Workshop on
Super Intense Laser Atom Physics
Zion National Park, USA
21-23 September 2009
SILAP 2009  www.physics.byu.edu/silap
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Super Intense Laser Atom Physics
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Topics
Relativistic Quantum Dynamics, High-Energy-Density Interactions, Laser-Particle Interactions, Intense Ionization Dynamics, Short Wavelength & Attosecond Science, Strong-Field Molecular Dynamics, Ultra High Intensity Laser Technologies

Conference Chair
Justin Peatross (Brigham Young University)

Advisory Committee
Jens Biegert (Institute for Photonic Sci., Barcelona)
Eric Constant (University of Bordeaux)
Joseph Eberly (University of Rochester)
Todd Ditmire (University of Texas)
Louis DiMauro (Ohio State University)
Mikhail Fedorov (General Phys. Institute, Moscow)
Rainer Grobe (Illinois State University)
Misha Ivanov (National Research Council, Canada)
Henry Kapteyn (University of Colorado)
Christoph Keitel (Max Planck Institute Heidelberg)
Jon Marangos (Imperial College London)
Katsumi Midorikawa (RIKEN Wako, Japan)
Chang Hee Nam (KAIST, Korea)
Luis Roso (University of Salamanca)
Ken Schafer (Louisiana State University)
Don Umstadter (University of Nebraska)

Conference Administrator
Nan Ah You (Brigham Young University)
SUNDAY

7:00PM-9:30PM RECEPTION (Switchback Grille)

MONDAY

7:30AM  BREAKFAST (Switchback Grille)

8:45AM  Opening Remarks, Announcements
         (Conference Room, Zion Park Inn, Downstairs)

Session M1, Chair: Rainer Grobe

8:55AM  Jerome Hastings (Invited) – Stanford Linear Accelerator Center, USA
        The LCLS: A High Field Angstrom Wavelength Source
        The performance and capabilities of the Linac Coherent Light Source (LCLS) for high field physics will be discussed.

9:20AM  Sudeep Banerjee, N. Powers, V. Ramanathan, N. C.-Smith, S. Kalmykov, B. Shadwick, and D. Umstadter (Invited) – University of Nebraska, USA
        Generation and Applications of GeV-Class Laser-Driven Electron Beams
        We report results on the generation of near-GeV electron beams using a laser wakefield accelerator. Optimal matching of the laser to the plasma produces stable, high brightness beams scalable to multi-GeV energies using petawatt laser pulses.

9:45AM  Dieter Bauer (Invited) – University of Rostock, Germany
        Laser-Generated Relativistic Attosecond Electron Bunches
        The generation of relativistic attosecond electron bunches is observed in three dimensional, relativistic particle-in-cell simulations of the interaction of intense laser light with droplets. The mechanism behind the multi-MeV attosecond electron bunch generation is investigated using Mie theory.

10:10AM Donald Umstadter (Featured) – University of Nebraska, Lincoln, USA
        Ultra-Intense Laser Interactions with Matter
        We review some basic physics problems that can be studied when a petawatt laser is focussed to ultra-high intensity (10$^{23}$ W/cm$^2$) and interacts with highly relativistic matter.

10:25AM  X. Q. Yan, J. Meyertervehen (Contributed) – Max-Planck-Institut fuer Quantenoptik, Garching, Germany
          Self-Organizing GeV Nano-Coulomb Collimated Proton Beam from Laser Foil Interaction
          We report on a self-organizing, quasi-stable regime of laser proton acceleration, producing 1 GeV nano-Coulomb proton bunches from laser foil interaction at an intensity of 7x10$^{21}$ W/cm$^2$. 
10:40AM  BREAK

SESSION M2, Chair: Stan Haan

11:00AM  T. Ditmire, B. Murphy, K. Hoffman, H. Thomas, G. Dyer, A. Bernstein and J. Keto (Invited) – University of Texas, Austin, USA  
High Intensity XUV Pulse Interactions with Atomic and Metallic Clusters  
We examine interactions of intense extreme ultraviolet (XUV) pulses with atomic clusters.

11:25AM  Chul Min Kim, Karol A. Janulewicz, Hyung Taek Kim, and Jongmin Lee (Invited) – Advanced Photonics Research Institute, Gwangju, Korea  
Propagation of a High Harmonic Pulse through an Active Medium of a Plasma-Based X-Ray Laser  
We investigate theoretically the propagation of a high harmonic pulse through an amplifying medium of an x-ray laser. By using a Maxwell-Bloch model, the temporal characteristics and properties of the output pulse are discussed.

11:50AM  Hui Chen (Invited) – Lawrence Livermore National Laboratory, USA  
Relativistic Positron Creation Using Ultra Intense Short Pulse Lasers  
We report on experiments using the Livermore Titan laser shooting a millimeter-thick solid gold target where billions of positrons were created.

12:15PM  Zoltán Harman, Yousef I. Salamin, Benjamin Galow, Christoph H. Keitel (Featured) – Max-Planck-Institute for Nuclear Physics, Heidelberg, Germany  
High-Power Laser-Ion Acceleration for Medical Applications  
As shown in our theoretical simulations, tightly focused and thus extremely strong laser beams should permit the direct acceleration of light nuclei up to energies that may offer the potentiality for applications in cancer radiotherapy.

12:30PM  Igor Pogorelsky (Contributed) – Brookhaven National Lab, USA  
Ultra-Fast CO2 Lasers in Ion Acceleration Research  
We review merits of long-wavelength terawatt CO2 lasers for strong-field physics research due to favorable wavelength scaling of ponderomotive effects.

12:45PM  LUNCH (Switchback Grille)

SESSION M3, Chair: Donald Umstadter

2:00PM  Joachim Ullrich (Invited) – Max-Planck-Institute for Nuclear Physics, Heidelberg, Germany  
Atoms, Molecules and Clusters in the Brilliant Light of Free Electron Lasers  
Recent advances in Free Electron Lasers will be highlighted and a preliminary report given on pioneering experiments at the Free Electron Laser at Hamburg (FLASH) as well as at the Spring8 Compact SASE Source (SCSS) in Japan.

2:25PM  Akira Suda, Samuel Bohman, Tsuneto Kanai, Shigeru Yamaguchi, and Katsumi Midorikawa (Featured) – RIKEN Advanced Science Institute, Japan  
Generation of TW, 2-cycle Pulses Focussable to Relativistic Intensities  
We report the generation of 5 mJ, 5 fs pulses using a pressure-gradient hollow fiber. The beam after pulse compression could be focused to a diffraction-limited spot with an intensity in excess of 5x10^18 W/cm^2.
C. Müller, M. Ruf, E. Lötstedt, C. Deneke, A. Shahbaz, A. Pálffy, J. Evers, K. Z. Hatsagortsyan and C. H. Keitel (Invited) – Max Planck Institute for Nuclear Physics, Heidelberg, Germany

**High-Energy Processes in Very Intense Laser Fields**

An overview of recent theoretical studies devoted to highly energetic processes in superintense laser fields is given, comprising various schemes of lepton pair production and laser-induced nuclear excitation.

Howard Reiss (Featured) – Max-Born-Inst., Berlin, Germany

**Limitations of Gauge Invariance and Consequences for Laser-Induced Processes**

Some aspects of physical processes are not preserved in a gauge transformation, such as conservation rules. The plane wave field of a laser requires a vector potential, and tunneling theories can lead to fundamental errors.

1-Minute Poster Advertisements

**BREAK**

SESSION M4, Chair: Kenneth Schafer

Louis DiMauro (Featured) – Ohio State University, USA

**Top Ten Experimental Results in Super-Intense Laser-Atom Physics**

Joseph Eberly (Invited) – University of Rochester, USA

**Review of and Outlook for Super-Intense Laser-Atom Physics**

**POSTER SESSION**

Johan Boullet, Yoann Zaouter, Jens Limpert, Stéphane Petit, Yann Mairesse, Baptiste Fabre, Julien Higuet, Eric Mével, Eric Constant and Eric Cormier – Université Bordeaux, France

**MHz Repetition Rate High-Order Harmonic Generation Driven by a Fiber Laser System**

We use a home-made CPA femtosecond fiber laser system to generate high order harmonics in Ar, Xe and Kr and observe XUV emission at very high and adjustable repetition rate (100 kHz to 1 MHz).

N. Brimhall, N. Heilmann, N. Herrick, J. Peatross – Brigham Young University, USA

**High-Order Harmonics as an Extreme Ultraviolet Light Source for Determination of Material Optical Constants**

We use high-order harmonics as a light source for measuring optical constants of materials in the EUV. With this source and a ratio reflectance technique, we extract optical constants for uranium, copper, and their oxides.
Bohmian Trajectories in a Free Electron Wave Packet Experiencing a Relativistic Laser Field

We analyze Bohmian trajectories associated with an electron wave packet in a relativistic electromagnetic plane wave pulse. Quantum effects typically cause the trajectories to deviate only a small amount from the trajectory of classical point charge.

Strong-field multiphoton double ionization of Helium

We have investigated the role of the electron-electron correlation in the multiphoton double ionization of He by a short, superintense XUV laser pulse.

Study of Bremsstrahlung from Relativistic Laser-Plasma Interactions

We examine relativistic bremsstrahlung from high-intensity laser-plasma interactions when the motion of electrons in the plasma becomes ultrarelativistic.

Three Dimensional Momentum Imaging of Electron Wave Packet Interferences

Electron Wave Packet (EWP) interferences, manifested in the photoelectron momentum spectra of single ionization in atoms with intense (0.4 PW/cm²) Carrier Envelope Phase (CEP)-stabilized few-cycle (~5 fs) laser pulses are investigated by a ‘reaction microscope’.

Bohmian Perspective on High Harmonic Generation

We consider the Bohmian interpretation of wavepacket behavior during high harmonic generation. Surprisingly, electron trajectories that remain caught in the atomic potential exhibit the strongest high-harmonic behavior, as they are influenced by returning portions of the scattered pilot wave.

Controlling the bound Electron motion in dissociating H2+ by CEP stabilized Few-Cycle Laser Pulses

Fully differential data on H2-dissociation in carrier-envelope-phase (CEP) stabilized 6fs laser pulses were recorded with a reaction microscope. By varying the CEP control over the proton emission direction, and, thus, the charge localization was achieved.

Two-Photon Double Ionization of He and Ne with Intense VUV Free-Electron-Laser Pulses

Using a Reaction microscope we studied two-photon double ionization (TPDI) of He and Ne with short (~25 fs) intense ($10^{13}$ – $10^{14}$ W/cm²) VUV pulses at the Free Electron LASer Hamburg (FLASH) for different photon energies (44 and 52 eV). We observe characteristic signatures of direct (He) and sequential (Ne) ionization imprinted in the momentum distributions of the doubly charged ions.

P10  Gerd Leuchs, Alessandro Villar, Simon Heugel, Markus Sondermann, and Norbert Lindlein – Max Planck Institute for the Science of Light, Erlangen, Germany

The Threshold for Pair Production when Focusing High Power Laser Radiation in Vacuum

We propose that the back reaction of the vacuum may reduce the focal spot size and enhance the electric field at the focus for a given input power – much like in resonant near field enhancement.

P11  K.B. Oganesyan, A.S. Gevorgyan – Yerevan Physics Institute, Armenia

Formation of 2D Positron Atoms and Stimulation of Their Resonant Decay

We investigate technical aspects of the possibility of producing high-frequency monochromatic electromagnetic radiation ($\gamma$-laser) based on channeling of positrons in crystal undulators.

P12  Tala Palchan, Shmuel Eisenmann, and Arie Zigler, Hebrew University, Israel

Generation of Fast Ions from SNOW Nano-Wires Using High Laser Intensities

We report on experimental demonstration of fast protons (>1 MeV) from the interaction of modest laser intensities ($\sim 10^{17}$ W/cm²) and micro-structured targets such as snow nano-wires.


Controlling High-Order Harmonic Cut-Off Extension Using Two Delayed Pulses of the Same Colour

We present a novel method to extend the cut-off frequency up to 5.5 Up based on double-pulse high-order harmonic generation. We explore the mechanism involved during the interaction with such field.

P14  A. Picón, J. Mompart, J. R. Vázquez de Aldana, L. Plaja, G. F. Calvo, and L. Roso – JILA, University of Colorado, USA / Universitat Autonoma de Barcelona, Spain

Photoionization with an Extra Angular Momentum

We analyze the interaction of an hydrogen atom with a beam transporting spin and orbital angular momentum, showing large transfer of angular momentum to the atom and unveiling new phenomena for photoionization.
P15  V.S. Rastunkov and V.P. Krainov, Moscow Institute of Physics and Technology, Dolgoprudny, Russia

Theory of High-Order Harmonics Generation Due to Brunel Electron Heating in Relativistic Laser Interaction with Overdense Plasma

High-order harmonics generation in the interaction of superintense femtosecond laser pulse with overdense plasma is considered. Intensities of even and odd harmonics are calculated.

P16  M. Ruf, G. R. Mocken, C. Müller, K. Z. Hatsagortsyan, and C. H. Keitel – Max-Planck-Institute for Nuclear Physics, Heidelberg, Germany

Magnetic-Field Effects in Electron-Positron Pair Creation by Counterpropagating Laser Pulses

The production of electron-positron pairs from vacuum by counter-propagating laser beams of linear polarization is numerically investigated. Extending previous studies of this process the magnetic component of the laser fields is explicitly taken into account.

P17  M. Ware and J. Peatross – Brigham Young University, USA

Photoemission by Large Electron Wave Packets Emitted out the Side of a Relativistic Laser Focus

We provide an update on an experimental effort to measure the radiation from individual electron wave packets that are spread over an area on the scale of an optical wavelength.

P18  Zhiyi Wei, Hao Teng, Zhaohua Wang, Hainian Han, Jinglong Ma and Jie Zhang – Institute of Physics, Chinese Academy of Sciences, Beijing, China

Push Laser Field to Multi-100TW Peak Power, CEP Control and Attosecond Pulse at XUV

A 720TW Ti:sapphire laser at single shot, 100TW Ti:sapphire laser at 0.1Hz repetition rate and CEP controlled 5fs laser was developed in the Institute of Physics. The detail results will be introduced in this talk.

7:00PM  DINNER (Switchback Grille)

TUESDAY

7:30AM  BREAKFAST (Switchback Grille)

SESSION Tu1, Chair: Margaret Murnane

8:45AM  S.L. Haan, Z.S. Smith, K.N. Shomsky, P.W. Plantinga, and T.L. Atallah (Invited) – Calvin College, USA

3D Classical Modeling of Non-Sequential Double Ionization: Recollision Excitation, Escape, Drift, and Possible Reattachment

We employ 3d classical ensembles to study Non-Sequential Double Ionization (NSDI) of atoms by visible and infrared lasers. We consider how laser wavelength and intensity, the e-e interaction, and the nucleus influence final electron momenta.

9:10AM  N. Ekanayake, L. Barclay, A. Watts, B. Wen, S. Wells, T. Stanev, M. Videtto, C. Mancuso, L. Howard, B. C. Walker (Invited) – University of Delaware, USA

Mechanisms behind Ultra-strong Field Interactions with Atoms and Molecules

Atomic xenon ionization in ultra-strong laser fields is measured to give megaelectron volt photoelectrons. The yields and angular distributions for electrons above and below the ponderomotive energy are compared to a semi-classical model.
9:35AM  Cosmin Blaga (Invited) – Ohio State University, USA
**Strong Field Ionization in the Tunneling Regime**
Strong field ionization of atoms and molecules in the tunneling regime has been investigated experimentally. The existence and behavior of an unexpected and seemingly universal low energy structure in the photoelectron spectra will be discussed.

10:00AM  Xu Wang and J.H. Eberly (Featured) – University of Rochester, USA
**Double Ionization Momentum Structure Under Elliptical Polarization**
Using a purely classical ensemble method, we calculate the end-of-pulse momentum distribution of double ionization under various ellipticities from linear to circular polarization.

10:15AM  M. Guehr, J. P. Farrell, B. K. McFarland and P. H. Bucksbaum (Invited) – Stanford University, USA
**Strong Field Cooper Minimum**
We report on the observation of a Copper minimum in the high harmonic spectrum of argon. The minimum shifted with respect to the photoionization minimum and is accompanied by a π phase shift.

10:40PM  F. Frank, L. Brugnera, D. Hoffmann, C. Arrell, L. Chipperfield, J.W.G. Tisch and J.P. Marangos (Contributed) – Imperial College, London, UK
**Optimising Fields for HHG**
We present recent work that goes beyond simply using single frequency drive fields at 800nm for control of electron re-collision and HHG and instead try to approach more optimum conditions for HHG by using two-color fields.

10:55  BREAK

SESSION Tu2, Chair: Carsten Müller

11:15AM  Henry C. Kapteyn and Margaret M. Murnane (Invited) – University of Colorado, USA
**Phase Matching of High Harmonic Generation in the Soft and Hard X-Ray Regions Using Mid-Infrared Lasers**
Ultrafast short-wavelength light sources using high-harmonic generation provides a tabletop coherent EUV light source for new science. Recent rapid advances show that bright sources at soft and even hard x-ray wavelengths are now feasible.

11:40AM  Johan Mauritsson (Invited) – Lund University, Sweden
**Attosecond Electron Interferometry**
We present an interferometric method to characterize a bound electron wave packet that fully spectrally resolves its individual states, while providing phase information that allows us to follow its evolution on an attosecond time scale.

12:05PM  Luis Plaja (Invited) – University of Salamanca, Spain
**Mid-Infrared High-Order Harmonic Yield Scaling**
Studies in the short-wave infrared show a departure between Strong-Field-Approximation models and the time-dependent Schrödinger equation. We will present a S-Matrix formalism beyond the Strong-Field-Approximation, with good quantitative agreement with the TDSE, that reproduces correctly the scaling of the high-order harmonics with wavelength.
12:30PM  Kenneth J. Schafer (Invited) – Louisiana State University, USA
Attosecond Spectroscopy and Strong Field Physics
We study the use of combined XUV and IR fields as a way to understand and control strong field processes.

12:55AM  P. Arpin, T. Popmintchev, N. Wagner, A. Lytle, O. Cohen, H.C. Kapteyn, M.M. Murnane (Contributed) – University of Colorado, USA
Pulse Self-compression combined with High Harmonic Generation in Multiply Ionized Argon
By combining laser pulse self-compression and high harmonic generation within a single gas-filled waveguide, we demonstrate harmonic emission from a multiply ionized gas, extending the cutoff photon energy in Ar to >530 eV.

1:10PM  Sack Lunches Distributed, Afternoon in Zion National Park

7:00PM  CONFERENCE BANQUET (Switchback Grille)

WEDNESDAY

7:30AM  BREAKFAST (Switchback Grille)

SESSION W1, Chair: Johan Mauritsson

8:45AM  Robert Moshammer (Invited) – Max-Planck-Institute for Nuclear Physics, Heidelberg, Germany
Fragmentation of Atoms and Molecules in CEP Stabilized Laser Pulses
A new mechanism for the control of molecular dissociation via electron localization in CEP stabilized laser pulses (6 fs) as well as “two-slit” interference effects in single ionization of He will be discussed.

9:10AM  J. Higuet, Y. Mairesse, B. Fabre, E. Mével, E. Constant (Invited) – University of Bordeaux, France
Observing Molecular Dynamics Via High Order Harmonic Generation
We use HHG as a way to observe molecular structure and dynamics even in the presence of non excited molecules or buffer gas. Polarization resolved spectroscopy and HHG in structured media will be considered.

9:35AM  J. McKenna, F. Anis, D. Ray, B. Gaire, M. Zohrabi, Bret Polopolus, Brant Abeln, B. D. Esry, K. D. Carnes, C. L. Cocke, and I. Ben-Itzhak (Invited) – Kansas State University, USA
Controlled Dissociation of a Molecular Ion Beam Using Intense Two-Color Laser Fields
Electron localization on specific nuclei during strong-field dissociation of molecular-ion beams is controlled by the relative phase between the 790 and 395 nm components of an ultrashort laser pulse.
10:00AM  **O. Faucher**, V. Loriot, E. Hertz, B. Lavorel, P. Béjot, S. Henin, J. Kasparian, J.-P. Wolf (Invited) – University of Bourgogne, France
**Negative and Positive Kerr Nonlinearity of Air Calibrated with Transient Molecular Alignment**
Nonlinear electronic Kerr index of the major air constituents has been measured up to high order terms using transient molecular alignment as a reference. Sign reversal associated to negative nonlinearity is observed above a pulse intensity of 26 TW/cm².

10:25AM  **Xibin Zhou**, Robynne Lock, Wen Li, Henry Kapteyn, and Margaret Murnane (Contributed) – JILA, University of Colorado, USA
**Molecular Structure and Dynamics Probed by Coherent Electrons and X-Rays**
High harmonic emission is a new spectroscopic tool for determining molecular structure as well as the dynamic coupled motions of electrons and atoms polyatomics.

10:40AM  **Anh-Thu Le**, R. R. Lucchese, and C. D. Lin (Contributed) – Kansas State University, USA
**Influence of Multiple Orbitals on High Harmonic Generation from Aligned Molecules**
We present theoretical multiple molecular orbital calculations for both parallel and perpendicular polarizations of high harmonic generation from aligned molecules. We will discuss the implication of our results and compare them with recent experiments.

10:55AM  **BREAK**

**SESSION W2**, Chair: Olivier Faucher

11:15AM  **Chii-Dong Lin** (Invited) – Kansas State University, USA
**A Robust All-Non-Optical Method for the Characterization of Single-Shot Few-Cycle Laser Pulses**
From the left/right asymmetry of high-energy photoelectrons generated by few-cycle infrared laser pulses, we show that the peak laser intensity, pulse duration and carrier-envelope-phase can be easily and accurately retrieved.

12:40PM  **Phay J. Ho** and Robin Santra (Featured) – Argonne National Laboratory, USA
**X-Ray Diffraction Imaging of Strong-Field-Aligned Molecules**
We theoretically demonstrate that strong-field-aligned molecular sample can be exploited for coherent imaging experiments using x-ray pulses from a synchrotron radiation source. Most interestingly, atomic-scale molecular structure can be retrieved from the obtained diffraction patterns.

11:55PM  **Olivier Chalus**, Philip Bates, Alexander Grün, Daniele Faccio, Arnaud Couairon, Jens Biegert (Featured) – ICFO, Barcelona, Spain
**Novel Near to Mid-IR Sources for Strong Field Experiments**
We present two approaches, for strong field experiments, for near to mid-IR sources with the attractiveness being compactness, simplicity and CEP self-stabilization.
12:10PM  
F. Légaré, B. E. Schmidt, I. Bocharova, M. Giguère, P. Lassonde, P. B. Corkum, I. Litvinyuk, and J-C. Kieffer (Contributed) – INRS-EMT, Qc, Canada  
**Measuring Inelastic Rescattering Processes with Tunable Intense Few-Cycle Laser Pulses**  
Using tunable few-cycle pulses with intensities below $2 \times 10^{14} \text{ W/cm}^2$, we can suppress the sequential double ionization of $\text{D}_2$, and the inelastic rescattering processes can be carefully investigated as a function of carrier frequency, intensity and ellipticity.

12:25PM  
T. Cheng, C.C. Gerry, E. Gospodarczyk, M. Ware, Q. Su and R. Grobe (Invited) – Illinois State University, USA  
**The Visualization of Quantum Field Theory**  
We have solved simplified model versions of the time-dependent Dirac and Yukawa equation numerically to study the time evolution of electrons, positrons and photons with full spatial resolution.

12:50PM  
LUNCH (Switchback Grille)

**SESSION W3, Chair: Kenneth Schafer**

2:00PM  
Q. Su, T. Cheng and R. Grobe (Invited) – Illinois State University, USA  
**Computational High-Intensity Quantum Field Physics**  
We examine the spontaneous breakdown of the matter vacuum triggered by an external force of arbitrary strength and spatial and temporal variations.

2:25PM  
**Relativistic Quantum Dynamics in Strong Laser Fields**  
Relativistic effects in the interaction of super-strong laser fields with atomic systems are investigated. Strong-field ionization properties and high-order harmonic generation, the role of radiation reaction and vacuum polarization effects are considered.

2:50PM  
Nikolay B. Narozhny (Invited) – National Research Nuclear University, Russia  
**New Prospect for Studying Fundamental Processes in Super Intense Laser Fields**  
An overview of the vacuum polarization effects in strong field QED and the prospects of observing them at ELI facility are presented.

3:15PM  
K. Krajewska and J. Z. Kaminski (Contributed) – Inst. of Th. Phys., U. of Warsaw, Poland  
**Electron-Positron Pair Creation - Relevance of Recoil Effect**  
We consider electron-positron pair creation by the impact of very powerful laser pulses with highly charged nuclei, taking into account the recoil effects.

3:30PM  
N. Ekanayake, I. Ghebregziabher, A. D. DiChiara, L. R. Barclay, C. A. Mancuso, S. J. Wells and B. C. Walker (Contributed) – U. of Delaware, USA  
**Relativistic MeV Photoelectrons from the Single Atom Response of Xenon to a $10^{19} \text{ W/cm}^2$ Laser Field**  
Atomic xenon ionization in ultra-strong laser fields is measured to give megaelectron volt photoelectrons. The yields and angular distributions for electrons above and below the ponderomotive energy are compared to a semi-classical model.
Abstracts are in alphabetical order by first author
Pulse Self-compression combined with High Harmonic Generation in Multiply Ionized Argon

P. Arpin, T. Popmintchev, N. Wagner, A. Lytle. O. Cohen, H.C. Kaptyn, M.M. Murnane
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Abstract: By combining laser pulse self-compression and high harmonic generation within a single gas-filled waveguide, we demonstrate harmonic emission from a multiply ionized gas, extending the cutoff photon energy in Ar to >530 eV.

High-order harmonic generation (HHG) is a useful source of ultrafast, fully spatially coherent, soft x-ray beams with applications in ultrafast molecular and materials spectroscopy as well as in high resolution imaging. To date, most applications have been limited to the extreme ultraviolet (EUV) region of the spectrum due to the challenge of extending bright harmonic emission above ~100 eV. One approach to extend the efficient region of HHG is to generate harmonics in ions. The very high ionization potentials of ions make it possible to extend the HHG cutoff to very high photon energies.

In this work, we demonstrate experimentally that by combining laser pulse self-compression [1], with high harmonic generation within a single gas filled waveguide, we can enhance the laser intensity to generate harmonics from multiply ionized species for the first time, in particular doubly-ionized Ar. We also extend the cutoff photon energy in Ar to > 530 eV [2], which is significantly higher than the previous limit of 360 eV [3].

We focus 3 mJ pulses from a Ti:sapphire laser amplifier system into a gas filled hollow core waveguide. With low pressure Ar (4 Torr) in the waveguide, the laser pulse self-compresses due to nonlinear spatio-temporal interactions from a chirped 38 fs pulse to 19 fs inside the waveguide, without the need for external dispersion compensation (Fig. 1 (a)). Under these conditions, we measure our high harmonic spectrum (Fig. 1 (b)) and find that it extends to ~540 eV. Numerical simulations show that these harmonics must be generated from Ar$^{2+}$ being ionized to Ar$^{3+}$.

Fig. 1(a) Measured input and output pulses, showing a reduction in the pulse duration from 38 to 19 fs with 4 torr of Ar gas in the waveguide. (b) Measured HHG spectrum from Ar extending to 540 eV. The highest harmonics are emitted from Ar$^{3+}$.

Generation and applications of GeV-class laser-driven electron beams

Sudeep Banerjee, N. Powers, V. Ramanathan, N. C.-Smith, S. Kalmykov, B. Shadwick, and D. Umstadter

Department of Physics and Astronomy, University of Nebraska, Lincoln NE 68588
(sudeep@unl.edu)

Abstract: We report results on the generation of near-GeV electron beams using a laser wakefield accelerator. Optimal matching of the laser to the plasma produces stable, high-brightness beams scalable to multi-GeV energies using petawatt laser pulses.

High-power, ultrashort laser pulses have been shown to generate quasi-monoenergetic electron beams from underdense plasmas. Several groups worldwide have reported generating high-energy electron beams using either supersonic nozzles [1] or a capillary based system [2] to guide the laser pulse. Optical injection with a second laser pulse has been shown to generate stable monoenergetic electron beams [3]. While, significant progress has been achieved in the last several years, many issues still remain having to do with the pointing and energy stability of the beam, charge in monoenergetic component, energy spread and robustness of the acceleration device. Our results demonstrate for the first time the generation of $300 - 400$ MeV electron beams, with $600$ pC of charge using self-guided laser pulses and a stable, high-quality laser pulse.

The experiments were done with the $100$ TW Diocles laser system. The laser, based on chirped pulse amplification, produces $3.5$ J pulses at $30$ fs with an energy stability of $1 - 2\%$ over several hours, and a pointing stability on target of $< 10$ $\mu$rad. The use of multipass amplifiers ensures a high-contrast output with a nanosecond contrast of $10^{-8}$ for the amplified, compressed pulse. The laser pulses are characterized with all amplifiers operating at full power by using a beam-sampling system. After compression, a deformable mirror is used to correct the phase-front of the pulse and results in a beam with a Strehl ratio of $0.95$ making it possible to obtain nearly diffraction limited focus.

The high-power laser pulse is focused onto a supersonic helium jet with a 1-m focal length paraboloid. The focused spot size is $16$ $\mu$m with $75\%$ of the energy in the central spot. The foot of the pulse interacts with the neutral gas and ionizes it. The peak of the pulse interacts with this ionized medium and drives a wakefield which accelerates electrons. Experiments were performed using cylindrical nozzles with diameter of $1 - 4$ mm and slit nozzles with length of $5 - 10$ mm. Using $30 - 50$ TW of incident laser power monoenergetic electron beams with energy in the range $100 - 400$ MeV could be obtained as depicted in the figure. Near-GeV electron beams are produced using $100$ TW laser power and longer interaction lengths.

The crucial role of matching in the acceleration process can be understood based on the fact that the laser pulse undergoes self-modulation in the plasma and the rising edge becomes temporally resonant. In the matched regime of acceleration, the laser pulse un-
Fig. 1: High energy electrons beams produced in the matched regime of laser wakefield acceleration. On the left is shown a 320 MeV beam with a beam charge of 600 pC produced at a plasma density of $7 \times 10^{18}$ cm$^{-3}$ using a laser power of 45 TW and a 3 mm nozzle. The dark current is $<10^{-3}$ of the detected electron beam. On the right are shown stability measurements of the accelerator using 60 TW of laser power at a plasma density of $6.5 \times 10^{18}$ cm$^{-3}$. The data represents an average of 30 shots.

dergoes minimal evolution. Fluid simulations indicate that for our case, the laser pulse evolves only over 300 µm and does not extend into the plasma bubble. The small distance over which the pulse evolves, leads to rapid formation of the bubble, and the particles forming the bunch are quickly swept up from the background plasma leading to spatio-temporal localization of the electron beam source. This explains the low beam divergence and energy spread as well as the observed stability of the beam. In this regime the laser pulse does not extend into the bubble, there is no perturbation of the electron orbits resulting in beams with a negligible low energy tail. Our results are consistent with theoretical predictions [4] and indicate it will be possible to generate multi-GeV energy electron beams using PW laser pulses.

Laser-Generated Relativistic Attosecond Electron Bunches

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Abstract: The generation of relativistic attosecond electron bunches is observed in three-dimensional, relativistic particle-in-cell simulations of the interaction of intense laser light with droplets. The mechanism behind the multi-MeV attosecond electron bunch generation is investigated using Mie theory.

The understanding of the laser energy conversion into fast electrons and ions is of utmost importance for the design of efficient “table-top” particle accelerators. Of particular interest are finite-size targets where fast particles cannot escape into the field-free bulk material but yet the density of the accelerated particles may be sizable. In small clusters the effect of the cluster on the propagation of the laser pulse needs not be taken into account. Although the plasma, which is created via field ionization on a sub-cycle time scale, is overdense, screening of the cluster interior only occurs due to polarization but not due to a skin effect. Technically speaking, the dipole approximation can be applied to the nonrelativistically intense laser field. In my presentation I will focus on electron acceleration in the regime where cluster radius and laser wavelength are of the same order of magnitude (i.e., rather droplets than clusters), the laser intensity is relativistic, and thus the self-consistent electromagnetic field needs to be calculated.

Fig. 1: Electron isocontour surfaces of a $R = \lambda/4$ He-droplet in a laser pulse of intensity $2 \times 10^{18}$ W/cm$^2$ [1].

I show that multi-MeV attosecond electron bunches are produced when intense laser fields interact with overdense droplets of diameters comparable to the laser wavelength. The attosecond electron bunches are emitted each half laser cycle under plus/minus a certain angle in the polarization plane (see Fig. 1). The preferred electron emission angles and the high kinetic energies arise due to local field enhancements at the droplet surface that can be calculated using Mie theory. Relativistic attosecond electron bunches may be used for the generation of short-wavelength radiation via scattering of a counter-propagating laser pulse, time-resolved structural imaging, or plasma diagnostics.

Strong-field multiphoton double ionization of Helium

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Abstract: We have investigated the role of the electron-electron correlation in the multiphoton double ionization of He by a short, superintense XUV laser pulse.

In this theoretical work, the role of correlation in the double ionization of ground and excited states of He is investigated in the nonlinear (multiphoton) regime. The time dependent Schrödinger equation is solved within the framework of a recently developed software package [1]. The He atom is exposed to a 6-cycle laser pulse with central frequency \( \omega = 5 \) a.u., i.e. the highly correlated non-sequential one-photon double ionization channel is open. The atom is initially prepared in either a singlet or a triplet state, ground or excited state. Total as well as differential ionization probabilities are calculated for varying laser intensities, ranging from weak fields (perturbative regime) up to intensities of a few times \( 10^{19} \) W/cm\(^2\).

Some aspects of the fully correlated system can be caught by a simplified model, in which the wave function is assumed to be a product of two single particle states. In this "simple model", correlation between the electrons is partly taken into account by assuming that both electrons "sees" and effective charge \( Z \simeq 1.7 \) (chosen so that the ground state has the correct energy, \( E_1 + E_2 = -2.903 \) a.u.) It is found that the two-photon double ionization process overtakes the one-photon double ionization process as the dominating double ionization process with increasing intensity (c.f. Fig. 1). Furthermore, the multiphoton energy distributions, as calculated from the "simple model", very much resemble the spectra obtained from the full calculations. However, the two-photon differential angular distributions show that the electrons are most likely ejected back-to-back, illustrating the fact that correlation effects are still important in the multi-photon regime.


Fig. 1: Double ionization energy distributions \( \partial^2 P/\partial E_1 \partial E_2 \) and single ionization energy distributions (thin horizontal/vertical bars) \( \partial P/\partial E \) for the laser intensities, \( I_0 = 3.5 \times 10^{16} \) W/cm\(^2\) (left), \( I_0 = 3.5 \times 10^{18} \) W/cm\(^2\) (middle), and \( I_0 = 1.4 \times 10^{19} \) W/cm\(^2\) (right). The He atom is initially prepared in the ground state.
Abstract: Strong field ionization of atoms and molecules in the tunneling regime has been investigated experimentally. The existence and behavior of an unexpected and seemingly universal low energy structure in the photoelectron spectra will be discussed.

The development in the last few years of tunable optical parametric amplifiers in the mid-infrared has allowed us to push the study of strong field ionization from the multiphoton to the tunneling regime. The motivation for such a study is appealing from a theoretical as well as practical perspective. Theoretically, because in the visible-near infrared wavelengths (below 1 \( \mu \text{m} \)) no neutral molecule and only two atoms (helium and neon) can survive the intensity needed to reach the tunneling regime as defined by Keldysh. On the other hand, from a practical point of view, the tunneling regime necessarily comes with large ponderomotive potentials. This quantity is the key ingredient for generating soft X-ray attosecond pulses through high harmonic generation or generating recollision wavepackets whose associated de Broglie wavelengths can be considerably smaller than the molecular size, possibly allowing us to “visualize” molecules through diffraction and interference.

In the current presentation I will discuss the existence and the behavior of an unexpected low energy structure (LES) in the photoelectron spectra in the tunneling regime [1]. Prior to our experimental investigations it was assumed that the photoelectron spectra should look “classical” in the sense that Keldysh-Faisal-Reiss (KFR) theories should describe well the measurements. The existence of the LES combined with its apparent universal and scaling law behavior challenges this assumption. Although the 3D numerical time dependent Schrödinger equation does reproduce the LES, its physical origin is not yet identified.

MHz repetition rate high-order harmonic generation driven by a fiber laser system

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Abstract: We use a home-made CPA femtosecond fiber laser system to generate high order harmonics in Ar, Xe and Kr and observe XUV emission at very high and adjustable repetition rate (100 kHz to 1 MHz).

High order harmonic generation is becoming a tool that develops a lot but as it grows, it requires more and more qualities: stability of the source, high repetition rate, long wavelength for the fundamental beam, high energy in the fundamental and XUV pulses and short pulse duration combined with the possibility to use that as a turn-key system. We present here a new type of femtosecond source, developed at the CELIA laboratory, that is devoted to strong field physics and fulfills many of the above mentioned requirements. Based on a fiber laser system (Yb:KGW, CPA and large core photonic crystal fiber amplifier) centered at 1030 nm, delivering sub-300 fs pulses at adjustable repetition rate of 100 kHz to 1 MHz and with energy in the range 30 µJ to 100 µJ.

![Figure 1: Harmonic spectra generated by the FCPA laser system at high repetition rate.](image)

These characteristics are sufficient to achieve intensities of ~10¹⁴ W/cm² or above and we designed a specific high order harmonic generation setup compatible with tight focusing. We could indeed observe XUV emission with this source by using Xe, Kr and Argon as shown in figure 1. These observations show that strong field experiments can now be performed with fiber laser system.

High-Order Harmonics as an Extreme Ultraviolet Light Source for Determination of Material Optical Constants

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Abstract: We use high-order harmonics as a light source for measuring optical constants of materials in the EUV. With this source and a ratio reflectance technique, we extract optical constants for uranium, copper, and their oxides.

We present a neat work-horse application of high harmonics: extreme ultraviolet polarimetry. Our polarimeter uses 800 nm, 10 mJ, 35 fs laser pulses at 10 Hz to produce polarized and directional high-harmonic light in the wavelength range from 10 to 47 nm. Compared to synchrotron-based systems, this polarimeter represents a compact and affordable ‘in-house’ instrument helpful for developing EUV thin films. The instrument facilitates rapid turn-around time for film characterization and increases opportunities for in situ measurements during the thin-film deposition process, helping to circumvent challenges with sample contamination, oxidation, and deposition control.

Because the high-harmonic source is prone to fluctuations, we extract optical constants for materials from the ratio of p-polarized to s-polarized reflectance, rather than from the absolute reflectance of either polarization. This technique exploits the fact that the linear polarization of high harmonics can be easily rotated with a waveplate in the generating laser beam. We show that this method greatly reduces systematic measurement errors for our conditions and allows a more accurate determination of optical constants of materials in this wavelength range.

We use this high harmonics-based polarimeter along with the ratio reflectance technique to characterize the optical constants of uranium, copper, and their natural oxides from 10-47 nm, shown in Fig. 1. These constants have not been well characterized previously. This is an instance of using high harmonics to make a beyond-proof-of-principle measurement important to another field.

Fig. 1 The optical constants of (left) copper and naturally oxidized copper and (right) uranium and naturally oxidized uranium measured with a high-harmonic source.
Novel Near to Mid-IR Sources for Strong Field Experiments

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Abstract: We present two approaches, for strong field experiments, for near to mid-IR sources with the attractiveness being compactness, simplicity and CEP self-stabilization.

Both sources draw from the requirements for strong field experiments and we will highlight our new OPCPA [1] source for the mid-IR as well as a Ti:Sapphire back-end based on 4-wave mixing and parametric amplification in a gas-filled capillary [2].

The OPCPA source is a new design which combines a center wavelength of 3.2 µm, for experiments in the tunneling regime, few-cycle pulse duration with optical CEP stability, ideal for attosecond experiments, and a repetition rate of 100 kHz which is superior for coincidence experiments where signal to noise and stability of current laser sources is the limiting factor. The energy of 10 µJ is sufficient to reach intensities of $10^{13}$ to $10^{14}$ W/cm$^2$. The layout is described in Ref. [1] and the source is based on a fiber laser (Toptica) from which two phase-coherent output pulses at different center wavelengths are mixed to reach the mid-IR at 3.2 µm. Two OPCPA stages, pumped by a 100 kHz picosecond laser (Lumera), amplify the CEP stable seed to currently 10 µJ. Previous compressed energy was 1.2 µJ, and the pulse duration was measured to be 96 fs, corresponding to 9.0 cycles at 3.2 µm, within a factor of two of the transform limited pulse duration. The capillary source is a simple back-end behind an existing Ti:Sapphire laser. Combining the broadband and short pulse fundamental together with a weak second harmonic into a gas-filled extended medium results in mainly 4-wave mixing, DFG as well as parametric amplification. The result is a self-CEP stable output with measured emission in the near to mid-IR with currently micro-Joule level energy [2].

Summarizing, two new sources of CEP stable ultrashort laser pulses in the near to mid-IR are presented. The OPCPA emits at a repetition rate of 100 kHz and yields focussed intensities in excess of $10^{13}$ W/cm$^2$. The gas-filled capillary is a simple extension to an existing Ti:Sapphire laser and is expected to give self-CEP stability.

Relativistic positron creation using ultraintense short pulse lasers

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At Lawrence Livermore National Laboratory we studied the pairs creation using ultra-intense lasers. Although has been studied in theory [1] and demonstrated experimentally [2], the use of lasers as a valuable new positron source had not been established. In May and September 2008, we performed new experiments on the Livermore Titan laser [3] where we observed billions of positrons by shooting a millimeter thick solid gold target [4]. We found positrons produced predominately by the Bethe-Heitler process and have an effective temperature of 2-4 MeV, with the distribution peaking at 4-7 MeV. The angular distribution of the positrons is anisotropic. In this talk, I will present details of these experimental results.

This work was performed under the auspices of the U.S. DOE by LLNL under Contract DE-AC52-07NA27344 and was funded by LDRD-08-LW-058.

Quantum electrodynamics as the most fundamental description of all electromagnetic properties and the associated photon and electron creation and annihilation processes has been used mainly to determine time-independent quantities such as the energies of atomic sublevels, the scattering cross-sections, the life times of metastable bound states, the spin and the magnetic moments of various particles. In addition to these highly accurate calculations for static properties, quantum field theory provides also the framework to explore the temporal evolution of quantum systems. Due to many conceptual and especially computational problems, however, this dynamical aspect of the theory has received much less attention.

We have solved simplified model versions of the time-dependent Dirac and Yukawa equation numerically to study the time evolution of electrons, positrons and photons with full spatial resolution. The goal is to better understand how various particle creation and annihilation processes that require quantum field theory can be visualized. There are many open ended questions that we will address. Are particles and their antimatter companions created instantly, or do they require a certain minimum amount of time? Are they created at precisely the same location? What is the difference between a bare and a physical particle? Forces between two particles are usually understood on a microscopic level as the result of an exchange of bosonic particles. How can the same microscopic exchange mechanism lead to a repulsion as well as an attraction? Do these force intermediating particles “know” about the charges of the two interacting particles? How can one visualize this exchange? Does it really make sense to distinguish between virtual and real particles? We also examine how a bare electron can trigger the creation of a cloud of virtual photons around it.

This work has been supported by the NSF. We also acknowledge support from the Research Corporation.
Bohmian Trajectories for an Electron in a Relativistic Laser Field

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Abstract: We analyze Bohmian trajectories associated with an electron wave packet in a relativistic electromagnetic plane wave pulse. Quantum effects typically cause the trajectories to deviate only a small amount from the trajectory of classical point charge.

We use the Klein-Gordon equation to explore behavior of a spreading Gaussian wave packet representing an electron in a strong laser field (neglecting spin effects).[1] The solution is constructed of Volkov States associated with positive energies, which ensures a positive definite probability density

$$\rho = -\hbar (mc^2)^{-1} \text{Im} \{\Psi^* \Psi\}. \quad (1)$$

Meanwhile, the probability current density is given by

$$J = m^{-1} \text{Im} \{\Psi^* (\hbar \nabla - iq\hat{A}) \Psi\}. \quad (2)$$

In the Bohmian interpretation, the wave function acts as a de Broglie ‘pilot wave’, which sets up a velocity field $$\vec{v} \equiv J/\rho$$.[2] The velocity field governs possible point-like trajectories for an electron associated with the wave, one of which is depicted in Fig. 1. For a spreading Gaussian wave initially the size of an atom, the Bohmian trajectories differ almost imperceptibly from classical point-like motion in the strong field. At high intensities, the laser potential overwhelms the so-called quantum potential unless pieces of the wave packet interfere with extreme relative momentum. Bohmian trajectories associated with pure Volkov states are shown to be identical to classical trajectories at any intensity.

Fig. 1 Probability density (contours) and probability current (arrows) together with a possible Bohmian trajectory. The wave packet, experiencing $$2 \times 10^{18} \, \text{W/cm}^2$$, 800 nm light, drifts to the right, owing to the Lorentz force.


High Intensity Femtosecond XUV Pulse Interactions with Atomic Clusters

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Abstract:

The nature of the interactions between high intensity, ultrafast, near infrared laser pulses and atomic clusters of a few hundred to a few thousand atoms has been well studied over the past few years by a number of groups world wide. Such studies have found some rather unexpected results, including the striking finding that these interactions appear to be more energetic than interactions with either single atoms or solid density plasmas and that clusters explode with substantial energy when irradiated by an intense laser. We have extended these studies with intense IR lasers by examining interactions of intense extreme ultraviolet (XUV) pulses with atomic clusters. These experiments look toward high intensity cluster interaction experiments on the Linac Coherent Light Source (LCLS) under development at SLAC. The clusters studied range from a few hundred to a few hundred thousand atoms per cluster (ie diameters of 1-30 nm). Our studies with XUV light, in the 20-40 nm wavelength range, are designed to illuminate the mechanisms for intense pulse interactions in the regime of high intensity but low ponderomotive energy. This regime of interaction is very different from interactions of intense IR pulses with clusters where the laser ponderomotive potential is significantly greater than the binding potential of electrons in the cluster.

We have been conducting these studies by converting a high-energy (1 J) femtosecond laser to the short wavelength region through high order harmonic generation. These harmonics are focused to an intensity of ~10^{12} W/cm^2 into a cluster jet and the ion and electrons ejected are analyzed by time-of-flight methods. Our first experiments have been on Xe clusters irradiated by intense 31 eV pulses. We have observed surprising high charge states from the Xe clusters. We surmise that continuum lowering in the nanoplasma that gets created in the cluster makes possible single photon ionization of the cluster atoms to higher charge states than are possible in free atoms.

In this talk we will present our results on these Xe clusters as well as preliminary results on metallic clusters. We will also present our plans for creating much higher XUV intensities by high order harmonic conversion of the Texas Petawatt Laser.
Relativistic MeV Photoelectrons from the Single Atom Response of Xenon to a $10^{19}$ W/cm$^2$ Laser Field

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Abstract: Atomic xenon ionization in ultra-strong laser fields is measured to give mega-electron volt photoelectrons. The yields and angular distributions for electrons above and below the pondermotive energy are compared to a semi-classical model.

We used an ultra-strong laser field with linear (LP) and circular (CP) polarization to ionize Xe gas in the low density, single atom limit. Our experiment used a chirped pulse amplification Ti: Sapphire terawatt laser system [1] which delivers pulse energies of 85 mJ±2.3% with 35±5 fs pulse duration at a wavelength of 800 nm. Photoelectrons emitted from the interaction region are deflected using an electromagnet and analyzed with an energy resolution of $\Delta E/E=0.3$ with a dynamic range of $10^4$ (Fig. 1). The maximum detected photoelectron energy is 1.35 MeV for a CP laser field with peak intensity of $1.2\times10^{19}$ W/cm$^2$. For a LP laser field the maximum detected energy is 1.02 MeV at $\varphi=0^\circ$ (Fig. 2(a)) and 0.7 MeV at $\varphi=90^\circ$. The azimuthal distributions for electrons with energies of 60 keV, 0.55 MeV and 1 MeV (Fig. 2(b-d)) show directional high energy electrons above $U_p$ and isotropic low energy electrons in the vicinity of 50 keV. To better understand the relativistic production of the photoelectrons, we have used a semi-classical 3D relativistic model of ionization [2]. The essential photoelectron spectrum features above 0.5 MeV including the high energy cutoff are in reasonable agreement with the model. The observed energy spectrum and angular distributions at 60 keV is lower than the calculated result by an order of magnitude indicating existence of multi-electron processes which are not included in the model. This work is supported by the National Science Foundation (Grant No. 0757953).

Fig. 1 (a) Schematic of the experimental setup. (b) The highlighted region shows the pressure range at which the photoelectron collections were made.
Fig. 2 Photoelectron energy spectrum and azimuthal angle distributions from LP light

Negative and positive kerr nonlinearity of air calibrated with transient molecular alignment

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Abstract: Nonlinear electronic Kerr index of the major air constituents has been measured up to high order terms using transient molecular alignment as a reference. Sign reversal associated to negative nonlinearity is observed above a pulse intensity of 26 TW/cm².

Modification of the refractive index through optical Kerr effect (OKE) is one among the various nonlinear effects experienced by a short and intense laser pulse propagating through a medium. In atmospheric air at 800 nm, OKE must be considered when the pulse intensity is typically of the order of several tens of TW/cm². In perturbative theory, the index of refraction \( n \) is expanded as a power series \( n = n_0 + n_2 I^2 + n_4 I^4 + \cdots \), with \( n_0 \) the linear refractive index and \( n_{j=2,4,\cdots} \) the nonlinear terms of the electronic Kerr effect. So far the investigation of OKE in air has been limited to the first term \( n_2 \), although the higher order \( n_4 \) has been considered in some work. The present work extends the determination of the Kerr index of air up to \( n_8 \). The method that has been employed is based on the comparison of the electronic and the rotational contribution to the OKE, the former resulting in the modification of the refractive index occurring during the pulse excitation, whereas the latter produces a retarded response related to the alignment of the molecules induced by the short laser pulse [1]. In practice, the Kerr index is obtained through transient birefringence pump-probe measurements combined with an heterodyne detection. With this technique, the signal produced by transient molecular alignment [2, 3] serves as a reference for the calibration of the electronic Kerr index.

Separate measurements have been conducted in \( \text{O}_2 \) and \( \text{N}_2 \). In all cases, unforeseen sign inversion resulting from negative Kerr nonlinearity is observed above an intensity of few tens of TW/cm². Since the same effect was also observed in argon measured up to \( n_{10} \), we believe that it should also be present in various atomic and molecular gases. Considering the impact of OKE on the spectral, temporal, and spatial properties of an intense laser pulse propagating through a medium, the present work is of particular interest to the community of super intense laser physics.

**Optimising Fields for HHG**

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**Abstract:** We present recent work that goes beyond simply using single frequency drive fields at 800nm for control of electron re-collision and HHG and instead try to approach more optimum conditions for HHG by using two-color fields.

By using more than one color new experimentally accessible parameters are introduced, thus the electronic motion can be controlled with more degrees of freedom. Furthermore, applying fields that are orthogonally polarized, the dynamics are no longer one-dimensional, giving rise to new possibilities in probing atoms or molecules [1]. Recently, the use of a two-color laser field have shown to have a fascinating effect on the efficiency of HHG [2, 3] as well as the reduction of attosecond harmonic pulse durations [4]. We present preliminary results of high harmonic generation (HHG) with orthogonally polarized two-color fields (1300nm and 650nm) – to our knowledge the first 2 color work at this wavelength. The effect of a relative phase between the fields is examined and a difference of efficiency by more than two orders of magnitude is presented.

Additionally, a robust method for producing multiple color beams that are phase locked is presented. Here, the output of a hollow fiber system is split into two wavelength regions (eg. 500-600nm and 650-900nm), where each of the beams can be compressed below 10fs. This is a first step towards the generation of the best waveform for HHG as recently published by our group [5].

When laser pulse intensity interacting with solid density plasma is higher than $10^{22} - 10^{23} \text{ W/cm}^2$ the motion of electrons in the plasma becomes ultrarelativistic and various number of nonlinear effects can be observed. We focus on the relativistic bremsstrahlung from high intensity laser – plasma interactions. The properties of this bremsstrahlung in such formulation depend significantly not only on single electron – ion collisions but on collective relativistic nonlinear plasma dynamics. The plasma dynamics was studied by 3D PIC code simulation. The properties of the bremsstrahlung and the optimal parameters of laser pulse and plasma target are discussed in detail in our study.
Three Dimensional Momentum Imaging of Electron Wave Packet Interferences

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Abstract: Electron Wave Packet (EWP) interferences, manifested in the photoelectron momentum spectra of single ionization in atoms with intense (0.4 PW/cm²), Carrier Envelope Phase (CEP)-stabilized few-cycle (~5 fs) laser pulses are investigated by a ‘reaction microscope’.

2D electron momentum spectra (Fig. 1) at certain fixed CEP reveal in addition to enhanced emission into one P-hemisphere, regular interference stripes, parallel to the transverse momentum axis in the corresponding hemisphere and radial structures in the opposite hemisphere, in good qualitative agreement with theoretical predictions and TDSE calculations. The spacing between the peaks, significantly smaller than the multi-photon peak structure previously observed for longer pulses, agrees with those calculated in a simple Strong Field Approximation (SFA)-based model. This model, invoking the interference of two quantum paths leading to the same final drift momentum, captures the basic mechanism of a ‘holographic’ imaging scheme via the superposition of a re-scattered, modulated EWP on an unaffected, directly launched ‘reference’ EWP (of the same electron!) [1].

Holographic imaging through EWPs has the potential to obtain unprecedented information on ultra-fast correlated electron dynamics, for example, the details of the (time dependent) scattering potential in atoms and aligned molecules.

Abstract: We report on the observation of a Cooper minimum in the high harmonic spectrum of argon. The minimum shifted with respect to the photoionization minimum and is accompanied by a $\pi$ phase shift.

Using the example of atomic Ar, we show that high harmonic generation (HHG) amplitude and phase are subject to a Cooper minimum known for a long time in photoionization [1]. In vacuum ultraviolet (VUV) photoionization of Ar, electronic population is transferred from the 3P electronic ground state of Ar to the d or s continuum state, described by the photoionization dipole matrix element. In the recombination step of HHG, an electronic dipole transition between the continuum states and the electronic ground state occurs under emission of radiation, described by the complex conjugate of the photoionization dipole element. Thus any information gained with photoionization or absorption spectroscopy can in principle be applied to the HHG spectrum [2-4]. The Cooper minimum results from the nodal structure of an electronic ground state, which results in a sign change dipole matrix element as a function of the continuum state energy. Since the sign changes, the excitation or recombination amplitude must go to zero at a particular energy, commonly referred to as the Cooper minimum. The matrix element sign change is reflected by a phase change of the emitted dipole in HHG.

We measured the harmonic amplitude and the VUV absorption spectrum of argon with a VUV spectrometer that we have calibrated using plasma emission lines of various rare gases. Both spectra show a minimum in the expected range, however the HHG minimum is shifted by one odd harmonic (3 eV) to higher energies. The uncertainty is determined by the fact that only odd harmonics were recorded. We measure the Ar harmonic phase in an interferometric experiment using N$_2$ HHG as a reference [5]. The measured $\pi$ phase shift of the Ar harmonics around the HHG minimum fully confirms the Cooper minimum interpretation. In contrast to [2-4], we explain the shift between absorption and HHG Cooper minimum by the strong laser field acting on the Ar continuum during recombination. We calculate the Stark shift of the continuum states under the influence of this strong laser electric field. Only the uphill states contribute to recombination events in our case, and the corresponding matrix elements show a blue shift in agreement with experimental findings. Our interpretation is supported by Cooper minimum shifts in HHG spectra for long and short trajectories corresponding to recollision events at different field strengths.

Abstract: We employ 3d classical ensembles to study Non-Sequential Double Ionization (NSDI) of atoms by visible and infrared lasers. We consider how laser wavelength and intensity, the e-e interaction, and the nucleus influence final electron momenta.

Classical modeling of Non-Sequential Double Ionization (NSDI) provides considerable insight into the dynamics of the recollision and double-ionization processes [1]. In this presentation we examine classical recollision and ionization dynamics for laser wavelengths from 248 to 2017 nm and over a wide range of laser intensities, from below recollision threshold to saturation. We examine also the importance of the electrons’ interactions with the nucleus and with each other.

We consider situations, such as intensity \( I = 0.5 \) PW/cm\(^2\) and wavelength \( \lambda = 800 \) nm, in which recollision leads to one free electron and one bound electron, and we discuss how either of them may achieve energy above \( 2U_p \), the free electron by scattering off the nucleus or the bound electron through the nuclear boomerang [2]. We also consider situations, such as \( I = 0.5 \) PW/cm\(^2\) and \( \lambda = 483 \) nm in which recollision is more likely to lead to doubly bound states, and we examine the decay of those states [3]. We note that these electrons can also achieve energy above \( 2U_p \) through a boomerang, through e-e interaction after ionization, or after making additional oscillations in the nuclear well and absorbing additional laser energy before the boomerang. In addition, we consider directions of electron escape and subsequent drift in the oscillating laser field. We note that at longer wavelengths the recollisions are more energetic and can result in having one or both electrons drift out in the forward direction relative to the recollision [4]. Among other results, we note that electrons that escape the nuclear potential-energy well with small drift velocity may reattach to the nucleus by the end of the pulse [5]. This classical reattachment is analogous to frustrated tunneling discussed in [6]. Whether a specific trajectory leads to reattachment in this nonlinear system is very sensitive to electron velocity as it escapes over the barrier. Thus a solid link to chaos theory is established.

High-Power Optical Acceleration of Ions for Medical Applications

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Abstract: As shown in our theoretical simulations, tightly focused and thus extremely strong laser beams should permit the direct acceleration of light nuclei up to energies that may offer the potentiality for applications in cancer radiotherapy.

Energetic beams of protons and heavier ions are being used to treat cancer at a number of places around the world. The ions (e.g., \( p, \text{He}^{2+}, \text{C}^{6+}, \text{O}^{8+} \)) are required to have kinetic energies \( K \) in the 100 MeV/nucleon range. The ion beam also ought to have an energy spread \( \Delta K/K < 1\% \) so that it may be focused on the tumor while sparing the neighboring healthy tissue. Using a laser system to accelerate the ions will may result in a cut on the cost and physical space required by the presently used conventional accelerators. We put forward the direct laser acceleration of ions. We study the dynamics of an ensemble of particles injected into the focal region by relativistic simulations [1].

Fig. 1: Schematic geometry of the acceleration scenario in the case of radially polarized lasers. The red arrows illustrate the radial and longitudinal field vectors and the propagation direction of the beam.

The focused fields are described by accurate analytic expressions. Employing linearly polarized laser beams with powers of 1-10 PW, the kinetic energies reached fall within the domain required and their spread is around 1-6\%. In the case of radially polarized lasers, the energy gains are even larger compared to that obtained from the linearly polarized ones. These energies, together with their low spread of 0.7-2.5\%, cover the domain of application in radiotherapy. In further studies we show that even more efficient laser-to-particle energy conversion can be achieved by cyclotron autoresonance in the presence of a strong external magnetic field or by applying two crossed laser beams instead of a single one.

LCLS: A unique source for short wavelength high field physics

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Abstract: The Linac Coherent Light Source (LCLS) at SLAC is the world’s first hard x-ray free electron laser operating between 1.5 and 0.15 nm. The LCLS has demonstrated saturation over the full wavelength range and will provide unprecedented intensities at these wavelengths. The performance and capabilities of LCLS for high field physics will be discussed.
Relativistic quantum dynamics in strong laser fields

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Abstract: Relativistic effects in the interaction of super-strong laser fields with atomic systems are investigated. Strong-field ionization properties and high-order harmonic generation, the role of radiation reaction and vacuum polarization effects are considered.

High-order harmonic generation (HHG) with relativistically strong laser pulses employing highly charged ions is a promising way towards coherent hard x-rays and extremely short pulses. We continue to elaborate on the HHG schemes proposed by us recently to realize efficient rescattering despite the drastic hindering effect of the relativistic drift. This is achieved via assisting the infrared strong laser field with a weak attosecond pulse train of XUV photons employing strong tailored laser pulses or counter-propagating attosecond pulse trains [1]. Our investigation of relativistic features of the nonlinear ionization dynamics of multiply charged ions in strong laser fields shows that the resulting ionization yields and angular distributions can provide a sensitive method to determine the intensity of ultrastrong short laser pulses [2].

The radiation emitted by a single-electron wave packet in an intense laser field is analyzed [3]. A relation between the quantum mechanical formulation and its classical counterpart is established. We show that the interference effects are generally suppressed in the radiation of a single electron wave packet. In a focused laser beam, however, quantum interference in the scattered radiation is possible with a special preparation of the electron wave packet.

Investigating the role of radiation reaction on multiphoton Thomson scattering in a strong laser field, we found a new radiation dominated regime of interaction when the angular distribution of the radiation is significantly modified [4]. This regime can be established when a special relationship exists between the electron initial energy and the laser intensity. In extremely strong laser fields, vacuum-polarization effects occur. Thus, in the collision of a high-energy proton beam and a strong laser field, merging of laser photons can occur due to the polarization of vacuum [5]. This non-perturbative vacuum-polarization effect can be experimentally measured by combining the next-generation of table-top petawatt lasers with presently available proton accelerators.

Observing molecular dynamics via high order harmonic generation

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Abstract: We use HHG as a way to observe molecular structure and dynamics even in the presence of non-excited molecules or buffer gas. Polarization resolved spectroscopy and HHG in structured media will be considered.

High order harmonic generation in molecules is now considered as a direct probe of the structure of the generating medium\textsuperscript{[1]} and harmonic spectra are now viewed as a signature of this structure. The polarization state (ellipticity and direction of the main axis) of the xuv light is also very dependent on the molecular structure and can give complementary informations on this structure (fig. 1). By using a specially designed xuv spectrometer we could study the evolution of the ellipticity of the harmonic generated in aligned N\textsubscript{2}\textsuperscript{[2]} and CO\textsubscript{2} which are very different.

If structural informations are accessible via HHG, probing molecular dynamics with HHG is very appealing. However, studies of molecular dynamics induced by short pulses always faces the fact that only a small portion of the molecules are excited and techniques must be developed to extract the interesting signal emitted by the excited molecules from the background signal. Usually, the shorter the exciting pulse, the less molecules are excited if one considers single photon excitation.

Using polarization resolved spectroscopy\textsuperscript{[3]} is a way to extract the signal coming from the excited molecules in the presence of a background signal (coming from un-excited molecules or buffer gas). Similarly, generating harmonics in a structured molecular medium (excitation grating)\textsuperscript{[4]} is another way to selectively observe a signal coming from few excited molecules and I will present new results obtained with these approach.

\textsuperscript{[4]} Y. Mairesse \textit{et al.}, PRL \textbf{100}, 143903 (2008).
X-ray Diffraction Imaging of Strong-field-aligned Molecules
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Abstract: We theoretically demonstrate that strong-field-aligned molecular sample can be exploited for coherent imaging experiments using x-ray pulses from a synchrotron radiation source. Most interestingly, atomic-scale molecular structure can be retrieved from the obtained diffraction patterns.

X rays are a powerful tool for probing the structure and dynamics in matter. Third-generation synchrotron radiation facilities such as Argonne’s Advanced Photon Source (APS) deliver tunable, polarized x rays with high photon flux and a pulse duration of about 100 ps. This pulse duration imposes a restriction on the kind of dynamical processes that may be studied or exploited in molecules at a third-generation synchrotron radiation facility. Using a short, intense optical laser pulse, a spatially aligned molecular sample in gas or liquid phase can be created during or following the laser pulse [1]. We theoretically investigate whether this molecular alignment technique may be exploited for coherent diffraction imaging experiments using x-ray pulses from a third-generation synchrotron radiation facility.

A theory of x-ray diffraction from an ensemble of laser-aligned symmetric-top molecules at finite rotational temperature is presented [2, 3]. Employing quantum electrodynamics, we describe the x-ray-molecule interaction as an electronically elastic one-photon scattering process. We treat the short x-ray pulse as a multimode radiation field and examine the effect of its coherence properties. In the practically important case that the x-ray pulse is quasimonochromatic and its coherence time is much shorter than the time scale of molecular rotational dynamics in the laser field, there is a simple connection between the rotational wave-packet dynamics and the diffraction pattern obtained. Most interestingly, we find that the diffraction pattern from an ensemble of molecules can reveal the structure of single molecule with atomic scale resolution, provided that a high degree of molecular alignment is achieved. Our theory thus opens up a new perspective for quantum imaging of molecular dynamics and strong-field-induced structure in molecules [4] using x rays.

Bohmian Perspective on High Harmonic Generation

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Abstract: We consider the Bohmian interpretation of wavepacket behavior during high harmonic generation. Surprisingly, electron trajectories that remain caught in the atomic potential exhibit the strongest high-harmonic behavior, as they are influenced by returning portions of the scattered pilot wave.

The Schrödinger equation can be recast into two coupled real-variable equations

\[ \nabla \cdot \vec{J} + \frac{\partial \rho}{\partial t} = 0 \quad \text{and} \quad \frac{\partial S}{\partial t} + \frac{1}{2} \left( \nabla S \right)^2 \frac{1}{2m} + V + Q = 0, \]

where the usual complex wave function is connected to real variables \( R \) and \( S \) through \( \Psi = Re^{iS} \). [1] Here \( \rho \equiv R^2 \) and \( \vec{J} \equiv R^2 \nabla S / m \) are the usual probability density and current. The quantity \( Q \equiv -\hbar^2 \nabla^2 R / (2mR) \), called the quantum potential, enters the latter Hamilton-Jacobi equation on equal footing with the usual potential \( V \). Under the Bohmian interpretation, the quantum potential represents the influence of a de Broglie pilot wave on a point-like trajectory associated with a given wave function. There are an infinite number of possible point trajectories, each equally likely, consistent with a given wave function. Their motions are governed by velocity \( \vec{v} = \vec{J} / \rho \), consistent with Hamilton-Jacobi theory.

Researchers in the field of high-intensity laser physics, often speak of high harmonic generation using a language reminiscent of Bohmian mechanics: “Only those electrons that return to the nucleus can emit harmonics by recombining to the ground state.” [2] We investigate Bohmian trajectories in a 1-D Su-Eberly potential, representing an electron experiencing an intense interaction with an external oscillating electric field. We examine trajectories both that remain bound and that break away, accompanying pieces of the wave function that are accelerated in the field and then returned to the potential well.

Surprisingly, the trajectories that remain bound exhibit by far the strongest high harmonic spectra associated with their motion, even including harmonic orders with energies well above the ionization threshold. On the other hand, the trajectories that escape the potential and return for a re-collision exhibit relatively weak high-harmonic spectral components. The returning pieces of the wave function (i.e. the pilot wave) jostle bound trajectories repeatedly, giving them motion associated with high harmonics.


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Abstract. Ultrafast short-wavelength light sources using high-harmonic generation provides a tabletop coherent EUV light source for new science. Recent rapid advances show that bright sources at soft and even hard x-ray wavelengths are now feasible.

Advances in x-ray science and technology have resulted in breakthrough discoveries ranging from unraveling the structure of DNA and proteins, to visualizing atoms, molecules, and materials at the nanoscale level. These continuing successes have spurred the development of x-ray free-electron laser sources that promise to create super-excited states of matter, and to capture the structure of a single biomolecule. Simultaneous with these advances has been exciting progress in coherent x-ray science using ultrafast (≈ 0.1 − 10 fs) coherent x-rays from tabletop-scale ultrafast lasers, making use of the extreme nonlinear optical process of high-order harmonic generation (HHG). The unique characteristics of HHG have opened up many new opportunities. The femtosecond-to-attosecond pulse duration has made it possible to capture the motions of electrons, atoms, and molecules in real time. Moreover, the full spatial coherence has made possible static and dynamic diffraction and imaging with resolutions of tens of nm.

However, to date, most techniques that make use of HHG light have been limited to the extreme ultraviolet (EUV) region of the spectrum, at ~50-100 eV. This is because, although each atom emits harmonics over a broad range of photon energies, in order to generate a bright output beam the emission from a large number of atoms over an extended region of the nonlinear medium must add in phase. The grand challenge for extending bright HHG to shorter wavelengths is the development of new phase matching and quasi-phase matching techniques that can enhance the brightness of HHG at high photon energies. The past two years have seen rapid progress in this area, essentially solving the high-harmonic phase matching problem. Our recent experiments have shown that full phase matching of HHG in a “plane wave” geometry (i.e. hollow waveguide or very large focus) scales very strongly with wavelength of the driving laser, making it possible to obtain bright phase-matched emission in the water window around 330 eV using ultrashort pulses at ~1.3 µm wavelength.[1] Extrapolating this approach further by employing mid-infrared driving pulses, bright phase-matched high harmonic emission should extend even into the hard x-ray region of the spectrum, above 1 keV.[2, 3] In other work, we have shown that quasi phase matching techniques can be very effectively implemented that make use of coherent control of the harmonic generation process by interference with counterpropagating light pulses.[4, 5] This coherent control process represents a useful manipulation of electronic wave function on attosecond time-scales. By making use of a combination of phase matching techniques, coherent tabletop x-ray sources with carefully engineered source properties will be possible.

At the same time, the use of high harmonic sources to study dynamics in atomic, molecular, materials, and engineered systems has expanded rapidly. I will briefly discuss recent experiments in our group in observing molecular “radiation femtochemistry,”[6, 7] high-resolution imaging,[8] “ballistic” heat transport in nanoscience [9, 10], and ultrafast studies of magnetism dynamics [11, 12].

References:
Propagating a high harmonic pulse through an active medium of a plasma-based x-ray laser

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Abstract: We investiagte theoretically the propagation of a high harmonic pulse through an amplifying medium of an x-ray laser. By using a Maxwell-Bloch model, the temporal characteristics and properties of the output pulse are discussed.

The propagation of a high harmonic pulse through a plasma-based x-ray lasing medium is investigated by using a Maxwell-Bloch model. In this model, the medium consists of two-state atoms with radiative/collisional relaxations and external pumping. To incorporate spontaneous emission properly, statistical random source function is used [1]. Atomic parameters are obtained with MCDFGME [2], and plasma parameters and time-dependent pump function are with EHYBRID [3]. In this way, the evolution of a fs-long pulse through a ps-long resonant active medium is investigated in detail. The temporal shape of the output pulse after 5-mm propagation and gain curve are depicted in Fig. 1. The output pulse consists of three parts: amplified spontaneous emission (t < 10 ps), coherent transient phase involving Rabi oscillation (10 < t < 12 ps), and coherent decay (t > 12 ps). The property of each part, the dependence of the pulsewidth on the input harmonic energy, and saturation behaviour are discussed.

Fig. 1 Temporal shape of the harmonic pulse after 5-mm propagation (filled line) and time-dependent gain of the active medium (dotted line).

Electron-positron pair creation - Relevance of recoil effects

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Abstract: We consider electron-positron pair creation by the impact of very powerful laser pulses with highly charged nuclei, taking into account the recoil effects.

Continued technological progress and experimental availability of extremely powerful lasers have opened a new area of research on laser-matter interactions. Since the ponderomotive energy of electrons driven by such radiation can now be significantly larger than the electron rest mass, it has become advantageous to reexamine fundamental processes of quantum electrodynamics [1, 2]; in particular, the formation of electron-positron pairs by means of laser radiation.

The electron-positron pair production was predicted by Howard R. Reiss [3], and it was experimentally realized at the Stanford Liniac facilities [4]. In this experiment, the laser field was involved only indirectly, since it was backscattered by a relativistic electron beam to produce γ-rays that were finally colliding with the ingoing laser beam to produce pairs. Another scenario for pair creation was proposed in Refs. [5–10]. In particular, we considered laser-induced pair creation by the collision of a powerful, linearly polarized laser beam with a heavy and highly charged ion [7–10]. The aim of this contribution is to extend our foregoing investigations to account for the recoil effects imparted on the ion during the pair creation. As long as the duration of the laser pulses is in the fs-regime, it is permitted to describe the laser field by a monochromatic, linearly polarized infinite plane wave; in other words, in our calculations we use the Volkov states for representing the laser-dressed electrons and positrons generated during the process.

Controlling the bound Electron motion in dissociating $\text{H}_2^+$ by CEP stabilized Few-Cycle Laser Pulses

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Abstract: Fully differential data on H$_2$-dissociation in carrier-envelope-phase (CEP) stabilized 6fs laser pulses were recorded with a reaction microscope. By varying the CEP control over the proton emission direction, and, thus, the charge localization was achieved.

Recent experiments [1] showed the possibility to measure and even control electron localization in the dissociating D$_2$ molecule by intense, ultra short laser pulses.

A measure for the asymmetry in the proton (deuteron) emission direction, is the asymmetry parameter $A = (N^\uparrow - N^\downarrow) / (N^\uparrow + N^\downarrow)$, where $N^\uparrow$ ($N^\downarrow$) is the number of protons emitted to the upper (lower) hemisphere, respectively.

In contrast to earlier asymmetry measurements we used a reaction microscope [2] that allows the reconstruction of the full three dimensional momenta of all outgoing (charged) particles as well as coincidence measurements of ions and electrons.

Contrary to [1] we see clear changes in the asymmetry for different CEP and kinetic energy releases (KER) in the range between 0-3 eV. Furthermore we see a tilt in the asymmetry stripes that was not observed in the higher energetic fragments measured in [1], where the stripes were vertical. The result of our experiment is shown in Fig. 1.

The tilted asymmetry stripes shift for molecules with different orientations with respect to the laser polarization axis.

The experimental data as well as the results of wave-packet propagation simulations will be presented.

Two-photon double ionization of He and Ne with intense VUV free-electron-laser pulses

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Abstract: Using a Reaction microscope we studied two-photon double ionization (TPDI) of He and Ne with short (≈ 25 fs) intense (10^{13} − 10^{14} W/cm^2) VUV pulses at the Free Electron LASer Hamburg (FLASH) for different photon energies (44 and 52 eV). We observe characteristic signatures of direct (He) and sequential (Ne) ionization imprinted in the momentum distributions of the doubly charged ions.

Photo double ionization is one of the most fundamental reactions probing the complex quantum dynamics of a three-body Coulomb system. Whereas one-photon double ionization has now been studied for several decades and is generally considered to be well understood, the most basic non-linear two-electron reaction, i.e. two-photon double ionization (TPDI) became experimentally accessible only very recently, with the advent of novel VUV light, and continues to attract enormous theoretical interest (see e.g. [1] and references therein). Two different channels are usually distinguished in TPDI. The so-called ”sequential” double ionization is allowed if the photon energy is larger than the ionization potential of the singly charged ion. It is usually seen as proceeding sequentially in time, with two independent photo absorption events. The direct or ”non-sequential” TPDI instead is characterized by a simultaneous emission of both electrons, and is considered to be highly correlated.

We present the results of the first differential measurements on TPDI of He and Ne by 44 eV FLASH photons [2]. The momentum distributions of doubly charged ions enable a clear separation of direct and sequential ionization pathways. In case of He\textsuperscript{2+} the momentum distribution displays a clear maximum at the origin, indicating that both electrons are preferentially emitted back-to-back with similar energies, while for Ne, where in contrast to He the sequential TPDI is energetically allowed, we observe a dipole like-distribution, which reflects the convolution of the two emission patterns emerging from single ionization of the neutral atom and the singly charged ion.

Influence of multiple orbitals on high harmonic generation from aligned molecules

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Abstract: We present theoretical multiple molecular orbital calculations for both parallel and perpendicular polarizations of high harmonic generation from aligned molecules. We will discuss the implication of our results and compare them with recent experiments.

Until very recently high harmonic generation (HHG) has been understood as due to tunneling of an electron from the highest occupied molecular orbital (HOMO) and recombining back to the HOMO. Tunneling ionization is a highly nonlinear process and therefore highly selective to the HOMO. Thus the contribution from lower molecular orbitals has been routinely neglected. In general, the neglect of the contribution from lower molecular orbitals is not justified for systems with nearly degenerate molecular orbitals close to the HOMO. Furthermore, tunneling ionization from the HOMO might be suppressed due to symmetry of the wavefunction for some molecular alignment. Clearly, in that case the neglect of lower molecular orbitals is questionable.

Fig. 1 Harmonic yields from N2 as functions of delay time near half-revival. The laser intensity is 2x10^14 W/cm^2.

Recent measurements on HHG from N2 aligned perpendicular to the driving laser polarization [1] have shown a maximum at the rotational half-revival. By using the recently developed quantitative rescattering theory (QRS) [2] combined with accurate photoionization transition dipole moments, we show that the maximum at the rotational half-revival (see Fig. 1) is indeed associated with the HOMO-1 contribution. Our results also show that the HOMO-1 contribution becomes increasingly important in the HHG cutoff and therefore depends on the laser intensity. We also extend our calculations for the perpendicular polarization to provide theoretical explanation for the recently observed elliptically polarized harmonics [3].

Measuring inelastic rescattering processes with tunable intense few-cycle laser pulses

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Abstract: Using tunable few-cycle pulses with intensities below $2 \times 10^{14}$ W/cm$^2$, we can suppress the sequential double ionization of D$_2$, and the inelastic rescattering processes can be carefully investigated as a function of carrier frequency, intensity and ellipticity.

The observation of doubly charged ions with a probability larger than expected assuming sequential double ionization has been the key process to reveal laser induced rescattering [1]. For D$_2$ molecule, it is very difficult with multi-cycle pulses to isolate rescattering processes from sequential ionization since D$_2^+$ is easily sequentially ionized due to enhanced ionization [2]. Here, we present results showing that with few-cycle laser pulses, we can fully suppress the sequential ionization and carefully investigated the inelastic rescattering processes as a function of carrier frequency, intensity and ellipticity. We have recently demonstrated sub-13 fs pulse duration at 1.4 micron [3].

In figure 1, we show the D$^+$ kinetic energy spectra for two different laser intensities at 800 nm; $1 \times 10^{14}$ W/cm$^2$ and $1.5 \times 10^{14}$ W/cm$^2$. The D$^+$ fragments with kinetic energy (KE) more than 2 eV were attributed to rescattering using ellipticity dependence. At the highest intensity, the spectra have two peaks; one near 8.5 eV and the second one at 6 eV. Only the 8.5 eV peak is present in the correlated spectra arising from the double ionization channel (D$_2^+ \rightarrow$ D$^+$+D$^+$), i.e. non-sequential double ionization. At a lower intensity, coincidence of D$^+$ fragments was not observed and the peak at 6 eV is explained by rescattering inducing electronic excitation. We are currently measuring those spectra at 1400 nm and will present comparison with 800 nm.

Fig. 1. D$^+$ kinetic energy (KE) spectra at $1.5 \times 10^{14}$ W/cm$^2$ (top) and $1 \times 10^{14}$ W/cm$^2$ (bottom). The dotted curve is the correlated D+ KE spectra, i.e. D$_2^+ \rightarrow$ D$^+$+D$^+$.

The threshold for pair production when focusing high power laser radiation in vacuum

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Abstract: We propose that the back reaction of the vacuum may reduce the focal spot size and enhance the electric field at the focus for a given input power – much like in resonant near field enhancement.

Quantum electrodynamics predicts the spontaneous creation of electron-positron pairs from vacuum in the presence of strong electromagnetic (EM) fields. Schwinger first considered a static electric field to predict the necessary critical strength of $E_{\text{crit}} = 8 \times 10^{18}$ V/m [1]. For oscillating fields in the optical domain, details of its polarization state and spatial mode of propagation become relevant to compute the probability of $e^-e^+$ pair production from vacuum. In particular, in this regime non-negligible pair creation probability could in principle be achieved even with field strengths as low as 1% of $E_{\text{crit}}$ [2]. Given the strong non-linearity of this process, the pair creation probability depends sensitively on the electric field strength.

In this presentation we note that there might be a close analogy to the interaction of light with a single nanoscopic antenna. Using a time reversal symmetry argument one might conjecture on an enhanced success probability for the process [3].

The question of how to maximize the peak intensity of a focused beam at a given point in space has been addressed in the context of classical optics [4]. The problem is easily stated by considering the multipole decomposition of the electromagnetic field, in which it reduces to the question of how to maximize the contribution of the dipole component. It can be shown that a geometry allowing for $4\pi$ solid angle incidence and possessing the appropriate properties in the far field is able of producing such a dipole wave. Moreover, its experimental feasibility can be greatly enhanced by focusing a ‘doughnut’ mode with a parabolic mirror [5].

The maximum energy density achieved with a dipole wave, however, is limited by classical optics even in this particularly favourable case to a spot size given by the light wavelength and pulse duration. In order to concentrate the EM energy to an even smaller spot size, sub wavelength structures are necessary, eventually converting the light to a different form of energy, such as atomic excitation. In fact, the placement of a single atom at the focus of the dipole wave is expected to lead to full absorption of the EM energy as long as only a single photon is present and its temporal profile matches the time-reversal of the atomic decay [6]. Two general aspects then emerge as necessary to an efficient coupling: In the spatial domain, the atom seems to act as a sub-wavelength...
antenna, accomplishing the full EM energy collapse to its small volume through the near field it creates. On the temporal domain, the knowledge of how the time-reversed process occurs, i.e. how the atomic excitation decays to a single photon, permits the tailoring of the correct photon pulse maximally coupling to the atomic dipole.

We argue that a similar situation holds in vacuum for high energy fields. The natural decay of a bounded $e^-e^+$ pair, the positronium atom, into two $\gamma$-photons could offer guidance for the efficient realization of its time-reversed process, namely pair production. For instance, the positronium in a singlet state is well known to decay into a pair of strongly correlated $\gamma$-ray photons (in fact, entangled both in spin and in propagation direction). Therefore, given time reversibility, it is reasonable to assume that the collision of a pair of suitably prepared $\gamma$-photons would produce with very high probability a positronium.

At this point, it is interesting to estimate the maximum electric field strength $E_f$ achieved in the focal region during such collision. We take the electron rest mass as the energy of each $\gamma$-photon, and the volume where each photon energy is localized as $V = (\lambda_e/2)^2 c \tau$, where $\lambda_e \approx 2.4 \times 10^{-12}$ m is the Compton wavelength of the electron, $c$ is the speed of light in vacuum, and $\tau \approx 1.2 \times 10^{-10}$ s is the $^1S_0$ positronium decay time, to obtain $E \approx 10^{12}$ V/m. This value is many orders of magnitude smaller than the Schwinger critical field [2]. The reason why such a weak field is capable of producing one positronium atom with high probability resides in the fact that we deal with a resonance phenomenon. The example shows that also in this case there is resonant near field enhancement.

Finally turning back to optical fields, one would at first sight not expect such an enhancement because the time reversed process, i.e. the decay of positronium into one million visible photons, occurs with a vanishing probability. However, from the point of view of energy conservation a laser pulse of one Joule can generate about $10^{13}$ $e^-e^+$ pairs. We suspect that a whole ensemble of pairs may show plasmon like resonances in the optical regime, even if the pairs are only virtual at that particular time in the evolution. The hope is that such a plasmon type resonance exists and results in a resonant near field enhancement reducing the threshold for pair production with laser light in vacuum.

We acknowledge fruitful discussions with Pierre Chavel and Gérard Mourou.

A robust all-non-optical method for the characterization of single-shot few-cycle laser pulses

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Abstract: From the left/right asymmetry of high-energy photoelectrons generated by few-cycle infrared laser pulses, we show that the peak laser intensity, pulse duration and carrier-envelope-phase can be easily and accurately retrieved.

An all-non-optical method for accurately determining the pulse parameters of individual few-cycle laser shots is presented. By analyzing the high-energy photoelectron spectra on the left- and the right- side of the polarization axis using the recently developed quantitatively rescattering theory [1], we show that the peak laser intensity at the laser focus, the pulse duration, as well as the absolute values of the carrier-envelope-phase (CEP) of few-cycle pulses can be easily retrieved with high accuracy for individual single shots. The method was used to retrieve the laser parameters of the recent single-shot data of Wittmann et al [2] and it is shown that the CEP retrieved can be accurate to about three degrees. Using the same method to retrieve the CEP of the “phase-stabilized” short pulses, the error of the CEP from many-shot measurements is of the order of about twenty degrees, indicating that the CEP of such phase-stabilized short pulses still vary from shot to shot. The present method is very robust and only needs high-energy photoelectron spectra for each single-shot measurement.

Attosecond Electron Interferometry

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Abstract: We present an interferometric method to characterize a bound electron wave packet that fully spectrally resolves its individual states, while providing phase information that allows us to follow its evolution on an attosecond time scale.

The basic properties of atoms, molecules, and solids are governed by ultrafast electron dynamics. Attosecond pulses bear the promise to resolve these electronic dynamics on their natural time scale, the atomic unit of time, which is 24 attoseconds. The high frequency of the pulses, however, means that in most of the experiments performed so far the electrons that are excited by attosecond pulses are directly moved into the ionization continuum, where they rapidly disperse [1,2]. More interesting dynamics arise when electrons are excited into bound [3] or autoionizing states [4]. Here we present a method to determine the dynamics of a bound wave packet excited by an attosecond pulse, while – for the first time – keeping track of its spectral content with high precision.

The key idea is that coincident with the creation of the bound wave packet, we also launch a broad continuum wave packet. This free wave packet serves as a reference when, after a variable delay, the bound wave packet is ionized by a 7 fs infrared laser pulse, locked in phase with the bound wave packet. The interference fringes observed in the photoelectron spectrum enable precise determination of the bound electron wave packet. As in Ramsey spectroscopy, the spectral precision is here set not by the bandwidth of the excitation pulse, but by the delay between the pump and probe pulses as well as the experimental energy resolution of the photoelectron spectrometer used.

We demonstrate the technique by exciting Helium with an isolated attosecond pulse generated in Xenon gas using an ultrashort carrier-envelope-phase stabilized infrared laser with a time-dependent polarization state linear only during a short time at the pulse maximum [5]. Our approach, however, can be applied to bound wave packets irrespective of the way they are created (photo-excitation, shake-up, Auger decay etc.).

The experiment was performed at Politecnico Milano in collaboration with groups from Lund University, Louisiana State University, FOM-Institute AMOLF, Max-Planck-Institut für Quantenoptik Garching and Université Lyon 1.

Controlled dissociation of a molecular ion beam using intense two-color laser fields

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Abstract: Electron localization on specific nuclei during strong-field dissociation of molecular-ion beams is controlled by the relative phase between the 790 and 395 nm components of an ultrashort laser pulse.

The dissociative ionization of neutral hydrogen molecules in a two-color laser field has been of interest for over a decade [1,2]. Such fields are generated by mixing the laser fundamental with its second harmonic – the relative phase between the two colors provides a control knob for the molecular dynamics. In this study we demonstrate control over the dissociation of a few different molecular ion-beam targets in intense 45 fs pulses as a function of the phase between the 790 and 395 nm components. For example, the dependence of the electron localization in D$_2^+$ dissociation on this phase is a result of the interference between two different dissociation paths. This is illustrated in Fig. 1 by the appearance of vibrational structure in the two-color spectra on top of the low kinetic energy release (KER < 0.4 eV) that is present when only 790 nm light is used. In addition to this electron localization, we demonstrate control over the dissociation products of an HD$^+$ molecular-ion beam, namely H$^+$ + D or H + D$^+$

![Fig. 1 KER-cosθ distributions of D$_2^+$ dissociation in a 45 fs laser pulse, with a peak intensity of 6×10$^{14}$ and 4×10$^{12}$ W/cm$^2$ for the 790 and 395 nm, respectively. Note the vibrational features marked by red arrows appearing when both 790 and 395 nm are present.](image)

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Fragmentation of Atoms and Molecules in CEP Stabilized Laser Pulses

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Abstract: A new mechanism for the control of molecular dissociation via electron localization in CEP stabilized laser pulses (6 fs) as well as “two-slit” interference effects in single ionization of He will be discussed.

Fully differential data for ionization of He as well as dissociative ionization of H\textsubscript{2} in ultra-short (6 fs, 800 nm) linearly polarized and carrier-envelope-phase (CEP) stabilized laser pulses have been recorded using a reaction microscope. Depending on the CEP a pronounced asymmetry was observed in the emission direction of the ejected electron and the outgoing H\textsuperscript{+} fragment for ionization of He or H\textsubscript{2}, respectively. For dissoziation of H\textsubscript{2}\textsuperscript{+} we observed a CEP dependent localization of the remaining electron on either proton (charge localization) for selected orientations of the molecule at unexpected low kinetic energy releases (KER) between 0 and 2 eV. Simple wave-packet calculations are in qualitative agreement with our experimental results and shed light onto the main mechanism of charge localization. For single ionization of He with intense (4·10\textsuperscript{-14} W/cm\textsuperscript{2}) CEP stabilized laser pulses the recorded 3-D electron (and ion) momentum spectra exhibit a preferential emission of low-energy electrons (E\textsubscript{e}< 15 eV) to either hemisphere as a function of the CEP. In qualitative agreement with simple model and TDSE calculations clear parallel interference stripes emerge in momentum-space at CEPs with maximum asymmetry. Their appearances are interpreted as attosecond interferences of rescattered and directly emitted electron wave-packets which both lead to the same final momentum. In analogy to holographic imaging this method might be used to obtain unprecedented information on the short-time evolution of the scattering potential, a topic of particular interest if molecular targets are considered.
High-energy processes in very intense laser fields

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Abstract: An overview of recent theoretical studies devoted to highly energetic processes in superintense laser fields is given, comprising various schemes of lepton pair production and laser-induced nuclear excitation.

The availability of ultrastrong laser pulses allows to extend the field of laser-matter interactions in the near future towards studies of high-energy QED, nuclear, and particle physics phenomena. In light of this, we first discuss the feasibility of electron-positron pair creation in combined laser and nuclear Coulomb fields, addressing both free [1] and bound-free [2] pair production where in the latter case the electron is created in a bound atomic state of the nucleus. A pronounced channeling of the particles is demonstrated when the pair creation process by a single $\gamma$-photon in the vicinity of a nucleus is assisted by a strong laser field [3]. We also consider electron-positron pair creation in a standing electromagnetic wave formed by two counterpropagating laser pulses and show that the laser magnetic-field component plays an important role at high laser frequencies [4]. By combining very high ion energies with x-ray laser frequencies, even muon-antimuon pairs can be produced in XFEL-nucleus collisions [5]. The process is shown to be sensitive to the nuclear form factor, due to the small muonic Compton wavelength. Muon pairs may also be generated via coherent electron-positron recollisions when a sample of positronium atoms is strongly driven by a near-optical laser field [6]. Finally, we discuss both resonant [7] and nonresonant [8] schemes of nuclear excitation by external laser fields. All of these processes are likely to be realized experimentally by near-future laser technology.

New Prospect for Studying Fundamental Processes in Super Intense Laser Fields

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Abstract: An overview of the vacuum polarization effects in strong field QED and the prospects of observing them at ELI facility are presented.

The nowadays development of laser technologies promises very rapid growth of laser intensities. The realization of the Extreme Light Infrastructure (ELI) project will make available a laser facility of about 1 Exawatt power and intensity $10^{26}$ W/cm$^2$ or even higher. The respective field strength is very close to the "critical" Sauter field $E_S = m^2c^3/e\hbar = 1.32 \cdot 10^{16}$ V/cm. QED becomes fully nonlinear in the presence of such fields and hence the fundamental vacuum polarization effects, e.g. pair creation or higher harmonic generation by a focused laser pulse in vacuum, could be investigated experimentally for the first time in history.

The process of $e^+e^−$ pairs creation by focused laser pulses in vacuum is considered. A realistic 3d-model [1] based on an exact solution of Maxwell equations is used for description of the focused laser pulse. It is shown [2] that the threshold value of intensity $I_{th}$, when only one pair per pulse is created, for a single focused laser pulse is one order of magnitude lower than $I_S = c/4\pi E_S^2 = 4.65 \cdot 10^{20}$ W/cm$^2$. Collision of two or more pulses essentially enhances the effect of pair production. For the case of 12 colliding pulses $I_{th}$ could be as low as $I_{th} = 4.2 \cdot 10^{24}$ W/cm$^2$ [3]. The number of created pairs grows with intensity so fast that at $I \sim I_S$ the total energy of created pairs becomes comparable with the energy of the pulse itself. Thus the effect of pair creation leads to collapse of the laser pulse.

It is shown that there exists another mechanism for depletion of a laser pulse. At intensities $I > 10^{24}$ W/cm$^2$ electromagnetic cascades, i.e. chains of successive acts of photon emission and pair production, arise in vacuum [4]. Therefore transformation of the energy of the colliding laser pulses into macroscopic jets of lepton plasma and photons. The cascade can also arise in collision of a laser pulse with high energy particles. This effect could be considered as a possible mechanism for gamma bursts observed in astrophysics.

Another vacuum polarization effect, namely generation of odd harmonics by a superstrong focused laser beam in the vacuum, is considered [5]. It is shown that the number of generated photons reaches the value of one photon per period when the peak value of the electric field is one order of magnitude lower than $E_S$.

Formation of 2D Positron Atoms and Stimulation of Their Resonant Decay

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The phenomenon of anomalous passage of ions along definite crystallographic axes and planes was discovered experimentally and known as the channeling effect [1]. In 1965 Lindhard theoretically explained this phenomenon within the limits of the classical mechanics [2]. The quantum theory of channeling for electrons and positrons has been elaborated by many authors [3-5]. As is well-known, electron in a crystal can commit both planar and axial channeling. However, only one type of pure channeling for the positrons is known, the regime where a particle is localized between two adjacent planes. Axial channeling of positive particles has not been investigated, seriously up to recently time, because the crystallographic axes, irrespective of grade of crystal are been charged positively and at first sight the positively charged particles can't be localized along axes. However investigation of possibilities of axial channeling of positrons and, hence, the formation of metastable relativistic positron systems is a problem of utmost importance for the radiation physics. For the solution of this problem, was proposed the method of creation of positroniums with the help of mixing of beams of relativistic electrons and positrons in vacuum with the subsequent stimulation of their decay on two photons \( 2\gamma \) [6,7]. Another way of creation of positron atoms it is a method of scattering of energetic photons on a strong atomic fields [8-10]. However, all these methods virtually are ineffective for applications, because the probabilities of positron-atoms formation by mentioned methods are extremely low.

In present time an ambitious project is being designed which has aim to investigate the possibility of creation of new powerful sources of high-frequency monochromatic electromagnetic radiation: crystal undulator and \( \gamma \)-laser based on channeling of positrons in crystals [11]. In earlier studies [14, 15] we have focused our attention on the capabilities of ionic crystals of the CsCl type, with the aim finding of new possibilities for the channeling of light positively charged relativistic particles. In particular, we have studied in detail the effective interaction potential of a charged particle with a crystal and have shown that along the axes <100> of negatively charged chlorine \( Cl^- \) ions; there are strong fields which allow channelized of positively charged particles. Besides, formed by these way positron-atoms as has shown of detail investigation, practically doesn’t interact with the phonons subsystem of lattice. This fact does of positron-atoms by stable enough 2D formations which it is possible to influence by means of external fields. We have shown that the 2D positron-atoms in media can spontaneously decay up to one or two \( \gamma \)-photons. We were interested by various possibilities to strengthen spontaneous disintegrations and have found very interesting way. The point is that in a regime of axial channeling on formed positron-atoms step-type behavior of a lattice influences as external electromagnetic perturbation which under certain conditions can stimulate resonant decays. In particular, when energy of a positron of an order ~ 5 \( \div \) 20MeV, the relativistic factor of an order 10 \( \div \) 40 and correspondingly the frequencies of the pseudo-photons of an order \( 10^{20} \div 10^{22} Hz \) that is sufficient condition for stimulation of resonant decay of positron atom. In the work analyzed the possibilities of controlling of decays processes in the some range of parameters of positron beam and medium.
Generation of fast ions from snow nano-wires using high laser intensities

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Abstract: We report on experimental demonstration of fast protons (>1 MeV) from the interaction of modest laser intensities (~10^{17} W/cm^2) and micro-structured targets such as snow nano-wires.

Recently we have demonstrated very efficient coupling of laser energy and snow nano-wire grown on a Sapphire substrate [1] and the generation of fast multi-charged Oxygen ions (>100 keV) measured using x-ray emission spectra [2].

Here we report on measurements of protons with energies above 1 MeV generated from a snow-wire target grown on a Sapphire substrate and irradiated with relatively modest laser intensity (10^{16}-10^{17} W/cm^2). These were measured using time of flight and CR39 stacks.

Usually, protons at these energy levels are measured when different targets such as thin-foils or gas jets are irradiated by very intense laser beams, I>10^{18} W/cm^2. Here we use lower intensities, but still get fast protons. The generation of fast protons is attributed to a field enhancement. The field enhancement is due to high charge separation induced by the geometry of the snow nano-wires (0.1µm diameter X 1 µm length).

The ability to generate fast proton from small and relatively inexpensive systems is of great importance to radiation cancer treatments. The presented scheme of using snow nano-wires removes the restriction on laser intensities and bringing us closer to the goal.

Controlling high-order harmonic cut-off extension using two delayed pulses of the same colour

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Abstract: We present a novel method to extend the cut-off frequency up to 5.5 Up based on double-pulse high-order harmonic generation. We explore the mechanism involved during the interaction with such field. Through numerical simulation of the Time Dependent Schrödinger Equation (3D-TDSE), we have found an alternative method of extending the cut-off that is simpler to implement than using a multicolour field [1,2,3] or highly chirped fundamental pulses [4]. We use two pulses of the same colour with a fixed CEP difference and control the delay between them. This enables us to shape the intra-cycle waveform of the combined laser pulse. Given the advances in CEP stabilised systems, the quantities we control here are experimentally achievable.

We explain the physical origin of this dramatic extension using both classical and quantum descriptions. We conclude that the extension results from recombination of the electronic wave packet with the parent ion after following quantum paths with extended excursion times that are induced by the double pulse waveform. In particular, we also explore the parameter range in which the extension is optimal and can be controlled.

We remark that this technique is of special interest in order to avoid the high intensity limit presented by the barrier suppression (BS) regime. Indeed, the total amplitude corresponding to our double pulse configuration is always equal to or lower than the amplitude of the single pulse configuration. This mechanism is wavelength independent, so that different wavelengths generate the same relative cut-off extension. Therefore, our novel technique, together with high Ip atoms and micrometer wavelength laser pulses, has the potential to generate highly energetic photons in the water window. Finally, we demonstrate that by using our double pulse technique we can generate sub-femtosecond pulses more energy than in the single pulse configuration.

Photoionization with an Extra Angular Momentum

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Abstract: We analyze the interaction of an hydrogen atom with a beam transporting spin and orbital angular momentum, showing large transfer of angular momentum to the atom and unveiling new phenomena for photoionization.

In the past few years a great interest has been raising in helical beams that are able to transport spin and orbital angular momentum (OAM) in its propagation direction [1, 2], such as Laguerre-Gaussian beams. OAM is related to the transverse profile of the beam, exhibiting also an angular-momentum-like behavior. Here, we address the problem of photoionization by means of the interaction of a pulse beam carrying orbital angular momentum with the simplest atom that one can consider, the hydrogen. This academic problem clarifies a fundamental question: the OAM transfer from light to the electron quantum state. With this end, we need to resolve numerically the Schrödinger equation of the complete system. We consider the following vector potential:

\[ A_\ell(r, t) = A_0 w_0 \sin^2 \left( \frac{\omega_e}{c} (y + a_0) - \omega_e t \right) \left[ e^{i \pi (y - ct)} LG_{\ell, p}(\rho, \phi; \nu) + \text{c. c.} \right] \times \theta(y - ct + \pi c/\omega_e + a_0) - \theta(y - ct + a_0), \] (1)

where \( \omega_e = \pi/N_{\text{cyc}} \tau, N_{\text{cyc}} \) the number of cycles, \( \tau \) the period of the carrier wave, \( \theta \) the Heavyside function, \( a_0 \) the Bohr radius, \( c \) the speed of light, \( \omega \) the frequency of the carrier wave (which is propagating in the \( y \)-direction), \( A_0 \) the amplitude of the wave which also includes the polarization, and \( LG_{\ell, p} \) the Laguerre-Gauss function [2]. The vector potential (1) has a well-defined OAM related to \( \ell \), given by the Laguerre-Gaussian contribution [2].

The electron quantum state, bound and unbounded, can be expanded in spherical harmonics as \( \psi(r) = \sum_{L,M} u_{L,M}(r) Y^M_L(\theta, \phi) \). Taking into account the vector potential given by expression (1), and considering the dipolar and transverse spatial approximation (\( \lambda \gg a_0 \) and \( w_0 \gg a_0 \)), we can deduce, after some calculations, the selection rules for beams carrying any unit of orbital angular momentum: \( |\Delta L| \leq |\ell| + 1, \Delta M = \ell \pm 1 \), and \( \Delta L + |\ell| + 1 \) is even, where we have considered the quantization axis in the beam propagating direction (\( y \)-direction). These selection rules are in prefect agreement with the numerical results, in which we simulate the final ionized electron state for different scenarios, with their respective spherical harmonics numerical projections.

Mid-infrared high-order harmonic yield scaling.

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Abstract: Studies in the short-wave infrared show a departure between Strong-Field-Approximation models and the time-dependent Schrödinger equation. We will present a S-Matrix formalism beyond the Strong-Field-Approximation, with good quantitative agreement with the TDSE, that reproduces correctly the scaling of the high order harmonics with wavelength.

The interaction of ultraintense lasers with atoms constitutes a paradigmatic example among non-perturbative phenomena. The convergence of theory and experiments models this field as a privileged test-ground our theoretical understanding of non-perturbative processes. In a simplified view, theory is based either in the ab-initio numerical integration of the relevant equations (for instance Schrödinger’s) or in the development of models. Among the later, S-matrix approaches combined with the strong-field approximation (SFA) \cite{1} are shown to provide an excellent description of the single and multielectron ionization rates, as well as constituting an adequate formalism to study the process of high-order harmonic generation (HOHG). In this later case, a standard approach \cite{2} combines SFA with a saddle point approximation to compute the harmonic spectra. Despite of its achievements, recent studies on the scaling of the harmonic yield with wavelength show a departure between the predictions of this model and the exact TDSE \cite{3}. In this contribution we shall, first, develop a critical perspective to some recent works approaching the issue of the adequate choice of the spectral regions to test SFA theories (we propose to use the end of the plateau). Second, we will show that the physics behind the scaling law may be understood beyond the strong-field approximation as field dressing of the bound states becomes crucial. Finally, we will discuss an S-Matrix formalism that goes beyond the SFA, holds good quantitative agreement with the exact integration of the TDSE and reproduces the correctly the yield scaling.

Fig. 1 Harmonic yields at the end of the plateau computed for a 6-cycle pulse of $I=1.58\times10^{14}\text{ W/cm}^2$ and for wavelengths ranging from 800 to 1600 nm (results from the TDSE in blue and our model in green). Scaling powers $\lambda^{-n}$: TDSE $n=5.59$, model $n=5.62$.

References

Ultra-fast CO$_2$ lasers in ion acceleration research
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Abstract: We review merits of long-wavelength terawatt CO$_2$ lasers for strong-field physics research due to favorable wavelength scaling of ponderomotive effects.

A terawatt picosecond CO$_2$ laser has been used in a number of experiments that explore advanced methods of particle acceleration and x-ray generation. We illustrate advantages of the wavelength upscaling from optical to mid-IR region by the example of proton acceleration from thin foils and a gas jet. These experiments are conducted at the BNL in collaboration with Univ. of Stony Brook, Imperial College, RAL, and Stratchcliffe Univ. With just $10^{16}$ W/cm$^2$ of a CO$_2$ laser intensity focused on a 8 µm Al foil, we demonstrated intense proton beams in the MeV range. This observation agrees with predicted scaling of the proton energy $E_p \sim I^{1/2} \lambda$. The integral proton flux and spectral brightness also scale according to predictions demonstrating the high potentials of CO$_2$ lasers for driving high-flux proton sources. Replacing CR39 plate with a luminescent screen allows faster optimization of the process by dramatic increase in a number of productive shots per day.

We now initiated new proton acceleration runs using a hydrogen gas jet as a target. At the CO$_2$ laser wavelength ($\lambda=10$ µm), a critical density is 100 times lower ($10^{19}$ cm$^{-3}$) than for a glass laser. This opens new opportunities for time-resolved interferometric diagnostic of over-critical laser/plasma interactions in the regime that is far below critical for an optical probe beam.

We present the latest results from both foil and gas jet ion acceleration experiments and give an outlook on possibilities of attaining multi-terawatt femtosecond pulses with CO$_2$ lasers.
Theory of high-order harmonics generation due to Brunel electron heating in relativistic laser interaction with overdense plasma

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Abstract: High-order harmonics generation in the interaction of superintense femtosecond laser pulse with overdense plasma is considered. Intensities of even and odd harmonics are calculated.

The action of strong laser fields \( \gtrsim 10^{18} \text{ W/cm}^2 \) on a dense or rarefied medium induces one of the fundamental nonlinear processes, viz., generation of higher harmonics of the laser field. In particular, when laser radiation interacts with solid targets, a preplasma and a dense plasma consisting of multiply charged atomic ions and electrons are formed. Our task is to study induced emission of free electrons from solid targets in extremely strong laser fields. Two mechanisms of harmonic generation can be singled out, namely, the emission from bound and free electrons. The efficiency of even harmonic generation is found to be much lower than for odd harmonics in gaseous He, while these efficiencies are comparable in gaseous N\(_2\) and Ar. Harmonic generation in a rarefied (subcritical plasma) was also studied theoretically in [1, 2].

In the present work generation of even and odd harmonics in the skin layer formed during the interaction of a short relativistic laser pulse with solid targets is investigated. Vacuum heating at the front surface in the summary field of incident and reflected laser fields is considered as a main mechanism of electron heating up to relativistic ponderomotive energies [3].

High-order harmonics arise as a result of elastic collisions of free electrons with atomic ions inside the skin layer in the presence of the weak laser field. The elastic relativistic scattering of electrons through small angles is defined by the Mott formula [4]:

\[
\sigma_m = 4\pi Z^2 \Lambda \rho^2 (t) \nu^2 (t) \quad \text{(relativistic units)}.
\]

The complex motion of free electrons in the skin layer along the electric field vector and along the direction of propagation of a laser wave is analyzed. The Fourier expansion of the trajectory of this motion is used to obtain the components of the conductivity tensor and of the amplitude of the transverse electromagnetic field of harmonics propagating along the electric field. Even harmonics appear due to relativistic effects. The efficiency of generation of even and odd harmonics on the leading edge of a laser pulse is calculated.

Limitations of Gauge Invariance and Consequences for Laser-Induced Processes

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Abstract: Some aspects of physical processes are not preserved in a gauge transformation, such as conservation rules. The plane wave field of a laser requires a vector potential, and tunneling theories can lead to fundamental errors.

Static and quasistatic electric fields (longitudinal fields) are most simply describable by a pure scalar potential $\phi$, and plane wave fields (transverse fields) are most simply describable by a pure vector potential $\mathbf{A}$. When the dipole approximation is valid, there is a simple gauge transformation that connects the two types of fields. The principle of gauge invariance would seem to imply that there is no essential difference between quasistatic electric fields and plane-wave fields. This is fundamentally incorrect because any formulation other than a classical Newtonian approach depends upon the potentials and not just the fields. It is shown how this is true despite the unquestioned validity of the rules concerning gauge invariance. This is another way of saying that potentials convey more information than do the fields. This leads to the inference that there is a physical gauge appropriate to a given laboratory setting. For laser-induced processes, a vector potential is required, and the nature of the qualitative errors that arise in a scalar potential approach are shown. The final conclusion as applied to strong laser fields is that there is no such thing as laser-induced tunneling ionization, and adopting a tunneling viewpoint can lead to fundamental errors.
Magnetic-field effects in electron-positron pair creation by counterpropagating laser pulses

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Abstract: The production of electron-positron pairs from vacuum by counterpropagating laser beams of linear polarization is numerically investigated. Extending previous studies of this process the magnetic component of the laser fields is explicitly taken into account.

Until now the study of electron-positron pair production by counterpropagating laser fields has been based on the dipole approximation, where the spatial dependence of the fields is neglected. This approach is expected to be justified for long wave lengths in the optical domain. However, the process of pair creation is also intensively discussed at short wave lengths in connection with upcoming x-ray laser facilities.

We employ a numerical approach [1] by propagating a negative-energy Dirac electron on a two-dimensional grid via the split-operator algorithm. This enables us to take the magnetic field of the laser pulses into account. We show that the latter strongly affects the creation process at high laser frequency: the production probability is reduced, the resonant Rabi-oscillation pattern is distorted and the resonance positions are shifted, multiplied and split [2, 3].

Attosecond Spectroscopy and Strong Field Physics

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Abstract: We study the use of combined XUV and IR fields as a way to understand and control strong field processes.

The combination of an attosecond extreme ultraviolet (XUV) pulse with an infrared (IR) laser field has been the mainstay of attosecond metrology. It has been used to characterize both attosecond pulse trains and single attosecond pulses. Over the last few years it has been demonstrated that this same combination can also be used to study and control strong field processes such as high harmonic generation [1], strong field ionization [2] and electron rescattering [3].

In the typical XUV + IR scenario, the attosecond XUV field is used to control the time at which photo excitation and/or ionization occurs in a strong laser field. By changing the time delay between the two fields one can control the precise phase of the IR field at which ionization takes place. The initial energy and spectral width of the excited electron can also be controlled by tuning the central frequency and bandwidth of the XUV light. This control over the initial timing, spectral width, average energy (and even chirp) of the electron wave packet is not possible with tunnel ionized wave packets and affords a unique opportunity for gaining understanding of strong field processes such as non-sequential double ionization. We will illustrate these principles with examples from our most recent work on the absorption of XUV radiation in strong IR fields, and discuss recent experiments as well.

This work was supported by the National Science Foundation, the Center for Computing Technologies, and the Ball Family Professorship at LSU.

Numerical investigations of the matter creation processes have recently lead to valuable insights into issues such the Klein paradox [1,2], Schrödinger’s Zitterbewegung [3,4], and the formation of supercritical bound states [5]. In this work we examine the spontaneous breakdown of the matter vacuum triggered by an external force of arbitrary strength and spatial and temporal variations. We present a non-perturbative framework that permits for the first time the computation of the complete time evolution of various multiple electron-positron pair probabilities and their connection with the solution of the single-particle Dirac equation [6]. Based on the multi-particle counting numbers, which are potentially accessible by experiment, we present a general theoretical procedure that permits the computation of the vacuum probability for sub- and super-critical fields with arbitrary spatial and temporal profiles. When the field is supercritical, the theory leads to the expected exponential decay of the vacuum in the long time limit. For the special case of an infinitely extended electric force field, we establish the validity of an effective decay constant obtained by averaging the Schwinger rate over the spatial force profile. The time-dependent multi-pair quantum field theoretical probabilities for arbitrary field conditions can be computed from a generating function as well as from solutions to a set of rate-like equations [7,8].

This work has been supported by the NSF. We also acknowledge support from the Research Corporation.

Generation of TW, 2-cycle pulses focusable to relativistic intensities

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Abstract: We report the generation of 5 mJ, 5 fs pulses using a pressure-gradient hollow fiber. The beam after pulse compression could be focused to a diffraction-limited spot with an intensity in excess of $5 \times 10^{18}$ W/cm$^2$.

Intense few-optical-cycle pulses are crucial for ultrafast nonlinear optics including the generation of isolated single attosecond pulses from gases and plasmas. Since the first demonstration of sub-10 fs pulse generation using a hollow-fiber pulse compression technique [1], much effort has been directed towards upscaling the compressed power. We have proposed and developed a pressure-gradient hollow fiber compression technique to increase the intensity to TW class in the few-optical-cycle regime [2,3].

In the pressure gradient method, the gas pressure is distributed from zero at the entrance of the fiber to the maximum at the exit of the fiber. We can prevent the beam from detrimental nonlinear processes such as self-focusing and plasma defocusing at the entrance to the fiber. After the beam has been well coupled to the fundamental mode of the fiber, the beam undergoes self-phase modulation for spectral broadening in gaseous medium such as neon and helium.

We demonstrated the generation and characterization of intense 2-cycle pulses at a repetition rate of 1 kHz. We obtained 5 fs, 5 mJ pulses that can be focused to a nearly diffraction-limited spot size with an intensity in excess of $5 \times 10^{18}$ W/cm$^2$. Further upscaling of the intensity together with the use for high-order harmonic generation from gases and plasmas is now under progress.

Upcoming 4th generation lights sources, Free Electron Lasers (FEL), will provide, for the first time, intensities, coherence properties, short-time and pump-probe options in the VUV to X-ray regimes comparable to those presently realized by intense, ultra-short laser pulses in the visible. At least three completely new fields of research are expected to open up in atomic and molecular physics. First, the huge integrated radiation flux enables to investigate in unprecedented detail dilute samples, as for example positive ions up to the highest charge states, negative atomic ions, negative or positive state-prepared molecular and size-selected cluster ions. Second, the tremendous peak intensities allow investigating, for the first time, fundamental non-linear processes where few photons interact with few electrons in atoms, molecules, clusters or ions. Third, the short-time properties will enable unique time dependent experiments with any of these targets and first femtosecond VUV-VUV pump-probe measurements have been demonstrated recently. In the talk, these novel fields will be highlighted and first results of pioneer experiments at the Free Electron Laser at Hamburg (FLASH) [1-6] as well as at the Spring8 Compact SASE Source (SCSS) in Japan will be discussed. Future possibilities opened e.g. by the integration of large area imaging photon CCD detectors into reaction microscopes (REMI) [7] or by providing ultra-cold targets via a magneto-optical trap (MOT) in a REMI, the streaking of electrons and ions by overlapping phase stabilized THz radiation etc. will be envisioned.

Ultra-Intense Laser Interactions with Matter

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Abstract: We review some basic physics problems that can be studied when a petawatt laser is focused to ultra-high intensity \((10^{23} \text{ W/cm}^2)\) and interacts with highly relativistic matter.

The Diocles laser, has recently been developed at the Extreme Light Laboratory. At the laser’s focus, light will soon be able to reach a hitherto unattainable intensity level: \(10^{23} \text{ W/cm}^2\). With this new capability, the fundamental interactions of light with matter at extreme field strengths can be studied,\(^1\) and numerous scientific opportunities in a new sub-field of physics, Relativistic Optics,\(^2\) can be exploited. The field of optics can cross—for the first time—several physical thresholds. For instance, when matter is exposed to extreme light, not only do electrons quiver in the electromagnetic fields relativistically, but so too do protons. When electrons are exposed to extreme light, it is predicted that they will emit strong signatures of radiation reaction.\(^3\) In fact, the Schwinger field limit can be reached in the boosted frame of GeV energy electrons.

It is anticipated that by crossing these thresholds, a deeper understanding of relativistic optics will result, and that radiation sources with novel and extreme characteristics will emerge. For instance, theoretical designs for novel, compact, vacuum-based (rather than plasma-based) electron accelerators and x-ray free-electron lasers can be tested. It is also predicted theoretically that x-rays with pulse duration of only zeptoseconds \((10^{-21} \text{ sec})\) will be generated, which will allow matter to be probed for the first time on the nuclear time-scale.\(^4,5\) Just as occurred with the advent of conventional nonlinear optics, it is anticipated that strongly relativistic nonlinear optics will also enable advancements in the generation of even higher fields than are possible from lasers alone, such as novel pulse compression technology to achieve shorter pulses.

The extreme light from ultra-high-power lasers has already produced hyperspectral radiation spanning the entire electromagnetic spectrum, from terahertz to gamma rays, as well as high quality beams of electrons and ions. Diocles was used to accelerate a high quality beam of electrons to energy of 0.8 GeV in a distance of only 1 cm. Numerous potential applications of this technology for defense and security have been identified, such as the detection of shielded special nuclear materials by means of active interrogation.

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Mechanisms behind Ultra-strong Field Interactions with Atoms and Molecules

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Abstract: We present results on photoionization for atoms and methane compounds in $10^{17}\text{W/cm}^2$ to $10^{19}\text{W/cm}^2$ fields. The energy scale for ultrastrong interactions is ~0.1MeV and new excitation process are needed to explain recent experiments.

A basic physics question at ultrahigh intensities is “How do atoms and small molecules absorb energy from the field? We will present studies on the response of gas phase atoms and methane compounds (CH$_4$, CH$_3$X, CH$_2$X$_2$, C$_n$H$_m$). The experimental studies include ionization yields, the more detailed energy and angle resolved photoelectron energy distributions, and the dependence of the ionization to the field polarization. Our theoretical efforts model the experiment with known strong field physics including quasi-static tunnelling ionization, relativistic continuum dynamics, non-paraxial field effects, and recollision phenomena. The photoionization of methane and related compounds are reported for intensities up to $10^{19} \text{W/cm}^2$ with linear, elliptical, and circular polarized light. While fragmental ions (e.g. CH$_3^+$, CH$^-$, C$^-$) created from $10^{14} \text{W/cm}^2$ to $10^{15} \text{W/cm}^2$ involve molecular mechanisms, ionization to form C$^{+3}$ and C$^{+4}$ involves both a molecular and atomic ion response. In ultrastrong fields, removal of a carbon K-shell electron from methane proceeds exclusively via “atomic” mechanisms, i.e. atomic tunneling and rescattering ionization. This effect is due to a reduction in the interaction length scale to less than the bond distance in ultrastrong fields due to the higher energy (see Fig. 1).

The ionization of Ar and Xe at $10^{19} \text{W/cm}^2$ is studied with ion yield and photoelectron measurements. Photoelectrons with energies above the pondermotive energy, $U_p$, including a 1.2 MeV cutoff show a peaked azimuthal angular distribution. This data is in quantitative agreement with a semi-classical, relativistic 3D ionization model that includes a non-paraxial laser field. Photoelectrons from the field ionization of inner shells have energies and momentum dominated by the field, including the acceleration out of the focus. Yields and angular distributions below $U_p$, i.e. kinetic energies at 60 keV, are not in agreement with our model and indicate the possible role of additional physics, i.e. ultrastrong field rescattering, inner shell excitation, and higher energy atomic processes that are traditionally neglected for nonrelativistic strong field interactions.

Fig. 1 Potential energy surfaces of H$^+$-C$^{+4}$-H$^+$ at 5 $10^{18} \text{W/cm}^2$ (left) and H$^+$-C$^{+4}$-H$^+$ at 3 $10^{18} \text{W/cm}^2$ (right)
Double Ionization Momentum Structure Under Elliptical Polarization

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Abstract: Using a purely classical ensemble method, we calculate the end-of-pulse momentum distribution of double ionization under various ellipticities from linear to circular polarization.

Using a purely classical ensemble method, we calculate the end-of-pulse momentum distribution of double ionization under various ellipticities from linear to circular polarization. A new four-band structure is predicted and identified as originating from sequential double ionization (SDI) by trajectory back analysis. We show that sequential and non-sequential double ionization can be cleanly distinguished under elliptical polarization. Detailed and analytical physical process about SDI is discussed and the four-band structure can be very well explained.
Photoemission by large electron wave packets emitted out the side of a relativistic laser focus

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Abstract: We provide an update on an experimental effort to measure the radiation from individual electron wavepackets that are spread over an area on the scale of an optical wavelength.

The quantum wave packets of free electrons naturally spread, quickly reaching the scale of optical wavelengths. Moreover, an electron wave packet born through ionization in an intense laser focus is pulled apart by sharp field gradients. Different parts of the same electron wave packet may even be propelled out opposite sides of the laser focus. The question naturally arises as to how wave packets scatter laser radiation if they undergo such highly non-dipole dynamics.

If one uses quantum probability current (multiplied by the electron charge) as a source current for Maxwell’s equations, the radiated field is strongly suppressed by interferences between different portions of the wave packet. This approach predicts dramatic suppression of radiation scattered out the side of an intense laser focus, relative to what one would expect if electrons are treated as point charges. This effect is illustrated in Fig. 1 for a large electron wavepacket created through natural spreading. An electron born through ionization will have a more complicated spatial wavepacket. If, instead, the wave packet represents the probability of where a point electron emitter is located, the dramatic suppression due to interference will not occur. These two viewpoints predict emission rates that differ by orders of magnitude.

In this poster, we give a progress report on an experiment designed to measure the photoemission rates. In this experiment, we create electron wave packets through ionization in a focus at the center of a large vacuum chamber. Radiation emitted out the side of the focus is collected by 1-to1 imaging into 105µm fiber which carries the light to a single photon detectors located outside the chamber. The electron radiation is red-shifted due to the mildly relativistic acceleration, and we use this signature to spectrally filter the outgoing light to discriminate against background. In addition, the temporal resolution of the electronics allows distinction between light that travels directly from the focus into the collection system and laser light that reflects from a surface inside the chamber.
Push laser field to multi-100TW peak power, CEP control and attosecond pulse at XUV

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Abstract: A 720TW Ti:sapphire laser at single shot, 100TW Ti:sapphire laser at 0.1Hz repetition rate and CEP controlled 5fs laser was developed in the Institute of Physics. The detail results will be introduced in this talk.

Development of the chirped pulse amplification (CPA) has revolutionary the progress of laser science, peak power of around multi-100TW has been obtained on tabletop scale with all Ti:sapphire laser crystals as gain medium, which will enable people to carry out the advanced research such as the generation of ultrafast x-ray radiation, ultrahigh-order harmonics, particle accelerating etc. In additional, push the laser pulse to single cycle and control the carrier-envelope phase (CEP) also open the gates for frequency metrology and attosecond pulse generation. In this presentation, we will report the new progresses on femtosecond laser research at the Institute of Physics in Beijing. First, a compact 720TW femtosecond Ti:sapphire facility was constructed with only three stage amplifiers. By efficiently using the available pump energy from the 120J Nd:glass laser. At 527nm, it is capable of the peak power of higher than 1 PW by further eliminate the parasitic lasing and the spontaneous amplified emission. Second, a new upgrade system with peak power of 200TW at repetition rate of 0.1Hz is under constructing pumped by a glass laser with 527nm energy of 25J. Beam quality and contract ratio can be improved with our new ring regenerative amplifier. Third, we developed a series of 6~8fs Ti:sapphire laser oscillators by controlling the dispersion with chirped mirrors, a MgO:PPLN crystal was used to generate the difference frequency laser for CEP measurement. Based on this work we realized the waveform control with a monolithic scheme. In addition, we successfully compressed the laser pulse from a CPA Ti:sapphire laser at 1kHz repetition rate to 5.1fs with energy of 0.4mJ by injecting a CEP controlled 7fs laser as the seeding, the stabilization accuracy of CEP within 53mrad was obtained by the combination of spectra-interference technology and slow loop electronics, which demonstrated a technology to finely control the waveform. Further, by focusing the CEP controlled 5fs laser into the flow Ne gas, we measured continuous high order harmonic with cut off wavelength to 17nm, which indicates a feasible way to single attosecond laser generation.
Self-organizing GeV nano-Coulomb collimated proton beam from laser foil interaction

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Abstract: We report on a self-organizing, quasi-stable regime[1,2,3] of laser proton acceleration, producing 1 GeV nano-Coulomb proton bunches from laser foil interaction at an intensity of $7 \times 10^{21}$ W/cm².

The results are obtained from 2D PIC simulations, using circular polarized laser pulse with Gaussian transverse profile, normally incident on a planar, 500 nm thick hydrogen foil. While foil plasma driven in the wings of the driving pulse is dispersed, a stable central clump with 1 - 2 \( \lambda \) diameter is forming on the axis. The stabilisation is related to laser light having passed the transparent parts of the foil in the wing region and reflected by the central clump that is still opaque.

Fig.1 ~GeV monoenergetic proton beam (color is for energy)

Molecular Structure and Dynamics probed by Coherent Electrons and X-Rays

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Abstract: High harmonic emission is a new spectroscopic tool for determining molecular structure as well as the dynamic coupled motions of electrons and atoms polyatomics.

Recently, high harmonic generation (HHG) has been investigated as the fastest probe of molecular structure and dynamics. The attosecond electron recollision process that gives rise to the generated harmonics is sensitive to molecular structure, and thus can be used to capture dynamic structural information. Moreover, new experimental approaches now allow simultaneous characterization of the intensity, phase and polarization state of HHG emission from molecules.

In this work, we report the use of extreme-ultraviolet interferometry to measure the amplitude and phase of high-order harmonic generation from transiently aligned CO₂ molecules [1]. We unambiguously observe a reversal in phase of the HHG emission resulting from molecular-scale quantum interferences as the electron recombines with the molecule. We find that a plane-wave electron recombination model can explain HHG from CO₂ but not N₂. We also perform an accurate polarimetry measurement of HHG from aligned molecules [2]. Surprisingly, we find that harmonic emission from N₂ molecules can be strongly elliptically polarized even when driven by linearly polarized laser fields. We extract the phase difference between the parallel and perpendicular components of the high harmonic field, which strongly depends on the harmonic order. This nontrivial phase indicates a breakdown of plane wave approximation.

Finally, we show that HHG from dynamically changing molecules can reveal coupled electronic and nuclear dynamics in polyatomic molecules [3]. By exciting large amplitude vibrations in the N₂O₄ molecule, we show that tunnel ionization accesses the ground state of the ion at the outer turning point of the vibration, whereas the first excited state is populated at the inner turning point of the vibration motion. This state switching due to the coupled electronic and nuclear motions is manifested as bright bursts of high harmonic light that are emitted mostly at the outer turning point of the vibration.

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