BACHELOR

Characterization of fusor jets

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Bachelor Thesis:

Characterization of Fusor Jets

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Abstract

This bachelor thesis is about the characterization of Fusor Jets observed at low pressures (0.5 Pa) in an inertial electrostatic confinement device at the University of Technology in Eindhoven. The mentioned jets are beams of light emitting from the center of the Fusor that appear for a certain regime, which is known as Jet mode. During the experiments an extra mode has been observed, that has been called Mini-jet mode. This mode separates the Jet mode from Star mode and causes two transitions to occur. The report treats hypotheses about both the transition from Star mode to Mini-jet mode and the transition from Mini-jet mode to Jet mode and looks at the effects of the different modes on neutron production. Furthermore it characterizes the settings for which the different modes are created.

Contents

CHAPTER 1

Introduction

With the increasing global demand for energy and the depleting stocks of fossil fuels, comes the responsibility to search for more *sustainable energy sources.* Large scaled projects based on solar-, wind- or bio-energy have proved to be pretty effective in contributing in this quest, but they will not be able to supply the total amount of energy consumed. It simply is too much.

A promising "new" technology is *Nuclear Fusion.* It is based on the nuclear reaction in which two atomic nuclei join together to form a single nucleus. This technology has been studied for decades and is finally about to get profitable. At this moment, the *ITER-project* is ongoing. The worlds largest Fusion reactor is under construction in southern France, *Cadarache.* This reactor is supposed to prove that it is possible to get a net energy profit out of nuclear fusion. If this test is successful, power plants can be designed that will supply our future generations with plenty of non-polluting energy.

Already in 1964, Philo T. Farnsworth designed an apparatus called the *Farnsworth-Hirsch Fusor.* Hopes were high that this *Fusor* would become a source of fusion power, but this has proven to be difficult. However, it has become a practical source of free neutrons, and an interesting study object for people from all over the world.

This bachelor thesis is focussed on the beams of light, the so called *Jets*, which emit from the center of the Fusor under certain circumstances. Characterizing the Fusor Jets will hopefully add to our understanding of the Fusor in general. One of the important questions will be if this *Jet Mode* of the Fusor will have a positive or negative effect on the amount of neutrons produced. Even though the Fusor probably will not be profitable, this knowledge may be used for other Fusion purposes.

CHAPTER 2

Plasma modes

As has been said, the Farnsworth-Hirsch Fusor is designed in 1964, almost fifty years ago. Since then it has been studied a lot and it has been used as a free neutron source. Most of those researches are aimed at getting more neutrons out of the Fusor and focus on using the so called *Star mode*.

2.1 Star mode

When the Fusor is activated a certain pressure is applied. By increasing the voltage until it reaches the *breakdown voltage* a plasma is created. With the used setup, this plasma is located in the center of the grid. The plasma looks like a star because it emits light through the holes of the grid, see fig. 2.1. This beams of light are caused by the geometry of the grid. Ions that move towards the grid have the possibility to fly through it, escaping through the other side. After this crossing, they will be pulled backwards and this process will repeat itself some times. The luminous effect is caused by excitation.

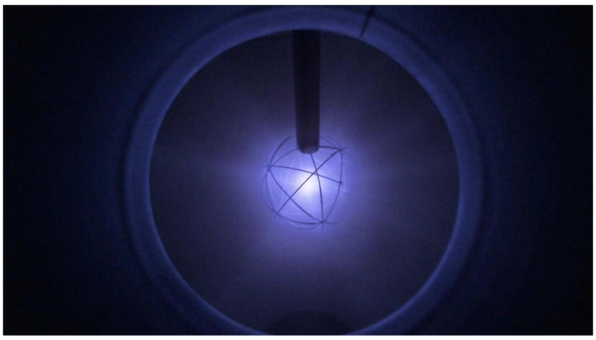

Figure 2.1: Star mode.

2.2 Jet mode

When reaching higher voltages or pressures in Star mode at some point a very bright beam of light emits from one of the holes whilst there is a bright spot in the middle. This effect is shown in fig. 2.2. It is important to know that the transition to jet mode goes accompanied by a multiplication of the current. This bachelor thesis is about the characterization of this Fusor Jet. It is further discussed in the chapter *Results and discussion*.

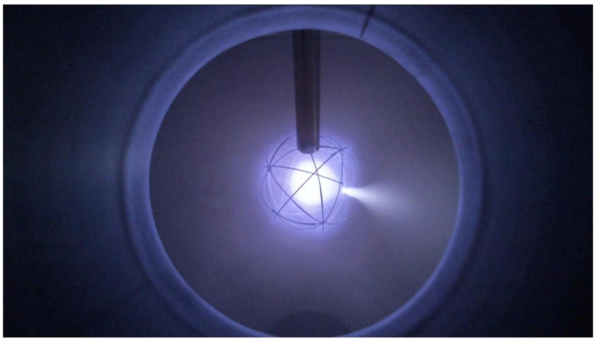

Figure 2.2: Jet mode.

2.3 Mini-jet mode

At some point between Star mode and Jet mode there is a transition mode (fig. 2.3) which exists over a small domain. It is rarely ever mentioned in literature and has only once been referred to as *Halo mode*, because of the bright halo concentric to the grid with a bright spot in the middle. This can be considered an unpretentious name though, because the mentioned halo exists for all the modes. *Mini-jet mode* might be more accurate since the bright spot in the middle appears for both Jet and Mini-jet mode and both modes emit a bright beam of light. This mode can be hard to achieve, but it gives a good insight in the transition between Star mode and Jet mode and might help to explain the origin of Jet mode.

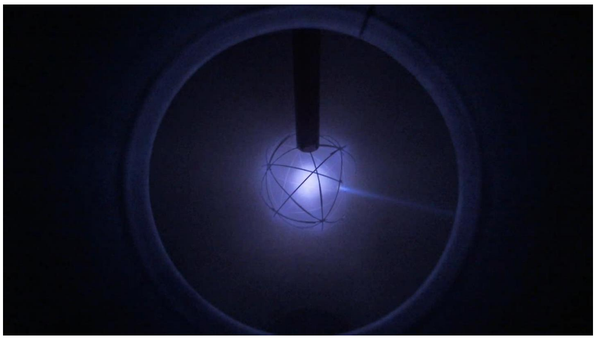

Figure 2.3: Mini-jet mode.

CHAPTER 3

Paschen's Law

The plasma in the Fusor requires a breakdown voltage before it is created, because of the fact that a certain degree of ionization is required. The ionizating collisions add extra ions and electrons to the system to maintain the discharge. The potential needed for the plasma to be created can be calculated using Paschen's Law:

$$V = \frac{apd}{ln(pd) + b}. \tag{3.1}$$

It describes the breakdown voltage V of a gas between parallel plates as a function of the pressure p in Pascal and the gap distance d in cm, with a and b constants based on the composition of the gas.

Needless to say the Fusor does not consist out of two parallel plates, but the principle still is the same. Paschen's curve therefore can be used to get an indication about the potential needed for the breakdown. It has been determined by E.C.G. Hermans [1] that for a spherical setup, the breakdown potential is indeed different than for a cylindrical setup, which is shown in fig. 3.1. The same reasoning still applies.

According to Paschen's Law the voltage needed to arc across a gap decreases as the pressure is reduced but increases gradually after reaching a minimum. The same effect occurs when changing the width of the gap. This effect is visualised in fig. 3.2.

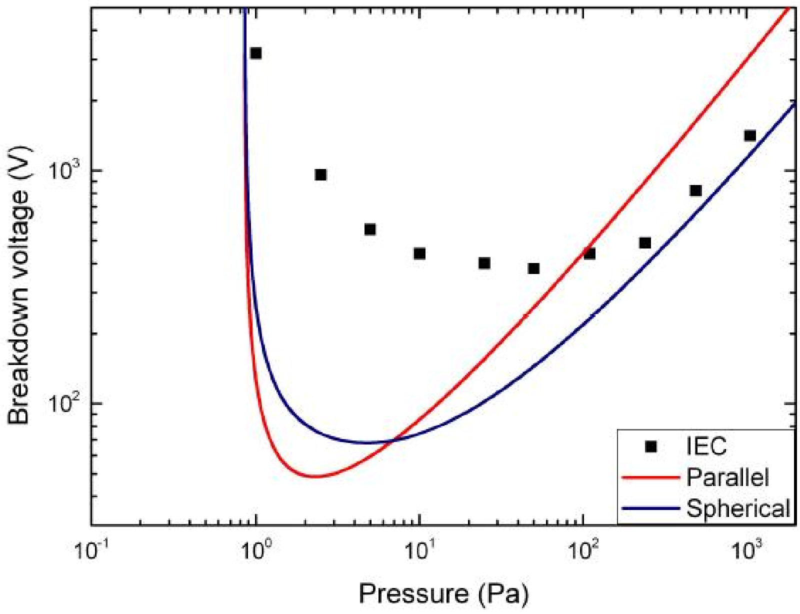

Figure 3.1: The Paschen curve for cylindrical as well as for spherical systems for hydrogen. The black squares show the Paschen curve of the Fusor [1].

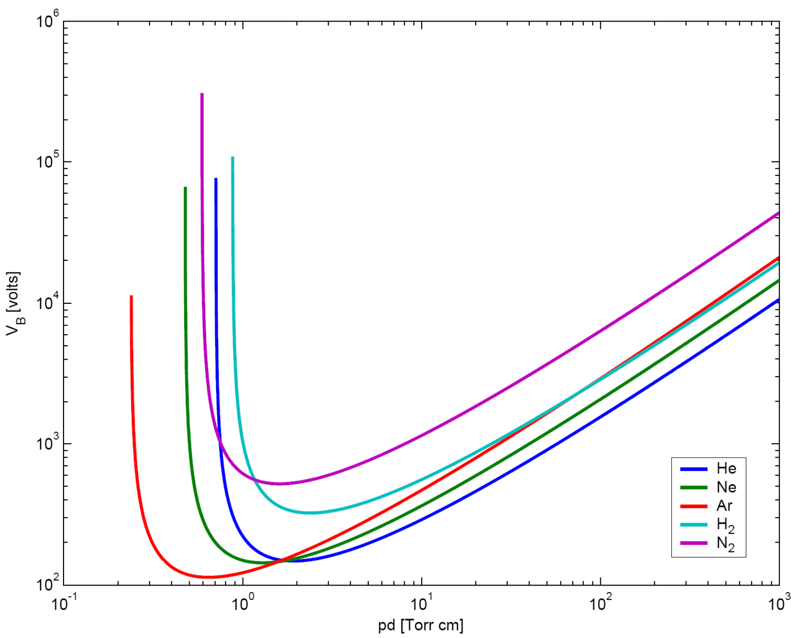

Figure 3.2: Paschen Curves. It can be seen that the breakdown voltage depends on both the gas pressure and the gap width. Also, the breakdown voltage depends on what gas is used [2].

CHAPTER 4

Electrostatics

The Farnsworth-Hirsch Fusor is based on a well known concept using an *anode* and a *cathode*. The anode is the inner surface of a spherical vacuum-vessel and the cathode is a grid of a certain shape which is positioned in the center of the sphere. When applying a negative voltage to the cathode while keeping the anode grounded, electrons are pulled towards the anode and ions are attracted in the direction of the grid. For this research, the grid is spherical, but consists of nine circular wires welded together. To get more insight in the forces acting on the particles in the Fusor some information about electrostatics is required.

4.1 Electric Field & Potential

As a start the equation for the *electric field* caused by applying a voltage to the cathode is given by

$$\vec{E} = \frac{1}{4\pi\epsilon_0}\frac{Q}{\vec{r}^2} \tag{4.1}$$

in which Q is the charge on the grid and ϵ_0 and π are constants. The field lines are in the radial direction. The electric field is related to the *electric potential* according to

$$\vec{E} = -\nabla V \tag{4.2}$$

which is mainly useful because it is more easy to visualize the electric potential than the electric field. The electric potential can be calculated with the equation

$$V = \frac{1}{4\pi\epsilon_0}\frac{Q}{r}. \tag{4.3}$$

These equations are pretty straight-forward, but it would be a tremendous amount of work to calculate the electric potential for every position by hand. Therefore COMSOL Multiphysics® is used to create 3D-models of the electric potential in the Fusor.

4.2 COMSOL Modelling

To be able to compare the electric potential field of a solid sphere grid and the 9-wired grid, two models have been made using COMSOL Multiphysics®.

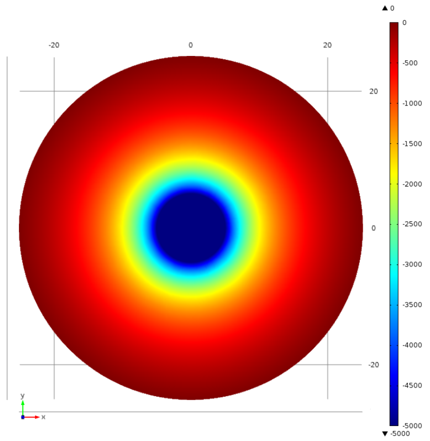

Figure 4.1: Electric potential (V) of a solid sphere

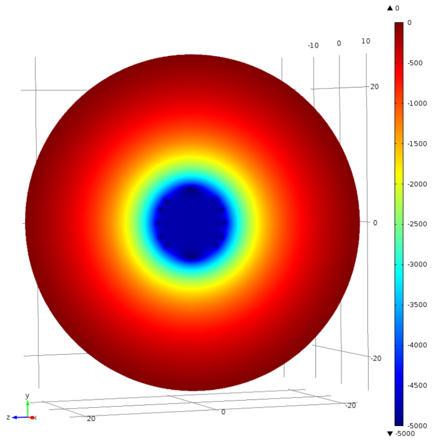

Figure 4.2: Electric potential (V) of the 9-wired grid

Both electric potential fields are similar when looking outside of the grid. Only when getting really close to the grid the field differs. This results in the fact that ions attracted towards the grid experience an electric field as if the cathode was a solid sphere.

It is good to know that the shape of the grid does not affect the electric potential field outside of the grid really much. For the research on the Fusor jets, however, it is even more important to know what the changes are inside the grid. To study the field of the interior of the grid, the range of the electric potential has to be adapted. In fig. 4.3 the voltage range is set from -5000 V to -4700 V. This gives a better look at the potential field within the grid. An important thing about fig. 4.3 is the fact that the potential is pretty constant in the center. This is more easily visible in fig. 4.4, which shows the potential on a line from the center to a point 5 cm outside of the grid. Difference has been made between a path which crosses the gridline and a path that is directed through a hole in the grid.

Besides the fact that the potential is constant in the center, fig. 4.4 also shows that the electric potential on a path through a hole is monotonically increasing. This is an interesting result, since its consequence is that electrons created in the center would be able to escape through a random hole without encountering a potential barrier. Which might be true for Star mode, but in Jet mode a preference is definitely visible. This preference will be further discussed in the chapter *Results and discussion*.

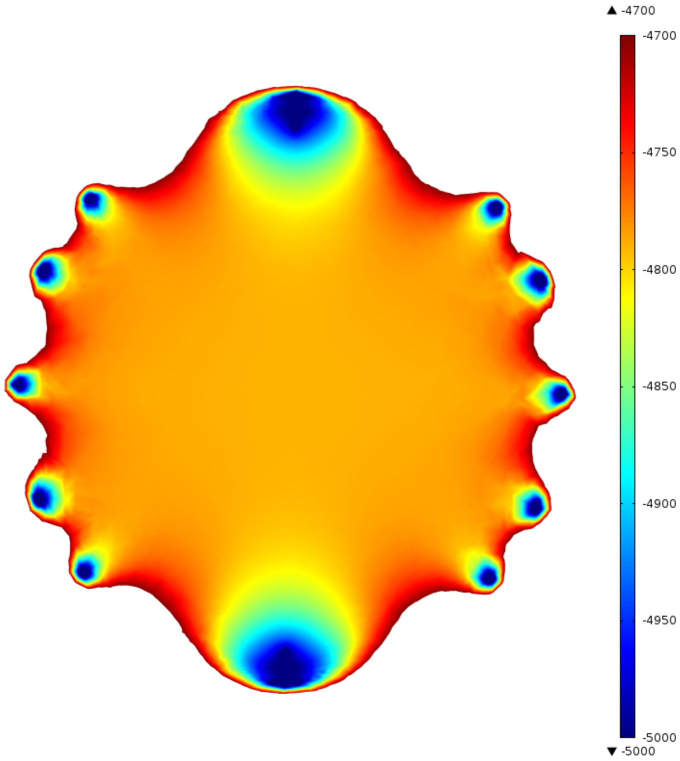

Figure 4.3: Electric Potential (V) within the grid

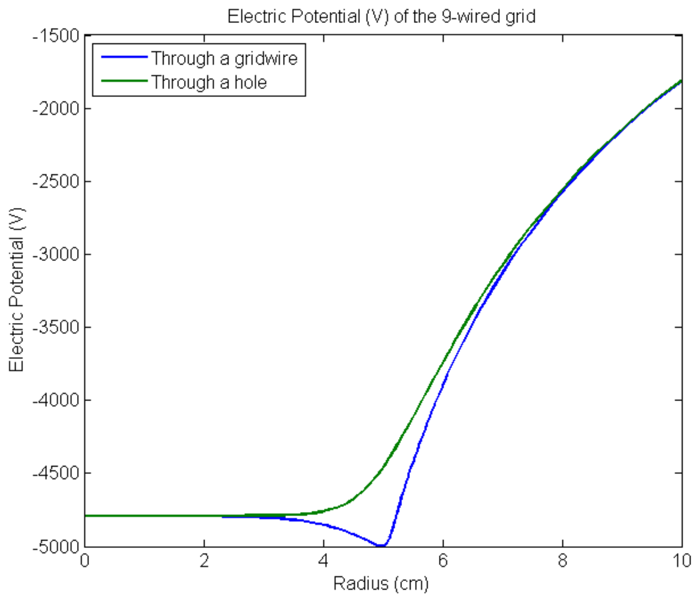

Figure 4.4: Line graph of the electric potential in- and outside of the grid(V)

CHAPTER 5

Collisions and interactions

The performance of the Fusor depends on both the pressure in the vessel and the applied electric potential difference. An increase in pressure will result in more particles to collide with, whereas a change in the potential difference affects the probability of the different kinds of collisions. Both the particle density and the energies are required to find the average paths travelled through the Fusor.

5.1 Cross Sections

The strong potential difference calculated in chapter 4, enables the ions and electrons to acquire a lot of energy. This results in very fast moving particles which occasionally collide with background particles or with each other. Dependent on the amount of energy, different kinds of collisions occur, as is shown in fig. 5.1 for argon and in fig. 5.2 for hydrogen. The experiments for this thesis are performed with argon, but the cross sections of hydrogen are also shown. This has been done because other measurements on the Fusor have been done with hydrogen and this enables comparison.

In these graphs, the chance on a collision is expressed as an effective cross section which depends on the size of the particle, its energy and the kind of collision it will have. It is important to notice that the chances of charge exchange and momentum transfer are dominant in the working domain 0 - 10 keV. This results in the fact that many ions are slowed down or changed in direction before they would undergo an ionizing collision. Although, by increasing the voltage applied to the cathode, more ions are able to obtain a higher ion energy, which results in a higher probability of ionisating collisions. Furthermore, the increased cross section of excitation makes the Fusor shine brighter.

For this thesis, the probability of ionisating collisions is most important, since it is responsible for the amount of electrons created in the center.

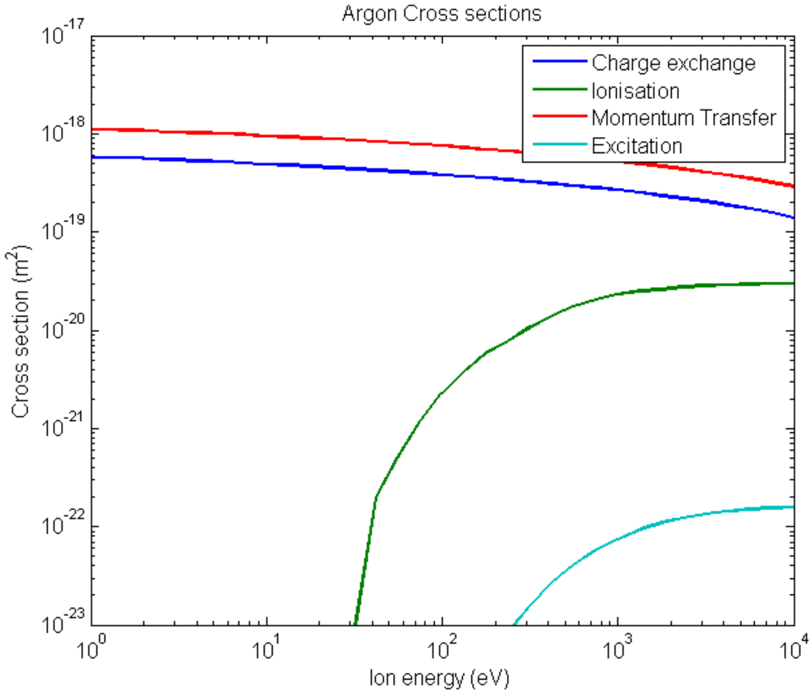

Figure 5.1: Cross sections of the most important collisions of Ar^+ with Ar.

The effective cross section enables a comparison of the probabilities of the collisions. However, it is even more comprehensible if the cross section is used in order to determine the *mean free path* of the particles. The mean free path is used to express the length of the path a particle travels before it collides. This distance depends on the particle density n and the cross sections σ and is more easy to compare with system measurements. It is given by

$$\lambda = \frac{1}{\sigma n}. \tag{5.1}$$

The required cross sections are shown in fig. 5.1 and fig. 5.2, but for the amount of atoms per m^3 some more calculations need to be done.

5.2 Particle density

The molar density of atoms in a gas with a certain pressure is given by

$$n_{molar} = \frac{p}{k_B T} \tag{5.2}$$

in which p is the pressure in Pascal, T the temperature of the background gas in Kelvin (300 K) and k_B the constant of Boltzmann.

Since the molar volume of an ideal gas V_{molar} is 24.465 L at room temperature and the volume of a cubic meter V_{m^3} is 1000 L, the amount of atoms per m^3 is given by

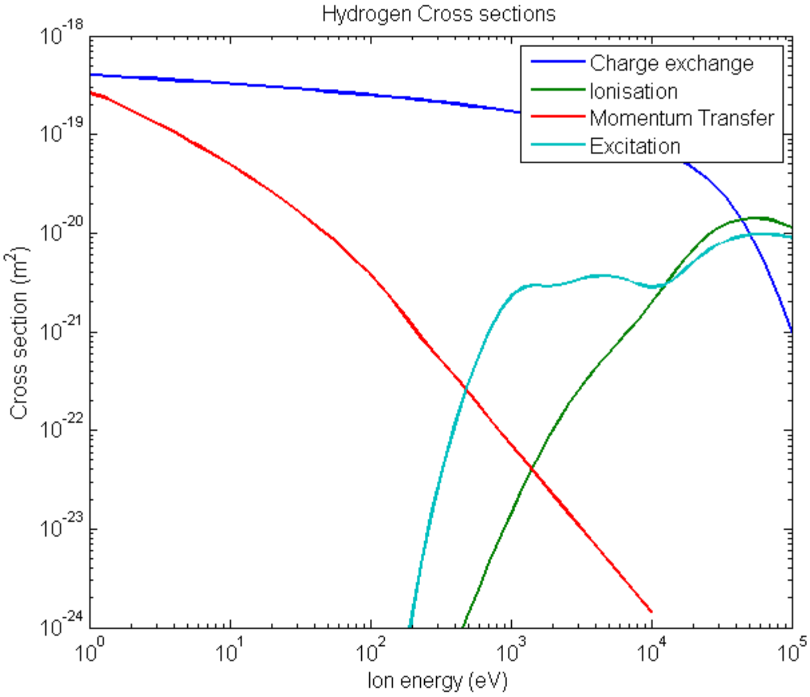

Figure 5.2: Cross sections of the most important collisions of H^+ with H_2.

$$n_{m^3} = n_{molar} \cdot \frac{V_{m^3}}{V_{molar}} \tag{5.3}$$

which results in

$$n_{m^3} = 9.87 \cdot 10^{21} \cdot p. \tag{5.4}$$

This equation can be used to calculate the amount of particles per m^3 for a certain pressure, which can then be used to plot a graph of the mean free path using eq. (5.1). The mean free paths for ions at a pressure of 0.5 Pa are shown in fig. 5.3. The mean free paths of the $Ar^+ - Ar$ and $e^- - Ar$ ionizating collisions are also shown for different pressures at the end of this chapter. They are shown in fig. 5.4 and fig. 5.5 and will be used in the chapter *Results and discussion*.

5.3 Grid collisions

The basic idea of the Farnsworth-Hirsch Fusor is that many ions will not collide with the grid because it has a physical transparency of 93%. This transparency allows ions to fly through the center of the Fusor until they pass the other side of the grid and are pulled back inwards. This process will repeat itself a couple of times and according to literature by *Robert L. Hirsch* [3], an average ion in the Fusor will travel 6.9 times through the grid.

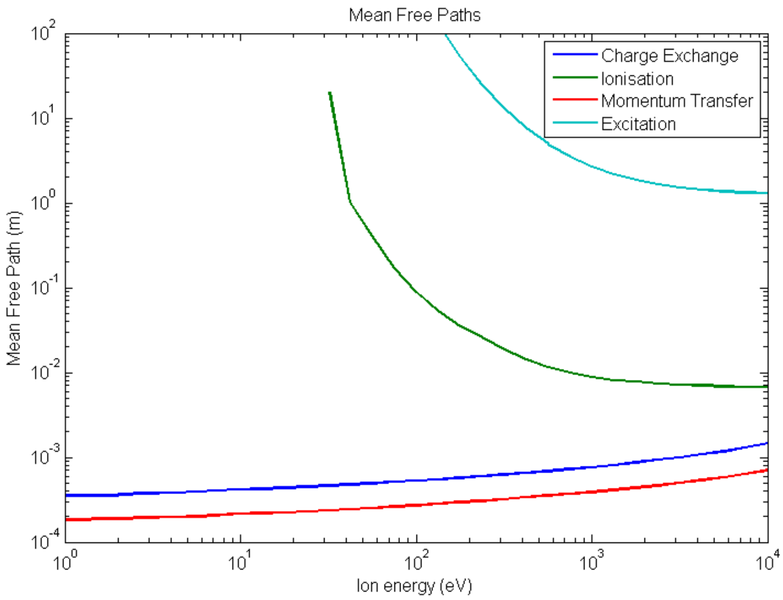

Figure 5.3: The mean free paths of the different kind of collisions of Ar^+ with Ar at a pressure of 0.5 Pa.

The reasoning behind this number is that the electric field of the 9-wired grid is pretty similar to the electric field of a solid sphere. Therefore ions that reach the grid have a 93% chance to advance towards its center. The same number applies for exiting the grid, due to the high amount of charge exchange and momentum transfer collisions, which adapt their direction.[1] Taking I_g as the current to the grid and ν as the transparency of the grid, the ions that reach the center are given by

$$I_c = \nu I_g + \nu^3 I_g + \nu^5 I_g + ..., \tag{5.5}$$

$$I_c = I_g \sum \nu^{2n+1}. \tag{5.6}$$

The sum of this geometric progression is known and the number of trips an average ion makes to the center is defined as the ratio of I_c and I_g:

$$\delta = \frac{I_c}{I_g} = \frac{\nu}{1-\nu^2}. \tag{5.7}$$

Which is, for a transparency of 93%, equal to 6.9. [3]

[1] If the directions would not be altered by these collisions, the average amount of trips would be much higher, since the holes are positioned opposite each other.

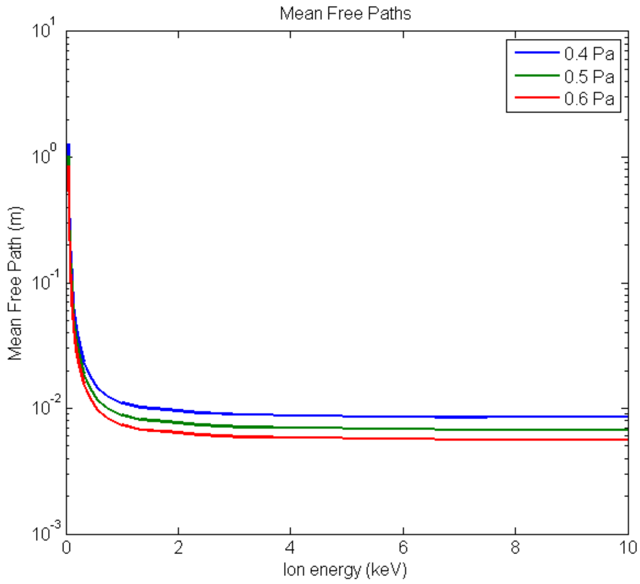

Figure 5.4: The mean free paths of the $Ar^+ - Ar$ collisions for the pressures 0.4, 0.5 and 0.6 Pa.

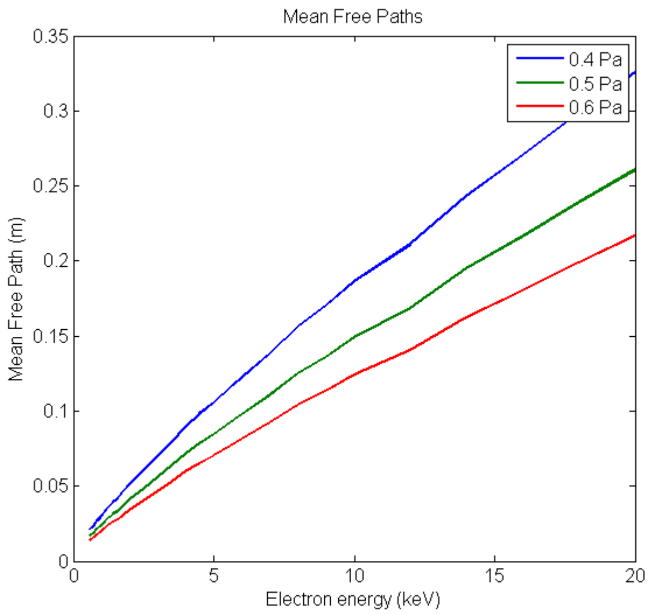

Figure 5.5: The mean free paths of the $e^- - Ar$ collisions for the pressures 0.4, 0.5 and 0.6 Pa.

CHAPTER 6

Space Charge

All the electrons and ions moving through the system are respectively negatively and positively charged. This has several effects on the space charge, and also on the electric field, in the Fusor. One important difference between electrons and ions is their mass. Electrons are much lighter than ions so they are accelerated much faster. This mainly causes the *electric glow discharge* to separate in different columns.

6.1 Glow discharge

The mentioned electric glow discharge is the plasma that is formed by the passage of the electric current through the low-pressure gas in the Fusor, when the voltage is above the breakdown voltage. This current is carried by the electrons and the ions in the system. In Mini-jet mode different columns are observed. Those columns are known to appear at glow discharges but were not earlier witnessed in the Fusor. For a cylindrical setup the columns are shown in fig. 6.1.

The columns observed in the Fusor are: C, the *Cathode Dark Space*, D, the *Negative Glow* and F, the *Positive Column*. The other columns will also exist, but they are difficult to distinguish. The three observed regions will be discussed in more detail.

Cathode Dark Space

From the regions mentioned, the Cathode Dark Space is closest to the cathode. It has a strong electric field which accelerates the electrons in the direction of the Negative Glow and the ions towards the cathode. Electrons move away from this region much faster because of the mass difference so the space charge is mainly positive. Since most electrons do not have enough energy for ionization and excitation yet, it is a relatively dark zone. Because the fact that this region possesses almost the entire potential difference, it is also called 'cathode fall'.

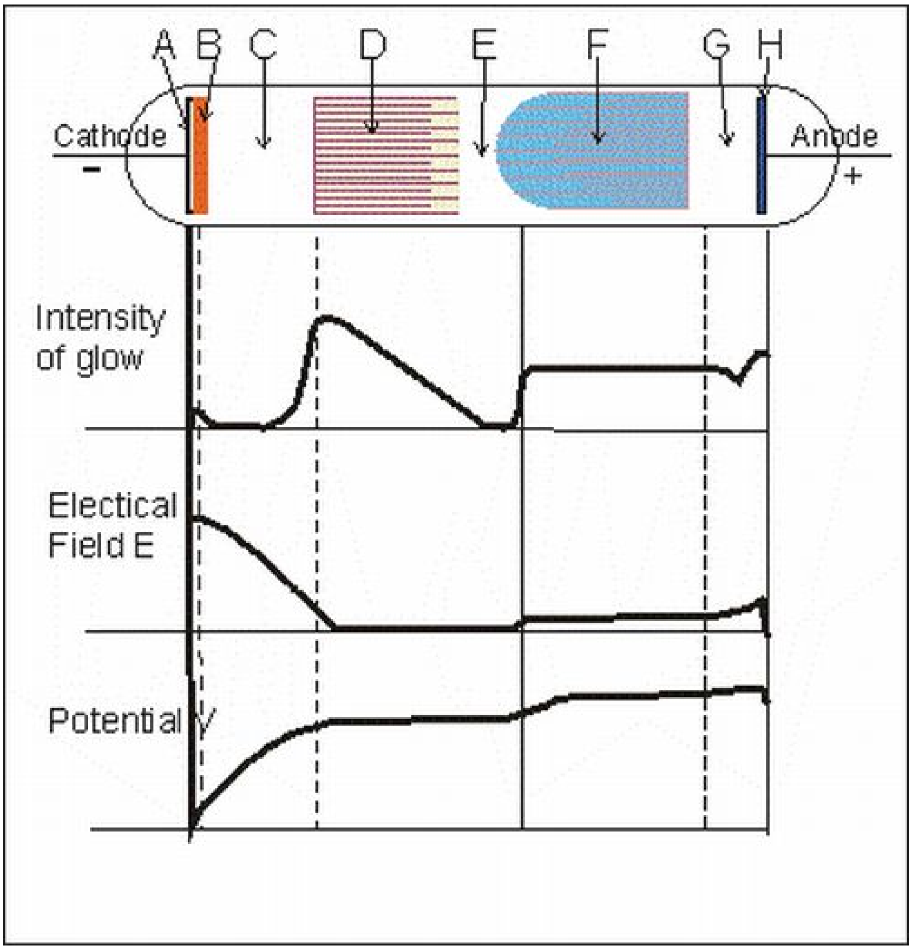

Figure 6.1: Glow Discharge for cylindrical setup.

Negative Glow

This column has the brightest intensity of all the zones. The electrons accelerated to high speeds in the Cathode Dark Space produce ionization and the slower electrons that have had inelastic collisions produce excitation. Because of the equal amount of charge carriers its space charge is neutral, although the current is mostly carried by the electrons since they have a higher mobility.

Positive Column

The Positive Column is less bright than the Negative Glow because it has a small electric field. This field gives electrons just enough energy to maintain the degree of ionization to reach the anode. The Positive Column is the region that expands when the length of the discharge tube, or the radius of the sphere, is enlarged. In the spherical setup, the positive column also exists around the Negative Glow.

CHAPTER 7

Experimental Setup

This bachelor thesis is based on measurements performed on the TU/e Fusor, an inertial electrostatic confinement device designed and built by E.C.G. Hermans [1]. A schematic drawing of the used setup is shown in fig. 7.1.

7.1 Fusor Setup

As can be seen, the Fusor setup consists of several parts, namely the vacuum system, the cathode grid, the gas inlet, the diagnostics and the power supply. First of all, the vacuum vessel with the grid inside is shown in fig. 7.2.

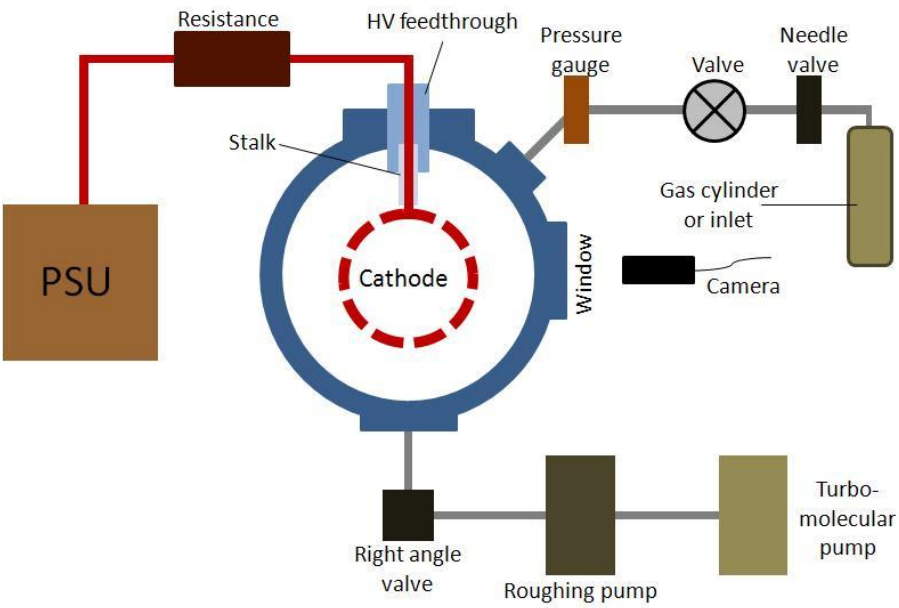

Figure 7.1: A schematic drawing of the used IEC setup. [1]

Figure 7.2: A picture of the vacuum vessel with the grid inside. The pump also can be seen at the bottom of the picture.

Vacuum system

The vacuum system is required to get the gas in the the vessel at a low pressure. The pump that has been used is a HiCube 80 Eco, which is capable of creating a pressure smaller than 10^{-5} Pa.

Gas Inlet

In combination with the vacuum pump, a stable pressure can be achieved by allowing a certain amount of gas to enter the vessel. The gas is let into the system by a Pfeiffer EVN 116 gas dosing valve. For this thesis, argon has been put into the vessel.

To be able to determine the pressure in the vessel, a pressure gauge has been used, which has been placed between the gas inlet and the vacuum vessel. The gauge is an active hot cathode transmitter IMR 265 from Pfeiffer, with a pressure range of 2×10^{-4} to 10^{6} Pa. The repeatability is 2% between 10^{-3} and 10 Pa. The signal of the gauge is connected to a TPG 26 DualGauge™ controller readout to display the pressure.

Cathode Grid

The cathode grid is created out of 9-circular nickel wires welded together. They form a spherical grid, as is shown in fig. 7.3. The performance of the Fusor depends on the shape and the size of the grid. More research has to be done to determine what kind of grid is the best. Some adaptations have been investigated in the chapter *Results and discussion*.

Figure 7.3: The regular grid. 9 circular wires welded together to form a spherical grid.

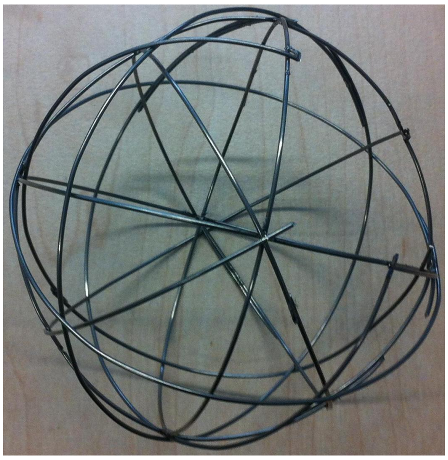

Figure 7.4: The adapted grid. One octant is removed in order to create an assymetric grid with a large hole.

For reasons which will be mentioned later on, one adapted grid has been created. This grid is a copy of the regular grid, but in this case one octant is removed. A picture of this grid is shown in fig. 7.4.

Diagnostics

Besides the pressure gauge that can be used to determine the pressure in the vessel, a Logitech C525 HD web camera is installed. This camera is used to make pictures and movies of the plasma. For working at higher potentials, it is even required because of the safety distance that has to be taken into account.

Power Supply

To apply a high voltage to the grid a power supply from FuG Elektronik has been used. With the model HCN 700-12500, a maximum potential of 12.5 kV can be applied. A resistance of 60 kis added in order to stabilize the gas discharge. Because of the small currents the voltage drop over the resistance is small.The potential of 12.5 kV is enough for the measurements required for this bachelor thesis. However, in order to create fusion reactions, a stronger power supply must be used. A description of this stronger power supply as well as more information about the other devices is treated in the master thesis by E.C.G. Hermans [1].

CHAPTER 8

Results and discussion

It has been seen in the theoretical part of this thesis that the performance of the Fusor depends on numerous variables. The same goes for the behaviour of the Fusor Jet. Whether or not a Jet is created depends on the pressure in the vessel, the ion- and electron energies, the space charge distribution and the shape and the symmetry of the grid. To be able to distinguish the effects caused by the several variables they are all inspected individually.

8.1 Grid Adaptation

The electric field in the Fusor depends on the shape of the grid, so it is important to take a closer look at it. Many shapes are possible, but a spherical symmetry seems to be important, due to the ions oscillating through the grid. With COMSOL Multiphysics®, several possibilities have been modelled. By varying the size of the grid, several graphs have been made which are shown in fig. 8.1.

From fig. 8.1 it can be seen that increasing the radius of the grid affects the potential in the center of the grid and the slope of the electric potential outside the grid. Instead of changing the radius, the amount of wires also can be changed. Therefore, three different grids are constructed with three, five and nine wires and their electric potential is shown in fig. 8.2.

The center potentials that can be drawn from fig. 8.1 are shown in table 8.1, together with the radius, the transparency and the amount of trips an average ion makes through the center. Same can be done for the data from fig. 8.2. This data is shown in table 8.2.

It is hard to draw conclusions from table 8.1 and table 8.2 because by increasing the transparency, and thus increasing the amount of trips an average ion makes, the voltage in the center increases. This will result in a weaker electric field and ions with less energy.

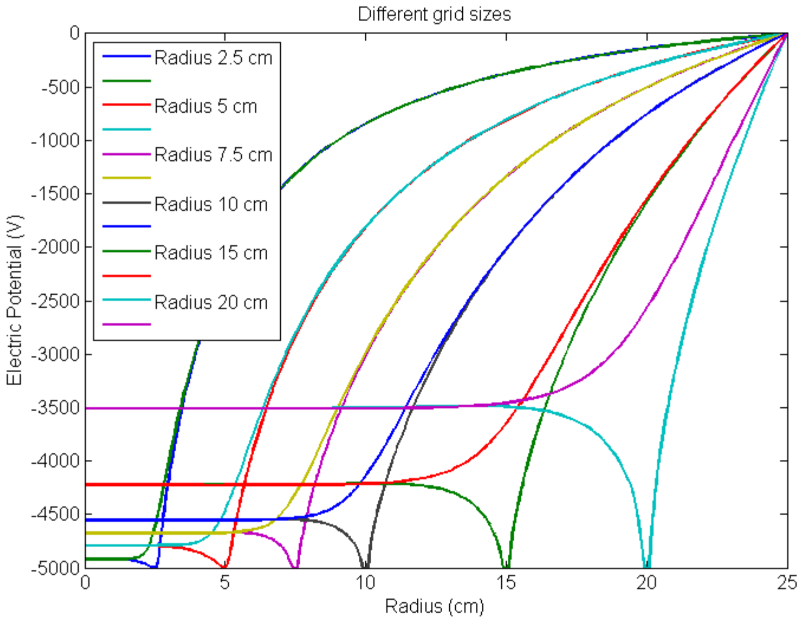

Figure 8.1: Changing the radius of the grid changes the electric potential. The lines that reach -5000 V are paths that cross a wire at the grids radius. The lines that are monotonically increasing pass through the center of a hole.

Radius	Center potential	Transparency	Ion trips
(cm)	(V)	(%)	(#)
2.5	-4918	86.5	3.44
5	-4790	93.25	7.15
7.5	-4679	93.5	10.86
10	-4556	96.625	14.56
15	-4225	97.75	21.97
20	-3511	98.3125	29.38

Table 8.1: Data of grids with different radiuses. All grids exist out of 9 wires.

Amount of wires	Center potential	Transparency	Ion trips
(#)	(V)	(%)	(#)
3	-3956	97.75	21.97
5	-4451	96.25	13.08
9	-4790	93.25	7.15

Table 8.2: Data of grids with 3, 5, or 9 wires. The radius is 5 cm for all grids.

Both the amount of trips an average ion makes and the energy it gets contribute to the amount of Fusion collisions that occur, therefore an optimum should be found. This optimum should be a grid with a high transparency and a center potential that is close to the grid potential.

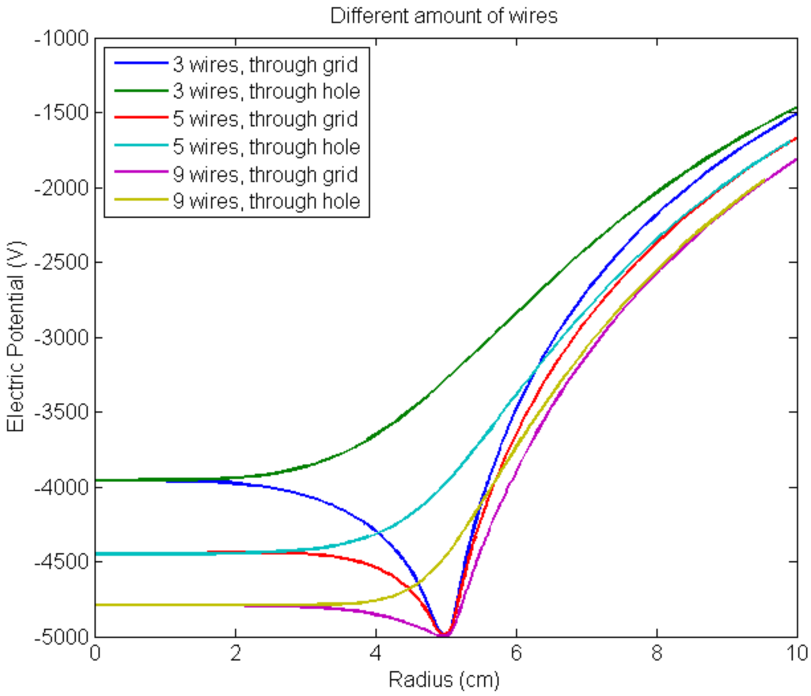

Figure 8.2: By changing the amount of wires, the transparency of the grid changes. This influences the electric potential created by the grid.

8.2 Fusor Characteristics

Another important part of understanding the Fusor is knowing when a plasma will be created. This depends on the voltage applied to the cathode, the pressure in the vacuum vessel and the gas used, as is shown in eq. (3.1). The distance between the anode and the cathode is kept constant. Several measurements have been performed to acquire information about the breakdown voltage of the Fusor, as a function of the pressure. This is shown in fig. 8.3.

It has been tried to create a fit through the data by using Paschens law, but it was unsuccesful for some reasons. Firstly, Paschen's law as shown in eq. (3.1) is based on a cylindrical system rather than a spherical setup. It has been determined by E.C.G. Hermans [1] that the breakdown voltage for a spherical geometry is higher than for a spherical geometry. Besides that, the domain of the dataset is so small it only describes a small part of the Paschen Curve which makes the fit less accurate, especially because of the uncertainties in the pressure.

Jet Mode

To find out for which circumstances Jet mode occurs the same kind of experiment has been performed. Further increasing the potential or the pressure

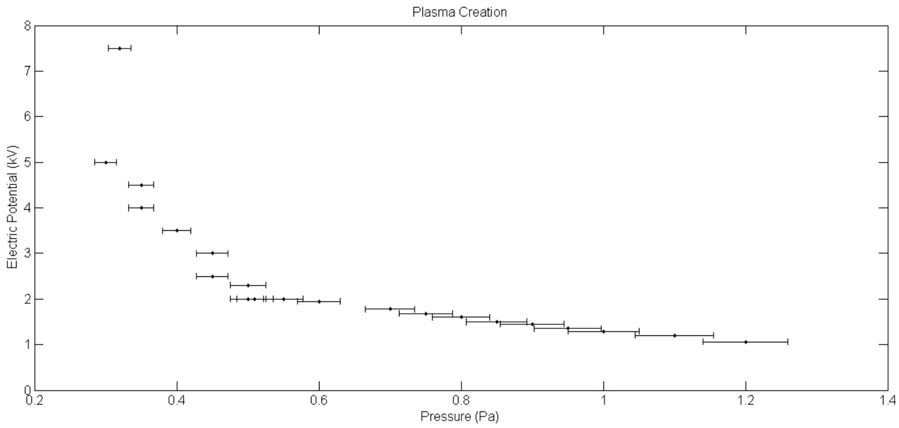

Figure 8.3: The creation of a plasma in the Fusor. The dots show the values for which the plasma is created or fades out. The error-bars are horizontal because the errors in the electric potential are negligible. The deviation in the pressure is approximately 5% of its value.

results in a transition from Star mode to Jet mode. The transition results in a brighter plasma and a multiplication of the current. By gathering information about when this transition occurs it might be possible to figure out why it happens. The combined data is shown in fig. 8.4.

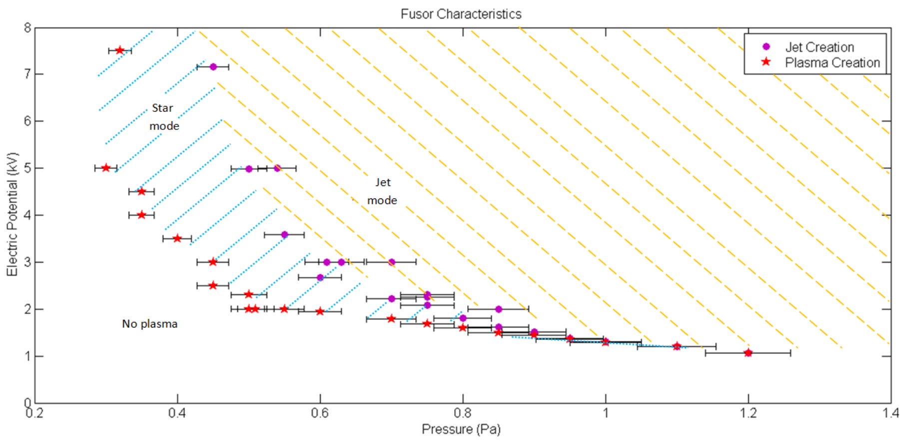

Figure 8.4: Measurements on the mode-transitions of the Fusor. The areas for which the Fusor is in Star- or Jet mode are shaded. It is important to keep in mind that Star mode goes accomponied by a mini-jet for most settings in this specific regime.

Several conclusions can be drawn from fig. 8.4. First of all, Jet mode can be reached by either increasing the potential or the pressure. Although, the deviation needed for a transition depends on the settings. For low pressures, at the left side of fig. 8.4, a big increase in potential is possible before Jet mode takes place. Although, a relatively small change in the pressure also realizes this transformation. On the other hand, when working at higher pressures at the right side of the graph, a slight increase in potential will cause jets. In this case it is the pressure that can be alternated a lot without changing the mode.

After characterizing the circumstances for which Jet mode occurs, the reason why a jet emits from a certain hole has been inspected. In COMSOL Multiphysics® an adapted grid has been modellated. The grid is the same as the one used for fig. 4.2, but with one octant removed (fig. 8.5). This way one hole is a lot bigger than the others, which makes it an exaggerated version of the not perfectly symmetric grid used before. The effect of this change on the electric potential is shown in fig. 8.6.

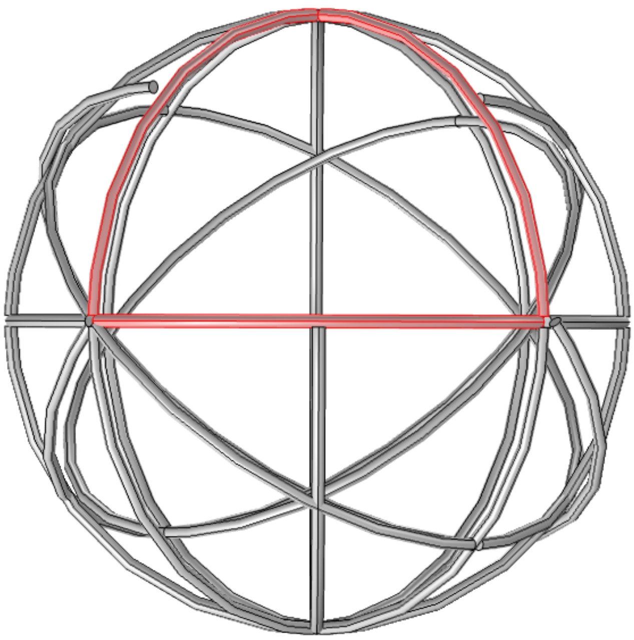

Figure 8.5: The adapted grid. To make the hole more easily visible, its edges have been shaded red.

In fig. 8.6 it can be seen that the asymmetric grid has a big influence on the potential inside the grid. The potential at a large hole is much more positive than at a small hole. An experiment has been performed to check if this change in potential would cause the jet to come out of the large hole. The adapted grid has been constructed and put in the Fusor. As expected, the jet emits through the largest hole, as is shown in fig. 8.7.

It is important to know that, due to the highest potential, the jet only occurs at the largest hole. But it is still unknown why the jet appears at all.

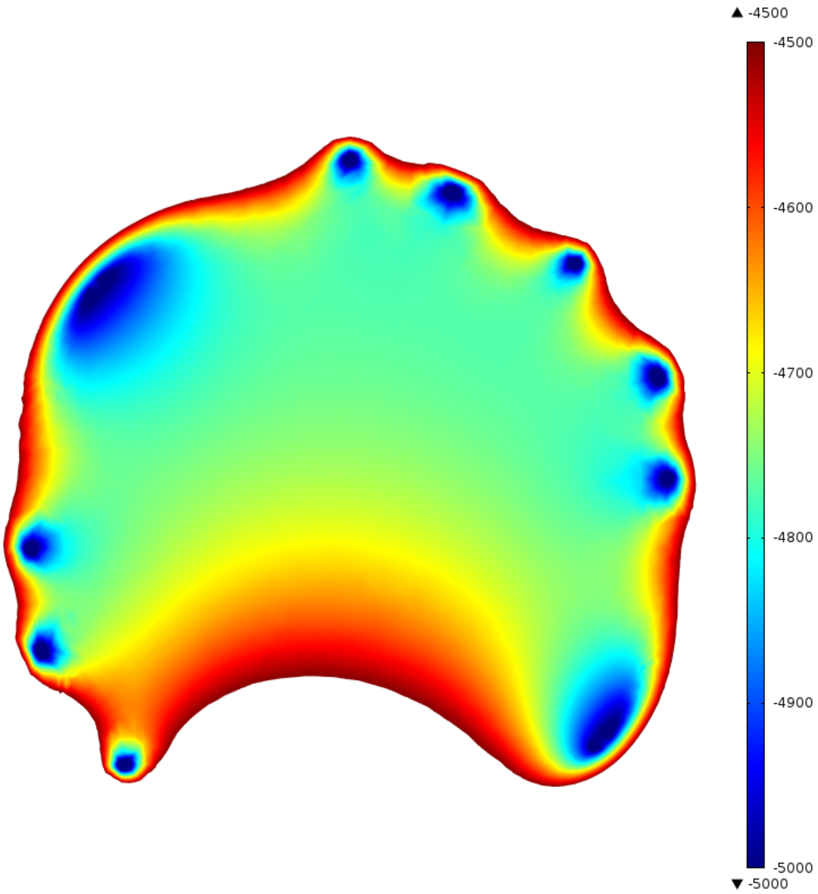

Figure 8.6: Electric potential (V) within the adapted grid

8.3 Potential Hill

By looking at fig. 4.4, you can see that the electric potential is monotonically increasing on a path through any hole. This should result in the fact that electrons which are created in the center of the grid are directed through all holes. This is in contrary to what actually happens in Jet mode, where a single jet is seen. But it should be kept in mind that fig. 4.4 is based on vacuum, so it ignores space charge. In the article *Convergence, electrostatic potential, and density measurements in a spherically convergent ion focus* [4], the authors have measured the electric potential in the center of their grid using high-voltage electrostatic probes. They found that due to a high ion density in the center, an equilibrium will be formed at which the potential in the center is higher than it would be in the model. See fig. 8.8.

This result means that the electrons created in the center are trapped by the *potential hill* and that they must overcome a certain potential difference before they can escape through a hole. This potential difference is determined by the

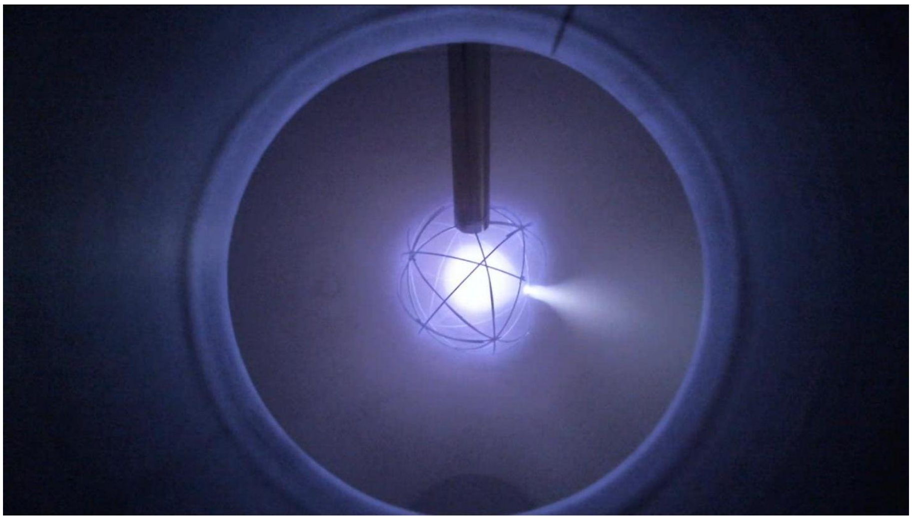

Figure 8.7: Jet mode: the electrons escape through the largest hole

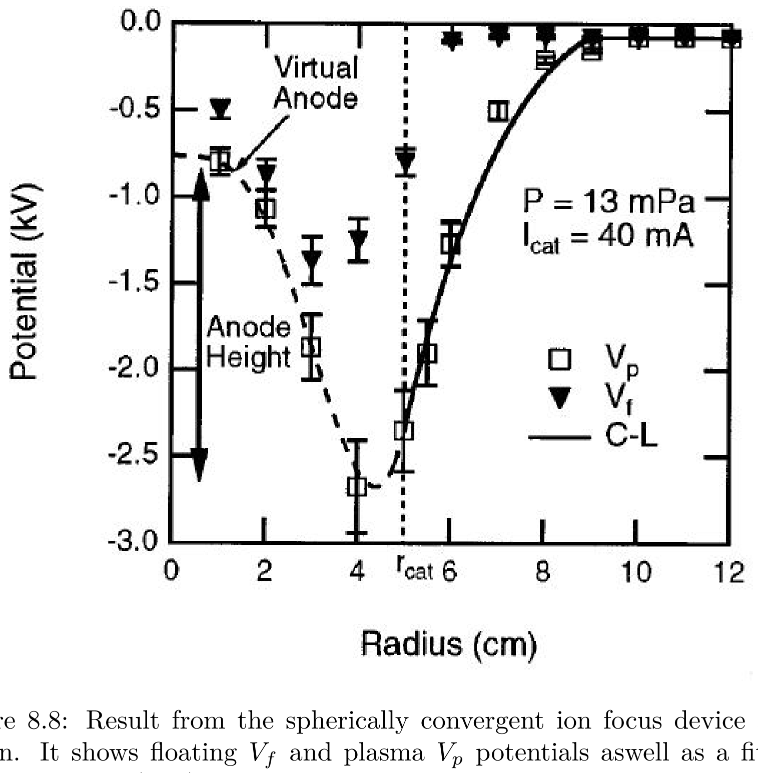

Figure 8.8: Result from the spherically convergent ion focus device at Wisconsin. It shows floating V_f and plasma V_p potentials aswell as a fit of the Child-Langmuir (C-L) potential distribution outside of the grid. For the study of jets, it is most important to notice that there exists a big potential hill for low background pressures. [4]

electric potential in the center and the potential at the largest hole, since this brings about the easiest escape. Whether or not an electron can overcome this potential difference depends on the energy it has.

Center potential

The potential in the center is determined by the ratio of ions and electrons present. The fact that most of the electrons in the center originate from ionizating collisions from ions with atoms, will result in a lower ion/electron ratio when more of those collisions occur. This frequency depends on the pressure and the energy of the ions, so it can thus be said that the change in center potential caused by the space charge depends on the pressure and on the potential applied to the grid.

Pressure effects

The experiments executed by Thorson, Durst, Fonck and Wainwright [4] were performed at a low pressure hydrogen gas ($\leq$53 mPa) and they measured a high center potential whilst B.E.N. Spijkers' [5] measurements on hydrogen of a higher pressure (0.3 Pa) indicate a much lower center potential. The emissive probe measurements by M.G. Ham [6] also report a low center potential for a high pressure (1.4 Pa). These two independent measurements make it very acceptable that the center potential gets lower for higher pressures, resulting in a smaller potential difference. This hypothesis indicates that Jet mode is more easily accesible at higher pressures, which agrees with the results from fig. 8.4.

Potential effects

Increasing the ion energy by applying a higher potential to the grid would result in a bigger cross section for ionisating collisions and in electrons with a higher energy. The first result would make the potential hill smaller and the second one affects the ability of electrons to escape. The hypothesis therefore states that increasing the grid potential, also causes Jet mode to occur. This also matches the results from fig. 8.4.

To verify these hypotheses and to describe these effects quantitatively, more research is required. Comments and remarks about this research are treated in the chapter *Conclusions*.

8.4 Mini-jet mode

Until now, not much attention has been given to Mini-jet mode. It does not show in fig. 8.4 because of its small domain of existence and the vague transition from Star to Mini-jet mode, although the transitition from Mini-jet mode to Jet mode is very important and highly informative.

In the former section the transition from Star mode to Jet mode has been characterized. What has been left out so far, however, is that for most settings in this specific regime the Star mode actually changes into Mini-jet mode first.

The fact that electrons are able to escape without being in Jet mode requires a revision of the hypotheses. It means that the asserted hypotheses about the transition from Star- to Jet mode do not directly apply to this transition, but they do in fact describe the transition from Star mode to Mini-jet mode. The same ideas still apply.

By stating that the hypotheses only declare the mini-jets, an other explanation of the transformation into Jet mode must be found. Research about this hypothesis is treated in the next section.

8.5 Jet Mode Transition

It has to been taken into account that even though the hypotheses do not directly apply to Jet mode, the escaping electrons still are the cause of both Mini-jet mode and Jet mode. Having this said, it is time to take a closer look at the transition from the mini-jet to the jet in fig. 8.9 - fig. 8.12.

Figure 8.9: Pressure: 0.4 Pa. Full Mini-jet mode. Plasma created at 0.3 Pa. Measurements at 5 kV.

Figure 8.10: Pressure: 0.5 Pa. Mini-jet broadens from a certain point. Front visible.

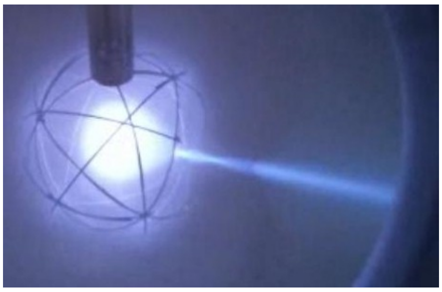

Figure 8.11: Pressure: 0.55 Pa. The front is getting closer to the grid.

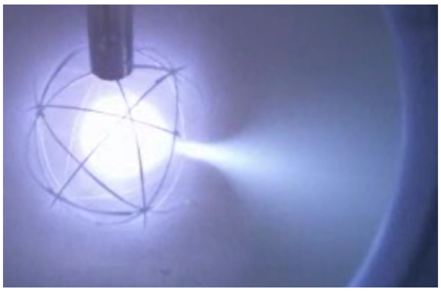

Figure 8.12: Pressure: 0.6 Pa. Full Jet mode. Front reached the grid.

An interesting effect shows in fig. 8.10 and fig. 8.11. Instead of having a regular mini-jet or jet the pictures show a combination of both. There seems to be a reason for the electrons to start spreading instead of staying confined. The visible front can be compared to the glow discharge fronts caused by the space charge, which are discussed in the chapter *Space Charge*.

At the position of the mini-jet a special glow discharge occurs. Instead of electrons coming from the grid, it is based on the electrons escaping from the center. The point where they escape the potential hill can be seen as a virtual cathode. The electrons moving from this virtual cathode to the anode start to create a glow discharge by increasing the electron density at the anode and thus changing the plasma potential. The local potential will change into the potential shown in fig. 6.1. The plasma will be much brighter than anywhere else outside of the grid due to the large amount of electrons.

The visible front may be compared to the Negative Glow. The electrons are accelerated in the dark zone and start ionizing at the front. The position of the front is thus determined by the mean free path of the electrons. The mean free paths are shown in fig. 5.5. The slow electrons that remain from the collisions drift towards to the anode in a random direction, because of the weak field in the Negative Glow. Some of those electrons do gain enough energy to be able to excitate or ionize atoms on their way.

The ions created at the collisions slowly move towards the grid until they are accelerated in the dark zone. Most of them pass towards the center and contribute to the production of electrons. The mean free paths of the ion ionization impact collisions are shown in fig. 5.4.

At a certain moment, the mean free paths of both the $e^- - Ar$ and the $Ar^+ - Ar$ ionizating collisions are small enough to cause ionization at a rate which starts a chain reaction. Due to this chain reaction a new equilibrium is set, which is known as Jet mode.

This is only a qualitative description of the process that explains Jet mode. To find the exact mean free paths required for the breakdown into Jet mode more research is required.

8.6 Neutron Production

After characterizing the jets, it now is time to look at the effects on neutron production. In order to create fusion reactions, deuterium has to be used instead of argon. The potential applied to the cathode has a big effect on the amount of fusion collisions. This is caused by the fact that in order to obtain as much D^+-D^+ reactions as possible the ion energies should be around 100 keV, because the fusion cross sections are relatively large for these energies. Another condition that affects neutron production, is the pressure. It must be low enough for ions to be able to obtain their maximum energy, but a decrease in pressure also reduces the amount of ions in the system. Therefore an optimal pressure should be found that results in the maximum neutron production.

These conditions also affect the Fusor modes, so the effects of the different plasma modes on neutron production are discussed in this section.

Star mode

Taking the conditions into account, one might say that Star mode is not the best mode for neutron production. This is caused by the fact that according to fig. 8.8, a low pressure Star mode plasma has a high center potential. This potential hill slows down ions crossing the center of the Fusor, resulting in relatively slow ions in the center, where the ion density is the highest. In order to have lots of fusion reactions, it is important that the ions have a high energy at positions of high ion density.

Mini-jet mode

Mini-jet mode might be a better solution. The grid will still be able to withstand the temperatures it reaches because of the current flowing through the system. The advantage of Mini-jet mode in respect of Star mode, however, is that the potential hill is smaller. This results in faster ions and thus in more neutrons.

There is only one problem with Mini-jet mode. It is not expected to exist for the settings required for fusion collisions. This is caused by the fact that as soon as electrons will be able to escape from the potential hill in the center, Jet mode instantly will take place due to the high potential.

Even though Mini-jet mode might not exist, it is still profitable to increase the pressure towards the boundary between Star- and Jet mode so that the potential hill gets as small as possible.

Jet mode

Jet mode might be an interesting mode for neutron production, since its current is much higher than the current in Star mode. The current depends on the amount of ions and electrons in the system, and an increase of the amount of ions will result in an increase of the neutron production. However, the problem with Jet mode is that the increase in current also increases the temperature of the grid.

The grid that is currently used is constructed from nickel, which melts at a temperature of 1728 K. Therefore it can not withstand the currents caused by Jet mode. By creating a grid out of tungsten, which only melts for temperatures above 3695 K, it will be possible to make use of Jet mode.

When it will be decided to use Jet mode for neutron production, it should be taken into account that the jet might have a big impact on the space charge within the Fusor. More research is required to determine what the effects of Jet mode on the plasma potential are and if it will still be possible to create neutrons using Jet mode.

CHAPTER 9

Conclusions

Experiments on the IEC device, that has been recently constructed at the University of Technology in Eindhoven, have shown that it operates in three different modes, namely Star mode, Jet mode and Mini-jet mode. The objective of this bachelor thesis was to characterize the Fusor Jets which appeared at Jet mode in order to increase the understanding of the Fusor.

During the process of characterizing the Fusor, the third mentioned mode, called Mini-jet mode, has been discovered. This mode has a small domain of existence but is very informative. Its presence alone already causes the transition from Star- to Jet mode to be split into two parts. The first part is based on the possibility of the electrons to escape from the center, whereas the second part describes the sudden broadening of the mini-jet into a jet. Two hypotheses have been formed to declare both transitions.

The first hypothesis states that the transition from Star- to Mini-jet mode depends on the potentiall hill at the center of the grid. This potential hill is caused by the high ion density at the center and traps the electrons that are formed by the ionizating collisions. Measurements performed at the University of Wisconsin as well as measurements performed at the University of Technology in Eindhoven have showed that the height of the potential hill depends on the pressure. For low pressures there is a big potential hill, whilst relatively high pressures are accomponied by a small potential hill. The decrease of the height of the potential hill reduces the electron energy required to escape from the center. Therefore a mini-jet will be formed for certain potentials and pressures. In order to validate and quantify the changing center potential the measurements performed by B.E.N. Spijkers [5] should be repeated for lower pressures.

The reason a mini-jet changes into a jet so suddenly is declared by the second hypothesis. During the experiments fronts have been observed which have been compared with glow discharge regions. The brightest front is caused by the ionizating $e^- - Ar$ collisions and is quite similar to the Negative Glow which appears in a regular glow discharge. It has been observed that the front shifts closer towards the grid when either the pressure or the potential is increased. Therefore it has been said that the position of the front depends on the mean free paths of ionization by electrons, which are in the order of centimeters and depend on the pressure in the vessel. Every ionizating collision creates an extra ion and electron which in their turn are able to ionize the background gas if the mean free paths are short enough. The hypothesis thus states that Jet mode is created by a chain reaction of ionizating collisions which is able to occur at certain breakdown settings. Although, in order to validate and quantify these effects, more research is required.

The last part of this bachelor thesis reports on the effect of the different modes on neutron production. The amount of neutrons produced is determined by the amount of fusion reactions that occur so it is a good indication of the quality of the Fusor. Until now, neutrons only have been produced by using Star mode, since it is accompanied by the smallest current, and thus by the least production of heat. The problem of Star mode, however, is that the ions do not get their maximum speed because of the potential hill in the center. For Mini-jet mode, this potential hill is smaller and therefore it might be a better solution. But, the problem with Mini-jet mode is that it does not exist for the required settings, since electrons escaping from the center will instantly cause Jet mode. Lucky enough, increasing the pressure within Star mode also decreases the height of the potential hill, so some improvement can still be made without needing Mini-jet mode.

With the current grid, Jet mode will not be an option for fusion, since the heat produced at a high potential will destroy the grid. A grid created out of tungsten, should be able to withstand the heat and would thus enable the use of Jet mode for fusion. It is expected that when the maximum neutron production rate is reached within Star mode, a multiplication of the neutron production can still be achieved by switching to Jet mode. This expectation is based on the fact that the transition towards Jet mode is accomponied by a multiplication of the current, which is a measure for the amount of ions and electrons in the system. Due to this big improvement, creating a new grid is definitely worth the while.

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