user facility
- Applications of attoscience at ELI-ALPS

Roadmap of European Strategic Forum on Research Infrastructures (ESFRI)

Two Large Laser Infrastructures were selected

- **HIPER (European High Power laser Energy Research facility): for civilian laser fusion research ("fast ignition scheme")**

- **ELI (Extreme Light Infrastructure): reaching highest laser intensities and related applications**

ELI: "Extreme Light Infrastructure"

- ELI will be the world's first international laser research infrastructure, pursuing unique science and research applications for international users

- ELI will be implemented as **a distributed research infrastructure** based initially on 3 specialised and complementary facilities located in CZ, HU and RO

- ELI is the first ESFRI project to be **fully implemented in the newer EU Member States**

- ELI is **pioneering a novel funding model combining the use of structural funds** (ERDF) for the implementation and **contributions to an ERIC** for the operation

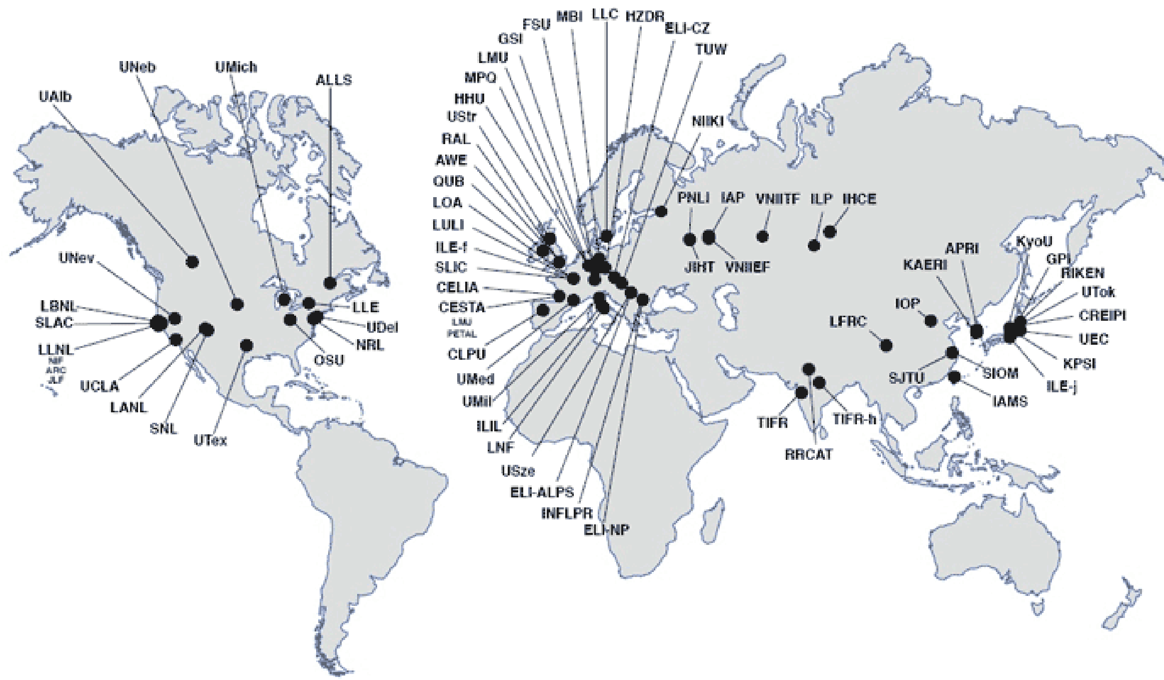
ELI – borne by the international scientific laser community

delivery consortium

Integrated Initiative LASERLAB-Europe

30 National Laser Facilities from 16 European countries

National high-power laser facilities world-wide



Ultra-high intensity laser systems worldwide in 2010 eli delivery consortium

ELI: Scientific Case

"Grand Challenges"

Attosecond Laser Science: temporal investigation of electron dynamics in atoms, molecules, plasmas and solids at attosecond time scale

High Energy Beam Science: development and usage of dedicated beam-lines with ultra short pulses of high energy radiation and particles reaching almost the speed of light

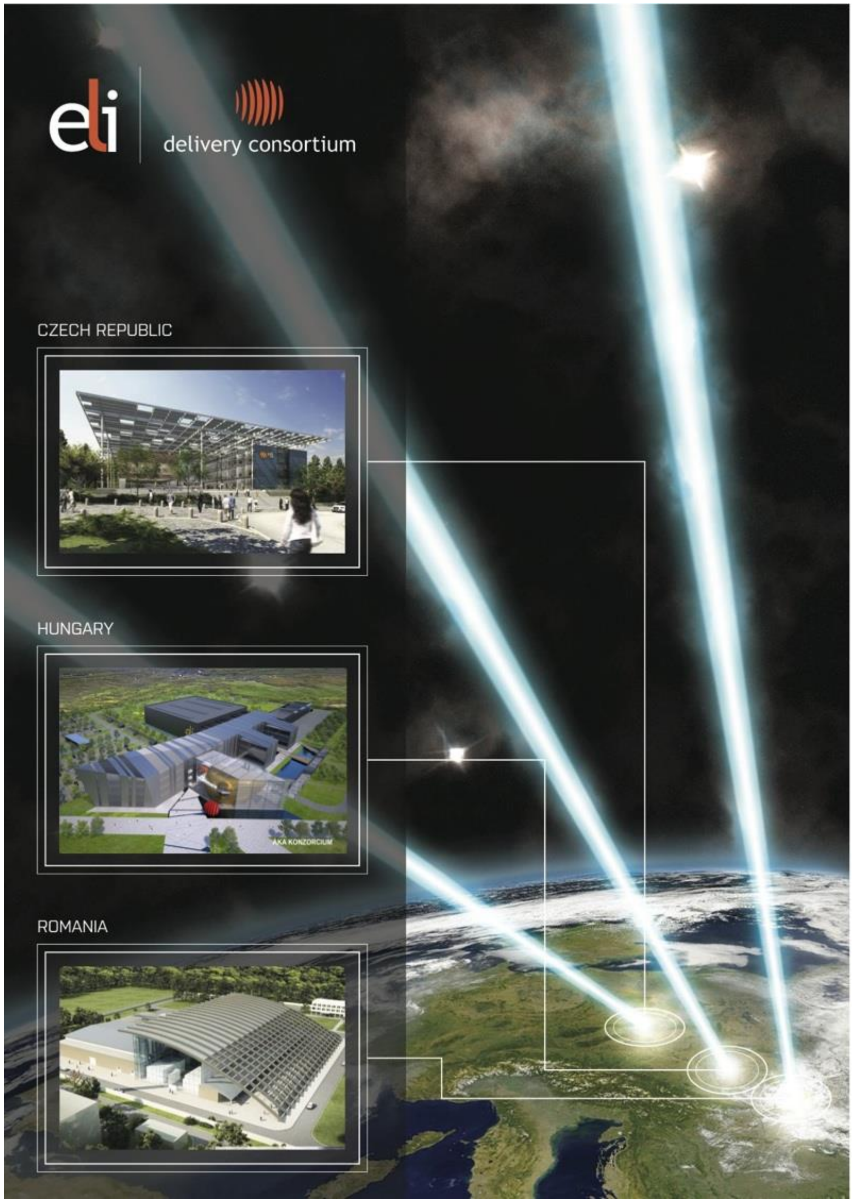
Laser-Induced Photonuclear Physics: nuclear physics methods to study laser-target interactions, new nuclear spectroscopy, new photonuclear physics, etc.

Ultra-High Field Science: investigation of laser-matter interaction in an intensity range where relativistic laws could stop to be valid and vacuum could break ($I>10^{24}$ W/cm^2)

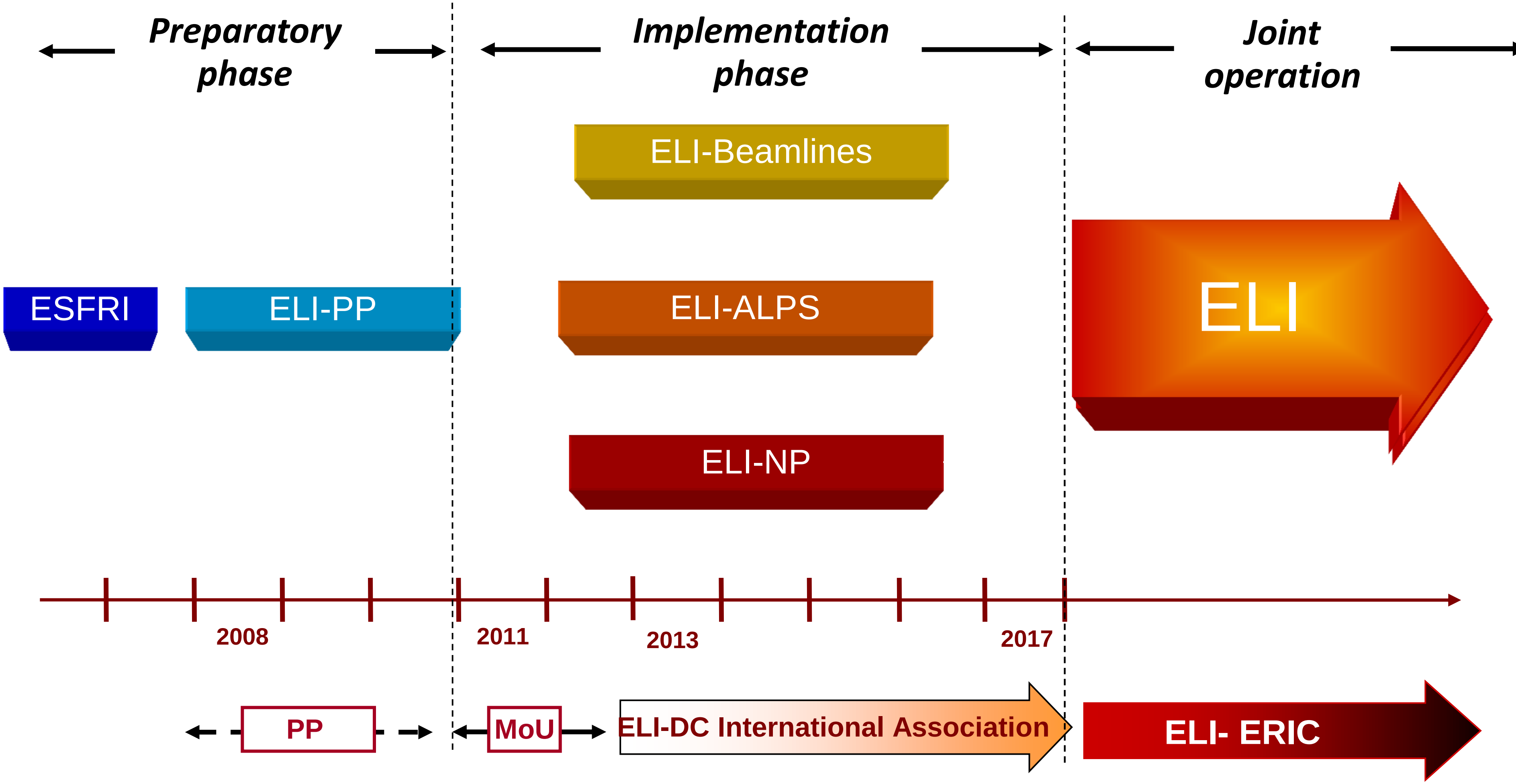
ELI: Implementation Phase

Three Pillars

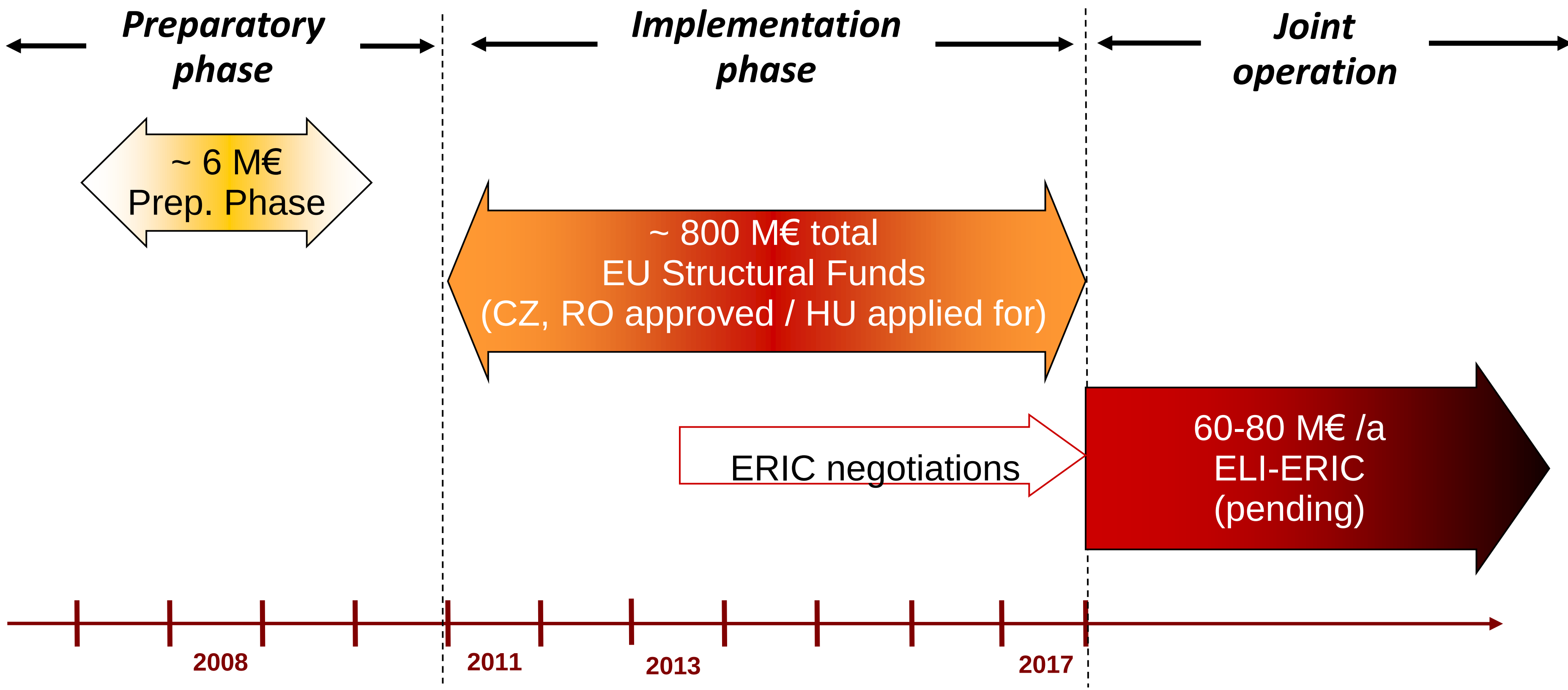
- **ELI Attosecond Light Pulse Source (ELI-ALPS) (Szeged, Hungary):** will capitalize on new regimes of time resolution
- **ELI High Energy Beam-Line Facility (ELI-Beamlines) (Prague, Czech Republic):** responsible for development and application of ultra-short pulses of high-energy particles and radiation
- **ELI Nuclear Physics Facility (ELI-NP) (Magurele, Romania):** with ultra-intense laser and brilliant gamma beams (up to 19 MeV) enabling novel photonuclear studies



Roadmap & Governance



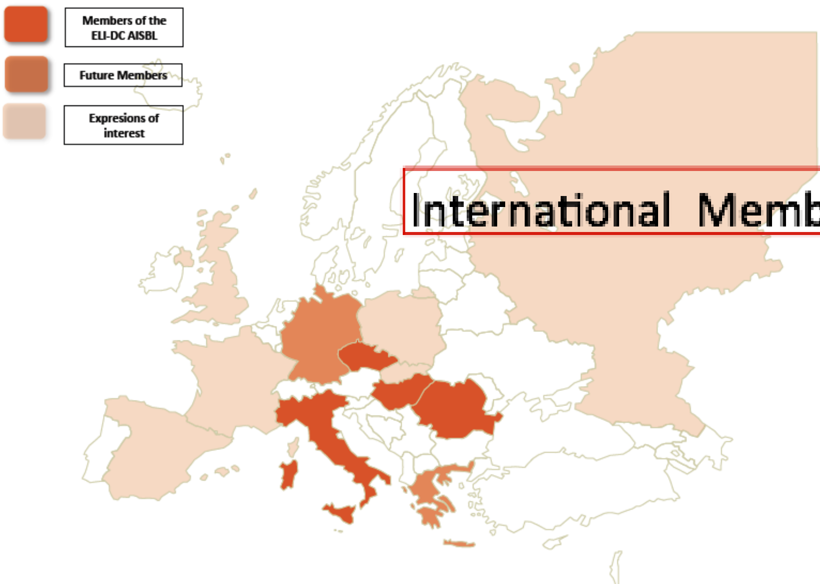
Financial Structure



Investment costs (buildings, instrumentation, services)

Czech Republic (Prague)	**272 M€**
Hungary (Szeged)	**216 M€**
Romania (Magurele)	**293 M€**

ELI-DC Organisation



International Members → **General Assembly** ← 3 Host Members

General Assembly

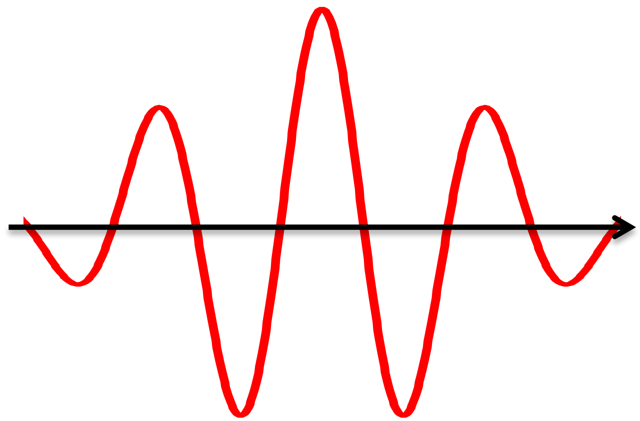
Director General CEO

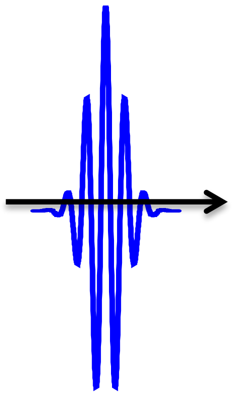
Management Board
Director General
+ 2 other members

Coordination Council
Director General
3 site representatives

- Legal & Admin.
- ERIC Preparation
- Sci & Tech Coordination
- User Relations / publicity
- IT & E-Infrastructure

From Femtosecond to Attosecond Science

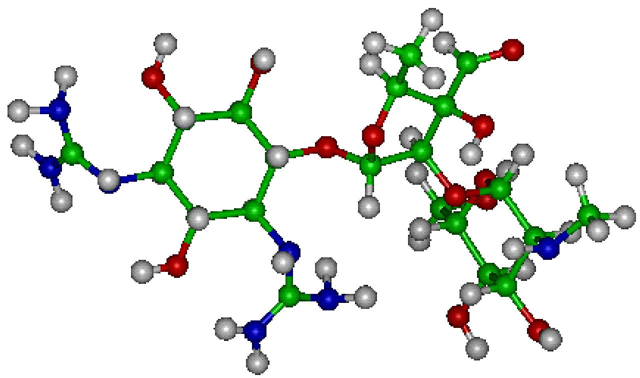


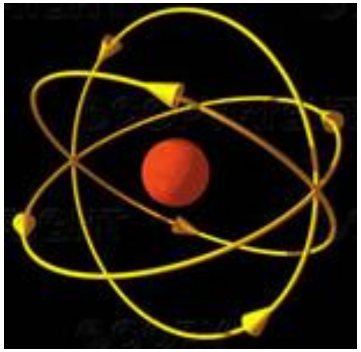


Space-Time Scale of Matter Dynamics

micron | nanometer | picometer

10^{-6} m | 10^{-9} m | 10^{-12} m

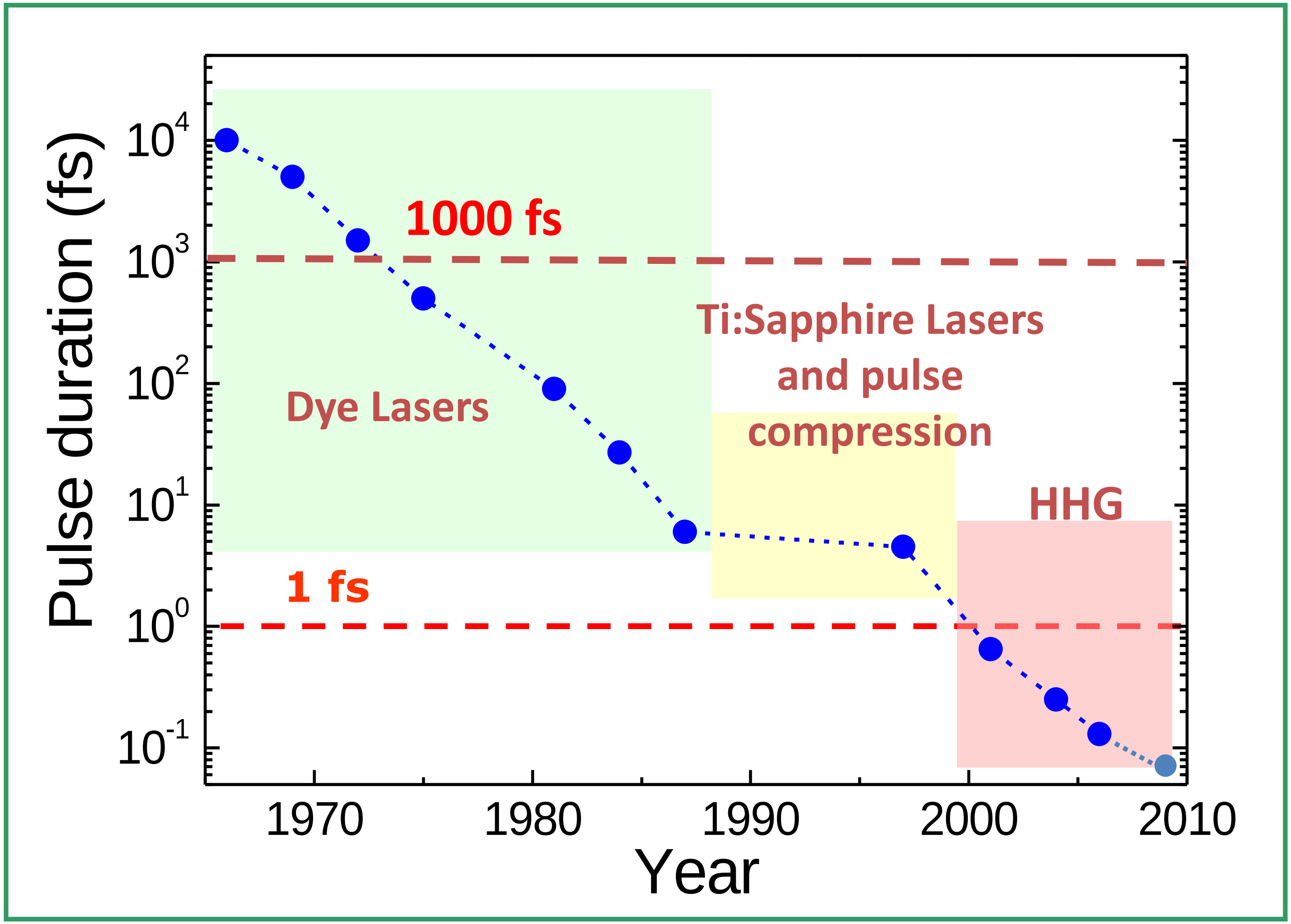




nanosecond | picosecond | femtosecond | attosecond

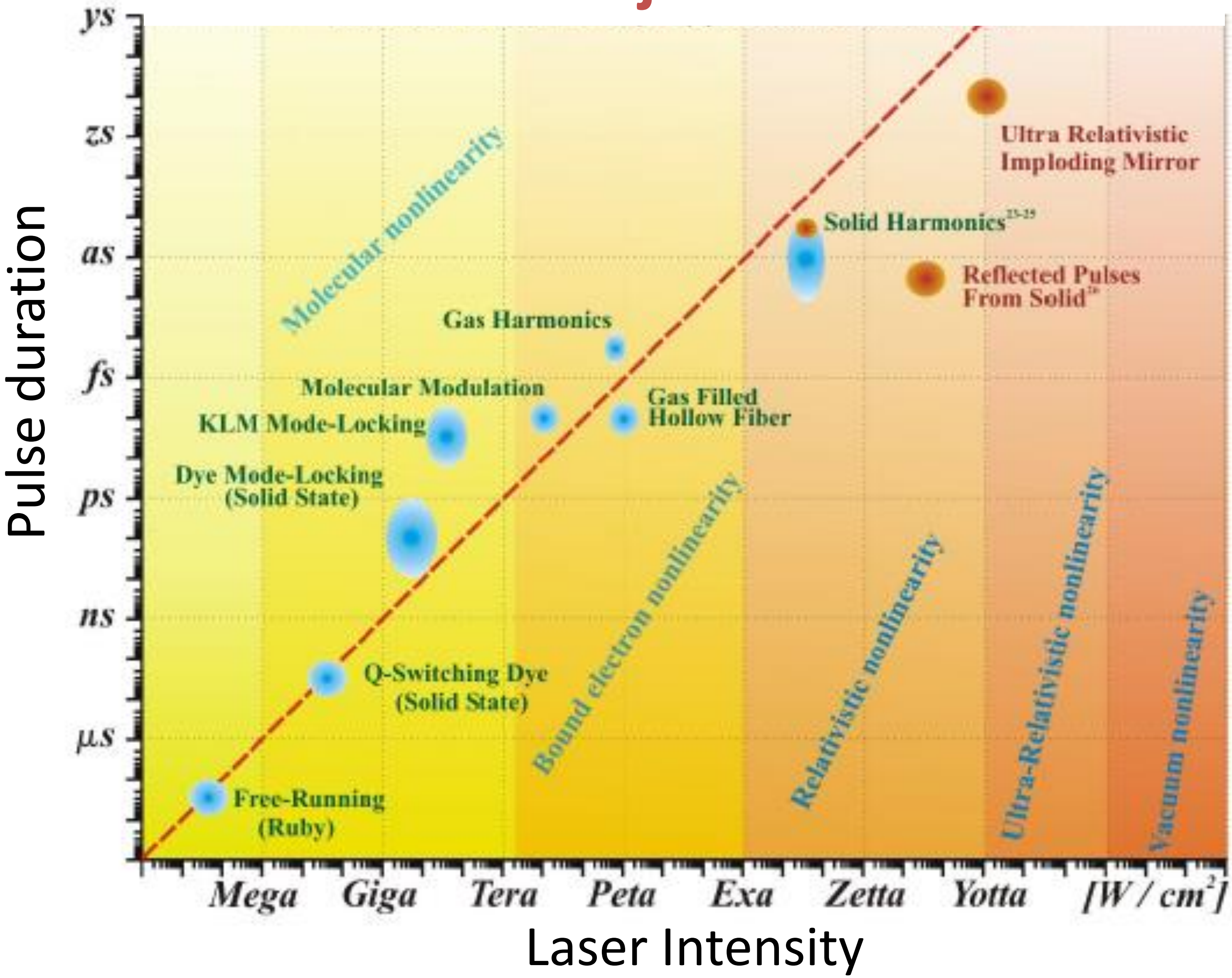
10^{-9} s | 10^{-12} s | 10^{-15} s | 10^{-18} s

Time Line of Ultrafast Optics



HHG: High Order Harmonic Generation

Pulse Duration vs. Intensity Conjecture



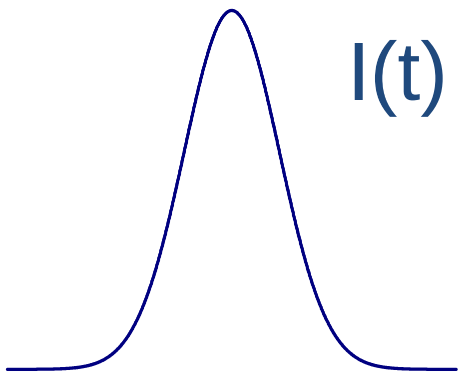
*G. Mourou and T. Tajima, **Science** 331,41 (2011)*

Light-Matter Interaction: an epochal transition

Classical nonlinear optics

<u>Dependence on the intensity envelope</u>

- *Second harmonic generation*
- *Self-phase modulation …. etc*

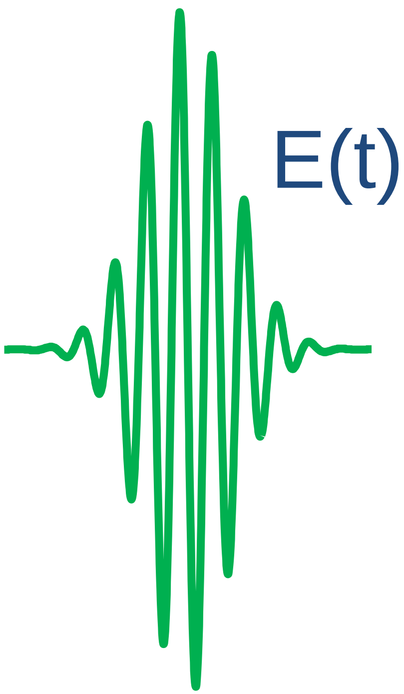


Intensity >10^{14} W/cm^2

Extreme nonlinear optics

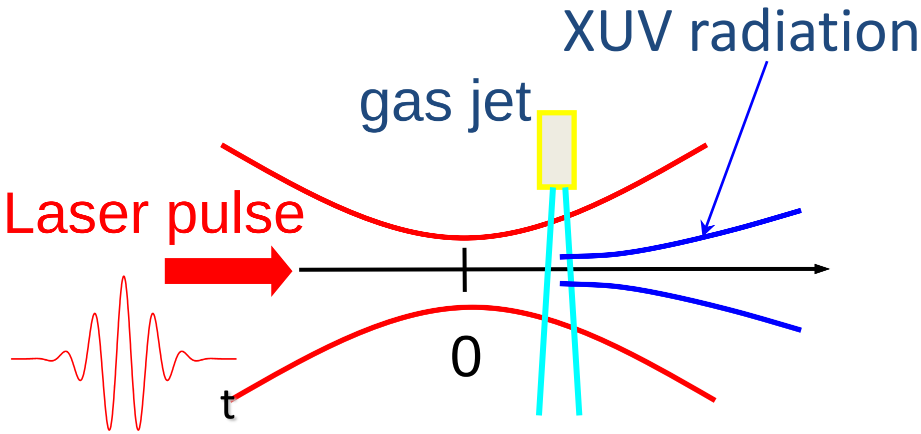
<u>Dependence on the electric field</u>

- *Above threshold ionization (ATI)*
- *<u>High order harmonic generation (HHG)</u>*

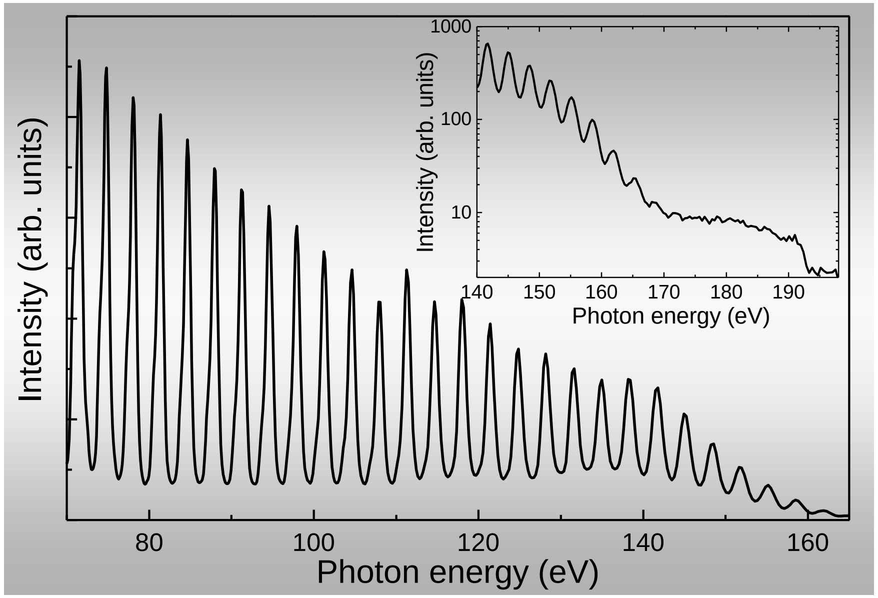


High-order Harmonic Generation (HHG)

An intense laser pulse is focused on a noble gas jet



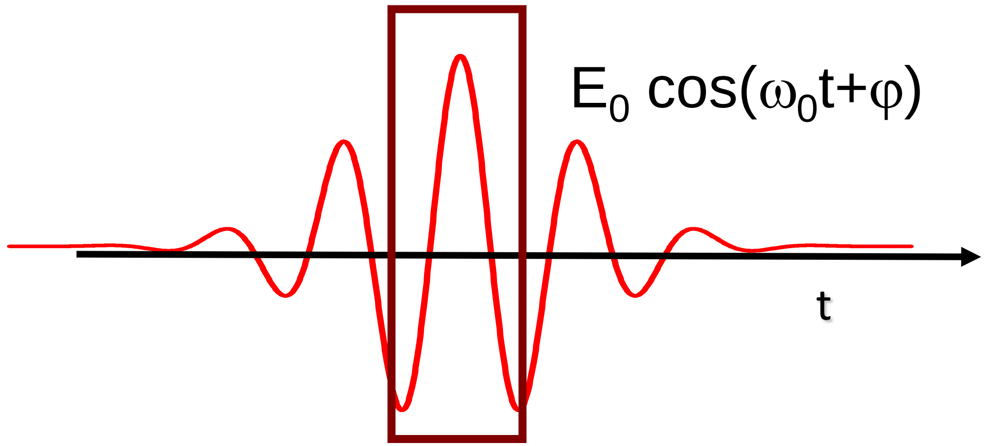
Typical spectrum (Helium)

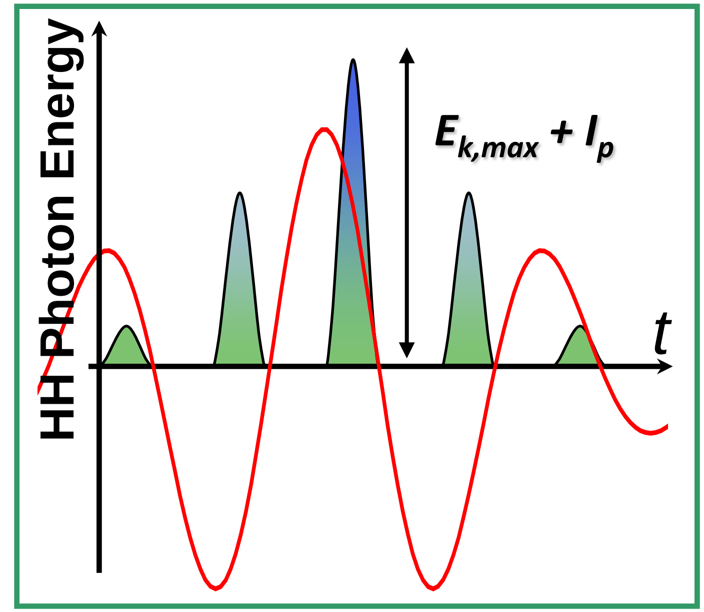


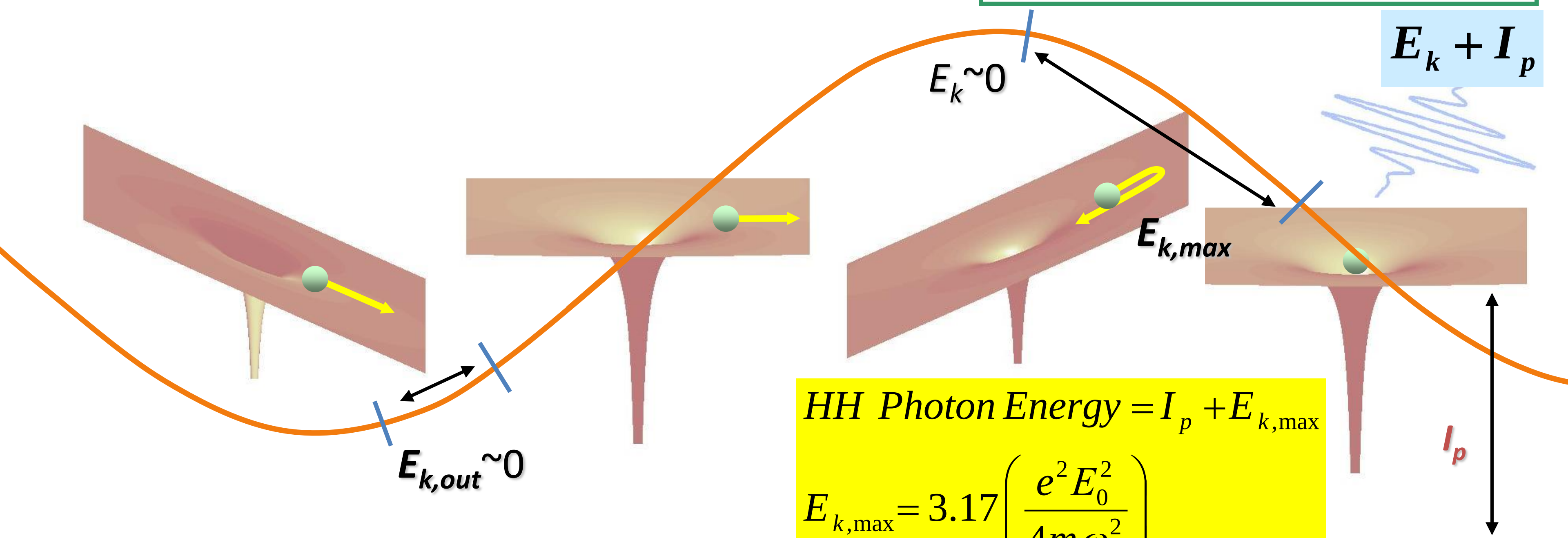
- ➔ **Odd harmonics of the visible light are generated up to the soft-X-ray region**
- ➔ **A periodic spectrum comes from a periodic process in time domain**

Modeling the HHG Process

Few optical cycle pulse on a noble gas jet





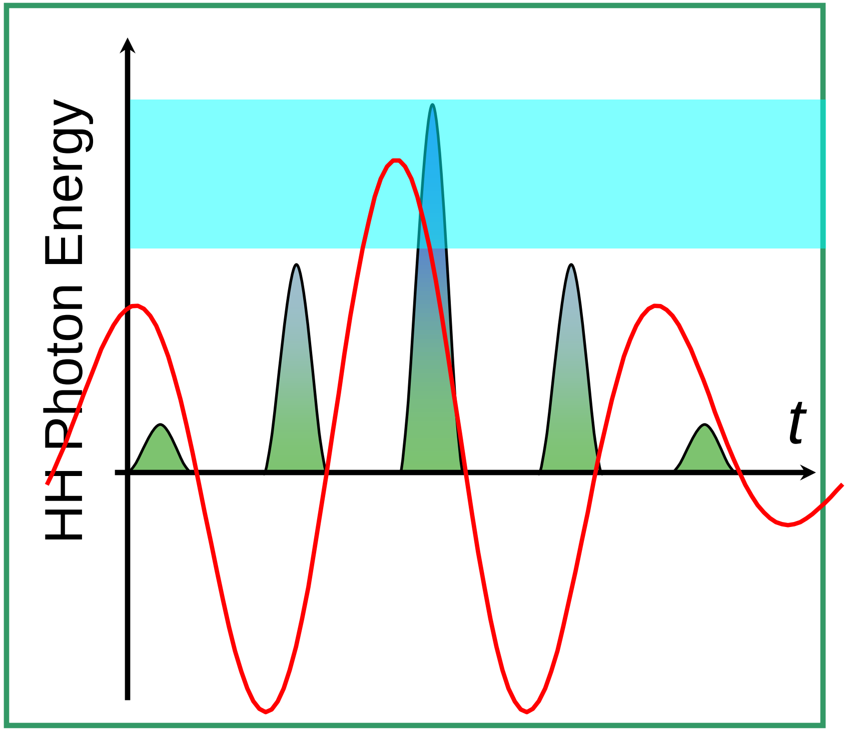


$$HH\ \ Photon\ Energy = I_p + E_{k,\max}$$

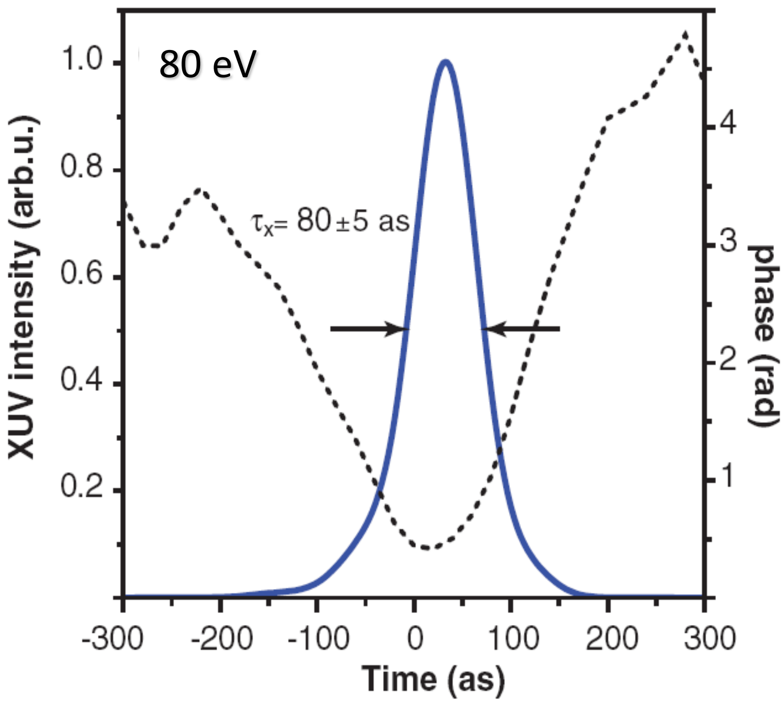
$$E_{k,\max} = 3.17\left(\frac{e^2 E_0^2}{4m\omega_0^2}\right)$$

Isolated Attosecond Pulses (1)

Frequency filtering HHG



Using quasi-monocycle driving pulses: 3.3 fs

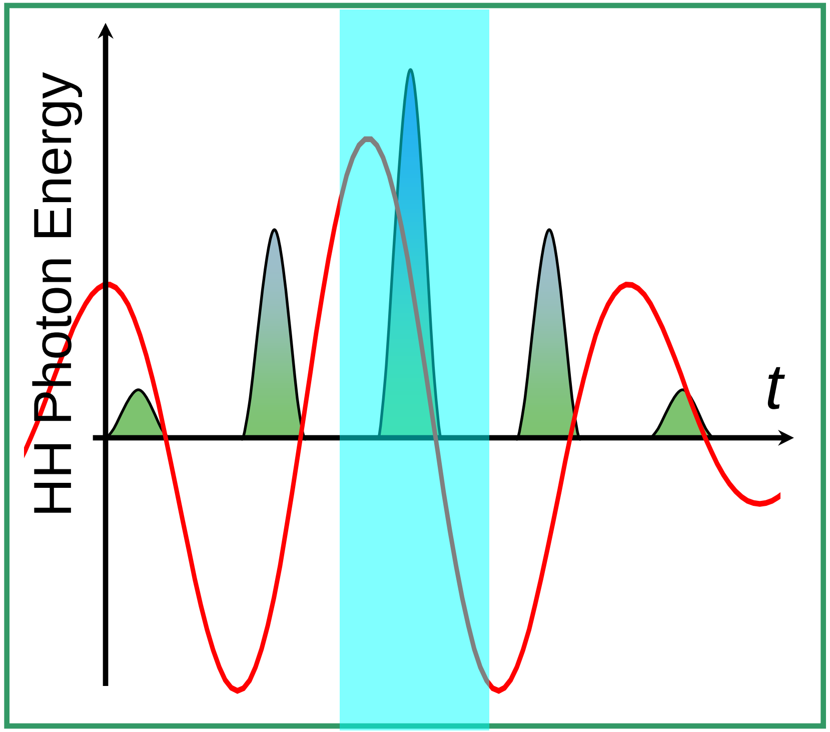


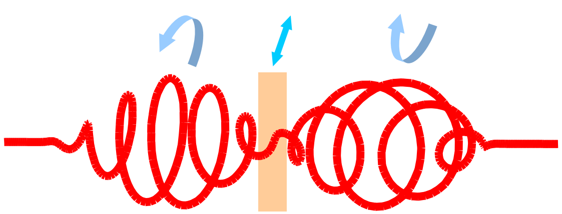
Carrier-envelope phase stabilization

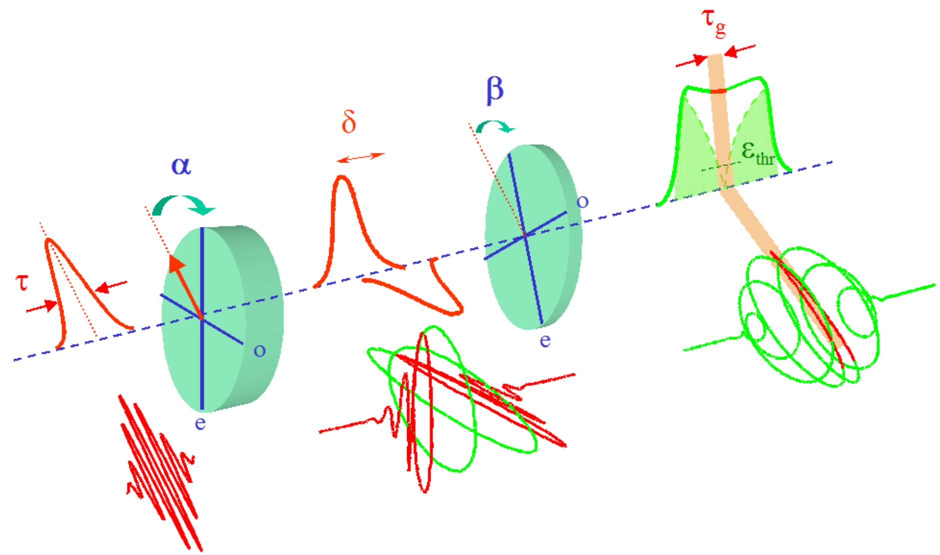
E. Goulielmakis,et al. Science 320, 1614 (2008)

Isolated Attosecond Pulses (2)

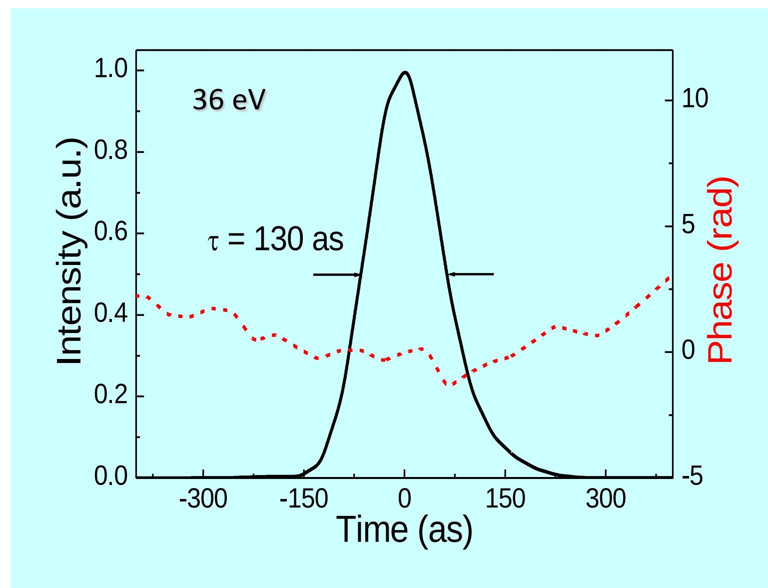
Time gating (polarization modulation)







Chirp compensation: 300 nm aluminum foil

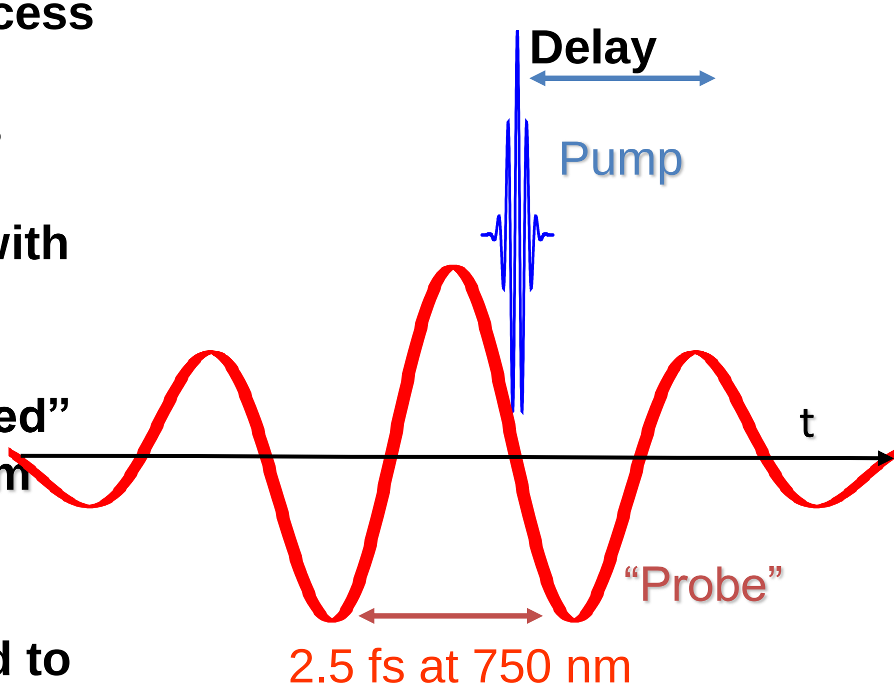


Carrier-envelope phase stabilization

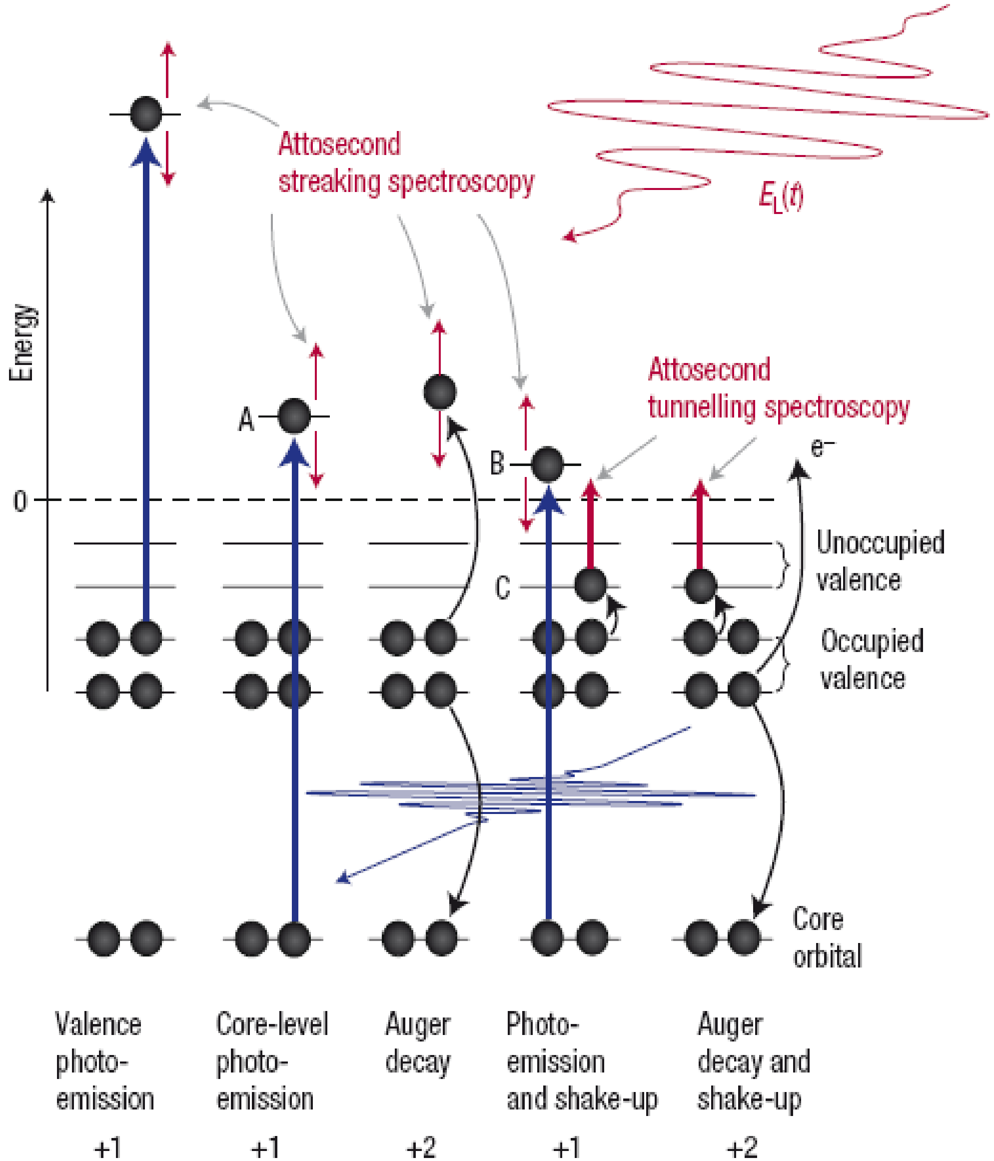
G. Sansone et al., Science ***314****, 443 (2006)*

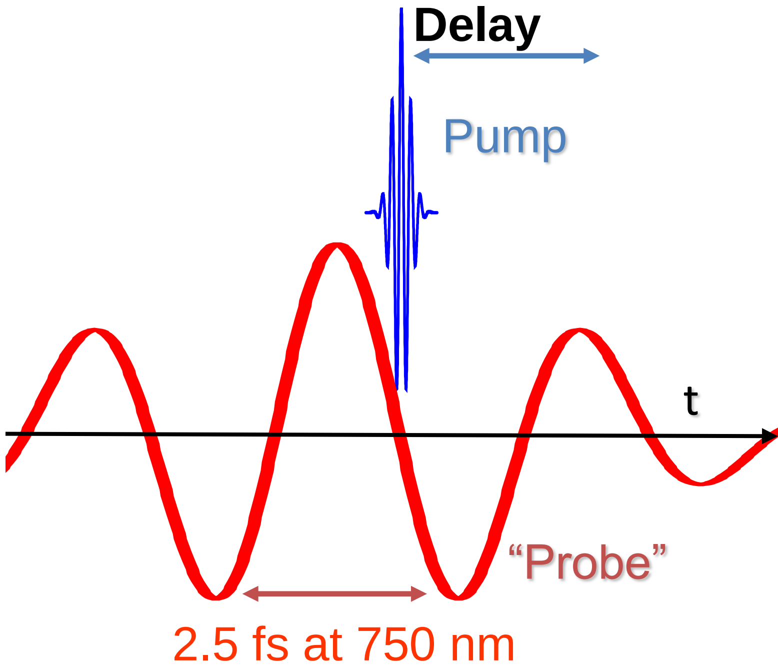
Attosecond Spectroscopy nowadays (1)

- Attosecond pulse energies of only <u>few hundred pJs</u> are available:
  - Attosecond Pump - Attosecond Probe not yet feasible !
- An attosecond pulse in most cases ionizes the sample:
  - Emission of an electron burst
- The high order harmonic generation process helps:
  - An electric field waveform is always available synchronized <u>on an attosecond time scale</u>: interacting with the electron burst
  - The electron burst is "energy steered" by the electric field and the spectrum detected by a time of flight (TOF)
  - The electron burst can be redirected to the parent atom/molecule for "electron diffraction" studies (resolution close to 1 Å)



Attosecond Spectroscopy nowadays (2)





ELI-ALPS - Attosecond Light Pulse Source
Szeged (Hungary)

eli attosecond

MAGYARORSZÁG MEGÚJUL

A projekt az Európai Unió támogatásával, az Európai Regionális Fejlesztési Alap társfinanszírozásával valósul meg.

ELI-ALPS: a step forwards

attosecond

Synchrotrons and X-ray free-electron lasers (FEL) offer:

- Angstrom wavelengths
- High flux and brilliance
- Ability to explore the structure of matter with sub-atomic resolution from crystalline solids, through nanoparticles to individual molecules.

LASER driven high order harmonic sources allows

- Flashes of XUV-soft X ray light with duration < 100 attosecond
- Direct time-domain insight into both structural and electronic motion

ELI-ALPS (Attosecond Light Pulse Source) combines both cutting edge characteristics of modern photon sources

- Short wavelength and High photon flux
- An incomparable pulse duration

ELI-ALPS' energetic attosecond X-ray pulses will have the dream of atomic, molecular and condensed-matter scientists come true:

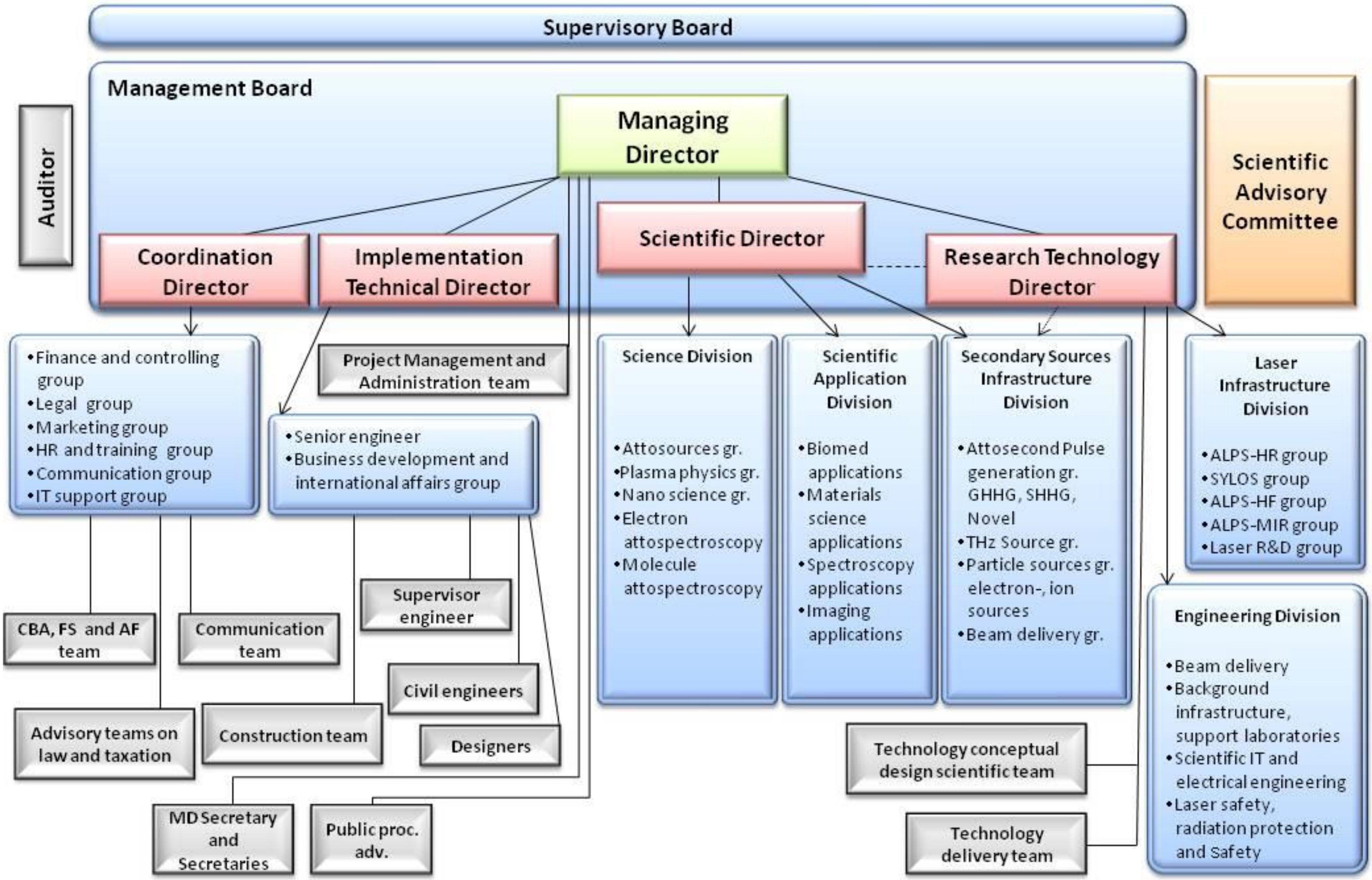
- "Recording freeze-frame images of the dynamical electronic-structural behaviour of complex systems with attosecond-picometer resolution"

Major Mission of ELI-ALPS

- ATTOSECOND Beamline & User Facility
  - Generation of X-UV and X-ray attosecond pulses
  - Investigation at the attosecond time scale of electron dynamics in atoms, molecules, plasmas and solids

- LASER TECHNOLOGY at the forefront
  - Contribution towards development of a 200 PW laser source
  - High intensity beamline

Organization Structure for the ELI-ALPS project implementation Stage 1 (2013-2015)



ELI-ALPS: implementation and layout

attosecond

Investment cost (216 M€) breakdown (2012-2017)

Buildings 78 M€
Scientific equipment 99 M€
Services 39 M€
(EU Contribution 184 M€)

Buildings

- A (Lasers/Experimental halls)
- B (Additional scientific-technical areas)
- C (Reception, Library, Conference hall, Cafeteria)
- D (Services)

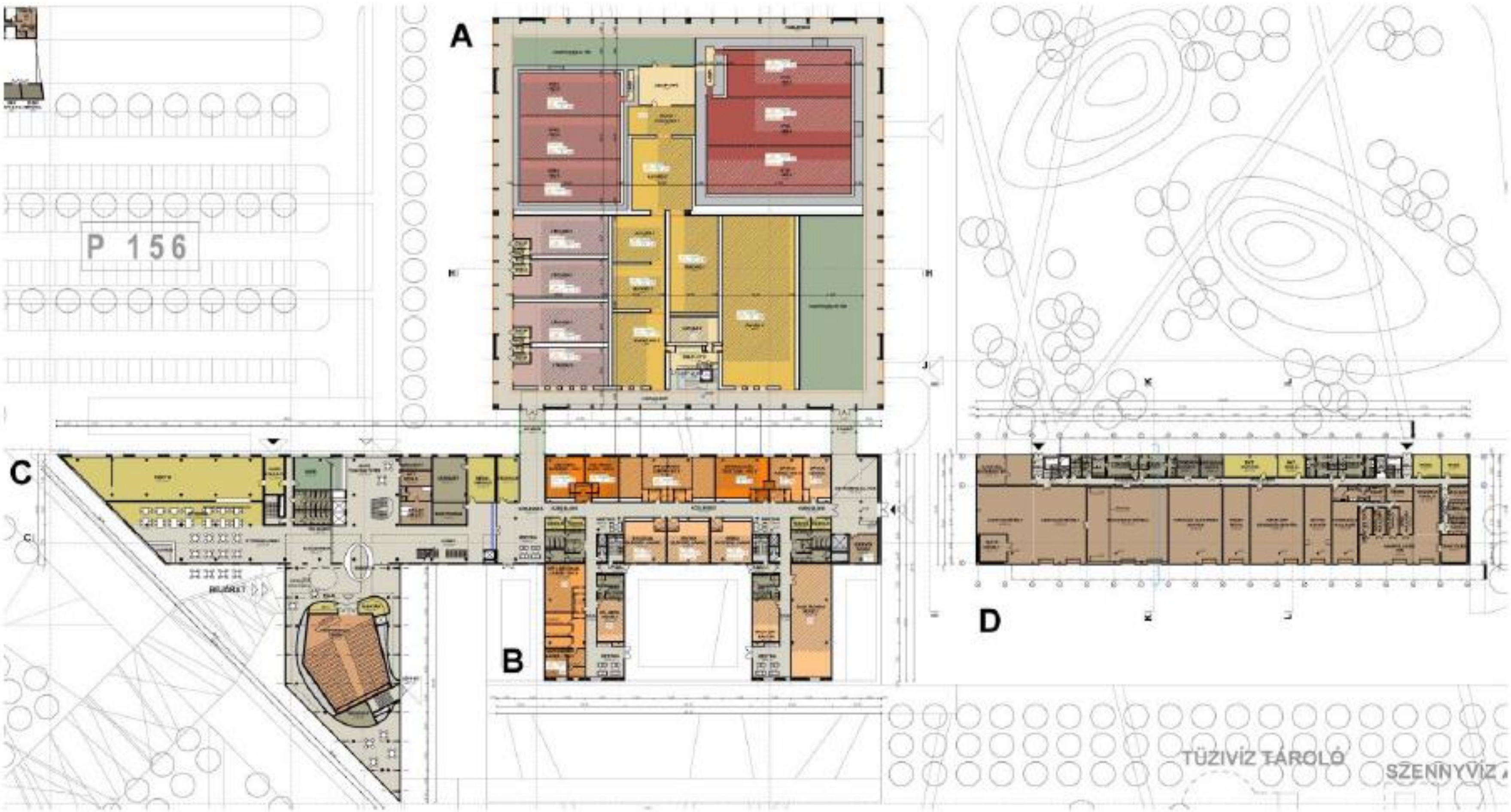
Personnel

Scientific: 44(2013) – 130(2018)
Technical: up to 54(2018)

ELI-ALPS: Instrumentation schematics

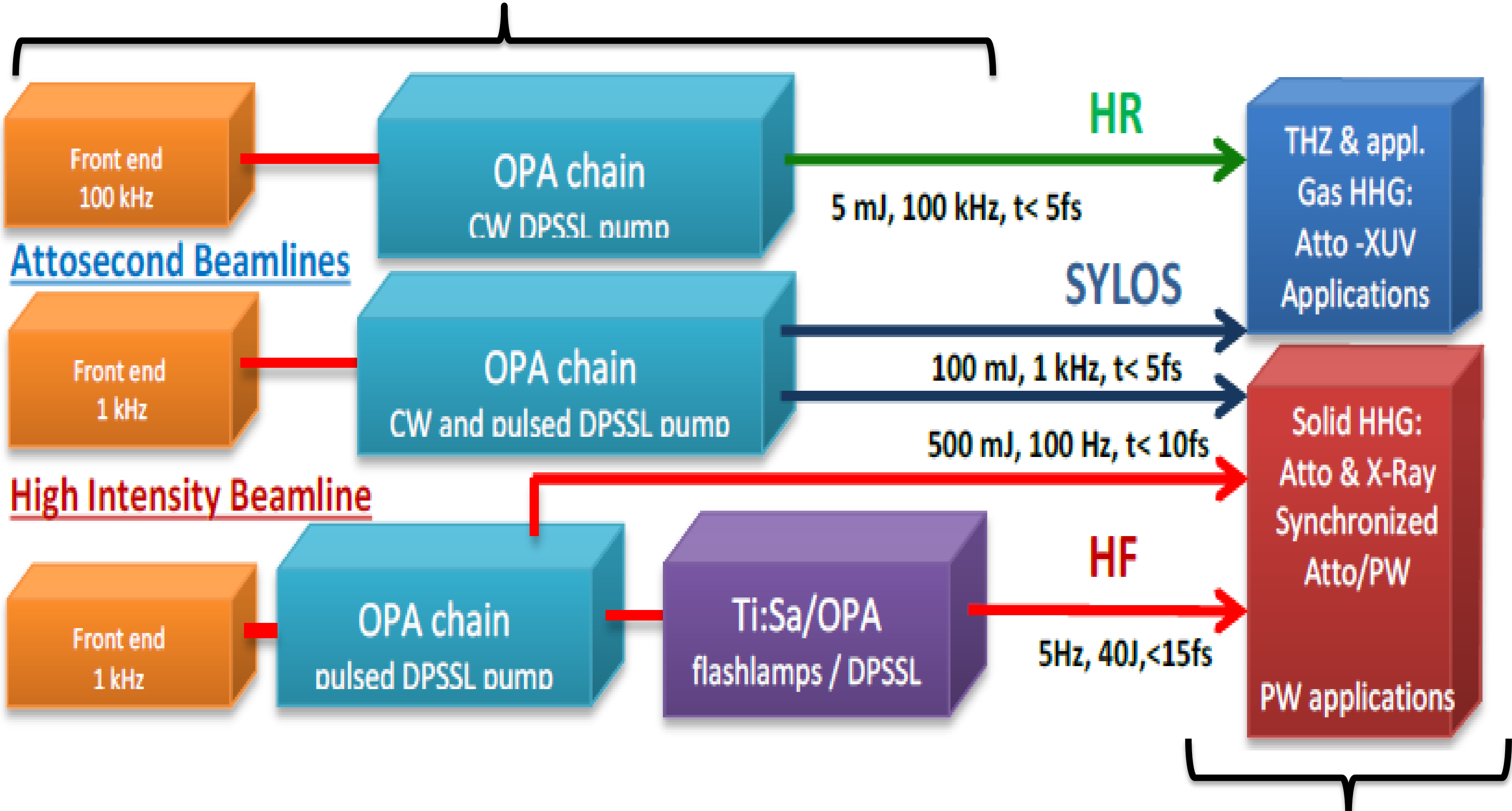
Primary sources (laser beams) → **Secondary sources (atto X-ray, particles etc.)** → **Experiments/ user stations**

Primary sources (laser beams) → **Experiments/ user stations**



Light Sources at ELI-ALPS

Primary Sources (Phase 1 by Dec. 2015, Phase 2 by Dec. 2017)



Secondary Sources

Secondary Sources at ELI-ALPS

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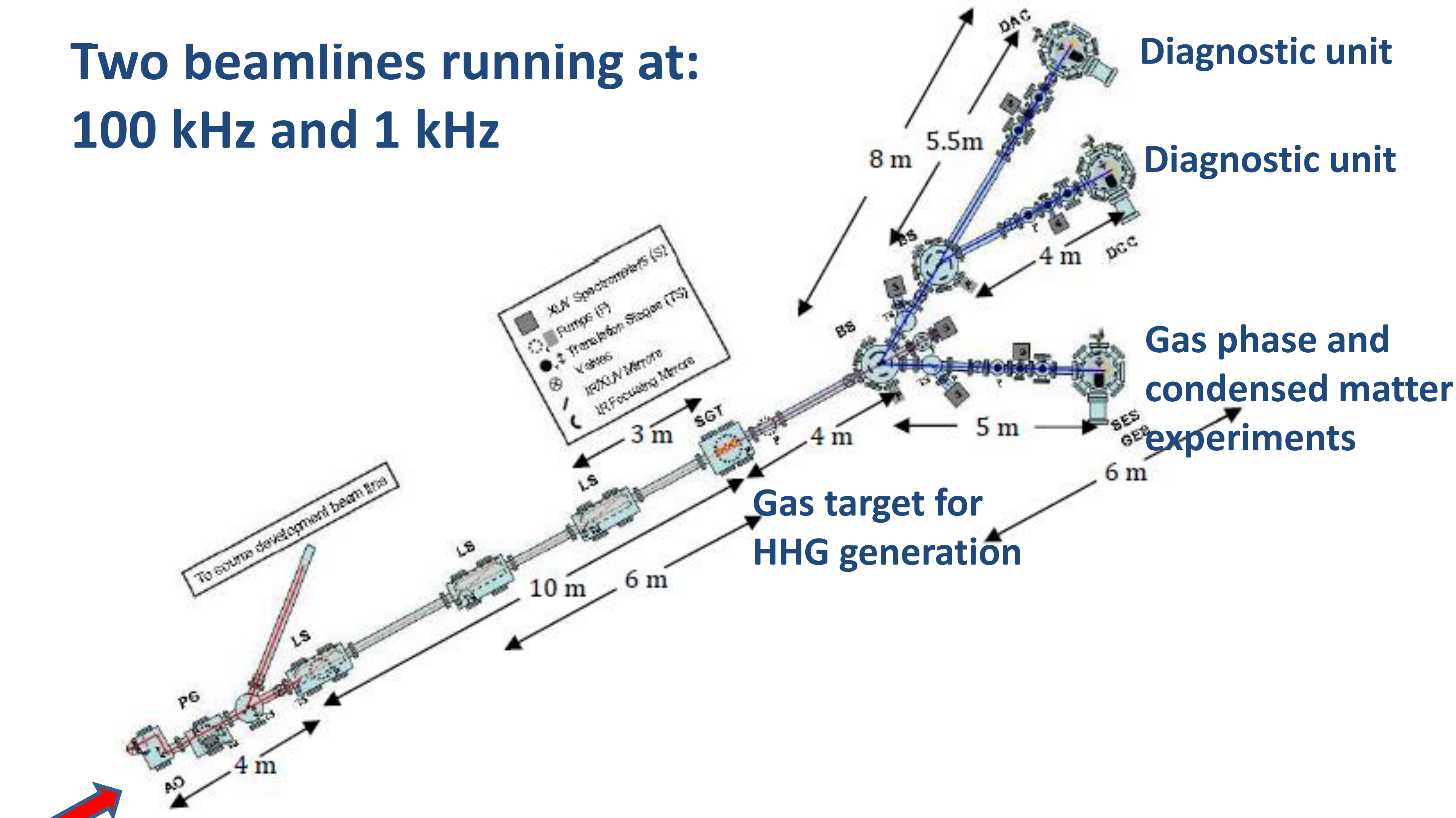
Target values by Jan. 2016 (end of Phase 1)

Repet. rate	UV/XUV	X ray
100 kHz	4-100 eV (10 – 1 nJ)	100-400 eV (<0.1 nJ)
1 kHz	10- 1000 eV (10 μJ -0.01 nJ)	1-10 keV (<0.01 nJ)
10 Hz	10-1000 eV (500 μJ-500 nJ)	1-10 keV (<500 nJ)
5 Hz	10-1000 eV (3 mJ-3 μJ)	1-10 keV (<3 μJ)

About a factor 10 improvement in the performances is expected from Jan. 2018 (end of Phase 2)

Layout of HHG Beamline in Gases

Two beamlines running at: 100 kHz and 1 kHz



SYLOS Laser Source at 1 kHz

High Order Harmonics: a step forwards

attosecond

The main goals in XUV attosecond pulse generation are:

- Substantially increasing the photon flux in order to use attosecond pulses **both as the "trigger" (or "pump") and as the"hyperfast-shutter camera" (or "probe")** of the microscopic motion
- Pushing the photon energy **towards keV spectral region**

These goals cannot be achieved by gaseous targets:

- Increasing the laser intensity produces **ionization of all atoms at very early beginning of the laser pulse**

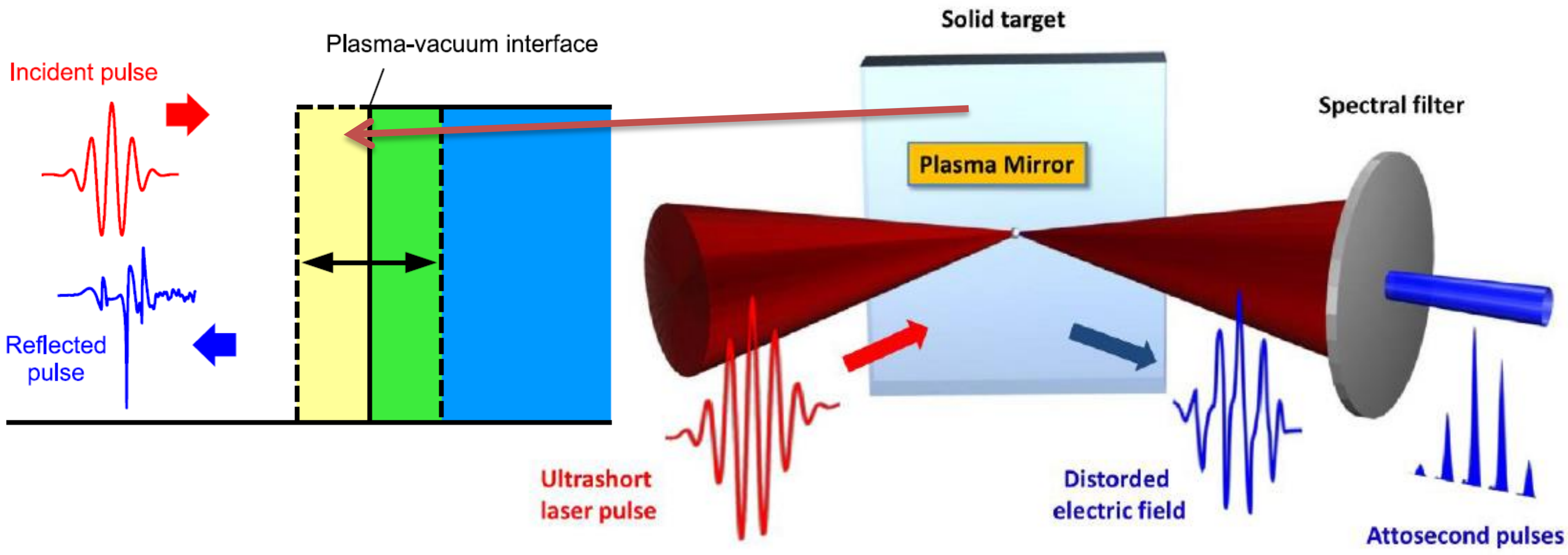
Exploitation of state of the art multiple-terawatt and petawatt class laser systems to increase photon flus and photon energy:

- **Achievable using plasma-vacuum interfaces** as the nonlinear medium for the conversion of intense few-cycle optical pulses into attosecond pulses

High Order Harmonics from solids

An intense laser pulse is focused onto a solid target:

- A plasma is generated on the surface
- The plasma-vacuum interface is driven back and forth
- The pulse experiences a huge Doppler shift upon the reflection on the oscillating surface leading to generation of high frequency component.



Attosecond pulses can be extracted with an appropriate filter

Science at ELI-ALPS

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Main topics

- Valence electron science
- Core electron science
- Attosecond imaging in 4D
- Relativistic interactions
- Compact high brilliance sources for biological, medical, and industrial applications
- Manipulation of matter by intense THz fields

Valence Electron Science in Molecules

Attosecond experiments in molecules would allow to establish and study the so-called "post Born–Oppenheimer" regime in molecules:

- formation of a coherent superposition of excited electronic states (wave packet)
- occurrence of large-scale changes in the electronic wave function on timescales preceding any nuclear motion.

Controlling the composition of the electronic wave packet allows to control both:

- ✓ nuclear motion and the chemical reactivity: **leading to 'charge-directed chemical reactivity'**

Scenarios become possible where nuclear motion is controlled by forces:

- not deriving from a particular Born-Oppenheimer potential energy surface
- **deriving from the time dependent motion of the electronic wave packet**

Molecular Electronic Wave Packet Formation

Existence of a universal attosecond response to the ultrafast removal of an electron from a neutral molecule:

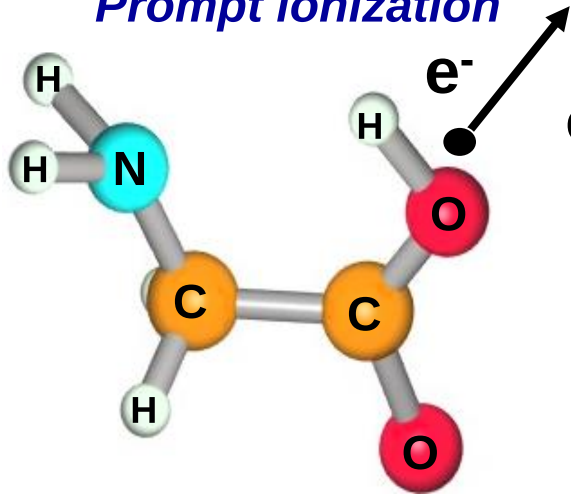
- XUV/X-ray photoionization commonly **produces the ion in several electronic states**
- **A coherent superposition of ionic states can thus be formed that may evolve on an ultrafast timescale**, depending on the specific symmetry and energy spacing of the states

(J. Breidbach, L.S. Cederbaum, Phys. Rev. Lett. 94 (2005) 033901)

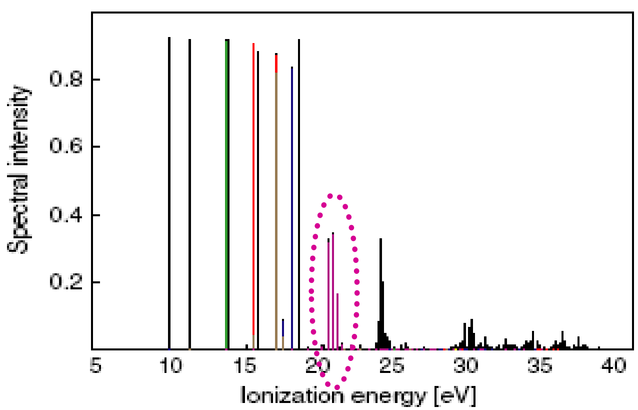
In linear molecules the hole can propagate from one end to the other in a few femtoseconds: giving rise to a rapid charge oscillation.

Charge Migration in Amino Acids

Prompt ionization



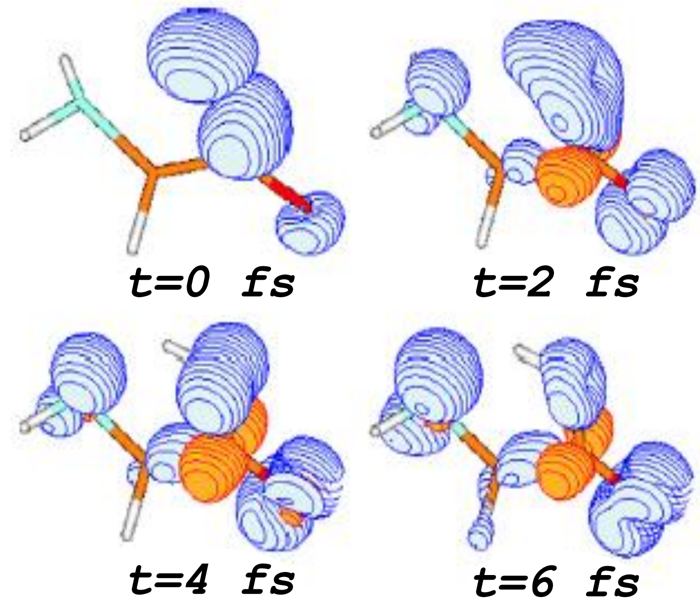
Glycine (amino acid)



Superposition of cataionic states

Ultrafast energy delocalization in amino-acids and polypetides

Charge oscillation



--- Hole density

--- Electron density

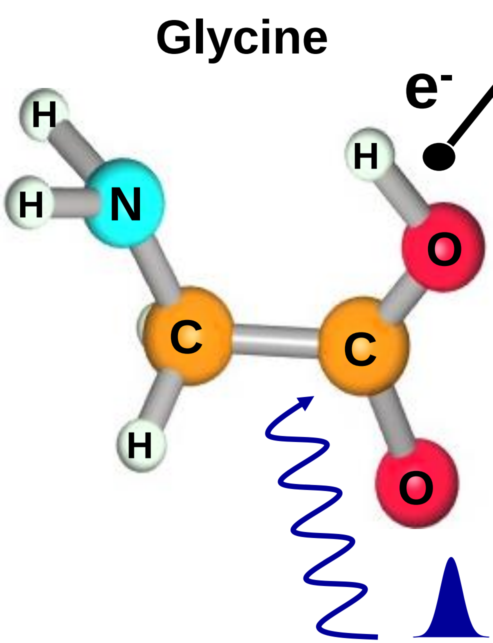
F. Remacle and R.D. Levine PNAS **103**, 6793 (2006)
A. Kuleff *et al.* J. Chem. Phys. **123**, 044111 (2005)
R. Weinkauf et al. J. Phys. Chem. A **101**, 7702 (1997)

Ultrafast Charge Migration in Glycine

Pump pulse: Extreme Ultraviolet (XUV) pulse

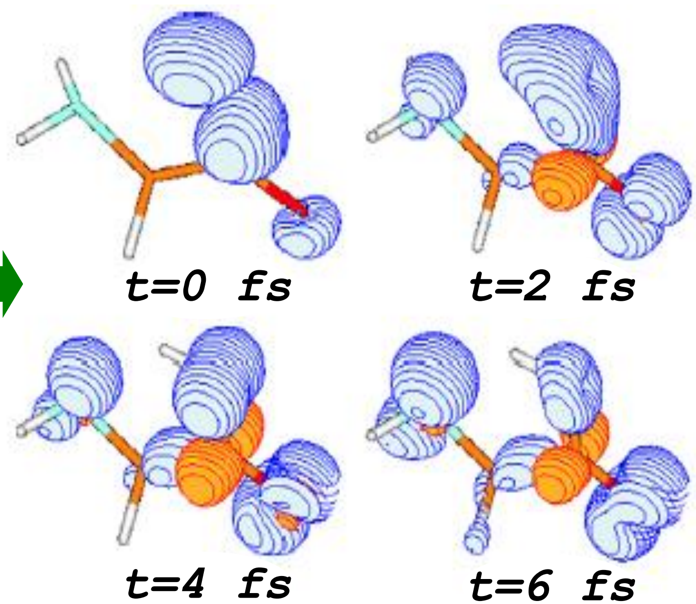
Probe pulse: Infrared (IR)/XUV pulse

Attosecond ionisation



Attosecond Pulse

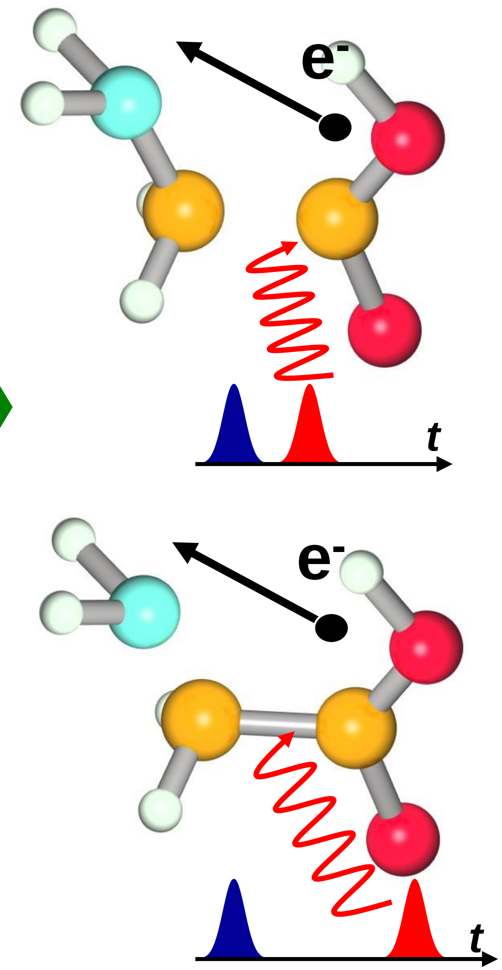
Charge oscillation



--- Hole density

--- Electron density

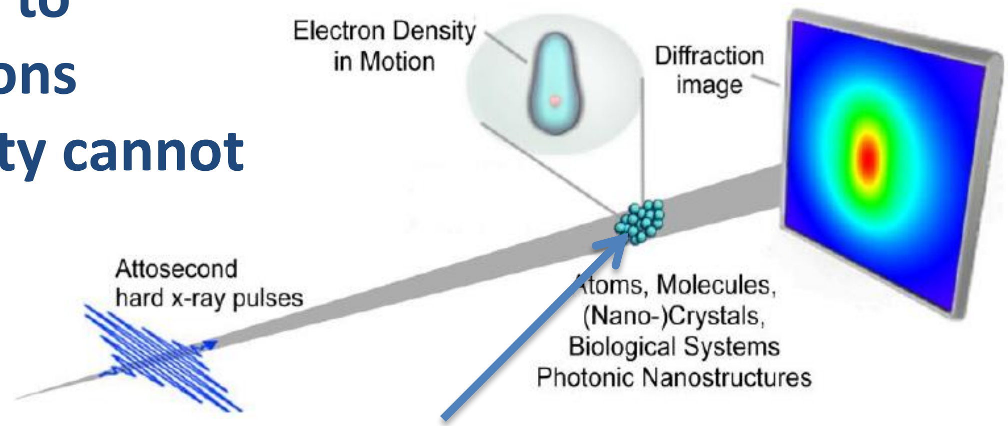
Fragmentation

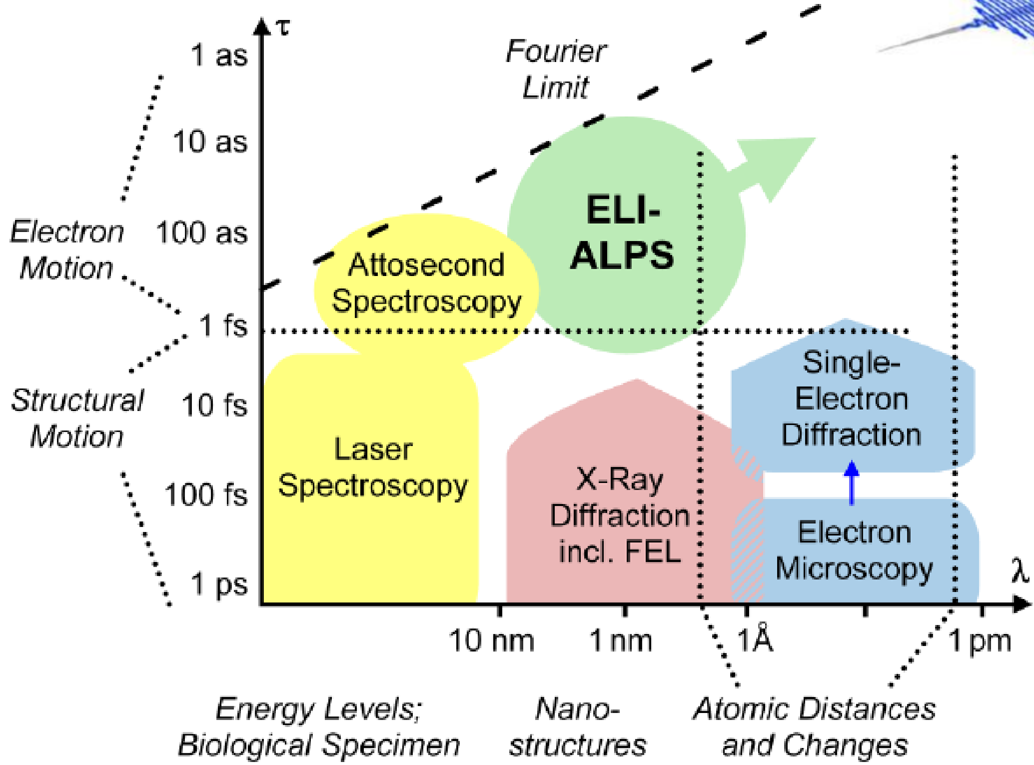


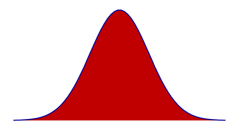
A. Kuleff et al. Chem. Phys. 338,320 (2007)

Attosecond Imaging in 4D (space+time)

- Imaging is currently limited to structural and atomic motions
- Dynamics of electron density cannot be accessed







By virtue of ELI-ALPS

- An ultrashort excitation pulse induces an electronic motion
- A delayed X-ray pulse of attosecond duration will advance 4D imaging into the regime of electronic motion

Scientific Management – Preparation and CDR (2012-13)

NEW SZÉCHENYI PLAN

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K. Osvay (ELI-Hu, Univ. Szeged, Szeged)

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Zs. Diveki (Imperial College, London)
P. Dombi (Wigner RI, Budapest & MPQ, Garching)
J. A. Fülöp (Univ. Pécs, Pécs)
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National Development Agency
www.ujszechenyiterv.gov.hu
06 40 638 638
HUNGARY'S RENEWAL
The projects are supported by the European Union and co-financed by the European Regional Development Fund.

ELI-ALPS: Scientific Advisory Committee

Gyula Faigel	Aladár Czitrovszky
Sandro De Silvestri (Chairman)	János Hebling
Pascal Salieres	Jon Marangos
Gerhard Paulus	John Tisch
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Thanks for your attention!

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