The ELI ALPS Research Institute
Status and Perspectives

attosecond

Katalin Varjú
Science Director

US – ELI Joint Workshop
OSA, Washington DC – 25 September 2019

The ELI project

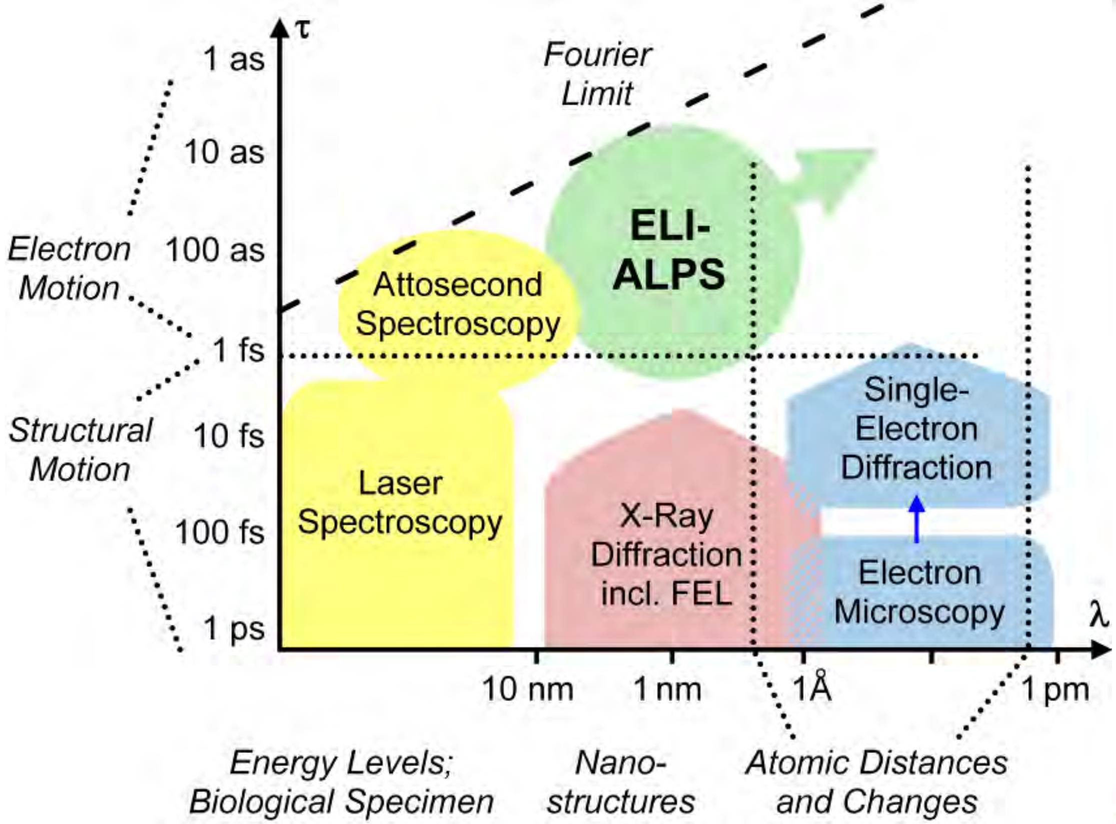
A distributed RI of the ESFRI roadmap

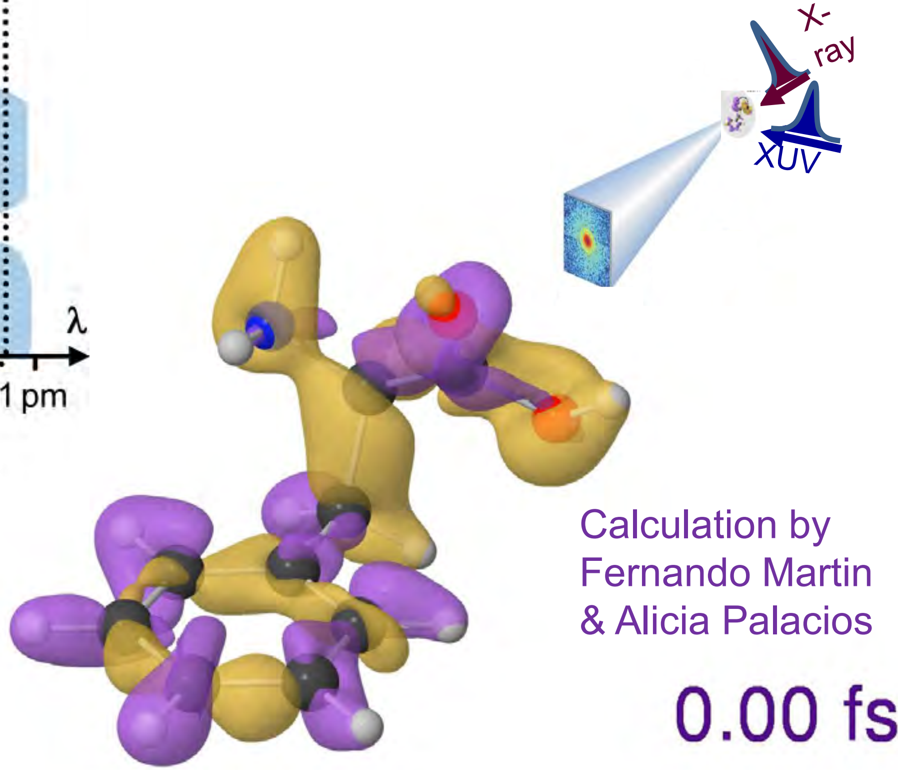
Mission of ELI ALPS

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.

Scientific mission of ELI-ALPS

Visualizing structural ultrafast dynamics

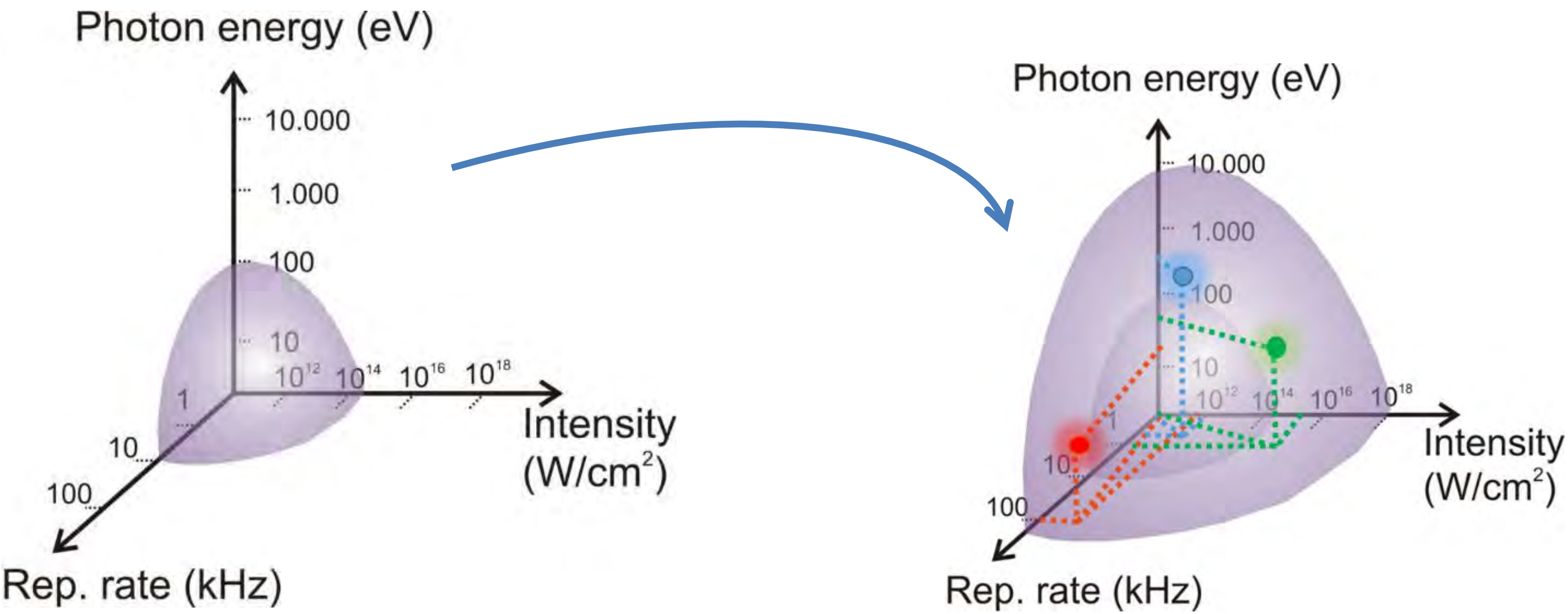




Calculation by Fernando Martin & Alicia Palacios

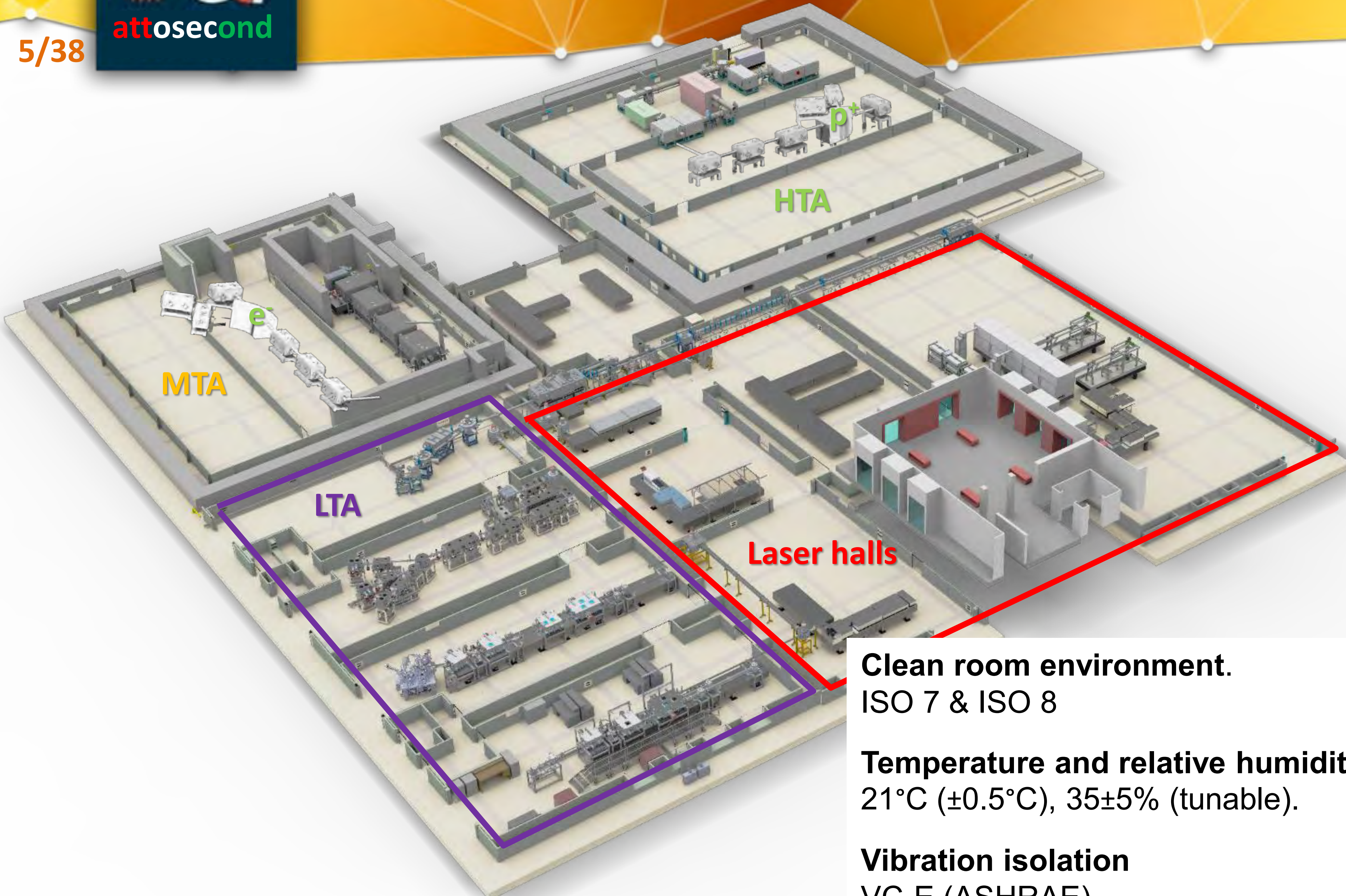
Video from: F. Calegari et al. Science **346**, 336 (2014)

New directions in attosecond science



- **Higher reprate** (few Hz-**100 kHz**) – coincidence spectroscopy
- **Higher XUV intensity** (10^9-**10^{16} W/cm^2**) – nonlinear processes
- **XUV photon energy** (10-**few keV**) – strongly bound states

Experimental areas



Clean room environment.
ISO 7 & ISO 8

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

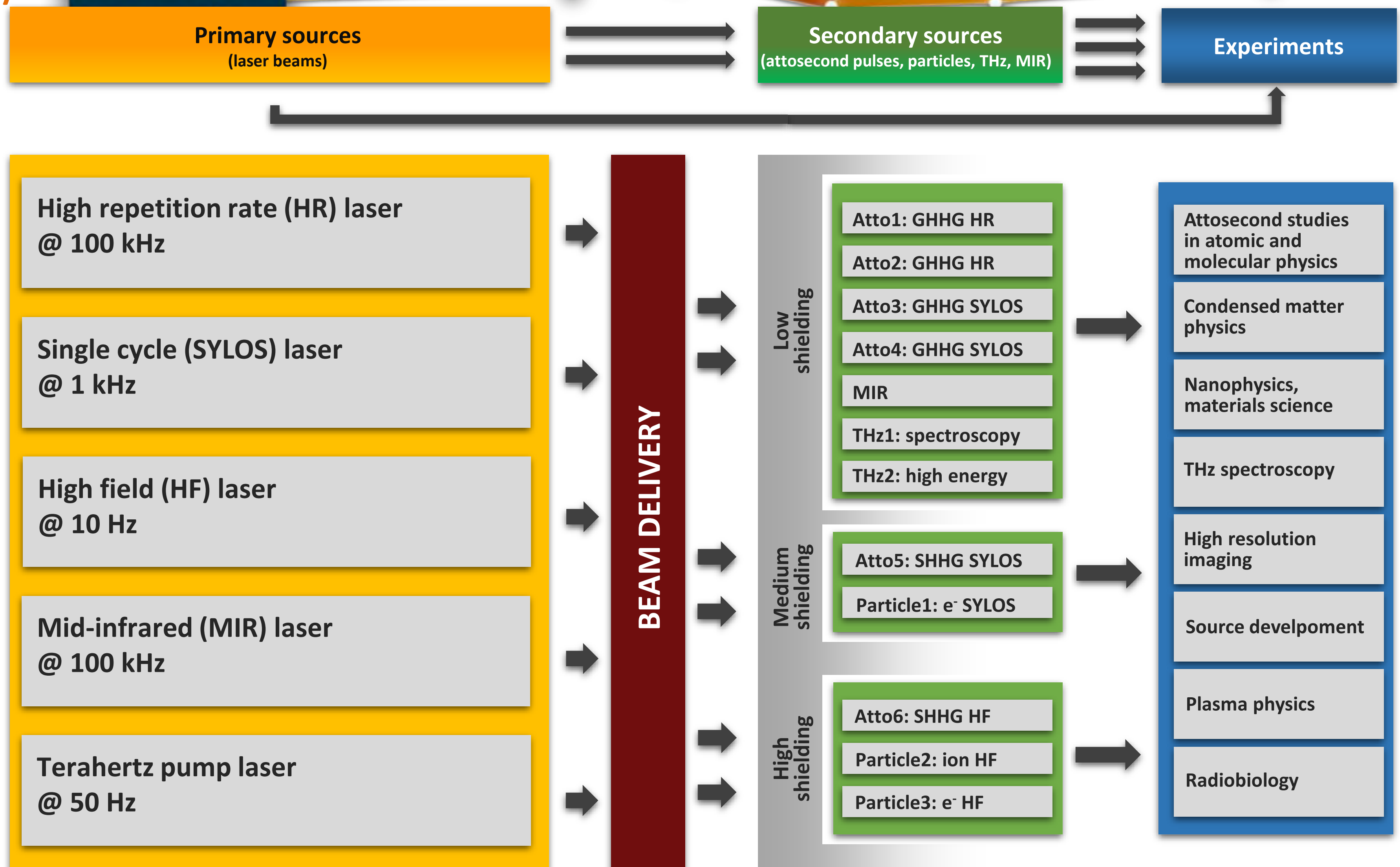
Vibration isolation
VC-E (ASHRAE)


09-25-2019 Wed 08:14:05
LTA2-01
09-25-2019 Wed 10:26:01
LTA1-02
09-25-2019 Wed 08:45:20
LTA3-01
09-25-2019 Wed 00:43:21
AL-01
EKSPLA
09-25-2019 Wed 07:11:16
LTA4-02


09-25-2019 Wed 08:47:07
HR-01
09-25-2019 Wed 10:46:57
THZ-03
09-25-2019 Wed 08:52:10
SYLOS
SYLOS
09-25-2019 Wed 07:39:38
FASTLITE
09-25-2019 Wed 09:23:43
HF-04

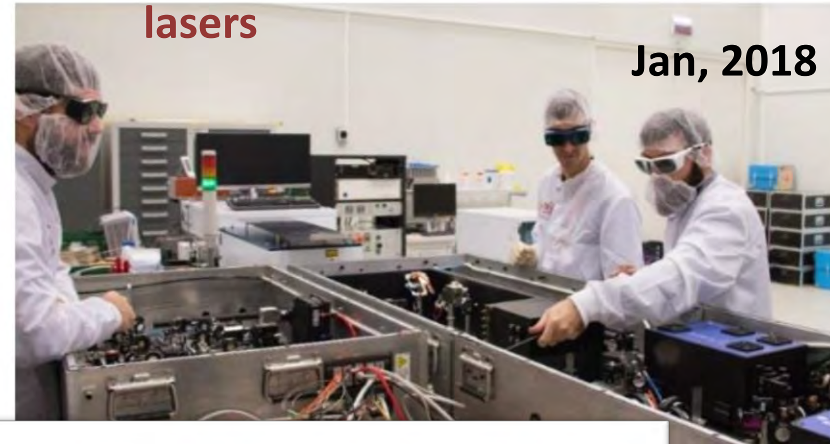
Scheme of ELI-ALPS

Unprecedent stability conditions for operation



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

„Construction”



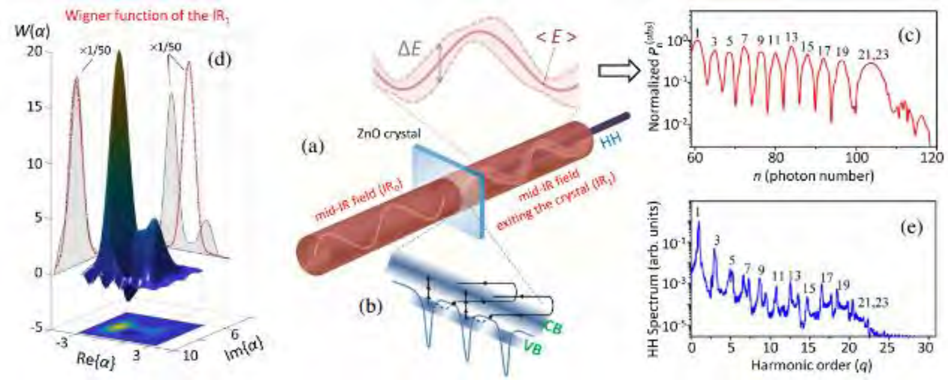

Are we
there, yet?
tbs

ELI ALPS Achievements

3 Laser systems commissioned

1st attosecond pulses

1st User paper from ELI-ALPS



PHYSICAL REVIEW LETTERS **122**, 193602 (2019)

Quantum Optical Signatures in a Strong Laser Pulse after Interaction with Semiconductors

N. Tsatrafyllis,[1] S. Kühn,[2] M. Dumergue,[2] P. Foldi,[2,3] S. Kahaly,[2] E. Cormier,[2,4] I. A. Gonoskov,[5] B. Kiss,[2] K. Varju,[2,6] S. Varro,[2,7] and P. Tzallas[1,2,*]

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(Received 28 September 2018; published 14 May 2019)

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Laser parameters & status

	Parameters	Status	Operation / due date
MIR	**100 kHz, <40 fs, 0.15 mJ, CEP<100 mrad**	**Operational**	**since Oct 2017**
SYLOS alignment	**10 Hz, <12 fs, >40 mJ, ~850 nm**	**Operational**	**since Jan 2019**
SYLOS 2	**1 kHz, <6.5 fs, >30 mJ, CEP<250 mrad**	**Operational**	**since May 2019**
HR1	**100 kHz, 40 fs, 1.5 mJ** **100 kHz, <7fs, 0.8 mJ** 100 kHz, <7 fs, 1 mJ, CEP<100 mrad	**Operational** Installation	**since Dec 2017** **since Aug 2019** by Q2 2020
HF PW	**10 Hz, 10 J, compr. 17fs** 10 Hz, <17 fs, 34 J	**Operational** Installation	**since Sep 2019** by Q4 2020
HR2	100 kHz, <6 fs, 5 mJ, CEP<100 mrad	In development	by Q2 2020
THzP	1 kHz, 100 fs, 1 mJ & 50 Hz, <0.5 ps, 0.5 J	In development	by Q2 2020
MIR HE	*1kHz, < 40 fs, 15 mJ*	*Conceptual*	*by Q4 2021*
SYLOS 3	*1 kHz, <6.5 fs, >105 mJ, CEP<250 mrad*	*Conceptual*	*by Q1 2022*

SYLOS 2 performance

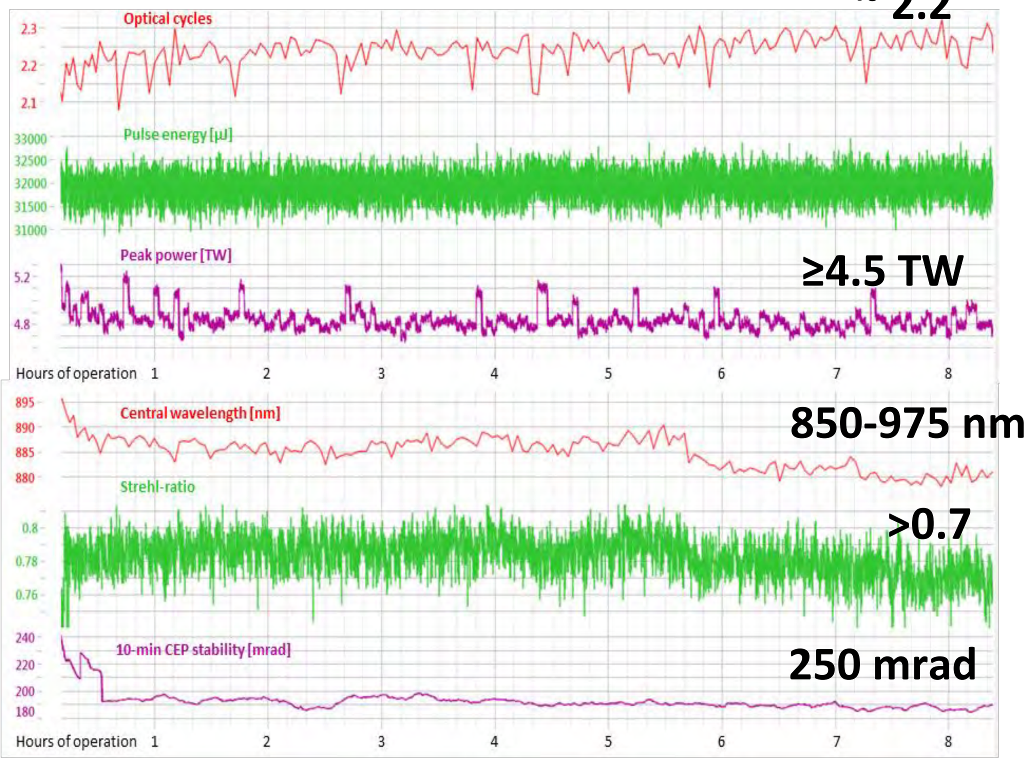
Site Acceptance test (12-14 May, 2019)

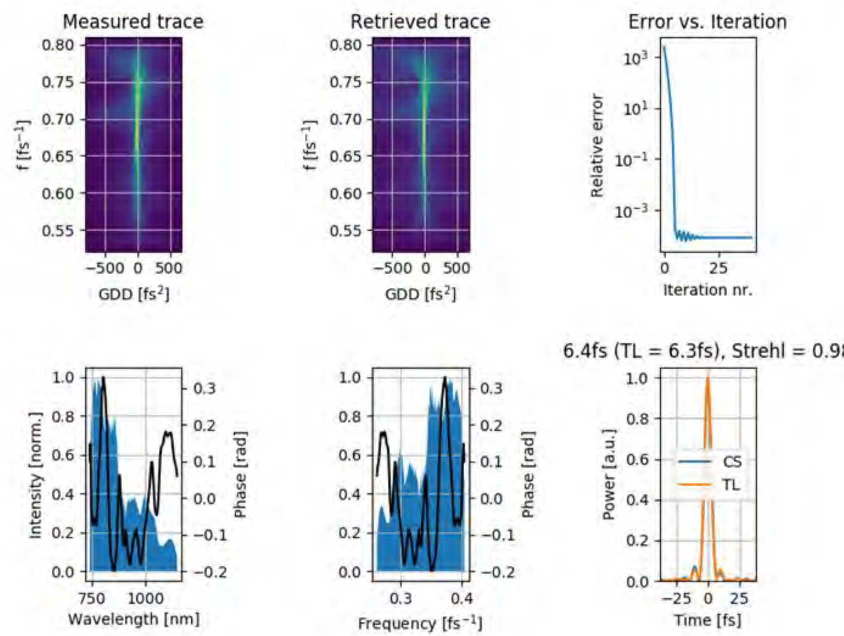
Long term (>8h) operation

Energy stability: <1%rms

CEP stability: <200mrad

Pulse duration: <6.4fs





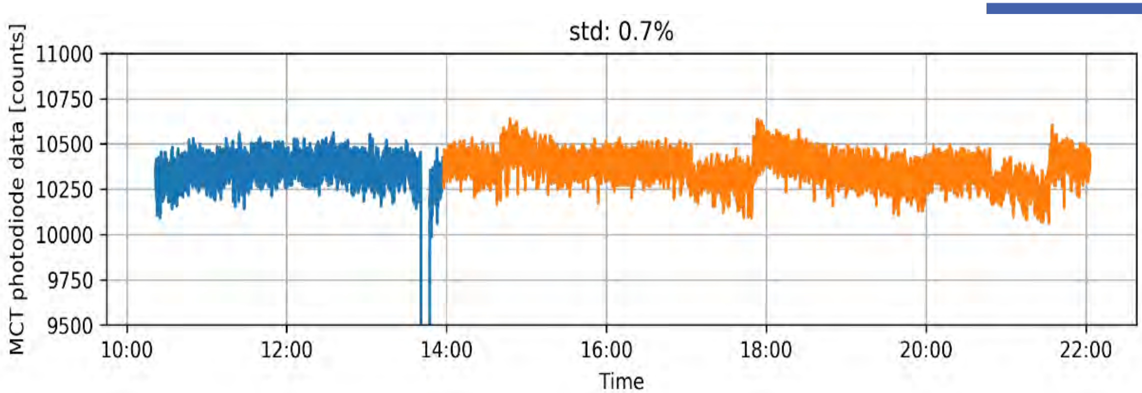
LIGHT CONVERSION

EKSPLA

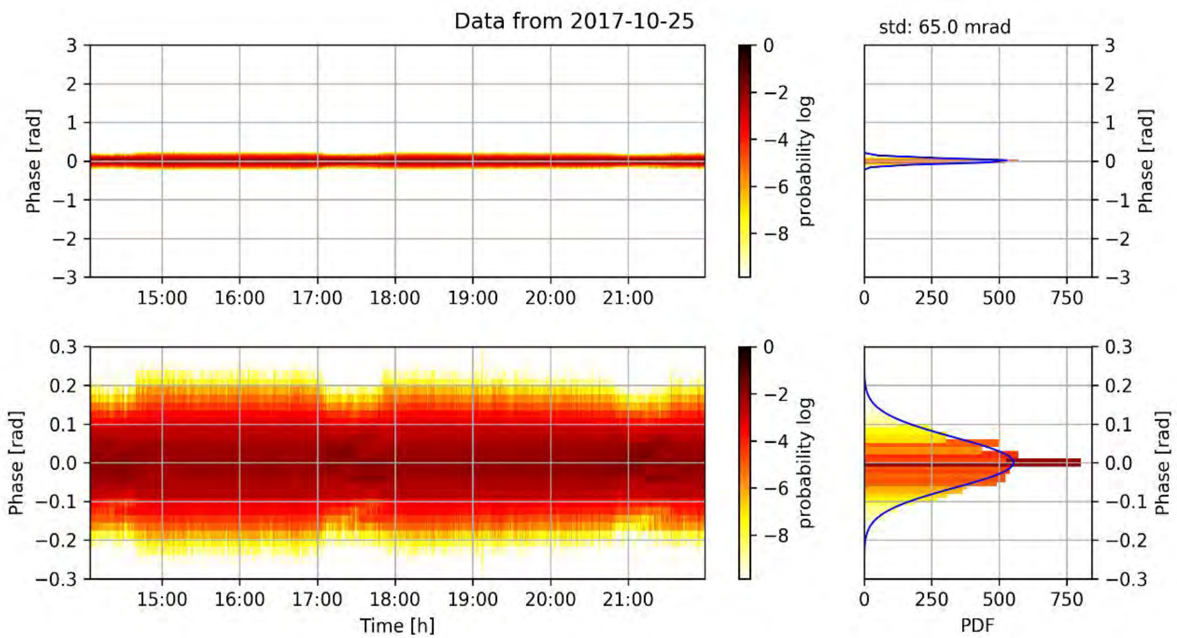
MIR laser

FASTLITE

Energy stability
0.7% rms

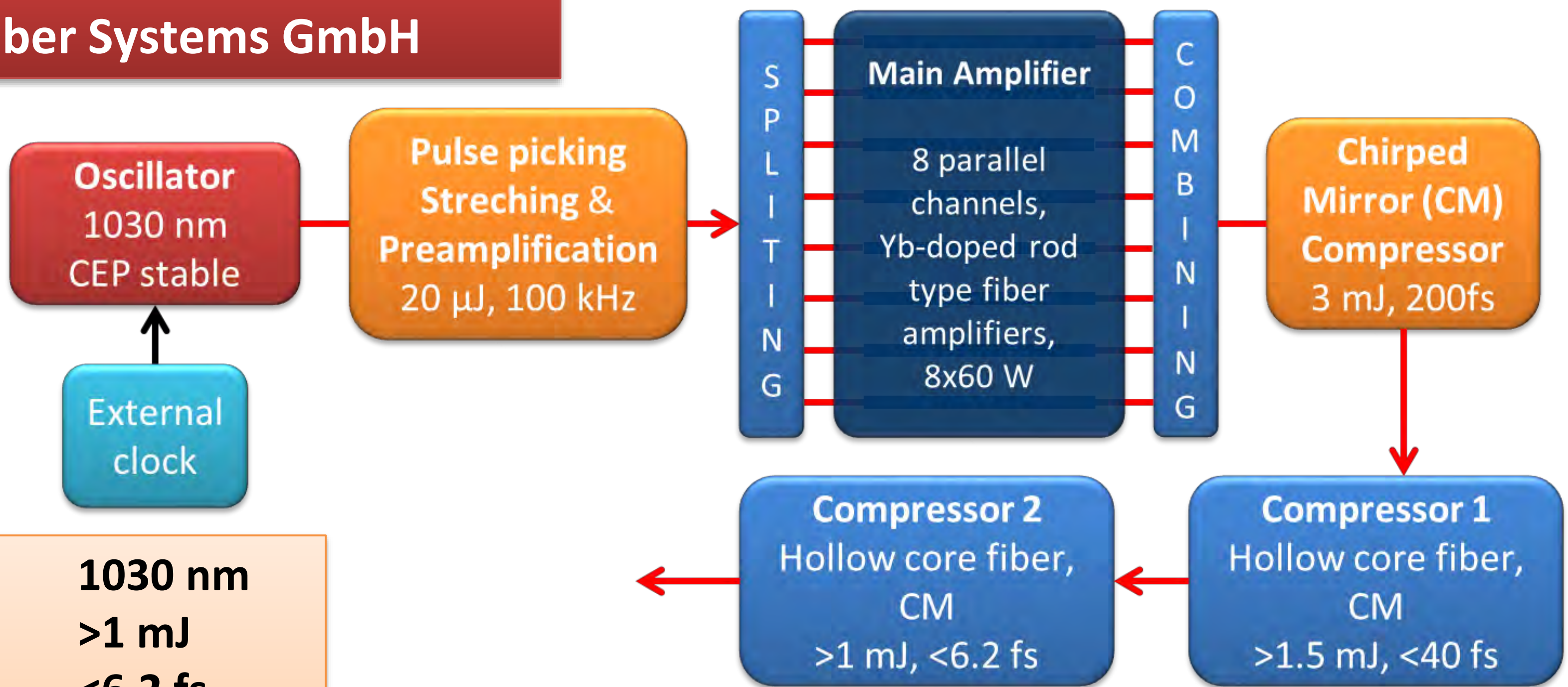


CEP drift:
65mrad rms



HR lasers

IAP FSU Jena + Fraunhofer IAF + Active Fiber Systems GmbH



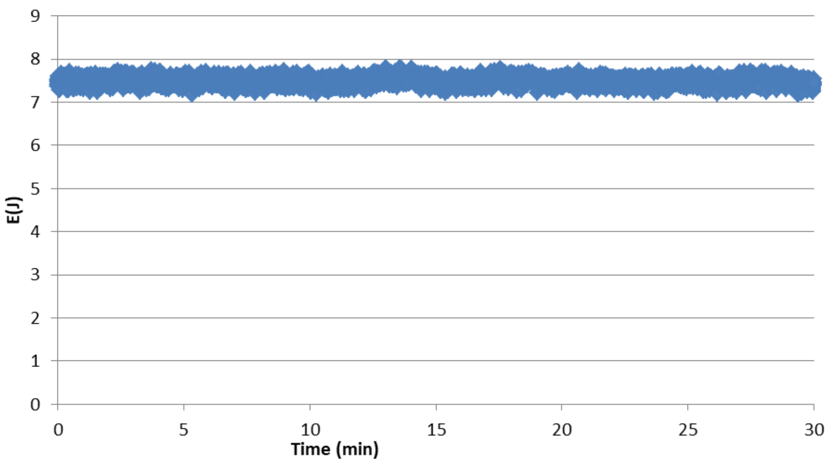
Wavelength	**1030 nm**
Energy	**>1 mJ**
Pulse duration	**<6.2 fs**
Rep.rate	**100 kHz**
CEP stability	**<100 mrad**
Energy stability	**0.8%**
Strehl ratio	**0.9**

HF-2PW

Front end+ first amp (>7.5J, <17fs, 5Hz)

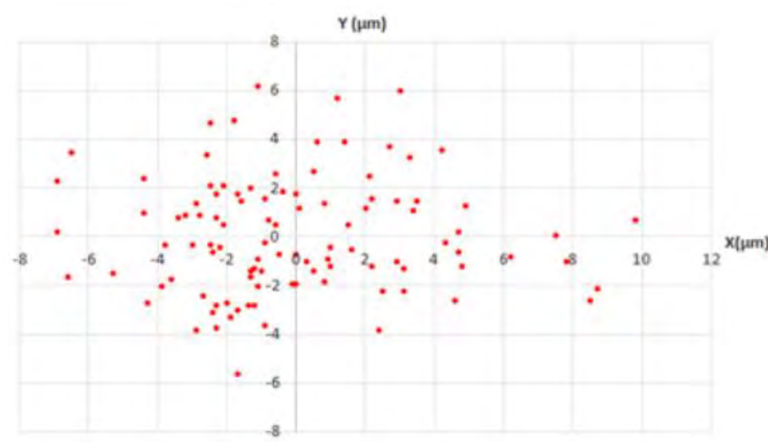
Energy stability: 1.1%

(specs: <1.5%)



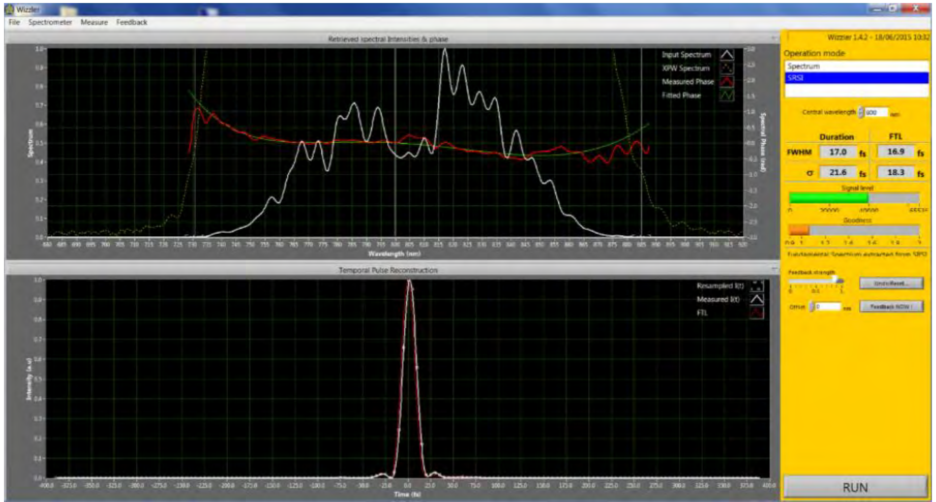
Pointing stability: 7.7% of beam div.

(specs: <10%)



Pulse duration: 17fs

(Tr.Lim: 16.9fs)



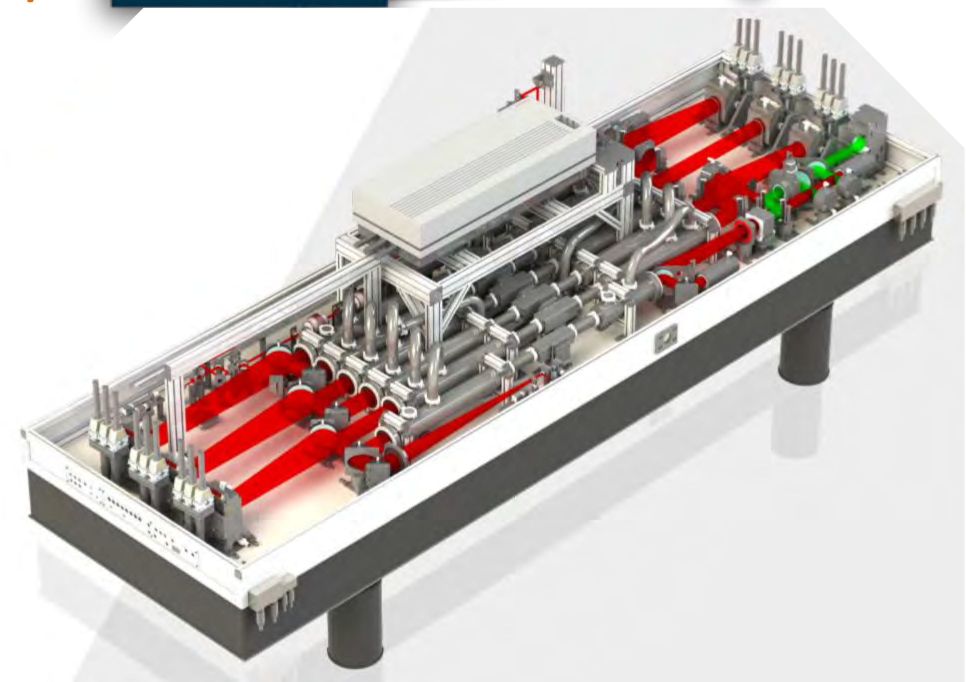
HF-2PW

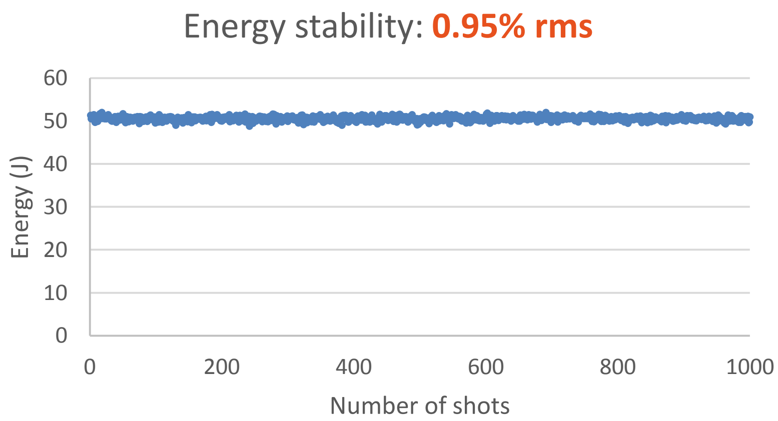
P50 pump laser

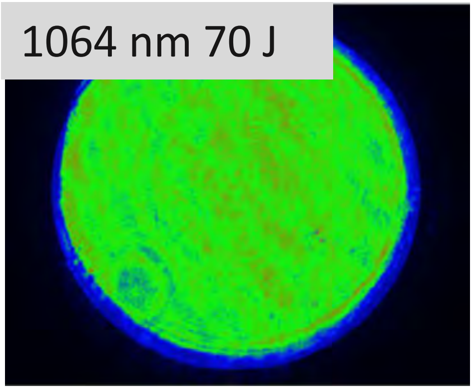
Flashlamp-pumped lasers

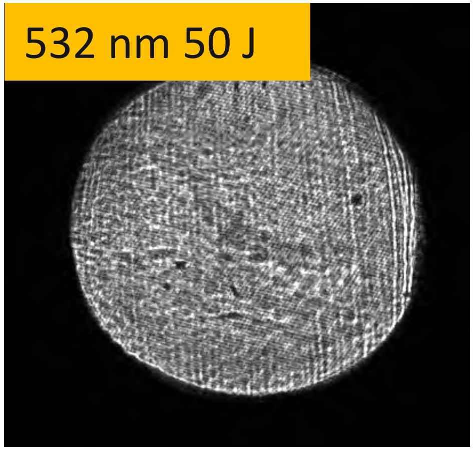
500 W average power @ 532 nm

- Pseudo Active Mirror Disk Amplifier Module (PAMDAM)
- Switchable between 1 Hz and 10 Hz









The MIR Laser System

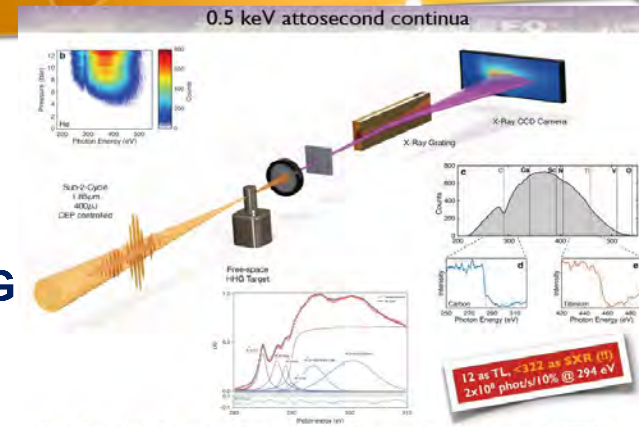
Scientific Case Examples

- Up $\propto \lambda^2 \cdot I$
- HHG_{cutoff} $\propto \lambda^2 \cdot I$ keV photons
- E_{el} $\propto \lambda^2 \cdot I$ LIED

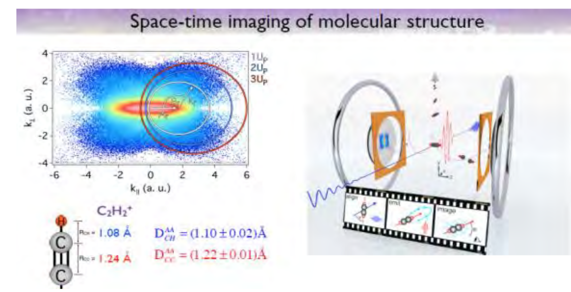
October 2017

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

1 kHz, > 10 mJ,
< 2 cycles, 4 μm-12 μm



- **Water window HHG** (Nat. Com. **6**, 661 (2015))



- **High resolution LIED** (Nat. Com. **5**, 4635 (2014)) (Nat. Com. **6**, 661 (2015))

- **"Low" laser intensity relativistic interactions ?**

$$a_L = \left(\frac{2e^2 \lambda_0^2 I}{\pi m_e^2 c^5} \right)^{1/2}$$

@ λ = 12 μm $a_L = 1$ @ ~ $5 \cdot 10^{15}$ W/cm^2

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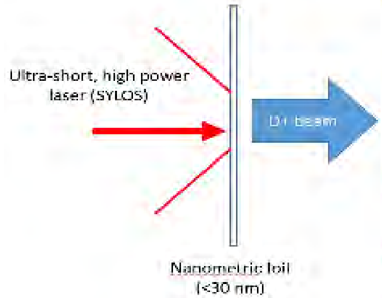
The SYLOS System
A collaborative ELI experiment proposed by T. Tajima & G. Mourou

Project: **Transmutation of** TransUranic Minor Actinide (Np, Am, Cm) **spent nuclear waste** via "cheaply" produced 14 MeV neutrons generated via DT or DD fusion reactions

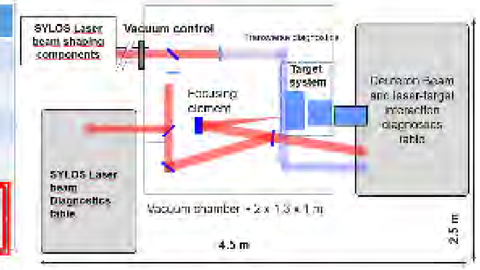
Driven 100 keV deuteron acceleration by ultra-short, ultra high rep. rate lasers (SYLOS)

Phase 1:
Acceleration of deuterium nuclei to **~100 keV** by the **SYLOS** laser.
@ 100 keV the DT fusion reactions **cross-section** is **maximised**.

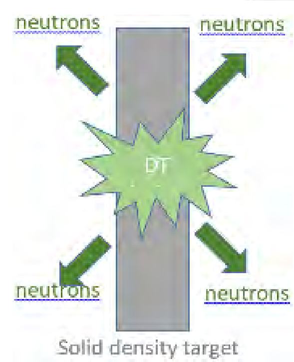


Laser pulse (fs)	Efficiency (%)
114	0.8
45	1.8
20	3.7
15	4.8
8	9
2	40

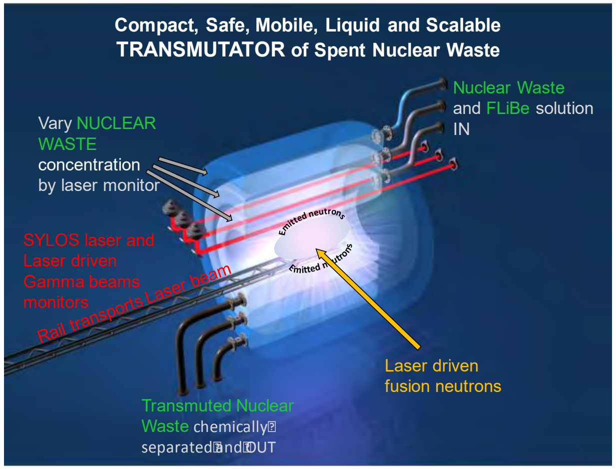
Laser energy to Deuterium energy conversion efficiency



Phase 2:
Creation of copious amounts of DT (or DD) fusion **neutrons** by the deuterium beams @ a Tritiated (or Deuterated) target ($>10^{12}$-10^{13} neutrons/laser shot)

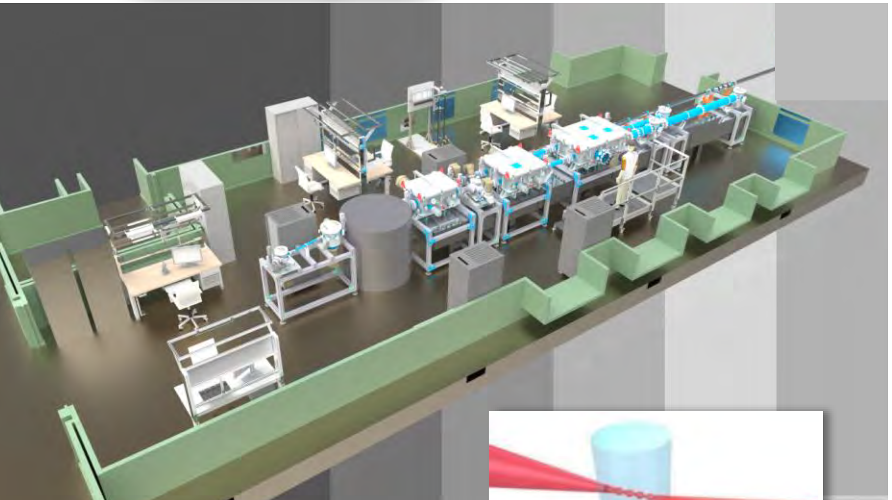


Phase 3:
Transmutation to safe radiotoxicity levels and volumes **of TRU spent nuclear waste** interacting with the isotopically emitted neutrons

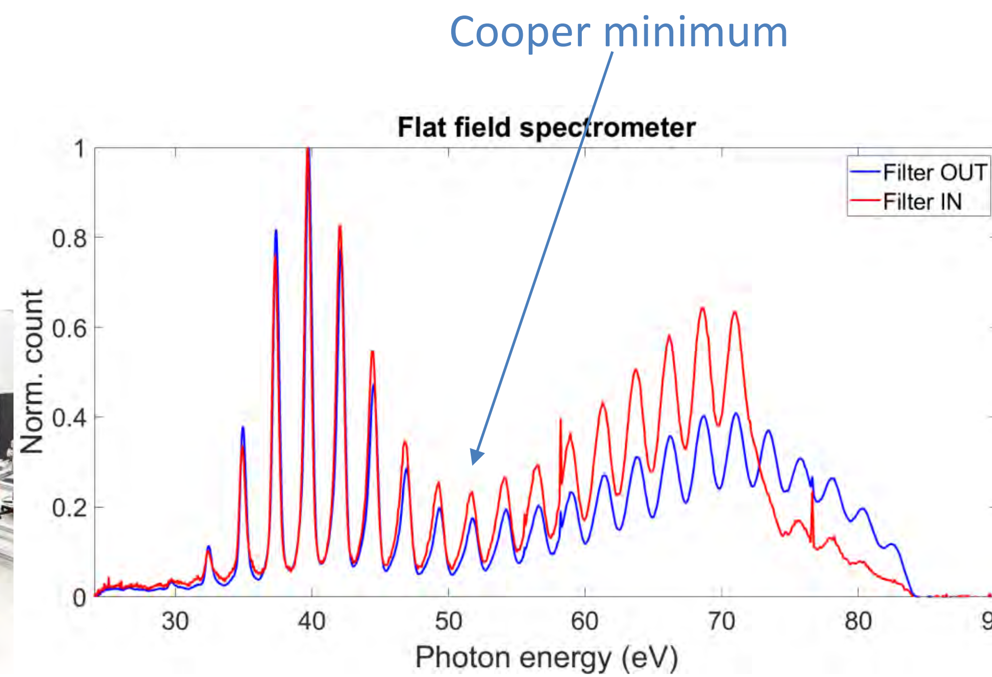


The HR GHHG beamline

Developers: CNR-IFN Milano / Padua, Italy

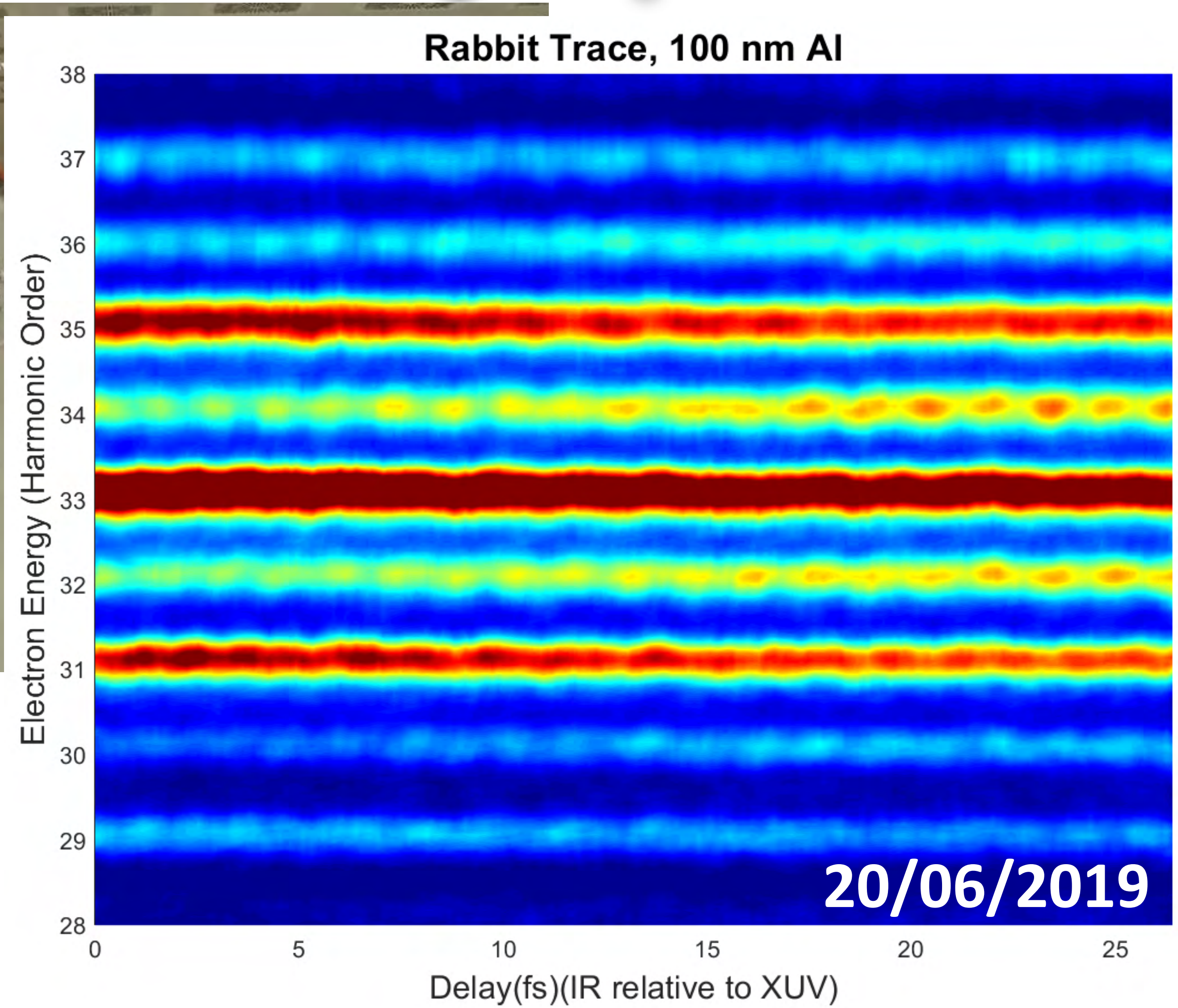


Harmonics in Ar at 100 kHz

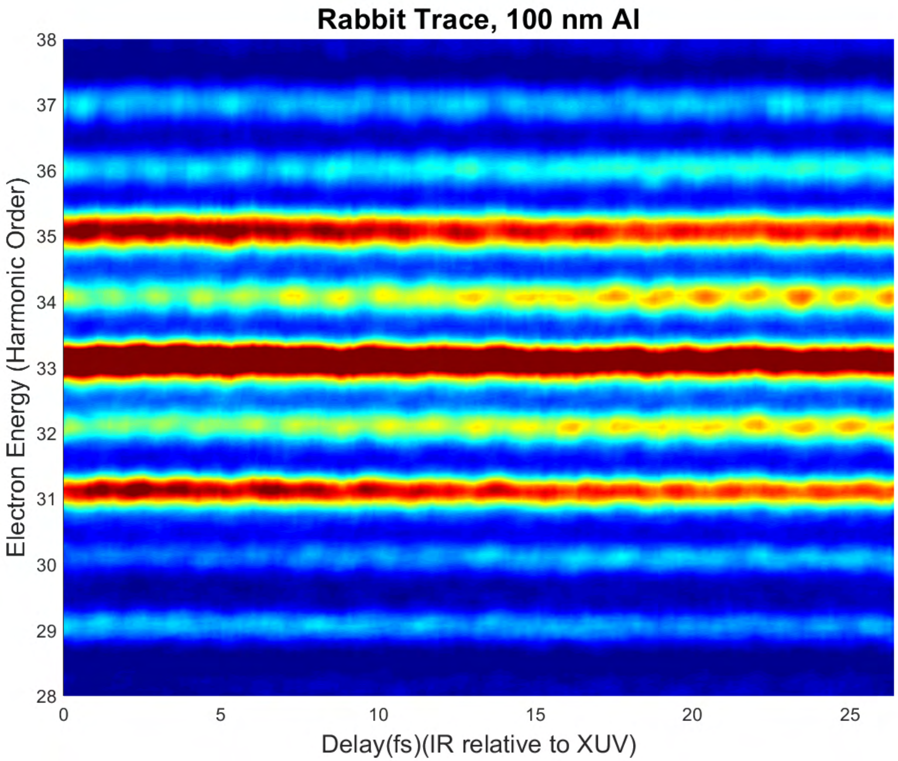


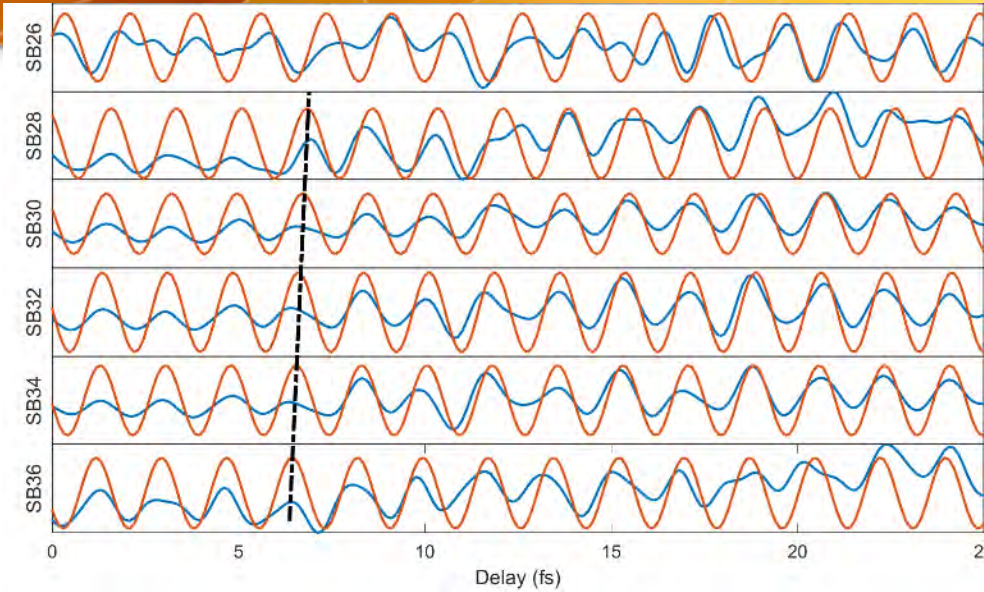
Vibration isolation

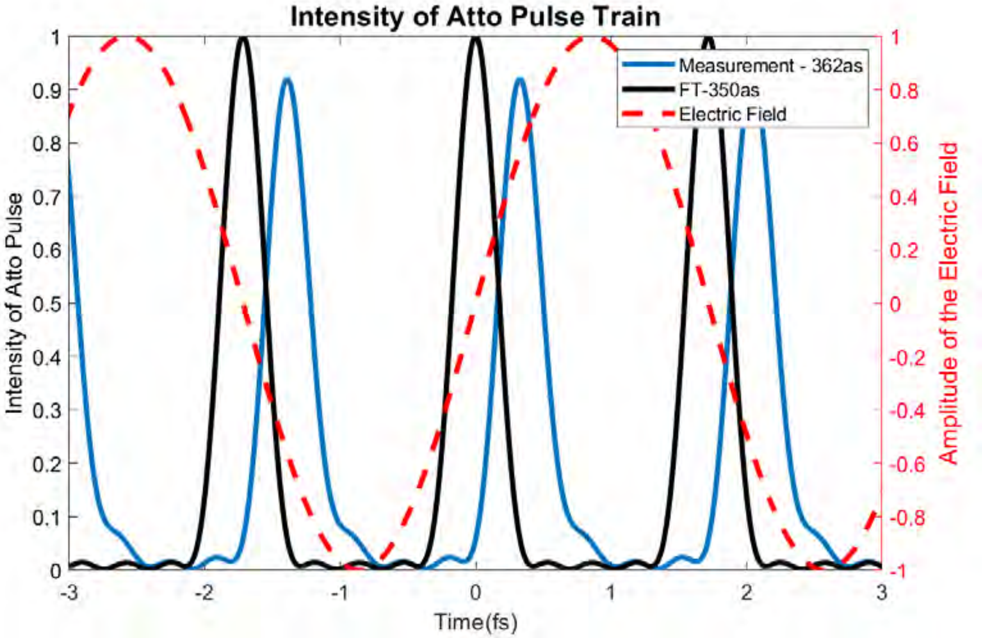
length of beamline: 856 cm
area of interferometer:
0,8 m x 3,6 m



RABBITT „reconstruction”







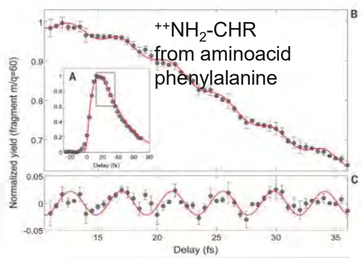
attosecond pulse train: 362 as

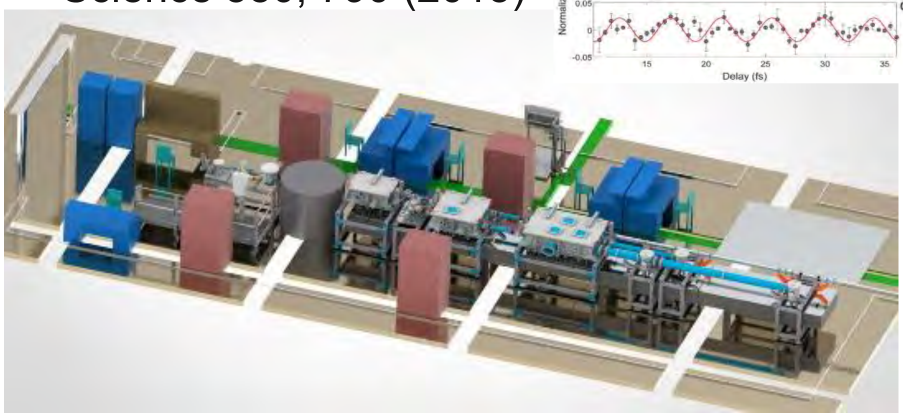
HR (100 kHz) GHHG Beamline I

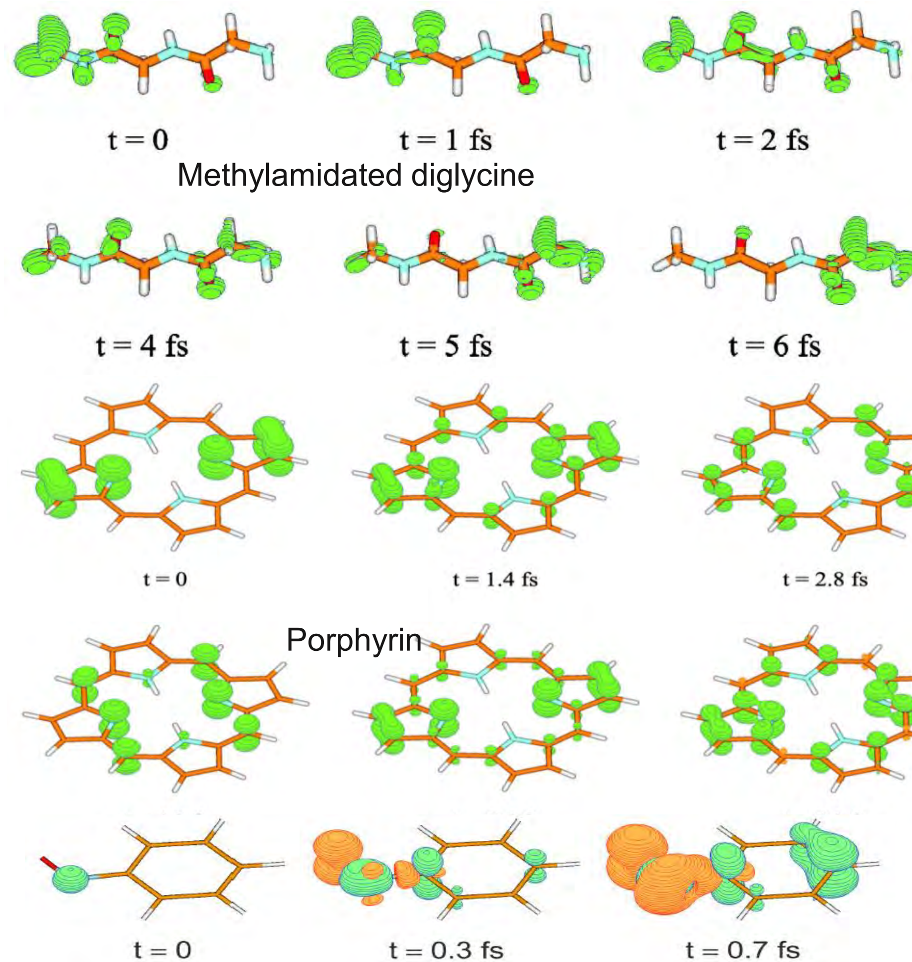
Gas Phase Experiments

F. Calegari et al.
Science **346**, 336 (2014)

H.-J. Wőrner et al.
Science **350**, 790 (2015)





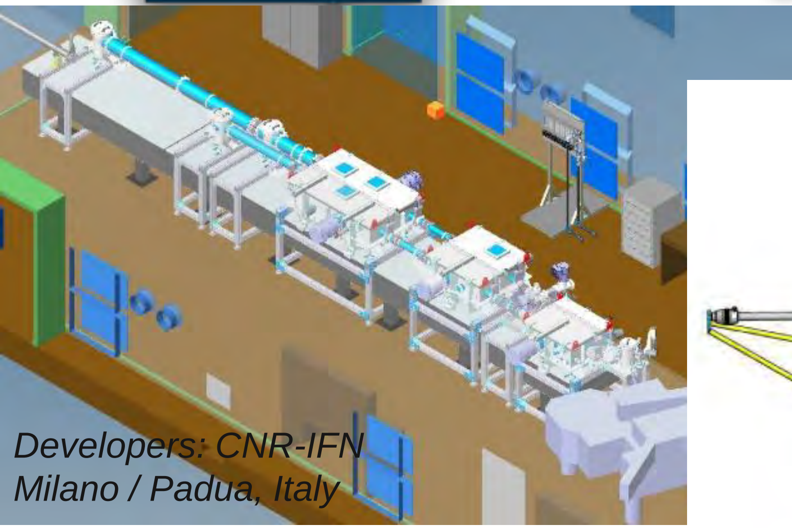


By A. Kuleff

- **TOFs, Reaction Microscope**
- **Fast structural changes during**
  - proton transfer
  - isomerization
  - motion through conical intersections
  - selective bond breaking by charge localization
  - ………………

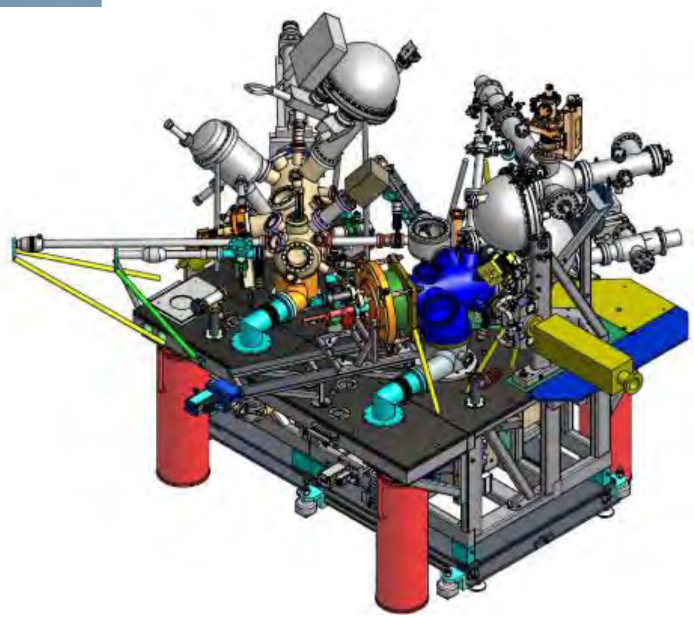
HR (100kHz) GHHG beamline II

Condensed Phase/Surface Science Experiments



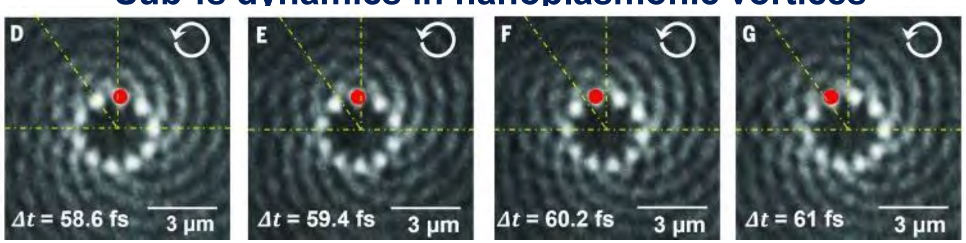
Including a time compensating XUV monochromator

NanoEsca end-station



Real and k-space mapping
Band structure
Spin diagnostics
Magnetic imaging
Plasmonics
ARPES
with
Energy (few tens of meV), spatial (nm) & temporal (fs/asec) resolution

Sub-fs dynamics in nanoplasmonic vortices



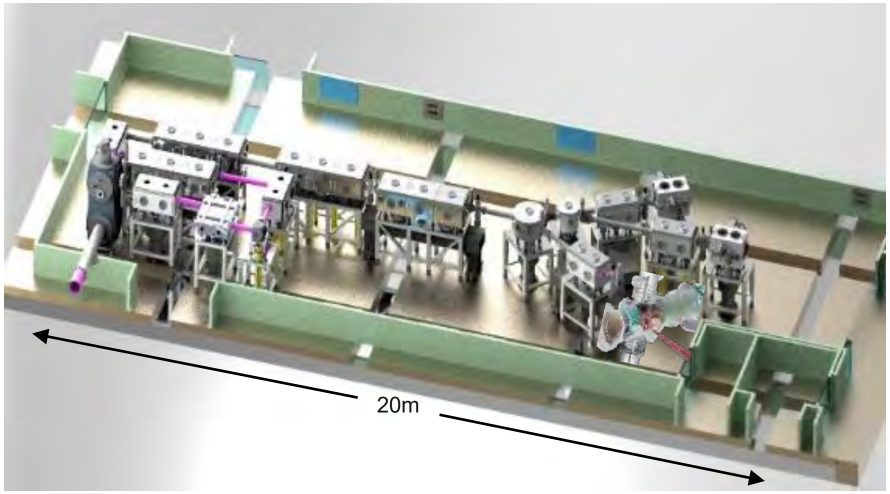
Science 355, 1187 (2017)

Developers:
Scienta Omicron / Focus, Germany

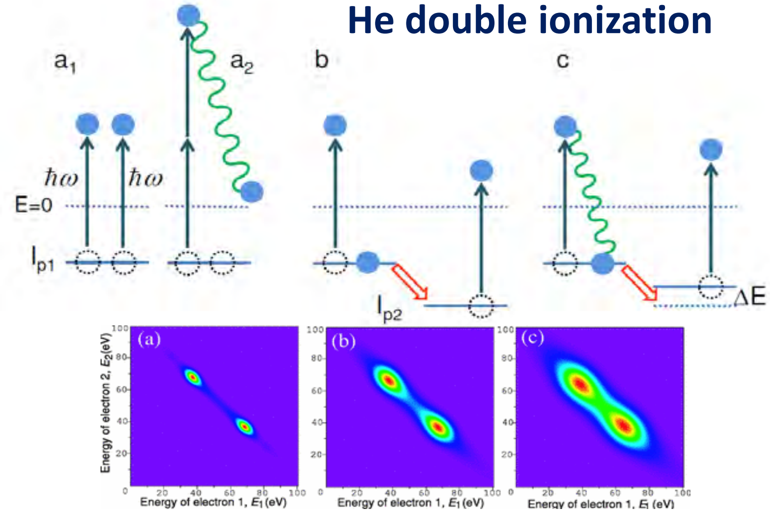
SYLOS GHHG "compact" source

Non-linear processes with XUV-pump-XUV-probe

Developer: FORTH, Crete, Greece

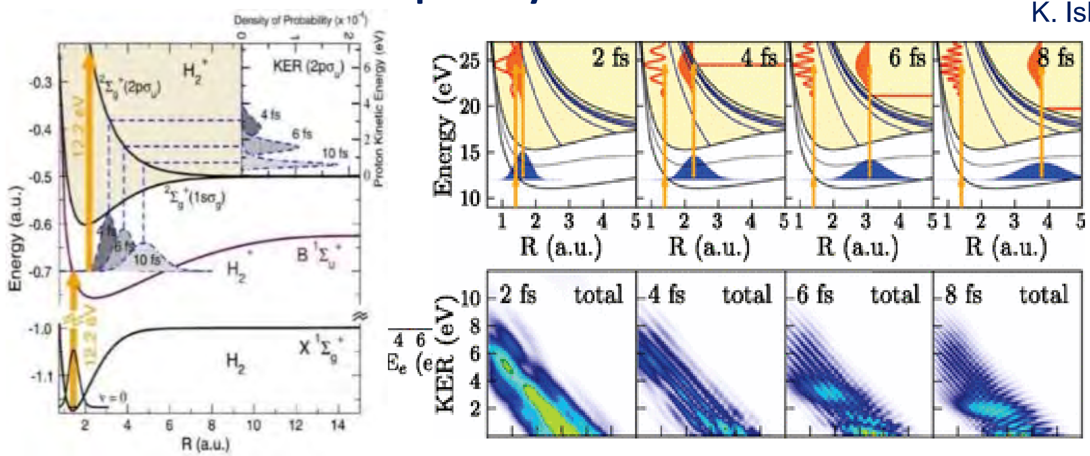


He double ionization



K. Ishikawa et al. *Phys. Rev.* A **72**, 013407 (2005)

Molecular coupled dynamics



A. Palacios et al. PNAS 111, 3973 (2014)

- ✓ **Reaction Microscope for two-electron coincidences**
- ✓ **High XUV intensities (10^{15}-10^{16} W/cm^2)**
- ✓ **High rep rate (≥1kHz)**
- ✓ **High temporal resolution (~100 asec)**

Collaboration with: Univ. Heidelberg, FORTH, Univ. Freiburg

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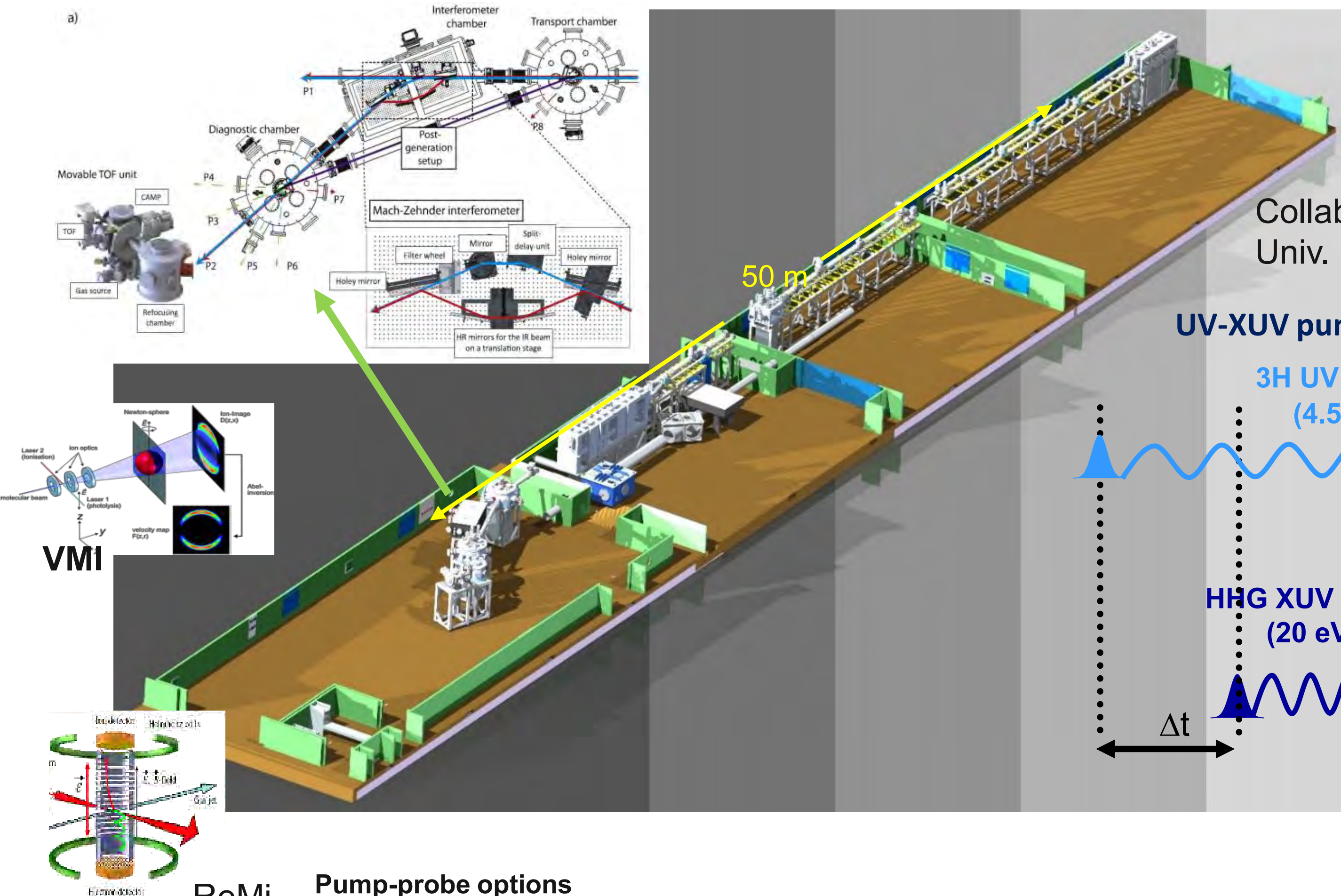
The SYLOS GHHG "long" beamline

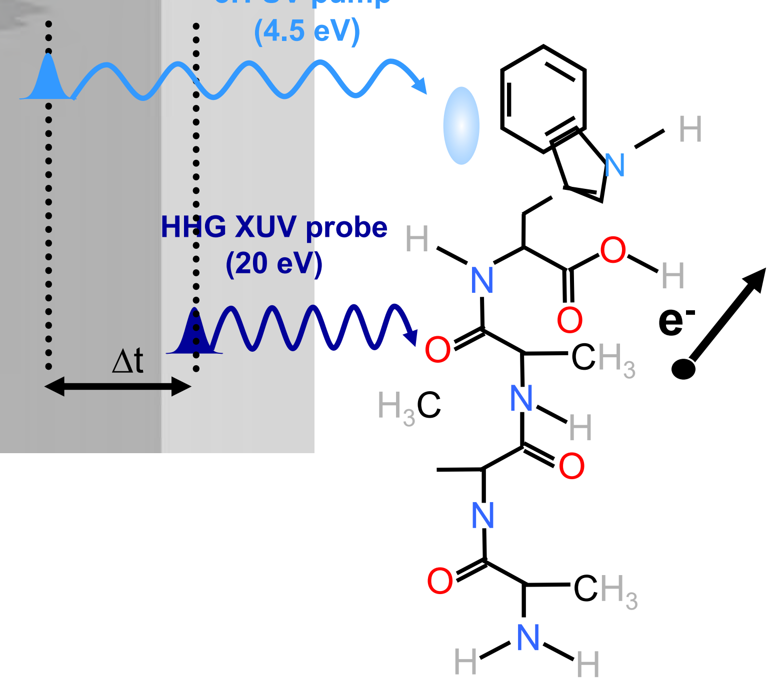
Gas Phase Experiments

Developer: Lund University, Sweden



Collaboration with: Univ. of Lund, Univ. Freiburg

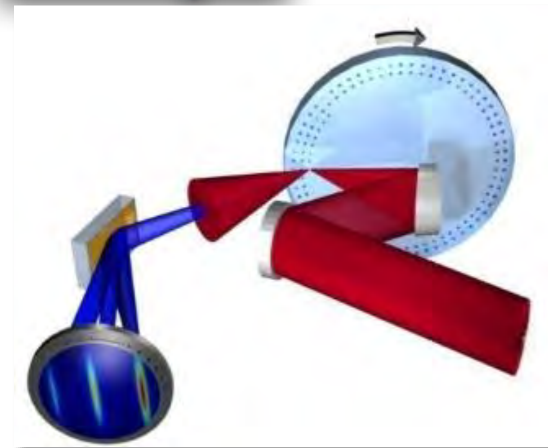
UV-XUV pump-probe on aminoacids' chains



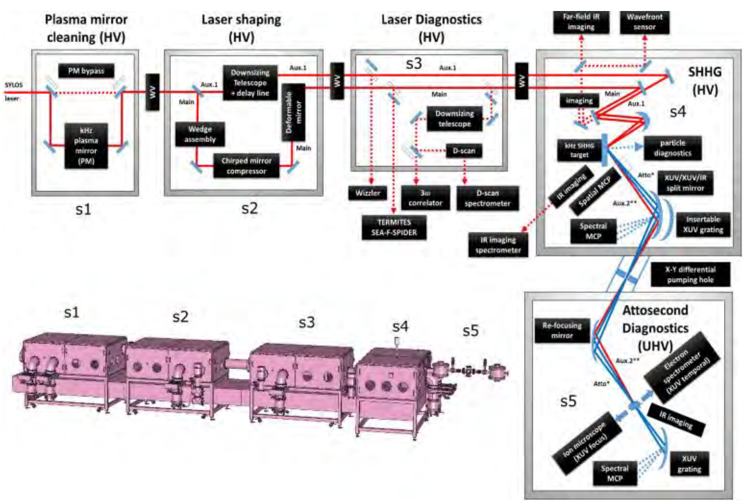
Pump-probe options

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

The SHHG beamlines



SYLOS driven



The first 1 KHz SHHG source !

PW driven

Spectrum cut-off 500eV – 1 keV

Output energy 70mJ (all orders 10<n< 20)
700 μJ (orders >20)

SHHG pulse duration <100 asec for ROM
< 200 asec for CWE

Nonlinear THz Spectroscopy Facility

Expected readiness date: Oct 2019

- THz pump—THz probe measurements
- Charge carrier dynamics
- Lattice anharmonicity
- THz nonlinearities
- Charge separation dynamics in biological molecules/complexes
- [spectrally resolved THz imaging]

Pump laser (cryo-cooled Amplight)

- Wavelength: 1.03 µm
- Pulse duration: 200 fs
- Pulse energy: ≥6 mJ
- Repetition rate: 1 kHz
- Jitter to an external clock signal: ≤100 fs

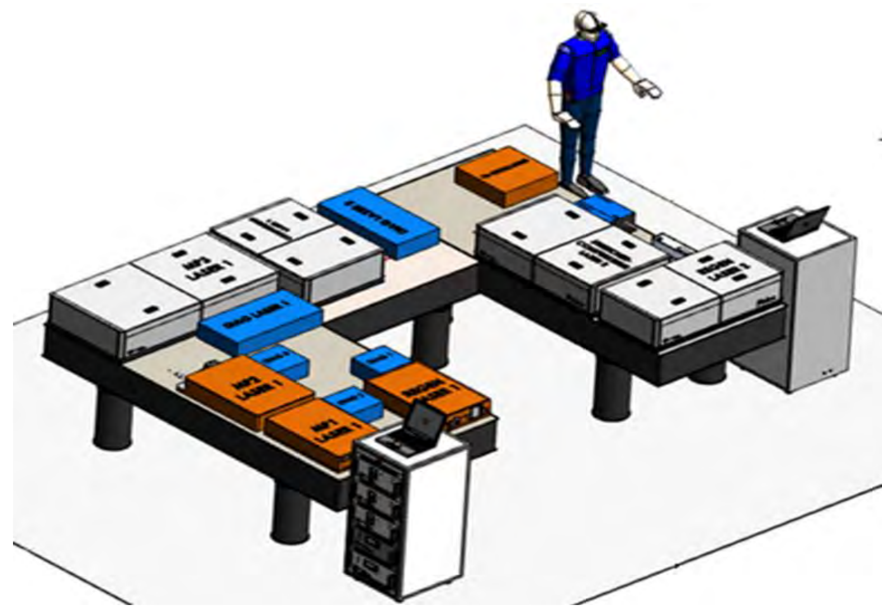
THz source:

- pulse energy: ≥10 µJ
- spectral maximum: in the 0.3÷0.6 THz range
- useful spectral content: 0.15÷1.5 THz
- peak THz field at the sample: ≥200 kV/cm

High Energy THz Beamline

- Materials in extreme THz fields, phase transitions
- Molecule orientation & alignment
- Electron acceleration, manipulation, and bunch characterization
- Relativistic (~1 MeV) ultrashort electron source for time-resolved diffraction & imaging (microscopy)
- Proton post-acceleration

Development beamline
Expected readiness date: Q3 2020



Pump laser: Amplitude Technologies

•Wavelength: 1.03 μm

•Pulse duration: 500 fs

•Pulse energy: ≥500 mJ

•Repetition rate: 50 Hz

•Synchronized short-pulse output: 0.8 μm | 100 fs | 1 mJ | 1 kHz

THz source:

•pulse energy: ≥1 mJ

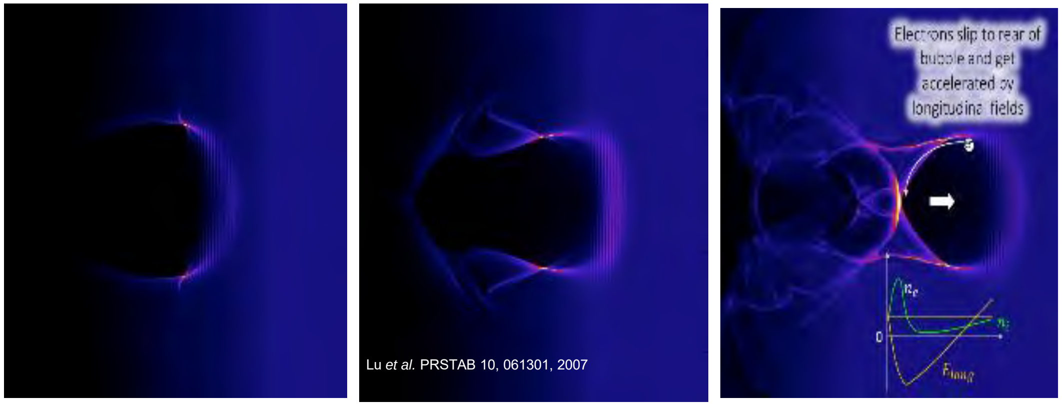
•spectral maximum: in the 0.3÷0.6 THz range

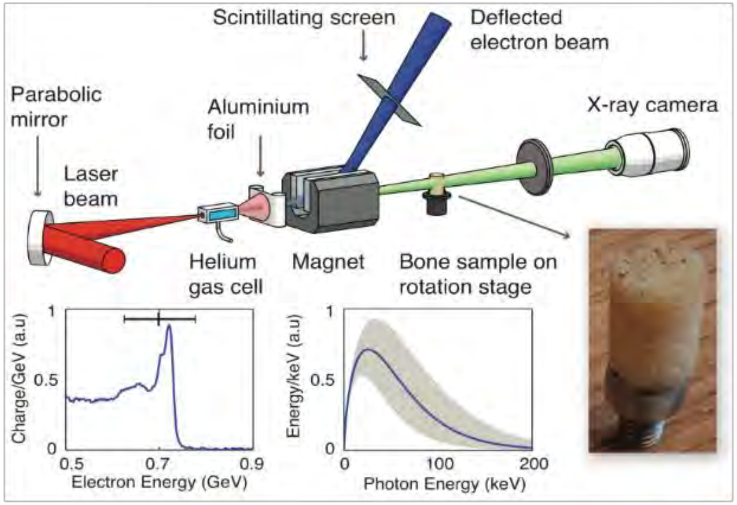
•useful spectral content: 0.15÷1.5 THz

•waveform: <2 cycles

Laser driven electron acceleration

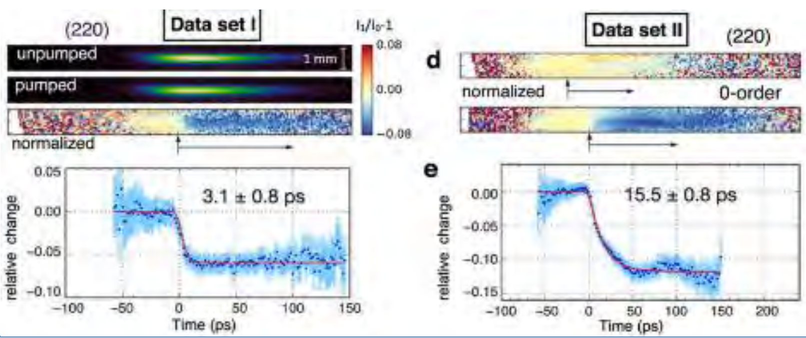
Examples of applications





Ultrafast Electron Diffraction

Si



First proof-of-principle laser wakefield driven UED experiments

e⁻ beam: 100 keV, 1kHz, 100fs

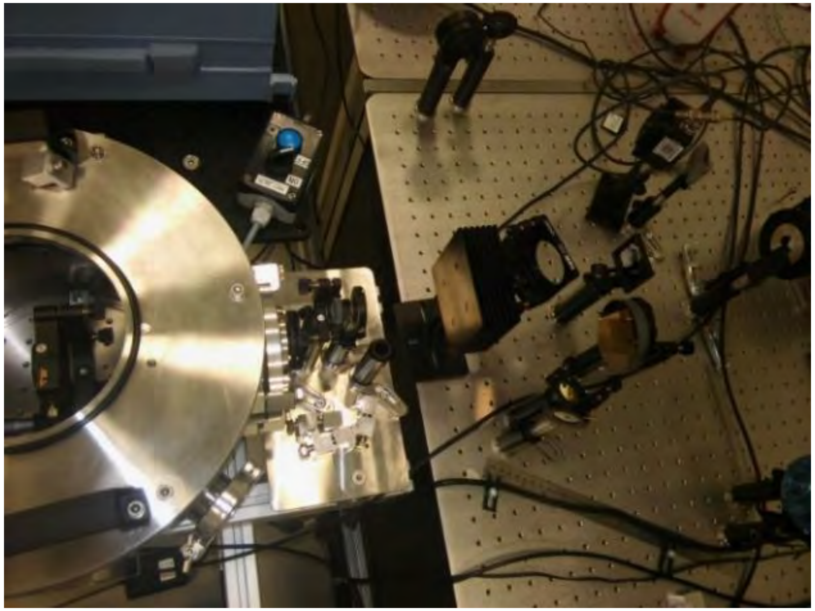
He et al., Sci. Rep. 6, 36224 (2016)

Cole et al.
Scientific Reports 5, 13244 (2015)

Betatron radiation tomography

Experiments at long last…

commissioning user experiments

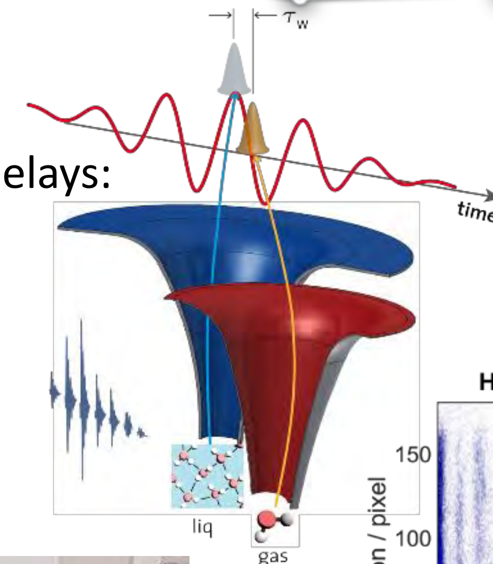


Why would you want to do your expt at ELI?

Study of dynamics in liquid phase

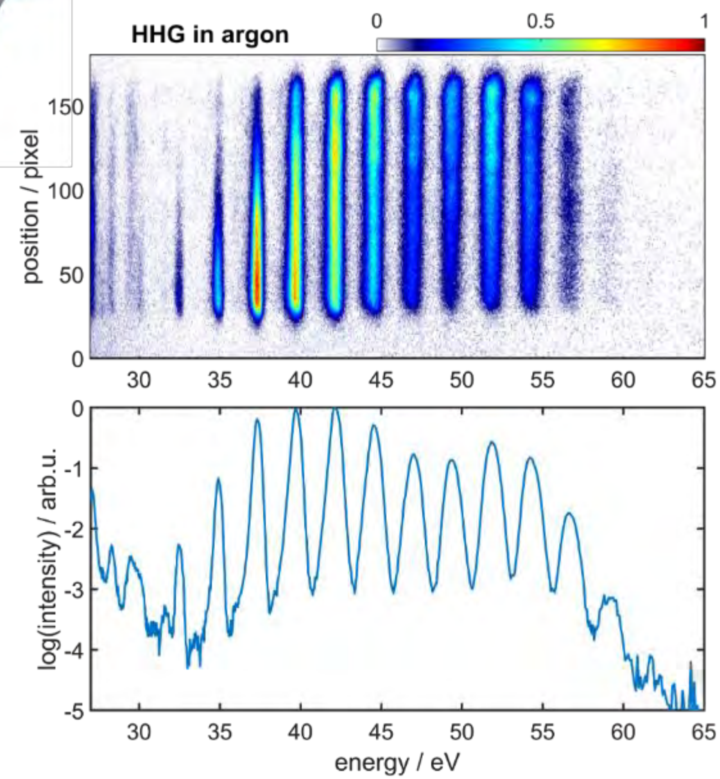
Goals of the experiment @ ELI-ALPS

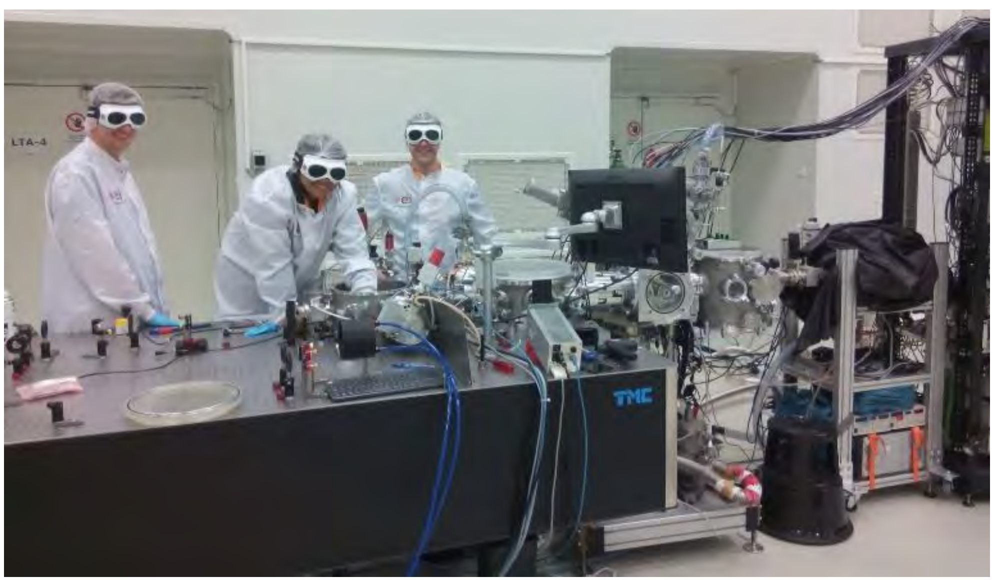
- Measure attosecond photoemission delays:
- First attempts to observe and time-resolve intermolecular Coulombic decay in liquid water



The ETH Zurich team

HJ Wörner,
A Jain, Th Gaumintz, A Schneider,
P Zhang, C Perry, D Hammerland

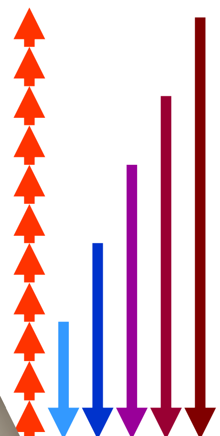




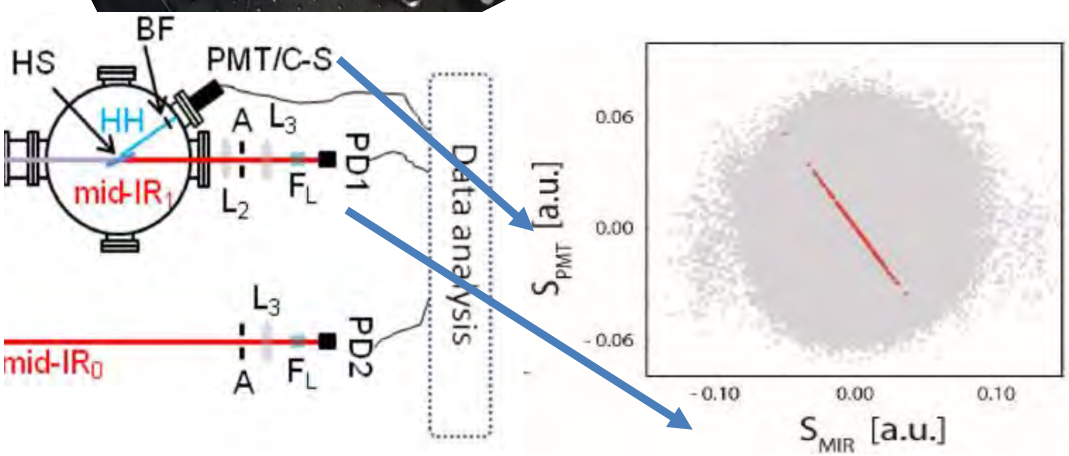
Harmonic gen in bandgap materials
The quantum-spectrometer

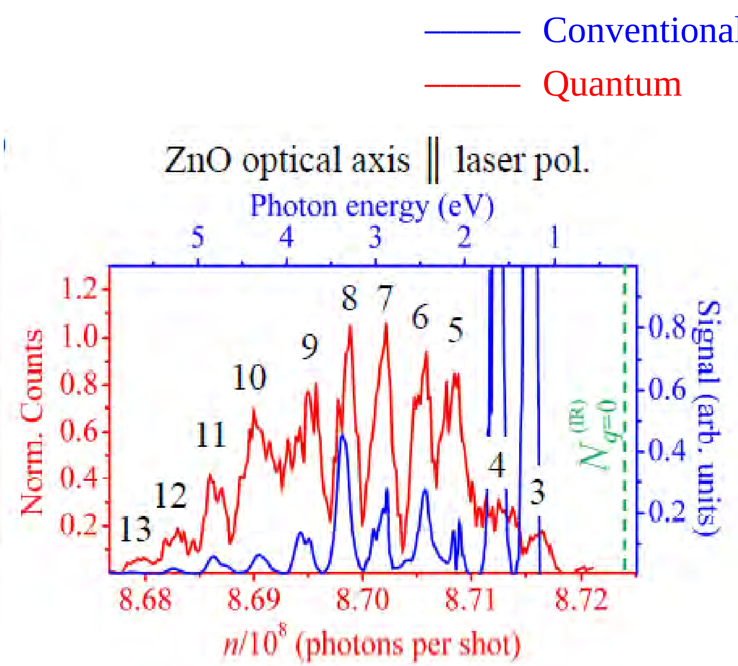
The **quantum** (photon) HHG **spectrometer**
Principle: photon statistics

PI: Paris Tzallas (FORTH-IESL)



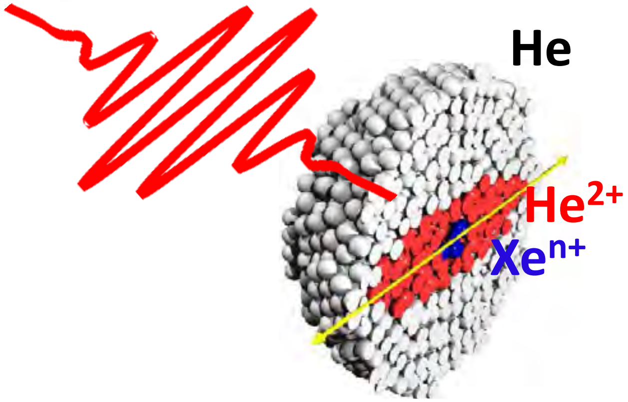
- **"Creation" of one** n-th order harmonic photon results from **"annihilation" of n** laser photons
- **Statistics of the missing laser photons** reveal the **harmonic spectrum**





Doped He droplet photoionization

Electron VMI of doped He nanodroplets



Prof. Marcel Mudrich (Univ. of Aarhus)
Prof. Frank Stienkemeier (Univ. of Freiburg)

Project:

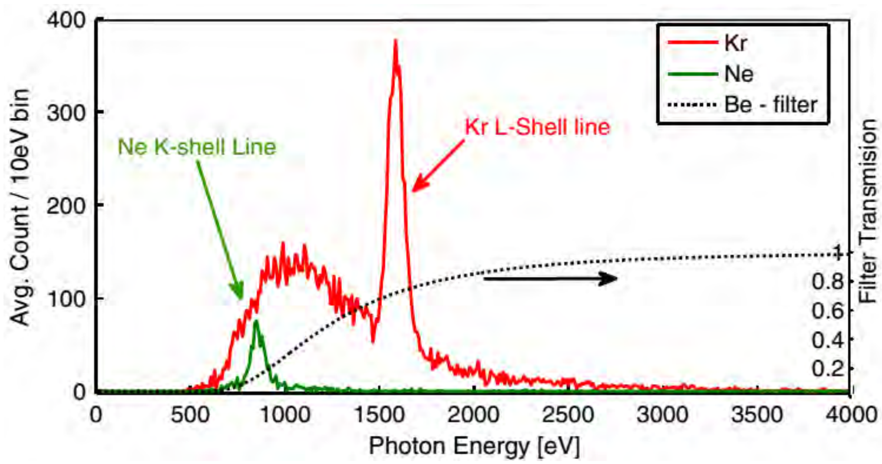
„Study of photoionization of Helium dropplets of different size and, eventually with different dopant atoms (usually alkali atoms)"

1. **Tunnel ionization**
2. **Quiver motion of electrons inside the cluster → impact ionization**
3. **Coulomb explosion (VMI imaging)**

Inner Shell x-ray Fluorescence

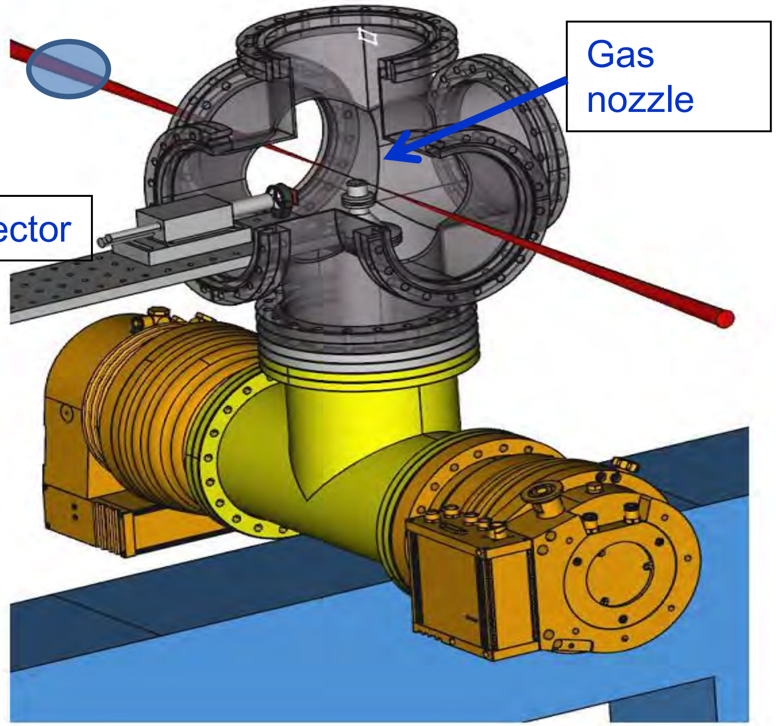
sub femtosecond excitation of core-hole dynamics by the recolliding electron

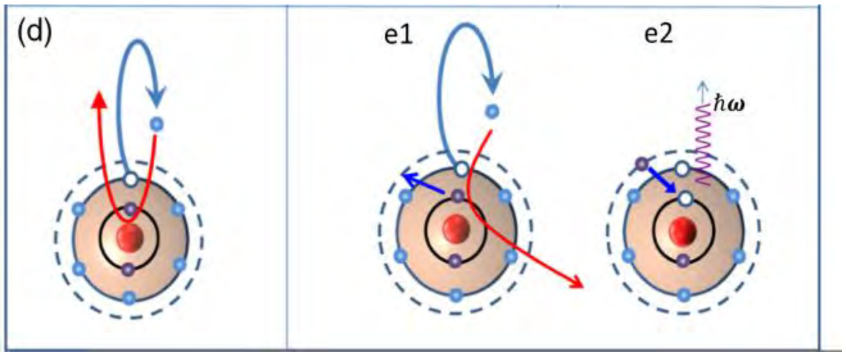
PI: Gilad Marcus
The Hebrew University at Jerusalem



Ne K-shell and **Kr L-shell + continuum**

60 fs, 3200nm, CEP stable OPA,
$I \approx 2 \times 10^{15} \frac{W}{cm^2}$





Auger, x-ray Fluorescence

In house services
Workshops & Laboratories

Mechanical and electrical workshops

Optical workshop for custom optics and coatings

Nanofabrication unit (EBL, FIB)

Radiobiology lab (zebrafish embryos)

Chemistry lab

ELI-ALPS: the users

Collaborative commissioning experiments

1 **ETH Zürich, Switzerland**
Principal Investigator & used equipment: Hans Jakob Wörner – HR1
Subject: Investigation of dynamics in liquids using attosecond pulses and high-harmonic generation in liquid phase

2 **FORTH, Heraklion, Greece**
Principal Investigator & used equipment: Paris Tzallas – MIR
Subject: Investigation of photon statistics in crystal harmonics

3 **CEA, Saclay, France**
Principal Investigator & used equipment: Thierry Ruchon – MIR
Subject: Investigation of gas high-order harmonic generation with the MIR laser

4 **Hebrew University of Jerusalem, Israel**
Principal Investigator & used equipment: Gilad Marcus – MIR
Subject: Investigation of atomic inner-shell processes induced by intense, coherent Mid-IR radiation

5 **FORTH, Heraklion, Greece**
Principal Investigator & used equipment: Manolis Skantzakis – MIR
Subject: MIR harmonic HBT experiment

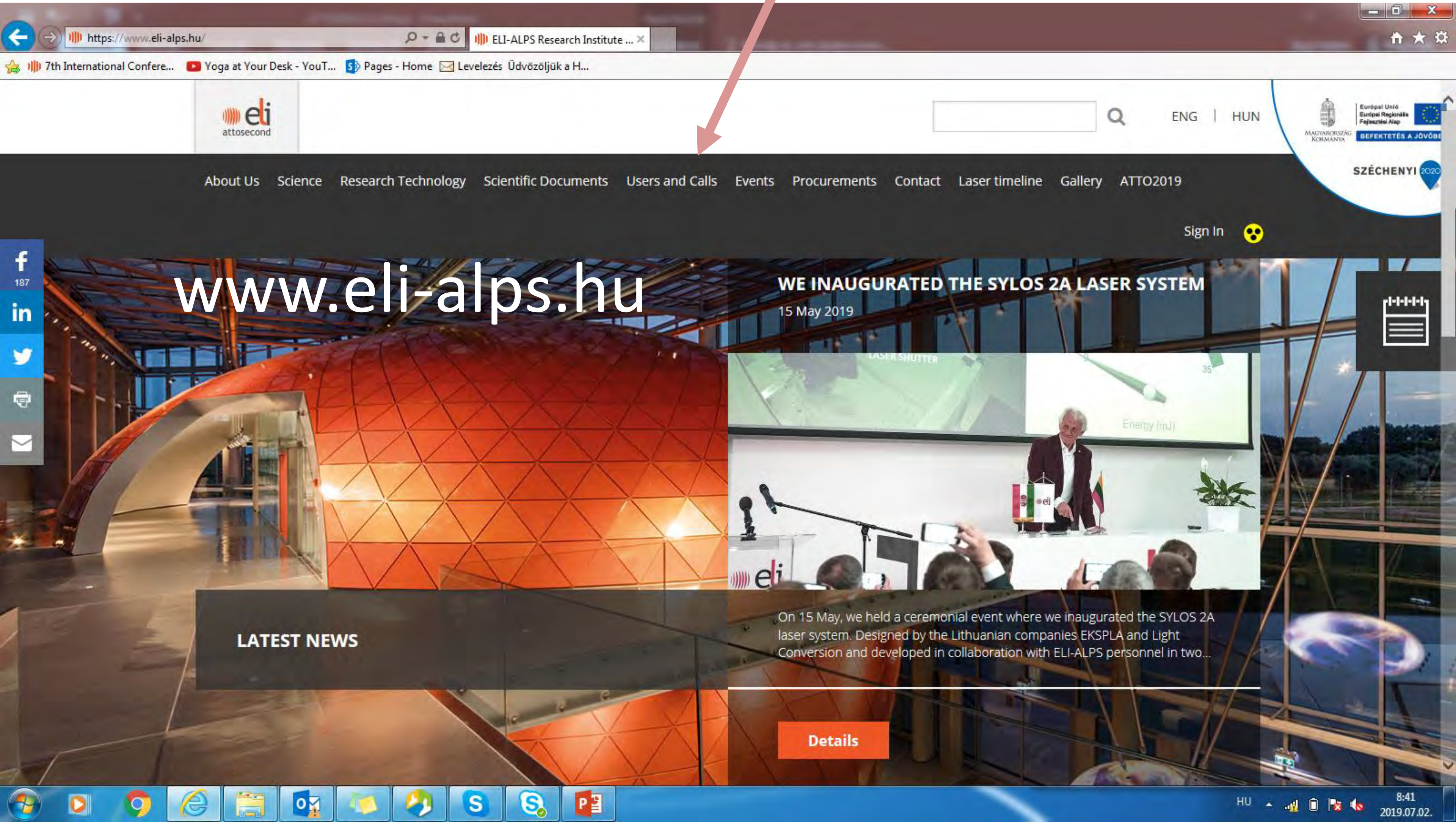
6 **University of Freiburg, Germany**
Principal Investigator & used equipment: Frank Stienkemeier – MIR
Subject: Investigation of ultrafast dynamics in helium droplets initiated by long-wavelength laser radiation

7 **Université de Limoges, France**
Principal Investigator & used equipment: Martin Maurel – MIR
Subject: Single cycle mid-IR pulses through post compression in Kagome fiber

8 **University of Freiburg, Germany**
Principal Investigator & used equipment: Frank Stienkemeier – MIR
Subject: Investigation of ultrafast dynamics in Argon droplets initiated by long-wavelength laser radiation

	HR 1 (40 fs)	MIR laser
Prep & expt:	*39 weeks*	*35 weeks*
Maintenance:	*7 weeks*	*2 weeks*

Open commissioning user call



eli attosecond

Thank you for your attention

& see you at ELI