STEREO ABOVE THRESHOLD IONISATION:-PHASE METER

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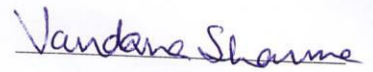
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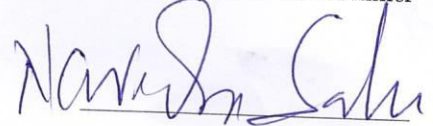
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Approval Sheet

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Abstract

The carrier envelope offset phase or the so called "absolute phase" governs the spatio-temporal evolution of the electric field of a short laser pulse, and this field in turn governs the interaction of matter with such pulses. The precise measurement and stabilization of this quantity is of great importance for attosecond physics and virtually every other application that benefits from ultrashort laser pulses. The aim of this project is to build a spectrometer, which we call the Stereo ATI Phasemeter, for measuring the absolute phase of short laser pulses. It involves the stereo –measurement of photoelectrons of Xenon gas ejected after ATI(Above Threshold ionisation). This approach to phase measurement is based on the belief that the spatial symmetry of photoelectron emission from a gaseous medium should be governed by the symmetry of the pulse.

Contents

Chapter 1

Introduction

It was Albert Einstein with his publication on the quantum nature of radiation in 1917, who laid the foundations for the invention of the laser ('light amplification by stimulated emission of radiation') and its predecessor, the maser. Therein, Einstein introduced probability coefficients for the absorption, the spontaneous emission and the induced emission of electromagnetic radiation. Later on, Rudolf Ladenburg could confirm this experimentally. In 1953, Charles H. Townes developed a microwave amplifier which was already operating similarly to a laser. This device, however, was incapable of continuous outputs, a problem that was solved by Nikolay Basov and Aleksandr Prokhorov shortly after, leading to the Nobel price for the three physicists. In 1960, Theodore Maiman developed the first ruby laser that was emitting visible red light. From that time on, the evolution of continuous wave (cw) and pulsed lasers diverged. While the cw-community tried to enhance the stability of their lasers in order to accomplish high resolution spectroscopy on atoms and molecules, the other part of the community tried to create shorter pulses and hence higher peak intensities. Techniques like mode-locking already allowed reaching nanosecond pulses in the early 1970s. In the following decades, the limits on pulse shortness and peak intensities were raised even further by important developments like chirped pulse amplification. It turned out that trains of laser pulses created with high repetition short-pulse lasers can be employed for high resolution spectroscopy as well, by making use of the fact that such pulse trains form an equally spaced comb of lines in the frequency domain, a so called frequency comb.

Today ultrashort lasers represent an indispensable tool in science to resolve physical and chemical processes on very short timescales. The characterization of single ultrashort laser pulses as needed for spectroscopy requires the precise knowledge

of the offset between the electric field and the pulse envelope, the so called carrier envelope phase. Control of the absolute phase delivers subcycle precision. This is of key importance for the quickly unfolding area of attosecond science. Therefore, the self-referencing (or f-to-2f) phase stabilization technique invented for frequency metrology revolutionized not only that field but also attosecond science. In fact, the hollow-fiber technique owes much of its significance to the achievement of phase stabilization for amplified few-cycle pulses .However the self-referencing technique stabilizes the absolute phase only indirectly. This can lead to systematic errors and respective drifts of the absolute phase in time-domain applications. Evidently, a precise measurement and stabilization of the absolute phase is of pivotal importance for virtually every application of ultra-broadband laser pulses. Currently, few-cycle pulses and attosecond science are the focus of interest as few-cycle laser pulses offer the possibility to strongly drive electronic transitions with isolated optical cycles. And considering the rapid progress of recent years, it is very conceivable that ultra-broadband optical fields will become controllable to a degree similar to microwave fields today. This would create entirely new perspectives for fields like attosecond science, coherent control, and information technology. An ultra-broadband optical frequency synthesizer will require not only a precise but also an accurate meter of the absolute phase.

The aim of this project is to build a phase meter which will be able to detect the laser phase. The phase meter essentially is the stereotype measurement of the electrons coming from above threshold ionisation. Ultra short pulses can cause the phenomenon of multiphoton ionisation in atoms. And it is observed in experiments that as the intensity is increased, the ejected electron could absorb photons in excess of the minimum required for photo-ionisation. This process is called above threshold ionisation (ATI) and it manifests itself in a discrete photoelectron energy spectrum. In the experiment, an ultrafast laser pulse from a Ti-Sapphire laser is to be focused on Xenon gas target(inside a vacuum tube) and the left-right distribution of photo electrons, which are emitted along the laser polarization axis, is measured using a stereo set-up. This is achieved by placing two micro channel plate detectors facing each other inside the vacuum tube. The carrier envelope phase can be determined by comparing the left-right asymmetries of photo electrons at different electron energy regions. Using this spectrometer, one will be able to precisely measure the absolute phase of the pulses. Furthermore, this method can in principle determine the phase for every single shot such that one does not has to integrate over many pulses. The thesis is organized in such a way as to start with a brief overview about short laser

pulses and its important characteristics, going on to explain the experimental set up, finally ending with a discussion on the results obtained.

Chapter 2

Ionisation in short laser pulses

This chapter gives a brief overview of short laser pulses and its important characteristics. We will also see the behaviour of an atom in an intense laser field and the effect of phase on multiphoton processes.

2.1 Short Laser Pulses

An electromagnetic pulse whose time duration is of the order of a picosecond or less is called an ultrashort pulse. Such pulses are characterized by high peak intensities and their wave amplitude follows a Gaussian envelope. The electric field of such a pulse is written as

$$\epsilon(t) \quad = \quad \epsilon_0(t) cos(\omega t + \varphi) \tag{2.1}$$

where $\epsilon_0(t)$ denotes the envelope of the pulse, which for few-cycle pulses—varies barely more slowly than the laser frequency $\omega/2\pi$. And φ denotes the absolute phase. Ultrashort pulses play a pivotal role in the study of atomic and molecular dynamics. Reactions and process at the atomic level occur in the attosecond regime. Therefore such pulses are vital in conducting time-resolved measurements on the quantum dynamics of atoms and molecules. In the study of systems, one has to usually wait till the end of the perturbation, to analyze the consequences of the perturbation. But some processes are so fast that they get completed before the perturbation stops. To get information on these processes the perturbation has to be of shorter duration, and hence the need for an ultrafast pulse as probe. Also, the faster processes may be the reason for some slower processes that are observed, and hence will give information about the slower processes too. Thus the unique property

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of ultrashort pulses, i.e their shortness make them suitable for initial perturbation of a sample.

A laser that emits ultrashort pulses of light is known as an ultrashort pulse laser. Ultrashort pulses are usually generated with passively mode-locked lasers, but sometimes also with optical parametric amplifiers (possibly using a supercontinuum as input) or with free electron lasers. The discovery of Kerr-lens mode-locking in Ti:sapphire lasers has ignited a revolution in ultrafast laser technology and science. Ti:sapphire lasers are tunable lasers which emit redand near-infrared light in the range from 650 to 1100 nanometers. The gain medium is a crystal of sapphire (Aluminium oxide) doped with titanium ions . Ti:sapphire lasers operate most efficiently at wavelengths near 800 nm. In this experiment a Ti:Sapphire laser (FEMTOPOWER COMPACT PRO, FEMTOLASERS) laser operating at wavelength of 780 nm and pumped by a Nd-YAG(527-532nm) is used for generating femtosecond pulses.

2.2   Carrier Envelope Offset Phase

The carrier envelope offset(CEO) phase or the absolute phase of a short laser pulse is defined as the relative phase of the highest amplitude of the electric field with respect to the maximum of its envelope. Ultrashort pulses consist of two or even less than two optical cycles in full width at half maximum. Therefore, the amplitude of the laser field changes almost as fast as the field itself and the temporal evolution of the latter depends on the phase of the carrier frequency with respect to the maximum of the envelope. Thus physical processes that depend on electric field strength will thus show a phase difference that can be measured in experiments.

The term, absolute phase has no literal meaning, it can be found in many fields of science, in particular acoustics and optics.Generally, the reason for choosing it is the presence of a self-evident or a global reference and the desire to avoid length names like "carrier-envelope offset phase" in the present case. For ultrashort laser pulses, the term has generally been used in discussions of phase matching of high harmonics in Gaussian beams(years before the advent of few-cycle laser pulses) and, in particular, in pulse metrology and the discussion of higher order dispersion (chirp). For the latter, the absolute phase appears as the zeroth-order term of the Taylor expansion of the spectral phase, usually with the comment that it cannot be measured and is of no significance. However, recent experiments have been successful
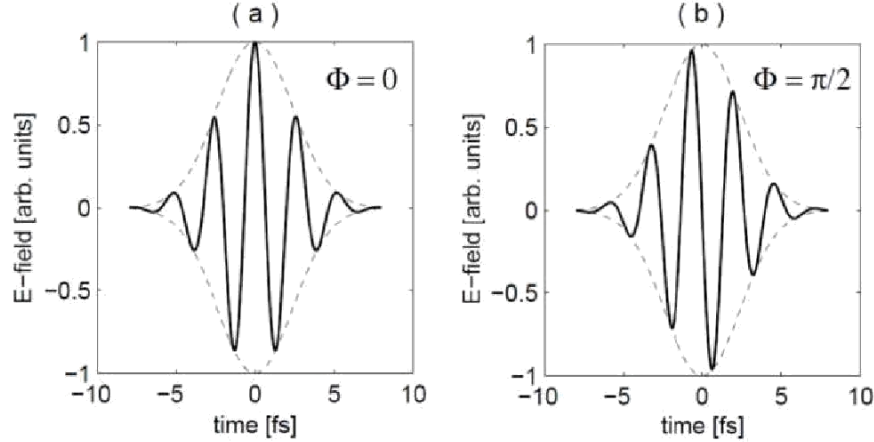
Figure 2.1: Electric field of a 6-fs pulse for absolute phase = 0 (a) and absolute phase = $\pi/2$ (b). In (a) the maximum of the envelope coincides with a maximum of the electric field (cosine-like pulse); In (b) the maximum of the envelope coincides with a zero-crossing of the electric field (sine-like pulse).

in not only measuring, but also controlling the absolute phase of intense short laser pulses.

For defining the absolute phase we use the convention that the pulse has its maximum at time t=0. This makes pulses with phase equal to 0, $-\pi/2, \pi$ and $\pi/2$ cosine-like, sine-like, minus cosine-like and minus sine-like respectively as is evident from Fig. 2.1. This absolute phase governs the temporal evolution of the pulse, thereby governing the interaction of matter with the field of few cycle laser pulses. By determining and stabilizing the absolute phase we may even control reactions in attosecond regime.

2.2.1   Controlling the CEO Phase

Many experiments require the stabilization of CEO phase over a prolonged period of time. This makes it necessary to control the CEO phase by manipulating the experimental set-up. The pulse envelope and the carrier wave propagate at different velocities, the group velocity and the phase velocity respectively, in a dispersive medium. This causes a displacement of the electric field inside the envelope during propagation and hence the CEO phase changes continuously. This phase change,

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when passing through a dispersive material of thickness 'd' is given by

$$\Delta\varphi \;=\; \omega d(\tfrac{1}{V_{ph}} - \tfrac{1}{V_g}) \tag{2.2}$$

where V_{ph} and V_g are phase and group velocity respectively.

Therefore by moving glass wedges in and out of the laser beam, CEO phase can be shifted.

2.3 Atoms in Intense Laser Field

Intense laser fields are characterized by the involvement of many photons in absorptions and emissions. In laser filed intensities as high as 10^{13} W/cm^2 multiphoton ionisation occurs (since the typical energy of a single photon is not sufficient to ionize an atom through photo-effect) and the probability of its occurrence is dependent on the number of photons incident per unit time on the atom or molecule.

2.3.1 The Three Step Model

In this experiment, Xenon atoms are exposed to the strong, oscillating field of the ultrashort laser. The laser field rival the electric field inside the atom ,leading to multiphoton ionisation of the atom. The electrons are first detached (presumably by tunneling) and absorb energy while following the laser, only to be hurled back at the ionic core when the laser reverses direction, where they can ionize more electrons or generate very high harmonics of the driving laser. This so-called "three-step" or "recollision" model(Fig. 2.2)is the workhorse in the field of intense laser pulses. The first step is the ionisation of the atom, which occurs at the maximum of the field amplitude. The second step is the evolution of the ejected electron , following the field of the laser pulse. And the final step is the recollision of the ejected electron with the atom, upon the reversal of the laser field. On recollision, any one of the three below mentioned processes can occur. These are high harmonic generation, above threshold ionisation and non sequential double ionisation. High-order harmonic generation is probably the most known of these processes. It consists of efficient coherent radiation emission at frequencies that are odd multiples of the laser frequency. However, the lesser known, but older, ATI process has recently been discovered as the ultimate tool for the investigation of extremely high non-linear phenomena in the visible spectral region.
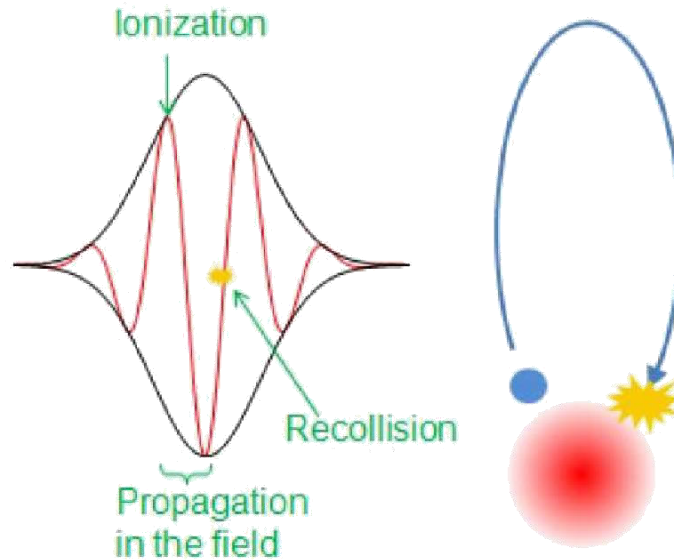
Figure 2.2: The three step collision model

2.3.2 Above Threshold Ionisation

Since its discovery in 1979, above-threshold ionisation (ATI) has been extensively investigated to reveal the photoionisation dynamics of atoms under intense laser fields . Strong field ionisation of atoms induces such interesting phenomena as high harmonic generation (HHG) , nonsequential double ionisation (NSDI) , and ATI as already mentioned. While all three phenomena are results of photoionisation of atoms in a strong laser field, HHG emits harmonic photons due to the recombination of the released electron with its parent ion, and NSDI happens when the returning electron kicks out another electron from the ion. ATI produces photoelectrons separated by incident photon energy in a photoelectron spectrum due to the absorption of photons in excess of the minimum required to overcome the ionisation threshold of an atom. This can be seen by measuring the photoelectron kinetic energy spectra, which consist of a series of peaks separated by the photon energy(Fig. 2.3). The peak heights decrease as the order is increased. The measurements of ATI spectra
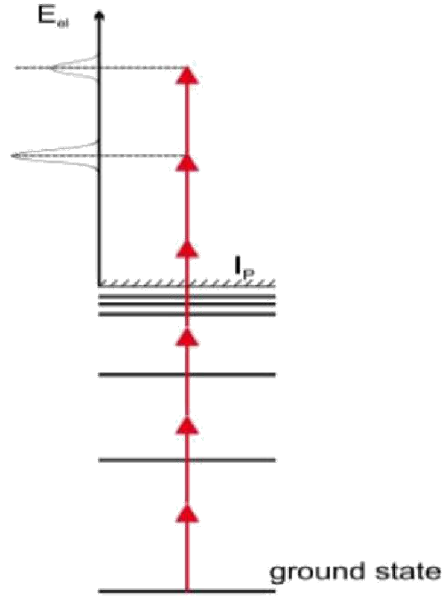
Figure 2.3: Above threshold ionisation of an electron.The electrons absorbs more photons than required to overcome the ionisation potential(I_p). This produces an energy spectrum that has discrete peaks at a spacing of $hw/2\pi$.

have revealed structural information on atomic bound states and the rescattering process of the freed electron.

ATI process depends on the CEO phase of few cycle laser pulses, thus revealing the physics of strong field interaction of atoms and molecules. And this is exactly why ATI is a valuable tool in the determination of absolute phase of short laser pulses. The phase induced asymmetry of the photoelectron emission from ATI translates into an anti-correlation of the electrons emitted to the left and the right. Stereo-ATI scheme uses the electrons that were elastically scattered back under 180° from the ion to reconstruct the CEP. By simultaneously detecting electrons emitted into the left and right hemisphere with respect to the laser polarization axis, a CEP-dependent asymmetry parameter

A = (N$_L$-N$_R$) / (N$_L$+N$_R$)

can be calculated from the number of electrons emitted into the left (N$_L$) and and right (N$_R$) hemisphere, respectively.

Chapter 3

The Stereo ATI Phasemeter

In this chapter the setup of the stereo-ATI spectrometer that was built during this diploma thesis is explained.Finally, the method of obtaining the kinetic energy of the electrons from the time of flight spectrum is explained in detail.

3.1 Experimental Set-up

The laser pulses are reflectively focussed (f=150mm) into a small stainless steel tube which is connected to a gas bottle and mounted inside a vacuum chamber (DN 63 CF cube). The tube has a diameter of about 1cm and four holes drilled into it. Two for the laser (100um diameter) and two for the ionized electrons (500um diameter) to escape the interaction region. Two micro-channel plate detectors (MCP, 20mm diameter Chevron) record the escaped electrons in the left and right hemisphere, respectively. From the time-of-flight the electron energy can be calculated. To increase the energy resolution of the spectrometer, the MCPs are placed at the end of 23cm long drift tubes. The read-out of the MCP detectors is done by fast 8-bit analog-to-digital converters (Agilent Technologies DC271) with a time resolution of 0.5ns. In combination with the long drift tubes this yields to an energy resolution between 0.2eV for slow ($\approx 10eV$) and 2.5eV for fast ($\approx 60eV$) electrons. To shield against the earth magnetic field and to increase the solid angle, the flight tubes are surrounded by two cylindrical coils creating a magnetic field of about 1-2mT. The schematic Stereo-ATI design is shown in figure 3.1.
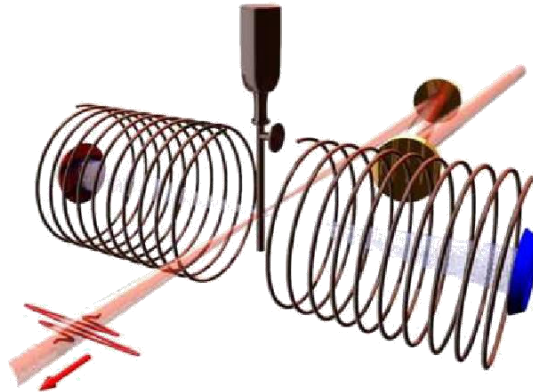
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Figure 3.1: Scheme of the stereo-ATI spectrometer. A pair of glass wedge plates is used to control the absolute phase of the pulses.

3.1.1 The Laser System

For conducting time resolved measurements of atomic and molecular dynamics we need to measure time scales in order of femtoseconds. Therefore we need a femtosecond laser and the laser used here is a Ti:sapphire laser. With the development of modelocking technique using Kerr-lens model, for creating ultrafast laser pulses, Ti:sapphire laser has become a popular candidate. The laser pulses are created in the oscillator of the laser, using dispersion compensated mirrors. These pulses are still too weak, and is amplified using an additional Ti:sapphire crystal that is pumped with a Nd-YAG crystal. As the main purpose of our Stereo-ATI spectrometer is to use it for CEP-tagging in strong-field experiments, only a small fraction (typically a few percent) of the laser intensity should be used for the CEP determination. Therefore we use Xenon as a target gas because of its low ionisation potential (12.17eV)

3.1.2 The Vacuum System

In our experimental frame , we need the ionisation of one atom at a time. For this pressures as low as 10^{-8} millibar is required. Hence the copper cell is placed in a vacuum chamber. The unique design of our spectrometer in combination with the small holes in the target tube allow for a high differential pressure gradient.
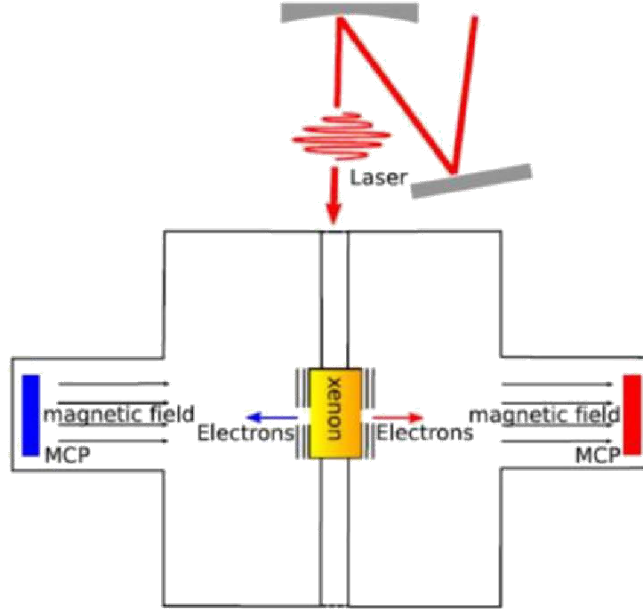
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Figure 3.2: Working principle of the stereo-ATI spectrometer. A Stainless steel cell is mounted on a tube. The cell can be flooded with xenon gas (yellow). Electrons are emitted after getting ionized by laser pulse and can escape to the left or right direction through two small holes. After a traveling through certain drift length (through a magnetic field) they are registered by the detectors.

We reached 10^{-3} mbar in the interaction region while the pressure in the CF cube stayed well below 10^{-6} mbar by using a single 75 l/s turbo molecular pump, thus, allowing a save operation of the MCP detectors.

3.1.3 Electron Detection

The stereoscopic measurement of the photoelectrons eject along both sides of the laser polarization axis is taken by the microchannel plate detectors. The MCP detectors detect the electrons and determine their time of flight. They are made of resistive plates that contain tiny channels, all parallel to one another, which are 10 to 100 micrometer in diameter. Voltage is applied between MCP –in and MCP –out so as to accelerate the electrons. These electrons collide with the walls creating secondary electrons which repeat the process. The final result is an electron avalanche which hits the anode of the detector to create a continuous voltage signal. The voltage signal for a given flight time is proportional to the amount of electrons hitting the detector at the same time.
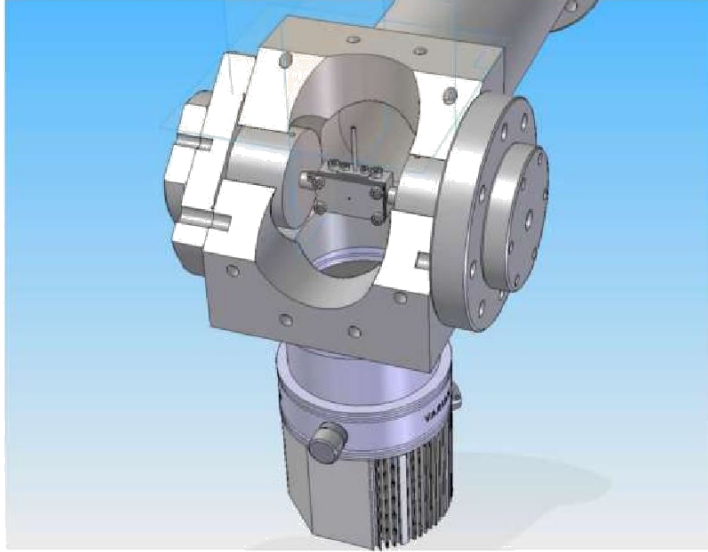
Figure 3.3: Cut through the stereo ATI spectrometer

In order to extract the electron kinetic energy from their time-of-flight, the absolute time zero has to be determined. The measured time signal t_{tof} is given by

$$t_{tof} = t_{MCO} + t_o$$

where t_{MCP} is the relative delay between the MCP signal and the laser trigger and t_0 is an unknown time offset. This offset can be determined by the magnetic field in the drift tubes. The time of flight spectrum exhibits contributions from high-energetic (fast) electrons around -130ns originating from the aforementioned re-collision process and low-energetic (slow) electrons around -120ns from direct ionisation events. Note that the electrons arrive earlier than the laser trigger as the latter undergoes a time delay caused by electronic shaping (converting the photo diode signal into a NIM pulse). For sufficient high magnetic fields, nearly all emitted electrons are guided onto cyclotron trajectories toward the detectors. By reducing the magnetic field strength however, more and more electrons will miss the relatively small MCP detectors leading to a characteristic wiggle-structure . As the positions of the emerging peaks are linear in time, we can plot the wiggle number versus the corresponding time-of-flight and perform a linear regression. By repeating this procedure for different (low) magnetic field strength we obtain straight lines with different slopes. The point in time where the lines cross each other is the unknown time offset t_0.
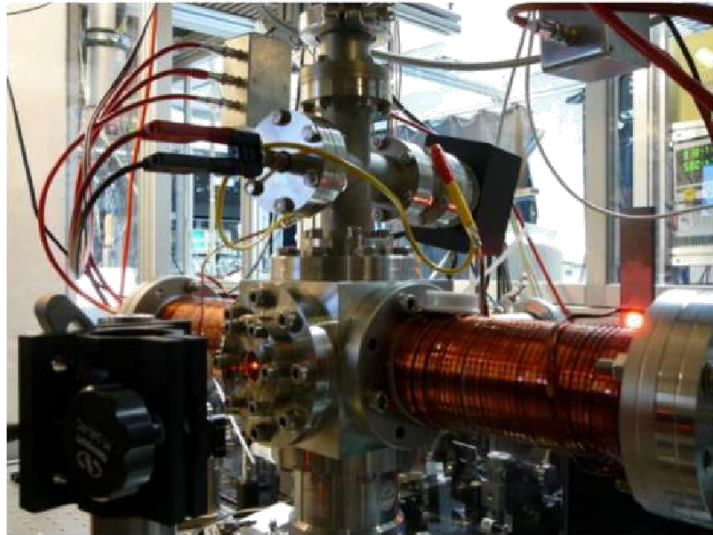
Figure 3.4: Picture of the assembled setup showing the vacuum chamber along with the drift tubes and the magnetic coils. The laser pulse is focussed into the chamber from the front side of this apparatus.

Chapter 4

Results and Discussion

ATI spectra consist of a low-energy ("direct") and a high-energy (plateau) part. The latter is due to recolliding electrons, whereas the former is created by electrons that leave the atom directly without a second encounter with the atom. Both parts of the spectrum depend on the absolute phase in a characteristic way. In Fig. 4.1 a series of measurements is shown for different laser intensities ranging from $0.04 PW/cm^2$ (a) to $1 PW/cm^2$(p). The laser intensity was estimated by the maximum kinetic energy of the electrons. As follows from classical considerations within the three-step model, an electron that is elastically scattered at the ion can gain an energy of up to 10 Up, where Up is the cycle-averaged quiver motion in the laser field and given by Up = $I/4\omega^2$, with laser intensity I and central frequency ω. For the measurements shown in Fig. 3 the CEP of the laser was actively stabilized. The oscillator was fast-loop frequency-comb stabilized while the amplified and compressed pulses were stabilized by a home-build f-2f interferometer in combination with a control loop that changed the amount of dispersion in the beam path to compensate small CEP drifts. From the figure it is evident that the asymmetry is prominent at strong intensities only. This is because the phase effects are well pronounced in strong fields only and ATI occurs in strong fields. Also, it is clear from the figure that as the intensity increases the asymmetry shifts to the higher energy regions as expected. This is because at higher intensities the ionized electrons will have more kinetic energy as a result of multiphoton ionisation. It is evident that the obtained results are very much in agreement with the available literature.

Figure 4.1: Photo electron spectra obtained for experimental test data.

Figure 4.2: Measured left/right asymmetries for different laser intensities as a function of the CEP.

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Chapter 5

Conclusion and Future Work

The ATI spectrometer determines the left-right distribution, according to the direction of pulse propagation, of photoelectrons that are ionised by a linearly polarised laser pulse. This left-right distribution is sensitive to the carrier envelope phase, which is the relative phase of the highest amplitude of the electric field with respect to the maximum of its envelope. A laser pulse is focused into a gas cell that is flooded with xenon gas and the photoelectrons, which are thereby emitted to the left and right side, are measured by two detectors. With these two detector signals, the carrier envelope phase can be determined. Our next aim will be to the come up with the necessary code to calculate the absolute phase from the photo electron spectra. During the construction period, emphasis was put on an easy adjustment and precise alignment of the different components of the spectrometer in order to make it as easy as possible to use as an auxiliary device during the experiments. In addition, the data acquisition software was developed and the high speed digitiser that was used to read the analogue detector signals had to be programmed. The fast data acquisition system as well as the high signal strength allow to measure the electron signals for every single laser pulse at a laser repetition rate of 3 kHz. In contrast to the previously reported ATI spectrometer, this new device is able to measure time resolved spectra and can hence determine the longitudinal momentum and the kinetic energies of photoelectrons. Having this ability, energy resolved phase asymmetries of photoelectrons emitted from xenon gas have been measured that showed clear energy dependent structures. Apart from using the spectrometer to recognise phase drifts, it has been confirmed that the stereo-ATI spectrometer has the ability to accurately measure the carrier envelope phase with a precision that is equal to or even higher than that obtained by the f-2f technique. It has therefore the potential

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to replace the f-2f interferometer. High harmonic generation or terahertz emission are just a few of those strong field phenomena that are directly related to the carrier envelope phase and where a precise knowledge about the phase is important. We could prove that the phase measurement with the stereo-ATI spectrometer works even in the limit of single pulses that were not phase controlled, although the single shot phase measurement suffered from a low signal-to-noise ratio. Once the problem of the bad signal-to-noise ratio is overcome, singe shot phase detection is possible which will allow to completely replace the rather complicated phase stabilisation that has been used so far. The left-right asymmetry of the emitted photoelectrons, as measured by the stereo-ATI spectrometer, increases for shorter pulses. Therefore, this device has also the ability to characterise the three most important properties of a few cycle laser pulse that is the carrier envelope phase, the pulse duration and the intensity, with the latter one being directly related to the high energy cutoff in the photoelectron spectra. Consequently, this apparatus can be utilised as a tool for optimising the laser system to yield short optical pulses and high intensities. An increase of the target density in order to increase the signal-to-noise ratio would be the largest improvement of the current setup. This then should allow to reliably perform single shot phase detection with a high resolution. In addition, a larger and more homogeneous magnetic field would improve the low energy time of flight spectrum. With the increased resolution, it might be interesting to look for quantum mechanical interference effects that have been predicted in the electron spectra and that were also confirmed in earlier experiments These interferences arise because of two different ionisation times that are close to each other and lead to the same final energy at the detector. A behaviour that is the temporal analogue of the conventional double slit experiment where the interferences are caused by two slits that are separated in space. In addition, it is worth using different gas species like neon or krypton to measure energy resolved phase dependent asymmetry spectra that might show differences to the one obtained for xenon in the present study.

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ANNEXURE:

1)Field vs Time

```matlab
clear all
%eqn for temporal
  envelope I=10;
  t_p=3.5; t=-
  120:.1:120;
  e_t= sqrt(I)*exp((-2*2.303*log(2) *((t.^2)/t_p^2))) %-
  ------------------------------------------------
 w=4
 phi=0
 phi_CEO=0
 E_cor=(sin(w*t+phi).*((sqrt(I)*exp((-2*2.303*log(2)
*((t.^2)/t_p^2))))/t_p^2)*2.*t*sqrt(I)*(-
2*2.303*log(2))/(t_p^2))/w E_t= e_t.*cos(w*t+phi_CEO)+E_cor
 E=e_t.*cos(w*t+phi_CEO)
plot(t,E,'r-')
hold on;
plot(t,E_t)
%_____
xlabel('time(fs)') % x-axis label
ylabel('E(t)') % y-axis label
legend('y = E','y = E + Ecor')
title('Electric field vs Time')
%blue line-with correlation
%red line-without correlation
```

2)Energy vs CEO phase

```matlab
clear all
 %constants
 I=10^13;
 w=10*10^12;
 t_p=6;
  m= 9.1*10^-31;
  e=1.6*10^-19;
  I_p=15.7596;
  %variables
  t=5;
```

```
  phi_CEO=0:(3.14/2):(4*3.14);
  e_t= sqrt(I)*exp((-2*2.303*log(2) *((t.^2)/t_p^2))); %---
 ---------------------------------------------------
 e_t= sqrt(I)*exp((-2*2.303*log(2)
 *((t.^2)/t_p^2))); E_t= e_t.*cos(w*t+phi_CEO);
 U= e^2*E_t.^2/(4*m*w^2)/(1.6*10e-
 19); KE=2*U.*(sin(w*t)).^2+I_p;
 I_p=15.7596;
 plot(phi_CEO,KE);

 %plot(phi_CEO,U)


 %_____
 xlabel('CEO phase') % x-axis label

 ylabel('Energy') % y-axis label

 title('Energy vs CEO phase')
```

3)Field vs Energy

```
clear all
 %constants
 I=10^13;
 I_p=15.7596;
 w=10*10^12;
 t_p=6;
  m=  9.1*10^-31;

  e=1.6*10^-19;

  phi_CEO=0;

  %variables  t=-
  120:.1:120;
  e_t= sqrt(I)*exp((-2*2.303*log(2) *((t.^2)/t_p^2))); %---
 ---------------------------------------------------
 e_t= sqrt(I)*exp((-2*2.303*log(2)
 *((t.^2)/t_p^2))); E_t= e_t.*cos(w*t+phi_CEO);
 U= e^2*E_t.^2/(4*m*w^2)/(1.6*10e-

 19); KE=2*U.*(sin(w*t)).^2+I_p;

 %%%%%%%%%%%%%%%%%%%%%%%%%%%%%
 %90 degree CEO

 Et= e_t.*cos(w*t+(3.14/2));
 u=e^2*E_t.^2/(4*m*w^2)/(1.6*10e-
 19); KE=2*u.*(sin(w*t)).^2+I_p;
 %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
 %plot
```

```matlab
plot(KE,E_t,'r-
'); hold on;
plot(KE,Et);
%_____
xlabel('Kinetic Energy') % x-axis
label ylabel('E(t)') % y-axis label
legend('y=CEO-0','y=CEO-90')
title('Electric field vs Time')
```