Summary of the PhD Thesis

DIAGNOSTICS OF THE ULTRASHORT, ULTRAVIOLET LASER PULSES AND HIGH-HARMONICS

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1. Introduction

Nowadays, one of the fastest developing area of physics is the investigation of ultrafast phenomena examined by ultrashort laser pulses. The shorter time scale we examine very fast processes in the nature, the more information can be obtained about them. Thus, we can make the phases of the atomic and molecular physics processes visible by the ultrashort laser pulses.

The femtosecond lasers can allow the examination of the physical, chemical and biological processes with high temporal resolution. With the help of the light pulse beside the detection of the movement of atoms in the molecule it is possible to influence the biological and chemical processes consciously.

Compared to solid-state lasers the minimum focal spot area is 10-100 times smaller for excimer laser systems, provided by the significantly shorter wavelength and by the less non-linearity. Thus high focused intensity can be obtained short-wavelength laser systems, as the intensity of the focused laser pulse is proportional to the third power of the wavelength. When the KrF laser pulse interacts with the solid target the plasma-mirror effect can be used as a contrast improvement method. By increasing the intensity of the KrF laser pulse, the pulse can be converted into high frequency spectral domain and high-order harmonics can be generated in gas or in solid target. High spatial resolution is obtained due to the short wavelength.

My dissertation intends to integrate into this direction by the high harmonics analysis, and developing the infrastructure required for the laser experiment. Since during several experiments the controlling of the KrF laser parameters is of great importance, such as the laser energy, the temporal contrast, the directional and temporal stability of the laser pulse. My aim was to design and realize instruments suitable for the solving of these diagnostic problems. I took part in an international experiment where the conversion efficiency of the harmonics generated by the relativistically oscillating mirror mechanism (ROM) was investigated. Our goal was to determine the energy of the individual attosecond pulse caused by a few-cycle laser.

The most of the results which presented in my thesis was achieved in the High Intensity Laser Laboratory (HILL) founded by the Department of Experimental Physics (University of Szeged) and the Department of Plasma Physics (MTA Wigner Research Centre of Physics) and a small part was obtained in the Max Planck Institute of Quantum Optics (MPQ) in Garching.

2. Theoretical background

In the last decade coherent lasers with wide spectral range have enabled a high temporal resolution of different chemical, physical and biological processes. Our goal is the generation of the shortest laser pulse, because the pulse length determines the time resolution of the process, moreover a higher peak power can be achieved in a short time. The molecular and atomic processes have a duration of femtosecond (10^{-15} s), attosecond (10^{-18} s), so short laser pulses are required for the investigation. The development of various laser systems and their applications can play an important role in the basic and applied research.

It is necessary to control the laser pulses for the investigation of these fast processes. During experiments using high intensity laser systems several laser parameters may be required to monitor or control. In addition to improving the temporal and spatial contrast of the laser pulse, the pulse energy can be mentioned as an important parameter. For instance energy monitoring is essential at the generation of attosecond pulses. In the laser-matter interactions the energy measurement of the laser pulse plays an important role in our laboratory (HILL). Both the energy monitoring and the temporal contrast of the pulse is dominant in the experiments of high harmonics generation. Because of the short duration of the measured pulses the electronic circuit requires careful planning, since most of the electronic circuits are slower than the duration of the laser pulse. In addition noise elimination also becomes necessary in the laboratory for accurate measurement results. Besides the laser energy the direction stability of the laser pulse is also important at the laser material processing. In the real laser experiments the stability of the laser beam depends on several factors, such as temperature changes or mechanical vibration. This type of influential factors are not ignored in laser experiments. If the stability of the laser beam does not comply with the required accuracy, beam-pointing system is needed to be used. Several studies have been written about directional stability of different type of lasers, especially for the elimination of the long-term drift. The stability of the laser beam direction is also crucial importance in experiments using KrF laser systems. The excimer laser amplifiers have a low saturation energy, therefore in order to obtain an intense radiation of an excimer-amplified UV laser, large beam diameters have to be used. Most of the commercially available position-sensitive detectors are produced for small-size beams of the infrared radiation of solid-state laser systems. Contrarily large-sized position-sensitive UV detectors are difficult to obtain and are very expensive. Besides the spatial stability of the laser pulses, the temporal synchronization of the KrF pulses is also an important criteria.

3. Objectives

The aim of my study was to monitor and control the parameters of UV laser system during various laboratory experiments. I have been developed electronic devices for the energy monitoring, direction stabilization and the time synchronization of the KrF laser pulse. Besides I have been participated in an experiment where the conversion efficiency of the ROM harmonics was investigated.

- I proposed to develop an energy monitoring system that can measure the energy of the high-intensity KrF laser pulses. Due to the fiber optical communication the instrument is less sensitive for the electrical noise. Besides an USB interface is between the computer and the device, so the measuring data can be stored and evaluated digitally. Using the energy measuring system my further goal was to investigate the plasma-mirror effect because the experiment gives answer that the plasma-mirror as a contrast enhancing method might be adaptable, i.e. implement between the pre- and final amplifier (operates in saturation) without significant energy reduction.

- My second goal was the directional stability of the ultrashort KrF laser beam, because the beam-pointing stability is essential in the investigation of high harmonics generation and plasma spectroscopy when the beam is focused into a very small focal spot by a parabolic mirror. Because of the mechanical vibrations and the temperature changes may change the direction of the laser beam, the quality of the focus is deteriorated. My aim was to build an active beam-pointing stabilization system to detect the spatial position of the KrF laser beam and control the directional position with an automatic feedback stabilization system with the help of motor-driven mirror.

- Finally I participated in a laser-plasma experiment in the Max Planck Institute of Quantum Optics. With my knowledge of the energy monitoring and the detector technology I aimed to obtain the conversion efficiency of the ROM harmonics using solid-state laser. I was involved in the design of the experimental setup, I built the detector unit into the system which can measure the energy of the harmonics generated by the relativistically oscillating mirror mechanism. By the absolutely calibrated X-ray photodiode the conversion efficiency was obtained for the 17 nm - 80 nm range.

4. Scientific results

The experimental results obtained in the HILL laboratory and in the MPQ are summarized in the following thesis points:

1. **I built an energy measuring system for monitoring the energy of the high-intensity KrF laser pulses. The system has a fiber optical coupling between the personal computer and the energy monitor, besides USB interface is applied for the data communication. The energy monitor was used in the investigation of laser-matter interactions [T1].**

I designed an energy monitor which can measure the ~600 fs KrF laser pulses on the 248 nm wavelength, therefore convenient for the receiving of the short pulses i.e. measuring the signal proportional of the laser energy. A system is based on an analog-peak hold and a digital peak-hold part provided the detection of the short pulses. By this method after the digitization the experimental results can be evaluated on the computer side. The energy measuring system has 0.42% of statistical error. In contrast to previous energy monitors the innovations are the connection to the computer via USB interface and the fiber optical coupling to reduce the electrical noises from potential ground loops and electromagnetic pulse interference originating from the discharge pumped excimer lasers and also from the high power laser-plasma interactions.

2. The plasma-mirror effect was investigated using the energy monitor for KrF laser system and the measured maximum reflectivity was found to be 50%. The energy measuring system was also used in the generation of the resonant third harmonic in Ar gas [T2, T3].

I used the newly developed energy monitor during the experiments in the HILL laboratory such as in the plasma-mirror experiment and the generation of gas harmonics. In the plasma-mirror experiment the KrF laser beam had two off-axis passes in the preamplifier and in this case the optimal reflection was investigated. Using the plasma-mirror effect as a contrast improvement technique the reflectivity was found to be ~50% for 12° angle of incidence. In case of the generation of the gas harmonics the KrF laser pulse of 600 fs was focused in Ar gas. The conversion of the resonant 3^{rd} harmonic of the laser pulse of 248 nm was measured with silicon and diamond semiconductor detectors developed by guest researcher. The conversion efficiency was obtained ~0.23% which is lower by a factor of 3 than obtained in other experiments.

3. I developed an active beam-pointing stabilization system has for the high-power KrF laser system to improve the directional stability of the laser beam. Due to the short-term fluctuation and the long-term drift the direction of the laser beam can be changed during high-intensity laser experiments. The direction of the beam was readjusted with an accuracy of ~5 μrad [T4].

I achieved the stabilization of the long-term drift by the beam-pointing stabilization system for KrF laser system. The long-term drift originates from the temperature-induced mechanical deformations. Due to the spatial position of the ultrashort laser pulse the active stalibization system controls the beam to the proper position by an automatic feedback system and a motor-driven mirror. The shot-to-shot fluctuation was ~12 μrad (14% standard error). By the simulation of the long-term drift after the stabilization the directional distribution of the focal spot was ~14 μrad (15% standard error). In six day when the direction of the beam was changed with ~61 μrad without the stabilization, the system corrected the deviation with an accuracy of ~5 μrad. From the width of the 0^{rd} order of the focal spot, the diffraction-limited divergence of ~15 μrad (7%-os standard error) is found. When focusing by a parabolic mirror with a small F-number the elimination of the astigmatism is crucial. The directional stability provided by the beam-stabilization system is nearly one order of magnitude better than the one required for optimum focusing by an F/3 parabolic mirror.

4. **The conversion efficiency of ROM harmonics was obtained in a laser-plasma experiment using the multi-terawatt titanium:sapphire laser system (ATLAS) in the Max Planck Institute of Quantum Optics. The conversion efficiency was ~10^{-4}. In this experiment my task was the energy measuring by the absolutely calibrated X-ray photodiode [T5].**

I built the detector in the experiment for the measurment of the energy of the ROM harmonics then I measured the energy converted into the harmonics using an IRD AXUV100 absolutely calibrated photodiode, an MCP detector with a phosphorus screen and a CCD camera. After the extrapolation of the images of the beaming the conversion efficiency of the harmonics was $\eta_1 = 1.67 \cdot 10^{-4} \pm 0.71 \cdot 10^{-4}$ by the averaging the results of 10 single shot energy records. By the measuring of the harmonics efficiency the average energy of an individual attosecond pulse can be estimate. E_{XUV} = 30 μJ average energy of the harmonics was obtained for λ = 17 nm - 80 nm range. Thus $E_{as} \approx 6$ μJ energy was converted into an attosecond pulse, the estimated power into the beam is $P_{as} \approx 60$ GW.

5. Publications

Related publications:

[T1] A. Barna, I. B. Földes, Z. Gingl, R. Mingesz (2013) Compact energy measuring system for short pulse lasers, Metrology and measurement systems XX:(2) pp. 183-190.

[T2] I. B. Földes, A. Barna, D. Csáti, F. L. Szűcs, S. Szatmári (2010) Plasma mirror effect with a short-pulse KrF laser, Journal of Physics: Conference Series 244, 032004.

[T3] R. Rakowski, A. Barna, T. Suta, J. Bohus, I. B. Földes, S. Szatmári, J. Mikołajczyk, A. Bartnik, H. Fiedorowicz, C. Verona, G. Verona Rinati, D. Margarone, T. Nowak, M. Rosiński, L. Ryć (2014) Resonant third harmonic generation of KrF laser in Ar gas, Review of Scientific Instruments 85:(12) pp. 123105.

[T4] A. Barna, I. B. Földes, J. Bohus, S. Szatmári (2015) Active stabilization of the beam pointing of a high-brightness KrF laser system, Metrology and measurement systems 22:(1) pp. 165-172.

[T5] P. Heissler, A. Barna, J. M. Mikhailova, G Ma, K. Khrennikov, S. Karsch, L. Veisz, I. B. Foldes, G. D. Tsakiris (2015) Multi-µJ harmonic emission energy from laser-driven plasma, Applied Physics B 118: pp. 195-201.

Other publications:

1. R. Mingesz, A. Barna, Z. Gingl, J. Mellár (2012) Enhanced control of excimer laser pulse timing using tunable additive noise, Fluctuation and noise letters, 11:(1) pp. 1240007-1-1240007-10.

2. S. Szatmári, R. Dajka, A. Barna, I.B. Földes (2013) Improvement of the spatial and temporal contrast of short-pulse KrF laser beams, EPJ Web of Conferences 59, 07006.

3. L Ryc, A Barna, Lucia Calcagno, Istvan B Foldes, Piotr Parys, Ferenc Riesz, Marcin Rosinski, Sandor Szatmari, Lorenzo Torrisi (2014) Measurement of ion emission from plasmas obtained with a 600 fs KrF laser, Physica Scripta T161 014032.

Conference posters, presentations:

4. I. B. Földes, A. Barna, D. Csáti, F. L. Szűcs, S. Szatmári (2009) Plasma mirror effect with a short-pulse KrF laser, Proc. of the Sixth International Conference on Inertial Fusion Sciences and Applications, San Francisco USA, 6-11 September, poster presentation

5. I.B. Földes**,** A. Barna, D. Csáti, S. Szatmári (2010) Plasma mirror for cleaning KrF laser pulses, 31st European Conf. on Laser Interaction with Matter, Book of Abstracts, p. 135., Budapest, szeptember 6-10 September, poster presentation

6. S. Szatmári, R. Dajka, A. Barna**,** I.B. Földes (2011) High contrast UV laser beam based on active nonlinear temporal and spatial filtering, Meeting of COST Action MP0601, Short Wavelength Laboratory Sources, Dublin, Írország, 30-31 May, poster presentation

7. R Mingesz, Z Gingl, A Barna (2011) Enhanced control of excimer laser pulse timimg using tunable additive noise, Fluctuation and Coherence: from Superfluids to Living Systems, Book of Abstract p. 18, Lancaster UK, 13-16 July

8. S. Szatmári, R. Dajka, A. Barna, I.B. Földes (2011) Improvement of the spatial and temporal contrast of short-pulse KrF laser beams, 7th Int. Conf. on Inertial Fusion Sciences and Applications, Book of Abstracts, P.74, Bordeaux, Franciaország, 12-16 September, poster presentation

9. S. Szatmári, R. Dajka, A. Barna, I.B. Földes (2011) Nonlinear temporal and spatial filtering of high-power laser beams, Light at extreme intensities, Book of Abstract p. 40, Szeged, 14-16 November

10. A. Barna, P. Heissler, J.M. Mikhailova, K. Khrennikov, S. Karsch, L. Veisz, F. Krausz, G.D. Tsakiris and I.B. Földes (2012) Conversion efficiency measurement of relativistic harmonics, Laserlab User Meeting, Book of Abstracts, p. 7., Szeged, 16-17 February

11. I.B. Földes, A. Barna, R. Dajka, S. Szatmári (2012) Pulse cleaning methods of short-pulse high power KrF lasers, IZEST Conference, Darmstadt, Németország, 23-25 April, poster presentation

12. S. Szatmári, R. Dajka, A. Barna**,** B. Gilicze, I.B. Földes (2013) Contrast improvement by nonlinear temporal and spatial filtering of high-power laser beams**,** 3rd Conference on High Intensity Laser and Attosecond science, Izrael, 2-4 December

13. A. Barna, I. B. Földes, B. Gilicze, S. Szatmári (2014) Plasma mirror for cleaning short-pulse high power KrF laser, LMJ-PETAL scientific programme and COST action MP1208 kick-off meeting, Bordeaux, Franciaország, 5-7 March, poster presentation

14. S. Szatmári, B. Gilicze, R. Dajka, A. Barna, I B Földes (2014) Nonlinear Fourier filtering of high-brightness KrF laser beams, 1st International Symposium on High Power Laser Science and Engineering, Suzhou, Kína, 16-19 March, poster presentation