ICEL 2017 - International Conference on Extreme Light

Monday, 6 November 2017 - Thursday, 9 November 2017

ELI-ALPS Research Institute

Book of Abstracts

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Collimated beams of high-energy protons from helical coil targets driven by Petawatt-class lasers

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Ion acceleration is of significant interest due to its applications in a number of areas, including clinical cancer therapy, spallation neutron sources, radioisotope production, ion implantation in semi-conductor industry, and many more. Laser driven ion beams provide a promising alternative to conventional accelerators, which, in addition to the compactness and possible cost-effectiveness, exhibit remarkable properties such as high particle flux, short pulse duration and laminarity [1]. However, the intrinsic large divergence and energy spread of ion beams driven by target normal sheath acceleration (TNSA) mechanism make it hard to utilize the full flux of the beam for many potential applications, for example, clinical proton therapy [1].
Recently a technique exploiting the strength of laser driven EM pulses [2] has been developed, which not only controls the intrinsic shortcomings of TNSA driven ion beams, but also address the slow TNSA scaling with laser intensity by post accelerating the ions [3]. In this target geometry, a helical coil (HC) is attached to the rear surface of the interaction foil. The ions accelerated from the rear surface of the foil propagate along the HC axis, while an EM pulse generated due to impulsive charging of target [3] during the same interaction travels along the coil. The electric field (>109 V/m) inside the coil, associated to the travelling EM pulse, acts to simultaneously focus and accelerate a section of the transiting protons synchronous with the EM pulse [3]. In a proof of principle experiment at ARCTURUS laser system, post-acceleration of laser driven protons at a rate of 0.5 MeV/mm was observed [3]. The rate at which protons are accelerated inside the coil depends, in addition to the coil dimensions, on the strength of the EM pulse created by the laser interaction with the foil target. Employing this technique on higher power lasers, such as Vulcan Petawatt, CLF (UK) and Titan, LLNL (USA), collimated and quasi-monoenergetic proton beams containing >108 particles at ~ 45 MeV were obtained by simultaneous focusing and post acceleration of ~30 MeV protons. Particle tracing simulations are in agreement with the experimental data, suggesting an accelerating gradient of ~ 2 GeV/m in both experiments. The results underpin the potential of the technique for producing high-energy collimated ion beams for future applications.

References: -
1. A. Macchi, M. Borghesi and M. Passoni, Rev. Mod. Phys, 85, 751 (2013).
2. H.Ahmed et. al., NIMA, 829, 172 (2016); K. Quinn et. al., Phys. Rev. Letts., 102, 194801 (2009).
3. S.Kar et. al., Nat. Commun, 7, 10792 (2016).

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PEnELOPE – amplifier benchmarks and 10 J performance

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I. INTRODUCTION

Diode-pumped solid state laser (DPSSL) systems using trivalent ytterbium (Yb3+) showed major interest in recent years. Most notable nanosecond laser systems are Lucia [1], GENBU (using TRAM)

[2], PFS [3] and Dipole [4]. Yb3+-doped YAG crystals or ceramics tend to be first choice due to their high small signal gain and good thermo-optical properties. The second type of afore mentioned DPSSL systems aim at direct ultrashort chirped pulse amplification (CPA), e.g. Polaris [5] and PEnELOPE (Petawatt, Energy-Efficient Laser for Optical Plasma Experiments) [6].
In order to keep the necessary bandwidth, choices for a direct diode-pumped laser system doped with Yb3+ are relatively limited to a few selected materials besides glasses. One of the most promising candidates is Yb3+:CaF2 [7].

II. PEnELOPE SYSTEM OVERVIEW

The PEnELOPE project, a fully and directly diode-pumped laser system under development at the Helmholtz-Zentrum Dresden-Rossendorf, Germany, aims at 150 fs long pulses with energies of up to 150 J at repetition rates of up to 1 Hz.
The system consists of an oscillator generating pulses of ~60 fs, which are stretched by ~200 ps/nm and a hardclip of 50 nm. Subsequent amplification in several stages (High-Gain Broadband Amplifers HGBA I to III) increases the energy to the sub-J level. The last two amplification stages (High-Energy Power Amplifiers HEPA I and II) are designed to increase the energy to 200 J before final compression takes place. The peak power is foreseen to reach 1 PW.
With increasing energy, concepts for amplification change mainly due to the drastic increase in required pump power. While first amplification stages rely on an active-mirror approach, the last two amplifiers work in transmission with several He-gas cooled gain medium slabs.

III. EXPERIMENTAL RESULTS MPA III

One of the main uncertainties lies in the energetic performance of the amplifiers due to the very low gain cross section of Yb3+:CaF2. As HEPA I and II show in total 2x12 passes, we set up HEPA I in a double-pass scheme using polarization coupling to simulate both final stages.
The 10 J operation of HEPA I is shown by injecting only ~30 mJ (see Figure 1, gain of ~340) with about 5 nm of bandwidth. Here, HGBA I and II were taken as seed source providing cavity-dumped, 6 ns long pulses. As the first 12 passes of HEPA I doesn't exhibit gain saturation, it is safe to assume a similar energetic performance for 12 passes with about 600 mJ of input energy.
In order to compensate for further reduction in gain due to a higher bandwidth of about 20 nm, HGBA III with an output pulse energy of 1 J will be inserted in the amplifier chain.
As pump performance at HEPA II is designed to perform better than HEPA I, we can consequently estimate to meet the target performance of up to 200 J for HEPA II.

REFERENCES

1 T. Goncalves-Novo et al., Optics Express, 21 (1), 855-866 (2013).

2 M. Divoky et al., Optics Letters, (6), 855-858 (2015).

3 C. Wandt et al., Laser & Photonics Reviews 8 (6), 875-881 (2014).

4 S. Banerjee et al, Optics Letters, 41 (9), 2089 (2016).

5 M. Hornung et al., Optics Letters 41, (22), 5413–5416 (2016).

6 M. Siebold et al., Proceedings of SPIE 8780, 878005-878014 (2013).

7 M. Siebold et al., Applied Physics B 97, 147-158 (2009).

Summary:

We present the status of the PEnELOPE laser, especially the performance of the second to the last amplifier, boosting the available energy to the 10 Joule-level. This benchmarks the performance of the whole last two amplifier sections.

Applications of light sources driven by laser-wakefield acceleration

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Betatron x-ray radiation, driven by electrons from laser-wakefield acceleration, has unique properties to probe high energy density (HED) plasmas and warm dense matter. This source is produced when relativistic electrons oscillate in the plasma wake of a laser pulse. Its properties are similar to that of a synchrotron, with a 1000-fold shorter pulse. This presentation will focus on the experimental challenges and results related to the development of betatron radiation for applications at large scale HED science laser facilities. We will present recent experiments performed at the Linac Coherent Light Source (LCLS) at SLAC and the Jupiter Laser Facility (JLF) at the Lawrence Livermore National Laboratory.
At JLF, we used the Titan laser (150 J, 1 ps), showing evidence of betatron x-ray production in the self-modulated regime of laser-wakefield acceleration (SMLWFA). We will show a detailed source characterization, as well as electron spectra above 200 MeV and forward laser spectra indicating a strongly self-modulated laser-wakefield acceleration regime. The results, benchmarked against Particle-In-Cell (PIC) simulations, are promising for future applications of the source at larger scale laser facilities such as OMEGA and NIF.
At LCLS, we have recently commissioned the betatron x-ray source, driven by the Matter under Extreme Conditions (MEC) short pulse laser (1 J, 40 fs). The source is used as a probe by investigating the X-ray absorption near edge structure (XANES) spectrum at the K- or L-edge of several materials (iron, silicon oxide) driven to a warm dense matter state (temperature of a few eV, solid densities). The driver is either LCLS itself or optical lasers. With these experiments we are able to study, with sub-picosecond resolution, the electron-ion equilibration mechanisms in warm dense matter.
Work performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under contract DE-AC52-07NA27344, supported by the LLNL LDRD program under tracking code 13-LW-076, 16-ERD-024, 16-ERD-041, supported by the DOE Office of Fusion Energy Sciences under SCW 1476 and SCW 1569, and by the DOE Office of Science Early Career Research Program under SCW 1575.

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Ultra-intense K-shell emission from stainless steel foils irradiated by ultra-intensive femtosecond laser pulses

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We report about x-ray spectroscopy advantages observed at recent experiments on J-KAREN-P laser facility [1]. The high-resolution X-ray spectroscopic diagnostic was applied to observe x-ray emission from dense laser plasma generated via ultra-intense (I$\sim 3 \times 10^{21}$ W/cm^2) femtosecond laser pulses irradiated thin stainless steel foils. The spectrometer with high spatial resolution equipped by spherically bent mica crystal was implemented to measure X-ray emission from the front side of target at the wavelength range 1.7 - 2.1 Å. We for the first time demonstrate experimentally from high-intensity laser generated plasma that the highest temperature emission region had electron density $\sim$ 30 times higher than the typically observed critical density for the laser wavelength, corresponding to the value of the relativistic critical density. Kinetic modeling using open access code FLYCHK was provided to estimate main plasma parameters. Assumed that x-ray radiation emits from some plasma regions [2-4] which have notably different parameters and are responsible for the emission of different spectral lines, we obtained a good match between theoretical modelling and experimental measurement. Also we observed the non-liner growth of X-ray emission from stainless steel plasma. X-ray emission intensity increases exponentially with laser intensity on target. Laser contrast vs amplified spontaneous emission ration influence on highly charged Fe ions generation was investigated to demonstrate that for effective formation of fast multiply charged ions source in femtosecond laser plasma of medium and heavy chemical elements, laser pulses of ultra-high contrast > 10^{10} are required. With growth of Z elements, the laser pulse contrast stays the most crucial parameter for x-ray emission and highly charged ion source formation [5].

1. H. Kiriyama et al., "High-Contrast, High-Intensity Petawatt-Class Laser and Applications, "IEEE J. Sel. Top. Quantum Electron 2(1), 232–249 (2015).
2. S.A. Pikuz et al., "Formation of a plasma with the determining role of radiative processes in thin foils irradiated by a pulse of the PEARL subpetawatt laser," JETP Lett. 105(1), 13–17 (2017).
3. S.A. Pikuz Jr. et al., "Production of exotic states of matter with the use of X-rays generated by focusing a petawatt laser pulse onto a solid target," Physics-Uspekhi 57(7), 702 (2014).
4. A.Ya. Faenov. et al., "Nonlinear increase of X-ray intensities from thin foils irradiated with a 200 TW femtosecond laser," Sci. Rep. 5, 13436 (2015).
5. A. Ya. Faenov et al. "The effect of laser contrast on generation of highly charged Fe ions by ultra-intense femtosecond laser pulses," App. Phys. B 123(7), 197 (2017).

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The interaction of intense short laser pulses with nano-scale structered targets

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Ultrahigh intensity (UHI) laser radiation produces fast particles and radiation at interaction with solid targets. UHI laser pulses may accelerate electrons and then ions in nano-scale foils to energies of tens MeV per nucleon and highly collimated ion beams may be formed. Anyway, the efficiency of such targets is not so high. Particle acceleration and X-ray generation in different nanostructured targets irradiated by UHI laser pulses has been studied here with analytical model and PIC simulations. The absorption of laser energy in such target is close to 100%. The factor of conversion of laser energy into energy of fast ions for such target can be significantly enhanced. It follows that the optimal scale should be of several lengths of the skin layer of the electrical field and has to be in the order of magnitude of tens of nanometers. By means of analytical and numerical modeling are constructed the dependences of numbers and temperatures of hot and cold electrons from the parameters of a relief targets irradiated by a short laser pulse of relativistic intensity. It is shown, that changing of a relief size, period and a thickness of a target substrate, it is possible to manipulate parameters of two temperature electron energy distribution function and to increase selectively transformation of laser energy into K-α radiation or into proton acceleration. The results of the simulations were compared with the experimental data and have shown a good coexistence

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Signature of light-induced conical intersections in strongly coupled diatomics

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Nonadiabatic effects arise due to avoided crossings or conical intersections that are either present naturally or induced by a classical laser field in a molecule. Sodium-iodine, which exhibits a pronounced natural (intrinsic) avoided crossing is investigated in the present work and a competition between the light-induced avoided crossing and the natural one is demonstrated.
Furthermore, rotating molecules exhibit light-induced conical intersections (LICIs) in classical laser light, and we also investigate the impact of these intersections. By studying the electronic state populations and the angular distributions of the dissocating NaI fragments, we undoubtedly demonstrate the strong impact of the LICI on the dynamics of the molecule [1,2,3].

[1] A. Csehi, G. J. Halász, L. S. Cederbaum, Á. Vibók: J. Phys. Chem. Lett. 8 (7), 1624 (2017).

[2] A. Csehi, G. J. Halász, L. S. Cederbaum, Á. Vibók: Phys. Chem. Chem. Phys. 19, 19656 (2017).

[3] A. Csehi, G. J. Halász, Á. Vibók: Chem. Phys. (submitted).

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The European Cluster of Advanced Laser Light Sources (EUCALL)

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The European Cluster of Advanced Laser Light Sources (EUCALL) generates collaboration and synergy between large scale sources of laser-driven and accelerator-driven X-ray radiation.
The lead project partner is European XFEL, while the other partners are DESY, the Extreme Light Infrastructure (ELI) in Czech Republic, Hungary and Romania; ESRF in Grenoble, Helmholtz Zentrum Dresden-Rossendorf, Lund University, the Paul Scherer Institute and Elettra Sincrotrone Trieste. The networks Laserlab-Europe and FELs of Europe are also involved, while representatives from the user communities of FELs and Optical Lasers are members of EUCALL's steering committee. EUCALL is the first serious effort to bring together the two scientific communities who have been using X-ray light in parallel to each other, and from different scientific and technological backgrounds.

EUCALL's scientific outcomes are devoted to the development of new software for simulation and processing of advanced radiation experiments, as well as for new hardware for standardised sample delivery and beam diagnostics for ultra-fast laser experiments. This presentation will outline the significant achievements that EUCALL has delivered during the first two years of the project period.

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Conceptual study of single-shot Faraday rotation and transverse interferometry for plasma diagnostic experiments at ELI-NP

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A Titanium: Sapphire Laser with two arms to generate pairs of 0.1PW, 1PW and 10 PW beams, was installed at Extreme Light Infrastructure Nuclear Physics (ELI-NP). The two 10PW pulsed laser beam, with 810nm central wavelength, 20 to 25 fs pulse duration and frequency 1 pulse per minute, will be used for: "Laser driven nuclear physics" at the E1 interaction area **[1]** and "High Field Physics and Quantum Electrodynamics experiments" at E6 interaction area **[2]**. In the E1 vacuum chamber, the 10PW pulsed laser beam will be focused in solid thin targets to accelerate secondary particles (electrons, protons, ions). The protons and ions will interact with other targets to initiate nuclear reactions (fission and fusion) and generate neutron reach isotopes. In the E6 vacuum chamber the beam of relativistic electrons accelerated in plasma will further interact with the high intensity field in the focus of the second (counter-propagating) 10PW laser beam, to generate electron and positron pairs or interact with their own Radiation Reaction.
Interferometric pump-probe experiments will be implemented at the E6 experimental area. Such experiments are needed to study the plasma dynamics with femtosecond time resolution, in the plasma density range 10^{17} cm^{-3} to 10^{19} cm^{-3}. The optical system for the transport and conditioning of the probe beam for these experiments, was designed. The numerical calculations of the evolution of the probe pulse beam-waist and group dispersion along the probe beam propagation path in air, were done to know to conditions for self-focusing of a less than 30 femtosecond probe pulse, with energy between 0.5 mJ and 5 mJ.
The transverse Nomarski interferometry **[3, 4]** and the Faraday rotation diagnostic **[5, 6, 7]** are the two techniques required at E6 interaction area, to design the efficient laser-driven plasma Wakefield accelerator of electrons up to 10 GeV. The transverse pump and probe Nomarski interferometer with variable length (up to 15 cm long) gas cell, will be used for the time-resolved measurement of plasma dynamics. Faraday rotation diagnostic is a complementary technique for the single-shot measurement of plasma dynamics and for imaging the plasma Wakefields that accelerate the electrons. We present a conceptual design of the two plasma diagnostics and the calculation procedure for the rotation angle of the probe-beam polarization plane, upon its interaction with the azimuthal magnetic field induced by the current of accelerated electrons.

References

[1] F. Negoita, et al, *Laser Driven Nuclear Physics at ELI–NP*, Romanian Reports in Physics, 68(supplement), S37-S144, 2016
[2] I.C.E.Turcu, et al, *High field physics and QED experiments at ELI-NP*, Romanian Reports in Physics, 68(supplement), S145-S231, 2016
[3] Hiromitsu Terauchi et al, *Observation and numerical analysis of plasma parameters in a capillary discharge produced plasma channel waveguide*, Journal of Applied Physics 109, 053304, 2011
[4] Oh Y. Seong et al, *Interferometric measurement of a laser produced plasma using Nomarski Interferometer*, Transactions of the Korean Nuclear Society Spring Meeting, Gwangju, Korea, May 30-31, 2013
[5] A. Buck et al. *Real-time observation of laser-driven electron acceleration*, Nature Physics 7, 543, 2011
[6] M. C. Kaluza et al, *Measurement of Magnetic-Field Structures in a Laser-Wakefield Accelerator*, Physics Review Letters, 105, 115002, 2010
[7] Yen-Yu Chang et al, *Single-shot, ultrafast diagnostics of light-speed plasma structures and accelerating GeV electrons*, AIP Conference Proceedings 1812, 080008, 2017

Summary:

We present a conceptual study of single-shot Faraday rotation and transverse interferometry for the plasma diagnostics at E6 interaction chamber at Extreme Light Infrastructure Nuclear Physics. The two

diagnostics techniques are designed for the 10 PW laser beam focused in a gas cell with variable length, up to 15 cm long. The probe pulse used in these pump-probe interferometry techniques, passes through air before it enters in the E6 interaction chamber. In consequence, the spectral bandwidth of the probe pulse (with initial pulse duration between 20 and 25 femtoseconds and energy between 0.5mJ and 5mJ) is broadened. We present the calculation of the bandwidth broadening and chromatic dispersion of the probe pulse after its nonlinear interaction with air.

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Electron laser wakefield acceleration for production of nuclear isomers

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The ELI-NP facility presents a unique opportunity for exploring problems in fundamental physics, combining a 2x10 PW high-power laser system (HPLS) and a high-brilliance gamma-beam system (GBS) with energies of up to 19.5 MeV [1]. The laser system consists of two synchronized arms, each with three optical compressors that allow pulse extraction at different powers, ie. 100 TW at 10 Hz, 1 PW at 1 Hz, and 10 PW at 0.016 Hz, with a pulse duration around 20 fs. The GBS photons are produced by inverse Compton backscattering of laser pulses off electron bunches accelerated by a LINAC at more than 720 MeV.

One of the proposed first-phase experiments [2] aims at studying in the laboratory the conditions normally encountered in nuclear astrophysics, namely inducing photoexcitation on a nuclear isomeric state. In a nutshell, electrons are accelerated by the 100 TW laser pulse to MeV energies, and they hit a tungsten target, producing Bremsstrahlung gamma radiation that impacts a secondary target with the nucleus of interest, producing isomers. These isomers are photo-excited just above the neutron threshold by the GBS. In the final phase, the photoneutrons resulting from the isomer-gamma interaction can be measured by using a custom-built detector.

We performed 3D PIC simulations using the EPOCH code [3] in order to study the electron beam generated by laser wakefield acceleration (LWFA), as follows. An electron beam with a total charge of 3.3 nC is produced from a LWFA consisting of a 1-mm-long gas cell filled with pure nitrogen. The relevant parameters of the LWFA can be determined by using the scaling law of nonlinear plasma wakefields in the bubble regime [4-6]. A laser pulse with 121 TW peak power and 20 fs duration is focused on a spot with a 20 μm radius at the entrance of the gas cell, operated at a plasma density of ~1019 cm-3. As a result, strong nonlinear wakefields can be generated so that the electron bunch could be trapped due to ionization-induced injection [7,8] and accelerated up to ~250 MeV.

References:

[1] D. L. Balabanski et al., EPL 117, 28001 (2017)

[2] K. Homma et al., Rom. Rep. in Phys. 68, S233 (2016)

[3] T. D. Arber et al., Plasma Phys. Control. Fusion 57, 113001 (2015)

[4] I. Kostyukov, A. Pukhov, S. Kiselev, Physics of Plasmas 11, 5256 (2004)

[5] W. Lu et al., Phy. Rev. Special Topics: Accelerators and Beams 10, 061301 (2007)

[6] K. Nakajima, High Power Laser Science and Engineering 2, e31 (2014)

[7] A. Pak et al., Phys. Rev. Lett. 104, 025003 (2010)

[8] M. Chen et al., Physics of Plasmas 19, 033101 (2012)

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Photonuclear reactions measurements with a time projection chamber at the ELI-NP-GBS facility

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Gamma-induced reaction spectroscopy offers a complementary and yet vital tool for accessing nuclear properties. In the recent years, a marked interest has emerged in near-threshold photo-dissociation reactions for applications in the nuclear structure and nuclear astrophysics fields [1]. Understandably, many of these applications demand precise knowledge of inherently small reaction cross sections.

For instance, recent experiments [2] suggest that a detailed description of α-clustering in the ^{12}C and ^{16}O light nuclei can be inferred from measuring the multi-particle reaction channels ^{12}C(γ,xα) and ^{16}O(γ,xα) respectively. Similarly, the time-reverse ^{16}O(γ,α)^{12}C reaction is a prime candidate for constraining ^{12}C stellar He-burning rates at the lowest achievable energies in the laboratory.

The Gamma Beam System, GBS, facility at ELI-NP will deliver unique opportunities for photonuclear reaction investigations, reuniting high-luminosity, narrow-bandwidth, and > 90% polarized gamma photon beams. For charged-particle emitting reaction studies, an electronic-readout time projection chamber instrument, ELI-eTPC, is currently being developed. The choice of an eTPC instrument stems from a number of compelling advantages. An extended gas target material favors higher reaction rates while, simultaneously, allowing lower energy detection thresholds. In addition, the e-TPC imaging principle enables complex reaction events disambiguation.

An overview of the projected photonuclear case studies at the GBS facility and advances in the ELI-eTPC instrument development will be presented in this contribution.

References

[1] D. Filipescu et al., Eur. Phys. J. A 51, 185 (2015).

[2] W.R. Zimmerman et al., Phys. Rev. Lett. 110, 152502 (2013).

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Strong Field Physics at Midinfrared Physics

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Recent advances in laser technologies had greatly extended strong field ultrafast physics into new directions. One such development has been the rapid proliferation of mid-infrared laser sources, capable of delivering significant increases in ponderomotive forces compared to their visible and near-infrared counterparts. Although for many phenomena and applications the ponderomotive increase proved successful, as expected, early experiments also revealed novel and unexpected physical phenomena. In this presentation, I will provide a broad overview of how fundamental strong field physics processes manifest themselves as they transition from near-infrared to mid-infrared wavelengths and discuss (i) high harmonic generation in solids, (ii) electron wave packet dynamics with its application to low energy structures and ultrafast molecular imaging and (iii) the role of molecular vibrations during strong field ionization.

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Performance evaluation during the trial operation period of the 5 TW, 1 kHz few-cycle SYLOS laser system of ELI-ALPS

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The Hungarian site of the Extreme Light Infrastructure, ELI-ALPS aims to host the next generation of attosecond science [1], hence its primary pump sources require breakthrough developments also in terms of pulse duration, average power, stability and reliability. One of the five main laser systems for driving plasma and gas-based HHG stages, is a state-of-the-art 1 kHz repetition rate, few-cycle laser called SYLOS. Output parameters to be reached before 2020 are 20 TW peak power, a pulse energy of 100 mJ and a duration shorter than two optical cycles (<5 fs), with outstanding energy, carrier-envelope phase (CEP) and pointing stabilities as well as high spatiotemporal quality.

The current state of the SYLOS laser system already sets a new standard in ultrafast laser technology [2]. During the recently finished first implementation phase and subsequent trial operation period, the laser system demonstrated outstanding performance and reliability while it was running with full specifications for 6 months at least 8 hours a day. The front-end utilizes passive difference frequency generation method to provide excellent CEP-stabilization [3]. The overall stability is primarily ensured by an advanced diode-pumped solid state pump system [4], which drives a sequence of NOPCPA stages [5]. This technology allows the central wavelength of the pulses to be easily tunable and the spectrum could be tailored by simply changing the pump pulse delays and phase-matching angles. Compression of the pulses carried out in large aperture bulk glass blocks and then positively chirped mirrors under vacuum conditions. The recently measured output peak parameters are 54 mJ pulse energy and sub 9 fs duration, which translates into 5.5 TW peak power, long-term CEP stability around 220 mrad RMS, energy stability better than 0.9% while the spectrum spans over 300 nm around 880 nm central wavelength at the highest peak power.

During the half-year long trial period, various experiments were performed to verify the pulse characteristics. Chirp-scan, autocorrelation, Wizzler and stereo-ATI measurements have independently confirmed the sub-9 fs pulse duration. The in-loop and out-of-loop CEP stability was cross-checked between f-to-2f and stereo-ATI devices. Moreover, the inherent CEP stability of the system without feedback loop was also found to be surprisingly good thanks to the passive CEP stabilization of the front-end. The polarization contrast was better than 1000:1. The temporal contrast was also measured independently with Sequoia and Tundra cross-correlators, and on the ns scale with a fast photodiode and GHz oscilloscope as well. According to these measurements, the pedestal consists of parametric superfluorescence almost exclusively and stays below the 10⁻⁷ level on about 100 ps long duration, which correlates to the pump pulse length. By proper adjustment of the pump pulse delay, a pre-pulse contrast of 10⁻¹¹ was reached at 30 ps before the pulse peak. In order to reveal the influence of temperature changes, pointing- and wave front stability was recorded for more than eight hours on several occasions. Except for the short warm-up times caused by intentional pump energy level changes, the wavefront and the beam pointing stability remained constant during these long-term logging periods.

To sum up briefly, the ELI-ALPS SYLOS laser system has demonstrated excellent long-term stability and reliability. While its development is still ongoing, it already exhibits state-of-the-art output parameters and expected to be one of the flagship laser sources of ELI-ALPS in the near future.

References:
[1] http://www.eli-alps.hu/
[2] R. Budriūnas et al. Opt. Exp. 25, 5707 (2017)
[3] R. Budriūnas et al. J. of Opt. 17,094008(2015)
[4] J. Adamonis et al. Appl. Opt. 55,8007 (2016)
[5] T. Stanislauskas et al. Opt. Exp, 22, 1865 (2014)

Summary:

The 5 TW, 1 kHz, passively CEP-stabilized ELI-ALPS SYLOS few-cycle laser system demonstrated state-of-the-art output parameters, excellent overall stability and reliability during the recently finished half-year trial operation period. Long-term performances were cross-checked by several different experimental methods.

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The impact of GDD and phase difference of ultrashort light pulses on the THz radiation generation from two-color asymmetric air plasma

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The terahertz radiation from two-color asymmetric air plasma receive great attention recently, since its potential use in all air terahertz spectrometers is very promising. In this scheme, the second-harmonic field of a femtosecond laser field is combined with its fundamental, which accelerates charges of air plasma produced by the focused laser pulses. This process ultimately generates an intense THz pulse with very broad frequency spectrum. Both the initial group delay dispersion (GDD) and the phase difference of the combined ultrashort light pulses play an important role in the quality and the quantity of the produced terahertz radiation. Our goal is to study the role of these two parameters during the generation of THz radiation.
A Ti:Sa frontend (TeWaTi laboratory at University of Szeged) is used as a light source (30 fs, 1.2 mJ, 200 Hz, 800 nm) The dispersion of the light pulses is controlled by an acousto-optical programmable dispersive filter (AOPDF), manufactured by Fastlite (Dazzler). The phase difference between the fundamental and its second harmonic is controlled by the distance between the SHG crystal and the focal plane. The THz radiation is detected by electro-optic sampling in a ZnTe crystal.
The key findings are that the GDD and the phase difference between the pulses together have a significant impact on the terahertz peak amplitude and spectrum. The THz peak amplitude shows interesting oscillation as a function of initial GDD of the infrared pulse, since nonlinear conversion strongly depends on the phase difference between the fundamental and SH fields. The observation was the shift in chirp from the transform limited duration in terms of the generation of the strongest THz pulse. Group velocity mismatch in the BBO separate the ultrashort pulses, therefore stretched pulses have better overlap than transform limited ones.
Numerical simulations are performed and confirmed our theories. The simulation is based the core

of the codes similar to the one presented by Kim et al. [1], but included more detailed ultrashort pulse propagation models. Group velocity is taken into account, in air the SH beam fall behind the fundamental beam. THz field generation is more optimal when the fundamental pulse is stretched to achieve better temporal overlap with the SH pulse, instead of being transform limited [2]. The relative phase between the fundamental and SH fields have huge impact on the THz signal [1]. This phase changes with the dispersion tuning and creates oscillation, which we experienced experimentally. The simulations and experiments are in reasonable agreement.
In conclusion, it has been shown that the dispersion has important impact on the terahertz radiation producing strong oscillations as function of GDD and the phase difference of the ultra-short pulses. A key observation is that the maximum terahertz intensity is found shifted from the transform-limited duration of the fundamental pulse, which has been the result of the group-delay mismatch of the fundamental and second harmonic light pulse through the type I BBO crystal. The next step in this work to further explore the dispersion at higher order, and to investigate the impact of dispersion on the frequency composition of the terahertz radiation.

1. K. Y. Kim et al. IEEE J. QElectronics 48(6) 797-805 (2012)
2. R. Flender et al Proc. SPIE 10228 102281B (2017)

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ATTOLAB: a versatile and integrated facility for attosecond physics and chemical physics

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In recent years, increased reliability and stability of ultrafast energetic lasers based on Ti:Sapphire technology has raised the interest of a broad community of users appealed by ultrashort Vacuum UltraViolet (VUV) sources. In particular, focusing these lasers on gas targets, the process of High order Harmonic Generation (HHG) supplies an XUV spectrum that shows unique specificities as for its high degree of coherence, its low duration, which lies in the attosecond to femtosecond range, and its excellent synchronization to a Visible-IR laser that may be used for pump-probe experiments. Starting from a λ=800 nm wavelength, typical HHG spectra lie in the 10 eV-120 eV range, which can address a large variety of applications from solid state physics (e.g. spin dynamics, dynamics of the so-called Dirac fermions in topological insulators, multi-ferroic materials, e.g., oxides) and gas phase chemical physics (e.g. time-resolved photoionization in the core- and valence shell of atoms/molecules, highly non linear harmonic spectroscopy…).
Based on this scientific landscape, we designed an ultrafast XUV facility which offers free-ports to users from solid state and chemical physics backgrounds. The laser system, which has been developed at Attolab, in collaboration with Amplitude Technologies, is a Ti:Sapphire system which delivers 23 fs CEP stabilized pulses of 2 mJ at a 10kHz repetition rate. The beam is focused in a continuous gas jet to produce HHG spectra. A first XUV beamline, currently under commissioning, has be designed by consensus among potential users and coupled to this HHG source. It finally offers three kinds of XUV light beams, that can be commuted within 15 min without changing any other experimental parameter: a very broadband, broadband, and narrowband operating points. The spectral bands extend over the full 10-100 eV range, with respectively 20 eV, 1 to 5 eV and 100 meV FWHM, corresponding to pulse durations in the 100 as, 1 fs and 10 fs ranges. All are synchronized,

down to attosecond precision with laser pump beams. Extreme care has been taken to provide a very stable and reproducible beamline which meets the needs of the scientific community. In this communication, the performance and technological choices for this beamline will be presented.

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Octave-spanning, CEP stabilized, repetition rate-scalable OPCPA frontend based on Yb:KGW laser

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Optical parametric chirped pulse amplification (OPCPA) is the state-of-the-art technique for producing powerful ultrashort light pulses for advanced scientific applications. We present a cascaded OPA setup that takes advantage of reliability, compactness and stability of mature femtosecond Yb:KGW laser systems, and exploits these properties to produce broadband multi-μJ pulses ideal for seeding OPCPA systems operating in the NIR range.

The experimental setup, shown in fig. 1, consists of two white light generation stages and several optical parametric amplification stages, which can be based on BBO or LBO crystals.

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Difference frequency generation between 515nm second harmonic pulses and the Stokes extension of WLG pumped at 515nm results in passively CEP stabilized pulses tunable from 1.3μm to 2μm. Filamentation of these pulses in YAG or sapphire produces CEP stabilized white light, smoothly covering the 500nm-1.7μm range, well suited to seed subsequent NOPA stages. Since parametric fluorescence is confined to the ~250fs duration of the Yb:KGW pulses, excellent temporal contrast is maintained on longer timescales.

We tested 3 different OPCPA frontend setups based on this general scheme. The systems differed in OPA configurations (BBO only or BBO+LBO) and repetition rate (1kHz or 100kHz). With the Yb:KGW laser we used, several microjoule pulses can be produced at 100kHz, while up to 110 microjoule can be delivered at 1kHz repetition rate, while maintaining bandwidth and energy stability. The parameters achieved with different setups will be discussed in more detail in the conference.

Furthermore, we demonstrate the capability of the setup to run for extended periods of time without user intervention (fig. 2a) and produce amplified pulses with octave-spanning spectra, when BBO and LBO amplification stages are combined (fig. 2b)

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Overall, the presented OPCPA frontends produce broadband, multi-μJ pulses with high CEP and energy stability and long-term reliability. Our systems will facilitate continued progress in the development of pump sources for attosecond science.

Summary:

We present developments of seed sources for broadband OPCPA systems operating in the NIR. A compact cascaded OPA setup for transforming femtosecond Yb:KGW laser radiation into broadband, passively CEP stabilized pulses with ~100 microjoules of energy at 1kHz repetition rate, near-single-cycle bandwidth at ~900nm central wavelength and <150mrad CEP stability, is shown. We also discuss the scaling of the setup to 100kHz repetition rate and capabilities of long-term operation.

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Experiments on laser-driven proton acceleration at PEARL facility

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We present the results of laser-driven proton acceleration experiments in TNSA regime at femtosecond sub-petawatt level OPCPA-based laser facility PEARL. Laser pulse with wavelength 910 nm, duration 60 fs and energy up to 10 J was focused to the surface of aluminum foil with thickness from 0.5 µm to 10 µm with help of f/4.2 parabolic mirror in the vacuum chamber. Target was arranged at an angle of 45^0 to the incident radiation. The accuracy of the positioning of the target in the focal spot was provided by original method of fine alignment of the target and by use of adaptive wavefront correction system.
We used two different methods of energetic proton beams detection. First were the radiochromic films (RCF) assembled in a stack. Darkening of films by proton radiation allows restoring the energy and angular spectra of accelerated proton beams. Thomson parabola spectrometer in which accelerated particles deviate from its original path under the influence of collinear magnetic and electric fields, depending on speed and charge-mass ratio, also allowed to identify the variety and energy spectra of accelerated light positive ions. The K-alpha emission of the target was measured with help of spatially resolved x-ray spectrometer. The temporal contrast of OPCPA laser systems supposed to be very high, thus we did not utilize any contrast enhancement techniques.
Maximum energies of accelerated protons measured by the RCF-stack were in the range of 43.3 to 44.1 MeV and generated by 7.5 J laser pulse focused upon a 0.8 µm aluminum foil. To the best of our knowledge this is a world record for laser pulse with energy less than 10 J. The proton energy spectra measurements are in a good agreement with the data from Thomson parabola data and temperature estimations made with help of X-ray diagnostics. Thomson parabola also registered the signs of accelerated carbon and oxygen ions.

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Single plasma mirror solutions for back-reflection mitigation in 10 PW high-power laser experiments

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Recent measurements with PW class lasers demonstrated that energies of up to 3% of the incident laser energy can be back-reflected in the laser system 1 and that modulations of the target surface can occur due to the radiation pressure [1, 2]. Given the foreseen intensities in the ELI-NP experiments in the range of 1022-1023 W/cm2, back-reflections of the main laser pulse can occur from the distorted plasma, leading to irreversible damages of the beam transport system optics or even to the laser amplification chain. Moreover, the debris generated from the laser – target interaction can damage the focusing optics and decrease their performance from only a few shots. Therefore, different solutions for suppressing the back-reflection are being investigated based on a single plasma mirror configuration. We present hydrodynamic and PIC simulations for an ultra-high contrast 10 PW laser pulse interaction with different plasma mirror targets, and discuss their limitations.

References

1 S. Ter-Avetisyan, et al., Optics Express 24 (24), 28104 (2016)

2 H. Vincenti, et al., Nature Commun. 5, 3403 (2014)

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Effect of viscosity on propagation of MHD waves in astrophysical plasma

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We determine the general dispersion relation for the propagation of magnetohydrodynamic (MHD) waves in an astrophysical plasma by considering the effect of viscosity with an anisotropic pressure tensor. Basic MHD equations have been derived and linearized by the method of perturbation to develop the general form of the dispersion relation equation. Our result indicates that an astrophysical plasma with an anisotropic pressure tensor is stable in the presence of viscosity and a strong magnetic field at considerable wavelength.

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Future photo-fission studies at ELI-NP – the beginning of a new era

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The Extreme Light Infrastructure - Nuclear Physics facility, ELI-NP, a state-of-the-art laboratory dedicated for nuclear physics research with extreme electromagnetic fields, is expected to become operational by the end of 2018. Along with two 10 PW high power laser system (HPLS), it will host a brilliant gamma beam system (GBS) [1,2] delivering photon beams with high spectral density (~10^4

photons/s/eV), high resolution (band width ≥ 0.5%) and high degree of linear polarization (>95%) [3]. This will enable precise photo-nuclear measurements in the 0.2-19.5 MeV energy range and will also overcome the existing limitations on photo-fission experiments carried out till date, hence opening a new era for high resolution measurements of sub-barrier transmission resonances in the fission decay channels with cross sections down to $\Gamma\sigma \approx 0.1$ eV b [4].

The photo-fission experimental campaign at ELI-NP mainly aims at measuring the absolute photo-fission cross section of actinide nuclei with high precision, and to study the fission fragment characteristics like energy, mass, charge and angular distributions, as well as the ternary fission products using the high-intensity, quasi mono-energetic γ-ray beams produced at ELI-NP. The study of ternary photo-fission will become possible for the first time due to the high intensity of the ELI-NP γ beam. An important goal is to resolve the so-far unobserved fine structure of the isomeric shelf by decomposing it into individual transmission resonances, and to observe the predicted nucleon clusterization phenomena in super- and hyper-deformed states of the actinides [4]. The polarized γ beams provide an excellent opportunity to study the space asymmetry of the angular distribution of the fission fragments and the correlation between the space asymmetry and the asymmetry of the fission process [4,5].

In order to make these measurements possible, we are developing two new detector arrays based on existing, well-understood cutting-edge technologies. The first setup, called ELITHGEM, is an array of 12 thick gas electron multipliers (THGEM) inside a low-pressure gas chamber, dedicated to the measurement of cross sections and fission fragment angular distributions as a function of the photon energy. This detector array covers almost a full solid angle (around 80% of 4π) and has an angular resolution of about 5°. The second setup, called ELI-BIC, includes a set of four double-sided Frisch-grid Bragg ionization chambers to investigate the fission fragment characteristics. Each ionization chamber will be coupled with eight ΔE-E detectors (covering about one π solid angle) for the study of ternary fission [4].

The present status of development of the above mentioned detector arrays will be reported along with the results from test experiments carried out to check the sensitivity and functionality of the detectors. The near future plans for in-beam test experiments at the existing neutron and γ-beam facilities will also be presented along with our future plans for photo-fission experiments with the GBS at ELI-NP.

1 N. V. Zamfir, Nucl. Phys. News 25:3, 34 (2015).

2 S. Gales et al., Physica Scripta 91, 093004 (2016).

[3] O. Adriani et al., arXiv:1407.3669v1 [physics.acc-ph].

[4] D. L. Balabanski et al., Rom. Rep. Phys. 68, S621 (2016).

[5] L. Csige et al., Phys. Rev. C 87, 044321 (2013).

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Acceleration of electrons and positrons in beam-driven plasma accelerators

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Plasma accelerators driven by particle beams promise high electric fields and high efficiencies, and are increasingly considered as a mean to make future electron-positron colliders more compact and affordable. Beam-driven plasma acceleration of electrons and positrons has recently seen a rapid experimental progress, in particular with experiments conducted at the FACET facility (Facility for Advanced Accelerator Experimental Tests) at SLAC National Accelerator Laboratory.

I will present an overview of the key results for plasma acceleration of both electrons and positrons, obtained by the E200 collaboration during the 2012-2016 FACET experimental runs. For electrons,

the acceleration of a distinct bunch was achieved with high energy efficiency 1, and the field structure of the highly nonlinear plasma wake has been characterized 2. Very high fields in a beam-ionized high-ionization-potential gas were also generated, unveiling important physical processes such as particle beam self-focusing [3]. The more challenging problematic of positron acceleration will also be reviewed. A new regime where energy is efficiently transferred from the front to the rear within a single positron bunch was discovered. The self-loading of the wake leads to the formation of a narrow energy spread bunch of positrons [4]. The acceleration of a distinct positron bunch in a plasma wake was also demonstrated at the culmination of the five-year campaign, in an experiment spanning nonlinear to quasi-linear regimes and unveiling beam loading effects. Finally, the use of hollow plasma channels for positrons was also investigated [5], and positrons have been successfully accelerated in these tubes of plasma.

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1 M. Litos et al., Nature 515, 92 (2014).
2 C. E. Clayton et al., Nat. Commun. 7, 12483 (2016).
[3] S. Corde et al., Nat. Commun. 7, 11898 (2016).
[4] S. Corde et al., Nature 524, 442 (2015).
[5] S. Gessner et al., Nat. Commun. 7, 11785 (2016).

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Meter-size Gratings for ELI-NP 10PW Laser

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In the frame of the ELI-NP (Romania) dual 10PW beamlines laser [3] currently under integration by Thales Optronique, HJY has successfully manufactured the Gold-coated, 1480gr/mm, Meter-size gratings for the two pulse compressors. We will describe our new Meter-size gratings facility (handling equipments, manufacturing processes, characterization instruments) and the key performances obtained on these 10PW laser pulse compression gratings.
For 10PW class laser, the grating groove profile has to be perfectly tailored to allow a high efficiency over a broadband spectrum centered around 800nm and also able to work for an angle of incidence far from the Littrow configuration. On the other hand, we will demonstrate how we have achieved a high wavefront quality of the Meter-size Gratings by using state-of-art polishing technology and associated metrology for the substrate in addition to a well-controlled holographic recording process.

The resulting performances of absolute efficiency, diffracted wavefront and laser induced damage threshold (LIDT) measurements of the manufactured Meter-size gratings will be described in details.

1 Tae Jun Yu et al, "Generation of high-contrast, 30 fs, 1.5 PW laser pulses from chirped-pulse amplification
Ti:sapphire laser", Opt. Express 20 (10), 10807-10815 (2012).
2 D. Papadopoulos et al, "The Apollon-10P project: Design and current status", Advanced Solid State Lasers
(2013). doi:10.1364/ASSL.2013.ATu3A.43
[3] F. Lureaux et al, "Design and initial results of 10 PW Laser for ELI-NP", The European Conference on
Lasers and Electro-Optics (2015).

Summary:

We present the latest developments of Meter-size gratings production for multi-Petawatt laser pulse compression. Multi-Petawatt laser projects [1, 2] in progress all over the world (ELI, ILE Apollon, GIST, SIOM, …) require Meter-size gratings to recompress the tremendous amplified energy (≥ 200J) in a very short pulse (≤ 20fs) and achieve the 10PW-class laser peak power. A pulse compressor with 4 gold-coated holographic gratings optimized in near-IR wavelength and having a more than one meter length

is needed. A new facility (NANOLAM) has been built at HORIBA Jobin Yvon (HJY), dedicated to the production of the world largest diffraction gratings.

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Quantum entanglement in strong-field ionization

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Strong-field ionization of an atom by a suitably strong laser pulse plays a fundamental role in attosecond physics 1: it liberates an electron from its atomic bound state into the continuum 2, which is the first step of the very successful three-step model [3] underlying our understanding of high-order harmonic generation [4]. Currently, the resulting experimental techniques enable to measure the electrons' dynamics in atoms and molecules with attosecond time resolution [5, 6]. The above strong-field process can also create quantum entanglement between the liberated electron and the parent ion-core, which has a time-dependence closely related to that of the driving laser pulse [7-9], thereby opening the possibility to control their pair entanglement by the features of the laser pulse.

In this contribution, we present 3D simulation results of an atom with a single active electron, driven by a strong, linearly polarized few-cycle laser pulse, which were computed with a novel numerical solution of the Schrödinger equation [10]. We discuss in detail how pair entanglement [8, 9] is created during this process. We present the time evolution of several entropy-based measures, borrowed from quantum information theory and adapted to our method to quantify the quantum entanglement between the ion-core and the liberated electron. The mutual entropy of the electron and the ion-core motion along the direction of the laser polarization has important features analogous to those of the 1D model case [8]. However, taking into account also the dynamics perpendicular to the laser polarization reveals a surprisingly different time evolution above the laser intensity range corresponding to pure tunneling [11].

References

1 F. Krausz and M. Ivanov, Rev. Mod. Phys. **81**, 163 (2009)

2 L. V. Keldysh, Zh. Eksp. Teor. Fiz. **47**, 1945 (1964) [Sov. Phys. JETP **20**, 1307 (1965)]

[3] P. B. Corkum, Phys. Rev. Lett. **71**, 1994 (1993)

[4] M. Lewenstein et al., Phys. Rev. A **49**, 2117 (1994).

[5] M. Uiberacker et al., Nature **446**, 627 (2007).

[6] A. N. Pfeiffer et al., Phys. Rev. Lett. **109**, 083002 (2012).

[7] A. Czirják et al., Opt. Com. **179**, 29-38 (2000);

[8] A. Czirják et al., Phys. Scr. **T153**, 014013 (2013).

[9] M. G. Benedict et al., J. Phys. A: Math. Theor. **45**, 085304 (2012).

[10] Sz. Majorosi and A. Czirják, Computer Physics Communications **208**, 9-28, (2016); arXiv:1604.00947v2 [physics.atom-ph]

[11] Sz. Majorosi et al., Phys. Rev. A, accepted (2017); arXiv:1707.04155 [quant-ph]

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Analytical approach to the Coulomb-focusing effects in the non-dipole regime of strong field tunneling ionization

Authors: Christoph H. Keitel[1]; Jiri Danek[1]; Karen. Z. Hatsagortsyan[1]

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An analytical framework for treating Coulomb interaction of tunneled electrons with the parent ion in strong-field ionization is introduced within classical mechanical approach. Analytical expressions for the momentum transfer during recollisions are derived, which allow accurate description of the main features of the asymptotic photoelectron momentum distribution (PMD). We demonstrate the strength of our approach by quantifying PMD in the non-dipole regime, and analyzing of Coulomb focusing modification due to non-dipole effects.

Summary:

Recent experimental advancements in strong-field tunnel ionization physics with linearly polarized mid-IR lasers open new possibilities for measurements of atoms or molecules via time-resolved photoelectron holography 1. The fundamental principle behind the strong field holography is readily explained in terms of interference of two classical trajectories of the ionized electron in the continuum, and the precise retrieval of information from the holography images requires accurate description of the electron trajectories in the field of the atomic core and the laser field. The non-triviality of tunneled electron's evolution in the continuum and combined fields of the laser and of the parent ion was demonstrated by other experiment which discovered unexpected features in the photoelectron energy spectra known as the low energy structures 2 arising due to focusing properties of the Coulomb field. Moreover, advancement of the strong field laser technique into mid-infrared region revealed breakdown of dipole approximation, manifesting in a counterintuitive bend of the photoelectron momentum diagram [3].

The aim of this work is to quantify the dynamics of the tunneled electrons in the laser field and the Coulomb field of the parent ion. We put forward perturbative analytical framework which allows us to account for the momentum transfers between the electron and ion through restriction of the interaction to only specific and well defined recollision points on the electron's classical trajectory [4]. In this way we obtain an analytical description of the final electron's momentum and hence of Coulomb focusing, which allows qualitative understanding of different caustic properties of the photoelectron momentum distribution.

We demonstrate the strength of our framework by analyzing the modification of the Coulomb focusing due to the non-dipole effects and by explaining several new features of the photoelectron momentum distribution, in particular, the exact mechanism behind the time-dependent counterintuitive bend as a fine interplay between the magnetic force and Coulomb focusing.

1 Y. Huismans et al., "Time-Resolved Holography with Photoelectrons," Science, 331, 61 (2011)

2 C. I. Blaga et al., "Strong-field photoionization revisited," Nat Phys, 5, 335 (2009).

[3] A. Ludwig et al., "Breakdown of the Dipole Approximation in Strong-Field Ionization," Phys. Rev. Lett. 113, 243001 (2014).

[4] J. Danek, K. Z. Hatsagortsyan and C. H. Keitel, "Analytical approach to Coulomb focusing in strong field ionization"
arXiv:1707.06921 [physics.atom-ph].

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Optical vortices at ultra-high intensity

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Laser beams carrying orbital angular momentum (OAM) have found major applications in a variety of scientific fields, and their potential for ultrahigh-intensity (UHI) laser-matter interactions has since recently been considered theoretically, up to the relativistic regime [1,2]. Indeed, the remarkable phase and intensity properties of these vortex beams could provide a new way to control UHI interactions as well as new properties for the resulting particles and XUV sources. Despite a large number of theoretical studies done on this topic until recently, no experiment had demonstrated such effects, espacially because of the difficulty to induce
helical wavefronts in large and intense laser beams.

We show for the first time the possibility to induce OAM on such intense laser beams, as well as to transfer it to relativistic XUV harmonic beams, which are generated on solid targets at intensities higher than 10^{19} W/cm^2 [3]. This was done on the UHI100 facility thanks to a spiral phase plate and the physical effects determining the field mode content of the twisted harmonic beams were elucidated. Moreover, thanks to an interformetric technique using a fork-shape binary transmission grating, we measure the helical phase of each harmonic beam and we validate the conservation of OAM in highly non-linear optical processes at extreme laser intensities, which was challenged in gases [4,5].

Finally, we introduce a new holographic method, called plasma holograms, based on the controlled extension of structured plasma on the surface of the solid target to induce an optical vortex on the ultra-high intense laser beam as well as on its high-order harmonics [6]. In particular, this all-optical technic should be very interesting to manipulate Petawatt lasers.

References

1 J. Vieira and J. T. Mendonca, Phys. Rev. Lett. 112, 215001 (2014).
2 X. Zhang et al., Phys. Rev. Lett. 114, 173901 (2015).
[3] A. Denoeud, L. Chopineau, A. Leblanc, and F. Quéré, Phys. Rev. Lett.
118, 033902 (2017).
[4] M. Zürch et al., Nat. Phys. 8, 743 (2012).
[5] G. Gariepy et al., Phys. Rev. Lett. 113, 153901 (2014).
[6] A. Leblanc, A. Denoeud, L. Chopineau, G. Mennerat, Ph. Martin and F. Quéré, Nat. Phys. 13, 440-443 (2017).

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The design and implementation of the Positron Spectroscopy Laboratory at ELI-NP

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In the last decades, positron spectroscopy has proven to be an effective tool for performing non-destructive studies on the properties of materials at an atomic scale. At the Extreme Light Infrastructure – Nuclear Physics (ELI-NP) facility a slow e^+ source will be obtained through e^-e^+ pair production in a convertor made of tungsten foils by a brilliant gamma beam, E_γ < 3.5 MeV, I_γ = 2.4 $\times$ 10^{10} γ s^{-1}. Numerical simulations have shown that through the interaction of the γ-rays with the designed convertor, a slow e^+ beam with an intensity of $\sim 1 \times 10^6$ s^{-1} can be obtained. Due to the limited γ-beam time dedicated for positron production, the laboratory will also be equiped with a ^{22}Na positron source through which a positron beam with intensity of $\sim 1 \times 10^4$ s^{-1} will be obtained. This will allow full year operation of the laboratory. The development of a solid Ne moderator, to replace the W moderator is also under development. This would improve the intensity of the e^+ beam by one order of magnitude.

Several spectrometers will be implemented: Positron Annihilation Lifetime Spectrometer (PALS), Coincidence Doppler Broadening Spectrometer (CDBS) and Positron annihilation initiated Auger Electron Spectrometer (PAES). By measuring the lifetime of a thermalized e^+ (PALS), which depends on the electron density in its vicinity, information regarding the size and density of defects that exist in the sample can be obtained. CDBS measurements are based on the fact that prior to the annihilation, the e^+ is thermalized, so the e^- momentum part determines the e^-e^+ annihilation momentum, and this can be used to determine the chemical surrounding around the annihilation site. PAES uses an electron energy analyser to detect Auger electrons that are emitted through the annihilation of low energy e^+ with the inner atomic shell electrons, and thus create core excitations. PAES is a powerful surface analytical technique and is employed for determining the composition of the surface layers of a sample.

The combination of all the experiments which will be carried using the very intense slow e^+ beam at ELI-NP will provide unique and insightful data for material science.

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Generation and diagnostics of rubidium plasma generated by intense femtosecond laser pulses: Theory and Experiment

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We present recent results on generation of plasma in rubidium vapors by strong laser pulses in femtosecond duration range from a Ti:Sa laser system. An interferometric scheme of real-time diagnostics is applied for determination of main parameters of the created plasma including its density and recombination time parameters.
The presented experimental setup is a table-top analogy of the plasma source for the Advanced Proton Driven Plasma Wakefield Acceleration Experiment (AWAKE) at CERN that is a proof of principle experiment that utilizes the proton bunch available at CERN for acceleration of electrons (positrons) to TeV energies in a single acceleration stage. The diagnostics techniques developed in our lab may find applications in the AWAKE experiment at CERN, as well for diagnostics of plasma generated in gases, or on the surfaces of solid state targets.
We also present results of numerical simulations of propagation of strong ionizing ultra-short laser pulses in Rb vapor. The parameters of the laser pulses and those of the Rb vapors are taken similar to the parameters of the plasma source in AWAKE experiment. The results show a rich variety of nonlinear optical effects taking place during the propagation of the ionizing laser pulses in the resonant and highly nonlinear medium of Rb vapors. The back-action of the medium on the propagating laser pulses is taken into account by simultaneous solution of Schrödinger equations for the relevant multilevel system of the Rb model atom and wave equation for the laser pulse electric strength amplitude. The multi-photon and tunneling models of ionization are being used in calculations of the ionization probabilities from different atomic states of Rb atoms.
The results of simulations may be directly applied for optimization of the parameters of the laser pulses for generation of spatially extended extremely homogeneous plasma necessary in the AWAKE experiment.

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Nanooptical near-field probing with ultrafast photoelectrons

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In recent years, there is increased interest in photoemission as an ultrafast probe for nanooptical near-fields. With the discovery of strong-field plasmonic photoemission [1,2], a new avenue was opened toward applications of nanoplasmonic field probing [3] with the help of photoelectrons. Field probing, in turn, will foster the optimization of plasmonic templates for spectroscopy, sensorics, photocathodes etc. In addition, ultrafast studies with plasmonic photoelectrons have the potential to give insight into the dynamics of collective electron phenomena taking place on unprecedented timescales.

In this talk, I will review the fundamental phenomena related to ultrafast nanoplasmonic photoemission and show how this phenomenon can be exploited for new understanding of light-matter interactions and applications.

1 P. Dombi et al., "Ultrafast strong-field photoemission from plasmonic nanoparticles," Nano Lett. 13, 674-678 (2013).
2 S. M. Teichmann, P. Rácz et al., "Strong-field plasmonic photoemission in the mid-IR at <1 GW/cm2 intensity," Sci. Rep. 5, 7584 (2015).
[3] P. Rácz et al., "Measurement of nanoplasmonic field enhancement with ultrafast photoemission," Nano Lett. 17, 1181-1186 (2017).

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Measurement of preheat due to electron transport in warm dense matter

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A novel approach was used to study the effect of preheat by hot electrons originating in hot plasma near the ablation front through dense regions. This approach used a unique combination of experimental and theoretical methods. The experiment was carried out at the OMEGA laser facility. Temperature of shocked CH foam was determined using x-ray Thomson Scattering (XRTS) which was combined with VISAR and optical pyrometry (SOP) providing a robust equation-of-state measurement 1. An evidence of significant preheat contributing to elevated temperatures reaching 17.5 – 35 eV in shocked CH foam was measured by XRTS. These measurements were complemented by abnormally high shock velocities observed by VISAR and early emission seen by SOP. The experimental results were first compared to EOS tables [2, 3] and matched with hydrodynamic simulations carried out by high- energy density code Cassio to confirm that preheat modified the shock jump conditions [4, 5]. In order to study the contribution of the nonlocal electron transport to the observed preheat we used the Plasma Euler and Transport Equations Hydro code (PETE), which is a Lagrangian fluid model that includes nonlocal transport hydrodynamic model (NTH) [6]. These simulations provided excellent agreement with the experiment. Additional simulation confirmed that the x-ray contribution to this preheat is negligible. These findings enable bench-marking of electron conduction models in conditions relevant to ICF, such as those employed in the modelling of experiments performed at the National Ignition Facility (NIF) and convection phenomena in white dwarfs.

References:

1 K.Falk et al.,Phys. Rev. Lett. 112,1 55003 (2014). 2 S. P. Lyonand, J. D. Johnson, LANL Report, LA-UR-92-3407 (1992). [3] S.X.Hu et al. ,Phys. Rev. E 92, 43104 (2015). [4] M.Gittings et al., CS&D 1, 015005 (2008). [5] T. J. Urbatsch and T. M. Evans, LANL Report LA-14195-MS (2005). [6] M. Holec et al., Int. J. Numer. Meth. Fluids, DOI:10.1002/fld.4288 (2016).

Summary:

An invited talk introducing a novel approach to study electron transport in warm dense matter with relevance to inertial confinement fusion based on an experiment carried out at the Omega laser facility and the new hydrodynamic code PETE developed at ELI Beamlines.

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Resonantly-enhanced ultraviolet filamentation in gases

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Femtosecond filamentation is a self-organization phenomenon during which an ultrashort high power laser stays confined in a very small channel over very long distances [1-2]. Here, we experimentally report a low-loss Kerr-driven optical filament in Krypton gas in the ultraviolet. The reported resonantly-enhanced filaments are one order of magnitude longer than their off-resonant counterparts. A three-photon resonantly-enhanced quintic nonlinearity is identified as the underlying physical mechanism responsible for intensity saturation during the filamentation process, while ionization plays only a minor role [3]. The resonant nature of the process creates also conducive conditions, i.e., a significant population inversion, for forward and backward infrared lasing. Preliminary experimental results suggest that such lasing emission takes place. Beyond its theoretical interest, resonantly-enhanced filamentation could benefit to all applications deriving from the filamentation process. For instance, the extension of this work to molecular gases such as oxygen and nitrogen could lead to numerous atmospheric applications such as nonlinear spectroscopy, remote sensing, and lightning protection, in which the transport of high energies over long distances is of prime importance.

1 A. Couairon and A. Mysyrowicz, "Femtosecond filamentation in transparent media", Phys. Rep. 441, 47–189 (2007).

2 L. Bergé, S. Skupin, R. Nuter, J. Kasparian, and J.-P. Wolf, "Ultrashort filaments of light in weakly ionized, optically transparent media", Rep. Prog. Phys. 70, 1633–1713 (2007).

[3] J. Doussot, G. Karras, F. Billard, P. Béjot, and O. Faucher, "Resonantly enhanced filamentation in gases", Optica 4, 764-769 (2017).

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Harmonic generation in laser-kicked molecules

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Harmonic generation conducted in aligned and spinning molecules leads to the production of circularly polarized, Doppler shifted, up-converted coherent radiation.

A fascinating way to control molecular rotation is to kick molecules with an intense laser pulse of well-defined amplitude, shape, and polarization. When the duration of the pulse is short on the scale of molecular rotation, the impulse delivered to the molecule leads to the periodically occurring angular localization of the molecular axis after the pulse is turned off.

This talk presents two intriguing phenomena observed in strongly-driven molecular rotors. The first one is about the production of coherent extreme ultraviolet radiation (XUV) of controlled polarization 1. A circularly-polarized (CP) laser pulse is used to generate high-order harmonics in a gas jet of linear molecules previously aligned by a linearly polarized short laser pulse. By varying the temporal delay between the two pulses, a control over the polarization state of the generated XUV radiation can be achieved. High-order harmonics generated with high ellipticity (close to unity) are thus demonstrated.
The second one is related to the observation of the rotational Doppler effect in the nonlinear interaction of a CP laser pulse with fast spinning molecules 2. A gas ensemble of spinning molecules prepared by a pulse exhibiting a linear twisted polarization is exposed to a CP fundamental pulse driving a third-harmonic generation process. By recording the harmonic spectra for various handednesses of the photon polarization and molecule rotation, the whole set of nonlinear rotational Doppler frequency shifts envisioned by Simon and Bloembergen almost 50 years ago [3] was observed.

1 E. Skantzakis, S. Chatziathanasiou, P.A. Carpeggiani, G. Sansone, A. Nayak, D. Gray, P. Tzallas, D. Charalambidis, E. Hertz, O. Faucher, Polarization shaping of high-order harmonics in laser-aligned molecules, Sci. Rep. 6, 39295 (2016).
2 O. Faucher, E. Prost, E. Hertz, F. Billard, B. Lavorel, A.A. Milner, V.A. Milner, J. Zyss, I.S. Averbukh, Rotational Doppler effect in harmonic generation from spinning molecules, Phys. Rev. A 94, 051402(R) (2016).
[3] H.J. Simon, N. Bloembergen, Second-Harmonic Light Generation in Crystals with Natural Optical Activity, Phys. Rev. 171, 1104-1114 (1968).

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Studying the supersonic astrophysically-relevant plasma jets collimating via poloidal magnetic field in laboratory.

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This paper aims at investigating the studying the supersonic plasma jets via poloidal magnetic fields in laboratory. Recent laboratory studies 1 and astrophysical simulations have shown the viability of observationally-detected poloidal magnetic fields to directly result in the collimation of outflows and the formation of jets in astrophysical accreting systems such as young stellar objects (YSO). Application of external magnetic field to a laser-generated plasma flows allows to investigate stable, large aspect ratio plasma jets which are relevant to a number of astrophysical cases. The experiments were conducted in laboratory LULI of Ecole Polytechnique in Palaiseau, France. The laser with pulse duration t= 0.6 ns and energy E=40 J was focused to 700 um focal spot at solid CF2 target in presence of 20 T poloidal magnetic field. The parameters of the plasma jets were studied by means of spatially resolved X-ray spectroscopy and Mach-Zehnder interferometry. The electron temperature Te and density Ne profiles of the plasma were obtained using the method 2. It is shown that Ne decreases monotonically in the case without B-field, but demonstrates an extended density profile up to 10 mm when 20 T magnetic field is applied. While at the laser irradiated target surface Te peaks at 250-280 eV, at 3 mm distance it cools down to ~ 20 eV. Then, due to the impact of B field providing the collimation of the jet, Te and Ne are measured to keep at almost constant values along many mm's along the jet. By the way, the role of angle between poloidal B field and jet disk has been studied. It is demonstrated that collimation of jet is high up to 20 degrees.

References:

1. B. Albertazzi et al., Science 346, 325 (2014).
2. S. N. Ryazantsev et al., JETP letters 102, iss. 11, 817 – 822 (2015)

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Time-delay compensated monochromator for pump-probe experiments: spatio-temporal characterization

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Femtosecond pulses tunable in the extreme-ultraviolet (XUV) spectral region are particularly important in many research areas, for example for time- and angular-resolved photoemission spectroscopy or femtosecond pump-probe spectroscopy of core and valence levels. A crucial prerequisite for all applications is the accurate measurement of the temporal characteristics of these pulses.
We show that ultrashort XUV pulses, produced by high-order harmonic generation in gas and spectrally filtered by a time-compensated monochromator, can be completely characterized in terms of temporal intensity and phase. This is achieved by adapting an experimental technique used in the case of attosecond XUV pulses: the frequency-resolved optical gating for complete reconstruction of attosecond bursts (FROG CRAB). We demonstrate the generation and complete temporal characterization of XUV pulses with duration down to 5 fs.
High-order harmonics have been generated by using ~14-fs pulses at 800-nm central wavelength. Spectral selection was accomplished by employing a time-delay compensated monochromator composed by two sections, each based on the use of two toroidal mirrors and one plane grating, working in a subtractive configuration to compensate for the temporal and spectral dispersion. After the monochromator, XUV and IR pulses are recombined with a close-to-collinear geometry and focused into an interaction region equipped with a gas nozzle and a time-of-flight (TOF) spectrometer. The IR spatial profile in the focus has a full-width at half-maximum (FWHM) of ~150 µm. After selection, the XUV beam size in the focus, measured by using a Ce:YAG crystal, is <50 µm. Typical single harmonic energies are of few tens of pJ per harmonic pulse.
The temporal characteristics of the XUV pulses have been measured by using a cross-correlation technique. The photoelectrons generated by combined action of the XUV and IR pulses were collected by a TOF spectrometer, which recorded the spectrum as a function of the delays between the two pulses. When the two pulses overlap in time and space on a gas jet, sidebands appear in the photoelectron spectrum, spectrally shifted by the IR photon energy, determined by the absorption of one harmonic photon plus the absorption or the emission of one IR photon. By applying a reconstruction technique based on the extended ptychographic iterative engine it was possible to retrieve the intensity profile and phase of the XUV pulses. We obtained a pulse duration of 9±0.5 fs for the 19th harmonic and 5±0.5 fs for the 27th harmonic. The latter represents, to the best of our knowledge, the shortest XUV femtosecond pulses ever measured at the output of a XUV monochromator.

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Nano-optics for ultra-high power, tailored laser-matter interaction

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Nano-optics for ultra-high power, tailored laser-matter interaction

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Recently, increasing efforts were dedicated to target design and manufacturing for high power laser – plasma interaction experiments [Prencipe]. Motivated by the laser characteristics and by secondary radiation output, this work started to shed light on a rich physics domain at the frontier of plasma physics, solid state physics and optics. In this context, nano-optics concepts were applied in high power laser experiments [Ji, Kaymak] to control efficiently the coupling of light with targets.

At ELI-NP we plan to enhance the optical response of our targets, ultimately to control the local, near-field polarization, intensity and preplasma profile. We explore beyond simple planar target design, the structuration of targets being one of our core activities, both in 3D features and dielectric profile. Here we will present a short overview of this work.

References

[Prencipe] Prencipe et al., High Power Laser Science and Engineering 5, 00201717, (2017)

[Ji] Ji et al., Scientific Reports 6, 23256 (2016)

[Kaymak] Kaymak et al., Phys. Rev. Lett. 117, 035004 (2016)

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Overview on targets capabilities at ELI-NP

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At ELI-NP, a dedicated Target Laboratory has been implemented in order to insure the target demands for high power laser and gamma beam experiments. For this purpose, the 270 m^2 Target Laboratory currently accommodates a wide range of state-of-the-art 6 inch Si wafer equipment necessary for the fabrication, characterization and micro-assembly of a broad range of solid targets.1

In order to meet the demands, different types of targets can be prepared with our technical capabilities: thick/thin foils of metals, nitrides and oxides, free-standing films, mono- or multi-layered, multi-components, micro/nano-structured targets (with additional gratings2, microspheres[3,4], microwires[5], nanoparticles[6]), 3D micro-machined targets and reduced mass targets[7] among others. For the first stage of experiments at ELI-NP, the main focus will be directed towards free-standing thick (a few microns) and ultra-thin/thin (few tens of nanometers) target films, of low-Z materials (polymer) for proton acceleration and high-Z materials (Si_3N_4, Al, Cu, Au) for high fluence ion bunch acceleration. A description of the fabrication methodology for the proposed targets correlated with our manufacture and diagnosis capabilities is presented in this work.

1 C.C. Gheorghiu et al., *Journal of Instrumentation* 11, 10 (2016).
2 T. Ceccotti et al., *PRL* 111, 185001 (2013).
[3] D. Margarone et al., *Phys. Rev. ST Accel. Beams* 18, 071304 (2015); D. Margarone et al., *PRL* 109, 234801 (2012).
[4] J. Limpouch et al., *EPJ Web of Conferences* 59, 17011 (2013); P. L. Poole, et al., *Physics of Plasmas* 21, 063109 (2014).
[5] S. Jiang et al., *Phys. Rev. E* 89, 013106 (2014); S. Jiang et al., *Eur. Phys. J. D* 68 (2014), 283; S. Jiang et al., *PRL* 116, 085002 (2016).
[6] M. Dalui et al., *Scientific Reports* 5 (2015) 11930.
[7] K. Zeil et al., *Plasma Phys. Control. Fusion* 56 (2014) 084004; O Tresca et al., *Plasma Phys. Control. Fusion* 53 (2011) 105008.

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Overview of FERMI, the first externally seeded Free Electron Laser user facility in the extreme ultraviolet and soft X-ray spectral regions

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FERMI is a seeded Free Electron Laser (FEL) user facility at the ELETTRA-Sincrotrone laboratory in Trieste. We provide an overview of FEL performances of this externally seeded source based on the high gain harmonic generation scheme, where the light from an optical laser is up-converted in frequency and amplified the the VUV to EUV and soft X-rays spectral range. This fourth-generation light source is characterized by a number of desirable properties, such as wavelength stability, low temporal jitter and longitudinal coherence.

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On the EMP Shielding and Damage Mitigation at ELI-NP

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The experiments planned with the unique in the world laser and gamma beam systems at ELI-NP 1, 2, are expected to lead to important breakthroughs in the study of nuclear physics. Designing and implementing experiments at these machines involve significant engineering challenges, including on the laser side, the EMP [3] shielding and damage mitigation. Due to operation of dual 10 PW lasers the problems with EMP are particularly acute, because measurements of the unique physical phenomena produced can be hampered by EMP pick-up. There is also a need to ensure that the level of personnel exposure to EMP, in the occupied areas, is below any risk.

In order improve the devices functionality in the EMP environment and to protect the human beings, the conductive and radiative coupling shall be reduced. Thereby, the configuration of the target chamber shall be strictly controlled. In this context, an overview of the shielding strategy applied at ELI-NP is presented and the current status of the implementation of the EMP shielding for experiments within building is reviewed. While EMP is a highly complex challenge, some important aspects which should be considered in design of experimental setups in order to obtain and maintain the overall integrity of electromagnetic shield are pointed out.

References:

1 N.V. Zamfir, Romanian Reports in Physics, Vol. 68, Supplement,
P. S3–S4, 2016,
2. S. Gales, Romanian Reports in Physics, Vol.
68, Supplement, P. S5–S10, 2016,
[3]. M. Mead et.al, Review of
Scientific Instruments, Vol. 75, 4225-4227, 2004.

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Nonlinear Thomson backscattering as a source of CEP controlled isolated attosecond pulses

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Nonlinear Thomson scattering, i.e. classical electromagnetic radiation of a relativistic electron beam driven by an intense laser pulse, is a promising method for the generation of high-order harmonics and attosecond light pulses. As it is well-known, such isolated attosecond pulses are the best tools

to investigate the real time electron dynamics in atoms, molecules and solids, which is among the primary aims of the ELI-ALPS research institute. In our recent theoretical work, we already demonstrated the possibility of isolated attosecond pulse generation in the XUV–soft X-ray regime, assuming the head-on collision of a mono-energetic non-interacting electron bunch with a high-intensity near-infrared laser pulse, based on an explicit analytical formula for the relativistic electron's motion in the field of a few-cycle laser pulse with sine-squared envelope. We also emphasised the importance of the correct treatment of the initial values, especially in the case of several electrons.
In the present contribution, we report about our new results regarding feasibility and important features of these pulses. Our calculations of the angular dependence of the radiation, predict that these isolated attosecond pulses propagate in a narrow beam around the direction of the initial velocity of the electron bunch. The pulse energy is in the nJ range, i.e. it is comparable to the pulse energies obtained by gas-HHG. We have also computed the carrier-envelope phase difference (CEP) of the isolated attosecond pulses which turns out to be shifted by π with respect to the CEP of the driving laser pulse, thereby providing the ability to control this parameter also.

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What is an X-Ray Free Electron Laser and Why You Should Care?

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The concept for high gain free electron lasers (FELs) dates to the early 1980s. The first realization of these ideas is the FLASH facility in Hamburg Germany. The LCLS, which started operation in 2009, is the first FEL to reach the hard x-ray regime with wavelengths near 1Å. Following initial operation of LCLS there are an additional 4 FELs worldwide operational or nearly so. The first part to this talk will discuss what an FEL is, the rapid development of performance, and the possible future. Reference will be made to seeded operation which is highlighted by the XUV/soft x-ray FEL FERMI in operation in Trieste, Italy. The attention will then turn to what has been demonstrated using these unique light sources that can only be done with FELs and what ideas have been spawned that are now pursued at other accelerator based light sources.

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Attoclock Revisited

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The attoclock is a recently developed approach for the extraction of tunneling delay time in the context of strong field ionization. The most recent experimental measurements found sub-luminal tunneling times over a wide intensity range.
However, while the experiments seem to agree that quantum tunnelling does not happen instantaneously, there is no consensus yet on the theoretical side.
This talk will survey recent theoretical and experimental developments in the attoclock approach to extracting tunneling delays, and discuss the implications of new discoveries on the interpretation of attoclock experiments

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Stellar Photoreactions at ELI-NP

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In stellar environments, nuclei undergo photoreactions while occupying thermally populated, nuclear excited states. These states have not before been accessible in laboratory environments. Extreme Light Infrastructure – Nuclear Physics (ELI-NP) presents researchers with a unique set of tools to induce and detect these stellar photoreactions. Utilizing an ultrafast petawatt laser system, we propose to excite nuclei using bremsstrahlung radiation derived from electron acceleration in a gas jet. Depending on the lifetime of the excited states, this procedure can be preformed using one or more laser pulses. The isomers will then be photoexcited by an intense, highly synchronized γ-ray beam and the reaction verified by the detection of photoneutrons.

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Spatial shaping of high harmonics generated from plasma mirrors

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Focussed ultrashort intense light can transform any solid surface into an instantly ionised plasma reflector. This type of exotic plasma optics can operate at ultra-high intensities making them extremely attractive and also the only optics available at such high light fields. We show that they can act as tuneable reflective 1 or diffractive 2 elements which can be controlled for surface sharpness 1, shape [3,4], structure [2,5] and can be driven over ultrafast timescales to relativistic motion in phase with the driving laser field [3]. The last property lets it also act as a coherent XUV light emitter [6] as well as a novel energetic charge particle source [7,8]. These solid density surface plasmas can undergo nonlinear sub-cycle interaction at relativistic light intensities, and alter the light pulse itself by introducing attosecond spikes in the reflected field. We show that one can design and utilize diffractive plasma optics and control the spatial beam profile of attosecond pulses emanating from relativistically driven surface plasmas.

In this presentation I would introduce different exciting schemes to create plasma optics at high intensity and control their various properties that we developed recently. Finally I would present few recent examples to show how these properties allow one applications which are not possible otherwise [9]. I would also discuss the cases where different regimes of high harmonic diffraction [1,2,9] is accessed with active or passively controlled diffractive element 2. These coherent sources [6] have tremendous potential for further scientific applications [10]. The high repetition rate operation modes like the beamlines at ELI-ALPS [11] would provide opportunities in this direction.

References

1 S. Kahaly, et al.Phys. Rev. Lett. 110, 175001 (2013).

2 S. Monchose, et al., Phys. Rev. Lett. 112, 145008 (2014).

[3] H. Vincenti, et.al Nat. Commun. 5, 3403 (2014).

[4] M. Nakatsutsumi, et al. Opt. Lett. 35, 2314 (2010).

[5] M. A. Purvis et al., Nature Photonics 7, 796 (2013).

[6] S. Chatziathanasiou, et. al., Photonics 4, 26 (2017).

[7] M. Thevenet, M. et al. Nat. Phys. 12, 355–360 (2015).

[8] M. Bocoum, et.al., Phys. Rev. Lett. 116, 185001 (2016).

[9] A. Leblanc, et.al., Nat. Phys. 12, 301 (2015).

[10] M. Reduzzi, et al., J. Electron Spectros. Relat. Phenomena 204, 257 (2015).

[11] S. Kühn, M. Dumergue, S. Kahaly, S. Mondal et. al J. Phys. B: At. Mol. Opt. Phys. 50, 132002 (2017).

Summary:

Sub-cycle charge dynamics in relativistic plasmas can lead to attosecond pulse trains in the reflected laser pulse. Analysis and control of the spatial properties of this high harmonic radiation can be done through different approaches. Here I would be talking about in-situ control of these spatial properties by using a phase mask in the interaction region. Finally the technique is extended and used to measure the spatial phase and amplitude profile of the high harmonic beam as well as properties of this phase mask supporting the relativistic interaction.

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Future of Ti:Sapphire lasers: combining high peak and average power

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Ti:Sapphire gain medium has exceptional spectral and thermal properties. This determines their wide use in most of modern high peak laser systems. As any laser medium the bandwidth of Ti:Sapphire lasers is limited by gain narrowing, while the maximum repetition rate, or average power are limited by the efficiency of the homogeneous heat removal. A research and development project at ELI-ALPS, HF-100 is assigned to the development of specific technologies that applied to Ti:Sapphire medium will allow to overcome the currently existing technological limits of bandwidth and average power. The basis for that are the two new developments: Thin Disk Ti:Sapphire amplifiers with energy distributed pumping (EDP-TD) 1 and Polarization encoded Chirped Pulse Amplification (PE-CPA) 2. A combination of these technologies is able to support laser pulses of few oscillations at hundreds of TW peak and kW [3] average power.

1 V.Chvykov, H. Cao, R. Nagymihaly, M. Kalashnikov, N. Khodakovskiy, R. Glassock, L. Ehrentraut, M. Schnuerer, K. Osvay, Opt. Lett. 41 (2016) 3017-3020.

2 V. Chvykov, R. S. Nagymihaly, H. Cao, M. Kalashnikov, K. Osvay , Optics Express 24 (2016) 3721-3733

[3] R. S. Nagymihaly, H. Cao, D. Papp, G. Hajas, M. Kalashnikov, K. Osvay, and V. Chvykov, Optics Express, 25, (2017), 6664-6677

[4] M. Kalashnikov, H. Cao, K. Osvay, V. Chvykov, Optics Letters, 41 (2016) 25-28

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High-order harmonic generation in hydrogen-like atoms: Floquet approach

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The interaction of strong laser fields with atoms has been extensively investigated 1 since the discovery and construction of the first lasers. Floquet analysis has been proved to be an extremely useful tool for the non-perturbative theoretical description of strong-field phenomena. It can appropriately treat various high-order processes like high-order harmonic generation (HHG) or ionization of atoms.
The numerical integration of the time-dependent Schrödinger equation is difficult by the usual way of solving partial differential equation. Also the perturbative methods can handle only weak excitation with acceptable numerical errors. However, Floquet method transforms the TDSE to an infinite dimensional eigenvalue problem 2. This problem is computationally easy, provided the corresponding matrix has finite dimensions. (Obviously, it is impossible to take all the free atomic states into account numerically.) This means that we have to truncate the Hamiltonian matrix. As a first approach, one may use the free hydrogen eigenstates for calculations, but the truncation causes reflections of the wavefunction at the boundaries. Instead, we use Sturmian basis [3] which contains a certain part of the continuum and provides appropriate solution.

Summary:

We apply the newly developed method to examine the influence of the initial state on the high-order harmonic generation (HHG) spectra, in hydrogen-like atomic gases.
We optimized the high harmonic generation process (driven by monochromatic excitation) to produce short attosecond pulse trains. By examining the dynamics corresponding to initial atomic superposition states, we can optimize the process to find the best (shortest, most intense) response signal. The initial states were found to have influence also on the HHG spectra.

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Attoclock revisited on quantum tunneling time

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Quantum tunneling is a fundamental and ubiquitous effect that sparked a long-standing debate on the time duration of this process (1, 2). The main theoretical contenders, such as the Keldysh, Buttiker-Landauer, Eisenbud-Wigner (also known as Wigner-Smith), and Larmor time give contradictory answers.
The attoclock is a recently developed approach for the extraction of tunneling delay time in the context of strong field ionization (3, 4). Our most recent attoclock experimental measurements (5) found a finite tunneling time over a wide intensity range and therefore a large variation of tunnel barrier width. This result sparked a number of theoretical developments (6–9). Only two theoretical predictions are compatible within our experimental error: the Larmor time, and the peak of the probability distribution of tunneling times constructed using a Feynman Path Integral (FPI) formulation. The FPI

theory matches the observed qualitative change in tunneling time over a wide intensity range, and predicts a broad tunneling time distribution with a long tail. The implication of such a probability distribution of tunneling times, as opposed to a distinct tunneling time, would imply that one must account for a significant, though bounded and measurable, uncertainty as to when the hole dynamics begin to evolve (5). The FPI theory also agrees well when we take into account all non-adiabatic corrections. Another independent attoclock experiment (10) recently found finite tunneling delay times as well.

While the experiments seem to agree that quantum tunneling does not happen instantaneously, there is no consensus yet on the theoretical side (6–9). However this topic is important not only to the interpretation of time-resolved studies in attosecond physics, but also in the treatment of many experimental schemes in the AMO community which are based on a semiclassical view of strong-field ionization (11–13).

In this keynote talk we will review why tunneling time is such a highly debated theoretical concept in quantum mechanics and why both statements "cannot be measured because time is not an operator" and "just follow the peak of the wavepacket" do not resolve this issue. Following the peak of a wavepacket, for example, can be tricky and often misleading. In contrast to a light pulse, an electron wavepacket disperses even in vacuum. Since the propagation of the peak of the wavepacket is defined by the group delay, almost any group delay can be measured during propagation in combination with an appropriate energy-dependent transmission filter. In fact strong-field ionization in the dipole approximation (i.e. tunnel ionization) is much faster than the group delay of the electron wavepacket (i.e. Wigner delay).

We will review the recent theoretical and experimental developments in the attoclock approach to extract tunneling delays with regards to the typical approximations such as the dipole approximation, non-adiabatic effects, photoelectron momenta at the tunnel exit, electron correlation and exit coordinate. We will review the initial conditions of semiclassical models. These describe the photoelectron wavepacket at the tunnel exit, and how their choice affects the delays extractd from the attoclock experiment (6, 7, 9, 14–16). Furthermore non-adiabatic effects and their interplay with the field strength calibration of strong-field ionization experimental data will be discussed (15, 17). Another section would present the role of multi-electron effects (18–20) and the dipole approxmiation (21)

References

(1) Landsman, A.S.; Keller, U. Physics Reports 2015, 547, 1–24.
(2) Landauer, R. Nature 1989, 341 (6243), 567–568.
(3) Eckle, P.; Smolarski, M.; Schlup, P.; et al. Nature Physics 2008, 4 (7), 565–570.
(4) Eckle, P.; Pfeiffer, A.N.; Cirelli, C.; et al. Science 2008, 322 (5907), 1525–1529.
(5) Landsman, A.S.; Weger, M.; Maurer, J.; et al. Optica 2014, 1 (5), 343.
(6) Zimmermann, T.; Mishra, S.; Doran, B.R.; et al. Physical Review Letters 2016, 116 (23), 233603.
(7) Ni, H.; Saalmann, U.; Rost, J.M. Physical Review Letters 2016, 117 (2), 023002.
(8) Teeny, N.; Yakaboylu, E.; Bauke, H.; et al. Physical Review Letters 2016, 116 (6), 063003.
(9) Torlina, L.; Morales, F.; Kaushal, J.; et al. Nature Physics 2015, 11 (6), 503–508.
(10) Camus, N.; Yakaboylu, E.; Fechner, L.; et al. Physical Review Letters 2017, 119 (2), 023201
(11) Meckel, M.; Comtois, D.; Zeidler, D.; et al. Science 2008, 320 (5882), 1478–1482.
(12) Lin, C.D.; Le, A.T.; Chen, Z.; et al. Journal of Physics B: At. Mol. Opt. Phys. 2010, 43 (12), 122001.
(13) Bruner, B.D.; Soifer, H.; Shafir, D.; et al. Journal of Physics B: At. Mol. Opt. Phys. 2015, 48 (17), 174006.
(14) Ivanov, I.A.; Kheifets, A.S. Physical Review A 2014, 89 (2), 021402.
(15) Boge, R.; Cirelli, C.; Landsman, A.S.; et al. Phys. Rev. Lett. 2013, 111 (10), 103003.
(16) Klaiber, M.; Hatsagortsyan, K.Z.; Keitel, C.H. Physical Review Letters 2015, 114 (8), 083001.
(17) Hofmann, C.; Zimmermann, T.; Zielinski, A.; et al. New Journal of Physics 2016, 18 (4), 043011.
(18) Pfeiffer, A. N.; Cirelli C.; Smolarski M.; et al. Nature Physics 2012, 8, 76
(19) Emmanouilidou, A.; Chen, A.; Hofmann, C.; et al. Journal of Physics B: At. Mol. Opt. Phys. 2015, 48 (24),245602.
(20) Majety, V.P.; Scrinzi, A. Journal of Modern Optics 2017, 1–5.
(21) Ludwig, A.; Maurer, J.; Mayer, B. W.; et al. Physical Review Letters 2014, 113, 243001

Summary:

Quantum tunneling time is a highly debated topic – we explain why. We discuss the attoclock technique to extracting tunneling delays with regards to the typical approximations such as the dipole approximation, non-adiabatic effects, photoelectron momenta at the tunnel exit, electron correlation and exit coordinate.

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14-W, 100-kHz, few-cycle mid-infrared source at ELI-ALPS

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ELI-ALPS aims to provide the scientific community with novel light sources having extreme properties towards the attosecond edge of science. Each of its driving laser sources exhibit unprecedented specifications concerning average and peak power, pulse duration and most importantly, excellent long term stability which can substantially improve experimental reproducibility. Compared to the other laser systems of the facility, whose wavelengths are either centered in the near-infared (SYLOS, HR and HF) or in the THz spectral region (THz laser), the mid-IR laser (MIR) operates in the highly demanded wavelength region around 3 µm.
It is well known, that the extension of High order Harmonic Generation (HHG) up to soft-x-ray domain requires driving sources with specific properties: mid-infrared wavelength, few-cycle pulses, high peak intensity, carrier-envelope phase stability and control, high energy and/or high-repetition rates. While long wavelength optical carriers extend the cutoff energy through the λ2 dependency of the ponderomotive energy, shortening the pulses to few cycles increases the peak intensity and improves the HHG conversion yield. Moreover, the number of generated attosecond bursts is decreasing with the decreasing number of optical cycles of the driving electric field, up to the generation of a single isolated attosecond pulse for 2 or less optical cycles. In this regime, CEP stability and control is paramount to ensure a shot-to-shot reproducibility of the driving electric field as well as of the HHG yield and spectrum.
Hereby, we report on the outstanding final performance of the MIR laser, developed within a successful R&D collaboration between Fastlite and ELI-ALPS. The system is a supercontinuum self-seeded optical chirped-pulse parametric amplifier (OPCPA) generating few cycle, CEP-stable pulses at ~3.2 µm. It is pumped by a Yb:YAG regenerative amplifier delivering ~1.1 ps pulses with a pulse energy of 1.75 mJ at 100 kHz, and combines chirp-reversal with acousto-optic pulse shaping (Dazzler) at 100 kHz to ensure compressibility in bulk material and extremely high CEP-stability.
The pump energy distribution is optimized among the four parametric stages in order to reach the highest overall extraction and the broadest spectrum at the output simultaneously. The first two stages are based on MgO-doped periodically poled Lithium Niobate (MgO-PPLN) crystals, pumped in collinear geometry The last two stages are non collinear parametric amplifiers made of a bulk LiNbO3 crystals heated to 120°C. The output pulse energy reaches ~155 µJ before compression for a full pump energy of 1.7 mJ. Compression, at full power, in an AR-coated Silicon window yields a pulse duration of sub-40 fs pulses and an output pulse energy >140 µJ, which corresponds to a duration below four optical cycles at 3.2 µm, and a peak power of 3.5 GW. In order to reach <100 mrad single shot CEP stability and monitor some of the major parameters continuously during operation, a few portion of the main beam is sampled by the properly coated output window. Due to sampling the pulse energy of the final output is reduced to ~130 µJ.
The long term power stability of the compressed output is measured to be 0.8% RMS, with an average power of 14 W, measured over 10 hours of uninterrupted operation (Fig 1.); the simultaneously monitored beam pointing stability is 17 µrad RMS. The measured non-averaged CEP stability is <85 mrad measured over 6 hours, achieved by an efficient proportional feedback loop where the error signal (measured by 2f-to-f interferometry) is send to the pulse shaper. Moreover, the system is able to reach the 14 W output within 2 minutes - counted from the opening of the main shutter, after the pump laser is in hot (stable) state.

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Few-cycle mid-infrared source with sub-100 mrad CEP stability

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At present, light bursts with few tens/hundreds of attoseconds duration are the primary tools to reveal, understand and control the ultrafast events of the microworld, related to the motion of electrons and charge carriers of substances ranging from nanostructured semiconductors to the DNA of living species. The generation of such attosecond pulses/pulse trains is realized by the technique of High order Harmonic Generation (HHG) processes driven by laser sources with few femtosecond pulsed output.
As the ultrafast driving laser sources for HHG has reached the few optical cycle regime, it becomes necessary to provide high precision stabilization and control of the relative phase between the carrier wave and its pulse envelope (CEP). This feature is paramount to ensure shot-to-shot reproducibility of both HHG yield and spectrum. For the extension of the harmonic cut-off up to soft-x-rays (and keV regime), a long wavelength driving laser is required due to the λ² dependency of the ponderomotive energy. In other words, a few cycle, high peak and average power laser is preferred in the mid-infrared, with extreme stability of the CEP.
The mid-infrared laser (MIR) of ELI-ALPS operates in the highly demanded wavelength region around 3 µm; the system has developed within a fruitful R&D collaboration between Fastlite and ELI-ALPS. Here, we report on the outstanding performance of the MIR laser, focusing on the unprecedented CEP stability and control of the system. The MIR is a supercontinuum self-seeded optical chirped-pulse parametric amplifier (OPCPA) generating few cycle, CEP-stable pulses at ~3.2 µm. It is pumped by a Yb:YAG regenerative amplifier delivering ~1.1 ps pulses with a pulse energy of 1.75 mJ at 100 kHz, and combines chirp-reversal with acousto-optic pulse shaping (Dazzler, Fastlite) at 100 kHz to ensure compressibility in bulk material and extremely high CEP-stability.
Compression, at full power, in an AR-coated Silicon window yields a pulse duration of sub-40 fs pulses at 3.2 µm and an output pulse energy >140 µJ, which corresponds to a duration below four optical cycles, and peak power of 3.5 GW. The output has a long term power stability of 0.8% RMS over 10 hours of uninterrupted operation, combined with 17 µrad (rms) beam pointing stability.

In order to reach <100 mrad single shot CEP stability a small portion of the compressed sub-40 fs pulses (<4 cycles at 3.2 µm) are sampled to drive the CEP diagnostics system consists of a 2f-to-f interferometer and a fast spectrometer with onboard calculation capabilities (Fringeezz, Fastlite). The device records the spectral fringes generated in the 2f-to-f (analog beating signal), then computes and stores the phase drift of the interferogram at 10 kHz. With a minimum integration time (3 µs) of the detector array, it is possible to measure the CEP drift between isolated pulses, however the readout time is insufficient and limit the single shot measurement to one pulse out of ten.
The measured error signal is fed back (proportional feedback) to the Dazzler at 10kHz to correct for CEP fluctuations. As demonstration of the capabilities of the system, the results of a 6 hours long CEP stability measurement is displayed on figure 1. The non-averaged CEP noise is below 85 mrad rms, which is to date, the smallest recorded value measured on an amplified system. Moreover, it is possible to add an offset to the CEP, and perform a controlled relative shift of the phase whenever it is necessary.
Reducing the duration to the single-cycle regime by post-compression techniques based on waveguides (Kagome fibers), may open up the door for CEP-sensitive experiments like charge dynamics in solids or electron dynamics in molecules.

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Analysis of gas-filled capillary plasma discharge systems

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The gas-filled capillary plasma discharge system built at PTE-TTK with the help from SZTE-TIK, has been further investigated. We will describe in detail the operation of the gasfilled capillary plasma discharge related to the different component arrangements. Meanly the performance of the different sparkgaps(gas-filled versus water-filled), electrodes and capillaries. To achieve the most stable operation with minimal jitter at repetative high discharge current pulses (~20kA) for our capillary soft X-ray laser (neon-like Ar8+, lasing at 47 nm) and also for the future experiments which would raise the discharge current pulse to 30-40kA.

Summary:

The optimized capillary Z-pinch plasma system could be also used to produce waveguides for wake-field acceleration of electrons in future experiments at the ELI facilities.

This project was supported by the grant “Ultrafast physical processes in atoms, molecules, nanostructures and biological systems”(EFOP-3.6.2-16-2017-00005)

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Simulations for proton diagnostics in high-power laser experiments based on population of nuclear isomeric states

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Simulations for a method to characterize protons accelerated in high-power laser-solid target interactions are presented. A prospective setup and possible experimental conditions were simulated using the Geant4 toolkit 1. Protons with energies up to 150 MeV were considered as primary particles in the present approach. In addition to the processes which are part of the Geant4 physics, cross sections for (p,n) reactions calculated with the TALYS code 2 were implemented.

The simulated setup includes a stack of a Ta degrader on which the protons are impinged, a target of natural Zr behind it, and a layer of Ti, enriched to 82.5% ^{46}Ti placed behind the Zr target. A setup of five $LaBr_3$:Ce scintillators was included to detect the gamma decays of isomeric states in ^{90}Nb and ^{46}V populated via (p,n) reactions. The relation between the detected gamma ray yields and the proton beam properties is discussed.

The gamma background events in such experimental conditions were estimated. Simulations were performed for processes that do not lead to the population of the isomeric states of interest but still contribute to the $LaBr_3$:Ce detectors output. The background related to laser shots at different rates was simulated.

Population of isomeric states with half-lives in the millisecond region is possible also via gamma induced reactions. Calculations of cross sections for several gamma induced reactions were performed using the TALYS code. The opportunities to use them in the presented experimental conditions are discussed.

1 Geant4 development team, "Geant4 - a simulation toolkit", NIM A 506, 250 (2003).

2 A. J. Koning et al., "TALYS-1.0", Proceedings of the International Conference on Nuclear Data for Science and Technology, 211 (2008).

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Under-the-barrier recollisions in strong field ionization

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A new mechanism of strong laser field induced ionization of an atom is identified which is based on recollisions
under the tunneling barrier. Developing an enhanced strong field approximation, the interference of the direct
and the under-the-barrier recolliding quantum orbits are shown to induce a measurable shift of the peak of the
photoelectron momentum distribution. The scaling of the momentum shift is derived relating the momentum
shift to the tunneling delay time according to the Wigner concept. This allows to extend the Wigner concept for
the quasistatic tunneling time delay into the nonadiabatic domain. The obtained corrections to photoelectron
momentum distributions are also relevant for state-of the art accuracy of strong field photoelectron spectrograms
in general.

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Protein structure and dynamics using X-ray free-electron lasers

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Protein crystallography using synchrotron radiation sources has had tremendous impact on biology, having yielded the structures of thousands of proteins and given detailed insight into their working mechanisms. However, the technique is limited by the requirement for macroscopic crystals, which can be difficult to obtain, as well as by the often severe radiation damage caused in diffraction experiments, in particular when using tiny crystals. To slow radiation damage, data collection is typically performed at cryogenic temperatures.

The femtosecond X-ray pulses provided by X-ray free-electron lasers (FELs) allow the acquisition of high resolution diffraction data from micron-sized macromolecular crystals at room temperature beyond the limitations of radiation damage imposed by conventional X-ray sources. Moreover, the short duration of the pulses enable time-resolved studies at the chemical time-scale of femtoseconds. The approaches used as well as recent results obtained will be presented.

5

Nanometer characterization of expanding solid density plasmas during ultra-intense laser irradiation

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We report on a recent experiment studying the expansion of solid density plasmas under ultra-intense short-pulse laser irradiation with an unprecedented spatial and temporal resolution.
We employ Small Angle X-ray Scattering 1 of the LCLS XFEL pulse (SLAC) to probe the MEC short-pulse laser interaction (10^{18} W/cm², 80 fs) with thin carbon wires and silicon membranes. The silicon membranes were covered with a grating structure that allowed very sensitive probing of the plasma expansion down to single nanometer resolution at a spatial resolution limited only by the XFEL pulse duration (40 fs) and timing jitter (~100 fs). The wire targets showed deformation upon laser irradiation on a few ps time scale which was studied as a function of laser intensity.
The SAXS method now allows to directly compare our results to simulations. We find a remarkable agreement for example for the expansion velocity and expansion duration of the silicon gratings.

With the successful demonstration of the SAXS technique on ultra-intense short-pulse laser – solid interaction we expect to be able to develop a much clearer picture of the underlying physics, in a field which has so far mostly relied on indirect diagnostics such as radio-chromatic films or spectrometers. This might have far-reaching applications and implications for the development of laser based ion accelerators, fast ignition fusion science and the study of complex instability physics, isochoric laser heating and related fields.

References

1 T. Kluge et al., PoP 21, 033110 (2014)

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ELI beamlines: Status of facility and first experiments with high field power laser

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We will be giving an overview on the development of the "ELI-Beamline facility" being built within the Extreme Light Infrastructure (ELI) project based on the European ESFRI (European Strategy Forum on Research Infrastructures) process.
ELI-Beamlines will be a high-energy, repetition-rate laser pillar of the ELI (Extreme Light Infrastructure) project. It will be an international facility for both academic and applied research, slated to provide user capability since the beginning of 2018. The main objective of the ELI-Beamlines Project is delivery of ultra-short high-energy pulses for the generation and applications of high-brightness X-ray sources and accelerated particles. The laser systems will be delivering pulses with length ranging between 10 fs and 150 fs and will provide high-energy Petawatt and 10-PW peak powers. For high-field physics experiments it will be able to provide focused intensities attaining >1022-23 Wcm-2, while this value can be increased in a later phase without the need to upgrade the building infrastructure to go to the ultra-relativistic interaction regime in which protons are accelerated to energies comparable to their rest mass energy on the length of one wavelength of the driving laser.
We will discuss the status of the building and its infrastructure concerning the availability of experimental areas, the development of the lasers including highly stable beam transport solutions and secondary sources of particles and x-rays in the wavelength range between 20 eV-100 keV and their practical implementation in the ELI-Beamline user facility. The sources are either based on direct

interaction of the laser beam with a gaseous targets (high order harmonics) or will first accelerate electrons which then will interact with laser produced wigglers (Betatron radiation) or directly injected into undulators (laser driven LUX or later X-FEL). The direct interaction (collision) of laser accelerated electrons with the laser again will lead to short pulse high energy radiation via Compton or Thomson scattering. The planned first commissioning experiments on x-ray generation, particle acceleration (electrons and protons) as well as on plasma physics and their applications together with the available experimental infrastructure will be introduced.

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Multi-parameter optimization of the ELI-ALPS SYLOS high-harmonic beamline

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One principal workhorse of the ELI-ALPS infrastructure will be the SYLOS laser which is planned to deliver laser pulses of <10 fs duration around 800 nm central wavelength with up to 45 mJ pulse energy (for Phase 2) at 1 kHz repetition rate 1. This laser will drive the high-harmonic generation process in order to obtain high flux coherent XUV attosecond pulses. The targeted spectral range is between 10 and 70 eV, depending on the generating gas medium.

There are no experimental evidences which could guarantee the best parameter set for the highest possible yield, therefore reliable simulations are mandatory. When performing the simulations exploring the 3D non-adiabatic numerical code 2 specially adapted to the demands of ELI-ALPS, we rely on the scaling principles already demonstrated and validated both mathematically and experimentally [3].

Here we perform a multidimensional parameter scan which has the main purpose to find the macroscopic conditions that optimize the harmonic yield in specific spectral domain for further applications. For this particular case study we chose to optimize the yield around 40 eV which corresponds to the 25-27th harmonic of the 800 nm fundamental pulse in Argon gas. We keep fixed: the gas type, beam type (Gaussian), laser wavelength, initial beam diameter and the focal length. The scanned parameters are the following: laser pulse energy, gas pressure, gas position relative to laser focus, gas medium length. The raw simulation results are an impressive amount of data with high information content.

The main conclusion of the multi-dimensional parameter scan is the following: the best configuration is when the gas cell is placed **before** the geometrical focus and the pressure is between 5-20 mbar. We scanned also for the optimal cell length (up to 20 cm) and observed a clear tendency: as we increase the pressure and as the medium comes closer to the focus, shorter cells are more advantageous.

Due to the enormous amount of data we chose to closely examine only several representative cases which provide the highest yields. In these configurations we perform a detailed analysis of the underlying macroscopic mechanisms that lead to promising results.

We are convinced that such a multi-dimensional scan over several parameters is of great help in the design and construction of the SYLOS beamline.

References

1 S. Kühn et al., J. Phys. B: At. Mol. Opt. Phys. **50**, 132002 (2017)

2 Tosa V, Kim H T, Kim I J and Nam C H, Phys. Rev. A **71**, 063807 and 063808 (2005)

[3] C.M. Heyl, H. Coudert-Alteirac, M. Miranda, M. Louisy, K. Kovacs, V. Tosa, E. Balogh, K. Varjú, A. L'Huillier, A. Couairon, C.L. Arnold, Optica **3**, 75 (2016)

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Dispersion Measurement on the Large Aperture SYLOS1 Beam Transport Mirrors at Arbitrary Incidence Angle and Polarization State

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The mirrors of femtosecond high peak power lasers have to comply with strict requirements in bandwidth, spectral phase shift, and laser damage threshold. Nowadays, PW class lasers with sub-30 fs pulse duration are operating 1, while the pulse duration would be further shortened below 15 fs 2. To achieve the highest possible intensity on the target, a precise control of spectral intensity and spectral phase is required. One needs to ensure that the spectral phase is homogeneous over the entire mirror surface well exceeding 10 cm. Due to the technical limitations or requirements of experiments, some of the mirrors are intended to use at an angle of incidence far from normal or 45°, and for a pulse with linear polarization between S and P. In this paper we demonstrate a robust technique, which offers unique opportunity to scan the dispersion of large mirrors at an arbitrary degree of incidence and polarization state.
The measurement is based on Spectrally Resolved Interferometer [3], consisting of a Michelson interferometer illuminated by a tungsten halogen lamp with 10 mW average power. A combined visible and infrared spectrometer makes possible to measure the dispersion properties over 500-1300 nm spectral range. The sample arm of the Michelson interferometer contains the mirror to be measured. Using an adjunct mirror, it was possible to change continuously the angle of incidence at the chirped mirror within 3 and 55°. A wire-grid polarizer has been placed on the input part of the interferometer and the sensitivity of the chirp mirrors to the polarization state have been measured at different angles of incidence.

Summary:

To demonstrate the reliability of the measurement, Group Delay Dispersion (GDD) and Third Order Dispersion (TOD) are obtained up to ±0.5 fs2 and 2 fs3 accuracy from the Fourier Transform method of the interference fringes at one specific point. We scanned the polarization sensitivity of the dispersion of a nominally -500 fs2 chirped mirror with respect to the angle of incidence, which specified for below 10°. Furthermore, we measured a 115 fs2 positively chirped, 16 cm diameter mirror dispersion on the entire surface and observed the effect of the deposition from the manufacturing process.

1 Cs. Toth et al. AIP Conference Proceedings 1812, 110005 (2017)
2 F. Giambruno et al. Applied Optics 50(17) 2617-21 (2011)
[3] A. Börzsönyi, A. P. Kovács, M. Görbe, K. Osvay, Opt.Commun. 281, 3051-3061 (2008)

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Coherent Signatures of Conical Intersections in Ultrafast X-Ray Spectroscopy

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The rates and outcomes of virtually all photochemical and photobiological processes are dominated by conical intersections (CIs), which provide a fast sub-100-femtosecond nonradiative pathway back to the ground state. At a CI, the electronic and nuclear degrees of freedom frequencies are comparable and strongly mix due to the breakdown of the Born-Oppenheimer approximation.

A major challenge for their direct detection is the rapidly varying gap between the electronic surfaces in their vicinity. Modern XUV/X-ray light sources provide spectral broad and temporal short pulses, which potentially allow for monitoring CIs directly. We present theoretical studies on novel spectroscopic methods, which make use of ultrashort X-Ray laser pulses. The presented methods include Raman (TRUECARS), time resolved photo electron spectroscopy and possible signatures of electronic coherences in time resolved X-Ray diffraction.

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Design update and recent results for the Apollon 10 PW facility

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1. Introduction The Apollon facility is currently under construction in France. Once the location of the building was decided mid 2010, it took roughly 4 years for refurbishing this former underground LINAC facility that is located close to the SOLEIL synchrotron at CEA Orme des Merisiers. This facility has been inaugurated in September 2015 and its installation is being carried out by the Laboratory for the Use of Intense Lasers (LULI), in partnership with CNRS and CEA. The Apollon laser system is a laser designed for delivering pulses as short as 15 fs (10-15s) with an energy exceeding 150 Joules on target. The peak power delivered by this laser system will be 10 Petawatts (1016W). The laser system is based on Ti-sapphire amplifiers pumped by frequency doubled solid-state lasers. The repetition rate of the high energy part is 1 shot per minute. The main beam at the output of the last amplifier will be split and dispatched to two experimental areas. Apollon will deliver 4 beams: one 10-PW beam (F1 beam, 400 mm diameter), one 1-PW beam (F2 beam, 140 mm diameter) and two additional beams, F3 an uncompressed one with up to 250 J energy and F4 a 10 TW probe beam. The 4 beams will be sent alternatively to the two experimental areas: the short-focal-length area dedicated for plasma physics experiments and the long-focal-length area dedicated for electron acceleration experiments.
2. Apollon architecture and project updates The Apollon laser architecture is illustrated by the Figure 1 and can be described with the following key subsystems [1-3]:

Fig. 1. Schematic of the Apollon-10 PW laser installation

1) The Front End source is based on a combination of a XPW and OPCPA configuration. Excellent spatial beam distribution with good stability has been obtained and compressed pulses demonstrating an excellent temporal contrast better than 1012 [4].
2) Once stretched to 1ns duration in an Offner-type stretcher, the pulses are amplified in four multipass Ti-sapphire amplifiers pumped by frequency doubled solid-state lasers (Nd:YAG or Nd:Glass

nanosecond lasers). The four amplifiers are designed to deliver respectively 0.3, 3, 30 and 300 J when pumped by an expected total energy of 700 J. To compensate for gain shifting and gain narrowing during the amplification process, two spectral filters are inserted between the amplifiers. To reach the right fluence on the crystal, the last amplifier stage requires large size Ti-sapphire crystals (198-mm diameter for the 300-J amplifier). Given the high pump energy required, parasitic effects like transverse lasing occur if no precaution is taken to reduce the reflection of photons at the periphery of the Ti-sapphire crystal. We are using an index-matched liquid, diiodomethane (or Methylene Chloride - CH2I2) mixed with an absorbing dye (HITCI) and we have demonstrated a transverse lasing threshold in the range of 200-220 J pump energy for both sides of a 150-mm diameter pumped zone. Combination of the typical liquid index matching technic with the extraction during pumping (EDP) [5] scheme will allow efficient energy storage and extraction in the last amplification stage. While the low part (up to 3 J) are pumped by conventional green pump lasers, the high energy part is using the Atlas 100-J laser from Thales for pumping the 30-J amplifier and a powerful pump laser built by Continuum and National Energetics for pumping the 100-J amplifier. The current progress in output energy from the high energy amplifiers is only limited by the pump laser availability.

3) After amplification, an active wave-front correction is performed by a closed-loop integrated at the end of amplification section, based on a large aperture high-end technology deformable mirror.
4) After splitting, the main beam is compressed in a vacuum chamber with four-meter-size Livermore gold gratings. The beam is enlarged to 400 mm before the compressor in order to preserve the gratings. The 1 PW beam is compressed in a standard folded two-gratings compressor.
5) Four beams (the 10 PW main beam combined with 3 auxiliary beams including a 1 PW), will be available for the Apollon international users community. Two dedicated experimental areas will allow the demonstration of both ultra-intense laser plasma interaction experiments, using short focal length configurations (f = 1m), and exploratory electrons experiments, based on two stage laser-plasma acceleration in two independent vacuum chambers under long focal length configurations (f = 8m up to f = 32 m).
3. Commissioning phase
Apollon laser commissioning phase consists of five distinct commissioning sequences: 1/ front-end, 2/ Ti-Sapphire amplifiers, 3/ pump lasers, 4/ transport and switchyard and 5/ compressors.

Figure 2. Top-left are near-fields at the front-end output, 0.3-J and 3-J amplifiers outputs. Centre-left 30-J amplifier output with vertical and
horizontal profiles; FWHM is 55 mm. Right is the near-field output of the CNE400 pump laser when run at 200J; FWHM is 60 mm.

We have finished commissioning the front-end and the current operating point is 10 mJ at 10-Hz repetition rate
with a 90-nm spectral bandwidth (FWHM) resulting in a real 14-fs compressed pulse (FWHM). We are currently
commissioning the Ti-sapphire amplifiers up to the 30-J level. Uniform flat-top like beam at 32 Joules over 1 hour at 1 shot/mn with stable operation better than 5% (peak-to-valley) shows that we have a potential 1-PW beam if we compress these pulses. Our current challenge is first to get the expected performance level in a highly stable and reliable way and second to optimise the spectral management of the beam transport system to allow the 15 fs pulse generation at high energy. We are currently constructing the 300-J amplifier, limited for the moment by the availability of the full energy pump system, scheduled for the end of 2018. A first demonstration of the final stage amplifier operating at 100 J output is possible with the currently operating pump system and it is scheduled for the spring of 2018.

1. Spatio-Temporal coupling investigation For a highly sophisticated laser system such as Apollon, the in-depth study of the spatio-temporal coupling effects is of critical importance. These effects could degrade both the laser pulse and the focal spot quality on the target. We have studied these effects and we will discuss the limitations to achieve the targeted pulse duration and the temporal contrast.

References
1 D. N. Papadopoulos et al. Advanced Solid State Lasers, OSA Technical Digest, ATu4A.3 (2015).
2 J. P. Zou et al, High Power Laser Science and Engineering / Volume 3, (2015).
[3] D. N. Papadopoulos et al. High Power Laser Science and Engineering/ Volume 4. (2016).
[4] D. N. Papadopoulos et al. Optics Letters, Vol.42, Issue 18, pp 3530-3533 (2017).
[5] V. Chvykov et al. Optics Communications 285 (8), 2134–2136 (2012).

Summary:

The objective of the Apollon 10 PW project is the generation of 10 PW peak power pulses of 15 fs at 1 shot/minute. In this presentation an update on the current status of the Apollon project will be presented, followed by a detailed presentation of our experimental and theoretical investigations of the temporal characteristics of the laser. More specifically the design considerations as well as the technological and physical limitations to achieve the targeted pulse duration and contrast will be discussed.

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Frequency domain Nonlinear Optics

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Over the recent years, we have introduced the concept of Frequency domain Optical Parametric Amplification (FOPA) [1,2]. Using this approach at the Advanced Laser Light Source (ALLS), we have developed a high energy infrared laser system delivering two-cycle 1.8 micron pulses with up to 30 mJ of energy, corresponding to 2.5 TW peak power (in preparation). This laser system paves the way for high flux water window soft X-ray pulses, high-field THz pulses, and high brightness ultrashort electron bunches. Among various applications of these sources, we are working to combine THz and soft X-ray pulses for probing ultrafast dynamics in solids including femtosecond magnetization dynamics and ultrafast phase transition. Furthermore, we are planning to upscale FOPA to peak power of 10 TW and current laser Ytterbium laser technologies [3] allow to dream making this laser operating at kHz repetition rate for merging high peak and high average power. By combining these technological advances, we are now working to commercialize the FOPA through a recently founded spin-off company few-cycle Inc.
While the concept of Frequency domain Nonlinear Optics has been introduced with FOPA, we have recently generalized this approach to other nonlinear optical processes. Specific results on second harmonic generation will be presented [4].

References
1 B. E. Schmidt, N. Thiré, M. Boivin, A. Laramée, F. Poitras, G. Lebrun, T. Ozaki, H. Ibrahim, and F. Légaré, "Frequency domain optical parametric amplification," Nature Commun. 5, 3643 (2014).
2 P. Lassonde, N. Thiré, L. Arissian, G. Ernotte, F. Poitras, T. Ozaki, A. Laramée, M. Boivin, H. Ibrahim, F. Légaré, B. E. Schmidt, "High gain Frequency domain Optical Parametric Amplification," IEEE J. Sel. Top. Quant. Electr. 21, 8700410 (2015).
[3] C. Baumgarten, M. Pedicone, H. Bravo, H. Wang, L. Yin, C. Menoni, J. Rocca, and B. Reagan, "1 J, 0.5 kHz repetition rate picosecond laser," Opt. Lett. 41, 3339-3342 (2016).
[4] B. E. Schmidt, P. Lassonde, G. Ernotte, M. Clerici, R. Morandotti, H. Ibrahim, and F. Légaré, Decoupling Frequencies, Amplitudes, and Phases in Nonlinear Optics, Scient. Rep. 7, 7861 (2017).

Summary:

Frequency-domain Nonlinear Optics (FNO) merges the simplicity of linear optics with the power of nonlinear optics. Employing FNO, we demonstrate pulse shaping in the deep UV and amplification of two-cycle infrared pulses to 2.5 TW.

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Fiber baser high performance few-cycle lasers

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The achievements and perspectives of coherently combined ultrafast fiber laser setups followed by nonlinear pulse compression will be reviewed. Few-cycle pulses in the near- and mid-infrared with average powers in the kW range and pulse energies exceeding 10mJ will be feasible with this approach in the near future. Such systems will enable a number of scientific applications.

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Attosecond time-resolved dynamical Franz-Keldysh effect in polycrystalline diamond

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The increasing demand for faster and more efficient electrical circuits drives the current development of electronics and optoelectronics. A deep understanding of the ultrafast electron dynamics occurring in solids is thus at the basis of the next generation of important technological fields.

The interaction of intense and short light pulses with solid targets enables to explore a mixed regime of light-matter interaction where the photon energy becomes comparable to the cycle-averaged kinetic energy of the electrons in the optical field. So far only very little research has been reported on this regime. As the optical response of the material transitions from a classical to a quantum-mechanical description many intriguing effects co-exist and the importance of inter- versus intra-band transitions is unclear. We used intense few-femtosecond infrared (IR) pulses (Ip $\approx 10^{12}$ W/cm^2, center frequency ≈ 786 nm) to start ultrafast electron dynamics in a 50-nm polycrystalline diamond film. A short attosecond pulse (duration of ≈ 250 as) in the extreme-ultraviolet spectral range (center energy ≈ 40 eV) is used to probe the dielectric function by attosecond transient absorption spectroscopy (ATAS). The recorded pump-induced change in absorbance shows transient features around zero pump-probe delay. These features oscillate with twice the IR center frequency. Moreover, their phase is characterized by a non-trivial energy dependence which appears as a V-shaped structure centered around a probing energy of 43 eV. Simultaneous photoelectron acquisition from a gas nozzle placed in front of the diamond target allowed us to obtain an on-the-fly calibration and study the phase relation of the oscillating features and the IR pumping field. We found that the timing of the diamond response does not always follow the IR field adiabatically.

In order to understand the physical mechanisms at the basis of the observations we performed ab initio calculations by coupling time-dependent density functional theory (TDDFT) in real time with Maxwell's equations. The calculation results fully reproduce the experimental data. In a top-down approach, we subsequently simplify the theoretical model to a two-band system. This allowed us to conclude that intra-band motion, namely dynamical Franz-Keldysh effect, is the dominant effect in this light-matter interaction regime. In conclusion, by demonstrating the possibility to manipulate virtual carriers in solids at frequencies close to Petahertz, our result constitutes an important step towards a complete understanding of ultrafast electron dynamics in dielectrics.

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High-order harmonic amplification by multiple reflection

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The interaction of intense laser pulses with over-dense plasma surfaces results also in generation of highorder
harmonics. In the regime of low intensity the shortest wavelength is defined by the electron density in the
target, which allows us to generate harmonic numbers up to ~30. It has been shown that by combining the laser
fundamental with its low-order harmonics the significant enhancement of high harmonic intensity can be achieved,
even above this cut-off 1. Since the laser pulse reflected from a plasma inherently contains the low order
harmonics, a second reflection from a fresh plasma surface leads to the increase of spectral intensity. This process has
been proven by simulations in one-dimensional geometry [3], where multiple reflection between two plasma slabs
was considered. Our goal is to propose an experimental setup, where the intensity of harmonics above 20th can be
significantly increased. In this work we have made an extensive study of multiple reflections at oblique incidence,
with the help of 1D and 2D Particle-in-Cell simulations. A loosely focused pulse is considered which can propagate
between two flat foils over consecutive reflections without significant energy loss through diffraction or divergence
of the laser pulse. We will show that for optimal parameters the intensity of 10th to 30th harmonics of a 10 mJ pulse
can be amplified by three orders of magnitudes.
References

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Transition to Light Sail Acceleration Using Ultraintense Femtosecond Pulses

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Acceleration of ions using ultrashort intense laser pulses is an ongoing area of research with a wealth of possible applications. Ions are typically accelerated via the target normal sheath acceleration (TNSA) mechanism 1, whereby the laser generates a hot electron sheath on the rear surface of the target, creating a very large electric field, which accelerates protons and heavier ions present on the target rear surface to MeV energies over much shorter distances compared to conventional RF accelerators.

Beyond TNSA, as the laser ramps up in intensity (above 1021 W/cm2), if the target remains opaque to the laser pulse, radiation pressure acceleration (RPA) starts to dominate. In this regime, if the target is

sufficiently thin, the bulk of the target is accelerated as a whole, known as the light sail (LS) regime. In order for LS to work, the plasma must remain opaque to the laser, meaning effects such as relativistic transparency must be suppressed. This is achieved by using circularly polarized laser pulses as opposed to linearly polarized. Circular polarization suppresses j×B heating of electrons, resulting in an overall lower temperature plasma and stalling the onset of relativistic transparency.

We will present here the latest results from an experimental campaign recently undertaken on the Gemini laser system at the Central Laser Facility in the UK. In this experiment amorphous carbon targets ranging in thickness from 2nm to 100nm were irradiated with high contrast 40fs pulses with an intensity up to 1021 W/cm2, for both circular and linear polarizations and the resulting proton and ion spectra compared. Examining the highest energies achieved for a given polarization and target thickness, allows to identify the transition from TNSA to LS. Observations of the optimal target thickness for ion acceleration are compared to analytical predictions from LS theory, in addition to results from Particle in Cell modelling.

1 A. Macchi, M.Borghesi, M.Passoni, Rev. Mod. Phys., 85, 751 (2013)

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Quadruple detector array for dosimetric characterization of laser accelerated particle beams

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In-beam dose measurements are paramount for any application seeking to harness the effects of the radiation beam, so all the future applications of the laser accelerated beams (as generated in the ELI and CETAL projects) will need such measurements. With a very long history in measuring doses in charged particle beams, the medical and industrial applications set up a number of methods that could be also used for the dosimetry of the beams generated by laser pulses.

Dose measurements rely heavily on what is seen as the gold standard in dose measurement: the ion chambers. Ion chambers have both limitations and advantages, and in our case the disadvantage could be the large number of corrections to be applied in order to calculate a correct dose from the measured charge.

Our team tries to address these problems by proposing an array detector that would allow the simultaneous measurement of the recombination and polarity corrections, and also of the dose. We propose a new design based on 4 identical ion chambers mounted together in a PMMA frame and we aim to analyze the detector response to various charged particle beams and the reciprocal influences of the chambers on each other.

As a preliminary step before building the array, we tested a PTW Advanced Markus chamber in proton beams of 3 MV, at the TandetronTM accelerator from IFIN-HH as well as in medical LINAC electron beams of known energies. The technical design drawings of the detectors and the experimental conditions have been fed into the FLUKA calculations, after which the experimental and the simulations results have been compared. Deposited energy and dose values were computed in the active volume of the detector placed in air, at the maximum dose position. Also, the fluence and fluence energy spectra of the primary and secondary particles were recorded. The comparison between the actual measurements and the simulations lead us to the conclusion that a scaling factor must be introduced in the simulation parameters, in order to account for the less known geometry and structure of the accelerating installation.

Acknowledgements: This work has been supported in the frame of the national project PN III 5/5.1/ELI-RO, Projects 20-ELI/2016 (ELIDOSE) and 04-ELI/2016 (QLASNUC), under the financial management of Institute for Atomic Physics - IFA.

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Spatio-temporal investigation of few-cycle laser beams propagation in dispersive media

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The spatio-temporal equivalence s=c•t, where c is the speed of light and s is the spatial extent of ultra-short laser pulses of duration t is investigated after the propagation through four dispersive media (air, quartz, ZnO, and TiO2) using 2D modeling of the electromagnetic pulses. The spatial extension of the ultra-short pulses has been quantified using the finite difference time domain (FDTD) method. A comparative analysis has been made between the numerically obtained beam waist values and the analytical evaluations calculated with the complex Gaussian formalism providing a particular description of spatial and temporal aspects of focused few-cycle laser beams in the four different dispersive media previously mentioned. The obtained results show that the spatial extent of the EM field in the focus of ultra-short pulses depends on Rayleigh range and it is shorter than the temporal duration of the pulse c•t for all four media investigated. The approach described in this paper aims to contribute to ultra-short pulse laser experiments by offering necessary details concerning the overview on the dynamics of the electromagnetic field propagation in predefined conditions. This work has been financed by the national project PN III 5/5.1/ELI-RO, Project 04-ELI/2016 ("QLAS-NUC") under the financial support of Institute for Atomic Physics - IFA.

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Next generation high-order harmonic sources

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High-order harmonic generation (HHG) is now established as a high-output coherent light source in the XUV region and the sole source of attosecond pulses. Here, I present recent efforts on HHG in RIKEN by using novel ultrafast laser technology for intense isolated attosecond pulses (IAP) and MHz repetition rated XUV pulses.

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Mapping Atomic Motions with Ultrabright Electrons: Realization of the Chemists' Gedanken Experiment

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One of the dream experiments in chemistry has been to watch atomic motions on the primary timescales of chemistry. This prospect would provide a direct observation of the reaction forces, the very essence of chemistry, and the central unifying concept of transition states that links chemistry to biology. This experiment has been referred to as "making the molecular movie" with respect to observing net rms atomic motions during structural changes. Due to the extraordinary requirements for simultaneous spatial-temporal resolution and brightness, it was thought to be an impossible quest and has been previously discussed in the context of the purest form of a Gedanken experiment. With the development of ultrabright electron sources capable of literally lighting up atomic motions, this experiment has been realized (Siwick et al. Science 2003). The first studies focused on relatively simple systems. Further advances in source brightness have opened up even complex organic systems and solution phase reaction dynamics to atomic inspection. A number of different chemical reactions will be discussed from electrocyclization with conserved stereochemistry (Jean-Ruel et al JCP B 2013), intermolecular electron transfer for organic systems (Gao et al Nature 2013), metal to metal electron transfer (Ishikawa et al, Science 2015), to the recent observation of coherently directed bond formation using the classic I3- system, in a process analogous to a quantum Newton's cradle (Xian et al Nature Chem 2017). These studies have discovered that these nominally 100+ dimensional problems, representing the number of degrees of freedom in the system, distilled down to atomic projections along a few principle reaction coordinates. The most dramatic example will be shown for the first all atom resolved chemical reaction with sub-Å (.01)and 100 fs timescale resolution (Ishakawa, Hayes et al Science 2015) – the fundamental space-time resolution to following the primary processes of chemistry. At this resolution, without any detailed analysis, the key large-amplitude modes can be identified by eye from the molecular movie. This reduction in dimensionality appears to be general, arising from the very strong anharmonicity of the many body potential in the barrier crossing region. We now are beginning to see the underlying physics for the generalized reaction mechanisms that have been empirically discovered over time. The "magic of chemistry" is this enormous reduction in dimensionality in the barrier crossing region that ultimately makes chemical concepts transferrable. How far can this reductionist view be extended with respect to complexity? With further advances in space-time resolution/sensitivity, even quantum aspects will be resolvable, which will be discussed. The ultimate goal in scaling system complexity is to obtain atomically resolved protein functions to understand how nature tamed chemistry over all conceivable length scales. This study will provide a definitive test of the collective mode coupling model (Miller Acc. Chem. Research 1994) to bridge chemistry to biology, which will be discussed as the driving force for this work.

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Mapping Atomic Motions with Ultrabright Electrons: Realization of the Chemists' Gedanken Experiment

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One of the dream experiments in chemistry has been to watch atomic motions on the primary timescales of chemistry. This prospect would provide a direct observation of the reaction forces, the very essence of chemistry, and the central unifying concept of transition states that links chemistry to biology. This experiment has been referred to as "making the molecular movie" with respect to following structural changes. Due to the extraordinary requirements for simultaneous spatial-temporal resolution and brightness, it was thought to be an impossible quest and has been previously discussed in the context of the purest form of a Gedanken experiment. With the development of ultrabright electron sources capable of literally lighting up atomic motions, this experiment has been realized (Siwick et al. Science 2003). The first studies focused on relatively simple systems. Further advances in source brightness have opened up even complex organic systems and solution phase reaction dynamics to atomic inspection. A number of different chemical reactions will be discussed from electrocyclization with conserved stereochemistry (Jean-Ruel et al JCP B 2013), intermolecular electron transfer for organic systems (Gao et al Nature 2013), metal to metal electron transfer (Ishikawa et al, Science 2015), to the recent observation of coherently directed bond formation using the classic I3- system, in a process analogous to a quantum Newton's cradle (Xian et al Nature Chem 2017). These studies have discovered that these nominally 100+ dimensional problems, representing the number of degrees of freedom in the system, distilled down to atomic projections

along a few principle reaction coordinates. The most dramatic example will be shown for the first all atom resolved chemical reaction with sub-Å (.01)and 100 fs timescale resolution (Ishakawa, Hayes et al Science 2015) – the fundamental space-time resolution to following the primary processes of chemistry. At this resolution, without any detailed analysis, the key large-amplitude modes can be identified by eye from the molecular movie. This reduction in dimensionality appears to be general, arising from the very strong anharmonicity of the many body potential in the barrier crossing region. We now are beginning to see the underlying physics for the generalized reaction mechanisms that have been empirically discovered over time. The "magic of chemistry" is this enormous reduction in dimensionality in the barrier crossing region that ultimately makes chemical concepts transferrable. How far can this reductionist view be extended with respect to complexity? With further advances in space-time resolution/sensitivity, even quantum aspects will be resolvable, which will be discussed. The ultimate goal in scaling system complexity is to obtain atomically resolved protein functions to understand how nature tamed chemistry over all conceivable length scales. This study will provide a definitive test of the collective mode coupling model (Miller Acc. Chem. Research 1994) to bridge chemistry to biology, which will be discussed as the driving force for this work.

Summary:

The fundamental space-time limits to imaging chemistry has been achieved (100 fs, +/- .001 nm) to directly observe the collapse of innumerable possible nuclear motions collapse to a few key modes that direct chemical processes. This enormous reduction in dimensionality of a high dimension, nonlinear, problem arises from some relatively simple physics involving the strong anharmonic coupling of low and high frequency modes in the barrier crossing region that lead to the localized motions. It is this reduction in dimensionality that makes chemistry a transferable concept, scaleable in complexity from small molecule to biological systems. The talk will provide a roadmap to a new conceptual basis for chemistry and by extension biology that naturally links dynamics and structure.

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Ultra-high peak field terahertz pulses from relativistic laser-plasma interaction

Authors: Sudipta Mondal[1]; Tsuneyuki Ozaki[2]

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High intensity femtosecond laser-plasma interaction is a good source of high-energy particles and photons1. Laser plasma interaction at relativistic intensities are opening new avenue of ultra high peak field THz pulse generation[2-4]. These ultra-high peak field and ultra-broadband THz pulses can be used in several applications in scientific and industrial purpose such as nonlinear optics at THz domain, single-shot THz imaging and spectroscopy and many more. However, precise characterization of such THz pulses are required before any such application. Characterization of such THz pulses are extremely challenging due to lower repetition rate and ultra-broadband nature of the THz pulses which limits its practical application.

In this study, we first develop a tabletop intense broadband terahertz (THz) source in the medium frequency range ($\leq$ 20 THz) based on the interaction of a relativistic intensity femtosecond laser with solid density plasmas and then systematically characterize generated THz pulses using nonlinear absorption bleaching of THz pulses in InGaAs thin film[5].

When an unpolished copper target is irradiated with a high-intensity (3.5×10^{18} W/cm^2) femtosecond laser, a maximum of $\sim$ 2.2 μJ of THz pulse energy is collected and detected with a calibrated pyroelectric detector in the spectral range $\leq$ 20 THz. The THz spectrum was measured by using a series of bandpass filters, which shows a bandwidth of $\sim$ 7.8 THz full-width at half-maximum (FWHM) with a peak at $\sim$ 6 THz. By refocusing these THz pulses on a heavily n-doped InGaAs thin film we first demonstrate THz nonlinearity which is a result of THz absorption bleaching of carriers in the InGaAs thin film[5]. By measuring THz transmission through InGaAs thin film and with the help of numerical simulation we are able to estimate the peak field associated with the THz pulses generated by this mechanism which we found at least 2.5 MV/cm[4].

References:

1. Mourou, G. A., Tajima, T. & Bulanov, S. V. Optics in the relativistic regime. Rev. Mod. Phys. 78, 309–371 (2006).
2. Liao, G. Q. et al. Bursts of Terahertz Radiation from Large-Scale Plasmas Irradiated by Relativistic Picosecond Laser Pulses. Phys. Rev. Lett. 114, 255001 (2015).
3. Mondal, S. et al. Aligned copper nanorod arrays for highly efficient generation of intense ultra-broadband THz pulses. Sci. Rep. 7, 40058 (2017).
4. Mondal, S., Hafez, H. A., Ropagnol, X. & Ozaki, T. MV/cm terahertz pulses from relativistic laser-plasma interaction characterized by nonlinear terahertz absorption bleaching in n-doped InGaAs. Opt. Express 25, 17511 (2017).
5. Razzari, L. et al. Nonlinear ultrafast modulation of the optical absorption of intense few-cycle terahertz pulses in n-doped semiconductors. Phys. Rev. B 79, 193204 (2009).

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Magnetic inhibition of sheath-accelerated high-energy protons

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Laser-based proton beams have remarkable properties, enabling ultrafast radiography of plasma phenomena or isochoric heating of dense materials. In view of longer-term multidisciplinary purposes, the current challenge is to achieve proton energies well in excess of 100 MeV. I'll present our experimental and numerical results demonstrating that magnetostatic fields self-generated on the target surface may pose a fundamental limit to target normal sheath ion acceleration for high enough laser intensities. Those fields can be strong enough (Giga-Gauss level at laser intensities ~10^21 W cm^-2) to magnetize the sheath electrons and deflect the protons off the accelerating region.

If time allows, I'll briefly present an overview of the HED instrument at European XFEL in Germany that will enable to probe such plasmas with unprecedented temporal and spatial resolution.

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Investigation of spectral phase stability issues in ultrafast laser systems by spectrally resolved interferometry

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Ultrahigh peak power light fields are generated in laser systems based on chirped pulse amplification (CPA) schemes, mostly by using Ti:Sapphire (Ti:Sa) as gain material. Requirements on the quality of these laser pulses are trending towards lower pulse durations, higher pulse energies and well controlled electric fields at the highest repetition rates possible 1. These requisites put high demands on the laser systems. Controlling the electric fields, thus producing spectral and carrier-envelope phase (CEP) stable pulses requires the investigation of stability issues related to subsystems in the amplifier chain. The amplifier stages in CPA and Double-CPA systems can have large amount of phase drift and noise contributions, which have to be accounted for in the design and operation process. Phase stabilization schemes for complete amplifier systems could be simplified significantly, if the specific issues could be considered during the design and operation stages.
Amplification in water cooled Ti:Sa stages was investigated for their CEP drift and noise contribution by using spectrally resolved interferometry [2,3]. Effects of different laser parameters, like pump and seed energy, repetition rate, cooling conditions and gain saturation were determined. Significant CEP drift was found with changing coolant temperature. On the other hand, CEP noise was linearly increasing with pump pulse energy, and inversely proportional to repetition rate of pulses. Pump energy stability was found to be crucial to get high inherent CEP stability of the amplifier stage.
Cryogenically cooled Ti:Sa amplification was also studied, where the effects of vacuum and cooling devices were thoroughly studied. Thermally and mechanically originated CEP noise contributions of amplification at < 30 °K were determined and compared to room temperature operation at different repetition rates. Noise spectra obtained from interference fringes and from an accelerometer were analyzed and compared, where the specific frequencies affected by the vacuum and cryogenic devices were identified [4].
The technique of polarization-encoded CPA (PE-CPA) was just recently proposed [5], which could provide a gain bandwidth that supports few-cycle pulses after amplification and compression. The study of inherent CEP-stability of PE amplification has high importance due to the applicability to few-cycle pulse generation. The CEP stability was compared to the conventional amplification with the same laser parameters, which indicated a slight degradation due to the PE and gain induced effects. The effect of PE amplification on the CEP stability was also investigated for different gain factors.
Cooling of reflective optics in high average power laser systems can also be the source of phase fluctuations due to path length fluctuations. For this reason, two different water-cooled mirror-mounts were tested for their effect on the spectral phase of broadband pulses. Multiple reflections were applied to increase the sensitivity of the measurement. Different coolant flow velocities inside the tubes and mounts were investigated. Phase and mechanical noise spectra were compared to determine the noise frequencies, for which stabilization should be applied.

Summary:

Experimental investigation on the phase stability of different types of Ti:Sa amplifiers, and water-cooled mirror mounts were performed. In case of the Ti:Sa amplifier stages, cooling stability was found crucial to avoid CEP drift. On the other hand, pump pulse energy stability affects the CEP-stability significantly, which suggests that diode pumped solid state lasers should be used to pump the amplifiers to avoid serious CEP-stability degradation. Path length fluctuations due to cooled reflective optics are also the source of phase instabilities, which can affect coherent beam combination efficiency and can cause temporal jitter in laser systems.

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Applications of self-injecting laser wakefield accelerators

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Laser wakefield accelerators have now produce electron beams with GeV energy gain in distances of only centimetres in many experiments around the world.

Here we detail experiments performed with the 10J, 40fs Astra Gemini laser focussed in an f/40 optic onto a gas-cell of variable length. Despite the initial focussing being larger than the matched spot size, a high charge (>100 pC) electrons beam with energies in excess of 2GeV. This simple method of producing high-charge high-energy beams has a number of immediate uses. We have demonstrated that the beams can be used for producing near-neutral electron-positron beams, and high brightness gamma rays through Thomson scattering. These interactions allow us to test the quantum nature of these high energy interactions. The electron beam also produces a bright x-ray beam simultaneously. The unique properties of this x-ray beam makes it interesting for imaging a number of interesting medical and biological samples. Here, we will highlight a number of proof-of-principle trials that we have performed.

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Nuclear Physics Studies with High Power Lasers at ELI-NP

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High power laser driven ion acceleration produces short duration high density particle bunches enabling new methods in experimental nuclear physics. The changes of reaction cross sections and of apparent lifetimes in hot plasma environments, new techniques for heavy unstable nuclei ion production, are examples of nuclear physics studies proposed at ELI-NP facility under construction in Magurele, Romania. Details on such topics will be given in the presentation together with their foreseen experimental implementation at ELI-NP and ongoing developments of needed detection systems, including the demonstration of in-situ gamma spectroscopy of short lived nuclear isomers produced in high power laser induced nuclear reactions.

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Pre-pulse formation from pump modulations in Optical Parametric Chirped Pulse Amplification systems

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[1] *ELI-ALPS, Early stage researcher*

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Optical parametric chirped pulse amplification (OPCPA) has undergone rapid development in the last decade because of its ability to deliver ultrashort pulses with high intensity. The temporal contrast of the recompressed amplified pulses has been a major concern in applications as the light preceding the main pulse, either in the form of a pre-pulse or a pedestal, can significantly affect interaction properties. Pre-pulse formation in OPCPA systems has been investigated and it has been shown that temporal modulations in the pump 1 or the presence of post-pulse of the seed 2 can lead to the contrast degradation. However, the impact of post-pulse of the pump has not been considered.

A new mechanism for pre-pulse formation in an OPCPA system is presented in this paper. The pump passes through optics during propagation, e.g. when a CPA scheme is used for pump amplification, and consequently, can have post-pulses due to reflections. Small scale modulation of the pump may arise from interference of this post-pulse with the main chirped pump pulse. An OPCPA system was modelled to study the above phenomena, using numerical methods [3]. These investigations show that when the chirped pump is followed by a post-pulse, several pre- and post-pulses appear in the signal after recompression, leading to the contrast degradation. The contrast of the recompressed

signal is proportional to the contrast of the pump and depends on the time delay of the post-pulse. The temporal position of the pre- and post-pulses is also affected by the pump parameters.

1 C. Dorrer, J. Opt. Soc. Am. B, 24(12): 3048-3057; 2007

2 J. Wang et al. Opt. Express, 21(13): 15580-15594; 2013

[3] A. Adrianov et al. Opt. Express, 24(23): 25974-25982; 2016

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Waveform-dependent laser-induced conduction band currents

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We consider the interaction of conduction band electrons and carrier envelope phase (CEP) stabilized laser pulses. We use a quantum mechanical model to calculate the total charge displaced by the laser pulse, and show that it has a strong CEP dependence. We analyze the parameters in order to find optimal values for the construction of an all-solid-state CEP measuring device.

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Nuclear-spin-polarized hydrogen isotopes from UV molecular photodissociation, for polarized laser fusion experiments

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The UV photodissociation of hydrogen-isotope halides (e.g. HCl, DI, TBr), with circularly polarized light, can produce, at first, highly electron-spin-polarized H/D/T atoms [1,2,3]. Subsequently, the electron polarization is transferred to the nuclei via the hyperfine interaction. By ionizing at the appropriate time delay, highly spin-polarized H/D/T nuclei can be produced, at very high densities and production rates. I discuss proposals, based on this method, for measuring polarized laser fusion of D-T, D-3He, and D-D reactions [4], where it is expected to increase the fusion cross section by 50% for the D-T and D-3He reactions, whereas the result is uncertain for the D-D reaction. We note that polarized fusion in plasmas has not yet been measured, due to a lack of sufficiently dense samples of spin-polarized hydrogenisotope nuclei, using traditional methods (e.g. Stern-Gerlach spin separation, spin-exchange optical pumping, or cryogenic cooling).

References

1 T.P. Rakitzis, P.C. Samartzis, R.L. Toomes, T.N. Kitsopoulos, Alex Brown, G.G. Balint-Kurti, O.S. Vasyutinskii, J.A. Beswick, "Spin Polarized Hydrogen Atoms from Molecular Photodissociation," Science 300, 1936 (2003).

2 Dimitris Sofikitis, Luis Rubio-Lago, L. Bougas, Andrew J. Alexander, T. Peter Rakitzis, "Laserdetection of spin-polarized hydrogen from HCl and HBr photodissociation: Comparison of H- and halogen-atom polarizations" J. Chem. Phys. 129, 144302 (2008).

[3] T.P. Rakitzis, "Pulsed-Laser Production and Detection of Spin-Polarized Hydrogen Atoms" ChemPhysChem 5, 1489 (2004).

[4] D. Sofikitis, P. Glodic, G. Koumarianou, H. Jiang, L. Bougas, P. C. Samartzis, A. Andreev, T. P. Rakitzis, "Highly nuclear-spin-polarized deuterium atoms from the UV dissociation of Deuterium Iodide" Phys. Rev. Lett. 118, 233401 (2017).

6

Modular architecture of affordable small footprint and low ownership cost 1 TW-class laser based on Yb:YAG CPA and OPCPA

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Significant efforts have been made all over the world to create complex TW-class lasers systems that take up a lot of space, while the development and maintenance costs limit their distribution. Therefore, such systems are usually shared by many scientists with limited access time. For the wide dissemination of high peak power lasers to the scientific community, it is vitally important to pay special attention to reducing the size and cost. We report on the current status of the development of a compact and inexpensive modular layout of the 1 TW-class laser system containing a fiber laser seeder, two-cascaded double-pass CPA based on Yb:YAG rods, pulse compressor, supercontinuum generation and OPCPA. With the expected output from the pump source and pulse compressor of ~40mJ, ~1ps and OPCPA output of ~10mJ, ~10fs at a repetition rate of 100Hz, the laser includes commercially available components and is easily reproduced.

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Solid targets for a high repetition sources from relativistic laser plasma interactions and contrast management

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We report the development of two fast rotating targets for relativistic laser plasma interactions. The first target is for the production of ultrashort incoherent X-ray pulses from bremsstrahlung. These short X-ray pulses are produced in the lambda cube regime with a 35 fs, 1 mJ, 1 kHz Ti:Sa laser pulse and solid metallic targets. The target design improves the stability of this micron size source of ultrashort X-rays and allow corrections of the wobbling which become important for the very small Rayleigh length. We describe the methods we have developed to measure and adjust the stability of the focus on target which allow us to develop applications of the source such as the ultrafast tomography. The second rotatory target is designed for a high repetition source (10 Hz) of protons from relativistic laser plasma interactions in the TNSA regime. We describe the experiments that we will perform with the 48 TW (1.2J, 25 fs, 10Hz) laser at the USC to study the production of radioactive isotopes for medical imaging such as PET. The multishot target will permit the use of thin foils or nanostructurated targets with a high rep rate to produce protons with max energy of 10 MeV. Finally we discuss the diagnostics and contrast management developed for these experiments.

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Imaging nanoparticles and ultrafast nanoplasma dynamics

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Extremely intense pulses from short-wavelength free-electron lasers (FELs) turn condensed matter into highly excited plasma within only a few femtoseconds. While this plasma formation constitutes an unpleasant artifact termed 'ultrafast radiation damage' for coherent diffractive imaging (CDI) applications, it promises unparalleled opportunities to prepare and study highly non-equilibrium plasma states in a well-controlled way. A precise understanding of ultrafast interactions of matter under intense extreme ultraviolet (XUV) and X-ray pulses is therefore a major focus of FEL research. Atomic clusters and nanodroplets in the gas phase are fascinating nanoscale laboratories for laser-matter interaction studies due to their simple geometric and electronic structure and the possibility to change their size from the molecular to the bulk limit.
Single-shot diffractive imaging allows to determine the shape of the short-lived and non-depositable specimen such as rare-gas cluster. More importantly, the light-induced dynamics during and after the illumination with the intense short wavelength pulse become visible in the diffraction patterns. An outlook will be given on our recent demonstration of diffractive imaging of single helium nanodroplets with intense XUV pulses from a laser-based HHG source (Rupp et al., Nature Communications 8, 493 (2017)). This opens a door to ultrafast coherent diffractive imaging of electron dynamics with phase-controlled multicolor fields and attosecond pulses.

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Complete reconstruction of complex visible pulses using a two-source attosecond interferometer

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The complete characterization of optical pulses requires that it is possible to sample in time oscillating electric fields on a sub-femtosecond timescale. Nowadays, attosecond technology provides the experimental tools to resolve in time these oscillations [1,2]. The electric field is, in general, a (time-dependent) vector quantity E(t). The variation of the two perpendicular components of the field defines its polarization state, which plays a fundamental role in the description of the light-matter interaction.
In this communication, we present a novel method to reconstruct the electric field of pulses with low energies (in the nJ domain) characterized by a linear or time-dependent polarisation [3]. Our approach gives access to the complete field, and, therefore, also to the carrier-envelope-phase (CEP). The method is based on the interference between two isolated coherent attosecond pulses, which are generated in two-closely spaced focal spots and overlap in the far field. One attosecond pulse acts as reference, while the generation of the second one is slightly perturbed by the unknown field to be characterized. The amplitude and the phase of the second attosecond pulse are modified by the instantaneous value of the perturbing electric field during the motion of the electronic wave packet leading to the attosecond pulse emission.
The effect of the unknown field strongly depends on the relative alignment between E(t) and the direction of motion v(t) of the electronic wave packet: it is maximized when the two directions are parallel and it is negligible (in a suitable intensity range) if the two directions are perpendicular. This observation opens the possibility for the
full three-dimensional reconstruction of the field E(t) of the unknown pulse.

Experimentally, the two-source attosecond interferometer is realized through a binary pi phase step plate that causes a phase jump halfway across the driving beam and consequently two independent, coherent HHG regions separated by roughly the focal spot diameter [4]. The HHG process is driven by a polarization gated few-cycle field to create two isolated attosecond electronic wave packets at the moment of linear polarization. The XUV interference pattern is measured using an astigmatic XUV spectrometer composed of a cylindrical mirror, a spherical grating and an MCP-Phosphor assembly coupled to a CCD camera.
The unknown pulse E(t) is then overlapped on only one of the two foci with a variable delay tau with respect to the generating pulse. The interference pattern is recorded as a function of tau for two perpendicular orientations of the linear half central cycle of the driving field. The two components Ex/y(t) can then be reconstructed either from the variation of the fringe contrast or from the shift of the interference pattern. We will show that while the variation of the contrast depends on the modification on the tunnelling probability, the shift of the interference fringes can be related to the phase accumulated by the electronic wave packet during its motion in the continuum.
We will present results showing the reconstruction of linearly polarized pulses, as well as pulses characterized by a complex time-dependent polarization. Finally, we will show how the method allows for the determination of the CEP of the pulses, by comparing the experimental outcome with theoretical simulations.

References
1 F. Krausz and M. Ivanov Rev. Mod. Phys. 81, 163-234 (2009).
2 M. Nisoli and G. Sansone Prog. Quantum. Electron. 33, 17-59 (2009).
[3] P. Carpeggiani, et al Nat. Phot. 11, 383-389 (2017).
[4] A. Camper, et al. Phys. Rev. A. 89, 043843 (2014).

3

Theoretical investigation of the Ar-gas filled capillary discharge waveguide

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Raising problems: In terms of rapid development of high energy technologies, investigation of the non-LTE high density plasmas is a subject of growing interest among scholars and researchers. Due to capillary discharge X-ray laser constructed by our research group, we are also interested in understanding of physical processes of plasma generated by high peak (13…20 kA) electric current pulse flowing in an alumina capillary. For this purpose the MHD model 1 proved to be the most suitable one. Beside the reviled connections between initial parameters and the plasma dynamics obtained by the model, it turned out, that there is a time range, when the radial electron density profile of Ar-plasma is also suitable for the waveguiding, like in case of hydrogen-gas filled capillary discharge waveguides [2,3].

Achieved results: The waveguide properties of the discharge plasma generated in a 3 mm inner diameter and 50 mm in length Ar-gas filled capillary channel was examined. Wave optics simulations performed on collisionless plasma showed, that in accordance with analytical formulation of the matched spot size [4], there is a spot size, the FWHM and the peak of the coupled ideal Gaussian-beam remain constant over the whole capillary length both in CW and in pulse mode. The latter mode is widely used in laser-wakefield accelerators (LWFA), so the above property plays a key role in in extension of interaction length.

Acknowledgment: This study was supported by the Human Resource Development Operational Program within the project called "Ultrafast physical processes in atoms, molecules, nanostructures and biological systems" (contract EFOP-3.6.2-16-2017-00005).

References

1 P.V. Sasorov, N.A. Bobrova, O.G. Olkhovskaya, *The two-temperature equations of magnetic hydrodynamics of the plasma*, (Keldysh Institute preprints, Moscow 2015), 1-18.

2 A.J. Gonsalves, T. P. Rowlands-Rees, B.H.P. Broks, J.J.A.M. van der Mullen, and S.M. Hooker, Phys. Rev. Lett. **98**, 025002 (2007).

[3] N.A. Bobrova, A.A. Esaulov, J.I. Sakai, P.V. Sasorov, D.J. Spence, A. Butler, S.M. Hooker, and S.V. Bulanov, Phis. Rev. E **65** 016407 (2001).

[4] P. Sprangle and E. Esarey, Physics of Fluids B, Plasma Physics **4**, 2241 (1992).

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Scaling laser plasma acceleration to the Petawatt laser level

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Applications of laser plasma accelerated particle beams ranging from the driving of light sources to radiation therapy require controlled scaling of particle beam energy and charge as well as reproducible operating conditions. Both issues have motivated the development of novel table-top class Petawatt laser systems (e.g., 30J pulse energy in 30fs) with unprecedented pulse control, here represented by the dual beam Draco-PW system recently commissioned at HZDR Dresden.

First results will be presented on laser wakefield electron acceleration where in the beam loading regime high bunch charges in the nC range could be efficiently accelerated with good beam quality 1, and on PW class proton acceleration scaling. Several methods relying on target tailoring 2 will be summarized to reliably provide about 10 MeV cut-off energy per Joule of laser energy up to the range of 25 MeV ready for applications. Here, pulsed magnet beam transport ensures depth dose distributions allowing for tumor irradiation in dedicated animal models. Experimental work is complemented by the development of dedicated simulation capabilities aiming for predictive capabiliy [3].

1 J.P. Couperus, et al., Demonstration of a beam loaded nanocoulomb-class laser wakefield accelerator, Nat. Comms. 8, 487 (2017)

2 L. Obst, et al., High-Performance Proton Acceleration from a Renewable Cryogenic Hydrogen Target, Sci. Rep. 7, 10248 (2017)

[3] M. Bussmann, et al., PIConGPU, see https://www.hzdr.de/db/Cms?pNid=3227

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Laser driven proton acceleration from near solid density plasmas at ELI-ALPS

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With the recent availability of large temporal contrast ratios at high power laser facilities the use of ever thinner targets becomes possible to empower the focus on the development of novel compact and brilliant sources of energetic particle beams and to imapct the potential applications, e.g., in the field of radiation oncology. The recent development of ELI facility which will host the laser system capable of generating ultra-short pulses in the multiterawatt or even petawatt power range at high

repetition rate, which is crucial for the investigation of new regimes of laser-matter interactions, especially laser driven proton acceleration. The most stable and well understood mechanism is the TNSA (Target Normal Sheath Acceleration), which usually requires long pulse duration in order to reach high cut-off energy. The schemes of interest (for short pulse laser) are the collision-less Shock Wave Acceleration 1, Magnetic Vortex Ion Acceleration [2-4] and Radiation Pressure Acceleration dominated regime [5], which is more efficient in near-critical density plasma.
We demonstrate here proton acceleration in new regime of laser-plasma variables from hydrogen gas target (via MVA mechanism) and cryogenic hydrogen target (via RPA dominated TNSA regime) driven by short - petawatt laser pulse which is witnessed by three dimensional (3D) particle-in-cell simulation. 3D simulations are performed in this research via the fully relativistic electromagnetic code PIConGPU [6] to suit the experimental conditions for ion acceleration application, to employ the high repetition petawatt laser facility of ELI-ALPS http://www.eli-alps.hu/). In particular, we also investigate [7] the acceleration of a proton beam driven by intense tera-hertz (THz) laser field from a near critical density hydrogen plasma. Two-dimension-in-space and three-dimension-in-velocity particle-in-cell simulation results show that a relatively long wavelength and an intense THz laser can be employed for proton acceleration to high energies from near critical density plasmas. The potential advantages of long-wavelength lasers as ion-beam drivers are based on the interplay of physical parameters, such as the ponderomotive energy conveyed to a charged particle by the laser field (~⊠^2), and the critical plasma-density (~1/⊠^2). In conclusion, the 3D PIC simulation results (focusing towards utilisation of ELI-ALPS facility) confirm the theoretical predictions and pave the way for the production of compact and affordable ion accelerators based on laser-produced plasmas for wide ranging potential applications in many fields of science and medicine.
References
1 D. Haberberger et. al., "Collisionless shock in laser-produced plasma generate monoenergetic high energy proton beams", Nat. Phys. 8, 95 (2012).
2 T. Nakamura, S. V. Bulanov, T. Z. Esirkepov, and M. Kando, "High-Energy Ions from Near-Critical Density Plasmas via Magnetic Vortex Acceleration", Phys. Rev. Lett. 105, 135002 (2010).
[3] S. S. Bulanov et. al., "Generation of GeV protons from 1 PW laser interaction with near critical density targets", Phys. Plasmas 17, 043105 (2010).
[4] A. Sharma and A. Andreev, "Effective laser driven proton acceleration from near critical density hydrogen plasma", Laser and Part. Beams 34, 219 (2016).
[5] T. Esirkepov et .al., "Highly Efficient Relativistic-Ion Generation in the Laser-Piston Regime", Phys Rev. Lett. 92, 175003 (2004).
[6] M. Bussmann et. al., "Radiative Signatures of the Relativistic Kelvin-Helmholtz Instability", Proc. Int. Conf. High Performance Comp., Networking, Storage Anal. 5-1 (2013).
[7] A. Sharma et al., "Intense tera-hertz laser driven proton acceleration in plasmas", Phys. Plasmas 23, 063111 (2016).

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Diagnostics of size of dust particles using by laser scattering method

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Dust particles are observed in various plasmas, and understanding of dusts is important for stable operation of fusion plasma. This paper is focused on dusts size diagnostics by using laser light scattering method.
The scattering of small particles can be described by Mie theory and Rayleigh theory. Rayleigh theory is suitable for when the particles are small ($\frac{2\pi}{\lambda} = x << 1$), and Mie theory can be applied to the calculation of scattering cross section for all particle sizes. Fig.1 is the calculation result of the scattering cross section of silver dust and tungsten dust using Mie theory. As can be seen in the figure, the scattering cross section of dust particle depends on the radius of particle. Therefore, dust particle size can be determined by measuring the scattering intensity.
As shown in Fig. 2 silver dusts with various sizes (250nm~3.5μm) were injected into a plasma chamber by using a dust dispenser, and dust particles were irradiated with pulsed ND:YAG laser beam

(energy per pulse : 250mJ, repetition rate : 20Hz, pulse width : 4ns). Dust dispenser was made up of speaker unit (size : 2 inch, max power : 12W, resistance : 8 Ohm). The amount of dust particles were adjusted by controlling the operating frequency and voltage of the dust dispenser. The magnitude of scattering intensity was measured and the distribution of dust particle size was deduced. The result was discussed comparing the particle size distribution with the measured values of sizes of collected dust particles.

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Summary:

Silver dusts with various sizes (250nm~3.5μm) were diagnosed by the laser light scattering method. Laser source was ND:YAG pulse laser(energy per pulse : 250mJ, repetition rate : 20Hz, pulse width : 4ns). The magnitude of scattering intensity was measured and the distribution of dust particle size was deduced. The result was discussed comparing the particle size distribution with the measured values of sizes of collected dust particles.

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Design for Evanescently-coupled Multicore Fiber Laser beyond Self-focusing Limit

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Arraying fiber lasers is being focused for power and energy scaling and multicore fibers can be a promising format. We have investigated phase locking in evanescently-coupled multicore fiber lasers by various supermode selection methods. Our calculation shows a power scaling limit given by nonlinear propagation instability below self-focusing power: the in-phase mode suffers from serious instability at a power below a few MW, on the other hand the out-of-phase mode shows excellent stability and can manage the power scaled by the core number. In this presentation we will discuss the multicore fiber design suitable for lasing with the out-of-phase mode.

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Coherent synchrotron radiation through relativistic interaction of laser with plasma

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The emergence of coherent attosecond XUV sources has allowed unprecedented spatio-temporal resolution in photonics studies of ultrafast nanoscale systems 1. High-order harmonic generation (HHG) through the interaction of ultra-short ultra-intense laser pulses (at the peak laser intensity

$I > 2.1 \times 10^{18}$ W.cm^{-2} at 800nm carrier wavelength) with solid state matter shows the potential to extend this fascinating attoscience to studies of charge particle dynamics in a relativistically driven collective systems 2. These processes also offer reasonable energy conversion efficiency, favourable energy scaling and feasibilities of higher photon energies 2 leading to a viable source for these kind of studies. Complete understanding of HHG processes in this regime is essential to optimise the source as well as to gain insignt on the ensuing interaction. Several competing theories have been proposed to simplify the physics. Among these relativistic oscillating mirror (ROM) [3] and coherent synchrotron emission (CSE) [4] have recently attracted a lot of attention due to their experimental validations [5].

The cornerstone of the ROM harmonics is attributed to the balance between ponderomotive force of the incident pulse along the propagation direction and the electrostatic force of the (roughly) fixed background ions, which drive periodic electron density spikes on the plasma surface at the point of interaction. The reflection of the light off this relativistic oscillating overcritical layer of in-phase electrons induces relativistic Doppler upshift-frequency on the incoming fields, leading to temporal distortions on the reflected electromagnetic fields which appear as a train of sub-cycle (attosecond) pulses. Under different interaction conditions in the case of CSE, extremely dense (compared to the initial plasma electron density) and narrow bunches of electrons are produced and accelerated, emitting coherent radiations in specular direction. This applies additional temporal modulations on the reflected pulse.
CSE process is efficient when the electron bunch width is on the order of a few nanometers [6].

Both ROM and CSE processes depend sensitively on specific interaction conditions, like angles of incidence, sharpness of plasma density profile, polarization state and strength of the driving laser field, etc. The phase-space analysis of charge dynamics in either case indicates that the electrons attain relativistic velocities at the moments of high harmonics radiation. In this study we computationally explore these two regimes over a parameter space where an intense ultrashort few cycle laser interacts with a low density target. We perform spacio-temporal analysis of plasma electron dynamics and investigate the relevant phase-space. The time resolved spectra of the reflected radiations confirm that at certain moments of the interaction, emitted harmonics from nano-meter electron bunches improve the efficiency of the process compared to other moments of interaction, at which only ROM harmonics are generated. In addition, the polarization state of driving laser seems to enhance CSE mechanism.

References:

1
F. Krausz and M. Ivanov
Attosecond physics
Rev. Mod. Phys. 81, 163 (2009).

2
C. Thaury and F. Quere
High-order harmonic and attosecond pulse generation on plasma mirrors: basic mechanisms
Journal of Physics B: Atomic, Molecular and Optical Physics 43, 21 (2010).

[3]
T. Baeva, S. Gordienko, and A. Pukhov
Theory of high-order harmonic generation in relativistic laser interaction with overdense plasma
Phys. Rev. E 74, 046404 (2006).

[4]
J. M. Mikhailova, M. V. Fedorov, N. Karpowicz, P. Gibbon, V. T. Platonenko, A. M. Zheltikov, and F. Krausz
Isolated Attosecond Pulses from Laser-Driven Synchrotron Radiation
Phys. Rev. Lett. 109, 245005 (2012).

[5]
B. Dromey, S. Rykovanov, M. Yeung, R. Hörlein, D. Jung, D. C. Gautier, T. Dzelzainis, D. Kiefer, S. Palaniyppan, R. Shah, J. Schreiber, H. Ruhl, J. C. Fernandez, C. L. S. Lewis, M. Zepf and B. M. Hegelich.
Coherent synchrotron emission from electron nanobunches formed in relativistic laser–plasma interactions

Nature Physics 8, 804–808 (2012).

[6]
M. Cherednychek and A. Pukhov
Analytical approach to high harmonics spectrum in the nanobunching regime
Physics of Plasmas 23, 103301 (2016).

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Ultrafast Electronic Band Gap Control and Self-Protection from a Photoinduced Phase Transition in an Excitonic Insulator

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Ta₂NiSe₅ is proposed to support an excitonic insulator phase below T_C ≈ 328 K combined with a structural change. The former occurs in small gap semiconductors with strong electron-hole interaction where excitons form spontaneously and condense into a new insulating ground state. We study the ultrafast electron and lattice dynamics of Ta₂NiSe₅ by means of time- and angle-resolved photoemission spectroscopy1 (trARPES) and time-resolved coherent optical phonon spectroscopy. We find that the low temperature structural phase persists even for high excitation densities and the photoinduced structural phase transition is hindered by absorption saturation of excitation pulses at a fluence of F_C = 0.2 mJ cm⁻². We also show that the electronic band gap can be optically controlled by tuning the excitation density. Below F_C, the band gap shrinks transiently due to photoenhanced screening of the Coulomb interaction. However, above F_C, the band gap transiently widens at the Gamma point and recovers to its equilibrium value
after ≈ 1.5 ps. Hartree-Fock calculations reveal that the band gap widening is due to
photoenhancement of the exciton condensate density, persisting until interband carrier
relaxation occurs. These results demonstrate the possibility to manipulate exciton condensates with
light and gain ultrafast band gap control.

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Development and operation of 20 fs, 4 PW Ti:sapphire laser

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Ultrahigh intensity lasers have been developed around the world to explore relativistic laser-matter interactions, laser-driven particle acceleration and gamma-ray generation. Currently, we operate a 20 fs, 4.2 PW Ti:sapphire laser developed recently at CoReLS 1. In this talk, the system configuration and performance of the 4 PW laser with a 0.1 Hz repetition rate are presented.

The 4 PW laser was developed by upgrading the existing 1.5 PW
beamline 2. The pulse duration was reduced and the output energy
was boosted. For the pulse duration reduction, the spectral width of
the seed laser pulse to amplifiers was broadened by adopting XPW and
OPCPA techniques, and the amplified spectral width was maximized by
compensating for the gain depletion effect during the amplification

through booster amplifiers. Moreover, the spectral phase distortion was minimized by employing a spectral shaping device. The output energy was boosted by adding a high-energy booster amplifier. Consequently, the amplified laser pulses with 83-J energy and 19.4-fs duration were generated with a low energy stability of 1.5% (RMS). The temporal contrast was enhanced by 4 orders of magnitude by implementing the XPW stage, and the wavefront was corrected with two adaptive optics systems before and after the pulse compressor. This multi-PW laser has been applied for a series of commissioning experiments in this year. The operational characteristics of the 4 PW laser will be reported.

References

1 J. H. Sung et al, Opt. Lett. 42, 2058 (2017)

2 T. J. Yu et al, Opt. Express 20, 10807 (2012)

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Two-color waveforms driven high harmonic generation from bulk solids

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High-order harmonic generation (HHG) is a strongly nonlinear process that reveals fundamental aspects of light-matter interaction in the strong field regime [1,2]. Additionally, it can be used for creating attosecond pulses [3,4]. The effect of two- and multicolor laser fields have already been investigated on gas HHG [5]. Theoretical investigation showed that isolated attosecond pulses can be generated from solids by adopting a two-color field [6].

Our theoretical model provides a quantum mechanical description of high-order harmonic generation in solids. We consider a one-dimensional periodic lattice as a model for the target. In the single-electron picture, the corresponding Hamiltonian can be written as
\begin{equation}
H(t)=H_{0}+H_{ext}(t),
\end{equation}
where the operator H_0 contains the kinetic energy and the periodic potential. The term $H_{ext}(t)$ takes light-matter interaction into account. In velocity gauge, $H_{ext}(t) = \frac{1}{2m}\left[-2e\mathbf{p}\cdot\mathbf{A}(t) + e^2A^2(t)\right]$, i.e., the driving field (laser pulses) is described by the corresponding vector potential:
\begin{equation}
A(t)=A_{1}f_{1}(t)\cos(\omega_{1} t+\phi_{1})+A_{2}f_{2}(t-\tau_{d})\cos(\omega_{2} (t-\tau_{d})+\phi_{2}),
\end{equation}
where τ_d is the delay between the two pulses with different central frequencies ω_1 and ω_2. A_i denote the vector potential amplitudes, the time-dependent envelope functions $f_i(t)$ are assumed to have sine square profiles, and the carrier-envelope phases (CEPs) are denoted by ϕ_i $(i = 1, 2)$. Pulses with subscript $i = 1$ and 2 can be referred to as the assisting pulse and the main pulse, respectively.

By solving the time-dependent Schrödinger equation, the expectation value of the time-dependent dipole moment operator and the HHG spectra are calculated. Applying a weaker assisting pulse, we determined non-trivial high-order harmonic radiation spectra. The structure of the harmonic peaks can be modulated by tuning the ratio of central wavelengths λ_1/λ_2.

REFERENCES
1 S. Ghimire, A. D. DiChiara, E. Sistrunk, P. Agostini et al., Nat. Phys. 7, 138 (2011).
2 Y. S. You, D. A. Reis, S. Ghimire, Nat. Phys. 13, 345 (2017).

[3] Gy. Farkas, Cs. T´oth, Phys. Rev. A 168, 447 (1992).
[4] F. Krausz, M. Ivanov, Rev. Mod. Phys. 81, 163 (2009).
[5] Peng-C. Li, C. Laughlin, Shih-I. Chu, Phys. Rev. A 89, 023431 (2014).
[6] Jin-B. Li, X. Zhang, Sheng-J. Yue, Hong-Mei Wu et al., Opt. Express 25, 018603 (2017).

Summary:

We developed a model for the description of high-order harmonic generation (HHG) in bulk solids. External two-color field induced multiband electron dynamics produces the HHG signal.

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Status of ELI-NP Project

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Since chirped pulse amplification scheme 1 has been invented, the available laser intensity has kept increasing, can reach 10^23 W/cm^2 or even higher, and can deliver radiation higher than the previously used in nuclear facilities. In order to make use of this capability in full depth, the European Forum of Infrastructure (ESFRI) has selected in 2006 a proposal of constructing two beams of 200J laser system with intensities up to 10^22-10^23 W/cm^2, called ELI at the site of Bucharest-Magurele, Romania. The rest of two large scale high intensity ELI laser facilities are built in The Czech Republic, and Hungary 2. The scientific research at ELI-NP includes two areas where only little experimental results were reported until now. The first one is laser-driven experiments related to nuclear physics, strong-field quantum electrodynamics and associated vacuum effects. The second area is that of experiments based on a Compton-backscattering high-brilliance and intense low-energy (< 20 MeV) gamma beam, a combination of laser and accelerator technology at the frontier of knowledge.

The installation of the systems are in progress and in time. The International Scientific Advisory Board has selected experiments to be performed at the commissioning and Day 1 phases. Typical experiments planned in this early stage [3] are introduced after the system over-view.

Reference

1. D Strickland and G Mourou, Opt. Commun. 56, 219 (1985).
2. https://eli-laser.eu/
3. Romanian Reports in Physics, 68, Supplement, pp. S3-S443 (2016).

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Polychromatic proton beam acceleration in PW laser-foil interaction regime

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Using a proton beam for any projection imaging purpose, e.g., in proton radiography or deflectometry measurements, source size largely affects the spatial resolution of the image. Here we examined spatial and spectral characteristics of proton beam accelerated with high contrast, ultrashort, PW laser pulse using proton radiographs of the mesh. It is demonstrated that laminar proton beam accelerated from the target has distinct different emission characteristics along and perpendicular to the laser polarisation directions. It is demonstrated that the protons in a broad energy range are accelerated with a similar partial divergence which may suggest a scenario where whole proton spectrum is accelerated instantaneously. These observations are somewhat different from the scenarios discussed before. The beam normalised transverse emittance value along the laser polarisation ε_t < 0.05 mm mrad was measured.
PIC simulation being in a good agreement with experimental findings has further elucidate the behaviour of proton beam and its "virtual source". It was found, that the momentum of particles is still changing during the propagation due to longitudinal and transverse electric fields in a beam, which results beam divergence change. However, due to almost no transvers electric field at the centre of the beams, their transvers profile at the centre is fully conserved for all energies, while longitudinal electric field is still causing a longitudinal spreading of the beam at each energy during the propagation.
This phenomena was not considered before. As a result the position of "virtual source" of protons depends on particles energy. The protons "virtual source" position is changing towards to the target when particles energy is increased. These findings may have an impact on measuring the transient dynamics of electromagnetic plasma fields and show the complex dynamic of the ion acceleration process at PW laser power.

Summary:

To summarise, we examine proton source and beam characteristics in TNSA interaction scheme at PW laser power with ultrashort pulse using proton radiographs of the mesh. It is demonstrated that laminar proton beam accelerated from the target has distinct different emission characteristics along and perpendicular to the laser polarisation directions. Additionally, the protons "virtual source" position was changing towards to the target when particles energy is increased.These phenomena were not considered before. These findings may have an impact on measuring the transient dynamics of electromagnetic plasma fields and is shows the complex dynamic of the ion acceleration process at PW laser power.

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Experiments with multiple beam types at ELI-NP

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The Extreme Light Infrastructure – Nuclear Physics (ELI-NP) facility is under implementation in Romania and features two ultra-short pulse, 10PW laser beams and a high intensity gamma-ray beam that will form a unique beam combination worldwide.

One of the eight experimental areas in this new facility will be devoted to experiments of nuclear astrophysics and fundamental QED physics with a combination of laser and gamma or electron beams. A gradual approach in terms of complexity was adopted for each experiment, in order to ensure successful implementation in the preparatory and intermediary phase of this challenging project.

The first commissioning experiment for the laser-gamma capabilities of ELI-NP will be the production and photoexcitation of isomer states, relevant for astrophysical context. We will start with the optimization of the isomer production setup using one laser beam of 1 PW at 1 Hz repetition rate, while the tunable gamma ray beam will be employed in a second step of the experiment in order to study the characteristics of these isomer levels. Several scenarios are envisaged depending on the nuclide of interest, and computations and numerical simulations have been performed for more than 70 species.

The study of radiation reaction, pair creation in vacuum and vacuum birefringence are also topics of interest, starting when the electron beam from the linear accelerator will be available for experiments in the combined beams area at ELI-NP.

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Laser-plasma accelerator based single-cycle attosecond pulse

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Abstract: A laser-plasma accelerator based carrier-envelope-phase (CEP) stable single cycle attosecond source is investigated numerically. Pulses with 6 nJ energy and 240 attosecond duration are predicted at 60 nm wavelength

Summary:

Pulses from a TW/PW power laser are focused into a gas jet to generate a relativistic electron beam, which is then sent through a first quadrupole triplet to reduce its divergence. The energy spread of an LPA electron beam is typically much larger than that of a LINAC, therefore, a reduction of the slice energy spread is necessary, which can be accomplished by the first chicane. The electron beam passes through a modulator undulator along with a TW laser beam (ELI-ALPS' SYLOS). Here, the interaction between the electrons, the magnetic field of the undulator, and the electromagnetic field of the laser introduces a periodic energy modulation. The electrons propagate through a second chicane and the energy modulation leads to the formation of a train of nanobunches. The nanobunched electron beam then moves through the radiator undulator consisting of a single or a few periods and creates CEP-stable attosecond pulses.
Our simulations show that CEP-controlled attosecond pulses with about 10 nJ energy can be generated by employing a TW-scale laser. These pulses are suitable for time-resolved field-sensitive measurements with sub-100-attosecond resolution and as attosecond pump pulses in pump-probe measurements.

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Material analysis with ultrafast electrons produced by laser acceleration

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In recent times the recoil energies of scattered electrons for atoms with large mass differences can be well resolved by using an energetic electron beam in the range of a few keV 1 to a few tens of keV, and with large scattering angles in the measurements 2. This technique is called as Electron Rutherford Backscattering Spectroscopy (ERBS), which relies on the quasi-elastic electron- atom scattering. In this case, we take advantage of the fact that the energy of the elastically scattered electrons is shifted from the primary values, due to the momentum transfer between the primary electron and the target atoms (recoil effect), and thereby the peak, due to electrons scattered elas¬tically, splits

into component peaks, which can be associated with the electrons scattered mainly from different target atoms of the sample, respectively. Furthermore, the thermal motion of the scattering atoms causes broadening in the primary electron energy distribution, usually referred to as Doppler broadening. So, from the accurate determination of the full width at half maximum (FWHM) of the peaks, the average kinetic energy of the atoms in a solid can be determined. Moreover, from the ac¬curate peak shape analysis we can determine the Compton profile or we can prognosticate different fine interaction processes, such as, final state interactions.
In this work we show that the ultrafast electrons in the MeV or GeV energy range produced by the laser acceleration technique [3] give a unique technique for the material analysis based on the ERBS.

Acknowledgement
This work was supported by the European COST CM1405 (MOLIM). Partial support by the ELI-ALPS project is acknowledged. The ELI-ALPS project (GOP-1.1.1-12/B-2012-000, GINOP-2.3.6-15-2015-00001) is supported by the European Union and co-financed by the European Regional Development Fund.

References
1] K. Tőkési, D. Varga, Z. Berényi, Nuclear Instruments and Methods in Physics Research B 354 (2015) 75.
2] K. Tőkési, D. Varga, Nuclear Instruments and Methods in Physics Research B 369 (2016) 109.
[3] S.X. Hu, and Anthony F. Starace, Phys, Rev. E 73 (2006) 066502.

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Semiclassical model for strong-field ionization of H2 molecule

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In the original formulation, the two-step semiclassical model does not take into account the effect of the Coulomb potential of the parent ion on the electron motion after ionization. Recently we developed a semiclassical two-step (SCTS) model 1 based on the theory of semiclassical time-dependent propagators that accounts for the Coulomb potential beyond the perturbation theory. We applied a semiclassical expression for the transition amplitude for strong-field ionization that differs from the one used in the quantum trajectory Monte-Carlo (QTMC) and Coulomb-corrected strong-field approximation (CCSFA) models improving the agreement with full quantum simulations (see Ref. 1).
In this work the model is extended to molecules. For our calculations we use molecular hydrogen. We describe the H2 as a two-body system consisting of: 1) the active electron (e-) with effective binding energy of 0.567 a.u., and 2) the remaining hydrogen ion (H2+) with effective charge of 1.165 a.u. The target is modeled like a tiny solar system, in which the electron moving on Kepler orbit around the molecular hydrogen ion. We present two-dimensional momentum distributions, the energy spectra, and the angular distributions of the photoelectrons ionized by a few-cycle linearly polarized laser pulses.

Acknowledgement
This work was supported by the European COST Action CM1405 (MOLIM) and by the Deutsche Forschungsgemeinschaft Grant No. SH 1145/1-1. Partial support by the ELI-ALPS project is acknowledged. The ELI-ALPS project (GOP-1.1.1-12/B-2012-000, GINOP-2.3.6-15-2015-00001) is supported by the European Union and co-financed by the European Regional Development Fund.

References
1 N. I. Shvetsov-Shilovski, M. Lein, L. B. Madsen, E. Rasanen, C. Lemell, J. Burgdörfer, D. G. Arbo, and K. Tőkési, Phys. Rev. A 94, 013415 (2016).

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Modeling high order harmonics generation in gases at ELI intensities

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We present schemes for the generation of high order harmonics in conditions of very high intensities specific to ELI configurations. One scheme proposes generation of harmonics by focusing annular beams in the target and having an advantage in easier separation of the intense driving pulse from the XUV pulse. The other is using ions instead of neutral noble gas atoms as target for laser interaction. Both IR and UV pulses are assumed to be the driving fields, assuming the use of Ti:Sa laser or its third harmonic respectively. We explore the cases of multiple ionized Ne and Ar and show that one can reach phase matching regime despite the high plasma density and obtain harmonics in the water window region.

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Petawatt (PW) Laser Facility for Particle Acceleration Studies at the BELLA Center

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The Berkeley Lab Laser Accelerator (BELLA) is currently the world's highest repetition rate (1 Hz), PW-scale, regularly operating laser facility dedicated for laser plasma acceleration (LPA) research. Initial test operations 1 of the Ti:sapphire-based CPA (Chirped-Pulse Amplification) laser system in 2013 followed by high-peak-power laser-plasma interaction and LPA studies in 2014/2015, quickly achieving cutting edge results [2,3]. The facility now routinely provides high quality focused laser pulses in the range of 10e19 W/cm^2 intensity with controllable spatial distribution in the focus (FWHM ~50 um) by a deformable mirror, exceptional beam pointing (<1.5 urad), shot-to-shot energy (<6%) and pulse duration stability (<5%) for high precision experiments [4]. The thoroughly characterized and monitored femtosecond laser pulses (32-35 fs) are delivered into radiation shielded target area for laser-plasma-driven electron and ion acceleration experiments, including the use of gas-jet and capillary discharge based LPAs, and thin-foil target studies to improve the properties of ion beams produced by laser-solid interactions. Operational experience (enhanced maintenance and safety training, experiment planning and implementation, standardized data acquisition, data analysis, data archiving systems) and latest results by 'users' of the facility are described.
This work is supported by the U.S. Department of Energy, Office of Science Office of High Energy Physics, under Contract No. DE-AC02-05CH11231.

1. W. P. Leemans, et al., in Proc. of 2013 Particle Accelerator Conference, Pasadena, CA, USA, http://accelconf.web.cern.ch/AccelConf/PAC2013/papers/thyaa1.pdf, Paper THYAA1
2. W. P. Leemans, et al., Phys. Rev. Letters, 113, 245002 (2014).
3. A. J. Gonsalves, et al., Phys. Plasmas, 22, 056703 (2015).

4. K. Nakamura et al., IEEE J. QE, 53, 1200121 (2017).

Summary:

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Thomson Parabola (TP) spectrometer design for 60-200MeV energy range of protons

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In this work an extended range Thomson Parabola (TP) spectrometer design is presented, based on analytical calculations and simulations made with SIMION v7 1, a specific software for charged particle trajectory simulations, which measure the energy distribution of accelerated protons and ions resulting from the high power laser (TW, PW) interaction with matter. This device has a high versatility due to its architecture, which uses a pinhole, one permanent magnetic core, an electrostatic deflector and a detection screen. In this configuration the TP spectrometer is able to measure with high resolution the energy spectra of several protons, Oxygen and Carbon ions, in a single laser shot 2, as part of the laser-accelerated particles bunch characterization required in terms of energy, angular divergence, as well as shot-to-shot reproducibility. In the configuration used for these simulations, the energy range for protons covers a range from 60 MeV to 200 MeV, with variation of the energy resolution between 0.5 MeV (at 60 MeV of protons) and 3.7 MeV (at 200 MeV of protons). The TP spectrometer is able to measure a small part of particle emission due to the low angular acceptance, but has a large acceptance in terms of energy, and when coupled to passive detectors is immune to electromagnetic pulses (EMP) [3].

References:

1. www.simion.com

2. Massimo De Marco et al, Electromagnetic pulses produced by expanding laser-produced Au plasma, NUKLEONIKA;60 (2):239-243 doi: 10.1515/nuka-2015-0043, 2015.

[3]. A. Mančić et al, Absolute calibration of photostimulable image plate detectors used as (0.5-20 MeV) high- energy proton detectors, Review of Scientific Instruments 79, 073301, doi:10.1063/1.2949388, 2008.

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Attosecond ionization dynamics in the vicinity of Fano resonances

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Introduction

Ionization through a Fano resonance, i.e. autoionization, is a prototypical example of ultrafast photoemission dynamics governed by electron correlation. This dynamics is encoded in the scattering phase and amplitude of the released electron wavepacket (EWP).
The phase variation across Fano resonances 1 was first measured in argon using the RABBIT technique 2, or attosecond streaking [3]. Then, in Gruson et al. [4], we fully characterized the EWP emitted through the sp2+ Fano resonance in helium, using spectrally-resolved RABBIT. This allowed reconstructing the complete autoionization dynamics, including the resonance buildup.
In this work, we go a step further compared to [4] and 2. On the one hand we investigate the coherent excitation of both sp2+ and sp3+ Fano resonances by two consecutive harmonics. This creates a correlated 2-electron EWP in excited helium [5] that decays into the continuum, resulting in a very structured shape of the photo-emitted EWP. On the other hand we show that it is possible to measure the scattering phase across the $3s^1 3p^6 4p$ Fano resonance in argon for both spin-orbit components of Ar^+.

Methods and results

We used the rainbow RABBIT technique developed by Gruson et al.[4] in combination with a high-resolution (< 100meV) 2m-long magnetic bottle electron spectrometer.
The wavelength of the driving Ti:Sapphire laser is tuned with a DAZZLER in order to hit the desired resonances.

In helium we excite coherently the sp2+ and sp3+ Fano resonances with harmonics H39 and H41, respectively. The 2-photon XUV-IR sideband (SB) 40 oscillations as a function of the delay between the two pulses carry the phase information on the two resonances. The measured spectral phase and amplitude include the print of both resonances with the sp3+ being less resolved since it is ~4 times narrower than the sp2+. These results compare very well with the predictions of an analytical model [6] taking into account the actual pulses' bandwidths.

In argon we excite the $3s^1 3p^6 4p$ Fano resonance at 26.65eV with harmonic H17. We observed two phase variations inside the neighbouring sidebands SB16 and SB18 (see Fig.1). These phase variations are separated by the argon spin-orbit splitting and correspond to the two resonant EWPs associated with Ar^+ with angular momentum J=1/2 and J=3/2. Preliminary simulations show good agreement with experimental data, and indicate how a better resolution of each component can be obtained by slightly detuning H17 with respect to the resonance.

References

1U. FANO Phys. Rev. 124, 1866 (1961).
2M. KOTUR et al. Nat. Com. 7, 10566 (2016).
[3]M. SABBAR Phys. Rev. Lett. 115, 133001 (2015).
[4]V. GRUSON et al. Science 354, 6313 (2016).
[5]C. OTT et al. Nature 516, 374 (2014).
[6]A. JIMENEZ-GALAN et al. Phys. Rev. A 93,023429(2016).

Summary:

We create a correlated two-electron wave packet in helium by simultaneous excitation of two Fano resonances with a comb of coherent high harmonics. Using spectrally resolved electron interferometry (Rainbow RABBIT technique), we measure the phase of the photo-emitted electron wave packet and reconstruct its structured time evolution.
Moreover we demonstrate that the same technique allows for spin-orbit resolved spectral phase measurements. In particular, we measure for the first time the scattering phase across the $3s^1 3p^6 4p$ Fano resonance in argon for both spin orbit components of the ion.

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Extreme THz fields from sculptured ultrashort intense laser beams

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The nonlinear propagation of ultrashort laser pulses in the form of solitons, filaments and light bullets is an exciting research field 1. Beyond the basic studies on the complex spatio-temporal phenomena involved, the field is driven significantly by its numerous applications, like for example in materials engineering 2, remote spectroscopy [3], but also for their use as powerful secondary sources across the electromagnetic spectrum [4].
Here we discuss our recent advances in developing intense THz secondary sources using tailored laser filaments. We demonstrate that one may obtain powerful THz radiation using unconventional media, like liquids, where the medium presents strong linear absorption [5]. The mechanism responsible for this counterintuitive result is a phase locked second harmonic component in the filament that results in strong transient electron currents that radiate intense THz fields.
We will also be discussing the way in achieving extreme THz electric and magnetic fields, in excess of GV/cm and kT strengths respectively, using intense two-color mid-infrared filaments [6].

1 P. Panagiotopoulos, D. G. Papazoglou, A. Couairon, and S. Tzortzakis, "Sharply autofocused ring-Airy beams transforming into nonlinear intense light bullets," Nature Communications 4, 2622 (2013)
2 M. Chanal, V. Y. Fedorov, M. Chambonneau, R. Clady, S. Tzortzakis, and D. Grojo, "Crossing the threshold of ultrafast laser writing in bulk silicon," Nature Communications 8, 773 (2017)
[3] S. Tzortzakis, D. Anglos, and D. Gray, "Ultraviolet laser filaments for remote laser-induced breakdown spectroscopy (LIBS) analysis: applications in cultural heritage monitoring," Opt. Lett. 31, 1139-1141 (2006) [4] Kang Liu, D. G. Papazoglou, A. D. Koulouklidis, S. Tzortzakis, X.-C. Zhang, "Enhanced terahertz radiation emission from abruptly autofocusing beams," Optica 3, 605-608 (2016)
[5] Dey I., Lad A.D., Fedorov V. Y., Koulouklidis A. D., Couairon A., Tzortzakis S. & Kumar G.R., "Highly efficient broadband terahertz generation from ultrashort laser filamentation in liquids," Nature Communications, doi:10.1038/s41467-017-01382-x (2017)
[6] V. Fedorov and S. Tzortzakis, "Extreme THz fields from two-color filamentation of mid-infrared laser pulses," arXiv:1708.07310 (2017)

Summary:

We demonstrate how tailored ultrashort laser filaments in the near and mid-ir can be used to generate extreme THz fields.

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Strong Field dissociative ionization of the D_2^+

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Despite being the simplest molecular system, the complete dynamical description of the D_2^+ considering all electronic and nuclear degrees of freedom is not a trivial task. Present-day theoretical approaches employed for the investigation of photoionization usually solve the problem in reduced dimensions, and commonly neglect the rotation of the molecule. Our previous studies on the photodissociation of D_2^+ [1,2] showed the importance of the molecular rotation as the resulting light induced conical intersections (LICIs) influenced strongly the dynamical properties of the molecule.

In this work we incorporate the ionization in our two-state (ground and first excited) model [1,2] by considering a third ionized state corresponding to a well defined asymptotic momentum $\vec{k}$. Here we report our results obtained for the dissociative ionization of D_2^+ in the multiphoton regime [3]. Although our long term goal is to describe the dynamics in the LICI picture, the present results were obtained for fixed molecular axis orientations.

In order to better understand the undergoing processes we also investigated the time-dependent nuclear wave packet density. Taking into account also the topology of the electronic potential energy surfaces we were able to identify the time moment and location (i.e. internuclear separation) where the population transfer between the considered potential energy surfaces occurred [4].

References

1 Gábor J. Halász, Ágnes Vibók, Hans-Dieter Meyer, and Lorenz S. Cederbaum, J. Phys. Chem. A 2013 117 (36), 8528-8535

2 Gábor J. Halász, Ágnes Vibók, Nimrod Moiseyev, and Lorenz S. Cederbaum, Phys. Rev. A 88, 043413

[3] A. Tóth, S. Borbély, G. Zs. Kiss, G. J. Halász, and Á. Vibók, J. Phys. Chem. A 2016 120 (47), 9411-9421

[4] A. Tóth, S. Borbély, G. Zs. Kiss, G. J. Halász, and Á. Vibók, Chem. Phys. Lett. 683 (2017) 567-572

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High efficiency, chirped pulse amplification in a cascaded extraction optical parametric amplifier design

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In the past few decades, due to its appealing features like broad gain bandwidth and low thermal load, optical parametric chirped pulse amplification became an indispensable technique in producing high average power, energetic ultrashort pulses 1. However, the rather low efficiency of optical parametric amplification and the stringent requirements on the pump pulse quality limited the number of high peak power OPCPA systems. So far only a few petawatt class OPCPA systems are demonstrated and 10 to 20 petawatt system are planned [2,3].

In this work a highly efficient final amplifier design called cascaded extraction OPA (CE-OPA) is proposed for high energy, high repetition rate laser amplifiers. This scheme uses the wings and central lobe of the signal pulse to successively extract energy from the pump pulse using two custom designed crystal. The idler is extracted after the first crystal in order to prevent pump back-conversion in the second one. The suitability and effectiveness of CE-OPA is shown by advanced 3+1D numerical simulations and compared to conventional OPCPA scheme with the same pulse parameters using DKDP as the nonlinear crystal. Two scenarios were examined regarding the temporal shape of the pump pulse: In the first case the pump was 1st order, while in the second case it was 6th order Gaussian. In both scenarios the peak intensity of the pump pulse was kept at 1 GW/cm2 level, thus it was possible to reveal how the extraction efficiency depends on the pump pulse shape.
The numerical simulations suggest that approximately 10% higher conversion efficiency could be achieved in CE-OPA than in conventional OPA. The highest conversion efficiency, 50%, is achieved in the second case and is very close to the quantum efficiency, which is 56.6% at pump and signal wavelengths of 515 nm and 910 nm respectively. Furthermore, CE-OPA pumped with a temporal Gaussian pulse is as effective as a conventional OPA pumped with temporal sixth order Gaussian pump pulse. Consequently, the complexity of the pump system can be highly reduced with a CE-OPA setup instead of the conventional OPA system with carefully engineered pump shape. The output energy stability and alignment sensitivity of CE-OPA are also superior compared to the conventional OPA and even counteracts gain narrowing.

1. R. Budriunas, T. Stanislauskas, J. Adamonis, A. Aleknavičius, G. Veitas, D. Gadonas, S. Balickas, A. Michailovas, and A. Varanavičius, "53 W average power CEP-stabilized OPCPA system delivering 5.5 TW few cycle pulses at 1 kHz repetition rate," Opt. Express 25(5), 5797-5806 (2017).

2. V. V. Lozhkarev, G. I. Freidman, V. N. Ginzburg, E. V. Katin, E. A. Khazanov, A. V. Kirsanov, G. A. Luchinin, A. N. Mal'shakov, M. A. Martyanov, O. V. Palashov, A. K. Poteomkin, A. M. Sergeev, A. A. Shaykin, and I. V. Yakovlev, "Compact 0.56 Petawatt laser system based on oiptocal parametric chirped puse amplification in KD*P crystals," Laser Phys. Lett. 4(6), 421-427 (2007).

3. C. Danson, D. Hiller, N. Hopps, and D. Neely, "Petawatt class lasers worldwide," High Power Laser Science and Engineering 3(e3), (2015).

Summary:

A cascaded extraction optical parametric amplifier (CE-OPA) has been proposed as a final amplifier for laser systems. 3+1D numerical simulations show that a CE-OPA system pumped with a temporal Gaussian pump pulse can achieve efficiency similar as a conventional OPA pumped with a temporal super Gaussian pump pulse and the conversion efficiency in the CE OPA with a temporal super Gaussian pump pulse could approach quantum efficiency. The CE-OPA system has better output energy stability with lower alignment sensitivity to phase-matching detuning and non-collinear angles when compared to conventional OPA amplifiers.

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Simulation of optical parametric amplifier stages of ELI-ALPS SYLOS laser

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In ELI-ALPS, one of the main laser systems for driving plasma and gas-based HHG stages is a state-of-the art 1 kHz laser called SYLOS. Targeted pulse parameters are 100 mJ pulse energy and 6 fs pulse duration, with outstanding energy, phase and pointing stability as well as high spatiotemporal quality. The first phase of the laser system has already set a new standard in kHz laser system engineering and technology 1.
The aim of this work was to numerically investigate the OPCPA stages of SYLOS1 laser using the experimentally measured parameters. The modelling was carried out using a 3+1D numerical code for three-wave-mixing developed for ELI-ALPS. The software is written in C++ and uses a computationally efficient algorithm for Fourier transform of highly chirped pulses 2. The code takes into account dispersion, diffraction, crystal anisotropy and parametric fluorescence as well, giving a very accurate description of the optical parametric chirped pulse amplification phenomena. The beam profiles and spectra of both the signal and pump pulses and their in- and output energies were measured before and after each NOPCPA stage. The input pulse profiles and temporal shapes, required by the numerical code, were imported from these measurement files instead of approximating them with perfect, analytical functions. As a result, the calculated output pulse parameters were in good agreement with the experimentally measured ones.
As a conclusion, by using measured pulse shapes as the input to the numerical code, very accurate results were obtained. Therefore, the numerical code for three-wave-mixing is now experimentally verified and it can be used for the development of the second phase of the SYLOS laser.

1 R. Budriunas, T. Stanislauskas, J. Adamonis, A. Aleknavicius, G. Veitas, D. Gadonas, S. Balickas, A. Michailovas, and A. Varanavicius, "53 W average power CEP-stabilized OPCPA system delivering 5.5 TW few cycle pulses at 1 kHz repetition rate," Opt. Express 25(5), 5797-5806 (2017).

2 A. Adrianov, A. Szabo, A. Sergeev, A. Kim, V. Chvykov, and M. Kalashnikov, "Computationally efficient method for Fourier transform of highly chirped pulses for laser and parametric amplifier modeling," Opt. Express 24(23), 25974-25982 (2016).

Summary:

Numerical simulation of the non-collinear optical parametric chirped pulse amplifier (NOPCPA) stages of ELI-ALPS SYLOS laser is presented in this work. The modeling was carried out using an advanced 3+1D numerical code based on the measured pulse parameters of the laser system including beam profiles and pulse spectra. This way very accurate results were obtained from the simulations which were in good agreement with the experimentally measured ones.

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Classical trajectory Monte Carlo simulation of ionization of atoms by few-cycle laser pulses

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During the ionization of atoms by few-cycle laser pulses, beside the dominant ionization, secondary processes with significant impact on the final momentum distribution of the continuum electrons also occur. These partly can be the result of interference between electronic wave packets following different spatial and temporal paths 1. The formed radial interference pattern, in a simplistic picture 2, is a result of the interference between the direct (i.e., unscattered) and the scattered wave packets, where the direct wave packet can be considered as a reference, while the scattered wave packet as a signal wave. Thus, this interference structure can be interpreted as the holographic mapping (HM) of the states of target atoms or molecules 2.
In this work we performed classical trajectory Monte Carlo calculations for the ionization of the H, He, Ne, Ar targets in collision with a laser pulse with the form of E= E0 sin(ωt)sin2(πt/τ), where the

laser pulse parameters are the following ω = 0.4445 a.u., E0 = 1 a.u., and τ = 28.26 a.u. The use of this driving pulse ensures that the spatial interference (HM pattern) is dominant. Our calculations were performed in the framework of the single active electron approximation, where the interaction between the active electron and the rest of the target atom is modeled by the Garvey-type potential [3]. Among the momentum distributions of the ejected electrons we also analyze the individual trajectories during the interaction. We show that significant fraction of the electrons return to the target nucleus.

Acknowledgement
This work was supported by the Hungarian Scientific Research Fund OTKA No. K103917 and by the and by the European COST Action CM1204 (XLIC) and CM1405 (MOLIM). Partial support by the ELI-ALPS project is acknowledged. The ELI-ALPS project (GOP-1.1.1-12/B-2012-000, GINOP-2.3.6-15-2015-00001) is supported by the European Union and co-financed by the European Regional Development Fund.

References
1 Xue-Bin Bian, Y. Huismans, O. Smirnova, Kai-Jun Yuan, M. J. J. Vrakking, and André D. Bandrauk, Phys. Rev. A 84, 043420 (2011).
2 Y Huismans, A Rouzée, A Gijsbertsen , J H Jungmann , A S Smolkowska , P S W M Logman , F Lépine , C Cauchy , S Zamith , T Marchenko , J M Bakker , G Berden , B Redlich , A F G van der Meer , H G Muller , W Vermin , K J Schafer , M Spanner , M Yu Ivanov , O Smirnova , D Bauer , S V Popruzhenko , M J J Vrakking, Science 331, 61 (2011).
[3] Garvey R.H., Jackman C.H. and Green A.E.S., Phys. Rev. A12 (1975) 1144.

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Ultrafast electron dynamics in two-dimensional structures

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Recent graphene research has triggered enormous interest in new two-dimensional ordered crystals constructed by the inclusion of elements other than carbon for bandgap opening and controlled engineering. Suitable design of seperior multifunctional two-dimensional materials with proper and tunable bandgap has wide-ranging applications, such as in opto-electronics. In the presentation, we will discuss structure-function relationships in two-dimendional materials such as graphene, phosphorene, and similar low-dimensional structures using first principles density functional theory and time dependent density functional theory. We show how the high anisotropy between the in-plane and out-of-plane mechanical properties in these systems result in easy and efficient band structure modulation through strain engineering. We find that the resulting modification in electronic properties has prominent implication on the local charge densities, allowed inter-band, intra-band transitions and therefore the inherent electron dynamics. The ultrashort time dynamics in graphene and phosphorene materials is addressed.

1

Two physical realizations of regular phase coherent states: Rydberg atoms in a microwave field; and two quantized circularly polarized radiation modes interacting with free electrons.

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In studying the quantum phase properties of electromagnetic radiation fields, recently we have derived the regular phase coherent states parametrized by complex numbers in the unit disc 1. They

are in fact SU(1,1) coherent states, introduced earlier by Perelomov 2 in a more general context. In the one-mode representation these states are generated by a perturbed electromagnetic oscillator Hamiltonian containing an intensity-dependent coupling term [3].

In the present contribution we discuss two distinct, new physical realizations of the Perelomov states, which may be relevant in the non-perturbative theory of some strong-field processes. First we show that the motion of a charged particle in a Coulomb field can be naturally described by using SU(1,1) generators and a fictitiuos time parameter, the so-called excentric anomaly. By analysing the interaction of a Rydberg atom with a microwave field at the main resonance, we describe squeezing and stretching in real space, as a result of the generation of SU(1,1) coherent states for the Coulomb problem. As a second physical situation, we consider the interaction of free electrons with two co-propagating circularly polarized electromagnetic waves of the same frequency but opposite polarizations. We present the exact solutions of the corresponding quantum-mechanical problem, which can be expressed by two-mode SU(1,1) coherent states.
Acknowledgments.
The ELI-ALPS Project No. GINOP 2.3.6-15 is supported by the European Union and co-financed by the European Regional Development Fund.

References.
1 Varro S, Regular phase operator and SU(1,1) coherent states of the harmonic oscillator. Physica Scripta 90 (2015) 074053 (18pp). E-print: arXiv:1412.3218v2.
2 Perelomov A M 1972 Coherent states for arbitrary Lie group. Commun. Math. Phys. 26 222-236.
[3] Aharonov Y, Lerner E C, Huang H W and Knight J M 1973 Oscillator phase states, thermal equilibrium and group representations J. Math. Phys. 14 746-756.

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Electronic and Nuclear Quntum Dynamics in Ozone on few Femtosecond Timescale: Theory and Experiment

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Photodissociation of ozone following absorption of biologically harmful solar ultraviolet (UV) radiation is key for the life protecting mechanism of the ozone layer. Even though its photolysis is described successfully by post-Hartree-Fock theory it has been evading from experimental access so far [1-4].
Here we present the first observation of femtosecond timescale the electronic and nuclear dynamics of ozone triggered by sub-10 fs short, ~ 2 μJ DUV pulses. Experimental evidence has been found for molecular fragmentation being accompanied by ~ 20 fs periodic oscillations of parts of the launched excited B-state related nuclear wave packet (NWP) around the Franck-Condon (FC) point [5]. These oscillations are attributed to closed trajectories on the B-state related potential energy surface (PES). Full-quantum mechanical electronic structure and ab-initio multi-configurational time-dependent Hartree (MCTDH) simulations support this interpretation [5].

References

1. G. J. Halász, A. Perveaux, B. Lasorne, M. A. Robb, F. Gatti and Á. Vibók:
Coherence revival during the attosecond electronic and nuclear quantum photodynamics of the ozone molecule. Phys. Rev. A. 88, 023425, (2013).

2. A. Perveaux, D. Lauvergnat, B. Lasorne, F. Gatti, M. A. Robb, G. J. Halász, and Á. Vibók: Attosecond electronic and nuclear quantum photodynamics of ozone: time-dependent Dyson orbitals and dipole. J. Phys. B. 47, 124010 (2014).

3. A. Perveaux, D. Lauvergnat, F. Gatti, G. J. Halász, Á. Vibók and B. Lasorne: Monitoring the birth of an electronic wavepacket in a molecule with attosecond time-resolved photoelectron spectroscopy. J. Phys. Chem. A. 118, 8773 (2014).
4. P. Decleva, N. Quadri, A. Perveaux, D. Lauvergnat, F. Gatti, B. Lasorne, G. J. Halász and Á. Vibók: Attosecond electronic and nuclear quantum photodynamics of ozone monitored with time and angle resolved photoelectron spectra. Scientific Reports,| 6:36613 | DOI: 10.1038/srep36613, (2016).
5. T. Latka1, V. Shirvanyan, M. Ossiander, O. Razskazovskaya, A. Guggenmos, M. Jobst, M. Fieß, S. Holzner, A. Sommer, M. Schultze, B. Bernhardt, W. Helml, F. Gatti, B. Lasorne, D. Lauvergnat, P. Decleva, G. J. Halász, Á. Vibók, R. Kienberger: Femtosecond Electronic and Nuclear Dynamics in Ozone. Submitted to Nature Phys. (2017).

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Nanoimaging using soft X-rays and extreme ultraviolet (EUV) produced using laser plasma light sources

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Visualizing small objects in the nanometer scale with high spatial resolution is very important from the point of view of modern science and technology. To extend the diffraction limit associated with the wavelength of radiation, one possible way is to reduce the wavelength, allowing smaller features to be resolved and visualized.
This requires short wavelength sources, capable of delivering sufficient flux to achieve high signal-to-noise ratio images with nanometer spatial resolution. These sources are synchrotrons, free electron lasers, but also compact sources, such as laser-plasma, discharge-pumped, or high harmonic generation sources, among others.
The goal of achieving nanometre spatial resolution can be accomplished both with specialized optics, often dedicated for specific spectral range, mostly, reflective and diffractive, sometimes refractive optics for keV-range photon energies, or without optics at all. Moreover, many unique imaging techniques were developed so far, some of them will be mentioned in the presentation, including: holography, zone plate based imaging, and contact microscopy, which were used in variety of applications, related to nanotechnology, material science, bioengineering, etc.
Of course this brief overview of our recent works cannot address all available possibilities to achieve short wavelength photon-based nanoscale imaging, however, its aim is to be an introduction to this interesting and novel topic.

Acknowledgements:
Some experiments, which are the part of this lecture, were supported by the National Centre for Research and Development, LIDER programme, grant #LIDER/004/410/L-4/12/NCBR/2013, the National Science Centre, Opus programme, grant agreement number UMO-2015/17/B/ST7/03718 and UMO-2015/19/B/ST3/00435, the Education, Audiovisual and Culture Executive Agency (EACEA) Erasmus Mundus Joint Doctorate Programme Project No. 2012-0033 and from the European Union's Horizon 2020 research and innovation program, under Laserlab-Europe IV, grant agreement No. 654148.

Summary:

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Attosecond electron dynamics in molecules and liquids

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Photoionization and electron transport in the condensed phase are phenomena that entirely take place
on the attosecond time scale. I will present our recent experimental and theoretical work investigating
the photoionization dynamics of molecules [1, 2]. We have measured relative photoionization delays between the two outermost valence shells of two polyatomic molecules, H2O and N2O. Whereas the measured delays all lie below 50 as in the case of H2O, the delays reach up to 160 as in the case of N2O 1. These large delays are shown to originate from the transient trapping of the photoelectron in
shape resonances that have calculated lifetimes on the order of 110 as 2.

Fig. 1: (a) Photoelectron spectrum of N2O generated by an attosecond pulse train transmitted through a Sn filter (black line) and in the presence of the dressing IR field (orange line). Difference spectra, obtained by subtracting XUV only from XUV + IR photoelectron spectra and vice versa, are shown in red and

blue, respectively. (b) Difference spectrum as a function
of the IR-XUV delay.
We have moreover extended attosecond science from
gases to liquids by coupling an attosecond beamline
with a liquid microjet [3]. This advance has enabled us
to perform the first attosecond time-resolved
measurements on liquids. We have studied the relative
photoemission delays between the highest-occupied
molecular orbitals of water molecules in the gas and liquid phases. The measured energy-dependent delays range from 50 to 70 as. Our analysis shows that these delays reflect the effects of solvation on
the water molecules and the signatures of scattering dynamics during electron transport. Specifically,
we find that in transparent materials, the interaction of the electron wavepacket with the XUV and IR
fields can take place at spatially distinct positions, i.e. a non-local mechanism of attosecond
interferometry [4]. Finally, I will report on our very recent realization of the first time-resolved X-ray
absorption experiment with a water-window high-harmonic source [5], which brings attosecond
transient absorption experiments on solvated molecules within reach.

REFERENCES

1 M. Huppert, I. Jordan, D. Baykusheva, A. von Conta, and H. J. Wörner, Phys. Rev. Lett. 117, 093001 (2016)
2 D. Baykusheva and H. J. Wörner, J. Chem. Phys., 146, 124306 (2017)
[3] I. Jordan, M. Huppert, M. A. Brown, J. A. van Bokhoven, H. J. Wörner, Rev. Sci. Instrum. 86, 123905 (2015)
[4] D. Rattenbacher, I. Jordan, L. Seiffert, T. Fennel, H. J. Wörner, submitted (2017).
[5] Yoann Pertot, Cédric Schmidt, Mary Matthews, Adrien Chauvet, Martin Huppert, Aaron von Conta,
Andres Tehlar, Denitsa Baykusheva, Jean-Pierre Wolf, Hans Jakob Wörner, Science 355, 264 (2017).

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Waveform control of electron emission from isolated nanospheres with circularly polarized two-color laser fields

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Spatio-temporal tailoring of the near-fields of nanostructures illuminated with laser pulses of well-defined waveform enables sub-cycle control of electron dynamics at the nanoscale 1. Linearly polarized few-cycle laser pulses have been applied for phase control of the electron emission from metal nanotips 2, isolated dielectric nanoparticles [3], and field propagation-induced tuning of the energetic electron emission direction [4]. Here we extend the waveform control of the strong near-field dynamics by applying circularly polarized two-color femtosecond laser pulses to isolated nanospheres.

In the experiment a beam of isolated nanoparticles was prepared via aerosol techniques and aerodynamic lens focusing. Circularly polarized ~30 fs laser pulses of opposite helicity centered at 780 nm and 390 nm were combined to form cloverleaf shaped laser fields. The electron emission resulting from interaction of the two-color pulses with nanoparticles was recorded via single shot velocity map imaging. For tomographic reconstruction of the electron distribution the laser field was rotated in the polarization plane by varying the time delay between the two colors and a set of the electron emission projections was recorded. Measurements with rare gas served as a reference to extract laser field parameters in the interaction region. To examine impact of the field propagation, nanoparticles of different diameter were studied. Similar to the experiments with atomic gas [5] the electron emission from nanoparticles exhibits three-fold rotation symmetry, reflecting the structure of the driving field. The experimental results were compared with trajectory-based Mean-field Mie Monte-Carlo (M3C) simulations.

1 P. Hommelhoff and M. F. Kling, Attosecond nanophysics: from basic science to applications (Wiley, 2015).

2 M. Krüger, M. Schenk, and P. Hommelhoff, "Attosecond control of electrons emitted from a nanoscale metal tip", Nature 475, 78 (2011).

[3] S. Zherebtsov et al., "Controlled near-field enhanced electron acceleration from dielectric nanospheres with intense few-cycle laser fields", Nature Phys. 7, 656 (2011).

[4] F. Süßmann et al., "Field propagation-induced directionality of carrier-envelope phase-controlled photoemission from nanospheres," Nature Commun. 6, 7944 (2015).

[5] C. A. Mancuso et al., "Strong-field ionization with two-color circularly polarized laser fields", Phys. Rev. A 91, 031402 (2015).

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Nuclear Photonics at ELI-NP

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Photons in the range of several MeV are an ideal tool to investigate the atomic nucleus. The pure electromagnetic interaction allows to derive absolute values of various nuclear properties in a completely model independent way. For decades the "white" and mostly unpolarized spectrum from electron bremsstrahlung has been used as a photon source. With the advent of photons from Laser Compton Backscattering (LCB) more "mono"-energetic beams with a width of several 100 keV became available which are in addition completely polarized.

The Gamma Beam System (GBS) at ELI-NP will deliver a photon beam in the per mille bandwidth range and with unprecedented intensity and spatial dimensions. This opens several frontiers for basic research and applications because the selective manipulation of nuclear excitations becomes possible.

The talk will give an overview about the reaction mechanism and discusses a few examples for experiments planned at ELI-NP.

Supported by the BMBF (research collaboration 05P2015 ELI-NP).