BACHELOR

Investigating the tungsten contamination and velocity distribution of helium ions in the fusor using spectroscopy

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Investigating the tungsten contamination and velocity distribution of helium ions in the fusor using spectroscopy

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Abstract

The fusor is a fusion device that uses an electrostatic field to accelerate ions to conditions where fusion is possible. These devices however do not produce net energy but can still be used for neutron production. The cathode of the fusor is a tungsten cage in the center and collisions with this cage can cause energy losses and sputtering of the tungsten. If this happens the tungsten could leave traces in the plasma, contaminating it and reducing the neuron production. Analyzing the light that is emitted by this plasma and comparing the spectrum to known tungsten peaks gives insight on the presence of tungsten in the plasma. By using helium and argon plasmas different sputtering yields are achieved because of the mass difference, while avoiding the harmful neutron production. In neither of the plasmas traces of tungsten were found in their spectrum.
If the average velocity of the ions is lower than expected, less effective collisions take place which also reduces the neutron production. The average velocity can be found by investigating the broadening of the spectral lines. The full width at half maximum can be related to the root mean square velocity of the ions due to Doppler broadening. A negative correlation has been found between the voltage of the fusor and the root mean square velocity of the plasma. These velocities range from $4.3 * 10^4$ to $4.9 * 10^4\ m\,s^{-1}$ and decrease linearly with the voltage.

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Introduction to fusion

Nuclear fusion is a reaction in which two light nuclei fuse into a heavier nucleus. Energy is released in the process if the mass of the nucleus after the reaction is less than the total mass before the reaction. This is because some of the mass is converted to energy using Einstein's famous equation:

$$E = mc^2$$

The reaction with the largest cross section is the reaction between deuterium (^{2}H) and tritium (^{3}H):

$$^{2}H + \ ^{3}H \rightarrow \ ^{4}He + \mathrm{n}$$

On earth we have been trying to replicate this process to use it for our own energy generation. The conditions required for fusion however are so extreme that scientists have yet to figure out how to gain energy out of the process. Currently an international project is running which is building a fusion plant in France. The reactor, ITER, will be the largest fusion device ever built and is estimated to be the first fusion device to generate more power than it requires to be powered.

While fusion needs large, complicated plants to generate net energy, smaller devices also have their uses. They can be used to produce neutrons or be used for educational purposes. One way of achieving this is through the fusor. This device uses electrostatic fields to confine and accelerate particles to conditions where fusion is possible. At the Tue there is also a fusor available.

Previous experiments using the fusor have found the neutron production to be lower than expected. This could be caused by the collisions between ions not happening as frequently or effectively as was predicted. A reason for this could be that collisions between ions and the tungsten cage causes sputtering of the tungsten. This contaminates the plasma and reduces the amount of effective collisions between ions. Analyzing the light emitted by a plasma and comparing it to the expected peaks of tungsten and of the gas used, can give information about the presence of tungsten in the plasma.

Another reason could be that the average velocity of the ions is lower than expected. To investigate this, the Doppler broadening of the spectral lines will be examined.

Introduction to the Fusor

The fusor used in this experiment is a spherically symmetrical device which uses an electrostatic field to generate fusion. It is one of the most simple fusion reactors and was already invented in 1964 by Philo T. Farnsworth[1]. Figure 1 shows a simplified schematic of a fusor.

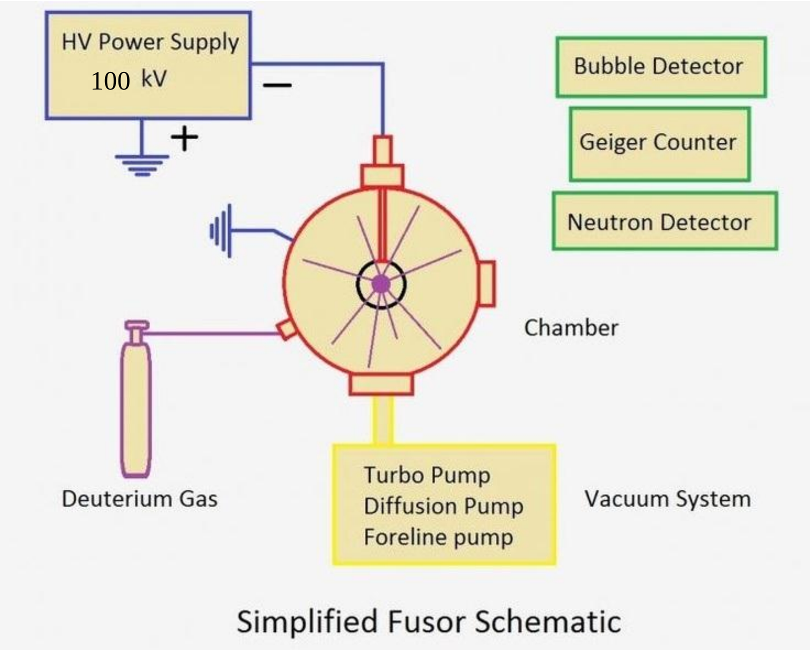

Figure 1: Simplified fusor schematic, Source: Pinterest user Mark Wilson

The fusor itself is a vacuum chamber with a negatively charged cathode in the center. The cathode is a wired cage made out of tungsten. The anode of the system is the wall of the vacuum chamber which is grounded. This set-up creates a radial electrostatic field which pulls the ions directly to the center. In the center there is a chance for the ions to collide.

The chamber can be filled with deuterium gas which has the possibility to fuse into helium in two different ways: directly and indirectly:

$$2\ {}^{2}H \rightarrow {}^{3}He + n$$

and

$$2\ {}^{2}H \rightarrow {}^{3}H + p$$
$${}^{2}H + {}^{3}H \rightarrow {}^{4}He + n$$

Both of these reactions release energy into the system, but there is still a net energy loss in the system. This is caused by the losses inside of the reactor

The complete setup consists of more than just the vacuum chamber. There is a high voltage generator with manually adjustable current and voltage. This is what powers the cathode inside the fusor.

This entire system is monitored by a Matlab script. It is also possible to change the variables using this script. The software displays information about the generator, the current and voltage, as well as the pressure in the fusor and counts from the installed neutron detectors.

Spectroscopy on the fusor

A smart way to get information about what is happening inside the fusor is spectroscopy. This non-destructive measurement technique can get information from the plasma by analyzing the emitted light.

The light from the fusor is caught by a lens which is attached to the fusor. This lens has a focal length of 75.0 mm and focusses the light on the spot where a fiber can be attached. This can be seen in figure (2).

Figure 2: Fusor with lens setup

This fiber is optimized for light in the visible spectrum and transports the light to a spectrometer. The spectrometer used is an Andor Shamrock 500i which is a grating spectrometer. These kinds of spectrometers use mirrors and a grating to decompose the light based on the wavelength. This causes different wavelengths of the light to hit different parts of the detector. This is illustrated in figure (3).

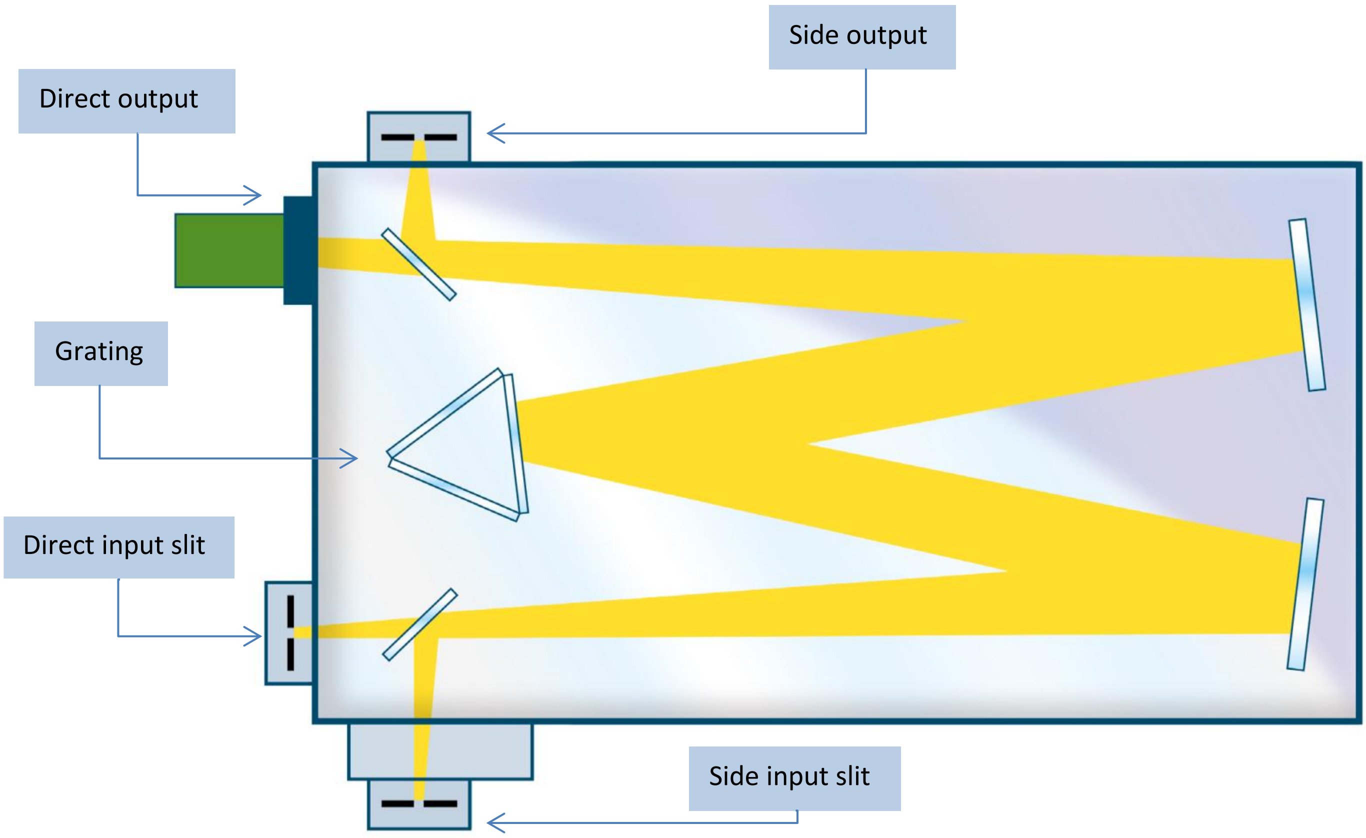

Figure 3: Schematic of the Andor Shamrock 500i spectrometer, Source: Andor Shamrock 500 specifications

This spectrometer has different gratings ranging from 300 lines/mm to 1199 lines/mm. More lines give a more accurate result, but a smaller range of wavelengths which can be examined. 300 lines/mm results in a band pass of 177 nm and a resolution of 0.26 nm and 1199 lines/mm has a band pass of 40 nm and a resolution of 0.06 nm [2].

This data can be used to plot the wavelength of the light versus the counts. The counts are a direct representation the intensity.

Besides the grating the spectrometer has a couple of other parameters which can be altered. The slit size determines the amount of light that enters the spectrometer. Making the slit not wide enough can make the signal too weak, but opening the slit too far can cause oversaturation and a bad resolution. The exposure time also influences the strength of the measured signal. Making it longer increases the counts and vice versa.

There are also different capture modes but because the spectrum is the only thing being looked at, full vertical binning can be used. This bundles all the counts with the same wavelength together [3].

Finding Tungsten peaks in the spectrum.

If sputtering is the reason that the neutron detection is lower than expected because the plasma in the fusor gets contaminated, traces of tungsten should be visible in the plasma. This could be the case because high energy ions are constantly hitting the tungsten. To investigate this, the spectrum of different plasmas were analyzed and compared to the spectrum of the pure gases. If there are differences between the spectra, this could mean the plasma in the fusor is contaminated. The gases helium and argon were used to avoid the harmful neutron production. If there are traces of the tungsten in the plasma, these are expected to be larger for the argon plasma as the sputtering yield will be larger for argon. This is due to the larger ion mass when compared to helium ions.

Both gases were kept inside the fusor for an extended period of time to increase the possible contaminations. During this time, the voltage was slowly raised to increase the electric field and the energy of the ions. For five minutes, the spectrum was measured with stable pressure. These measurements were done using a kinetic series on the spectrometer using a cycle time of 0.5 seconds. This allows the spectrometer to make rapid measurements and save them as one file. This file can be read and examined by a Matlab script. The data could be analyzed to see if any new peaks would appear in the spectrum or if the existing peaks would just get larger due to brighter plasma.

No new peaks were found and the only part of the spectrum that changed significantly was in the ranges above 600nm. At higher power levels a Planck distribution seems to appear which could be caused by the heating of the cage. Because of this, the average of the measurement can be used to further examine which peaks belonged to what substances and if there are traces of tungsten.

The measurements used the crudest grating which has 300 lines/millimeter. This allows the spectrometer to capture the entire visible part of the spectrum with two series. Each of the series spans 177 nanometers so there will be an overlap of 54 nm. Figures (4) and figure (5) show the measured spectrum of the helium plasma while figures (6) and (7) show that of the argon plasma. In both spectra the five largest expected peaks are displayed by red vertical lines [4].

The first observation when comparing the spectra is that the argon plasma is much weaker in terms of light emission. There are also no obvious peaks that appear in both spectra as would be expected from tungsten peaks. To further analyze these spectra, table (1) shows the highest peaks for tungsten in range from 400nm to 700nm [4].

Table 1: Tungsten peaks [W I] with highest relative intesities

Tungsten [W I]
peaks (nm)
400.88
407.44
424.44
426.94
429.46
484.38
505.55
525.93
551.47

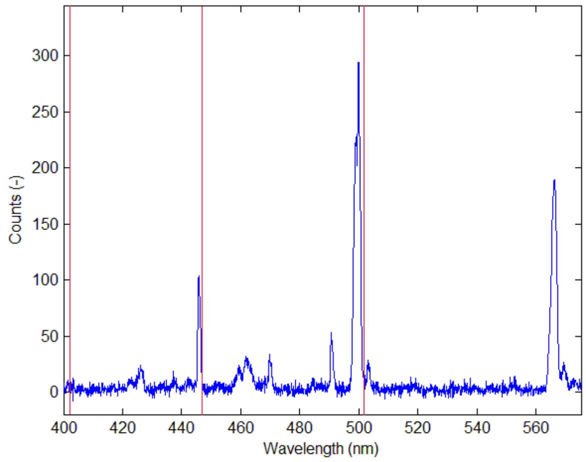

Figure 4: Helium spectrum from 400nm to 577nm, the red lines are the expected locations of helium peaks.

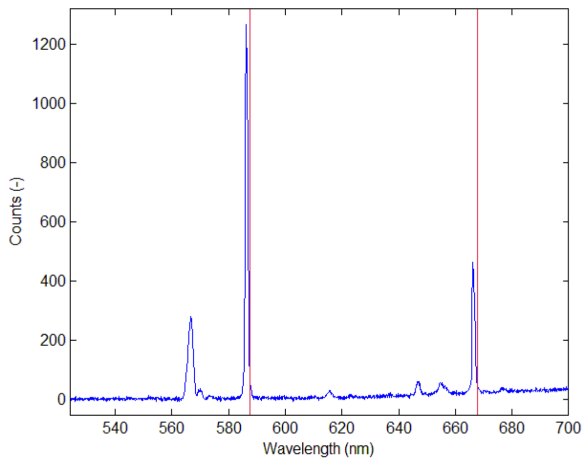

Figure 5: Helium spectrum from 523nm to 700nm, the red lines are the expected locations of helium peaks.

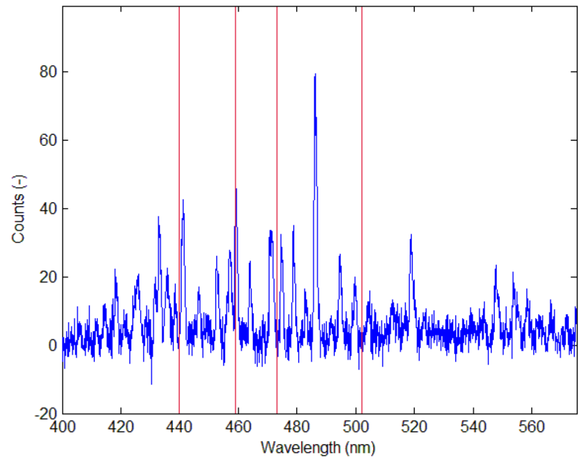

Figure 6: Argon spectrum from 400nm to 577nm, the red lines are the expected locations of argon peaks.

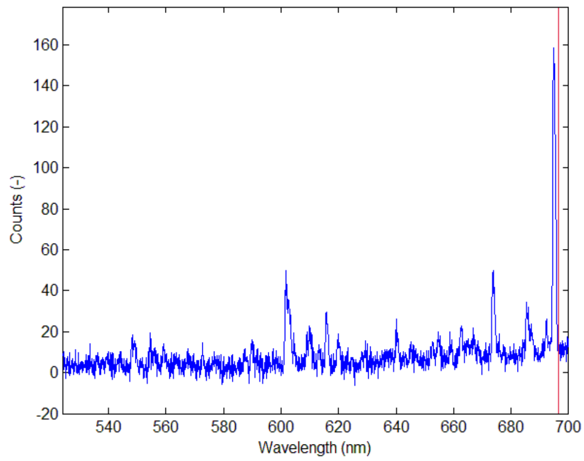

Figure 7: Argon spectrum from 523nm to 700nm, the red lines are the expected locations of argon peaks.

Looking at the helium spectrum the peaks seen in the figure match the expected values. The red lines that match are located at 447.15 nm, 501.57 nm, 587.56 nm and 667.82 nm. The only peak not clearly seen is the one at 402.62 nm. At 566.3 nm there is an unknown peak that is seen in both figures.

The argon spectrum is not as clear as the helium one and the only line that can be attributed to argon with some certainty is the line at 696.54 nm. There are peaks at 440.10 nm and 458.99 nm but they are not as representative and clear as the peaks in the helium spectrum. There are also a lot of unidentified peaks in this spectrum, but none that can be directly matched with tungsten.

Finally, comparing the figures from helium and argon, there are no unidentified peaks that can be seen in both spectra. Looking at table (1) and comparing this to the graphs also confirms that in these measurements no tungsten is found.

Investigating Doppler broadening

Another reason why the neutron counts were lower than expected could be that the velocity distribution in the plasma is lower than predicted. Using the spectrometer a relation between the voltage or power and the velocity distribution of the plasma can be found. This can be done using the broadening of the spectral lines. This effect is caused by the Doppler effect and is therefore called Doppler broadening.

When the ions inside the plasma travel relative to the camera, the frequency is Doppler shifted. When they travel towards the camera, the frequency increases and if they move in the opposite direction it decreases as shown in equation (1)

$$f = f_0\left(1 + \frac{v\cos(\theta)}{c}\right) \tag{1}$$

This causes the spectral lines to not be as sharp as they should be. The single wavelength peaks transform into a distribution centered around the spectral line. This distribution is dependent on the thermal velocity distribution of the particles. Equation (2) shows this relation written in wavelengths instead of frequencies [5]

$$\Delta\lambda_{thermal} = \lambda_0\sqrt{\frac{8\ln(2)}{mc^2}k_bT} \tag{2}$$

Here $\Delta\lambda_{thermal}$ is the full width at half maximum of the peak caused by thermal particles and k_bT is the thermal energy. Figure (8) shows the measured spectrum of the helium peak at 587.20 using the grating with 1199 lines/mm.

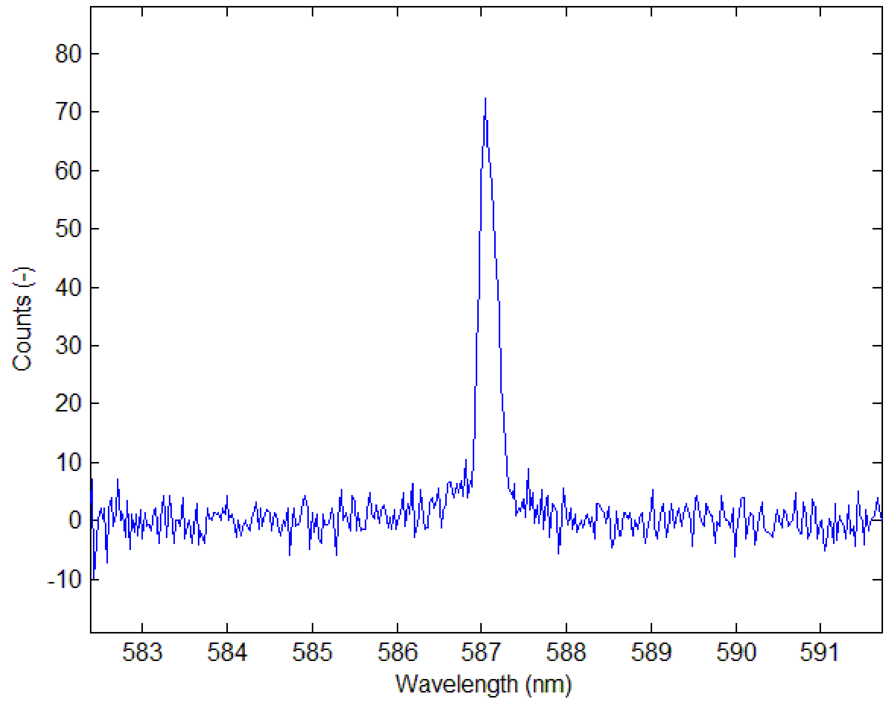

Figure 8: Helium spectrum, zoomed in on the 587.0 peak

This spectrum should be made up out of thermal particles as well as fast particles. The fast particles are expected to make the bottom of the peak much broader than the top or middle. This is only observed on a small scale compared to the thermal particles. Because of this, only the thermal part is taken into consideration in the next calculations.

Equation (3) takes the internal translational energy of the particles and assumes it is all kinetic energy.

$$\frac{3}{2}k_bT = \frac{1}{2}mv_{rms}^2 \tag{3}$$

In which v_{rms} is the root mean square velocity. Combining equations (2) and (3) grants equation (4).

$$\Delta\lambda_{thermal} = \lambda_0\sqrt{\frac{8\ln(2)v_{rms}^2}{3c^2}} \tag{4}$$

Which can be rewritten to find an expression for v_{rms} as seen in equation (5).

$$v_{rms} = \sqrt{\frac{3\Delta\lambda_{thermal}^2c^2}{8\ln(2)\lambda_0^2}} \tag{5}$$

This can be solved for the root mean squared velocity if the full width at half maximum and center of the peak are known. A Matlab script that analyses the data from the spectrometer is used find the FWHM value [6]. This value however is not caused completely by the thermal broadening. There is broadening caused by the spectrometer as well: instrumental broadening. This relation is shown in equation (6)[5].

$$\Delta\lambda_{fwhm}^2 = \Delta\lambda_{instrumental}^2 + \Delta\lambda_{thermal}^2 \tag{6}$$

Using an argon lamp which could be considered a perfectly cold light source, this instrumental broadening was found to be $0.2155 \pm 0.0006nm$ when using the grating that has 1199 lines/mm. Equation (7) now only contains known or measurable quantities and can solved for v_{rms}. The value used for λ_0 is 587.0 nm.

$$v_{rms} = \sqrt{\frac{3(\Delta\lambda_{fwhm}^2 - \Delta\lambda_{instrumental}^2)c^2}{8\ln(2)\lambda_0}} \tag{7}$$

These measurements require the conditions to be as stable as possible because the data from the spectrometer will be used together with the power and voltage from the fusor. To do this, the cycle time has been reduced to 0.01 seconds with a total run time of 5 seconds which lets the spectrometer take 500 measurements. During this time, the voltage and current of the fusor will be kept constant. After each measurement either the voltage or current will be increased. Figure (9) shows the FWHM of the helium peak plotted against the power of the fusor.

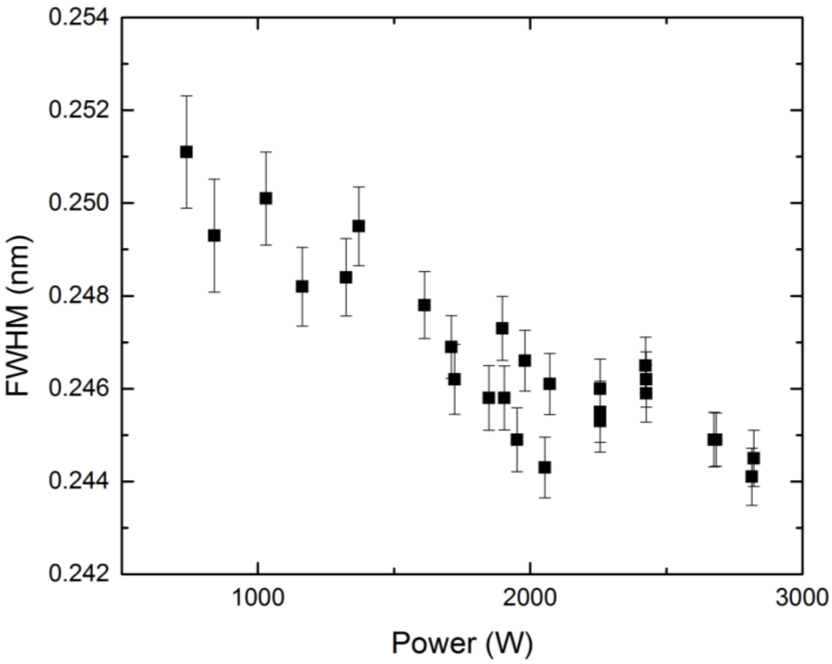

Figure 9: Power of the fusor plotted against the full width at half maximum of the helium peak at 586nm, with one-σ error bars

This data however was not collected with the current kept constant. This is because the voltage and current of the fusor cannot be varied completely independently. However, the difference in potential is the only variable that changes the electric field and thus the energy of the charged particles. This is because the helium ions are accelerated by the electric field. For this reason Figure (10) which shows only the voltage versus the FWHM.

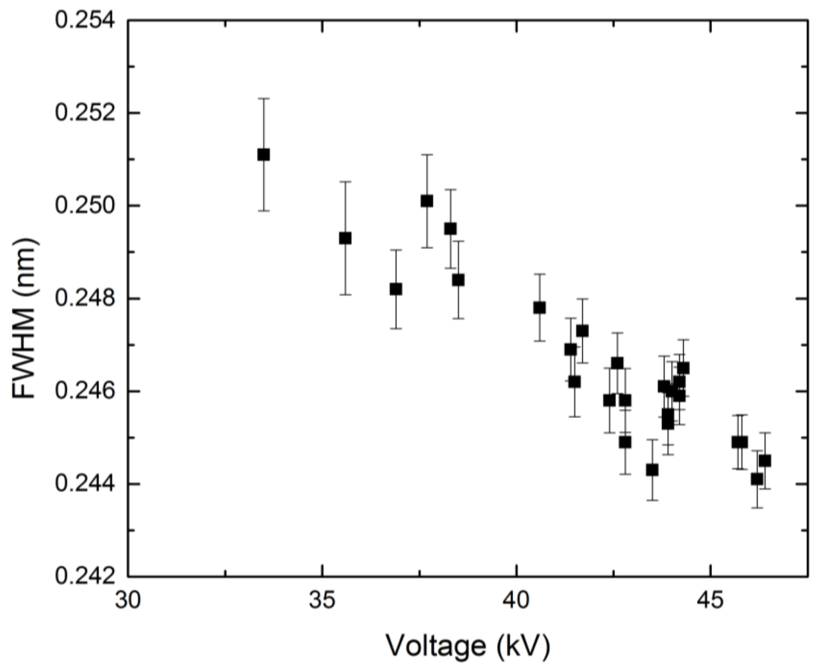

Figure 10: Voltage of the fusor plotted against the full width at half maximum of the helium peak at 586nm with one-σ error bars

Even though the graphs are not identical, the general trend is the same. Reducing the voltage (and thus the power) also reduced the FWHM of the helium peak linearly. Now using equation (7) the room mean square velocities van be calculated and plotted. No error bars are used here because the error in the instrumental broadening, which should be a constant, is dominating.

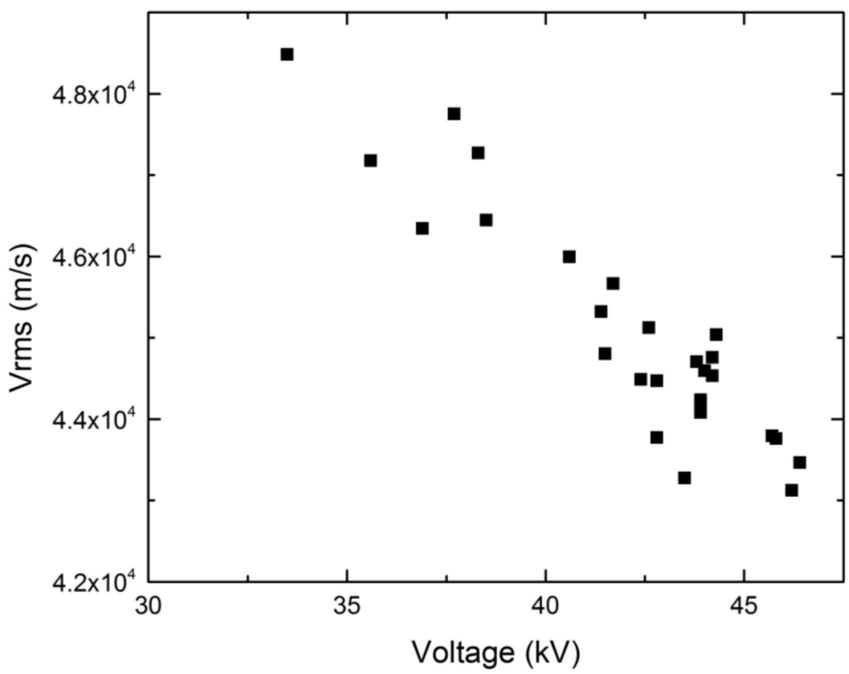

Figure 11: Voltage of the fusor plotted against the calculated root mean square velocity of the helium ions

Figure (11) shows velocities ranging from $4.3 * 10^4$ to $4.9 * 10^4\ m\ s^{-1}$. From this data the theoretical temperature could also be calculated by rewriting equation (2) into equation (8)

$$T = \frac{\left(\Delta\lambda_{fwhm}^2 - \Delta\lambda_{internal}^2\right)}{\lambda_0^2} * \frac{mc^2}{8\ln(2)k_b} \quad (8)$$

Entering the found values and rewriting them into electronvolts gives temperatures ranging from 25 to 32 eV. The temperature shows the same linear decrease when plotted against the voltage. This is shown in figure (12).

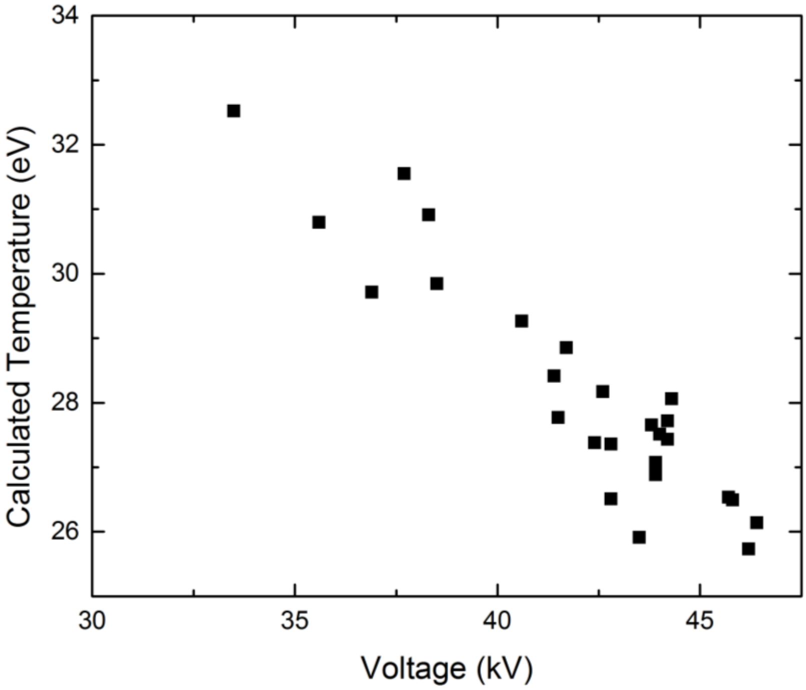

Figure 12: Voltage of the fusor plotted against the calculated root mean square velocity of the helium ions

Discussion and conclusion

Looking back at figures (4) through (7) it can be concluded that no tungsten was found in the spectrum. This could be the caused by the spectrometer not being sensitive enough around lower wavelengths, which could be why the 402.62 helium peak is not observed. Another cause could be that the tungsten is not contaminating the plasma enough to be seen in the spectrum. However there still are quite some unidentified peaks in the spectrum meaning the gas could be contaminated in another way.

Improvements on the measurements should first check the sensitivity of the spectrometer and optical fiber in the 400 nm range. This is because both the fiber and the spectrometer are only accurate with wavelengths starting at 400 nm[2]. This is the range where the most obvious tungsten peaks are to be seen.

Looking at figure (10) there is a negative correlation between the voltage of the fusor and the full width at half maximum of the peak. The root mean square velocities might be plausible, but the conversion to temperature is most likely not accurate. The motion of the ion is not purely thermal or random but also directional. This makes the calculated temperature much higher than the real temperature. The assumption made in equation (3) is therefore not completely correct.

The way the quantities are correlated is also not expected. When the voltage increases the full width at half maximum of the peak decreases. This in turn results in lower root mean square velocities which seems counterintuitive. A larger difference in potential translates into a larger electric field. The ions are charged particles and are accelerated by the electric field so a larger field would logically lead to larger velocities.

An explanation for this could be that because of the increase in potential, there are more collisions farther away from the center of the fusor. This results in more particles not being able to achieve the maximal velocity resulting in lower average velocities.

This could be further investigated by looking at where the light originates from. The temperatures could be further investigated by using a thermal camera. This eliminates the assumptions regarding purely thermal movements by the particles.

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