Atoms in strong laser fields

Laboratory Exercise
Light Matter Interaction
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1 Outline of this laboratory exercise

This laboratory exercise will give you an introduction to some selected strong-field phenomena. The term “strong-field” refers to the situation when a system, e.g., an atom or molecule, is exposed to the strong electromagnetic field of a high-power laser. This lab exercise will cover two processes, the above-threshold ionization and high-order harmonic generation of the fundamental laser field. The first process will be investigated experimentally while the second will be treated in the preparatory exercises.

The first part will be done in the “kilohertz laboratory” of the Lund high-power laser facility. You will ionize argon atoms with pulsed laser radiation at a central wavelength of 800 nm. Each pulse has a duration of 25 fs containing the energy up to 0.5 J. After ionization the energy distribution of the emitted electrons is detected with a velocity map imaging electron spectrometer.

2 Introduction

The field of research “atoms in strong laser fields”, born a few years after the invention of the laser in 1960, has evolved considerably during the last two decades owing to the rapid technological development of high-power short-pulse lasers. When a high-power laser is focused into a gas of atoms, the electromagnetic field becomes of the same magnitude as the Coulomb field, which binds a 1s electron in a Hydrogen atom ($5 \cdot 10^{11}$ Vm$^{-1}$). Three highly nonlinear phenomena, schematically pictured in Figure 1, can happen:

- Electrons initially in the ground state absorb a large number of photons, many more than the minimum number required for ionization, thus being ionized with a high kinetic energy. This process, shown for the first time in 1979, is called Above Threshold Ionization (ATI).

- Not only one, but two or more electrons can be emitted from an atom subject to strong laser fields (MI). They can be emitted one at a time, in a sequential process, or simultaneously, a mechanism called direct or non-sequential. Double ionization of alkaline earth atoms was observed as early as in 1975 and the first evidence for non-sequential ionization of rare gas atoms was first demonstrated in 1983.

- Finally, efficient photon emission in the extreme ultraviolet (XUV) range in form of high-order harmonics of the fundamental (linearly-polarized) laser field can occur (HHG), shown for the first time in 1987.

First the field of research remained rather small and exotic through the 1970’s and part of the 1980’s. The restrictions were experimental ones. Only a few well-funded research institutes could afford the expensive laser systems needed to create the required electromagnetic field strength. About thirty years ago, a new laser material, Ti:Sapphire, and a new amplification technique, chirped pulse amplification (CPA), made high-power lasers accessible to many university laboratories. This research has become one of the most exciting fields in atomic, molecular and optical (AMO) physics.

Figure 2 schematically depicts an experimental setup for studying atoms in strong laser fields. The most crucial element is the short-pulse laser. The laser
Figure 1: Phenomena taking place when an atom interacts with a strong laser field: (left) Above-Threshold Ionization. (center) Multiple Ionization (green indicates direct ionization, red sequential ionization). (right) High-Order Harmonic Generation.

Pulses used are often in the femtosecond range, the shortest are well below 10 fs. Focused intensities needed to get into the strong field regime are of the order of $10^{14} - 10^{15}$ W cm$^{-2}$. In the last couple of decades the Ti:Sapphire laser became the most favorite tool. It operates at 800 nm in the near-infrared and provides very short pulse duration with high laser intensity at a high repetition rate. A large part of the experimental activity is to make front-line lasers work, and it is no coincidence that many laboratories successful in this field of research also develop these laser systems and their diagnostics.

The second part of the experimental setup is a vacuum chamber where a gas of atoms (often rare gases) is introduced in a cell or pulsed jet. Ions and/or electrons are detected and analyzed using various techniques. In addition, the angular distribution of the photoelectrons can be recorded using imaging techniques. This has been particularly useful to unravel the mechanism responsible for non-sequential ionization. In high-order harmonic generation experiments, the gas density is much higher than in ionization experiments, up to a few hundreds mbar. The radiation emitted on axis can be detected and analysed using a standard XUV spectrometer.

The theoretical problem that describes the interaction of an atom with a laser field consists in solving the time-dependent Schrödinger equation (TDSE). During many years, theorists have concentrated their effort on solving the problem
of a hydrogen atom, or more generally, a single-active electron atom in a strong laser field. A number of methods have been proposed to solve this problem. Two of them stand out: the numerical solution of the TDSE and the semiclassical strong field approximation (SFA). Many insights in the physical understanding of the interaction between atoms and strong laser fields have been provided by a simple semi-classical model, called the “simple man’s theory”. This model gives an intuitive understanding of the processes of atoms in strong fields and is the basis for this laboratory exercise.

3 The simple man’s model

This simple semi-classical model gives an intuitive understanding of the processes when atoms are exposed to strong fields. In the simple man’s model the interaction between atom and laser field is divided into three steps. The first step describes the ionization: In presence of the relatively slowly-varying strong electric field\(^1\) the atomic potential gets strongly distorted as illustrated in Figure 3. When the external electric field is near its maximum, the total potential of the atom and the laser field forms a barrier through which the electron may ionize by tunneling. While tunneling is a purely quantum-mechanical process the following electron propagation in the continuum is described classically. It is accelerated by the oscillating electric field, gaining kinetic energy. The acceleration marks the second step. When the field changes sign, the electron may be accelerated back to the vicinity of the ion core where it can scatter off. This can happen either elastically, inelastically or it recombines and its energy is released in form of a photon (third step). Whether the electron is actually driven back to the ion core or not depends on the time of tunneling with respect to the phase of the driving laser field as shown in Figure 4. The graph shows electron trajectories (blue) for different tunneling times \(t_i\). Depending on \(t_i\) the electron can either be driven back to the position of its

\(^1\text{This is true for considerably long wavelengths like 800 nm.}\)
Figure 3: Tunneling ionization: The Coulomb potential gets distorted by a strong laser field opening the possibility for the electron to tunnel through the reduced potential barrier.

ion (black) or it moves away while wiggling in the electric field (red). As part of the simple man’s model it is assumed that the electron will be born at the position \( x(t_0) = 0 \) and with zero velocity \( v(t_0) = 0 \). Furthermore the Coulomb interaction between electron and ion is considered to be small and therefore neglected.

Figure 4: Electron trajectories in the oscillating laser field.

3.1 Above-threshold ionization

The second step of the classical model describes the evolution of the electron trajectory in the oscillating laser field. Figure 4 depicts that some of the electron trajectories. Assume the electron after tunneling is exposed to an linearly polarized electric field \( E(t) = E_0 \sin(\omega t) \), where \( \omega \) is the laser frequency and \( E_0 \) the amplitude. The force that the electron will experience originates from
the electric field $F(t) = -eE(t)$, where $e$ is the electron charge. The electron’s momentum is then given by

$$mv(t) = \frac{eE_0}{\omega} (\cos(\omega t) - \cos(\omega t_i)),$$

where $m$ is the electron mass. The momentum consists of a constant term that depends on the time of tunneling $t_i$ and therefore on the instantaneous electric field strength at the time of tunneling. This is the drift momentum $mv_D$ that will be measured at the detector. The second term oscillates in phase with the electric field and describes the wiggling motion of the electron, this is also visible in Figure 4.

We introduce the ponderomotive energy $U_P$, i.e. the average energy an electron can gain in an electric field. $U_P$ is given by

$$U_P = \frac{e^2 E_0^2}{4m\omega^2}.$$  \hspace{1cm} (2)

The maximum in drift energy $E_D$ that an electron can get through tunneling, without further interaction with the atomic potential is $2U_P$ for linearly polarized light while it is restricted to the value $U_P$ for circularly polarized light.

As mentioned in the introduction ATI describes the case where an atom absorbs more than the minimal number of photons needed to reach the ionization limit. The corresponding photoelectron spectrum shows a series of peaks separated by the photon energy. Figure 5 shows a typical ATI spectrum. The reason why the spectrum shows discrete photoelectron peaks and not a continuum of kinetic energies as suggested by (1) lies in the periodicity of this process in time. Because it is periodic in time it will also be periodic in energy. The period of the process is exactly the laser period $T$, this leads to a periodicity of $\hbar\omega$ in the

Figure 5: ATI-spectrum generated in Xe using a picosecond laser.
energy spectrum being exactly the photon energy of the laser.\(^2\)

Figure 6: ATI-spectrum generated in Xe using a femtosecond laser enabling to reach a higher laser intensity. The data were taken with an extremely good dynamical range.

The electron count rate depends on the probability for tunneling ionization at a given \(t_i\). This is a highly nonlinear function of the electric field strength \(E(t)\). If the wavelength is long compared to the dimension of the atom, the electric field can be approximated as quasi-static. The probability can be calculated using the expression for the dc tunneling rate:

\[
\Gamma(t) = 4\omega_0 \left(\frac{I_P}{E_h}\right)^{5/2} \frac{E_a}{E(t)} \exp\left[\frac{2}{3} \left(\frac{I_P}{E_a}\right)^{3/2} \frac{E_a}{E(t)}\right],
\]

where \(\omega_0 = 4.13 \cdot 10^{16}\) s\(^{-1}\) is the atomic frequency unit, \(E_h\) is ionization potential of hydrogen and \(I_P\) the ionization potential of the atom species in question. \(E_a = 5.14 \cdot 10^{11}\) V/m is the atomic unit of the electric field. Notice that the tunneling rate shows a strong maximum at times when the electric field reaches its maximum. The actual number of electrons tunneling at \(t_i\) has to be weighted according to \(\Gamma(t_i)\). As Figure 6 shows the probability drops fast for high electron energies.

As mentioned above, it is possible that the electron is driven back to the ion by the laser field. When the electron returns one of the following can happen:

- The electron scatters elastically. In this case it can acquire much higher drift energies up to \(10\, U_p\).
- The electron scatters inelastically. It may kick out an additionally electron (or more) leading to higher charged ions.
- The electron recombines with the ion emitting its energy in form of a photon. This process is called high-order harmonic generation (see next section).

\(^2\)The quantum mechanical description reproduces the experimental results in a more rigorous way.
3.2 High-order harmonic generation

When an intense laser field is focused to a high intensity in a gas, high-order harmonics of the driving field are generated, propagating collinearly with the laser field. Only odd multiples of the driving frequency can be seen in a typical harmonic spectrum (see Figure 7) where the intensity drops rapidly for the first few harmonics. This is what one would expect from a perturbative approach where the efficiency of the process rapidly decreases with order. What cannot be explained with this model is the far-reaching plateau, in which the harmonics have almost constant intensity, ending in an abrupt cut-off. High-order harmonics were first seen in 1987 and the harmonic plateau may extend up to very high orders (>200).

Figure 7: A typical harmonic spectrum calculated in argon using a laser peak intensity of $1.4 \cdot 10^{14}$ W/cm$^2$.

We now examine the prediction of the simple man’s model for harmonic generation (see Figure 8). An electron returning to the core can recombine and the energy that it has gained from the acceleration in the field is emitted as a photon. The kinetic energy gained by the electron in the field, and hence the emitted photon energy depend not only on the time of tunneling but also on the time of recombination. The maximum kinetic energy that the electron theoretically can gain from the laser field is $3.2 U_p$. The total maximum photon energy, or the cut-off energy, is then $I_p + 3.2 U_p$, where $I_p$ is the ionization potential of the atom.

In the semi-classical model, we consider what happens to a single electron accelerated along a certain trajectory by the electric field of the laser. Figure 9 depicts the different trajectories available for the electron under the premise that it might return to the core. In a quantum mechanical description, the single electron does not follow a single trajectory and instead we have to use a picture where the electron wave packet is distributed over the different trajectories. Figure 9b shows the return energy of the electron along with the excursion time, i.e., the time spent in the continuum, as a function of the time at which the electron tunnels through the Coulomb barrier. From this simple picture it is possible to explain the position of the cut-off, corresponding to the part of the electron wave packet returning with the maximum energy.

When the electron recombines with its parent ion, a short burst of light is
emitted. The properties of the emitted pulse are directly linked to those of the recolliding electron wave packet, making the temporal profile of the emitted light crucially dependent on the electron dynamics in the continuum. From figure 9b it can also be concluded that there are actually two different trajectories leading to each single return energy. The two trajectories are often denoted "short" and "long". The two trajectories differ in excursion time, i.e. they have different continuum dynamics, leading to a significant difference in the properties of the emitted light. (Under most experimental conditions, the short trajectory is favored by phase-matching conditions, making it completely dominate over the long trajectory.)

All possible photon energies up to the maximum energy have approximately equal probability, leading to the long plateau of peaks of almost equal amplitude. The reason why we get peaks at the harmonic frequencies and not just a broad continuum is because the process is also periodic in time, and hence in frequency. The period is actually $T/2$. Since the gas is isotropic there is no difference when the electric field is $-E$ or $+E$. This leads to the periodicity of $2\omega$ in the frequency domain or $(2\hbar\omega)$ in energy, and we only observe odd harmonics.

**Outlook** From this simple qualitative discussion we can conclude that for each half-cycle of the driving frequency a broad spectral continuum of light is emitted, corresponding in the temporal domain to a short pulse, with a pulse duration in the order of attoseconds ($\text{as} = 10^{-18}\text{s}$). As discussed above, we observe discrete peaks at the odd harmonic frequencies due to the fact that the process is periodic with a period of $T/2$. In the temporal domain this means that instead
of generating a single attosecond pulse, we obtain a train of attosecond pulses. Attosecond pulses, only available for less than ten years, opened a complete new field of research where electron dynamics are studied and manipulated on their natural time scale using attosecond pulses.

4 Experimental setup & technique

In this laboratory exercise we will study two phenomena in the same beamline, but with two different beams. One part of the laser beam will be used to investigate the strong field ionization, while the high-order harmonic generation will be processed with the other part of the beam.

4.1 Properties of light

One important tool to manipulate the ATI and HHG process is the control of the polarization. Therefore it can be useful to recall some properties of polarized light.

Polarization describes the orientation of the electric field vector when the electromagnetic wave is propagating in space. Consider a monochromatic plane wave traveling in z direction, then the electric field vector lies in the xy-plane. At this point it is sufficient to restrict our self to elliptically polarized laser field. The total electric field at a fixed value for z then can be written as

\[ E(t) = \frac{E_0}{\sqrt{1 + \alpha^2}} (e_x \sin(\omega t) + \alpha e_y \cos(\omega t)), \]

where \( \alpha \) varies between \(-1 \leq \alpha \leq 1\). At a fixed value of z the tip of the electric field vector \( E(t) \) describes a ellipse while rotating periodically in the xy-plane. For the special case of \( \alpha = 0 \) the ellipse collapses to a line. The light is said to be linearly polarized. While for \( \alpha = \pm 1 \) the ellipse becomes a circle. For \( \alpha = 1 \) it rotates counterclockwise and the light called right circularly polarized while for \( \alpha = -1 \) the light is left circularly polarized where the electric field vector rotates clockwise.

Another useful thing to keep in mind are the properties of Gaussian beams. A laser beam can be modeled with a Gaussian intensity distribution transverse to the direction of propagation. The intensity at a distance \( r \) from the center is expressed as

\[ I(r) = I_0 e^{-\frac{r^2}{w^2}} \]

where \( I_0 \) is the peak intensity and \( w \) is the radius of the beam, i.e. where the intensity has decreased to \( e^{-2} \) of the peak intensity. Gaussian beams are cylindrically symmetrical. A Gaussian beam that is focused keeps its Gaussian shape, and the following expression can be used to calculate the beam diameter at focus \( (d) \) from the beam diameter at the focusing lens \( (D) \)

\[ d = \frac{4\lambda f}{\pi D} \]

where \( \lambda \) is the laser wavelength and \( f \) is the focal length of the lens. This expression is valid when \( d \ll D \).
Another useful relationship is the one between intensity \( (I) \) and electric field amplitude \( (E) \), reading

\[
I = \frac{1}{2} \varepsilon_0 c |E|^2
\]

where \( \varepsilon_0 \) is the permittivity of free space and \( c \) the speed of light in vacuum.

### 4.2 The ionization experiment

Figure 12 shows a schematic of the setup used for the study of ionization in strong laser fields. An intense laser beam is focused into a gas jet of argon atoms with a lens having a focusing length of 75 cm. After ionization the electrons are detected with an electron spectrometer which records their momentum. An iris is inserted in the beam path to vary the light intensity.

The laser used in this part of the laboratory exercise is a Ti:Sapphire-based laser system with a repetition rate of 1 kHz. The system uses a technique called Chirped Pulse Amplification (CPA), resulting in a typical output 25 fs pulse length at 800 nm central wavelength and of 5 mJ pulse energy. The beam will only be a fraction of its maximum energy, about 1 mJ. Furthermore, the 15 mm diameter beam will be apertured down by an iris with variable diameter (with a diameter typically around 5-10 mm), so that only about 0.2-0.6 mJ of infrared energy is actually sent into the experimental setup. The beam is focused by a toroidal mirror of 30 cm focal length into the detector.

The electron spectrometer used is a so-called velocity map imaging spectrometer (VMIS). This kind of spectrometer allows imaging the momentum of charged particles. In our case we will use the VMIS to gain information about energy distribution of the released electrons. Figure 10 shows how the velocity of electrons can be imaged with a position sensitive detector. The focused laser beam is crossed with a gas jet to ionize the gas atoms resulting in a 3-dimensional distribution of outgoing electrons. The ionization takes place between two electrodes: the repeller and the extractor. On both electrodes potentials of the order of several kV are applied \((V_{\text{repeller}} < V_{\text{extractor}} < 0)\) resulting in a strong acceleration of the electrons towards the detector. The position, where the electron hits the detector, is related to its initial velocity and the point within the interaction volume the electron originates from. The initial velocity \( v \) can be divided into two components: a component \( v_\parallel \) parallel to the spectrometer axis and a component \( v_\perp \) transverse to it. Due to the acceleration the former 3-dimensional distribution will be squeezed along the spectrometer axis so that no direct information about \( v_\parallel \) can be obtained. The component \( v_\perp \) however is unchanged under the acceleration, so that the position \( R \) at which the electron hits the detector is directly related to its transverse velocity component as \( R = v_\perp t \), where \( t \) is the time-of-flight (TOF) to the detector. By choosing the ratio \( f = V_{\text{repeller}} / V_{\text{extractor}} \) between the repeller and extractor potentials properly it is possible to achieve velocity focusing, so that all electrons with the same initial velocity end up at the same position on the detector independent of their origin in the interaction volume. Thus, the resulting image on the detector is a 2D projection of the former 3D velocity distribution.

To obtain high quality images the interaction volume should be as small as possible. This is done by sending the gas jet through a skimmer blocking out
Figure 10: Schematic drawing of the VMIS: After ionization the electrons are accelerated in electrostatic potential between repeller and extractor towards a position sensitive detector. The position $R$ where the electron hit the detector is proportional to the transverse velocity components $v_\perp$ resulting in an image of the electron momentum.

everything but a central collimated gas beam. Additionally the gas jet is pulsed to keep the background pressure as low as possible. The detector assembly consists of a stack of MCPs (multi-channel plates) coupled to a phosphor screen. A CCD camera is then used to image the phosphor screen. The camera is connected to a computer to store and analyze the images.

Figure 11 shows a recorded image for a sphere of monoenergetic photoelectrons originating from ionization of helium by a XUV pulse with a central energy of 26 eV. The image shows a blurry ring with a sharp maximum radius $R_{\text{max}}$ corresponding to electrons emitted transversely to the spectrometer axis. When the 3D momentum distribution shows an axis of symmetry in the detector plane, it is mathematically possible to retrieve the 3D distribution from the 2D projection (inverse Abel transformation). Usually these inversions are done numerically. Figure 11 shows the result of such an inversion. One can see a 2D section through the 3D electron distribution retrieved by inverting the 2D projection. The VMIS allows us to record the angular distribution of the emitted electrons. We will not use this feature explicitly but when looking at the ATI signal, one can see that the distribution is highly peaked along the polarization axis of the light for linearly polarized light.
4.3 The harmonic generation experiment

The second part of the laboratory exercise consists of generating high-order harmonics by focusing the laser beam into a gas target. The setup is described by Figure 13. For this we use a copy of the beam used in the ionization experiment, with the same repetition rate, pulse duration and central wavelength (1 Hz, 25 fs, 800 nm), but with a higher power of about 2.5 mJ. The generated high harmonics, which spectrally fall in the XUV range, are directed into a flat-field XUV spectrometer. They are focused using a 30 cm focal length toroidal mirror, and this focus is imaged by a curved diffraction grating onto a photosensitive detector. The grating diffracts different wavelength in different angles and therefore spectrally resolve the radiation, while its variable-line-spacing makes it possible to create the spectral image on a flat surface. A position sensitive detector captures the final image of the spatially separated harmonics.

5 Preparatory exercises

Due to the limited time available in the laboratory, it is important that you have worked through and understood these exercises before the laboratory exercise. The intention of the exercises is to provide a good understanding of what we will study during the practical, and it should be possible to solve them using only the information provided in these instructions. If you have any questions or problems with the exercises, please feel free to contact the lab supervisors. Helene: helene.coudert@fysik.lth.se and Maite: maite.louisy@fysik.lth.se.
Figure 12: Setup ionization laboratory: An intense laser beam is focused into an atomic gas jet and the outgoing electrons are detected using a VMIS as an electron spectrometer.
Figure 13: Experimental setup for the generation and detection of high-order harmonics.
5.1 Laser intensity

Using the laser system data from section 4, estimate the laser peak intensity in the focus for the laser system in the kilohertz laboratory for the HHG experiment (see sec. 4.3). You can assume that the beam diameter before focusing is $D = 20 \text{ mm}$ and the pulse energy is 2 mJ. What is the intensity, the amplitude of the electric field in the focus and the ponderomotive energy?

5.2 Electron motion in a laser field

An atom is exposed to a linear polarized laser field $E(t) = E_0 \sin(\omega t)$ where $E_0$ is the field amplitude and $\omega$ the laser frequency. The electron tunnels through the Coulomb barrier and is released into the continuum with zero velocity at time $t = t_i$. Assume that the only force experienced by the electron is the force from the electric field $F(t) = -eE(t)$ where $e$ is the elementary charge and show that the position of the electron as a function of time $t \geq t_i$ is given by

$$x(t) = \frac{eE_0}{m\omega^2} [\sin(\omega t) - \sin(\omega t_i) - \omega (t - t_i) \cos(\omega t_i)], \quad (8)$$

where $m$ is the electron mass.

5.3 ATI energy distribution

If the electron is instead released in a laser field of arbitrary polarization, the experienced force is then proportional to the electric field

$$E(t) = \frac{E_0}{\sqrt{1 + \alpha^2}} (\cos(\omega t) \hat{e}_x + \alpha \sin(\omega t) \hat{e}_y), \quad (9)$$

where $\alpha$ gives the polarization state of the laser light; $\alpha = 0$ corresponds to a linear polarization and $\alpha = \pm 1$ to a circular polarization. Show that the electron’s drift energy $E_D$ differs between 0 and $2U_P$ for the case of linear polarization while it is strictly restricted to the value $U_P$ for circular polarization. (You can solve this problem analytical or numerical, as you wish.)

5.4 Return of the electron - HHG

Use equation 8 above to find the tunneling times ($t_i$) for which the electron is able to return to the ion core. Consider linear polarized light only. The easiest way to do this is to numerically look for zero-crossings of the function for a range of tunneling times. In appendix B you find a Matlab-function that looks for zero-crossings in a given vector. Note that it is only necessary to examine tunneling times in the range $0 \leq \omega t_i < \pi$ since the process is periodic with the frequency $2\omega$.

For the tunneling times for which it is possible for the electron to recombine with the ion core, i.e., the found tunneling times, calculate the return times and return energies for the electrons. The return time is simply the times $t = t_r$ for which (8) has a zero-crossing and the return energy is the kinetic energy of the electron at time $t_r$. Make a plot of the return energy and the return time as a function of tunneling time. This plot should look very similar to Figure 9b. Verify from the plot that the cut-off energy for harmonic generation is...
$I_P + 3.2 \, U_P$ ($I_P = 15.7$ eV of argon). Note that the classical approach that is used here is not strictly correct. For example we also have to include effects of the actual tunneling process to get the complete picture. Qualitatively however, the classical results are in good agreement with both more complete methods and with experiments.

Hint: If you express your time variables in $\omega t$ and the energy in $U_P$, you do not need to explicitly state the intensity and frequency of the field.
6 Tasks during the laboratory exercise

6.1 ATI experiment

6.1.1 Getting started

Make yourself familiar with the setup in the kilohertz laboratory used for the ATI laboratory:

- Laser system (Oscillator, compressor and stretcher for CPA and amplification stages)
- Beam path from compressor to electron spectrometer
- VMIS (general setup, applied potentials, synchronization between laser and pulsed valve, data acquisition)

6.1.2 Measurements of ATI in Argon

- Check the compressor alignment to minimise pulse dispersion: Generate white-light by focusing the laser in air. Adjust the compressor so that the white-light is as white (broadband) as possible.
- Use the spectral filter (DAZZLER) to correct for the dispersion induced by the air and optics between the compressor and the HHG/ionization setup.
- Beam path in the kHz lab, from the compressor to the HHG/ionization setup.
- Alignment of the laser beam to the setup. The beam alignment can be checked with cameras and irises, and adjusted with mirrors, if necessary. The alignment is prepared by the lab instructors.
- Start the VMIS (Apply the HV at the repeller and extractor, then carefully apply voltages on the MCP/Phosphor screen).
- Aperture the beam with a small iris and let it into the VMIS.
- Fix the Ar backing pressure for the gas jet pulsed valve to 4-5 bar. Slowly open the valve until you see a signal on the phosphor screen or with the CCD camera.
- Optimize the gas jet alignment using the VMIS in spatial mode.
- Take an image of the ATI signal. Describe what you can see on the image.
- Take several images for different intensities by varying the iris diameter. Measure the mean power to calculate the pulse energy for each diameter. Make sure the beam is blocked in the meantime. Does the angular distribution change for different intensities? If so, could you think of an explanation for this behavior?
- Plot the ATI maximum energy as a function of intensity. Does that fit the expected behavior?
• Why does the ATI signal drops so fast for high energy electrons?
• Place a quarter-wave plate in the beam to get circular polarized light. Take another image. How does the velocity distribution change compared to the linear case?

6.2 HHG experiment

6.2.1 Getting started

• The HHG setup, the focusing optics and the gas target.
• The XUV-Spectrometer and the MCP detector.
• Detection method and analysis software

Note that the radiation partially runs in vacuum - why? (lab report)

6.2.2 Spectral measurements in argon

• Turn on the piezo actuators with the voltage control unit for the pulsed gas cell. Make sure the high voltage supply is running.
• MCP detector. Check that the pressure in the spectrometer is below $10^{-5}$ mbar, and that the high voltage supplies for the detector are running.
• Check the pressure both in the generation chamber and the recombination chamber, and open the valve between them.
• Optimize the spectrum. You can adjust the gas pressure by changing the piezo voltage, or the IR intensity by opening or closing the iris. Lastly, the pulse energy can be changed by rotating the polarizer in front of the telescope. Record an image for the optimized spectrum. A calibration curve for calibrating the wavelength scale (lab report) will be provided.
• Measure a harmonic spectrum for four different laser pulse energies. Estimate the laser intensity for each case by determining the cut-off energy (lab report).
• Put a quarter-wave plate into the beam path to study the high-harmonic intensity dependence on the polarization of the fundamental laser field. Remember, prior to insertion of the plate into the setup, to block the laser beam. Why is that important? Record spectra for different polarizations. Plot the intensity of one selected harmonic as a function of polarization and discuss the results (lab report).
A Laser safety

The light from the laser used in this laboratory exercise is very intense and may cause severe eye damage if the laser beam or a reflected beam hit the eye. At all time during the laboratory exercise, safety goggles have to be used. Be very careful with the laser beam and follow the advice below.

Hold your head above the laser beam during the laboratory exercise. Never sit down or bend yourself down to pick up something while the laser is running (except for at the computer desk).

Take off watches and rings during the laboratory exercise, they might accidentally reflect the beam.

Never insert or remove optical components in the laser beam while the laser is running. After inserting an optical component, be sure you know where the reflexes from it is going before turning the laser on again.

You will be using sensitive and expensive research equipment, handle it with care.

B Useful Matlab-function

% Finds the position of zero-crossing in the vector y, % on the grid specified by the vector x % If no zero-crossing is found, NaN is returned function x0 = findzerocrossing(x,y)
x0 = NaN;
tmp = abs(diff(sign(y)));
ind = find(tmp==2 | (tmp==1 & circshift(tmp,[0 -1]) == 1));
if ~isempty(ind),
    ind = ind(1);
    x0 = x(ind) - y(ind) * (x(ind+1) - x(ind)) / (y(ind+1) - y(ind));
end