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Martin Teichmann

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Studies of Clusters Irradiated by High Intensity Lasers

by

Martin Teichmann

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Martin Teichmann

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Studies of Clusters Irradiated by High Intensity Lasers

Martin Teichmann, M.A.
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Supervisor: Todd Ditmire

This thesis discusses the effects of irradiating argon and hydrogen clusters with a high-intensity, ultra-short-pulse laser beam. It presents the most common theories about these effects and compares the theoretical predictions with the results from the experiment. We analyze the exploding clusters with a time-of-flight spectrometer; the resulting spectra are then fit to the theoretically predicted curve. Then we discuss the changes in those curves when we vary the cluster size or the laser’s polarization, pulsewidth or energy.
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Chapter 1

Introduction

Laboratory, table-top fusion greatly advanced physics. This only became a possibility with the advent of high intensity lasers in conjunction with new knowledge of clustering in gasjets. This new and exciting method led to many applications: from a cheap source for high-energy neutrons to the hope of getting a new source for energy in fusion power plants.

Comparing this to other techniques to achieve the same results shows the great advantage this technology has: for more than 50 years people have tried to build a fusion power plant using magnetic confinement techniques. But despite all true advances, the break-even point, the point where more energy is produced in the burning plasma than had to be put in, was never reached. Plasma machines that allow fusion are vast and require equally vast special laboratories. Costs of operating such machines can easily exceed one million dollars per year. Although the table-top fusion will never be used directly in a power plant, the possibility of studying the same effects in a normal laboratory are obvious.

The same holds true for creating high energy neutrons. This is usually done in nuclear power plants. With table-top fusion we can get neutrons that have the same energy without having to handle radioactive material and the disposal of them.
This technology can also be used even when not doing fusion. When clusters explode, high-energy electrons and ions are produced that would otherwise require large accelerators to create them using conventional methods.

To improve this technique we have to understand the basic physics that happens in the exploding clusters. In this work, I will show some of the major features of these explosions.

In our experiment, the clusters were created by expanding either argon or hydrogen gas in a vacuum. The gas was injected into the vacuum through a nozzle with a pulsed solenoid valve. The clusters were then irradiated by the University of Texas' THOR-laser. The exploding clusters were then analyzed with a time-of-flight spectrometer.

To begin, I will explain the theoretical background of this experiment. There has already been much work done in this field describing cluster explosion. The theories developed from that work lead to different results. This is mainly because they are applicable only in certain parameter ranges, which are often not known. Therefore we tried to find the right conditions to show the accuracy of some theories.

Later on, I will describe our experimental setup and discuss how the data we obtained can be analyzed. Lastly, I will show the results we obtained from this experiment and interpret it.
Chapter 2

Background

2.1 Why cluster explosions?

When it comes to fusion, most people, especially physicists, think of large experiments and national lab facilities. This is because we need atoms with an energy of the order of some keV to make it happen. Usually, those energies can only be reached in large accelerators. Other approaches require big plasma vessels or gigantic lasers.

But it turns out that clusters which are irradiated by high intensity lasers can explode into ions that are within the energy range that is needed to make fusion work. Until today, the processes going on in those clusters have not been understood well. Consequently we started to look at those explosions in detail.

2.2 Prior work

The explosion of clusters in high-intensity, short-pulse laser radiation has been intensely studied over the past years. The first comprehensive treatment of the cluster explosion process was done by Ditmire et. al. in 1995 [1]. It first shows the creation of electrons which have a greater amount of energy than would be expected if the
clusters were compared to gases of the same density. This made it clear that unique processes exist when clusters are involved.

The distribution of ion energies was measured with an experiment very similar to ours with xenon clusters. [18][20] They found xenon ions up to $1MeV$, and charge states up to $Xe^{40+}$. Similar results were found in argon, with charge states up to $Ar^{9+}$ [21].

A detailed analysis on scaling of the energy of ions with cluster size, laser intensity, and laser wavelength was done by Springate et. al. [22] By using a magnetic deflection time-of-flight spectrometer, Lezious et. al. [21] were able to select the charge states of the outgoing ions and were able to determine the distribution thereof.

Just a few years later, in 1999, Ditmire et. al. first report success in doing fusion with deuterium clusters irradiated by a high intensity femtosecond laser [2][23]. This work largely inspired our experiment, since our whole project was once started to optimize the fusion done in this experiment.

Detailed analysis on the neutron yield were done by Madison et. al. [24] Last and Jorter suggested in a theoretical work to use compounds of deuterium for improving the fusion yield [25][26]. This was realized using $CD_4$ by G. Grillon et. al. in 2002 [27].

Over the years, the interest in this topic became more widespread. When the DESY in Hamburg opened its new X-ray free electron laser in the Tesla Test Facility, the very first experiment to be done was to irradiate xenon clusters with this new apparatus [19]. They found the behaviour of xenon clusters to be surprisingly different from xenon gas, as they only found $Xe^+$-ions when shooting into gas, while they found charge states up to $Xe^{8+}$ for clusters.

Several groups have now started to study those cluster explosions. Important to this work is the first observation of an anisotropy in the explosion by V. Kumarap-
pan et. al [3]. They explain this result with a dependence of the surface charge of the cluster on the polarization of the laser. They also postulated that this effect is different for high energy and low energy ions [12], something which is treated here in a much more detailed manner. A more sophisticated treatment of this anisotropy was done by Breizman and Arefiev [4]. They proposed that the clusters have two shells of different ionization states that can move with respect to each other. Our interpretation of the data is based on this work which we will describe later in detail.

The process of heating in irradiated clusters can not only be theoretically described but also be tested in a pump-and-probe experiment. This was first done by E. Springate et. al.[5]

Modern cluster physics would not be possible without the help of the older generations. The knowledge about how to create clusters in gasjet, and much work in classifying the kind of clusters produced, was pioneered by O. F. Hagena [6].
Chapter 3

Theory

In this chapter I will introduce the theoretical background of the various physical phenomena involved. I will begin with the core part of this work: the explosion of clusters. After a general overview of all the concepts, I will start looking at the details of calculating the models. Finally, I will discuss the creation of the clusters in the gasjet.

3.1 Cluster explosions

There are various models about laser-irradiated clusters, but they apply to different ranges of the parameters.

The simplest one is the model of a Coulomb explosion. It happens at high intensities and small cluster sizes. Currently, it is the best understood model. A Coulombic explosion happens if the laser has such a high intensity that it can strip the cluster of all its electrons, and has such a fast rise time that this happens without the ions being able to move before they leave the cluster. The Coulomb force between the leftover ions makes the cluster explode.

At the other end of the parameter range are big clusters and low intensities.
Above a certain intensity, all the atoms in the cluster get ionized. This represents a non-confined nanoplasma, which are known to expand rapidly.

The range between those two extremes is the most interesting one. If medium sized clusters are hit by a medium intensity pulse, some of the electrons are stripped off the cluster while other atoms are only ionized, with the electrons remaining in the cluster. In this situation, many things can happen. Recent theoretical studies have shown that those remaining electrons can form a cold ion core in the cluster that will move with the laser’s electric field. The result is a dependency of the electron- and ion energies from the polarity of the laser, whereas the two other models are both isotropic.

The intermediate range is the range when the clusters just don’t get stripped of all the electrons anymore. This range can be estimated with a simple model: the cluster gets stripped of ions because the pondermotive potential of the laser is higher than the binding energy of the electron. The pondermotive potential is the potential used to describe the effect of lasers onto electrons. It is [28]

$$\Phi_{\text{pond}} = \frac{e}{4m_e \omega^2} E^2$$

with $E$ the electric field of the laser. The intermediate range starts where the binding potential is equal to this. The electron binding potential is

$$\Phi = \frac{R^2 \rho}{3\varepsilon_0}$$

with $R$ the cluster radius and $\rho$ the charge density. For a cluster of size $10nm$ and our laser wavelength of $800nm$ leads to a laser intensity of $1.5 \times 10^{15}$

### 3.2 The Coulomb explosion in detail

The Coulomb explosion model is simple enough to be presented here and it is also important later for understanding the time-of-flight spectra. We found that most of
our data fits nicely to the curves predicted by this theory. This is not surprising, as an attentive reader will realize, most of this theory does not depend on the physical details of the Coulomb model but does apply for any theory, as long as the cluster explodes in a self-similar way. Nevertheless, the parameters in our function which connect the shape of the curves to the physically relevant quantities depend on the theory's detail. That is something we should keep in mind when trying to extract those quantities from our measured data.

The model starts with a cluster that is totally stripped of electrons. This cluster is now treated classically as a constant charge distribution with a constant charge density \( \rho \). From Maxwell's Equations we get (in cylindrical coordinates with \( r \) the distance from the center of the cluster)

\[
\varepsilon_0 \int \varepsilon dA = \frac{4}{3} \pi r^3 \rho
\]

This gives us the electrical field \( \varepsilon \) at a radius \( r \).

\[
\varepsilon = \frac{r \rho}{3 \varepsilon_0}
\]

Integrating that gives us the electrical potential \( \Phi \) inside the cluster:

\[
\Phi = \int \varepsilon \, dr + C = \frac{r^2 \rho}{6 \varepsilon_0} + C
\]

Outside the cluster this potential is simply the potential given by Coulomb's law,

\[
\Phi = -\frac{R^3 \rho}{3 \varepsilon_0 r}
\]

with \( R \) the radius of the cluster. Thus we can find the integration constant \( C \) by making the function continuous, from which in turn we can calculate the potential energy \( E \) of the ions by the radius to be

\[
E = \frac{(3R^2 - r^2) e \rho}{6 \varepsilon_0}
\]
This means the outermost ions have a potential energy of

\[ E = \frac{R^2 e \rho}{3 \varepsilon_0} \]  

(3.8)

Only those ions lose all of their potential energy in the explosion. The inner ions still see the potential of the surrounding ions. Because of that, this formula cannot be extended to all ions. However, since the electrical field inside a charged sphere is zero, the outer ions do not affect the inner ions. This is why we treat the inner ions as a smaller cluster, thereby letting us know that the ion energy depending on their initial radius is

\[ E(r) = \frac{r^2 e \rho}{3 \varepsilon_0} \]  

(3.9)

The charge density \( \rho \) is the only unknown left, and for hydrogen we can simply replace it with the particle density \( n \) via \( \rho = e n \), since hydrogen can only have a charge state of 1. This is different for other gases, because they can have higher charge states. In this case, we would have to set \( \rho = \bar{q} e n \) with \( \bar{q} \) the average charge state. To simplify the calculation, I am only looking at hydrogen, the reader may insert the charge state into the rest of the calculation for any other gas.

When we look at a spectrum, we look at the distribution of the energies. Obviously there are different numbers of ions for the different energies. On a shell of thickness \( dr \), we have \( 4\pi r^2 n dr \) ions with the same energy. Certainly only as long as \( r < R \) with \( R \) the radius of the cluster. This means that for an energy range from \( E \) to \( E + dE \) we have, in combination with \( r^2 = 3\varepsilon_0 E/e \rho \)

\[ f(E)dE = 4\pi \frac{3\varepsilon_0}{e^2} E \frac{dr}{dE} dE \propto \sqrt{E}dE \]  

(3.10)

ions.

Again, the distribution is 0 for \( E \) higher than the maximum ion energy, which is reached for the outermost ions. An interesting result from that is that the distribution of energies is not a function of cluster size. The only dependency that
is found is that bigger clusters have ions of higher energy. The number of ions in a
cluster is \( N = \frac{4}{3} \pi \left( \frac{3\varepsilon_0 E}{e^2 n} \right)^{3/2} n =: CE^{3/2} \) (3.11)
with introducing the variable \( C = \frac{4}{3} \pi \left( \frac{3\varepsilon_0}{e^2 n} \right)^{3/2} n^{1/2} \) for convenience. Solving this
equation for \( E \) would give us a function for the maximum ion energy, but in this
calculation we only need this version.

The calculation so far has only considered a single cluster. But the sizes
of the clusters is a distribution of several sizes. The distribution is known to be a

\[
f(N)dN = \frac{1}{\sigma \sqrt{2 \pi N}} \exp - \frac{(\ln N - \mu)^2}{2\sigma^2} dN
\] (3.12)

This is a gaussian distribution where we exchanged the variable with its
logarithm. The parameters \( \mu \) and \( \sigma \) of the log-normal-distribution are not directly
the average and standard deviation, as for the normal distribution. Instead the
average number of atoms per cluster is \( \bar{N} = e^{\mu + \sigma^2} \)

In terms of the maximum energy of a cluster this is

\[
f(E)dE = \frac{1}{\sqrt{2\pi CE^{3/2}}} \exp - \frac{(\ln CE^{3/2} - \mu)^2}{2\sigma^2} dN dE
\] (3.13)

\[
= \frac{3}{2\sqrt{2\pi \sigma E}} \exp - \frac{(\ln E^{3/2} - \mu)^2}{2\sigma^2} dE
\] (3.14)

To find the energy distribution for all cluster sizes, we only have to integrate
over the curves for a single cluster multiplied with the number of those clusters.
Here it comes in handy that the distribution for different sizes differs only in the
maximum energy. Therefore we need to change only the limit of the integral to get
our result:

\[
f(E)dE = \frac{3}{2} C \sqrt{E} dE \int_E^{\infty} \frac{1}{E'} \exp - \frac{(\ln CE'^{3/2} - \mu)^2}{2\sigma^2} dE' \] (3.15)
The resulting curve looks like a square root at its beginning, because all the clusters contribute to the low energy part in the same way. If we had only one size of clusters, this would end in a sharp edge, but since we have a distribution of cluster sizes, this edge smoothes. This is shown in figure 3.1. All curves look the same, the only difference is that they a cutoff at some energy which corresponds to the energy of the outermost atoms. With many clusters this smoothes as shown in the red curve, which is the $\sqrt{E}$-dependency multiplied with $1 + \text{erf}(-E)$.

![Figure 3.1: The energy distribution of all clusters](image)

This integral cannot be solved analytically, but it can be done using the error-function, which leads to $f(E)dE = \frac{27}{8}C\sqrt{E}(1 + \text{erf}\left(\frac{\ln E^{1/2} - \mu}{\sigma}\right))$. In our experiment we don’t measure the energy directly, but instead we measure the time it takes an ion to travel a certain distance $l$. Therefore it is more interesting for us to know this formula.
in terms of this traveled time rather than the energy. The kinetic energy an ion has if it traveled a distance \(l\) in the time \(t\) is \(E = \frac{1}{2} m \frac{l^2}{t^2}\). Plugging this in, not forgetting the differentials, gives

\[
f(t)dt = \frac{27}{16} C \frac{1}{\sqrt{2\pi}} m^{3/2} l^3 \frac{1}{t^4} (1 + \text{erf} \left( \frac{\ln C (1/2 m l^2)^{3/2} t^{-3} - \mu}{\sigma} \right)) dt,
\]

or, with the constant \(C\) plugged in:

\[
f(t)dt = \frac{9}{4} \pi (3\varepsilon_0 m)^{3/2} \frac{1}{\sqrt{2\pi n}} (el)^3 \frac{1}{t^4} (1 + \text{erf} \left( \frac{\mu + 3 \ln t - \ln 2\pi n (3\omega m l^2)^{3/2}}{\sqrt{2\pi}} \right)) dt \quad (3.16)
\]

Figure 3.2: The distribution of times as seen in the experiment

This function has two important characteristics: as the erf-function is nearly constant and equal to 1 if its parameter is big enough, it does not contribute to the function anymore, which means for higher energies the \(1/t^4\) term dominates. This is not surprising, the later times correspond to lower energies, therefore the small
clusters contribute to this function as much as the big ones.

For earlier times, the $1 + \text{erf} \ t$-function dominates, as it approaches 0 at $t = 0$. This leads to a function as shown in figure 3.2.

### 3.3 Exploding Nanoplasmas

For larger clusters or lower laser intensities the pulse cannot strip the cluster completely off electrons. This situation is a lot more complicated to calculate.

As a first approximation to the problem, we can treat the clusters in the jet as a gas. The effects happening when a high-intensity laser pulse hits a gas are well-known. First tunnel ionization occurs: the electric field from the laser is strong enough to distort the potential well that the electron is in, and the electron can tunnel free. Together with the resulting ions they form a plasma. The electrons can absorb more photons than actually needed for the atom to ionize, and thus we get some high energy electrons. This process is known as “Above Threshold Ionization”. Measurements by Glover et. al. [16] showed that this results in electron energies around 50 eV for a laser intensity of $2 \times 10^{17} \frac{W}{cm^2}$, which is the same range as our measurements.

All this certainly happens in clusters as well, because all those effects are single-atoms effects. After the atoms have been ionized, more important processes occur. Because the density in a cluster, which is at the order of solid material, is a lot higher than in gases, collisions play a bigger role. Once we have the free electrons just mentioned, higher charge states are produced by collisional ionization.

When the cluster is ionized, the laser pulse heats the cluster as the free electrons follow the electric field. The energy deposited into the cluster can be calculated by treating the cloud of electrons in the cluster as a harmonic oscillator. For low frequencies the energy transfer is low, increasing for higher frequency and reaching a maximum when the laser field and the electron motion are in resonance.
For even higher frequencies the energy transfer drops rapidly, as the electrons can’t follow the electric field anymore, or, as it is usually described in plasma physics, the wave can’t enter the cluster anymore [14].

The typical frequency for this process is the plasma frequency $\omega_p = \sqrt{4\pi e^2 n_e/m_e}$ with $n_e$ the electron density. Since we can’t change the frequency of the laser, but the density does change, it is more convenient to write this formula in terms of a critical density $n_{\text{crit}} = m_e\omega^2/4\pi e^2$. For a uniform sphere it turns out that the resonance condition is fulfilled for $n_e/n_{\text{crit}} = 3$ [1].

But what causes the cluster to explode? The ionized cluster is nothing else than a freely expanding plasma. From plasma physics it is known that those expand with the plasma sound speed [17]

$$c_s = \sqrt{Z T_{\text{electron}}/m_{\text{ion}}}$$

(3.17)

with $Z$ the ion charge state, $T_{\text{electron}}$ the electron temperature and $m_{\text{ion}}$ the mass of an ion. Another reason for the cluster to explode was just described in detail in the last section: some electrons leave the cluster and thus build up a charge in the cluster. The Coulomb force will then make the ions repel each other, therefore making the cluster explode.

### 3.4 The intermediate range

All the cluster explosion theories so far implicitly contain the assumption that the cluster explodes homogeneously. There are new theories which try to explain possible inhomogeneities in the exploding cluster.

The basic idea is the following: when a laser pulse is strong enough to strip the cluster of some electrons, but not completely, the remaining electrons will certainly end up in the center of the cluster, as then their potential energy will be minimal. This means that in the center of the cluster a core of rather cold electrons
To be more precise, this core will not be in the center but displaced into the direction of the electric field, to the border of the cluster. This cold electron core will follow the field while the laser oscillates. Admittedly, we should mention that this treatment requires the electrons to have a fairly high mean free path, otherwise collisions will make this effect disappear.

The results of this treatment depend on the total ionization of the cluster that the laser could achieve, see figure 3.3. In the case that the ionization was fast but incomplete, we call this the Coulombic limit. Along the oscillation of the cold core we have a lower average charge state over time. This leads to lower ion energy in the direction to the field. The sides of the cluster on the other hand are completely ionized and thus explode Coulombically. Therefore, the ion energy in the direction of the field will be lower than the energy of the ions emitted perpendicular to it.

In the hydrodynamic limit the cluster ionization is negligible and the exact opposite happens: the electrons from the oscillating core gain energy from the laser, that they will transfer to the ions by collisions. This heating occurs in the direction of the polarization, giving the ions in this direction a higher energy than the ions that leave the cluster perpendicular to the electric field.
3.5 Clustering in gasjets

When a gas expands through a nozzle into vacuum, it instantly cools down according to the ideal gas law. The heat energy that the gas had previously converts into directed kinetic energy. The cooling causes the gas to condensate.

This process depends on the initial pressure $p$ of the gas, the initial temperature $T$ and the geometry of the nozzle as well as the kind of gas used. We are using two kinds of nozzles: the sonic nozzle and the supersonic nozzle. The sonic nozzle is nothing more than a orifice.

The supersonic nozzle is conically shaped, see our specific model in figure 4.1. It directs the random velocity of the gas molecules to the axis of the nozzle. This way the total speed of the gas increases. The final velocity of the gas can be higher than the sound speed of the gas, which gives the nozzle its name. At the same time the density of the gas in the jet is higher, which increases condensation. It turns out that a supersonic nozzle is equivalent to a sonic one with a smaller diameter regarding the size of clusters generated in the jet. This diameter is $d_{eq} = d / \tan \alpha$, where $d$ is the diameter of the supersonic nozzle and $2\alpha$ is the cone angle [8].

Previous experiments done by Hagena et. al. [6] have shown that the onset of clustering can be described by one empirical parameter, the “Hagena parameter” $\Gamma^\ast$. It is defined to be

$$\Gamma^\ast = \frac{\kappa d^{0.85}p}{T^{2.59}}$$

(3.18)

with $\kappa$ a constant specific for the used gas (1650 for Argon, 184 for Hydrogen)[7], $d$ the diameter of the nozzle, or the equivalent sonic nozzle in case of a supersonic one.
Chapter 4

The Experimental Setup

In our experiment we create clusters, irradiate them with a laser and then analyze the exploded ions with a time-of-flight spectrometer.

The clusters are produced with a gasjet. The gas to be studied is shot with a valve through a nozzle into a vacuum chamber, see figure 4.2. As the gas expands into the vacuum it condensates to clusters.

A General Valve Corporation series 99 solenoid driven pulsed gas valve is used to let the gas into the chamber, see figure 4.1. We have two kinds of nozzles: a sonic nozzle and a supersonic nozzle. The latter is a conically shaped aluminum nozzle with a throat diameter of 750\(\mu m\) and a opening diameter of 5\(mm\) with a length of 12.7\(mm\). This kind of nozzle is known to improve the formation of clusters tremendously, as described in the section about the cluster size. The sonic nozzle is a hole in an aluminum plate that is screwed onto the gas valve. The supersonic nozzle can then be screwed onto that sonic nozzle, if desired.

We can also cool the gasjet, because the condensation point of some gases, in our case hydrogen, is too low to produce clusters at room temperature. To do that the valve is surrounded by a jacket through which we can pump liquid nitrogen. A thermocouple gauge is attached to that jacket for having control over
the temperature of the gasjet.

In order to form a collimated beam the clusters have to pass through a skimmer into another part of the vacuum chamber. Both parts are independently pumped by turbo molecular pumps, thus we can sustain a relevant difference in pressure in both parts. This is necessary as we need a considerably low pressure in the time-of-flight part of the chamber in order to have a long enough mean free path of the generated ions such that they hit the detector without colliding with gas atoms. This also limits the repetition rate that we can achieve. In the case of argon the pumps need about 3s to pump down the injected gas, while in the case of hydrogen this can exceed 15s.

After having travelled into the center of the time-of-flight part of the chamber, the clusters get hit by a laser beam coming from the side. This beam is focused onto the gasjet with a 20.5cm lens with a diameter of 4.2cm. It is an aspheric lens made out of an axial gradient index glass to reduce spherical aberrations.
It is essential to our experiment to know the spot size of the laser, as this gives us the maximum intensity of the laser. A first hint is the diffraction-limited beam size. The $f^\#$ is 4.9 and as the beam waist is known to be $w_0 = f^\# \lambda$ [15] with a laser wavelength of 800 nm we get a minimal beam waist of 3.9 $\mu m$. This underestimates the real spot size, as it calculates with a perfect lens. Later we will show a technique to determine the maximum intensity directly.

The beam leaves the vacuum chamber through a window. Behind that window are a photodiode and a power meter to detect the time at which the pulse hits the target and to measure the pulse energy of the laser.

The actual spectrometer is a 1.14 m long vacuum tube with a micro-channel-plate detector at the end. Some of the ions fly down this tube and hit the detector. The clear aperture of the mcp is 18 mm. This means it covers about 1/16000 of the sphere around the focal spot. From the time it takes the ions from the focal spot to the detector we can determine the energy of the ions. Therefore the detector is
connected to an oscilloscope to get the time of arrival of the ions.

We are using the Texas High-Intensity Optical Research laser THOR. It is worth mentioning some details about this laser to understand our experiment. The THOR laser is based on the concept of chirped-pulse amplification. The initially low-intensity short pulses from a commercial femtosecond laser are stretched in time by shining the beam onto a grating that diffracts the beam in space by the frequencies it contains. By giving the different colors different pathlength the pulse gets stretched in time. This even lower intensity beam now gets amplified with usual lasing materials until we reach a pulse energy of about 1 J. This pulse is sent onto another grating, which again separates the colors in space, and by having the pathlengths exactly the other way around we can recompress the beam, theoretically to the same time as it had in the seed laser, but with the amplified energy. We typically used the laser with a pulse energy of around 30 mJ, which leads to a maximum intensity in the focus of $10^{17} \text{ W cm}^{-2}$.

### 4.1 The Several Possible Experiments

Our setup is very flexible in the way that many parameters can be changed in a wide range. In order to get results that can be interpreted, we have to keep constant all the parameters while varying one. This results in several parameter scans that we can do.

#### 4.1.1 Pressure scan

By changing the backing pressure of the gasjet we can change the average size of the clusters. As mentioned above the size of the clusters depending on the backing pressure is well-known.

Nevertheless, it is still interesting to know the cluster size in a more direct way. This is why we always scanned the backing pressure of the gasjet.
4.1.2 Polarization scan

Both the coulombic and the hydrodynamic model for cluster explosion are widely accepted in the scientific community. The theory for the intermediate range, however, has yet to be proven. The most evident difference between the conventional models and our new model is the anisotropy that our model predicts. This makes the polarization scan particularly interesting: a dependence of the ion energy on the laser polarization would prove the conventional models to be inappropriate and suggest that our new model is true.

The polarization is changed with a waveplate that we put in front of the lens that focuses the beam onto the gasjet.

Our $\lambda/2$-waveplate has a clear aperture of $2.2cm$, thus the diffraction-limited beam waist gets bigger, to some $7.5\mu m$.

4.1.3 Energy scan

Depending on the total energy, and thus its intensity, that hits a cluster, it can behave in many different ways. From the lowest energies, where only some atoms are ionized, to a cluster completely stripped off electrons, everything can happen and can be seen in the TOF-spectra. But as the focus of the laser has no uniform intensity but has a gaussian shape, many of the effects can happen at the same time making the analysis of the data a harder job.

The laser energy scan is directly bound to the pressure scan, as there is found that small clusters irradiated by low intensities behave about as big clusters hit by high intensities.

4.1.4 Pulsewidth scan

The Coulomb explosion model expects the cluster to be ionized instantaneously. This approximation is valid if the ionization happens on a smaller timescale than
the cluster explosion. If the ionization time is too long, the cluster starts already expanding before it is completely stripped. This means that we have a different particle density at the point the cluster is finally completely stripped. This in turn will lead to lower energy ions coming from the cluster.

The ionization rate for the tunnel ionization strongly depends on the strength of the electric field. This gives us the opportunity to vary the time it takes to ionize the cluster. During the raising edge of the laser pulse there is a time in which the intensity is just high enough for the tunnel ionization to just start. This time is usually short enough that the cluster can not explode. But we can change this by varying the pulsewidth of the laser. A longer pulsewidth should lead to less energetic ions.

This effect was first observed when doing fusion in deuterium [13]. The neutron yield resulting from the fusion was strongly dependend on the pulse duration. This was explained using the reasoning above. We try to show that this theory actually is correct.

The design of the Thor-Laser gives the possibility to change its pulsewidth in a wide range, starting from 30 fs up to some ps. With very short pulslength we can prove the theory whereas the electrons gain energy by the alternating field with every cycle. With very short pulses this effect must be directly visible.

But this scan also leads to a bigger problem: as we change the pulsewidth, the same energy per pulse gets stretched over a longer time, lowering the maximum intensity. We can eliminate this effect by changing the laser energy accordingly.

The change of the pulsewidth is done by changing the distances from the compressor grating to the mirrors, int the way that we get wrong pathlength differences in the compression of the beam, which leads to longer pulsewidth. We then measure the width of the pulse with a second-order autocorrelator. In a frequency-doubling crystal the pulse gets overlapped with itself but entering the crystal in a
different angle. As the frequency doubling is an effect quadratic in the intensities of the laser, we only get doubled light where the pulses overlap. From the width of this area we can determine the pulsewidth.

Unfortunately we have dispersion in the optical elements: especially the lens on our vacuum chamber that focusses the beam onto the cluster jet causes dispersion which finally makes the pulses get longer. This makes the data from the autocorrelator unreliable, as it measures the pulsewidth at the output of the laser, not in our chamber. Fortunately we can compensate for that by purposely misaligning the compression grating in a way that we get the shortest pulsewidth not at the output of the laser but inside our chamber. This seems to make the measuring of the pulsewidth by autocorrelation being pointless, as the autocorrelator is placed at the end of the laser. Therefore we put some glass slides into the beam between the laser and the autocorrelator to simulate the effect of the lens.

Admittedly, this method is not really convincing; one might argue that we may have forgotten other places in our system where the pulse could get stretched, for example on our mirrors, or even in air. It is obviously necessary to have a method to measure the pulsewidth in the chamber itself.

A solution to this problem was found in the ionization of gases by high intense lasers. This has been subject to a lot of experimental studies [9]. It was found that the amount of ions generated by the laser is strongly dependent on the intensity of the laser. When the laser hits an atom, its electric field distorts the potential well in which the electrons of the atom are. If the laser electric field is strong enough, the electron can tunnel free. The tunnel probability increases with increasing laser intensities. Once the electric field is such high that the electron can escape without tunneling, the ionization saturates. This results in a knee in the curve of number of ions vs. laser intensity. The critical laser intensity is [9]

\[ I_{\text{crit}} = \frac{E^4}{16Z^2} \]  

\[ (4.1) \]
with $E$ the ionization potential of the charge state $Z$.

Therefore, we simply fill the chamber with low-pressure helium and shoot the laser into it. There are grids installed in our chamber just around the laser spot that we can put a voltage on. By putting a voltage of $10\, kV$ onto those grids we accelerate the ions generated by the laser onto the micro-channel-plate. On the oscilloscope we can then see two peaks, resulting from the $He^+$ and $He^{2+}$-ions. When we vary the intensity of the laser, at the same time the peaks grow and shrink, just as it was found by the other workgroups. We then plot the peak height dependent on the laser energy and get the same curves as known before. This results in the graph of figure 4.3. We can see the knee and such know the laser intensity at this point. Using formula 4.1 leads to a threshold intensity of $10^{16}\, W/\, cm^2$. This way we can calibrate the photodiode to know the laser intensity at the focal spot. The intensity on this graph was therefore written afterwards: the scale was not known at first, only because we saw this knee we had a scale.

### 4.1.5 Pump-probe experiments

The plasma frequency is one of the most important quantities in plasma physics. Besides being one of the quantities easiest to be determined, it tells much about parameters like density of the plasma. Fortunately we already have all the tools needed to measure it: a laser and a detector. We simply split the laser pulse into two pulses and retard one of them, then the first pulse makes the plasma explode and the second one can be used to study the plasma. This technique is called pump-probe-experiment.

When an electromagnetic wave travels through a plasma, the electrons follow this wave. This way energy is transferred from the wave to the electrons in the plasma, the plasma is heated. As already described in the theory section, this heating is increased with the frequency, until the plasma frequency is reached at
Figure 4.3: The helium gas ionization data. Each datapoint represents one laser shot. The $\text{He}^{2+}$-yield depends on the laser energy and rolls over at a certain point, which the electrons resonate with the incident wave and energy transfer reaches a maximum. The standard technique to determine this frequency is to vary the laser frequency until the absorption, i.e. energy transfer to the plasma, hits a maximum. In our case it is even easier: we can directly see the heating of the plasma, as we can measure the energy of the resulting ions.

On the other hand it seems much harder to do this experiment, as we can’t change the frequency of our laser. But this disadvantage disappears when we recall that our clusters are expanding. As the plasma frequency depends on the density of particles, it changes with time. This means we only have to wait long enough until we are in resonance with the electrons, or, in other words we scan the time delay between the two pulses and look for a maximum in the heating of the cluster, i.e.
for cluster explosions with higher energy ions.

This means that we can study the time evolution of the explosion. This way we unfortunately only get one datapoint: the time at which the cluster reaches the size at which the electrons are in resonance with the laser. But there is one way to retrieve another point: with a frequency doubling crystal we can double the frequency of our laser and therefore test the explosion at a different time.

But this is not only a method to determine the plasma frequency, it can also be used constructively: as the cluster gets additionally heated, the ions have a higher energy. This means that we can use this pump-probe experiment to get even higher energy ions. This immediately leads to the question: can we not hit the cluster again to heat it even more? Well, yes, but we can hit the plasma frequency only once, as it changes. Although, if we put in the doubling crystal, even that is not true anymore. This reasoning lead to a three-shot experiment: a first pulse causes the cluster to explode, and two successive pulses of two different frequencies additionally heat the cluster and create even higher energy ions.

In order to perform this experiment, we added new optics, see figure 4.4. The core part of those optics is the frequency doubling crystal. We chose a 5cm diameter KDP crystal which should give a doubling efficiency of more than 50%. The beam is then split by a dichroic beamsplitter into a blue (400 nm) and red (800 nm) part. The red beam now passes through a normal beamsplitter and is sent onto two movable mirrors to get two pulses that can be shifted in time.

The blue beam passes through a fixed delay leg to compensate for the distance the other pulses have to travel, and then enters the chamber. As the lens on the chamber is not an achromatic lens, the blue beam does not get focused onto the gasjet. Therefore we have to telescope it to perfectly hit the gasjet again.
4.2 Data analysis

Unfortunately the time-of-flight spectrum does not directly give the physical quantities of interest. Therefore the spectrum needs to be interpreted.

A typical spectrum consists of three parts: the photon peak, the electron peaks and the ion distribution. Figure 4.5 shows the very beginning of such a spectrum, containing the photon and electron peaks. The photon peak comes first: it results from scattered laser light that hits the detector. It can be used to find the zero time when the laser hit the clusters, as the speed of light is constant and well-known. In the graph shown we simply set the beginning of the peak to 4\text{ns}, which is the time the light needs to travel down the tube. Another way to find the zero point is to look at the oscilloscope trace of the photodiode that is placed at the exit side of the chamber. It gives a big peak when the laser pulse arrives. Nevertheless, it makes sense to look at the photon peak too, in order to not get fooled by different cable length to the oscilloscope.

Figure 4.4: The optics added for the two color experiments
Figure 4.5: The photon and the electron peak. To show that the right peak indeed is the electron peak we repeated the same measurement, with the only difference that we had a 4.6\textit{kV} retarding potential in front of the detector in order to repel the electrons. The result is the fine red curve.

The Electrons reach the detector after some tens of \textit{ns}. This corresponds to electrons with an energy of about 4\textit{keV}. The electron peak is much bigger in argon than in hydrogen, simply because argon has many more electrons.

The left graph of figure 4.6 shows the arrival of the ions. This starts at around a microsecond after the laser has hit the clusters. The trace that we get on the oscilloscope is the distribution of times that the ions need to travel down the tube. Note that you can still see the photon and electron peak at the very left.

A single shot gives not enough information to interpret it alone. Therefore, we average over multiple shots. Especially in argon a single shot shows nearly no structure, as illustrated in the upper left graph of figure 4.7.
Figure 4.6: A typical ion spectrum for argon, dependent on time, and a spectrum of ion energies for both argon and hydrogen. In the left trace the peaks are counted and binned into 50ns bins.

We have used two different ways of combining several shots: The argon data turned out to show the separate ions arriving at the detector as separate peaks, as shown in the upper right graph of figure 4.7. The data analysis program takes all the shots and determines the position of all the peaks. It then creates bins for every time interval of typically 50ns and counts how many peaks fall in every interval. The result is the left graph of figure 4.6. Another method of analyzing the data is not to create time intervals, but intervals of energies. In order to do that the program calculates the energies the ions had for every peak it found and then again counts the peaks that fall in each interval. This results in the right graph of figure 4.6.

This is not as easy for the hydrogen: that data looked by far less uniform. We got some shots where we see the same peaks as in argon, but for many shots the signal is that big that we cannot see the different peaks anymore, as illustrated in the two lower graphs of figure 4.6. This gets even worse if you consider the fact that hydrogen is much lighter than argon and such travels a lot faster at the same energy. On the Oscilloscope this makes the whole curve much narrower. Therefore, for the hydrogen data we simply averaged the oscilloscope signal over the various
shots. We also average over a time window of 50\,ns, to smoothen the curve. In the same way as for the argon data we can instead choose an energy window and such generate the right plot of figure 4.6.

This only makes sense if every peak from an ion has the same area. This is unfortunately not the case. Therefore, we looked at the distribution of peak sizes and found them to be distributed equally over the full range of peak sizes. This means that the effect of different peak sizes is not important when averaging over many shots.

![Figure 4.7: Raw data from the oscilloscope for argon (top) and hydrogen (bottom). The left data is an overview, the right data a zoom into the same data.](image)

Another important information is the overall shape of the curve. For high intensities and small clusters the spectrum clearly has the shape expected for a
Coulomb explosion.

This kind of curve is definitely a curve of artificial quantities. The time a ions flies has obviously no physical relevance, but instead we want to know its energy. Therefore we didn’t only break down the data in time bins, as mentioned above, but also in energy bins. Those make it easier to understand the meaning of the curve.

The last task to be done is to extract the actual physical quantities out of the measured curves. This can be done in two different ways: one is to simply get the values with statistical methods. Such we can determine the average energy of the ions by summing the current at the micro-channel-plate multiplied with the ion energy that corresponds to the arrived ion, dividing by the total number of ions obviously gives us the average ion energy. We can also determine the maximum energy by looking at the cutoff of the curve on the left side. The area under the curve tells us about how many ions have reached the detector.

The other way of analyzing the data is to create a theoretical model and fit it to the curve. In our case we are using the function that was developed in the previous chapter for the Coulombic explosion case. For fitting the function we are using the program gnuplot, which uses the Marquardt-Levenberg algorithm to fit the function. As the function we use \( f(t) = a(1 + \text{erf}(b(\ln t + c)))t^{-4} \) This is the same as before, only the constants have been replaced by ones that have no intrinsic physical meaning but can be fit more sane. The original physical parameters can be easily calculated from the ones used here. Most interesting at this point is the average number of atoms per cluster, which is related to the parameters \( b \) and \( c \) as

\[
\bar{N} = \frac{4}{3} \pi n \left( \frac{3 \varepsilon_0 m l^2}{2 e^2 n} \right)^{3/2} e^{3c+\frac{2}{3b}}
\]  

(4.2)

with \( n \) the particle density, \( m \) the mass of an ion, and \( l \) the length of the tube to the detector. As the particle density we took the density of liquid argon or hydrogen, which is 1420 kg/m^3 for argon and 70 kg/m^3 for hydrogen.
4.3 The cluster size

To enable us to interpret the data theoretically, we need to know the size of the clusters. Unfortunately this is not simple. We were following three different ways to determine the cluster size.

The first one is the pure theoretical approach: we use the Hagen parameter mentioned in the theory section. It helps a lot when comparing the clustering between hydrogen and argon. For the same value of $\Gamma^*$ we should get the same size of clusters. The difference in $\Gamma^*$ for the different gases relies on the factor $\kappa$. An interesting exercise is to calculate the temperature of the gasjet that results in the same value of $\Gamma^*$. The result is that we have to cool the gasjet to 112 K to get the same value for hydrogen as for argon at room temperature. As we are cooling with liquid nitrogen (boiling point 76 K) we can reach this range.

There is an empirical formula developed by Hagen to get the cluster size from $\Gamma^*$: $N = 33(\Gamma^*/1000)^{2.35}$[8]. Unfortunately this formula was only tested for $\Gamma^* < 5000$, and we are sometimes far off this range. But still this approach gives a first hint for the cluster size.

The simplest way to determine the cluster size is to look at our own data: as shown above, the earliest arriving ions come from the outermost shell of the cluster, thus telling us about the size of the cluster. But this works only if the clusters are Coulomb exploding, for the other exploding scheme we have to find something new.

The third way to measure the cluster size is to do a Rayleigh-scattering experiment. Rayleigh-scattering is used to describe what happens when light hits a particle that is small compared to the wavelength of the light. The particle is treated as an electric dipole with a dipole moment $p$. The laser electric field $E$ causes a separation of charge until the electric field of the displaced charge $Q$ and the laser field cancel. This happens if $E = Q/\varepsilon_0 A$ with $A$ the cross-section of the particle. The displacement of the charge is the cluster diameter $d$. This leads to a
dipole moment of \( p = Qd \approx \varepsilon_0 AD E \approx \varepsilon_0 V E \).

This can be seen as an antenna. If it oscillates with frequency \( \omega \), it irradiates the power \( P = \omega^4 p^2 / 6\pi\varepsilon_0 c^3 = \omega^4 \varepsilon_0 V^2 E^2 / 6\pi c^3 \). This energy comes from the incident beam. It has an intensity of \( I = c\varepsilon_0 E^2 \). From this we can calculate the scattering cross-section to be [14]

\[
\sigma = \frac{P}{I} \approx \frac{\omega^4 V^2}{6\pi c^4} \quad (4.3)
\]

To perform this Rayleigh-scattering experiment we guided the beam of a continuos wave Argon-Ion laser onto our gasjet and measured the scattered light with a CCD-camera.
Chapter 5

Results

In this chapter I present the results of the experiments we did.

5.1 The Polarization Scan

The polarization scan is the most interesting scan as it can be used to show the correctness of our theories. The theory about the intermediate range does not result in different shape of spectra. Therefore we cannot prove our theories using one spectrum. But as the ion energy in our model depends on the energy, a polarization scan can clarify the effects happening.

A short note about the notation: in this chapter the polarization angle $\theta$ always denotes the polarization in the direction of the detector, while an angle of 90 means perpendicular to the detector. The polarization can be turned out of the direction of the detector by rotate it to the left or to the right. This should make no difference in physics, as it should only depend on the angle between detector and polarization. Nevertheless, we measured both directions, denoting the rotation to the right with positive numbers while using negative numbers for the rotation to the left. The resulting curves should always be symmetric around the polarization.
angle 0. This is a good way to test the validity of our results.

5.1.1 Argon

For argon we did a detailed scan with many polarities at different pressures. It showed that the cluster explosion is non-isotropic for a range of cluster sizes, but isotropic for others, at least to the precision we could measure it. The strongest dependency was found for a gasjet pressure of 286psi and a laser energy of 30mJ. The polarization dependency completely vanishes when doubling the pressure to 610psi. Interestingly, this is the data that fits best to the log-normal distribution of Coulombic explosion, although we expect the cluster sizes to be bigger at higher pressures and so the expansion should be hydrodynamic.

![Figure 5.1: The mean ion energy as a function of the polarization angle. This was done at a backing pressure of 286psi and a laser pulse energy of 30mJ.](image)
Figure 5.2: The mean ion energy as a function of the polarization angle. This was done at a backing pressure of 610 psi and a laser pulse energy of 30 mJ.

The anisotropy can be seen in a lot of parameters. From the physical standpoint the most important one is the change in the average energy of the ions. We calculated that by averaging over the ion energy of every ion peak we found in the data. Figure 5.1 shows that the ion energies for a backing pressure of 285 psi are about 30% higher in the direction of the polarization than perpendicular to it. This vanishes in figure 5.2: the data shows only some random behaviour, that does not depend on the polarization.

Another way of looking at the data was to fit the functions mentioned in the data analysis section to the curves. For both argon and hydrogen it turns out that the theory does not perfectly fit the curve. There seem to be some interesting things happening, as we do have functions that fit the curve. In the argon case we
have to shift the $1/t^4$-dependency mentioned in the last chapter to the left by some microseconds. In this case the curves fit perfectly. This first seems to lead to the fact that the clusters actually explode earlier and we just see the ions coming in later. But this can’t be true, as we do see the photons and the electrons at the right place, and some microseconds are by far too much to be explained by the time the signal takes to travel in the cables.

Another idea arose while looking at the data for hydrogen. They are completely different: instead of being shifted to the left, the low energy part of the curve is always too high for a $1/t^4$-dependency. This gave us the idea that there could be a second peak of the curve at a later time which is smaller than the first one but still big enough to give the curve a new shape. The fits in figure 5.7 show that this is the case. This idea got manifested when we found that this second peak seems to depend on the polarization. Fueled by this success we started to look for the same effect in the argon data. And indeed, this two peaks perfectly fit to the curve, see figure 5.3. The crosses are the original data, averaged over 200 shots and binned in 50$\text{ns}$ bins. The curves that goes through the data is the two-peaks-fit. For clarification those two peaks are plotted below the curve, their sum is the curve that fits the data. We can clearly see how the right peak grows larger in comparison to the left one as we change the polarization to orthogonal to the detector. As the fitting function we are using the sum of two of the functions that we got from the Coulomb explosion theory, only with different parameters which we independently fit to the function.

The parameters of this fit show a nice polarization dependency. The parameter $a$ (see the definition of the function on page 31), which represents the height of the curve, behaves exactly oppositional when the polarization is changed, as seen in figure 5.4 Red is the left peak, green the right peak. One can clearly see that the total weight of the curve moves from one peak to the other when the polarization...
Figure 5.3: The TOF-traces from three different polarizations tested in argon.
is changed. The high energy peak is higher for the polarization in the direction of the detector than perpendicular, while the low energy peak behaves the other way around. This means that the high energy ions rather fly along the polarization, while the low energy ions travel perpendicular to the electric field. This is the reason for the shift in the average energy mentioned earlier. The higher energy peak has an average energy of 35keV, while the lower energy peak is around 7keV only.

![Graph](image)

Figure 5.4: The dependence of the height of the two peaks the total signal consists of on the polarization angle

There were doubts if this is an actual effect or if the two peaks come from flaws in our current setup. Therefore we compared our data with the data from previous experiments done at the Lawrence Livermore National Labs with their JanUSP Laser. The goal of those experiments was different, there was actual fusion done. Also the data was not taken with a micro-channel-plate but with a simple
faraday cup, which is simplified a piece of metal that collects ions and whose data is plot on the oscilloscope besides other data. The result, shown in figure 5.5, was promising: in the JanUSP data we also see the same two peaks as we see in our data.

![Graph](image)

Figure 5.5: A shot from the experiment at the JanUSP laser in green with the two peaks fit to the curve, and the total curve. As a comparison in the back is data from our experiment. The pulse energy was 100mJ.

A look at the electrons in figure 5.6 is also interesting: they also show a dependency on the polarization. This is less surprising, as it is the electric field which directly accelerates the electrons. It is still worthwhile to look at the electrons, especially because we found out, that there are two distinct electron peaks in the argon data. One comes at 28ns, which corresponds to an energy of 4.7keV, the other one at 31ns or 3.8keV. The electron peaks are astonishingly peaked: they
have a width of one point only. This first leads to the assumption that they could be noise only, but as they are in all polarization data (only in varying intensities), we can expect them to be real.

Prior experiments have found for xenon clusters\cite{10}, that there are two electron peaks, that have a bigger difference in energy and the property that one of them changes with polarization, while the other does not change. In our experiment one peak strongly depends on the polarization, the other a lot weaker. But it still depends on the polarization. There is a big technical difference in the two experiments: while we get the electron energies by looking at the TOF-trace only, Shao et. al. are using a retardation grid to repell low energy electrons. As we also have such a retardation grid, future experiments should again try to verify those results.

5.1.2 Hydrogen

We repeated the same measurement with hydrogen. Here we have only three different polarization angles (horizontal, vertical and something in between). As already mentioned, we see the same effect of two peaks which are fittable into the curves as in argon. In the third graph of figure 5.7 the second peak even gets so big that we can see it in the overall shape of the curve. This was initially the reason to look for a two-peak distribution.

For hydrogen the mean energy of the right peak seams to increase from $380\text{eV}$ to $785\text{eV}$ when the polarization is changed from parallel to the detector to perpendicular, while the left peak varies around $3\text{keV}$.

5.2 The Pulsewidth Scan

We have done two different kinds of pulsewidth scans: one with constant energy, the other with constant intensity. For the one with constant energy we found that there are two results changing: first we get more ions the longer the pulse is, but
Figure 5.6: The electron peaks at the beginning of the spectrum. This is averaged data over 200 datapoints from the polarization scan in argon. Below that is the dependency of the peaks with polarization.
Figure 5.7: The same data as in figure 5.3 in argon now in hydrogen. This are the only polarizations taken, averaged over 500 shots.
those ions have slightly smaller energy. This gets stronger if you look at the two sub-peaks as they were postulated in the polarization section. There you can see a clear drop of the average energy of the ions, see figure 5.8.

This conforms to the predictions we made in the theory section: as the pulsewidth increases the cluster already has time to expand before it gets completely ionized, which makes the final energy drop.

It would have been interesting to see the same results for even longer pulsewidths. Unfortunately, the current setup for our autocorrelator did not allow us to measure longer pulsewidths. It is up to future experiments to fill in this gap.

![Graph showing the average ion energy vs pulsewidth](image)

**Figure 5.8:** The average energy of the high energy peak in hydrogen

The other pulsewidth scan was done with constant intensity. To determine the intensity we did a helium ionization scan as described in the last chapter before
every data run. The pulsewidth was changed in a broader range: from 50\(fs\) to 800\(fs\). This was only possible by having a pulse on the autocorrelator that is broader than the camera that was used to measure it. This makes the pulsewidth quite unreliable; one should only understand them as an estimation. Due to the tedious work of having to test both the pulsewidth and the intensity we were not able to take more than three datapoints. This sadly makes it questionable to see any trends in the data. Again the average ion energy of the left peak in the distribution drops with increasing pulsewidth, as it can be seen in figure 5.9

![Figure 5.9: The average ion energy as a function of the pulsewidth with constant intensity](image)

In addition to that the data shows some other interesting feature: the second peak that we discussed deeply already seems to strongly depend on the pulsewidth, as it can be seen in figure 5.10. For the shortest pulsewidth we see two really
pronounced peaks, which vanish for longer pulsewidths.
Figure 5.10: The mcp data for different pulsewidths
Chapter 6

Conclusion

This thesis describes studies about explosions of clusters irradiated by a high-intensity ultra short pulse laser.

We present three models about those explosions. For high laser intensities and short raise times the cluster gets stripped of all its electrons and explodes because of the Coulomb forces. This is the Coulomb explosion model. For low intensities only the atoms in the cluster get ionized, but the whole cluster stays quasi-neutral. The cluster forms a nanoplasma that expands hydrodynamically, this is the hydrodynamic explosion model.

For the intermediate range we present a new model. In the partially ionized cluster a cold electron core forms that oscillates with the laser. This is the only model that can explain the anisotropy that we see in the experiment.

We found that the cluster explosions for both argon and hydrogen clusters is dependent on the polarization of the laser, in agreement with the new model for the intermediate range. For higher cluster sizes this effect vanishes, which can also be expected with the theory.

On the other hand we found the time-of-flight traces of the explosion to consist of two peaks added on top of each other. The polarization dependency just
mentioned turns out to affect the two peaks in the opposite way, as if the change in polarization would shift some electron from higher to lower energies. This effect can’t be explained by any of the proposed theories yet. The height of the peak is also dependent on the pulsewidth. For higher pulsewidths the second peaks seems to disappear. We compared our data taken in Austin with the data taken at the Lawrence Livermore National Labs, and found them to show the same features as far as the data is comparable.

We could not do all the experiments possible: an energy scan done in the future will show if the transition between the different cluster explosion theory actually exists. A pump and probe experiment will enable us to study the cluster explosions in time. In this experiment we will have one pump pulse which lets the clusters explode and one or two following probe pulses of the same wavelength or the second harmonic. Those pulses will additionally heat the clusters, which we hope to see in our data. From the amount of additional heating dependent on the time difference of the pulses we hope to be able to see the time evolution of the explosion.
Bibliography


The role of laser pulse duration in Coulomb explosions of deuterium cluster targets, submitted to Phys. Rev. A.


Vita

Martin Teichmann was born in Lahn-Gießen, Germany, on April 7th, 1978 the son of Gerhild and Günther Teichmann. After receiving the Abitur in 1997 from the Liebigscule Gießen, Germany, he entered the Universität Karlsruhe (TH), Karlsruhe, Germany. In summer 1999 he received the Vordiplom degree in computer science. In the same year he switched to the Bayrische Julius-Maximilians-Universität Würzburg. In summer 2001 he received the Vordiplom degree in physics. After one year of graduate studies in Würzburg, he entered the Graduate School of the University of Texas at Austin in Fall 2002.

Permanent Address: Baumgarten 25
35394 Gießen
Germany

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