The ELI ALPS Research Institute
Status and Perspectives

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Science Director

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

- **Higher reprise** (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
Clean room environment. ISO 7 & ISO 8

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

Vibration isolation VC-E (ASHRAE)
Scheme of ELI-ALPS

Unprecedented stability conditions for operation

Primary sources (laser beams)

- High repetition rate (HR) laser @ 100 kHz
- Single cycle (SYLOS) laser @ 1 kHz
- High field (HF) laser @ 10 Hz
- Mid-infrared (MIR) laser @ 100 kHz
- Terahertz pump laser @ 50 Hz

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

- Low shielding
  - THz1: spectroscopy
  - THz2: high energy
- Medium shielding
  - Atto5: SHHG SYLOS
  - Particle1: e− SYLOS
- High shielding
  - Atto6: SHHG HF
  - Particle2: ion HF
  - Particle3: e− HF

Experiments

- Attosecond studies in atomic and molecular physics
- Condensed matter physics
- Nanophysics, materials science
- THz spectroscopy
- High resolution imaging
- Source development
- Plasma physics
- Radiobiology

green field
June, 2014

building construction
June, 2017

lasers
Jan, 2018

attosecond pulses
June, 2019

„Construction”
Are we there, yet?
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,3 S. Káhaly,2 E. Cormier,2,4 L. A. Gonoskov,2,4 B. Kiss,2 K. Varju,3,4 S. Varro,2,4 and P. Tzallas1,2,4

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(Received 28 September 2018; published 14 May 2019)
<table>
<thead>
<tr>
<th>Laser Type</th>
<th>Parameters</th>
<th>Status</th>
<th>Operation / due date</th>
</tr>
</thead>
<tbody>
<tr>
<td>MIR</td>
<td>100 kHz, &lt;40 fs, 0.15 mJ, CEP&lt;100 mrad</td>
<td>Operational</td>
<td>since Oct 2017</td>
</tr>
<tr>
<td>SYLOS</td>
<td>10 Hz, &lt;12 fs, &gt;40 mJ, ~850 nm</td>
<td>Operational</td>
<td>since Jan 2019</td>
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<tr>
<td>SYLOS 2</td>
<td>1 kHz, &lt;6.5 fs, &gt;30 mJ, CEP&lt;250 mrad</td>
<td>Operational</td>
<td>since May 2019</td>
</tr>
<tr>
<td>HR1</td>
<td>100 kHz, 40 fs, 1.5 mJ</td>
<td>Operational</td>
<td>since Dec 2017</td>
</tr>
<tr>
<td></td>
<td>100 kHz, &lt;7fs, 0.8 mJ</td>
<td></td>
<td>since Aug 2019</td>
</tr>
<tr>
<td></td>
<td>100 kHz, &lt;7 fs, 1 mJ, CEP&lt;100 mrad</td>
<td>Installation</td>
<td>by Q2 2020</td>
</tr>
<tr>
<td>HF PW</td>
<td>10 Hz, 10 J, compr. 17fs</td>
<td>Operational</td>
<td>since Sep 2019</td>
</tr>
<tr>
<td></td>
<td>10 Hz, &lt;17 fs, 34 J</td>
<td>Installation</td>
<td>by Q4 2020</td>
</tr>
<tr>
<td>HR2</td>
<td>100 kHz, &lt;6 fs, 5 mJ, CEP&lt;100 mrad</td>
<td>In development</td>
<td>by Q2 2020</td>
</tr>
<tr>
<td>THzP</td>
<td>1 kHz, 100 fs, 1 mJ &amp; 50 Hz, &lt;0.5 ps, 0.5 J</td>
<td>In development</td>
<td>by Q2 2020</td>
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<tr>
<td>MIR HE</td>
<td>1kHz, &lt; 40 fs, 15 mJ</td>
<td>Conceptual</td>
<td>by Q4 2021</td>
</tr>
<tr>
<td>SYLOS 3</td>
<td>1 kHz, &lt;6.5 fs, &gt;105 mJ, CEP&lt;250 mrad</td>
<td>Conceptual</td>
<td>by Q1 2022</td>
</tr>
</tbody>
</table>
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

- Optical cycles
- Pulse energy [μJ]
- Peak power [TW]
- Central wavelength [nm]
- Strehl ratio
- 10-min CEP stability [mrad]

~ 2.2

≥4.5 TW

850-975 nm

>0.7

250 mrad
Energy stability
0.7% rms

CEP drift:
65 mrad rms
IAP FSU Jena + Fraunhofer IAF + Active Fiber Systems GmbH

- **Oscillator**: 1030 nm, CEP stable
- **Pulse picking Streching & Preamplification**: 20 μJ, 100 kHz
- **Main Amplifier**: 8 parallel channels, Yb-doped rod type fiber amplifiers, 8x60 W
- **Chirped Mirror (CM) Compressor**: 3 mJ, 200fs
- **Compressor 2**: Hollow core fiber, CM >1 mJ, <6.2 fs
- **Compressor 1**: Hollow core fiber, CM >1.5 mJ, <40 fs

**Specifications**

- **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
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

Energy stability: \textbf{0.95\% rms}

Energy (J)

0 10 20 30 40 50 60

Number of shots

0 200 400 600 800 1000

1064 nm 70 J

532 nm 50 J
The MIR Laser System
Scientific Case Examples

- **Up** \( \propto \lambda^2 I \)
- **HHG\text{cutoff}** \( \propto \lambda^2 I \) keV photons
- **\( E_{el} \)** \( \propto \lambda^2 I \) LIED

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?

\[
a_L = \left( \frac{2e^2 \lambda^2 I}{\pi n_e^2 c^5} \right)^{1/2}
\]

\[ @ \lambda = 12 \mu m \quad a_L = 1 @ \sim 5 \cdot 10^{15} \text{ W/cm}^2 \]
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.

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
Harmonics in Ar at 100 kHz

Cooper minimum
Vibration isolation
VC-E (ASHRAE)

length of beamline: 856 cm
area of interferometer: 0,8 m x 3,6 m
attosecond pulse train: 362 as
TOFs, Reaction Microscope

Fast structural changes during
- proton transfer
- isomerization
- motion through conical intersections
- selective bond breaking by charge localization
- ....................

By A. Kuleff
HR (100kHz) GHHG beamline II
Condensed Phase/Surface Science Experiments

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

Including a time compensating XUV monochromator

Sub-fs dynamics in nanoplasmonic vortices

Developers: Scienta Omicron / Focus, Germany

Science 355, 1187 (2017)
SYLOS GHHG “compact” source
Non-linear processes with XUV-pump-XUV-probe

He double ionization

Molecular coupled dynamics


- Reaction Microscope for two-electron coincidences
- High XUV intensities ($10^{15}$-$10^{16}$ W/cm²)
- High rep rate ($>1$kHz)
- High temporal resolution (~100 asec)

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

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

3H UV pump
(4.5 eV)

HHG XUV probe
(20 eV)
The SHHG beamlines

**SYLOS 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

**PW driven**

The first 1 KHz SHHG source!
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

Development beamline
Expected readiness date: Q3 2020

- 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

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)


Betatron radiation tomography
Why would you want to do your expt at ELI?
Study of dynamics in liquid phase

The ETH Zurich team
HJ Wörner,
A Jain, Th Gaumintz, A Schneider,
P Zhang, C Perry, D Hammerland

Goals of the experiment @ ELI-ALPS

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

The quantum (photon) HHG spectrometer

Principle: photon statistics

- “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

PI: Paris Tzallas (FORTH-IESL)
Prof. Marcel Mudrich (Univ. of Aarhus)
Prof. Frank Stienkemeier (Univ. of Freiburg)

Project:

„Study of photoionization of Helium droplets 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)
sub femtosecond excitation of core-hole dynamics by the recolliding electron

Ne K-shell and Kr L-shell + continuum

Auger, x-ray Fluorescence

PI: Gilad Marcus
The Hebrew University at Jerusalem

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

SSD detector
Gas nozzle
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

Map:

- HR 1 (40 fs)
- MIR laser

Prep & expt: 39 weeks
Maintenance: 7 weeks

Open commissioning user call

www.eli-alps.hu
Thank you for your attention & see you at ELI