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Time-resolved extreme ultraviolet spectroscopy of a z-pinch plasma

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Abstract

The goal of this work is to investigate and understand a continuum in the Extreme Ultraviolet in a hydrogen plasma, that has been reported by Mills and investigated in a similar setup by van Gessel. In addition, the goal is to expand these results to obtain the dependence on time of this continuum.

The radiation source is a pulsed plasma source. This source is a hollow cathode discharge externally triggered with an electron gun to have good control over the discharge. Gases used are helium, hydrogen and a mix of the two. The discharge itself lasts for about 1.4 μs, the voltage is usually set to -9 kV. The light from this source is analysed with a grazing incidence EUV spectrometer and is detected with a Channel Electron Multiplier (CEM). The time-dependent CEM signal was stored on an oscilloscope and averaged typically 20 times. The results are either shown in a time-resolved way or time-integrated.

A continuum is observed in hydrogen and a mix of hydrogen and helium. Pure helium shows a weaker continuum at approximately the same wavelengths. This continuum in pure hydrogen has a sharp edge at the low wavelength end, around 23.7 nm and extends to 28-29 nm at the high wavelength end. The continuum is also visible in the time-resolved signal of the CEM during the discharge, although the difference between continuum and not-continuum is significant, but not large. On the time dependence of the continuum, it can only be said that it is produced during the discharge. The spectrum of the helium-hydrogen mixture can be approximated very well by averaging the spectra of the helium and hydrogen discharges.
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Chapter 1

Introduction

In the past several years, the American scientist Randell Mills has published results of experiments which have attracted interest and stirred up controversy[1, 2, 3]. These results are as of today not conclusively explained. This focus of this work is to reproduce and possibly explain one of these results: the observation of a continuum at 22 nanometer in hydrogen discharges. The same continuum has been studied before by Bram van Gessel (results pictured in figure 1.1) using a setup similar to the one used in this work.[4] In comparison with his work, the goal is to give a time-resolved picture of this continuum.

Mills’s theory boils down to the following: he proposes that there are energy levels of hydrogen with energies below the ground state. He names thes states ‘hydrinos’. Mills tries to prove the existence of these theoretical particles by several experiments, including the one we are aiming to reproduce independently, where he uses the continuum at 22 nanometer to argue for the existence of hydrinos. Other claims he makes are the production of excess energy in calorimetric experiments, extreme broadening of hydrogen lines in glow discharges and nuclear magnetic resonance experiments showing evidence of hydrinos. Of these claims, only the extreme broadening and the continuum in the EUV of
hydrogen have been independently observed.

The goal of the research was to reproduce the results by Van Gessel, to expand this into a time-resolved picture of the continuum and in general to get a better understanding of it. The extreme ultraviolet spectrum of helium, hydrogen and a mixture of those two gases is investigated. Visual spectra of the same gases are also made.

Chapter 2 contains the theoretical background needed. Chapter 3 contains information about the experimental setup, mostly focusing on the plasma source and detection system. The experimental results are given and discussed in chapter 4. Chapter 5 consists of conclusions.
Chapter 2

Theory

To understand the emission spectra obtained during this project, this chapter will say something about the possible ways that radiation can be emitted by an atom or a molecule. It will also explain the physics of the plasma source and the spectrometer.

2.1 Energy states and radiation

2.1.1 Hydrogen-like atom

The hydrogen atom consists of one proton and one electron. The energy states of this atom can be given in approximation (it does not include the fine structure) by the famous Bohr formula:

\[ E_n = -\frac{m}{2\hbar^2} \left( \frac{e^2}{4\pi\varepsilon_0} \right)^2 \frac{1}{n^2} = -\frac{13.6 \text{ eV}}{n^2}. \]  

(2.1)

in which \( n \) is the principal quantum number, which can only have integer values. At \( n = 1 \) the atom is said to be in the ground state, at an energy of 13.6 eV. Higher values of \( n \) are the excited states, with higher energies. An electron in an excited state can fall back spontaneously to the ground state or a lower excited state. In this case a photon is emitted with a wavelength of

\[ \frac{1}{\lambda} = R_\infty Z^2 \left( \frac{1}{n_1^2} - \frac{1}{n_2^2} \right), \]

(2.2)

where \( n_1 \) and \( n_2 \) are the principal quantum numbers of the final and initial states, respectively. \( R_\infty = 1.0974\cdot10^7 \text{m}^{-1} \) is the Rydberg constant, \( Z \) the atomic number (1 in the case of hydrogen, the formula is also valid for hydrogen-like ions).

2.1.1.1 Hydrogen atom

The formula describes a series of emission lines characteristic for hydrogen. For \( n_1 = 1 \), this series is called the Lyman series, which lies roughly between 122
and 91 nm. For \( n_1 = 2 \) it gives the Balmer series, with wavelengths in the visible area. Further series also exist, with increasingly longer wavelengths. At the same time, they get increasingly fainter. The binding energy for hydrogen is 13.5 eV, so that it is impossible for atomic radiation of hydrogen to be below approximately 91 nm, the end of the Lyman series.

2.1.1.2 Helium atom

The Rydberg formula, equation 2.2, only applies to helium in the case of ionized helium. So the \( \text{He}^+ \) ion has a Lyman-like series of emission lines at a one fourth of the wavelength, and the Lyman \( \alpha \)-like line of \( \text{He}^+ \) for example is at 30.4 nm. This is right in the EUV region we are measuring.

Neutral atomic helium is a three body system. This is more difficult to solve than the two body hydrogen atom and an exact quantum mechanic description of the helium atom is not possible.

2.1.2 Molecular hydrogen

A diatomic molecule (such as hydrogen) can be represented as two point masses connected by a spring. The motion of this molecule can be broken down into the translational, rotational and vibrational states. The translational energy is simply the kinetic energy of the molecule. Because angular momentum \( L \) is quantized according to \( L^2 = l(l+1)\hbar^2 \), with \( l \) an non-negative integer and \( \hbar \) the reduced Planck constant, the rotational energy levels are \( E_{\text{rot}} = \frac{l(l+1)\hbar^2}{2\mu r_0^2} \), with \( \mu \) the reduced mass and \( r_0 \) the average separation between the atoms.

The vibrational energy levels can be approximated by a quantum harmonic oscillator, so that \( E_{\text{vib}} = \left(n + \frac{1}{2}\right)\hbar\omega \), with \( n \) a non-negative integer and \( \omega \) the angular frequency of the vibration. The approximation breaks down for higher values of \( n \).

The spacing between vibrational energy levels is about 100 times greater than that of a typical transition between rotational energy levels.

In practice, hydrogen is used in the form of deuterium in deuterium arc lamps for continuous spectra in the ultraviolet region. These lamps produce light down to approximately 100 nm.[5, 6] No light of lower wavelength can be produced by the hydrogen molecule.

2.2 The plasma source

The plasma source used in this study is a hollow cathode discharge. Such a discharge is usually created between two electrodes in a cylindrical symmetry. The electrodes are connected to a bank of capacitors that acts as the power supply for the plasma. These capacitors are in turn charged by an external high voltage power supply. The exact way the plasma is ignited depends on the specifics of the source.
2.2.1 Pinch effect

During the discharge there is a large current $I$ flowing through the plasma in the axial direction. This causes a magnetic field $B$ in the azimuthal direction (see figure 2.1). The current is carried by the charged particles in the plasma. The magnetic field causes a Lorentz force on the charged particles that is directed radially inward. This causes the plasma to compress, an effect that is known as a z-pinch. The compression is balanced by expansion of the plasma through either Ohmic or compressional heating. Compression can also end by a decrease of the current. This decrease can happen by the pinching itself, which causes an increase of plasma inductance and resistance, or by the inherent oscillating nature of the current in a RLC circuit.[7]

The basic z-pinch design is shown in figure 2.1. The discharge happens between two parallel electrodes that both have a hole in them. The discharge starts near the insulating wall, and moves to the discharge axis due to the pinch effect described above. Some form of active preionization is required to stabilize the discharge. A fast switch, such as a spark-gap switch, is required in the electrical circuit to build up the electrical potential between the electrodes fast enough.

Another possible way to make a z-pinch plasma is the hollow cathode discharge. In this design, there is an empty volume behind the cathode: the hollow cathode, which acts as a pseudospark switch, so the discharge can be operated without the need for a spark-gap switch and the need for pre-ionizing the background gas.

The operating pressure and voltage are such that the mean free path of the electrons is larger than the distance between the electrodes. No spontaneous discharge can take place between the plates. However, the electric field—which is too high in the region between the electrodes—penetrates in the empty volume behind the cathode, causing a weak field. Free electrons are generated.
in this region and initiate a discharge between the electrodes. Further evolution of the discharge is similar to a regular z-pinch discharge.

### 2.3 Spectrometer

A spectrometer is any instrument that disperses electromagnetic radiation (light) by frequency, forming a spectrum. The light typically enters the spectrometer through an entrance slit and is focused on an exit slit or a CCD. For light in the Extreme Ultraviolet (EUV) region the transmittance and reflectance of all materials is low. This requires that the number of optical components is kept to a minimum. The spectrometer used in this study uses a concave grating to both disperse and focus the incoming EUV light.

Although theoretically with any configuration of slits, it is possible to construct a grating and use the slits and grating as a spectrometer, the manufacturing of a high quality grating poses some limits to the setup. With this in mind there are two restrictions to our configuration: the grating must have a spherical surface and the rulings on the grating must be equidistant. Figure 2.3 shows a schematic representation of the spectrometer. Point $A(x_a + y_a + z_a)$ represents the entrance slit, point $B(x_b + y_b + z_b)$ the exit slit, while $P(x_p + y_p + z_p)$ lies on the grating. The center of the grating is chosen as the origin. The surface of the grating can be represented as:

$$x_p = \rho - \sqrt{\rho^2 - y_p^2 - z_p^2}.$$  \hspace{1cm} (2.3)

The theory of concave gratings has been extensively described in 1945 by Beutler\[8\]. The following presents only the very basics.

The optical path consists of two straight lines, $AP$ and $BP$. The squared length of these segments is:
Figure 2.3: Schematic drawing of a spectrometer with a curved grating.

\[
AP^2 = (x_a - x_p)^2 + (y_b - y_p)^2 + (z_a - z_p)^2 \quad (2.4)
\]

\[
BP^2 = (x_b - x_p)^2 + (y_b - y_p)^2 + (z_b - z_p)^2. \quad (2.5)
\]

The coordinates of \( A \) and \( B \) can also be represented in cylindrical coordinates:

\[
x_a = r_a \cos \alpha, \quad y_a = r_a \sin \beta \quad (2.6)
\]

\[
x_b = r_b \cos \alpha, \quad y_b = r_b \sin \beta. \quad (2.7)
\]

The grating has rulings (in the \( z \)-direction) that are at a constant distance \( d \), along the \( y \)-axis, from each other. The condition for point \( B \) to be a focus point is that the light must have a constant phase for all possible points \( P \) along the grating’s surface. The phase is given by:

\[
F = AP + BP + m\lambda \frac{y_p}{d}, \quad (2.8)
\]

where \( \lambda \) is the wavelength, \( m \) the order, which must be an integer and \( d \) is the distance between the rulings of the grating. For the phase to be constant at \( B \), \( F \) must be constant as \( P \) moves along the grating.
\[ \frac{\partial F}{\partial y_p} = 0, \frac{\partial F}{\partial z_p} = 0. \] (2.9)

This condition is known as Fermat’s principle. If the light path function is satisfied the optical path difference between two rays reflected by consecutive lines on the grating is an integer times \( \lambda \) and the light in \( B \) arrives with the same phase.

Combining the equations in this section to calculate \( F \) involves several series expansions and some elaborate algebra. For the full treatment see [8] or [9]. With the terms of the expansion written as \( AP_{1,2,...} \) and \( BP_{1,2,...} \), the full expression becomes:

\[ F = AP_1 + AP_2 + ... + BP_1 + BP_2 + ... + m\lambda \frac{y_p}{d}. \] (2.10)

The first two terms for \( AP \) and \( BP \) are:

\[ AP_1 = r_a - y_p \sin \alpha \] (2.11)

\[ AP_2 = \frac{1}{2} y_p^2 \left( \frac{\cos^2 \alpha}{r_a} - \frac{\cos \alpha}{\rho} \right) \sum_{n=0}^{\infty} y_p^n \left( \frac{\sin \alpha}{r_a} \right)^n \] (2.12)

\[ BP_1 = r_b - y_p \sin \beta \] (2.13)

\[ BP_2 = \frac{1}{2} y_p^2 \left( \frac{\cos^2 \beta}{r_b} - \frac{\cos \beta}{\rho} \right) \sum_{n=0}^{\infty} y_p^n \left( \frac{\sin \alpha}{r_b} \right)^n. \] (2.14)

Taking only the \( AP_1 \) and \( BP_1 \) terms into account the light path function is:

\[ F = r_a + r_b - y_p (\sin \alpha + \sin \beta) + m\lambda \frac{y_p}{d}. \] (2.15)

Applying Fermat’s principle (differentiating with respect to \( y_p \)) gives:

\[ \sin \alpha + \sin \beta = \frac{m\lambda}{d}. \] (2.16)

the well known grating equation. This equation is only exact for a flat grating, for a curved grating higher order terms have to be taken into account. Applying Fermat’s principle to the terms \( AP_1 \) and \( BP_1 \) gives:

\[ \frac{1}{2} y_p \sum_{n=0}^{\infty} (n+2) y_p^n \left( \left( \frac{\sin \alpha}{r_a} \right)^n \left( \frac{\cos^2 \alpha}{r_a} - \frac{\cos \alpha}{\rho} \right) + \left( \frac{\sin \beta}{r_b} \right)^n \left( \frac{\cos^2 \beta}{r_b} - \frac{\cos \beta}{\rho} \right) \right) = 0. \] (2.17)

There is an obvious solution to this equation:

\[ r_a = \rho \cos \alpha \text{ and } r_b = \rho \cos \beta, \] (2.18)
which is the equation of a circle in polar coordinates. The circle has a diameter of $\rho$, the radius of curvature of the grating. Equation 2.18 implies that the entrance and exit slits must lie on this circle, commonly called the Rowland circle.

The simplest way to use the Rowland circle is the Paschen-Runge mounting. This is the mounting used in the experiments. In this mounting, the entrance slit and grating are fixed and the exit slit is moved along the Rowland circle.\(^1\) The angle of incidence is grazing, as this is needed to measure a spectrum with sufficient resolution at low wavelengths (<100 nm).

The movement of the exit slit is controlled by a computer. Moving the slit will essentially change the distance between the grating and the exit slit, keeping it on the Rowland circle.

Scanning through the wavelengths with the exit slit is done by controlling the distance between the exit slit and the grating, $r_b$. The relation between $r_b$ and the wavelength $\lambda$ at that focus point can easily be determined given the grating equation 2.16 and solving 2.18 for $\cos \beta$.

$$\lambda (r_b) = \frac{d}{m} \left( \sin \alpha - \sin \left( \arccos \frac{r_b}{\rho} \right) \right) = \frac{d}{m} \left( \sin \alpha - \sqrt{1 - \frac{r_b^2}{\rho^2}} \right).$$ (2.19)

Of note is that this implies the wavelength $\lambda$ is proportional to the distance $BC$ in figure 2.4.

\(^1\)It is also possible to have a CCD or even a photographic plate constrained to the Rowland circle. This would also be a form of the Paschen-Runge mounting.
Chapter 3

Experimental setup

The experimental setups consists of three main parts, the vacuum system, the spectrometer and the plasma source. The vacuum system consists of pumps, gas supply, and support systems. It is required to keep the pressure in the setup at desirable levels. The plasma source is explained. This chapter also deals with the detection system and (initial) data processing.

3.1 Vacuum system

Figure 3.1: A schematic drawing of the experimental setup.

Figure 3.1 shows a schematic view of the setup. The microwave source pictured there was replaced by the pulsed DC source described in section 3.2. The setups has the possibility of using argon gas in the plasma, but no argon gas was used during the experiments.

Since wavelengths in the EUV region are strongly absorbed by all gases, it is essential to keep the pressure in the spectrometer and detector chamber as low as possible. The pressure in the plasma is typically in the order of 1 mbar, in
flow controller calibrated for | conversion factor
--- | ---
hydrogen | oxygen | 1.028
hydrogen | argon (95%) | hydrogen (5%) mix | 0.735
helium | oxygen | 1.433

Table 3.1: Conversion factors used to calculate the correct flow.

The reading from the flow controller control box has to be multiplied by this factor [10, 11].

3.2 Plasma source

The plasma source, pictured in figure 3.2, used in this study consists of a hollow cathode and an anode connected through a capacitor bank. The anode and cathode are approximately 3 mm apart. Both have a hole in the middle, through which gas can flow and light can escape the discharge towards the spectrometer entrance slit. These holes are 3 mm in diameter. The capacitor bank consists of 20 parallel capacitors of 5.2 nF, for a total of 104 nF. The capacitors are charged by a high voltage power source, that can generate up to -15 kV. We trigger the discharge with an electron gun, so we assume it is a hollow cathode triggered discharge. The discharge can also be spontaneously triggered, which confirms the assumption of a hollow cathode discharge.

This plasma source is almost identical to the source used by Mills [12]. The electrodes and the electron gun can be considered identical, the rest of the plasma source is similar, but not identical.

The electron gun is aimed at the hollow cathode and is basically a filament that is heated by an adjustable DC power source. It is essentially equal to the electron guns used in old-fashioned cathode ray televisions. The electrons are accelerated to the cathode by a high voltage pulse. The frequency of pulsing can be adjusted. The pulsing is done to have better control over the reproducibility of the discharge. If there is a constant time between discharges, we assume
Figure 3.2: Drawing of the pulsed plasma source. The yellow part is the high (negative) voltage part.
they all happen at identical circumstances. If not otherwise indicated, the pulse frequency is 5 Hz.

The electrodes are replaceable. They are available in either molybdenum (Mo) or tungsten-copper (WCu). In the experiments in this report, only Mo electrodes have been used.

To be sure that the gas composition between the electrodes is constant, the flow controllers are connected to a tube such that the gas input is directly between the electrodes. The gas flow is mainly through the anode, towards the spectrometer, since on this side the pumps are connected.

The plasma source generates some electromagnetic interference during the pulse. Several measures were taken to decrease this disturbance.

### 3.2.1 Current measurement

The current can be determined in two ways. Assuming that when the discharge happens the capacitors are charged and subsequently discharge through the plasma, modeled as a resistor, numerical differentiation of the voltage (for example using a Savitzky-Golay scheme[13] on the scope data) gives a current, through the well known relation between current through and voltage over a capacitor:

\[
I = C \frac{dV}{dt}
\]

Another way to find the current is to place additional resistors in series with the capacitors. The voltage over one of these resistors is proportional to the current.

For these measurements the high voltage probe was directly plugged into the measurement scope. The current was calculated from this data by numerically differentiating the voltage. This was done by applying a Savitzky-Golay filter of order 3 and 31 points to the voltage, then multiplying it by the capacitance.

For comparison with the voltage differentiation results, cylindrical resistors manufactured by HVR, type AB046, with a resistance of 0.33 Ω were placed between half of the capacitors and the discharge. In figure 3.2, this is between the capacitors to the right side of the yellow coloured plate and the rightmost grey coloured plate. Adding resistors to all the capacitors would have been ideal, but would have required an impractical rebuild of the entire pulsed plasma source. When the capacitors discharge, they do so through these resistors. The voltage over one of these resistors is monitored with a separate voltage probe, again connected to the measurement scope. Through Ohm's law, this voltage can be converted into the current through the resistor, which is assumed to be the current through the discharge. The results for a helium plasma are shown in figure 3.3.

There is only a small difference in phase between the two 'currents', although the numerical differentiation results give significantly larger (absolute value) currents. The difference in phase may be caused by difference in signal line lengths between the probes. The difference in absolute value can be explained
by either an overestimation in the numerical differentiation results or an underestimation of the resistor results. The former would infer the value of $C$ is too low, the latter that there is some parasitic resistance.

Similar measurements have been done for hydrogen plasma. There are more fluctuations in the current for helium, especially in the first quarter cycle. After that the current looks similar in both cases.

### 3.2.2 Electron gun

A discharge happens spontaneously if the voltage over the electrodes is high enough. To have a better control over the discharge it can be triggered by an electron beam aimed at the anode. When the electrons enter the space between the electrodes, a discharge occurs.

The electron beam is generated by an electron gun. It basically consists of a wire that emits electrons when heated. These electrons are then accelerated away from the wire by applying a short negative voltage pulse. The heating is done by a 24 V battery. The voltage over the wire can be adjusted with a potentiometer. The negative voltage pulse (-3 kV) is created in a circuit, which contains a high voltage power source (Hewlett Packard 6516A), a function generator (Agilent 33220A), a high voltage pulse generator (Directed Energy Inc. PVX-4140), the 24 V battery and several resistors and capacitors. This circuit is shown schematically in figure 3.4.
Figure 3.4: Schematic view of the pulse circuit.
The frequency of pulsing is usually set at 5 Hz. The electron beam is not (very well) focused, but enough electrons enter the space between the electrodes to initiate a discharge.

### 3.2.3 Power input estimation

The voltage of the cathode and the voltage of the e-gun during a discharge are measured with the voltage probe and an oscilloscope. The result is shown in figure 3.3 in section 3.2.1. It shows that the voltage on the cathode before the discharge is \(-8 \) kV. The voltage rises from \(-8 \) to \(0 \) kV in \(73 \) ns and oscillates for about \(1.4 \) μs. After that it builds up again for the next discharge. The oscillations are a common effect known as ringing. When the voltage rises above a certain threshold the oscilloscope generates a trigger signal that is used to start time resolved measurements. We know that the capacitance \( C = 104 \) nF, the voltage \( V = -8 \) kV at the start of the discharge and the voltage rises to \(0\) in approximately \( t = 73 \) ns. We can estimate the current \( I \) during the first part of the discharge by assuming all the charge stored in the capacitors drains until the voltage is \(0\).

\[
I = \frac{CV}{\Delta t} = -11 \text{ kA}. \tag{3.2}
\]

It is difficult to know the amount of pinching, and therefore the size of the plasma. We estimate that the plasma has approximately the size of the holes in the electrodes, which have a surface \( A \) of approximately \(7 \) mm\(^2\). The current density \( J \) is approximately:

\[
J = \frac{I}{A} = -1.6 \cdot 10^{-9} \text{ Am}^{-2}. \tag{3.3}
\]

The energy \( E \) that goes into one pulse is:

\[
E = \frac{1}{2} CV^2 = 3.3 \text{ J}. \tag{3.4}
\]

This can be compared to experiments by van Gessel, who reported a pulse energy of \(9 \) J on the same setup [4] and Kieft, who used pulse energies between approximately \(1.5\) and \(4.5 \) J[7]. Van Gessel used a somewhat higher voltage (-13 kV), which through the quadratical dependence of the energy on voltage results in a significantly larger energy.

Fully integrating the power derived from the current and voltage obtained in section 3.2.1 gives an input power of \(1.4 \) J. This is somewhat smaller than the rough estimate provided above.

### 3.3 Spectrometer

The spectrometer we used is a Minuteman Laboratories model 322G. The spectrometer is a grazing incidence EUV spectrometer of the Paschen-Runge type. It has a Rowland circle with a diameter of \(2.217 \) m. When the spectrometer is in operation, the grating and entrance slit are fixed, while the exit slit slides...
along the Rowland circle. The entrance slit is fixed, but replaceable. For the measurements presented a slit with a width of 30 micrometer was used. The exit slit is adjustable, but is usually set at a width of 8 micrometer. The position of the exit slit can be controlled continuously by a high precision mechanism that is connected to a stepper motor, which is controllable with a computer. The spectrometer is calibrated by using a EUV light source with lines at known wavelengths (such as a helium plasma). The position of the stepper motor is noted at two lines and entered in a calibration file of the measurement software, that then calculates the relation between the stepper motor counter and wavelength. More information about the measurement software can be found in section 3.4.2.

3.4 Detection circuit

3.4.1 Channel Electron Multiplier

A Channel Electron Multiplier (CEM) is a single-particle detector which in its basic form consists of a hollow channel of either glass or ceramic material with a semiconducting inner surface. The detector responds to one or more primary electron impact events at its input by producing, in a cascade multiplication process, a charge pulse of typically $10^4$ to $10^8$ electrons at its output. Because particles other than electrons can impact at the entrance of the channel electron multiplier to produce a secondary electron, which is then subsequently multiplied in a cascade, the channel electron multiplier can be used to detect (energetic) photons as well.

The CEM that we used is the Detector Inc. model 206-10C-SL. The CEM has a cone at the front to catch particles. There are two electrical connections on the CEM over which a voltage of 2.4 kV is applied. The gain of the detector is $5.6 \cdot 10^7$.

Figure 3.5 shows how the CEM is connected. The front electrode of the CEM is grounded, while the back electrode is connected to a $+2.4$ kV power source. The signal at this point is measured directly with an oscilloscope.
Triggering of measurement

The voltage at the high voltage side of the capacitors is monitored by a high voltage probe, which is connected to an oscilloscope. When this oscilloscope detects a rise in voltage it sends a trigger signal to a second oscilloscope and also to the multichannel scaler in order to start the measurement. This complicated setup with two oscilloscopes is used because the trigger oscilloscope can be placed relatively close to the setups, which causes electromagnetic interference. The measurement scope is placed further away to prevent this.

3.4.2 Measurement method

Measurements with the CEM can be performed in two ways. When few photons hit the detector, all the current pulses can be counted individually. This mode allows for the detection of single photons. When too many photons hit the detector, the pulses overlap and single photon counting is not possible anymore. Instead the current through the detector must be integrated. It must be assumed that every photon arriving at the CEM still gives a predictable current pulse so that the integrated current is proportional to the number of the photons hitting the detector.

It was observed, especially during the discharge, that the pulses coming from the CEM are overlapping. Counting does not work in this case. By integrating the signal of the CEM over time, an approximation of the number of photons emitted by the discharge is obtained.

Counting can give rise to inaccurate measurements by the dead time inherent in the system. A pulse arriving shortly after another in the counter system will not be counted. Depending on the type of counter, another dead time period may start, leading to an even larger underestimation of the intensity.

The exit slit is moved with a stepper motor which is controlled by the measurement program. This program was largely written by previous users of the setup [4, 14, 15], but some minor adaptations were made. The program allows one to control all measurement parameters, such as the starting and ending wavelength, wavelength resolution and number of discharges (repetitions). The program always saves the current position of the exit slit, so the calibration is not lost when an error ends the measurement prematurely.

3.4.3 Aluminium filter

In order to block possible unwanted stray light from the CEM, an aluminium filter, Luxel 1500 Å Al TFT-111, is placed before it. This filter blocks all light above 90 nm. Molecular hydrogen has some emission bands in this wavelength area, as well as the atomic Lyman lines between 90 and 120 nm. This light may be picked up by the CEM. The CEM is not sensitive for photons with wavelengths above 200 nm. The transmission properties of the filter are shown in figure 3.6.
Figure 3.6: Transmission properties of the aluminium filter [16]
Chapter 4

Results and discussion

This chapter presents the results of the experiments. The measurement method generates a three dimensional array of data (signal as function of wavelength, time). This data can be processed in several ways to create a spectrum. These spectra, time-resolved and time-integrated, of helium, hydrogen and a mixture of both gases are shown. Spectra in the visual range are also shown for these gases. These were obtained using the Ocean Optics HR2000, with an approximate range of 200-640 nm, and Ocean Optics HR4000, with a range of 500-900 nm. Helium was used because it has several lines in the region of interest. These measurements are to confirm the equipment is working correctly. Hydrogen has the continuum reported by Mills, which we want to study. The measurements in the mix of both are to check one hypothesis that suggests a thermal origin of the continuum. Because the helium discharge is cooler than the hydrogen discharge, it would show a weaker or no continuum.[17]

The voltage for these measurements, in all gases, was set to -9 kV unless otherwise noted. Pressures and flows were primarily chosen to get a stable discharge. A spontaneous discharge (breakdown) happens for different gases at a specific voltage (the breakdown voltage) that is a function of pressure and distance between the electrodes. Since the capacitors are continuously recharged by the high voltage power supply, in our setup spontaneous discharges will happen at a certain frequency. In order to have control over this frequency, triggering is used. It is still desirable to be close to the point of breakdown, because otherwise the discharge might not be triggered. The frequency of triggering is 5 Hz, unless noted otherwise.

First the measurement procedure is discussed, the visual and EUV measurements of helium, hydrogen and a mix of the two are presented. Finally the influence of the repetition frequency is investigated.

4.1 Measurement procedure

The measurements in this report consist of a series of single shot measurements. A discharge occurs, the high voltage probe and trigger scope detect a rise in voltage and the measurement scope records the CEM output voltage for 20 microseconds. An example of a single shot measurement is shown in 4.1.
Figure 4.1: A single shot measurement of helium at 34.9 nm. CEM signal as function of time.

Figure 4.2: Average CEM signal of a helium discharge at 34.9 nm.

A baseline is calculated for every single shot measurement and subtracted from the signal. This single shot is repeated and recorded typically 20 times (at 5 Hz) to average out any possible fluctuations, as is shown in figure 4.2. Then
the exit slit is moved and a series of single shot measurements is done at the next wavelength. This builds up the three-dimensional array containing all the measurement data.

In figure 4.2 structures in time are visible. At first the signal peaks, which corresponds to the discharge. Afterwards it oscillates for a few microseconds. These oscillations likely do not represent photons arriving at the detector, but are caused by electromagnetic interference from the pulse source. Several measures were taken to decrease this disturbance. The possibility of using a nonconductive housing for the CEM was briefly investigated. A semi-flexible coaxial cable was used instead of a regular coaxial cable to carry the signal from the CEM to the oscilloscope. Care was taken to properly ground the setup.

4.2 Results in helium

4.2.1 Visual spectra

Visual spectra were made of a helium plasma at a pressure of 1.20 mbar. The flow of helium was 29.4 sccm (standard cubic centimeter per minute).

![Figure 4.3: Helium spectrum in the visual range, covering 300-900 nm. Data from the HR2000 in blue, from the HR4000 in green.](image)

The well known lines of neutral helium can be seen in figures 4.3. This figure combines the spectra of the two Ocean Optics spectrometers, but cutting off the edges of the wavelength ranges, where the sensitivity is very low. The line at 588 nm dominates the emission. In the measurement with the HR2000
spectrometer it is saturated. Other strong lines of helium are visible at 389, 447, 668, and 706 nm.

4.2.2 Extreme ultraviolet spectra

The data files created by the Labview measurement program are imported by Matlab. They contain data as function of wavelength and time. Intricate three-dimensional graphs can be made from this. However the most intuitive way to represent the data is to create a two-dimensional graph: a time-integrated spectrum. The data is averaged over the discharge repetition, then integrated over time. These EUV measurements were done at the same time as the measurements in the visual.

![Integrated EUV spectrum](image)

Figure 4.4: Integrated EUV spectrum of a helium discharge. Several helium ion lines are indicated, as well as several lines that are attributed to oxygen, an impurity. The pressure was 1.20 mbar. The flow of helium was 29.4 sccm.

In figure 4.4 the helium ion lines at 30.4, 25.6 and 24.3 nanometer are clearly visible. In the group of lines between 23 and 24 nanometer, lines at 23.7 and 23.4 nanometer can also be identified. Ionic lines of oxygen (an impurity) can also be identified in this spectrum. They are indicated with an asterisk. The vast majority of these lines are lines of O$^{4+}$. 

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4.2.3 Partially integrated spectra

Instead of adding all data points in time at one wavelength together, it is also possible to integrate over only a part of the time domain. This makes it possible to compare intensities during the discharge itself and in the afterglow.

These time domains are indicated in figure 4.5. Time domain I (before the discharge happens) is used to determine the baseline. From the current measurements (section 3.2.1) it follows that the discharge itself lasts about 1.4 microseconds. Time domain II is somewhat overestimated at 1.5 microseconds, to be certain to catch the whole discharge in this domain. Time domain III is considered to be the afterglow.

In figure 4.6 it can be seen that most of the intensity is produced during the discharge. The helium lines are also clearly visible in the afterglow. The lines of oxygen impurity (again indicated with an asterisk) are not present in the afterglow.
Figure 4.6: Partially time-integrated EUV spectrum of a helium discharge. Several helium ion lines and several lines attributed to oxygen are indicated. The pressure was 1.20 mbar. The flow of helium was 29.4 sccm.

Figure 4.7: Time resolved EUV spectrum of a helium discharge. The pressure was 1.20 mbar. The flow of helium was 29.4 sccm.
4.2.4 Fully time-resolved spectra

This is the most fundamental way to present the measurement data. The data is still averaged by repetition of the discharge.

Although overall intensity seems quite low, the helium lines can be clearly seen in the afterglow in figure 4.7. Details of lines that appear only during the discharge are lost in the background. Structures in time, that can also been seen in the fully time-resolved one shot measurements, such as shown in figure 4.5, are also visible in this picture.

4.3 Results in hydrogen

The measurements described in section 4.1 were repeated with a hydrogen plasma to look for the continuum described by Mills[12] and Vän Gessel[4]. Visual spectra were made with the Ocean Optics spectrometers and EUV spectra with the spectrometer described in section 3.3. Time-integrated and time-resolved EUV measurements are also shown.

4.3.1 Visual spectra

Figure 4.8: Hydrogen spectrum in the visual range, covering 300-900 nm. Data from the HR2000 in blue, from the HR4000 in green.

Visual spectra were also made of a hydrogen discharge at 0.53 mbar. The flow of hydrogen was 15.2 sccm.
In figure 4.8 the first few Balmer lines are clearly visible at, respectively, 656, 486 and 434 nanometer. The line at 656 nm dominates the emission spectrum. No molecular band emission is seen.

Figure 4.9: Integrated EUV spectrum of a hydrogen discharge. The pressure was 0.52 mbar, the flow of hydrogen 15.2 sccm.

4.3.2 Extreme ultraviolet spectra

This spectrum was generated as described in section 4.2.3. The EUV measurements were not made at the same time as the visual measurements, so the conditions of these measurements may not be identical, although it was attempted to keep them so.

The integrated EUV spectrum of hydrogen is shown in figure 4.9. An continuum is visible centered around 24 nm.

The partially integrated spectrum is shown in figure 4.10. All light is generated during the discharge, there is no intensity produced in the afterglow. The afterglow appears slightly negative probably because an overshoot after the peak intensity during the discharge. This overshoot is likely caused by the electrical circuit.

In these two figures, the continuum described by Mills and van Gessel can be seen. The signal is, even when averaged over 20 discharges, still relatively noisy. The overall intensity is somewhat lower than in the helium spectrum.
Figure 4.10: Partially time-integrated EUV spectrum of a helium discharge. The pressure was 0.52 mbar, the flow of hydrogen 15.2 sccm.

Figure 4.11: Time resolved EUV spectrum of a hydrogen discharge. The pressure was 0.52 mbar, the flow of hydrogen 15.2 sccm.

The three-dimensional spectrum, shown in figure 4.11 confirms that there are no photons produced in the afterglow. Other details are lost in this picture. The
continuum is not visible.

For some more clarity, time-resolved, wavelength-averaged CEM signals from inside and outside the continuum are compared in figure 4.12. It can be seen that the difference between the two is not large, but significant and is present only during the discharge. The wavelength-averaged time-resolved signal of the CEM is somewhat higher during the discharge, but there is no difference in the afterglow.

Figure 4.12: Comparison between wavelength-averaged CEM signal on and outside of the continuum. On the continuum corresponds to the wavelength area 23.4-24.0 nm, outside to 21.0-21.6 nm.
4.3.3 Current measurement

Figure 4.13: Current and voltage, taken from section 3.2.1, compared with the CEM signal from a measurement of hydrogen plasma at 0.53 mbar and 15.2 sccm, taken at 32.42 nm, which is outside the continuum. The signal was averaged over 40 discharges.

The current through the plasma and voltage over the capacitor was measured for several different applied voltages, in addition to the regular experiments. This section compares the results with the time-resolved signals from the EMT. Figure 4.13 compares the current and voltage with a typical CEM signal. It can be seen that the current and voltage are shifted compared to the CEM signal. This is because the trigger signal to the measurement oscilloscope is delayed, which is not the case for the current and voltage. The oscillations in the CEM signal appear to be of the same frequency as the oscillations in the current and voltage.
4.4 Results in helium-hydrogen mixture

The measurements described in section 4.1 were repeated with a mixture of 76 % helium and 24 % hydrogen. The measurements in this mixture are to check the hypothesis that helium does not show a continuum because the discharge is cooler than the hydrogen discharge. Visual spectra were made with the Ocean Optics spectrometers and EUV spectra with the spectrometer described in section 3.3.

4.4.1 Visual spectra

![Figure 4.14: Spectrum of a helium (76%)-hydrogen (24%) mixture in the visual range, covering 300-900 nm. Data from the HR2000 in blue, from the HR4000 in green. The pressure was 0.99 mbar. The flow was set to 6.5 sccm hydrogen and 18.6 sccm helium.](image)

In figure 4.14 lines of atomic hydrogen and helium are visible. The strongest line is the Balmer alpha line of hydrogen. The Balmer beta and gamma lines are weaker, but also visible. The other strong lines are the helium lines also visible in 4.3, although the intensities differ considerably. This may be caused by a different plasma temperature.
4.4.2 Extreme ultraviolet spectra

Figure 4.15: Integrated EUV spectrum of a helium (76%)-hydrogen (24%) mixture discharge. Several helium ion lines are indicated, as well as several lines that are attributed to oxygen, an impurity. The pressure was 0.978 mbar. The flow was set to 6.5 sccm hydrogen and 18.6 sccm helium.

This spectrum was generated as described in section 4.2.3. The EUV measurements were not made at the same time as the visual measurements.

In figure 4.15 both lines of ionized helium and the continuum around 24 nanometer can be seen. Lines of oxygen are indicated with an asterisk.

In figure 4.16 the continuum is again visible, though it is somewhat obscured by helium ion lines in the same wavelength area. Just as in the case with only helium, the helium ion lines are again present in the afterglow, the oxygen impurity lines are not.
Figure 4.16: Partially time-integrated EUV spectrum of a helium (76%)-hydrogen (24%) mixture discharge. Several helium ion lines and several lines attributed to oxygen are indicated. The pressure was 0.978 mbar. The flow was set to 6.5 sccm hydrogen and 18.6 sccm helium.
Figure 4.17: Comparison of the EUV spectrum of a mix of a helium (76%)-hydrogen (24%) mixture with an spectrum that is artificially generated from the EUV spectra of these individual gases.

Figure 4.18: For comparison with figure 4.17, the spectra of helium and hydrogen plasmas used to create the average spectrum there.

Figure 4.17 compares the results as shown in figure 4.15 and an artificially
created spectrum by averaging figures 4.4 and 4.9 taking into account the relative fractions of helium and hydrogen atoms in the gas. The original spectra are shown for comparison in figure 4.18. From figure 4.17 it can be seen that the spectrum of the mix can be approximated well by averaging the spectra of helium and hydrogen. This makes it plausible that the continuum is caused by a temperature difference between the hydrogen and helium plasmas.

Also, in figure 4.18 it appears that helium also shows a continuum. At low wavelengths, it starts at approximately the same wavelength as the hydrogen continuum, but it does not extend as far to longer wavelengths. It is not as strong as the continuum in hydrogen. On the other hand, it cannot be completely ruled out that there is some contamination of water present and that the hydrogen from this water contributes to the spectrum.

![Figure 4.19: Time resolved EUV spectrum of a helium (76%)-hydrogen (24%) mixture discharge. The pressure was 0.978 mbar. The flow was set to 6.5 sccm hydrogen and 18.6 sccm helium.](image)

In figure 4.19 the lines of ionic helium are less pronounced in the afterglow, when compared to the hydrogen only case.

### 4.5 Influence of repetition frequency

In hydrogen, EUV measurements were also made at 2 Hz, instead of the usual 5 Hz. This was to investigate the influence of the repetition frequency. This frequency may have an influence if sputtered cathode material is involved in creating the observed continuum. With a different frequency this material has a different time to diffuse inward into the plasma.

For comparison with the results at 2 Hz, a control measurement has been done at 5 Hz. The wavelength range of this measurement was reduced in comparison to the results shown in the previous sections. Before these measurements it was
noticed that the intensity was suddenly greatly reduced. The spectrometer exit slit was consequently widened to 30 micrometer.

Figure 4.20: Integrated EUV spectrum of a hydrogen plasma, with repetition frequencies of 5 Hz (red) and 2 Hz (black and blue). Conditions for 5 Hz were: pressure 0.64 mbar, hydrogen flow rate 19.3 sccm. The voltage was set to -7.5 kV. The measurement for 2 Hz was done in two phases, as an error occurred when the measurement was almost finished. For both measurements the flow rate of hydrogen was set to 19.3 sccm. The pressure was 0.63 mbar for the first part of the measurement, in blue, and 0.62 mbar for the second part, in black. The voltage was set to -7.5 kV in all cases.

The results for a repetition frequency of 2 Hz are shown in figure 4.20. The measurement at 2 Hz was done in two steps because an error occurred when the first measurement (blue in figure 4.20) was almost finished. The second part (in black in the same figure) was done a day later, with some overlap in wavelength range to confirm that conditions were similar during both measurements.

In this figure a peak near 24 nm is visible. It is also, seen in the earlier results, for example in figure 4.9. In that figure it is narrower compared to figure 4.20, this is likely caused by the wider exit slit of the spectrometer. In these measurements the exit slit was set to 30 micrometer, in the previous measurements this was 8 micrometer. The continuum otherwise resembles the previous results, but it seems somewhat less noisy. Also the sudden drop-off towards shorter wavelength is notable.

In the figure it can be seen that there is no significant difference between the measurements at the two frequencies. However the broad peak at 23.9 nm is higher in the measurement at 2 Hz.
Chapter 5

Conclusion

The visual spectra of helium and hydrogen plasmas are dominated by lines of helium and atomic hydrogen respectively. This suggests that the plasma is dominated by these species and that the emission in the extreme ultraviolet should be dominated by these elements. The visual spectra of a mix of both gases likewise shows only atomic lines of both elements.

In the EUV spectrum, a continuum has been observed in a plasma of hydrogen and in a plasma of a helium (76%)-hydrogen (24%) mixture. A weaker continuum is observed in a pure helium plasma. The spectrum of the helium-hydrogen mixture can be approximated very well by averaging the spectra of the helium and hydrogen discharges. This spectrum partly reproduces the results of van Gessel and Mills. Differences in the results between this report and Mills should be mainly caused by differences in the spectrometer and detection system, as the plasma source is virtually identical. Difference in the amount of stray light from the plasma that somehow reaches the exit slit of the detector can be one explanation for this.

The lines of helium ions show a long afterglow. In contrast the continuum is only present during the discharge and is not visible in the afterglow. On the time dependence of the continuum, it can only be said that it is produced during the discharge, but nothing can be said of the time dependence during the discharge. This continuum has a sharp edge at the low wavelength end, around 23.7 nm and extends to 28-29 nm at the high wavelength end.

Investigating the repetition frequency, it can be concluded that there is very little influence of the repetition frequency on the EUV spectrum of hydrogen. However there is a small difference in intensity of the peak at 23.9 nm.

Comparison of the spectra of hydrogen and helium makes it plausible that the continuum is caused by a temperature difference between the hydrogen and helium plasmas. However, these measurements cannot be used to conclusively determine what is the cause of the continuum.
Bibliography


[17] Private communication with Jeroen Jonkers.