The ELI ALPS research infrastructure
New directions in attosecond physics

Katalin Varjú
ELI-ALPS, Hungary

Winter College on Extreme Non-linear Optics, Attosecond Science and High-field Physics
7 February, 2018
ICTP, Trieste, Italy

SZÉCHENYI 2020
Hungarian Government
European Union
European Regional Development Fund
INVESTING IN YOUR FUTURE

Contents

- Optimizing HHG for tailored attosecond pulse production
- The ELI project
- ELI ALPS: collection of sources
- New directions of attosecond science

Optimizing the HHG source

1, increasing the achievable photon energy („water-window”)

2, increasing the XUV photon flux (up-scaling)

3, producing a Single Attosecond Pulse (gating)

Spectral extension

$$\hbar\omega_{max} = I_p + 3.17\, U_p$$

$$U_p \propto I\, \lambda^2$$

typical values:

$I_p = 10..24$ eV

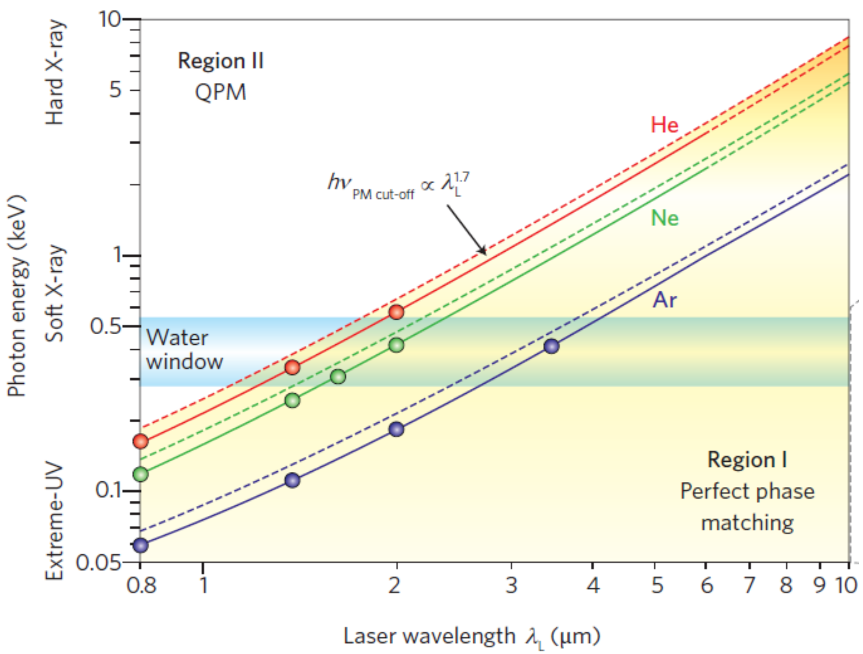
$I = 10^{15}$ W/cm^2 @ 800 nm gives $U_p = 60$ eV

$I_p + 3.17\, U_p \approx 200$ eV

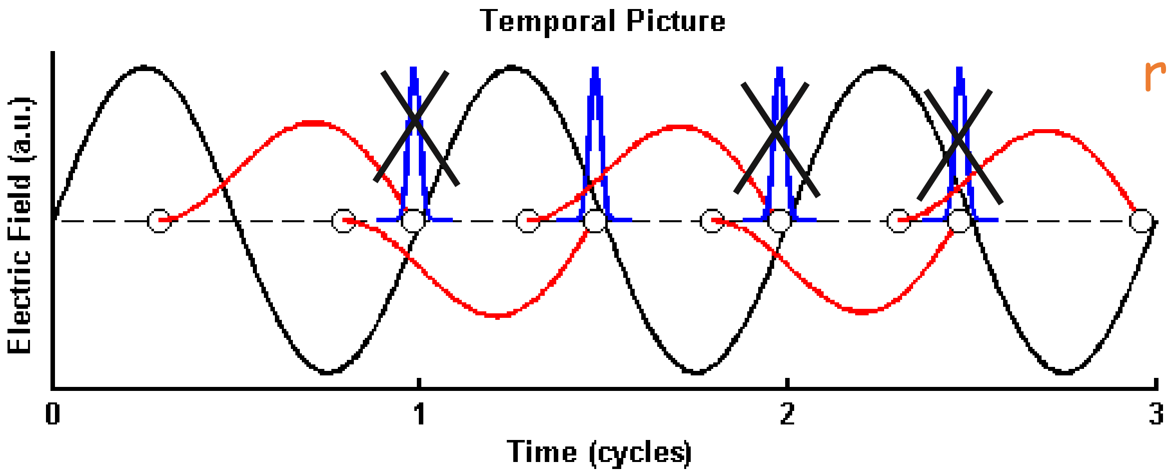
How to increase the cutoff?

- increase laser intensity
  limit: ionization of the medium
  (phase matching, depletion)
  avoid: short pulses, QPM
- increase laser wavelength
  limit: laser technology
- increase ionization potential
  e.g. generate with ions
  limit: phase matching

Phase-matching cut-offs

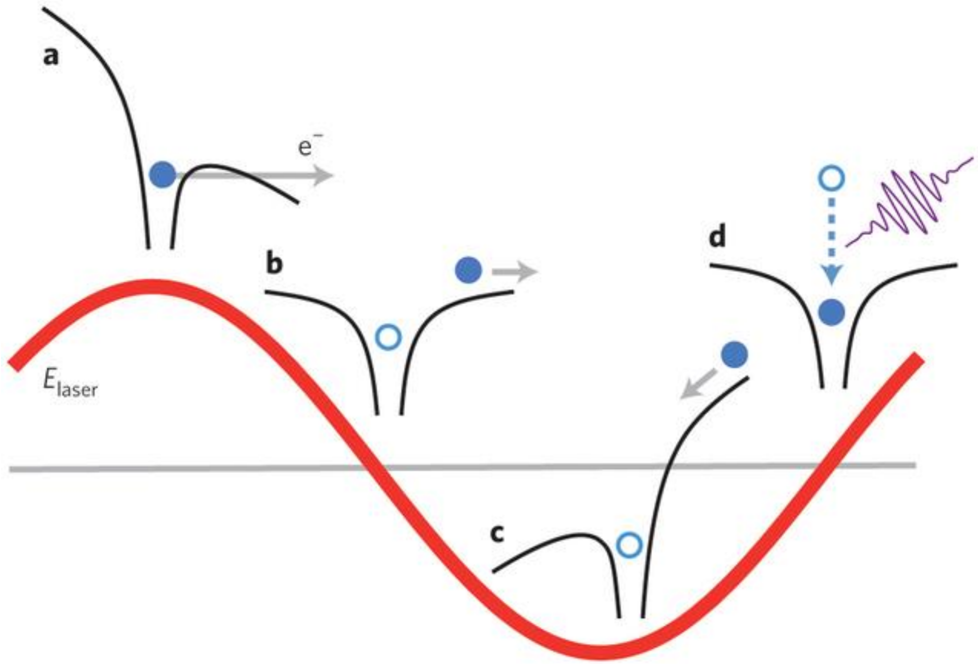


Temporal gating



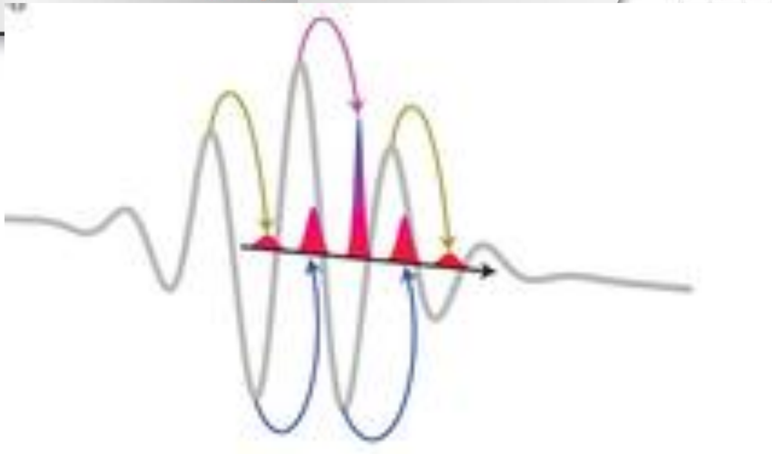
reduce the emission events

by avoiding ionization,
or recombination,
or shortening the generating pulse



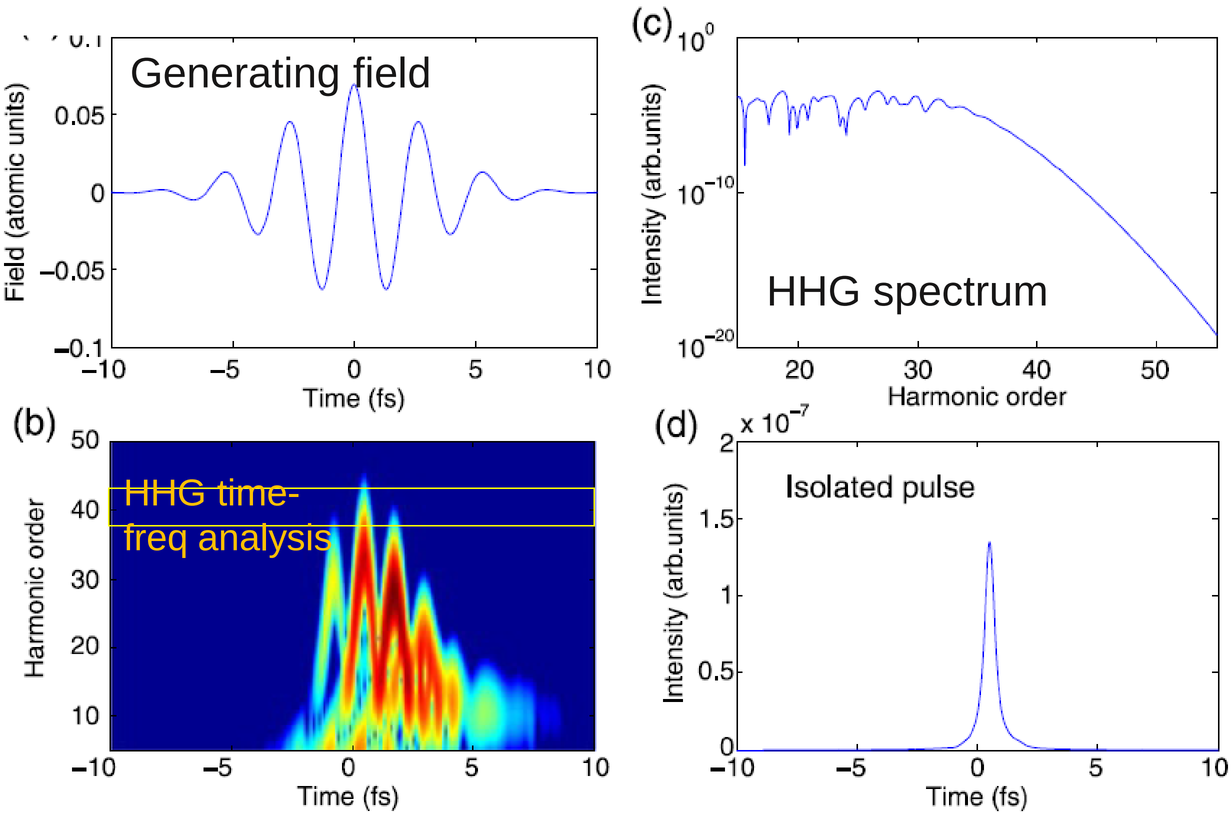
Amplitude/intensity gating

M. Hentschel et al., Nature (London) **414**, 509 (2001)
A. Baltuska et al., Nature **421**, 611 (2003)

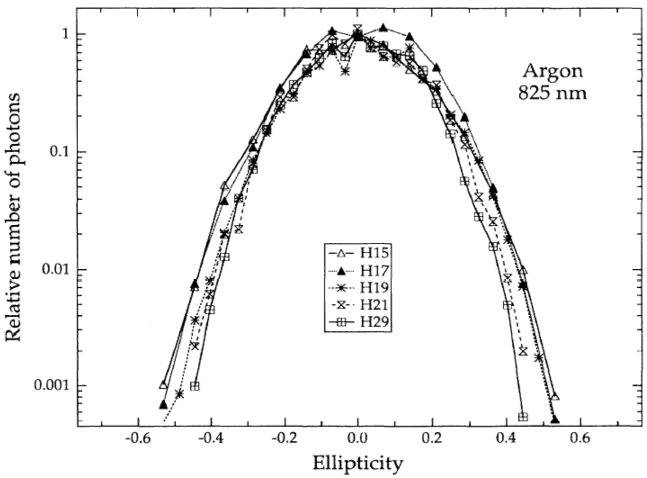


spectrally filtering the cutoff
small intensity
small bandwidth

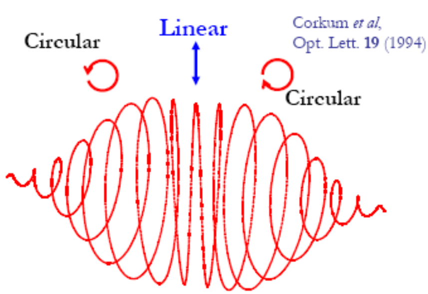
τ < 5 fs, CEP-stable
driving laser

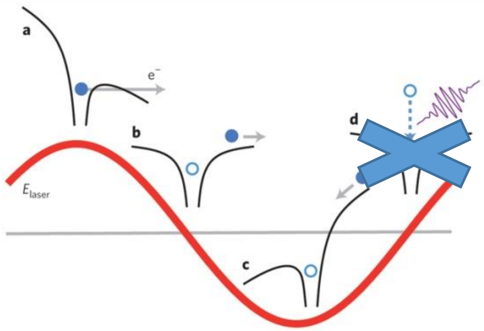


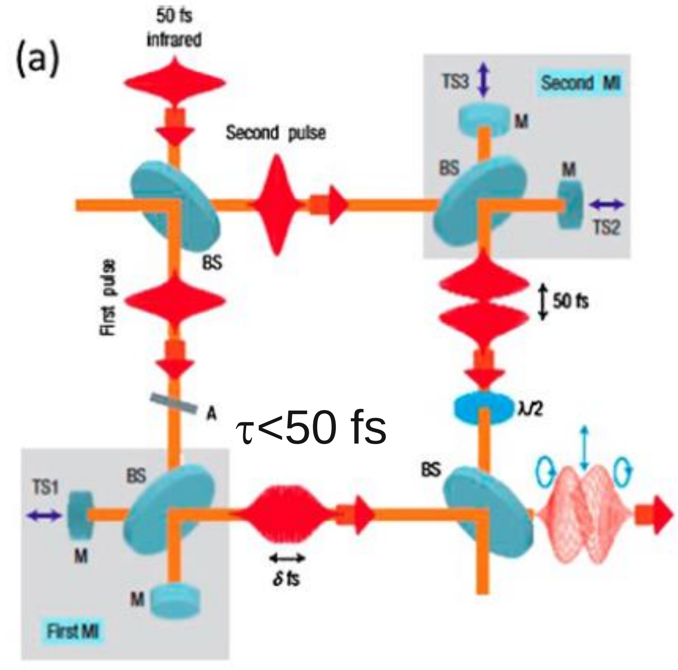
Ellipticity-gating



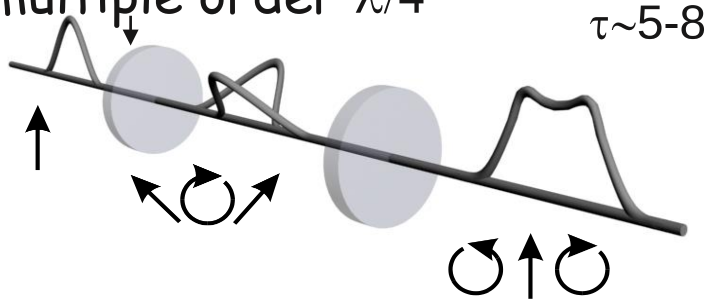
Budil et al., PRA 48, R3437 (1993)







multiple order λ/4



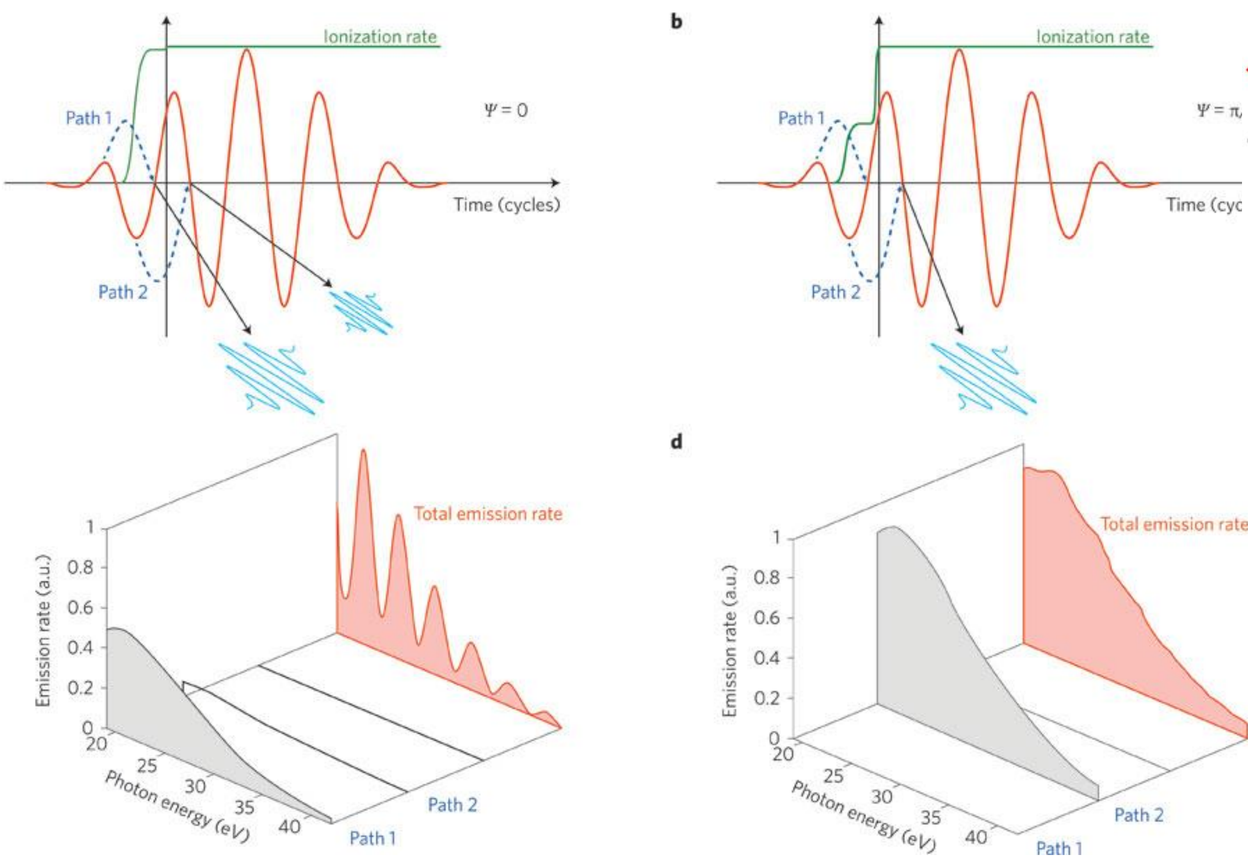
τ~5-8 fs

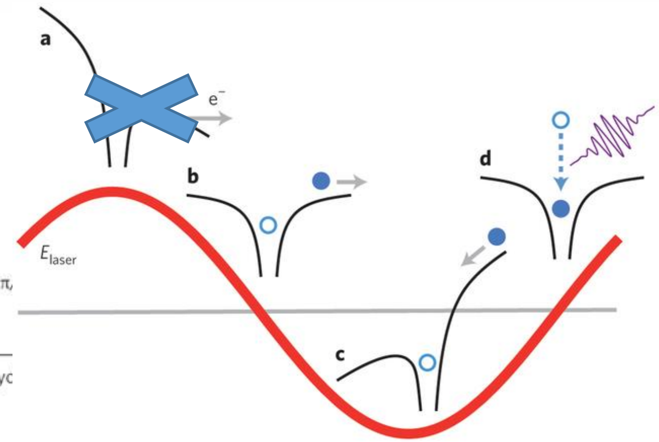
τ<50 fs

Sansone: Science 314 (2016)

Tzallas: Nature Physics 3, 846 - 850 (2007)

Ionisation gating I. single atom effect

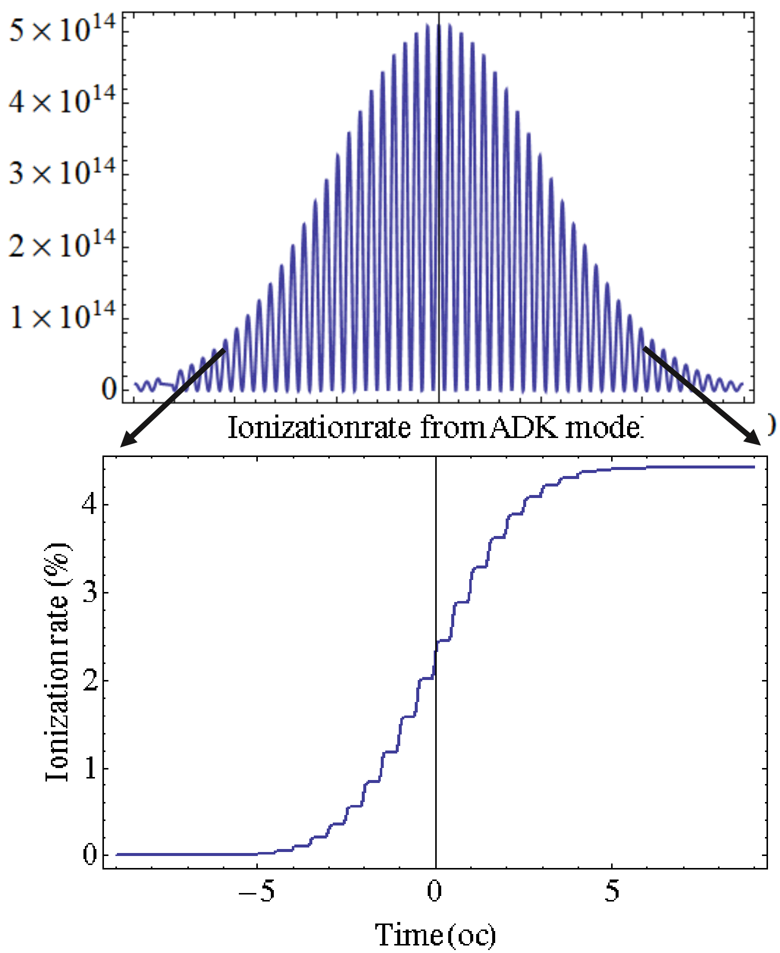




complete depletion of neutral atom population on the pulse leading edge

Sansone, Nphot 5, 655 (2011)

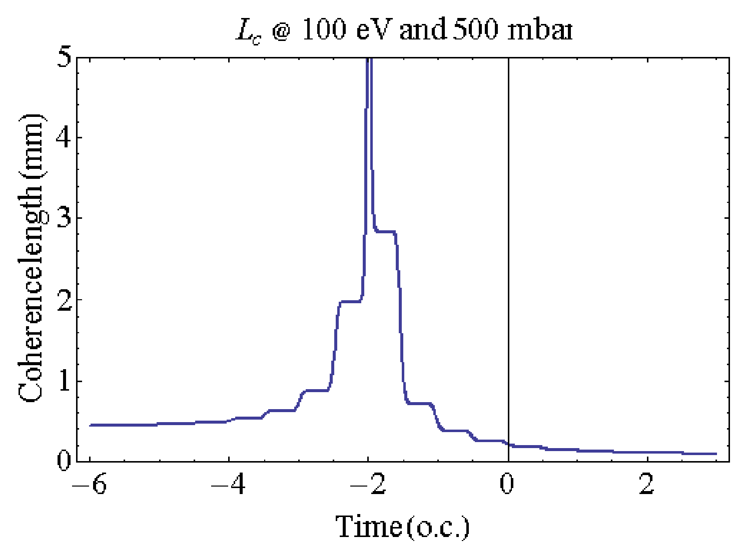
Ionisation gating II.
Macroscopic: time-dependent coherence length



for ex.: 5.1*10^{14} W/cm^2, 35 fs pulse

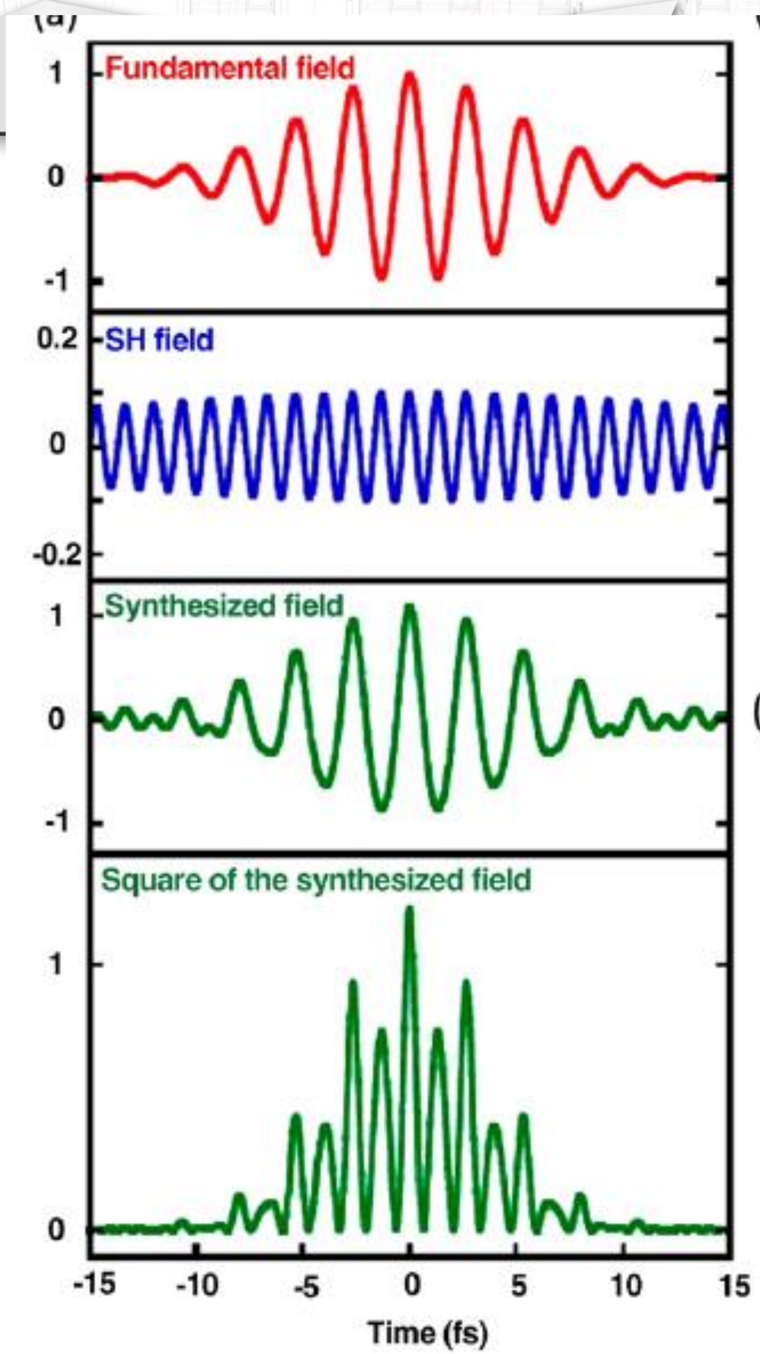
Lcoh > 1 mm for only 1 optical cycle

Temporal gating:
isolation of a single attosecond pulse



Balogh E, PhD dissertation

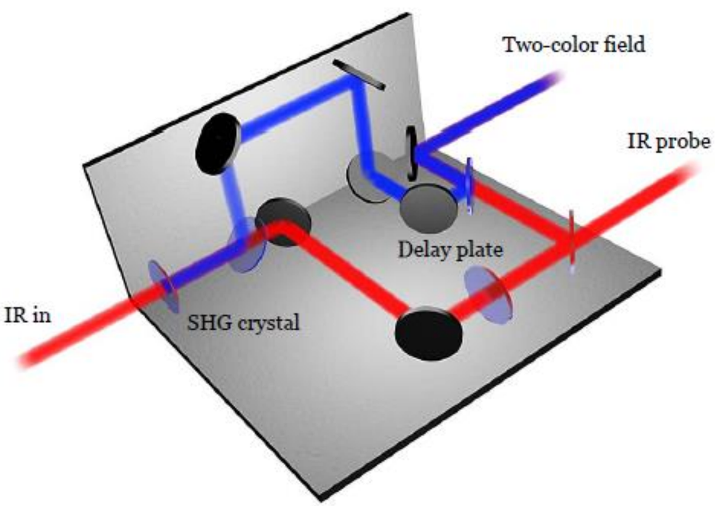
Two-color gating (with SH or MIR)



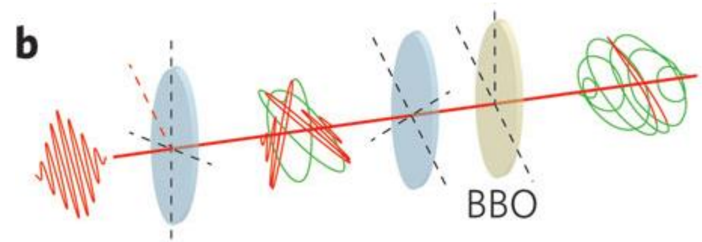
Tunable weak perturbing pulse (harmonic or longer wavelength)

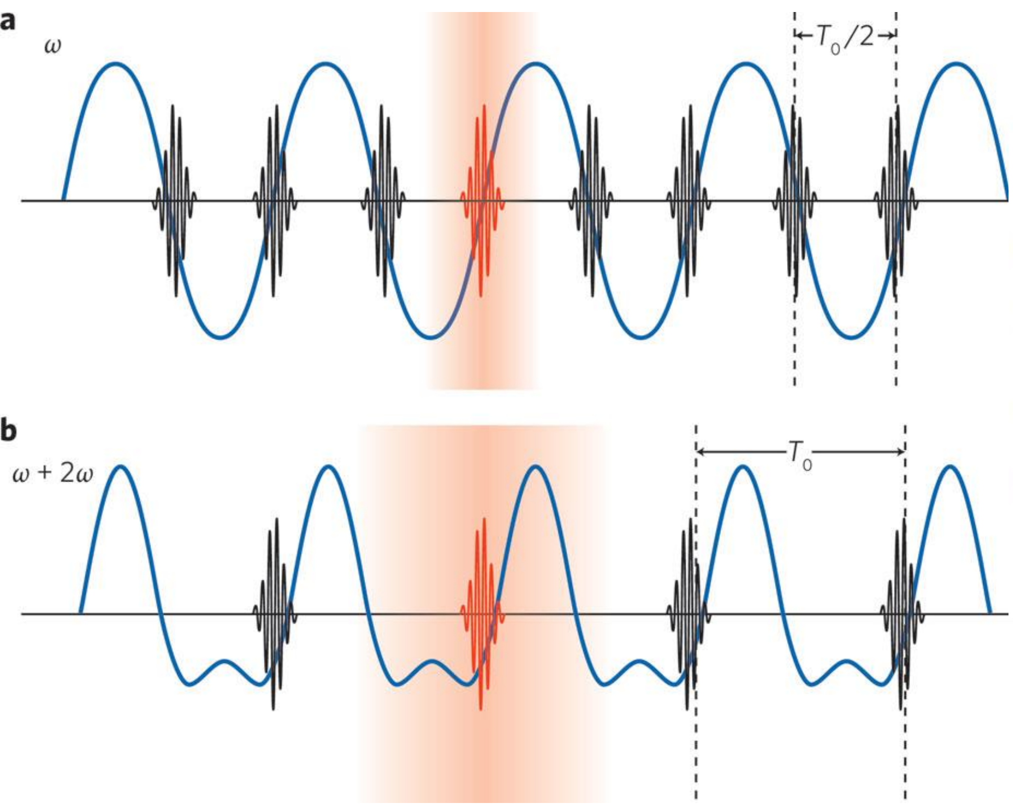
Increases the period of the process (least common multiple)

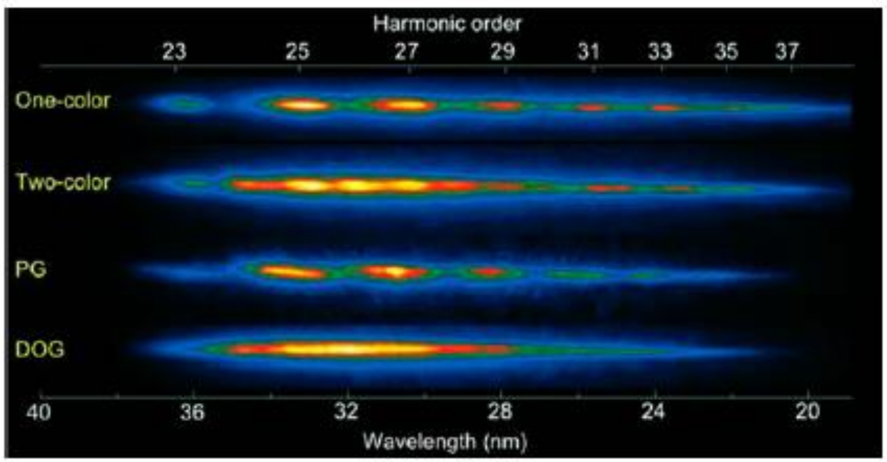
Can be combined with any other gating process



Polarization + two-color gating = Double Optical Gating (DOG)



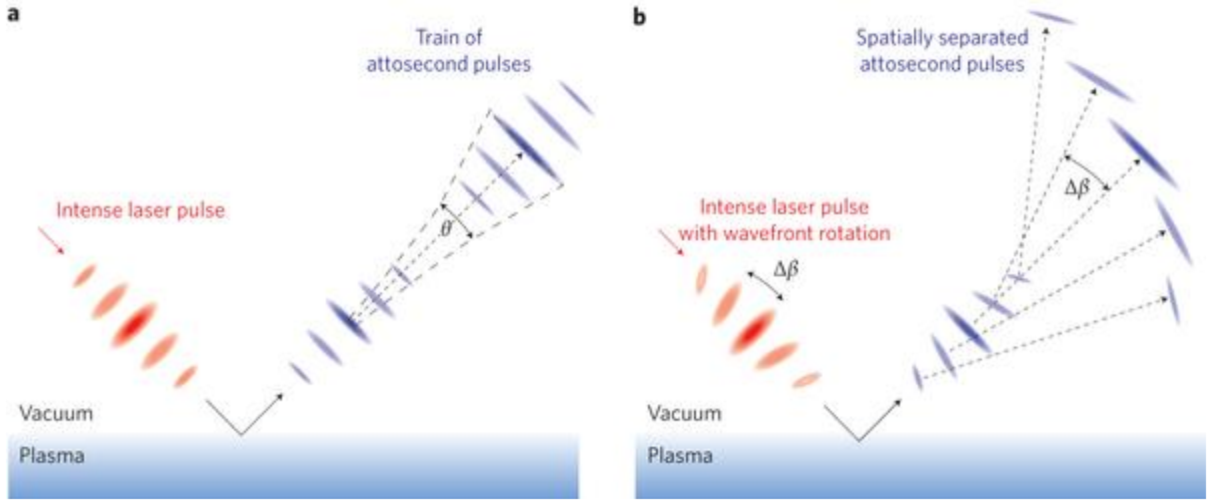




Mashiko: Phys. Rev. Lett. 100, 103906 (2008)

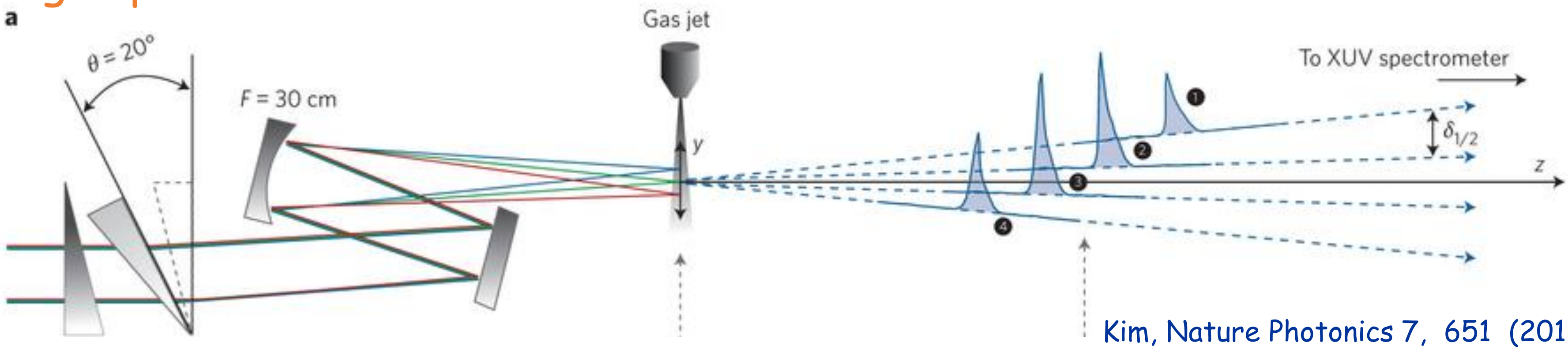
The attosecond lighthouse effect

surface plasma effect



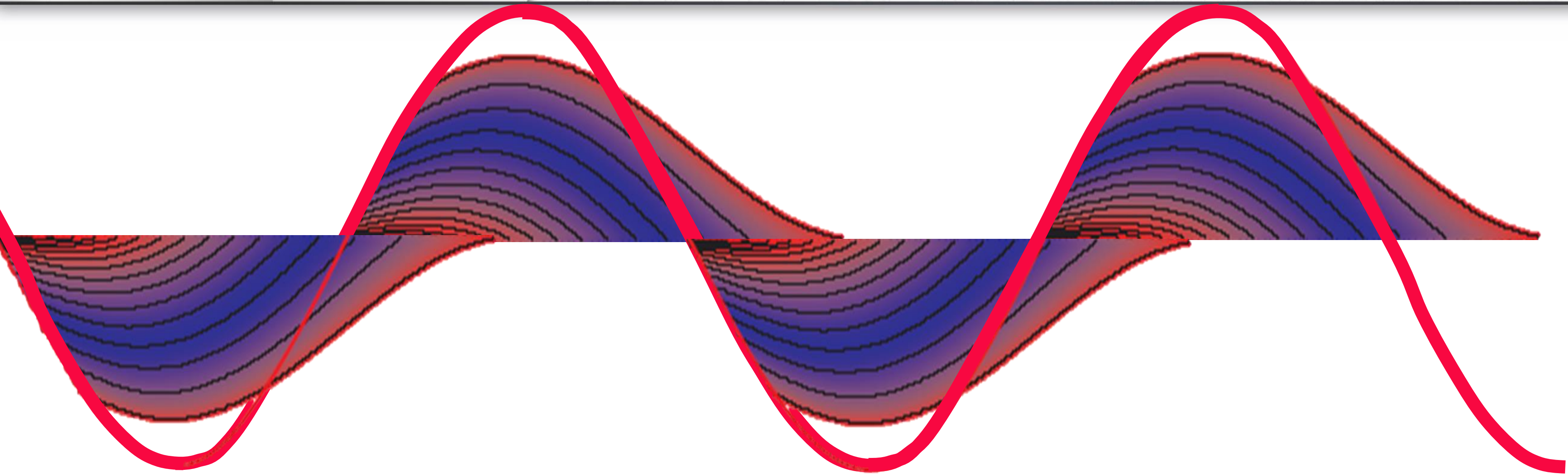
Wheeler, Nat Phot 6, 829 (2012)

gas phase effects



Kim, Nature Photonics 7, 651 (2013)

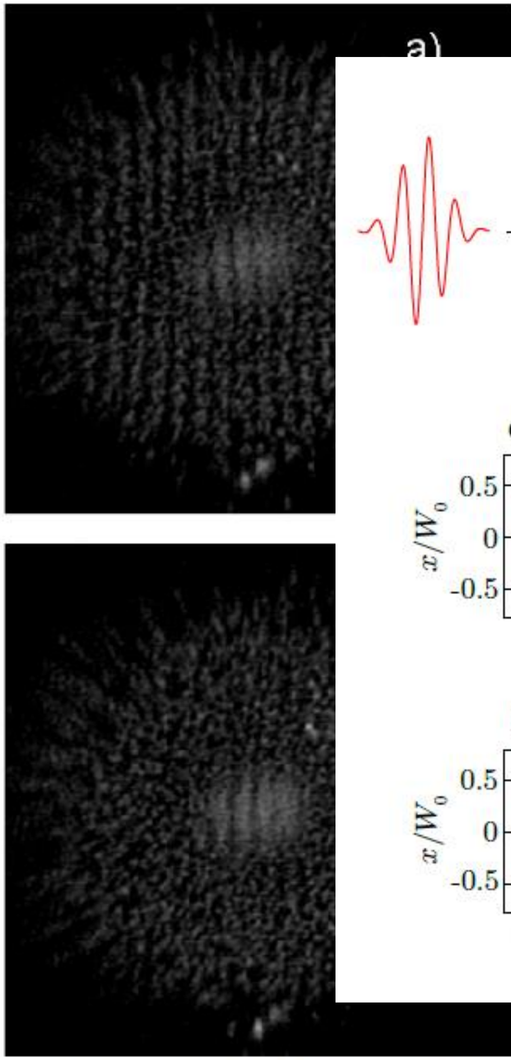
Short vs long trajectory

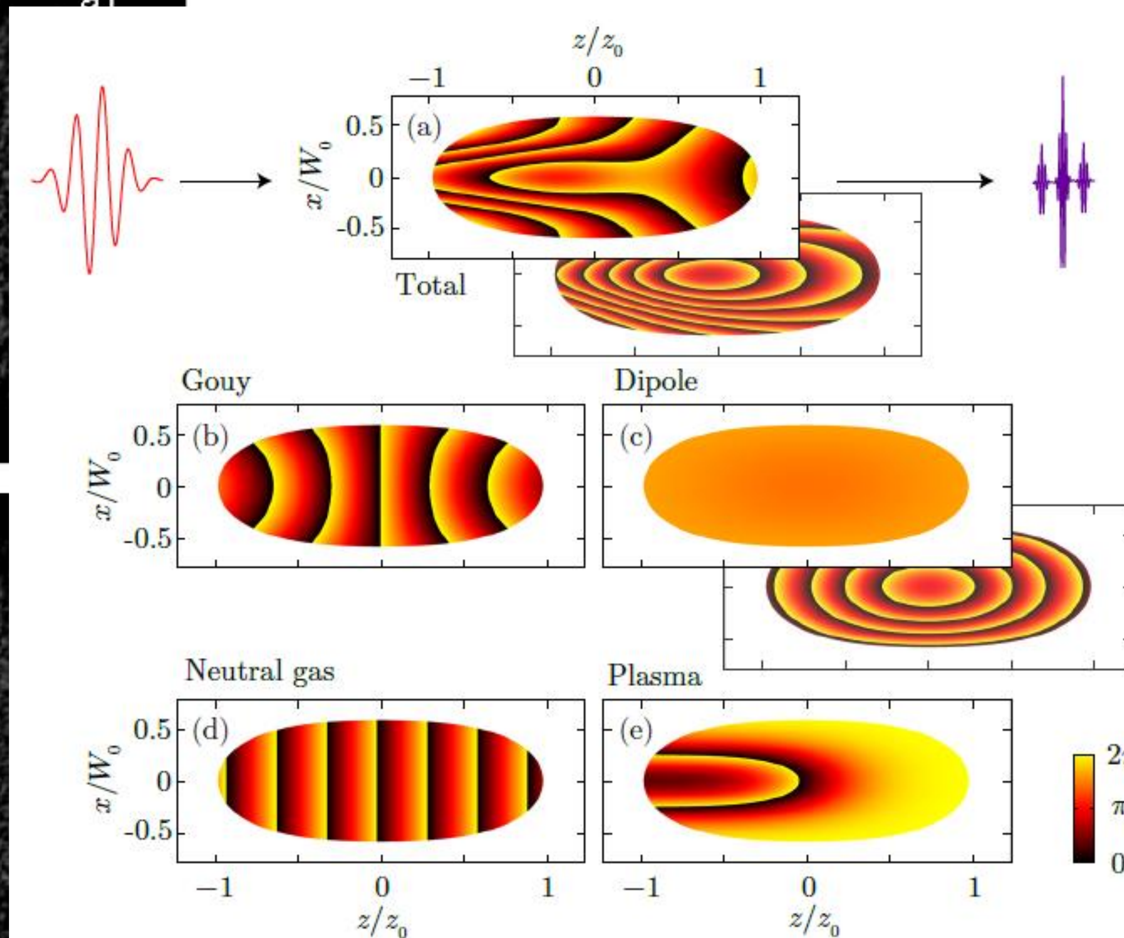


Harmonic radiation is complicated: contributions from short and long trajectories:

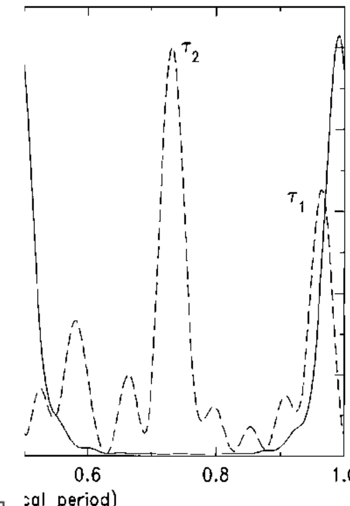
- delayed in time
- opposite chirp
- different intensity-dependent phase dependence, hence different divergence

Short vs long trajectory





cell after focus: short traj.



s: long traj.

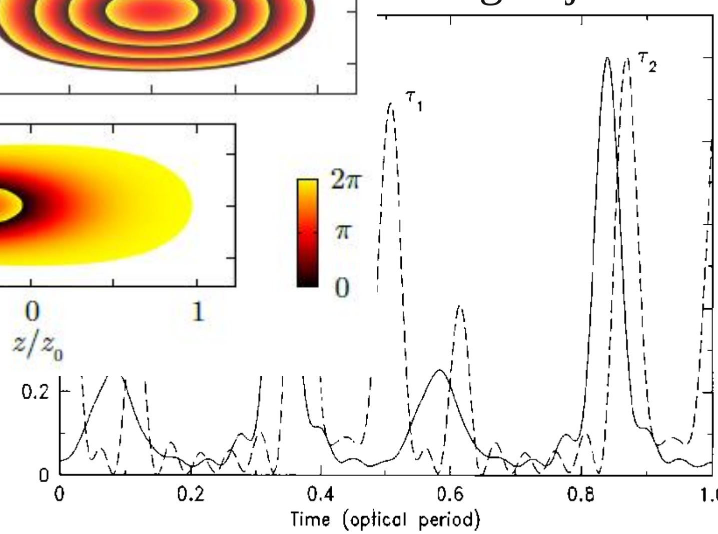


FIG. 3. Interference fringe pattern for the 15th harmonic. (a) $\tau \approx 0$ fs. (b) $\tau \approx 15$ fs.

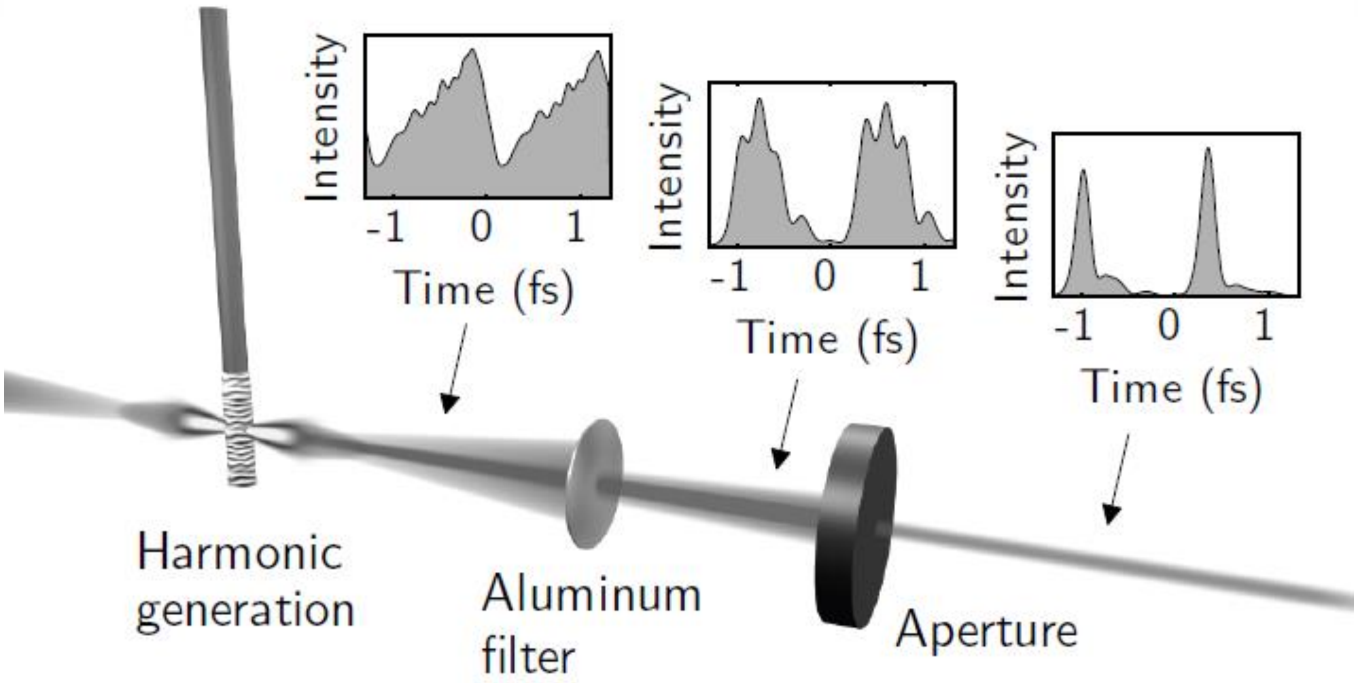
VOLUME 81, NUMBER 2 PHYSICAL REVIEW LETTERS 13 JULY 1998

Temporal Coherence of Ultrashort High-Order Harmonic Pulses

M. Bellini,[1,2] C. Lyngå,[3] A. Tozzi,[4] M. B. Gaarde,[3,5] T. W. Hänsch,[2,4,6] A. L'Huillier,[3] and C.-G. Wahlström[3]

P. Antoine, *Phys Rev Lett* **77**, 1234 (1996)

Filtering HHG for attosecond pulse production



Generation

Spectral filtering + postcompression

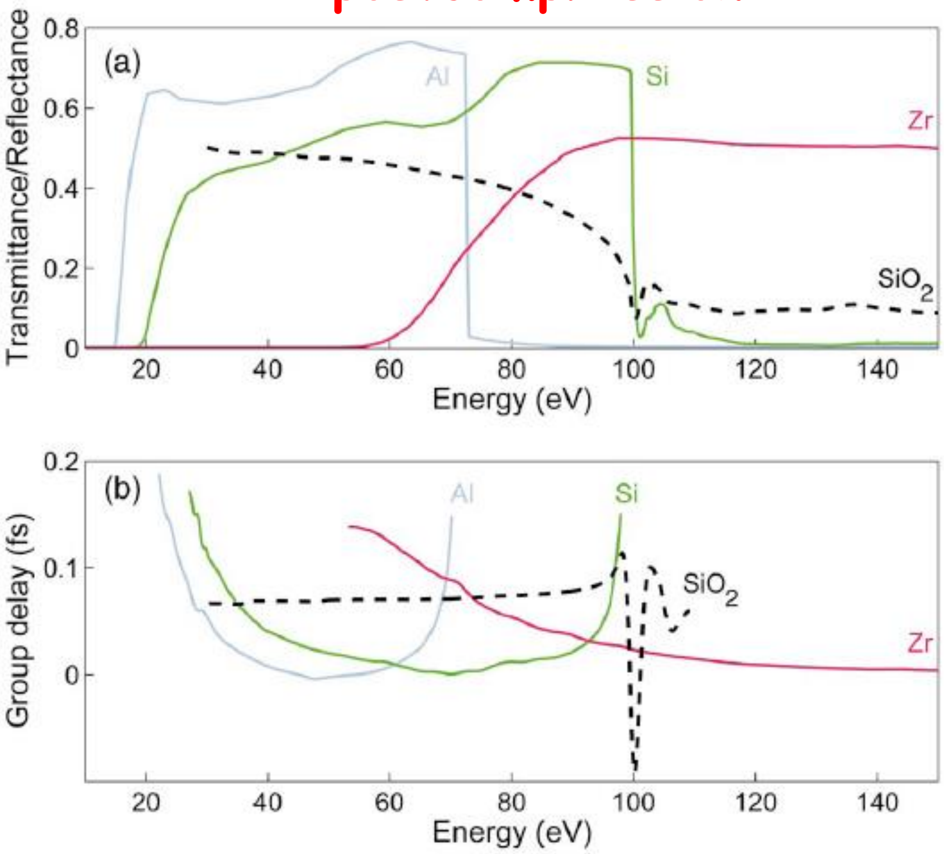
Trajectory filtering

postcompression is required for short pulse generation

López-Martens PhysRevLett (2005)

„Filters"

Spectral filtering + postcompression



Gustafsson, Opt Lett, 2007

Trajectory filtering

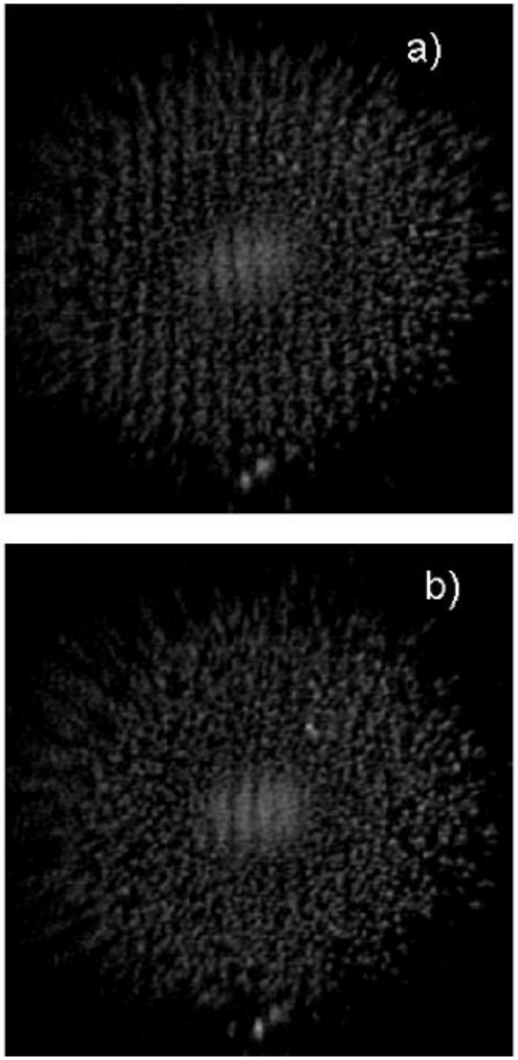
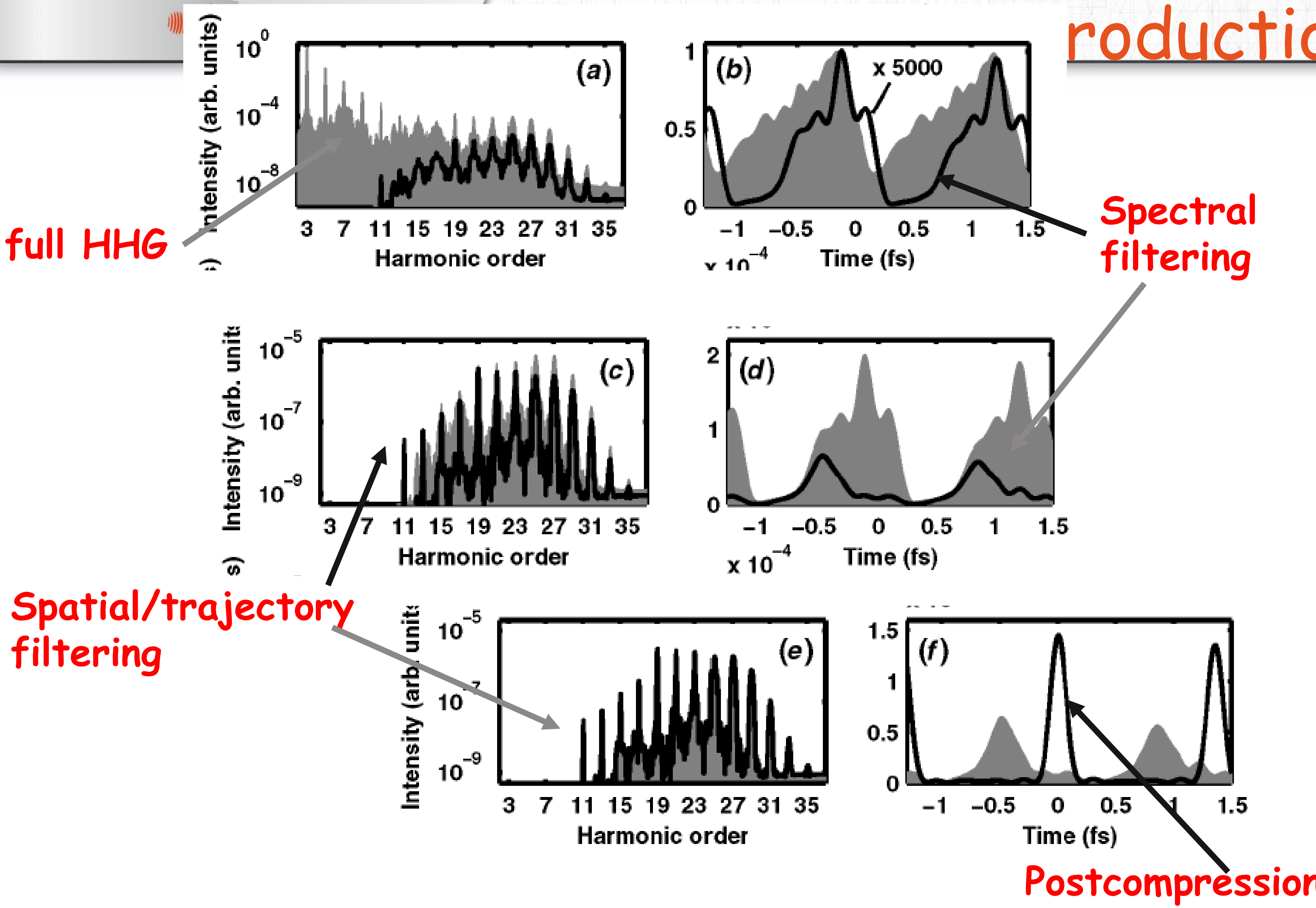


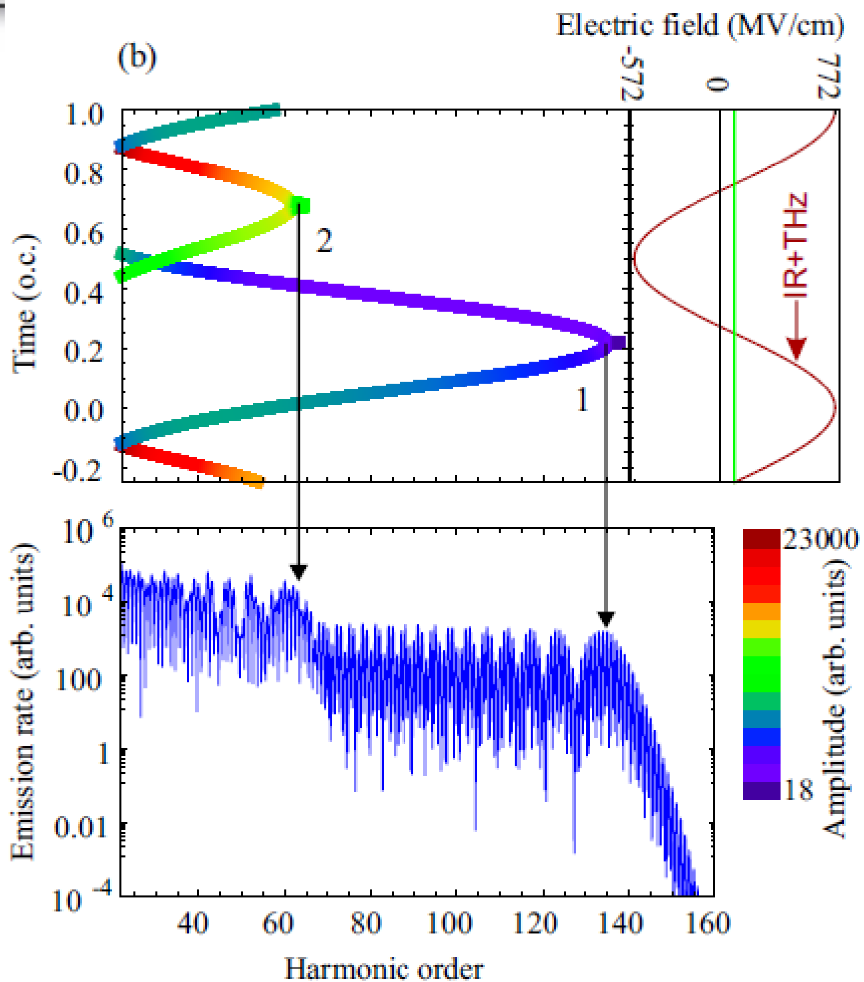
FIG. 3. Interference fringe pattern for the 15th harmonic. (a) $\tau \approx 0$ fs. (b) $\tau \approx 15$ fs.

Filtering HHG for ... roduction



Johnsson, JMO (2006)

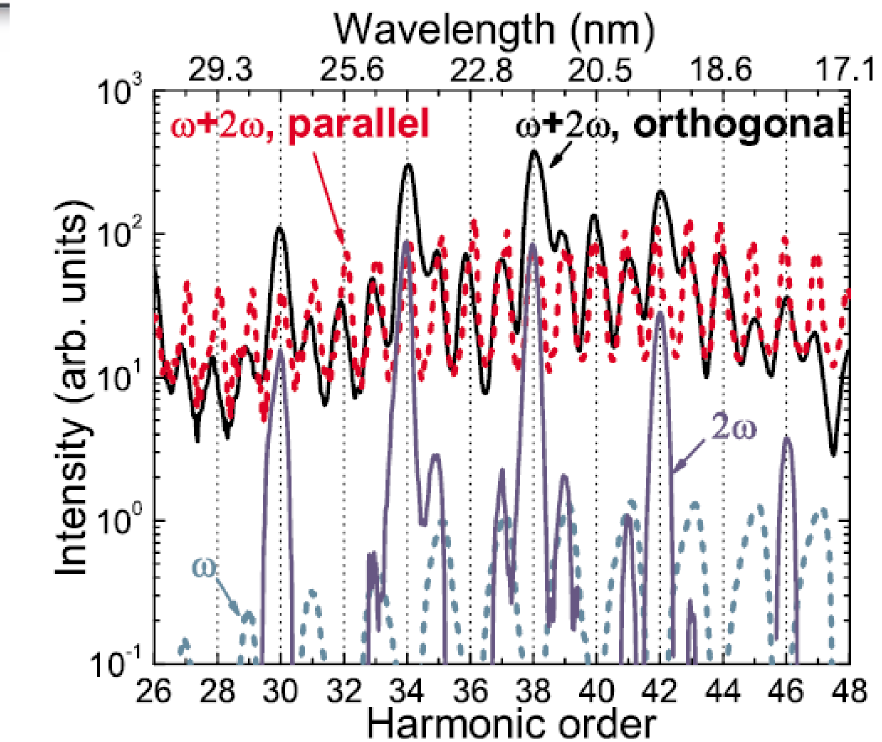
Combination of driving fields



J. Phys. B: At. Mol. Opt. Phys. **45** (2012) 074022 (5pp) doi:10.1088/0953-4075/45/7/074022

A case study for terahertz-assisted single attosecond pulse generation

Emeric Balogh[1], Katalin Kovács[1,2], Valer Toşa[2] and Katalin Varjú[1]



PRL **94**, 243901 (2005) PHYSICAL REVIEW LETTER

Highly Efficient High-Harmonic Generation in an Orthogonally P

I Jong Kim, Chul Min Kim, Hyung Taek Kim, Gae Hwang Lee, Yo
David Jaeyun Cho, and Chang Hee Nam*

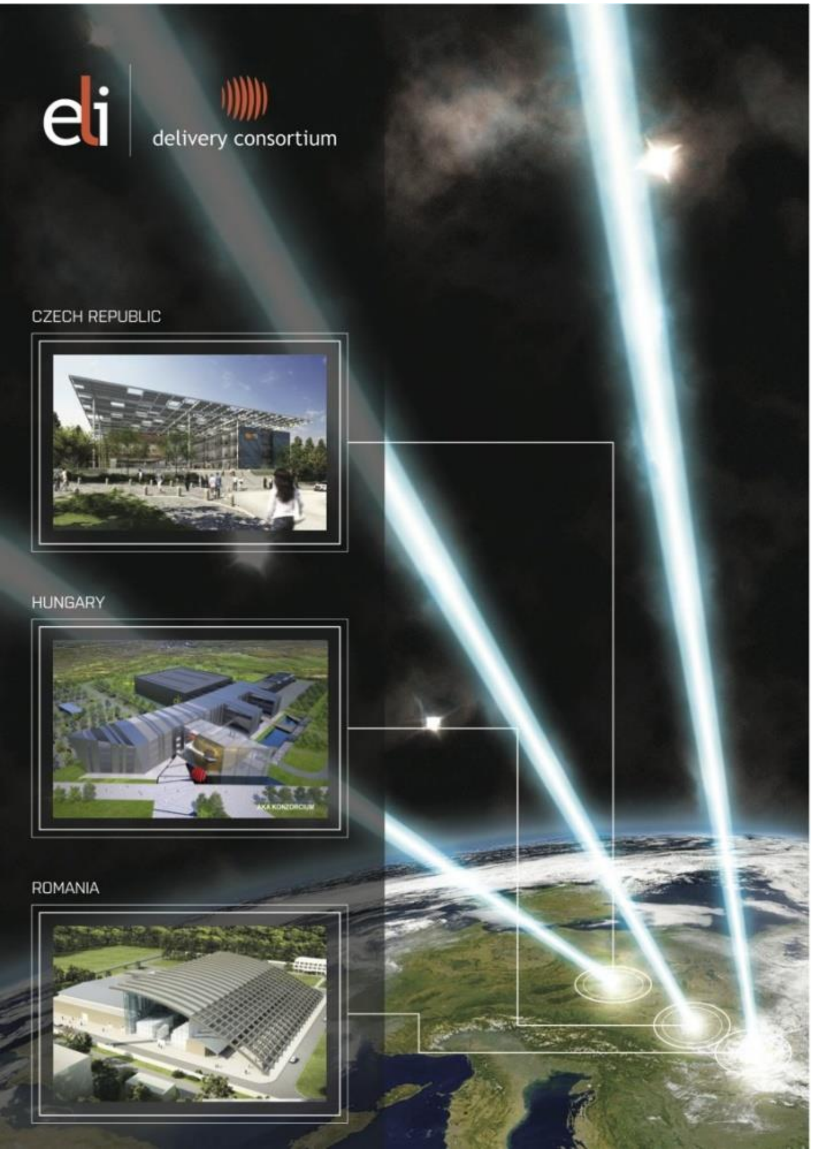
An attosecond experiment

www.attoworld.de

Contents

- Optimizing HHG for tailored attosecond pulse production
- The ELI project
- ELI ALPS: collection of sources
- New directions of attosecond science

The ELI project
A distributed RI of the ESFRI roadmap



- ELI Attosecond Light Pulse Source (ELI-ALPS) (Szeged, Hungary)
- ELI High Energy Beam-Line Facility (ELI-Beamlines) (Dolni Brezhany, Czech Republic)
- ELI Nuclear Physics Facility (ELI-NP) (Magurele, Romania)

Missions of ELI ALPS

1) To generate X-UV and X-ray fs and atto pulses, for temporal investigation at the attosecond scale of electron dynamics in atoms, molecules, plasmas and solids.

2) To contribute to the technological development towards high average power, high intensity lasers.

Scientific program

- Laser research and development
- Research and development of secondary sources
- Atomic, molecular and nanophysical research
- Applied research activities:
  biomedicine, materials science
- Industrial applications

See in details: www.eli-alps.hu

Generation of

the shortest possible light pulses (few cycles)

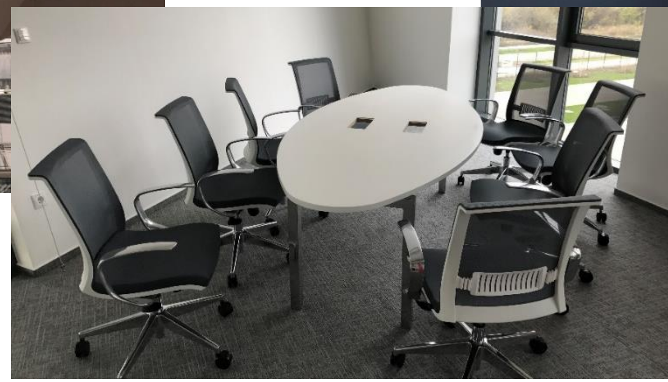
in the broadest possible spectral regime (XUV – THz)

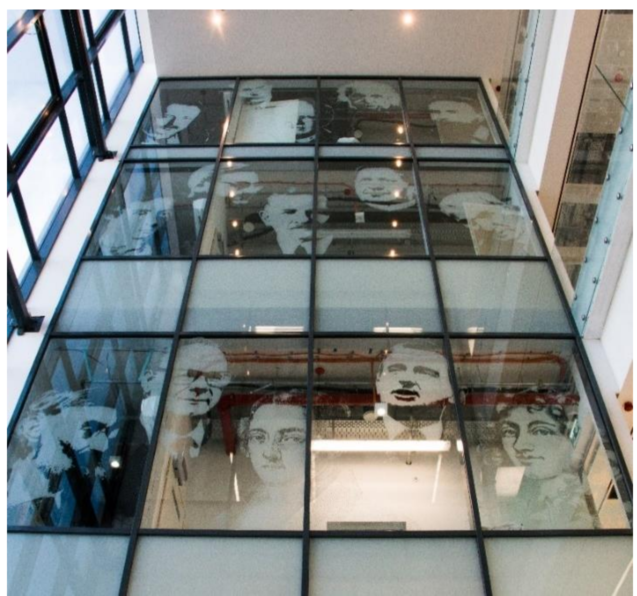
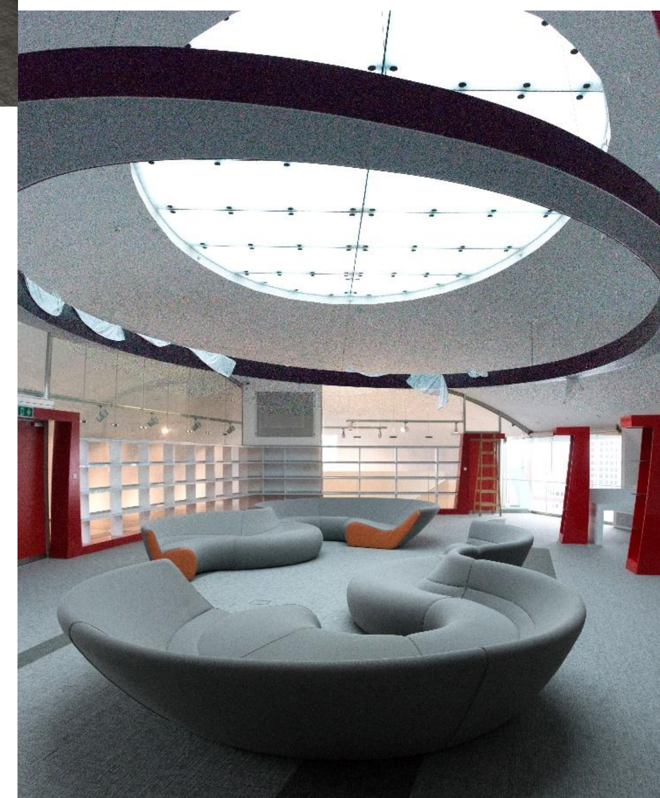
at the highest possible repetition rate (10Hz-100kHz)

Construction

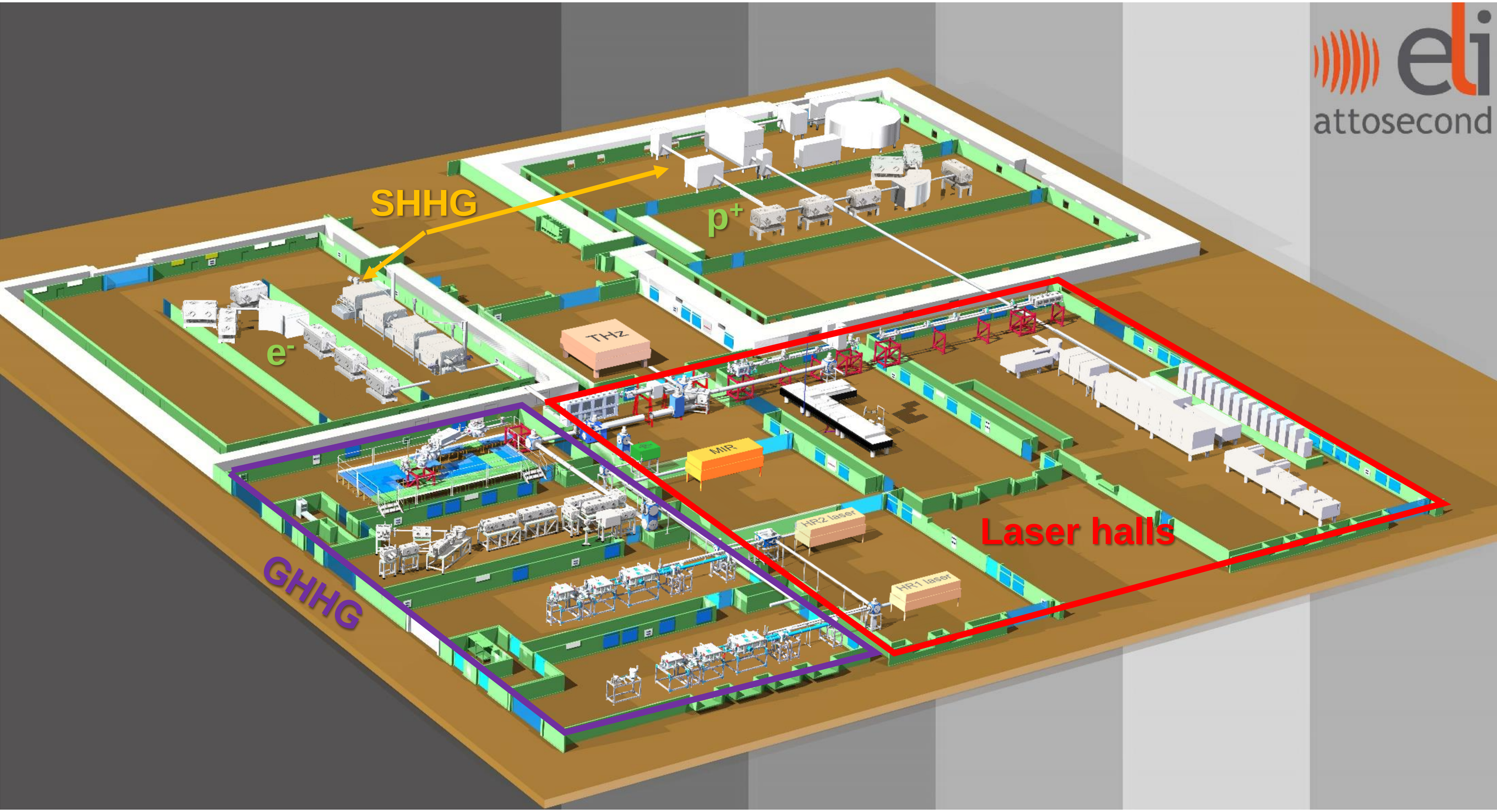
Construction completed



Experimental areas



Laboratories

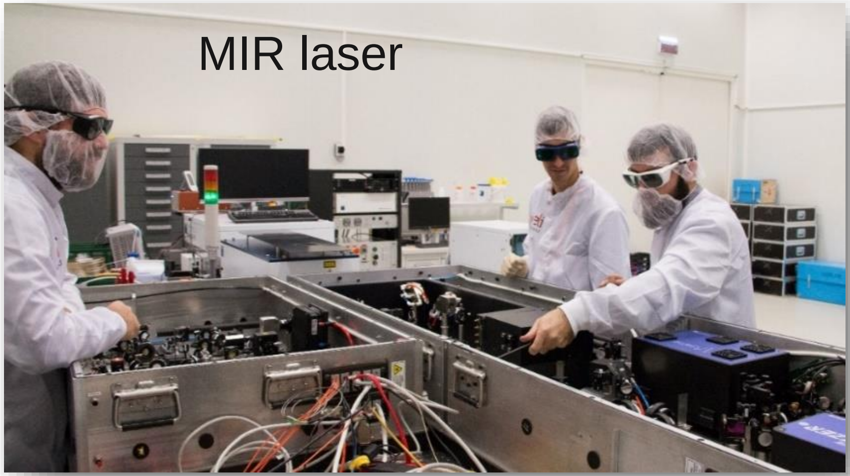
Clean room environment.
ISO 7 for laser halls, ISO 8 for secondary sources / user areas.

Temperature and relative humidity.
21°C (±0.5°C), 35±5% (tunable).

Vibration isolation
VC-E (ASHRAE)

High-shielded Target Area

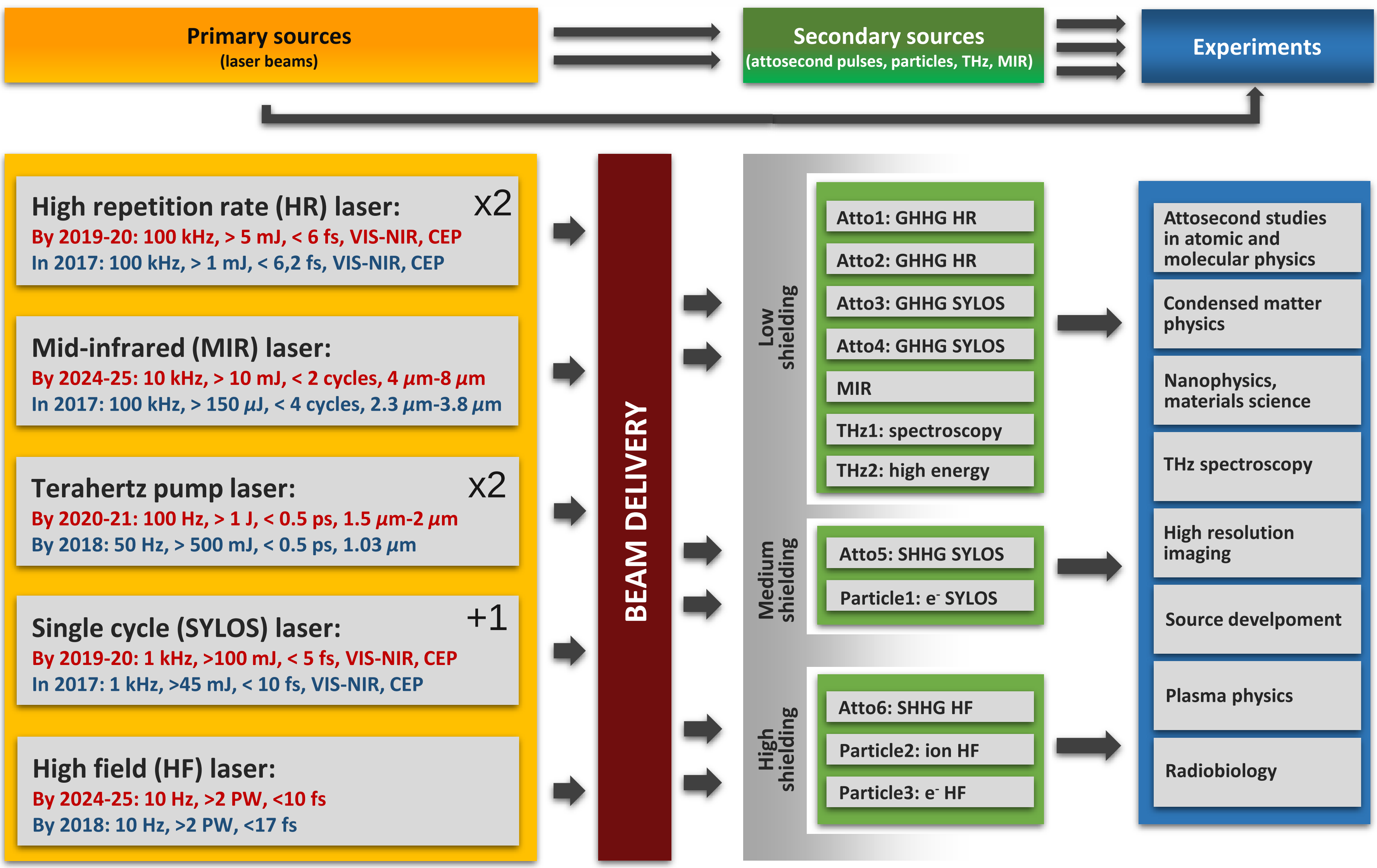
Laboratories



Contents

- Optimizing HHG for tailored attosecond pulse production
- The ELI project
- ELI ALPS: collection of sources
- New directions of attosecond science

Scheme of ELI-ALPS



Kühn, et al., Journal of Physics B, 50, 132002 (2017)

Lasers of ELI-ALPS

Unprecedent stability conditions for operation

Primary sources
(laser beams)

High repetition rate (HR) laser: x2

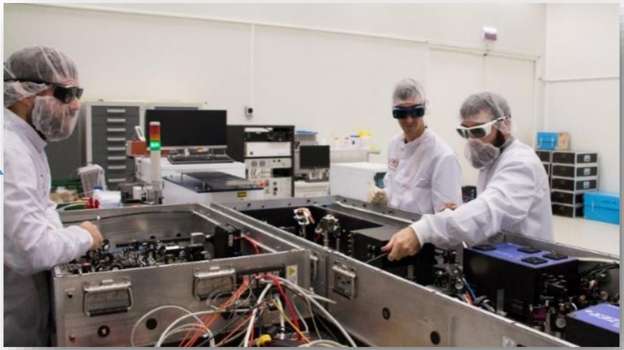
By 2019-20: 100 kHz, > 5 mJ, < 6 fs, VIS-NIR, CEP

In 2017: 100 kHz, > 1 mJ, < 6,2 fs, VIS-NIR, CEP

Mid-infrared (MIR) laser:

By 2024-25: 10 kHz, > 10 mJ, < 2 cycles, 4 μm-8 μm

In 2017: 100 kHz, > 150 μJ, < 4 cycles, 2.3 μm-3.8 μm



Terahertz pump laser: x2

By 2020-21: 100 Hz, > 1 J, < 0.5 ps, 1.5 μm-2 μm

By 2018: 50 Hz, > 500 mJ, < 0.5 ps, 1.03 μm

Single cycle (SYLOS) laser: +1

By 2019-20: 1 kHz, >100 mJ, < 5 fs, VIS-NIR, CEP

In 2017: 1 kHz, >45 mJ, < 10 fs, VIS-NIR, CEP

High field (HF) laser:

By 2024-25: 10 Hz, >2 PW, <10 fs

By 2019: 10 Hz, >2 PW, <17 fs

Breakthrough in laser science and technologies (mission 2)

Front end of large scale ultrafast laser systems

Change of paradigm

- Sub-ps fiber oscillators around 1µJ replace Kerr-lens mode-locked Ti:S oscillators
- White light generators
- Self-CEP stabilisation: DFG+OPA

The first TW-class few cycle fiber laser for users (HR laser)

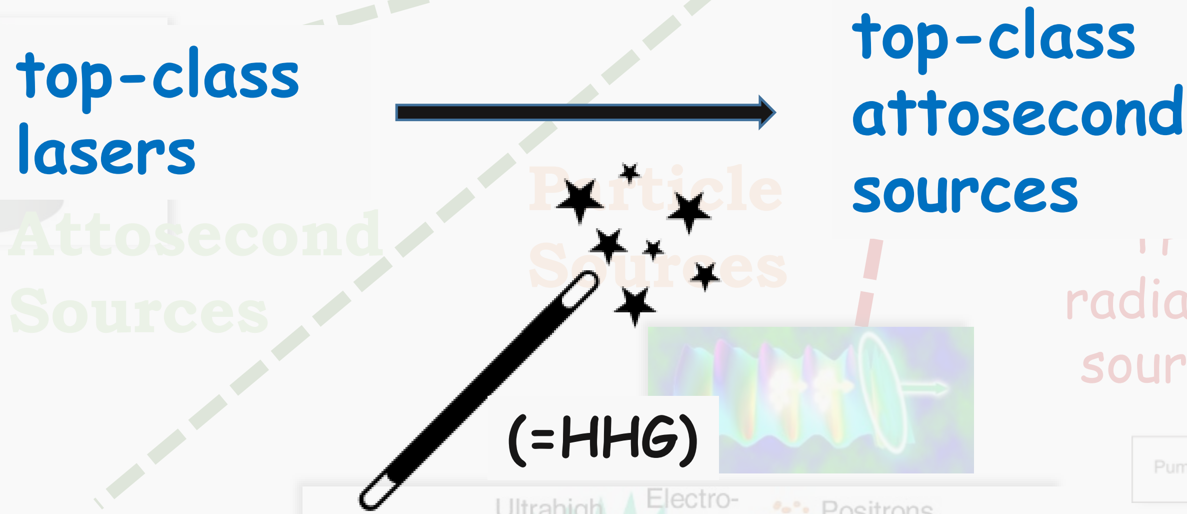
Change of paradigm – new generation of HAP / HI lasers.

Unprecedent stability conditions for operation (SYLOS, PW)

Trial period: 6 months, 4 months trouble-free operation

ELI-ALPS: collection of sources

Primary sources (laser beams) → **Secondary sources** (attosecond pulses, particles, THz, MIR) → **Experiments**

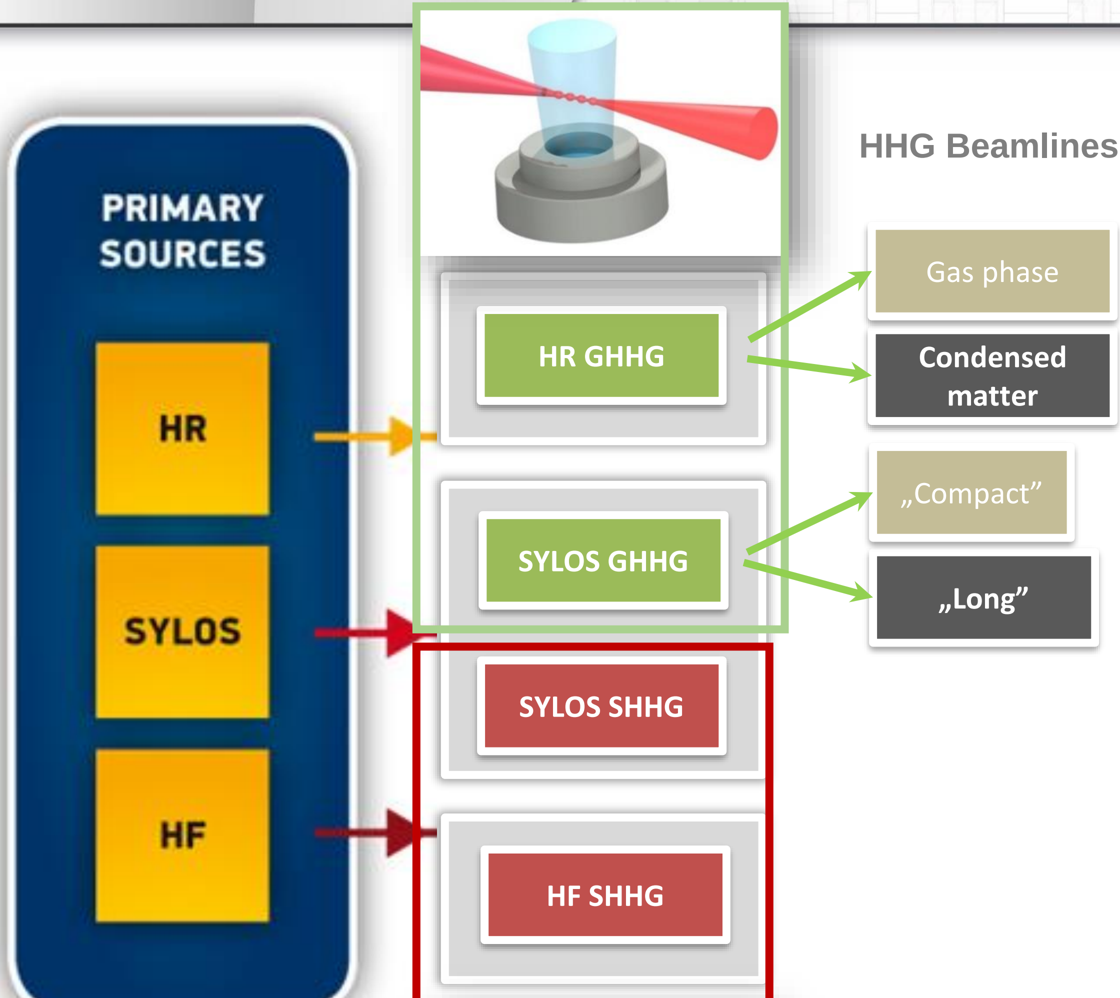


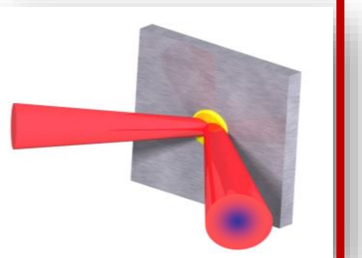
Clever use of the ever increasing laser power

High (but not too high) intensity, (10^{14} W/cm^2 - 10^{15} W/cm^2)

depletion of the medium
distortion of the driving pulse
phase-matching
increasing interaction volume

Attosecond Secondary Sources





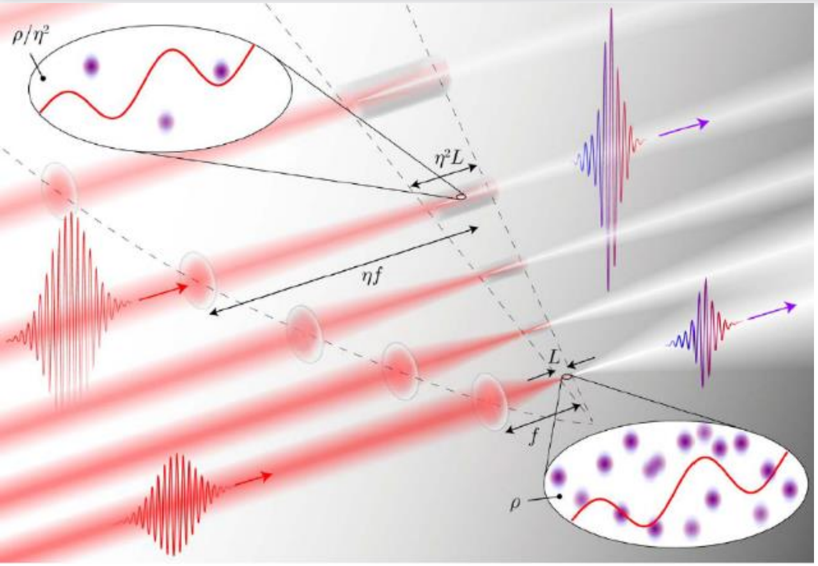
Development perspective

- Different focussing conditions
- New phase matching configurations
- Optimisation of pulse energy

- Measuring/optimising time domain characteristics
- Different plasma configurations
- Optimisation of generation efficiency

Challenge: up-scaling
High average power for optical components
High peak power for GHHG
High rep rate for SHHG

Scaling principles



Heyl, et al., Optica **3**, 75 (2016)

Gaussian beam:

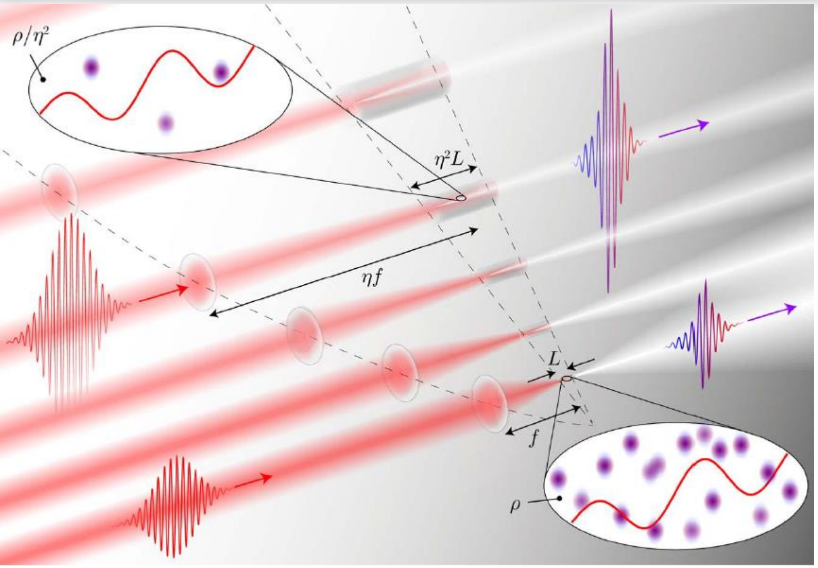
$$z_R \rightarrow \eta^2 z_R$$

$$W_0 \rightarrow \eta W_0$$

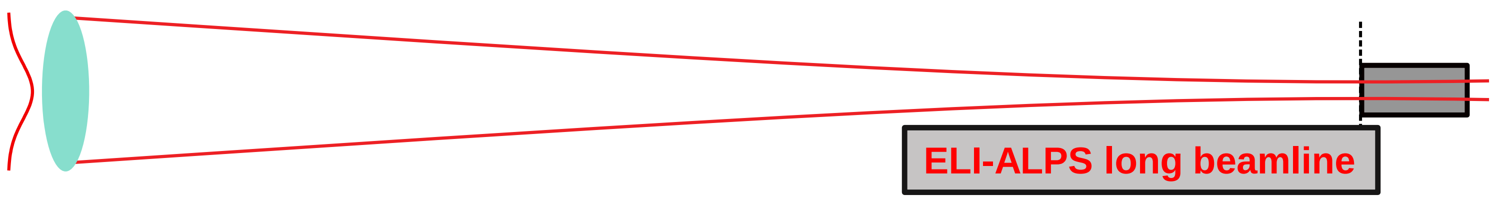
$$z_R = \frac{\pi W_0^2}{\lambda}$$

	Parameter	Scaled Parameter
Input Parameters		
Dimensions	z (longitudinal)	$\eta^2 z$
	r (transverse)	ηr
Other parameters	ρ (density)	ρ/η^2
	ε_{in}	$\eta^2 \varepsilon_{in}$
Output Parameters		
General	ε_{out}	$\eta^2 \varepsilon_{out}$
Filamentation	p_{cr}	$\eta^2 p_{cr}$
	z_{cr}	$\eta^2 z_{cr}$
HHG	ε_q	$\eta^2 \varepsilon_q$
	Γ_q	Γ_q

SYLOS-driven beamlines: scaling principles

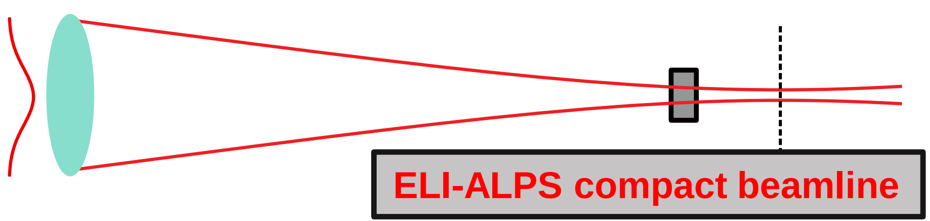


A. Long focus



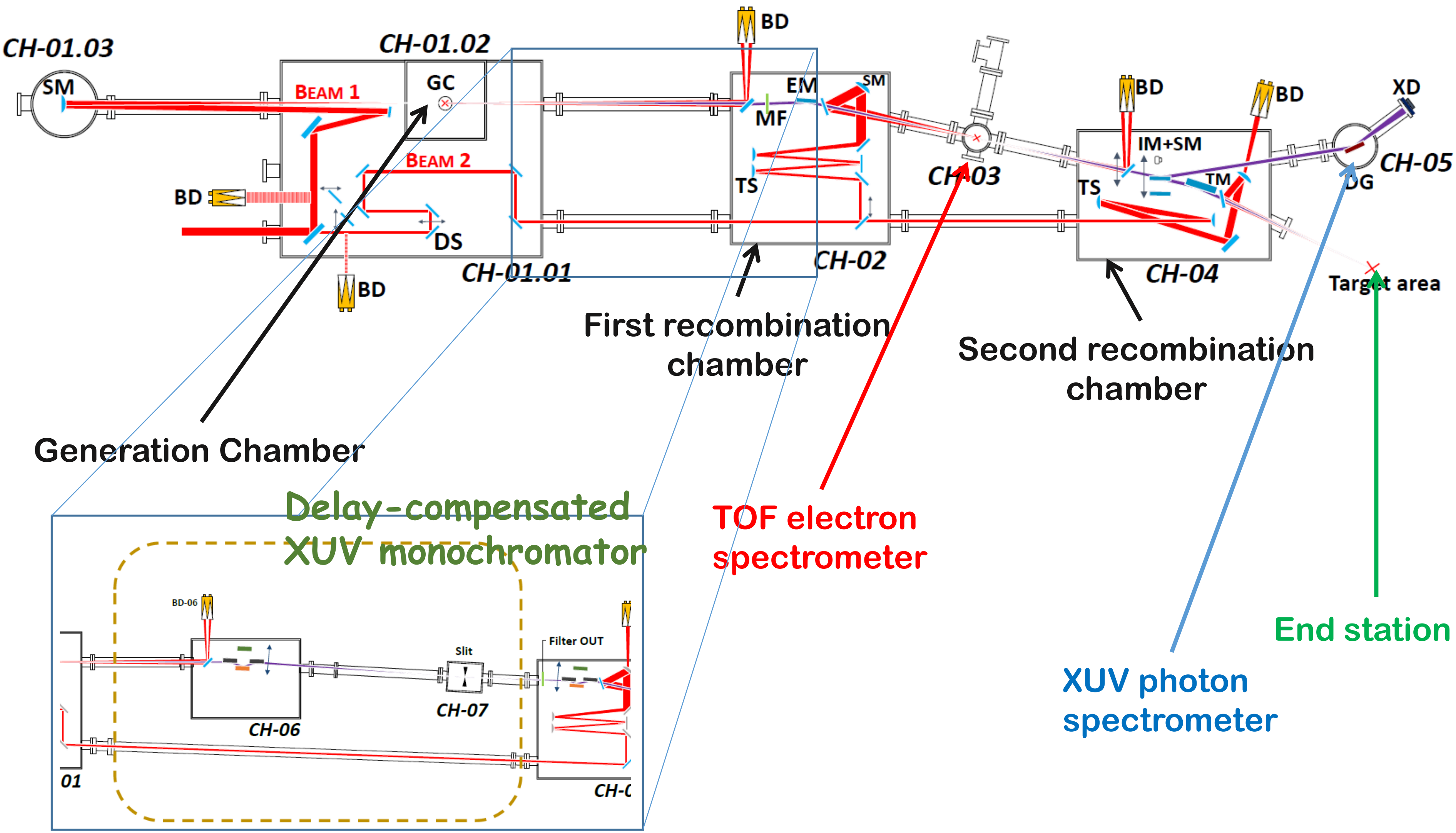
long, low pressure target

B. Compact



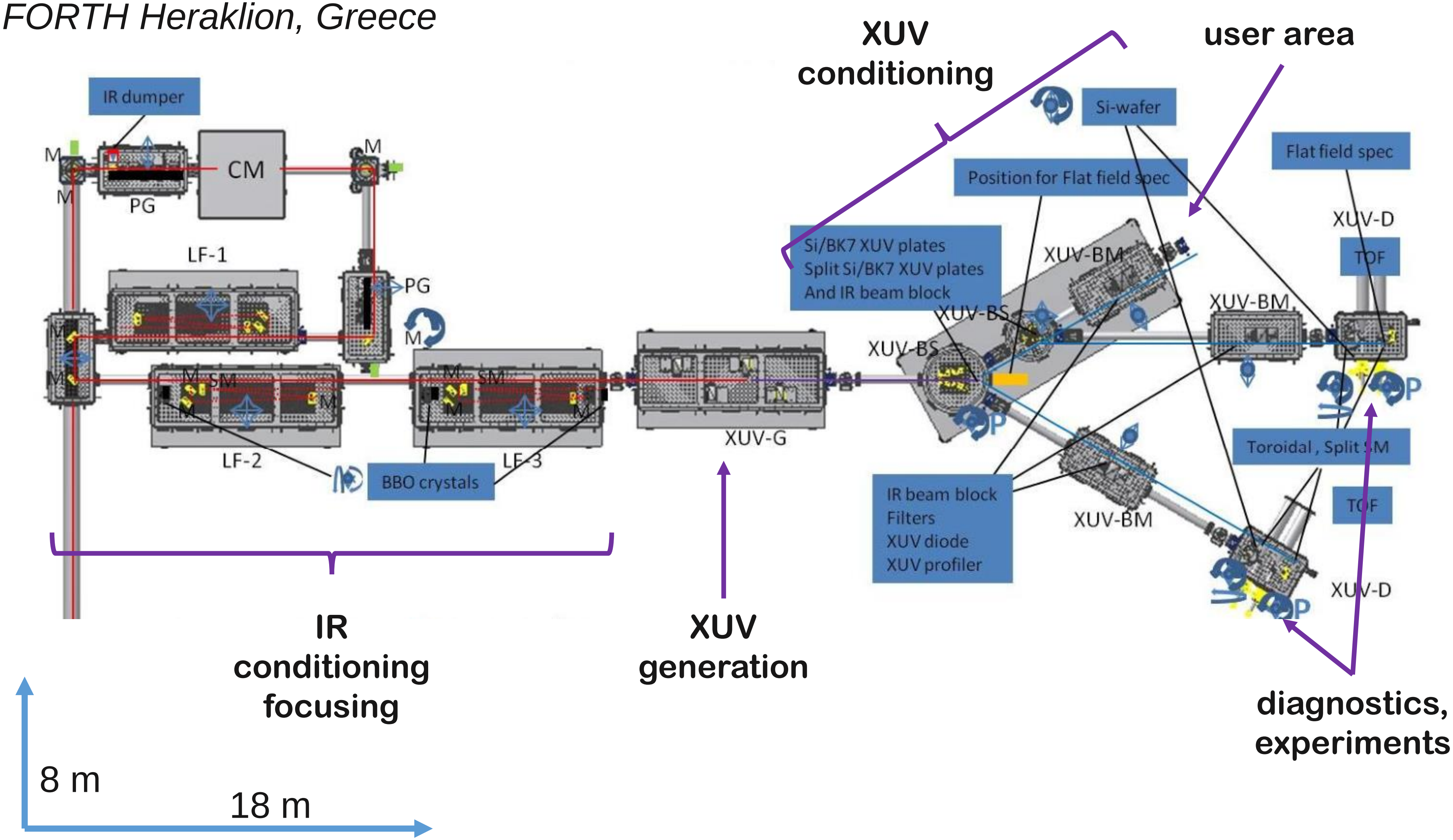
short, high pressure target

The HR GHHG beamlines



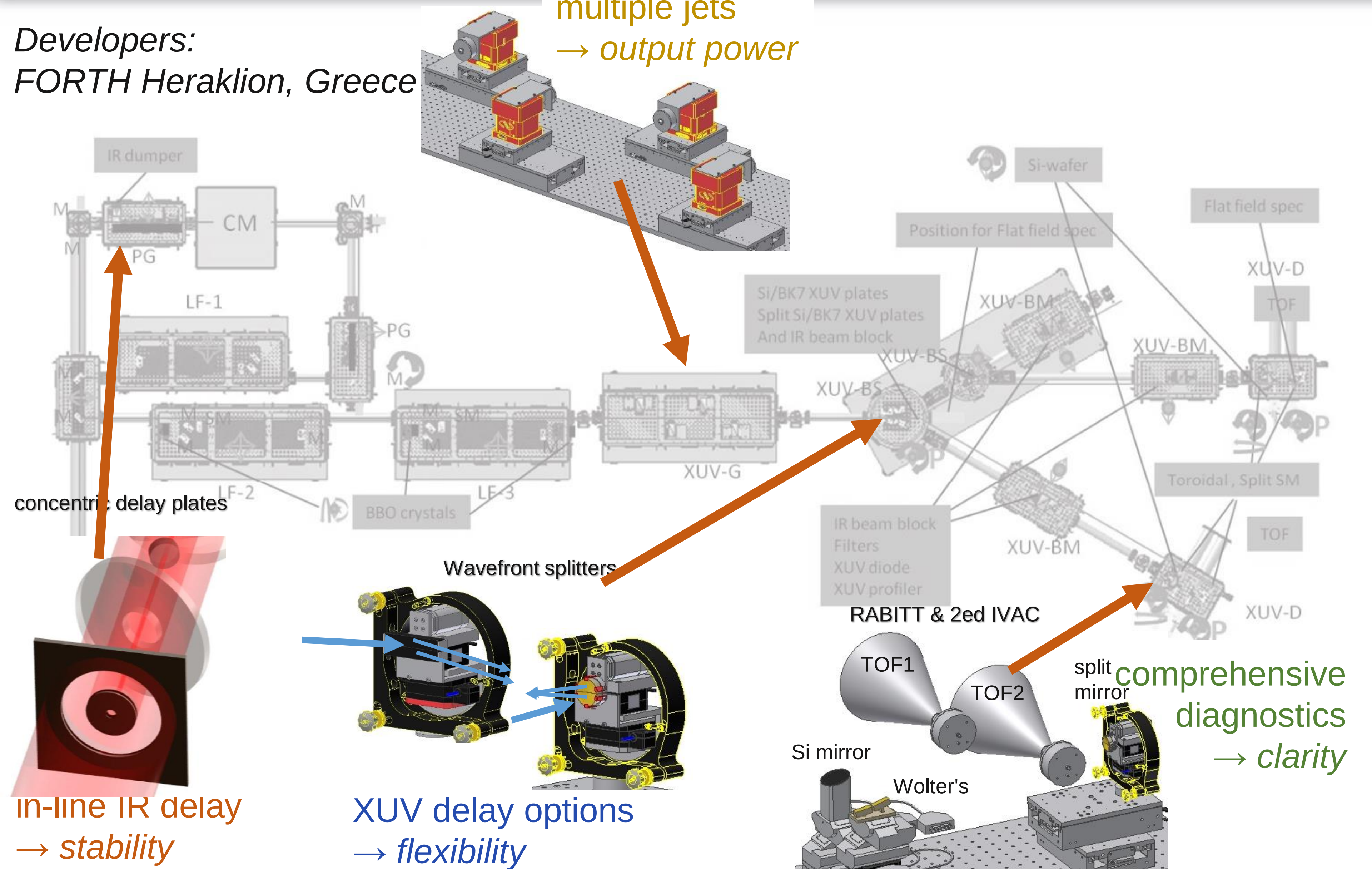
The SYLOS GHHG compact beamline

Developers:
FORTH Heraklion, Greece

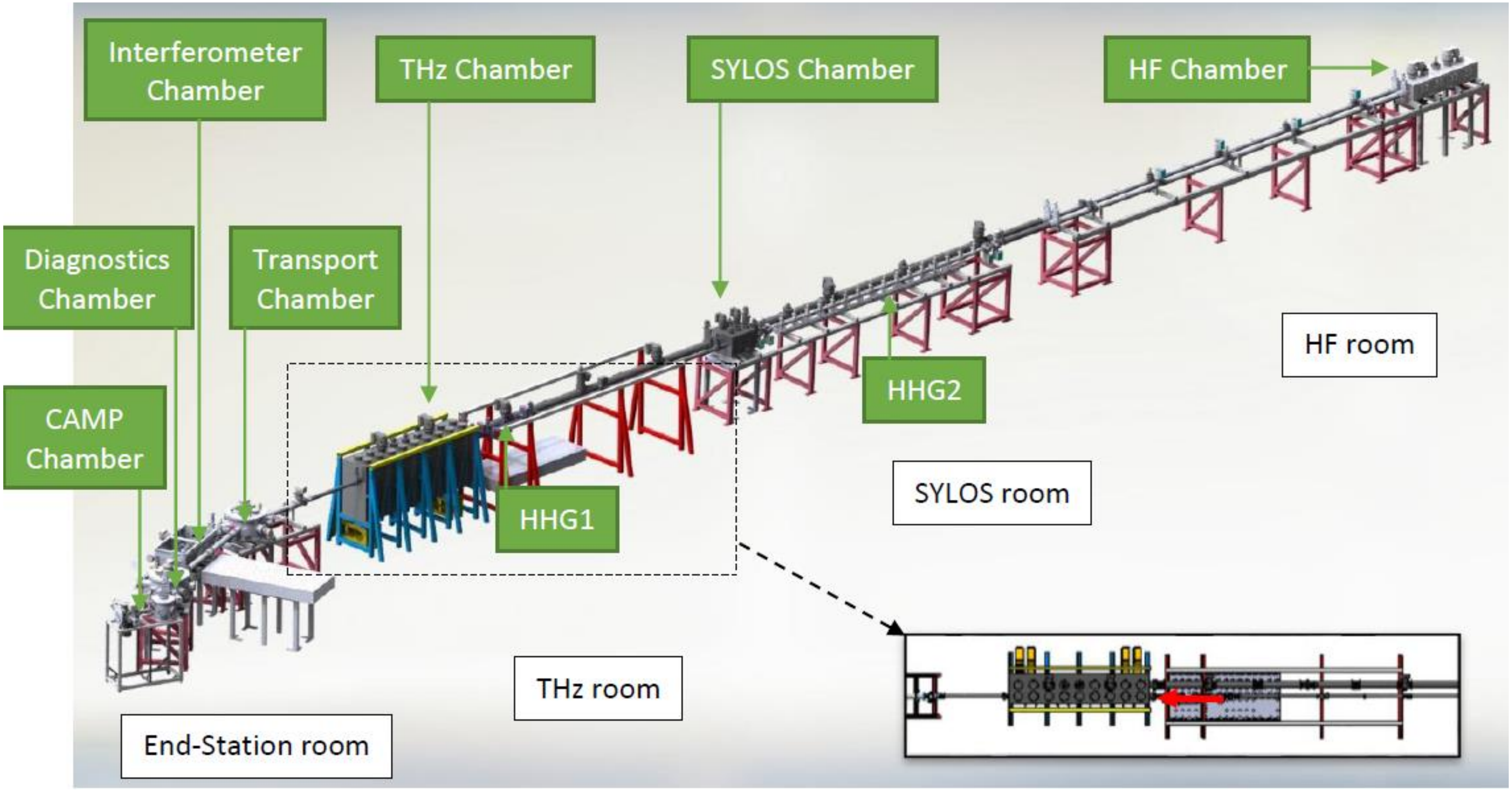


The SYLOS GHHG compact beamline

Developers:
FORTH Heraklion, Greece



The SYLOS GHHG long beamline

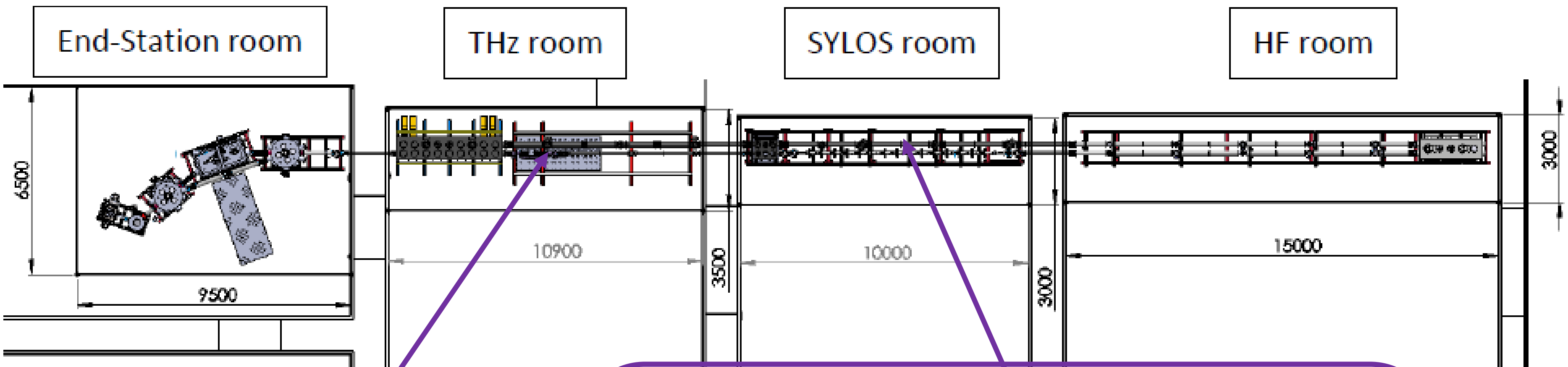


Developer: Lund University, Sweden

The SYLOS GHHG long beamline

Upscaling phasematching concept: loose focusing, long gas cell, low pressure

Heyl, C. et al., J. Phys. B, **45**, 074020 (2012).
Rudawski, P. et al., Rev. Sci. Instrum., **84**, 073103 (2013).



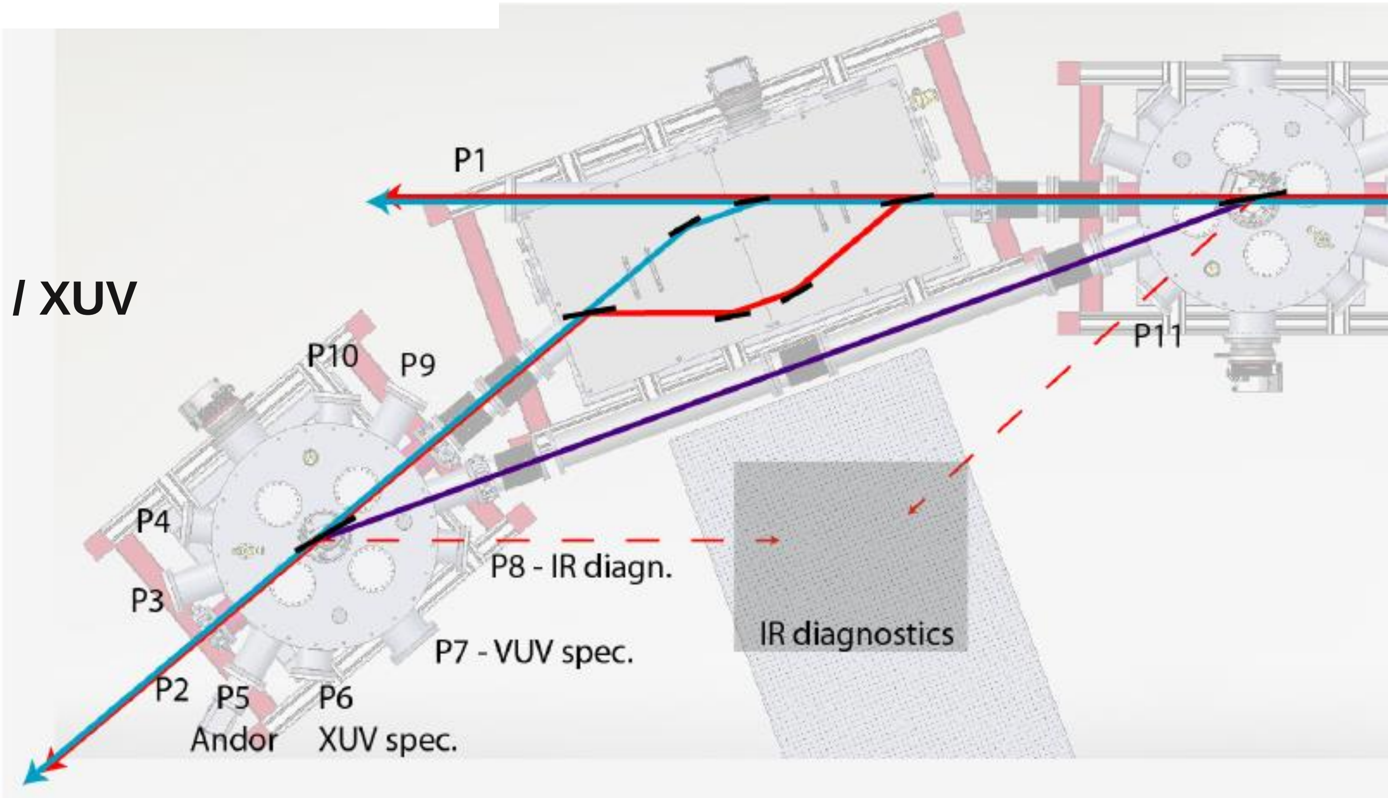
	SAP1	TAP1	SAP2	TAP2
$f_\#$	300-350	600	900	1100
f [m]	~20	~55	~55	~55
D [mm]	60	~90	60	50
Cell length	0.45 m	1.6 m	4 m	6 m
Gas pressure	15 mbar	3.5 mbar	1.5 mbar	1 mbar

Developer: Lund University, Sweden

The SYLOS GHHG long beamline

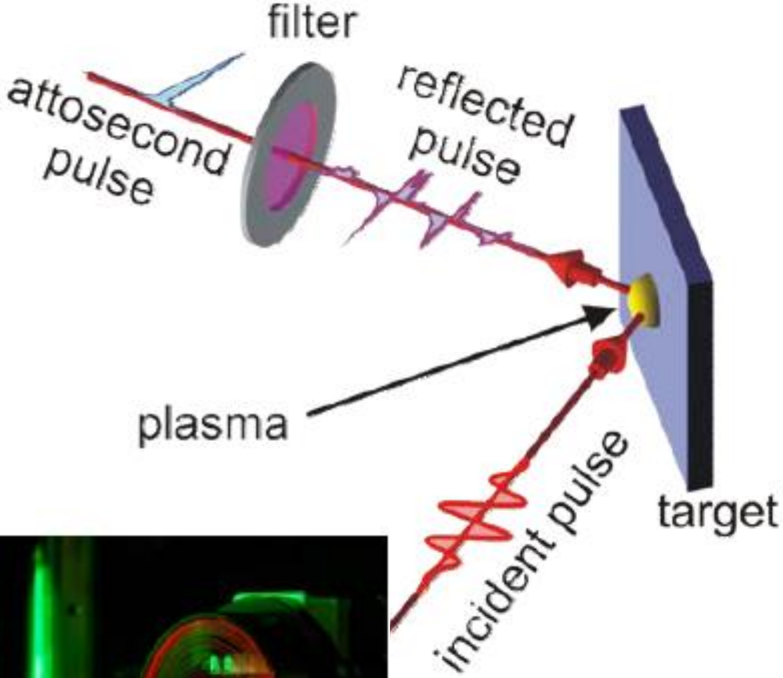
Pump-probe experiments with attosecond resolution

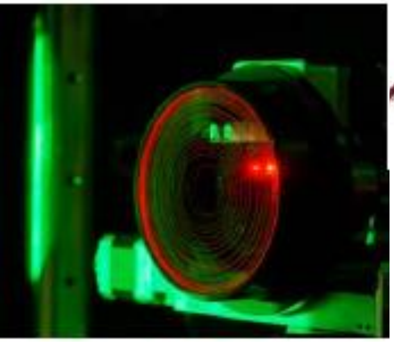
XUV
XUV
IR
IR / SHG / THG / VUV / XUV

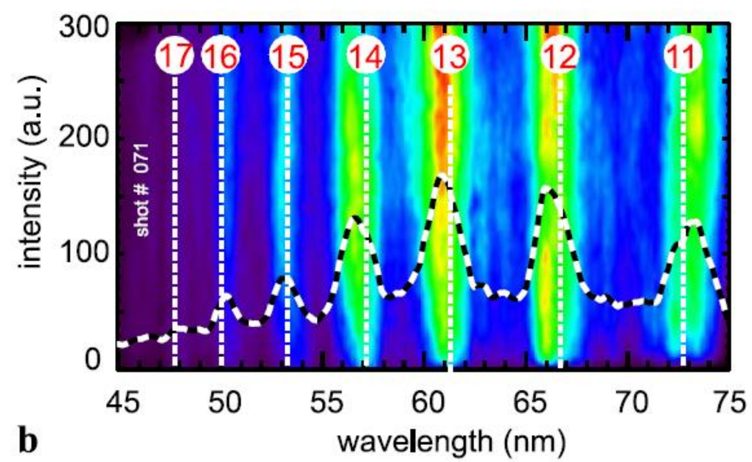


Developer: Lund University, Sweden

HHG at surface plasma

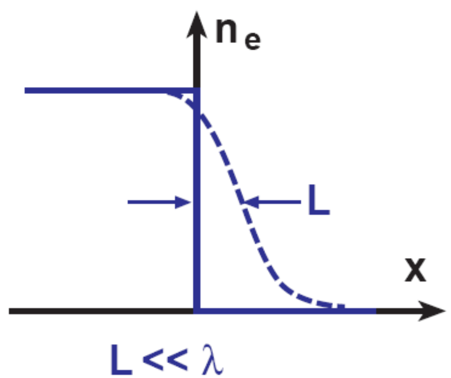






- no inversion symmetry
- all integer harmonics
- one XUV burst per laser cycle

Plasma density profile



Promising
- higher conversion efficiency, and no laser intensity limitation
- extension to shorter wavelengths

2 mechanisms

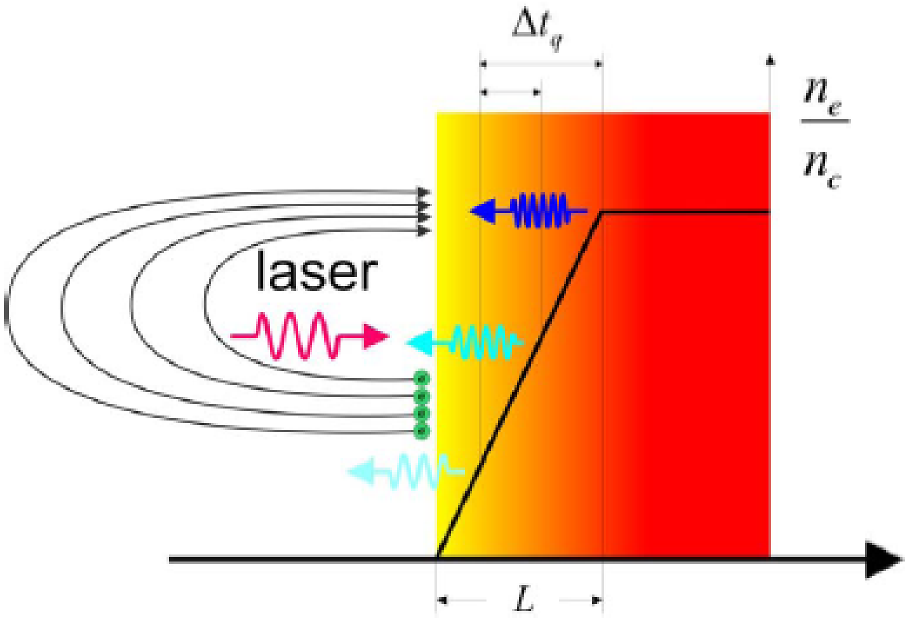
Coherent Wake Emission (CWE)

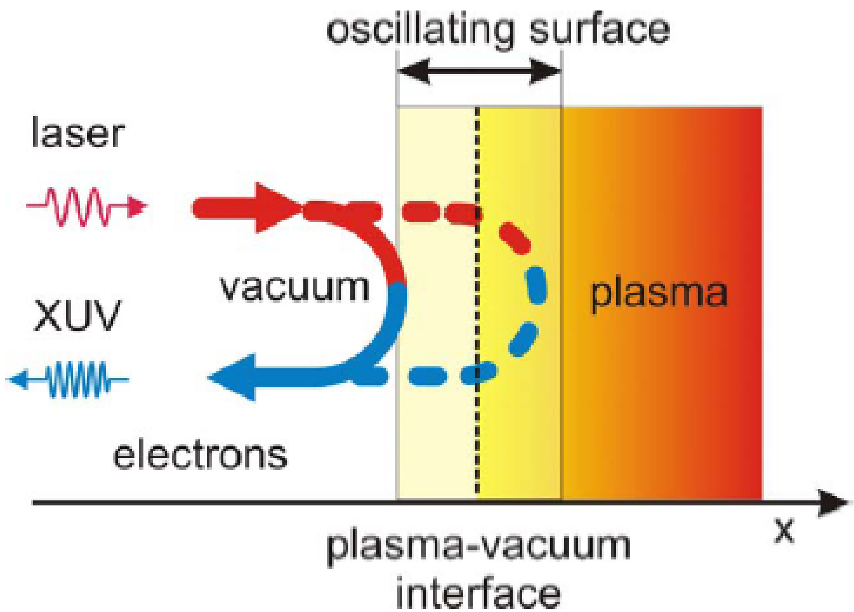
non-relativistic $a_L^2 \leq 1$

Relativistic Oscillating Mirror (ROM)

relativistic $a_L^2 \geq 1$

$$a_T^2 = I_T \lambda^2 / (1.38 \times 10^{18}\ \mathrm{W}\ \mu\mathrm{m}^2 / \mathrm{cm}^2)$$



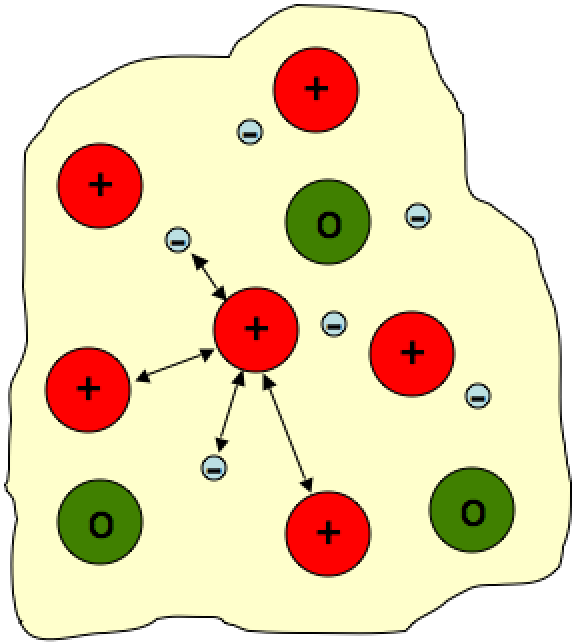


F. Quéré *et al.*, Phys. Rev. Lett. 96, 125004 (2006)
A. Tarasevitch *et al.*, Phys. Rev. Lett. 98, 103902 (2007).
F. Quéré *et al.*, Phys. Rev. Lett. 100, 095004 (2008).
C. Thaury *et al.*, Nat. Phys. 4, 631 (2008).

S.V. Bulanov *et al.* Phys. Plasmas, 1, 745 (1994)
S. Gordienko *et al.* Phys. Rev. Lett. 93, 115002 (2004)
R. Lichters *et al.* Phys. Plasmas 3, 3425 (1996)
G. D. Tsakiris *et al.* New J. Phys. 8, 19(2006)
T. Baeva *et al.*, PRE, 74, 046404(2006)

Description: Particle In Cell

Electromagnetic interaction among a high number of charged particles.



The Algorithm

Compute Charge Density: particle positions are scattered to the grid

Compute Electric Potential: performed by solving the Poisson equation

Compute Electric Field: from the gradient of potential

Move Particles: update velocity and position from Newton's second law.

Generate Particles: sample sources to add new particles

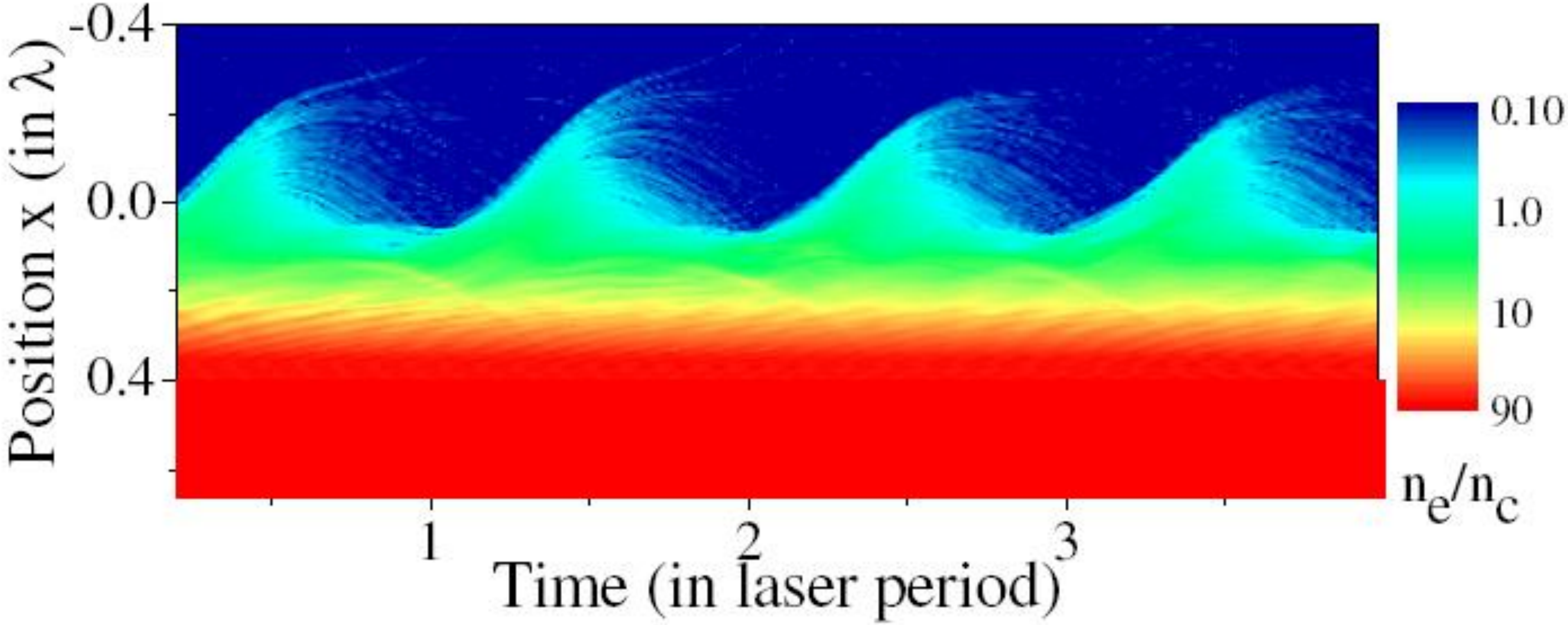
Output: optional, save information on the state of simulation

Repeat: loop iterates until maximum number of time steps is achieved or until simulation reaches steady state

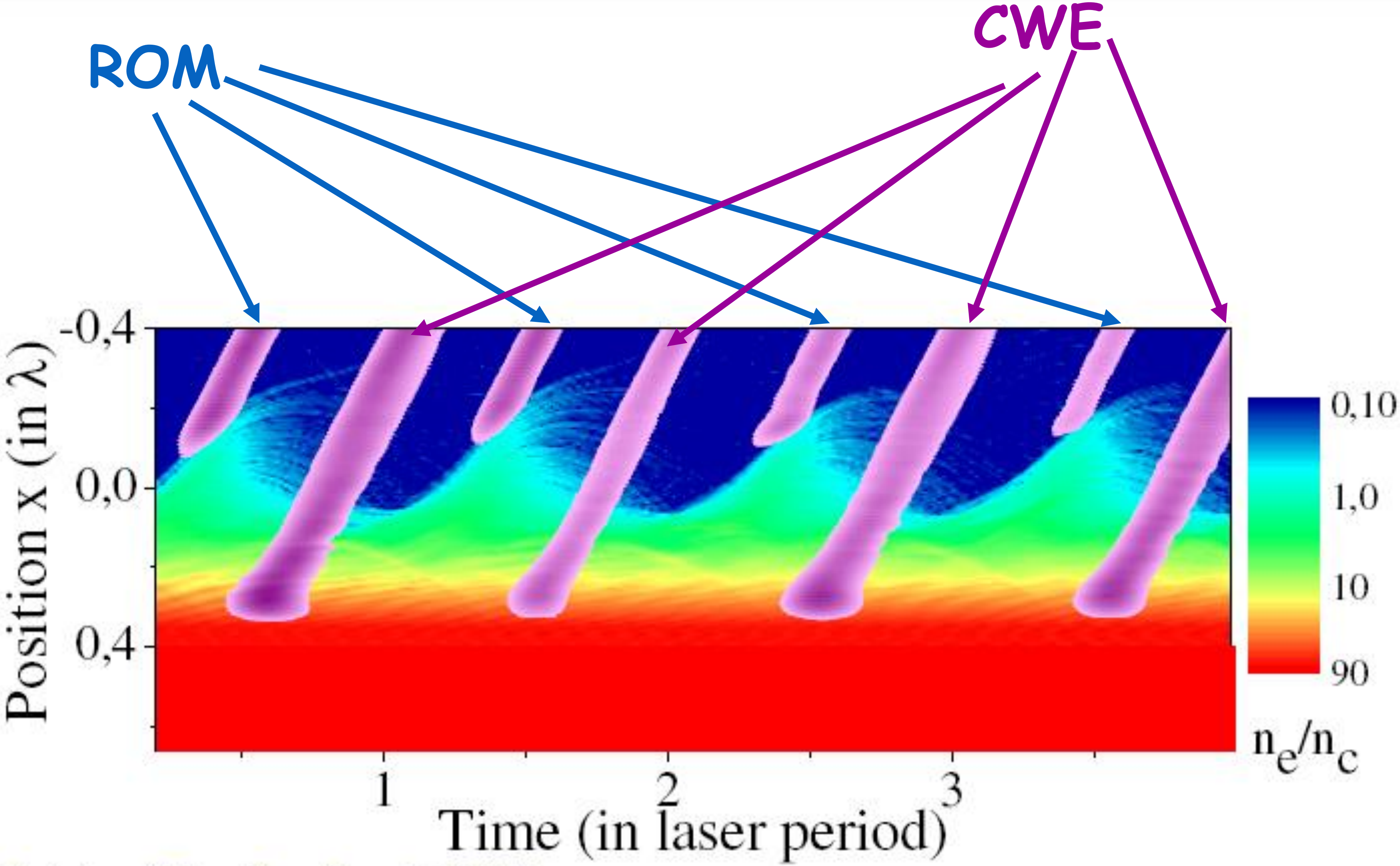
Results

PIC Simulation
Euterpe code
J.P. Geindre, LULI

Density=80.n_c
Short (non-vanishing) density gradient
I=6.10^{17} W/cm^2

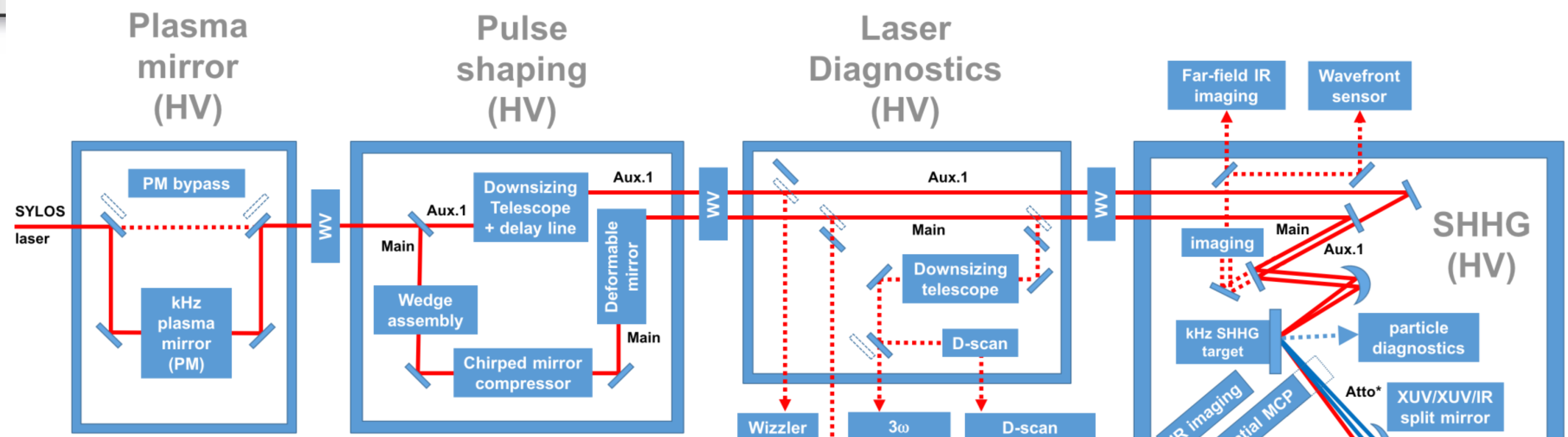


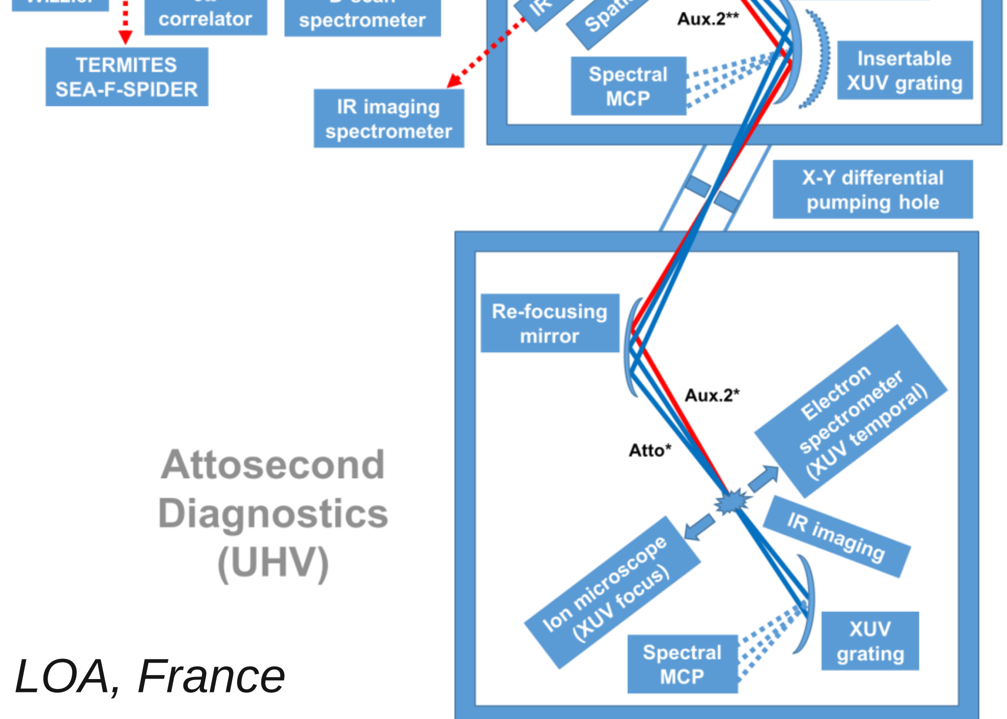
F.Quéré *et al*, Phys. Rev. Lett. **96** (2006)

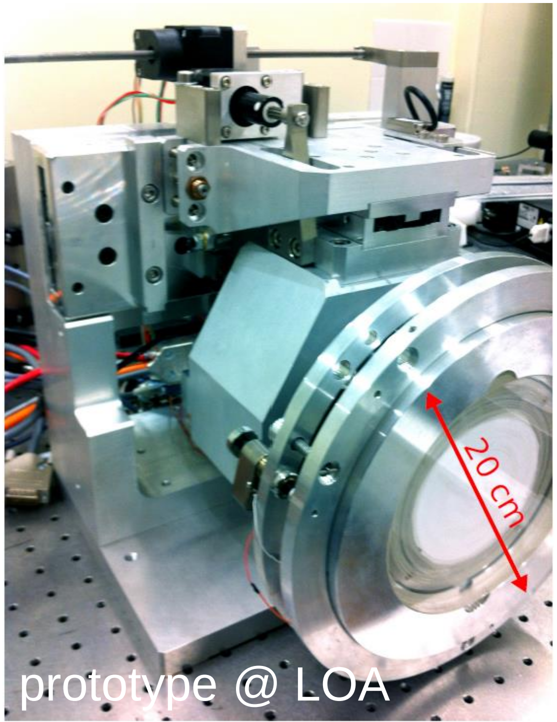


F.Quéré *et al*, Phys. Rev. Lett. **96** (2006)

SYLOS SHHG beamline



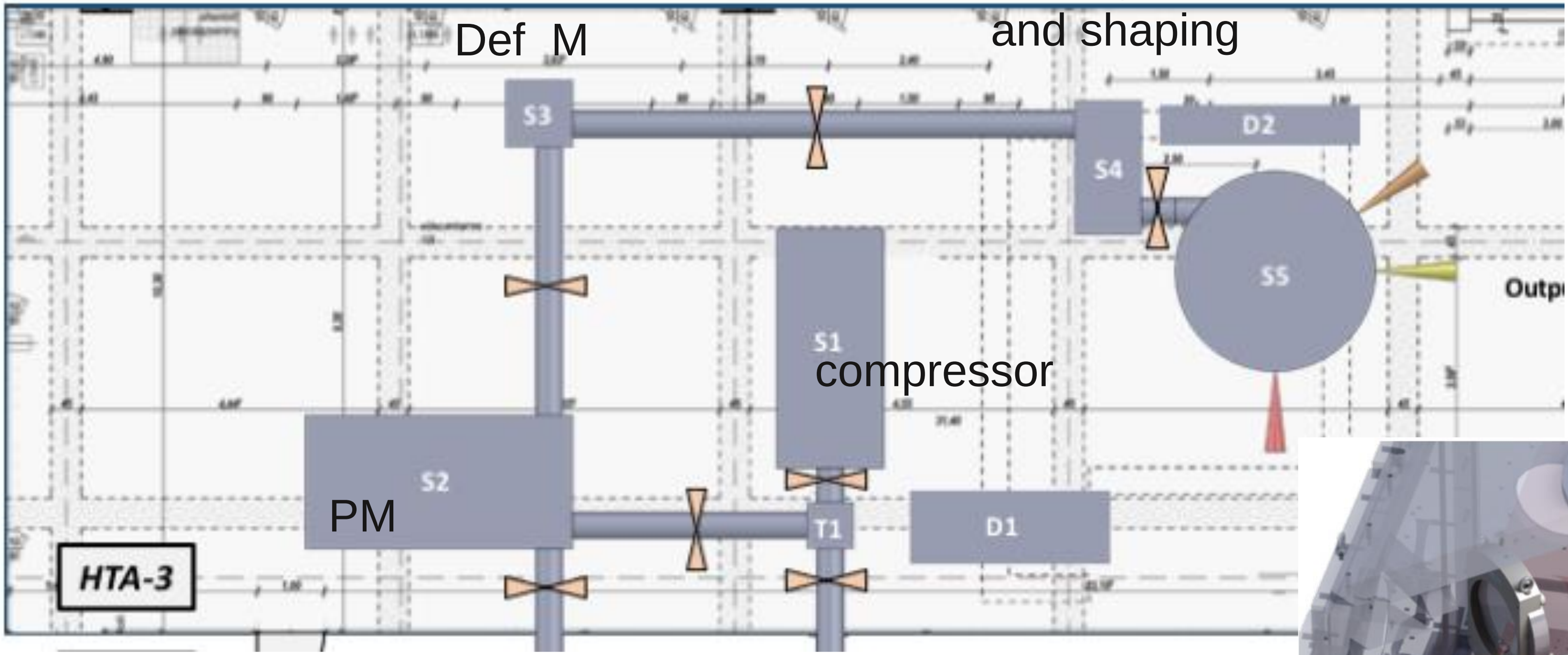


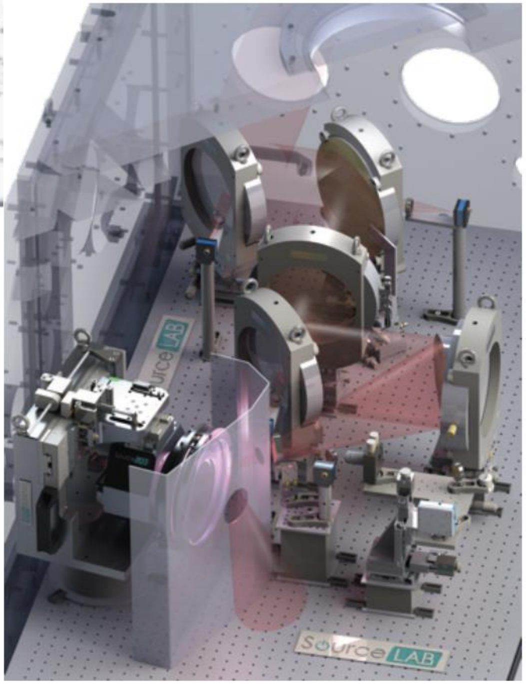


kHz target!

Designer: LOA, France

PW SHHG beamline





Designer: SourceLab, France

ELI-ALPS: experimental stations

Primary sources
(laser beams)

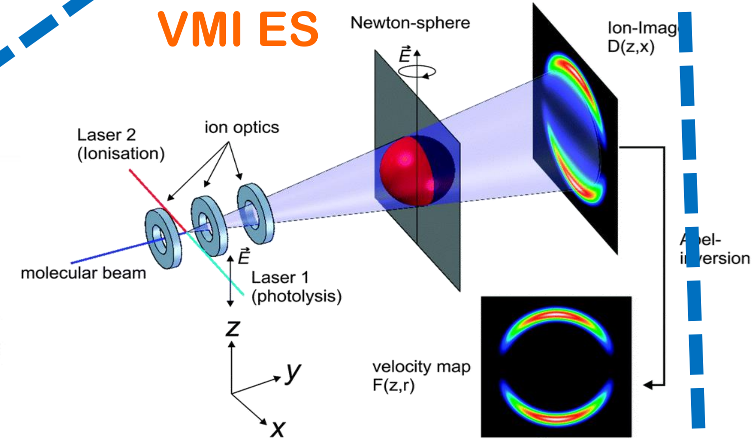
Secondary sources
(attosecond pulses, particles, THz, MIR)

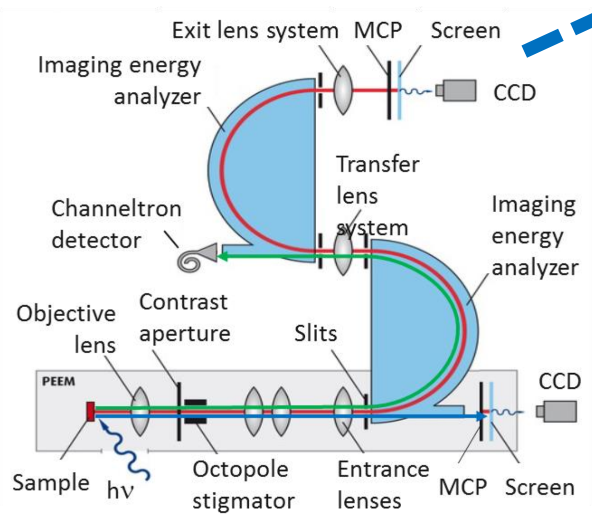
Experiments

Source outputs – standardized for docking **user end-stations**

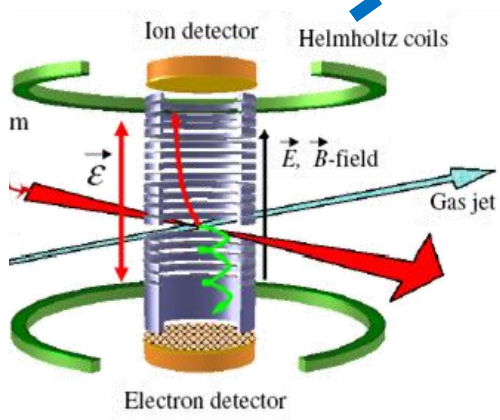
Customized end-stations – to realize **user ideas**

VMI ES



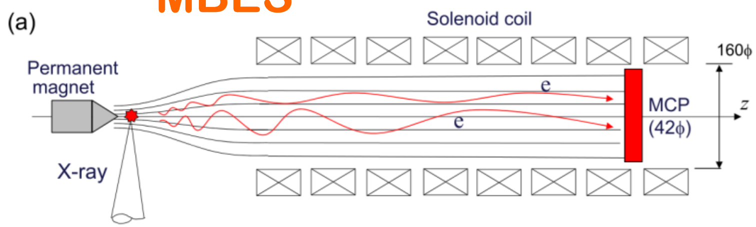


Condensed matter ES



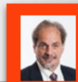
COLTRIMS / ReMi

MBES



SCIENTIFIC ADVISORY COMMITTEE
Chair: Sandro De Silvestri

ELI-ALPS: the people


Dimitris Charalambidis
Chief Scientific Advisor


Giuseppe Sansone
Scientific Advisor


Karoly Osvay
Research Technology Director

Attosecond and Strong Field Science


Franck Lepine

Laser Plasma Theory Group
Alexander Andreev

Strong Field and Quantum Optics Theory Group
Sandor Varro

Computational and Applied Materials Science Group
Mousumi Upadhyay Kahaly

Theoretical and Computational Group of Molecular Structure and Dynamics Group
Agnes Vibok

Attosecond and Strong Field Processes in Few-body Systems

Charge Dynamics in (Bio)materials
Sophie Canton

Scientific Application


Peter Dombi

Biomedical Application Group
Katalin Hideghety

Ultrafast 4D Imaging Group
Laszlo Ovari

Ultrafast Nanoscience Group
Peter Dombi

Ultrafast Dynamics in Semiconductors Group
Csaba Janaky

THz Reaction Control Group
Viktor Chikan

Service Diagnostics Laboratories

Attosecond Sources


Katalin Varju

HR Attosource Group
Miklos Füle

SYLOS Gas Attosource Group
Sergei Kühn

Surface Plasma Attosource Group
Subhendu Kahaly

Diagnostics of Attosources
Paraskevas Tzallas

Attosources R&D Group
Katalin Varju

Particle and Terahertz Sources


Patrizio Antici

Ion Acceleration Group
Patrizio Antici

Electron Acceleration Group
Christos Kamperidis

Terahertz Source and Applications Group
Jozsef Fulop

Laser Infrastructure


Karoly Osvay

Mid-Infrared Laser Group
Eric Cormier

High Field Laser Group
Mikhail Kalashnikov

Single Cycle Laser Group
Adam Borzsonyi

High Repetition Rate Laser Group
Zoltan Varallyay

Laser Research and Development Group
Mikhail Kalashnikov

Engineering and integration


Lajos Fulop

Beam Transport Group
Arpad Mohacsi

Infrastructure Liaison Group
Imre Kiss

Software Engineering Group
Lajos Schrettner

Electrical Engineering Group
Ferenc Horvath

Mechanical

Research Technology Service Unit

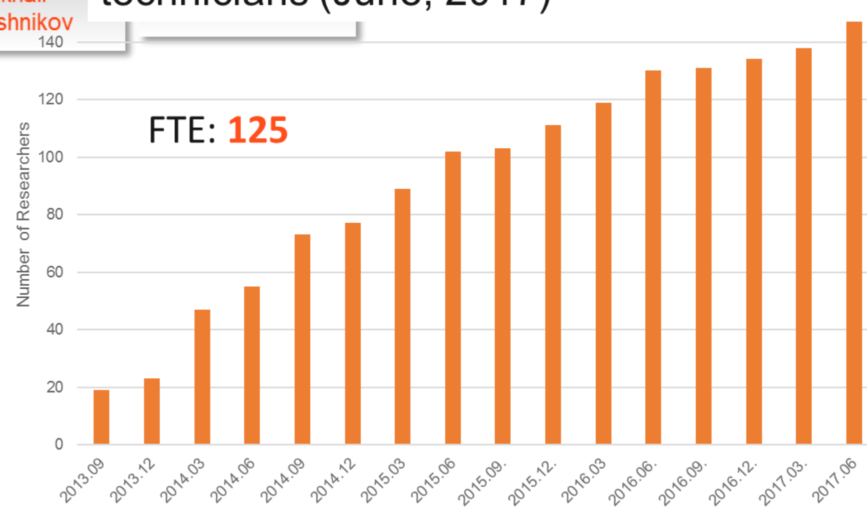

Gergo Meszaros

Optical Preparatory Workshop
Gergo Meszaros

Mechanical Workshop
Zoltan Vajna

Electrical Workshop
Viktor Varkonyi

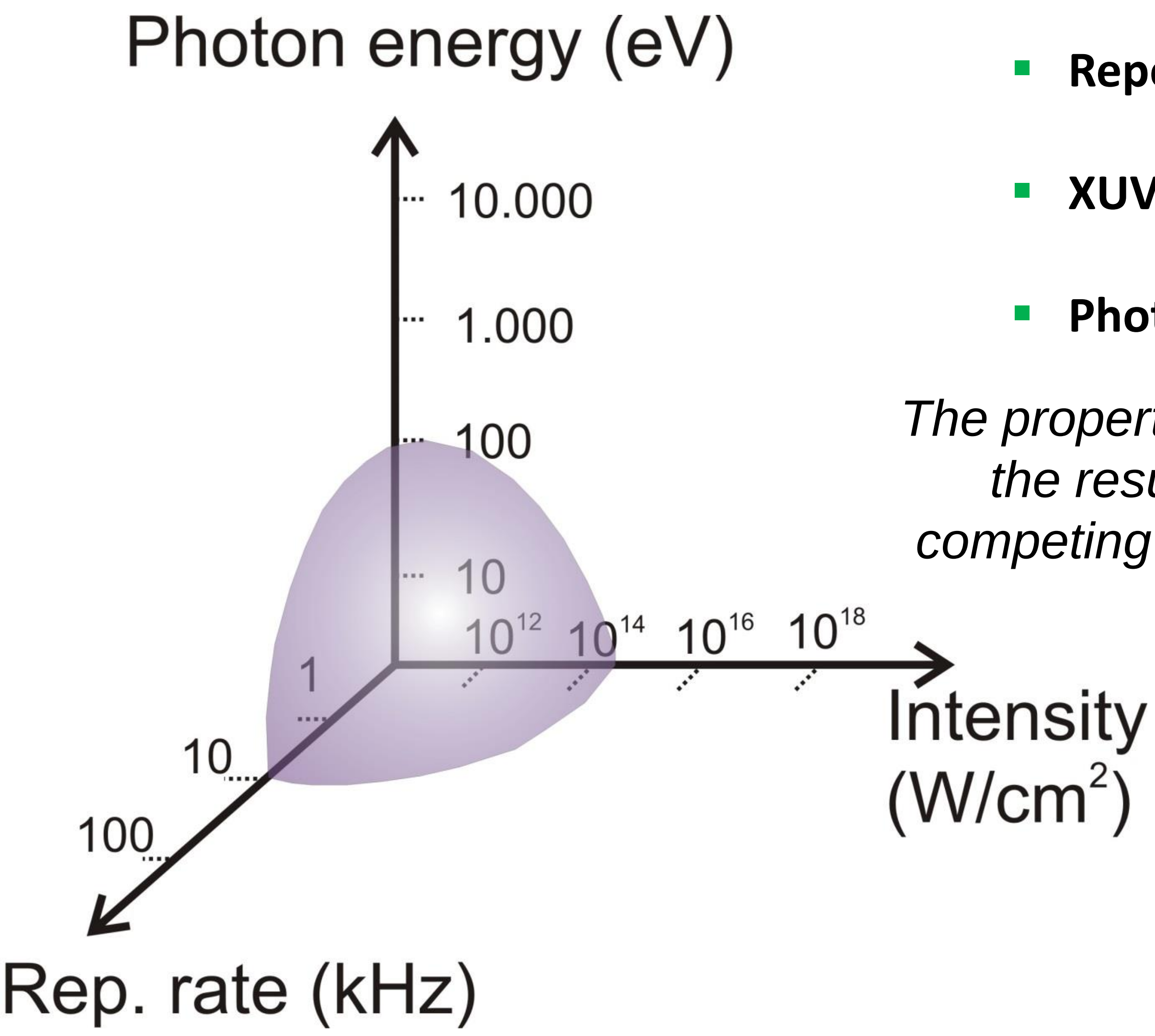
Number of researchers, engineers, technicians (June, 2017)



Contents

- Optimizing HHG for tailored attosecond pulse production
- The ELI project
- ELI ALPS: collection of sources
- New directions of attosecond science

New directions in attosecond science

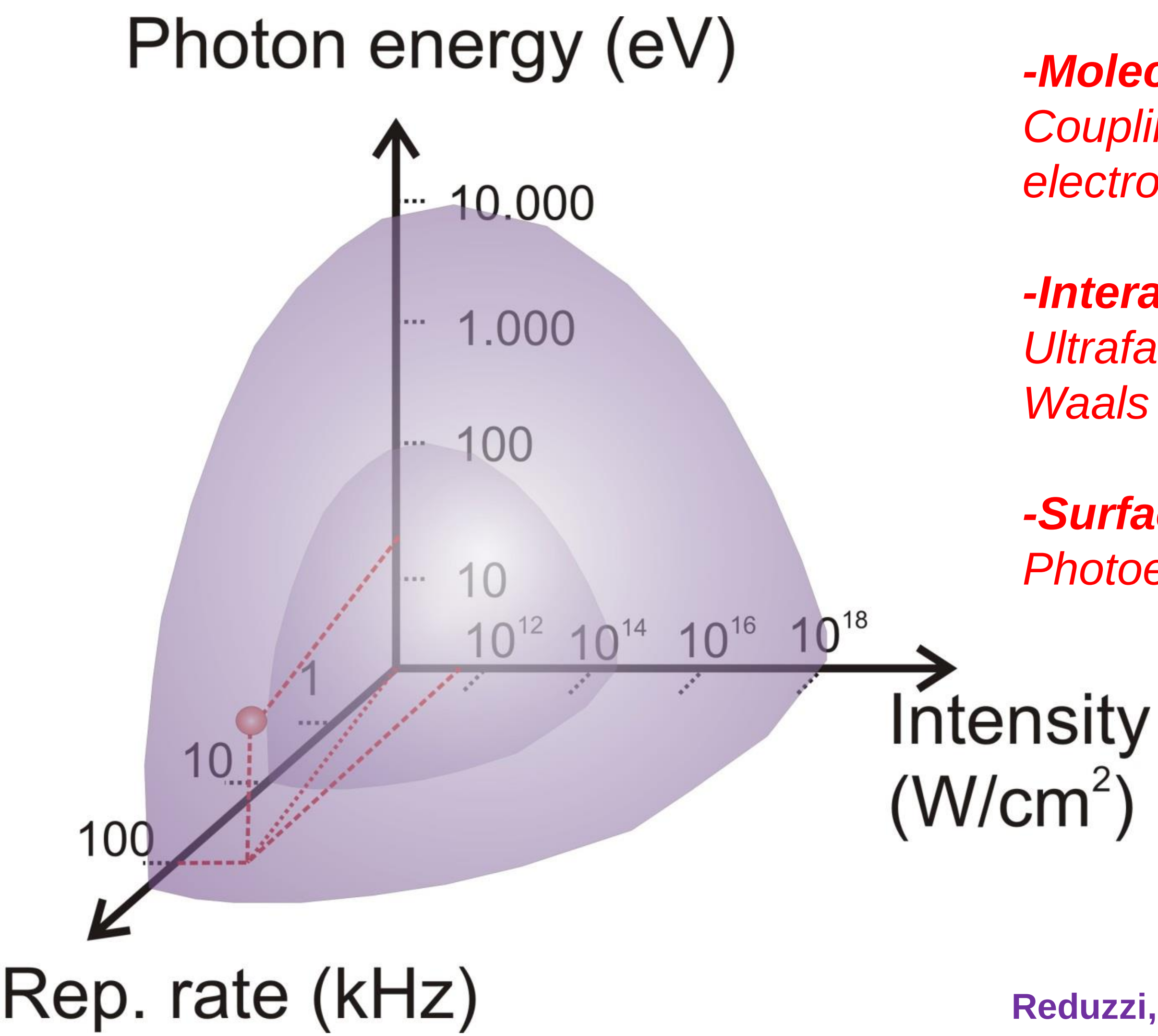


- **Repetition rate** (few Hz-10 kHz)
- **XUV Intensity** (10^9-10^{12} W/cm^2)
- **Photon energy** (10-150 eV)

The properties of attosecond pulses are the result of a trade-off between competing requirements on the driving sources.

Reduzzi, J Electron Spectr & Rel Phenom (2015)

High-rep. rate for coincidence spectroscopy



Repetition rate = 100 kHz

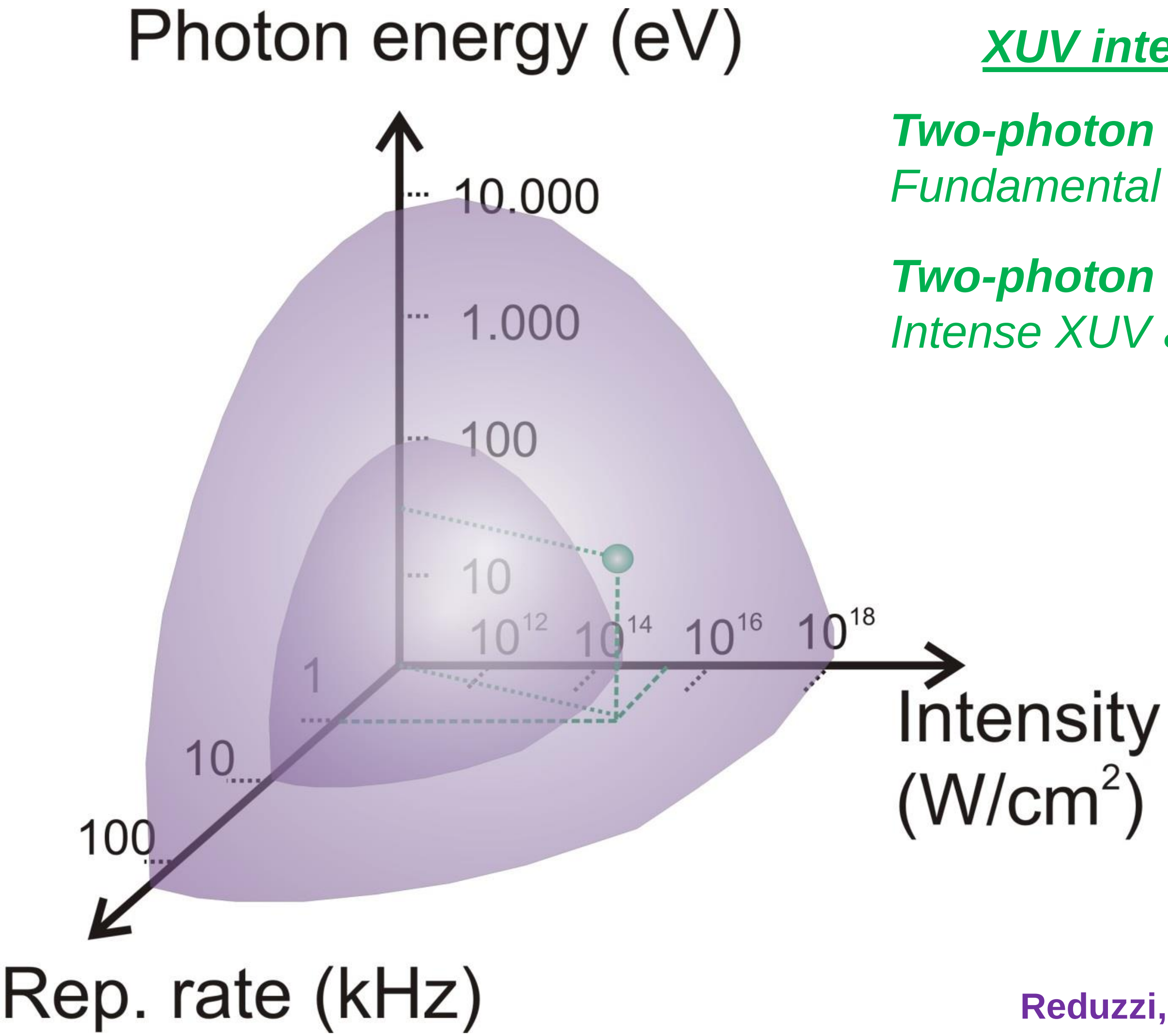
-Molecular-frame autoionization
Coupling between nuclear and electronic degrees of freedom

-Interatomic Coulombic Decay
Ultrafast energy relaxation in van der Waals and hydrogen-bonded clusters

-Surface attosecond science
Photoelectron emission microscopy

Reduzzi, J Electron Spectr & Rel Phenom (2015)

High-intensity for nonlinear XUV spectroscopy



XUV intensity= 10^{15}-10^{18} W/cm^2

Two-photon double ionization of helium

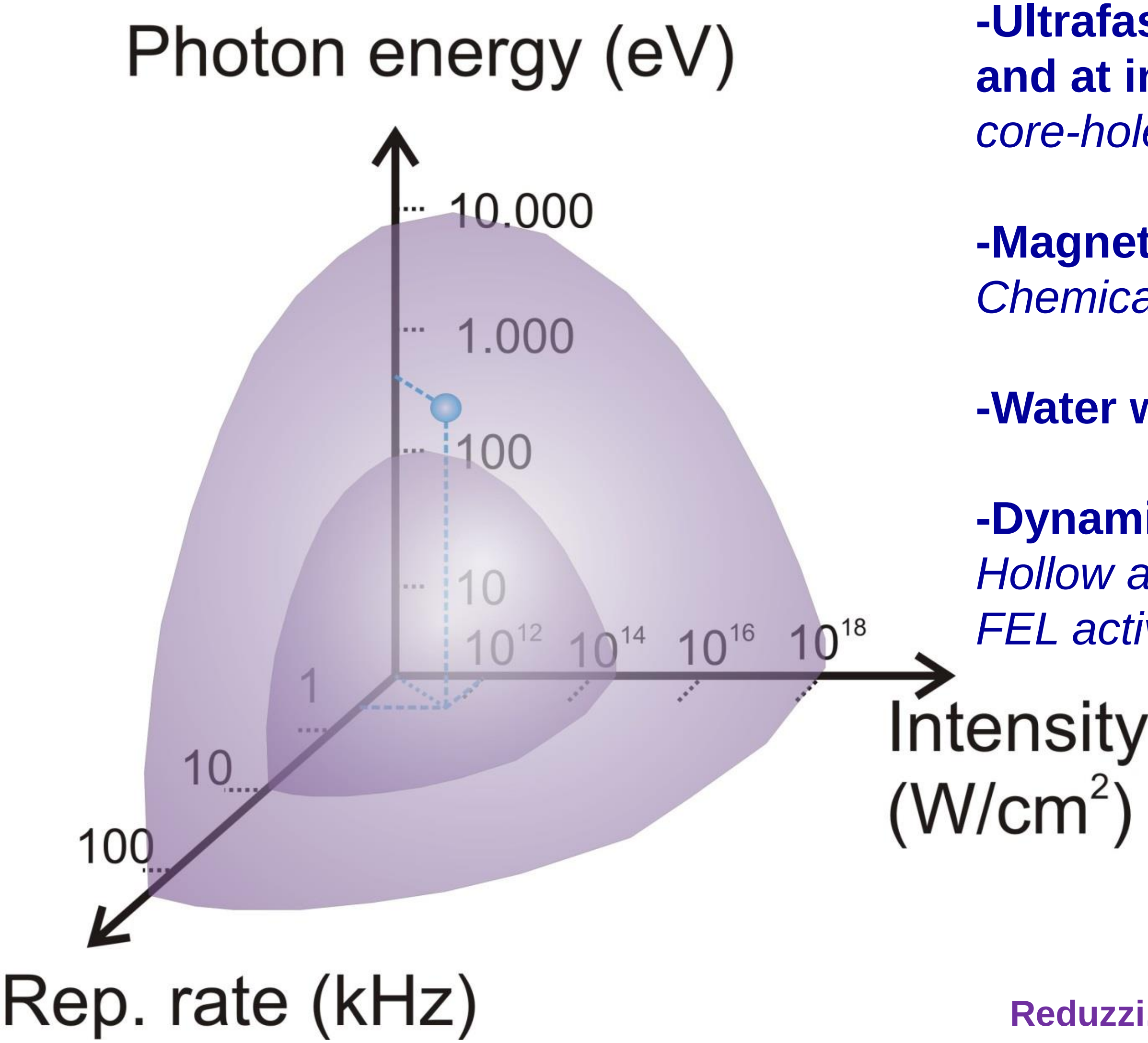
Fundamental problem of electronic correlation

Two-photon double ionization of neon

Intense XUV and soft-X ray physics

Reduzzi, J Electron Spectr & Rel Phenom (2015)

High photon energy for core electrons



<u>High photon energy= 200-10.000 eV</u>

-Ultrafast charge delocalization in DNA and at interfaces
core-hole spectroscopy

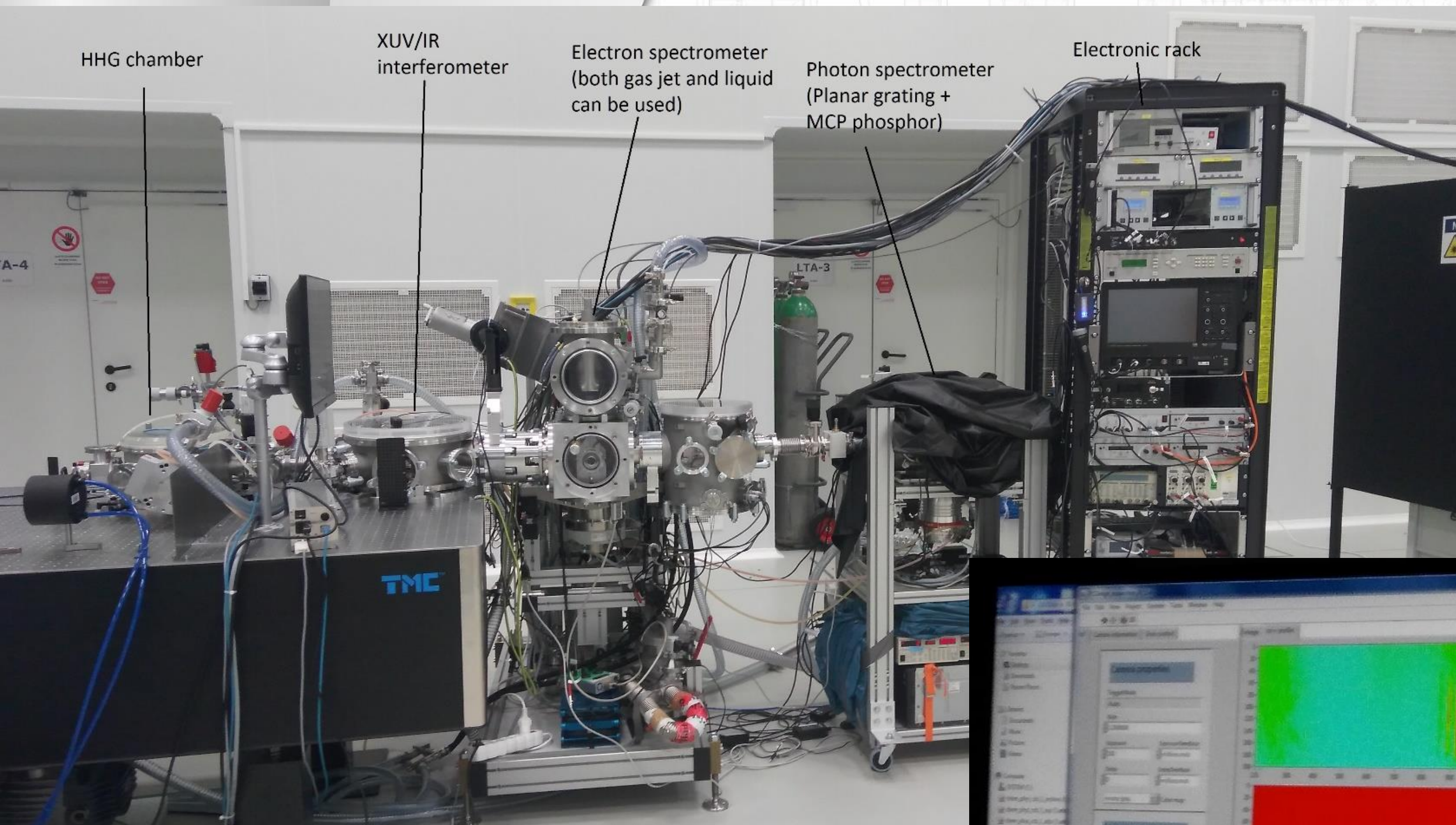
-Magnetic materials (L-shell)
Chemical selectivity

-Water window

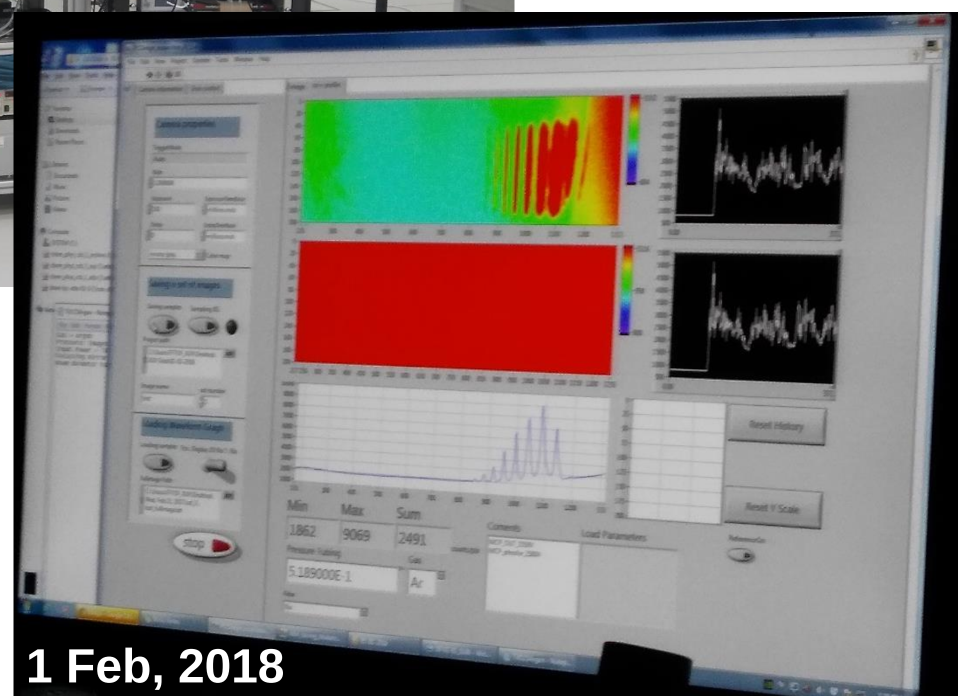
-Dynamics of highly excited ions
Hollow atoms and connection with FEL activity

Reduzzi, J Electron Spectr & Rel Phenom (2015)

HOT NEWS: harmonics at ELI ALPS



Setup of H-J Wörner, ETH, Zürich



Further reading

on HHG and attosecond physics

Boyd: Nonlinear Optics
Chang: Fundamentals of attosecond optics
Plaja (ed): Attosecond Physics
Vrakking (ed): Attosecond and XUV Physics

on ELI ALPS

http://www.eli-alps.hu/
M. Reduzzi, et al., J. El. Spec. Rel. Phen. 204, 257 (2015)
S. Kühn, et al., J. Phys. B, 50, 132002 (2017)

Thank you!

SZÉCHENYI 2020

HUNGARIAN GOVERNMENT

European Union
European Regional Development Fund

INVESTING IN YOUR FUTURE